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.

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) 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.

Note : 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.

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.
-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 were:

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: Assessment 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 were:
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 small and medium-sized enterprises (SME) 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.

Project Results:

Main Science and Tecnology (S & T) results/foregrounds are presented according to the core theme structure in the project.

The core theme structure in the project is explained in the website: https://http://www.eu-thor.eu/Core-Themes-Work-Packages.564.0.html

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-systems 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.

-Characteristics of AMOC and NASST variability in long-term simulations*
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) (List of reference: Nr.1), 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) (2), 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. On the other hand, this 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) (27), 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. (3) , 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) (4), 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. 2012) (5b), 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) (6) 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) (7) analyse 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) (8), 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 favouring 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. The findings obtained for BCM could be generally supported by studies using other coupled climate models. Mignot et al. (2011)(9) 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.) (10), analysing dedicated MPI-ESM-CR ensemble experiments covering early 19th century SVEs. Zanchettin et al. (2012) (11), using the MPI-ESM-CR model, have extended the Otterå et al. (2010) (12) 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.) (13).

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 cannot 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 (2011) (28) 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) (14). 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) (17), using the BCM, HadCM3, IPSL-CM4, IPSL-CM5, MPI-ESM-CR and KCM model, found 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. Response studies carried out with IPSL-CM4 (Msadek et al., 2011) (15) 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) (16) 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) (17) 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 favours a negative NAO state as found by Gastineau and Frankignoul (2012) (17) 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) (18) 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) (18) 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) (19).

-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 (II); Knudsen et al., 2010 (I)) 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) (20), 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. 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) (26), 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. 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 associated with AMV (e.g. GSR overflows and SPG geometry).

-Comparison of paleo-simulations and paleo-reconstructions

As discussed above, the reconstructed strength of the Iceland-Scotland overflow shows a strong similarity with paleo-reconstructions of the AMV. 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) (21) 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) (20). For IPSL-CM4, the low-frequency variability of the Iceland-Scotland overflow strength coincides well between the simulated and reconstructed time series. While the agreement with the overflow time series in the other models is less favourable, all three models show an in-phase variation between Iceland-Scotland overflow strength and AMV index. Lohmann et al. (to be submitted) (21) 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) (22). 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) (22). On multidecadal time scales, the reconstructed north-Icelandic SST shows a pronounced periodicity between 50 and 150 years. Menary et al. (2012) (2) and Sicre et al. (2011) (22) 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.

- Assessing uncertainties in ocean analysis (WP2.1)

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).

- Assessing modelling uncertainty: Greenland Ice sheet (WP2.2.)
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".

- Assessing modelling uncertainty: Ocean freshwater distribution (WP2.3)
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.

-Process studies

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 5'10'5. 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 skilful 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:
-the Bergen system, 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 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.

Ocean observations serve two main purposes in the prediction systems of the thermohaline circulation: 1) They provide the data used to construct the starting fields/ initialization fields from where a numerical simulation, a model, starts to calculate the future evolution and scenarios and 2) they can be used, at key locations in the ocean, to verify the simulated fields and as such test the simulations against the reality. Initialization fields are constructed from observational data sampled over large ocean areas thanks to ship surveys or through autonomously operating vehicles, such as ARGO floats.

For the verification of the simulated fields, scientists required adequate reference data collected at key locations, because these 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).

In the THOR project we have collected data with both systems: both systems collect and broadcast data that retrieved from multiple instrumentation connected to a main data collection node.

More in details:
-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/ online), 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://http://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 (see http://www.optimare.de online). 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 see http://www.soos.aq/ online), focusing 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.

-Coupled ocean-atmosphere assimilation capabilities

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.

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.

The THOR newly coupled adjoint assimilation model (Plasim) has the capability to assimilate climate data directly into a system that can be used subsequently for forecasting purposes. The THOR project 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. 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.

In brief:

-The coupled climate model was constructed by coupling the 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 online). 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).

-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.

