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Biogeochemical feedbacks in the climate system: from processes to large-scale effects

BIOFEEDBACK

Final report:

BIOFEEDBACK – Biogeochemical feedbacks in the climate system: from processes to large-scale effects
SKD Strategic Project July 2011 – June 2015

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I. Main objectives

BIOFEEDBACK aimed to quantify biogeochemical feedbacks to climate change and rising atmospheric CO_2, founded on the best understanding of the key governing processes combined with IPCC type climate projections. BIOFEEDBACK evaluated monitoring network design, to provide recommendations for the future observing strategy in order to best detect biogeochemical changes and the respective climate feedbacks.

II. State of the art and rationale

It is evident that the climate system interacts with biogeochemical Earth system reservoirs. Future climate change will therefore affect global biogeochemical cycles through changing the magnitude and variability of sources and sinks of major GHGs, in turn this will feedback on the climate system. However, in climate projections in the 4^{th} IPCC assessment report of Working Group I (Denman et al., 2007), only coupled physical ocean-atmosphere-sea ice models were used, driven by *prescribed concentrations* of greenhouse gases. In order to also take into account biogeochemical feedbacks in future climate projections, Earth system models (ESMs) have been developed. These ESMs can be more realistically forced by *prescribed emissions* of greenhouse gases (Friedlingstein et al., 2006; Tjiputra et al., 2010).

While sensitivity experiments with biogeochemical general circulation models (Friedlingstein et al., 2006) as well as process studies (Riebesell et al., 2007) show the potential importance of biogeochemical feedbacks to climate change and rising CO_2, there is still no consensus on the strength of these. Presently, there is no generally accepted set of state variables or equations to describe these causalities and increasing model complexity does not always lead to a better model-data comparison (Arhonditis and Brett, 2004).

From the ocean side, improved representation of the rate, regionality and variability of biogeochemical change can only be founded on the very best, yet limited, experimental evidence and ocean observations. Rudimentary model parameterisations can be developed and their skill assessed through a comparison of observed and simulated tracer distributions (Stow et al., 2009; Assmann et al., 2010; Kriest et al., 2010). There have been great advances on open-access databases (e.g. Pfeil et al., 2013; Key et al., 2010) that allow for this. For the terrestrial realm, further research is needed in order to quantify the soil carbon dynamics with climate change, the coupling between nutrient cycles and carbon uptake under climate change, and the role of wetlands/permafrost.

BIOFEEDBACK was structured into four work packages. WP1 identified relevant processes, their parameterisations and collated observations on biogeochemical tracers. WP2 implemented the processes in models and optimised them with respect to observations by adjusting the free model parameters. The validated/optimised models were then used in scenarios of the past (last 200 years), present, and future (coming few centuries), upscaling the processes to the regional and global scale in WP3. Finally, WP4 evaluated the current observational network and provides strategies for the earliest determination of whether the feedbacks are occurring or not.

III. Results

WP1: Identification of relevant biogeochemical processes from observations

Goal: Comparative analysis to define model parameterizations for key processes

1.1. Key processes identification (lead: C. Heinze)

A workshop was organized at GFI on November 22, 2011. The goal of the meeting was: *identification of processes for parameterisation (WP1) and implementation in models (WP2),* realised by determining: *which* feedback processes are the most important ones, *which* data sets are available as a basis for defining model evaluation, and *which* processes can realistically be included in the available models (if they are not already there). A large number of feedbacks were identified, followed by a discussion on their importance and on the available expertise within the project. Table 1 summarizes selected processes with their potential feedback signs. A more detailed and extended table (incl. feedback strength, evidence, etc.) is available in D1.1 report.

Forcing		***Associated feedback process***	***+/-***
OCEAN	Changes in ocean circulation: upwelling and ventilation	Biological prod. and its efficiency, org. C accumulation and change in nutrient	-
		Changes in stoichiometry Si:N and rain ratio $CaCO_3$:POC	-
		Changes in DMS emissions	?
	Ocean warming	Change in CO_2 solubility and buffer factor	+/-
		Mobilisation of CH_4 gas hydrates from continental shelf, but unclear if increasing or not	+
		Changes to phytoplankton metabolism	?
	Ocean acidification and dust delivery under changing climate	Change in bio-calcification and nutrient uptake kinetics	-
		Changes in ballast and stickiness	+
		Change in stoichiometry, carbon overconsumption, $CaCO_3$ sediment dissolution	-
		Change in Fe (and other nutrient supply) and biological production	?
LAND	Surface temperature increase, precipitation, evaporation, and permafrost melting	Vegetation albedo	+
		Chemical, physical, and biological weathering	-
		Soil organic carbon accumulation and degradation	+
		CH_4 release from wetlands	+

Table 1. *Selected climate forcing change and its associated biogeochemical feedback processes and signs*

1.2. Translation to model formulation (lead: J. Tjiputra)

Following the workshop, prioritisation of processes to be further pursued and up-scaled was discussed within the group. One of the potentially largest climate feedbacks is the change in Redfield ratio. However, due to the overall uncertainties associated with this process due to lack of observational evidence we decided not to pursue this option. We identified the following processes to be potentially important and feasible to be implemented in the Earth system model framework:

i) *Parameterization of the particulate organic carbon (POC) export*, crucial for the strength of the biological-mediated ocean carbon uptake. The POC parameterization in NorESM was too simple and represented by a single particle size with constant sinking and remineralization rates; this could also cause an oxygen bias in the ocean interior of the model.

ii) *Interactive marine-atmosphere emissions of DMS (Dimethyl Sulphate)*, which is the largest natural source of atmospheric gaseous sulphur. Once released and oxidized, the sulphate particles act as cloud condensation nuclei and alter the atmospheric radiative balance. Previously, marine DMS emissions were prescribed in NorESM on the basis of climatological data, hence no climate feedback was possible.

iii) *Terrestrial methane emissions*, which is important for climate feedback in high-latitude regions. The current NorESM model does not yet take into account methane emissions. This would be implemented and tested in the upgraded CLM model coming into NorESM2.

1.3. Progress in data synthesis (lead: A. Olsen, B. Pfeil)

A collation of observational data sets and data syntheses for evaluation of global and regional models was produced. The database includes surface and deep carbon observations and related tracers. The former was mainly obtained underway from voluntary observing ships (VOS), research vessels, buoys, and moorings. The Bjerknes Centre took a leading role in organizing the international quality control efforts. As a result, the Surface Ocean CO_2 Atlas (SOCAT) data compilation was officially released in 2012 (e.g., Pfeil et al., 2013; www.socat.into). Fig. 1 illustrates the spatial data coverage of SOCAT with regions where a full seasonal cycle observation is now available. The deep carbon observations were collated into the data product GLODAPv2 (Olsen et al., in prep). This includes observations from 800 research cruises, which have been subjected to consistency analyses and bias corrected whenever required and warranted. Fig. 2 illustrates the data coverage in GLODAPv2. In addition to carbon, GLODAPv2 includes temperature, salinity, oxygen, nutrients and many more biogeochemical tracers.

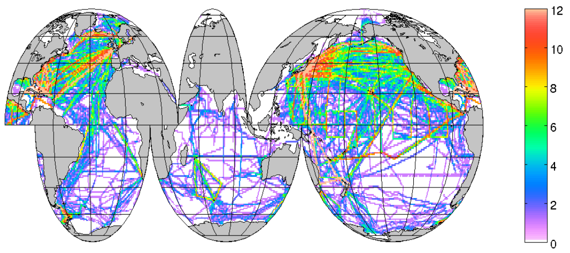


Figure 1. Spatial distribution of gridded fCO2 observations from 1970 to 2011 in SOCAT (adopted from Bakker et al., 2014). Colour shades represent the number of unique months available

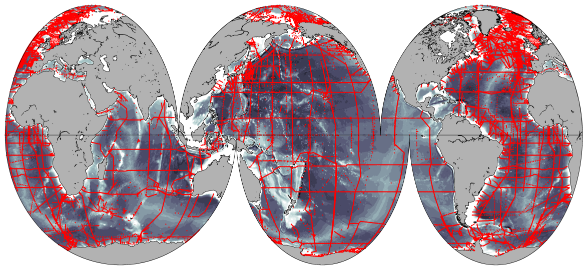


Figure 2. Spatial distribution of hydrographic stations included in GLODAPv2

WP2: Mathematical formulation of process and parameter optimization

Goal: To derive concise but realistic process description to be implemented in models

2.1. Implementation of new POC flux parameterization (lead: J. Schwinger)

For the improvement in POC export representation, the "Kriest" parameterization (Kriest and Evans, 1999) was selected. This distinguishes different particle sizes and prognostically estimates the sinking speeds. Two spin-up simulations ("REF" and "Kriest" schemes) were carried out to evaluate the performance.

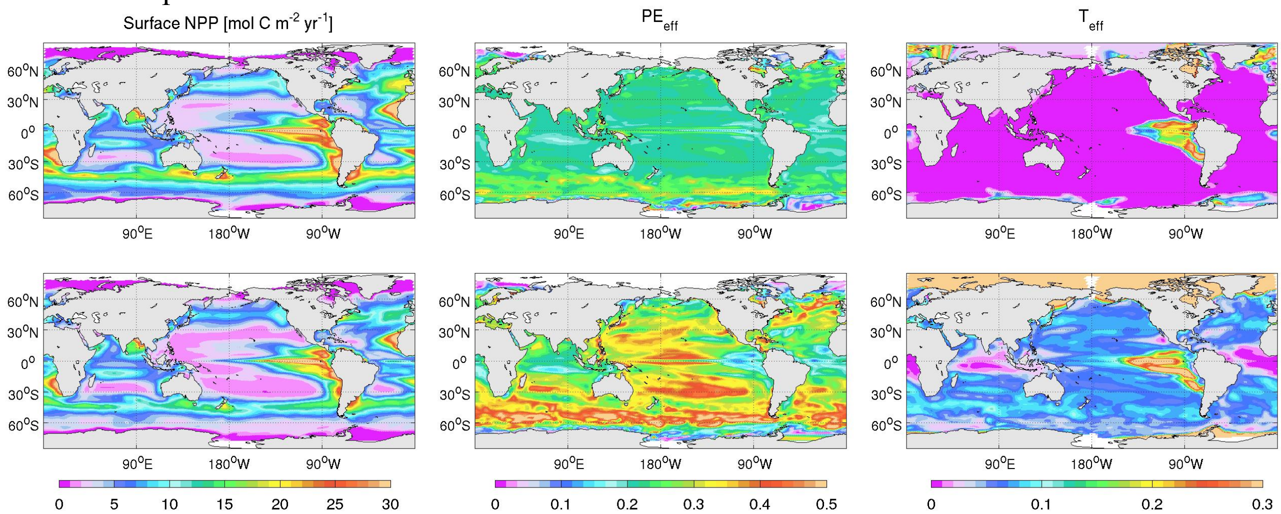


Figure 3. Maps of simulated pre-industrial (1st column) surface net primary production, (2nd column) particle export efficiency (PE_{eff}), and (3rd column) transfer efficiency (T_{eff}). Shown are results from (top) *REF* and (bottom) *KRIEST* schemes.

Both schemes produced global net annual primary production within the observational estimates of

35 and 29 Pg C yr^{-1}, with similar spatial patterns (Fig. 3, 1st column). Nevertheless, the '*export efficiency*' ($PE_{eff} = POC_{z100}/NPP$, Fig. 3, 2nd column) in the *Kriest* scheme shows more spatial variability. The '*transfer efficiency*' ($T_{eff} = POC_{z2000}/POC_{z100}$, Fig. 3, 3rd column) reveals that most of the POC in *REF* does not reach the sea floor. With the new '*Kriest*' scheme stronger sinking speed at depth allows more POC to descend below 2000 m. This leads to less consumption of dissolved oxygen at intermediate depth and, importantly, removes the low bias in deep equatorial Pacific and Atlantic oxygen in the *REF* simulation (not shown here).

2.2. Implementation of interactive marine DMS emissions (lead: J. Tjiputra)

In order to introduce the climate feedback associated with marine DMS, a processed-based marine DMS module in HAMOCC model was activated (Six and Maier-Reimer, 2006), tuned, and tested within the coupled model configuration. The DMS production (224.3 Tg S yr^{-1}) is determined as a fraction of net community production and depends on the abundance of diatoms (silicate) and coccolithophore (calcification rates). The loss of DMS is caused by bacterial consumption (163.8 Tg S yr^{-1}), photolysis (39.4 Tg S yr^{-1}) and outgassing (22.1 Tg S yr^{-1}) to the atmosphere.

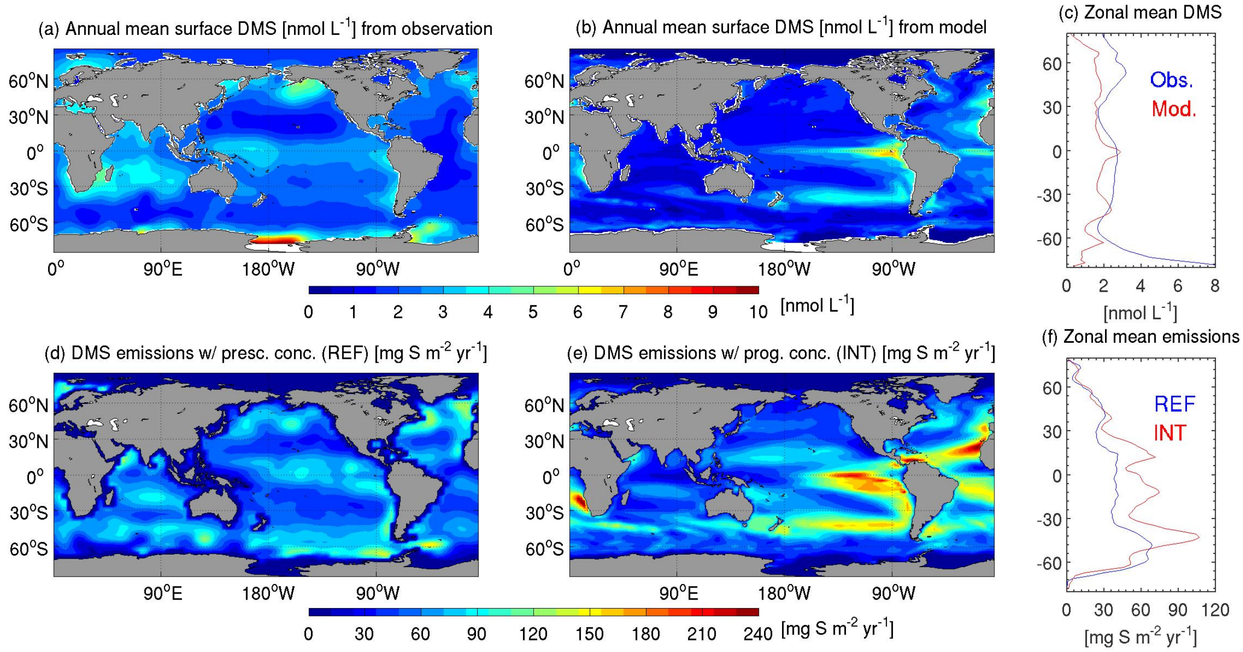


Figure 4. Annual mean maps of (a) reconstructed and (b) simulated surface DMS concentrations together with DMS fluxes computed from (d) observationally-prescribed DMS concentrations and (e) fully prognostic NorESM. Panels (c) and (f) show the zonally averaged mean values of surface DMS concentration and fluxes, respectively. For the model simulation, we use model mean average from the early preindustrial period (1850-1859).

The spatial distribution of the zonally averaged simulated surface DMS concentrations align with the climatology (Lana et al., 2011, Fig. 4). The DMS concentrations are high in productive regions, e.g., eastern equatorial Pacific and high latitude oceans during hemispheric summer. The model, however, simulates nearly zero DMS concentration during winter resulting in lower annual mean concentration at high latitude oceans. In the Indian Ocean, the model persistently fails to reproduce the observed high concentration. As for the air-sea fluxes, the outgassing of marine DMS in the fully prognostic model generally agree with the fluxes computed with prescribed observed DMS concentration. When zonally averaged, the fluxes in the fully prognostic model are higher than the observed fluxes in the tropics and the southern hemisphere (see Fig. 4).

2.3. Upgrade of terrestrial permafrost formulation in NorESM (lead: H. Lee)

To improve the representation of permafrost within the Earth System Model, we incorporated a representation of excess ice in the Community Land Model (CLM4.5, which is the next generation land model to be coupled into NorESM) and investigated how excess ice affects projected permafrost thaw and associated hydrologic responses (Lee et al., 2014). We initialized spatially explicit excess ice obtained from the Circum-Arctic Map of Permafrost and Ground-Ice Conditions, which allowed simulations of spatially explicit gridcell mean surface subsidence with projected warmer climate conditions. The ultimate goal is to develop dynamic wetland distributions to realistically simulate CH_4 production. As part of the project, we conducted several land-only simulations to understand the behavior of gridcell hydrology under changes in land surface topography (deliverable D2.5b).

We conducted a sensitivity test to understand how microtopography affects soil hydrology to influence CH_4 dynamics in the CLM by simply altering the existing spatially varying gridcell mean microtopography; increasing it by 200% and decreasing it by 50%. The fractional inundated area was directly, positively, correlated to microtopography (Fig. 5). Importantly, changes in microtopography affected the seasonality of hydrology: increasing microtopography lengthens the existence of inundated fraction in some regions. In addition, indirect effects were found in other hydrological parameters such as surface water depth, total water storage, and runoff - likely as a result of changes in the surface structure affecting hydrology.

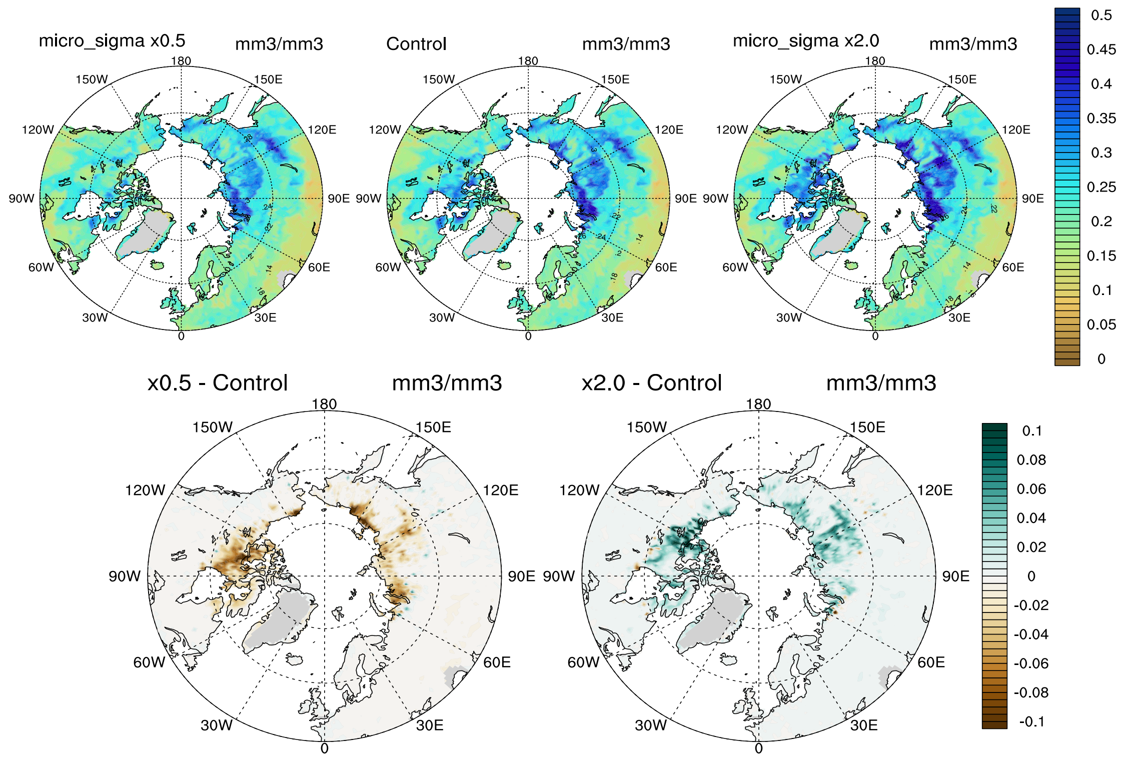
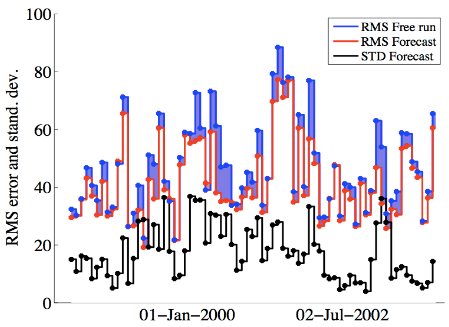


Figure 5. The effects of changing microtopography on July soil moisture (volumetric water content; mm^3/mm^3). The top three figures are from experiments with x0.5, Control (x1.0), and x2.0 microtopography in each gridcell. The bottom two figures are the difference x0.5 – Control and x2.0 – Control.

2.4. Data assimilation study with NorESM ocean biogeochemistry (lead: E. Simon)

We used SOCAT to explore large-scale data assimilation focusing on examining the stability of the data assimilation system and optimizing the biogeochemical parameterization in the NorESM. The SOCAT data were assimilated into the MICOM-HAMOCC model to estimate the phytoplankton growth rate (ω) and gas transfer rate (φ) parameters. A twin experiment was performed and the assimilation did not produce a significant reduction in RMS error with time for the ω parameter, which could be attributed to the low spatial and temporal coverage in biologically active regions. When assimilated with actual data, there is still only slight improvement in the forecast simulation (Fig.6).



It reveals some spatial pattern in the optimized ω parameter (see deliverable report D2.3), but no clear pattern for φ. Some experimental parameters may need to be better tuned prior to the assimilation experiment.

Figure 6. Time-evolution of root mean square (RMS) error of the assimilation experiment applying the SOCAT data. *The red line shows that the RMS error was improved with time, though still larger than the magnitude of standard deviation.*

2.5. Bias correction for DIC-ALK in BOGCM (lead: C. Heinze)

We used the computationally efficient low resolution HAMOCC2 model (Heinze et al., 2009) and explored a simple method to remove biases in both DIC and ALK tracers in the BOGCM through multiplication with constant offset factors resulting from a comparison with actual data (from GLODAP). Once adjusted, the model is re-spun up again. The method is applied iteratively whilst improvement of the fit is monitored, in particular with respect to atmospheric and surface pCO_2. The method appears to work and the overall "model score" can be improved without employing complex assimilation procedures. Further improvements of the method are currently under consideration (see deliverable report D2.4 for more details).

WP3: Upscaling of feedbacks to large scale under future emission scenarios and attribution of feedback strength to processes

Goal: To quantify the magnitude of the feedback processes on the large scale

3.1. Quantification of biogeochemical-climate feedback associated with new parameterizations in NorESM simulations of the future (lead: N. Goris)

In order to contribute to the ongoing biogeochemical-climate feedback assessment, we produced a set of fully interactive future scenario simulations with and without the newly implemented processes. Three new feedback processes have been implemented in the ocean biogeochemistry module: riverine nutrient and carbon supply (Bernard et al., 2011), an advanced POC sinking scheme and the marine DMS cycle (for a description of the latter two see WP2). All three processes introduce feedbacks to the climate system through the following processes: (a) the nutrients and carbon added through riverine fluxes could increase regional primary production, which then can alter the oceanic CO_2 uptake, (b) the new POC aggregation scheme could be altered with climate change and affect the biological-mediated carbon pump, and (c) interactive DMS-emissions could alter the atmospheric radiative balance. Marine DMS-emissions are dependent on NPP and on pH, yet their actual rate of pH-dependence is uncertain (Six et al., 2013).

Our results show that the nutrient supply by riverine fluxes, the new POC sinking scheme, and variable DMS emissions have globally no significant climate feedback. When the pH dependence of DMS is included, we identify a significant climate feedback of +0.36°C additional warming at the end of the simulation under the IPCC RCP8.5 emission scenario. Regional analysis shows no significant surface air temperature changes in response to riverine fluxes and the new POC sinking scheme, but a more distinct feedback for variable DMS (up to 2°C cooling in the Arctic) and pH dependent DMS (most distinct in high latitudes with an additional warming of up to 3.8°C, see Fig. 7).

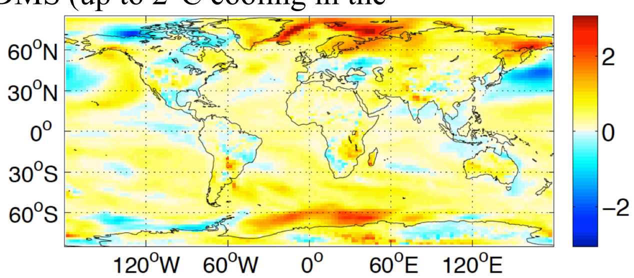


Figure 7. Map of the projected additional warming [°C] by the end of the 21st century (2091-2100) due to marine DMS-climate feedback.

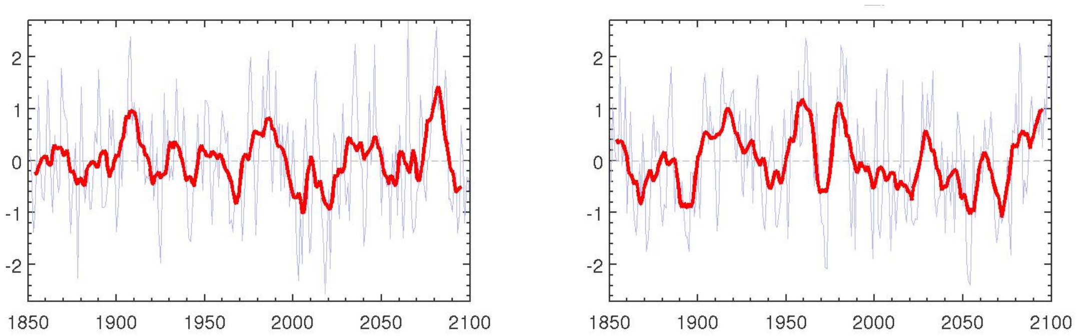


Figure 8. Time-series of the Pacific Decadal Oscillations (PDOs) as simulated by the NorESM for the 1850-2100 period (RCP8.5 scenario). The left and right panels depict indices from simulation without and with pH-dependent DMS emissions, respectively. The PDO indices represent the second mode of SST variability in the North Pacific, hence the indices at the beginning period differ despite starting from the same initial condition. The first mode of variability represents the long-term warming trend.

Furthermore, our simulations also show that biogeochemical processes, in addition to altering long-term climate, also alter the internal climate variability. Fig. 8 shows that the Pacific Decadal Oscillation is altered with different DMS simulations, despite both starting from the same initial climate states.

WP4: Development of early warning indicators and real world monitoring

Goal: To provide methods for checking whether the feedbacks identified and quantified are at work

4.1. Projection of ocean acidification in the Nordic Seas with NORWECOM.E2E (lead: M. Skogen)

In BIOFEEDBACK, we investigated the ocean acidification for a future climate (A1B, 2046-2065) and a control run (20C3M, 1980-2000) using downscaled physical forcing from the GISS-AOM climate model (Skogen et al., 2014) by adding a sub module for the carbonate system to the NORWegian ECOlogical Model system (NORWECOM, Skogen and Søiland, 1998). The model is spun up using initial fields for DIC for 1980 and 2050 derived from data collected during the joint Knorr and Oden survey of the Nordic Seas in 2002, the estimates of anthropogenic CO_2 concentrations derived from these data by Olsen et al. (2010) and assuming that the water would track the atmospheric increase in CO_2 proportionally to these.

In the future scenario simulation, the effect of the increased CO_2 is clearly simulated. Fig. 9 shows the change in modeled surface pH and DIC between December 2000 and December 2065. There is a decrease in surface pH of 0.15-0.25 in most areas. The largest decrease is seen in the Arctic waters to the northwest (> 0.30). The change in surface DIC has similar patterns, but the largest increase is in the northern Barents Sea.

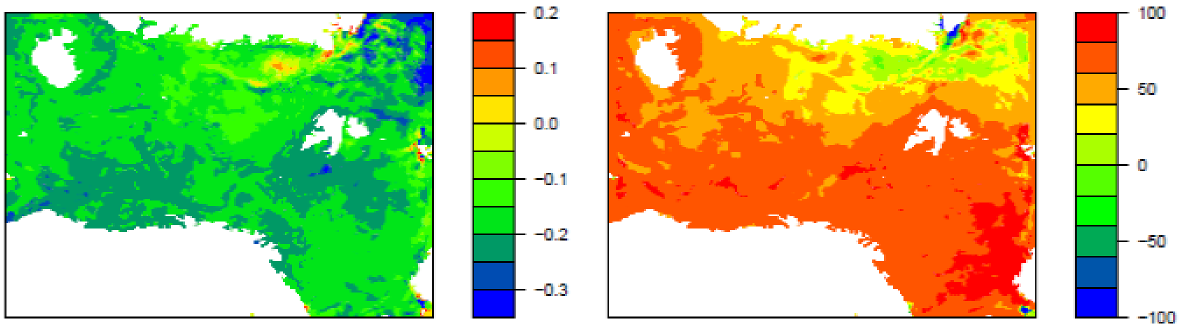


Figure 9. Simulated change in surface pH (left) and DIC (right, μmol kg^{-1}) from December 2000 to December 2065.

4.2. Decadal changes in the observed Apparent Oxygen Utilization (OUR) Rate (lead: E. Jeansson)

This activity aimed to deduce the global OUR climatology and identify significant changes on decadal time-scales using the GLODPAPv2 data (WP1). The OUR was calculated from apparent oxygen utilization (AOU) and water mass ages following Feely et al. (2004). For the latter we used CFC-12 data and the transit time distribution (TTD) method (e.g., Waugh et al., 2006). The derived

OUR can then be used to estimate organic carbon remineralisation, using the Redfield stoichiometric relationship between carbon and oxygen. The regional OUR profiles in Fig. 10 present the decadal mean OUR for different ocean regions. A first visual evaluation identifies some changes for certain layers/water masses, but the direction of change is not consistent. For example, the largest decadal differences are found in the southern parts of the Atlantic and the Indian Oceans (south of 30°S), with opposite directions for the change. It appears that changes in AOU are the main reason for these differences.

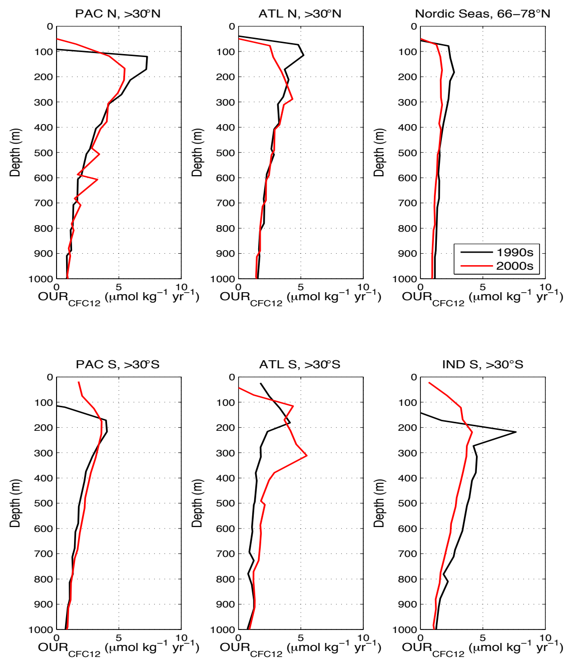


Figure 10. Vertical profile of apparent oxygen utilization rates for the different ocean regions computed for the 1990s and 2000s decades.

4.3. Optimization of global surface pCO$_2$ monitoring system (lead: C. Bradshaw)

Effective monitoring is critical for early warning of changes of the ocean carbon sink. However, clear identification of trends in ocean CO_2 uptake at regional or global scales requires consistent records with spatial/temporal resolution not yet adequately provided by the Surface Ocean CO_2 Atlas (SOCATv2: Bakker et al., 2014). Using an inverse diagnostic ocean mixed-layer scheme (Rödenbeck et al., 2013) and two global ocean biogeochemistry GCMs, NorESM1-ME (Tjiputra et al., 2013) and NEMOv2.3 with PlankTOM5.3 (Buitenhuis et al., 2013), the relative improvements in surface ocean pCO_2 estimation achievable through deployment of additional instruments on existing potential sampling platforms was demonstrated. The potential new observational locations were taken from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (Woodruff et al., 2011) and the Array for Real-time Geostrophic Oceanography (Argo) data. From the ICOADS data, 24 potential new shipping lines were identified as well as potential new drifting and moored buoys.

A conceptual framework approach was taken in which all of the model grid cells sampled over the period 2007-2011 by regular recording vessels in the SOCATv2 database were taken to be the 'optimal SOCAT coverage' dataset, and the assumption was made that each grid cell was sampled evenly in time, once every day across those years. This synthetic SOCAT dataset (pseudoSOCAT) is compared to a pseudoARGO, pseudoICOADS and a pseudoBUOYS dataset made in the same way but using the locations of the Argo floats, the entire ICOADS network and the drifting and moored buoys from ICOADS respectively, and pseudoSHIPS (the potential new shipping lines). The results show that the current observations in the SOCATv2 database are insufficient to accurately constrain the annual mean global pCO_2 in the surface ocean. For example, the inclusion of the 24 potential new shipping lines offers a 55% improvement in the ability to reconstruct the global annual mean pCO_2 in the surface ocean as compared to the current observational network, but it is still sub-optimal in comparison to the accuracy achievable with the inclusion of either the Argo network or the drifting and moored buoys because of deficiencies that remain in the observation of the Southern Ocean. Both the Argo network and the drifting and moored buoys offer an improvement of over 90% within the conceptual framework compared to the current observational network, giving an absolute accuracy of within 0.8 μatm of the NorESM and PlankTOM 'known truth' global mean surface ocean pCO_2 for the year 2007 (compared to an underestimate of around 2.2 μatm for SOCATv2).

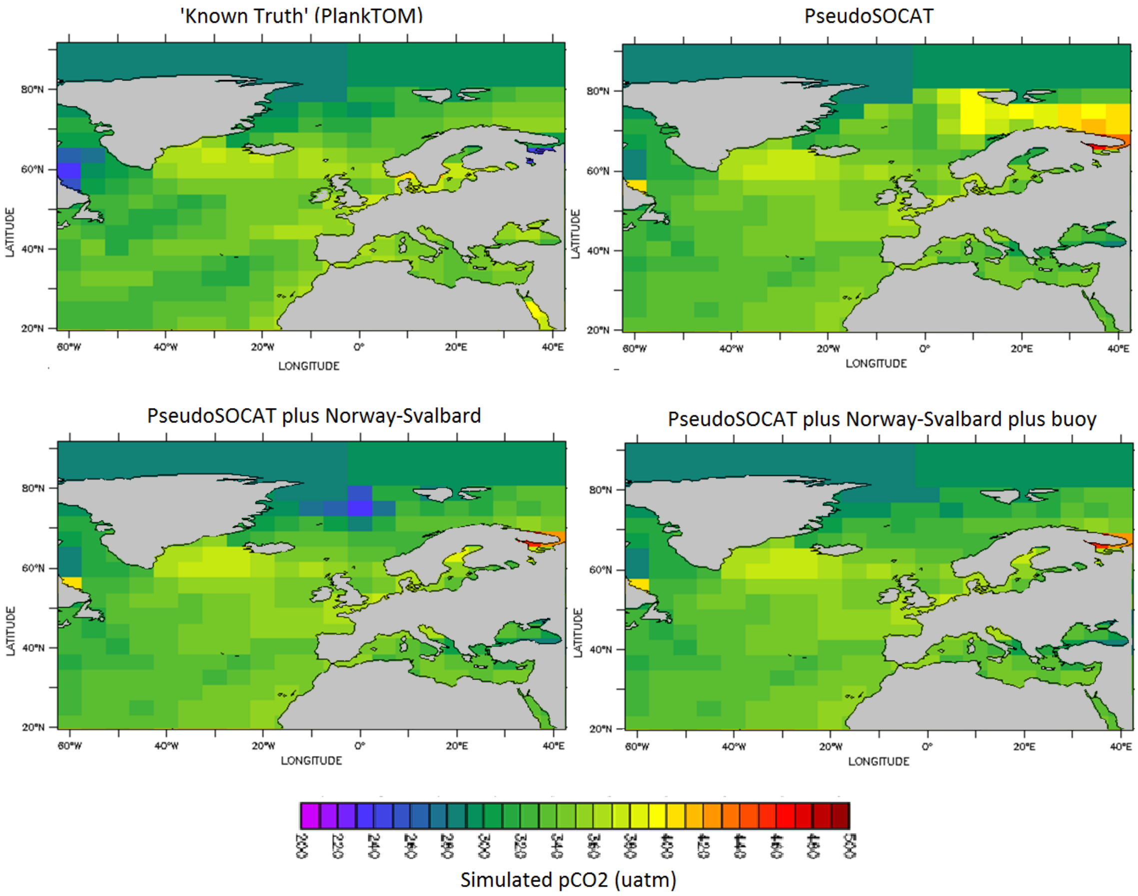


Figure 11. Surface ocean pCO_2 simulated in the high North Atlantic using the (top-left) PlankTOM model 'known truth' for the month of March 2008 as compared to those reconstructed from (top-right) SOCAT, (bottom-left) SOCAT and Norway-Svalbard line, and (bottom-right) SOCAT plus Norway-Svalbard line plus buoy in the Greenland Sea.

Fig.11 illustrates that by applying SOCAT observations only (pseudoSOCAT), the inferred surface pCO_2 map in the North Atlantic fails to capture the correct pCO_2 in the Nordic Seas and in the Barents Sea. The inclusion of the Norway-Svalbard line reduces this bias but because of the spatial correlations between data points, the pCO_2 reconstructed in the Greenland Sea then becomes significantly underestimated. This problem can be reduced by the additional inclusion of a new hypothetical mooring in the Greenland Sea.

IV. Future work

Through support from BIOFEEDBACK, we have implemented several new biogeochemical processes currently missing in the CMIP5 version of NorESM. We have quantified the magnitude of new biogeochemical climate feedback globally on the future high-CO_2 scenario. However, regionally, there remain many unanswered questions about how these new processes will alter climate variability and other physical processes. The model-data integration activity (Sect 2.4) will be extended to include full global observational coverage from Landschützer et al. (2014), and a full spectrum of ecosystem parameters will be tested. The above continuation will be pursued within the other ongoing projects, funded by the Research Council of Norway (e.g., SNACS, ORGANICS, VENTILATE, EVA, etc.).

The data synthesis work that have been carried out in the form of SOCAT and GLODAPv2 will continue, in collaboration with international colleagues, primarily within the framework of the H2020 project AtlantOS. GLODAPv2 and the OUR work is currently being written up.
The evaluation for the pCO_2 monitoring system (Sect. 4.3) is current being written up and new future scenario model simulations will be analyzed to identify the improvements possible for quantification of the ocean carbon sink under climate scenario RCP8.5. Relevant future challenges concerning quantification of the ocean carbon sink are summarized in Heinze et al. (2015). The

knowledge gained through BIOFEEDBACK will benefit the next SKD strategic project BIGCHANGE, which will elucidate the key carbon cycle feedback processes over the palaeo records and implement key processes in next generation climate projections (CMIP6).

References

Arhonditis and Brett (2004), Evaluation of the current state of mechanistic biogeochemical modelling. *Mar. Ecol. Prog. Ser. 271*, 13–26.

Assmann et al. (2010), An isopycnic ocean carbon model. *Geosci. Model Dev. 3*, 143-167.

Bakker et al. (2014), An update to the Surface Ocean CO_2 Atlas (SOCAT version 2). *Earth Syst. Sci. Data 6*, 69-90.

Bernard et al. (2011), Contribution of riverine nutrients to the silicon biogeochemistry of the global ocean - A model study. *Biogeosci. 8*, 551–564.

Buitenhuis et al. (2013), Combined constraints on global ocean primary production using observations and models. *Glob. Biogeochem. Cy. 27*, 847-858.

Denman et al. (2007).: Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon et al (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Feely et al. (2004), Oxygen utilisation and organic carbon remineralisation in the upper water column of the Pacific Ocean. *J. Oceanography 60*, 45-52.

Friedlingstein et al. (2006), Climate–Carbon Cycle Feedback Analysis: Results from the C^4MIP Model Intercomparison. *J. Clim. 19*, 3337-3353.

Heinze et al. (2009), Age offsets among different biogenic and lithogenic components of sediment cores revealed by numeric modeling. *Paleocanogr. 24*, PA4214.

Heinze et al. (2015), The ocean carbon sink – impacts, vulnerabilities, and challenges. *Earth Sys. Dyn.* 6, 327–358

Key et al. (2010), The CARINA data synthesis project: introduction and overview. *Earth Syst. Sci. Data 2*, 105-121.

Kriest and Evans (1999), Representing phytoplankton aggregates in biogeochemical models. *Deep-Sea Res. I 46*, 1841-1859.

Kriest et al. (2010), Towards an assessment of simple global marine biogeochemical models of different complexity. *Prog. Oceanogr. 86*, 337-360.

Lana et al. (2011), An updated climatology of surface dimethylsulfide concentrations and emission fluxes in the global ocean. *Global Biogeochem. Cyc. 25*, GB1004.

Landschützer et al. (2014), Recent variability of the global ocean carbon sink. *Glob. Biogeochem. Cyc. 28*, 927-949.

Lee et al. (2014), Effects of excess ground ice on projections of permafrost in a warming climate. *Env. Res. Lett. 9*, doi:10.1088/1748-9326/9/12/124006.

Olsen et al. (2010), Nordic Seas transit-time distributions and anthropogenic CO_2. *J. Geophys. Res. 115* (C5005).

Pfeil, et al. (2013), A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). *Earth Syst. Sci. Data 5*, 125-143.

Rödenbeck et al. (2013), Global surface-ocean pCO_2 and sea-air CO_2 flux variability from an observation-driven ocean mixed-layer scheme. *Ocean Sci. 9*, 193-216, 2013.

Six and Maier-Reimer, E. (2006), What controls the oceanic dimethylsulfide (DMS). *Glob. Biogeochem. Cyc.*, 20, GB4011.

Six et al. (2013), Global warming amplified by reduced sulphur fluxes as a result of ocean acidification. *Nat. Clim. Chang.* 3, 975–978.

Skogen and Søiland (1998), A user's guide to NORWECOMv2.0. The NORWegian ECOlogical Model system. *Tech. Rep. Fisken og Havet 18/98*, Institute of Marine Research, Bergen, 42 pp.

Skogen et al. (2014), Modelling ocean acidification in the Nordic and Barents Seas in present and future climate. *J. Mar. Sys. 131*, 10–20.

Riebesell et al (2007), Enhanced biological carbon consumption in a high CO_2 ocean. *Nature 450*, 545-549.

Tjiputra et al (2010), Bergen earth system model (BCM-C): Model description and regional climate-carbon cycle feedbacks assessment. *Geosci. Model Dev. 3*, 123-141.

Tjiputra et al. (2013), Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM). *Geosci. Model Dev. 6*, 301–325.

Stow et al. (2009), Skill assessment for coupled biological/physical models of marine systems. *J. Mar. Sys. 76 SI, 4-15*

Waugh et al. (2006), Anthropogenic CO_2 in the oceans estimated using transit time distributions. *Tellus*, *58B*, 376-389.

Woodruff et al. (2011), ICOADS Release 2.5: extensions and enhancements to the surface marine meteorological archive. *Int. J. Clim. 31*, 951-967.

SKD-BIOFEEDBACK

List of publications

In total, there are four manuscripts in the preparation, submitted, or in press status. A total of 45 manuscripts have been published between 2011-2015. Below are list of the project dissemination activities each list is sorted in time and alphabetical order.

I. Publication in international peer-reviewed journals

Goris, N., Tjiputra, J., Schwinger, J., and **Heinze, C.** (submitted), The effect of climate change on the biogeochemistry of the North Atlantic: A model study with the Bergen Earth System Model, submitted to *Global Biogeochemical Cycles*.

Eyring, V., - , **Heinze, C.** et al. (submitted), Infrastructure needs for routine Earth system model evaluation in CMIP6, *Bulletin of the American Meteorological Society.*

Jiang, L., - , **Tjiputra, J.**, et al. (in-press), Scale-dependent performance of CMIP5 Earth system models in simulating terrestrial vegetation carbon, J. Climate.

Olsen, A., Anderson, L. G. and **Heinze, C.** (2015) Arctic Carbon Cycle: patterns, impacts and expected change, in: *The New Arctic*, B. Envengård, J. Nymand Larsen, and Ø. Paasche, eds., Springer, 95-115.

Heinze, C., Meyer, S., Goris, N., Anderson, L., Steinfeldt, R., Chang, N., Le Quéré, C., and Bakker, D.C. E. (2015), The ocean carbon sink – impacts, vulnerabilities, and challenges, Earth Syst. Dynam. Discuss., 5, 1607–1672, www.earth-syst-dynam-discuss.net/5/1607/2014/ doi:10.5194/esdd-5-1607-2014.

Lauvset, S. K., Gruber, N., Landschützer, P. L., **Olsen, A.**, and **Tjiputra, J.** (2015), Trends and drivers in global surface ocean pH over the past 3 decades, Biogeosciences, 12, 1285-1298.

Larsen, A., Egge, J. K., Nejstgaard, J. C., Capua, lD., Thyrhaug, R., Bratbak, G., and **Thingstad, T. F.** (2015), Contrasting response to nutrient manipulation in Arctic mesocosms are reproduced by a minimum microbial food web model, Limnol. Oceanogr., 60, 360-374.

Gehlen, M., - , **Bertino, L., Simon, E., Samuelsen, A.,** et al. (2015), Building the capacity for forecasting marine biogeochemistry and ecosystems: recent advances and future developments, J. Operational Oceanogr., dii:10.1080/1755876X.2015.1022350.

Garcia, H.E., - , **Pfeil, B.**, et al. (2015), Data management strategy to improve global use of ocean acidification data and information. Oceanography28(2):226–228, http://dx.doi.org/10.5670/oceanog.2015.45.

Le Quere, C., - , **Olsen, A.**, **Pfeil, B.**, **Schwinger, J.**, et al. (2015), Global carbon budget 2014, Earth Syst., Sci. Data, 7, 47-85.

Nevison, C. D., - , **Tjiputra, J.**, et al. (2015), Evaluating the ocean biogeochemical components of Earth system models using atmospheric potential oxygen and ocean color data, Biogeosciences, 12, 193-208.

Sitch, S., - , **Heinze, C.**, et al. (2015), Recent trends and drivers of regional sources and sinks of carbon dioxide, Biogeosciences, 12, 653-679.

Skogen, M. D., Olsen, A., Børsheim, K.Y., Sandø, A.B. and **Skjelvan, I.** (2014). Modelling ocean acidification in the Nordic and Barents Seas in present and future climate. J.Mar.Systems. 131:10–20 doi:10.1016/j.jmarsys.2013.10.005.

Tjiputra, J., **Olsen, A.**, **Pfeil, B.**, **Heinze, C.**, et al. (2014), Long-term surface pCO2 trends from observations and models, Tellus B, 66, 23083.

Rödenbeck, C., Bakker, D. C. E., Metzl, N., **Olsen, A**., Sabine, C., Cassar, N., Reum, R., Keeling, R. F.

and Heimann, M. (2014), Interannual sea-air CO_2 flux variability from an observation-driven mixed layer scheme, Biogeosciences, 11, 4599-4613.

Dalpadado, P., Arrigo, K. R., **Hjøllo, S. S.**, Rey, F., Ingvaldsen, R. B., Sperfeld, E., van Dijken, G. L. Stige, L. C., **Olsen, A.** and Ottersen, G. (2014), Productivity in the Barents Sea - response to recent climate variability, PLoS ONE, 9, e95273, doi:10.1371/journal.pone.0095273

Bakker, D. C. E, **Pfeil, B.,** - **Olsen, A., Johannessen, T., Lauvset, S. K., Omar, A. M., Skjelvan, I., Tjiputra, J.** et al. (2014), An update to the Surface Ocean CO_2 Atlas (SOCAT version 2), Earth System Science Data, 6, 69-90.

Skaret, G., Dalpadado, P., **Hjøllo, S.S., Skogen, M.D.**, and Strand, E. (2014). Calanus finmarchicus abundance, production and population dynamics in the Barents Sea in a future climate. Prog. Oceanogr. 125:26-39, doi:dx.doi.org/10.1016/j.pocean.2014.04.008

Ciais, P., - , **Heinze, C.**, et al. (2014), Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system., Biogeosciences, 11, 3547-3602.

Garcon, V. C., - , **Olsen, A.**, **Pfeil, B.**, et al. (2014), Perspectives and Integration in SOLAS Science. In: Liss and M.T. Johnson (eds.), Ocean-Atmosphere Interactions of Gases and Particles, 307 Springer Earth System Sciences, DOI 10.1007/978-3-642-25643-1.

Gehlen, M., - , **Heinze, C.**, **Tjiputra, J.**, et al. (2014), Projected pH reductions by 2100 might put deep North Atlantic biodiversity at risk, Biogeosciences, 11, 6955-6967.

Hoffman, F. M., - , **Tjiputra, J.**, et al. (2014), Causes and implications of persistent atmospheric carbon dioxide biases in Earth system models, J. Geophys Res. Biogeosciences, 119, 141-162.

Laruelle, G. G., - , **Pfeil, B.**, et al. (2014), Regionalized global budget of the CO2 exchange at the air-water interface in continental shelf seas, Global Biogeochem. Cycles, 28, 1199–1214, doi:10.1002/2014GB004832.

Le Quere, C., - , **Omar, A.**, **Pfeil, B.**, **Schwinger, J.**, et al. (2014), Global carbon budget 2013, Earth Syst., Sci. Data, 6, 235-263.

Todd-Brown, K. E. O., - , **Tjiputra, J.**, et al. (2014), Changes in soil organic carbon storage predicted by Earth system models during the 21st century, Biogeosciences, 11, 2341-2356.

Heinze, C., and Gehlen, M. (2013), Modeling Ocean Biogeochemical Processes and the Resulting Tracer Distributions (Ch. 26), in Siedler, G., Griffies, S., Gould, J. and Church, J. (Eds.): Ocean Circulation and Climate, 2nd Ed. A 21st century perspective, Elsevier, 667-694.

