PROJECT FINAL REPORT

Grant Agreement number: 212643

Project acronym: THOR

Project title: Thermohaline Overturning-At Risk?

Funding Scheme: Collaborative project

Period covered: **from** 1 December 2008 **to** 30 November 2012

Name of the scientific representative of the project's co-ordinator[1]**, Title and Organisation:**

Prof. Detlef Quadfasel, University of Hamburg

Tel: +49 (0)40 42838 7478
Fax: +49 (0)40 42838 7477

E-mail: thor.eu@zmaw.de

Project website address: http://www.eu-thor.eu

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

Table of contents

4.1 Final publishable summary report

1) Executive summary

The excess radiative heat of the tropical and subtropical belt on earth is redistributed to the cooler higher latitudes through the atmospheric and oceanic circulation. The Atlantic Meridional Overturning Circulation (AMOC) is the major mechanism in the oceanic component. At depth it carries cold and dense water from the sinking or convection regions in the North Atlantic to the south. Near the surface this water is replenished by northward flowing warm subtropical water that heats the atmosphere and thus contributes to the mild climate of the eastern North Atlantic and Europe. Within THOR, a consortium of 21 scientific groups from 9 European countries explored the stability of this oceanic circulation and quantified the impact on the regional climate, using a suite of numerical models and direct oceanic observations.

Global coupled atmosphere-ice-ocean models and the analysis of sediment records from the ocean floor showed variability of the northward heat fluxes on time scales from decadal to centennial. These changes manifest themselves in varying sea surface temperatures in the North Atlantic and can partly be explained by internal coupled modes in the system but may also reflect changes in the external forcing of the Earth system such as varying solar radiation, volcanic eruptions and anthropogenic greenhouse gases and aerosols. A common finding of these experiments is the crucial role of the Subpolar Gyre which acts as the main interface between the upper and the deep ocean and feeds the oceanic memory of climate fluctuations.

The Subpolar Gyre is sensible not only to global climate changes but also to regional impacts. Increased melting of the Greenland Ice sheet injects freshwater into the gyre thus reducing the winterly buoyancy loss required for deep convection. Experiments with high resolution ocean models and analysis of observational data showed that this effect may have been overestimated in the past and, at least in the Nordic Seas, the deep water production has remained very stable. THOR has maintained and expanded a comprehensive observation system, monitoring the fluxes across key passages connecting the Arctic Mediterranean and the North Atlantic, as well as in the deep western boundary current from the Labrador Sea to the Subtropical Gyre at 26° N. These time series so far only span a decade or two and are thus rather short for the analysis of climate variability. The good agreement of these data with those from regional high resolution models puts confidence in the model results, which thus can be used on longer time scales. Both, observations and models, show a very stable circulation on time scales beyond a few years, but a continuous warming of the subpolar ocean, at rates several times larger than the global average. Adding to the observational programme two new systems for near real time data transmission from moored instrumentation were developed and tested in THOR.

Forecasting the state of the global ocean and atmosphere on a time scale of a decade was one of the main goals of THOR. State-of-the art Global Climate Models from leading European climate research institutions were initialized with the best known state of the ocean and provided reliable multi-year predictions, in particular for the key region of the North Atlantic. Good ocean state estimates, such as those based on measurements in the ARGO Programme are a prerequisite for skill full predictions, with the largest uncertainties arising from model uncertainties. First steps towards a new coupled model initialisation were made, showing that this new method may increase the forecast skill in the future.

THOR was a truly European project, bringing together expertise and intellectual resources from a number of different institutions. This holds for the multi-model climate analysis and forecast systems as well as the synergy of different observational programmes. The progress achieved in THOR in the understanding of European climate variability was only possible through this Europe wide and interdisciplinary cooperation.

2) Summary description of project context and objectives

The climate of Europe is strongly influenced by the North Atlantic Ocean circulation. Variations of the strength of the Thermohaline Circulation (THC[2]) or the Meridional Overturning Circulation (MOC) are in several studies implicated as a main driver for decadal and longer time-scale changes for European and Northern hemisphere climate. The Atlantic THC describes the Meridional circulation of water, heat and salt, associated with the northward volume flux in the upper part of the ocean and the southward flux at depth. Variations in THC are a commonly attributed mechanism for non-linear and abrupt (i.e. decadal scale) climate changes. Yet the observational and model underpinning of these hypotheses are at best sketchy making it very difficult to come to firm conclusions. Reliable quantification of the variability and stability of the THC and its atmospheric implications in todays and a warmer climate are therefore a major challenge in climate research. Whilst global models have been developed to produce long-term climate change projections, and short-term weather forecasts are carried out on a routine basis, there is a significant need for medium term regional climate forecasts, not only for the purpose of assessing the likelihood for and eventually detecting rapid climate changes, but also to assist planning in both public and private sectors.

THOR goal was to establish an operational system that could monitor and forecast the development of the North Atlantic THC on decadal time scales and assess its stability and the risk of a breakdown in a changing climate. Through the assimilation of systematic oceanic observations at key locations into ocean circulation models THOR project was meant to provide a set of geo-observational products that will be used to forecast the development of the system using global coupled ocean-atmosphere models.

More specifically, THOR goals are the following:

-Identifying induced climate impacts of changes in the THC and the probability of extreme climate events with special emphasis on the European/North Atlantic region. Assimilation of observational data into ocean models will provide comprehensive long-term data sets making it possible to quantify the impact of THC variability on climate parameters, both on the regional and the larger scales. Millennium time scale experiments with coupled climate models and analysis of paleo data will identify the relevant key processes and feedback mechanisms between ocean, atmosphere and cryosphere.

-Developing and operating an optimal ocean observing system for the North Atlantic component of the THC. This observation system, consisting of arrays of self-contained instruments as well as ship- and space-borne measurements, will provide accurate time series of mass, heat and salt fluxes at key locations, allowing for the first time to assess the strength of the Atlantic THC, and THC variability on time-scales from multiannual up to decadal.

[2] The Atlantic THC describes the meridional circulation of water, heat and salt, associated with the northward volume flux in the upper part of the ocean and the southward flux at depth. In this proposal we will use the expression THC exclusively.

-Forecasting the Atlantic THC and its variability until 2025. Coupled model simulations will provide forecasts of the ocean state on decadal time scales and at the same time quantify the significance of these predictions. Parameters predicted are strength of the THC, fluxes of mass, heat and salt, sea surface temperature and salinity and interior ocean fields, and associated climate variables for Europe and more widely.

-Assessing the stability of the THC to increased fresh water run-off from the Greenland ice sheet for various global warming scenarios. Increasing rates of fresh water from the Greenland ice sheet may reduce the strength of the THC. In THOR, the combined effect of global warming scenarios and melting of the Greenland ice sheet will be thoroughly assessed in a coupled climate model.

THOR builds upon techniques, methods and models developed during several projects funded within FP5 and FP6 as well as many other projects funded at national level in our partner countries. The project is going to contribute to Global Monitoring for Environment and Security (GMES), to Global Observing Systems such as to the Global Ocean Observing system (GOOS), and to the International Polar Year (IPY).

The specific scientific objectives of the project are:

1) Identification of key processes and feedback mechanisms driving the THC variability and quantification of their respective impact:

The relative importance of internal ocean dynamics, stochastic atmospheric forcing, coupled atmosphere-ocean dynamics and feedbacks with the continental ice sheets for the THC variability on decadal and longer time scales will be quantified through the analysis of a series of uncoupled and coupled model experiments and through the analysis of high-resolution paleo and *in-situ* data time series.

Delivery: *Assessment of the physical processes and feedbacks with other components of the Earth climate system determining THC variability*

2) Assessing sources of model uncertainties:

Estimates from reanalyses and simulations of the ocean, ice and surface state for the North Atlantic and Arctic Ocean over the past 50 years will be evaluated with particular emphasis on the THC. The relationship and associated timescales between ocean circulation, ocean heat- and salt content and air-sea interface properties will be quantified.

Delivery: *Assessment of the THC variability during the past 50+ years*

3) Quantification of the THC related mass, heat and salt fluxes in the subpolar and in the subtropical Atlantic on seasonal to decadal time scales:

An observing system for measuring the fluxes will be established, consisting of self contained moorings, ship- and space borne measurements and autonomous instrumentation. These time series will be supplemented and extended in time with flux estimates from models with data assimilation.

Delivery: Asses*sment of THC variability over the GSR, in the Labrador Sea and at 26°*

4) Quantification of the contribution from the Irminger and Labrador seas and of entrainment processes in the overflows to the THC:

The contribution of upper layer water to the THC through entrainment and mixing into the overflow plumes south of the ridge will be quantified through monitoring arrays and the underlying mechanisms explored in detailed process experiments. The transformation of water masses within these seas and the respective imports and exports will be measured with moored arrays and ship- and space borne techniques. Integrated inventories and their variability on seasonal to decadal time-scales will be provided from models with data assimilation.

Delivery: *Assessment of the role of entrainment processes and of ventilation in the Irminger/Labrador Seas on the THC variability*

5) Assessment of the quality of THC forecasts: The robustness of decadal predictions of THC variability will be quantified through ensemble simulations using a number of candidate methods for assessing the forecast uncertainty due to uncertainty in initial conditions. Forecast uncertainty due to modelling uncertainty will be assessed using both multi-model and perturbed physics ensembles.

Delivery: *Assessment of the predictability of the THC variability*

6) Coupled model decadal forecasts of the THC: Dynamical decadal forecasts of the THC and climate over Europe will be produced by initialising coupled ocean-atmosphere-ice models with observations.

Delivery: *Assessment of the future development of the THC*

7) Recommendations for observational and modelling systems: Based on observation and model analysis specific recommendations will be made for the development of sustained observational and modelling systems, to improve the skill of decadal THC forecasts

Delivery: *Improvement of the skill of decadal forecasts*

The specific technical objectives of the project are the following.