The result of the THOR adjoint model development effort is an 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.

List of references

THOR scientist

1) Martin, T., W. Park and M. Latif, (2012), Multi–Centennial Variability Controlled by Southern Ocean Convection in the Kiel Climate Model, Climate Dynamics, doi:10.1007/s00382-012-1586-7, Published online: 28/11/2012

2) Menary, M., W. Park, K. Lohmann, M. Vellinga, M. Palmer, M. Latif, J. Jungclaus (2011): A multimodel comparison of centennial Atlantic meridional overturning circulation variability. Climate Dynamics, doi 10.1007/s00382-011-1172-4.

3) Ba, J., N. Keenlyside, W. Park, M. Latif, E. Hawkins and H. Ding (2013): A mechanism for Atlantic multidecadal variability in the Kiel Climate Model. Climate Dynamics, doi:10.1007/s00382-012-1633-4 , published January 2013

4) Medhaug, I, Langehaug, HR, Eldevik, T, Furevik, T, and Bentsen, M. , (2012), Mechanisms for decadal scale variability in a simulated Atlantic Meridional Overturning Circulation, Climate Dynamics, Volume 39, Issue 1-2, pp 77-93, doi:10.1007/s00382-011-1124-z, Published online: 25/06/2011

5a) Langehaug, H. R., P. B. Rhines, T. Eldevik, J. Mignot and K. Lohmann (2012b): Water mass transformation and the North Atlantic Current in three multicentury climate model simulations. Journal of Geophysical Research, 117 (C11), doi:10.1029/2012JC008021

5b) Langehaug, H. R., I. Medhaug, T. Eldevik, and O. H. Otterå (2011): Arctic/Atlantic exchanges via the Subpolar Gyre. Journal of Climate, doi: 10.1175/JCLI-D-11-00085.1

6) Born A. and J. Mignot (2011): Dynamics of decadal variability in the Atlantic subpolar gyre: a stochastically forced oscillator, Climate Dynamics, doi: 10.1007/s00382-011-1180-4

7) Escudier R., J. Mignot, and D. Swingedouw, (2012), A 20-yrs coupled ocean-sea ice-atmosphere variability mode in the North Atlantic in an AOGCM, Climate Dynamics, DOI: 10.1007/s00382-012-1402-4, published 10/06/2012

8) Ottera, O. H., M. Bentsen, H. Drange and L. Suo (2010): External forcing as a metronome for Atlantic multidecadal variability. Nature Geoscience, online 2010-09-12, doi: 10.1038/NGEO955

9) Mignot, J., M. Khodri, C. Frankignoul and J. Servonnat, (2011), Volcanic impact on the Atlantic ocean over the last millennium, Climate of the Past Discussions, Volume 7, Issue 4, 2011, 1439-1455, DOI: 10.5194/cpd-7-2511-2011, Published online: 21/12/2011

10) Zanchettin, D. and co-authors: Background conditions influence the decadal climate response to strong volcanic eruptions. Climate Dynamics, submitted

11) Zanchettin, D., C. Timmreck, H. Graf, A. Rubino, S. Lorenz, K. Lohmann, K. Krueger, J. Jungclaus (2011): Bi-decadal variability excited

in the coupled ocean-atmosphere system by strong tropical volcanic eruptions. Climate Dynamics, doi:10.1007/s00382-011-1167-11

12) Ottera, O. H., M. Bentsen, H. Drange and L. Suo (2010): External forcing as a metronome for Atlantic multidecadal variability. Nature Geoscience, online 2010-09-12, doi: 10.1038/NGEO955

13) Zanchettin, D. and co-authors: Delayed winter warming: a robust decadal response to strong tropical volcanic eruptions. Geophysical Research Letters, submitted

14) Ben B. B. Booth, Nick J. Dunstone, Paul R. Halloran, Timothy Andrews and Nicolas Bellouin, (2012), Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability, NATURE | VOL 484 | 12 APRIL 2012, doi:10.1038/nature10946