Pfeil, B., **Olsen, A.**, - , **Bellerby, R.**, **Heinze, C.**, **Johannessen, T.**, **Lauvset, S.**, **Omar, A.**, **Skjelvan, I.**, **Tjiputra, J.**, et al. (2013), A uniform, quality controlled Surface Ocean CO2 Atlas (SOCAT), Earth Syst., Sci. Data, 5, 125-143.

Skogen, M., **Olsen, A.**, Børsheim, K. Y., **Sandø, A. B.**, and **Skjelvan, I.** (2013), Modelling ocean acidification in the Nordic and Barents Seas in present and future climate, J. Mar. Sys., 131, 10-20.

Tjiputra, J. F., Roelandt, C., Bentsen, M., Lawrence, D. M., Lorentzen, T., Schwinger, J., Seland, Ø.**, and Heinze, C.** (2013), Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), *Geosci. Model Dev*., 6, 301–325, www.geosci-model-dev.net/6/301/2013/doi:10.5194/gmd-6-301-2013

Rödenbeck, C., Keeling, R. F., Bakker, D. C. E., Metzl, N., **Olsen, A**., Sabine, C. and Heimann M. (2013), Global surface ocean pCO_2 and sea-air CO_2 flux seasonality from an observation driven ocean mixed-layer scheme, Ocean Science, 9, 193-216.

Bopp, L., - , **Heinze, C.**, **Tjiputra, J.**, et al. (2013), Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models, Biogeosciences, 10, 6225-6245.

Cocco, V., - , **Heinze, C.**, **Tjiputra, J.**, et al. (2013), Oxygen and indicators of stress for marine life in multi-model global warming projections, Biogeosciences, 10, 1849-1868.

Ilyina, T., - ,**Heinze, C.**, et al. (2013), Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification, *Geophysical Research Letters*, 40, 1–6, doi:10.1002/2013GL057981

Le Quere, C., - , **Schwinger, J.**, et al. (2013), Global carbon budget 1959-2011, Earth Syst., Sci. Data, 5, 165-185.

Palastanga, V., Slomp, C. P., and **Heinze, C.** (2013), Glacial-interglacial variability in ocean oxygen and phosphorus in a global biogeochemical model, Biogeosciences, 10, 945-958.

Regnier, P., - , **Heinze, C.** et al. (2013), Anthropogenic perturbation of the carbon fluxes from land to ocean, *Nature Geoscience*, 6(8), 597-607, DOI: 10.1038/NGEO1830

Sabine, C., - , **Pfeil, B.**, **Olsen, A.**, **Bellerby, R.**, **Heinze, C.**, **Johannessen, T.**, **Lauvset, S.**, **Omar, A.**, **Skjelvan, I.**, et al. (2013), Surface Ocean CO2 Atlas (SOCAT) gridded data products, Earth Syst. Sci. Data, 5, 145-153.

Wanninkhof, R., - , **Heinze, C.**, **Schwinger, J.**, et al. (2013), Global ocean carbon uptake: magnitude, variability, and trends, Biogeosciences, 10, 1983-2000.

Simon, E. and **Bertino, L**. (2012), Gaussian anamorphosis extension of the DEnKF for combined state parameter estimation: Application to a 1D ocean ecosystem model. *J. Mar. Syst.* 89, 1–18.

Simon, E., Samuelsen, A., Bertino, L. and Dumont, D. (2012), Estimation of positive sum-to-one constrained zooplankton grazing preferences with the DEnKF: A twin experiment. *Ocean Sci.* **8,** 587–602.

Tjiputra, J.F., Olsen, A., Assmann, K., Pfeil, B., and **Heinze, C.** (2012), A model study of the seasonal and long–term North Atlantic surface pCO_2 variability, *Biogeosciences*, 9, 907–923, www.biogeosciences.net/9/907/2012/ doi:10.5194/bg-9-907-2012

Signorini, S., Häkkinen, S., Gudmundsson, K., **Olsen**, **A., Omar, A. M.**, Olafsson, J., Reverdin, G., Henson, S. A., McClain, C. R. and Worthen, D. L. (2012), The role of phytoplankton dynamics in the seasonal and interannual variability of carbon in the subpolar North Atlantic – A modelling study, *Geoscientific Model Development, 5,* 683-707, 2012.

Keller, K.M., - , **Tjiputra, J., Heinze, C.**, et al. (2012), Variability of the ocean carbon cycle in response to the North Atlantic Oscillation, *Tellus* B, 64, 18738, http://dx.doi.org/10.3402/tellusb.v64i0.18738

Bakker, D. C. E, **Pfeil, B., Olsen, A.** et al. (2012) Global data products help assess changes to ocan carbon sink, *EOS*, *93*, 125-126.

Palastanga, V., Slomp, C. P., and **Heinze, C.** (2011), Long-term controls on ocean phosphorus and oxygen in a biogeochemical ocean model, *Global Biogeochemical Cycles,* 25, GB3024, 19 p., DOI: 10.1029/2010GB003827.

Tschumi, T., Joos, F., Gehlen, M., and **Heinze, C.**, (2011), Deep ocean ventilation, carbon isotopes, marine sedimentation and the deglacial CO_2 rise, *Climate of the Past*, 7, 771-800, www.clim-past.net/7/771/2011/ doi:10.5194/cp-7-771-2011

Roy, T., - , **Tjiputra, J., Heinze, C.**, et al. (2011), Regional Impacts of Climate Change and Atmospheric CO_2 on Future Ocean Carbon Uptake: A Multimodel Linear Feedback Analysis. *J. Climate*, 24(9), 2300-2318, DOI: 10.1175/2010JCLI3787.1

Bernard, C., - , **Heinze, C.** et al. (2011), Contribution of riverine nutrients to the silicon biogeochemistry of the global ocean – a model study. *Biogeosciences*, 8, 551- 564, www.biogeosciences.net/8/551/2011/ doi:10.5194/bg-8-551-2011

II. Other published scientific manuscript and outreach materials:

Mc. Govern, E., - , **Olsen, A., Tjiputra, J.** et al. (2015), Final report of the joint OSPAR/ICES Ocean Acidification Study Group (SGOA), ICES CM 2014/ACOM: 67, 141 pp.

Lauvset, S. K, **Olsen, A.**, Key, R. M., Lin, X., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., **Jeansson, E.** van Heuven, S., Ishii, M., Suzuki, T., Velo, A., Schirnick, C. and **Pfeil, B.** (2014) GLODAPv2 - A new and updated global ocean data product, *IMBER News,* issue 27.

Bakker, D., O'Brien K., **Olsen, A.**, **Pfeil, B**. et al. (2014). The 2014 community event of the surface ocean CO_2 Atlas, *IMBER News,* issue 27.

Bakker, D. C. E., **Pfeil, B**, **Olsen,** A., R. Wanninkhof and all SOCAT contributors (2014). The Surface Ocean CO_2 Atlas (SOCAT) informs observation-based estimates of the ocean carbon sink and its seasonal to inter-annual variability, *SOLAS News*, issue 16, 35.

Heinze, C., (2014), The Role of the Ocean Carbon Cycle in Climate Change, *European Review*, 22(1), 97 – 105.

Samuelsen, A., (2014), Fact sheet: “Enhancing model simulations for the marine environment”, made for the GreenSeas project by Annette Samuelsen (NERSC), Marcello Vicci (CMCC), and Icaurs Allen (PML).

Schmidt, D., and **Heinze, C.** (2011), Breakout Group II-1: Learning from the past and present to predict the future, in: IPCC, 2011: Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems [Field, C.B., V. Barros, T.F. Stocker, D. Qin, K.J. Mach, G.-K. Plattner, M.D. Mastrandrea, M. Tignor and K.L. Ebi (eds.)]. IPCC Working Group II Technical Support Unit, Carnegie Institution, Stanford, California, United States of America, pages 33-35.

Wanninkhof, R., Bakker, D., Bates, N., **Olsen, A.**, Steinhoff, T. and Sutton, A. (2013), Incorporation of Alternative Sensors in the SOCAT Database and Adjustments to Dataset Quality Control Flags. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/OTG.SOCAT_ADQCF.

Bellerby, R, - , **Jeansson**, **E.**, - , **Olsen, A.** et al (2013). Acidification in the Arctic Ocean, 9-34 in *AMAP assessment 2013: Arctic Ocean acidification*, Arctic Monitoring and Assessment Progamme (AMAP) Oslo, Norway, vii+ 99pp.

Olsen, A., Bakker. D., and Pfeil, B., (2013), Second version of the Surface Ocean CO_2 Atlas to be released this summer for climate research, *SOLAS News,* issue 15, 21.

III. Presentation at international conferences, workshops, and seminars

Pfeil, B. et al., The Surface Ocean CO_2 Atlas (SOCAT) community effort: outlook for versions 3 and 4, IMBER Ocean Science Conference, Future Oceans, Bergen, Norway, June 2014.

Goris, N., et al., Performance of CMIP5 models in the Subpolar North Atlantic: Using control simulations to identify uncertainties in the prediction of key climate properties, EGU 2015, Vienna, Austria, 2015.

Goris, N., et al., Carbon uptake sensitivity of the North Atlantic to climate change: A model study with the Bergen Climate Model, EGU 2015, Vienna, Austria, 2015.

Goris, N., et al., The effect of climate change o the biogeochemistry of the North Atlantic: A study with the Bergen Climate Model, CarboChange final meeting, Bergen, Norway, January 2015.

Goris, N., et al., Quantifying the climate-driven processes leading to a reduced CO_2 uptake in the North Atlantic: A model study with the Bergen Climate Model, IMBER Open Science Conference, Bergen, June, 2014.

Goris, N., et al., Modelling and assessing climate change impacts on the CO2 uptake of the North Atlantic, CarboChange Annual meeting, Rekjavik, Iceland, January, 2014.

Goris, N., et al., North Atlantic variability of oceanic CO2 uptake in response to simulated past, present and future climate change, 9th International Carbon Dioxide Conference, 3-7 June 2013, Beijing, China.

Goris, N. et al., North Atlantic trends in ocean circulation ad stratification and their correlation to the oceanic CO2 uptake as simulated by Bergen Climate Mocel, , Bjerknes Centre conference, Bergen, September 2012.

Heinze, C., "Marine CO_2 modelling and inversions", plenary talk, Model-Data Fusion for Carbon Cycle Studies International Seminar, 18 February 2014, Lund University, Lund, Sweden **(invited)**.

Heinze, C.*, "The role of the ocean carbon cycle in climate change",* plenary talk, *Academia Europaea* The Academy of Europe, 24th Annual Conference, "Northern Seas - the European Dimension", Bergen, Norway, 11-13 September 2012 **(invited)**.

Heinze, C., *"Modelling the ocean carbon cycle - lessons from the past and entering new territory for the future",* Seminar for *Worldwide Universities Network* (WUN), Bergen, 16 May 2012, video seminar broadcast to 16 Universities in Europe and North America (including online discussion with the partners after the presentation, **invited**).

Heinze, C., *"CCDAS for Oceans" (keynote)*, *COCOS GEO Carbon Conference, Rome, Italy, 24-26 October 2011* **(invited)**.

Heinze, C., *"Ocean carbon uptake under changing climate"*, 6th EU-Japan Workshop on Climate Change Research, Brussels, Belgium, 10-11 October 2011 **(invited)**.

Heinze, C., *"Modelling the global marine carbon cycle 'end-to-end'"*, *plenary presentation,* International Workshop "Exploring knowledge gaps along the global carbon route: A hitchhiker's guide for a boundless cycle" (organised by P. Regnier, near Brussels, Belgium, 3-7October 2011 **(invited)**.

Heinze, C., *"Global Carbon Cycle Overview"*, Blue Carbon Scientific Working Group 1st Meeting, UNESCO, Paris, France, 15-17 February, 2011 **(invited)**.

Heinze, C., *"Report of Break Out Group II-1: Learning from the past and present to predict the future"*, plenary presentation (100 participants), IPCC WGII/WGI Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems, Okinawa, Japan, 17-19 January 2011 **(invited)**.

Olsen A., Ocean acidification threatens tropical coral reefs, The Rising Ocean: The Pacific Islands and Global Climate Change Symposium, Bergen, Norway, May 2015.

Olsen A., How climate change and rising CO_2 affect marine resources, Science-Policy event on ten years of ocean carbon and climate research in Bergen, Bergen, Norway, January 2015.

Olsen, A. et al., Presenting GLODAPv2, ocean biogeochemical trends and future plans, IMBER Ocean Science Conference, Future Oceans, Bergen, Norway, June 2014.

Olsen, A. et al., SOCAT - A global data product for quantification of air-sea exchange of CO_2, The Oceanflux Greenhouse Gases Project Science Workshop, Brest, France, September 2013.

Olsen, A. et al. Global datasets for OA research, Arctic Ocean Acidification, Bergen, Norway, 2013.

Olsen, A. et al. Moving from GLODAP, CARINA and PACIFICA to the Global Ocean Data Analysis v2, GLODAPv2, Bjerknes Centre 10-year Anniversary Conference, Climate Change at High Latitudes, Bergen, Norway, September 2012.

Samuelsen, A. et al., Variability in the modelled and observed spring bloom in the North Atlantic, ICES Annual Science Conference 2012, Bergen, Norway.

Schwinger, J., et al., Different response of the natural and the anthropogenically disturbed ocean carbon cycle to changing climate, IMBER Open Science Conference, Bergen, June, 2014.

Schwinger, **J.,** et al., Nonlinearity of ocean carbon feedbacks in CMIP5 models, 9th International Carbon Dioxide Conference, 3-7 June 2013, Beijing, China **Tjiputra, J.**, et al., Positive future climate feedback due to changes in oceanic DMS emissions, EGU 2015, Vienna, Austria, 2015 (oral).

Schwinger, J., et al., Non-linearity in ocean carbon cycle feedback from CMIP4 model, Carbon cycle workshop, Bristol, UK, September 2013

Schwinger, J., et al., Climate change impact on ocean acidification as modelled by CMIP5 earth system models,, Bjerknes Centre conference, Bergen, September 2012

Tjiputra, J., et al., Sensitivity and regional change of future biological carbon pump to POC flux parameterization, 3rd International Symposium Effects of climate Change on the World's Ocean, Santos city, Brazil, 2015.

Tjiputra, J., et al., Long-term surface pCO2 teends from observations and models, CarboChange final meeting, Bergen, Norway, January 2015.

Tjiputra, J., et al., Mechanism and detectability of basin scale surface pCO_2 variability in the North Atlantic and North Pacific, *Ocean Science Meeting, February 2014*, Honolulu, USA

Tjiputra, J., et al., Long-term trends in oceanic pCO_2 from models and observations, *International Carbon Dioxide Conference, June 2013,* Beijing, China

Tjiputra, J., Carbon cycle processes in Norwegian Earth system model, Earth system model workshop, Helsinki, October, 2013 (invited).

Tjiputra, J., et al., Long term trend in surface ocean pCO2, Annual CarboChange project, CarboChange annual meeting, 24-26 April 2013, Norwich, UK.

Tjiputra et al., Carbon cycle feedbacks, results from CMIP5, International Geosphere-Biosphere Programme (IGBP) sympossium, Bergen, May 2012.

Tjiputra et al., Ocean carbon cycle feedbacks in the tropics from CMIP5 models, CESM-annual workshop, Breckenridge, USA, July 2012.

Tjiputra et al., Change in carbon cycle to natural climate variability in CMIP5 models, Bjerknes Centre conference, Bergen, September 2012.

Tjiputra et al., Interactions between ocean carbon cycle and climate variability in the equatorial Pacific as simulated by CMIP5 models, 3rd International Conference on Earth System Modelling, September 2012.

Dynamics of Past Warm Climates

DYNAWARM

Final report:
DYNWARM – Dynamices of Past Warm Climates
SKD Strategic Project 2011-2014

Project PIs:
Camille Li, Bjørg Risebrobakken

Scientists involved:
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UiB: Hilary Birks (BIO), Cathy Jenks (BIO), Kikki Kleiven (GEO), Camille Li (GFI), Ulysses Ninnemann (GEO), Kerim Nisancioglu (GEO), Aleksi Nummelin (GFI)
NERSC: Igor Esau, Stephen Outten

Main objectives

DYNAWARM aimed to improve our understanding of the dynamics of the atmosphere, ocean and cryosphere in warm climates. The key objectives are summarized by the following questions:

1. What are the potential tipping points as climate warms, and are the changes irreversible? (focus on Arctic biota and cryosphere)
2. What does the paleoclimate record tell us about the dynamics of the Pliocene, a warm period with greenhouse gas concentrations close to those predicted for the future? (focus on polar amplification and tropical Pacific variability)

Motivation and relevance

The Earth is in a period of global warming, manifested in a net loss of land-based ice masses and sea ice cover. A major challenge in climate research is predicting the rate of future warming and the consequences of this warming for the climate system. Polar regions and the cryosphere are particularly sensitive to change due to their tendency to amplify trends and trigger irreversible changes. The tropics are also a sensitive region, able to undergo large scale reorganizations and to project their influence globally. Understanding the dynamics of and interactions within these regions is crucial for determining the response of the global climate system in the future.

Within this century, the Earth is expected to reach temperatures unprecedented during instrumental times. Past warm periods in the paleoclimate record are thus an important source of information for understanding climate dynamics in a future world. Examples of these warm periods include the Early Eocene Climate Optimum (EECO, 55 Ma), Pliocene (5-3 Ma) and Eemian (130-114 Ka). These cover a range of atmospheric CO_2 concentrations (above 2000 ppm, 400 ppm, 280 ppm, respectively), with Arctic temperatures estimated to be 25°C, 12°C and 5°C warmer than today (Miller et al., 2010; Ballantyne et al., 2011) and global sea level 50-100 m, 25 m and 4-6 m higher than today (Kopp et al., 2010; Dowsett & Caballero Gill, 2010; Zachos et al., 2008). Eemian warmth has been tied to stronger summer insolation at high northern latitudes, while enhanced greenhouse gas forcing is thought to be of importance for the Pliocene (Miller et al., 2010). However, given the uncertainties in determining atmospheric CO_2 concentrations and the amount of tropical ocean warming as one moves further back in time (Huber, 2008), there remain many questions about how and why these warm periods existed.

These examples from the past show that the climate system exhibits a range of behaviours under varying greenhouse and insolation conditions, with polar, cryospheric and tropical changes likely playing different roles during different periods. A better understanding of these behaviours, as well as of how the mechanisms responsible for these past warm periods may apply to projected warming, will provide critical knowledge for ascertaining the response of the climate system in the future.

By studying the characteristics and dynamics of warm climates, DYNAWARM has contributed substantially to the main scientific priorities of SKD by: 1) improving our understanding of natural climate *variability*; 2) improving estimates of climate *sensitivity*, including both fast and slow feedback processes; 3) improving our understanding of the dynamics and physical processes at work in a warm *Arctic*, and their representation in general circulation *models*; 4) investigating the possible existence of *thresholds (tipping points)* and *irreversible* climate changes as climate warms; and 5) studying the stability of the *cryosphere* in a warm climate and its impact on *sea level*.

Results

WP1: Tipping points and irreversible climate change

Key questions: *What are the potential tipping points as climate warms, and are the changes irreversible? (focus on Arctic biota and cryosphere)*

Task 1 – Synthesise data on flora and vegetation and characterize them in terms of past climate states

John Birks + Hilary Birks, Cathy Jenks

This task considered the response of plants to warming climates in the past as a means of evaluating predictions that future climate change will result in up to 35% of the world's plant species going extinct. The task simply asked what happened to plants during periods of warming climate at the end of the last glacial stage and during the so-called Holocene (post-glacial) thermal maximum (HTM). It also planned to consider the last interglacial (Eemian) and the Pliocene and the Palaeocene-Eocene Thermal Maximum (PETM). For reasons outlined below, work on these time periods was not pursued.

A DYNAWARM database of the occurrence and age of fossil records of 12 warmth-demanding plant taxa and one animal taxon in north-west Europe was completed. It contains 484 records from 347 sites in six countries based on 59 publications. The taxa considered (e.g. *Trapa natans, Cladium mariscus, Emy orbicularis*) are all known to be warmth-demanding and to have extended their geographical range northwards in Fennoscandia in the HTM. Many of the records pre-date the development of radiocarbon-dating in the 1950s and are only dated rather approximately by pollen chronostratigraphy to the nearest 1000 years. Preliminary maps show that although all these taxa expanded their ranges northwards in Scandinavia and north-eastwards in Finland during the HTM (8000–6000 years ago), the patterns of their subsequent retreat differ between species even though the species today have similar geographical distributions, highlighting the individualistic nature of biotic responses to climate change.

The database for the Eemian interglacial is very sparse due to the scarcity of interglacial sites where macrofossils have been studied. It is too limited to be of use.

A DYNAWARM database of Holocene elevational tree-line changes and chironomid-inferred temperatures for the HTM in Fennoscandia has been compiled. The relationships between pollen richness and diversity and chironomid-based temperatures in the Holocene will soon be studied by Vivian A. Felde (waiting for her PhD defence) and John Birks. Felde has developed numerically robust and ecologically realistic approaches for estimating richness and diversity from fossil pollen assemblages. Potential drivers of change in biodiversity including Holocene climate change will be investigated statistically soon after Felde's thesis defence in late March.

Major taxa only	AL-YD (cooling)		YD-H (warming)	
	Pollen	Macros	Pollen	Macros
Extinction (local)	0	0	10	9
Persistence (tolerance)	6	3	14	14
Decline but persistence	6	10	3	2
Habitat shift	0	1	1	2
Migration & expansion	12	9	6	5
Expansion & subsequent decline	0	0	8	9

Figure 1. The responses of major taxa to climate cooling during the Allerød (AL)–Younger Dryas (YD) transition and the climate warming at the YD–Holocene (H) transition at Kråkenes, central Norway.

The response of plant species to rapid warming at the onset of the post-glacial 11,700 years ago, in terms of local extinction, migration, persistence or toleration (stasis), and habitat shift was investigated. Detailed well-dated pollen and macrofossil data from late-glacial/early-Holocene sites in central and northern Norway were analysed. Chironomid-inferred temperatures were used as the palaeoclimate record. The predominant responses were persistence, migration and expansion, with some local extinctions and very few habitat shifts (Fig. 1) There were **no** regional extinctions. The responses are a complex mixture of individualistic and grouped responses, suggesting that past vegetation, as today, hovers between continuous (individualistic) and discontinuous (grouped) behaviour. This complex behaviour makes predictions of plant responses to future climate change difficult but the palaeobotanical record does not support the predictions of large numbers of plant extinctions in the coming decades or centuries due to climate change alone – habitat destruction is a much bigger threat to species persistence and migration in the future.

Task 2 – Assess the potential for tipping points in the Arctic sea ice and halocline system in warming climates

Lars Henrik Smedsrud with Camille Li, Kerim Nisancioglu, Aleksi Nummelin

For the Arctic Ocean at the end of this century, the CMIP5 models generally predict more runoff from rivers, loss of summer sea ice, a warmer Atlantic inflow, and an increase in the heat content of the Arctic Ocean itself. The effect of increasing river runoff to the Arctic Ocean is one of the more robust results. Runoff changes to the Arctic of approximately 3% per century are estimated from 18 CMIP5 models (39 ensemble members total) for the RCP8.5 scenario. The ensemble mean increases from ~0.10 Sv today to ~0.13 Sv by 2100 (Fig. S1 in Nummelin et al. 2015), and September sea ice cover disappears by the end of the century in about 90% of the CMIP5 models (IPCC AR5, Chapter 12). Changing runoff alters the stratification structure that allows Arctic sea ice to exist, and can potentially lead to "tipping point" or threshold behaviour in the ice cover. For these reasons, runoff was chosen as a focus for this task.

The effect of river runoff on the Arctic Ocean was investigated using a 1D process model developed for this task from an existing model (1DICEx; see Fig. 2). Runoff scenarios of up to 0.20 Sv (about a doubling of present day runoff) were tested, with no disappearance of the halocline or Arctic sea ice cover from runoff changes alone. The main result is that the warm waters of Atlantic origin move closer to the surface with increasing river runoff, but the effect is counteracted by the stronger stratification from freshening the surface surface. The net effect in 1DICEx is a small increase in sea ice thickness when runoff increases, with about half the increase explained by the decreasing freezing point as a result of the freshening itself (Nummelin et al. 2015).

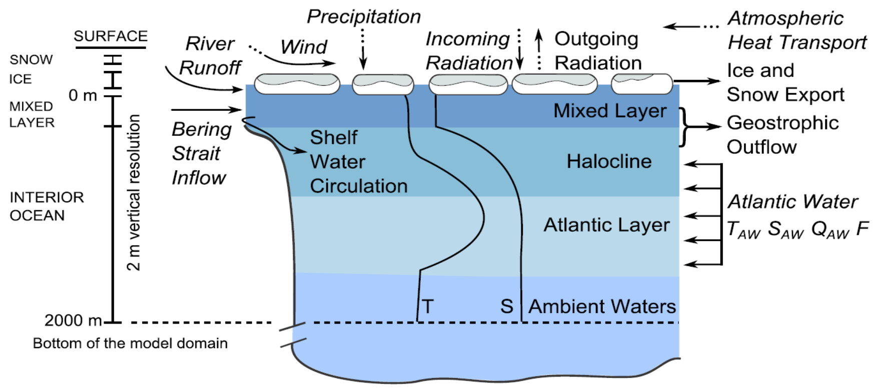


Figure 2. A simplified description of the Arctic Ocean processes determining stratification and regulating vertical ocean heat flux. These processes are simulated in the 1DICEx model used by Nummelin et al. (2015).

In addition, the 1DICEx process model has been used to test the impact of increasing radiative forcing. Results show an enhanced seasonal cycle in the Arctic, with annual mean sea ice thickness of 1 m and winter thickness of 1.5 m. These results will be followed up in the ice2ice project with an aim to publish a short paper with the main results compared to similar GCM studies.

Additional practical lessons:

- 1DICEx is an extended version of the original 1DICE model ("extended" by the addition of an interactive Atlantic inflow). We realized during the process that this was really only feasible for the Arctic Ocean proper. "Coupling" the Arctic column to a Nordic Seas column as originally planned would require consideration of an extra degree of freedom – the overturning loop of the double estuary circulation often used to describe the Arctic Mediterranean. We were not confident that we could get good constraints on the results given the amount of tuning that would be involved.
- Changes in ocean mixing are poorly constrained, but likely important. Other than NorESM, where mixing is a saved output variable, mixing would need to be calculated as a residual of horizontal ocean heat transport minus surface ocean-atmosphere (latent, sensible, radiative) heat flux. This turns out to be quite involved, as Bruno Tremblay's group at McGill University have seen with CCSM4.

Task 3 – Quantify ice sheet size, stability and threshold behavior during past warm climates

Petra Langebroek with Kerim Nisancioglu

The last interglacial (~130-115 thousand years ago) is the most recent period with high latitude temperatures slightly higher today. It is therefore often considered as an analogue for what might happen in the near future. During the last interglacial sea level was approximately 7 m higher than today. This indicates that (large) parts of the Greenland ice sheet, and possibly also parts of the Antarctic ice sheet, were melted. We investigated the cause of the high latitude warming during this period, and the effect of the warming on the size and stability of the Greenland ice sheet.

We performed several climate model simulations with the low-resolution version of the in-house Norwegian Earth System Model (NorESM-L). In these simulations, we set orbital and greenhouse gas forcing to values representing the last interglacial. We showed that annual mean temperatures did not vary much over the last interglacial. In contrast the variations in seasonal temperatures were large. In the Northern Hemisphere, an enhanced seasonal cycle is found during the early last interglacial, with summers warmer and winters colder than today. During the later part of the last interglacial, the opposite is simulated, with relatively cold summers and warm winters in the Northern Hemisphere. These variations in seasonal temperatures are the result of varying orbital configurations. In general, the last interglacial greenhouse gas concentrations were similar to pre-industrial values (~280 ppm CO2), and therefore did not cause a temperature increase. During the glacial period, preceding the last interglacial, greenhouse gas concentrations were much lower (180 ppm for CO2). In the early part of the last interglacial, greenhouse gas concentrations were still slightly lower than during the pre-industrial. This caused a small global and season-independent cooling.

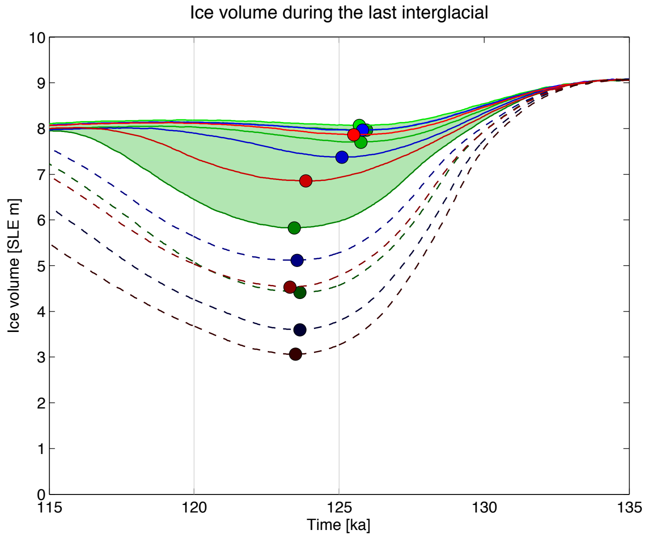


Figure 3. Simulated Greenland ice volume change over the last interglacial using various ice model parameters. Solid lines indicate solutions in accordance with ice core data. Dashed lines show rejected solutions. The maximum amount of ice loss is 1-3 meter in sea level equivalent. The timing of the ice sheet minimum is indicated by coloured dots, and occurred approximately 125 ky before present.

Despite the fact that the last interglacial warmth was caused by insolation, and not enhanced greenhouse gas concentrations, it remains an interesting period to assess the stability of the Greenland ice sheet under a warmer than present climate. We used the ice sheet model SICOPOLIS to investigate the effect of last interglacial climate on the Greenland ice sheet. As expected, the ice sheet melted during the early last interglacial, and re-grew during the later part of the last interglacial. The melting occurred mostly on the rims and on the south-western flank of the ice sheet. The central height of the ice sheet only decreased by a few hundred meters. The total amount of melt largely depends on the ice sheet model parameters and the climate forcing set-up. Using ice core data we could eliminate the simulations suggesting a largely melted Greenland ice sheet. The total amount of Greenland melt during the last interglacial is found to be between 1 to 3 meter in sea level equivalent, which is similar to the amount found in previous studies.

WP2: Pliocene (2.6-5.3 Ma)

Key questions: *What does the paleoclimate record tell us about the dynamics of the Pliocene, a warm period with greenhouse gas concentrations close to those predicted for the future?*

Task 4 – Characterizing polar amplification

Bjørg Risebrobakken with Carin Andersson

Polar amplification occurred during the Pliocene, but large uncertainties exist regarding the magnitude of the amplified warming. In reconstructions, the largest ocean temperature anomaly is found in the Nordic Seas. However, this warming has not been well constrained. Within DYNAWARM, existing data has been collected, and new data has been produced to better constrain the warming.

The new compilation of previously published Pliocene SST data have focused on U_K^{37} records from the Atlantic Ocean. The Pliocene latitudinal temperature gradient was reduced relative to the present temperature gradient, both in the South and North Atlantic. Even though most records are of low resolution, or only cover part of the Pliocene period, it is clear that Pliocene ocean temperatures were quite variable and that the latitudinal temperature gradient has changed over time.

Through DYNAWARM, we have improved our knowledge of the Pliocene conditions in the Nordic Seas. In collaboration with ESM and OCCP, climate reconstructions have been done for ODP site 642B in the eastern Nordic Seas based on several proxies; U_k^{37}, foraminifer faunal counts, stable isotopes ($\delta^{18}O$) and trace element ratios (Mg/Ca) of the non-extant planktic foraminifer *Neogloboquadrina atlantica*. Absolute values of estimated SSTs depend on the reconstruction method used. The U_k^{37} SSTs show warmer Pliocene than Holocene temperatures, but less so than indicated by previous studies from the Nordic Seas (a mean warming of about 2°C vs. 3-12°C). SSTs calculated based on both foraminifer faunal counts and Mg/Ca are on average lower compared to late Holocene estimates of summer (JAS) SSTs for the same area (10-11°C). The cold temperatures recorded by foraminifer fauna and Mg/Ca are supported by *G. bulloides* and *N. Atlantica* $\delta^{18}O$. However, all records also document periods with warmer than Holocene temperatures. Our results emphasize the importance of being aware of which proxies are used, and on what information they provide. Furthermore, we document that several shifts in climate conditions occurred in the Nordic Seas during the Pliocene.

Looking at the overall trends, there is a good agreement between the Mg/Ca-based and foraminifer-based SST estimates in terms of absolute values, while on finer scales, there are notable differences among the different SST proxies. These differences illustrate the challenges of working with non-extant species (i.e. *N. atlantica*), both for geochemical and fauna analysis. *Neogloboquadrina atlantica* (sin) is the dominant species of the Pliocene foraminifera fauna in the Nordic Seas. Since the climatic preference and calibration of *N. atlantica* is unknown, a large uncertainty is introduced when calculating temperatures. Independent of this increased uncertainty, both Mg/Ca and foraminifer fauna based temperatures as well as planktic $\delta^{18}O$ indicate that the subsurface water was mostly colder during the Pliocene than during the present interglacial.

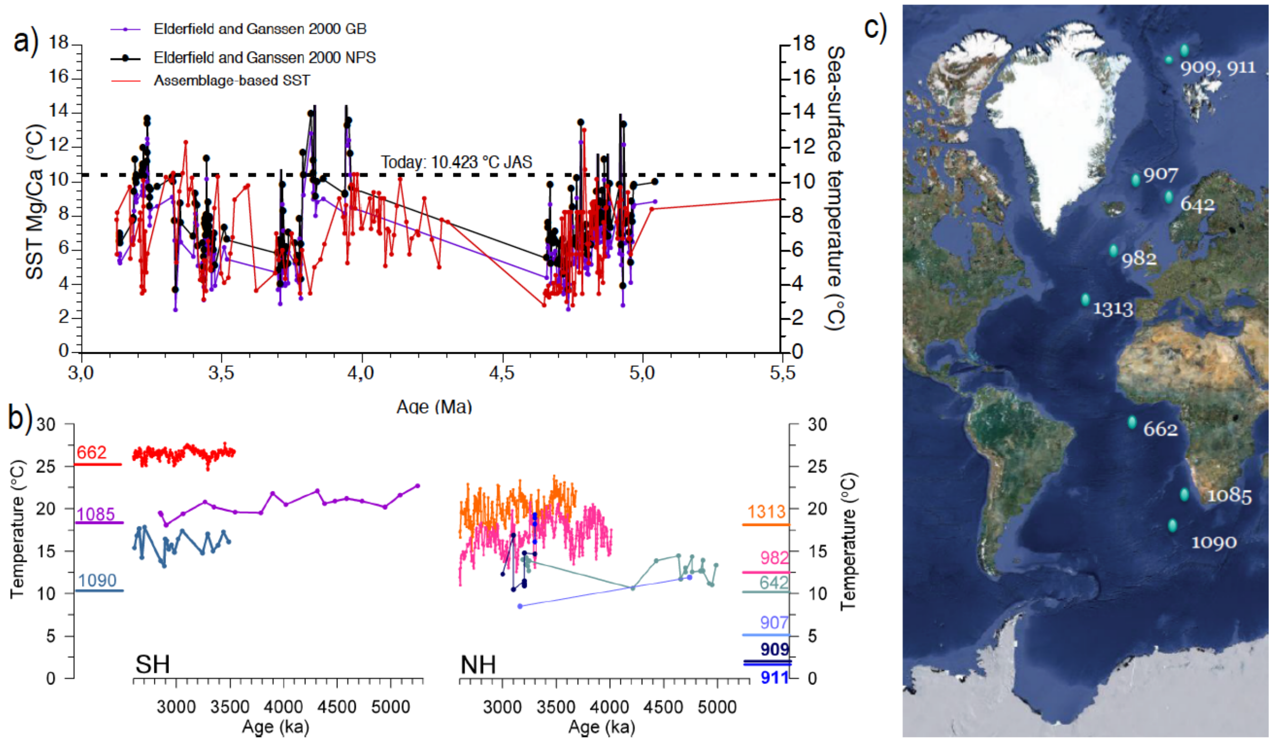


Figure 4. a) 642B SSTs calculated based on foraminifer faunal counts (red) and Mg/Ca (blue and black, different color reflects different calibrations) are on average lower compared to late Holocene estimates of summer (JAS) SSTs for the same area, i.e., below 10-11°C. b) Compiled previously published and new Pliocene U^{k}_{37} SSTs records from the Atlantic Ocean. 662: Herbert et al., 2010; 1085: Rommerskirchen et al., 2011; 1090: Etourneau et al., 2010; 1313: Naafs et al., 2010 and Naafs et al., 2012; 982: Lawrence et al., 2009; 642: Risebrobakken and McClymont, unpublished data; 907: Schreck et al., 2013; 909 and 911: Robinson, 2009. The horizontal lines indicate the modern temperature at the corresponding color-coded site. c) Map showing the location of site 642 and the other sites included in the compilation.

Additional practical lessons:

- Calculating foraminifer-based temperatures for the Pliocene has normally been done following the "PRISM-lumping" into a *Neogloboquadrina*–cold and a *Neogloboquadrina*-warm group. This approach appears to work less well at Site 642, primarily due to a high abundance of the non-extant species *N. atlantica* and the lumping of *N. pachyderma* (sin) and *N. pachyderma* (dex). In Holocene SSTs reconstructions, it is basically the relative abundances of *N.*

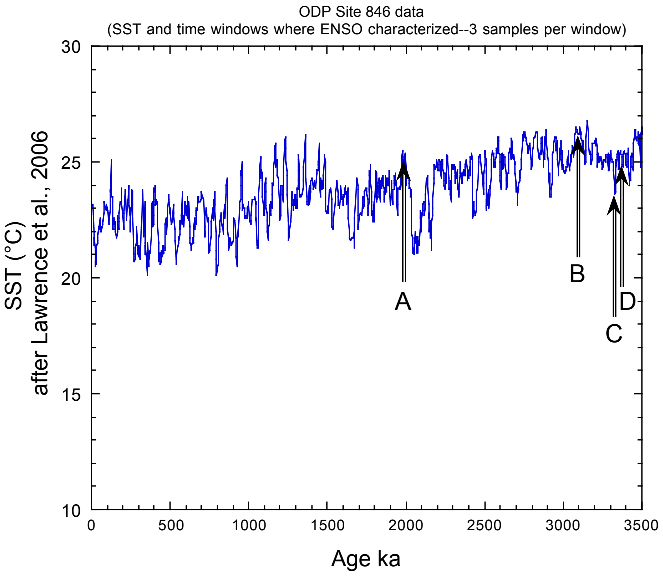
pachyderma (sin) and *N. pachyderma* (dex) that drive the pattern of estimated SSTs in this area. Hence, lumping these two species is counterintuitive and likely to result in spurious SST signals. At Site 642, there is an abundance of *N. atlantica* (belonging to the cold group) but very few species belonging to the warm group. In the modern ocean, high percentages in the cold group are primarily the result of an almost mono-specific assemblage comprising of *N. pachyderma* (sin), found at very high latitudes and/or during cold periods. Hence, samples with abundant *N. atlantica* in the Pliocene assemblage may result in too conservative, cold SST estimates. The PRISM method of *Neogloboquadrina* lumping produces a slight deterioration in the overall performance of the transfer function.

Task 5 – Assessing the sensitivity of the tropical Pacific climate system

Ulysses Ninnemann with Kikki Kleiven

The goal of task 5 was to produce new constraints on ENSO variability during the Pliocene. The Pliocene offers an excellent case study to assess ENSO behavior during a period with elevated CO_2 and warmer/thicker tropical thermocline conditions. While mean zonal temperature gradients were clearly reduced during the mid Pliocene (Chaisson & Ravelo, 2000; Wara et al., 2005; Dekens, 2008) it is not clear if this was due to a permanent El Nino like state (Ware et al,. 2005; Ravelo et al., 2006), implying less interannual variability, or was the result of increased frequency and/or intensity of ENSO (e.g. Wunsch, 2009).

In order to differentiate between these two Pliocene scenarios, decreased interannual variability (permanent ENSO state) and increased variability (frequent/intense ENSOs), we analyzed the $d^{18}O$ of single foraminifera from 4 different time slices; 3 within the warm Pliocene and 1 within the early Pleistocene (see figure left panel). We extended the approach of Scraxton et al., 2011 who analyzed single foraminifera in ODP Site 846. Located in the eastern equatorial Pacific, ENSO is the main source of variability in both surface and thermocline temperatures at this location (see Scraxton et al., 2011). We analyzed both surface (*Globigerina ruber*) and thermocline (*Neogloboquadrina dutertrei*) dwelling foraminifera in order to assess the scale and frequency of extraseasonal variability and their relationship to mean thermocline properties and vertical temperature gradients. While this approach was used previously (e.g. Scraxton et al., 2011) the low number of analyses (9-40 individuals) raised questions about the significance and representativeness of the results.



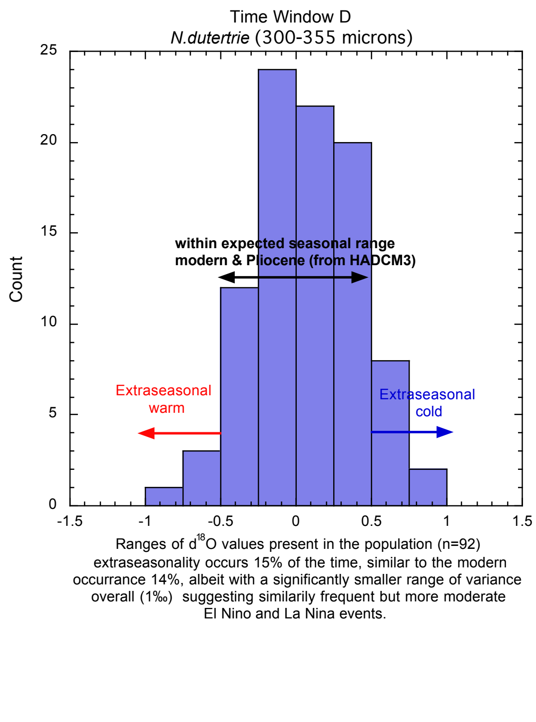


Figure 5. Pliocene ENSO.

For DYNAWARM, we increased the total data constraints on mid-Pliocene ENSO variance by approximately an order of magnitude. While laboratory analyses were only completed in late 2014, and the data and statistical analysis is still ongoing, initial results suggest that ENSO variability did persist in the warmer Pliocene, tentatively confirming previous findings of persistent Pliocene ENSO (Figure 5). However, the total range of variance was reduced, at least in some time windows suggesting weaker intensity of interannual events.

While low frequency variance was discounted/neglected in previous Pliocene studies (Scraxton et al., 20011), it can significantly increase total variance and must be accounted for (Koutavas et al., 2006; Koutavas pers. comm.) as there is still significant millennial to orbital scale climate variability within Pliocene sea surface temperatures (Lawrence et al., 2006). Our sampling strategy was designed to account for this. We sampled 3 adjacent samples in each time window to assess inter-sample trends in mean temperatures and also the (ir)regularity of interannual variability within a given time window. These analyses will provide a robust estimate of whether Pliocene ENSO intensity is similar to that observed in the Holocene and whether Pliocene ENSO activity is as variable as in the recent past (Holocene; e.g. Cobb et al., 2013) or is more regular and periodic as previously suggested (Scraxton et al., 2011; albeit based on very few data points).

WP3: Climate Sensitivity

Key questions: *What is the range of observed climate sensitivity?*

Task 6 – Assessing the Sensitivity of High-Latitude Climate Dynamics

Igor Esau with Stephen Outten

Warm climate periods are characterized by Arctic sea ice retreat and enhanced northward heat transport in the atmosphere (HTRA) and the ocean (HTRO). The heat transport from lower latitudes balances the surface energy deficit in the region, but simultaneously makes the polar climate highly sensitive to variations in this heat inflow. This feature is known as the polar amplification (PA) of global warming. Several mechanisms have been proposed to explain PA, both local (related to the processes of the heat trapping in the lower atmosphere and insolation of the upper ocean layers) and non-local (related to modulation of the heat inflow by the large-scale climate dynamics). Whether the recently observed PA is an intrinsic feature of natural climate variability during the modern warm interglacial period is of academic and practical interest. The analyses performed here of published high-resolution paleoclimate and instrumental temperature data suggests that PA is essentially a stochastic fluctuation. In northern regions (Greenland, Svalbard, Franz Joseph Land, Northern Ural and Severnaja Zemlja) these fluctuations are seen in some decadal intervals (notably 1920-40s and 1990-on) over the last century but not earlier. In more southern regions (Island, the Nordic Seas), PA fluctuations are seen back to 1000 A.D.

Do the data from different locations show a geographically distributed signature of the same large-scale phenomenon? Alexeev et al. (2005) suggested that PA could be seen as a response eigenmode to low-latitude warming anomalies. Earlier, J. Bjerknes (1964) suggested that a response to an anomaly in the heat transport should cause oscillations between HTRA and HTRO controlled by sea ice and the ocean mixed layer depth. Analysis of a 600-year long integration of the Bergen Climate Model (BCM) revealed quasi-regular oscillations between HTRA and HTRO, with nearly compensating anomalies (correlation coefficient -0.87) on multi-decadal time scales. Unlike the integrations with ECHAM5 model analyzed in Jungclaus and Koenigk (2010), BCM data did not show sporadic synchronous changes in the heat inflow that could lead to drastic decadal warming or cooling of the Arctic. The approximate period of this Bjerknes oscillation (BO) was found to be of 60-90 years. The geographical pattern of the corresponding surface air temperature anomalies is shown in Fig. 6. Unfortunately, the majority of paleorecords are found at locations where the BO signal is expected to be weak. The model response is relatively robust in terms of overall geographic patterns in other CMIP5 models, but there are significant shifts in the maxima.

In conclusion, we tend to see the Bjerknes oscillation as a real mode of the polar multi-decadal variability despite somewhat weak support from the paleoclimate data. The specific dynamics and relative role of components of the Bjerkenes heat transport compensation mechanism remain rather unclear. The BO predicts that the long-term polar warming should be less pronounced than indicated by linear extrapolation of the warming over the recent three decades if new physical feedbacks do not emerge.

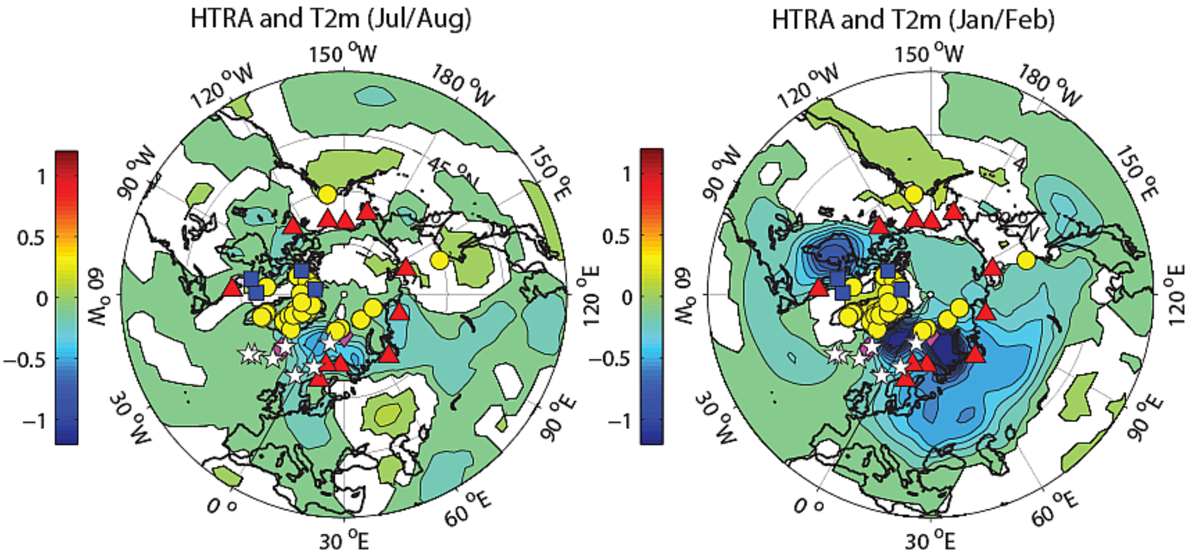


Figure 6. Regression of the multi-decadal meridional atmospheric heat flux variations on the surface (2 m height) air temperature field in the summer and winter season obtained in 600 years run of the Bergen Climate Model. The different symbols show location of the paleo-climate data samples from PANGEA (last checked at the end of 2013).

Ongoing work and future plans

Task 1: This task led directly to the NoAClim project (2014–2018) involving DYNAWARM scientists John Birks, Bjørg Risebrobakken, Camille Li, and Cathy Jenks plus other researchers in Norway, Finland, Germany, UK and USA (www.uib.no/en/rg/EECRG/56799/noaclim). As part of NoAClim, the past and present distributional data of the 13 taxa compiled in D1.1 will be plotted on 1000-year fine-resolution maps of paleoclimate data based on the HadCM3 model being prepared by Paul Valdes (Bristol University) for NoAClim. The time-series of proxy temperatures (D1.2) will also be used in NoAClim. Work on climate and plant diversity will be completed soon after Vivian Felde (UniClimate and Department of Biology) has defended her PhD thesis.

Task 2: DYNAWARM was a nice platform for input to the new ERC project ice2ice (2014-2019), in which all participants of this task and some from Task 4 will play an active role. Runoff experiments in an ocean general circulation model (MICOM) show results that are generally consistent with the 1DICEx results, but with interesting regional differences (e.g., ice thickness increases in the Canadian basin, decreases on the European side) that we are currently analysing.

Task 3: This research will be continued in several ongoing projects. The size and stability of the Greenland ice sheet during past warm periods will be further investigated in Petra Langebroek's postdoc project IceBed. Here we will also determine the CO_2 levels under which the Greenland ice sheet glaciates and deglaciates. Currently, a Master's student is investigating the impact of sea ice loss on the mass balance of the Greenland ice sheet by exploring our Pliocene climate model simulations. In addition to this, the topic of Greenland ice sheet stability during the Last

Interglacial, MIS3 (60-30ka BP) and Holocene Thermal Optimum (~8 ka BP) will be further addressed in the ERC ice2ice project.

Task 4: Activities related to DYNAWARM Task 4 will continue through the projects OCCP (Ocean Control on high latitude climate sensitivity – a Pliocene case study), BIGCHANGE and PEGSIE, in which participants from this task and Task 2 will play a role. Following the last Pliocene workshop, Barcelona September 2014, the workshop organizers have applied for support to establish a PAGES working group on Pliocene climate. If established, several DYNAWARM personnel will aim to be active within this working group. It was also suggested that the next Pliocene workshop be held in Bergen in 2016.

