

climate changes spatial planning

Climate scenarios

North Atlantic Monitoring and Modelling

H.M. van Aken

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Author

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Summary in Dutch

Binnen het CS1 programma zijn waarnemingen verricht aan de Noord-Atlantische component van de thermohaliene circulatie, die van bijzonder belang is voor het West-Europese klimaat. Aan de hand van de data en computersimulaties werd de variabiliteit van watermassavorming, het gekoppeld warmtetransport van de oceaan en de atmosfeer en de rol van verticale menging in de oceaan bestudeerd. Een beter begrip hiervan is cruciaal voor de verbetering van regionale klimaatmodellen voor West-Europa. Kennis, verkregen uit dit project, ondersteunt het op maat maken van de klimaatscenario's (Tailoring, CS7) en geeft eveneens belangrijke informatie voor het project "Patterns of Climate Change" (CS5). Het resultaat is een herkenbare Nederlandse bijdrage aan een internationale inspanning, o.a. via het World Climate Research Programma (WCRP) CLImate VARiability (CLIVAR) om klimaatmodellen te verbeteren zodat de onzekerheidsmarges van deze modellen uiteindelijk verkleind worden. Dit project is ook een Nederlands bijdrage aan de oceaancomponent (GOOS) van het internationale Global Climate Observing Program (GCOS).

Belangrijkste resultaten:
De publicaties beschrijven de volgende inzichten: (1) een belangrijke observatie dat klimaatverandering deels een interne oscillatie is van het (natuurlijke) klimaatsysteem. De projectresultaten doen vermoeden dat het toekomstige West-Europese Klimaat meer variabel is dan de huidige beschikbare klimaatscenario's suggereren. Natuurlijke variabiliteit dient een belangrijke rol te spelen in een nieuwe generatie klimaatscenario's. Hier zal in KNMI-next expliciet aandacht aan gegeven worden. (2) Het zeeniveau is, uitgaand van regionale waarnemingen van de temperastuur in de oceaan lager dan berekend door gekoppelde (atmosfeer-oceaan) klimaatmodellen zonder extra forcering (=huidig klimaat), gebruikt voor het 4-de IPCC-rapport. (3) de waarnemingen geven verschillen in turbulente mengingsprocessen in de oceaan aan, welke consequenties heeft voor de kracht en ruimtelijke locatie van de AMOC (basin-wide meridional overturning circulation in the Atlantic Ocean). Bij de verkregen inzichten hoort de nuancering dat ook de waarnemingen hun onzekerheden/limitaties hebben (en er zijn ook meer metingen dat alleen die van CS1). (4) het onderzoek onderschrijft het belang van empirisch onderzoek, in situ waarnemingen, naast modelonderzoek en satellietwaarnemingen.

Abstract

Fundamental climate research on the role of the ocean for the West European climate was carried out in the CS1 project, as a contribution to the "Climate changes Spatial Planning" research theme on climate scenarios. Research focused on four different research fields, using observations as well as numerical simulations:

- The climatic variability of the north-western North Atlantic was monitored by means of repeated hydrographic surveys as well as moored self recording instruments. Also data from archives were studied. A large natural variability at all water mass horizons could be described from daily to multi-decadal time scales. Because of that natural variability, one can expect that the West European climate that depends on heat flux from the Atlantic Ocean will be more variable than suggested by climate scenarios simulations.

- By means of simulations with coupled climate models the feedback between the heat transport in the Atlantic Ocean and the atmospheric circulation and the resulting climate variability was studied. The simulations with these coupled climate models appeared to differ significantly from regional observations of ocean thermal stratification in the north-western North Atlantic. The erroneous subsurface temperatures in climate models will also have consequences for the predicted sea level rise.
- The climatology of the internal wave band in the North Atlantic Ocean was monitored, while also historic current meter data were studied. A considerable spatial variability of the wave kinetic energy was found. The energy conversion by internal tides and inertial waves was determined at some locations, and key processes for the wave-to-turbulence conversion were established. The resulting differences in turbulent mixing in the ocean will have consequences for the large-scale deep upwelling, and therefore on the strength and spatial structure of the cold, deep branch of the Atlantic overturning circulation.
- The influence of the spatially varying production of turbulent motion should be studied by means of an ocean general circulation model with homogeneous density layers. However, because of the spurious numerical diffusion in this model, it appeared that this model was unstable for simulations on the long, climate relevant time scales to study effects of the turbulence parameterization.

