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PROJECT FINAL REPORT

Grant Agreement number: 308299

Project acronym: NACLIM

Project title: North Atlantic Climate

Funding Scheme: FP7 Large Scale Collaborative Project

Period covered: **from** 01.11.2012 **to** 31.01.2017

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:
Prof. Dr. Detlef Quadfasel

Tel: +49 40 42838 5756; +49 40 42838 7478

Fax:

E-mail: Detlef.Quadfasel@uni-hamburg.de

Project website address: www.naclim.eu

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

4.1 Final publishable summary report

4.1.1 An executive summary (not exceeding 1 page)

In the North Atlantic the upper ocean layer strongly communicates with both, the overlying atmosphere and the deep ocean. A large part of the deep waters are created here. The region can be considered as important driver of global climate variability on time scales beyond seasonal. The sea surface state (SST and sea ice) also determines to a large extent the weather in Europe. In NACLIM researchers from 11 different nations have worked together to evaluate uncertainties of climate forecasts and to review and optimize the North Atlantic observation system. The forecasts from the coupled climate models were applied to topics in the marine eco-system and in urban societies.

The predictability of the North Atlantic/Arctic Ocean surface state, its temperature, freshwater content, ice cover and circulation was studied with a suite of state of the art coupled climate models. For the sea surface temperature and upper-ocean heat content in the subpolar North Atlantic we were able to show predictive skill of up to ten years, related to the northward advection of warm and saline subtropical water by the Atlantic meridional overturning circulation. Likewise the decline in Arctic sea ice area and thickness during the last decade could be related to an increased poleward ocean heat transport. Teleconnections between sea-ice cover and the climate over Europe were identified providing some long-term predictability of the atmospheric circulation based on ocean forecasts. The quality of forecasts largely depends on our ability to derive a reliable description of the surface ocean state and to understand the major drivers of its variability. These are still challenging goals as the number of relevant observations in these regions is still poor and the accuracy of the prediction model need to be improved.

NACLIM's core observation areas were in the North Atlantic subpolar gyre and along the Greenland-Scotland Ridge (GSR). This is where the waters sink into the deep Atlantic Ocean to feed the lower limb of the AMOC. The observations also included the RAPID array, at 26^{o}N, to capture the AMOC farther south. These efforts resulted in time series of basin-wide volume, heat and freshwater fluxes that by now are up to 20 years long and to which NACLIM has contributed data for the past five years. Some of the arrays were redesigned using long term and low cost instrumentation developed in NACLIM. The volume fluxes across the GSR have been remarkably stable during the past decades but the northward heat fluxes have increased significantly due to a warming of the water masses carried. In contrast the volume fluxes in the AMOC at 26 N have declined, leading to a heat divergence in the North Atlantic and an associated slowing of the general warming.

We have assessed potential extensions of the observational system in terms of decadal hindcast skill. We suggest an extension of the global ocean observing system to below 2,000 m, in particular over the Southern Ocean and the North Atlantic. Second, we conclude that salinity observations need to be enhanced, e.g. by using satellite information. We also argue the current RAPID observation is worth continuing particularly to diagnose and understand the variability of the oceanic general circulation, as can be represented by the AMOC, and to verify climate models.

A multivariate data assimilation technique for optimizing model parameters on longer timescales periods and improving the model climate state has been successfully implemented and tested. By using data assimilation based on the adjoint method, we find that the model can be brought into consistency with estimated volume transports from observations. However individual components of the AMOC have a limited skill, linked to the inability of coarse resolution models to simulate overflow across the ridge with the implication that ocean heat transport towards the Arctic is biased.

In NACLIM we also examined the opportunities for forecasting marine ecosystems, exploiting living marine resources in a sustainable and economically efficient manner. We demonstrated predictive skill of biological variables, namely the availability of suitable foraging habitat for Bluefin Tuna and the spatial distribution of suitable spawning habitat for blue whiting. Climate variability and change also affects urban societies. The simulations revealed a nearly tenfold increase in the number of urban heatwave days towards the end of the century, reaching around 30 days with heatwave conditions annually. We had a very close contact with representatives of three target cities, both through bilateral contacts and formal workshops. In the final phase of the project, we organised an international workshop 'Towards urban climate services' in Brussels.

4.1.2 A summary description of project context and objectives (not exceeding 4 pages).

NACLIM aims at investigating and quantifying the predictability of the climate in the North Atlantic (European) sector related to North Atlantic and Arctic sea surface temperature (SST) and sea ice variability and change on seasonal to decadal time scales.

The overarching goals of NACLIM were

- To quantify the uncertainty of state-of-the-art climate forecasts by evaluating the ability to model the most important oceanic and atmospheric processes in the North Atlantic and Arctic Oceans and by comparing key quantities with observations.
- To optimize the present North Atlantic observation system by evaluating the impact of its components on the quality and quality control of model forecasts, and their value in determining the present ocean state and its past variability.
- To quantify the impact on oceanic ecosystems and on European urban societies of predicted North Atlantic/Arctic Ocean variability.
- To critically assess the use of climate forecast parameters for use by stakeholders in society, politics and industry

To reach these goals NACLIM was organized in ten scientific work packages clustered in 4 scientific core themes. The specific context and objectives of these work packages were as follows:

WP 1.1 – Accessing the predictability of the North Atlantic and Arctic Ocean surface state as well as of key quantities controlling it. These comprise sea surface temperatures, the upper ocean salt content respectively the freshwater content, the changes in Arctic sea Ice coverage and thickness and the subpolar gyre strength. The assessment has been based on existing decadal prediction experiments from the fifth phase of the Coupled Model Intercomparison Project (CMIP5), allowing a multi-model approach and providing more robust and reliable results than previously available. Apart from assessing the predictive skill, WP1.1 has attempted skill attribution, i.e. understanding the mechanisms underlying the predictive skill.

WP 1.2 – To identify the regional pattern and time evolution of the sea surface temperature (SST), surface salinity, and sea ice patterns that strongest influence the atmosphere in the North Atlantic/European sector on seasonal to decadal time scales and quantify their climatic impacts. The novel approach in his WP was the use of an adjoint climate model, known as PLASIM that was developed during the previous FP6 project THOR. The goal was to assess the ability of climate models to reproduce these impacts, identify their potential predictability, and use observations to downscale the model predictions from global to local scales. A second topic in this WP was to quantify the impact of Arctic changes on the generation and activity polar meso-cyclones. The intense low-pressure systems are a potential danger for Arctic shipping.

WP 1.3 – In order to identify the North Atlantic and Arctic surface changes that most affect the atmosphere and to better evaluate their role in the climate predictability, this WP had three main objectives: (1) to characterize the time-space sea surface variability in the Arctic/North Atlantic region, (2) to identify the mechanisms underpinning this variability and link them to indices of variability of the ocean circulation, and (3) to provide information on the respective roles of the atmosphere and the ocean in this variability and identify feedback mechanisms between ocean anomalies and the overlaying atmosphere. Based on the most relevant patterns and feedbacks, anomalous atmospheric fields were constructed and used to force stand-alone ice-ocean simulations in order to evaluate the contribution of the atmosphere to the observed surface variability.

WP 2.1 – In order to verify model-based climate predictions, long-term observations of relevant ocean parameters were necessary. The meridional exchange across the Greenland-Scotland Ridge is of key importance for the North Atlantic climate system and observations of these exchanges are therefore very important in the context of understanding climate variability. The objectives of this WP were thus to provide updated time series of volume and heat transports for all the Atlantic inflow branches to the Nordic Seas and volume and freshwater transports for the most important overflow branches. The variability and trends in these flows were also to be estimated and these data sets served as input to several of the other work packages in NACLIM. It is very costly to maintain these long-term monitoring system, thus in order to make the systems more accurate and sustainable the existing measuring systems were also to be modified within NACLIM.

WP 2.2 - Existing and newly acquired observational data was analysed to derive reference time series suitable for the assessment of the hindcast predictive skill of the CMIP5 models. The focus was on time series of critical variables (volume, heat, and freshwater transport) in focus areas as the warm water inflow region, the deep western boundary current, and the subpolar North Atlantic deep water formation areas. Dedicated observations as well as data available via the GOOS (e.g. satellites, Argo) also have been considered. The options in formatting time series data in a CMOR2 compliant output format have been evaluated. A close cooperation with the US – Canadian – European project OSNAP was envisaged at the beginning of NACLIM and could be started after the funding of this partner project came into place. The WP contributed with a moored array on the Reykjanes Ridge was used to derive transport of volume, heat and freshwater in the northward flowing Irminger Current. Other data sources were considered for the analysis. A major goal was to ensure the sustainability of observations and the linkage to other projects such as the Ocean Observatories Initiative OOI, FixO3, EMSO, RAPID and in particular in the framework of GOOS including Argo.

WP 2.3 – This WP is to large extent a synthesis package. The goal was to develop strategies and corresponding methods for a systematic quantitative comparison of model and observational data. To investigate to what degree models run and analyzed within NACLIM, are capable of reproducing observed variations of hydrographic and kinematic components of the exchanges, across the Greenland-Scotland-Ridge, of the deep western boundary current and of the overturning circulation at 26.5°N. To synthesize observational and model output for the estimate of large-scale and regional budgets we investigated to what extent and to within which accuracy observational data can be used to verify estimates of key ocean parameters and quantities from simulations using the different models employed in NACLIM. We provided, on an annual basis, the observational time series to the NACLIM modelers. The main goal was to close an budgets for the circulation of water masses, both horizontally and vertically, for the North Atlantic and Arctic Oceans.

WP 3.1 – The skill of any dynamical forecast depends critically on the quality of the initial conditions. For climate forecasts these are derived from observations in the ocean and atmosphere that are assimilated in either stand-alone models or in coupled models. Another critical point is the nature of the observations and their distribution in time and space. Rather than being able to freely choose the best data for the initialization, their use is constrained by their availability. This work package aimed to explore the impact of the constraints by working in an ideal model world allowing a free choice of parameters and locations and to find out which components of the observing system are the most important. Detailed objective includes (1) investigating the benefit of the different ocean observing system components for the initialization of decadal climate prediction systems, (2) quantifying the impact of the different observing system components in terms of decadal hindcast skill, and (3) identifying the necessary enhancements and potential reductions of the present observing systems. We investigated whether individual components can be reduced without losing the beneficial effects on the decadal predictive skill as well as potential needs that are not captured by the present ocean observing system in order to enhance decadal predictive skill.

WP 3.2 – Observed changes in the Arctic Ocean have highlighted the role of the Arctic in storage and release of liquid and solid freshwater pools to the North Atlantic on interannual to decadal scales. Redistribution of freshwater constitutes a control on the local air-sea heat exchange and with direct and indirect impact on the regional climate including modification of the Atlantic overturning circulation. Atmospheric tele-connections link Arctic sea-ice and snow cover with climate over the northern hemisphere. The goal in this

WP was to develop a broader understanding of the potential predictive skill associated with the initialization of the upper Arctic Ocean, also in order to focus and improve future monitoring systems. This included the development of a new and innovative ice surface temperature remote sensing product that improves the initialization of the Arctic region and to better constrains the heat fluxes associated with the interface. Improvement of model skill, climate and realism was to be achieved through novel developments of systems and techniques that allow systematic parameter optimization - an adjoint assimilation. This system will be trained using climate observations obtained over the Arctic sector. A secondary goal was to evaluate mechanism of the simulated transport variability after the assimilation with those based on observations.

WP 4.1 - Recent years have seen a rapid expansion in the ability of earth system models to describe and predict the state of the ocean: skilful forecasts ranging from seasonal (3 months) to decadal (5-10 years) time scales are now a reality. Such forecasts are potentially of great value in the management of living marine resources and for all of those that are dependent on the ocean for both nutrition and their livelihood. However, translating these forecasts of physical variables (e.g. temperature, salinity) into biological outcomes (e.g. fish distribution and catches) is neither automatic nor straightforward. In this WP we aimed to pioneer the development of so-called “Marine-Ecosystem Climate Services”, whereby the skill of physical forecasts is translated into biological forecasts. We employed three approaches to address this challenge. Firstly, we reviewed the state-of-the-art methods, tools and knowledge for prediction of ecosystem variables in the North Atlantic. We also considered the use of generic biological hypotheses as a basis for making such predictions. We then applied this knowledge to make biological predictions and assess the quality of these forecasts. In the process of this work, we also focused on identifying key gaps in the knowledge and potential areas for future research.

WP 4.2 - While cities occupy only a small fraction of the European continent, the majority of Europeans lives and works in cities. At the same time, urban agglomerations are particularly vulnerable to climate extremes, especially heat wave events. Therefore, it was of particular relevance to investigate the impact of large-scale climate (variability) on urban areas and their populations. The main goal of this WP was apply a deterministic urban climate model to three cities from different areas within Europe, with a rather direct exposure to North Atlantic climate influences (Almada – Portugal, Antwerp – Belgium and Berlin – Germany). This work was to be carried out in close co-operation with the local stakeholders and included a downscaling of the spatially coarse resolution CMIP5 climate predictions to the urban scale, with particular focus on regions where North Atlantic SST variability and changes have a significant influence on the climate. The topic was an investigation of the relation between heat waves and the urban-rural temperature increment, i.e. the urban heat island effect. In an extension of the work these physical parameters were then set into relation to relevant socio-economic data, focusing on health aspects, leading to spatially explicit vulnerability maps (population density, housing quality, age structure …) and heat risk maps.

4.1.3 A description of the main S&T results/foregrounds (not exceeding 25 pages)

WP 1.1 – Predictability of the North Atlantic/Arctic Ocean surface state and key oceanic quantities controlling it

The evaluation of sea surface temperature predictability in the Nordic Seas was based on hindcast prediction experiments with three coupled climate models. Domains of relatively high predictive skill appear to move northward along the flow path of Atlantic water, resulting in predictive skill well above the persistence forecast at lead times of five to ten years in the eastern part of the Nordic Seas (Figs. 1 and 2). This skill is linked to the poleward propagation of sea surface temperature anomalies, as indicated by historical simulations with the same coupled climate models. Comparing the Atlantic Water in the subpolar North Atlantic and the Nordic Seas in a high and a medium resolution version of the Norwegian Earth System Model suggests that the northward propagation of temperature and salinity anomalies into the Nordic Seas and the Arctic is, especially with respect to the advective time lag, more realistic in the high resolution version.