Task 5: This work will continue with efforts to find additional support for the preliminary conclusion that ENSO variability did persist in the warmer Pliocene, tentatively confirming previous findings of persistent Pliocene ENSO. The next step is to assess (statistically) the data collected from adjacent samples in order to quantify the contribution of low frequency trends (e.g., due to bioturbative mixing of millennial scale trends in temperature) within these sample windows.

Task 6: Ongoing work involves a long climate model run without ocean forcing. This run will help to identify the oscillation modes that are driven by atmospheric interactions with the ocean mixed layer (essentially the Bjerknes Compensation Mechanism) and modes of internal (stochastic) atmospheric variability. The result will be a publication. In addition, decadal resolution paleoclimate data are now accessible, which would support reassessment of the variability in the affected region over longer time scales.

References

Alexeev VA, PL Langen, JR Bates, 2005: Polar amplification of surface warming on an aquaplanet in "ghost forcing" experiments without sea ice feedbacks, Climate Dynamics, 24 (7), 655-666

Bjerknes J, 1964: Atlantic air-sea interaction, Advances in Geophysics, 10, Academic Press, 1-82

Etourneau, J., R. Schneider, T. Blanz, and P. Matrtinez, 2010. Intensification of the Walker and Hadley atmospheric circulation during the Pliocene-Pleistocene climate transition, Earth and Planetary Science Letters, 297, 103-110.

Herbert, T. D., L. C. Peterson, K. T. Lawrence, Z. Liu, 2010. Tropical Ocean Temperatures over the Past 3.5 Myr, Science, 328, 5985, 1530-1534.

Jungclaus JH, T Koenigk, 2010: Low-frequency variability of the arctic climate: the role of oceanic and atmospheric heat transport variations, Climate dynamics 34 (2-3), 265-279

Lawrence, K. T., T. D. Herbert, C. W. Brown, M. Raymo, and A. M. Haywood, 2009. High-amplitude variations in North Atlantic sea surface temperatureduring the early Pliocene warm period, Paleoceanography, 24, PA2218, doi:2210.1029/2008PA001669.

Naafs, B. D. A., R. Stein, J. Hefter, N. Khélifi, S. De Schepper, and G. H. Haug, 2010. Late Pliocene changes in the North Atlantic, Earth and Planetary Science Letters, 298, 434-442.

Naafs, B. D. A., J. Hefter, G. D. Acton, G. H. Haug, A. Martinez-Garcia, R. D. Pancost, R. Stein, 2012. Strengthening of North American dust sources during the late Pliocene (2.7 Ma), Earth and Planetary Science Letters, 317-318, 8-19, doi:10.1016/j.epsl.2011.11.026

Robinson, M. M., 2009. New quantitative evidence of extreme warmth in the Pliocene Arctic, Stratigraphy, 6(4), 265-275.

Rommerskirchen, F., T. Cordon, G. Mollenhauer, L. Dupont, E. Schefuss, 2011. Miocene to Pliocene development of surface and subsurface temperatures in the Benguela Current system, Paleoceanography, 28, PA3216, doi: 10,1029/2010PA002074

Schreck, M., M. Meheust, R. Stein, and J. Matthiessen, 2013. Response of marine palynomorphs to Neogene climate cooling in the Iceland Sea (ODP Hole 907A), Marine Micropaleontology, 101, 49-67.

List of publications

Published

1. Birks, H.H., South to north: Contrasting late-glacial and early-Holocene climate changes and vegetation responses between south and north Norway, The Holocene, 25, 37-52, 2015.
2. Birks, H.H., I. Aarnes, A.E. Bjune, S.J. Brooks, J. Bakke, N. Kühl and H.J.B. Birks, Late-glacial and early-Holocene climate variability reconstructed from multi-proxy records on Andøya, northern Norway, Quaternary Science Reviews, 89, 108-122, 2014.
3. Birks, H.H. and H.J.B. Birks, Vegetation responses to late-glacial climate changes in western Norway, Preslia 85, 215-237, 2013.
4. Birks, H.H., V.J. Jones, S.J. Brooks, H.J.B. Birks, R.J. Telford, S. Juggins and S.M. Peglar, From cold to cool in northernmost Norway: Late-glacial and early-Holocene multi-proxy environmental and climate reconstructions from Jansvatnet, Hammerfest, Quaternary Science Reviews, 33, 100-120, 2012.
5. Brown, K.J., H. Seppä, G. Schoups, R. Fausto, P. Rasmussen, and H.J.B. Birks, A spatio-temporal reconstruction of Holocene temperature change in southern Scandinavia, The Holocene 22, 165-177, 2012.
6. Davy R. and I. Esau, Global climate models' bias in surface temperature trends and variability, Environmental Research Letters, 9, 2014.
7. Davy, R. and I. Esau, Surface air temperature response in global climate models, Atmospheric Science Letters, 15, 13-20, 2013.
8. Felde, V.A., S.M. Peglar, A.E. Bjune, J.-A. Grytnes and H.J.B. Birks, The relationship between vegetation composition, vegetation zones and modern pollen assemblages in Setesdal, southern Norway, The Holocene, 24, 985-1001, 2014.
9. Kapfer, J., H.J.B. Birks, V.A. Felde, K. Klanderud, T. Martinessen, L.C. Ross, F. Høistad Schei, R. Virtanen and J.-A. Grytnes, Long-term vegetation stability in northern Europe as assessed by changes in species co-occurrences. Plant Ecology and Diversity 6, 289-302, 2013.
10. Langebroek, P.M. and K.H. Nisancioglu, Simulating last interglacial climate with NorESM: role of insolation and greenhouse gases in the timing of peak warmth, Clim. Past, 10, 1305–1318, 2014.
11. Trondman, A.-K., M.-J. Gaillard, F. Mazier, F. and 38 co-authors including H.J.B. Birks, Pollen-based quantitative reconstructions of Holocene regional vegetation cover (plant functional types and land-cover types) in Europe suitable for climate modelling, Global Change Biology, 21, 676-697, 2015.

In review

1. Felde, V.A., S.M. Peglar, A.E. Bjune, J.-A. Grytnes and H.J.B. Birks, Modern pollen–plant richness, diversity, and evenness relationships in Setesdal, southern Norway, The Holocene.
2. Nummelin, A., C. Li and L.H. Smedsrud, Response of Arctic Ocean stratification to changing river runoff in a column model, Journal of Geophysical Research (February 2015)
3. Vasskog, K., P.M. Langebroek, P.M., J.T. Andrews, J.E.Ø. Nilsen, A. Nesje, The Greenland ice sheet during the last glacial cycle: current ice loss and contribution to sea-level rise in a palaeoclimatic perspective, Earth-Science Reviews

In preparation

1. Outten, S., V. Alexeev and I. Esau: Bjerknes compensation and its role in the Arctic, for Climate Dynamics
2. Langebroek, P.M. and K.H. Nisancioglu, The Greenland ice sheet during the last interglacial constrained by present-day observations and paleo ice core reconstructions, for The Cryosphere
3. Andersson C. et al., Pliocene sea-surface temperatures for the eastern Norwegian Sea
4. Risebrobakken et al., Pliocene climate state changes in the eastern Nordic Seas
5. Nummelin, A. et al., see "Ongoing work and future plans" Task 2

List of conference presentations

1. Andersson, C., Estimating Pliocene foram-based sea-surface temperatures at ODP 642. DYNAWARM meeting, Bergen, May 2014.
2. Andersson, C., Telford, R., and Risebrobakken, B., Pliocene foraminifer-based sea-surface temperature estimates for the eastern Norwegian Sea (ODP Site 642). Multiproxy approach to the reconstruction of the Pliocene climate, Barcelona, Spain, September 2014.
3. Andersson, Carin; Risebrobakken, Bjørg; McClymont, Erin; Jensen, Lisbeth. Surface ocean conditions in the eastern Nordic Seas during the Pliocene. PAGES 4th Open Science Meeting, Goa, February 2013. Poster.
4. Contoux, C., Z. Zhang, C. Li, K.H. Nisancioglu, B. Risebrobakken, How to sustain warm Northern high latitudes during the late Pliocene? Roles of CO2, orbital changes and increased Mediterranean salinity on oceanic circulation, ICREA Workshop on Pliocene climate, 2014.

5. Contoux, C., Z. Zhang, C. Li, K.H. Nisancioglu, B. Risebrobakken, How to sustain warm Northern high latitudes during the late Pliocene? Roles of CO2, orbital changes and increased Mediterranean salinity on oceanic circulation, ICREA Workshop on Pliocene climate, Fall Meeting, AGU, San Francisco, December 2014.
6. DYNAWARM members, SKD Days, Bergen, December 2011.
7. DYNAWARM members, SKD Days, Bergen, November 2012.
8. DYNAWARM members, SKD Days, Bergen, October 2013.
9. Langebroek, P.M. and K.H. Nisancioglu, On the importance of reduced greenhouse gas concentrations during the early Last Interglacial, EGU General Assembly, Vienna, Austria, May 2014. Talk.
10. Langebroek, P.M. and K.H. Nisancioglu, The response of the Greenland ice sheet to Last Interglacial climate, EGU General Assembly, Vienna, Austria, May 2014. Poster.
11. Li, C., Towards untangling winter sea ice-atmosphere interactions, CanSISE Meeting, Toronto, Canada, July 2014. Talk.
12. Li, C., Atmosphere-ice-ocean interactions and Dansgaard-Oeschger cycles, Abstract PP11E-06, Fall Meeting, AGU, San Francisco, USA, December 2014. Invited talk.
13. Li, C., Earth Science Colloquium, LDEO and Columbia University, USA, 2013. Talk.
14. Nummelin, A., C. Li and L.H. Smedsrud, Role of changing river runoff in the Arctic Ocean Stratification, FAMOS (Forum for Arctic Modelling and Observation Systems), Woods Hole, USA, October 2013. Poster.
15. Nummelin, A., C. Li and L.H. Smedsrud, Arctic water masses under changing runoff, Ocean Sciences Meeting, AGU, Honolulu, USA, February 2014. Talk.
16. Nummelin, A., C. Li and L.H. Smedsrud, Arctic water masses under changing runoff, McGill University, Montréal, Canada, March 2014. Talk.
17. Nummelin, A., C. Li, L.H. Smedsrud and M. Ilicak, Arctic water masses under changing runoff, Finnish Meteorological Institute, Helsinki, Finland, August 2014. Talk.
18. Nummelin, A., C. Li, L.H. Smedsrud and M. Ilicak, Arctic water masses under changing runoff, NGF Annual Meeting, Oslo, September 2014. Invited talk.
19. Nummelin, A., C. Li and L.H. Smedsrud, Role of changing river runoff in Arctic Ocean stratification, FDSE Summer School, Cambridge, UK, September 2014. Poster.
20. Nummelin, A., C. Li, L.H. Smedsrud and M. Ilicak, Arctic water masses under changing runoff, FAMOS (Forum for Arctic Modelling and Observation Systems), Woods Hole, USA, October 2014. Poster.
21. Nummelin, A., C. Li, M. Ilicak and L.H. Smedsrud, Arctic runoff, ocean stratification and vertical heat fluxes, High Latitude Dynamics workshop, Rosendal, March 2015. Talk.
22. Nisancioglu, K.H. and A. Born, The Greenland ice sheet during the last interglacial. International Symposium on Contribution of Glaciers and Ice Sheets to Sea Level Change, 2014.
23. Nisancioglu, K.H. and Z. Zhang, Modeling Cenozoic climate and the Greenhouse to ice house transition - 50 million years of climate change, Centre for Earth Evolution and Dynamics, 2014. Talk.
24. Outten, S. and I. Esau, Bjerknes compensation and its role in the Arctic, G7-P2, Third International Symposium on the Arctic Research (ISAR-3), Tokyo, Japan, January 2013.
25. Risebrobakken, B., Andersson, C., McClymont, E. L. and Jensen, L., The Nordic Seas in the Pliocene – a hot spot or not?, EGU, Vienna, Austria, April 2012. Poster.
26. Risebrobakken, B., Andersson, C., McClymont, E. L. and Jensen, L., The Nordic Seas in the Pliocene: A hot spot or not? Goldschmidt, Montreal, Canada, June 2012. Talk.
27. Risebrobakken, B., Andersson, C., McClymont, E. L. and Jensen, L. The Nordic Seas in the Pliocene : A hot spot or not? Climate Change at high latitudes, Bjerknes Centre 10-years anniversary conference, Bergen, September 2012. Poster.
28. Risebrobakken, B., Andersson, C., Bachem, P. E., Contoux, C., Jansen, E., Li, C., McClymont, E., Nisancioglu, K. H., Ramstein, G., DeSchepper, S. Zhang, Z. OCCP: Ocean Controls on high-latitude Climate sensitivity – a Pliocene case study, Barcelona, September 2014. Poster.
29. Risebrobakken, B., Andersson, C., McClymont, E., Bachem, P. E. Globally warmer, but colder Nordic Seas. EGU General Assembly, Vienna, April 2014. Talk.
30. Risebrobakken, B., Andersson, C., McClymont, E., Jensen, L. Characterizing conditions of the Nordic Seas water column through the Pliocene. PAGES 4th Open Science Meeting, Goa, February 2013. Poster.
31. Risebrobakken, B., Andersson, C., McClymont, E. Characterizing conditions of the Nordic Seas water column through the Pliocene. 11th Conference on Paleoceanography, Barcelona, September 2013. Poster.
32. Risebrobakken, B., Andersson, C., McClymont, E. Characterizing conditions of the Nordic Seas water column through the Pliocene. 2nd workshop on Pliocene Climate, Bristol, September 2013. Talk.
33. Smedsrud, L.H., Arctic sea ice loss - a tale of two seasons, EGU General Assembly, Vienna, Austria, April 2012. Invited talk.
34. Smedsrud, L.H., Sea Ice work in Bergen - suggestions for future cooperation, Tromsø, Climate and the Cryosphere, Norwegian Sea Ice Workshop, February 2013. Talk.
35. Smedsrud, L.H., Challenges of the Changing Arctic: Continental Shelf, Navigation and Fisheries, Causes of Arctic Sea Ice Loss and a future outlook, Bergen, June 2013. Talk.
36. Zhang, Z., K.H. Nisancioglu, U.S. Ninnemann, Increased ventilation of Antarctic deep water during the warm mid-Pliocene, Fall Meeting, AGU, San Francisco, USA, December 2014.

Outreach activities

1. Website compilation of climate indicator values for native Nordic flora as a guide for estimating local climate from plant vegetation data or fossil assemblages: http://www.uib.no/en/rg/EECRG/78893/nordic-plant-attribute
2. Website translational tables between plant species and their pollen or spore types in Norway) to enable modern plant data to be translated into pollen types thereby permitting comparisons between plant richness and diversity and pollen richness and diversity: http://www.uib.no/en/rg/EECRG/55321/vascular-plants-and-their-pollen-or-spore-types-norway
3. Langebroek, P.M., Hvorfor stiger ikke havet like mye over alt? Tograder magasine, Nr 2, 2014.
4. Nilsen, J.E.Ø., K.H. Nisancioglu, T. Furevik, Arven fra polene, Dagens næringsliv, 2014.
5. Nisancioglu, K.H., Isen på Grønland og Arktis - Å finne ut hvor raskt isen smelter på Grønland og i Arktis er nordens største forskningsprosjekt, NRK P1 Her og Nå, 2014.
6. Nisancioglu, K.H., Klima, is og havnivå. Faglig-pedagogisk dag, 2014.
7. Nisancioglu, K.H., En temperaturrevolusjon på Grønland, Bjerknesdagen, 2014.
8. Nisancioglu, K.H., En insjø i ett hav av is. NRK P2 Ekko, 2014.
9. Nisancioglu, K.H., F. Ims, Understanding climate change in Greenland, Science Nordic, 2014.
10. Nisancioglu, K.H., Ø. Paasche, Det svake punkt, Dagens næringsliv, 2014.
11. Paasche, Ø., K.H. Nisancioglu, Verdens (hittil) raskeste klimaendringer. Aftenposten Innsikt, V8, s.88-89, 2014.
12. Risebrobakken, B., Kan fortidsklima fortelle oss noe om fremtiden? Hva vet vi om tidligere varmeperioder? Fana Gymnas Miljødager, 13-14. November, 2012, Bergen. Muntlig presentasjon.
13. Smedsrud, L.H., Arctic Sea Ice melting, Workshop on impacts on Europe of crossing climate tipping points, Seville, Spain, June 2012. Talk.
14. Ådnanes, J.H. (contributors C. Li, B. Risebrobakken), The grand puzzle of climate research, HUBRO, 2012/2013.

Integrated Model-data approach for understanding MUltidecadal Natural climate variabilITY

IMMUNITY

Final report SKD strategic project 2012-2015:
IMMUNITY – Integrated Model-data approach for understanding MUltidecadal Natural climate variabilITY

Project PI:
Odd Helge Otterå
Scientists involved:
Uni Research Climate: Carin Andersson Dahl, Trond Dokken, Odd Helge Otterå, Martin Miles, Thomas Toniazzo, Øyvind Lie
UiB: Kikki Kleiven (GEO), Ulysses Ninnemann (GEO), Kristian Vasskog (GEO), Atle Nesje (GEO), Tor Mjell (GEO), Jostein Bakke (GEO), Marthe Gjerde (GEO), Eivind Støren (GEOG), Svein Olaf Dahl (GEOG), Iselin Medhaug (GFI), Noel Keenlyside (GFI), Tor Eldevik (GFI)
NERSC: Yongqi Gao, Helene Langehaug, Yanchun He
IMR: Øystein Skagseth

Main objectives:
The primary objective of IMMUNITY has been to to integrate new, high-resolution palaeoclimatic time series and instrumental data with simulations with climate model simulations in order to explore the long-term climate variations during the last 1500 years.
Specifically the aim was to:
1) Collect and generate high-resolution marine and terrestrial proxy data reflecting changes in oceanic and atmospheric dynamics during the past 1500 years
2) Explore mechanisms of decadal to multidecadal variability in the Atlantic region through analysis of new and existing climate model simulations

Motivation and relevance
The climate system of the Earth is governed by forcing factors such as solar irradiance, volcanic particles, aerosols and atmospheric greenhouse gasses, and plays host to patterns of internal variability. The interaction between the forcing and internal processes of the climate system give rise to natural variability, which must be quantified before we can distinguish the temporal-spatial effects of human-induced changes on the climate system. In the North Atlantic Ocean, multidecadal variations in sea surface temperatures (SSTs), often referred to as the Atlantic Multidecadal Oscillation (AMO), is a dominant feature in the observational records. A wide range of regional climate variations of great societal importance have been linked to the AMO (e.g. Knight et al. 2006). For instance, recent studies indicate that the Atlantic warming during the recent decades could influence the Indian summer rainfall and also the East Asian monsoon. For Norway, multidecadal changes in the ocean climate are of particular relevance as they have a large impact on the marine ecosystem. Understanding the mechanisms generating these changes is therefore broadly important.

Some predictions for the next decades have been published recently emphasizing how multidecadal variability may impact both on hemispheric and more regional scales (e.g. Keenlyside et al. 2008). Such predictions, however, lack a solid physical basis, because the governing mechanisms behind such variability are poorly understood. Part of the problem is related to the fact that the instrumental observations of key climate variables are only available for the last 50 years from the ocean interior and for the last 150 years from atmosphere/land/sea surface, while satellite observations cover just the last few decades. Thus, while observational records are an essential starting point for detecting such variability, longer records and other tools are needed to fully characterize and understand variability with characteristic timescales of more than a few decades. In IMMNITY the research has revolved around the following research question/hypothesis: *Is the Atlantic Multidecadal Oscillation (AMO) intrinsic oceanic mode associated to changes in the Atlantic merdional overturning circulation (AMOC).* In order to address this, and related question, IMMUNITY has: 1) generated new and novel high-resolution paleo-data constraints on key ocean-atmosphere dynamics, 2) performed multi-centennial historical coupled climate simulations and ocean hindcast simulations for the last millennium, 3) carried out extensive model analyses of potential mechanisms for Atlantic multidecadal variability, 4) shed further light on mechanisms for East Asian summer monsoon variability on decadal scales and 5) performed extensive model evaluation and comparison to instrumental records and proxy data. The large amount of data and analyses that have been generated through IMMUNITY has thus contributed to a significant advance of our understanding of multidecadal variability in the climate system, and has built a great foundation for further studies on the topic in the future.

Results

WP1: Collecting, reconstructing and synthesizing observational based data

Task 1.1: Reconstructing Atlantic multidecadal variability in the ocean (H. F. Kleiven, U. Ninnemann, T. Dokken, C. A. Dahl, T. Mjell)

In this task the focus has been to provide new paleoclimatic proxy reconstructions of key ocean state variables over the last two millennia, such as the sea surface temperature and salinity, the intensity of Nordic Seas overflows, variations in ocean fronts and gyre circulation and thermocline variability. The core sites are situated at key locations in the North Atlantic in terms of describing surface and deep ocean circulation features (Fig. 1).

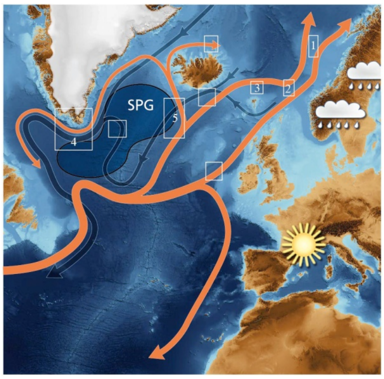


Figure 1.1: Map of North Atlantic and Nordic Seas. Red arrows denote main surface currents. Blue arrows denote deep water overflow and deep water flow. SPG = Sub Polar Gyre. The white boxes represent areas from where decadal-resolution paleoceanographic proxydata has been used and genrated in IMMUNITY. Symbols over land indicate the out-of-phase behaviour between weather patterns in Northern and Southern Europe on decadal time scales.

Very few temperature records exist over the North Atlantic that resolve temperature reconstruction on time scales less than decades. The Ormen site (area 2 in the map in Fig. 1.1) allows for paleoreconstruction of extraordinary temporal resolution, ie. 3-5 years per investigated sample. Temperature reconstructions over the past 1300 years based on Mg/Ca and $\partial^{13}C$ measurements of *G. bulloides* are displayed in Fig.1.2. Over the studied time period (1300 years) we observe a temperature shift of more than $4^{o}C$ from, what we expect to be peak Medieval Warm Period around 1000AD, to the Little Ice Age between 1300 and 1800AD. There are also very pronounced signals in temperature on multidecadal to centennial time scales, with amplitude of $2^{o}C$ (blue and red lines in Fig. 1.2, left). In the $\partial^{13}C$ record a very clear multidecadal signal is seen from the data, together with a multi-centennial and millennial signal. On longer time scales the Little Ice Age period appear as a very positive $\partial^{13}C$ signal, indicating a more subpolar source of the water reaching the Ormen site. On shorter time scales we observe a very strong multidecadal signal in the $\partial^{13}C$ record probably associated to changes in the relationship between subtropical and subpolar water entering the Nordic Seas, which may be controlled by mechanisms connected to the subpolar gyre circulation.

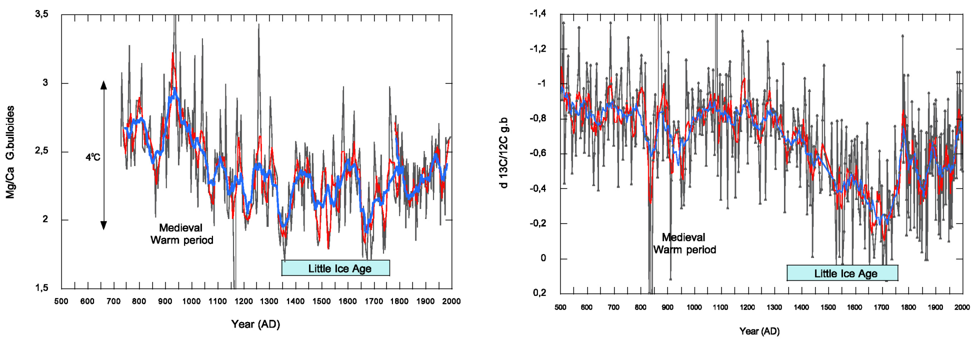


Fig. 1.2: Time series of Mg/Ca measurements of *G.bulloides* from the present back to about 700AD. The Mg/Ca data are not converted into temperature (left panel). Time series of $\partial^{13}C$ of G.bulloides from the present back to 500AD (right panel). Grey lines represent raw data, red lines 5pt average, and blue lines 11pt smoothed average

At the Eirik Drift (area 4 in the map in Fig. 1.1) near surface physical properties have also been reconstructed (Fig. 1.3). Changes in SST are strongly correlated with salinity, warm-salty vs. cold-fresh - resulting in near surface density changes in the subpolar gyre. The most extreme T-S anomaly (cooling-freshening) occurs at the onset of the LIA - confirming regional cooling and hydrographic changes in the Southern Greenland region as inferred from historical events.

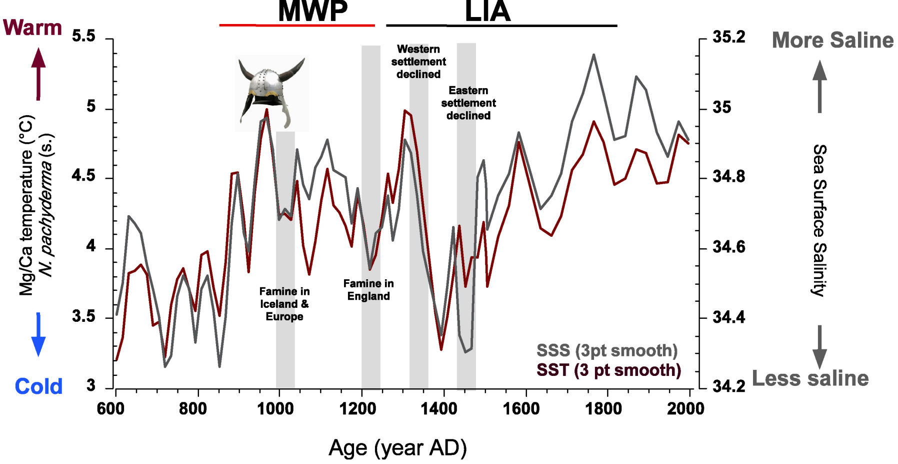


Fig. 1.3: Reconstructed SST/SSS from 600-2003 A.D. related to historical events in the Norse settlements on Greenland.

Finally, by applying a multicore recovered from a high accumulation rate site on the northern Gardar Drift (area 5 on the map in Fig. 1.1) we have reconstructed the Iceland-Scotland Overflow Water (ISOW) variability over the last millennium using the paleocurrent proxy “sortable silt” (SS). The SS record reveals that the flow speed across the Gardar Drift have varied on multidecadal to centennial timescales during the past ~600 years (Fig. 1.4). During this period the changes in ISOW vigor are occurring on similar timescales as observed and reconstructed AMV, with periods of strong overflow associated with warm climate, suggesting a link between deep circulation and basin-wide climate changes (Mjell et al. 2015).

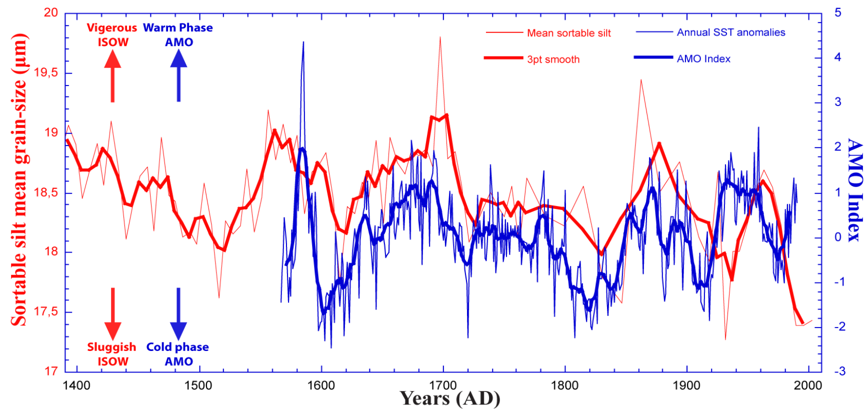


Figure 1.4: Reconstructed SS record from the Gardar drift (red line) and a reconstructed AMV time series based on tree-ring chronologies (Grey et al. 2004).

Task 1.2: Collecting and analyzing terrestrial reconstructions (J. Bakke, A. Nesje, M. Gjerde, S. O. Dahl, E. Støren, K. Vasskog)

The key objective in this task has been to provide reconstructions of multidecadal variations in temperature and precipitation on a seasonal basis in the North Atlantic and Arctic regions from instrumental data, historic data, tree rings, glacier records (mass balance and length change) and lake sediments.

In IMMUNITY, we have attempted to develop a new method for reconstructing winter precipitation and wind along the western coast of Norway and Svalbard over the last couple of millennia. By analysing the concentration of silica in the sediments, which is closely linked to the sandflux from the beach, one can then say something about the storm frequency at the site. Sediment traps have been deployed in a lake at Andøya, Arctic Norway. A potential ‘wind site’, where assumed influx of sand during periods of stronger westerlies-southwesterlies are prevailing, will be used as a proxy for periods of increased storminess. The sediment traps have been monitoring the sand influx for nearly 2 years, and will be collected in late June 2015 for analysis. The results from the monitoring period will be compared with instrumental data on wind activity as well as palaeodata on storm-induced sandy layers in lake sediments retrieved from the same lake. The results will then indicate if the lake sediment silica content can be applied for reconstructing storminess going back in time before meteorological measurements commenced.

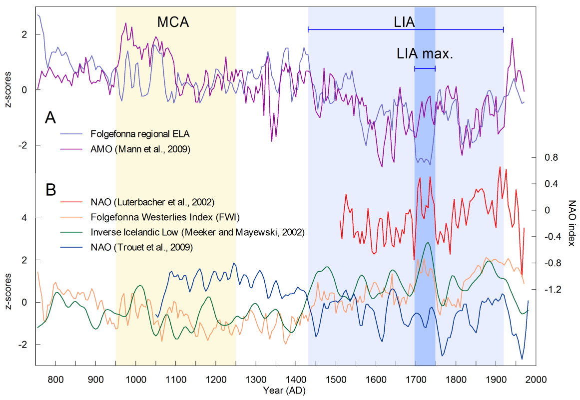


Figure 1.5. A) Reconstructed regional ELA from Folgefonna compared to a reconstruction of the Atlantic Multidecadal Oscillation (AMO). B) The Folgefonna Westerlies Index (ELA-tilt) compared to reconstructions of the NAO. MCA=Medieval Climate Anomaly; LIA=Little Ice Age.

As part of the IMMUNITY project, an entirely novel approach was applied in order to isolate the winter signal in a glacier reconstruction from the northern Folgefonna ice cap (Nordfonna). The approach is based on the principle of wind-transported snow, and that the Equilibrium Line Altitude (ELA) of an east-facing outlet glacier will be lowered relative to a west-facing outlet glacier during winters featuring strong westerly winds. A continuous reconstruction of ELA tilt across the ice cap was obtained by analysing two distal glacier-fed lake records located downstream from the Dettebrea (east-facing) and Botnabrea (west-facing) outlet glaciers. The tilt of the ELA is interpreted as an index for the strength of the wintertime westerlies across Folgefonna (Fig. 1.5), which is strongly linked to the NAO (Vasskog et al., 2015a). While centennial-scale changes in regional ELA is seemingly driven by large-scale North Atlantic temperatures, the approach applied here shows promise with regards to isolating the imprint of wintertime westerly winds and shows the potential of distal glacier-fed lakes to record changes in hydroclimate down to decadal timescales (Vasskog et al., 2015b).

Finally, we have also been analyzing high-resolution lake sediments from eastern Norway in order to reconstruct past flood frequency and to study the long-term impact of climate change on flood frequency (Støren and Paasche 2014; Paasche and Støren 2014). Preliminary results from investigations and monitoring of high-resolution lake sediment archives in the Glomma catchment in eastern Norway, indicate a potential for decadal scale paleo-reconstructions and show that flood frequencies are highly variable over long time scales and may be connected to large-scale climatic shifts. A comparison of reconstructed winter precipitation from five records in Scandinavia with data from two flood records from southern Norway over a period of 6000 years show a positive non-linear correlation between amount of winter precipitation and inter-arrival times of floods on centennial timescale and indicate that the spring snowmelt flood peak is dominating on long timescales (Støren and Paasche 2014).

Task 1.3: Paleoclimate data syntheses (M. Miles)

In this task a set of multicentury historical records of Atlantic Arctic sea ice, supplemented with high-resolution paleoproxy records, each reflecting primarily winter/spring sea ice conditions, has been synthesized (Miles et al. 2014). A signal of pervasive and persistent multidecadal (~ 60–90 years) fluctuations was established, that is most pronounced in the Greenland Sea and weakens further away. Covariability between sea ice and Atlantic multidecadal variability as represented by the AMO index is evident during the instrumental record, including an abrupt change at the onset of the early twentieth century warming. Similar covariability through previous centuries is evident from comparison of the longest historical sea ice records and paleoproxy reconstructions of sea ice and the AMO (Fig. 1.6). This observational evidence supports recent modeling studies that have suggested that Arctic sea ice is intrinsically linked to Atlantic multidecadal variability.

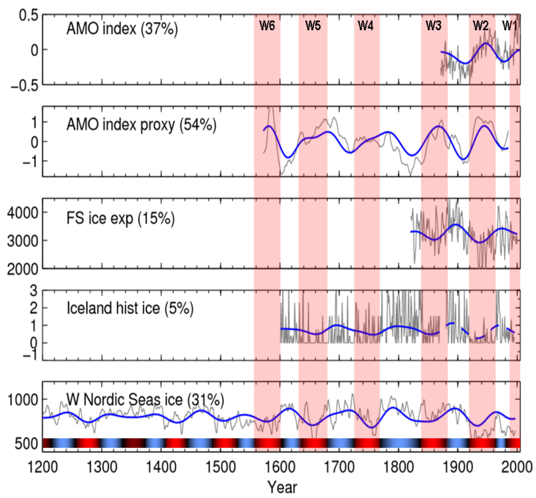


Figure 1.6: Persistent multidecadal fluctuations in sea ice linked to the AMO. Original time series (gray) and multidecadal 50–120 year component (blue) reconstructed from wavelet decomposition: (a) AMO modern index, not detrended, i.e.,North Atlantic SST anomaly. (b) AMO proxy index, not detrended, 10 year running average [Gray et al., 2004]. (c) Fram Strait ice export reconstructed from historical observations along SW Greenland. (d) Icelandic sea-ice severity index (1600–1870) and sea-ice incidence index (1880–2000) (sigma units). (e) Western Nordic Seas sea-ice extent proxy reconstruction.

Task 1.4: Assembly and analysis of instrumental records (Ø. Skagseth, T. Eldevik, Ø. Lie)

The objective of this task was to combine and synthesize multiple instrumental records in order 1) to provide benchmarks against which the model simulations, and 2) to act as a means of validation for the proxy-based reconstructions. As part of this task a new and novel concept to describe the relationship between the AMO and other ocean and atmospheric indices has recently been put forward (Lie et al. 2015). Rather than considering AMO-index itself, we have transferred this SST-anomaly into its *rate of change* (AMOROC). A comparison of the AMOROC index with the observed evolution of the extra-tropical atmosphere's third principal component during winter, the so-called "Scandinavian Pattern (ScP)", shows a strong correspondence on multidecadal time scales. The Scandinavian atmospheric mode describes anomalies in the meridional flow of the atmosphere over the eastern North Atlantic, being perpendicularly oriented to the zonal flow-anomalies resulting from variations of the NAO.

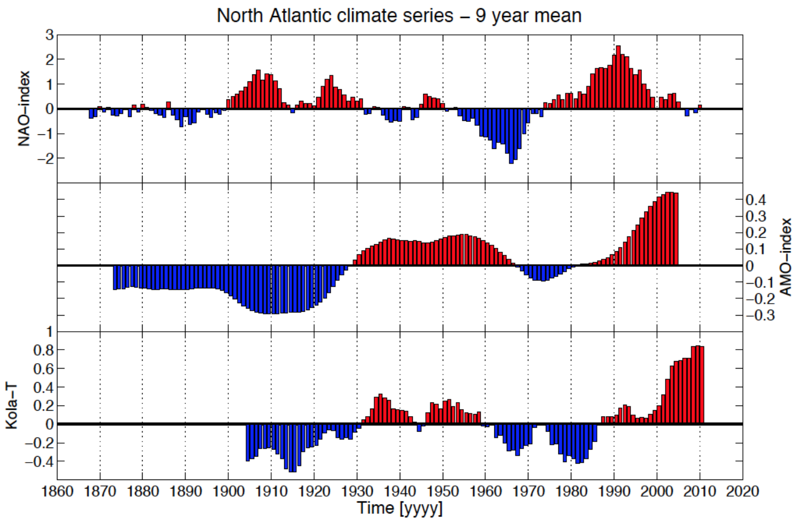


Fig 1.7: Time series of the NAO-index (upper), the Atlantic Multidecadal Oscillation (AMO) index (middle), and the Kola section mean temperature (lower graph). The series were filtered using a 9-year moving average. The AMO index is based on the sea surface temperature in the region 0–60° N and 7.5–75° W. The Kola section data were obtained from PINRO.

Also as part of IMMUNITY, the instrumental record from the Barents Sea region has been examined. The longest instrumental record of the Barents Sea climate is from the Kola section. Focusing on the multidecadal scales, the series shows substantial variations; cold at the beginning of the 20th century, a warm period in the 1930–1940s, followed by a cold period in the 1960–1970s and finally, a still ongoing warming (Fig. 1.7). A comparison with the Atlantic Multidecadal Oscillation (AMO) shows a remarkable similarity with that of the Kola section, demonstrating that the climatic variation found in the Kola section is a local manifestation of a larger-scale climate fluctuation covering at least the entire North Atlantic Ocean. After the 1930s the NAO-index leads the oceanic temperature series by some 5–10 years. In the earlier part of the time series this relation apparently vanish. The cause of this is unclear, but one reason could be the more sparse the base in the beginning of the record.

WP2: Model simulations of the last 1500 years

Task 2.1: Transient simulations from AD 500 to present day (T. Toniazzo, O. H. Otterå, Y. Gao, Y. He)

In this task the focus has been on setting up and conducting long transient model simulations for the last millennium using the NorESM. NorESM uses the Community Earth System Model (CESM) framework to jointly integrate atmosphere, ocean, land and ice sub-models. For IMMUNITY we adopted a configuration of the ocean model MICOM discretisized on 53 isopycnal layers on a tripolar grid with variable resolution of 2ºx(2º-1/2º). The atmospheric component has been CAM4 - L26 with the finite-volume dynamical core at 2.5ºx1.9º resolution. Compared with standard CAM, our configuration has two major changes and some parameter tuning. The first major change is a different surface flux computation over ocean that follows the COARE v3.0 algorithm of Fairall et al. (2003). This algorithm uses up-to-date self-similarity functions, which are commonly used today in weather forecast models. It produces less evaporation per wind stress than the default CAM-scheme (Large et al. 1994), which results in a weaker Hadley circulation and better zonal winds, with a positive impact on ENSO. The second major change is the correction to the energy errors of CAM (Williamson et al. 2015). This change involves three aspects: 1) a corrected updating for the air temperatures, 2) the inclusion of hydrostatic pressure work associated with layer mass changes and 3) inclusion of enthalpy fluxes associated with transfers of moisture within the atmosphere and between the atmosphere and the surface. These corrections have contributed to significant improvements in terms of precipitation, surface heat fluxes, windstress curl and the Hadley circulation. In order to achieve a better TOA balance in the coupled configuation, we tuned the model by lowering the cloud-formation threshold relative humidity and increasing the albedo of snow on ice. This helped mitigate a warm error in the Southern Ocean, and increases the sea-ice area.

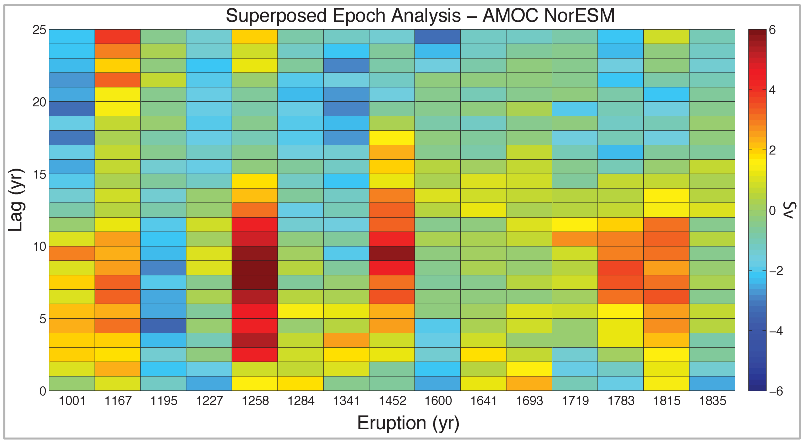


Figure 2.1: Superposed epoch analysis of simulated post–eruption annual mean AMOC strength in a NorESM simulation of the last millennium forced only by known historical volcanic eruptions.

For the transient historical model runs we used available natural and anthropogenic forcing data sets. We used total solar irradiance variations from Steinhibler et al. (2009), scaled to match the nominal 1850 value of 1360.89 W/m2 adopted for NorESM PI-control integrations in CMIP5. The TSI is updated once per year, and we do not include an 11-year cycle. For the volcanic forcing we adopt the mass mixing-ratio of volcanic sulphate aerosol given by Gao et al. (2008) in 18 height layers as a function of time and latitude. The mixing ratio is interpolated on model pressure levels, preserving integrated column density, using the climatology of the PI-control integration. We take into account the subsequent published corrections for the original data-set. For the greenhouse gases we use the CMIP5 historical GHG concentrations from 1850 onwards. Before 1850, the GHG concentrations are held constant at 1850 values. Finally, the non-volcanic aerosol loadings are held constant at 1850 values until 1850, then allowed to vary according to CMIP5 historical time-series. A total of three last millennium runs have been generated as part of IMMUNITY: one with only volcanic forcing, one with only solar forcing and a one include all forcings (also well-mixed greenhouse gases). We have in particular looked into the response of the Atlantic Merdional Overturning Circulation (AMOC)to volcanic forcing in NorESM. The NorESM simulation incorporating volcanic forcing for the last millennium show enhanced AMOC after some of the major eruptions in the last millennium, while minor changes or even a decrease in AMOC are simulated for others (Figure 2.1). This response is in line with previous studies (e.g. Otterå et al. 2010; Zanchettin et al. 2011; Ding et al. 2014).

Task 2.2: Hindcast ocean model simulations for the period 1900-2010 (Y. Gao, Y. He)

The objective in this task has been to set-up and carry out hindcast experiments with the Bergen isopycnic coordinate model. For this we have used new extended reanalysis data sets covering the whole 20th century (20CRv2) to force the model (Compo et al. 2011). The commonly used Coordinated Ocean-ice Reference Experiments phase-II (COREv2) for 1948-2007 is also used to force the model to serve as a reference simulation. The simulated AMOC in 20CRv2 and COREv2 simulations have comparable variability as well as mean state during the last three decades (Fig. 2.2). The simulated AMOC in the two experiments undergoes, however, very different evolutions during the period 1950-1970, with a sharply declining strength in COREv2 and a near inverse change in 20CRv2. Sensitivity experiments suggest that differences in the wind forcing between 20CRv2 and COREv2 have major impact on the simulated AMOCs during the 1950s-1970s (Fig. 2.2). It is furthermore found that differences in air temperature contribute to the difference in AMOC, but to a lesser extent than the wind. Comparisons with the International Comprehensive Ocean-Atmosphere Data (ICOADS) indicate the winds in 20CRv2 are relatively closer to the shipboard-observed wind compared to COREv2. However, both the reanalysis wind data and shipboard-based measurements have uncertainties especially in the Southern Ocean.

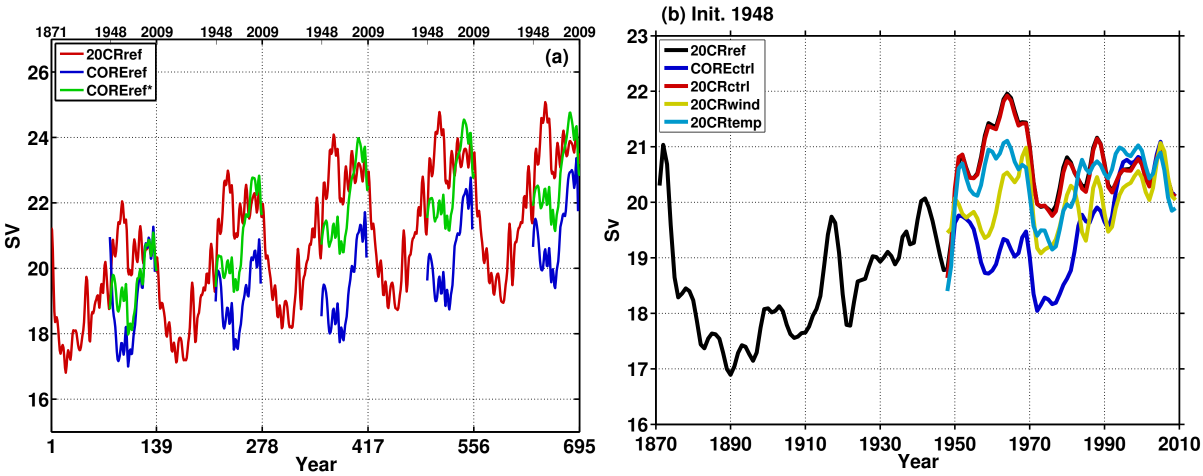


Fig. 2.2: (a) Timeseries of the simulated AMOC (Sv) from 20CRref (red) and COREref (blue) initialized from climatology of observation-based hydrography (PHC3.0; Steele et al., 2001). COREref* (green) is the same as COREref, but restarting in 1948 from the 1948 state from each cycle of 20CRref; (b) Timeseries of AMOC from the first cycle of 20CRref as in panel (a), and the coloured lines are from simulations starting from ocean condition in 1948 extracted from 20CRref. 20CRwind denotes simulation like 20CRref but with global wind fields replaced by CORE winds; 20CRtemp is as 20CRref but with air temperature over the North Atlantic and Arctic Ocean substituted by the COREv2 temperature.

An additional factor for the diverging AMOC in the decades following 1950 is the inevitable swopping of atmospheric forcing fields in 1948 in COREv2 during the cyclic spin-up of the ocean model. The latter is a fundamental issue for any ocean model experiments forced and spun-up with atmospheric reanalysis products of duration less than needed for a proper spin-up of the ocean. It may take about two decades for the AMOC to adjust to the new atmospheric states but a dynamically balanced ocean initial state tends to reduce the adjustment time and magnitude, and it implies that active use of model runs with atmospheric forcing fields extending back in time, like 20CRv2, can be favorable.

WP3 Data analysis and model-data comparison

Task 3.1: Model-data comparison (H. Langehaug, T. Eldevik, O. H. Otterå, T. Mjell, U. Ninnemann, K. Kleiven, T. Dokken, C. A. Dahl, I. Medhaug)

In this task various model outputs have been confronted with the high-resolution paleoclimatic proxy reconstructions and instrumental records generated in the project. In particular we have used the long historical model simulation with the BCM for the last 600 years and reconstructions of northward flowing Atlantic water mass properties (see WP1) to examine the potential relationship between changes in Atlantic ocean circulation and large-scale atmospheric circulation patterns during recent centuries (Otterå et al. 2015). Our hypothesis is that the ∂^{13}C measurements of the spring-dwelling planktic foraminifer, *G. bulloides,* can be used as a tracer of water masses with more Atlantic subtropical origin. A model – proxy data comparison suggests a strong link between the reconstructed water mass properties in the Nordic Seas and the simulated Intergyre Gyre (IGG) circulation in the North Atlantic (Fig. 3.1). When the IGG is strong in the model there is a northward extension of the subtropical gyre and warmer and more saline waters are advected into the Nordic Seas with a few years lag. The IGG is in turn strongly linked to the NAO, but with potential important interaction with the large-scale meridional overturning circulation. If the strong similarities between the Nordic Seas reconstruction and the simulated IGG reflect real changes in nature it would imply that natural forcings have been a major player in terms of decadal to multidecadal variations in Atlantic ocean circulation during the recent three centuries.

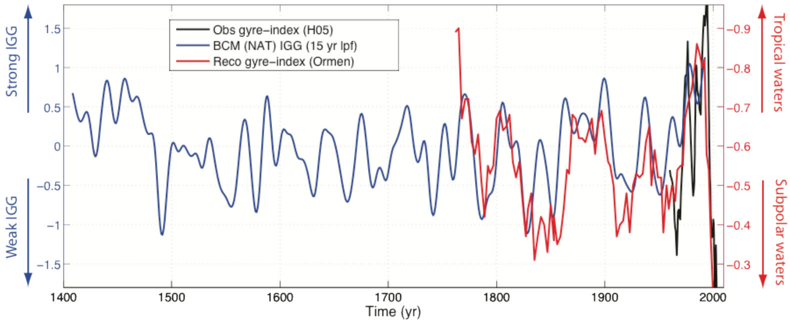


Figure 3.1: Simulated IGG index in the natural forced simulation with BCM (blue), reconstructed water mass characteristics from the Ormen site in the Nordic Seas based on *G. bulloides* $\delta^{13}C$ (red) and the SPG-index in black from Hatun et al. (2005).

Sediment based reconstructions of bottom water velocity at the Gardar Drift are commonly interpreted to reflect changes in the eastern Nordic Seas overflows. In IMMUNITY, we have tested this assumption by using a 500-year long historical simulation of the BCM to investigate the relationship between changes in the water that overflows through the Faroe Shetland Channel (FSC) and downstream bottom velocity at the location of the Gardar Drift. We identify a region in our simulation proximal to the geographical location of the northern Gardar Drift where 76 % of the variance in bottom velocity can be explained by changes in the transport and density of the FSC overflow (Fig. 3.2). Our findings support the assumption in the paleo literature that reconstructions of bottom water velocity at the Gardar Drift reflect past changes in the eastern Nordic Seas overflows. However, our results suggest that velocity changes downstream of the actual overflows are not a simple metric for upstream changes in transport, with density playing the largest role (Mjell et al. 2015).

