THOR Publishable summary

Summary description of the project context and its main objectives

The climate of Europe is strongly influenced by the North Atlantic Ocean circulation. Variations of the strength of the Thermohaline Circulation (THC[1]) 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. Likewise, variations in THC is a commonly attributed mechanism for non-linear and abrupt (i.e., decadal scale) climate changes. Reliable quantification of the variability and stability of the THC and its atmospheric implications in today's 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. Under these circumstances the project THOR (Thermohaline Overturning – at Risk?) was originated by 20 partner institutions from nine European countries and was launched in December 2008 under the FP7 programme "Stability of the Thermohaline Circulation/THC" within the activity "Climate Change, Policy and Risks".

THOR aims at establishing an operational system that monitors and forecasts the development of the North Atlantic THC on decadal time scales and accesses its stability and the risk of a breakdown in a changing climate. Direct ocean observations and a suite of modeling tools are used to describe the ocean circulation and related heat transports as well as their variability. Interactions and feedback loops with the Atmosphere and the Cryosphere are assessed and their relative importance is quantified. Pre-existing data sets, ongoing observations within the project are used to quantify the strength and variability of the Atlantic THC and its sources. This allows, for the first time, an assessment of the strength of the Atlantic THC and its sources in a consistent manner and provides early identification of any systematic changes in the THC that might occur. Analysis of paleo observations covering the last millennium, and millennium time scale experiments with coupled climate models are being carried out to identify the relevant key processes and feedback mechanisms between ocean, atmosphere, and cryosphere. In THOR, the combined effect of various global warming scenarios and melting of the Greenland ice sheet are also being assessed in coupled climate models. Through all these studies and through the

[1] 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 report the expression THC will be used exclusively.

assimilation of systematic oceanic observations into ocean circulation models, THOR will forecast the development of the Atlantic THC and its variability until 2025, using global coupled ocean-atmosphere models. THOR also assesses induced climate implications of changes in the THC and the probability of extreme climate events with special emphasis on the European/North Atlantic region. THOR builds upon techniques, methods and models developed during several projects funded by the European Commission as well as many nationally funded projects. The project also contributes 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 project is made up of five core themes, linked to several milestones and deliverables. The aim of **Core Theme (CT) 1** is to understand and quantify the THC variability on decadal to centennial time scales. **CT2** focuses on assessing the uncertainty in ocean analyses and forecasts on time scales of decades. **CT3** focuses on direct ocean observations in the subpolar and subtropical North Atlantic. **CT4** focuses on performing decadal prediction experiments. **CT5** aims at improving observational and modeling techniques.

Description of the work performed and the main results achieved so far (from the beginning of the project)

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 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. A consortium of 21 partners 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.

Expected final results and their potential impacts and use

After the end of the third and last period of the project, we can state that the activities in THOR have provided improved quantification of the risk, time horizon and possible scenarios for THC breakdown and related abrupt/rapid climate change for Europe and the Arctic/sub-Arctic region.

The focus has been on detecting low-frequency and long-term changes in the strength of the THC, which is a major factor influencing the atmospheric circulation, and thus the European/Arctic climate. The goal was to identify the major processes and feedback mechanisms determining the variability, respectively the stability of the THC, and for predicting the THC evolution in the future. Observations, process studies, paleo-studies, and modelling have been integrated and serve as a basis for predicting the development of the European, Arctic, and sub-Arctic marine climate, the atmospheric circulation, and the hydrological cycle.

THOR has developed the background for strategies for the establishment of a medium term climate forecast service for Europe. This is a prerequisite to predict the THC in the future, and the associated consequences for the atmospheric climate. THOR data and results also form an important basis for developing management strategies for economic and societal issues, may they be concerned with fishery resources, ocean pollution, sea level rise, shipping, offshore exploration, transportation, agriculture, hydropower production, tourism or others.

By its nature, a change in the THC would have the character of an extreme event for the population of Europe. Although the implications of an altered THC are important for all regions bordering the North Atlantic, Europe has particular reason to take the consequences of any changes seriously, since its mild climate is partly determined by ocean circulation and the biggest effects will be felt here. Thus Europe has a particular interest in further investigating the risk for breakdown or sudden reduction of the Atlantic THC, and for forecasting these changes.

The project has contributed to establishing a common European data base. The project's output has also been made available to national and international data centres, and international programmes (e.g. CLIVAR, GOOS and IPY), and provides feed for other observational programmes (e.g. ARGO).

The final results of the project include:

1. Identification of key processes and feedback mechanisms driving the THC variability and quantification of their respective impact.
2. Assessing sources of model uncertainties.
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.
4. Quantification of the contribution from the Irminger and Labrador seas and of entrainment processes in the overflows to the THC.
5. Assessment of the quality of THC forecasts.
6. Coupled model decadal forecasts of the THC.
7. Recommendations for observational and modelling systems.

8. Development of coupled ocean-atmosphere assimilation capabilities.
9. Development of near real time data transmission for moored observatories.
10. Development of strategies for the routine decadal forecasting facility for Europe.