The predictability of upper-ocean salt content respectively freshwater content in the subpolar North Atlantic and the Nordic Seas was studied using hindcast prediction experiments with six coupled climate models. In the eastern subpolar North Atlantic, predictive skill of upper-ocean salt content of up to ten years is found. Domains of relatively high predictive skill appear to first move westward along the northern rim of the subpolar gyre and then northward into the Nordic and Barents Sea. Consequently, predictive skill well above the persistence forecast is found at lead times of five to ten years in the entire subpolar North Atlantic and the eastern part of the Nordic Seas. Whether this skill, similarly to what has been suggested for sea surface temperature, is related to the advection of subtropical water by the oceanic circulation is an interesting question to be investigated beyond NACLIM.

In both studies, though individual models show different predictability, our results are encouraging for assessing predictability and thus forecasts based on a multi-model ensemble mean. To understand the differences in predictability among models, an increased understanding of the mechanisms responsible for the predictability is inevitable.

Regarding the predictability of key oceanic quantities controlling the North Atlantic / Arctic Ocean surface state, the key results of this WP are:

The relation between Arctic sea ice decline and ice export through Fram Strait was studied based on historical simulations with six coupled climate models. For the model with the largest ensemble size, an increase of the ice export through Fram Strait similar to the estimated observed trend can explain almost 20% of the total simulated decline in Arctic sea ice. Arctic sea ice changes related to poleward ocean heat transport based on historical simulations with three coupled climate models: Increased heat transport in the Barents Sea Opening has first of all an influence on sea ice area in the Barents Sea in terms of reduced congelation growth, while bottom melting is important for the sea ice variability in the central Arctic Ocean.

The strength of the subpolar gyre of the North Atlantic and its zonal extension impacts strongly on the exchanges with the Nordic Seas and the Arctic Ocean across the Greenland-Scotland-Ridge. The predictability of this system has been explored based on hindcast prediction experiments with the Max Planck Institute for Meteorology coupled climate model. One focus has been on the strong weakening of the gyre in the mid-1990s. Our results suggest that this weakening could have been predicted using prediction experiments initialized with the ocean state from about year 1993 onwards. The predictability of this event is based on the ability to predict the mid-1990s warming of the subpolar North Atlantic and the related decrease in the doming of the subpolar isopycnals.

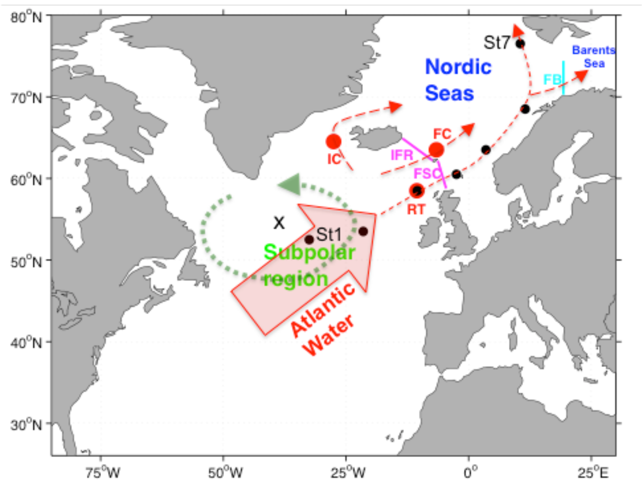

Figure 1: The map shows the key regions for this study; the warm Atlantic Water pathway via the Subpolar Gyre (green dashed curve), across the Greenland-Scotland Ridge, and along the eastern rim of the Nordic Seas. Seven stations (black circles) are located along the pathway (St1, St2,...St7), and are used to track northward propagation of hydrographic anomalies in the Atlantic Water.

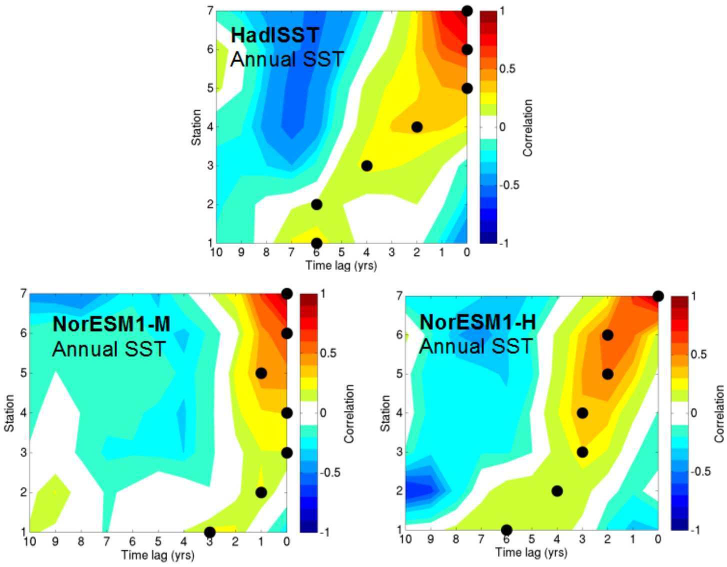

Figure 2: Cross-correlation of annual mean SST between the northernmost station and all seven stations (Fig. 1). Black circles mark the maximum positive correlation for each station. Time series are filtered by a 3-30 year Butterworth band-pass filter.

WP 1.2 – Predictability of the atmosphere related to the ocean's surface state

The investigation of how anomalies in ocean state affect the atmosphere was done with the aid of adjoint and statistical analysis. The PLASIM adjoint assimilation system was used to identify sensitivities of surface air temperature over northern Europe to predictable elements such as SST, SIC, or SSS. These sensitivities helped unravelling the processes leading to potential predictability. The idea of sensitivity analysis is based on the fact that the gradient of any function is directed towards the maximal increase of that function. Hence the sensitivity (or gradient) of the atmospheric state to an ocean state variables gives the corresponding spatial patterns that should have maximal impact on it. In order to verify whether the estimated sensitivities really have the expected impact on northern Europe SAT, these patterns were added to the corresponding model variables (SST, SSS, SIC), and their impacts on the atmosphere over northern Europe after one month were investigated. It was found that addition of SST sensitivity to SST field strengthens westerly winds and increases the heat transfer from the sea; warming northern Europe, while subtraction of SST sensitivity results in north-easterly wind anomalies and SAT cooling. The experiments with addition of SIC sensitivity to the corresponding field revealed weakly significant response of SAT while the addition SSS showed no statistically significant response.

The statistical analysis of observational data sets and reanalysis products has identified the main SST, SIC and snow cover anomaly patterns that affect the atmospheric circulation in the North Atlantic/European sector on seasonal to decadal time scale, and established their seasonality. It was found that during winter different SST and SIC anomaly patterns influence the NAO, the atmospheric mode that most influences the European Climate, which could be used in statistical climate forecasting. In particular, it was shown that the Atlantic Multidecadal Oscillation (AMO), the main mode of decadal climate variability in the North Atlantic Ocean, drives a negative phase of the North Atlantic Oscillation (NAO) during winter, and a SIC reduction in autumn in the northern Barents-Kara Seas precedes a negative NAO in winter (and cold winters in north-western Europe). The hemispheric influence of the observed variability of the Kuroshio and the Oyashio Extensions in the North Pacific was established, and its mechanisms established. In-depth analysis has shed light on the dominant processes that control the atmospheric response, and revealed an important role of the stratosphere-troposphere coupling.

The observational results have been compared to response studies with atmospheric general circulation models with prescribed boundary forcing and to similar statistical analysis using the state-of-the-art CMIP5 climate models. The results provide a benchmark for model testing that will be used in the next generation of climate models (CMIP6). The influence of Arctic amplification and sea ice retreat in global warming conditions on the Northern Hemisphere climate has also been investigated using both observational analysis and numerical experiments. As projected summer Arctic sea ice would disappear by mid-to-late 21st century, the atmospheric response during the autumn-winter to the projected autumn sea-ice free Arctic (September to November) has been simulated with a large ensemble of climate model simulations, showing both local and remote effects. The analysis and modelling work will be extended in other research projects such as Blue-Action, with further emphasis on the influence of Arctic sea ice on Northern Hemisphere climate and weather. The influence of the variability of the AMOC has also been extensively investigated in climate models, since sufficiently long AMOC observations are not available. The impact of the AMOC on the NAO has been detected in all the investigated climate models, with a negative phase of the NAO lagging AMOC intensification in most, but not all the models. Progress was made in establishing the main mechanisms of the AMOC impact, linking the response diversity to model biases, and in relating the AMOC impact to the observed and modelled atmospheric response to the Atlantic Multi-decadal Oscillation.

Observational analysis was conducted to better understand the role of SIC and SST in the development of Polar Lows (PLs) over the North Atlantic. A smaller Arctic SIC cover in September is associated with decreased tropospheric instability over the Nordic Seas in December and January, which is unfavourable to PL development, but the SIC decrease in January-February is associated with more favourable atmospheric conditions in March over the Barents Sea. The links between PL development and weather regimes was established, and the predicted evolution of weather regimes with climate change used to discuss PLs in a warmer climate. Because PL development would become less dependent on lower-atmospheric conditions, the importance of upper forcing, such as stratospheric intrusions, would be reinforced. As the relationship between the local and larger-scale circulation differs between present and future climates, a statistical downscaling based on the present-day climate may not be reliable under a warmer climate.

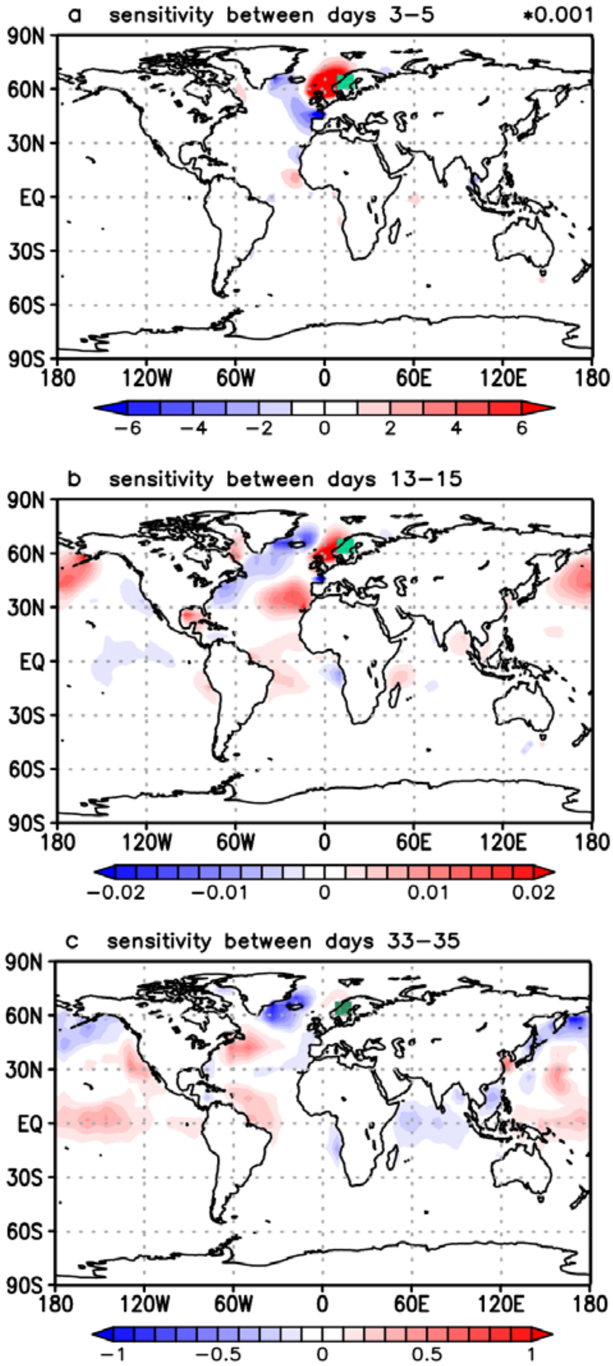

Figure 3: *(a) The 5-member ensemble mean of averaged sensitivity of the near land air temperature over Northern Europe to SST (between days 3-5) of backward integration. The air temperature is the mean over the last day. (b) The 5-member ensemble mean of averaged sensitivity of the near land air temperature over Northern Europe to SST (between days 13-15) of backward integration. The air temperature is the mean over the last day. (c) The 5 member-ensemble mean of averaged sensitivity of the near land air temperature over Northern Europe to SST (between days 33-35) of backward integration. The air temperature is the mean over the last day. The signal is normalized by the maximum value of the mean over day 33-35. The green square designates the target area.*

WP1.3 – Mechanisms of ocean surface state variability

Over the past 25 years the decline in the sea ice cover has accelerated over wide regions of the Arctic Ocean as revealed by the detection of a “breakpoint” in the time series of sea ice concentrations (SIC). Breakpoints are found in all seasons but are more ubiquitous in the summer season when they are found over a major portion (70%) of the Arctic Ocean. In summer, the timing of the acceleration of the decline of the Arctic sea ice cover is strongly regionally dependent, with a difference of up to 20 years between the various sub-regions. These regional contrasts can often be explained regional-scale mechanisms.

The dominant mode of Arctic sea ice variability in winter is often maintained to be represented by a quadrupole structure, comprising poles of one sign in the Okhotsk, Greenland and Barents Seas, and opposing sign in the Labrador and Bering Seas, forced by the North Atlantic Oscillation. We find that this quadrupole structure does not describe a significant covariance relationship amongst all four component poles but only explains covariability in the sea ice of the Barents, Greenland and Okhotsk Seas. This covariability is linked to the Siberian index, a regional sea level pressure index which controls the sea ice drift in the Kara-Barents Sea, rather than the North Atlantic Oscillation (NAO). The NAO, on the other hand, exhibits a significant relationship only with the winter Labrador Sea ice, which varies independently as the second mode of sea ice variability. In all modes, there exists a strong low-frequency signal which is not well resolved by the short satellite record. A study of the covariability of the weekly Arctic SIC and atmosphere in the North Atlantic sector over the period 1979-2007 revealed that interaction between the NAO and the Labrador Sea / Greenland-Barents Sea seesaw dominates in winter and spring. The seesaw, which is forced by the NAO was found to exert a negative feedback by driving a 6 week delayed NAO like response with opposite sign. Statistical significance increases when North Pacific SIC is included.

In the Atlantic sector of the Arctic, there are several regions where model simulations suggest an ocean control on the inter-annual variability of the sea ice margin. In the Barents Sea, the usual view of a sea ice margin controlled by the warm inflow of Atlantic water is not confirmed by our ocean simulations which rather highlight the predominance of wind-driven sea ice anomalies. Yet the ocean may be play a pivotal role in storing subsurface heat anomalies in response to the wind, which subsequently trigger, though a re-emergence process at the ice margin and enhanced air sea interaction, a positive feedback on the sea ice cover anomalies. This mechanism would provide some predictability to the sea ice anomalies in the northern Barents Sea. On the other hand, land snow cover anomalies over Eurasia were found to reinforce the back interaction of the atmosphere on the sea ice in the Barents and Kara Sea.