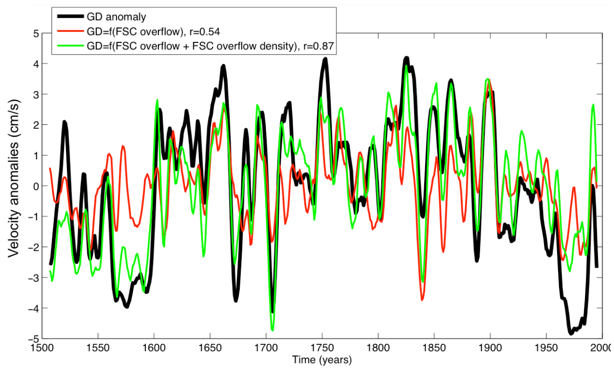


Figure 3.2: Cross correlation between the BCM GD and the transport (red) and density (green) at the FSC overflow. The dashed line is the 95% confidence intervals. B: Multiple linear regression (green) based upon the overflow transport and the overflow density. The black line is the 11-year smoothed BCM GD time series plotted as velocity anomalies. The correlation (r) given in the legend is between the BCM GD and the reconstruction of the BCM GD (red and green line).

Task 3.2: Mechanisms in the Atlantic region from models (H. Langehaug, O. H. Otterå, Y. Gao, T. Eldevik, N. Keenlyside, I. Medhaug)

In this task, key aspects of decadal and multidecadal-scale variability in the Atlantic region have been analyzed. In particular, a review of the mechanisms responsible for the AMO and a brief discussion of the linkages between the multidecadal variability in the northern and southern hemispheres, including between the Arctic and Antarctic, have been made (Drinkwater et al. 2013). In addition, a multi-model study of the Atlantic Multidecadal Variability (AMV) has been performed where different aspects of the governing mechanisms for AMV in the models have been examined (Ba et al. 2014). Despite large differences in model configurations, we find quite some consistency among the models in terms of processes. In eight of the ten models the mid-latitude SST variations are significantly correlated with fluctuations in the AMOC, suggesting a link to northward heat transport changes. Most models present strong evidence that high-latitude winter mixing precede AMOC changes. However, the regions of wintertime convection differ among models. In most models salinity-induced density anomalies in the convective region tend to lead AMOC, while temperature-induced density anomalies lead AMOC only in one model (BCM). However, analysis shows that salinity may play an overly important role in most models, because of cold temperature biases in their relevant convective regions.

The relative role of sub-polar deep water formation and Nordic Seas overflows for explaining variations in the AMOC has been examined through a detailed inter-mode comparison study (Lohmann et al. 2014). For all models, the maximum influence of variations in subpolar deep water formation is found at about 45°N, while the maximum influence of variations in Nordic Seas overflows is rather found at 55 to 60°N. Regarding the two overflow branches, the influence of variations in the Denmark Strait overflow is, for all models, substantially larger than that of variations in the overflow across the Iceland–Scotland Ridge.

The reconstruction of Iceland Scotland Overflow Water (ISOW; Mjell et al. 2015) suggests a close link to the AMO. Historical simulations for the last millennium have been used to explore the potential underlying mechanism for this potential relationship (Lohmann et al 2015). A similar link between the ISOW overflow and the AMO is also largely found in the model simulations. The analysis indicates that the basin-wide AMO index in the externally forced simulations is dominated by the low-latitude sea surface temperature (SST) variability and is not predominantly driven by variations in the strength of the Atlantic meridional overturning circulation (AMOC). This result suggests that a large-scale link through the strength of the AMOC is not sufficient to explain the (simulated) similar variation of Iceland–Scotland overflow strength and AMO index. Rather, a more local link through the influence of the Nordic seas surface state and density structure, which are positively correlated with the AMO index, on the pressure gradient across the Iceland– Scotland ridge is responsible for the (simulated) similar variation.

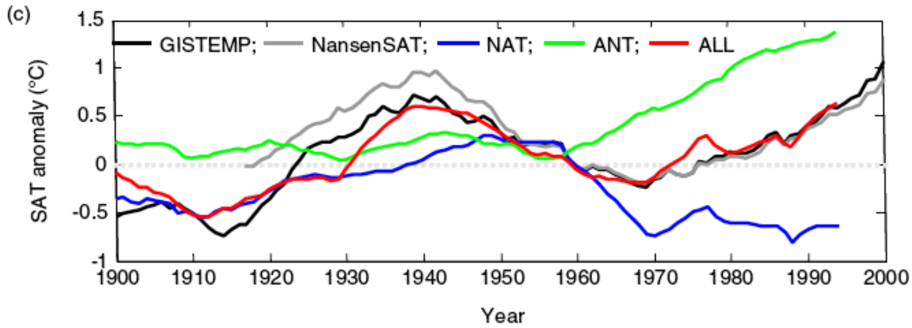


Figure 3.3: Annual mean surface air temperature (SAT) anomaly in the Arctic (north to 60°N) in observations and BCM simulations (5 member ensemble) with all forcing (red), natural forcing only (blue) and anthropogenic forcings only (green). Observations are the GISTEMP (black) and NansenSAT (grey).

The potential causes for the early 20th century warming in the Arctic (north of 60°N) have also been addressed (Suo et al. 2013). The simulations using the BCM can successfully reproduce the surface air temperature fluctuations in the Arctic during the 20th century (Fig. 3.3). Our results presented, based on model simulations and observations, indicate that an intensified solar radiation and a lull in volcanic activity during the 1920s–1950s can explain much of the early 20th century Arctic warming. The anthropogenic forcing, on the other hand, played a role in getting the timing of the peak warming correct. Melting and freezing of sea ice play a vital role in the heat exchanges between the ocean surface and the air, especially in sea-ice marginal regions, in particularly important through the well-known ice albedo feedback. An increased Barents Sea warm inflow and anomalous atmosphere circulation patterns in the northern Europe and north Atlantic also contributed to the warming.

Task 3.3: Teleconnections and monsoon variabilty (Y. Gao, O. H. Otterå)

In this task we have attempted to identify the causes of rainfall variability in East Asia regions, and in particular how various forcings may impact on rainfall patterns, either directly or via its impact on SST. The work in this task has benefitted from the ongoing strong and ongoing collaboration between BCCR and the Nansen-Zhu Center in Beijing. In particular we have used multi-ensemble historical BCM simulations to examine the potential causes for the inter-decadal shift in summer precipitation over eastern China during the second half of the 20th century (Wang et al. 2013). Our model results suggest that the anthropogenic forcing during this period was the main driver for this shift. The rapidly increasing greenhouse gases induced a notable Indian Ocean warming, causing a westward shift of the western Pacific subtropical high (WPSH) and a southward displacement of the East Asia westerly jet (EAJ) on interdecadal timescales, leading to more precipitation in Yangtze River valley. At the same time the surface cooling effects from the stronger convection, higher precipitation and rapidly increasing anthropogenic aerosols contributed to a reduced summer land–sea thermal contrast. Because of this the East Asian summer monsoon weakened resulting in drought in northern China.

Subsequent analysis of an unforced control simulation with BCM has shown that the Pacific Decadal Oscillation (PDO) could have played an equally important role in explaining the so-called ‘‘southern flood and northern drought’’ pattern that occurred during the late 1970s– 1990s (Yu et al. 2014). During positive PDO phases, the warm winter sea surface temperatures (SSTs) in the eastern subtropical Pacific along the western coast of North American propagate to the tropics in the following summer due to weakened oceanic meridional circulation and the existence of a coupled wind–evaporation–SST feedback mechanism, resulting in a warming in the eastern tropical Pacific Ocean. This in turn causes a zonal anomalous circulation over the subtropical– tropical Pacific Ocean that induces a strengthened western Pacific subtropical high (WPSH) and thus more moisture over the YRV region.

Ongoing work and future plans.

The new SKD project “Mechanisms of multidecadal variability in the climate system (MEDEVAC)” will be a natural follow-up and continuation of IMMUNITY. In this new project we will assemble and further develop the unique high-resolution paleoclimatic proxy reconstructions we have developed in IMMUNITY. New annually resolved marine reconstructions based on long-lived bivalve from the Nordic Seas will be generated, and a new tephra chronology will for constraining the timing of decadal ISOW variability over the last 600 years will be developed. In addition, high resolution lake sediment records from northern Norway, Bjørnøya and Svalbard with improved, high precesion chronologies based on PB210, tephra and paleo secular variations will be made. A particular focus in MEDEVAC will be on assessing the role of poleward atmospheric oceanic heat transports and their coupling through the socalled Bjerknes Compensation (BC). We will in particular identify the BC signal in the long pre-industrial control runs of a range of CMIP5 models. We will also carry out dedicated sensitivity experiments using coupled and uncoupled configurations of NorESM in order to estimate the effects of ocean-atmosphere coupling for BC. Finally, there are plans for new historical millennium runs using an updated and improved version of NorESM as part of CMIP6. Some of these runs are planned within the MEDEVAC project and will contribute to several of the associated MIPs in CMIP6, most notably PMIP and VolMIP.

The work in MEDEVAC will also be linked to ongoing NFR projects such as “Northern constraints on the Atlantic Thermohaline circulation (NORTH)” led from University of Bergen and “Long-range memory in Earth´s climate response and its implications for future global warming” led from University of Tromsø. The work on Atlantic multidecadal variations and potential linkages to East Asian Monsoon will be continued through ongoing collaboration with the Nansen-Zhu Center in Beijing, aided by a recently established common Bergen/Beijing PhD position at the Geophysical Institute in Bergen.

References

Compo, G.P. et al. The twentieth century reanalysis project, *Q. J. R. Meteorol. Soc.* **137**: 1–28 (2011).
Ding, Y., et al. Ocean response to volcanic eruptions in Coupled Model Intercomparison Project 5 simulations, *J. Geophys. Res. Oceans*, 119, 5622-5637 (2014).
Fairall, C. W., et al. Bulk Parameterization of Air–Sea Fluxes: Updates and Verification for the COARE Algorithm. *J. Clim.* 16, 571-591 (2011)
Gao, C., A. Robock, & C. Ammann. Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. J. Geophys. Res., 113, D23111, doi:10.1029/2008JD010239 (2008).
Grey, S. T., et al. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 A.D. *Geophys. Res. Lett.* **31**, L12205 (2004).
Keenlyside, N. S., et al. Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature* **453**, 84-88 (2008).
Knight, J.R., et al. Climate impacts of the Atlantic Multidecadal Oscillation. *Geophys. Res. Lett.* **33**, L17706 (2006).
Large, W. G., J. C. McWilliams, & S. C. Doney. Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parametrization. Reviews of Geophysics, 32, 363-403 (1994).
Luterbacher, J., et al. Extending North Atlantic oscillation reconstructions back to 1500. *Atm. Sci. Lett.* 2, 114-124 (2002).
Otterå, O.H., et al. External forcing as a metronome for Atlantic multidecadal variability. *Nature Geosci*., 3, 688–694 (2010).
Steinhilber F, J. Beer, & C. Fröhlich. Total solar irradiance during the Holocene. *Geophys. Res. Lett.* 36, L19704, doi:10.1029/2009GL040142 (2009).
Zanchettin, D., et al. Bi-decadal variability excited in the coupled ocean-atmosphere system by strong tropical volcanic eruptions, Clim. Dyn., doi:10.1007/s0038201111671 (2011).

Peer-reviewed publications

2015

Balascio NL, Francus P, Bradley RS, Schupack BB, Miller GH, Kvisvik BC, Bakke J and Thordarson T (2015) Investigating the use of scanning x-ray fluorescence to locate cryptotephra in minerogenic lacustrine sediment: Experimental results. Springer, I. Croudace, G. Rothwell (eds.), "*Micro-XRF Studies of Sediment Cores, Developments in Paleoenvironmental Research*", DOI 10.1007/978-94-017-9849-5_11.

Kolstø, S. M. (2013) North Atlantic climate and deep water variability since ~700 AD. Ph. D. thesis, University of Bergen, Juni 2013.

Lohmann K, Mignot J, Langehaug HR, Jungclaus JH, Matei D, Otterå OH, Gao Y, Mjell TL, Ninnemann U and Kleiven HF (2015) Using simulations of the last millennium to understand climate variability seen in palaeo-observations: similar variation of Iceland-Scotland overflow strength and Atlantic Multidecadal Oscillation, *Clim. Past.*, 11, 203-216, doi:10.5194/cp-11-203-2015.

Mjell, T.L., U.S. Ninnemann, T. Eldevik, and H.F. Kleiven, 2015: Holocene multidecadal-to-millennial scale variations in Iceland-Scotland overflow and their relationship to climate. *Paleoceanography*, in press.

Omrani, N.-E., J. Bader, N. S. Keenlyside and E. Manzini (2015) Troposphere-stratosphere response to large-scale North Atlantic Ocean variability in an atmosphere/ocean coupled model, *Clim. Dyn.* DOI 10.1007/s00382-015-2654-6.

Røthe TO, Bakke J, Vasskog K, Gjerde M, D'Andrea WJ, Bradley RS (2015) Arctic Holocene glacier fluctuations reconstructed from lake sediments at Mitrahalvøya, Spitsbergen. *Quaternary Science Reviews* 109: 111-125.

Pellitero R, Rea BR, Spagnolo M, Bakke J, Ivy-Ochs S, Hughes P, Lukas S, Ribolini A (2015) A GIS tool for automatic calculation of glacier equilibrium-line altitudes. Computers and geoscience, doi:10.1016/j.cageo.2015.05.005

Skardhamar J, Skagseth Ø, Albretsen J (2015) Diurnal tides on the Barents Sea continental slope. Deep-Sea Res, March 2015, Pages 40–51.

Solomina, O., Bradley, R., Hodgson, D.A., Ivy-Ochs, S., Jomelli, V., Macintosh, A.N., Nesje, A., Owen, L.A., Wanner, H., Wiles, G.C. and Young, N.E. (2015) Holocene glacier fluctuations. *Quaternary Science Reviews 111*, 9-34.

Williamson DL, Olson JG, Hannay C, Toniazzo T, Taylor M, Yudin V (2015) Energy considerations in the Community Atmosphere Model (CAM). Accepted for *J. Adv. Mod. Earth Sys.*

Yu L, Gao Y and Otterå OH (2015) The sensitivity of the Atlantic merdional overturning circulation to enhanced freshwater discharge to the entire, eastern and western coast of Greenland, *Clim. Dyn.*, in press.

2014

Ba J, Keenlyside N, Latif M, Park W, Ding H, Lohmann K, Mignot J, Menary M, Otterå OH, Wouters B, Salas y Melia D, Oka A, Belluci A, Volodin E (2014) A multi-model comparison of Atlantic multidecadal variability, *Clim. Dyn.*, DOI 10.1007/s00382-014-2056-1.

Cui XD, Gao Y, Sun JQ, Guo D, Li S, Johannessen OM (2014) Role of external forcing factors in modulating the Indian summer monsoon rainfall, the North Atlantic Oscillation and their relationship on inter-decadal timescale *Climate Dynamics,* 43, 2283-2295, DOI: 10.1007/s00382-014-2053-4.

Drinkwater K, Miles M, Medhaug I, Otterå OH, Kristiansen T, Sundby S, Gao Y (2014) The Atlantic Multidecadal Oscillation: Its manifestation and impacts with special emphasis on the Atlantic region north of 60°N, *J. Mar. Syst.*, http://dx.doi.org/10.1016/j.jmarsys.2013.11.001.

Eldevik T, Risebrobakken B, Bjune AE, Andersson C, Birks HJB, Dokken TM, Drange H, Glessmer MS, Li C, Nilen JEØ, Otterå OH, Richter K, Skagseth Ø (2014) A brief history of climate – the northern seas from the Last Glacial Maximum to global warming, *Quat. Sci. Rev.*, 106, 225-246, http://dx.doi.org/10.1016/j.quascirev.2014.06.028.

Laumann, T. and Nesje, A. (2014) Spørteggbreen, western Norway, in the past, present and future: Simulations with a two-dimensional dynamical glacier model. *The Holocene 24*, 842-852.

Lohmann K, Jungclaus JH, Matei D, Mignot J, Menary M, Langehaug HR, Ba J, Gao Y, Otterå OH, Park W, Lorenz S (2014) The role of subpolar deep water formation and Nordic Seas overflows in simulated multidecadal variability of the Atlantic merdional overturning circulation, *Ocean Sci.*, 10, 227-241. doi:10.5194/os-10-227-2014.

Miles, M. W., Divine, D. V., Furevik, T. Jansen, E., Moros, M., and Ogilvie, A. E. J. (2014): A signal of persistent Atlantic multidecadal variability in Arctic sea ice. *Geophys. Res. Lett.* 41, doi:10.1002/2013GL058084.

Mork, K. A.,Ø. Skagseth, V. Ivshin, V.Ozhigin,S. L. Hughes, and H. Valdimarsson (2014), Advective and atmospheric forced changesin heat and fresh water content in the Norwegian Sea, 1951–2010, Geophys. Res.Lett., 41, 6221–6228, doi:10.1002/2014GL061038.

Nesje, A., Bakke, J., Brooks, S.J., Kaufman, D.S., Kihlberg, E., Trachsel, M., D'Andrea, W.J. and Matthews, J.A. (2014) Late Glacial and Holocene environmental changes inferred from sediments in Lake Myklevatnet, Nordfjord, western Norway. *Vegetation History and Archeobotany 23*, 229-248.

Paasche, Ø., and E. W. N. Støren (2014), How Does Climate Impact Floods? Closing the Knowledge Gap, *Eos, Transactions American Geophysical Union*, *95*(28), 253-254.

Støren, E. N., and Ø. Paasche (2014), Scandinavian floods: From past observations to future trends, *Global and Planetary Change*, *113*(0), 34-43.

Svendsen, L., S. Hetzinger, N. S. Keenlyside, and Y. Gao (2014) Marine-based multi-proxy reconstruction of Atlantic multi-decadal variability. Geophys. Res. Lett., 41, 2013GL059076.

Yu L, Furevik T, Otterå OH, Gao Y (2014) Modulation of the Pacific Decadal Oscillation on the summer precipitation over East China: a comparison of observations to 600-years control run of Bergen Climate Model, *Clim. Dyn.*, DOI 10.1007/s00382-014-2141-5

2013

Bakke, J., Trachsel, M., Kvisvik, B. Chr., Nesje, A. and Lyså, A. (2013) Numerical analyses of a multi-proxy data set from a distal glacier-fed lake, Sørsendalsvatn, western Norway. *Quaternary Science Reviews 73*, 182-195.

Cui X, Gao Y, Gong D, Guo D, Furevik T (2013): Teleconnection between winter Arctic Oscillation and southeast Asain summer monsoon in the pre-industry simulation of a coupled model. *Atmos. Sci. Lett.,* 6(5), 349-354.

Diodato, N., Støren, E.W.N., Bellocchi, G. and Nesje, A. (2013) Modelling sediment load in a glacial meltwater stream in western Norway. *Journal of Hydrology 486*, 343-350.

Eldevik T, Nilsen JEØ (2013): The Arctic/Atlantic thermohaline circulation. *J. Climate,* DOI: 10.1175/JCLI-D-13-00305-1.

Lilleøren, K.S., Humlum, O., Nesje, A. and Etzelmüller, B. (2013) Holocene development and geomorphic processes at Omnsbreen, southern Norway: Evidence for glacier-permafrost interactions. *The Holocene 23*, 796-809.

Smedsrud LH, Esau I, Ingvaldsen RB, Eldevik T, Haugan PM, Li C, Lien VS, Olsen A, Omar AM, Otterå OH, Risebrobakken B, Sandø AB, Semenov VA, Sorokina SA (2013) The role of the Barents Sea in the Arctic climate system, *Rev. Geophys.*, 51, 1-35.

Suo L, Otterå OH, Bentsen M, Gao Y, Johannessen OM (2013) External forcing of the early 20th century Arctic warming, *Tellus A*, 65, 20578.

Trachsel, M., Kvisvik, B.C., Ringkjøb Nielsen, P., Bakke, J. and Nesje, A. (2013) Inferring organic content of sediments by scanning reflectance spectroscopy (380–730 nm): applying a novel methodology in a case study from proglacial lakes in Norway. *Journal of Paleolimnology* DOI 10.1007/s10933-013-9739-1.

Vasskog, K., Waldmann, N., Bondevik, S., Nesje, A., Chapron, E. and Ariztegui, D. (2013) Evidence for Storegga tsunami run-up at the head of Nordfjord, western Norway. *Journal of Quaternary Science 28*, 391-402.

Wang T, Wang H, Otterå OH, Gao Y, Suo L, Furevik T, Yu L (2013): Anthropogenic forcing of shift in precipitation in Eastern China in late 1970s, *Atmos. Chem. Phys.*, 13, 12433-12450, doi:10.5194/acp-13-12433-2013.

2012

Imhof, P., Nesje, A. and Nussbaumer, S.U. (2012) Climate and glacier fluctuations at Jostedalsbreen and Folgefonna, southwestern Norway and in the western Alps from the 'Little Ice Age' until the present: The influence of the North Atlantic Oscillation. *The Holocene 22,* 235-247.

Langehaug, H.R., P.B. Rhines, T. Eldevik, J. Mignot, and K. Lohmann (2012) Water mass transformation and the North Atlantic Current in three multi-century climate model simulations. J. Geophys. Res., 117, C11001, doi:10.1029/2012JC008021.

Langehaug, H.R., I. Medhaug, T. Eldevik, and O.H. Otterå (2012) Arctic/Atlantic exchanges via the Subpolar Gyre. J. Climate, 25, 2421–2439.

Medhaug, I., H.R. Langehaug, T. Eldevik, T. Furevik, and M. Bentsen (2012) Mechanisms for decadal scale variability in a simulated Atlantic Meridional Overturning Circulation. Clim. Dyn., 39, 77–93.

Nesje, A. and Matthews, J.A. (2012) The Briksdalsbre Event: A winter precipitation-induced decadal-scale glacial advance in southern Norway in the AD 1990s and its implications. *The Holocene 22*, 249-261.

Vasskog, K., Paasche, Ø., Nesje, A., Boyle, J.F. and Birks, H.J.B. (2012) A new approach for reconstructing glacier variability based on lake sediments recording input from more than one glacier. *Quaternary Research 77*, 192-204.

Wang T, Otterå OH, Gao Y, Wang H (2012) The response of North Pacific decadal variability to large tropical volcanic eruptions, *Clim. Dyn*, DOI 10.1007/s00382-012-1373-5.

Theses

Kolstø, S. M. (2013) North Atlantic climate and deep water variability since ~700 AD, Master Thesis, June 2013.

Mjell, T. L. (2014) Decadal to millennial scale variability in Iceland-Scotland overflow water and its relationship to climate, Ph.D thesis, December 2014.

Submitted publications and/or publications in preparation

Antuna, JC, Otterå OH, Robock A and Mesquita M. (2015) Modeled and observed sea surface temperature trends for the Caribbean and Antilles, in revision for *Int. Jour. of Clim.*

Gjerde M, Bakke J, Vasskog K, Nesje A, Hormes A (2015) Holocene glacier variability and Neoglacial hydroclimate at Ålfotbreen, western Norway, in revision *Quaternary Science Reviews.*

He, Y.C., Drange, H., Gao, Y.Q., Bentsen, M. et al. (2015) Twentieth century Atlantic Meridional Overturning Circulation in an ocean general circulation model forced by two reanalysis-based atmospheric datasets. (To be submitted).

Lie Ø, Otterå OH, Dokken T (2015): On the Atlantic Multidecadal Oscillation coupling to the winter atmosphere, in preparation for *Science.*

Medhaug I, Drange H (2015): Global and regional surface cooling in a warming climate - a multi-model analysis, in revision *Clim. Dyn.*

Mjell TL, Langehaug HR, Otterå OH, Eldevik T, Ninnemann U, Kleiven HF (2015): Reconstructing ocean circulation and climate based on the Gardar drift, in prep for *Paleoceanography.*

Skagseth, Ø, et al (2015) Characteristics of the Norwegian Coastal Current during years with high recruitment of Norwegian Spring Spawning herring (Clupea harengus L.), PlosOne (submitted).

Solomina, O., Bradley, R.S., Jomelli, V., Geirsdottir, A., Kaufman, D.S., Koch, J., McKay, N.P., Masiokas, M., Miller, G., Nesje, A., Nicolussi, K., Owen, L.A., Wanner, H., Wiles, G.: Glacier fluctuations during the past 2000 years. Submitted to *Quaternary Science Reviews*.

Conference proceedings

Andersson C, Dokken T, Nyland B, Otterå OH (2013): Multidecadal variability of surface ocean conditions in the eastern Norwegian Sea. Poster at the *11th International Conference in Paleoceanography* in Barcelona, September 2013.

Balascio N, D`Andrea W, Anderson RS, Gjerde M, Bakke J and Bradley R (2014): Reconstructing Hydroclimate Changes During the Holocene using Leaf Wax Hydrogen Isotope Records from the Norwegian Arctic. PP21B-1323-AGU, 16/12 2014.

D`Andrea W, Balascio N, Bradley R, Bakke J, Gjerde M, Kaufamann D, Briner J and von Gunten L (2014): Holocene temperature reconstructions from Arctic lakes based on alkenone paleothermometry and non-destructive scanning techniques. PP23E-03 – AGU, 16/12 2014.

D`Anjou R, Bradley RS, D`Andrea W, Bakke J, Røthe TO, Gjerde M (2013): High-latitude North Atlantic Holocene climate reconstruction from Svalbard lake systems: Insights on the Atlantic Multidecadal Oscillation (AMO) in the Arctic North Atlantic. Arctic Workshop 2013, UMASS, Amherst.

Gjerde M, Bakke J, Nesje A (2012): Tracking changes in palaeo winter precipitation and palaeo wind along the western coast of Norway and Svalbard. Talk at the SKD days in Bergen, November 2012.

Gjerde M, Bakke J, D'Andrea WJ, Balascio NL, Hormes A, Bradley RS (2015): Reconstructing Climate Change Since The Late Glacial At Amsterdamøya, NW Svalbard (~80°N), Based On Lake Sediments From Lake Hakluytvatnet. Talk at EGU in Vienna, April 2015.

Gjerde M, Bakke J, Vasskog K, Nesje A, Hormes A (2015): Reconstructing Holocene glacier activity and Neoglacial winter precipitation at Ålfotbreen, western Norway, using distal glacier-fed lake sediments. Poster at the Arctic Workshop, Bergen 2015.

Kleiven, H.F., Rosenthal, Y. and Ninnemann, U. S. (2012): Climate and North Atlantic Deep Water since 600 AD. Climate change in high latitudes. Bjerknes Centre’s 10-Year Anniversary Conference, Bergen, Norway, September 3-6 2012.

Kleiven, H. F. (2012): What may cause the “Gulf Stream” to fail? Academia Europaea 24th Annual Conference, University of Bergen, Norway, September 10-13. 2012.

Kleiven, H. F., Ninnemann, U. S. and Irvali, N. (2012): Multi-proxy evidence for climate and North Atlantic Deep Water variability spanning the mid to late Holocene at the Erik sediment drift. American Geophysical Union Fall Meeting, San Francisco, USA, 2012.

Kleiven, H. F., Rosenthal, Y. and Ninnemann, U. S. (2011): *Greenland Climate and North Atlantic deep-water variability since 600 A.D."* Amundsen day at NASA/GISS and the Explorers Club, New York, USA, 14 December 2011.

Kleiven, H. F., Y. Rosenthal and U. S. Ninnemann (2011): Climate and North Atlantic Deep Water variability since 600 AD. XVIII INQUA Conference, Bern, Switzerland 22-27 July, 2011.

Kleiven, H. F., Y. Rosenthal and U. S. Ninnemann (2011): North Atlantic climate and deep water variability since 600 AD. Norwegian Geological Union Winter meeting. Stavanger 11.01.2011.

Langehaug HR, Mjell TL, Otterå OH, Eldevik T, Ninnemann US, Kleiven HF (2015): On the reconstruction of ocean circulation and climate based on the “Gardar Drift”. Talk at the Arctic Workshop 2015, Bergen, May 2015.

Langehaug HR, Rhines PB, Eldevik T, Mignot J, Lohmann K (2013): Water mass transformation in the North Atlantic. Talk at the International Workshop on Modeling the Ocean, Bergen, June 2013.

Langehaug HR, Rhines PB, Eldevik T, Mignot J, Lohmann K (2012): Water mass transformation and the North Atlantic Current in three multi-century climate model simulations. Talk at Ocean Sciences Meeting, Salt Lake City, February 2012.

Langehaug HR (2012): Circulation and transformation of Atlantic and Arctic water masses in climate models, Talk at Physical Oceanography Dissertation Symposium (PODS), Hawaii, October 2012.

Medhaug, I. and H Drange (2015): Global and regional cooling in a warming climate from CMIP5 models**.** Oral presentation at *EGU General Assembly 2012* in Vienna, 2015

Medhaug, I. and A. Czaja (2014): Using surface drifters as a diagnostic of the North Atlantic Ocean circulation and heat transport in climate models. Oral presentation at the *Ocean Science conference in* Honolulu, February 2014.

Medhaug, I. and A. Czaja (2013): A lagrangian view of the North Atlantic surface circulation and heat transport in the Bergen Climate Model. Oral presentation at the *Challenger Society Modelling meeting*, London, October 2013.

Medhaug, I. and H. Drange (2012)**:** Global cooling in a warming climate, Oral presentation at *The Bjerknes Center's 10th Anniversary Conference*, Bergen, September 2012.

Medhaug, I., H.R. Langehaug, T. Eldevik, O.H. Otterå, T. Furevik, and M. Bentsen (2012)**:** Mechanisms for decadal scale variability in the North Atlantic Ocean circulation in the Bergen Climate Model. Oral presentation at *EGU General Assembly 2012,* Vienna, March 2012.

Miles, M.W. (2012): Signal of persistent multidecadal variability in wintertime sea-ice records: Linkages to the Atlantic Multidecadal Oscillation. Oral presentation at the 42nd Arctic Workshop, Winter Park, Colorado, USA, March 2012.

Mjell TL, Ninnemann US, Kleiven HF (2013): Late Holocene variability in the vigor of ISOW and its relationship to climate. Poster at the *11th International Conference in Paleoceanography* in Barcelona, September 2013.

Otterå OH, Dokken T, Lie Ø, Langehaug H, Medhaug I, Andersson C (2013): Simulated and reconstructed Atlantic gyre circulation and its relationship with the North Atlantic Oscillation during the past 600 years. Talk at the PAGES Open Science meeting in Goa, India, February 2013.

Otterå OH, Tjiputra J, Wang T (2013): The role of volcanic forcing on northern hemisphere decadal to multidecadal climate variability and future carbon cycle. Invited talk at the IAVCEI 2013 Scientific Assembly: Forecasting volcanic eruptions in Kagoshima, Japan, July 2013.

Otterå OH, Toniazzo T (2014): The role of volcanic forcing for climate variability during the last millennium. Talk at the *High Latitude Volcanic eruptions and Climate* workshop in Stockholm, November, 2014.

Røthe, Torgeir Opeland; Bakke, Jostein; Hormes, Anne, Gjerde M, D`Anjou R, D`Andrea W, Bradley RS (2013): Holocene glacier fluctuations reconstructed from the distal glacier-fed lake Kløsa at Mitrahalvøya, Spitsbergen. Arctic Workshop 2013, UMASS, Amherst.

Støren, E. W.N.; Paasche, Ø. (2014): Scandinavian floods: from past observations to future trends. EGU General Assembly 2014; 2014-04-27 - 2014-05-02

Vasskog K, Bakke J, Nielsen PR, Kvisvik BC, Birks HJB (2013): North-Atlantic Holocene climate variability reflected in the dynamical response of Norwegian maritime glaciers. 43rd Arctic Workshop; 2013-03-11 - 2013-03-13.

Vasskog, K., Bakke, J., Nielsen, P. R., and Meidell, S. (2015a): North Atlantic westerlies during the last millennium. EGU General Assembly, 12.-17. April, 2015, Vienna, Austria

Vasskog, K., Bakke, J., Nielsen, P. R., and Meidell, S. (2015b): High-resolution hydroclimate records from glacier-fed lakes. Arctic Workshop, 10.-12. May, 2015, Bergen, Norway

Outreach

Kleiven, H. F. (2014): Eirik den Raudes "badetemperatur" på 1400-talet, kvifor er det spanande?. Sunnhordaland Kraftlag bedriftsmøte; 2014-11-07.

Kleiven, H. F. (2014): Med kunnskap og begeistring skal framtida vinnast; Eirik den Raude's badetemperatur på 1400-talet, kvifor er det spanande?. Sunnhordalandskonferansen 2014-09-18.

Kleiven, H. F. (2014): På jakt etter Eirik den Raude's badevannstemperatur. Christian Michelsens Gebursdagsforedrag; 2014-03-14.

Kleiven, H. F. (2013): Jakten på Eirik den Raudes badevatn-Klimautfordringene frå eit lokalt og globalt perspektiv. Sunnhordaland Kraftlag Energiseminar; 2013-06-28.

Kleiven, H. F. (2013): The ocean's role in natural climate variability: North Atlantic Deep Water changes since 600 A.D. Geo Partner dag; 2013-02-07.

Langehaug, H. R. (2012): Article at the Bjerknes Centre webpage (www.bjerknes.uib.no): 'Varmetap styrker gyre-sirkulasjonen', 18/5/2012.

Medhaug I. (2014): Orden i værkaoset. For *2^{o}C*

Medhaug I. (2013): If temperatures aren't rising, where does the heat go? For *ClimateSnack.com*
Medhaug I. (2013): To index or not to index? For *ClimateSnack.com.*
Medhaug I. (2013): Kalde vinder fra Arktis kan gi varmere klima. Forskningsrådets klimakonferranse, Oktober, 2013.
Mjell, T. L., Ninnemann, U. S., Kleiven, H. F. (2013): Late Holocene variability in the vigor of ISOW and its relationship to climate. 11th International Conference on Paleoceanography; 2013-09-01.
Mjell, T. L., Ninnemann, U. S., Kleiven, H. F., Hall, I. R. (2013): Variability in the vigor of the eastern branch of the Nordic Seas overflows during the last two millennia and its relationship to climate. GEO Partner Seminar Day; 2013-02-07.
Paasche, Ø., Støren, E.W. N. (2014) Langtidsvarsel: Mer flom. *Dagens næringsliv* 2014.
Støren, E. W. N., Paasche, Ø. (2014) Hvor ødeleggende flommer har vi i vente?. *Forskning.no* 2014.
Omrani,N., Keenlyside, N., Bader, J., Manzini, E., Otterå, O. H. (2013) The importance of the stratosphere for the wintertime atmospheric response to Atlantic multidecadal variability. Ocean science meeting, February 2013.
Otterå O.H. (2014) Eit klima i endring. Klimautfordringar lokalt og globalt. Lecture at KOSMOS naturfagkurs, Cappelen Damm, Oslo, 10/4/2014. Online: https://icecube.cc/ShowPlayer.aspx?program=7d0f65d2-5f18-43fd-8995-126033ae6f50&station=06fb7a47-f23a-4b13-a26b-45defeb1c123
Otterå OH (2012) På jakt etter dirigenten for klimaorkesteret – om naturlige og menneskeskapte klimaendringer, Lecture at the *Horisonter* lecture series at the University of Bergen, Bergen, Norway.

IPCC

SKD IPCC Final Report

Coordinator: Asgeir Sorteberg, UiB

Project purpose

SKD is funding activities related to the development of the global fully coupled Norwegian Earth System Model (NorESM) and simulations that goes into the Coupled Model Intercomparison Project Phase 5 (CMIP5). These simulations are the backbone of several analyses for the newly released International Panel on Climate Change (IPCC) Assessment Report 5 (AR5). In addition, the project funds the persons within the Bjerknes Centre that are involved in the writing process of the AR5 as lead and review authors.

The NorESM family of models now consist of three members:

- The coupled atmosphere-ocean-land-ice model **NorESM1-M** which can be run with prescribed greenhouse gas concentrations,
- The fully coupled **NorESM1-ME** containing biogeochemistry to describe the full carbon-cycle in order for the model to run with prescribed greenhouse gas emissions.
- A coarse resolution version **NorESM1-L** suitable for millennia type studies of past climates.

SKD funding is involved in the development of all three components through nine scientific work packages (see list below) with main focus on model development, simulations and analysis relevant for Arctic climate.

List of work packages:

Model development and new simulations

- WP 1.1: CMIP5 Carbon cycle simulations, model development and analysis (Lead: J. Tjiputra (UNI))
- WP 1.2 Representation of high latitude ocean processes in NorESM (Lead: M. Bentsen, UNI)
- WP 1.3 Simulation and analysis of glacial climate state with NorESM1-L (Lead: K. H. Nisancioglu, UiB)

Arctic climate

- WP 2.1 Planetary boundary layer processes in climate models and observational climatology (Lead: I. Esau, NERSC)
- WP 2.2 Regional assessment of IPCC AR5 model runs (Lead: C. Schrum, UiB)
- WP 2.3: Explore the relationship between Sea Ice and Arctic Climate and Impact on Sub-Arctic Climate (Lead: Y. Gao, NESRC)

Mid and low latitudes

- WP 3.1: Response of storm tracks to global warming in an energy transport perspective (Lead: L. Ciasto, UiB)
- WP 3.2: Change and variability in the Indian monsoon (Lead: E. Viste, UiB)

Main results

The SKD- IPCC project has been instrumental in keeping the core personnel for further development of what was the Bergen Climate model into the Norwegian Earth System model with its three versions. The data from the different model versions of NorESM has been so far (Jan. 2014) been used in over 200 peer review publications showing that the data has successfully been disseminated to researchers worldwide through the participation in the Coupled Model Intercomparison Project 5 (CMIP5).

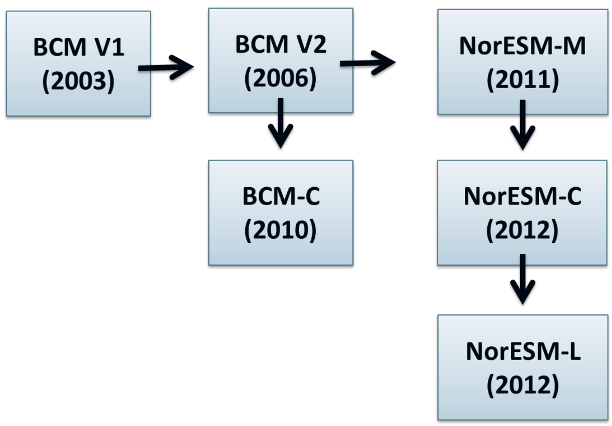


Figure 1: Showing the development steps of the global coupled atm-ocean model over the last 10 years.

WP 1.1: CMIP5 Carbon cycle simulations, model development and analysis

For CMIP5 and the last IPCC-AR5, the Earth system modelling group at BCCR had decided to contribute with the newly developed Norwegian Earth system Model (NorESM). In WP1, our main objective was to configure the NorESM model, focusing on the carbon cycle components, to perform the required interactive carbon cycle simulations within CMIP5. In total, excluding the spin up, a total of 21 CMIP5 carbon-cycle related experiments were completed, which amount to >3000 simulated model years. Model evaluation and quality control were done by comparison with the observed key climate and biogeochemical metrics. The model assessment is summarized in the next paragraph. In addition, scientific highlights from two recent publications are presented below.

The evaluation of the terrestrial and ocean carbon cycle of the NorESM was published as part of the special issue in the GMD journal (Tjiputra et al. 2013). Here, we show that the relatively strong AMOC in NorESM model distorts the structure of biogeochemical tracers, particularly in the Atlantic section, whereas improvement in the biogeochemical tracer distribution and air-sea gas exchange in the Southern Ocean is evident when compared to previous BCM model. Despite the good agreement in the spatial variability of terrestrial net ecosystem exchange of CO_2, the NorESM simulates high-bias and low-bias in the tropical and high latitude gross primary production, respectively, when compared with estimates from

FLUXNET. Soil carbon content is significantly underestimated by the present model, and could have implication on future carbon cycle climate feedback.

The NorESM and other CMIP5 models project consistent trends in ocean warming, acidification, deoxygenation and reduced primary production for each of the future RCP scenario (Bopp et al., 2013). Despite the fact that these stressors operate globally, they display distinct regional patterns and thus do not change coincidentally. For example, large decrease in O_2 and pH are simulated in intermediate and mode waters, whereas large reductions in biological production are simulated in the tropics and in the North Atlantic. Projection of temperature and pH are more robust among models but uncertainties remain in the projection of subsurface O_2 concentration in the tropics and regional change in net primary production. The projected model spread in certain parameters calls for caution when using CMIP5 models to force regional impact models.

In Mora et al. (2013), we linked the projected changes on ocean biogeochemistry over the 21st century to vulnerability of marine biological system and coastal society. The biological response of marine habitats and hotspots for several marine taxa to simultaneously exposure multi-stressor change could be considerable. In addition, these co-occurring biogeochemical changes may influence the delivery of ocean goods and services, which could have a substantial effect on human welfare. The study called for a significant reduction in global CO_2 emissions, which is necessary to avoid substantial degradation of marine ecosystem and the associated human hardships.

WP 1.2 Representation of high latitude ocean processes in NorESM

During the course of the project we have contributed with NorESM simulations to the Coordinated Ocean-ice Reference Experiments (COREs) proposed by the WCRP/CLIVAR Working Group on Ocean Model Development. In this working group we have together with colleagues at the Alfred Wegener Institute initiated a model intercomparison of the Arctic Ocean. This study provided us with valuable insight into how CMIP5 class coupled ocean sea-ice models represent the Arctic hydrography and circulation. We investigated the temperature and salinity biases of eleven different models and compared the results to the World Ocean Atlas climatology in the Arctic Ocean. Figure 1(a) shows the horizontal climatological temperature field at 400 meter. Incoming warm Atlantic water passes through the Fram Strait and circulates around the Eurasia basin. A cold water intrusion is also visible around the St. Anna Trough. The temperature field of the NorESM is shown in Figure 1(b). The NorESM has a very strong cold bias in the Arctic Ocean. We found that this cold bias is coming from the dense water formation in the Barents and Kara Seas. Salt fluxes due to freezing of sea water (i.e. brine rejection) is one of the main mechanisms of this dense shelf water (DSW) formation. The NorESM performs poorly in representing the brine rejection process and the gravity currents that forms when the DSW spills over the shelf break.

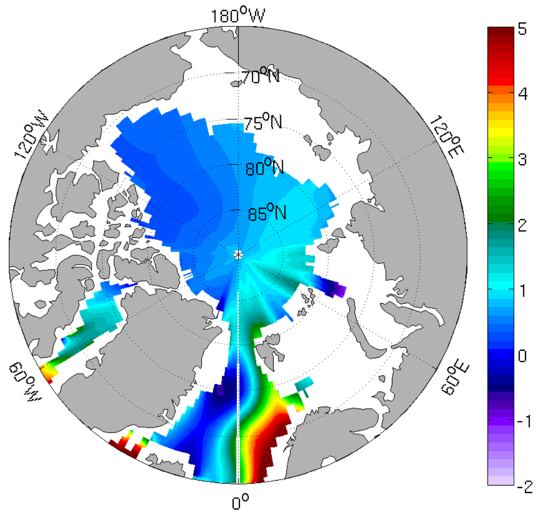


Figure 1: (a) Horizontal temperature field of the climatology at 400 meter. (b) Same as Figure 1(a) for the NorESM simulation.

Temperature profiles in the Eurasia basin of the different IPCC type models are shown in Figure 2. Dashed black line represents the climatology. The maximum temperature at around 450 m is the core of the Warm Atlantic inflow water. Five of the eleven models have a cold bias similar to the NorESM and all these models suffer from poor representation of dense flow coming from the shelves.

We decided to study the brine rejection process further and try to improve the current parameterization in the NorESM. To this end, we performed idealized Large Eddy simulations (LES) using the non-hydrostatic version of the MITgcm. The model has 512x512x512 in x, y, and z directions with 0.25 m spatial resolution. There is a lead in the middle of the domain with a length of 128 meter and a width of 6.4 meter. Initially there is a 2 m thick sea-ice outside the lead area. We also set the air temperature to -25°C to induce the brine rejection process. We integrated for 3 model days that is long enough before the rotation effects kick in. Snapshot of the salinity field across the lead (x-z plane) is shown in Figure 3 (a). The dense water plume sinks to the bottom of the mixed layer and then spreads horizontally. Figure 3(b) shows multiple plumes in the center of the lead (y-z plane). We performed eight different simulations changing the initial stratification and buoyancy forcing. We found that the plume always sinks to the bottom of the mixed layer but does not penetrate through it. We also found that the passive tracer field has a parabolic profile in the mixed layer. This indicates that the sinking of dense water is not uniformly distributed. The results from the LES simulations suggest that we have to reconsider our current brine rejection parameterization in the NorESM that distributes the rejected salinity uniformly below the mixed layer down to the depth with a density contrast of 0.4 kg m-3 compared to the surface.

During the project period we investigated the parameterization of shear instability mixing in NorESM, which is crucial in gravity currents. An optional parameterization based on a second order closure (k-ε model) has been implemented but the impact on gravity currents downslope of high latitude shelf breaks has not yet been thoroughly investigated.

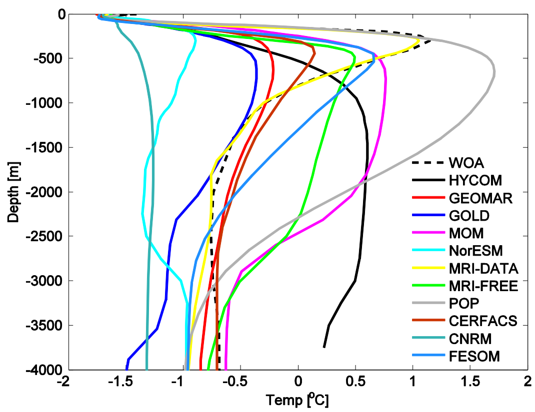


Figure 2: The temperature profiles in the Eurasia Basin for different global ocean models.

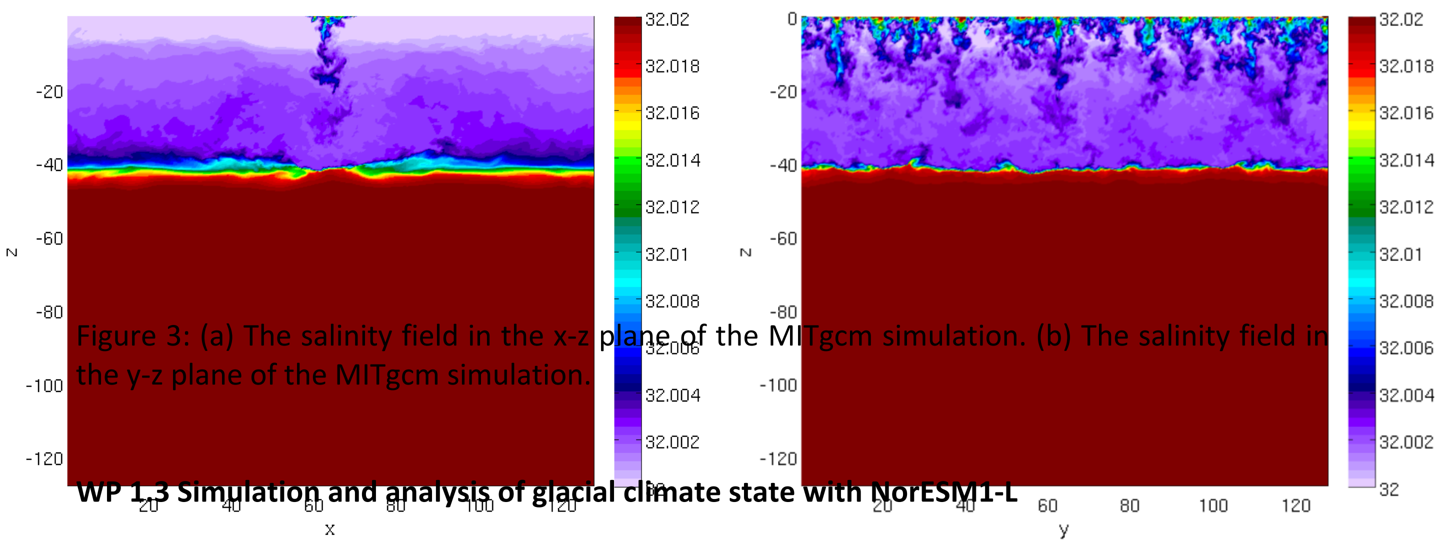


Figure 3: (a) The salinity field in the x-z plane of the MITgcm simulation. (b) The salinity field in the y-z plane of the MITgcm simulation.

WP 1.3 Simulation and analysis of glacial climate state with NorESM1-L

The main motivation for this study was to test the ability of the NorESM model to simulate climates different from the present. This is crucial in order to assess the performance of the model and is not possible to do if constrained to the instrumental record. The instrumental period covers only a small fraction of Earth's climate history, and does not give a full picture of natural climate variability and the sensitivity of the climate system to changes in external forcing.

One well documented period of the past is the Last Glacial Maximum (LGM), however recent studies have shown that there is a large range in the response of current IPCC climate models to LGM climate forcing (e.g. Pausata et al., 2009, 2011). This can be expected because the models have been tuned to best represent the present climate. The choice of tuning parameters differs from model to model, and there is no guarantee that the resulting climate sensitivities of these models are realistic.

In this project the aim was to evaluate the climate sensitivity of the low-resolution version of NorESM using the LGM as a test case and contribute the results to CMIP5 and PMIP3.

During the first project year a low resolution version of NorESM was developed and implemented on Hexagon, in collaboration with the ESM project at the Department of Earth Science and scientists at UNI Climate. Extensive testing and tuning was performed and a preindustrial control run was completed and documented in a publication (Zhang, Nisancioglu, et al., 2012). Subsequently a 1%CO2 experiment was run following the CMIP5 guidelines as well as the LGM simulation following CMIP5 and PMIP3 guidelines. These runs were completed in 2012, but a delayed analysis of the results (due to maternity leave of the postdoc funded on the project) showed that the version of NorESM-L used was lacking sufficient layers in the ocean in the cold LGM climate runs. This meant that the runs could not be completed in time for IPCC AR5 and had to be rerun with an updated version of NorESM-L, which has been developed during 2013 with the help of new dedicated SKD funding.