8) Development of coupled ocean-atmosphere assimilation capabilities: The forecast skill of coupled models will be improved by constraining the models directly through climate observations. Assimilation techniques will be applied to the coupled system through a number of tests. Model experiments will be used to suggest key priorities for an observational/data assimilation system to improve initialisation of THC forecasts.

Delivery: *Improved initialisation of coupled forecast models*

9) Development of near real time data transmission for moored observatories: A low cost – high efficiency data transmission system for moored observations will be tested and implemented to allow fast access to in-situ data that previously have only become available with time delays of months to years. Several SMEs are engaged in this work that will allow a rapid transfer of ocean flux estimates to the model community.

Delivery: *Near real-time access to moored data for assimilation into models*

10) The dissemination objective of the project is the establishment of a routine decadal forecasting facility for Europe: A number of the partners are already involved in making short term weather forecasts and long term climate projections. Through them, and through a programme of dissemination and education of the techniques and results to a targeted group of end users, the project will initiate a medium term climate forecast service for Europe.

3) Description of the main S&T results/foregrounds

Main S & T results/foregrounds are presented according to the core theme structure.

++Core Theme 1: Quantifying and modeling THC variability using palaeoclimate observations and simulations. CT leaders: Johann Jungclaus (MPG-M), H. Kleiven (UiB)++

Variations in the Atlantic Meridional Overturning Circulation (AMOC), the dynamic manifestation of the Thermohaline Circulation (THC), and the associated heat transport changes are of crucial importance for the climate in the North Atlantic/European sector. The time scales involved range from decadal to centennial. Taking these variations into account is crucial for reliable predictions of the North Atlantic/European climate on decadal time scales. Of particular importance for the near term predictions are low-frequency variations of North Atlantic sea surface temperature (NASST), which are subject to both ocean-internal generation (mainly through AMOC variability) and external radiative forcing (such as solar variations, volcanic eruptions or anthropogenic greenhouse gases and aerosols). The assessment of low-frequency AMOC and NASST variability and the related predictability also requires studying interactions between the sub-sytems ocean and atmosphere. Motivated in this way, THOR WP1.1 has contributed to improved understanding of AMOC and NASST fluctuations on time scales from decades to centuries in a multi-model framework. We have assessed the relative role of internally generated and externally forced variations and explored the influence of the AMOC on the atmosphere.

Within THOR WP1.2, reconstructions of NASST and sea surface salinity as well as of dynamical quantities related to the AMOC, such as the strength of the overflows across the Greenland-Scotland-Ridge or the strength of the inflow of Atlantic water into the Nordic Seas, have been deduced from sediment cores spanning the last millennium. The new time series provide the first ever reconstruction of the individual (western and eastern) deep branches of the AMOC on these timescales—demonstrating a close coupling between surface climate and the properties of proto North Atlantic Deep Water, primarily on centennial timescales. Coeval changes in both kinetic and chemical deep-water proxies provide strong support that both the intensity and properties of proto NADW vary on multi-decadal timescales throughout the last millennium.

In collaboration between WP1.1 and WP1.2 we have compared long-term simulations of the last millennium with paleo-oceanographic proxy records and interpreted the dynamics of the reconstructed quantities with the help of numerical models.

<u>*Characteristics of AMOC and NASST variability in long-term simulations*</u>

The millennial scale long control integrations with coupled climate models provided by the THOR WP1.1 partners indicate similar features of AMOC and NASST variability in the various models, but also important differences, for example in the time scale of the variations or the mechanisms and feedbacks involved. The diversity in the representation of AMOC variations and NASST expression has led to a detailed investigation of the mechanisms underlying the interdecadal to centennial scale variability in the different models.

Martin et al. (2012), using the KCM model, identified a multi-centennial mode of open ocean deep convection in the Atlantic sector of the Southern Ocean. The quasi-periodic occurrence of the deep convection causes variations in surface air temperature, sea ice cover and AMOC. The deep convection is stimulated by a strong built-up of heat at mid-depths, where the heat originates from relatively warm deep water formed in the North Atlantic. Menary et al. (2012), using the HadCM3, KCM and MPI-ESM-CR models, link centennial scale variability of the AMOC to changes in oceanic salinities and surface temperatures, and atmospheric phenomena such as the Intertropical Convergence Zone. As a result of the heat transport changes associated with the AMOC fluctuations all three models show enhanced warming in the sub-polar North Atlantic with slightly different amplitude (Figure 1). On the other hand, this Figure also indicates a diverse spatial distribution of warm and cold anomalies. While a strong positive AMOC anomaly is associated with warm conditions in the Nordic Seas in HadCM3, the opposite is true for KCM. Differences also exist in the strength of the cross-hemispheric character of the response: much stronger negative loading in the South Atlantic appears in KCM compared to the other models. Park and Latif (2010), using the KCM model, investigated the two leading modes of observed Northern Hemisphere sea surface temperature, Pacific Decadal Variability and Atlantic Multidecadal Variability (AMV; basically reflecting the mutidecadal NASST variations). They suggest that the two modes are independent from each other and link the AMV to variations in the AMOC. Ba et al. (submitted), also investigating AMOC and AMV in the KCM model, identified an out-of-phase interaction between horizontal and vertical ocean circulation, coupled through Irminger Sea convection. Medhaug et al. (2012), using the BCM model, have investigated the mechanisms for decadal scale AMOC variability and find, as is representative also for other models, that the Labrador Sea convection is more directly linked to AMOC variations, while the linkage between deep-water formation north of the Greenland Scotland Ridge and the deeper limb of the AMOC is more indirect.

An important common finding is the crucial role of the SPG. Its geometry, strength and dynamics determine not only deep water formation processes in the Labrador Sea, but also the heat and salt exchange between the North Atlantic and the Nordic Seas. Present day coupled climate models are able to simulate the mean state and variability generally well compared to observations, although deficits still exist in terms of water mass properties (Langehaug et al, 2012b). Langehaug et al. (2012a), using the BCM model, find that the SPG strength is closely related to the variability of the Labrador Sea Water, the atmospheric East Atlantic Pattern, and the overflows across the Greenland Scotland Ridge. Born and Mignot (2012) investigate variability in the range of 15-20 years in the IPSL-CM4 model and interpret the oscillation in the subpolar gyre (SPG) to be excited stochastically by the atmosphere. Escudier et al. (2012) analyze a 20-year mode of variability in the IPSL-CM5 model and find a connection between near-surface temperature and salinity anomalies propagating along the SPG and sea-ice variations in the Nordic Seas.

External forcing of AMOC and NASST

Externally-driven changes of AMOC and NASST have been found to be more important than previously thought. In particular, strong volcanic eruptions (SVEs) shape the climate evolution not only during the relatively short time when aerosols disturb the radiation balance, but also on decadal time scales through feedback mechanisms involving ocean heat transport and sea-ice changes.

Otterå et al. (2010), using the BCM model, demonstrated that volcanoes play an important role in the phasing of the AMV. They showed that the most prominent mode of variability is associated with the external forcing and can be clearly distinguished from the AMOC-driven variability. The cooling effect of the volcanic aerosols together with a dynamic response of the atmospheric circulation favoring a positive phase of the North Atlantic Oscillation (NAO) leads first to cold SST anomalies in the tropical and subtropical Atlantic and, with a time lag of several years, to a strengthening of the AMOC. Thus, during times of strong volcanic disturbances, AMOC changes would be even anticorrelated to the NASST and the AMV index (Figure 2). The findings obtained for BCM could be generally supported by studies using other coupled climate models. Mignot et al. (2011) find a significant AMOC increase as a response to volcanic forcing in the IPSL-CM4 model, although only in the second half of their last-millennium simulation. The latter result points to the important role of background conditions and the timing of subsequent SVEs for the actual realization of the simulated mechanism. Such a role has been confirmed by Zanchettin et al. (submitted to Clim. Dyn.), analyzing dedicated MPI-ESM-CR ensemble experiments covering early 19th century SVEs. Zanchettin et al. (2012), using the MPI-ESM-CR model, have extended the Otterå et al. (2010) study by an evaluation of SVEs in ensemble simulations over the last millennium The large number of SVEs allowed for a robust statistical analysis by means of a superposed epoch method. Also in the MPI-ESM-CR model, SVEs cause a stronger AMOC and a more positive NAO. The most important finding of both studies is that the short-lived volcanic disturbances cause a coherent fluctuation in the ocean-atmosphere system with a time scale of more than 20 years. The variation includes a strong amplification of the signal in the Arctic, a long-lasting positive NAO, and positive AMOC deviations. The oceanic heat transport changes associated with the latter lead to an anomalous surface warming over Scandinavia/Western Russia after 10-12 years. Such warming patterns have also been identified in European climate reconstructions (Zanchettin et al., submitted to Geophys. Res. Lett.).

The implications for decadal predictions are two-fold: On the one hand, the more limited role of internal variability and oceanic inertia through low-frequency AMOC variability may also limit prospects for decadal-scale forecasts, in particular because volcanic eruptions can not be predicted. On the other hand, the systematic post-eruption fluctuations over one or two decades may hold promise for near-term predictions as long as the volcanic effect is taken into account.

Park and Latif (2012) investigated the role of external forcing by applying periodically modulated idealized solar irradiance to the KCM model and detected an imprint in the AMOC variability. At sufficiently strong amplitude, while the surface temperature variability is channeled into a relatively narrow band around the forcing period, the AMOC variability is enhanced on a certain mode of internal variability that is not the strongest mode. Thus it is not necessarily the most unstable mode that is excited by the external forcing, and we need to understand the full modal structure of the internal AMOC variability to understand the circulation’s response to external forcing. The role of AMOC variability in shaping the 20th century has been questioned further by Booth et al. (2012). Using the HadGEM2-ES model, they suggest that the observed NASST variations can largely be explained by effects of anthropogenic aerosol emissions and volcanic eruptions. They claim that forcing by aerosols has been underestimated previously because earlier models did not include the aerosol-cloud-microphysical effect.