The ice ocean interaction identified in the Barents Sea may however be sensitive to the period considered. Ocean simulations suggest a different mode of variability of the Atlantic Water current before and after the mid-1990s, with a wider spatial coherence along the Atlantic water pathway across the Nordic Seas is found in the earlier period and is associated with the variability of the Norwegian slope current while a more regional mode of variability is found in the Barents Sea afterwards. However, recurrent signals of upper ocean variability have been identified in the Nordic Seas and subpolar North Atlantic in several CMIP models, which have been evaluated as potential constraints/drivers on the Arctic surface variability. In the Labrador Sea region, we also found some influence of the ocean on the sea ice cover: surface fresh water anomalies formed on the shelf off southeast Greenland and transported in the East Greenland Current have the potential to control the stratification and the sea ice thermodynamics in the northern Labrador Sea.

The outflow of freshwater from the Arctic Ocean was found to play a key role in setting the antiphase relation between the freshwater content of the Arctic and that of the subpolar North Atlantic. Investigation of the components of the freshwater balance in the subpolar gyre indeed revealed that, despite the exchange with the subtropical gyre and the surface freshwater flux are as important as the export from the Arctic; compensation exists between the anomalies of the first two components.

Active air-sea coupling was also identified in the North Atlantic in late fall-early winter, at the seasonal to decadal time scale. At the seasonal to inter-annual time scale, the East Atlantic (EA) pattern was found to be reinforced by summer NAO like geopotential anomalies responding to the SST dipole. The North Atlantic (NDJ) SST anomaly tripole, exerts a backward influence, which is significant for the SST anomaly leading by up to 9 months, onto the fall and early winter NAO. The influence, which mainly occurs via the extratropical component of the tripole, manifests as an anomalous warming in the subpolar region preceding a negative NAO-like pattern, a positive feedback which acts to amplify the SST variability. The same covariance analysis performed on low-passed filtered observations shows that the AMO influences the NAO, with some positive feedback between the ocean and the atmosphere. This suggests that the AMO-like SST anomalies may have some predictive value for the winter NAO.

Considering that the AMOC has a strong impact on the SST variability in the subpolar North Atlantic and that ocean temperature in this region shows a large persistence (leading to large predictability in the decadal forecasts), the impact of ocean-atmosphere feedback on the AMOC variability was investigated comparing coupled simulations with ocean-only simulations forced by the surface forcing fields retrieved from the coupled experiments. It was shown that the feedback is dependent on the resolution of the coupled simulations and possible links to the subpolar gyre variability are currently under analysis.

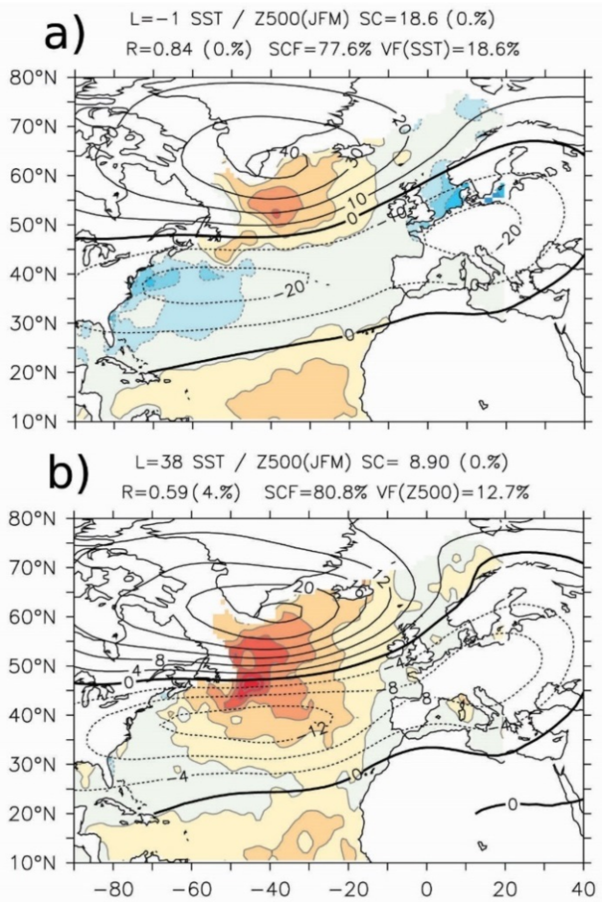

Figure 4: *Covariance map of low-pass filtered Z500 (contour in m) and SST (shading in K), when (a) the JFM atmosphere leads SST by 1 month. (b) the JFM atmosphere lags SST by 38 months. The SC, R, the associated significance, and the SCF (SC fraction) of the MCA modes are indicated at the top of each map*

WP 2.1 – Exchanges across the Greenland-Scotland-Ridge

The time series of Atlantic Water transports in the three inflowing branches have all been extended until mid-2015 or more. The estimates of the Faroe-Shetland Channel inflow and the Iceland-Faroe inflow are now based on a combination of in-situ measurements and satellite altimetry data and thereby the time series have been extended back to 1993 when the satellite observations were initiated. Thus the need for expensive in-situ measurements has decreased. The previous moorings have partly been replaced by less costly measurements making the monitoring of these branches more sustainable. The Iceland-inflow (Hornbanki section) measuring system on the other hand has been extended, using more in-situ deployments. Greatest progress in monitoring the inflow during NACLIM in terms of the Hornbanki array has been the addition of mooring HB4 which has improved the estimate considerably.

The Wyville Thomson Ridge overflow has previously been measured close to the Ridge, but in NACLIM the measurements were re-designed to take advantage of the added value of the Extended Ellett Line hydrographic time-series in collaboration with the OSNAP mooring array. A water mass analysis revealed a persistent core of deep overflow water within the Rockall Trough and the first transport estimates for overflow water in the Rockall Trough have been calculated. Although the flux is highly variable but the time series is too short to reveal any trend.

At the end of the NACLIM project period all of the inflow branches and the two most important overflow branches – accounting for ≈80 % of the total – have now been monitored for two decades. During this time the branches have varied with inter annual variations in volume transport on the order of 10 % for the total inflow as well as for the sum of the two main overflow branches. Neither the inflow nor the overflow has, however, shown any indications of weakened volume transports.

Although stable in volume transport, the exchanges across the Greenland-Scotland-Ridge have exhibited pronounced changes in properties of the water masses. From the mid-1990s to the early 2000s all the inflow branches warmed on the order of 1 °C; at the same time the salinity increased. This implies increased heat and salt transports towards the Arctic. For the strongest inflow branch, the Faroe Current, we estimated an increase of (18 ± 9) % for the heat transport (relative to 0 °C) from 1993 to 2013. For the overflow branches property changes are smaller and more difficult to monitor but for the Faroe Bank Channel overflow it has been possible to show a clear warming on the order of 0.1 °C from 2002 to 2013. This was accompanied by increasing salinities so that the density of the overflow water has remained stable; the warming of the overflow waters implies an increased heat transport from the upper ocean and atmosphere to the deep ocean on the order of 1 TW (10^{12} W).

In order to explore the sources of the Denmark Strait overflow a moored array was deployed north of the Denmark Strait from summer 2011 to summer 2012. The results have been analysed within NACLIM, where it was found that potential overflow waters are formed throughout the interior Iceland Sea in winter, but formation of the densest water masses that are transported by the North Icelandic Jet appears to take place only to a limited extent. It is also suggested that the supply of dense water to the deep North Icelandic Jet may have diminished over the past 20 years. Concurrent reductions in the turbulent heat fluxes and wind stress curl over the Iceland Sea are consistent with these findings and mixed-layer model simulations imply that further decreases in atmospheric forcing of the Iceland Sea may significantly impact the supply of the densest overflow waters to the AMOC.

In order to fill observational gaps the amount of Arctic freshwater that flows from the Nordic Seas into the North Atlantic Subpolar Gyre has been estimated. Within NACLIM observations were made of the flow on the shallow East Greenland Shelf. Through this effort time series of the freshwater flow on the shallow shelf were obtained, illustrating that there is a highly variable flow present on the shelf with events of strong northward flow in late summer/autumn. In general the flow was weaker from midwinter through summer.

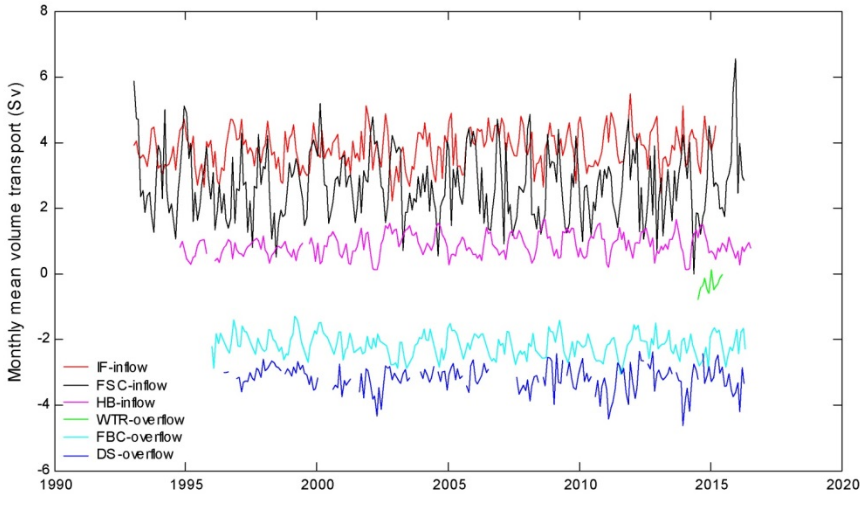

Figure 4: *Main inflow (reddish and black) and overflow (bluish and green) branches across the Greenland-Scotland Ridge. Positive transports are towards the Arctic. The time series are monthly means. The East Greenland Current freshwater transport is not shown. Abbreviations are: IF –Iceland-Faroe; FSC – Faroe-Shetland Channel; HB: Hornbanki; WTR: Wyville-Thomson Ridge; FBC: Faroe Bank Channel; DS: Denmark Strait.*

WP 2.2 – Transports in the subtropical and subpolar North Atlantic

The NACLIM project covered a period of substantial changes in the subpolar gyre. After a couple of years with a low North Atlantic Oscillation (NAO) index the last years were characterized by NAO high conditions, with deep convection activity. These fortunate circumstances enabled studies on the impact of NAO high on transport through key sections and related hydrography changes. In particular the Deep Western Boundary Current (DWBC) at the exit of the Labrador Sea (53°N array), the boundary current east and west of the Reykjanes Ridge (OSNAP moorings), and the inflow to the Nordic Seas (OSNAP; EEL line) provide important key metrics for model/observation comparisons. In NACLIM, but embedded in the OSNAP project, for the first time the temporal variability of the transport on the western side of the Reykjanes Ridge was recorded. Besides transport, another important metric for model/observations comparison that was evaluated was the maximum (winter) convection depth in the deep convection centres of the Labrador and Irminger Sea. In NACLIM a clear link between convection activity in the two areas was found and could be related to surface forcing as well as the exchange processes between the regions. A spreading from Labrador Sea Water into the Irminger Sea after deep convection was observed. For an analysis of the coherence between signals and the transformation in the deeper water masses the time series from moored sensors is mandatory.

One other important topic was the optimization of observing efforts in the SPNA. On the one side the project worked on closely link its efforts with other projects and programs in the area. A focus region was the Irminger Sea were since the beginning of the 2000's long term observing efforts from the Natherlands (LOCO) and from Germany, UK, Spain (CIS) have been established. Moreover, the Ocean Observing Initiative (OOI) installed in 2014 a complex mooring array and glider observatory in the region of the CIS mooring. The very dense observing in the Irminger Sea allowed evaluating and optimizing the observing efforts. Because this installation was done during a period of deep convection, the impact of such high spatial resolution could be investigated. The long-term, sustained observing efforts envisioned with the OOI infrastructure Irminger Sea operated successful during its first 2 deployment periods (2014/2015 and 2015/2016, now again in water). An immediate recommendation was to decommission the CIS mooring in summer 2018 (the fate of the LOCO mooring is to be decided). In contrast, the situation in the Labrador Sea is less clear – so far no comparable sustained observing effort is identified. Part of the K1 (GEOMAR; Germany) mooring shall be maintained, but including a closer collaboration with Canadian institutions.

The eastern boundary of the subpolar North Atlantic has been monitored by four glider missions supplementing an already existing (and on-going) annual ship-based time series dating back to 1975. Whilst the European Slope Current exhibits both inter-annual and seasonal variations in water properties, no significant seasonality has been found in transport estimates of the current. However, upper water transports between Scotland and Iceland do show seasonality with the lowest transports observed in the summer.

The conversion of the time series data into a CMOR 2 compatible format was investigated. All preparatory work was successful completed (conversion of time series data into CF2 netCDF compatible data) but the favourite (see proposal) CMOR 2 format Obs4MIPS seems not ready yet to take up the available time series data. The activity will be continued in the OceanSITES network, part of the Global Ocean Observing System (GOOS) observing networks, but also in other groups. The work on surface telemetry buoys for real time access to deep sea mooring data continued with moderate success. An air pressure sensor was implemented in a surface telemetry buoy and showed some potential for future routine observations of this important atmospheric variable.

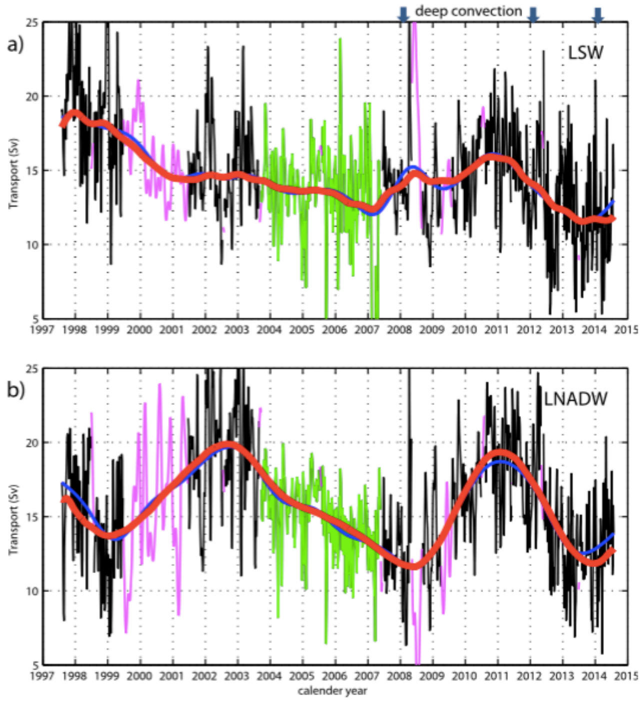

Figure 5: Export from the Labrador Sea at 5-day resolution and without gaps; LSW (a) with intense convection periods indicated, LNADW (b), which is al waters below 1850 m. black lines are for periods of full array coverage; green lines for periods with reduced coverage but with central mooring K9 in place, and magenta lines for gaps filled by SSA (EOF) modes. The low- frequency variation is dominated by a pair of SSA modes at quasi-decadal time scales.