Although the results from the preliminary LGM are not thought to be accurate, due to the lack of isopycnic layers in the deep ocean, the atmospheric fields were analysed and are thought to give a first order picture of the atmospheric response to glacial conditions. However, we decided to wait with writing a manuscript based on the LGM results until the new runs with the updated and better validated NorESM-L are completed (these are due in spring 2014).
Fortunately the NorESM-L developed for the PMIP type simulations performed well when simulating warm climates of the past, as there was no issue in resolving the deeper layers of the ocean. This has resulted in several published and submitted papers by the participants of this work SKD project over the past 3 years. In particular we were able to study the relatively warm Pliocene and Last Interglacial (LIG) climates with NorEMS-L. The Pliocene (~3Ma BP) is the last period in Earth's history with greenhouse gas levels comparable to the present (400ppm) and the LIG (125ka BP) is a period with reconstructed high latitude temperatures above present. Both periods are also signified by high sea level with a significant reduction in the size of the Greenland and Antarctic ice sheets.

Highlights from these studies with NorESM-L are the following:

- A multi-model ensemble of simulations shows a robust seasonal and regional temperature response to last interglacial climate forcing with a significant agreement between the models. However, the models are shown to underestimate the magnitude of response seen in available proxy data (Lunt et al., 2013).
- NorESM simulations show enhanced ventilation of Antarctic circumpolar deep water during the warm mid-Pliocen. Providing an alternative explanation for the reconstructed weak mid-Pliocene Atlantic meridional d δ13C gradient, which in the literature has been considered as evidence for an enhanced Atlantic Meridional Overturning Circulation (Zhang et al., 2013).
- A multi-model ensemble of mid-Pliocene ocean circulation shows a consistent shoaling of the Atlantic Meridional Overturning Circulation (AMOC), and reduced influence of North Atlantic Deep Water (NADW) at depth in the Atlantic. However, the simulated northward heat transport by the Atlantic ocean is similar to the pre-industrial, demonstrating that the reconstructed high latitude warming of the mid-Pliocene cannot be explained by an intensification of the AMOC (Zhang et al., 2013).

- A joint study of the mid-Pliocene comparing a PMIP model ensemble with the comprehensive PRISM3 palaeoenvironmental reconstructions of sea surface temperatures documents significant discrepancies between the proxy data and the models. One important difference is the underestimate of high latitude warming by the models. However, it is unclear if this is due to problems with the model physics (including representation of sea ice) or if there are errors in the proxy data (Dowsett et al., 2013).
- NorESM simulations show how insolation forcing can explain seasonal and hemispheric differences in temperature at the last interglacial (w.r.t. pre-industrial), whereas changes in greenhouse gas forcing explains a smaller global and seasonally independent cooling. Further, the model captures the general trend in North Atlantic summer temperatures based on proxy reconstructions for the period 130 – 110ka BP (Langebroek and Nisancioglu, 2013).

WP 2.1 Planetary boundary layer processes in climate models and observational climatology

The Earth has warmed in the last century with the most rapid warming occurring in the arctic. This enhanced surface warming in the Arctic is partly because the extra heat is trapped in a thin layer of air near the surface due to the persistent stable-stratification found in this region. The warming in the surface air due to the extra heat depends upon the amount of turbulent mixing in the atmosphere, which is described by the depth of the atmospheric boundary layer (ABL). In this way the depth of the ABL determines the effective response of the surface air temperature on perturbations of the climate forcing. The ABL depth can vary from tens of meters to a few kilometers which presents a challenge for global climate models which cannot resolve the shallower layers. Here we show that the uncertainties in the depth of the ABL within global climate models can explain up to 47% of the difference between the simulated and observed surface air temperature trends and 50% for the temperature variability in the Climate Model Intercomparison Project Phase 5 (CMIP5) ensemble mean. Previously the difference between observed and modeled temperature was thought to be largely due to differences in individual model's treatment of large-scale circulation and other factors related to the forcing, such as sea-ice extent. While this can be an important source of uncertainty in climate projections, our results show that it is the representation of the ABL in these models which is the main reason global climate models cannot reproduce the observed spatial and temporal pattern of climate change. This highlights the need for a better description of the stably-stratified ABL in global climate models in order to constrain the current uncertainty in climate variability and projections of climate change in the surface layer.

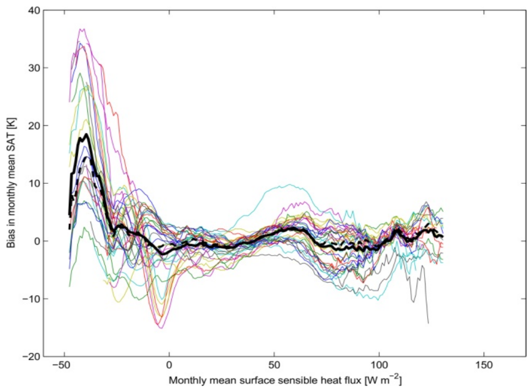


Figure 1: the bias in monthly mean surface temperatures in CMIP5 models for different surface sensible heat flux values.

WP 2.2 Regional assessment of IPCC AR5 model runs

The SKD IPCC project has contributed to North Sea Region Climate Change Assessment (NOSCCA), a book project to be published in early 2015. NOSCCA aims at a complete assessment of published scientific work about the North Sea region climate impacts. One chapter of the book deals with a review of climate change projections and will assess atmospheric, oceanic and terrestrial climate change impacts based on IPCC AR4 and AR5 global climate change projections and their regionalization. SKD-IPCC contributed to the marine chapter through the chapter lead author Corinna Schrum (Schrum et al. 2014, submitted). Specific downscaling contributions from SKD were multi-GCM and ESM forced ensemble projections for the North Sea hydrodynamics, the ecosystem dynamics (see Fig.1) and ocean acidification, among those the only regional projection utilizing AR5 global projections currently reported, which was completed as part of the SKD RegScen and IPCC projects.

The review has contributed an assessment of robust changes, uncertainties and specific recommendations for future research. Among the robust changes are ocean acidification impacts and projected increase in ocean temperature. In contrast, projected changes in salinity, primary production and nutrients were currently not considered to be robust. The uncertainties in regional projections diagnosed from multi-model ensembles remain large and the lack of consideration of terrestrial climate change impacts is a major issue. The consideration of terrestrial impacts, but also the sediment-water coupling were identified to be critical for the North Sea and the land ocean transition zone in general. Pronounced natural climate variability forms another important challenge for the North Sea region. The North Sea is located on the Northwest European shelf and influenced by both, the maritime climate of the North Atlantic and the continental climate. Due to the alternating dominance of these two regimes, the transition zone is characterized by very high variability and influenced by North Atlantic variations from annual to multi-decadal scales, which is highly relevant for nutrient and fresh water budgets, primary production and also for projected changes in sea level, storm surges surface heights.

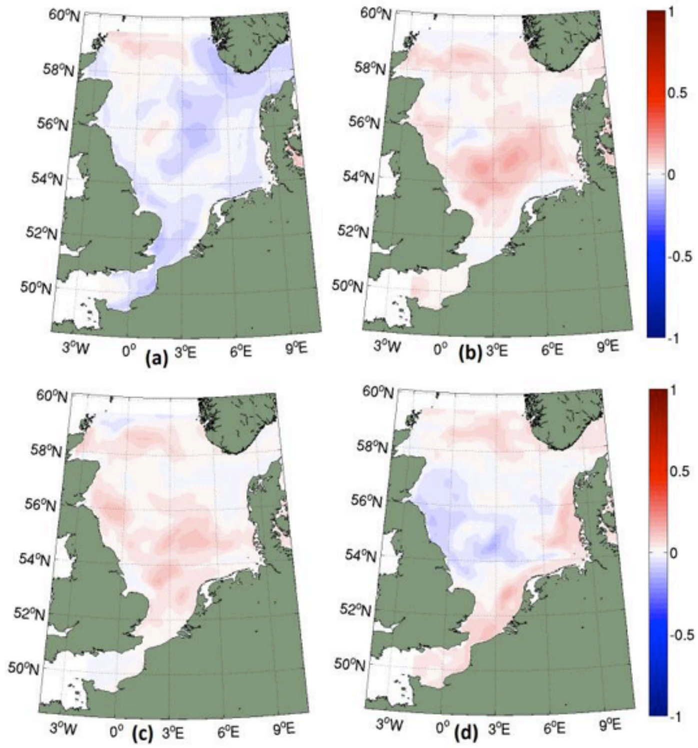


Figure 1: Projected changes in net primary production for the end of the century (2070-2100). Results from ECOMSO multi-model ensemble, A-only forced by a) IPSL-A1B, b) BCM-A1B, c)ECHAM-A1B, d) NORESM-RCP4.5 (from Schrum et al. 2014, submitted).

WP 2.3: Explore the relationship between Sea Ice and Arctic Climate and Impact on Sub-Arctic Climate

The Arctic sea ice loss has been attributed both to human influence and natural variability, but the contributions from each are still under debate. Various mechanisms have been suggested to explain parts of the sea ice loss. Under support of SKD IPCC project, we have investigated Arctic sea ice properties and Fram Strait ice export from six CMIP5 Global Climate and Earth System Models.

The study ’Arctic sea ice decline and ice export in the CMIP5 historical simulations’ is a first attempt to evaluate the Fram Strait ice area export in the CMIP5 models, and the role it has played for Arctic sea ice area and thickness. Five of the six models evaluated reproduce the seasonal cycle and the inter-annual variance of the ice area export in the Fram Strait reasonably well. The simulated southward export of sea ice in the Fram Strait constitutes a major fraction of the Arctic sea ice in these five models; 10–18% of the sea ice covered Arctic Basin is annually exported. For the same models the year-to-year variability in Fram Strait ice volume export carries 35% of the year-to-year variability in the Arctic Basin sea ice volume. We have found low but significant correlations on inter-annual timescales between the Fram Strait ice export, both in terms of area and volume, and the Arctic Basin sea ice thickness. All six models show that an increase in ice area export leads a decrease in the sea ice thickness. Focusing on the model with the largest number of ensemble members (10), we have been able to quantify the effect of the ice area export on the Arctic Basin sea ice for this particular model (Fig. 1) (Langehaug et al., 2013).

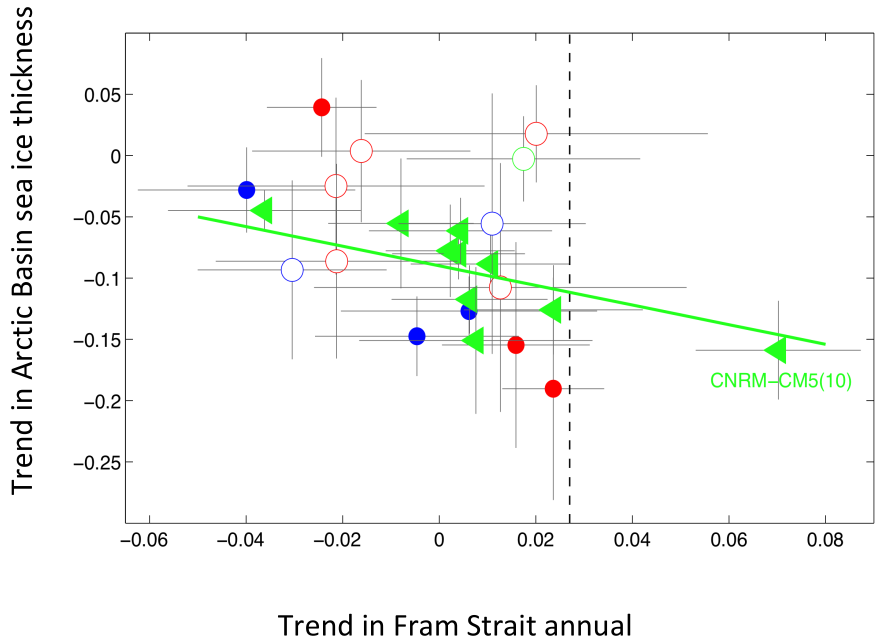


Figure 1: Six CMIP5 models (indicated by different colours), each having several simulations. The model with most simulations shows an inverse relationship between Arctic sea ice and Fram Strait ice export, considering long-term trends (1957-2005). The grey lines show uncertainty, whereas the black dashed line indicates the ice export trend based on NCEP data.

The SKD IPCC project has also supported the work ‘Poleward ocean heat transports, sea ice processes and Arctic sea ice variability in NorESM1-M simulations’. In this study, we investigate further the relationship between poleward ocean heat transports and sea ice area, and quantify contributions from freezing and melting processes to sea ice area variability. It is found that increased heat transport in the Barents Sea Opening has first of all an influence on sea ice area in the Barents Sea, while bottom melting is important for the variability in the Central Arctic Ocean. The model results in this study suggest that the ocean has stronger direct impact on changes in sea ice mass in terms of freezing and melting than the atmosphere, both in mean and with respect to variability (Sandø et al., 2014).

WP 3.1: Response of storm tracks to global warming in an energy transport perspective

The main objective was to examine the extent to which ocean forcing/coupling affects to the ability of CMIP5 models to simulate the behavior of the North Atlantic storm track.

Key Results are:

- Under RCP scenarios, future projections in CCSM4, CESM1-CAM5, and NorESM1-M models exhibit a poleward shift/eastward extension of the North Atlantic storm track, but the detailed structure of the shift varies between models.
- AGCM experiments demonstrate that the North Atlantic storm track response is sensitive to intermodel differences in the global projections of SST/SIC but it is primarily low level storm track activity that appears to be influenced by North Atlantic SST projections.

Analysis of 21st century climate projections suggests an overall poleward intensification of the North Atlantic storm track in CMIP5 models[1]. However, considerable spread exists amongst the projections with regard to the structure and magnitude of the storm track changes. Here, a subset of CMIP5 models (CCSM4, CESM1-CAM5, and NorESM1-M) is used to further examine the spread in the RCP8.5 storm track projections. Output from NorESM1-M suggests that the storm track is projected to undergo a poleward intensification. CCSM4 and CESM1-CAM5 model output, however, suggests a stronger eastward extension of the storm track in the next century. It has been suggested that the intermodel differences in storm track projections may be influenced by intermodel differences in the surface temperature projections[2]. Thus, the objective of the study is to compare the extent to which the spread in North Atlantic storm tracks is related to spread in SST projections. Analysis focuses on sensitivity experiments in which an AGCM is forced with (1) 21st century projections of *global* SST and SIC obtained from the CCSM4, CESM1-CAM5 and NorESM1-M CMIP5 historical and RCP8.5 runs and (2) 21st century projections of *North Atlantic* SST and SIC obtained from the CCSM4, CESM1-CAM5 and NorESM1-M CMIP5 historical and RCP8.5 runs (SIC/SST forcing elsewhere is based on monthly-varying observed climatology).

Results indicate that the North Atlantic storm track response is sensitive to intermodel differences in global SST/SIC projections. The low level response (band-pass filtered $\overline{SLP'^2}$) to CCSM4 and CESM1-CAM5 projections is marked by a strong eastward intensification. The response to NorESM1-M SST/SIC projections, however, exhibits a weaker poleward intensification. Upper level eddy activity (band-pass filtered $\overline{v'^2_{200}}$) responses to global SST/SIC projections from all 3 models reveals similar eastward intensifications, but the response to NorESM1-M projections is smaller in amplitude. However, the sensitivity of simulated storm track response to only North Atlantic SST projections from the 3 models does not extend throughout the troposphere. In particular, the simulated upper level eddy activity does not exhibit a significant response to North Atlantic SST projections from any of the 3 models. These results suggest that while low level indicators of storm track activity appear to be sensitive to intermodal differences in North Atlantic SST projections, the model spread in upper level storm track activity may be influenced by model spread in other surface factors such as sea ice variability or tropical Pacific SST.

WP 3.2: Change and variability in the Indian monsoon
Increasing temperatures will reduce annual snowfall in the Himalaya / Hindu Kush / Karakoram region, despite a likely increase in precipitation.
This is based on a comparison of snowfall today and the snowfall that would result from adding the temperature and precipitation changes expected to occur from 1971–2000 to 2071–2100.

Present-day snowfall was estimated by combining temperature and precipitation data from the MERRA reanalysis, as well as including bias-corrections with several observational data sets. Future changes in temperature and precipitation were taken from 16 CMIP5 models, for the RCPs 2.6 and 8.5.

Due to the lack of observations at higher elevations, the estimates of snowfall today vary by factors as high as 2–3. This makes it difficult to determine the total change in snowfall in the future. The relative change shows less variation. With the RCP 8.5, the reduction in annual snowfall is estimated to be 30–50 % in the Indus Basin, 50–60 % in the Ganges Basin, and 50–70 % in the Brahmaputra Basin.

In a warmer climate, a lower fraction of the region will receive precipitation in the form of snow at any time. The snowline (defined here as the mean elevation where rain changes to snow) creeps upward by 400–900 meters, in most of the region by 7–900 meters in the RCP 8.5. The effect of a higher snowline elevation on snowfall, depends on the terrain profile in different parts of the Himalayas.

The largest relative reduction in snowfall is seen in the upper, westernmost sub-basins of the Brahmaputra – despite increasing precipitation and despite the lowest change in snowline elevation (400–500 meters). This is because a large part of this region is near the snowline today. If the temperature increases as much as in RCP 8.5, most of the terrain will fall below the snowline, especially in the NH summer, the wettest time of the year in this part of the Himalayas. The projected reduction in annual snowfall is 65–75 %.

In the upper Indus, the effect of a warmer climate on snowfall is less extreme, as most of the ground lies well above the snowline today. There, the NH winter and spring brings most of the precipitation, and the projected snowline change of 6–800 meters during these months, would still leave most of the region in the snow. Still, a 20–40 % reduction in annual snowfall is projected with the RCP 8.5.

Personnel involved

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Publication list

Accepted

1. Arora, V. K., G. J. Boer, P. Friedlingstein, M. Eby, C. D. Jones, J. R. Christian, G. Bonan, L. Bopp, V. Brovkin, P. Cadule, T. Ha jima, T. Ilyina, K. Lindsay, **J. Tjiputra**, and T. Wu (2013), Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth system models, J. Climate.
2. **Bentsen M.,** I. Bethke, J. B. Debernard, T. Iversen, A. Kirkevåg, Ø. Seland, H. Drange, C. Roelandt, I. A. Seierstad, C. Hoose, and J. E. Kristjánsson**.** The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate. Geosci. Model Dev., 6, 687-720, 2013
3. Bopp. L., L. Resplandy, J. C. Orr, S. C. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, **J. Tjiputra**, and M. Vichi (2013), Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models, Biogeosciences, 10, 6225-6245.
4. Cocco, V., F. Joos, M. Steinacher, T. L. Froelicher, L. Bopp, J. Dunne, M. Gehlen, **C. Heinze**, J. Orr, A. Oschlies, B. Schneider, J. Segschneider, and **J. Tjiputra** (2013), Oxygen and indicators of stress for marine life in multi-model global warming projections, Biogeosciences, 10, 1849-1868, doi:10.5194/bg-10-1849-2013.
5. Davy, R. and **I. Esau**, 2013: Surface air temperature response in global climate models, *Atmospheric Science Letters* , on-line first, doi: 10.1002/asl2.456
6. Dowsett H. J., Kevin M Foley, Danielle K Stoll, Mark A Chandler, Linda E Sohl, **Mats Bentsen**, Bette L Otto-Bliesner, Fran J Bragg, Wing-Le Chan, Camille Contoux, Aisling M Dolan, Alan M Haywood, Jeff A Jonas, Anne Jost, Youichi Kamae, Gerrit Lohmann, Daniel J Lunt, **Kerim H Nisancioglu**, Ayako Abe-Ouchi, Gilles Ramstein, Christina R Riesselman, Marci M Robinson, Nan A Rosenbloom, Ulrich Salzmann, Christian Stepanek, Stephanie L Strother, Hiroaki Ueda, Qing Yan, Zhongshi Zhang (2013), Sea Surface Temperature of the mid-Piacenzian Ocean: A Data-Model Comparison, Nature Scientific Reports 3, 1-8, doi:10.1038/srep02013
7. T. Iversen, **M. Bentsen**, I. Bethke, J. B. Debernard, A. Kirkevåg, Ø. Seland, H. Drange, J. E. Kristjansson, I. Medhaug, M. Sand, and I. A. Seierstad
. The Norwegian Earth System Model, NorESM1-M – Part 2: Climate response and scenario projections. Geosci. Model Dev., 6, 389-415, 2013
8. Jones, C., E. Robertson, V. Arora, P. Friedlingstein, E. Shevliakova, L. Bopp, V. Brovkin, T. Hajima, E. Kato, M. Kawamiya, S. Liddicoat, K. Lindsay, C. H. Reick, C. Roelandt, J. Segschneider, **J. Tjiputra** (2013), 21st Century compatible CO_2 emissions and airborne fraction simulated by CMIP5 Earth System models under 4 Representative Concentration Pathways, J. Climate.
9. Keller, K., F. Joos, C. Raible, V. Cocco, T. Frolicher, J. Dunne, M. Gehlen, L. Bopp, J. Orr, **J. Tjiputra**, **C. Heinze,** J. Segschneider, T. Roy, and N. Metzl (2012), Variability of the ocean carbon cycle in response to the North Atlantic Oscillation, Tellus B, 64, 18738.
10. **Langebroek P**. and **Nisancioglu K.H**.: Simulating last interglacial climate with NorESM: role of insolation and greenhouse gases in the timing of peak warmth (2013), Clim. Past Discuss. 9, 4449–4473, doi:10.5194/cpd-9-4449-2013
11. **Langehaug, H**., Geyer, F., Smedsrud, L. and **Gao, Y.Q.** (2013): Arctic sea ice decline and ice export in the CMIP5 historical simulations. *Ocean Modeling*, http://dx.doi.org/10.1016/j.ocemod.2012.12.006
12. Lunt, D. J., Abe-Ouchi, A., Bakker, P., Berger, A., Braconnot, P., Charbit, S., Fischer, N., Herold, N., Jungclaus, J. H., Khon, V. C., Krebs-Kanzow, U., Langebroek, P. M., Lohmann, G., **Nisancioglu, K. H.,** Otto-Bliesner, B. L., Park, W., Pfeiffer, M., Phipps, S. J., Prange, M., Rachmayani, R., Renssen, H., Rosenbloom, N., Schneider, B., Stone, E. J., Takahashi, K., Wei, W., Yin, Q., and Zhang, Z. S. (2013), A multi-model assessment of last interglacial temperatures, Clim. Past, 9, 699-717, doi:10.5194/cp-9-699-2013
13. Mora, C., C.-L. Wei, A. Rollo, T. Amaro, A. R. Baco, D. Billett, L. Bopp, Q. Chen, M. Collier, R. Danovaro, A. J. Gooday, B. M. Grupe, P. R. Halloran, J. Ingels, D. O. B. Jones, L. A. Levin, H. Nakano, K. Norling, E. Ramirez-Llodra, M. Rex, H. A. Ruhl, C. R. Smith, A. K. Sweetman, A. R. Thurber, **J. F. Tjiputra**, P. Usseglio, L. Waitling, T. Wu, and M. Yashuhara (2013), Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century, PLOS Biology, 11 (10), 1-14.

14. **Outten, S**., Davy, R. and **I. Esau**, 2013: Eurasian winter cooling: Intercomparison of Reanalyses and CMIP5 data sets, *Atmospheric and Oceanic Science Letters* , 6(5), 324-331, doi:10.3878/j.issn.1674-2834.12.0112
15. Outten**, S. and I. Esau**, 2013: Extreme winds over Europe in the ENSEMBLES regional climate models, *Atmospheric Chemistry and Physics* , 13, 5163-5172, doi:10.5194/acp-13-5163-2013
16. **Pfeil, B**., et al. (2013), A uniform, quality controlled Surface Ocean CO2 Atlas (SOCAT), Earth Syst. Sci. Data, 5, 125-143, 2013.
17. Simpkins, G. R., **L. M. Ciasto,** and M. H. England, 2013: Observed variations in multi-decadal Antarctic sea ice trends during 1979-2012. *Geophysical Research Letters,* **40**, 3643-3648.
18. **Sandoe, A.B., Gao, Y.Q., Langehaug, H**. (2014): Poleward ocean heat transports, sea ice processes and Arctic sea ice variability in NorESM1-M simulations. Journal of Geophysical Research-Ocean, DOI: 10.1002/2013JC009435
19. **Tjiputra, J. F.,** C. Roelandt, M. Bentsen, D. M. Lawrence, T. Lorentzen, J. Schwinger, Ø., Seland, and **C. Heinze** (2013), Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), Geosci. Model Dev., 6, 301–325, doi:10.5194/gmd-6-301-2013.
20. Zhang Z., **K. H. Nisancioglu,** M. A. Chandler, A. M. Haywood, B. L. Otto-Bliesner, G. Ramstein, C. Stepanek, A. Abe-Ouchi, W.-L. Chan, F. J. Bragg, C. Contoux, A. M. Dolan, D. J. Hill, A. Jost, Y. Kamae, G. Lohmann, D. J. Lunt, N. A. Rosenbloom, L. E. Sohl, and H. Ueda, Mid-pliocene Atlantic meridional overturning circulation not unlike modern? (2013), Clim. Past Discuss. 9, 1297-1319, doi:10.5194/cpd-9-1297-2013
21. Zhang Z, **KH Nisancioglu**, US Ninnemann (2013), Increased ventilation of Antarctic deep water during the warm mid-Pliocene, Nature Communications 4, 1499
22. Zhang, Zhongshi; **Nisancioglu, K.H**.; **Bentsen, M**.; **Tjiputra, Jerry**; Bethke, Ingo; Yan, Qing; Risebrobakken, Bjørg; Andersson, Carin; **Jansen, Eystein**. Pre-industrial and mid-Pliocene simulations with NorESM-L. Geoscientific Model Development 2012 ;Volum 5.(2) s. 523-533.

Submitted

1. Davy R. and **I. Esau**: Global climate models' bias in surface temperature trends and variability, *Nature*, sent to reviewers
2. Holt, J., **Schrum, C**., Cannaby, H., Daewel, U., Allen, I., Artioli, Y., Bopp, L., Butenschon, M., Fach, B. A., Harle, J., **Pushpadas, D**., Salihoglu, B., and Wakelin, S. (2014): Physical processes mediating climate change impacts on regional sea ecosystems, Biogeosciences Discuss., 11, 1909-1975, doi:10.5194/bgd-11-1909-2014, 2014.
3. **Schrum, C**, Lowe, J, Meier, M., Caroline Katsman, Markus Meier, Thomas Pohlmann, Morten Skogen, Moritz Mathis, Andreas Sterl, Ralf Weisse, Judith Wolf, Bjørn Ådlandsvik (2014) Projected changes in the North Sea. In North Sea Region Climate Change Assessment, in NOSCCA- North Sea Climate Change Assessment, submitted.
4. Schwinger, **J., Tjiputra, J. F., Heinze,** C., Bopp, L., Christian, J. R., Gehlen, M., Ilyina, T., Jones, C. D., Salas-Melia, D., Segschneider, J., Seferian, R., and Totterdell, I. (2014), Non-linearity of ocean carbon cycle feedbacks in CMIP5 earth system models, submitted
5. Sørland S. and **Sorteberg A**. (2014) The climatology of monsoon low-pressure systems over India: the dynamical structure and the associated precipitation (2013). Quarterly Journal of the Royal Meteorological Society , under review
6. Wolf T. and **I. Esau**: Air quality hazards under present and future climate conditions in Bergen, Norway, *Urban climate* , under review

Planned submissions 2014

1. **Ciasto, L**., C. Li and **N.G. Kvamsto**: Understanding Model Spread in CMIP5: Sensitivity of North Atlantic Storm Tracks to Surface Boundary Conditions.
2. Daewel, U, **Schrum, C, Pushpadas, D.** Projecting habitat changes for Atlantic cod in the North Sea
3. Daewel, U, **Schrum, C, Pushpadas,** D, Castano Primo, R. Climate impacts on ocean acidification in the North Sea and Baltic Sea: a modelling study

4. **Pushpadas, D, Schrum**, C, Daewel, U. A regional climate change impact downscaling ensemble for the marine ecosystems of North Sea and Baltic Sea.
5. **Schrum C, Pushpadas D.,** Daewel U.. Regional North Atlantic performance analysis of sea surface conditions from CMIP5 model simulations: Consequences and implications for downscaling of climate change to marine systems.
6. **Viste, E., Sorteberg, A.:** Himalayan snowfall in a changing climate.

Outreach

1. **Davy, R. and I. Esau**, 2012: Surface air temperature variability in global climate models, arXiv:1210.2333, posted 8 Oct 2012 16:47:26 GMT
2. **Esau, I.,** Bergh, J., Davy, R., Outten, S., Xu, Y., 2012: Micro-climate on Mega-computers, META, 1, 13-17
3. **Langehaug, HR**, 2013: Vind flytter isen fra Arktis. Artikkel i Bergens Tidende, 10/2/2013.
4. **Langehaug, HR, Smedsrud, LH**, 2013: Ser på konsekvensen av iseksport gjennom Framstredet. Artikkel på Bjerknessenterets hjemmesider (www.bjerknes.uib.no), 10/1/2013.
5. Wolf T., **Esau I.** and L. Petersson, 2013: Modellering av luftkvalitet i Bergen under dagens of framtidig klima *NERSC special report* , 90, 48 pp. (in Norwegian)
6. **Esau I.** and O. Byrkjedal, Application of large-eddy simulation for optimization of the first-order turbulence closures for neutral and stably-stratified boundary layers, pp. 53-73 in monography *Atmospheric boundary layers. Nature, theory and applications to modeling and environmental safety*, eds A. Baklanov, B. Grisogono, G.S. Golytsin, 2012, Moscow, "GEOS", 260 pp (in Russian), ISBN 978-5-89118-595-1
7. **Sandø AB.** 2013: FNs femte klimarapport. Skolebesøk; 2013-02-06 - 2013-02-06.
8. **Sandø AB.** 2013: FNs femte klimarapport. Skolebesøk; 2013-10-22 - 2013-10-22.
9. **Schrum, C.** Können wir lokale Auswirkungen von Klimaänderung auf Nordsee und Ostsee vorhersagen? Wie gut sind unsere Modelle? Impulsworkshop Kueste, Delmenhorst, Germany. Nov. 2011.
10. **Schrum, C**, Daewel, U, **Pushpadas, D**. Modelling Marine Ecosystems in a Changing Climate (2012). META magazine from the Norwegian metacentre for computational science 2012-1.
11. **Viste, E.:** Vann i verden: Ekstremvær (Eng: Water in the world: Extreme weather). Public talk during the Norwegian Science Week, Bergen, Sep 2013.

Conference presentations

1. Alexeev,V.A., Y.Tachibana, J.E. Cohen**, I. Esau**, 2013: Is warming Arctic causing colder winters in Siberia?, *the Third International Symposium on the Arctic Research* (ISAR-3), January 14-17, Tokyo, Japan, S5-P18
2. **Ciasto, L.** (2012). Understanding the Role of Ocean Dynamics for Changes in the North Atlantic Storm Track in a Subset of CMIP5 Models. American Geophysical Union Annual Meeting, San Francisco, USA.
3. **Ciasto, L.** (2013). Relationships between Gulf Stream SST Variability and the North Atlantic Atmospheric Circulation. Climate Implication of Frontal Air-Sea Interaction Workshop, Boulder, USA.
4. **Ciasto, L.** (2014). Understanding Model Spread in CMIP5: Sensitivity of North Atlantic Storm Tracks to Surface Boundary Conditions. European Geophysical Union Meeting, Vienna, Austria.
5. Daewel, U **Corinna Schrum** and **Dhanya Pushpadas**. Simulating past and future acidification of the North and Baltic Sea, poster, EGU Annual meeting 8-12.04.2013, Vienna, Austria
6. Daewel, U **Corinna Schrum** and **Dhanya Pushpadas**. Modelling climate change impacts on North Sea Atlantic cod early life stages: long term hind cast and climate projection. SKD annual getaway, 21.-23.01.2013, Geilo, Norway
7. Daewel, U **Corinna Schrum** and **Dhanya Pushpadas**. Impact of climate changes on North Sea Atlantic cod (Gadus morhua) larval survival: a modeling study. Oral. Yeosu Climate Change Impacts on the Oceans. Yeosu, Korea, May 2012.
8. Daewel, U., **Schrum, C.** and **Pushpadas, D.** Simulating past and future acidification of the North and Baltic Sea. Bjerknes Center 10-years anniversary Conference. 3-6 September 2012, Bergen, Norway.

9. Daewel, U., **Schrum, C**. and Pushpadas, D. Modelling climate impacts on acidification in the North and Baltic Sea with ECOSMO II. ICES Annual Science Conference. 17-21 September 2012, Bergen, Norway.
10. **Davy, R., I. Esau and S. Outten**, 2013: Asymmetry of the surface air temperature response on climatologic heat imbalances due to differences in the planetary boundary layer height, *Geophysical Research Abstracts* , 15, EGU2013-4534-1
11. **Esau I.**, 2013: Planetary boundary layer in the earth's climate system, *RESCLIM annual workshop*, 20-22 March, Tromso
12. **Geyer F, Langehaug HR, Smedsrud LH**. Is Fram Strait ice export a driver for Arctic sea ice decline? (poster). European Geophysical Union. 2012.
13. Holt, J, **Corinna Schrum**, Heather Cannaby, Icarus Allen, Yuri Artioli, Momme Butenschon, Ute Daewel, Bettina Fach, Dhanya Pushpadas, Baris Salihoglu, Sarah Wakelin Physical processes mediating climate impacts in shelf sea ecosystems. EGU, 2013 Vienna.
14. Holt, J, Icarus Allen, Yuri Artioli, Laurent Bopp, Momme Butenschon, Heather Cannaby, Ute Daewel, Bettina Fach, James Harle, **Dhanya Pushpadas**, Baris Salihoglu, **Corinna Schrum**, Sarah Wakelin. Physical processes mediating climate impacts in regional sea ecosystems, PICES 2013.
15. **Langebroek, Petra**; **Nisancioglu, Kerim H**. Can variations in orbital and greenhouse gas forcing explain the North Atlantic seasurface temperature evolution during the Last Interglacial?. PAGES 4th Open Science Meeting; 2013-02-13 - 2013-02-16
16. **Langebroek, Petra**; **Nisancioglu, Kerim H**.. The Greenland ice sheet during the last interglacial. SKD Days 2013; 2013-09-17 - 2013-09-18
17. **Langebroek, Petra**; **Nisancioglu, Kerim H**. The last interglacial climate as simulated by NorESM – A classic paleo Earth System Model simulation. Stats+Climate Workshop; 2013-09-11 - 2013-09-13
18. **Langehaug HR, Geyer F, Smedsrud LH, Gao Y**. Arctic sea ice decline and ice export in the CMIP5 historical simulations (talk). Bjerknes Centre 10-years anniversary conference. 2012.
19. **Langehaug HR, Geyer F, Smedsrud LH, Gao Y**. Arctic sea ice decline and ice export in the CMIP5 historical simulations (poster). Summer School Monsoon Variability and Climate Teleconnection. 2012.
20. Mesquita, M, **Schrum, C**, et al. Synthesis/Review of the Downscaling Activities: Technical Considerations. Oral. Bjerknes Centre, Annual Getaway. Geilo, Norway, January 2012.
21. **Outten, S., Davy, R. and I. Esau**, 2013: Eurasian winter cooling: Intercomparison of Reanalyses and CMIP5 data sets, *International conference on 10th anniversary of Nansen-Zhu centre*, 22-25 October, Beijing, China
22. **Outten,S. and I. Esau**, 2013: Bjerknes compensation and its role in the Arctic, *the Third International Symposium on the Arctic Research* (ISAR-3), January 14-17, Tokyo, Japan, G7-P2
23. **Pushpadas, D, Schrum, C**, Daewel, U. Performance of AR4 GCMs in North Sea and Baltic Sea compared to reanalysis data. Poster, RESCLIM Meeting 2011, Bergen, March 2011.
24. **Pushpadas, D, Schrum**, C, Daewel, U. Challenges in climate impact assessment in the North Sea and Baltic Sea region using climate models, Poster, SARMA Workshop, Lund, April, 2011.
25. **Pushpadas, D, Schrum**, C, Daewel, U. Challenges in climate change impact assessment on marine ecosystems: A modelling study for the North and Baltic Sea. Oral, AMEMR Workshop, Plymouth, June, 2011.
26. **Pushpadas, D, Schrum**, C. Climate change impacts on the North and Baltic Sea ecosystem: An assessment based on IPCC AR4 and AR5 models. Yeosu Climate Change Impacts on the Oceans. Yeosu, Korea, May 2012.
27. Risebrobakken, Bjørg; Li, Camille; Andersson, Carin; Birks, Hilary H; Birks, Harry John Betteley**; Esau, Igor**; **Jansen, Eystein**; Jenks, Cathy; Kleiven, Helga Flesche; **Langebroek, Petra**; Ninnemann, Ulysses S; **Nisancioglu, Kerim Hestnes**; **Smedsrud, Lars Henrik**; Zhang, Zhongshi. DYNAWARM: Dynamics of Past Warm Climates. SKD opening; 2011-12-01
28. **Sandø AB.** Poleward ocean heat transports, sea ice processes and Arctic sea ice variability in CMIP5 simulations. SKD Days 2013; 2013-10-17 - 2013-10-18
29. **Schrum, C, D. Pushpadas,** U. Daewel. Climate change downscaling to marine ecosystems, lessons learnt from downscaling exercises of AR4 and AR5 GCM scenarios, Workshop on Regional Climate Modelling, Seoul Korea, Oct. 2011.
30. **Schrum, C, D. Pushpadas**, U. Daewel. Climate change downscaling to marine ecosystems, lessons learnt from downscaling exercises of AR4 and AR5 GCM scenarios. Center for Climate Dynamics Opening, Bergen Norway, Dec. 2011.
31. **Schrum, C Dhanya Pushpadas**. Climate Change Downscaling to North Sea and Baltic Sea

32. Can we produce meaningful predictions? Oral. ECODRIVE final meeting. Hamburg, Germany. February 2012
33. **Schrum, C**, B Ådlandsvik, R. Bellerby, U Daewel, S Hjøllo Sætre, T Kristensen, A Sandvik, M Skogen, D Pushpadas , A Sandø, F Vikdebø . Climate Change Downscaling to Marine Ecosystems. Oral, Bjerknes Centre, Annual Getaway, Geilo, Norway, Jan, 2012.
34. **Schrum, C Dhanya Pushpadas**. Climate Change Downscaling to North Sea and Baltic Sea. Can we produce meaningful predictions? Oral. ECODRIVE final meeting. Hamburg, Germany. February 2012
35. **Schrum, C**, Bjørn Ådlandsvik, Richard Bellerby, Ute Daewel, Trond Kristensen and **Dhanya Pushpadas**, Dynamic downscaling to marine ecosystems. Yeosu Climate Change Impacts on the Oceans. Yeosu, Korea, May 2012.
36. **Schrum, C**, Bjørn Ådlandsvik, Richard Bellerby, Ute Daewel, Trond Kristensen and **Dhanya Pushpadas**. Dynamic downscaling to marine ecosystems-Best practices and limitations. Oral. Yeosu Climate Change Impacts on the Oceans. Yeosu, Korea, May 2012.
37. **Schrum, C**, Ute Daewel, **Dhanya Pushpadas**. Climate change impacts to North Sea and Baltic Sea, results from ensemble simulations forced by CMIP3 and CMIP5 models. ICWRER 2013.
38. **Sorteberg A.** How important are glaciers for Indus water resources? Oral, AGU Fall Meeting, San Francisco Dec. 2013.
39. **Sørland S., Sorteberg A.,** Rasmussen R., Liu C., Monsoon low-pressure systems over India: a climatology study and high-resolution climate sensitivity simulations. Poster, AGU Fall Meeting, San Francisco Dec. 2013.
40. **Tjiputra, J**., J. Schwinger, N. Goris and C. Heinze, Mechanism and detectability of basin scale surface pCO2 variability in the North Atlantic and North Pacific, Ocean Science Meeting, February 2014, Honolulu, USA (Oral).
41. **Tjiputra, J**., A. Olsen, B. Pfeil and C. Heinze, Long-term pCO2 trends from observations and CMIP5 models, Center for Climate Dynamics days, October 2013, Bergen, Norway (Oral).
42. **Tjiputra, J**., K. Lindsay, J. Orr, J. Segschneider, I. Totterdell, and C. Heinze, Changes in carbon cycle to natural variability as simulated by CMIP5 models, Bjerknes Centre Conference: Climate change in high latitude, September 2012, Bergen. Norway (Oral).
43. **Tjiputra, J**., K. Lindsay, J. Orr, J. Segschneider, I. Totterdell, and C. Heinze, Ocean carbon cycle feedbacks in the tropics from CMIP5 models, 17th Annual CESM workshop, June 2012, Breckenridge, USA (Oral).
44. **Viste, E., Sorteberg, A.**; Estimating snowfall from temperature and precipation in data-limited Himalayan watersheds. Poster, AGU Fall Meeting, San Francisco Dec. 2013.
45. **Viste, E., Sorteberg, A.:** What we don't know about snow and ice in the Himalayas. Bjerknes Center annual getaway, Geilo, Jan 2014.
46. **Viste, E., Sorteberg, A.:** Snowfall in the Himalayas: An uncertain future from a little known present. Oslo-Bergen meteorology group meeting, Geilo, Jan 2014.
47. Zhang, Zhongshi; **Nisancioglu, Kerim Hestnes**; **Bentsen, Mats**; Bethke, Ingo; Yan, Qing; Risebrobakken, Bjørg; Andersson, Carin; **Jansen, Eystein**. Middle Pliocene simulation with NorESM-L. PlioMIP workshop; 2011-08-02 - 2011-08-04
48. Zhang, Zhongshi; **Nisancioglu, Kerim Hestnes**; **Bentsen, Mats**; Bethke, Ingo; Yan, Qing; Tjiputra, Jerry; Risebrobakken, Bjørg; Andersson, A; **Jansen, Eystein**. Middle Pliocene simulation with NorESM. PlioMIP workshop; 2011-08-02 - 2011-08-04
49. Zhang, Zhongshi; **Nisancioglu, Kerim Hestnes**; **Bentsen, Mats**; Bethke, Ingo; Yan, Qing; Tjiputra, Jerry; Risebrobakken, Bjørg; Andersson, A; Li, Camille; **Langebroek, Petra; Jansen, Eystein**. Was AMOC stronger in the Mid-Pliocene, simulation with NorESM. NZC annual meeting; 2011-11-23 - 2011-11-25

Predictability of Arctic/ North Atlantic climate

PRACTICE

Final SKD project report[1]

PRACTICE– Predictability of Arctic/North Atlantic climate

by project leader Tor Eldevik with input from WP leaders and PRACTICE members

Summary The overall objective of PRACTICE was *to establish a basis for interannual to decadal prediction of Arctic/North Atlantic climate*. The project and its status toward the end of the 2011–2015 project period can briefly be summarized as follows.

Will Norway experience cold and dry winters in the next few years? Årthun et al. (2015) suggest *yes* (Figure 1). Will the Northern Sea Route become more accessible? Onarheim et al. (2015) suggest *not so much in the short term*, but likely so in the long term (Figure 3).

Climate prediction models, principally like those for weather forecasting, are under development to answer such questions of large societal importance, or, more precisely, to provide a confident range and probability of possible outcomes.

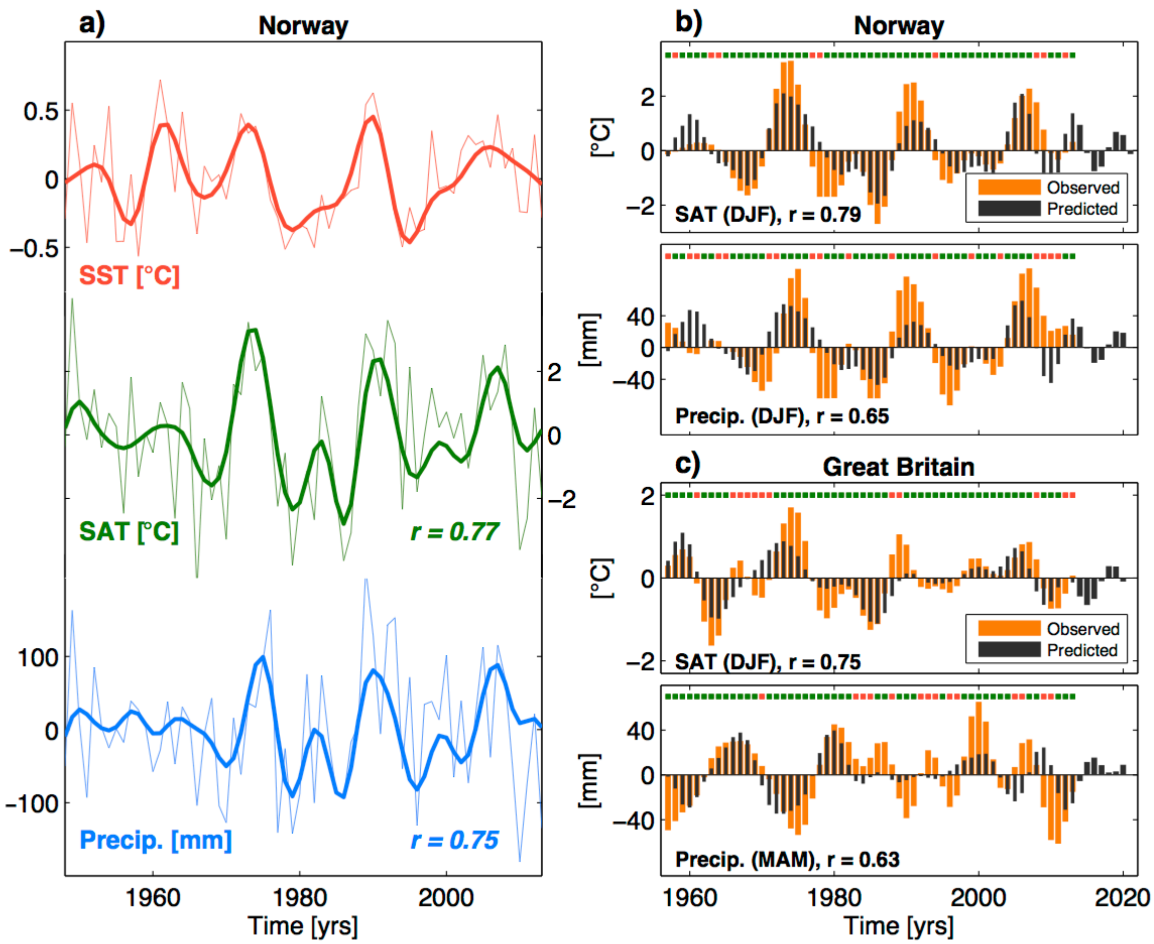

Figure 1 Observed predictability and forecast of European climate rooted in the ocean. Norwegian Sea surface temperature as reflected in winter mean Norwegian main land surface air temperature and precipitation (panel a). The ocean heat anomaly finds its source in propagating North Atlantic anomalies. The latter can accordingly be

[1] Note that project postdoc Marius Årthun's engagement runs through to 7/2017, and that the final NorCPM simulations (D2.4) are not due until 12/2015.

used to predict future Norwegian winter climate (b), and UK wintertime temperature and spring precipitation (c; Årthun et al. 2015).

Dynamical seasonal-to-decadal climate prediction is an emerging research field. Recent progress is documented in the IPCC WG1 Fifth Assessment Report (AR5); it is in general still unknown to what extent climate is predictable on interannual to decadal timescales – both from a theoretical and a practical perspective. In PRACTICE, the Bjerknes Centre has invested to make climate prediction a strategic priority. The Norwegian Climate Prediction Model (NorCPM) has accordingly been realized (Figure 4; Counillon et al. 2014). Simultaneously, the required observational basis to assess mechanisms and both initialize and evaluate models has been established (Figure 2; Mork et al. 2014).

With the NorCPM in place, the Bjerknes Centre is now engaging actively in the international research effort to resolve this scientific question of foremost societal importance. PRACTICE has in parallel kept a strong focus on assessing potential predictability from confronting possible mechanisms with the observational record. Key cause-and-effect relations have been indicated, e.g., for North Atlantic atmosphere–ocean heat exchange (Gulev et al. 2013), and for the strength and structure of the Gulf Stream's extension toward and into the Arctic (Glessmer et al. 2014; Lien et al. 2013). Such identified relations will increasingly be converted into corresponding frameworks for model evaluation (Sandø et al. 2014; Eldevik and Nilsen 2013).

At the conclusion of PRACTICE we are now in the position where we have documented predictability and can do skilful climate forecasts for the northern seas region, importantly *including continental climate,* based on the observational record (Figure 1, Årthun et al. 2015; Onarheim et al. 2015). The predictability identified for sea ice extends to a possible subsequent teleconnection to hemisphere-scale climate (King et al. 2015).

We are confident that we now in the next phase will be able to translate these insights and according skill into realistic predictions with the NorCPM forecast system developed as part of PRACTICE.

Project results

This section is ordered according to the Work Packages (WP) and their Deliverables (D).

WP 1. The observed operation of North Atlantic/Arctic climate PI Øystein Skagseth (IMR)**,** Co-PI Tor Eldevik (UiB); members Kjell Arne Mork (IMR), Jan Even Ø. Nilsen (NERSC), Mirjam Glessmer and Marius Årthun (UiB)

Objective: to advance the mechanistic and observation-based understanding of anomalous ocean circulation and northern climate variability.

The purpose of this work package was to identify key northern **observations and mechanisms** of predictive potential. It is generally understood, and for PRACTICE in particular, that a potential for climate prediction resides with the ocean.

D1.1 State-of-the-art observation-based data set for the interannual variability of the northern seas; to be continuously updated through the project

A state-of-the-art database and documentation of observed Norwegian Sea heat content have been developed (cf. Figure 2). The use of the NISE observational data set (Nilsen et al. 2008), a previous community effort largely within the Bjerknes Center realm, has further been corroborated through PRACTICE (e.g., Glessmer et al. 2014). There is also an increasing use of community-standard observational data for observation-based assessments of predictability, model-model intercomparison, and associated mechanisms (e.g., using data for the UK Hadley Center, HadISST; Årthun and Eldevik 2015, Langehaug et al. 2015; cf. also D.2.4).