Ocean-atmosphere feedbacks and climatic impact of AMOC changes

Previous studies have given different answers to the question if the observed and simulated low-frequency variations of the AMOC are the expression of a coupled ocean-atmosphere mode or of ocean dynamics either maintained internally in the ocean or externally forced by atmospheric noise. A fundamental task to answer this question is to assess the atmospheric response to AMOC changes and their impact on climate.

Gastineau and Frankignoul (2012), using the BCM, HadCM3, IPSL-CM4, IPSL-CM5, MPI-ESM-CR and KCM model, find that the main mode of variability corresponds to the response of the AMOC to the natural variability of the atmosphere. In some models, the NAO is the main driver of low-frequency variability in the ocean, while in others the East Atlantic Patterns plays a larger role. The influence of the AMOC onto the atmosphere was robustly detected in all models. An intensification of the AMOC leads to an atmospheric signal resembling a negative phase of the NAO (Figure 3). Response studies carried out with IPSL-CM4 (Msadek et al., 2011) have confirmed the influence of AMOC changes on the atmospheric circulation. Substantial seasonal dependencies were found in the geopotential height response to SST anomalies. Impacts of Atlantic SST anomalies are found over other parts of the globe so that Atlantic Ocean changes can drive large-scale atmospheric variability. Extending the investigation of AMOC/atmosphere interaction to another climate model featuring higher resolution (NCAR CCSM3), Frankignoul et al. (to be submitted) found a significant NAO-like response also in this model, but with an opposite polarity compared to the THOR models. This difference could be traced back to a different SST signature and subsequent changes in the atmospheric baroclinicity. Therefore, the relevance of the model-based findings has to be evaluated using observations. As a first step, Gastineau et al. (2012) compared seasonal to decadal ocean-atmosphere coupling in the IPSL-CM5 model and the 20th century reanalysis. Air-sea interactions are simulated realistically and the AMOC is shown to have a significant impact on the winter NAO via its influence on the AMV when it leads by about 9 years. The AMOC-induced warming favors a negative NAO state as found by Gastineau and Frankignoul (2012) for the THOR models.

In another approach, forcing an atmosphere model (ECHAM5) with heat flux anomalies representing peak-to-peak AMV states, Semenov et al. (2010) investigated the atmospheric response to NASST anomalies. They find that climate variability in the North Atlantic sector could have contributed considerably to climate change in the entire Northern Hemisphere in recent decades. The Arctic, although covering only a small part of the surface area, turned out to be a major conduit of the variability owing to massive changes in ocean-atmosphere heat fluxes in temporarily sea-ice-covered regions. Semenov et al. (2010) speculate that these changes are associated with the AMOC in the sense that a stronger AMOC and associated heat transport anomalies lead to large sea-ice free regions. Therefore, sea-ice extent variations form an important link between oceanic variations and pan-Arctic and Northern Hemisphere temperatures and it is likely that such relations played an important role in the observed early twentieth-century warming in the Arctic (Semenov and Latif, 2012).

Paleo reconstructions of AMOC and climate variability spanning the last millennium

Understanding the origin and expression of natural climate variability on multi-decadal timescales is crucial for constraining their potential role in current and future climate changes. Multi-decadal climate oscillations are often postulated to result from changes in the ocean's meridional overturning circulation. Testing this hypothesis for historically recorded climate changes such as the Little Ice Age (LIA) and Medieval Warm Period (MWP) requires decadally resolved constraints on the state of ocean circulation spanning these events. In THOR, WP1.2 targeted the high-resolution sediment drifts in the North Atlantic, which provide detailed archives of past ocean circulation and climate variability. Deposited by the lower branch of the AMOC, the drifts are the end result of sediments carried in suspension by the Nordic Seas overflow waters across the Greenland-Scotland ridge. The western branch of these overflows, the Danish Strait Overflow Waters (DSOW), were reconstructed from marine sediment cores taken at the Eirik sediment drift south of Greenland, whereas the eastern overflow branch, the Iceland-Scotland Overflow Water (ISOW) was reconstructed in marine sediment cores from the Gardar sediment drift south of Iceland. As noted above, these cores are the first paleo reconstructions from the North Atlantic region on century to multidecadal timescales.

AMV appears to be a persistent feature of the climate system (Gray et al. 2004; Knudsen et al., 2010) and, while clearly linked to AMOC in models, there has been little empirical evidence for constraining and confirming the ocean-climate linkages found in models.

Mjell et al (to be submitted), using high-resolution reconstructions of relative bottom water flow speed, found that the vigor of deep ocean circulation varied on similar timescales to AMV over the past 600 years on (Figure 4). This confirms the activity of the deep ocean on AMV timescales and, since the Iceland-Scotland overflow (ISOW) is the dominant influence at this location, suggests that Nordic Seas overflows and AMOC were also varying as found in models.

Kleiven et al (to be submitted), reconstructed physical properties (salinity and temperature) as well as deep ocean chemistry and flow over the last 1400 years from the Eirik sediment Drift. The co-registered detailed surface and deep ocean records provide new knowledge of the rate and nature of climate changes in this region in relation to variability of the deep-water masses. The result shows that the reconstructed NASST and North Atlantic Sea Surface Salinities (NASSS) exhibit significant natural variability on multidecadal-centennial timescales. The proxy records for ocean ventilation and water mass distribution (carbon isotopes) and kinetic flow speed (mean sortable silt) confirm variability in the deep-water masses on during these historically important climate events (Figure 5). This characterization of deep and surface ocean property and circulation changes provides the empirical constraints necessary for determining the mechanisms underlying known historical climate perturbations and their representation in model simulations.

Taken together, the paleo characterizations confirm that both the surface and deep ocean vary in properties (chemical and physical) and dynamics (e.g. GSR overflows and SPG geometry) associated with AMV (e.g. GSR overflows and SPG geometry).

<u>*Comparison of paleo-simulations and paleo-reconstructions*</u>

As discussed above, the reconstructed strength of the Iceland-Scotland overflow shows a strong similarity with paleo-reconstructions of the AMV (Figure 4). Paleo-reconstructions of SST and other oceanic quantities are, however, still very rare and do not allow a detailed investigation of mechanisms underlying the (co)variability suggested from them. A broader insight into the paleo-climate can be provided by paleo-simulations with coupled climate models. Lohmann et al. (to be submitted) compared the simulated Iceland-Scotland overflow strength in the MPI-ESM-LR, IPSL-CM4 and BCM model with the reconstruction from Mjell et al. (to be submitted). For IPSL-CM4, the low-frequency variability of the Iceland-Scotland overflow strength coincides well between the simulated and reconstructed time series (Figure 6). While the agreement with the overflow time series in the other models is less favorable, all three models show an in-phase variation between Iceland-Scotland overflow strength and AMV index. Lohmann et al. (to be submitted) investigated possible mechanisms underlying the observed and simulated in-phase variation and suggest a local through the influence of the Nordic Seas SST, which is positively correlated with the AMV index, on the hydrography and surface elevation north of the ISR. The latter affect the pressure north of the ISR and therefore modulate the strength of the Iceland-Scotland overflow.

Apart from the overflow strength, we also compared the SST from the externally forced simulations with reconstructions based on sediment cores located north of Iceland and in the subpolar North Atlantic (Sicre et al., 2011). The interannual standard deviation of the simulated north-Icelandic SST in the IPSL-CM4 model compares well with the reconstructed SST standard deviation; also the peak-to-peak amplitude of decadal northern North Atlantic SST variability agrees between the IPSL-CM4 simulation and reconstructions based on a sediment core composite (Sicre et al., 2011). On multidecadal time scales, the reconstructed north-Icelandic SST shows a pronounced periodicity between 50 and 150 years. Menary et al. (2012) and Sicre et al. (2011) find similar periodicities for the simulated north Icelandic SST in the MPI-ESM-CR, HadCM3 and especially KCM model and in the IPSL-CM4 model respectively. The most striking feature in the reconstructed northern North

Atlantic SST is a pronounced, nearly one-century long cold phase around year 1250 AD, which is also seen in the IPSL-CM4 model and coincides with a cluster of decadally-paced volcanic eruptions.

++Core Theme 2: Assessing sources of uncertainty in ocean analyses and forecasts. CT leaders: Steffen M Olsen (DMI). WP leaders: Uwe Mikolajewicz (ZMAW), Arne Biastoch (GEOMAR), Marie-Noelle Houssais (LOCEAN)++

Climate forecasts are inevitably subject to uncertainty or 'error bars' of various types. This includes structural sources of uncertainty that are generic to all currently practical forecasting systems. Such uncertainty arises from

- limitations of current observations and analysis systems
- generic limitations in climate models, specifically the lack of explicit modeling of fresh water input from the Greenland Ice Sheet and
- poor resolution of key, small-scale components of the thermohaline circulation

Processes such as sill overflows, eddies and boundary currents, play a key role in redistributing fresh water inputs and so modulating the thermohaline circulation and are the focus of Section 3. Section 2 deals with the generic limitations addressed in part in a multi model sensitivity experiment. Section 1 summarizes results on the
Science outputs of this core theme feed into an overall assessment of priority areas for the future development of observing systems, models and data assimilation capacities.

__Uncertainties in ocean analysis__

Evaluation of the ocean simulations has been pursued with a focus on improving the representation of some key THC variables in models. There are limitations of current ocean analysis and thermohaline circulation state estimates which relate to the model thermohaline circulation sensitivity and stability. Improvements have been identified in relation to model resolution and data assimilation. More specifically:

- The impact of assimilating various types of ocean observations in key regions of the THC has been further investigated. The work in assimilating the RAPID 26°N MOC observations into the Met Office Decadal Prediction System (DePreSys) has been carried out in an idealised setting where we know the exact MOC and the exact temperature and salinity at all locations.
- High resolution, eddy resolving simulations of the Nordic Seas/Greenland Scotland Ridge/North Atlantic subpolar region could be finalized and compared with reference experiments having coarser horizontal resolution in this region.