WP 2.3 – Joint model – observational data comparison

The direct comparison of model and observational data focused on integral properties such as volume transports through straits and passages. We considered mean fluxes, seasonal and longer term variability and trends. The comparison showed that the average transport of most passages agrees well between observations and model. An exception are the Faroe-Shetland Inflow, where the modeled average transport is significantly higher than the observed one, and the Faroe-Bank Channel Overflow, where the modeled average transport is substantially lower than observed. The agreement of volume transport variability between the model and measurements is poor, only in some passages and on a few time scales there is some significant correlation. No significant trends are seen in model and observational time series.

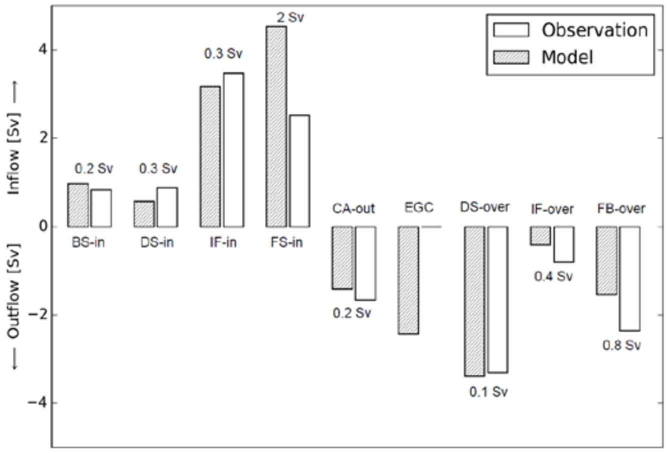

Figure 6: *Comparison of observed and modeled (Hamburg STORM model) in- and outflows of Arctic Mediterranean Ocean. The numbers on top or below the bars are the difference between model and observation.*

The large scale and regional budgets cover the whole of the North Atlantic and Arctic Ocean. The NACLIM core observation areas were in the North Atlantic subpolar gyre and along the Greenland-Scotland Ridge, separating the North Atlantic from the Arctic Mediterranean Sea (Fig. 7). This is where the waters of the lower limb of the Atlantic Meridional Overturning Circulation (AMOC) are formed as they sink into the deep to return southward, mainly in the Deep Western Boundary Current (DWBC). This core area was extended southward to the RAPID array located in the subtropical gyre at 26°N to capture the AMOC farther south, and northward into the Arctic Mediterranean Sea and the formation area of the densest water in the DWBC.

In the subtropical gyre the ocean circulation is mainly wind driven, whiles in the subpolar gyre the atmospheric influence, in addition to wind forcing, has a large thermodynamic component, changing the water mass characteristics and the density structure of the gyre. The importance of cooling and freshwater input increases in the Arctic Mediterranean Sea. Cooling and convection take place in the Nordic Seas, while a low salinity upper layer is maintained in the Arctic Ocean and in the western part of the Greenland and Iceland seas. Large inter-annual variability and a recent decline of the AMOC strength have been observed at the RAPID array. By contrast, both the northward flow across the Greenland-Scotland Ridge and the southward overflows have remained steady during the observation period. A warmer climate would reduce the cooling and the density in the Atlantic water, unless it is compensated by higher initial salinity. The increased northward atmospheric freshwater flux does not yet appear to affect the dense water formation in the Arctic Mediterranean, mainly because the low salinity upper layer is separated from the cooling areas in the Norwegian Sea and the Barents Sea. Sea ice drifting over and melting on the warm, saline Atlantic water might, however, create a fresh upper layer that prevents further cooling of the Atlantic core below the low salinity layer. The sea ice extent and volume are, however, presently declining and such ice drift is not likely to occur. The possibility is rather that not enough sea ice, formed elsewhere in the Arctic Ocean, drifts over the Atlantic layer. The formation of the low salinity upper layer in the Nansen Basin would then be reduced. Should this upper layer disappear, it could actually lead to more overflow water being produced.

When the NAO index is reduced, or changes to negative, the subpolar gyre contracts and becomes warmer, while the subtropical gyre expands into the northeast North Atlantic, bringing warmer water closer to the European continent. Surprisingly, the NAO- situation with warmer water in the northeastern North Atlantic leads to colder winters in northern Europe, suggesting that oceanic heat lost to the atmosphere remains at lower latitudes, and that cold Arctic air masses dominate northern Europe. This indicates that the transfer of water between the two gyres in the NAO+ phase takes place across the frontal zone in the North Atlantic Current, while in the NAO– situation the subtropical water joins the subpolar gyre at its eastern edge.

The two circulation patterns, with an extended and contracted subpolar gyre, also raise questions about the overturning circulation. With a contracted subpolar gyre the warm Atlantic water from the subtropical gyre extends much farther to the north, and it is likely that the direct recirculation in the subtropical gyre is weakened. More of the Atlantic water must be cooled and transferred into the lower limb of the AMOC, increasing the transport of the DWBC. This is the situation indicated in Figure 7, right panel. However, the situation with an extended subpolar gyre (Figure 7. left panel) is also one with strong cooling and convection and the formation of denser mode water in the Labrador Sea. These conditions were considered important for the strength of the AMOC, when the intense study of the Labrador Sea convection was carried out in the 1990s. However, it is possible that the created mode water in the NAO+ phase mainly increases the circulation in and extend the area of the subpolar gyre and only joins the DWBC when the subpolar gyre begin to contract and the, mainly wind forced, intrusion of the subtropical water to the northeast Atlantic has begun. No RAPID array was in the water during the positive NAO situation in the late 1980s and early 1990s and we have to wait for a change into a more strongly positive NAO situation and an expansion of the subpolar gyre to see if these speculations can be validated.

Once the Atlantic Water has entered the Arctic Mediterranean, the sustained heat loss will increase its density, transforming it into overflow water. In a warmer climate this cooling will be less severe and the overflow water less dense, unless it is compensated by a higher salinity of the Atlantic water. This is not seriously affecting the overflows, and the AMOC, as long as the water becomes denser. Problems arise with the increased meridional atmospheric freshwater flux that is expected in a warmer climate. This, as well as a smaller ice production, would increase the stability of the water column, and could, in an extreme situation, switch the direct overturning circulation into the reverse, estuarine circulation mode. However, this is not likely to happen in the near future.

The Atlantic Water moves northward, partly as a topographically steered barotropic current along the continental slope, and partly as a baroclinic current, following the front between the warm Atlantic water of the Norwegian Sea and the colder, denser Arctic intermediate water in the Greenland Sea, located above the Mohn-Knipovich Ridge. The low salinity upper layer of the Arctic Ocean, by contrast, is transported southward as buoyant boundary currents along the western side of Fram Strait and the passages in the Canadian Arctic Archipelago. The low salinity waters are confined within a Rossby radius from the coast and will be absent in the Norwegian Sea and not interact with the warm Atlantic inflow.

Sea ice acts differently. It is mainly driven by the wind and can drift over and melt on top of the Atlantic water in the Nordic Seas, as it presently happens in the Nansen Basin and in the northern Barents Sea. The sea ice area and volume are, however, diminishing, and this possibility becomes less likely. The reduction of sea ice in the Arctic Ocean is not primarily caused by the inflow of warmer Atlantic water, but due to changing radiation balances, especially the long-wave radiation balance caused by a warmer climate, which would transport more heat and water vapor northward in the atmosphere. Eventually, no export of latent heat (cold) as ice might be needed to balance the Arctic heat budget and only a seasonal ice cover will be present in the Arctic Mediterranean.

Reduced ice formation in the Arctic Mediterranean Sea might affect the conditions in the Nansen Basin and the production of overflow water in unexpected ways. The upper layer in the Nansen Basin, and likely also the upper layer in the northern Barents Sea, are created by sea ice melted by heat from the Atlantic water below. The melt water is mixed into the Atlantic water, creating an upper low salinity layer. If not enough ice is formed elsewhere in the Arctic Ocean and drifts over the Atlantic water in the Nansen Basin, the ice will disappear during winter and the buoyancy input due to ice melt stops. The upper layer becomes denser by cooling the entrained water, which might lead to convection into the underlying Atlantic layer. No upper Polar water will be created from the Fram Strait inflow, and the volume of overflow water would increase compared to the present day situation.

Not too much significance should perhaps be given to one year, but the ice cover, or the lack of it, this winter (2016-2017) with open water in late January both in the northern Barents Sea and in the Nansen Basin at the Barents Sea continental slope looks like a situation, when not enough freshwater is present in the upper layer to limit the entrainment of warm Atlantic water, which then prevents sea ice to form. Should the ice cover in the Nansen Basin and in the northern Barents Sea disappear in late winter, it will also increase the heat flux to the atmosphere. This in turn will affect the atmospheric circulation and induce changes that might influence the mid-latitude climate.

If, by contrast, more sea ice would be present, enough to drift over not only the Nansen Basin but also a part of the Norwegian Sea, the extent of the melt water layer above the Atlantic core could expand and reduce the heat loss to the atmosphere and stop the density increase in the Atlantic water. Such conditions may have been present during glacial periods. Sea ice drift over warm water, rather than increased freshwater input, could be the main process creating the low salinity upper layer that forces the overturning circulation to change from the thermal to the salinity dominated estuarine mode.

If the amount of Atlantic water arriving from the south remains constant, but the production of overflow water decreases, more water is returning in the upper layer. Such an overflow reduction has not yet been documented, but should it happen, the convection in the Labrador Sea must eventually transfer the low salinity surface water, including the polar outflow, into the deep. This implies that if the northward flow into the Arctic Mediterranean Sea remains constant, the overflow could diminish and the polar outflow increase. After the interactions between the East Greenland Current and the Irminger Current along the eastern Greenland slope and the convection in the Labrador Sea and Irminger Sea the Polar water will be mixed into the subpolar mode water and as the DWBC moves towards the RAPID array, the denser overflow water transport would be smaller, while the volume of the less dense deep water from the Labrador Sea remains the same or increases, while its density probably decreases.

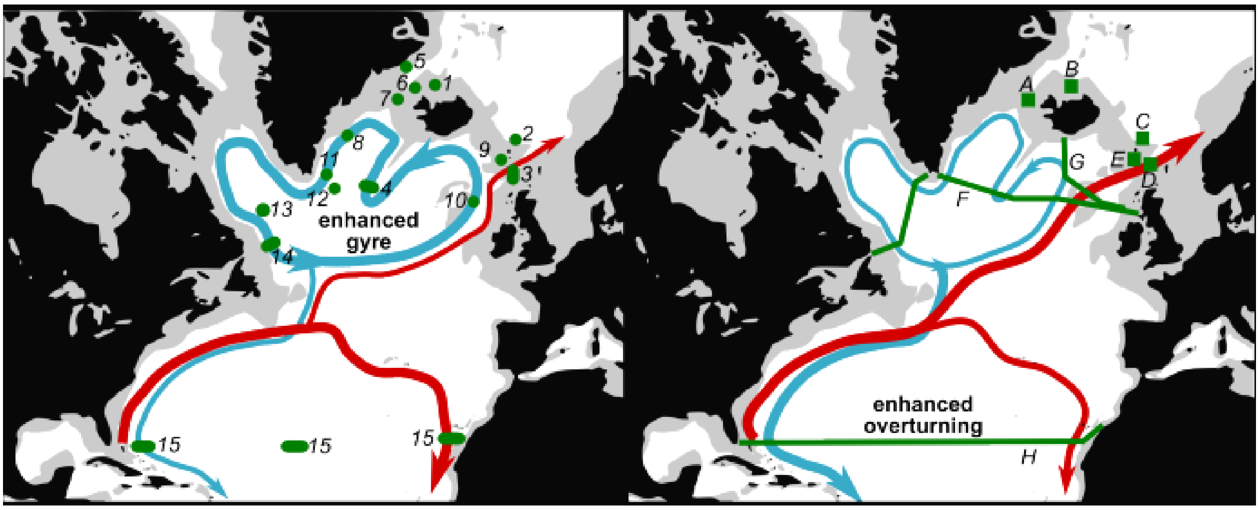

Figure 7. *The subtropical and subpolar gyres as indicated here follows the hypothesis that strong and deep convection in the Labrador Sea leads to an expanded subpolar gyre but a weaker overturning circulation (left panel), while the contracted subpolar gyre allows more subtropical water towards the north, reducing the circulation in the subtropical gyre and increasing the overturning circulation (right panel).*

The left panel shows the NACLIM Mooring arrays. 1: N. of Iceland. Volume and heat fluxes associated with North Icelandic Irminger Current. 2: N. of the Faroes. Volume and heat fluxes associated with the Faroe Current. 3: Faroe Shetland Channel. Volume, heat and salt fluxes associated with flow between Scotland and Faroe Islands. 4: W. flank of Reykjanes Ridge. Volume, heat and salt fluxes associated with the Irminger Current. 5: E. Greenland Shelf. Volume and freshwater flux associated with East Greenland Current. 6: N. of the Denmark Strait. Volume flux and properties of North Icelandic Jet. 7: Denmark Strait. Volume transport associated with Denmark Strait Overflow Water. 8: W. boundary of Irminger Sea. Volume, heat and salt fluxes of Denmark Strait Overflow Water. 9: Faroe Bank Channel. Volume flux associated with Faroe Bank Channel Overflow Water. 10: Wyville Thomson Ridge. Volume flux associated with Wyville Thomson Ridge Overflow Water. 11: Central Irminger Sea. Temperature, salinity, currents and chemical parameters in deep convection area. 12: Central Irminger Sea. Temperature, salinity and currents in deep convection area. 13: Central Labrador Sea. Temperature, salinity and currents in deep convection area. 14: 53°N array W. boundary Labrador Sea. Volume transport of various water masses (alongshore). 15: 26.5°N array. Volume, heat and salt fluxes.