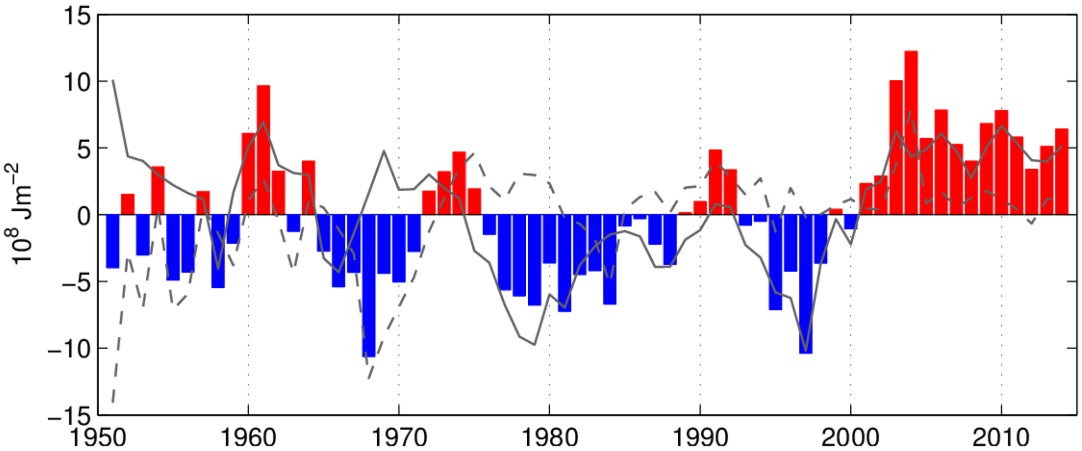

Figure 2 Observed heat content of the Norwegian Sea (deviation from climatology; Mork et al. 2014).

Independent but highly relevant and important developments yet to be capitalized on, have been the establishment of the Bjerknes Climate Data Center (bcdc.no), and the public release of Alexander Korablev's (GFI, UiB) *Climatological Atlas of the Nordic Seas* through NODC-NOAA.

D1.2 Synthesis of observed generation, propagation, persistence, and decay of ocean anomalies propagating through the northern seas, and

D1.3 Synthesis of mechanistic descriptions, including dedicated model simulations, of the generation, propagation, persistence, and decay of ocean anomalies through the northern seas

Both deliverables are met by the findings of PRACTICE papers such as Årthun and Eldevik (2015), Glessmer et al. (2014), Mork et al. (2014), and Eldevik and Nilsen (2013) largely based on the observations of D1.1, and the complementary use of climate or ocean model simulations. The papers can broadly be summarized as follows. Change in the northern seas – and associated climate predictability – is rooted upstream in the North Atlantic Ocean. This also includes anomalous freshwater content that is found to reflect low-salinity inflow from the Atlantic proper to the Nordic Seas (Glessmer et al. 2014), and thereby challenging the apparent standard concept of "Great salinity anomalies" and freshwater anomalies as something generically originating in the high Arctic.

Going more into details, there are important distinctions with respect to the specific inference made for key features such as anomalous ocean heat content and poleward ocean heat transport. Both Mork et al. (2014) and Årthun and Eldevik (2015) find the former to result from the latter, but with Mork et al. assigning also a more active role to the atmosphere (i.e., making it potentially less predictable from ocean heat content), and Årthun and Eldevik finding the strength of the current as opposed to anomalous temperature to be the dominant contributor.

D1.4 Updated comprehensive mechanical description of the generation, propagation, persistence, and decay of ocean anomalies through the northern seas; to be updated through the project

We are now in the position where skillful climate prediction has been documented from observations, and it largely or partly find its skill from poleward ocean heat transport. Specific cases are the Barents Sea ice cover (Figure 3; Onarheim et al. 2015), which essentially carries the variance to date in the observed Arctic winter cover, and northwest European continental climate, both temperature and precipitation (Figure 1; Årthun et al. 2015), with a forecast horizon of 1 up to 10 years.

The mechanisms and associated magnitudes and time scales of relations, guide what mechanisms one should similarly assess in model systems; model magnitudes and time scales accordingly diagnosed, should inform future model evaluation and forecast verification. A given forecast system may, e.g., have consistent mechanisms for sea ice cover but erroneous winds (and we now know from observations how the two contribute simultaneously to changes in Barents Sea ice cover; Onarheim et al. 2015). Such a systematic bias – when identified – can be accounted for in a forecast (for a lagged relation) and in retrospective forecast verification.

Oppositely, climate model systems of sufficient realism can be used to infer specific mechanisms and quantitative relations that cannot be inferred from an incomplete observational record alone. A pertinent example is how Årthun and Eldevik (2015) use a multi-century simulation with the Bergen Climate Model (BCM, the predecessor of NorESM) to qualify and quantify how anomalous Norwegian Sea air-sea fluxes and consequently surface air temperature is a lagged response to Atlantic heat transport into the sea.

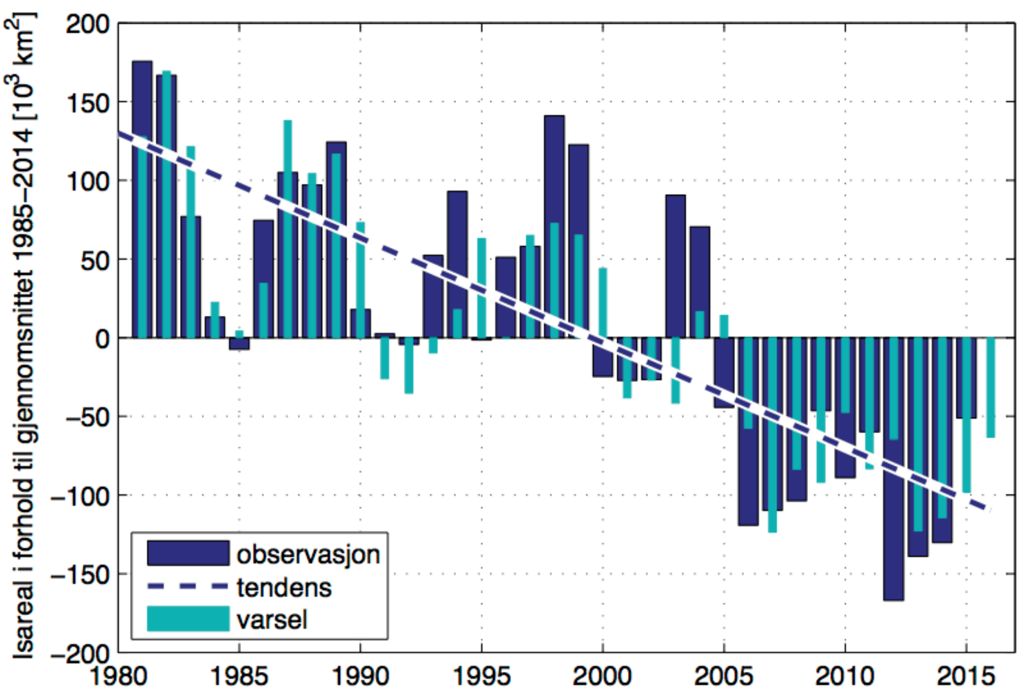

Figure 3 Observed and predicted sea ice cover for the Barents Sea (winter-centered annual mean; based on Onarheim et al. 2015). Anomalies are shown relative to the 1985–2014 mean that is the suggested reference period for the Norwegian Government's updated integrated management plan for the Barents Sea.

WP 2. A climate prediction model for North Atlantic/Arctic climate PI François Counillon (NERSC), Co-PI Mats Bentsen (uni); members Laurent Bertino and Yiguo Wang (NERSC), and Ingo Bethke (uni)

Objective: construct, test, and develop the Norwegian Climate Prediction Model (NorCPM)

This work package was literally about **building the "machinery"** of what eventually in the future may become an operational climate forecast model. More specifically, to merge the Norwegian Earth System Model (NorESM) with NERSC's established data-assimilation framework (based on the so-called ensemble Kalman filter, EnKF) into one model system, the Norwegian Climate Prediction Model (NorCPM), for initialized climate prediction.

The NorCPM has been constructed and documented (Counillon et al. 2014), and we are confident about its reliability, robustness, and future usefulness to the extent that the consortium – and NorCPM – will participate in the "Decadal Climate Prediction Project" as part of the upcoming Climate Model Intercomparison Project 6 (CMIP6) under the World Climate Research Programme (WCRP). The realization of NorCPM is a concrete and most substantial deliverable from PRACTICE in itself.

D2.1 Evaluation of first assimilation experiments with NorCPM, and

D2.2 Evaluation of first model-model predictability simulations with NorCPM

The paper Counillon et al. (2014) meets both deliverables. It was particularly found that the North Atlantic–Nordic Seas region has a large predictive potential in the NorESM model system. This part was based on "perfect model studies", that is the assimilation of synthetic data from previous simulations with the same model system. Such data, which are consistent with the model climate, will disagree less with the model than actual observations. Perfect model studies thus indicate an upper limit to predictability for a given model system. (The limit only applies to the given model version; models and model systems should of course continuously be re-assessed and improved through the verification and reanalyses of data and simulations).

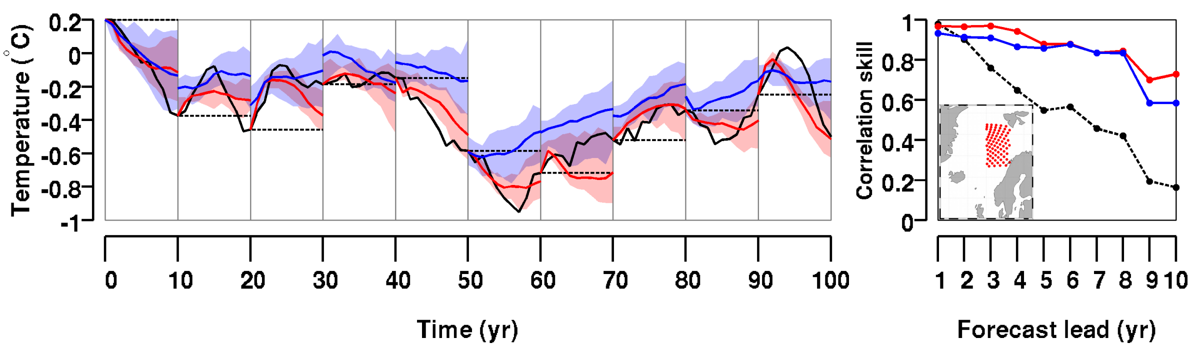

Figure 4 Prediction of Nordic Seas heat content using NorCPM (upper 300 m; red box area; Counillon et al. 2014). The reference to be predicted is the continuous simulation (in black). Forecasts are initialized every ten-year with synthetic observations from the reference simulation, using all data from all model fields (red) and only sea surface temperature (SST; blue). There is in general predictability, and the predictability achieved from assimilating only SST is in particular encouraging.

D2.3 Revised model and assimilation strategy

The NorCPM, being based on NorESM, has a model ocean that is density stratified (isopycnic) in its vertical discretization. The model is Lagrangian and some variables such as layer thickness have a physical constraint (non-Gaussian distributed). It was found that assimilation for such variables introduces a model drift. A cost-efficient solution reduces the drift by a factor 10, making the integration of long reanalysis possible (Wang et al. 2015).

A variety of data types with varying spatiotemporal coverage (such as altimetry, T-S profiles, ice concentration, and land snow-cover data) are considered for assimilation and being included as part of spin-off projects (e.g., EPOCASA, SNOWGLACE). There is in particular ongoing development to use the observed heat content data from WP1 (Mork et al. 2014; Skagseth and Mork 2012) for validation. The assessments are yet to be concluded, but the according choices and priorities are nevertheless of a nature that requires regular re-assessment also in the future (equivalent to the model and strategy improvement from so-called reanalysis in weather forecasting). The benefit and usefulness of assimilating SST, and the associated variance's progression through the model grid with the EnKF methodology, remain robust (Counillon et al. 2014).

D2.4 Report on first (pilot) climate predictions 201x–2020 for the Nordic Seas/Arctic Ocean, including Arctic sea-ice cover

The simulations are due by the end of 2015. The deliverable is nevertheless already well on its way, and we are confident that it will be met. The above encouraging predictability suggested for SPG and Ocean Heat content in the Nordic Sea based on SST (Figure 4), appears in particular to carry over to the assimilation of, and verification against, real observation-based data (HadISST; cf. WP1).

WP 3. Theoretical underpinning, evaluation, and coordination PI Noel Keenlyside (UiB), Co-PI Anne Britt Sandø (IMR); members Helene R. Langehaug (NERSC) and Odd H. Otterå (uni).

Objective: to extend the basis for interannual-to-decadal prediction of Arctic/North Atlantic climate, identify requirements – observational and model – of a prediction system, and coordinate its development

This work package is essentially about **the evaluation of forecast system**(s), NorCPM in particular (WP2), according to observations and robust mechanisms as those inferred in WP1. It is the objective and robust conversion of such predictability assessment into forecast verification and according forecast system improvement that eventually may constitute the basis for skillful and robust – i.e., *operational* – climate prediction. This is the conceptual basis for the Centre of Excellence (2017–2026) to be proposed this autumn.

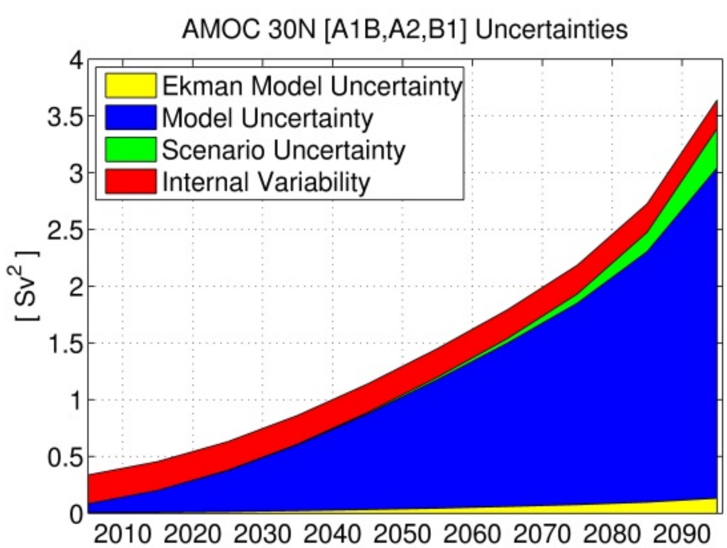

Figure 5 Estimates of the variance in AMOC change resulting from different components (CMIP4 repository; from Reintges et al. 2015); model uncertainty, i.e., from the specific model formulations, is found to dominate and increasingly so with time. A similar analysis has been done for CMIP5.

D3.1 Assessment of uncertainties in model projections for the coming decades of the meridional and horizontal circulation, and the connection between the North Atlantic, Nordic Seas, and Arctic

The largest uncertainty in future projections of the Atlantic Meridional Overturning Circulation has been found to be associated with climate model uncertainties (Figure 5; Reintges et al. 2015); a similar result is found for the strength of the Atlantic subpolar gyre.

D3.2 Assessment of impact of better resolving the stratosphere and surface temperature fronts on decadal atmospheric teleconnections

A key finding sustaining this deliverable, and a main finding of PRACTICE in general, is that observation-based (reconstructed) air-sea fluxes prove *Bjerknes' conjecture*: on decadal timescales it is the ocean that drives mid-latitude SST and turbulent heat fluxes (Gulev et al. 2013). This supports the main assumption that climate predictability is rooted in the ocean, and is a large-scale manifestation of the more specific similar relations assessed and supported in WP1. The impact of associated SST anomalies on the atmosphere could be reproduced for warm phases using stand-alone atmospheric models driven by observed SST (Omrani et al. 2014), and in coupled model configurations (Omrani et al. 2015).

D3.3 Assessment of first hindcast experiments focusing on climate impacts

Please confer D2.1–4 above. In addition there is the model-model intercomparison of Langehaug et al. (2015) of three prediction model systems (not NorCPM) with a focus on Nordic Seas inter-annual predictability. There is a maybe surprisingly large difference between the models with respect to model climatologies and specific (lack of) predictability, both individually and for cross-model consistency. A framework for model inter-comparison, including the comparison with observations, has nevertheless been outlined and documented.

D3.4 Recommendations for phase II of PRACTICE, or, if appropriate, the establishment of operational climate prediction at the Bjerknes Centre

The "phase II" is already being realized, e.g., through the Research Council of Norway project EPOCASA – Enhancing seasonal-to-decadal Prediction Of Climate for the North Atlantic Sector and Arctic (2014–2017), which can be considered the direct continuation of PRACTICE together with the strategic SKD project PARADIGM – Prediction and regional downscaling models (see also next section). The "recommendations" are the factual basis for these project descriptions and their realizations into project execution.

The PRACTICE/NorCPM group, as the international community in general (see also the summary above), finds that the realization of climate prediction as a skillful and robust operational service similar to weather forecasting is still someway off in the future. Our present assessment is that this should be made a concluding ambition of the Centre of Excellence (2017–2026) to be proposed this autumn.

Ongoing work and future plans

The PRACTICE team dedicated much of the last part of the project period to consolidating and further increasing the resources for climate prediction as a core activity at the Bjerknes Centre. Five projects were funded as a result, with EPOCASA, SNOWGLACE (RCN) and PREFACE (EU) for further testing and development of the NorCPM-system in a realistic framework, and GREENICE (NordForsk) and NORTH (RCN) more dedicated to mechanisms and associated frameworks for model evaluation. NorCPM and partly PRACTICE are also continued through the new SKD strategic projects PARA-

DIGM and INCREASE. Through the national and international consortiums thus established, links have been formalized with the main EU projects on climate prediction (NACLIM and SPECS). Last, but not least, PI Noel Keenlyside has secured an ERC consolidator grant on an alternative methodology to improve prediction (STERCP), and will lead a PRACTICE-based effort to apply for a RCN Centre of Excellence dedicated to climate prediction.

Peer-review publications

In the pipeline (non-exhaustive)

Årthun, M., and **T. Eldevik**, 2015: On anomalous ocean heat transport toward the Arctic and associated climate predictability. In revision *J. Clim*.

Årthun, M., et al. incl. **T. Eldevik**, **N. Keenlyside**, 2015: Skillful Decadal Prediction of Northwest European Climate Rooted in the North Atlantic *Ocean. To be submitted.*

Counillon, F., **I. Bethke**, **Y. Wang**, **N. Keenlyside**, and M.-L. Shen, 2015: Investigating the benefit of flow dependent covariance for assimilating SST in NorESM for the period 1950–present. *In preparation*.

Langehaug, H.R., D. Matei, **T. Eldevik**, K. Lohmann, and Y. Gao, 2015: Poleward propagation of ocean temperature anomalies as a source for the Nordic Seas inter-annual predictability. In review *Clim. Dyn.*

Reintges, A., T. Martin, M. Latif, and **N. S. Keenlyside**, 2015: Uncertainty in 21st Century Projections of the Atlantic Meridional Overturning Circulation in CMIP3 and CMIP5 models. *To be submitted.*

Skagseth, Ø., A. Slotte, E.K. Stenevik, and R.D.M. Nash, 2015: Characteristics of the Norwegian Coastal Current during years with high recruitment of Norwegian spring spawning herring (*Clupea harengus* L.). In revision *Plos ONE*

Wang, Y., **F. Counillon**, and **L. Bertino**, 2015: Alleviating the bias induced by the linear analysis update with an isopycnal ocean model. In review *Quart. Journal Royal Met. Soc*.

2015

King, M.P., M. Hell, and **N. Keenlyside**, 2015: Investigation of the atmospheric mechanisms related to the autumn sea ice and winter circulation link in the Northern Hemisphere. *Clim. Dyn*., doi: 10.1007/s00382-015-2639-5.

Omrani, N.-E., J. Bader, **N.S. Keenlyside,** and E. Manzini, 2015: Troposphere-stratosphere response to large-scale North Atlantic Ocean variability in an atmosphere/ocean coupled model, *Clim. Dyn*., doi: 10.1007/s00382-015-2654-6 .

Onarheim, I.H., **T. Eldevik**, **M. Årthun**, R.B. Ingvaldsen, and L.H. Smedsrud, 2015: Skillful prediction of Barents Sea ice cover. *Geophys. Res. Lett.*, doi: 10.1002/2015GL064359

2014

Counillon, F., **I. Bethke**, **N. Keenlyside**, **M. Bentsen**, **L. Bertino**, and F. Zheng, 2014: Seasonal-to-decadal predictions with the ensemble kalman filter and the Norwegian Earth System Model: A twin experiment. *Tellus* A, **66**, 21074.

Eldevik, T., B. Risebrobakken, A.E. Bjune, C. Andersson, H.J.B. Birks, T.M. Dokken, H. Drange, **M.S. Glessmer**, C. Li, **J.E.Ø. Nilsen**, **O.H. Otterå**, K. Richter, and **Ø. Skagseth**, 2014: A brief history of climate – the northern seas from the Last Glacial Maximum to global warming. *Quat. Sci. Rev.,* **106**, 225–246.

Glessmer, M.S., **T. Eldevik**, K. Våge, **J.E.Ø. Nilsen**, and E. Behrens, 2014: Atlantic origin of observed and modelled freshwater anomalies in the Nordic Seas. *Nature Geoscience,* **7**, 801–805.

Mork, K.A., **Ø. Skagseth**, V. Ivshin, V. Ozhigin, S.L. Hughes, and H. Valdimarsson, 2014: Advective and atmospheric forced changes in heat and fresh water content in the Norwegian Sea, 1951-2010. *Geophys. Res. Lett.*, **41**, doi:10.1002/2014GL06103.

Omrani, N.-E., **N.S. Keenlyside**, J. Bader and E. Manzini, 2014: Stratosphere key for wintertime atmospheric response to warm Atlantic decadal conditions. *Clim. Dyn*., **42**, 649–663

Sandø, A.B., Y. Gao, and **H.R. Langehaug**, 2014: Relation between ocean heat transports, sea ice processes and Arctic sea ice variability in NorESM1-M simulations. *J. Geophys. Res.*, **119**, 2095–2108.

2013

Eldevik, T., and **J.E.Ø. Nilsen**, 2013: The Arctic–Atlantic thermohaline circulation. *J. Climate,* 26, 8698–8705.

Gulev, S.K., M. Latif, **N. Keenlyside**, W. Park, and K. P. Koltermann, 2013: North Atlantic Ocean Control on Surface Heat Flux at Multidecadal Timescales. *Nature*, **499**, 464–467.

Lien, V.S., F.B. Vikebø, and **Ø. Skagseth**, 2013: One mechanism contributing to covariability of the Atlantic inflow branches to the Arctic. *Nature Com*., **4**, doi: 10.1038/ncomms2505.

Smedsrud, L.H., I. Esau, R.B. Ingvaldsen, **T. Eldevik**, P.M. Haugan, C. Li, V.S. Lien, A. Olsen, A.M. Omar, **O.H. Otterå**, B. Risebrobakken, **A.B. Sandø**, V.A. Semenov, and S.A. Sorokina, 2013: The role of the Barents Sea in the Arctic climate system. *Rev. Geophys.,* **51**, 415–449.

2012

Årthun, M., **T. Eldevik**, L.H. Smedsrud, **Ø. Skagseth**, and R. Ingvaldsen, 2012: Quantifying the influence of Atlantic heat on Barents Sea ice variability and retreat. *J. Climate*, **25**, 4736–4743.

Sandø, A.B., **J.E.Ø Nilsen**, **T. Eldevik**, and **M. Bentsen**, 2012: Mechanisms for variable North Atlantic-Nordic Seas exchanges. *J. Geophys. Res.,* 117, C12006.

Skagseth, Ø., and **K.A. Mork**, 2012: Heat Content in the Norwegian Sea, *ICES J. Mar. Sci.*, doi: 10.1093/icesjms/fss026.

Conference presentations (non-exhaustive, most recent contributions first)

Counillon, F., 2015: Seasonal-decadal prediction with the Norwegian Climate Prediction Model. 14th Coupled Data Assimilation symposium, Beijing, China, 5–8/7/2015.

Counillon, F., 2015: Seasonal-decadal prediction with the Norwegian Climate Prediction Model. *Theoretical aspects of ensemble data assimilation for the Earth system*, Les Houches, France, 5–10/4/2015.

Bethke, I., 2015: Norwegian Climate Prediction Model (NorCPM) getting ready for CMIP6 DCPP. *SPECS/MIKLIP project meeting*, Offenbach, Germany, 24–25/2/2015.

Eldevik, T. , 2015: The Arctic–Atlantic thermohaline circulation. *The Atlantic Meridional Overturning Circulation (AMOC) in a Global Perspective*. Workshop Bohlin Centre for Climate Research, Stockholm, 8–10/9/2015.

Eldevik, T., 2014: On the role of the northern seas in climate – predictor or predictable? *Transatlantic Science Week 2014*, Toronto, Canada, 26–29/11/2014.

Other outreach (non-exhaustive; most recent contributions first)

Onarheim, I.H., and **T. Eldevik**, 2015: Et sted må grensen gå. "Forskning viser at...", *Dagens Næringsliv*, 8/8/2015.

Eldevik, T., 2015: En kort historie om klima – de nordlige hav fra siste istid til global oppvarming. Nansen minneforelesning, *Det Norske Videnskaps-Akademi årbok 2014*.

Årthun**, M.**, and I. H. Onarheim, **T. Eldevik**. Tror på mer is i Barentshavet denne vinteren. Kronikk *forskning.no*, 25.01.2015.

Årthun, M., and I. H. Onarheim, **T. Eldevik**. Barentshavet – helt på grensen. Kronikk *Nordlys*, 15.01.2015.

Årthun, M., and I. H. Onarheim 2014. Havis på rømmen. Klima, CICERO, 2014.

Eldevik, T., 2014: Arktis smelter, Golfstrømmen består. *Aftenposten Viten*, 1/10/2014.

Eldevik, T., B. Risebrobakken, and A. Bjune, 2014: Tilbake til fremtiden. "Forskning viser at...", *Dagens Næringsliv*, 20/9/2014.

Eldevik, T., M. Reigstad, E. Falck, S. Gerland, S. Jentoft, G. Johnsen, U. Lindstrøm, T.L. Rasmussen, L.P. Røed, og P.F. Wassmann, 2014: *Arven etter Nansen*. Forskningsplan for det sentrale og nordlige Barentshavet. UiT Norges arktiske universitet. 48 pp. nansenlegacy.org

Eldevik, T., and **M. Årthun**, 2012: Nansen fikk rett. "Forskning viser at...", *Dagens Næringsliv*, 25/8/2012.

Regionalisation of Climate Scenarios

REGSCEN

Final report:
REGSCEN – Regionalisation of Climate Scenarios
SKD Strategic Project 2011-2015

Project PIs:
Anne Britt Sandø, Stefan Sobolowski

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Uni Research: Stefan Soblolowski, Muralidhar Adakudlu, Stephanie Mayer
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Goals and objectives:
REGSCEN's main objective has been to investigate how regional effects of global climate change can be modulated by internal variability on different time scales. Focus has been on ocean and land areas in the North Atlantic and Arctic region:

- Synthesize and evaluate methodologies of dynamical and dynamical-statistical regional climate modeling. Detect and attribute the role of surface boundary conditions, resolution, parameterization of small-scale perturbations.
- Evaluate, develop and assess methods for downscaling of climate change to regional ocean basins with specific emphasize to methodological and conceptual aspects related to the assessment of climate change impacts of the marine ecosystems and identification of uncertainty measures for regional projections
- Develop, evaluate and apply a regional coupled model system
- Perform downscalings of CMIP5 scenarios and analyze the results
- To enhance the value of the regional marine scenarios by including primary production

Main motivation
Climate change is global, but its magnitude and impact exhibit a significant regional component. This climate system variability, on a regional scale, has implications for mitigation and adaptation planning. The quest for a more realistic and quantitative description of this regional scenario component of the global climate change motivates this project effort on regional modeling for Norway and surrounding seas.

The horizontal resolution of the CMIP5 models is typical on the order of 100km. At this scale, the Norwegian coastal and mountainous geometry remains largely unresolved. In addition, global climate models with such a resolution represent many physical and dynamical processes only by coarse parameterization. Coarse resolution models are useful for studying large-scale phenomena, and they are cheap computationally with the advantage that many ensemble members can be produced. Regional climate models are probably better suited for adaptation and mitigation planning at regional scale, but they have the disadvantage that they are quite expensive to computationally.

Dynamical downscaling is an established method for regionalization, where a regional model with relatively high resolution is forced by lateral and surface boundary conditions from a global coupled climate model. This method has been heavily used for the atmosphere and to some degree for the ocean. It has been demonstrated to increase the value of the global scenarios regionally, both in the atmosphere and in the ocean (Ådlandsvik and Bentsen, 2007; Melsom et al. 2009). There are common alternative methods, such as statistical downscaling, but the present project will mainly concentrate on the dynamical method.

There are caveats to the use of dynamical downscaling. Large-scale errors in the global models cannot be totally rectified by applying a regional model. For instance in Arctic areas, sea ice causes problems, with the present generation of CMIP models having too much ice (Overland and Wang, 2007); and others. The sea-ice problem happens when a regional atmosphere model is forced with too much ice from the global model below. The heat flux from the ocean is then strongly reduced. Similarly, if an atmospheric model with too much sea ice is used to force an ocean model, the low air temperature induces a strong oceanic cooling, leading to excess ice cover in the regional ocean model as well. This project will therefore invest resources into improving the methods used for downscaling, and thereby provide a contribution to the climate community.

Main results

Work Package I: Methodology and model tools development

WP1.1 Methods for Atmospheric Downscaling

Public attention to the climate change agenda has significantly weakened over the last decade. This disengagement is likely caused by the lack of climate information about the changes in immediate personal environment, i.e. the relevant climate information connected to public cultural values and addressing the public needs. A common approach of the dynamic climate downscaling is presently unsatisfactory as it is unable to produce such a socially relevant information neither with sufficient certainty nor with fine enough details. Outten and Esau (2013) demonstrated these uncertainties in the extreme wind scenarios over Europe (Outten et al., 2013), which were related to differences in the climate change projections by a selection of the global and regional climate models. It must be emphasized that unlike temperature changes, which are projected to be rather modest for Norway, the issue with extreme winds, precipitation and their dynamical controllers – storm tracks and Atlantic blockings – is of primary interest for national/local climate scenarios. Understanding of these certainty and resolution problems motivated the REGSCEN team to explore novel approaches to process-based downscaling.

The idea of the process-based downscaling is rooted in the fact that regional/local scale processes can significantly modify large-scale climate patterns resulting in a specific diversity of regional climate responses. Wolf and Esau (2014) demonstrated the statistical component of the approach compiling local air quality hazard projections in Bergen on the basis of quasi-cyclic variations of the Atlantic storminess.

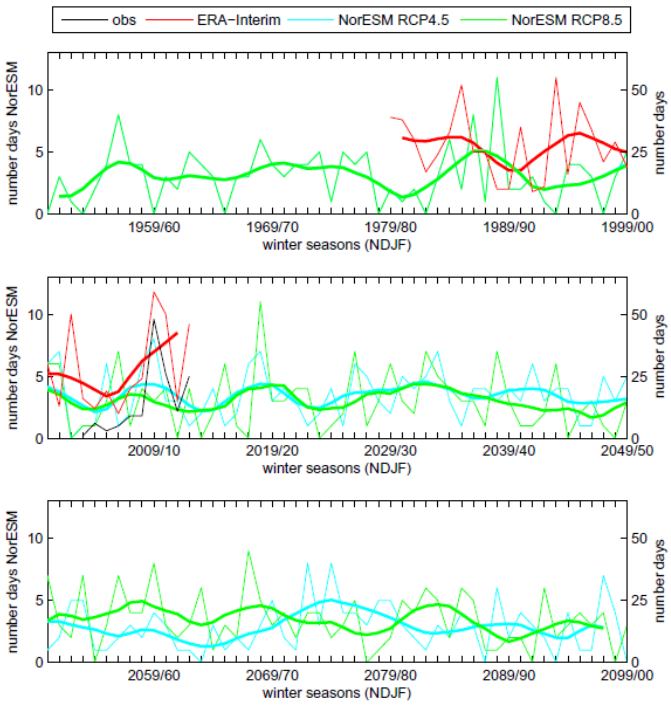


Figure 1. Seasonal sum of observed (obs) and predicted days with high NO_2 pollution based on the proxy in ERA-Interim (right y-axis) and the historic simulation combined with both the low (RCP4.5) and high (RCP8.5) future emission scenarios between 1950 and 2100 in NorESM (left y-axis). The thick lines show the smoothed 5 year running mean seasonal sum of predicted days with high NO_2 pollution based on the proxy in the two NorESM emission scenarios. The curves are different already from before 2005 (the end of the historic simulation) since dT1dr was calculated as a running mean over 30 years. After Wolf and Esau (2014)

Figure 1 from this work illustrates that such an essentially local phenomenon as a high concentration of the air pollutants in the Bergen central valley is statistical linked with persistence, and hence with the large spatial scales, of weather anomalies. The global climate models are much better in projecting those large-scale anomalies than in projecting their local impact. However, the local impact can be recovered statistically on the basis of improved understanding of the universal physical processes as they act locally.

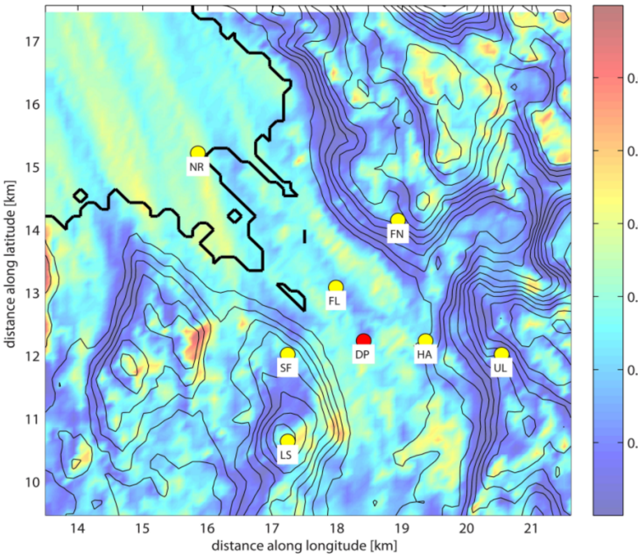


Figure 2. The extreme wind variations over the central Bergen valley simulated with the turbulence-resolving model PALM (27 m horizontal resolution). Red areas show particularly vulnerable places for the winds from South. Circles locate the model validation points. After Esau et al. (in prep).

Some processes of the small-scale turbulence dynamics (Esau et al., 2013; Zilitinkevich et al. 2013) are understood sufficiently well to draw their climate impact assessment (Davy and Esau, 2013; Smedsrud et al., 2013; Davy and Esau, 2014). Figure 2 illustrates the extreme wind field simulated with the turbulence-resolving model PALM (Esau et al., in preparation). Specifically, this work demonstrates that in places with complex surface geometry not so much the wind speed as changes in the wind direction are to be impactful.

In summary, the REGSCEN work has indicated a significant projective potential of connections between persistence of the large-scale circulation dynamics and regional climatology. It demonstrated that for the extreme wind scenarios a complete fine-resolution vulnerability assessment is feasible with the turbulence-resolving models. Finally, the work showed that the local climate change information could be communicated in a way to address influential 'sense of the place' attitudes of the public.

WP1.2 Methods for Ocean Downscaling

Here, methodological issues related to ocean downscaling are addressed. Specific focus is on BIAS correction methods, the development of consistent biogeochemical boundary conditions for assessment of climate change impacts to ocean regional biogeochemistry and lower trophic level production, and application of a multi-model ensemble to assess inter-model uncertainty on the regional scale.

A downscaling for a regional ocean system requires atmospheric, oceanic and terrestrial forcing from a global climate model (Figure 3). In addition to sea level, temperature and salinity, projecting the regional biogeochemistry requires also projected changes in regional boundary conditions for nutrients from an Earth System model and for terrestrial river loads. The latter are currently not available from global Earth System models (ESMs) since terrestrial load changes are typically neglected even for CMIP5 scenarios. They need therefore to be constructed based on plausible relations between regional river load, precipitation and runoff changes and assumptions on anthropogenic load scenarios. Moreover in dependence on the regional system to be investigated also construction of regional boundary conditions might be required. The regional system can either be directly forced by atmospheric data from global ESMs or a regional atmospheric downscaling can be applied. Alternatively, downscaling can also be performed by using a regional coupled atmosphere-ocean model.

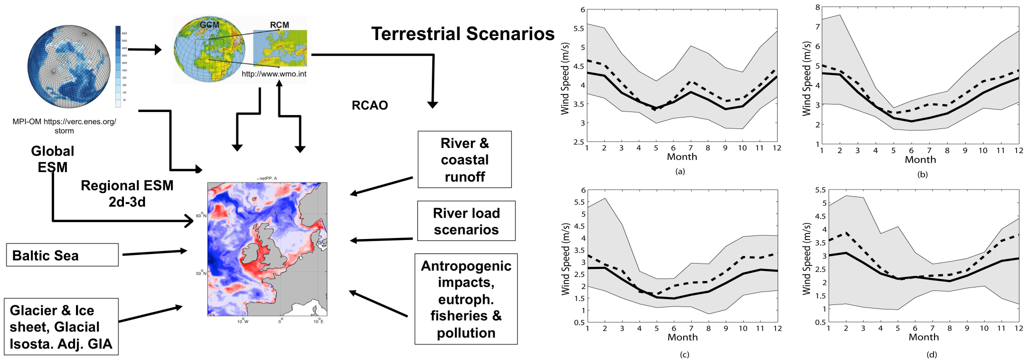


Figure 3: Left: Downscaling approach required to project the climate change impacts to the regional North Sea system. Right: Multi model mean (solid black) and NCEP (dashed black) monthly climatology (from 1948-2005) of surface wind speed for (a) North Atlantic Region, (b) North Sea, (c) Baltic Sea and (d) Barents Sea. Model range: Grey shaded area.

The regional scale modeling might furthermore require bias correction, which arise from global model bias (Figure 3, right). Without bias correction the sensitivity to climate change on the regional scale might be flawed, e.g. a regional model forced by climate model data without any bias correction might be unable to produce seasonal stratification over wide regions e.g. due to too low temperature or too high wind speed, and hence would not react sensitive to changes in these. Bias correction on the other hand destroys dynamic consistency of the forcing and, in dependence of the method applied, influences the sensitivity of the system to changes (e.g. Holt et al., 2014).

A great variety of different downscaling approaches have so far been applied to regional systems. For the North Sea these have been reviewed as part of NOSCCA (North Sea Climate Change Assessment). All methods have their advantages and disadvantages and add uncertainty to projected regional changes in addition to the choice of scenario and forcing global model, and no consensus has so far been reached on best practices (see for more detailed discussion Schrum et al., in press). Here it was decided to further use a delta change bias correction approach, and only the average change from the climate models as a monthly anomaly was considered to force the regional physical-biological model ECOSMO (Pushpadas et al., 2015, Chust et al., 2014). Biogeochemical boundary conditions were extracted from global ESMs, these were only freely available from CMIP5 onwards. For practical reasons it was therefore selected 3 ESMs for which access to both A1B scenario simulations and a range of RCP scenarios had been achieved.

WP1.3 WRF Coupling with ROMS

The WRF-ROMS coupling has been undertaken through the Model Coupling Toolkit (MCT) by using the Coupled-Ocean-Atmosphere-Wave-Sediment Transport modeling system (COAWST; Warner et al., 2010). In addition to WRF and ROMS, the system consists of a wave model and a sediment transport model that are not considered for this study. In order to implement and evaluate the model for high-latitude applications, a polar meso-cyclone (polar low) that developed over the Norwegian Sea during 3 – 4 March 2008 was chosen. The evaluation is carried out by comparing the simulations with the observations of the complete life cycle of the polar low that were made during the IPY-THORPEX field campaign (Kristjansson et al., 2011).

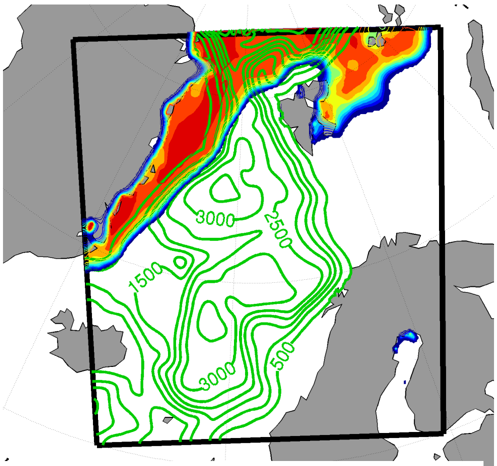


Figure 4: Model domain with the bathymetry contours (at 500 m interval). Colored area represents the sea-ice cover.

Model set-up Figure 4 shows the domain used for the simulations. It has 219x249 grid points in the horizontal at a 10 km resolution. The WRF model has 51 vertical levels and the ROMS has 40 levels. Initial and boundary conditions are obtained from the Climate Forecast System Reanalysis (Saha et al., 2010) for both the models. The simulation is carried out for the period between 2008.03.02 and 2008.03.05. Simulations are performed both in coupled and uncoupled modes to enable inter-comparisons. The ROMS model was run from 2007.01.01 independently for 14 months for spin-up before being coupled to WRF on 2008.03.02. During the spin-up, the model receives monthly surface wind, temperature and humidity fields from CFSR as the atmospheric forcing and estimates the heat and momentum fluxes according to the bulk formulae. Once coupled, it takes the fluxes from WRF and provides the SST to WRF.

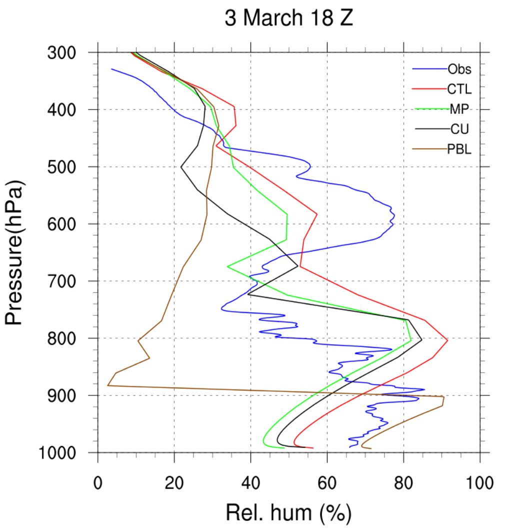


Figure 5: Profiles of relative humidity associated profiles represent (from top to bottom) dropsonde observations (Obs), the control simulation (CTL), experiments with a different microphysics (MP), the cumulus physics (CU) and the boundary layer physics (PBL).

Atmosphere-only simulations The WRF-only simulation appeared to capture the basic characteristics like the location, size, intensity and timing of the low fairly well (not shown). However, the vertical structure has deviations in the relative humidity profile with respect to the dropsonde measurements as shown in Figure 5. These deviations seem to be related to the choice of individual physics or parametrizations to some extent as evident from the figure. However, each choice has limitations leading to either an under- or over-estimation of the relative humidity associated with the polar low. The sensitivity of such characteristics of the polar low, particularly in the boundary layer, to atmosphere-ocean-ice coupling would be assessed in the coupled simulations.

Ocean-only simulations In order to simulate the complex inter-actions between ocean-ice-atmosphere in the area of interest, the application grid is designed so that it retains the complexity in the area in terms of steep bathymetry near the coastal areas (Figure 4) but at the same time would keep the simulation stable.

In spite of the optimized grid structure, the model behaves in an unusual way with extreme surface warming and reflection of tracers from the northern boundary as shown in Figure 6. A number of experiments with simple, idealistic physics and parametrizations show that this behavior is directly linked to atmospheric forcing and handling of the lateral boundary conditions.

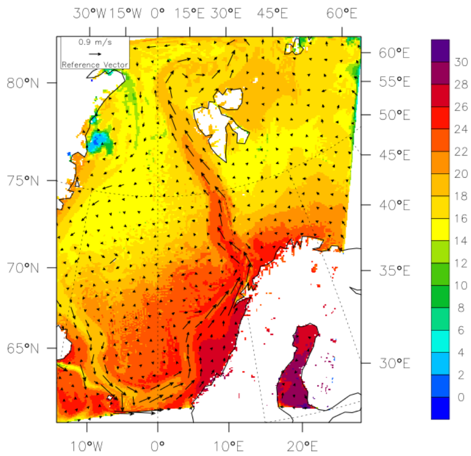


Figure 6: Potential temperature (color, in degrees) and wind vectors at the ocean surface at day 140.

To eliminate the reflection, a moderate nudging is applied at the northern boundary towards the CFSR climatology. However, the reflection still persisted. It might be necessary to look into the interpolation and the resolution jump from the driving data at lateral boundaries, particularly when a boundary cuts through certain land points. The cause of extreme surface warming is not clear, though, it is likely that the bulk flux computation becomes unstable due to the non-linearity of the problem. Currently, the flux computation is being de-activated and the flux components are prescribed at the surface from the ERA-Interim data.

Work Package 2: Specific Applications

WP2.1 - CMIP5 Downscaling Studies

Ocean Downscaling

The analyses on oceanic downscaling presented here describe results both from downscaled CMIP3 and CMIP5 models using the high resolution, coupled sea ice-ocean model ROMS on the Atlantic-Arctic grid (AA10km) (Figure 7).

The downscaling of CMIP3 models is a continuation of the work described in Melsom et al. (2009) where a downscaling of the global AOGCM from NASA Goddard (hereafter called GISS) for the present-day climate (20C3M) was extended by a downscaling of the coupled NCAR CCSM. The choice of global CMIP3 models, from which the atmospheric forcing is collected, was based on the study by Overland and Wang (2007) and their assessment of results of Arctic sea ice from AOGCMs. Both global and downscaled models were evaluated against hydrographic data along fixed cruise tracks in the Barents Sea. In addition, both models were downscaled for a future scenario (A1B).

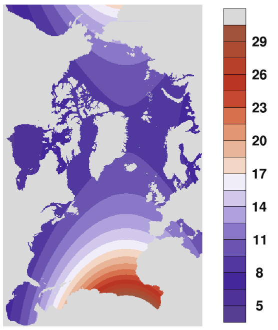


Figure 7: Model domain and horizontal resolution (km) for the Atlantic-Arctic grid.

In order to identify CMIP5 models suitable for downscaling in the Nordic Seas and Arctic Ocean, a subset of CMIP5 models were evaluated for ocean heat transports through the primary Arctic gateways in Sandø et al. (2014a) and sea ice extent in Langehaug et al. (2013). Based on this, NorESM1-M was found to be the best CMIP5 model suited for downscaling in this project, as heat transport is crucial for sea ice extent as well as biological production in the Barents Sea. Also, to evaluate the effect of downscaling on the sea ice extent, a downscaling with ROMS on the AA10km grid forced with CORE2 reanalysis were compared to a CORE2 forced NorESM simulaton. The comparison shows that the high resolution ROMS ice edge is much closer to observed ice edge than the coarser resolution NorESM (Figure 8), most likely due to more realistic circulation and heat transport into the Barents Sea through the Barents Sea Opening (BSO) as shown in Sandø et al. (2014b) for the CMIP3 models.

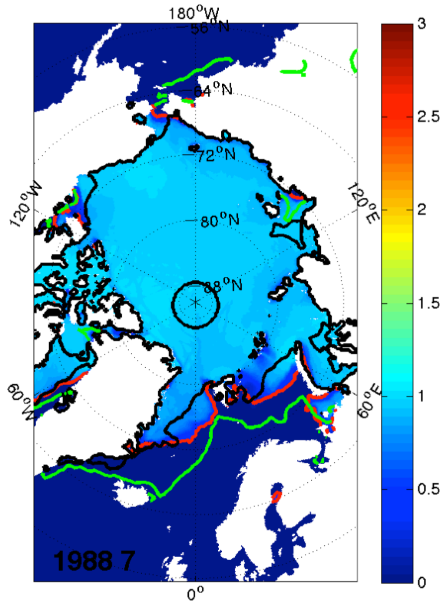


Figure 8: Sea ice extent (15% concentration) in July 1988 from NSIDC (black), ROMS (red) and NorESM (green). ROMS and NorESM are both forced with CORE2 reanalysis.

The change in sea surface temperature from present to future in the downscaled NorESM RCP4.5 is shown in Figure 9. Like the two downscalings in Sandø et al. (2014b), this model also shows a surface warming of about 1°C for March in most of the Barents Sea. This warming is reflected in the sea ice extent, with reductions in the central and northern parts of the Barents Sea. Such similarities are not seen for the future salinities in the Barents Sea, and the divergence in the regional simulations is found to be due to anomalies in the respective global models. This is supported by experiments described in Schrum et al., in prep: Regional downscalings of one global model using different regional models gave minor differences, while using only one regional model with forcing from different global models resulted in more pronounced divergence in the distinct model output. In the downscaled NorESM RCP4.5, reduced sea surface salinities are dominating, especially in the coastal regions.

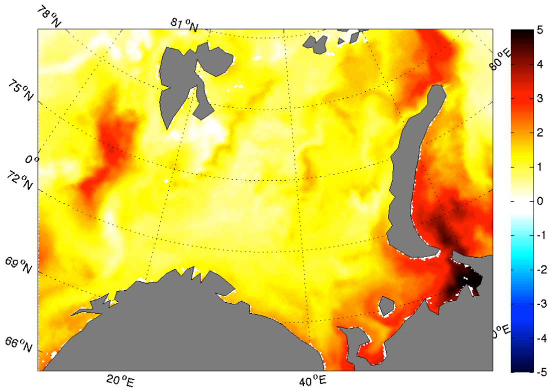


Figure 9: Change in SST (°C) in the Barents Sea from the period 2010-19 to 2060-69.

In combination with higher sea surface temperatures this gives increased stratification in most of the Barents Sea. These changes in sea ice extent and stratification affect light and nutrient availability for the lower trophic level in the ecosystem, which again cascade further to higher trophic levels. Results from this downscaled future scenario contribute to the NOU report Klima i Norge 2100 and to the AACA-C report, both in prep.

In addition to these downscalings, simulations done under WP1.2 also address WP2.1. Regional downscaling from 3 global Earth System Models (ESM) from CMIP5 simulations were performed and regional changes in hydrodynamics were projected. Projected changes cover a large range and are for some models (e.g. NorESM) significantly different compared to their AR4 precursor (Figure 10).