- Models have been evaluated against a series of key observations gathered within THOR (e.g., western boundary section at 53°N, Faroe-Shetland Channel) and from existing observations including satellite altimetry, hydrography and CFC distribution.
- A new dataset of validated historical surface salinities has been constructed which allows for reconstruction of the ocean surface variability in the Atlantic Ocean over the last decades and in the subpolar gyre over the last century. This data set can be used as suitable information to validate or constrain future ocean analyses.

Main results:

- Based on an idealized setting applied to the DePreSys system, it was shown that assimilating MOC transports at 26°N (the latitude of the RAPID array) improves the prediction of the MOC compared with assimilation of temperature and salinity only in the 13°-28°N latitude band.
- Realistic representation of ocean transports in keys passages of the Greenland-Shetland Ridge or in the Arctic Strait (Fram Strait and Arctic Canadian Archipelago) requires using high resolution models in order to capture the complex structure of the flow there. Still, ocean models with moderate resolution (0.25°-1°) appear to produce consistent estimates of the mean transports and, for some of them, of their interannual variations. This is a robust result across the different ocean simulations or analyses evaluated against observations.
- High resolution, eddy resolving models of the subpolar North Atantic/Nordic Seas have been shown to produce realistic eddy activity in the boundary currents.flowing around the different basins and at some locations of the Greenland-Scotland Ridge. Eddy flux calculation indicate that these eddies may be responsible for substantial heat and fresh water exchanges between the periphery and the interior of the basins (see also WP2.3).

Greenland Ice sheet

Climate forecasts are inevitably subject to uncertainty of various types. We have tackled 'structural' sources of uncertainty that arise from generic limitations in the current generation of climate models, specifically the lack of explicit modeling of fresh water input from the Greenland ice sheet in case of global warming.

The feedbacks between ice sheet and climate have been investigated with a novel coupled atmosphere-ocean-ice sheet model. The model yields a realistic climate and runs under conservation of mass and without any flux corrections. The model has been forced with different idealized scenarios of anthropogenic greenhouse gas concentrations. The melting of the Greenland ice sheet and its impacts have been assessed by comparing identical simulations with and without actively coupled ice sheet algorithms. Additionally these results have been evaluated against a single existing run using an entirely different climate model (HadCM3) coupled to a different ice sheet model. The comparison of all these simulations has shown the roles of modeling uncertainty and forcing scenario uncertainty; please inspect the already submitted deliverable D14 “Assessing modeling uncertainty: Greenland ice sheet”. One conclusion is that the uncertainty between different models is still significant and cannot be ignored.

To access further the earth system model uncertainty and to estimate the likelihood of a major THC change, we performed fresh water hosing experiments in an ensemble of five coupled climate/earth system models under a strong anthropogenic forcing climate projection. Since this work is part of the remaining work report, we like to direct you to the coming pages.

Our results indicate that:

- The reduction of the AMOC varies significantly between different climate models in a strong warming scenario regardless if additional melted fresh water enters the ocean along the coast of Greenland.
- In the coming decades the melt flux from the Greenlandic ice sheet seems to have a negligible influence on the AMOC.
- On longer time scale the impacts of the combined effects of warming and fresh water release around Greenland on the AMOC can be larger than the isolated effect, if the AMOC is more stable than the current generation of climate models suggests; please see deliverable D22 “THC sensitivity and ocean-ice-atmosphere feedback studies completed”.
- The computed melt fresh water release rates from the Greenland ice sheet are also subject to uncertainties in the ice sheet model. These have been discussed in the deliverable D33 “Assessing modelling uncertainty: Greenland ice sheet”.

*<u>**Ocean freshwater distribution**</u>*

Hindcast simulations were performed in a hierarchy of ocean-only models ranging from coarse-resolution and global coverage (0.5°) up to 0.05° high-resolution, regional coverage of the subpolar/subarctic North Atlantic. All experiments have been used to evaluate the impact of increased resolution on the dynamics in the subpolar North Atlantic and the Nordic Seas and the exchanges through the Greenland Scotland Ridge. A strong effort has been made to compare the experiments at different resolution with observations in the western boundary current system at 53°N (which made available through the observational components of EU-THOR). For the representation of deep western boundary current it was found that highest resolution (0.05°) is not only needed at this particular latitude but also further upstream, e.g. in the Denmark Strait where coarser (but still high resolved) models (0.125°) are not able to correctly simulate the spreading of deep water through the Denmark Strait and along the continental slope off Greenland. In contrast, the observed warming trend at 53°N was correctly represented independent of the resolution.

++Core theme 3 Observations of the North Atlantic thermohaline circulation. CT leaders: Svein Østerhus (UiB), S. Jónsson (MRI)++

__Fluxes across the Greenland-Scotland Ridge and in the boundary current__

THOR has maintained sustained observations on a number of different sections with the aim to generate time series of properties (temperature and salinity) as well as volume flux of various components of the North Atlantic THC. The observations include monitoring of the exchanges across the Greenland-Scotland Ridge, monitoring the outflow from the Labrador Sea, and monitoring the total Overturning Circulation at 26.5°N. This combination allows a comparison between independently measured contributions to the NA-THC to clarify how consistent values for various sources and total Overturning Circulation are with one another.

The flow of Atlantic water (Atlantic inflow) across the Greenland-Scotland Ridge (GSR) is critical for conditions in the Nordic Seas and Arctic Ocean by importing heat and salt. This flow has been monitored since the mid-1990s by those institutions which in 2008 joined the THOR project. Based on these observations and model results, we conclude that the volume transport of the Atlantic inflow has not changed significantly since 1950 whereas the temperature has increased after 1995. The deep return flow, the Greenland-Scotland Ridge overflow, is also monitored by THOR and from the more than 10 years long time series we can conclude that the volume transport has not weakened consistently. During the second half of THOR, we have put extra effort into the observation system in the Faroe-Shetland Channel where we have deployed additional ADCP moorings. These new observations have been combined with the existing ADCP measurements and altimeter data from satellites. From this effort we have managed to construct a 20 year long time series of the Atlantic transport through the Faroe-Shetland Channel.

The Atlantic inflow and the return flow across the Greenland-Scotland Ridge form the northern limb of the thermohaline circulation in the North Atlantic and we can conclude that the strength of this overturning circulation has not changed significantly over the last decades. Our now two decade long time series of volume transport have been used to validate ocean circulation models with good results.

__*Water mass formation south of the Ridge*__

One of the key areas for the ventilation of deep water masses is the central Labrador Sea and the Irminger Sea. Here THOR scientists have maintained moored stations which continuously observe the modification of Labrador Sea Water (LSW) year-round, resulting in one of the few decadal-plus time series in the world ocean. The export of this newly formed water occurs predominantly through the boundary current off Labrador. However, THOR-affiliated research has shown that while the upper ocean has slowly, yet significantly warmed for more than 10 years, the boundary current has not shown any long term trends of the deep circulation.

Throughout the whole THOR period we have monitored the water mass evolution of two areas in the source region of the Meridional Overturning Circulation (MOC). These areas, south of the Greenland-Scotland Ridge are the Labrador- and the Irminger Sea's, both of which are known or hypothesized to experience deep open ocean convection and water mass formation. The data are being used to provide information regarding the variability of the processes (convection and water mass formation) on time scales from weeks to several years. They also serve to validate products from the modelling / assimilation efforts, and in turn use model output for relating discrete observations to the basin wide scale. Also the Water mass mooring data are being used (T/S) in assimilations for an optimum 50-year THC-estimate. In the Labrador Sea, timely data transfer at 4-6 months periods was achieved through an innovative data shuttle system developed in core them 5.

<u>*Process studies*</u>

The turbulence activity and the mixing of overflow water masses beyond the Greenland-Scotland Ridge add, through entrainment, to the volume flux of the overflow plume and thus the strength of the deep western boundary current and the overturning circulation. In a number of field experiments, involving ship borne and moored observations, the processes triggering mixing have been studied south of the Denmark Strait and downstream of the Faroe Bank Channel.

Bottom generated turbulence as well as interfacial instabilities were found. The properties of the overflow water masses in Denmark Strait varies strongly in time, indicating that the overflow plume carries different waters that mix in the plume downstream from the sill. This suggests that much of the observed downstream property changes are due to internal mixing in the plume and the entrainment of ambient water is less conspicuous. It was found that two sources of turbulence exist, interfacial turbulence generated by Kelvin-Helmholtz instabilities and turbulence within the homogenous part of the plume created by bottom friction. The bottom generated turbulence appeared to be the strongest. In thicker plumes the turbulence intensity generally had two maxima, one close to the bottom, and the other around the interface. In such cases, and perhaps also more generally, the turbulence created at the interface might, because it is active close to the interface between the plume and the ambient water, contribute more to the entrainment into the plume. Only in cases of a thin overflow plume may the bottom induced turbulence contribute to the entrainment.

The entrainment ratio E, defined as the ratio between the vertical turbulent velocity and the horizontal average velocity, was in the observations 2012 found to be was about $5 \cdot 10^{-5}$. This is in the lower range of reported values of entrainment ratios.

Lateral mixing through eddy activity, however, appears to be an important mechanism for widening the overflow plume and exchange heat between the plume and its surroundings. During a METEOR cruise in summer 2010 three bottom mounted ADCP moorings with additional instruments measuring temperature and salinity were deployed some 150 km south of the Denmark Strait sill. These were recovered a year later and provided high resolution time series for up to 10 months length. The preliminary analysis of this pilot study in the Denmark Strait overflow confirmed the significant role played by energetic submesoscale processes in the region, and contributed important insights incorporated in the design of the more extensive follow-up experiment (MERIAN MSM21). This experiment that was carried out during late summer 2012 during the final phase of THOR will allow us to quantify the contribution of submesoscale dynamics to the entrainment in the overflow.