1. Context / Social problem

Climate change is one of the major environmental issues for the coming years, both regionally and globally. The Intergovernmental Panel on Climate Change (IPCC) writes that most of the global warming in the past 50 years is probably caused by human activities. The Netherlands are expected to face impacts of this climate change on all sectors related to land use and water management, and therefore on spatial planning in general. Although the co-dependency of spatial planning and climate change has largely been accepted, spatial planners and the climate change community have had mostly isolated (research) agendas so far. A major goal of the programme "Climate changes Spatial Planning" was to enhance joint-learning between those two communities and people in practice within spatial planning. Its mission was to get climate change and climate variability one of the guiding principles for spatial planning in the Netherlands.

For land use planning and management of natural resources information is needed about the expected climate in the foreseeable future. This information should be available at an adequate regional scale; e.g. the climate development in Western Europe or in the Netherlands, instead of global warming. Only then information becomes relevant to the local user. Regional climate simulations following climate scenarios are produced for research. These are incidentally used by policy makers and other stakeholders involved in mitigation activities and developing adaptation strategies.

The North Atlantic Ocean is of crucial importance for the regional climate in Europe and the Netherlands. Any change in the climatic state of the North Atlantic Ocean will lead to a change in the climate of Western Europe, while feedback mechanisms between ocean and atmosphere may strengthen or dampen climate variability. That variability may be natural or anthropogenic; the latter is expected to be due to manmade changes in the atmospheric greenhouse gases (e.g.

CO_2 and CH_4) and changes in land use (e.g. albedo, evaporation, and roughness). Society requires reliable forecasts of possible changes in the European climate, in order to be able to adapt to such changes. Examples are the expected sea level rise, the consequences of climate changes for agriculture, flood management for the Dutch rivers, etc. The CS theme within CcSP as a whole aims at the improvement of climate scenario forecasts and at the development of specific products, derived from such forecasts. However, one can question whether the state of climate science is advanced enough to trust such forecasts without hesitation. Within the CS theme, the CS1 project therefore aimed at the further development of generic fundamental climate science, especially with importance for the climate of the North Atlantic and Western Europe.

The intended climate research within CS1 focused on one hand on the collection of observational oceanographic data in a quasi-operational mode (monitoring) in the North Atlantic Ocean at intra-annual as well as inter-annual time scales. On the other hand it focused on the development of deeper theoretical understanding of the processes that control heat transport in that ocean. Numerical models of the ocean only, as well as coupled climate models, were used for that research. As a crossover between monitoring and modelling, the quality of the climate simulation with numerical models was studied by comparison of model output with observational time series. The results of the CS1 project will be a recognisable Dutch contribution to international scientific efforts via the World Climate Research Programme (WCRP), the CLlimate VARiability and predictability programme (CLIVAR), and other bodies to improve climate models, so that their margins of uncertainty can be reduced. Additionally, the collected oceanographic data are made publicly available to other scientists and for use in other climate reports like those used in advice on marine environmental and fisheries policies.

2. Goals

Recent studies have shown that large and rapid climate changes in Europe have occurred in the past and may occur again when the northward heat transport in the North Atlantic Ocean strongly changes in magnitude. An important contribution to this heat transport in the Atlantic Ocean is provided by the basin-wide meridional overturning circulation (AMOC). The AMOC transports warm water northward near the sea surface and cold water at depth flows southward through the whole Atlantic Ocean. Because of the resulting ocean-wide northward heat transport in the entire Atlantic Ocean the present winter temperatures over Western Europe are overall a few degrees higher than the world-wide average of the European latitudes. Changes in the ocean circulation may result in many regional climate variations on time scales from months to decades. Possible rapid climate changes resulting from a collapse or destabilization of the THC may have large consequences for the European society.