15) Msadek, R., C. Frankignoul and Z.X. Li (2011): Mechanisms of the atmospheric response to North Atlantic multidecadal variability: a model study. Climate Dynamics 2011, 36:1255–1276 doi 10.1007/s00382-010-0958-0

16) Frankignoul, C., G. Gastineau, and Y.-O. Kwon: The influence of the AMOC variability on the atmosphere in CCSM3. To be submitted to Journal of Climate

17) Gastineau, G., F. D'Andrea and C. Frankignoul, (2012), Atmospheric response to the North Atlantic ocean variability on seasonal to decadal time scales in IPSL-CM5, Climate Dynamics, DOI:10.1007/s00382-012-1333-0, Published online: 19/04/2012

18) Semenov, V. A., M. Latif, D. Dommenget, N. S. Keenlyside, A. Strehz, T. Martin, and W. Park, (2010), The Impact of North Atlantic-Arctic Multidecadal Variability on Northern Hemisphere Surface Air Temperature, Journal of Climate, VOL. 23, Issue 21, p.5668-5677, DOI: 10.1175/2010JCLI3347.1, Published online: 01/11/2010

19) Semenov, V.A. and M. Latif, (2012), The early twentieth century warming and winter Arctic sea ice, The Cryosphere, VOL. 6, 1–19, 2012, doi:10.5194/tc-6-1-2012, published on 04/12/2012

20) Mjell, T.L., Ninnemann, U.S., Kleiven, H.F., Rosenthal, Y. and Hall, I.R. (to be submitted), Variability in ISOW vigor over the last millennia and its relationship to climate

21) Lohmann, K. and co-authors (to be submitted), Influence of subpolar deep water formation and overflow variability onto the (multi)decadal variability of the Atlantic meridional overturning circulation

22) Sicre, M.-A., I. R. Hall, J. Mignot, M. Khodri, U. Ezat, M.-X. Truong, J. Eiríksson, K.-L. Knudsen, (2011): Sea surface temperature variability in the subpolar Atlantic over the last two millennia, PALEOCEANOGRAPHY, VOL. 26, PA4218, 10 PP., 2011 doi:10.1029/2011PA002169

23) W. Hazeleger, B. Wouters, G. J. van Oldenborgh, S. Corti, T. Palmer, D. Smith, N. Dunstone, J. Kröger, H. Pohlmann and J.-S. von Storch (2013), Predicting multiyear North Atlantic Ocean variability, Journal of Geophysical Research: Ocean, | DOI: 10.1002/jgrc.20117

24) W. Hazeleger, V. Guemas, B. Wouters, S. Corti, I. Andreu-Burillo, F. J. Doblas-Reyes, K. Wyser and M. Caian (2013), Multiyear climate predictions using two initialisation Strategies, 2013, Geophysical Research Letters, DOI: 10.1002/grl.50355

25) Swingedouw D., Impact of Greenland ice sheet melting on the Atlantic overturning: A multi-model assessment, 2013, to be submitted

26) Kleiven et al., North Atlantic climate and deep water variability since 600 A.D., to be submitted

27) Park, W. and Latif, M. (2010): Pacific and Atlantic Multidecadal Variability in the Kiel Climate Model. Geophysical Research Letters, 37, L24702. doi:10.1029/2010GL045560

28) Park, W. and M. Latif (2011): Atlantic Meridional Overturning Circulation Response to Idealized External Forcing. Climate Dynamics, doi:10.1007/s00382-011-1212-0.