++Core Theme 4: Predictability of the thermohaline circulation. CT leader: W. Hazeleger (KNMI)++

Retrospective multi-year global forecasts were set up and evaluated for the Atlantic region. State-of-the-art Global Climate Models from leading European climate research institutions were initialized with the best known observed state of the oceans, sea ice, land and atmosphere. Initializing the climate models with an estimate of the observed climate state leads to improved skill in multiyear predictions. It was found that the North Atlantic is the key region where skilful multiyear predictions can be constructed. The source of the predictability is both the oceanic state and the slowly changing external forcing by greenhouse gases and aerosols. Additional sensitivity experiments were setup to explore the impact of observational coverage, the impact of initial state versus external forcing and the impact of optimum perturbations. The various experiments address the impact of the Atlantic Ocean state in improving the skill of multiyear forecasts.

Predictability of the THC

Multi-model predictions up to 2030 have been analysed and compared to non-initialized historical simulations and projections using the RCP emission scenarios. The results show varying responses among models and further analysis indicates that it is hard to obtain a signal from initialization at these multidecadal time scales.

Work has been done on setting up a bench-mark statistical prediction in order to verify the increased skill by initialisation of the ocean and atmosphere in global climate models. The results indicate that for surface variables for multi-year lead times the dynamical models show better skill in the North Atlantic. Extension of the predictions up to 2030 is described in details in the deliverable report D40, where it is shown that model uncertainty dominates.

The groundwork has been laid down for a semi-operational decadal prediction facility. A first exchange of predictions between all major groups world-wide has been done and documented. Three THOR CT 4 modelling groups (MET O, KNMI, MPG) contribute to this and one of the partners (MET O) coordinates this activity. It will be updated each year with a new set of forecasts. UREAD contributed to this activity with statistical predictions that serve as a benchmark for dynamical coupled model forecasts.

The effect of initial state versus external forcing on the predictability has been quantified using two different start dates and exchanging the forcing and initial states and for different variables (including AMOC). This has been done in 4 different model systems (run by ECMWF, MET O, KNMI, MPG). At a few years lead time the effect of initial state dominates over external forcing in surface and subsurface variables. Pronounced differences between models are found, but also robust results are found.

The main conclusions are the following:

- There are indications of skillful multiyear predictions of climate variables associated with North Atlantic surface ocean variability, such as Atlantic tropical storm frequency and changes in precipitation in the southern USA following the rapid warming of the sub-polar gyre in the mid 1990s.
- Optimal perturbations for initializing decadal predictions (or 'singular vectors' - SVs) have been constructed for the THOR models and it is found that the most sensitive ocean regions to small perturbations were found in the far north Atlantic, and that these anomalies grew through a subsequent change in the Atlantic Meridional Overturning Circulation (AMOC).
- Multidecadal forecasts of the AMOC are strongly hampered by the large spread originating from model uncertainty. Some models show hardly any AMOC change in the next 2 decades and some a reduction.
- Model uncertainty is by far the largest contribution to the total uncertainty at lead times until the end of the 21th century. The internal variability significantly contributes during the first few decades, while the emission scenario uncertainty is relatively small at all lead times.
- Differences in the salinity budget in the Atlantic are one of the main sources of model uncertainty.

Impact of Ocean Observations on THC predictions

Retrospective decadal climate predictions and idealised model experiments have been performed to assess the impact of observations on forecast skill and to identify the key observations required.

Multi-model observing system simulation experiments (OSSEs) were performed using pseudo observations typical of the real world both before and after Argo became available. A range of different techniques for using the pseudo observations to initialise coupled models were used. To a lesser or greater extent all models showed predictability when either the 2008 (with Argo) or the 1990 (without Argo) type observations were used. Both sets of observations provided forecasts that were clearly better than a persistence forecast. The current observing system (2008), that includes the Argo array of profiling floats, gives better forecasts of the MOC than previous (1990) observing networks – although we only find this to be statistically significant for the first five years.

We present initialized predictions of the Atlantic Meridional Overturning Circulation (AMOC) up to 2030 according to the CMIP5 protocol. The models show substantial spread, with some model systems showing a slight decrease in strength and others no change at all.

In order to interpret these results we have investigated the strength of the AMOC and its link to the freshwater budget of the Northern Hemisphere by analyzing the Coupled Model Intercomparison Phase 3 (CMIP3) and Phase 5 (CMIP5) projections for the 21st century. The quantification of the different sources of uncertainty in the projections, i.e. scenario, internal and model uncertainty, reveals that model uncertainty is by far the largest contribution to the total uncertainty at lead times until the end of the 21th century. The internal variability significantly contributes during the first few decades, while the scenario uncertainty is relatively small at all lead times.

The individual contributions to the model uncertainty originating from wind stress and density (salinity and temperature contributions) have also been analyzed. We find that the uncertainty originating from the simulation of salinity contributes most to the total model uncertainty, which can be traced back to the uncertainties in the simulation of the North Atlantic freshwater budget. The strongest changes in the AMOC strength are projected around 40°N, whereas the largest signal-to-noise ratio is located further to the south. The signal-to-noise ratio of the freshwater flux is particularly low in the Arctic and in the subpolar latitudes, suggesting a strong need for atmosphere model improvement in these regions. Overall, the results from the CMIP5 model ensemble basically confirm those from the CMIP3 ensemble.

The main conclusions are the following:

- Initialization of climate models with observations leads to improved skill of predictions of variability of north Atlantic sea surface temperatures (SSTs) and subsurface ocean temperature and salinity variability up to 6-9 years.

- The reliability of multiyear predictions of temperatures in the north Atlantic and at adjacent continents increases when initializing prediction systems with an estimate of the observed state of the climate
- The skill of the initialized predictions at multiyear time scales (up to 6-9 years) in the subpolar gyre of the North Atlantic exceeds that statistical models and exceeds those obtained from models initialized from an equilibrium model state instead of observations.
- Observations of ocean temperature and salinity in the upper 2000m enable skilful initialization and prediction of the AMOC in idealized model experiments. **ARGO** floats provide such observations in near real time. The skill is improved with additional spatial sampling provided by **ARGO** floats.
- Experiments show improved skill with additional observations below 2000m, especially in the Southern Ocean. Full depth **ARGO** observations would therefore be desirable.
- Assimilation of atmosphere data improves the skill for the first year. Near real-time atmospheric data are therefore desirable for seamless predictions.
- The current observing system (2008), that includes the **ARGO** array of profiling floats, gives better forecasts of the AMOC than previous (1990) observing networks – although we only find this to be statistically significant for the first five years.

++Core Theme 5: Technological advancements for improved near-real time data transmission and Coupled Ocean-Atmosphere Data Assimilation (and initialization). CT leaders: M. Visbeck, Johannes Karstensen (GEOMAR), Detlef Stammer (UHAM)++

Core theme 5 was dedicated to the development of new near-real time data transmission systems and of coupled ocean-atmosphere data assimilation techniques. Both aspects are of importance for a thermohaline circulation decadal prediction system.

Ocean observations serve two main purposes in THC/ocean prediction systems: Provision of data that is used to construct **initialization** fields and which are used at the beginning of a numerical simulation to define the oceans state, and observations at key location to be used for **verification** of the simulated fields. Initialization fields are constructed from observational data that has been sampled over large ocean areas. As such recent and historical ship survey data or autonomously collected data (e.g. ARGO floats) is utilized for this purpose. For the verification of the simulated fields, adequate reference data, collected at key locations is required which allow deriving suitable metrics to compare model and observations, such as spectral characteristics of the flow, mass transport variability or temperature changes.

Near real-time data transmission

Essential for initialization as well as verification is the data access and in CT5 two subsurface data telemetry systems have been defined, designed and tested. Both systems collect and broadcast data that has been retrieved from multiple instrumentation connected to a main data collection node. For the **Bergen system**, which is a design effort from the University of Bergen and Aanderaa Data Instruments AS (AADI), this collection node is read out by underwater acoustics from bypassing ships. The system was tested at different locations and is now commercially available via AADI. For the **Kiel System**, a design effort from the GEOMAR and OPTIMARE, the data in the collection node is copied to data capsules, which rises, at defined time steps, to the surface and broadcast the data via satellite communication.

Coupled ocean-atmosphere assimilation capabilities

The initialization of state-of-the-art Global Climate Models requires the computation of estimates of the observed present day climate state from sparse observations. To this end data assimilation systems are designed to integrate information from observations and dynamical models into estimates of the time dependent state of the climate system. From the various existing assimilation techniques, the adjoint method was chosen because it allows to simultaneously adjust an arbitrary number model parameters in order to bring the model into agreement with the data, thereby producing initial states that are not only in consistent with the data but also in agreement with the model dynamics. This is important in order to reduce initialization shocks or model drifts after initialization. A pilot data assimilation system was built around a newly designed coupled earth system model and initialization experiments were carried out with the coupled MIT General Circulation Model /UCLA climate model in order to test the performance of different initialization techniques.

- A coupled climate model was constructed by coupling the MITgcm ocean model and the Planet Simulator (Plasim). These components were chosen because for the MIT model and one major component of the Planet Simulator (the Portable University Model of the Atmosphere, PUMA) already an adjoint model existed at project beginning.
- Model configurations of different resolution were created, tuned and tested.
- The adjoint of Plasim including all sub-components was created through the automatic differentiation tool Transformation of Algorithms in Fortran (TAF).
- The Plasim configuration was shown to be successful for the estimation of control parameters: First, identical twin experiments, which recover control parameters from pseudo-observations generated by the model. Second, assimilation of reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).
- In this simple set-up the optimized control parameters clearly improve the forecast quality.

- The adjoint and tangent linear model of the coupled MITgcm/Planet Simulator configuration was created and tested. Numerous assimilation experiments show that the performance is highly dependent on the selection of atmospheric processes and the implementation of their formulation. A reduced atmospheric configuration with a number of processes deactivated shows significantly better performance than the standard configuration, while inclusion or exclusion of the dynamical ocean component has only a minor effect.
- Hindcast experiments were run with the UCLA/MITgcm model initialized from the GECCO synthesis using different initialisation strategies: full state initialization (FSI), anomaly initialization (AI) and full state initialization employing flux correction (FC).
- Sea surface temperature (SST) anomalies remain significant for up to a decade over parts of the North Atlantic and the extratropical Southern Hemisphere in FC experiments, in contrast to FSI, which shows less persistent skill, and AI, which does not show high skill in the extratropical Southern Hemisphere.