However, although the global role of the oceans in the climate system has been well established, many specific aspects of the regional ocean-climate interaction are still poorly understood. One of the major reasons is that, contrary to atmospheric observations, there are only very few long-term *in situ* ocean time series. Thus, while covering more than 70% of the earth's surface, regular observations of the open oceans which resolve seasonal to inter-annual time scales are scarce. This lack of effort exists, despite the fact that many countries, including the Netherlands, have signed the international treaty on the establishment of an operational Global Ocean Observation System

(GOOS). The international CLIVAR research programme has been initiated under the WCRP to collect, analyse and interpret such long-term ocean observations in order to develop climate models with predictive capabilities with a wide range of time scales from seasonal to centennial. The CS1 project has as a leading goal to accept this challenge of obtaining reliable, comprehensive, and consistent ocean observations, and to provide a reliable interpretation of such observations. Scientific long-term ocean observing experiments have been carried out in CS1 using ship time for hydrographic surveys. New technology has allowed deployment of innovative self recording instrumentation at locations that are of critical importance to the world ocean circulation. These instruments provide accurate descriptions of a part of the present state of the oceans and form the basis for forecasts of climate change. By means of simulations with computer models of the ocean circulation and climate the regional variations and temporal feedbacks with the atmosphere have been studied.

Increasing our knowledge on the heat transport from the equator to the poles and, especially, on the heat transport by the oceans separately is a great challenge since any change in this transport must give a climatic response. Although recent estimates indicate that the largest share of this transport process at our latitudes is taken by the atmosphere, the ocean is certainly not negligible. By its large thermal inertia the ocean dampens the seasonal variations and contributes to our well known sea climate. However, the ocean is probably more important in driving climate variability on time scales of years or longer by its own dynamics as well as by feedbacks in its interaction with the atmosphere. An example of such an atmosphere-ocean feedback loop is the regular occurrence of the El Niño phenomenon in the equatorial Pacific Ocean, a regional phenomenon with global climatic consequences.

The mechanisms by which the ocean transports heat (and fresh water) are less well understood than those in the atmosphere. A lack of oceanographic data and the resulting relatively primitive state of ocean general circulation models are important causes of this lack of knowledge. Even after such successful international observation programmes as WOCE, the altimetric satellite missions TOPEX/POSEIDON, ERS1, and their follow-up satellites, and CLIVAR, our state of knowledge of the ocean circulation is still limited. Optimists, however, will state that large improvements in our oceanographic understanding of climate are still feasible.

The CS1 project therefore intended to contribute to the worldwide effort to increase our knowledge on the role of the oceans in the climate system, which is integrated within the international CLIVAR programme. Improvement of our knowledge is required to achieve reliable forecasts of regional climate variations for which the ocean plays an important role. Scientists within CS1 have contributed to the development of such knowledge by participating in the setup of a semi-operational long-term ocean observing system and by a scientific analysis of these observations and related model experiments.

Within CS1 the following specific research goals have been addressed:

- To measure and analyse the ocean climatic variability in the north-western North Atlantic Ocean and the state of the Atlantic Meridional Overturning Circulation by means of annual hydrographic surveys and high frequency observations with self-recording moored observational systems in the Irminger Sea
- To study the importance of internal waves in the ocean as a source of mechanical energy for the generation of oceanic turbulent mixing by carrying out systematic observations on the internal wave climatology and wave properties in the North Atlantic Ocean. Turbulent mixing in the ocean determines among others the time scale of the oceanic response to a changing atmospheric greenhouse warming. The analysis of the observations on internal waves was supported by theoretical and modelling studies.