Full list of publications of the THOR scientists can be consulted on the THOR website http://www.eu-thor.eu/Publications.553.0.html

Others (non THOR papers)

(I) Mads Faurschou Knudsen, Marit-Solveig Seidenkrantz, Bo Holm Jacobsen and Antoon Kuijpers (2011), Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years, NATURE COMMUNICATIONS, DOI: 10.1038/ncomms1186

(II) Gray, S., L. Graumlich, J. Betancourt and G. Pederson (2004): A tree-ring based reconstruction of the Atlantic multidecadal oscillation since 1567 A.D. Geophysical Research Letters, 31, L12205

(III) Weaver et al. (2012) Stability of the Atlantic meridional overturning circulation: A model Intercomparison, Stability of the Atlantic meridional overturning circulation: A model intercomparison Article first published online: 24 OCT 2012, DOI: 10.1029/2012GL053763

Potential Impact:

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 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.

Main dissemination activities

From 2008 to date, we have concentrated on several dissemination activities, targeting audiences of three sorts: the scientific community, the end-users/policy makers and a lay audience.

We have adopted a number of dissemination tools, varying according to our target audiences.

1. Dissemination to the scientific community
In the project we mostly used two channels for disseminating results to other scientists: through active participation in scientific conferences and through publications.

a) Dissemination through conferences
THOR scientists took active part in the following events for disseminating results and network with scientists in Europe and worldwide. The complete list of the events THOR scientists took part to is available in SESAM under "Dissemination". Here below we have listed the most significant ones.
Year 2008
15-19 December 2008 AGU Fall meeting 2008, San Francisco, USA
Year 2009
10-12 March 2009 Climate Change: Global Risks, Challenges and Decisions, Copenhagen (DK)
19-24 April 2009 EGU General Assembly 2009, Vienna, AT
21-25 Sept. 2009 OceanObs '09, Venice, IT
19-29 July 2009 IAMAS, IAPSO and IACS Joint Assembly 2009 (MOCA-09), Montreal, CA
8-9 September 2009 3rd GEO European Projects Workshop, Istanbul, TR
2-3 October 2009 European press briefing, Barcelona, ES
10-12 November 2009 Symposium on the Arctic Climate system, its present status, future evolution and potential impacts, Brussels, BE
December 2009 AGU Fall Meeting 2009, San Francisco, California, USA
Year 2010
21-26 February, 2010 AGU Ocean Sciences 2010, Portland, Oregon, USA
3-7 May 2010 EGU2010-6402-1. EGU General Assembly 2010, Vienna, AT
20-23 September 2010 CLIVAR Workshop on "Decadal Variability, Predictability and Predictions: Understanding the Role of the Ocean", Boulder, USA
8-12 June 2010 International Polar Year Science Conference, Oslo, NO
6-9 September 2010 Ocean Challenges in the 21st Century, 14th Biennial conference of the Challenger Society for Marine Science, Southampton, UK
29 August-3 Sept. 2010 10th International Conference of Paleoceanography, La Jolla, USA
December 2010 AGU Fall Meeting 2010, San Francisco, USA
Year 2011
March 2011 Atmosphere, Ocean and Climate Seminar Series, of Environmental Sciences, University of East Anglia, UK
3-8 April 2011 EGU General Assembly 2011, Vienna, AT
26 June-1 July 2011 Conference "Making sense of the multi-model decadal prediction experiments from CMIP5", Aspen Global Change Institute, Aspen, USA
12-15 July 2011 USAMOC-RAPID Past, Present and Future AMOC, Bristol, UK
21-27 July 2011 XVIII INQUA Conference, Bern, CH

24-28 October 2011 WCRP Open Science Conference, Denver, USA
25-27 October 2011 1st symposium on the Future of Operational Oceanography, Hamburg, DE
3-4 November 2011 French IMAGES/IGBP annual meeting, Aix en Provence, FR
5-9 December 2011 American Geophysical Fall Meeting, San Francisco, USA
Year 2012
22-27 April 2012 International Polar Year conference 2012 'From Knowledge to Action', Montreal, CA
27 March 2012 Seminar North Atlantic climate and ocean circulation variability during the last millennium in paleo reconstructions and simulations at MPG, Hamburg DE
28-29 February 2012 Consultive workshop Seas-era EUFP7 ERA-NET, Ostend, BE
7-8 May 2012 6th GEO European Projects' Workshop (GEPW-6), Rome, IT
22-25 October 2012 Workshop "Seeing Below the Ice Workshop", Hobart, Australia
29 November 2012 UN COP18, Doha, Qatar
5-9 November 2012 11th Biennial conference of Pan Ocean Remote Sensing Conference (PORSEC) 2012, Kochi, Kerala, India
Fall 2012 Generation Green: outreach lecture tour on climate, Bergen, NO