4) Potential impact (including the socio-economic impact and the wider societal implications of the project so far)

Incoming solar radiation heats the lower latitudes much more than the Polar Regions and creates a strong Equator-to-pole temperature gradient. The circulation systems of atmosphere and ocean (winds, currents) moderate this temperature difference. In the Atlantic, this transport of heat amounts to more than 1 Peta Watt which is more than 60 times the global energy production. One petawatt is a tremendous amount of energy. *Peta* stands for 1,000,000,000,000,000, or ten to the power of 15 (10**15): to put this into perspective, consider a huge nuclear power plant that produces a gigawatt (ten to the power of 9, or 10**9 Watt). It would need a million (10**6) such power plants to make up for a petawatt.

The associated Thermohaline Circulation (THC) manifests itself as a system consisting of warm surface currents, such as the Gulf Stream or the North Atlantic Current, deep return flows at the western boundaries of the Atlantic, relatively localized sinking and funnelling regions and the Southern Ocean as a connecting basin. While the energy driving the THC comes from input of turbulent energy from tides and winds, the strength of the overturning depends crucially on the ability of the northern sinking regions to produce dense-enough water. Variations in the water mass properties (temperature and salinity) in the Nordic Seas and the subpolar North Atlantic can modulate the THC. During Ice Ages and during the transition from the last Glacial Maximum to the present Interglacial, pulses of water from melting continental ice sheets freshened surface waters leading to temporary weakening of the THC with drastic consequences for the living-conditions of animals and humans and for early societies.

In addition to changes induced by melt-water input or variations in other external drivers, such as solar irradiance, feedbacks within the ocean or in the coupled ocean-atmosphere system can lead to substantial internal variations in the overturning circulation. For example, a temporary cooling in the sinking regions can lead to more deep water formation, which then causes a stronger THC. The increasing heat transport then carries warmer water into the sinking regions, warming the region and reversing the cycle. The situation is more complex in reality and involves interactions between the atmosphere and ocean and the heat and salt-budget of the ocean. The resulting variations in the overturning circulation and its associated heat transport have a measurable influence on climate, in particular in the regions surrounding the North Atlantic. For example, a warmer North Atlantic releases more heat to the atmosphere that is then redistributed by the wind systems that determine the climate of Western Europe.

The instrumental record of North Atlantic sea surface temperatures (SST) indicates substantial variations on decadal to multi-decadal time-scales. It is this low-frequency component of the climate system that THOR aims to explore for near term predictions (see WP4 Final Report). Unfortunately, SST observations are only available for the last 100 to 150 years. The time series, say of the average temperature of the North Atlantic, suggest a quasi-oscillatory behaviour as a type of internal variability of the ocean. However, it is not clear if a more-or-less sinusoidal character with a fixed period can be extended back into the past. Moreover, the SSTs may also be influenced by external drivers, such as the radiative cooling that occurs after a volcanic eruption when large amounts of ash are transmitted into the stratosphere shielding the sunlight. These uncertainties in how and why the ocean varies naturally, both with and without forcing, make it more difficult to predict its future behaviour.

++ Core Theme 1: Quantifying and modeling THC variability using palaeoclimate observations and simulations ++

In THOR Core Theme 1 we have explored the decadal to centennial-scale variability of the THC and investigated its evolution through the 1000 years preceding the industrialization (i.e. 850 – 1850 AD) using both long-term climate simulations (THOR work package WP 1.1) and paleoceanographic reconstructions (THOR work package WP 1.2). The last millennium provides a reference frame for the current climate change and includes also periods where climate and environmental conditions were important for the development of the civilization in the North Atlantic sector. This includes climate-related economic growth, but also hardships such as famines or even the collapse of societies, such as the Norse settlements on Greenland during the Little Ice Age.

The recent generation of climate models is able to reproduce the essential factors of the climate system, for example the overturning circulation and the heat transports in ocean and atmosphere. THOR WP1.1 assessed THC-related variability in a suite of coupled atmosphere-ocean models that were provided by the THOR partners.

Paleoceanographic observations are mainly based on marine sediment cores. The layering of sediments on the deep ocean floor over thousands of years provide a time-history of the properties of the overlying ocean. Sediment records have become increasingly detailed and reflect not only water mass properties, but also on the flow strength of bottom currents, or provide information on sea-ice coverage. THOR WP 1.2 targeted core sites on high-resolution marine sediment drifts in the North Atlantic Ocean, which provides unprecedented detailed climate archives. These sediment drifts are deposited over time as a result of the overflowing branches of deep water from the Nordic Seas that erodes, transport and deposits sediments along their flow-path. The two largest sediment drifts, the Erik drift south of Greenland and the Gardar drift south of Iceland are found along the flow-path of the Danish Strait Overflowing Water (DSOW) and the Iceland Scotland Overflow Water (ISOW) respectively.

In THOR WP1.1, we studied, as a first step, the internal variability in so-called control simulations. In these experiments, the boundary conditions reflecting external forcing (e.g., solar radiation) are kept constant over time. In the THOR models we diagnosed consistent features of AMOC variability. For interdecadal to multidecadal time-scales, the subpolar gyre (SPG) in the North Atlantic has been identified as a key region. The SPG geometry, its strength and dynamics determine not only deep water formation processes in the Labrador Sea but also the heat and fresh water exchange between the Atlantic and the Nordic Seas. These processes as well as the interaction of ocean the atmosphere, give rise to near-term predictability in the North Atlantic/European sector. For the centennial time-scales, the Southern Ocean becomes important, and the existence of pronounced Southern Ocean centennial variability is supported by climate model simulations, instrumental sea surface temperatures and multi-millennial reconstructions.

The influence of THC variations on the atmosphere has been assessed. In the THOR models we have detected a robust atmospheric response. As a consequence of a stronger-than-normal THC there is a typical atmospheric circulation pattern associated with the relative strength of the large-scale pressure systems over the North Atlantic.

While the THOR models generally agree with each other and with observations, we also identified differences between models in details of the changes and in the relative importance of the underlying mechanisms. . Further research is necessary on model improvement as well as a continuation of the observational campaigns, which provide a reference for the simulations.

As a second step, we investigated simulations where we prescribe time-varying estimates of external drivers for the last millennium (850-1850 AD). The forcing factors are: variations in the solar irradiance, input of volcanic aerosols into the stratosphere, changes in land-surface properties by land-use-changes, and the variations of trace gases that affect the atmospheric radiation budget (a.k.a greenhouse gases). We compared both simulations to identify the relative role of the forced vs. the internally varying changes.

A major outcome from CT1 is that external drivers have a larger and longer-lasting impact on the THC than previously thought. For example, it was demonstrated that the cooling of the subpolar waters together with atmospheric circulation changes in the aftermath of a volcanic eruption can lead to acceleration of the deep water formation and of the THC itself. The momentum introduced by such changes in the ocean circulation extends the time span of the volcanic effect to a decade or two, whereas the direct effect on the radiation only lasts for one to three years.

For decadal climate predictions the finding has two consequences. On the one hand, a potential volcanic eruption would overrule the internal variation of the ocean circulation, which is thought to be a carrier of the slowly-varying climate signal. In fact, a volcanic eruption could make obsolete a near-term climate prediction. On the other hand, knowing how the ocean and atmosphere system will react after an eruption reveals potential for predictions once an eruption has taken place. In particular the latter could be of important socio-economic value.

In THOR WP1.2 we reconstructed the decadal-centennial scale variability in the properties and intensity of the individual deep branches of the THC over the last millennium. Bottom water properties and vigor were determined with geochemical analyses of bottom dwelling calcareous microfossils and sediment grainsize measurement, whereas SST and sea surface salinity (SSS) reconstructions were determined from near surface dwelling calcareous microfossils. The paleoceanographic reconstructions in WP 1.2 provide evidence of significant natural climate variability on multi-decadal to century timescales over the last millennium. The most recently recorded climate oscillations such as the Little Ice Age are particularly well defined and thus offer a natural starting point for understanding their origins.

The surface water properties spanning the past 1400 years was reconstructed at the Eirik sediment drift site. The proxy data exhibit centennial-scale variations characterized by several distinct cooling trends, the most pronounced being abrupt coolings around 1000 and 1450 AD, the latter is coincident with the timing of the Little Ice Age. These cooling events are closely tied to historical events (cold and famine on Iceland and the demise of the Norse colonies on Greenland, respectively). There is furthermore evidence for persistent deep-water circulation and temperature/salinity changes over the past 1400 years, suggesting an active role for deep water—surface coupling in shaping our climate on multidecadal to centennial timescales.

The new paleoceanographic records from the Eirik drift imply that the THC have played an active role in the Little Ice Age. Having quantified how the ocean changed, we were then able to use the modeling results from WP 1.1 to explore the importance of external drivers to the climate system like volcanoes and solar irradiance in forcing the observed climate variability.

Our paleoceanographic reconstructions from the Gardar sediment drift which monitors the eastern Nordic Seas overflow document multi-decadal and centennial variability in ISOW vigor spanning the past 600 years. The proxy data shows covariance between variations in the eastern Nordic Sea overflows and basin wide climate and thus provide empirical support for the hypothesis that multidecadal climate variability is linked to changes in overturning circulation in the Nordic Seas.

As a synthesis of the work packages 1.1 and 1.2 we combined model simulations and reconstructions. Paleoceanographic reconstructions are available only point wise and are still rather scarce. Moreover, they do not give information on the processes and mechanisms that lead to the recorded variations, for example, changes in the ocean circulation. Here ocean and coupled climate simulation models come into play. In the models we have access to the complete field of properties and current speeds. We demonstrated that the properties and flow strength of the deep near-bottom flows to the south of the Greenland-Scotland-Ridge are quite well reproduced in the models and show variations over the last millennium that are similar to the ones obtained from reconstructions. Analyzing the models we were able to identify the reason why deep ocean flow strength and the basin-wide SST co-vary on decadal to centennial time scale.