- To analyse the importance of the spatial distribution pattern of veridical mixing on the meridional overturning of the North Atlantic Ocean, by means of an "ocean only" high-resolution numerical general circulation model of the Atlantic Ocean. This study also incorporated methods of data assimilation.
- To combine observational data and numerical simulations, in order to determine the quality and representativeness of the state-of-the-art models, used in climate research and forecasts.

The results of these researches till now have been published as contributions to international peer reviewed scientific journals. One PhD thesis has been successfully defended by M.F. de Jong in October 2010. Also some "outreach papers" have been published in more "popular" public journals and publications, in order to inform the general public about the CS1 project and about recent developments in our knowledge of climate.

3. Approach

The research within CS1 was divided into 4 subprojects. Two of these sub projects (1 and 3) dealt with the monitoring of the North Atlantic Ocean, and were carried out by scientists from NIOZ, Texel. Two other subprojects (2 and 4) dealt with numerical simulations of the Atlantic circulation, and were carried out by scientist from respectively KNMI, de Bilt, and IMAU, Utrecht. Additionally, combined research was carried out with contributions from different subprojects.

Subproject 1: Monitoring of the north-western North Atlantic Ocean. This subproject was divided into 5 work packages, W1 to W4, and W7. These are:

- W1: To carry research cruises with research vessels to collect data, and to produce reports on these cruises.
- W2: To deliver ocean monitoring data to data centres, in order to make these public.
- W3: To analyse the hydrographic variability between Ireland and Greenland, especially along the AR7E section in the north-western North Atlantic Ocean.
- W4: To analyse the daily to inter-annual variations of the stratification of temperature and salinity and of the currents, derived from the data collected with the self-recording instruments, deployed with moorings in the Irminger Sea.
- W7: To compare results of simulations with ocean general circulation models and coupled climate models, with oceanic data, derived from the monitoring programme.

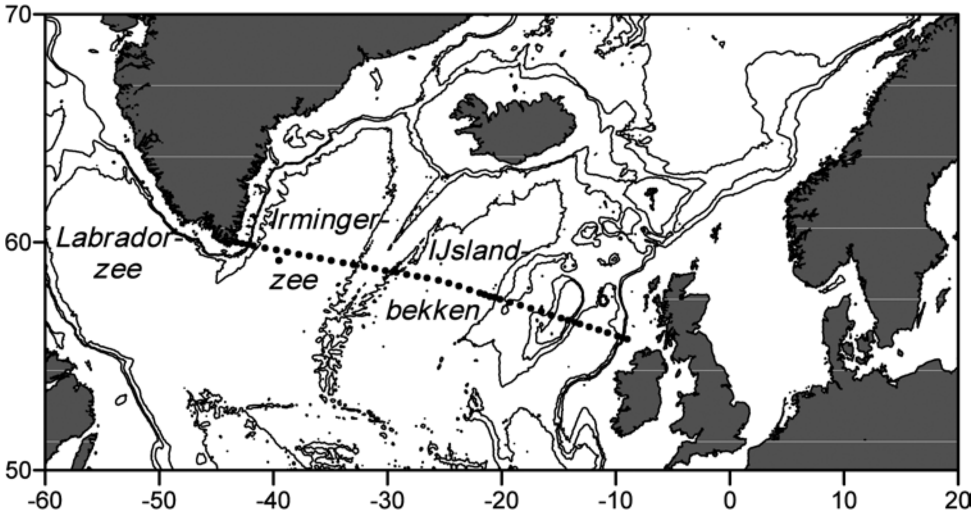
For the WOCE hydrographic programme hydrographic sections were designed in order to produce a reliable onetime survey of the state of the ocean in the early 1990s. Some of these sections were surveyed repeatedly to establish how representive a single survey of the section is for the longer term average state along these sections. In the North Atlantic Ocean the A1E/AR7E section between the Irish continental shelf and southern Greenland was such a repeat section, surveyed with near-annual coverage. After the end of the field phase of WOCE in 1997, monitoring of this section by Dutch and German groups was continued under the CLIVAR programme. Additional surveys of the western half of this section were carried out occasionally by American and Russian scientists. Data from these surveys in neighbouring ocean basins were exchanged via an informal international group, which also prepared publications on these data. Results from the annual surveys also have been used for the semi-operational production of the International Council for the