Additionally, our annual project meetings, held on a yearly basis, have always been combined with networking events, where scientists interested in THOR topics could bring their expertise and discuss and network with THOR scientists:
12-13 January 2009 THOR kick-off meeting, Hamburg, DE
25-26 November 2009 THOR annual meeting 2009, Paris, FR
16-18 November 2010 THOR annual meeting 2010, Copenhagen, DK
9-11 November 2011 ASOF-THOR joint workshop and THOR annual meeting 2011, Bergen, NO
24-26 September 2012 Nordatlantik Projekt-THOR project joint final meeting, Hamburg, DE (joint meeting of the German funded research project Nordatlantik and the THOR project)

b) Dissemination through publications
With the word "Publications", we refer to:
1. Peer-reviewed articles
2. Publications in preparation, to be submitted and submitted
3. Interventions and reports
4. Deliverables

More in details:
1) Peer-reviewed articles: The publications are listed with full titles, abstracts and information on how to retrieve the document (i.e. DOI). The peer-reviewed articles are all available in their full text in the intranet. All references have been uploaded in SESAM, in the section for the peer-reviewed articles. Open-access publications are available as well in http://www.openaire.eu under the project THOR. The full texts of the articles are available in the THOR website http://www.eu-thor.eu and in OpenAIRE, 2) The full list of the articles is also available on the THOR website ("List of publication" PDF document)http://www.eu-thor.eu/Publications.553.0.html, and in the EC SESAM database.
2) Publications in preparation, to be submitted and submitted: A table listing publications in plan, submitted, or to be submitted, with indication of title, authors, and journals is available in the PDF and in the intranet http://www.eu-thor.eu/Publications.553.0.html Our goal is to make publications available after the date of the official publication in the project website.

3) Posters and presentations: Interventions (presentations), posters for workshops/conferences based on THOR data are available on the website in their full version. http://www.eu-thor.eu/Presentations-and-posters.2284.0.html 2. A reference to all posters and presentations has been uploaded in EC SESAM database, section "Dissemination activities".
4) Deliverables: Project deliverables are available on the website and in the intranet (see http://www.eu-thor.eu/Deliverables.1677.0.html online), and in the EC SESAM database.

c) Sharing of data: observational data and modeling data

Observational data
The observational data collected within THOR have been made available to the international scientific community and to any other stakeholder by placing them into internationally recognized data banks. The publically available data have been quality controlled and condensed to integrated measures of interest to the community. For example do the individual current profiles obtained with moorings in the deep passages of the Greenland Scotland Ridge have a time resolution of 20 minutes and a vertical resolution between 8 and 16 m. These were averaged in time and space to produce daily values of volume transports through the passages that can be directly compared with model outputs of the same quantity. In addition the temperature and salinity data from ship surveys and moored instrumentation were combined with the current data to produce time series of heat and freshwater fluxes through key sections in the Nordic circulation system. The published time series have been frequently used by the modelling community to evaluate the quality of the circulation models and skill of forecasts.

More in details: observational data are available on the THOR website here https://www.eu-thor.eu/CT3-Data-Collection.1647.0.html In these pages, we have uploaded data related to the fluxes, the hydrography, entrainment and moorings. Data are structured according to the geographical areas in a information tree. Data are available according to location and with the details we collected during the project, and a contact person for further information and requests. These data are available to the entire scientific community; free access to the ASCII data, the documentation and the references can be granted by the data manager of THOR on the basis of a simple e-mail request.