THOR has improved our understanding of the variability in the North Atlantic Ocean and its surrounding regions and has put the observed climate variations into the context of the last 1000 years. The importance of this region for the world's economy and the possible societal impacts of THC-related climate variations reflect the important socio-economic value of the THOR research.

++ Core Theme 2: Assessing sources of uncertainty in ocean analyses and forecasts ++

Climate variability on decadal and longer time-scales is commonly accepted to be closely linked to the strength of the ocean thermohaline circulation and the associated heat transport toward the Arctic. Similarly, changes in the thermohaline circulation, or collapse of, is believed to have caused abrupt climate changes under glacial climate conditions.

The scientific basis for these hypotheses is yet not fully developed for two main reasons. On one side we can count on limited observations. On the other side, we have not yet successfully in modelled the climate variability of the past using coupled climate models (i.e. models which combine ocean and atmosphere elements).

Inevitably, forecasts based on models and thus assessment of the stability of the thermohaline circulation are subject to uncertainty (i.e. error bars) of various types. Structural sources of uncertainty are generic to all currently practical model forecasting systems. Assessing these uncertainties has been the focus of Core Theme 2 of the THOR project.

Confining the state of the ocean and thermohaline circulation

Science outputs of Core Theme 2 feed into an overall assessment of priority areas for the future development of observing systems, models and data assimilation systems. This includes identification of a set of minimum requirements for a quasi-operational decadal thermohaline circulation prediction system based on assessment of present limitations.

In the current ocean observing system, two types of data are found to provide the strongest observational constraints on the actual state of the ocean THC in the ocean analysis systems used to initialize forecast systems:

- The near real-time measurements obtained by the ARGO floats, a global array of 3,000 free-drifting profiling floats that measures the temperature and salinity of the upper 2,000 meter of the ocean.
- The global scale measurements by satellite of the sea surface height changes reflecting ocean dynamics.

The maintenance of these two systems is considered a high priority of central societal value for the understanding of the behaviour of the thermohaline circulation. Moreover, profiles in the high-latitude of the North Atlantic are shown to be particularly important for decadal forecasts of the thermohaline circulation.

The societal value of the decadal forecasts rests partly in our ability to assess the limitations of the prediction systems and in highlighting the uncertainties of the forecasts. To achieve this, the targeted sets of observations which provide absolute transport measurements of the thermohaline circulation are essential:

- The THOR measurements from deep sea moorings and ship surveys of the transport of warm Atlantic water towards the Arctic at each of the different gateways across the Greenland Scotland Ridge, a choke point of the Thermohaline circulation.
- The THOR mooring programs in the core the deep cold return flow from the Arctic feeding the abyssal circulation of the World Ocean.
- The basin-wide line of deep sea moorings and instrumentation at 26.5°North, known as the RAPID array.

These estimates of the transport by the thermohaline circulation serve as independent data for evaluating the estimates of the ocean models underlying the forecasting systems.

A key issue identified in the THOR project is the need to develop long (multi-decadal) time series of these data in order to quantify and assess model uncertainty in predicted variability. Additional basin-wide transport estimates would greatly enhance our understanding of the overturning circulation and provide a more powerful data set for evaluation of the state of the ocean circulation and guiding model developments.

Runoff from the Greenland Ice sheet

Very recently, the increase rate of Greenland Ice Sheet melting has raised with urgency the question of the impact on climate. Most of this melting is released into the subpolar Atlantic and may here induce large changes, potentially exceeding reported historical changes. An estimated sea level rise of 35cm in 2100 is plausible with an associated melting rate at that time of 80.000 cubic meters per second. If this additional freshwater shows sufficient to cap the sites of dense water formation in the central gyres of the subpolar and polar seas by light, brackish water, it may affect the stability of the thermohaline circulation and climate by affecting its supply of heat to the northern high latitudes.

Model experiments conducted in THOR Core Theme 2 tried to find out how stable the thermohaline circulation is when exposed to multiple stresses, such as global warming and additional freshwater input at high latitudes. Our findings partly contradict the expectations and are derived from climate sensitivity experiments to Greenland Ice Sheet mass loss by using current generation climate models.

In our experiments, the stability of the thermohaline circulation has been evaluated under past and future climate conditions. The results of THOR experiments are summarized below into a set of statements which also serve to prioritize future model development:

- During the next few decades plausible melt-water discharge rates from the Greenland Ice Sheet will only have a modest impact on the thermohaline circulation.
- In strong global warming conditions, ocean, thermohaline circulation n and climate sensitivity to Greenland Ice Sheet melting are reduced.
- Even under multiple stresses, the stability of the predicted thermohaline circulation rests in the climate models' ability to maintain a robust flow of warm water across the Greenland Scotland Ride and associated deep water formation and sinking in the Arctic.
- The main uncertainty in multi-decadal thermohaline circulation forecasts with current climate models arises from differences between climate models, the model uncertainty.

However, we also have to take into consideration the following issues:

- The assessments of climate model performance against observations have demonstrated that the models may systematically overestimate the stability of the thermohaline circulation and thus underestimate the sensitivity to melt water release from the Greenland Ice Sheet.
- Using process models with improved physics, we also found out that that the realism by which climate models represents key processes is inadequate. We are referring in particular to the representation of key processes of deep water formation and pathways of freshwater along the boundaries of ocean basins in the subpolar and subarctic domain.

++ Core theme 3 Observations of the North Atlantic thermohaline circulation ++

The northward flow of warm and saline Atlantic water across the Greenland-Scotland Ridge is one of the main factors determining the conditions in the Nordic Seas and the Arctic Ocean and it is considered to be the main reason for the relatively mild climate of north-western Europe. At the same time, the return flow of cold water that crosses the ridge at depth, the overflow, is the main contributor to the North Atlantic Deep Water, a key component of the global thermohaline circulation.

The heat carried northward by the Atlantic inflow is available to warm the ocean, atmosphere and land. The salt flux associated with the inflow balances the freshwater supply from atmosphere and rivers runoff to prevent the build-up of a thick freshwater layer in the convective gyres (e.g. the

Greenland Sea), thus allowing deep water to be formed. Paleo-oceanographic studies have demonstrated large variations in the North Atlantic Thermohaline Overturning Circulation and the North Atlantic- Nordic Seas exchanges (the northern limb of the THC).

In the last report from the Intergovernmental Panel on Climate Change (IPCC, 2007) scientists predicted that anthropogenic climate change may reduce the intensity of the Overturning circulation. This conjecture has been confirmed by most simulations using global climate models, but has been refuted by some models.

Within the THOR we have made direct observation of the exchanges across the Greenland-Scotland Ridge in order to observe the intensity of the northern limb of the THC. This is presently the only way to test this hypothesis. Adding the THOR observations to the existing observations we have manage to construct a almost 20 years long time-series of the transport of mass, heat and salt across the GSR. This unique time-series show no indication of a weakening of the intensity of mass exchange across the Greenland-Scotland Ridge. Despite of this, temperature and salinity is increasing. The increased temperature will amplified the rapid sea ice melting observed in the Arctic Ocean and have a strong influence on the migration routes for the rich fish stocks in the Nordic Seas.

South of the Greenland-Scotland Ridge in the Labrador and Irminger Seas the winter time deep water formation through open ocean convection is strongly reduced during the previous 15 years, leading to a steady increase in water temperature over the entire range of the subpolar North Atlantic, at a rate of 0.5°C in 10 years.

The deep water formed in the Irminger and Labrador Sea are mixed with the deep overflow from the Nordic seas and is floating southward in the Deep Western Boundary Current. The strength of this current is observed by the THOR array at the Labrador Sea exit. This reduced deep convection may have weakened the Deep Western Boundary Current and the thermohaline overturning circulation but the time series is too short to conclude.

++ Core Theme 4: Predictability of the thermohaline circulation ++

The weather of tomorrow is predictable, but the weather in two weeks from now is hardly predictable. Nevertheless, climate scientists may be able to predict the climate years ahead. It won't be possible to predict the weather on any particular day, for example the 19th of July of 2015, but scientists may be able to provide information such as the probability that the summer of 2015 will be warmer or cooler than normal in western Europe, or the number of very wet days to be expected in the next few years.

Such climate forecasts are possible because there are slowly varying factors that can influence the frequency of certain types of weather. An obvious example is the changing seasons, which enable us to say that there will be more European storms in winter than summer, although we cannot predict far ahead exactly when each storm will occur. Key for predicting the coming few years is the fact that the oceans contain large reservoirs of heat, and that climate is slowly changing due to increasing greenhouse gases and changes in aerosols in the atmosphere. Knowing the current state of the oceans, the mechanisms by which the slow ocean currents transfer heat from one place to another, and the release of this heat to the atmosphere forms the basis for predicting climate for the coming years. Also the slow changes in greenhouse gases and aerosols provide a source of predictions on top of the year to year variability. Complex climate models that describe the physics of the atmosphere, oceans, sea ice and land surface using fundamental laws of physics are used to make these predictions.

An ocean current of particular interest is commonly referred to as the ‘Warm Gulfstream’. To scientists this is better known as part of the Thermohaline Circulation, and has been the focus of the THOR project. This current system transports vast amounts of heat from the tropics towards the North where it is released to the atmosphere. Year-to-year variations in this current system can cause year-to-year variability in climate in many regions including Europe, Africa and North and South America, and forms the basis for multiyear predictions.

Within the THOR project predictions of the climate from 1 year ahead up to 10 years ahead were made. To do so, we used the complex climate models and knowledge of the state of the oceans.