The right panel shows the NACLIM repeated sections. A: Denmark Strait, B: North Icelandic Shelf. C: North of Faroe Islands. D: Faroe Shetland Channel (two lines). E: Faroe Bank Channel. F: Canada to Greenland to Scotland. G: Scotland to Iceland (EEL). H: the 26.5°N section.

WP 3.1 – Suitability of the ocean observing system components for initialization

We have assessed ensembles of hindcast experiments to identify potential observational needs and make recommendations on the future ocean observing system. Importantly two ensembles have been used. First, we have performed an ensemble of global warming simulations with the KCM, in which the model is forced by increasing carbon dioxide consistent with the trend observed during the last decades. Each ensemble member starts from different ocean and/or atmosphere initial conditions to investigate the influences of long-term internal variability on projected centennial trends, specifically the role of ocean observations in the initialization. Second, we have simulated two extended-range integrations of the KCM, one with application of surface salinity restoring in the North Atlantic, and the other without the restoring. Comparison of the two experiments provides an indication of the usefulness of surface salinity observations in improving models and enhancing predictions.

Two very important findings from the simulations and analyses lead to recommendations on further needs in the current ocean observing system.First, hindcast experiments with different ocean and/or atmosphere initial conditions suggest that excellent knowledge of ocean initial conditions is crucial in projecting future climate. This is illustrated by ocean diagnostics such as the AMOC strength and regional distribution of dynamic sea level (DSL), the deviation from the global average. Detailed investigations refined the regions where enhanced ocean observations are needed. More observations in the Southern Ocean and the North Atlantic are important to enhance decadal predictions and global change projections. In particular, deep ocean observations, particularly below 2000 m, should be enhanced as current ocean observations mainly cover the upper ocean.

Second, dedicated simulations with corrected salinity suggest that salinity observations are very important to better represent the mean ocean circulation and its variability in climate models. Ocean salinity is a key indicator of the water cycle between the atmosphere and ocean and important in determining the oceanic general circulation. The results suggest that surface salinity information, particularly over the North Atlantic, can greatly improve mean climate and decadal climate variability, which may enhance the skill of decadal predictions in that region. We argue that surface salinity observations, e.g. by satellites, should be enhanced.

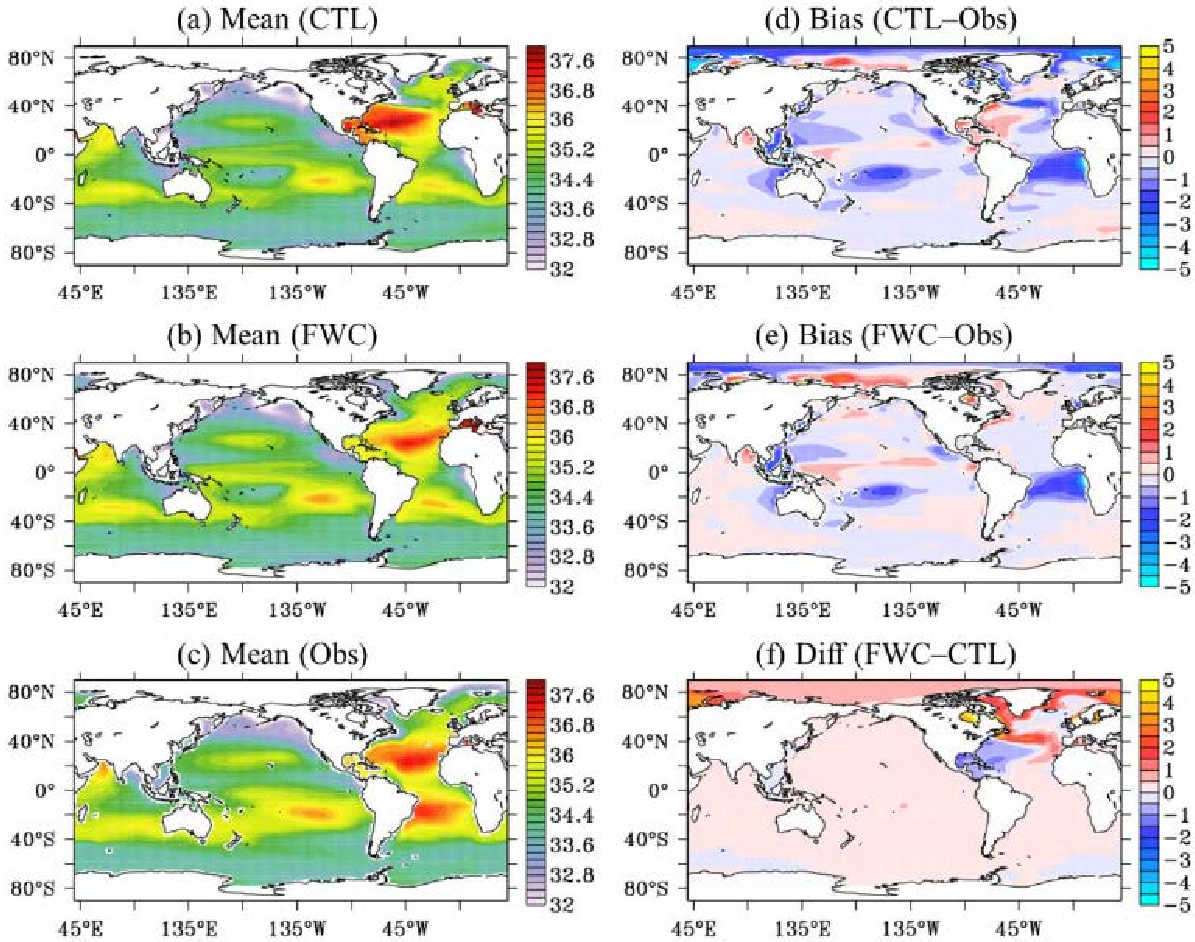

Figure 8: *Long-term annual-mean SSS (psu) in (a) the control run, (b) the freshwater flux-corrected integration, and (c) from Levitus climatology. SSS biases (psu) are depicted in (d) for the control run, (e) the freshwater flux-corrected integration, (f) depicts the difference in SSS between the two integrations.*

WP 3.2 – Impact of Arctic initialization on forecast skill

The northern limb of the ocean thermohaline circulation and its transport of heat towards the Arctic strongly affect the climate. The presence of warm surface waters prevents ice formation in parts of the Arctic Mediterranean and ocean heat is in critical regions directly available for sea-ice melt. By this process, ocean heat transport plays a disproportionally strong role in the climate system and realistic simulation is a requisite for reliable climate projections. Across the Greenland-Scotland Ridge this occurs in three well defined branches where anomalies in the warm Atlantic inflow across the shallow Iceland-Faroe Ridge have been shown particularly difficult to simulate in global ocean models. This branch (IF-inflow) carries about half of the total ocean heat transport into the Arctic Mediterranean and is well constrained by observations during the last two decades, but is associated with significant inter-annual fluctuations. The inconsistency between model results and observational data is explained by the inability of coarse resolution models to simulate the overflow across the IFR (IF-overflow) so that the simulated IF-inflow is in fact the net exchange across the IFR. Implications include a biased ocean heat transport towards the Arctic in the climate model.

The goal of implementing alternative assimilation schemes into the CESAM model was to overcome the limitations of the model due to its chaotic dynamics and related to transitions in parameterizations, to ultimately optimize the climate of the model and to improve its realism. By assimilating transport time series observed during the NACLIM project the associated changes in the simulation of the circulation can be revealed. As the realism of the underlying mechanism is a prerequisite to a realistic description of simulated circulation changes, the goal was to evaluate mechanism of the simulated transport variability after the assimilation with those based on observations.

As a first step, a stochastic method (Simultaneous Perturbation Stochastic Approximation SPSA) method was implemented and results were compared with the standard adjoint technique build into CESAM. This was done first in so called identical twin configurations in which synthetic data generated by the model itself were assimilated to retrieve model parameter that were perturbed prior to assimilation. Second, realistic data from the ERA interim reanalysis were assimilated and parameters estimated to reduce the disagreement of the model climate with the observed climate. Additionally, a recent variant of the adjoint method that is able to cope with the chaotic nature of the model was implemented and the suitability for parameter estimation was tested. The influence of observational errors on the parameter estimation was investigated. In an ocean only set up of the model, the impact of assimilating transport time series on the circulation was investigated. A focus of this study was an evaluation of the processes of transport variability in the model after assimilation of transports with those from the observations.

To study the effect of improved surface boundary conditions on the forecast skill, a new climate record of Sea and Ice surface temperatures were created. The Arctic and Antarctic Ice Surface Temperatures from thermal Infrared satellite sensors (AASTI), cover high latitude Seas, Sea Ice and Ice Cap surface temperatures based on satellite infrared measurements. The purposes of this integrated surface temperature data set was; to establish a data set with optimal data consistency to minimize temporal and spatial biases and, to create a climate record that enables studies of both large scale climate properties and that at the same time can resolve high resolution temporal and spatial variability's. AASTI is a supplement to existing data sets, with lower resolution, but with longer temporal coverage.

Seasonal to decadal forecast skill relies on the ability to initialize model systems with observations representing the slowly varying components of the earth system. A critical point is the uncertainty of available observations and their distribution in time and space. Methods to explore the potential impact of the constraints that exists on data include idealized predictive experiments in ensemble mode where model data are sub-sampled to represent observations or observational networks. Sparsity of ocean observations in the Arctic projects on the uncertainty of ocean syntheses and will limit the predictive skill of assimilated or initialized systems. In NACLIM we have employed the idealized or perfect model approach in combination with data withholding ensemble prediction experiments to identify the importance of Arctic observations. We show using this approach that liquid freshwater in the Arctic Ocean is predictable up to six years ahead. The skill is not spatially uniform and skill is confined to certain areas of the Arctic Ocean. Variability in liquid freshwater is found to be affected by a clockwise propagating mode with a multi decadal time-scale that also modulates the export of both liquid freshwater and sea ice from the Arctic. Extreme freshwater exchanges with the Arctic have a limited but detectable effect on the Atlantic surface state for a few years. It is shown that Air-sea coupling is prominent during such events. In the course of the year alternating phases, where the ocean leads the atmosphere and where the atmosphere leads the ocean can be identified.

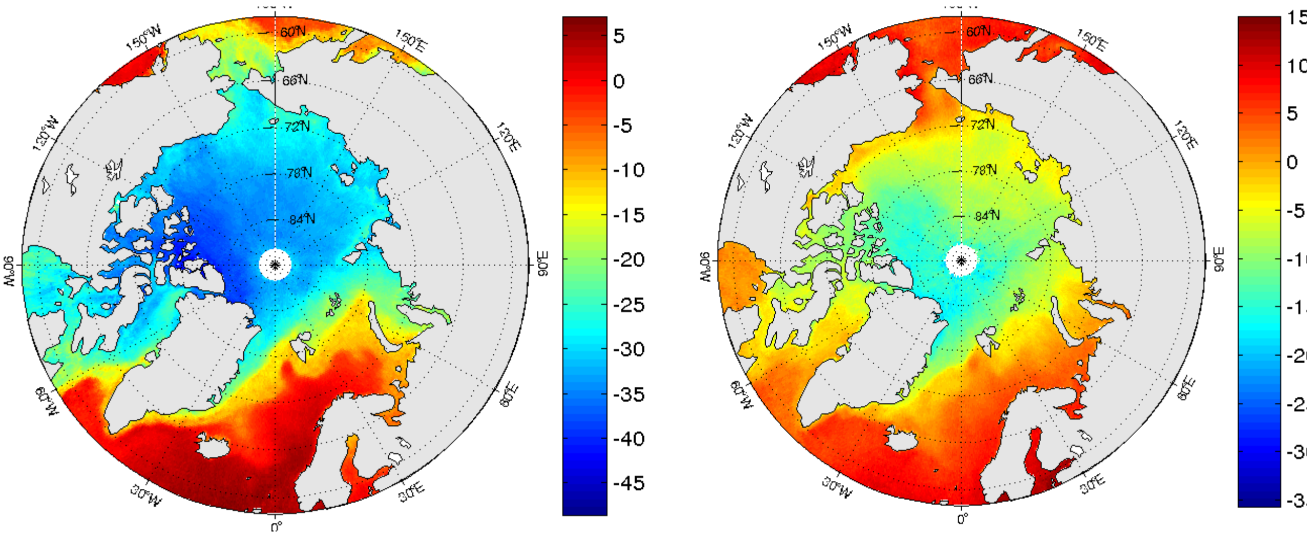

Figure 9: *Monthly minimum-mean temperature maps for March (left) and September (right), 2007, based on the new climatology of Sea and ice surface temperatures. .*

WP 4.1 – Impact on oceanic ecosystems

We examined the opportunities for forecasting marine ecosystems, and thereby the potential to develop marine ecological climate services. Such services could, in principle, play important roles in managing and exploiting living marine resources in a sustainable and economically efficient manner. The work package addressed this problem by reviewing the state-of-the-art, and then applying existing knowledge to make biological predictions and assess the quality of these predictions.

The newfound predictive skill of the physical and biogeochemical components of the ocean system represents a tremendous opportunity for society. The high variability of living marine resources is widely recognized as arising, at least partially and often largely, from their interaction with the physical environment. In total, we considered twelve different case studies from a wide variety of systems. Species considered range across all trophic levels, from plankton groups, through both small fish and large fish to seabirds and top predators such as pilot whales. We also considered a wide range of biological responses, including the distribution of organisms, their productivity and the timing of key events in their life cycle e.g. migrations. Some of the most promising results obtained were for the prediction of spatial distributions. We demonstrated the first known examples of decadal-scale predictive skill of biological variables for the availability of suitable habitat for Bluefin Tuna and the spatial distribution of suitable spawning habitat for blue whiting. In both of these cases, meaningful forecast skill was shown up to a decade into the future. These results are expected to be highly important in furthering this field.

In other cases, important negative results were reported. In particular, we have been able to reject the well-known match-mismatch hypothesis, that states that recruitment of fish stocks is driven by the match (or mismatch) in timing between the spring bloom and spawning: while we show that this mechanism is important in structuring the average timing of spawning of fish species, it appears to have little predictive skill at the interannual scale. Similarly, we demonstrated the poor predictive skill of species distribution models for plankton (a novel and important result for projecting climate change impacts on the ocean). We also documented the role of physical variables in shaping the distribution of plankton species and trait distributions in the ocean: however, while these important results have good explanatory power, their predictive potential appears limited.