After the end of the project, these series on the THOR website will be no longer updated. Fortunately, the NACLIM project (EU FP7) will take over the THOR series and provide updates on these on the http://www.naclim.eu website for the entire period 2013-2017.

Modeling data
Model Data collection and analysis of CT1 "Quantifying and modeling THC variability using palaeoclimate observations and simulations" and CT4 "Predictability of the THC" are coordinated by GEOMAR. The initiative of the Kiel group is to coordinate analysis of Atlantic Multi-decadal variability (AMV) in AOGCMs. The main aim of this analysis is to identify the key process that give rise to the wide variety of simulated AMV among these models. It may serve as the first step towards constraining the mechanisms for AMV and important in relation to ongoing decadal prediction efforts.

Data of CT1 and CT4 are accessible through s sftp site for sharing and downloading. Instructions and contact persons for accessing these data are available on the THOR website

-CT1 https://http://www.eu-thor.eu/CT1-Data-Collection.1084.0.html
-CT4 https://http://www.eu-thor.eu/CT4-Data-Collection.1646.0.html

d) Links to operational forecast systems and climate service provides
The synoptic scale measurements such as hydrographic profiles collected from research vessels are, after a preliminary quality control, have been made available to the operational meteorological and oceanographic centres. Several partners of the THOR project are climate service providers (i.e. MET O, KNMI, DMI, ECMWF) and have directly assimilated THOR observational data into the forecast models, and thus playing an important role in improving the forecast skill. After the final quality control the data a re-submitted to these centres where they enter into climatological data bases used for initializing hindcast experiments. Climate service providers receive their information from the operational centres rather than directly from the data originator.

2. Dissemination to end-users
The dissemination of THOR results to end-users has been mostly achieved through two specific workshops held in 2010 and 2012: 1st THOR End-user workshop, 01 October 2010 Hamburg, DE

And 2nd THOR End-user workshop, 24 October 2012London, UK.
In the first end-user workshop: we focused on an interactive exchange between the THOR group, the scientific community in the field of climate and marine research, boundary organizations such as European and Federal Environmental Agencies, instrumental manufacturers, other small and medium size enterprises and the general publics. We informed the end-users about the development and the risk of a breakdown of the THC and its impact on climate changes in Europe. The goal was to define communication routes and to identify such possible cooperation. A round-table discussion focussed on collecting feedbacks from the participants of the workshop on the following: What are the expectations concerning communication and cooperation among the different groups' What information and by which means should the results from a major project like THOR be made available to the societal groups outside the scientific community' The discussions' outcome was that a direct communication of the research scientists with end-users is - on a large scale - very inefficient and that information should rather be relayed through organizations or institutions like the IPCC, the EEA or the climate service centres. Direct communication between individual researchers and end-users should be included once a problem narrows down to a particular topic. The European Commission was encouraged to develop and provide additional communication links staffed by professional communicators who are able to translate scientific language into that of the respective end-user. At that time, it was decided that THOR would maintain the communication and the interactive exchange with the "end-users" and the general public for the rest of the project life time.

A second end-user workshop took place in October 2012 on the topic "Decadal predictions and the RAPID-WATCH Programme" and was organised with support of the British partners in THOR: MET O, UREAD, SAMS, CEFAS and NERC/NOC. The Atlantic Meridional Overturning Circulation (AMOC) plays a key role in the climate of regions surrounding the North Atlantic. Variations in the AMOC have been linked with variability in