Exploration of the Sea (ICES) Report on Ocean Climate (IROC) by the ICES Working Group of Ocean Hydrography (http://www.ices.dk). These reports are published annually for ecological, fisheries and environmental purposes as a volume of the scientific journal "ICES Cooperative Research Reports". The data have been submitted to international data centres and are also publicly available from the Data Management Group at NIOZ (dmg@nioz.nl).

The surface buoy of a mooring in the Irminger Sea, resurfaced after collecting data for one year. The buoy is fitted with an acoustic current profiler, while on the cable between the buoy and anchor weight other instruments were fitted.

During the CS1 funding period (2004-2009) scientists from the NIOZ Physical Oceanography Department carried out two hydrographic surveys of the AR7E section between Greenland and Ireland with the research vessel RV Pelagia, in 2005 and 2007. During these surveys the hydrographic stratification in the water column (of temperature and salinity) between sea surface and bottom was determined by means of a so called CTD system, lowered from the ship. The IfMH of Hamburg University discontinued their bi-annual survey of the section after the survey of 2004. In order to maintain the intended annual time resolution of the hydrographic information from the Irminger Sea, NIOZ collected CTD data along the AR7E section during its participation in research cruises in the Irminger Sea of the British RRS Charles Darwin in 2004 and RRS Discovery in 2006 and 2008. Also in 2009 the section has been surveyed with RV Pelagia, in this year funded from the EU THOR programme. These hydrographic surveys have a nominal horizontal resolution of ~30 n.mile (~55 km). Additional to the so called CTD casts, the water depth was measured with a 3kHz echo sounder and sea surface conditions (temperature and salinity) were recorded during the surveys with RV Pelagia, as well as the velocity structure of the upper 600 m, measured with a ship mounted acoustic Doppler current profiler. Also, meteorological data were recorded continuously.

In addition to the standard hydrographic parameters, the distribution of Total Inorganic Carbon ("CO_2") along the AR7E section was already studied by NIOZ in 1991, resulting in an estimate of the meridional overturning transport of mass and CO_2. During the hydrographic surveys by RV Pelagia in 2005 and 2007 such extended chemical surveys also have been have been carried out by chemical oceanographers of the Biological Oceanography Department of NIOZ. Water samples have been analysed for carbon dioxide, alkalinity, dissolved oxygen, dissolved nutrients (nitrate, phosphate, and silicate), and chlorofluorocarbons (CFCs). During the hydrographic survey of 2007, a sediment corer (~30 cm) was mounted with a rope to the lowered CTD frame. This enabled scientists from the Marine Geology Department of NIOZ, participating in this cruise, to sample the upper 30 cm of sediment of the ocean bottom with the high horizontal resolution of 55 km. The properties of these samples will be used to reconstruct the deep ocean circulation in the recent geological past. The hydrographic data, collected by the physical oceanographers from the CS1 project were also made available to the geological and chemical investigators who participated in these cruises.



The ocean area of sub-project 1. Along the line of dots shows hydrographic observations haven carried out near-annually since 1990 (the AR7E line) by an international group of research institutes.