A third set of case studies highlighted mechanisms that could potentially form the basis for developing predictive schemes in the future. In particular, promising results were revealed around the highly variable deep winter mixing and associated nutrient enrichment of the subarctic waters. This mechanism can drive predictive potential for the distribution of Mackerel, the productivity of seabirds, and productivity of shelf ecosystems adjacent to the North Atlantic. Qualitative predictive schemes for these variables have been proposed based on cause-effect understanding and the lead-times inherent in the system, and have been shown to possess some skill.

Finally, the remaining case studies showed little predictive potential. In particular, our results examining the prediction potential of fish stock recruitment appeared to be particularly poor: this is a well-known problem in marine science and arises due to a lack of knowledge and sampling of key processes affecting mortality rates associated with the early life stages of marine fish. Catches of pilot whales also showed little predictability, and may be driven by biotic and anthropogenic factors that cannot readily be assessed here.

Lessons learned in the project have also been collated and summarised in a form that can be readily picked up by other researchers. In particular, we highlighted the need to bridge the gaps between marine ecology and climatology on the one-hand, and between science and end-users on the other. Improved access to forecast products is also seen as important, as is the need to further improve biological models and understanding.

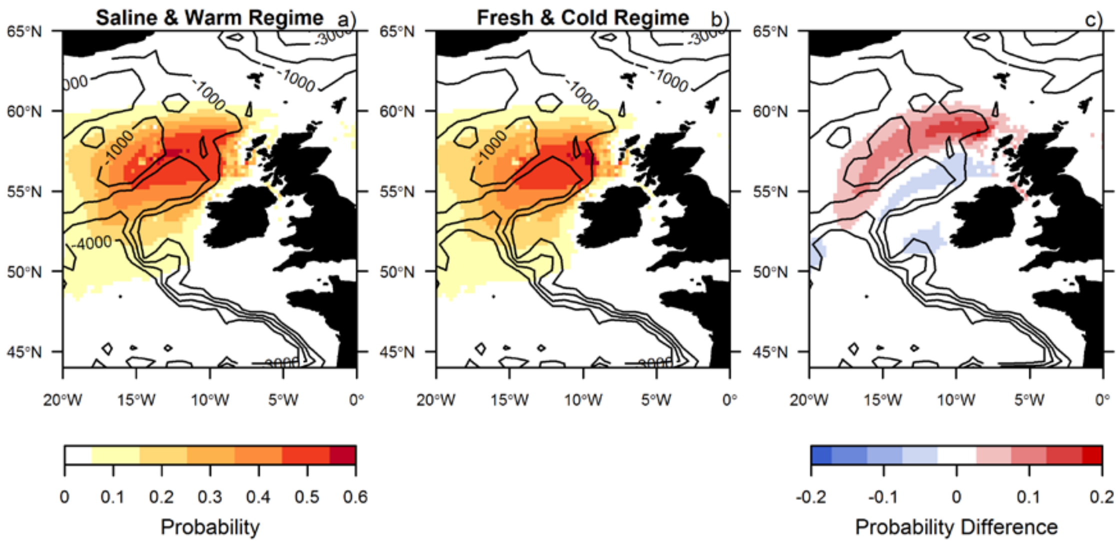

Figure 10: *Map of predicted larval-presence probabilities as a proxy for blue whiting spawning distributions produced by the SDM during the fresh and cold a), and saline and warm b) regime in April (1951-2016), and the probability difference between the two regimes c). The probability difference was calculated by subtracting the larval-presence probability (p) encountered during the saline & warm regime by p during fresh & cold regime. Accordingly, positive values (red) indicate a higher p during a saline & warm regime compared to the fresh & cold regime.*

WP 4.2 – Impact on urban societies

Cities occupy only a small fraction of the European continent, but the majority of Europeans lives and works in cities. At the same time, urban agglomerations are particularly vulnerable to climate extremes such as heat waves and flooding. We investigated the effect of predicted climate on human exposure to heat stress in cities, the central tool in this exercise being VITO's urban climate model (UrbClim). The first step of the work consisted of the selection of three user cities on which to implement urban downscaling. We selected the cities of Almada (PT), Antwerp (BE) and Berlin (DE) as study cases, which represent a diverse sample in terms of geography, size, and climate zones.

Initially we focused on the generation of urban morphological parameter maps, required as input for UrbClim. Based on fine-scale 3-D cadastral maps, provided by the user cities, we estimated certain urban morphological parameters such as the sky view factor, and planar and frontal area indices. Moreover, relations were established between the obtained parameter values, and imperviousness fractions contained in the 'Degree of Soil Sealing' digital raster map, which is distributed by the EEA, covering Europe at 100-m resolution. Robust statistical relations were obtained between the urban morphological parameters and the degree of soil sealing, thus yielding a new method for mapping of these morphological parameters for any European city.

Since the UrbClim model developed by VITO was going to be used to downscale CMIP5 global climate projections to the three user cities (see below), we first conducted a model validation, evaluating the model's capability to correctly reproduce observed temperature. To do so, UrbClim was configured for the three cities, using generic terrain and climatic forcing as inputs, and using the morphological parameters described above. Simulated air temperature was then compared to in-situ data. In particular, it was found that UrbClim is capable to correctly reproduce the observed urban heat island (UHI) intensity, i.e., the urban-rural temperature difference (Figure 11). Indeed, error statistics for this quantity showed, rather consistently among the three cities, a negligible bias, a root mean square error of approximately 1°C, and a correlation coefficient of around 0.7.

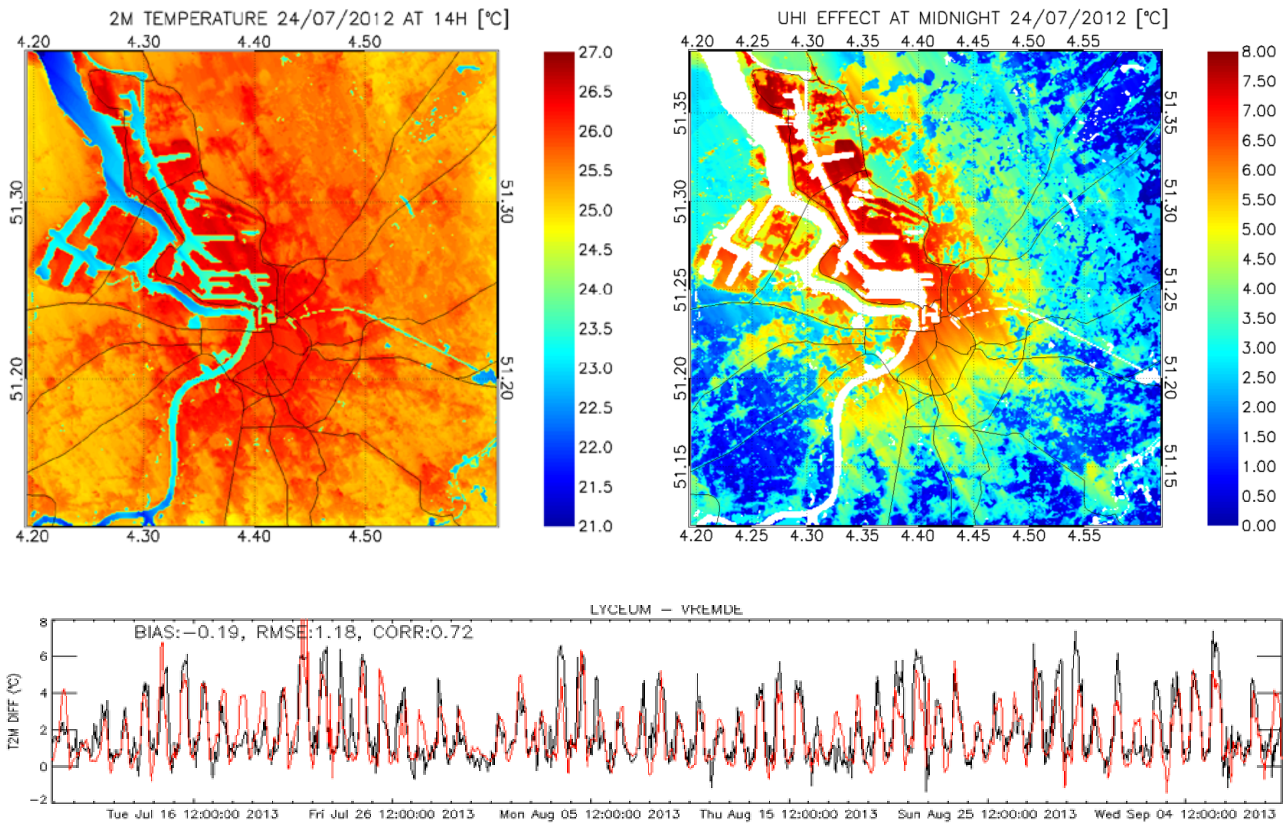

Figure 11: *(top) simulated 2-m air temperature at 14h (left) and the Urban Heat Island anomaly at midnight (right) on 24th of July 2012. (bottom) Simulated (red) versus observed (black) 2-m urban-rural temperature difference for Antwerp, July-September 2013.*

Subsequently, UrbClim was used to generate projections of present and future urban climate for the three target cities, which was based on running the model for 20-year periods, and considering a forcing by an ensemble of Global Climate Models. The hourly simulation results, which consumed nearly 15 years of computer time and many Terabytes of data, were aggregated to yield representative heat stress indicators for current and future climate conditions, including the annual average number of heat wave days (which was based on a definition involving thresholds for daily minimum and maximum temperatures).

The results suggest that, towards the end of this century, cities will be groaning under the strain of severely increased levels of heat stress. Indeed, the urban climate projection simulations show that the number of heat wave days in cities increases by nearly a factor ten, from the current value of a few per year, towards several tens per year at the end of the century. Apart from these future climate projection estimates, we also ran scenario simulations to evaluate the effect of certain adaptation measures such as enhanced green areas.

As a final step, we combined the urban climate projections with socio-economic data, including spatial data regarding population density, the share of elderly people, and the density of nursing and rest homes. This resulted in dedicated heat stress exposure maps for various future time horizons, climate scenarios, and local climate adaptation scenarios (e.g., involving urban green space). In addition, we also developed a new method to map daytime heat stress at a very high resolution, including a detailed visualization of the effects of vegetation as an adaptation measure. From that exercise it emerged that urban green does have the potential to generate a strong impact, yet mostly very locally.

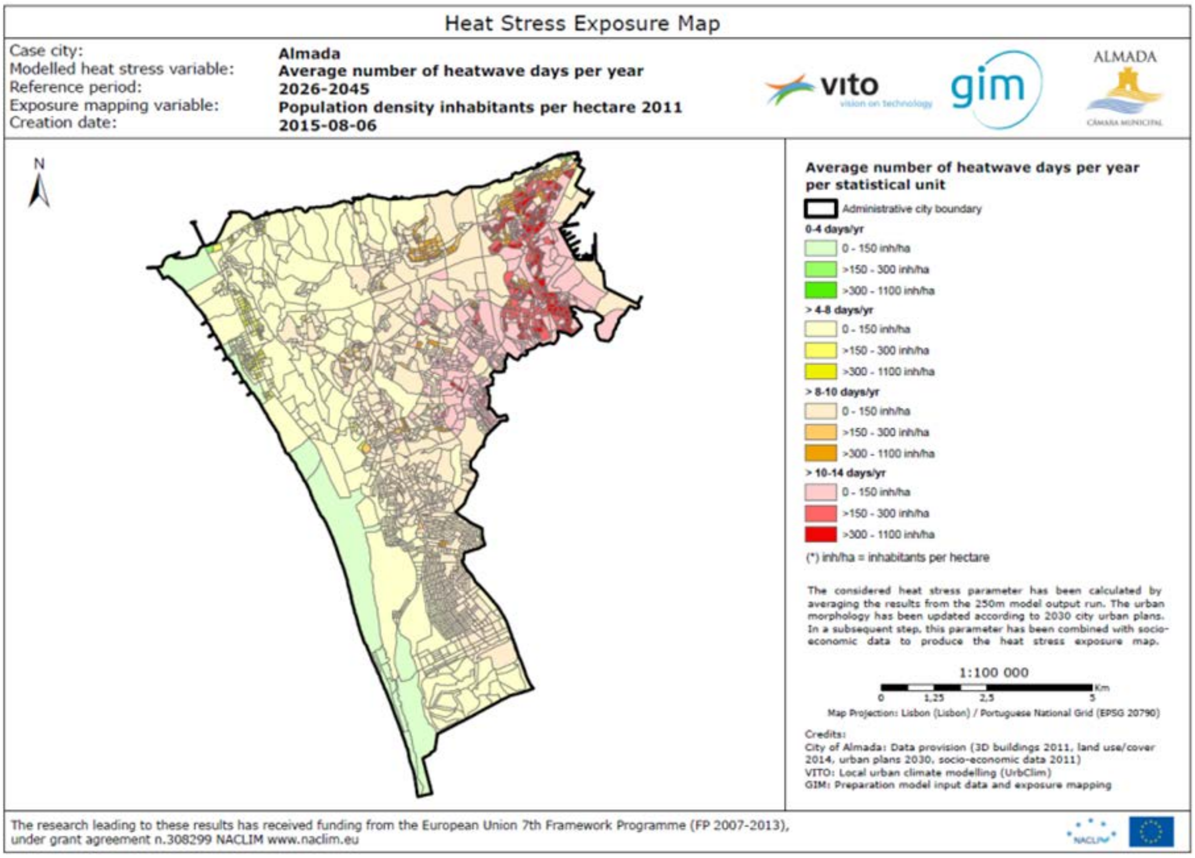

Figure 12: *Almada population density overlaid with annual number of heatwave days, 2026-2045.*

Addendum to the NACLIM Project Final Report
- concerning D21.59, as of 12.06.2017 -

One of the overarching goals of NACLIM was *"to optimize the present North Atlantic observation system by evaluating the impact of its components on the quality and quality control of model forecasts, and their value in determining the present ocean state and its past variability".* This goal was tackled in most of the NACLIM work packages, but most notably in WPs 2.1, 2.2, 3.1 and 3.2.