European climate, and in tropical weather systems such as Atlantic hurricanes, while palaeoclimatic evidence has linked the AMOC to some major global climate shifts in the past. Predictability of the AMOC holds out the prospect of improved climate predictions for seasons to decades ahead. The THOR project, along with a number of national and international programmes (e.g. international Argo, UK/USA RAPID, Germany/USA MOVE), has revolutionised the ability to observe and model the AMOC, leading to enormous steps forward in our understanding of AMOC variability and its links to climate. At the workshop we addressed the following question: How can climate predictions be affected and influenced by these factors and who (and how) could benefit from these data. This workshop focused on an interactive exchange between the THOR scientific community and the end-users. THOR scientists reported about the development and the risk of a breakdown of the Thermohaline Circulation and its impact on climate changes, particularly in the area of Great Britain. Presentations were aimed at bringing together scientific advances on decadal predictions with user and stakeholder perspectives. The target group of the workshop consisted of some 20 organizations based in UK and surrounding countries potentially interested in the THOR decadal predictions and overall results: universities, local governments, consulting companies, port authorities, insurance companies, engineering companies, companies providing provide marine support to offshore oil and gas industries, coastal service, land management service, policy maker advisors, and demographic institutes. The interest of the participant was focussed on how they could eventually benefit from THOR data and results for their specific areas of study/research and interest, and how eventually they could enhance their cooperation with the THOR community after the end of the project.

THOR final results are of great interest and need to be accessible on two levels:
-For those interested in the raw data and running climate models on their own, a privileged direct communication channel with the THOR scientist should be established, and the possibility of accessing predictions with downscaled data should be given.
-For those more general end-users not interested in the raw data, access should be granted to the final scientific reports, and to reports written in a register for a lay audience.

3. Dissemination to a lay audience
Dissemination has been achieved mostly through web based tools, and in particular through the website, Linkedin, Vimeo and Youtube. The lead of these activities has been mostly with UHAM, with an active contribution from all partners.

Website: One of the main communication tools addressing a lay audience is the project website. In the last year, the website has been enhanced with new sections dedicated to the dissemination activities (Video-audio materials), information on the closing event of the project (Closing event), and core theme data (Data system).

Video and audio materials: Video and audio materials which were broadcasted on the radio and on television are available on the website of the project http://www.eu-thor.eu/Video-audio-materials.2101.0.html
The THOR film "Is the thermohaline circulation really at risk'" was co-produced with the support of Alphafilm, and promoted on YouTube, Vimeo, and Linkedin. In Vimeo and Youtube, the film has been clicked and seen 900 times, with 12.800 estimated watched minutes. Viewers were located

not only in the partner countries and in non-partner countries. Our partner SAMS will open a marine outreach centre in May 2013 and will have a small audio visual area where the film will be shown for educational-purposes to students and the general public. The Italian network of the hybrid libraries (it. "Mediateca") for environmental issues, Mediatecambiente, is interested in making the THOR movie available on the website of the http://www.mediatecambiente.it for educational purposes, free of charge, in English, and with Italian subtitles. Mediatecambiente.it is the website of the network of regional environmental agencies (public bodies) in Italy, with links to similar networks in Central and Eastern Europe and in the Mediterranean area. Articles in the media: Reviews and magazines showed interest in the project results and THOR scientists have been given interviews for Spektrum der Wissenschaft, Current Biology, Forsking, Klimaloftet, På Høyden and regional/local newspapers. The full list is available in SESAM, in the participant portal, under "Dissemination".

Outreach lectures: The project consortium also encompasses senior scientists, which frequently contribute to popular scientific articles and broadcasting in the press and TV and are well known by the public of the respective country. A number of outreach lectures have been given in this third and last period. The full list is available in SESAM, in the participant portal, under "Dissemination".

Linkedin: A THOR group was established in 2012 in Linkedin, to connect most of the THOR scientists active on this network. The group is open to Linkedin members interested in the project and its themes and through this channel the project office has shared news and happenings in the project, invited participants to join the project meetings and end-user meetings and exchanged resources with other Linkedin users.

Wikipedia: The project has been added to the external links of the Wikipedia entries on "Thermohaline circulation" in English, German, French and Italian.