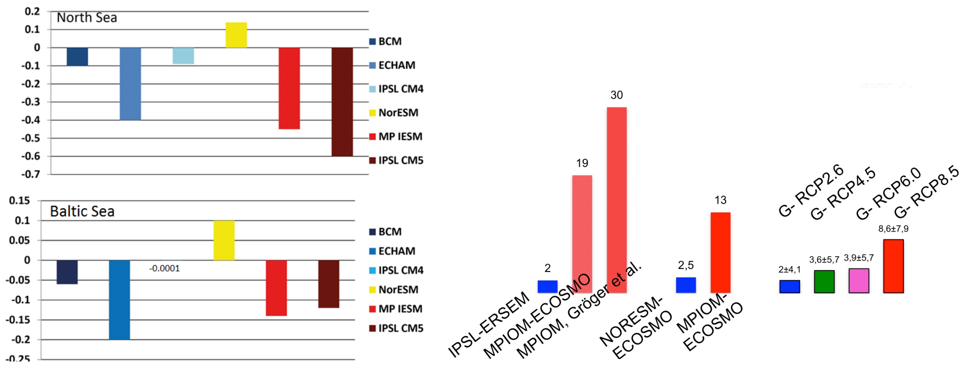


Figure 10: Left: Projected salinity change in the North Sea and the Baltic Sea. Multi-model ensemble forced by the BCM/NorESM, MPIOM and IPSL models, scenarios A1B and RCP4.5. Right: Inter-model ranges for regional North Sea primary production changes for different forcing global and regional models (1, 2, 3: A1B scenario, 4, 5: RCP4.5 scenario), compared to projected multi-model mean changes for the global scale.

Atmospheric Downscaling

In order to provide climate information on regional scales global models need to be downscaled to resolutions that matter for human and natural systems. Typically this is on the order of tens of kilometers over land. In REGSCEN the regional modeling group at Uni Research downscaled the NorESM to 50km over a domain covering all of Europe, the eastern North Atlantic and the Mediterranean. NorESM is Norway's contribution to CMIP5 and the fifth IPCC assessment report and these downscalings were completed for the historical period (1951-2005), an ERA-Interim based hindcast (1981-2010) and two future scenarios (RCP4.5 and RCP8.5, 2006-2100). While the downscaling itself is not a scientific activity but rather a technical exercise of no small magnitude, the output was part of the Bjerknes Centre's contribution to the WCRP's Coordinated Regional Downscaling Experiment (CORDEX, http://www.cordex.org/). The European region has the most active modeling community in CORDEX and the results of these simulations have been used in numerous manuscripts.

Currently data are available on Norway's ESGF node (http://noresg.norstore.uio.no/esgf-web-fe/live). The collaborations emerging from this activity continue to bear fruit and four manuscripts are in-prep on topics that include solar power potential, snow cover, extreme winds and uncertainty quantification, as well as two manuscripts in-prep on NAO variability and moisture transport. Two publications are already out on heat waves (Vautard et al., 2013) and model physics validation/evaluation (Katragkou et al., 2015). Figure 11 shows the main result from Vautard et al., (2013) which was that models, including ours, are generally too cool over Northern Europe and too warm over the Mediterranean.

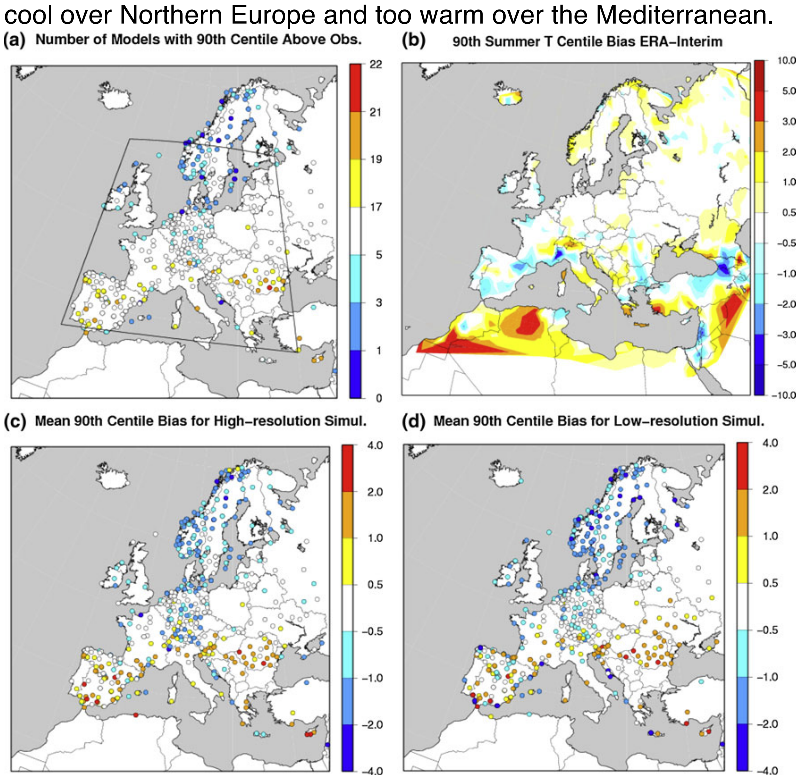


Figure 11: (a) Number of simulations [0–21] for which the 90th percentile exceeds that of observations. (b) ERA-Interim 2 m temperature 90th percentile bias relative to E-OBS data (c) Mean Ensemble 90th percentile bias (K) over the 6 high resolution simulations. (d) Same as for c but for the mean over the 9 low-resolution simulations.

WP2.2 - Biological production

IMR has a relatively complex ecosystem model, NORWECOM.E2E (Hjøllo et al., 2012), consisting of an Eulerian model for nutrients and phytoplankton and individual based models for zooplankton and higher trophic levels. This model system is running offline with forcing from an ocean circulation model.

Using the GISS-AOM A1B downscaling from WP 2.1 as input, this model system has been run for a reference period 1981-1999 and a future scenario 2046-2064 (Skaret et al. 2014). The focus was the zoo-plankton species *Calanus Finmarchicus* as reported in the SKD project BIOFEEDBACK, but the phytoplankton part of this study contributes to the deliverable in this work package. The modelled annual primary production is presented below on a map (Figure 12).

The projected annual primary production under the future climate scenario was on average 106 gC/m²/y implying a 36% increase from the reference scenario. The strongest increases occurred in the northern and eastern parts of the Barents Sea. This is most likely explained by the strong reduction in ice coverage in the future scenario. The investigation also suggests that the zooplankton is not able to utilize this increased production, due to low temperature in the new ice-free areas and mis-match

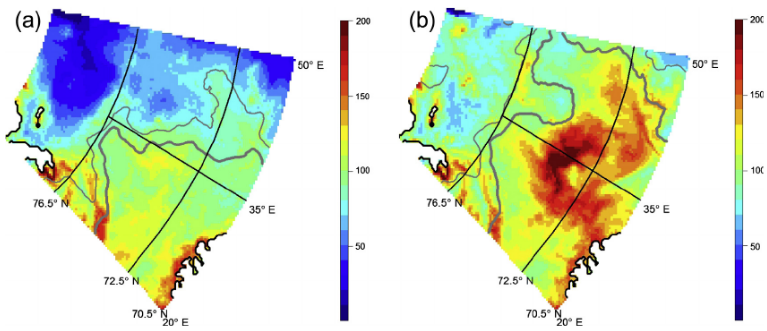
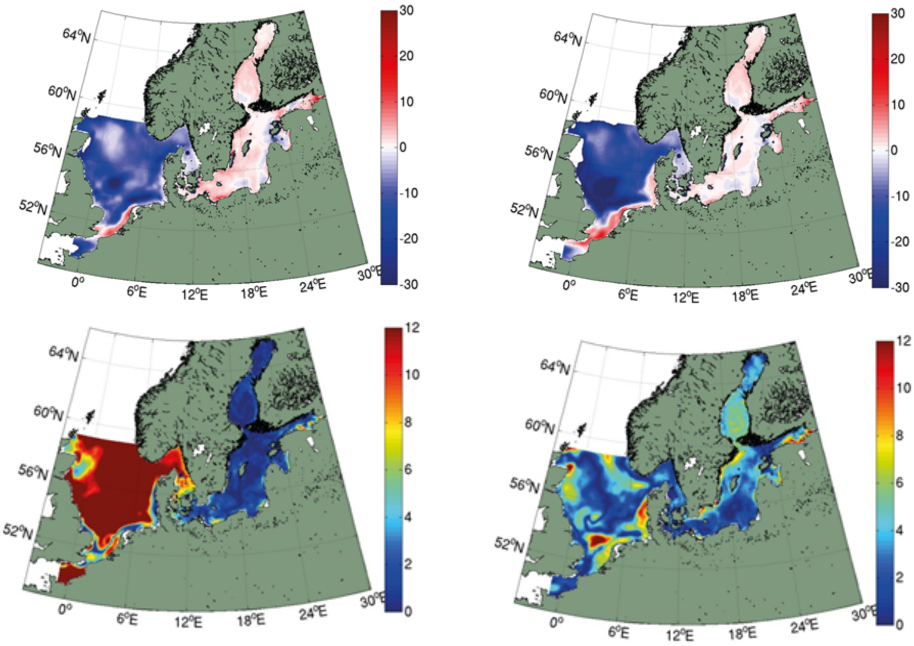


Figure 12: Annual primary production [gC/m²], left panel for control period and right for the future period. The thin and thick grey lines indicate winter and early summer ice edge position in the physical model. From Skaret et al. 2014.

in time between the phytoplankton bloom and the zooplankton spawning and advection.
To investigate the effect of further increase in atmospheric CO_2 in a future climate, numerical models have become an important tool, and using downscaled physics from a global climate model in WP2.1 to force an ecosystem model, Skogen et al, (2014) have compared the simulated carbonate system in 2000 and 2065 under the A1B emission scenario in the Nordic and Barents seas. The results showed that the saturation state of seawater with respect to aragonite would evolve, with a shallowing of the saturation horizon of approximately 1200 m in the Nordic Seas, and a large increase in area extent of under saturated surface waters. The simulated pH change in the surface water was −0.19 from 2000 to 2065, while the model estimated an almost doubling of the CO_2 air–sea flux in the Barents Sea increasing the uptake from 23 to 37 $gC/m^2/yr$.

No work was actually planned and funded for UiB using the ECOSMO model, but ECOSMO simulations done under WP1.2 also address WP2.2 and ensemble climate change projection were carried out to project future scenarios for regional primary production. Decreasing production in the range from -2,3% to -19% was projected for the North Sea and increasing production from 5% to 18% for the Baltic Sea.
The multimodel ensemble was performed using the regional ECOSMO model forced by results from 6 different GCMs, the MPIOM-HAMOCC, BCM/NORESM-HAMOCC and IPSL models (Pushpadas et al., submitted; Figure 13).
From these results and the review work in the frame of NOSCCA, it was in this work concluded that uncertainties are substantial in regional climate change projections, and that future climate change projections, which stem from only one downscaled global model have little significance.



proposal 13: Upper: Projected mean change in regional primary production in North Sea and Baltic (2070-2100) - (1970-2000), mean of 3-member ensemble A1B scenario (forced by ESMs BCM-HAMOCC, MPIOM-HAMOCC, IPSL CM4, left) and mean of 3-member ensemble RCP4.5 scenario (forced by ESMs NorESM-HAMOCC, MPIOM-HAMOCC, IPSL CM5, right). Lower: Spread of projected change, NPP in $gC/m^2/year$. Regional simulations performed with the ECOSMO model.

Future work

Statistical downscaling: To large degree our regional climate scenario work is still open-ended. We continue to work on socially relevant presentation of the climate change information. We aim to improve the fusion of the traditional environmental knowledge of the public (public weather reports) with the objective assimilation of the model and observational data at high spatial resolution. More theoretical work is required to describe the links between values-above-threshold and large-scale circulation persistence. Finally, we continue the modelling analysis to document the diversity of the regional climates under the global warming.

Dynamical downscaling: We expect new and improved physical downscalings to become available. Also the ecological models are improving. To take advantage of this new marine ecological scenarios should be produced.

Coupled downscaling: Set up and run an atmosphere-only simulation for big-brother-little-brother experiments in the Arctic region. Apply bias correction techniques to the coarse resolution data (Bruyere et al, 2014) if necessary, and repeat the same experiment with the atmosphere-ocean coupling.

Applications: Downscaling studies of the atmosphere and ocean will continue in the SKD project PARADIGM where generating, evaluating, and improving regional predictions of climate on land and in the ocean are the main objectives.

References

Bruyère, C. L., J. M. Done, G. J. Holland, and S. Fredrick (2013), Bias corrections of global models for regional climate simulations of high-impact weather, *Clim. Dyn.*, **43**, 1847–1856.

Hjøllo, S.S., G. Huse, M.D. Skogen and W. Melle, 2012, Modelling secondary production in the Norwegian Sea with a fully coupled physical/primary production/individual-based Calanus finmarchicus model system Mar. Bio. Res., 8, 508-526.

Kristjánsson, K.E., Barstad, I., Aspelien, T., Føre, I., Godøy, Ø., Hov, Ø., Irvine, E., Iversen, T., Kolstad, E., Nordeng, T.E., McInnes, H., Randriamampianina, R., Reuder, J., Saetra, Ø., Shapiro, M., Spengler, T., and Ólafsson, H., 2011: The Norwegian IPY–THORPEX: Polar Lows and Arctic Fronts during the 2008 Andøya Campaign. *Bull. Amer. Meteor. Soc.*, **92**, 1443–1466.

Saha, Suranjana, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.*, **91**, 1015–1057.

Warner, J.C., Armstrong, B., He, R., and Zambon, J.B., 2010: Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system. *Ocean Modeling*, **35(3)**, 230-24

Publication list

Castaño Primo, R., Schrum, C, Daewel, U., Thomas, H. Modelling Carbonate Chemistry in the North Sea and the Baltic Sea. Model description and validation, in prep.

Chust, Guillem, J. Icarus Allen, Laurent Bopp, Corinna Schrum, Jason Holt, Kostas Tsiaras, Marco Zavatarelli, Marina Chifflet, Heather Cannaby, Isabelle Dadou, Ute Daewel, Sarah L. Wakelin, Eric Machu, Dhanya Pushpadas, Momme Butenschon; Yuri Artioli, George Petihakis, Chris Smith, Veronique Garçon, Katerina Goubanova, Briac Le Vu, Bettina A. Fach, Baris Salihoglu, Emanuela Clementi, and Xabier Irigoien. Trophic amplification in a warmer ocean. Global Change Biology, 2014, 20, 7, 2124–2139, http://dx.doi.org/10.1111/gcb.12562

Daewel, U, Schrum, C, Gupta, A. About the predictive potential of early life stage IBMs: an example for Atlantic cod (Gadus morhua) in the North Sea. Accepted for publication by Marine Ecology Progress Series.

Davy, R. and I. Esau, 2013: Surface air temperature response in global climate models, *Atmospheric Science Letters* , on-line first, doi: 10.1002/asl2.456.

Davy, R., I. Esau and S. Outten, 2013: Asymmetry of the surface air temperature response on climatologic heat imbalances due to differences in the planetary boundary layer height, *Geophysical Research Abstracts* , 15, EGU2013-4534-1.

Davy R. and I. Esau, 2014: Global climate models' bias in surface temperature trends and variability, *Environmental research Letters*, 9.

Esau, I., R. Davy, S. Outten, S. Tyuryakov and S. Zilitinkevich, 2013: Structuring of turbulence and its impact on basic features of Ekman boundary layers, *Nonlinear Processes in Geophysics*, 20, 589-604, doi:10.5194/npg-20-589-2013.

Holt, J., C. Schrum, Heather Cannaby, Icarus Allen, Yuri Artioli, Laurent Bopp, Momme Butenschon, Bettina Fach, James Harle, Dhanya Pushpadas, Baris Salihoglu, Sarah Wakelin. Physical processes mediating climatic impacts in regional sea ecosystems, Biogeosciences Discuss., 11, 1909-1975, 2014.

Holt, J., C. Schrum, H. Cannaby, U. Daewel, I. Allen, Y. Artioli, L. Bopp, M. Butenschon, B. Fach, J. Harle, D. Pushpadas, B. Salihoglu, S. Wakelin, Potential impacts of climate change on the primary production of regional seas: a comparative analysis of five European seas. In revision, Progress in Oceanography.

Katragkou, S. E. , M. García-Díez, R. Vautard, S. Sobolowski, P. Zanis, G. Alexandri, R. M. Cardoso, A. Colette, J. Fernandez, A. Gobiet, K. Goergen, T. Karacostas, S. Knist, S. Mayer , P. M. M. Soares, I. Pytharoulis, I. Tegoulias, A. Tsikerdekis, and D. Jacob (2015), Regional climate hindcast simulations within EURO-CORDEX: evaluation of a WRF multi-physics ensemble, Geosci. Model Dev., 8, 603-618, doi:10.5194/gmd-8-603-2015.

Lappalainen H.K., Petäjä, T., Kujansuu, J., Kerminen, V.-M., Shvidenko, A., Bäck, J., Vesala, T., Vihma, T., de Leeuw, G., Lauri, A., Ruuskanen, T., Lapshin, V.B., Zaitseva, N., Glezer, O., Arshinov, M., Spracklen, D.V., Arnold, S.R., Juhola, S., Lihavainen, H., Viisanen, Y., Chubarova, N., Chalov, S., Filatov, N., Skorokhod, A., Elansky, N., Dyukarev, E., Esau, I., Hari, P., Kotlyakov, V., Kasimov, N., Bondur, V., Matvienko, G., Baklanov, A., Mareev, E., Troitskaya, Y., Ding, A., Guo, H, Zilitinkevich, S., Kulmala, M., 2014: Introduction: Pan Eurasian Experiment (PEEX) - A research initiative meeting the grand challenges of the changing environment of hte Northern Paen-Eurasian Arctic-Boreal areas, *Geography, Environment, Sustainability* , 2, 14-48.

Outten, S. and I. Esau, 2013: Extreme winds over Europe in the ENSEMBLES regional climate models, *Atmospheric Chemistry and Physics* , 13, 5163-5172, doi:10.5194/acp-13-5163-2013.

Outten, S., Davy, R. and I. Esau, 2013: Eurasian winter cooling: Intercomparison of Reanalyses and CMIP5 data sets, *Atmospheric and Oceanic Science Letters* , 6(5), 324-331, doi:10.3878/j.issn.1674-2834.12.0112.

Pushpadas, D., C. Schrum, U. Daewel: Downscaling climate change to the regional ecosystems of the North Sea and Baltic Sea: ensembles, forced by AR4 and AR5 ESM models, to be submitted June, 2015.

Sandø, A. B., Y. A. Melsom and W. P. Budgell (2014), Downscaling IPCC control run and future scenario with focus on the Barents Sea, *Ocean Dynamics,* doi:10.1007/s10236-014-0731-8.

Sandø, A. B., Y. Gao and H. R. Langehaug (2014), Relation between ocean heat transports, sea ice processes and Arctic sea ice variability in NorESM1-M simulations, *J. Geophys. Res. Oceans*, 119, 2095-2108, doi: 10.1002/2013JC009435.

Schrum, C, Lowe, J, Meier, M., Iris Grabeman, Jason Holt, Moritz Mathis, Thomas Pohlmann, Morten Skogen, Andreas Sterl, Sarah Wakelin. Projected changes in the North Sea. In North Sea Region Climate Change Assessment, in NOSCCA- North Sea Climate Change Assessment, accepted for publication.

G. Skaret, P. Dalpadado, S.S. Hjøllo, M.D. Skogen and E. Strand, 2014, Calanus finmarchicus abundance, production and population dynamics in the Barents Sea in a future climate Prog. Oceanogr., 125, 26-39.

Skogen, M. D., A. Olsen, K. Y. Børsheim, A. B. Sandø, I. Skjelvan (2013), Modelling ocean acidification in the Nordic and Barents Seas in present and future climate, Journal of Marine Systems, doi: 10.1016/j.jmarsys.2013.10.005.

Smedsrud, L, I. Esau, R. Ingvaldsen, T. Eldevik, P. Haugan, C. Li, V. Lien, A. Olsen, A. Omar, O. Otterå, B. Risebrobakken, A. B. Sandø, V. Semenov, S. Sorokina (2013), The role of the Barents Sea in the Arctic climate system, *Rev. Geophys.*,51, doi:10.1002/rog.20017.

Sobolowski, S.: On moisture transport in Euro-CORDEX simulations, in prep.

Vautard, R., A. Gobiet, D. Jacob, M. Belda, A. Colette, M. Deque, J. Fernandez, M. Garcıa-Dıez, K. Goergen, I. Guttler, T. Halenka, T. Karakostas, E. Katragkou, K. Keuler, S. Kotlarski, S. Mayer, G. Nikulin, M. Patarcic, J. Scinocca, S. Sobolowski, M. Suklitsch, C. Teichmann, E. van Meijgaard, K. Warrach-Sagi, V. Wulfmeyer and P. Yiou, (2013): The simulation of European heat waves from an ensemble of regional climate models within the EURO-CORDEX project. *Clim. Dyn.* http://link.springer.com/article/10.1007/s00382-013-1714-z.

Wolf T., Esau I. and L. Petersson, 2013: Modellering av luftkvalitet i Bergen under dagens of framtidig klima *NERSC special report* , 90, 48 pp. (in Norwegian).

Wolf T. and I. Esau, 2014: Air quality hazards under present and future climate conditions in Bergen, Norway, *Urban climate*, 10, 801-814, doi: 10.1016/j.uclim.2014.10.006.

Zilitinkevich, S. S., Elperin, T., Kleeorin, N., Rogachevskii, I. and I. Esau, 2013: A hierarchy of energy- and flux-budget (EFB) turbulence closure models for stably stratified geophysical flows, *Boundary-Layer Meteorology*, 146(3), 341-373, DOI: 10.1007/s10546-012-9768-8.

Conference presentations

Adakudlu, M and Sobolowski, S: Investigating the life cycle of a polar low with the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modeling system – preliminary results. EGU general assembly, 07–12 April, 2013, Vienna.

Adakudlu, M and Sobolowski, S: Role of atmosphere-ocean coupling in the simulation of a polar low. The 3rd Regional Climate Modeling Conference, 15–19 June, 2014, Lund.

Adakudlu , M: Investigating the life cycle of a polar low with the Coupled-Ocean- atmosphere-Wave-Sediment Transport Modeling System: SKD Days 2013, 17–18 October, 2013.

Castaño-Primo, Rocío, Cara Nissen, Ute Daewel, Corinna Schrum
Quantification of long-term variations in oceanic pH and uptake of CO_2: Comparative assessment in three different regional ecosystems . ICES ASC Reykjavik, September 2013.

Castaño-Primo, Rocío, Ute Daewel, Corinna Schrum, Helmuth Thomas. Differential response of the carbonate chemistry in three North Atlantic shelf systems and their underlying processes. IMBER conference, Jun. 2014, Bergen, Norway.

Castaño-Primo, Rocío, Corinna Schrum, Ute Daewel, Helmuth Thomas, Cara Nissen. Identifying the responses of the carbonate system and its governing processes in three high latitude shelf seas: Barents Sea, North Sea and Baltic Sea. EGU, May 2014. Vienna, Austria.

Daewel, U., Schrum, C. and Pushpadas, D. Impact of climate changes on North Sea Atlantic cod (Gadus morhua) larval survival: a modeling study. 2nd International Symposium Effects of climate change on the world's ocean, 15-19 May 2012, Yeosu, Korea.

Daewel, U., Schrum, C. and Pushpadas, D. Modelling climate impacts on acidification in the North and Baltic Sea with ECOSMO II. ICES Annual Science Conference. 17-21 September 2012, Bergen, Norway.

Daewel, U., Schrum, C. and Pushpadas, D. Modelling climate change impacts on North Sea Atlantic cod early life stages: long term hind cast and climate projection.
SKD Annual getaway, Geilo, 22.01.2013.

Daewel, U., Schrum, C. Processes relevant for decadal changes in primary production in two adjacent shelf sea ecosystems: hindcast and scenario modelling the North Sea and Baltic Sea, International Liege Colloquium on Ocean Dynamics, 13.-16.05.2013, Liege, Belgium.

Daewel, Ute, Corinna Schrum.
On the predictive potential of spatially-explicit IBMs: Can larvae fish IBMs be used to predict recruitment success, results from a Multi-decadal simulation of Atlantic cod (Gadus morhua) in the North Sea. ICES ASC Reykjavik, September 2013.

Daewel, Ute, Schrum, C, Pushpadas, D.
Simulating past and future acidification of the North and Baltic Sea, EGU Annual meeting 8-12.04. 2013, Vienna, Austria.

Daewel, Ute, Schrum, C, Pushpadas, D. Modelling climate impacts on ocean acidification in the North and Baltic Sea: scenario experiments with ECOSMO II SKD Regscen. SKD Days 2013; October 17-18 2013.

Daewel, Ute, Corinna Schrum,
About the predictive potential of early life stage IBMs: an example for Atlantic cod (Gadua morhua) in the North Sea, IMBER conference, Jun. 2014, Bergen, Norway.

Esau, I., 2014: High-Resolution Climate Services with Turbulence-Resolving Simulations, *Science of the Future* , international conference, Sankt-Petersburg, 17-19 September.

Esau, I., Varentsov, M., 2014: Fine-resolution mapping of micro-meteorological features in regions with heterogeneous landscapes, EGU2014-1516, sessions AS4.4/BG5.5/CL4.7/SSS.0.14, *European Geophysical Union Annual Assembly*, Vienna, 27 April - 2 May.

Esau, I., 2014: Turbulent fluxes over Barents Sea: Intercomparison of satellite and modeling data products, EGU2014-1545, sessions AS2.3, *European Geophysical Union Annual Assembly*, Vienna, 27 April - 2 May.

Esau, I., 2013: Wind regime of Svalbard fjords, *Studies of nature and climate of Spitzbergen*, 11 February, Moscow, Russia.

Esau, I., R. Davy, S. Outten, S. Tyuryakov and S. Zilitinkevich, 2013: Structuring of turbulence and its impact on basic features of Ekman boundary layers, *Frontiers of Nonlinear Physics*, 28 July - 3 August, Nizny Novgorod, Russia.

Esau I., 2013: Planetary boundary layer in the earth's climate system, *RESCLIM annual workshop* , 20-22 March, Tromso.

Esau, I., 2013: Turbulence self-organization in the Ekman boundary layer, *Geophysical Institute, University in Bergen, colloqium* , March 4, Bergen, Norway.

Holt, Jason, Icarus Allen, Yuri Artioli, Laurent Bopp, Momme Butenschon, Heather Cannaby, Ute Daewel, Bettina Fach, James Harle, Dhanya Pushpadas, Baris Salihoglu, Corinna Schrum, Sarah Wakelin. Physical processes mediating climate impacts in regional sea ecosystems. PICES 2013.

Mesquita, M et al. , Synthesis/Review of the Downscaling Activities: Technical Considerations Bjerknes Centre, Annual Getaway, Geilo, Norway, January, 2012.

Pushpadas, Dhanya, Schrum, C
Challenges in climate impact assessment in the North Sea and Baltic Sea region using climate models. Sarma workshop, Lund, Sweden, April 2011.

Pushpadas, Dhanya, Corinna Schrum and Ute Daewel
Challenges in climate change impact assessment on marine ecosystems: A modelling study for the North and Baltic Sea. AMEMR, 27-30 June, 2011, Plymouth, UK.

Pushpadas, Dhanya, Schrum, C
Climate change impacts on the North and Baltic Sea ecosystem: An assessment based on IPCC AR4 and AR5 models: Korean Symposium, May 2012, Yeosu Climate Change Impacts on the Oceans, Yeosu, Korea, May 2012.

Pushpadas, Dhanya, Corinna Schrum and Ute Daewel
Projected Climate change effects on North Sea and Baltic Sea: CMIP3 and CMIP5 Model-Based Scenarios, EGU, Vienna, Austria, April 2015.

Sandø, Anne Britt**,** Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales. NAFO/ICES Decadal Symposium 2000-2009; May 5-12 2011.

Sandø, Anne Britt; Melsom, Arne; Budgell, William Paul.
Downscaling IPCC models using ROMS. Bjerknes 10 Years Anniversary Conference; June 6 2012.

Sandø, Anne Britt; Melsom, Arne; Budgell, William Paul.
Downscaling IPCC models using ROMS. ICES Annual Science Conference; September 17 2012.

Sandø, Anne Britt; Sobolowski, Stefan Pieter.
SKD Regscen. SKD Days 2013; October 17-18 2013.

Sandø, Anne Britt; Langehaug, Helene R.; Gao, Yongqi.
Poleward ocean heat transports, sea ice processes and Arctic sea ice variability in CMIP5 simulations. SKD Days 2013; October 17-18 2013.

Sandø, Anne Britt; Budgell, William Paul; Melsom, Arne.
Downscaling IPCC models using ROMS. Biologisk modellering; April 3 2014.

Sandø, Anne Britt; Langehaug, Helene R.; Yongqi, Gao.
Poleward ocean heat transports, sea ice processes and sea ice variability in NorESM1-M simulations. Workshop on predictability of climate in the North Atlantic Sector; June 11-13 2014.

Schrum, Corinna, D. Pushpadas, U. Daewel. Climate change downscaling to marine ecosystems, lessons learnt from downscaling exercises of AR4 and AR5 GCM scenarios. Workshop on Regional Climate Modelling, Seoul, Korea, October 2011.

Schrum, Corinna, D. Pushpadas, U. Daewel.

Climate change downscaling to marine ecosystems, lessons learnt from downscaling exercises of AR4 and AR5 GCM scenarios. Center for Climate Dynamics Opening. Bergen, Norway, 2011.

Schrum, Corinna.
Können wir lokale Auswirkungen von Klimaänderung auf Nordsee und Ostsee vorhersagen? Wie gut sind unsere Modelle? Impulsworkshop Kueste. Delmenhorst, Germany, 2011.

Schrum, Corinna, B Ådlandsvik, R. Bellerby, U Daewel, S Hjøllo Sætre, T Kristensen, A Sandvik, M Skogen, D Pushpadas , A Sandø, F Vikdebø
Climate Change Downscaling to Marine Ecosystems, Bjerknes Centre, Annual Getaway, Geilo, Norway, January, 2012.

Schrum, Corinna, Bjørn Ådlandsvik, Richard Bellerby, Ute Daewel, Trond Kristensen and Dhanya Pushpadas
Dynamic downscaling to marine ecosystems, Yeosu Climate Change Impacts on the Oceans, Yeosu, Korea, May 2012.

Schrum, Corinna, Bjørn Ådlandsvik, Richard Bellerby, Ute Daewel, Trond Kristensen and Dhanya Pushpadas.
Dynamic downscaling to marine ecosystems-Best practices and limitations. Yeosu Climate Change Impacts on the Oceans, Yeosu, Korea, May 2012.

Schrum, Corinna, Dhanya Pushpadas, Ute Daewel,
Climate change impacts to North Sea and Baltic Sea, results from ensemble simulations forced by CMIP3 and CMIP5 models, IWMO, Bergen, Norway, 2012.

Corinna Schrum, Ute Daewel, Rocío Castaño-Primo,
Hydrodynamic-sea ice couplings in the Barents Sea and their consequences for marine productivity, Reykjavik, Island, ICES 2013, L:08.

Schrum, Corinna, Ute Daewel, Marius Årthun, Rocio Castano Primo, Cara Nissen, Alok Gupta, Tom Rossby. New developments and data sets: model results and ADCP data. ICES WGOOFE. Nov. 2013, La Coruna, Spain.

Schrum, Corinna.
Regional North Sea modelling at the Geophysical Institute. Invited talk, SMHI, Norrköping, Sweden, May, 2015.

Schrum, C. Current research challenges and new applications relevant for future coastal modeling. Invited talk, Bremen, Germany, Workshop on coastal modeling, May, 2015.

Schrum, Corinna, Lowe, Jason, Meier, H.E. Markus, Grabeman, Iris, Holt, Jason, Mathis, Moritz, Pohlmann, Thomas, Skogen, Morten, Sterl, Andreas, Wakelin, Sarah.
Projected climate change impacts to the North Sea marine system. Vienna, Austria, May, 2015, EGU.

Schrum, Corinna, Laurent Bertino, Morten Skogen, Ute Daewel and Annette Samuelsen, Ingrid Askeland Johnsen. Norwegian plans for ecosystem modeling, national and EU aspects. KDM meeting, May, June, 2015.

Outreach

Sandø, Anne Britt.
FNs femte klimarapport. Skolebesøk; February 2 2013.

Sandø, Anne Britt.
FNs femte klimarapport. Skolebesøk; October 22 2013.

Schrum, Corinna, Daewel, U, Pushpadas, D. Modelling Marine Ecosystems in a Changing Climate (2012). META magazine from the Norwegian metacentre for computational science 2012-1.

Schrum, Corinna (2015). From physics to Fish in 3D. Pan European NetWorks Science and Technology 15.

Schrum, Corinna and Pushpadas, D (2015). Ocean modelling from physics to fish, integrating ecosystem stress from climate to pollutants. Stand presentation at Christiekonferansen, University of Bergen, 29. April, 2015.

Schrum, C (a.o).
Skittent Spiskammer, det kompliserte liv i havet. (2015). Interview by hubro magasin.

Sea Level Change and Ice Sheet Dynamics

SEALEV

SKD-SEALEV Final Report

Project leader: J. Even Ø. Nilsen (NERSC); **Co-leader:** Stein Sandven (NERSC)

1. Goals and Objectives

The overall objective of Sea Level Change and Ice Sheet Dynamics (SEALEV) was **to understand sea level change** incorporating the effect of ocean circulation, steric height, isostatic adjustment, freshwater mass flux from ice sheets, glaciers and rivers **in order to improve projections** of sea level for the 21st century with focus on the **Norwegian coastal regions** and selected cooperating countries, such as for example Bangladesh, India, South Africa and China.

The project SEALEV was designed to understand past and present changes in the Greenland Ice Sheet (GrIS) and to project future rates of sea-level rise under climate change, for the Norwegian and other coastal regions. There is a strong focus on the processes in and over the ice sheet, and deliverance of freshwater to the ocean. With respect to regional sea-level rise, SEALEV has a strong observational basis, combining ocean density with remotely-sensed sea-surface height and gravity to assess the combined effect of mass exchange, steric changes and ocean dynamics on sea level rise across the oceans. The geology work package quantifies past changes in sea level and ice sheets. A consistent system to improve sea-level projections in the 21st century is ensured by a strong group of modeling activity is at the core of the project.

In sum, the project has been a collaboration between diverse groups of disciplines and scientific focus. It has produced and propelled a wide amount of good and relevant science. Although the synthesis is a weak part of the end results, it is beyond doubt that the project has contributed to elevate the understaning of sea level change, both within the Bjerknes centre and abroad, participated in improvements to the tools for sea level projections, and strengthened collaboration both within the Bjerknes Centre and in collaborations nationwide and abroad. It is also a very important outcome that new constellations and future projects related to sea level, has emerged from the involved group of scentists. In terms of synthesis, participants from SEALEV are now contributing to the national expert group on sea level, and are authors of the new official sea level information and data in Norway (to be published late 2015). There have been some challenges in availability of personnel and collaboration, but these have mostly been amended. Of the 38 deliverables described in the project description 75% is completed. There are 27 papers published (5 more in the pipeline), 49 registered presentations, and 18 registered public outreach efforts.

2. Main Results

WP1 Observed present sea level change

The Main Objective is to synthesise the effect of ocean processes on sea level rise by assessing the interactions between mean sea surface (MSS), mean dynamic topography (MDT) and steric height.

J. Even Ø. Nilsen, Kristin Richter, Johnny Johannessen

Present sea level change along the coast of Norway has been assessed, and the main contributors to the positive trends are warmer waters and the worldwide melting of land ice, with approximately equal importance (Richter et al., 2012). Through the combination in situ hydrographical data, surface drifter data and direct current-meter measurements, together with coupled sea ice–ocean models, altimeter data and the latest GOCE-based geoid, knowledge of the circulation and sea level in the Nordic Seas and Arctic Ocean has been improved (e.g, Johannessen et al., 2014). More accurate estimation of sea surface height and sea level trends from satellite altimetry has been achieved (Ablain et al., 2014; Koldunov et al., 2014).

The Arctic plays a fundamental role in the climate system and shows significant sensitivity to anthropogenic climate forcing and the ongoing climate change. Accelerated changes in the Arctic are already observed, including elevated air and ocean temperatures, declines of the summer sea ice extent and sea ice thickness. Arctic is expected to undergo changes although to date it is challenging to accurately quantify this. Johannessen et al. (2014) combine in situ hydrographical data, surface drifter data and direct current meter measurements, with coupled sea ice–ocean models, radar altimeter data and the latest GOCEbased geoid. Their findings add new insight into the ocean circulation and transport between the northeast Atlantic Ocean and the Arctic Ocean. They are also considered to be highly valuable for further studies of the regional sea-level change in the Nordic Seas and Arctic Ocean, notable via the contribution of steric height and changes in the volume transport.

In the past two decades, sea level has been routinely measured from space using satellite altimetry techniques. The accuracy of altimetry-based sea level records at global and regional scales needs to be significantly improved. The regional sea level trend uncertainty should become better than 0.5 mm/year (currently 1–2 mm/year). Similarly, interannual global mean sea level variations (currently uncertain to 2–3 mm) need to be monitored with better accuracy. Ablain et al. (2014) present data improvements using multi-mission satellite altimetry data over the 1993–2010 time span, such as: Reduction of orbit errors and wet/dry atmospheric correction errors, reduction of instrumental drifts and bias, intercalibration biases, intercalibration between missions and combination of different sea level data sets, and improvement of the reference mean sea surface.

The performance of several numerical ocean models is assessed with respect to their simula- tion of sea surface height (SSH) in the Arctic Ocean, and the main patterns of SSH variability and their causes over the past 40 years (1970–2009) are analyzed in Koldunov et al. (2014). All tested models broadly reproduce the observed mean SSH in the Arctic and reveal a good correlation with both tide gauge data and SSH anomalies derived from satellite observations. Although the models do not represent the positive Arctic SSH trend observed over the last two decades, their interannual-to-decadal SSH variability is in reasonable agreement with available measurements.
Overall, we show that present-day models can be used for investigating the reasons for low frequency SSH variability in the region.

WP2 Observed present Greenland Ice Sheet and outlet glaciers

WP2.1 Ice sheet elevation variability and changes

Main Objective: Estimate recent variability and changes in ice-sheet elevation, in order to improve mass-balance assessments.

K. Khvorostovsky, O.M. Johannessen.

Studies have shown acceleration of the Greenland ice sheet mass loss during the last decade representing significant contribution to sea level rise. Satellite altimetry is one of the methods for large-scale mass balance estimates of the ice sheet via measuring the surface elevation change rates. The radar altimeter observations from a series of ESA satellites provide for more than two decades of elevation measurements from 1992 over entire Greenland ice sheet. Here we created continuous time series of elevation changes using data from ERS-1, ERS-2 and Envisat satellite radar altimeters over period 1992 to 2012. Furthermore elevation change from 2011 to 2014 was estimated using data from Cryosat-2 satellite. For ERS-1 and ERS-2 we exploited new data reprocessed by ESA, providing more precise orbit and improvements in instrument and atmospheric corrections.

Elevation time series were formed by applying a crossover method, which provides the most accurate estimates of elevation change. Spatially variant biases between the measurements from different satellite missions were taken into account when creating continuous elevation time series (Khvorostovsky, 2012). Adjusting the time series obtained from different satellites provide the estimates with high resolution (~10 km), and are selected as a preferred method for reproducing changes over ice sheet margins where the largest thinning rates are currently observed.

Another essential problem of using radar altimeter measurements over ice sheets is the varying penetration of parts of the radar altimeter signal through the snow/firn surface. In order to find optimal algorithms for processing of radar altimeter data the elevation change results obtained from Envisat data were compared with estimates derived from ICESat laser altimeter (2003-2009). ICESat measurements are not affected by the errors associated with sub-surface scattering. The comparison shows that over central parts of Greenland, where sub-surface scattering is the largest, backscatter correction effectively corrects for penetration of the radar altimeter signal.

In order to adequately capture ice sheet margins by satellite radar altimetry a high-resolution interpolation based on ice velocity measurements was proposed in (Hurkmans et al., 2014) where the results produced in SEALEV project were exploited. In particular, it was found that mass changes are dominated by surface mass balance change until about 2001, when mass loss rapidly accelerated due to dynamic thinning at the ice sheet margins (Figure 1).

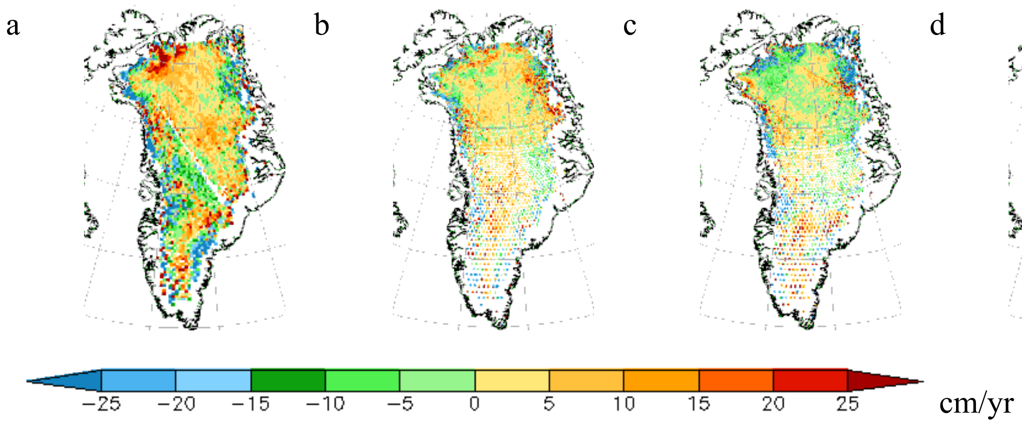


Figure 1: Surface elevation change rates (cm/yr) derived from ERS1, ERS-2 and Envisat satellite radar altimeter measurements for a) May1992 to April1996 (ERS-1 operation period), b) 1997-2001, c) 2002-2006, and d) 2007-2011. Maps (a) and (d) and maps (b) and (c) are obtained with coarser and finer resolutions respectively.

WP2.2 Variability of marine-terminating outlet glaciers

Main Objective: To estimate long-term variability and changes in mass flux from marine-terminating outlet glaciers in southeast Greenland.

V. Miles, O.M. Johannessen, A. Nesje, K. Vasskog, M. Miles.

Ice discharge from marine-terminating outlet glaciers accounts for approximately half of the recent mass losses from the Greenland Ice Sheet. Rapid changes in Helheim Glacier and other Greenland Ice Sheet outlet glaciers in the 2000s are well known, but knowledge on earlier decades is fragmentary. Here we have exploited the satellite image archives to produce and analyze a monthly-to-seasonal record of Helheim Glacier front position, 1980–2011, together with similar records for Fenris and Midgård glaciers – which also terminate in the Sermilik fjord. Here, focusing on Helheim glacier, we have identified decadal periods with abrupt changes in variability and mean. The record also reveals evidence of volatile advance–retreat behavior in the 1980s. In one of several cases of large sub-annual changes, the glacier front “surged” forward in 1984-85, advancing ~6 km within a few months – surpassing its Little Ice Age maximum position – and afterward retreated ~5 km within a few weeks. These findings challenge the prevailing view of stability in the decades before the multi-year retreat in the early 2000s, which is seen as a response to oceanic and/or atmospheric warming.

An essential question is the degree to which the observed variability in the 1980s represents a glacio-climatic response to atmosphere–ocean variations and/or unstable glacier dynamics. Figure 2 (from Miles et al., 2015) shows a comparison between Helheim glacier front position (1980–2011) and surface air temperature (SAT) and ocean–sea-ice conditions ('shelf index'). There is some correspondence between the glacier front position and fluctuations of air temperature and ocean conditions on decadal to interannual time scales; however the front-position variability is greater and more abrupt than would be expected as glacio-climatic response; thus glacio-dynamics may be even more important than previously recognized for Helheim Glacier.

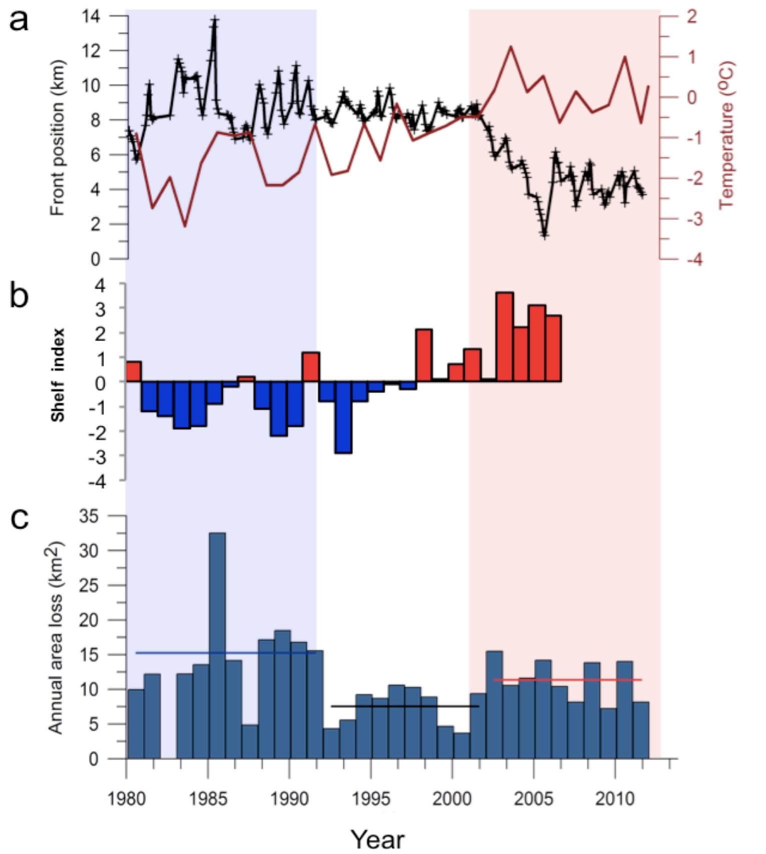


Figure 2: Helheim Glacier calving front and comparison with climate data, 1980–2011: (a) Calving-front position (black) and annual surface air temperature record (red) from the nearest station, Tasiilaq, (b) Shelf index, an indicator of the relative amount of polar water and sea ice on the southeast Greenland shelf (from Andresen and others, 2012), and (c) Indicator of calving activity; horizontal bars are the mean annual calving losses in each decadal period. 1982 – no observations. Source: Miles et al. (2015).

Further, these observations indicate that the dynamic behavior can result in greater calving amounts during a cold period (with net advance) than during warm periods (with net retreat) such as the early 2000s – bottom panel in Figure 2. This confounds the interpretation of increased calving activity as a response to warming, and underscores the complex dynamics of Greenland outlet glaciers. In the SKD MARGINS project, we will expand the records and further analyze Fenris and Midgård glaciers in order to test for covariability and the response of three proximal glaciers to essentially the same atmospheric and oceanic forcing.

Also part of this WP2.2 is a synthesis of Holocene Greenland glacier variability (Vasskog et al., 2015). During the Last Interglacial period (LIG), between 130 and 116 thousand years before present (ka BP), the Greenland Ice Sheet (GrIS) was considerably reduced in size, contributing to a global mean sea-level (MSL) rise of 0.5–4.2 m relative to the present. This is not sufficient to explain the 6–9 m MSL rise estimated for the LIG, which implies that a significant contribution to the LIG highstand came from West Antarctica. Following the LIG the GrIS grew and attained its maximum volume of about 12 m global sea-level equivalents (SLE) between 18 and 16 ka BP, i.e. during the Last Glacial Maximum (LGM). Since the LGM the GrIS margins have retreated on an order of several hundred km, following a general pattern of lagged response to changes in high-latitude summer insolation and global greenhouse gas concentrations. The GrIS probably reached its minimum Holocene extent around 4 ka BP, and modelling studies suggest that it contributed to a rise in global MSL of about 0.2 m SLE during this interval. A period of steady growth followed the Holocene minimum and in many areas the ice sheet advanced beyond its present limits during 'Little Ice Age' (i.e. the last few centuries). Currently the GrIS occupies an area of ~$1.7x10^6$ km^2

and features a volume of ~2.96x10^6 km^3, which in total amounts to 7.4 m SLE. In high-CO_2 emission scenarios (four times preindustrial levels) the entire ice sheet might disappear completely within less than three thousand years.

WP3 Atmospheric and ocean/fjord influence on ice sheet/outlet glaciers

WP3.1 Effect of atmospheric variability on GrIS variability

Main Objective: Quantify the effects of atmospheric variability (accumulation, temperature, atmospheric circulation, and storm activity) on the GrIS.

L.L. Chen, M. Miles, O.M. Johannessen.

Annual precipitation, evaporation, and calculated accumulation from reanalysis model outputs have been investigated for the GrIS, based on the common period of 1989–2001 (Chen et al., 2011). The ERA-40 and ERA-interim reanalysis data showed best agreement with observations. The validation of accumulation calculated from reanalysis data against ice-core measurements suggests that further improvements to reanalysis models are needed.

To validate the temperature data from different models over the Greenland Ice Sheet is difficult, because it's hard to find totally independent observational data in this area during recent decades. Most of the ice core data don't cover recent decades, and coastal weather station data are being used in reanalysis data already. Thus, the temperature validation is not delivered.

GrIS has experienced dramatic ice loss during recent decades, but the drivers of this surface mass balance (SMB) decrease remain unclear. From a dynamical perspective, extratropical cyclones and anticyclones are the major systems influencing Greenland weather conditions. Chen et al. (in press.) investigated the role of cyclonic and anticyclonic activities in determining snow accumulation (SA), surface air temperature (SAT) and, in turn, their possible impacts on the GrIS SMB. The covariability between SA and cyclonic activity reveals that strong cyclonic activity in Baffin Bay corresponds to high SA in west Greenland, and strong cyclonic activity in the Davis Strait and east coast of Greenland contributes to high SA in a belt crossing Greenland from the southwest to the northeast. Similarly, the analysis of SAT and the cyclonic or anticyclonic activity suggests that weak cyclonic activity in the Irminger and Greenland seas may induce high SAT in Greenland due to the association with the negative phase of the North Atlantic Oscillation, and strong anticyclonic activity in Greenland and the Arctic Ocean may result in high SAT. These two patterns that are related to positive SAT anomalies occur more often since 2000, meaning that the phase change of these patterns may have contributed to the accelerated GrIS surface ice loss during recent years. Finally, up to 80% of the SMB variation can be explained by meteorological activity around Greenland, with the highest impacts in west Greenland, where significant mass loss has been observed during recent decades.

WP3.2 Ocean–fjordwater variability and outlet glacier interactions

Main objective: Quantify shelf, fjord and outlet glacier interactions using numerical ocean models.

O.M. Johannessen, A. Korablev, S. de la Rosa, I. Fer, S. Maus.