WP 2.1 – Exchanges across the Greenland-Scotland Ridge
The inflow of warm Atlantic Water across the ridge is the major heat source for the Arctic Mediterranean and its overlying atmosphere. During the past decades the volume flux of this inflow has been monitored by several arrays of current meter moorings, while the temperature distribution was captured only on a seasonal time scale with synoptic ship surveys. To reduce the costs for the expensive mooring arrays and to improve the time resolution of the temperature measurements, colleagues from the Faroese Marine Research Institute designed a new system fulfilling these goals. Bottom temperature recorders that operate for 5 years or more and that can be interrogated acoustically provide information on the vertical location of the interface between the cold deep water and the warm upper layer Atlantic water. From this the baroclinic current structure can be obtained. The barotropic part of the flow is determined from the slope of the sea surface, derived from satellite altimeter data. Only a few of the traditional current profiler moorings serve as check for these estimates and allow to estimate possible non-geostrophic contributions. So far two of the arrays, the ones near the Faroe Islands, have been partly modified this way.

Hansen, B., Larsen, K. M. H., Hátún, H., Kristiansen, R., Mortensen, E., and Østerhus, S. (2015): Increasing transports of volume, heat, and salt towards the Arctic in the Faroe Current 1993–2013, Ocean Sci. Discuss., 12, 1013-1050, DOI: 10.5194/osd-12-1013-2015.

Mortensen, E., K. M. H. Larsen, B. Hansen, R. Kristiansen and S. Østerhus (2016) NACLIM ADCP Deployments in Faroese Waters 2015 – 2016, HAVSTOVAN NR.: 16-03, TECHNICAL REPORT

Berx, B., B. Hansen, S. Østerhus, K. M. Larsen, T. Sherwin, and K. Jochumsen (2013): Combining in-situ measurements and altimetry to estimate volume, heat and salt transport variability through the Faroe Shetland Channel. Ocean Science, 9, 639-654, doi:10.5194/os-9-639-2013

In contrast to the Faroe-Bank Channel overflow the cold water fluxes in Denmark Strait are located only on the north-western flank of the channel. Water mass analysis also shows that the dense water contributing to the lower limb of the AMOC can also be found on the East Greenland Shelf. In a one-year process experiment carried out by the University of Hamburg six current meter moorings instead of the usual 1 – 2 instrument were deployed in the deep trough and the adjacent shelf region. This array provided the basis for new calculations to estimate the DSOW transports. Furthermore, a correction was proposed for biases detected on some ADCPs, which led to earlier underestimation of the flow in the lower part of the plume. Using the new method, the mean DSOW transport is estimated to be 3.2 Sv in the period 1996–2016, without a significant trend. Uncertainties are typically 0.5 Sv. Beyond variations on the eddy scale, an empirical orthogonal functions analysis of the velocity field reveals three dominant modes of variability: the first mode is roughly barotropic and corresponds to pulsations of the plume, the second mode represents the laterally shifting component of the plume's core position, and the third mode indicates the impact of the varying overflow thickness.

Jochumsen, K., M. Moritz, N. Nunes, D. Quadfasel, K. M. H. Larsen, B. Hansen, H. Valdimarsson, and S. Jonsson (2017), Revised transport estimates of the Denmark Strait overflow, J. Geophys. Res. Oceans, 122, 3434–3450, doi:10.1002/2017JC012803.

WP 2.2 – Transports in the subpolar North Atlantic
One topic in this work package was the optimization of observing efforts in the Sub Polar North Atlantic. On one side the project worked on closely linked efforts with other projects and programs in the area. A focus region was the Irminger Sea, where in the beginning of the 2000s long-term observing efforts from the

Netherlands (LOCO) and from Germany, UK, Spain (CIS) had been established. Moreover, the Ocean Observing Initiative (OOI) installed in 2014 a complex mooring array and glider observatory in the region of the CIS mooring. The very dense observing array in the Irminger Sea allowed evaluating and optimizing the observing efforts. Because this installation was done during a period of deep convection, the impact of such high spatial resolution could be investigated and the representativity of a single mooring. The long-term sustained observing efforts envisioned with the OOI infrastructure in the Irminger Sea operated successfully during its first 2 deployment periods (2014/2015 and 2015/2016, now again in the water). An immediate recommendation was to decommission the CIS mooring in summer 2018 (the fate of the LOCO mooring is to be decided).

Lozier, M.S., Bacon, S., Bower, A.S., Cunningham, S.A., de Jong, M.F., de Steur, L., deYoung,B. , Fischer, J., Gary ,S.F., Greenan, B.J.W., Heimbach, P., Holliday, N.P., Houpert, L., Inall, M.E., Johns, W.E., Johnson, H.L., Karstensen, J., Li,F., Lin, X., Mackay, N., Marshall, D.P., Mercier, H., Myers, P.G., Pickart, R.S., Pillar, H.R., Straneo, F., Thierry, V., Weller, R.A., Williams, R.G., Wilson, C., Yang, J., Zhao, J., Zika, J.D. (2016). Overturning in the Subpolar North Atlantic Program: a new international ocean observing system. Bull. Am. Met. Society (BAMS) Online: 23 Aug 2016. AMS. DOI: 10.1175/BAMS-D-16-0057.1

WP 3.1 – Suitability of the ocean observing system components for initialisation

In this work package we investigated the benefit of the different ocean observing system components for the initialization of decadal climate prediction systems, we quantified the impact of the different observing system components in terms of decadal hindcast skill, and identified the necessary enhancements and potential reductions of the present observing systems. Two very important findings from the simulations and analyses lead to recommendations on further needs in the current ocean observing system. Hindcast experiments with different ocean and/or atmosphere initial conditions suggest that excellent knowledge of ocean initial conditions is crucial in projecting future climate. This is illustrated by ocean diagnostics such as the AMOC strength and regional distribution of dynamic sea level, the deviation from the global average. Detailed investigations refined the regions where enhanced ocean observations are needed. More observations in the Southern Ocean and the North Atlantic are important to enhance decadal predictions and global change projections. In particular, deep ocean observations below 2000 m should be enhanced as current ocean observations mainly cover the upper ocean. Secondly, dedicated simulations with corrected salinity suggest that salinity observations are very important to better represent the mean ocean circulation and its variability in climate models. Ocean salinity is a key indicator of the water cycle between the atmosphere and ocean and important in determining the oceanic general circulation. The results suggest that surface salinity information, particularly over the North Atlantic, can greatly improve mean climate and decadal climate variability, which may enhance the skill of decadal predictions in that region. We argue that surface salinity observations, e.g. by satellites, should be enhanced.

Park, T., Park, W., and Latif, M. (2016). Correcting North Atlantic sea surface salinity biases in the Kiel Climate Model: influences on ocean circulation and Atlantic Multidecadal Variability. Climate Dynamics, Springer. DOI: 10.1007/s00382-016-2982-1

WP 3.2 – Impact on Arctic initialisation on forecast skill

Observed changes in the Arctic Ocean highlighted the role of the Arctic in storage and release of liquid and solid freshwater pools to the North Atlantic on inter-annual to decadal scales. Redistribution of freshwater constitutes a control on the local air-sea heat exchange and with direct and indirect impact on the regional climate including modification of the Atlantic overturning circulation. In this work package we showed that seasonal to decadal forecast skill relies heavily on the ability to initialize the model systems with observations representing the slowly varying components of the earth system in the Arctic Ocean. A critical point is the low number of available observations and their inhomogeneous distribution in time and space. Methods to explore the potential impact of the constraints that exists on data include idealized predictive experiments in ensemble mode where model data are sub-sampled to represent observations or observational networks. Sparsity of ocean observations in the Arctic projects on the uncertainty of ocean syntheses and limits the predictive skill of assimilated or initialized systems. In NACLIM we employed the idealized or perfect model approach in combination with data withholding ensemble prediction experiments to identify the importance of Arctic observations. We show using this approach that liquid freshwater in the Arctic Ocean is predictable up to six years ahead. The skill is not spatially uniform and skill is confined to certain areas of the Arctic Ocean. Variability in liquid freshwater is found to be affected by a clockwise propagating mode with a multi decadal time-scale that also modulates the export of both, liquid freshwater and sea ice, from the Arctic. Extreme freshwater exchanges with the Arctic have a limited but detectable effect on the Atlantic surface state for a few years.

Conclusion

Observational and modelling studies carried out within several Work Packages of the NACLIM project confirmed the necessity of high quality and comprehensive ocean observations for the initialization of coupled climate modes. For decadal forecasts and beyond information from the convective regions of the world ocean, the North Atlantic and the Southern Ocean, hydrographic observations below the commonly covered upper 2000 m are important to improve the forecast skill of the models. Also information on the varying Sea Surface Salinity covering the global ocean does improve the model skill significantly. Here the recent developments with satellite derived products are promising. Common to these observation systems is that they certainly left the sphere of curiosity driven research and moved to operational observing system.

In the field of in-situ measurements NACLIM efforts have led to a substantial revision of the moored observing systems. The combination of dedicated process experiments with long term monitoring efforts both improved the quality of the data sets obtained as well as the logistical and financial efforts. This approach does not only help with getting better data in the future but also allows to revisit older data sets and to improve their quality.

We believe that the combined efforts of the researchers working within NACLIM have contributed to an improvement of climate forecasts and to clearly define the necessary observational frame that is pre-requisite for a good skill of the models.

To summarize the recommendations:

- To improve the forecast skill of the models deep hydrographic and sea surface salinity observations are necessary;
- Ocean observations in the Arctic Mediterranean and knowledge of freshwater fluxes are crucial for determining the inter-annual and longer term variability in the Atlantic;
- The current arrays for measuring heat and volume fluxes need to be maintained, but can be cut down in size, thereby reducing the logistical and financial efforts.

4.1.4 The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results (not exceeding 10 pages).

NACLIM has been characterized by carrying out inter-institutional and interdisciplinary research on different aspects of quantifying the interannual to decadal predictability of the climate in the North Atlantic/European sector related to the North Atlantic/Arctic ocean surface state (WP 1.1). SST and sea ice in the North Atlantic/Arctic region are major factors influencing the atmospheric circulation (WP 1.2) and thus the climate in Europe. In NACLIM we have quantified the uncertainties in predictions of state-of-the-art climate models related to the North Atlantic/Arctic Ocean surface state. This has been done by assessing the multi-model set of initialized decadal prediction ensemble experiments from the CMIP5 project. Based on a wide range of process-oriented modelling studies, we have identified predictable atmospheric circulation patterns related to the North Atlantic/Arctic ocean surface state (WP 1.3) and thus contributed to an increased preparedness to the climatic conditions in the North Atlantic/European sector. The impact of Arctic changes on polar meso-cyclone activity has been quantified (WP 1.2). Polar lows represent a danger for shipping, fishing and off-shore drilling activities due to their strong winds and heavy precipitation. From the modelling studies we have identified the most important feedbacks between the North Atlantic/Arctic Ocean and the atmosphere in the North Atlantic/European sector (WP 1.2) as well as optimal SST and fresh water perturbation patterns that lead to a maximum impact on the atmosphere. These patterns will help to identify where ocean surface state observations will have a maximum impact on improving predictions (WP 3.1). NACLIM has also empirically downscaled atmospheric predictions to local scales of interest for impact studies (WPs 4.2, 4.1).

To verify, initialize and improve model-based climate forecasts, monitoring of key oceanic quantities is necessary. NACLIM has extended the monitoring of the exchanges across the Greenland-Scotland-Ridge (WP 2.1), of the deep western boundary currents (WP 2.2), and of the overturning circulation at 26°N (WP 2.2) to duration that by now permits identification of decadal trends. NACLIM has also contributed to filling the existing gap of observing the basin-wide transports in the subpolar North Atlantic (WPs 2.1, 2.2). These activities have made an effective contribution to the Global Earth Observing System of Systems (GEOSS) through GEO (Group of Earth Observations). Based on hindcast prediction experiments performed in an ideal model world, NACLIM has identifies potential needs and possible reductions of the existing and future ocean observing system (WP 3.1) in order to enhance the forecast skill in the North Atlantic/European sector. In order to improve the Arctic initialization of climate prediction systems, a new and innovative dataset of Arctic sea (ice) surface temperatures has been constructed (WP 3.2). The project has also identified sources of predictive skill due to initializing the Arctic Ocean and sea ice based on data withholding experiments with a coupled climate model (WPs 3.1, 3.2). Based on these studies NACLIM made specific recommendations how to best initialize climate predictions as well as how to optimize the present ocean observing system WPs 2.3, 3.1).

Combining the CMIP5 decadal prediction experiments with knowledge about physical – biological links, NACLIM has quantified the reliability of these forecasts for case studies from the North Atlantic marine ecosystem (WP 4.1), including commercially exploited fish stocks, and made recommendations regarding future research requirements necessary to achieve reliable forecasts of high trophic levels of the oceanic ecosystem. The project has down scaled the CMIP5 European climate change predictions to the urban scale, using a deterministic urban climate model in order to match the scale of interest for local stakeholders (WP 4.2). The resulting high resolution urban climate predictions have been coupled to relevant socio-economic data for a number of European cities in order to produce heat risk maps. This latter task has be established by a Belgian SME, partner in the NACLIM consortium. It was also responsible for the dissemination of the urban climate risk results to local stakeholders such as city authorities, the private sector or the industry. To this end, several workshops with stakeholders from all over Europe have been carried out.

NACLIM research focused on the North Atlantic/European sector and the results are relevant for Europe as a whole and not only for a particular country. Furthermore, the project brought together a large number of experts to tackle its interdisciplinary approach of integrating existing model-based climate predictions, process-oriented modelling studies, ocean field and satellite observations as well as reanalysis products, oceanic ecosystem modelling, urban climate modelling and socio-economic data as well as dissemination to climate services. Also NACLIM's contribution to long-term, basin-wide observations of key oceanic parameters could not have been accomplished on a purely national level, not least due to the considerable costs of conducting field surveys, especially ship time. Benefits and efficiencies are also gained from pooling computing resources across national boundaries.

NACLIM was also heavily engaged in the umbrella project ECOMS, where the expertise of the three FP7 projects SPECS, EUPORIAS and NACCLIM were efficiently combined.

Particular aspects of individual work packages are listed below.

WP 1.1 - The ocean surface state in the subpolar North Atlantic, the Nordic Seas and parts of the Arctic Ocean significantly impacts the climate in Europe through air-sea heat exchanges and changes of the atmospheric circulation in the North Atlantic / European sector. Prior to and within NACLIM we demonstrated in a multi-model approach that surface temperature and salinity in the subpolar North Atlantic and the eastern part of the Nordic Seas are skilfully predictable up to a decade (and maybe beyond) due to the poleward advection of warm and saline subtropical water. Understanding the mechanisms underlying the predictive skill of the North Atlantic / Arctic Ocean surface state and the associated atmospheric predictability (WP1.2) and the differences between models is key to more reliable climate predictions in the North Atlantic / European sector. The work performed within WP1.1 is highly relevant for the predictability of marine ecosystem variability (as addressed in WP4.1). Prior to and within NACLIM, strong co-variability between physical oceanic quantities and abundance and distribution of marine species from various trophic levels, including economically important fish species, has been demonstrated for the north-eastern North Atlantic. Assessing and improving predictability of physical oceanic quantities thus translates into (improved) predictability of abundance and distribution of marine species which is highly beneficial for e.g. fisheries.