4. Outreach towards climate change debate
We can mention the following outreach activities relevant to climate change debate of THOR scientists:
-EC-Earth (i.e. CT4 / Wilco Hazeleger) contributes to coordinated model experiments, CMIP5, and contributes to the next IPCC assessment. More information is available on the EC-EARTH WIKI page http://ecearth.knmi.nl/
-Consultive workshop Seas-era EU FP7 ERA-NET: The scientific coordinator Detlef Quadfasel took part in the consultive workshop on the document "A draft Marine Research Plan for the European Atlantic Sea Basin", organised by Seas-Era in Ostend (BE) on 28-29 February 2012. His presentation and abstract are available on the website.
-International Polar Year conference 'From Knowledge to Action', Montreal, 22-27 April 2012: the THOR project was represented by several scientists contributing to the discussions: https://http://www.eu-thor.eu/Presentations-and-posters.2284.0.html
-In November 2012 THOR was invited at UN climate change conference COP18, in Doha, Qatar, 29 Nov. 2012. The United Nations climate change conference in Doha must start the hard work of turning last year's agreement to enhance global climate action into reality. The European Union wants an outcome that takes forward all elements of the package of decisions agreed in Durban towards a new global climate agreement by 2015. A presentation of Jean-Claude Gascard was given in the side event

organized by the European Commission on Global and Regional Impacts of Polar Warming, http://ec.europa.eu/clima/events/0062/calendar_en.htm#schedule Presentation on results of the THOR project, press release and summary by Summary by Luca Perez (EC) on the talks and discussions can be retrieved on home page of the website.

Exploitation of results
THOR scientists of all the core themes strove for scientific information to be published in scientific papers and for being publicly available. Within THOR CT1 "Quantifying and modeling THC variability using palaeoclimate observations and simulations" no commercial activities were employed. The model data is available for research and education purposes. The model data produced in THOR CT1 is for non-commercial use. Within the CT2 "Assessing sources of uncertainty in ocean analyses and forecasts" and CT3 "Observation of the North Atlantic THC", no commercial activities were employed. Within THOR CT4 "Predictability of the THC" no commercial activities are employed. Scientific information is published in scientific papers and publically available. The model data produced in THOR CT4 is for non-commercial use. Part of the model data is stored in the CMIP5 archive. The model data is available for research and education purposes.

Within CT5 "Technological advancements for improved near-real time data transmission and Coupled Ocean-Atmosphere Data Assimilation (and initialization)", scientists developed two data telemetry systems, the Bergen system and the Kiel OPTIMARE Mooring Pop-up system, 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 we have achieved the following. The partners UIB and UNIRES worked in close cooperation with AADI, a small-medium enterprise located in Bergen (NO) on the design and construction of deep sea data telemetry system transmitting acoustic data telemetry to bypassing ships. AADI will further invest in the commercialization of the prototype constructed during the THOR project. No patents are planned, and there is no owner, as the prototype has been dismounted after the project ends.

As explained more extensively already in the text (see para. *Near real-time data transmission*

Under the heading CT5), the two deep sea data telemetry systems focussed on the retrieval of observational data from deep sea moorings (ref: THOR Deliverable D42). These systems are not just tailored for operating in the Northern waters: They could be adapted to operate in the Southern Oceans too. In late 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 system will be used in the Southern Weddell Sea for process studies and long-term observations.

Within CT5 scientists developed a unique assimilation system that is able to provide an estimation of dynamically consistent initial conditions for climate prediction. This system is free for scientific and educational use, not for commercial use. Scientific use is immediately possible. Any operational use will likely not be possible within the next 5 years. No patent or other IPR exploitation is planned.

The data assimilation system developed in THOR already plays an important role in two new projects:

1) In the EU FP7 funded project NACLIM, in which the system will be used to identify where SST and sea ice observations will have a maximum impact on improving model-based climate predictions in the North Atlantic/European sector.

2) In the German Ministry of Science funded project MiKlip, in which the THOR coupled climate synthesis system will be used to determine initial conditions for coupled climate models and test their usefulness for decadal predictions. Since decadal predictions rely on initial conditions this is one of the key aspects of not only the associated module, but of the entire MiKlip project.

List of Websites:
http://www.eu-thor.eu