Data from 2007 (RV Håkon Mosby) and from Sermilik fjord 2008-2010 (Jotun Arctic) is available in vertical profiles and sections. The Nordic oceanographic database is available from 1900 – 2010. Field experiments were carried out in the Sermilik fjord in August 2011, showing the penetration of warm and saline Atlantic Water into the Hellheim ice front. "Arctic Eneavour" was damaged by ice and had to return to Iceland without deploying an ADCP mooring and performing fjord microstructure sampling. Instead a small speedboat was rented achieving very good sampling in the Sermilik fjord. As a back-up plan, a study on the circulation of an Arctic fjord, Storfjorden in Svalbard, was undertaken where data are available. In terms of fjord dynamics driven by ice-ocean interaction this study defines a similar goal as the original Sermilik fjord project.

Recent observations of ocean temperature in several Greenland fjords suggest that ocean warming can cause large changes in the outlet glaciers in these fjords. We have observed the vertical fjord temperature and salinity during three summer expeditions, 2008–2010 to the Sermilik Fjord (Johannessen et al., 2011). We show that the subsurface water below 250 m depth is the warm saline Atlantic Water from the Irminger Sea penetrating into the fjord and exposing the lower part of the Helheim glacier to warm water up to 4°C. Lagged correlation analysis spanning the 30-year time series, using the subsurface Atlantic Water temperature off the coast as a proxy for the variability of the subsurface warm Atlantic Water in the fjord, indicates that 24% of the Helheim ice-front movement can be accounted for by ocean temperature. A strong correlation (–0.75) between the ice-front position and the surface air temperature from a nearby meteorological station suggests that the higher air temperature causes melting and subsequent downward percolation of meltwater through crevasses leading to basal lubrication; the correlation accounts for 56% of the ice-front movement.

The precise contribution of air temperature versus ocean temperature, remains an open question, as more oceanographic and meteorological measurements are needed close to the glacier terminus.

WP3.3 Modelling shelf–fjordwater circulation and outlet glacier interactions

Main objective: Quantify shelf, fjord and outlet glacier interactions using numerical ocean models.

L. Asplin, M. Myksvoll, P. Budgell, K. Kalhagen.

This WP includes an implementation of the three-dimensional numerical ocean model Roms for the Sermilik fjord. Additionally we discovered that it was necessary to include non-hydrostatic momentum conservation in the vicinity of the glacier front due to strong vertical accelerations, and the Bergen Ocean Model non-hydrostatic version was implemented in an idealized 2D mode to simulate the melt rates and conditions close to the marine terminating glacier front.

The results of the idealized simulations of melting with the BOM model showed that in the summer when sub-glacial freshwater discharge is expected, the annual average melting of the glacier front is between 500 and 1500 m for ambient (Atlantic) water temperatures between 0 °C and 8 °C (Kalhagen, 2015). As to the simulations with the Roms model, we find its results to resemble a typical stratified fjord condition as previously reported by others. The model results indicate a dominating first internal mode with a varibility of 3-10 days and a realistic up-fjord intrusion of warm Atlantic water at depth.

The work of the WP3.3 has led to a master thesis (Kalhagen, 2015) and a continuation of the implementation of the combined modelling system (nested Roms from ocean to fjord plus inclusion of the non-hydrostatic BOM at the glacier wall) in the SKD internal project MARGINS.

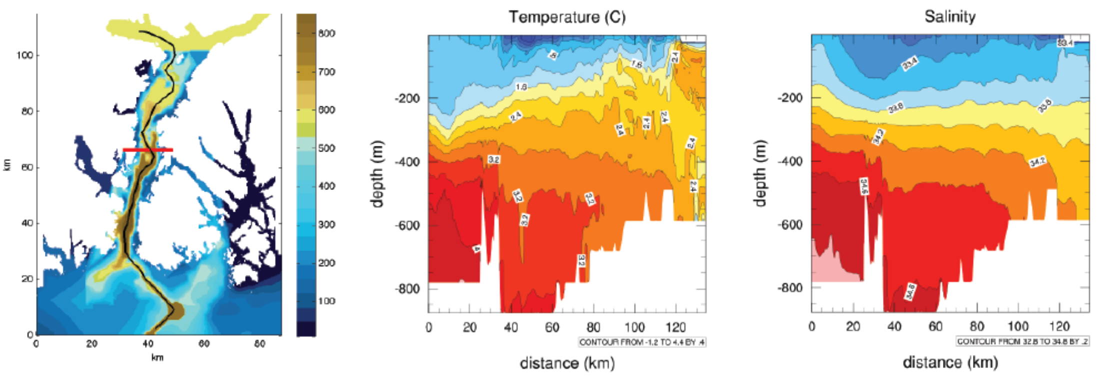


Figure 3. Left: The bottom depth of the Sermilik fjord indicating the domain of the 250 m horizontal resolution of the Roms model. Middle and right: The mean temperature (°C) and salinity for a 16 days period in November 2008 along the section marked by the black line in the left panel.

WP4 Greenland ice sheet modelling and mass balance

Main Objective: To provide a mass balance history of the GrIS on decadal to millennial timescales.

Qing Yan, O. M. Johannessen.

The accuracy of the modeled present-day Greenland Ice Sheet is crucial for future projections of GrIS changes. Yan et al. (2013) present a detailed evaluation of the modeled present-day GrIS sensitivity to different present-day climatology data sets and spin-up methods and further assess the influence of the modeled present-day GrIS on future sea level projections. Our study demonstrates that with present-day climatology data sets derived from the Regional Atmospheric Climate Model (RACMO2), the modeled ice volume, area, and elevation of the GrIS agree substantially better with observations compared to simulations with present-day climatology data sets from temperature parameterizations and ERA-interim reanalysis. With transient spin-up, the simulated rates of ice elevation changes for the 1993–2010 period are closer to observations than those with steady state spin-up. These results indicate that the RACMO2 forcing and transient spin-up may be preferable for use in the ice sheet model. Moreover, our results reveal that the present-day climatology data sets and spin-up methods affect future sea level projections. Using transient spin-up, the ice sheet model estimates a range of 26mm in projected sea level rise by 2098 under the A1B emissions scenario, due to different present-day climatology data sets. Compared to the results with transient spin-up, the estimated sea level rise by 2098 is reduced by 5–21mm with steady state spin-up. This discrepancy is attributed mainly to differences in ice thickness and ice velocity between the modeled present-day GrIS with transient and steady state spin-ups and the effect of paleoclimatic changes with transient spin-up.

Yan et al. (2014) used the ice sheet model SICOPOLIS (SImulation COde for POLythermal Ice Sheets) driven by climate projections from 20 models in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) to estimate the GrIS contribution to global SLR. Based on the outputs of the 20 models, it is estimated that the GrIS will contribute 0–16 (0–27) cm to global SLR by 2100 under the Representative Concentration Pathways (RCP) 4.5 (RCP 8.5) scenarios. In response to the results of the multimodel ensemble mean, the ice sheet model projects a global SLR of 3 cm and 7 cm under the RCP 4.5 and RCP 8.5 scenarios, respectively. In addition, our results suggest that the uncertainty in future sea level projection caused by the large spread in climate projections could be reduced with model-evaluation and the selective use of model outputs.

We have three main conclusions. (1) The RACMO2 forcing is more reasonable in terms of surface mass balance and surface ice topography; (2) The spin-up methods largely affect the simulated present-day GrIS basal temperature; (3) Through transient spin-up and steady-state spin-up as the initial state, modelling yields that GrIS melting contributes 77 mm and 56 mm respectively to the global sea-level rise by 2098 under the A1B scenario.

WP5 Reconstruction of former sea-level and ice sheets

The main objective is to document former sea-level changes in Northern Europe since the last glaciation and up to the present, identify the causal connections and provide quantitative characterizations of the underlying processes.

J. I. Svendsen, Ø. Lohne, J. Mangerud, A. Hughes.

A vast database of published geochronological data relating to the build-up of and retreat of the last Eurasian Ice Sheet (40,000-10,000 yrs ago) has been collated and the time evolution of the entire Eurasian Ice Sheet complex have been reconstructed using the database and other relevant information (Figure 4). The first version (DATED-1) has now been accepted for publication (Hughes et al. 2015). Such a compilation and reconstruction of the ice sheets has not been done since 1981 (Andersen 1981). Our new empirical reconstructions form a unique basis for testing of ice-sheet, GIA and paleoclimate modelling results, or, alternatively, as initial boundary conditions for such numerical models. Our results suggest a total ice-sheet volume of 25 m Sea Level Equivalent (SLE) occurring 21,000-20,000 yrs ago. The Scandinavian Ice Sheet was the largest component of the Eurasian Ice Sheet, approximately 14 m SLE at the peak of the last glaciation, followed by the Barents-Kara and the British ice sheets.

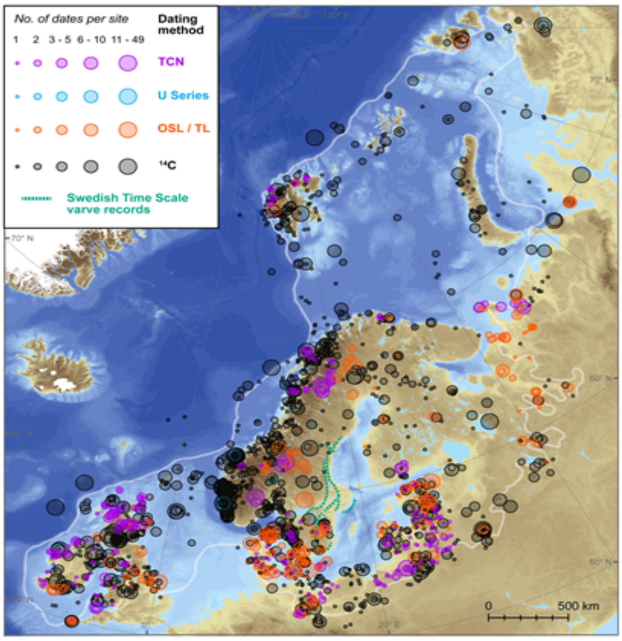


Figure 4: Distribution of dates contained within DATED-1 database (n = 5463). Colours show dating method; TCN = Terrestrial Cosmogenic Nuclide exposure dating, U = Uranium Series, OSL = Optically Stimulated Luminescence, TL = Thermally stimulated Luminescence, 14C = Radiocarbon. Graducated symbols show number of dates at each site.

In addition to the database work, comprehensive field work have been carried out in selected areas of southern Norway as well as in the Russian Arctic aiming at a better knowledge of the history of the Eurasian Ice Sheet, climate change and sea-level fluctuations (Lohne et al. 2014; Mangerud et al. 2013; Briner et al. 2014; Svendsen et al. 2015 and -2015). One important objective was to gain new knowledge about the thickness of the Scandinavian Ice Sheet, and how fast the ice front retreated in western Norway. Sediment cores from emerged lake basins have provided valuable data that will be used to reconstruct sea level changes and uplift rates along the coast. The results indicate that the western sector of the Scandinavian Ice Sheet retreated in several discrete steps, presumably as a response to oceanographic and climatic changes (Mangerud et al. 2013; Briner et al. 2014; Svendsen et al. 2015). During the cold Younger Dryas period (12,700-11,600 yrs ago) large outlet glaciers, resembling the present-day Jacobshavn Isbræ and other glaciers draining the Greenland Ice Sheet, were filling Sognefjorden and Hardangerfjorden. Dating results reveal that these outlet glaciers withdrew quickly in response to the abrupt Holocene climatic warming that started 11,600 years ago (Lohne et al. 2013) and that the front reached the head of the fjords within 500 years (Mangerud et al. 2013). The average calving rates for Sognefjorden and Hardangerfjorden were 340 ± 70 and 240 ± 70 m/yr respectively. We consider these values to be close to the maximum theoretical calving rates in such fjords and that they may serve as analogues for Greenland outlet glaciers and provide a realistic measure for the expected speed of deglaciation in response to future climate change.

We have earlier discovered significant regional differences in the pattern of relative sea-level change. The sea level change in southern Norway to a large extent reflects the glaci-isostacic uplift and the ice sheet history. For example, in SW Norway the uplift appears to have halted during the Younger Dryas period resulting in a pronounced relative sea-level rise in response to the continued eustatic rise and increased gravitational attraction of the ice sheet. We consider the new sea-level data in combination with the reconstructed ice sheet histories as an important tool for testing and improving existing GIA models that are used also for predicting future changes.

We have also studied the more recent sea-level changes on Sotra and Askøy (west of Bergen). Sediment cores retrieved from isolation basins indicate that relative sea level has dropped by about a meter during the last millennium, but that there has been very little change in relative sea level during the last 200 years. The levelling out of the long term sea level drop (1-2 mm/yr) at around 1800 AC may suggest that the present-day sea-level rise started this early.

WP6 Sea level modelling and analysis with focus on high northern latitudes

The main objective is to update and use NorESM as a state-of-the-art prognostic model for assessing present day and future changes in sea level with particular focus on high northern latitudes.

H. Drange, M. Bentsen, K. Richter.

WP6 has focused on extending capabilities of the Norwegian Earth System Model (NorESM) to make it better suited for sea level studies. This has involved developing a realistic mass exchange between NorESM model components and preparing the NorESM ocean component (MICOM) for ice shelf interaction.

NorESM is based on the Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR) and we have adopted CESM's convention of converting the ocean boundary freshwater flux to a virtual salt flux. With this approach no mass is actually exchanged between the ocean component and other components in NorESM. This is not ideal for sea level studies and a goal of this WP was to update NorESM so that the freshwater flux is handled as a true mass flux in the ocean component. After further investigations it became clear that this is a non-trivial modification in a coupled model system. The main issue is that if mass is exchanged between components, one also has to exchange the internal energy associated with that mass. Recently (2014), Thomas Toniazzo of Uni Research Climate, in collaboration with colleagues at NCAR, has revisited the energetics of the atmospheric component of CESM/NorESM and this component can now exchange mass in an energetically consistent way. Still lacking is for the land, sea ice and ice sheet components of CESM/NorESM to handle energetically consistent mass exchange.

With respect to ice sheet/ocean interaction only exchange of frozen runoff will likely be available in the next major release of CESM planned for 2016. More elaborate ice sheet/ocean interaction is expected to become available later and as a first step preparing for this in NorESM, functionality for dynamic and thermodynamic interaction with static ice shelves has been implemented in MICOM. This involves the ability of the ocean component to handle large spatial pressure variations of the upper ocean boundary, freshwater, heat, and momentum fluxes at the ice shelf/ocean boundary and pressure dependent sea water freezing temperature. To evaluate this functionality, idealized test cases as specified in the Ice Shelf – Ocean Model Intercomparison Project (ISOMIP, Hunter 2006) has been simulated with NorESM. Figure 5 (left panel) shows the simulated meridional overturning stream function in the ISOMIP Case 1 using MICOM. The circulation is purely buoyancy driven due to ice melting at the deepest portion of the ice shelf/ocean boundary and ice formation in shallower regions. The overturning stream function of MITgcm for the same test case is shown in Figure 5 (right panel) and the overall magnitude and structure of the circulation is similar to NorESM. However, particularly beneath the ice shelf slope there are differences and those might be due to less numerical mixing of the buoyancy driven current in the isopycnic vertical coordinate MICOM compared to the geopotential vertical coordinate MITgcm.

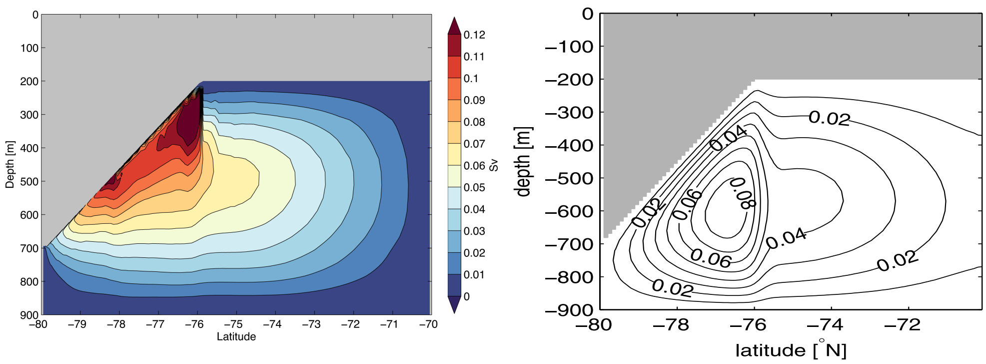


Figure 5: Meridional overturning stream function of the ISOMIP Case 1 as simulated by NorESM (left panel) and MITgcm (right panel). The MITgcm simulation is from Losch (2008).

The work with static ice shelf functionality in NorESM was presented at the West Antarctic Glacier-Ocean Model Workshop in Abu Dhabi in October 2014. This workshop gathered ice sheet and ocean modellers with the goal of designing new test cases to promote the development of more sophisticated ice sheet/ocean interactions. We will continue to stay connected with this community.

During the duration of SEALEV, Drange has been a member of the CLIVAR Working Group on Ocean Model Development. This working group has defined Coordinated Ocean-ice Reference Experiments (CORE) as a tool to explore the global ocean/sea-ice models with a common forcing protocol. A coupled NorESM ocean/sea-ice simulation with the interannually varying forcing protocol (CORE-II) has been carried out and results provided to various model intercomparison studies that included an assessment of the simulated global and regional sea level for the period (1993-2007) (Griffies et al., 2014). The sea level assessment showed that the ensemble mean of the CORE-II simulations broadly agree with various global and regional observation-based analysis during this period. The NorESM simulation was mostly in good agreement with the ensemble mean of the simulations except for the halosteric contribution to sea level where the NorESM simulations showed a severe drift since the surface restoring salt flux was not globally balanced.

Richter et al (2013) investigated the effect of self-attraction and loading (SAL) induced by the projected accumulation of sea-water on shallow continental shelf areas. This Is a process as of today not included in the regional sea level projections. Using output from a climate model, they compute 21st century changes in regional steric sea surface height and find that steric changes are largest over the deep ocean and relatively small on the shallow continental shelves. The resulting redistribution of sea water towards the shelf areas leads to mass accumulation on the shelves and therefore to increased gravitational attraction as well as increased loading on the sea floor. We find that, depending on the scenario and region, SAL effects may result in an additional sea level rise of 1–3 cm on the world's continental shelf areas by the end of the 21st century. These estimates are at most 15% of the combined changes in sea surface height induced by redistribution of water masses and steric expansion.

WP7 Synthesis of sea level assessment, future projections and dissemination

Main objective: To synthesize the results of all project activities, provide future projections of sea level changes and disseminate overall results.

J. Even Ø. Nilsen, H. Drange, J. A. Johannessen (lead).

The knowledge base gathered and developed in SEALEV has been put to use into the national report Projections of 21st Century Sea Level Changes for Norway (Simpson et al., 2015). This is a collaborative effort in Norway consolidating the knowledge on sea level projections, land uplift, and extreme sea level analysis, providing projections of sea level change, as well as future return levels, for each coastal municipality in Norway.

For effective coastal management it is important to understand how sea levels will change locally in the future. Changes to mean sea level and sea level extremes (e.g., storm surges) will lead to changes in coastal impacts. Preparedness is normally based on return levels from statistics of the water levels in the observed record. With changing mean sea levels due to climatic change and land uplift return levels will change accordingly. Simpson et al. (2015) first perform an extensive and comparative analysis of observed sea level from tide gauges and altimetry, in order to assess the current rates and natural variability. State of the art land uplift rates for the coastal municipalities are determined assessing new GPS observations as well as modelling of glacial isostatic adjustment.

Our regional sea level projections are based on findings from the Fifth Assessment Report (AR5) of the Intergovernmental Panel for Climate Change (IPCC), and the Coupled Model Intercomparison Project phase 5 (CMIP5) output, but using our own land uplift rates and corresponding gravitational effects on sea level, as well as estimates of self attraction and loading (SAL). The average projected

21st century relative sea level change in Norway is -0.10–0.35 m (90% uncertainty bounds) for RCP2.6, 0.00–0.45 m for RCP4.5, and 0.10–0.65 m for RCP8.5. However, the relative sea level projections can differ as much as 0.50 m from place to place, mostly governed by the land uplift pattern. Further, the extreme value analysis and return levels for Norway have been reassessed, and together with the sea level projections applied to a modified version of Hunter's method. We thus provide estimates for how much assets need to be raised so that the probability of flooding remains preserved. For RCP8.5 these allowances can reach up to 0.7 meters depending on location.

In addition to the abovementioned information product to governmental agencies and decision makers, there has been wide and continuous dissemination from SEALEV in newspapers, magazines, radio, etc., many popular talks to public institutions and in different public arenas. Also a course on sea level change has been established at the University of Bergen (GEOV223).

3. Future Work

Most of the members of the group involved in SEALEV have found projects for their sea level related research in the future.

Work on Greenland and Ice–Ocean Interaction

Kirill in ESA Ice Sheet CCI, continued work from SEALEV WP2. Martin in EASTGREEN. Martin, Victoria, Linling, Anna, Atle, Lars, Paul in MARGINS, related to WP2.2 & WP3.3. There are also collaborations within ICE2ICE and IceBed.

Work on the Steric and Dynamic Processes

Even, Helge, Mats, François, Johnny in iNcREASE, continued work from WP1 & WP6. Even, Johnny GOCE-MDT, ESA Sea Level CCI, REOCIRC, continued work from WP1. The intercomparison of steric anomalies between observations and NorESM will be ursued in iNcREASE.

Reconstruction of former sea-level and ice sheets

Anna, John Inge, Jan, Kristian in DATED, continued work from WP5. The database on former ice-sheets DATED-2 is underway. Some of the research questions that were addressed in WP5 have been followed up in EISCLIM, exploring the growth and decay of the Eurasian Ice Sheet during the last glacial cycle and the interaction with the climate.

Model Development for Sea Level Research

The model development described in the WP6 section above, will continue unabated. In the future.

4. People Involved

J. Even Ø. Nilsen (PI; NERSC), S. Sandven, L.L. Chen, F. Counillon, K. Khvorostovsky, V. Miles, A. Korablev, I. Keghouche, S. de la Rosa, Qing Yan, J. A. Johannessen, O. M. Johannessen (NERSC); H. Drange, I. Fer, A. Nesje, J. I. Svendsen, Ø. Lohne, J. Mangerud, S. Maus, K. Vasskog, A. Hughes (UiB); M. Bentsen, M. Miles, K. Richter (UNI); L. Asplin, M. Myksvoll, P. Budgell, K. Kalhagen (IMR).

5. Publications

1. Richter, K., J.E.Ø. Nilsen, H. Drange (2012). Contributions to sea level variability along the Norwegian coast for 1960-2010. J. Geophys. Res., 117, doi:10.1029/2009JC005884.
2. Nilsen, J.E.Ø., H. Drange, K. Richter., E. Jansen, A. Nesje. (2012). Endringer i fortidens, dagens og framtidens havnivå med spesielt fokus på vestlandskysten. NERSC Special Report 89, Bergen, Norge. 48 s.

3. Mangerud, J., Brent M. Goehring, Øystein S. Lohne, John Inge Svendsen, Richard Gyllencreutz (2013). Collapse of Marine-based Outlet Glaciers from the Scandinavian Ice Sheet. Quaternary Science Reviews, 67, pp 8-16.
4. Lohne, Ø. S., Mangerud, J., Birks, H. H. (2014). IntCal13 calibrated ages of the Vedde and Saksunarvatn ashes and the Younger Dryas boundaries from Kråkenes, western Norway. Journal of Quaternary Science 29, 506-507.
5. Svendsen, J.I., L. C. Krüger, J. Mangerud, A. Paus and A. Murray (2014): Glacial and vegetation history of the Polar Ural Mountains during the Last Ice Age. Quaternary Science Reviews, 92, 409–428.
6. Qing Yan, Zhongshi Zhang, Yongqi Gao, Huijun Wang, Ola M. Johannessen (2013). Sensitivity of the modeled present-day Greenland Ice Sheet to climatic forcing and spin-up methods and its influence on future sea level projections. JGR-Earth Surface, 118, p1-16, doi:10.1002/jgrf.20156.
7. Chen, L., Ola M. Johannessen, H. J. Wang, and A. Ohmura (2011). Accumulation over the Greenland ice sheet as represented in reanalysis data. Adv. Atmos. Sci., 28(5), 1030–1038, doi:10.1007/s00376-010-0150-9.
8. Khvorostovsky, K. , 2012: Merging and analysis of elevation time series over Greenland ice sheet from satellite radar altimetry. IEEE Trans. Geosc., Remote Sens., vol., 50, 1, pp. 23-36.
9. Miles, V. V., O. M. Johannessen and M. W. Miles. Rapid changes in advance–retreat (co)variability of Sermilik fjord outlet glaciers, southeast Greenland. Journal of Glaciology. In prep., to be submitted.
10. Richter, R., R. Riva, H. Drange (2013). Impact of self-attraction and loading effects induced by shelf mass loading on projected regional sea level rise. Geophys. res. lett. 40 (1-5), doi: 10.1002/grl.50265.
11. Chen L., O.M. Johannessen. Variability of precipitation and temperature over the Greenland Ice Sheet and associated cyclones. In prep.
12. Yan, Q., H. Wang, O. M. Johannessen and Z. Zhang (2014). Greenland ice sheet contribution to global sea-level rise based on CMIP5 models. Adv. Atmos. Sci., 31(1), 8-16, doi: 10.1007/s00376-013-3002-6.
13. Vasskog, K., Waldmann, N., Nesje, A., Bondevik, S., Chapron, E. and Ariztegui, D.: Evidence for Storegga tsunami run-up at the head of Nordfjord, western Norway. Journal of Quaternary Science, 28(4), 391-402, doi: 10.1002/jqs.2633
14. Vasskog, K., P. M. Langebroek, J. T. Andrews, J. E. Ø. Nilsen and A. Nesje. The Greenland ice sheet during the last glacial cycle: current ice loss and contribution to sea-level rise in a palaeoclimatic perspective. Earth-Science Reviews. Accepted.
15. Johannessen O.M., A. Korablev, V. Miles, M. W. Miles, K. E. Solberg (2011). Interaction Between the Warm Subsurface Atlantic Water in the Sermilik Fjord and Helheim Glacier in Southeast Greenland. Surv. Geophys., 32, 387–396, doi: 10.1007/s10712-011-9130-6.
16. Johannessen, J.A., R. Raj, J.E.Ø. Nilsen, T. Pripp, P. Knudsen, F. Counillon, D. Stammer, L. Bertino, O. B. Andersen, N. Serra and N. Koldunov (2014). Towards improved estimation of the dynamic topography and ocean circulation in the high latitude and Arctic Ocean: The importance of GOCE. Surv. Geophys. 35(1), doi: 10.1007/s10712-013-9270-y.
17. Miles, V. V., M. W. Miles and O. M. Johannessen. Satellite archives reveal unstable advance–retreat behavior of Helheim Glacier, southeast Greenland. Journal of Glaciology. In review., submitted 5/2015.
18. Johannessen, O.M., M. Babiker and M.W. Miles (2013). Unprecedented Retreat in a 50-Year Observational Record for Petermann Glacier, North Greenland. Atm. Oc. Sci. Lett. 6 (5), p 259265.
19. Hurkmans, R. T. W. L., J. L. Bamber, C. H. Davis, I. R. Joughin, K. S. Khvorostovsky, B. S. Smith, and N. Schoen. Time-evolving mass loss of the Greenland ice sheet from satellite altimetry. The Cryosphere, 8, 1725-1740.

20. Chen, L., X. Fettweis, E. M. Knudsen, and O. M. Johannessen. Impact of cyclonic and anticyclonic activities on the Greenland Ice Sheet surface mass balance variation during 1980-2013. International Journal of Climetology. In review.
21. Hughes, A.L.C., Gyllencreutz, R., Lohne, Ø.S., Mangerud, J., Svendsen, J.I. The last Eurasian Ice Sheets: a chronological database and time-slice reconstruction, DATED-1. Boreas. In review.
22. Ablain, M., A. Cazenave, G. Larnicol, M. Balmaseda, P. Cipollini, Y. Faugère, M. J. Fernandes, O. Henry, J. A. Johannessen, P. Knudsen, O. Andersen, J. Legeais, B. Meyssignac, M. Picot, M. Roca, S. Rudenko, M. G. Scharffenberg, D. Stammer, G. Timms, and J. Benveniste (2014), Improved sea level record over the satellite altimetry era (1993–2010) from the Climate Change Initiative Project, Ocean Science *11, 67–82, doi:10.5194/os-11-67-2015.*.
23. Koldunov. N. V. , Nuno Serra, Armin Köhl, Detlef Stammer, Olivier Henry, Anny Cazenave, Pierre Prandi, Per Knudsen, Ole Baltazar Andersen, Yongqi Gao, Johnny A. Johannessen (2014), Multi-model Simulations of Arctic Ocean Sea Surface Height Variability in the Period 1970-2009, Journal of Geophysical Research - *Oceans*, 119.(12) p. 8936-8954.
24. Stephen M Griffies; Jianjun Yin; Paul J Durack; Paul Goddard; Susan C Bates; Erik Behrens; Mats Bentsen; Daohua Bi; Arne Biastoch; Claus W Boening; Alexandra Bozec; Eric Chassignet; Gokhan Danabasoglu; Sergey Danilov; Catia Domingues; Helge Drange; Riccardo Farneti; Elodie Fernandez; Richard J Greatbatch; David M Holland; Mehmet Ilicak; William G Large; Katja Lorbacher; Jianhua Lu; Simon J Marsland; Akhilesh Mishra; A J George Nurser; Jaime B Palter; David Salas y Melia; Bonita L Samuels; Jens Schroeter; Franziska U Schwarzkopf; Dmitry Sidorenko; Anne Marie Treguier; Yu-heng Tseng; Hiroyuki Tsujino; Petteri Uotila; Sophie Valcke; Aurore Voldoire; Qiang Wang; Michael Winton; Xuebin Zhang (2014): An assessment of global and regional sea level for years 1993-2007 in a suite of interannual CORE-II simulations, *Ocean Modelling*, 78, 35-89, doi:10.1016/j.ocemod.2014.03.004
25. Svendsen, J.I., Briner, J.P., Mangerud, J., Young, N.E., 2015: Early break-up of the Norwegian Channel Ice Stream during the Last Glacial Maximum. Quaternary Science Reviews 107,232-242.
26. Lohne, Ø. S., Mangerud, J., Birks, H. H. (2014). IntCal13 calibrated ages of the Vedde and Saksunarvatn ashes and the Younger Dryas boundaries from Kråkenes, western Norway. Journal of Quaternary Science 29, 506-507.
27. Briner, J.P., Svendsen, J.I., Mangerud, J., Lohne, Ø.S., Young, N.E., 2014. A ^{10}Be chronology of south-western Scandinavian Ice Sheet history during the Lateglacial period. Journal of Quaternary Science 29, 370-380.
28. Alexanderson, H., Backman, J., Cronin, T.M., Funder, S., Ingólfsson, Ó., Jakobsson, M., Landvik, J.Y., Löwemark, L., Mangerud, J., März, C., Möller, P., O'Regan, M., Spielhagen, R.F. (2014). An Arctic perspective on dating Mid-Late Pleistocene environmental history. Quaternary Science Reviews 92, 9-31.
29. Bramham-Law, C.W.F., Theuerkauf, M, Lane, C.S. and Mangerud, J. (2013): New findings regarding the Saksunarvatn Ash in Germany. Journal of Quaternary Science 28, 248-257.
30. Goehring, B. M., Lohne, Ø. S., Mangerud, J., Svendsen, J. I., Gyllencreutz, R., Schaefer, J. & Finkel, R. (2012): Late glacial and holocene 10Be production rates for western Norway. Journal of Quaternary Science 27, 89-96.
31. Lohne, Ø. S., Mangerud, J. & Svendsen, J. I. (2012): Timing of the younger dryas glacial maximum in western Norway. Journal of Quaternary Science 27, 81-88.
32. Lane, C. S., Blockley, S. P. E., Mangerud, J., Smith, V. C., Lohne, Ø. S., Tomlinson, E. L., Matthews, I. P. & Lotter, A. F. (2012): Was the 12.1 ka Icelandic Vedde Ash one of a kind? Quaternary Science Reviews 33, 87-99.

33. Mangerud, J., Gyllencreutz, R., Lohne, Ø.S., and Svendsen, J.I. (2011). Glacial history of Norway. In Ehlers, J., Gibbard, P. L. and Hughes, P. D. (eds.): Developments in Quaternary Science, Vol. 15, 279-298.
34. Kalhagen, Kjersti (2015). Numerical modelling of the sub-surface melting of marine-terminating glaciers in Arctic fjords. Master thesis at the Geophysical Institute, University of Bergen, 58 pages.
35. Simpson, M. J. R., J. E. Ø. Nilsen, O. R. Ravndal, K. Breili, H. Sande, H. P. Kierulf, H. Steffen, E. Jansen, M. Carson, and O. Vestøl (2015). Projections of 21st Century Sea Level Changes for Norway. Norwegian Centre for Climate Services report 1/2015. ISSN 2387-3027, Oslo, Norway. In prep.

6. Conference Presentations

1. Richter, K., J.E.Ø. Nilsen and H. Drange (2012), Contributions to sea level variability along the Norwegian coast for 1960-2010, CRES workshop on Sea Level Rise and Ice Sheets, Copenhagen, Denmark, 23.05.2012 (oral).
2. Nilsen, J.E.Ø. (2012). Sea level change and ice sheet dynamics. ECRA pilot workshop on regional sea level change, Utrecht, Netherlands, 15.03.2012.
3. Chen, L.L. and O.M. Johannessen (2012). Greenland Ice Sheet surface mass balance and atmospheric variability. CRES workshop on Sea Level Rise and Ice Sheets, Copenhagen, Denmark, 23.05.2012 (oral).
4. Mangerud, J., Goehring, B.M., Lohne, Ø., Svendsen, J.I., Gyllencreutz, R. (2012). Collapse of marine-based out-let glaciers from the Scandinavian Ice Sheet. Bjerknes Centre 10-year anniversary conference: "Climate Changes in high Latitudes", Bergen 3-6 september 2012 (oral).
5. Svendsen, J.I., Mangerud, J, Gyllencreutz, R., Henriksen, M., Lohne, Ø., Krüger, L.C. (2012) Late Quaternary glacial and climate history of northern Russia. Bjerknes Centre 10-year anniversary conference: "Climate Changes in high Latitudes", Bergen 3-6 september 2012 (poster).
6. Lohne, Ø.S., Svendsen, J.I., Mangerud, J. (2012). Late Holocene relative sea-level changes in Western Norway. Bjerknes Centre 10-year anniversary conference: "Climate Changes in high Latitudes", Bergen 3-6 september 2012 (poster).
7. Hughes, A.L.C., Gyllencreutz, R., Mangerud, J., Svendsen, J.I., Lohne, Ø.S. (2012). DATED – Dates database and time-slice reconstruction of Eurasian Ice Sheet deglaciation. Bjerknes Centre 10-year anniversary conference: "Climate Changes in high Latitudes", Bergen 3-6 september 2012 (poster).
8. Mangerud, J., Lohne, Ø., Svendsen, J.I. (2012). Twisting of the lithosphere at right angle to the glaci-isostatic tilting. "Lithosphere-Cryosphere interactions" workshop, Ruhr University, Bochum, Tyskland, 26-27 Sept. 2012 (oral).
9. Mangerud, J., Goehring, B.M., Lohne, Ø., Svendsen, J.I., Gyllencreutz, R.(2012). Collapse of marine-based out-let glaciers from the Scandinavian Ice Sheet. "Lithosphere-Cryosphere interactions" workshop, Ruhr University, Bochum, Tyskland, 26-27 Sept. 2012 (oral).
10. Hughes, A.L.C., Gyllencreutz, R., Mangerud, J., Svendsen, J.I., Lohne, Ø.S. (2012). DATED – Dates database and time-slice reconstruction of Eurasian Ice Sheet deglaciation. "Lithosphere-Cryosphere interactions" workshop, Ruhr University, Bochum, Tyskland, 26-27 Sept. 2012 (poster).
11. Kvisvik, B. and Vasskog, K. (2012). Isolation basins and tsunami inundation in western Norway. CRES workshop on Sea Level Rise and Ice Sheets, Copenhagen, Denmark, 21-25 May (oral).
12. Johannessen, J.A. (2012). Towards improved estimation of the dynamic topography and ocean circulation for the high latitude and Arctic Ocean. ISSI workshop on “The Earth's Hydrological Cycle”, Bern, 6-10 Feb. 2012 (oral).

13. Miles, V. V., M. W. Miles and O. M. Johannessen: Sermilik fjord outlet glaciers, southeast Greenland: Coherent behavior or a drunkard's walk? 43rd Annual Arctic Workshop, Amherst, Massachusetts, USA, 11-13 March 2013 (oral).
14. Miles, V. V., M. W. Miles and O. M. Johannessen: Rapid changes in advance–retreat (co)variability of Sermilik fjord glaciers, southeast Greenland. 'PAST Gateways' Meeting, St. Petersburg/Zelenogorsk, Russia, 13-17 May 2013 (oral).
15. Miles, M. W., D. V. Divine, T. Furevik, E. Jansen, M. Moros and A. E. J. Ogilvie: Linking the Atlantic Multidecadal Oscillation to Greenland Sea ice in the Holocene. 'PAST Gateways' Meeting, St. Petersburg/Zelenogorsk, Russia, 13-17 May 2013 (oral).
16. Miles, V. V., O. M. Johannessen and M. W. Miles: Rapid changes in advance–retreat (co)variability of Sermilik fjord glaciers, southeast Greenland. CLIVAR 'GRISO' Workshop, Beverly, Massachusetts, USA, 4-7 June 2013 (poster).
17. Khvorostovsky K. (2013). Analysis of the Greenland ice sheet elevation time series from satellite altimetry. EGU General Assembly, 7-12 April, 2013, Vienna, Austria, Vol. 15, EGU2013-1004. (poster).
18. Budgell, W.P. (2013). A Nested High-Resolution Simulation of Circulation in Sermilik Fjord, Greenland. CLIVAR 'GRISO' Workshop, Beverly, Massachusetts, USA, 4-7 June 2013 (poster).
19. Hughes, A.L.C., Gyllencreutz, R., Mangerud, J., Svendsen, J.I., Lohne, Ø.S. (2013). New reconstructions of Eurasian Ice Sheet build up and deglaciation. Abstracts and Proceedings of the Geological Society of Norway, No. 1, 2013, pp 59-60.
20. Mangerud, J. (2013): A new reconstruction of the last deglaciation of northwest Europe. Shoreline displacement and archaeology workshop" 21/3-2013. Kulturhistorisk Museum, Universitetet i Oslo.
21. Mangerud, J, Lohne, Ø. and Birks, H.H. (2013). Comparison between the calibrated radiocarbon (IntCal09) and Greenland Ice Core (GICC05) time scales for the Vedde and Saksunarvatn ashes and the Younger Dryas boundaries based on 118 14C dates. Geophysical Res. Abstracts 15, EGU General Assembly 2013.
22. Mangerud, J, Lohne, Ø. and Birks, H.H. (2013): Comparison between the calibrated radiocarbon (IntCal09) and Greenland Ice Core (GICC05) time scales for the Vedde and Saksunarvatn ashes and the Younger Dryas boundaries. INTIMATE meeting, Blair Atholl, Scotland. 28nd April- 4th May. http://meetingorganizer.copernicus.org/EGU2013/orals/11618
23. Mangerud, J., Brent M. Goehring, Øystein S. Lohne, John Inge Svendsen, Richard Gyllencreutz (2013) : Collapse of marine-based outlet Glaciers from the Scandinavian Ice Sheet. Abstracts and Proceedings of the Geological Society of Norway, No. 1, 2013, p. 86.
24. Svendsen, J.I., Linn Cecilie Krüger, Jan Mangerud, Valery Astakhov, Aage Paus, and Andrew Murray (2013): Glacial and vegetation history of the Polar Ural Mountains in Northern Russia during the Last Ice Age, marine Isotope Stage 5e. Abstracts and Proceedings of the Geological Society of Norway, No. 1, 2013, pp. 125-126.
25. Svendsen, J.I., Mangerud, J., Briner, J., Hughes, A.L.C., Lohne, Ø.S., Goehring, B.M., Gyllencreutz, R. (2013). The Eurasian Ice Sheet and the deglaciation of western Norway. Geophysical Res. Abstracts 15, EGU General Assembly 2013. http://meetingorganizer.copernicus.org/EGU2013/orals/11664
26. Svendsen, J.I., Mangerud, J., Lohne , Ø. (2013). "Sea-level changes in western Norway" Shoreline displacement and archaeology workshop" 21/3-2013. Kulturhistorisk Museum, Universitetet I Oslo.
27. Svendsen, J.I., Mangerud, J., Briner, J., Hughes, A.LC, Lohne, Ø.S., Goehring, B.M., Gyllencreutz, R. (2013). The deglaciation history of western Noway since the Last Glacial Maximum. INTIMATE meeting. Blair Atholl, Scotland. 28 nd April- 4th May.

28. Chen, L. L., Ola M. Johannessen, H. J. Wang, and A. Ohmura (2012): Accumulation over the Greenland ice sheet as represented in reanalysis data. 4th WCRP International Conference on Reanalyses, Silver Spring, Maryland, USA. (poster)
29. Nilsen, J.E.Ø. (2014). Regional sea level rise - a multitude of contributions, effects, and interactions. UNIS lunch seminar, Spitsbergen, 29.01.2014 (oral).
30. Nilsen, J.E.Ø. (2013). Reconstructing sea level variability along a coast - contributions from ocean and atmosphere. India-EU workshop II, Cochin, India, 13.11.2013 (oral).
31. Nilsen, J.E.Ø. (2013). Regional sea level rise - a multitude of contributions, effects, and interactions. INDO-MARECLIM Winter School, Cochin, India, 06.11.2013 (oral).
32. Chen L.L, O. M. Johannessen, E. M. Knudsen, (2013), Atmospheric circulation change and associated accumulation/temperature changes over the Greenland Ice Sheet. Davos Atmosphere and Cryosphere Assembly 2013, 8 - 12 July. (oral)
33. Johannessen, J.A., D. Stammer, A. Cazenave, J.E.Ø. Nilsen and R. Raj (2014). Arctic Sea Level Change – Observation Requirements, Simulation Capabilities, Forward Projections and Challenges. The Climate Symposium, Darmstadt, Germany, October 13-17 (oral).
34. Johannessen, O.M. (2014). Indian Ocean Sea Level and potential impacts of Greenland Ice Sheet. Several venues, e.g., The Norwegian Embassy, Dhaka, Bangladesh, October 15 (oral).
35. Mangerud, J., Svendsen, J.I, Heggen, H.P., Slimak, L., Plisson, H., Brugère, A., Pavlov, P.Y., 2011: Breaking news on Ice Age Humans in Northern Russia. APEX Fifth International Conference and Workshop. Longyearbyen, Svalbard. June 1st – 4th 2011, p. 96.
36. Kirchner, N., Gyllencreutz, R., Mangerud, J. 2011: Novaya Zemlya - a nucleus for glaciation in the Barents-Kara Sea during MIS 3-2? APEX Fifth International Conference and Workshop. Longyearbyen, Svalbard. June 1st – 4th 2011, p. 83.
37. Mangerud, J., Svendsen, J.I. and Lohne, Ø. S. 2011 Younger Dryas glaciation of Scandinavia – the type area for the Younger Dryas. XVIII. INQUA Congress. Bern, Switzerland. July 21st - 27th 2011.
38. Gyllencreutz, R., Mangerud, J., Svendsen, J.I. and Lohne, Ø. S. 2011: The DATED chronology and Eurasian Ice Sheet reconstructions. XVIII. INQUA Congress. Bern, Switzerland. July 21st - 27th 2011.
39. Kirchner, N., Gyllencreutz, R., Mangerud, J. 2011: Novaya Zemlya - a nucleus for glaciation in the Barents-Kara Sea during MIS 3-2? XVIII. INQUA Congress. Bern, Switzerland. July 21st - 27th 2011.
40. Lane, C., Blockley, S., Smith, V., Tomlinson, E., Matthews, I., Mangerud, J. 2011: Is the Icelandic Vedde Ash one of a kind? XVIII. INQUA Congress. Bern, Switzerland. July 21st - 27th 2011.
41. Mangerud, J., Thordarson, T. and Stevenson, J. A. 2012: The Askja 1875 eruption: World's first map of an ash plume and properties of the ash from samples collected in Norway in 1875. 30th Nordic Geological Winter Meeting. Reykjavik, Iceland 9-12 January 2012. Programme and abstracts, p. 130.
42. Lind, E., Abbott, P., Lane, C., Lilja, C., Pearce, N., Mangerud, J. And Wastegård, S. 2012. A comparison of trace elements chemistry of the Saksunarvatn ash in lacustrine- and marine records as well as from the GRIP ice core. 30th Nordic Geological Winter Meeting. Reykjavik, Iceland 9-12 January 2012. Programme and abstracts, p. 191.
43. Hughes, A.L.C., Gyllencreutz, R., Mangerud, J., Svendsen, J.I., Lohne, Ø.S. 2012: DATED – Dates database and time-slice reconstruction of Eurasian Ice Sheet deglaciation. "Lithosphere-Cryosphere interactions" workshop, Ruhr University, Bochum, Tyskland, 26-27 Sept. 2012.
44. Hughes, A.L.C., Gyllencreutz, R., Mangerud, J., Svendsen, J.I., Lohne, Ø.S. 2012: New reconstructions of Eurasian Ice Sheet build up and deglaciation. AGU Fall Meeting 2012, December 3-7, San Fransisco.

45. Briner, J.P., Svendsen, J.I., Mangerud, J, Lohne, Ø. 2012: A preliminary ^{10}Be chronology of Scandinavian Ice Sheet retreat from southwestern Norway. AGU Fall Meeting 2012, December 3-7, San Fransisco. Suppl., abstract C51C-0788
46. Hughes, A.L.C., Gyllencreutz, R., Mangerud, J., Svendsen, J.I., Lohne, Ø.S. 2014: The last Eurasian Ice Sheet: a chronological database and time-slice reconstruction. 31st Nordic Geological Winter Meeting. Lund, Sweden, January 8-10 2014. Page 135.
47. Svendsen, J.I., Mangerud, J., Briner, J., Young, N. 2014: Rapid break-up of the Norwegian Channel Ice Stream of the Scandinavian Ice Sheet during the Last Glacial Maximum. 31st Nordic Geological Winter Meeting. Lund, Sweden, January 8-10 2014. Pages 145-146.
48. Mangerud, J., Lohne, Ø., Birks, H. 2014: Precise and accurate C-14 ages for the Younger Dryas from the type area in southern Scandinavia. Geological Society of America Annual Meeting. Vancouver 19-22 Oct.
49. Mangerud, J., Hughes, A.L.C., Gyllencreutz, R., Svendsen, J.I., Lohne, Ø.S. 2014: The last Eurasian Ice Sheet: a chronological database and time-slice reconstruction. Geological Society of America Annual Meeting. Vancouver 19-22 Oct.
50. Bentsen, M. 2014: Modelling interactions between ice sheets and the ocean in NorESM. West Antarctic Glacier-Ocean Model Workshop. Abu Dhabi 27-29 Oct.

7. Outreach

1. Nilsen, J.E.Ø. (2012). Sea level rise and ocean processes. Teaching in GEOV223, UiB, 06.03.2012 (oral).
2. Nilsen, J.E.Ø., H. Drange, K. Richter (2012). Havnivået stiger. In 2°C - Status fra klimavitenskapen, No 1, November 2012, Norway, p 20-21.
3. Nilsen, J.E.Ø., H. Drange, K. Richter, A. Nesje , E. Jansen (2012). Nytt fra havstigningsfronten. In Klima, 6-2012, Norway, p 11-12.
4. Kristin S. Grønli (2013). Havnivået kan krype nedover. Interview with H. Drange and J.E.Ø. Nilsen. Teknisk Ukeblad, 1813.
5. Nilsen, J.E.Ø. (2013). Sea level rise and ocean processes. Teaching in GEOV223, UiB, 19.02.2013 (oral).
6. Miles, M. W. (2012). Hav- og klimaendringer. Teaching in GEOG112, UiB, 25.10.2012 (oral).
7. Schrødingers Katt. Innslag med Jan Mangerud om havnivåendringer, November 8: http://tv.nrk.no/serie/schrodingers-katt1/dmpv73003112/08-11-2012#t=3m11s
8. Mangerud, J., J.I. Svendsen, Ø.S. Lohne (2013). Hardangerfjordbreen var et mektig syn for 11600 år siden. Kvinnheringen, May 27th 2013.
9. Havet stiger NRK Radio, 01.10.2014, Jan Even Øie Nilsen http://radio.nrk.no/serie/ekko-hovedsending/MDSP25019514/01-10-2014#t=58m9s
10. Nilsen, J.E.Ø., K. H. Nisancioglu, T. Furevik (2014). Arven fra polene, Dagens Næringsliv, 13.11.14.
11. Mangerud, J. 2011: Verdens første kart av et askenedfall. GEO 14, Nr. 1, side 44-45.
12. Mangerud, J. 2011: Historien om et tynt sandlag – og en askesky. GEO 14, Nr. 2, 28-33.
13. Mangerud, J. 2011: Der havet stiger mest. Klima 2-2011, 16-17.
14. Svendsen, J.I., Lohne, Ø.S., og Mangerud, J. 2011: Istidsforskning i Uralfjellene – om "uvanlige" breer og mammutjegere. Side 154-157 i "Polaråret 2007-2008. Det norske bidraget". Norges forskningsråd.
15. Mangerud, J. 2012: Ullensaker er ikke som resten av Norge. Ullensaker. Lokalhistorisk. 7. Årgang, nr. 2, 3-7.
16. Mangerud, J. og Svendsen, J.I. 2013: En fjelltur – og løsningen på et istidsproblem. GEO 7, 2013, 18-22.

17. Vorren, T. og Mangerud, J. 2013: Istider kommer og går. Side 496-547 i I.B. Ramberg, I. Bryhni, A. Nøttvedt og K. Rangnes: Landet vårt blir til – Norges geologi. 2. Utgave. Norsk Geologisk Forening, Trondheim.
18. Vorren, T., Mangerud, J., Blikra, L.H., Nesje, A. og Sveian, H. 2013: Norge av i dag trer fram. Side 548-575 i I.B. Ramberg, I. Bryhni, A. Nøttvedt og K. Rangnes: Landet vårt blir til – Norges geologi. 2. Utgave. Norsk Geologisk Forening, Trondheim.

Other references

Hunter, J. R., 2006: Specification for Test Models of Ice Shelf Cavities. Tech. rep., Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Australia.

Losch, M., 2008: Modeling ice shelf cavities in a *z* coordinate ocean general circulation model. *J. Geophys. Res.*, 113 (C08043), doi:10.1029/2007JC004368.