WP 1.2 - The socio-economic importance of predicting climate fluctuations and changes on seasonal to decadal time scale is well known, but progress will only be achieved by carefully analysing the observed regional impacts of SST, SIC, snow cover, and ocean circulation variability onto the atmospheric circulation, and by understanding the dominant physics at play, so that the observational evidence can be used to complement, test, and improve the climate models that are used in predictability studies. The most significant dissemination activities have been the publication of research articles, numerous communications and participation in international meetings and workshops, and the holding of seminars in universities and research institutes. These activities have largely contributed to the advancement of our scientific understanding of the ocean influence on climate. In addition, the project has contributed to career development and to training graduate students in atmospheric dynamics, numerical climate modelling, and statistical analysis.

WP 2.1 - One of the main uncertainties in projections of the future climate of Europe is the strength of the AMOC. Most climate models indicate a weakening during the 21st century but they disagree strongly on the magnitude of the weakening. This problem has been highlighted by reports that the weakening has already been initiated. The deep limb of the AMOC is fed from both the western North Atlantic and from the overflow with its entrained water masses but for Europe the most important component is the overflow and the associated warm surface inflow. With the results from NACLIM WP 2.1 it is clear that there has not been any weakening in this component during the last two decades. Another key uncertainty in climate projection is the future fate of Arctic sea ice and the many feedback processes associated with it. This problem has proven to be difficult to model reliably but some studies indicate a significant role for the oceanic heat transport from the Atlantic i.e. the inflows across the Greenland-Scotland Ridge. The increased heat transport documented by NACLIM WP 2.1 may therefore help explain some of the dramatic decreases in Arctic sea ice extent during the last decade. On long time scales a key role of the Greenland-Scotland Ridge exchanges is the removal of carbon dioxide and heat from the atmosphere and transport into the deep ocean. The documented stability of the two main overflow branches shows that this climatically important transport mechanism has remained stable during the last two decades and the documented warming of the Faroe Bank Channel overflow even implies increased heat transport into the deep ocean.

WP 2.2 – The potential impact of this WP is related to the sustained observing efforts in the Sub Polar North Atlantic and elsewhere. It could be shown that Argo floats alone do not provide the required temporal and local (spatial) resolution to substitute the moored observing effort. This is not only related to the fact that Argo does currently not provide data below 2000m but also because of the low (10 days) time resolution. The optimization will be continued for mixed, multiplatform and multidisciplinary observing objective in the currently running H2020 AtlantOS project. The close collaboration with the US/UK OSNAP program and the Canadian VITALS project had scientifically important impacts and related dissemination (conferences, workshops).

WP 2.3 – comprised an integral approach of observational and modelling studies of atmosphere, ocean and climate in the North Atlantic and Arctic oceans. This WP has made an attempt, so summarize the individual components of this effort to provide a comprehensive view on the present knowledge of the ocean circulation and water mass budgets that impact on Europe's climate. The long time series from the Greenland-Scotland Ridge and the subpolar gyre have provided the backbone that has stimulated new questions and generated additional observational project and theoretical studies of the AMOC. Long time series are not easily obtained. They require time and it is therefore vital that the NACLIM observations are continued. NACLIM and the preceding observation programs have introduced a new generation of sea going oceanographers now ready to continue the observational work.

WP 3.1 - Spatial and temporal coverage of ocean observations have been significantly enhance after introduction of the ARGO floats. However, its main observing areas are limited to the upper ocean, e.g. above 700 m. Results in this work package provide a value of deep ocean observation, e.g. below 2000 m, which in particular can provide invaluable information for better decadal prediction. Also another result pointing the importance of ocean salinity information supports surface ocean surface salinity as a key parameter for proper climate modeling, which strongly support continuous use of satellite information to ocean climate projections.

WP 3.2 - With the DSPE method a robust means for parameter optimization is at hand that enables the automatic tuning of climate models with observed data. As a result a tuned version of the CESAM in medium resolution is now available for climate sensitivity studies. The ice and sea surface temperature data set (IST/SST, AASTI) will be further developed in EU and EUMETSAT R&D projects. The achievements in NACLIM have been the foundation of the operationalization of a level-2 processing chain in the OSI SAF (OSI-205), and subsequently to the Copernicus CMEMS level-4 IST/SST product (CMEMS). Improvements of algorithm and uncertainties are done in the ongoing FP7 ICE-ARC and H2020 EUSTACE projects. Furthermore, the AASTI data set is an important input to the new global surface temperature data set in the EUSTACE project. The continuous work on AASTI heritage has led to highest quality uncertainties (Ghent 2016) and state-of-the-art IST performance (FICE 2017). Production of AASTI version-2, with improved uncertainties, improved cloud mask, various bug-fixes is in progress at DMI and Met Norway and the data set is expected finalizes by summer/autumn 2017. AASTI version-1 in level-3 is available from DMI on ftp from 2000-2009.

WP 4.1 - Taken as a whole, the most important single result from this work is the lesson that forecasting of marine ecosystems in Europe on the seasonal and particularly on the decadal scale is feasible. This result represents a significant advance beyond the state-of-the-art at the start of the project, where just a few marine seasonal forecasts could be found, none-of-which were in Europe. These proof-of-concept results from the NACLIM project can therefore, we believe, lead to a rapid blooming of marine ecological climate services and forecast products in Europe in the near future that will come to play an important role in both the management and exploitation of the oceans, and in the response of human systems to climate variability and climate change. In order to exploit and further develop the possibilities offered by these results, NACLIM

WP41 initiated several key activities to raise their profile in the scientific community. The most prominent of these was the creation of a Theme Session dedicated to the topic at the Annual Science conference of ICES (the International Council for the Exploration of the Seas) held in Riga, Latvia, in 2016. Between two and three hundred scientists from Europe and North America attended this session in the course of two days, and the session has already had the desired effect of bringing the potential of these results to the fore.

A further important legacy of NACLIM WP 4.1 has been the creation of a community of researchers that are now working together to develop marine ecological climate services. In 2016, ICES created a scientific working group, the Working Group on Seasonal-to-Decadal Prediction of Marine Ecosystems (WGS2D) to operationalise this knowledge and incorporate it into the routine management of living marine resources. The results of the NACLIM project will be integral to this undertaking and the group will represent one of the main scientific successors to NACLIM WP41. Furthermore, NACLIM has been successful in forming links to groups in other regions of the world that are also attempting to predict ecosystems, notably via several invited talks in the USA. An informal network linking researchers working on ecological prediction in Europe (via ICES WGS2D), the Pacific (via the PICES SG-CEP group) and globally (via IMBER CLIOTOP) has been established, and further joint activities and collaborations are envisaged. NACLIM has therefore played a key role in helping bring disparate groups together into a coherent body, and therefore, effectively establishing a new field of scientific research. The impacts of this project are therefore expected to be felt for well into the future, as this new field attempts to realise the exciting potential of marine ecological forecasting.

WP 4.2 - Scientifically, results obtained with the UrbClim model have already generated impact. Indeed, since the publication of the UrbClim model, requests from many institutes from around the globe have arrived for use of the model. Currently (March 2017), the model is being used, among others, at IC3 (through a collaboration launched from within the ECOMS cluster), and more recently also at the UNESCO-IHE Institute for Water Education in the Netherlands. Moreover, discussions related to installing the model at the Chinese National Climate Centre are ongoing. Most of this scientific impact has been generated through our numerous participations to scientific conferences journal publications. The potential future exploitation of UrbClim in China is largely the result of visits by VITO staff to the National Climate Center in Beijing in early 2016 and early 2017. It should be noted that, even though the UrbClim model itself is to be considered background to the project (i.e., it had been developed largely prior to the start of NACLIM), the results obtained during NACLIM and the subsequent publications have greatly contributed to establishing its reputation and scientific acclaim.

From a societal perspective, the work package ‘impact on urban societies’ has generated impact mostly in the three cities Almada, Antwerp, and Berlin. Representatives of each of these cities have been very actively involved in the project as users, and they have increasingly incorporated NACLIM results into their own policy and climate adaptation planning activities. This impact was achieved, on the one hand, in an informal manner, by regular bilateral contacts between the scientific and the user partners. On the other hand, formal events (user meetings) were organized, twice in Almada (2013 and 2015), and once in each of Antwerp (2013), Berlin (2014), and Brussels (2015). During these events, users were asked to help steer the research work, among others by suggesting the time horizons of the future climate projections and that were relevant for them, and also by suggesting climate adaptation measures to be implemented in the modelling. Users also actively provided local data sets required for the climate simulations, such as local 3-D building cadastre maps, and local in-situ measurement data.

Efforts were also conducted to create societal impact beyond the three formal NACLIM users (target cities). To do so, we organized an international workshop ‘towards urban climate services’ in Brussels, in June 2016. While a part of the this two-day workshop was devoted to communicating NACLIM’s principal urban climate results, another part was dedicated to an interactive panel/audience discussion regarding the way forward in the domain of urban climate services. The workshop was attended by several tens of participants, from academia, cities, and the European Commission.

4.1.5 The address of the project public website, if applicable as well as relevant contact details

Project webpage
www.naclim.eu

Project films
During the project life time four dissemination films were produced and made available in social media. The films can be found i.e. in youtube, please simply search for "NACLIM".

The North Atlantic Climate (Part 1): What we need to find out - a short introduction to the main challenges NACLIM's researchers are facing to in their investigations on climate variability in the project. In this video, one of our senior scientist, Mojib Latif of GEOMAR, explains the importance of understanding the mechanisms of climate variability in the North Atlantic area.
https://youtu.be/EAFHBvHmHyw?list=PLoqC0y5-eTV5qxBm_aJERRS0dBy4XIbg2

The North Atlantic Climate (Part 2): Monitoring the Atlantic Ocean - In this EU funded project, scientists from different European institutions take measurements in the ocean from Greenland to the Bahamas with concentration on 3 regions: the Greenland-Scotland Ridge, where the exchange between the North Atlantic Ocean and the Nordic Seas takes place, the Subpolar North Atlantic, and the Subtropical North Atlantic. The continuous observation data will form the input to improve the ability of models, and using these models future climate changes could be predicted.

In this part of the film, our scientists Barbara (Bee) Berx from the Scottish Association for Marine Science (MSS), Laura de Steur from the Royal Netherlands Institute for Sea Research (NIOZ), Gerard McCarthy from the Natural Environment Research Council UK (NERC) and the project coordinator Detlef Quadfasel at University of Hamburg (UHAM) speak about the observational activities carried out in the project and the findings so far.
https://youtu.be/g5qWDk_uDpc?list=PLoqC0y5-eTV5qxBm_aJERRS0dBy4XIbg2

The North Atlantic Climate (Part 3): Adapting to warmer cities - The project aims to better understand the effects of the North Atlantic and Arctic oceans on global climate change. Climate change is predicted to cause more frequent and higher intensity extreme weather events, such as heat waves. Within NACLIM, scientists are trying to find out how to prepare our society for this. In particular European cities which experience the urban heat island effect are being studied.

Three European cities have been involved in the research studies. Griet Lambrechts from the municipality of Antwerp, Sara Dionísio from the city council of Almada, as well as Jörn Welsch from the senate of Berlin explain the needs and expectations of their cities. Scientific clarification is provided by our scientists Dr. Dirk Lauwaet from the Flemish Institution for Technological Research (VITO) and Catherine Stevens from GIM Belgium. Dr. Andrea Tilche from the European Commission summarises the necessary measures to enhance climate science and climate services in Europe.
https://youtu.be/p5WmZsHF5hE?list=PLoqC0y5-eTV5qxBm_aJERRS0dBy4XIbg2

The North Atlantic Climate (Part 4, a summary): the project and what we've learnt - After 4 years of intensive work, the EU funded project NACLIM has come to an end. The project closed on the 31st of January 2017, with 60 reports to the European Commission and around 80 publications. NACLIM (02.2012 – 01.2017) stands for "The North Atlantic Climate". The project has enabled the scientists to gain a deeper understanding of the mechanisms that control the ocean circulation in the North Atlantic and Arctic oceans, how these mechanisms interact with each other and how they affect global climate change. The output of the observations in the North Atlantic and Arctic Oceans is integrated into a surveillance system that can operate as a prediction system for the climate of 15 to 25 years ahead.

Within the project our scientists also tried to understand the phenomenon of more frequent and higher intensity extreme weather events, such as heat waves and in particular the urban heat island effect, so that the end-users (such as European cities) can prepare for this better.
https://youtu.be/9J_Ky-_AUoU?list=PLoqC0y5-eTV5qxBm_aJERRS0dBy4XIbg2

The project was run by 18 research groups with over 60 scientists from 10 European countries. These institutes are:

1. University of Hamburg, Germany
2. Max Planck Institute for Meteorology, Germany
3. University Pierre et Marie Curie – Paris 6, France
4. University of Bergen, Norway
5. UNI Research Bergen, Norway
6. GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany
7. Danish Meteorological Institute, Denmark
8. Faroe Marine Research Institute, Faroe Islands
9. Finnish Meteorological Institute, Finland
10. Marine Research Institute, Island
11. Royal Netherlands Institute for Sea Research, Netherlands
12. The Scottish Association for Marine Science, UK
13. Natural Environment Research Council, UK
14. Nansen Environmental and Remote Sensing Center, Norway
15. Flemish Institute for Technological Research, Belgium
16. G.I.M. Geographic Information Management, Belgium
17. Technical University of Denmark
18. Marine Scotland, UK

The NACLIM project and all videos are funded by the European Commission, through the 7th Framework Programme for Research, Theme 6 Environment, Grant Agreement 308299.

Publications are available at:
1) http://naclim.zmaw.de/index.php?id=2225 and
2) https://zenodo.org/communities/naclim/?page=1&size=20 (ZENODO → Community: NACLIM)

Contact details:
Prof. Dr. Detlef Quadfasel, +49 40 42838 5756, Email: Detlef.Quadfasel@uni-hamburg.de
Chenbo Guo, +49 40 41173 285, Email: Chenbo.Guo@mpimet.mpg.de