We did this initially in retrospect to see how well it can be achieved. That is, we pretended to be in 1960 with no knowledge about the following 10 years and used our climate models starting from the state of the climate 1960 to “predict” 1961 to 1970. This process was repeated starting in several different years up to 2005. These tests show that the North Atlantic region is a special area where such predictions give more information than those obtained from very simple models using statistics or from just the response to rising greenhouse gases. In particular, changes in the oceans are sometimes predictable years ahead, together with related changes, such as hurricane activity and temperature and rainfall variations in some regions over adjacent continents.

To make these predictions, observations of temperatures in the oceans are needed up to at least 2 km depth. Currently this is provided by so-called ARGO floats. These floats sample every 10 days the upper 2 km of the oceans and send the data via satellite to a central data archive. Currently more than 3,000 floats are present in the oceans, each one lasting about 4 years. Measurements of winds, surface temperatures and ocean transports at key areas are also needed. It is a prerequisite of decadal predictions that the ocean observing system (such as that established by Global Climate Observing System, GCOS) is maintained. The other prerequisite is complex climate modelling system and access to state-of-the-art High Performance Computers and data storage.

THOR has been instrumental in setting up a quasi-operational decadal prediction system, where every year an update of the predicted climate of the next 10 years is produced. Such information is of great importance for emerging Climate Services. Many sectors of society are vulnerable to changes in climate, and therefore require reliable climate information at a regional scale in order to help them to adapt to climate variability and change. Since the time scales of investments in society are often months to years, decadal predictions can serve an important societal need. However, it is a challenge to organize the Climate Services in Europe, to provide the predictions to an operational service and tailor the climate information to the needs of stakeholders in the various sectors.

From a scientific point of view it is a challenge to improve the modelling systems (both the physics representation and the software), to maintain an integrated global ocean observing system and to maintain access to High Performance Computers. It is known that more detailed modelling, which requires larger computers, is beneficial for the skill of the predictions.

THOR demonstrated that skill in multiyear predictions does improve with better ocean data and multi-model prediction systems, especially in the North Atlantic region. Given the societal need for this type of information, continued effort is needed to address the scientific, observational and computing needs.

++Core theme 5 Technological advancements for improved near-real time data transmission and Coupled Ocean-Atmosphere Data Assimilation (and initialization)++

In the core theme 5 of the THOR project, scientists developed two data telemetry systems for oceanic observation and a numerical assimilation and initialization system that is able to provide an estimation of dynamically consistent initial conditions for climate prediction.

Deep sea data telemetry systems

Two deep sea data telemetry systems where developed in collaboration with small and medium enterprises in Norway and Germany.

Ocean observations serve two main purposes in the prediction systems of the thermohaline circulation. Observations provide the data used to construct the *starting fields*, also called initialization fields, from where a numerical simulation, a model, starts to calculate the future evolution and scenarios. Observations at key locations in the ocean can be used to verify the simulated fields and as such test the simulations against the reality. Initialization fields are constructed from observational data that has been sampled over large ocean areas. These data can be collected in two ways, thanks to ship surveys or through autonomously operating vehicles, such as ARGO floats. In the THOR project, during the entire period 2008-2012, we have collected data with the two systems.

For the verification of the simulated fields, scientists required adequate reference data, collected at key locations, because these data allow us to derive suitable metrics (i.e. mass transport variability or temperature changes etc.) for comparing model and observations with each other (ref: THOR Deliverable D42 “Report on the use of near real time data transmission systems and their potential to increase the accuracy of Atlantic Thermohaline Circulation assessments and predictions” can be requested to thor.eu at zmaw.de).

The observing system hardware design during the THOR project focussed on the retrieval of observational data from deep sea moorings. Two systems have been defined, designed and tested.

The **Bergen system** AADI SmartSub system, which is a design effort from the University of Bergen and Aanderaa Data Instruments AS (AADI http://www.aanderaa.com/), consists of a data collection unit that is read out by underwater acoustics from bypassing ships. The system was tested at sea at different locations (ref: THOR deliverables D18 “Report on test field deployment and system handling of the Kiel and Bergen systems” available: https://www.eu-thor.eu/Deliverables.1677.0.html and D29 “Report on the initial system performance of both systems”, which can be requested to thor.eu at zmaw.de). The tests can be considered a success and the system is fully operational, and is now commercially available via Aanderaa Data Instruments AS, a company located in Bergen (Norway).

The **Kiel OPTIMARE Mooring Pop-up system** is a design effort from GEOMAR and OPTIMARE, a company located in Bremerhaven, Germany (ttp://www.optimare.de). The Kiel system utilizes data capsules for telemetry. The capsules are stored subsurface and the observational data is subsequently uploaded. At predefined dates the capsules are released, rise to the surface and broadcast their data via satellite communication. The system was tested in the Baltic and the Irminger Sea and its functionality could be demonstrated (ref: THOR deliverables D18 “Report on test field deployment and system handling of the Kiel and Bergen systems” available: https://www.eu-thor.eu/Deliverables.1677.0.html and D29 “Report on the initial system performance of both systems”, which can be requested to thor.eu at zmaw.de). Some improvement of the data communications system is still required before commercialization. This system has proven to be a unique system, very suitable to the requirements of standard deep-sea mooring design.

The reason for implementing the systems into deep-sea moorings was to achieve intermittent data access without having to recover the instrumentation. Setting up and running a ship survey is quite costly, both in terms of staff, equipment and time. The two systems would allow for longer deployment periods of deep-sea mooring and for cost savings.

These systems are not just tailored for operating in the Northern waters: They could be adapted to operate in the Southern Oceans too.

In 2012, representatives of the THOR project joined presented both systems to the Southern Oceans Observing System (SOOS http://www.soos.aq/), focussing on sub ice observations. Both systems have been considered suitable for many of the planned observatories. Starting with 2013/2014, the Bergen AADI® SmartSub system will be used in the Southern Weddell Sea for process studies and long-term observations.

Numerical assimilation and initialization system

A new coupled adjoint assimilation model was developed within the THOR project: this is a new model that has the capability to assimilate climate data directly into a system that can be used subsequently for forecasting purposes.

The purpose of climate prediction is to provide information about climate variations and change one year to a decade and longer ahead. As opposed to Intergovernmental Panel on Climate Change type scenario computations, climate predictions – much like whether predictions – have to start from the actual present day climate state. This implies that an important step toward improved climate predictions is a best possible way to initialize coupled climate models from the observed state of the system. Until now initial conditions were constructed from observations either statistically or using only model-subcomponents, e.g., only an ocean model. Resulting fields were then incorporated into a coupled model system, causing several inherent problems. All this can be reduced or even avoided through an initialization procedure that is dynamically consistent with the coupled model used during the forecast procedure.

State of the art climate predictions rely on numerical models of the earth system. One of the major sources of uncertainty in these predictions is the correct representation and parameterization of the processes underlying the climate system the uncertainty in the initial state. The initialization of state-of-the-art Global Climate Models requires the computation of estimates of the observed present day climate state from sparse observations. To this end data assimilation systems are designed to integrate information from observations and dynamical models into estimates of the time dependent state of the climate system.

THOR made a unique contribution by constructing for the first time a coupled climate forecast system that is capable to estimate its own initial conditions through its data assimilation capabilities. For that purpose the adjoint of a fully coupled system was constructed and tested. From the various existing assimilation techniques, the adjoint method developed within THOR has the advantage that it allows to simultaneously adjust an arbitrary number model parameters in order to bring the model into agreement with the data, thereby producing initial states that are not only in consistent with the data but also in agreement with the model dynamics. Up to now, we have been using different models for prediction and for production of initial conditions, because no system capable of serving both objectives was at hand. Consequentially, currently available initial conditions are not consistent with the dynamics of climate models, which raises a major challenge because predictability is limited due to initialization shocks or model drifts after initialization. Several initialization techniques such as using different initialisation strategies e. g. full state initialization, anomaly initialization were tested to cope with inconsistences. We learned that a flux correction, which reduces the inconsistency, provides a small advantage. However, in order to fully address this problem a pilot data assimilation system based on the adjoint method was built around a newly designed coupled earth system model, which was constructed by coupling the MIT General Circulation Model (MITgcm, for more details on MITgmc: http://mitgcm.org/) ocean model and the Planet Simulator (Plasim, http://www.mi.uni-hamburg.de/index.php?id=216). These components were chosen because an adjoint model already existed both in the case of the MIT model and for one major component of the Planet Simulator (the Portable University Model of the Atmosphere, PUMA).

Initial test with this system provided confidence that such a system can be used for the estimation of initial conditions as well as model parameters in order to provide consistent initializations for coupled climate models. However, several limitations due to the nonlinearity of climate model became apparent, which need to be addressed in the future.

The result of the THOR adjoint model development effort is a internationally unique assimilation system which now can be used for coupled climate data assimialtion and which will be capable to improve our understanding of dacadal climate predictability by providing best possible initialization conditions. No other system will be capable to provide present day climate initial conditons that are optimal for this model forecast system. Resulting forecast therefore should be idel to test the predictive skill of various essential climate variables, test its limits and start to provide quantitative estimates of climate change as a function for time scale. The system offers more: it can be used to indentify new observations that, if incorporated could improve the forecasts. It also will help to identify the impact of different elements of the climate system on climate variability, such as changes over the Arctic versus the Atlantic, changes in sea surface termperature versus currents in the ocean, the impact of both on the climate of northern Europe, just to name a few.

5) Address of the project public website, if applicable as well as relevant contact details

Public website address

www.eu-thor.eu

Contact details

University of Hamburg, Institute of Oceanography, Bundesstr. 53, D-20146 Hamburg, Germany
Tel: +49 (0) 40 42838 7478 Fax: +49 (0) 40 42838 7447
Project coordinator: Prof. Dr. Detlef Quadfasel E-mail: detlef.quadfasel at zmaw.de
Project manager: Chiara Bearzotti E-mail: chiara.bearzotti at zmaw.de or thor.eu at zmaw.de
Data manager: Nuno Nunes E-mail: nuno.nunes at zmaw.de