The repeated hydrographic surveys of the AR7E section as well as studies of the height of the sea surface with satellite altimetry have shown that in the Irminger Sea, directly east of southern Greenland, the seasonal and inter-annual variability of the ocean circulation is relatively large, and surpasses the meso-scale eddy variability. Air-sea interaction, convective mixing, and re-stratification by eddies from the boundary currents all influence the hydrographic stratification in the ocean. Sea level anomalies in the centre of the Irminger Sea are directly connected with changes in the temperature and salinity of the upper 2000 m. Deep convection forced by atmospheric cooling of the water column in winter releases huge amounts of heat to the atmosphere. Such convection events seem to occur during some particular winters, but not in others. No certainty exists on the relative importance of this locally driven convection, compared to the effects of advection of cooled water from the Labrador Sea by ocean currents. This question had to be addressed with self recording moored instruments, which were deployed in the Irminger Sea as additional part of the CS1 project. The cold water masses, formed in this north-western part of the North Atlantic Ocean, contribute to the deep limb of the AMOC, which transport this water southward to the southern ocean. From there they spread into the Indian and Pacific Oceans and contribute to the ventilation of the world ocean.

During a repeat hydrographic survey of the AR7E line in 2003 two profiling moorings were deployed in the eastern half of the Irminger Sea near the centre of the basin and near the eastern boundary of this basin. Each mooring contained acoustic Doppler current profilers to measure the ocean currents, and a profiling CTD to measure daily the temperature and salinity stratification between 150 and 2400 m. Near the bottom a self recording CTD was mounted, which collected temperature and salinity data from the bottom layer of the Irminger Sea at about 3000 m depth. There Denmark

Strait Overflow Water contributes to the cold branch of the AMOC. The instrumentation for these moorings was purchased in 2003, previous to CcSP, with a special investment grant, obtained from the Dutch National Science Foundation, NWO. From 2004 until 2008 these profiling moorings have been recovered, serviced and re-deployed, as part of the CS1 project. After recovery, the data from these instruments have been made public according to CLIVAR rules via the NIOZ Data Management Group. With their high temporal resolution the moorings give insight into physical processes that cannot be resolved with the annual surveys of the AR7E section.

Scientist of the NIOZ Department of Marine Geology also had sediment traps deployed from 2003 until 2008, next to the westernmost CS1 mooring in the Irminger Sea. Data from the CS1 mooring have been made available to these scientists.

Additional to the data, collected by NIOZ from hydrographic surveys and moorings between 2004 and 2008, oceanographic data were retrieved from international oceanographic data centres, in order to extend the period of the studies. Hereby a 60 year time series of annual temperature, salinity and oxygen concentration profiles in the central Irminger Sea was constructed.

Subproject 2: Heat transport variations in the ocean and atmosphere, a modelling study (KNMI). This subproject was divided into 4 work packages. These are:

- W5: Analysis of the meridional heat transport in the atmosphere and the (Atlantic) ocean, derived from simulations with coupled climate models
- W6: Analysis of the mechanisms, responsible for the variations in the transport of heat and freshwater in the climate simulations with numerical coupled climate models
- W7: Comparison of the results of coupled climate models with observations from the Irminger and Labrador Sea on inter-annual to decadal time scales (also in subproject 1).
- W14: Analysis of freshwater budget and its influence on the meridional heat flux sustained by the AMOC, based on an analysis of the results of simulations with a coupled climate model.

As a modelling exercise this theoretical subproject on heat transport variations does not depend on the availability of ship time and oceanographic equipment. It mainly needs the availability of (the results of) an adequate coupled climate model that contains at least an atmosphere and an ocean and their mutual interaction, as well as computing time on a main supercomputer. However, another method to analyse the simulations of ocean and atmosphere for climate scenarios with state-of-the-art climate models is the use of the available archive of coupled atmosphere-ocean model output from climate models of the Intergovernmental Panel on Climate Change (IPCC). The use of these well tested and well documented climate models for standard simulation runs of well described climate scenarios has the great advantage over developing our own climate model, including the laborious task of calibrating and validating the model. The latter is an effort, well above the capacity of the available CcSP funding.

The main question to be addressed in subproject 2 is to what extent variations in heat transport in one medium (ocean) affect the heat transport in the other medium (atmosphere) and how the equator-to-pole temperature gradient near the sea surface reacts on such variations in heat transport. When variations in the radiation budget are small, variations in oceanic heat transport divergence should be associated with similar, but opposite variations in the atmosphere to ocean heat flux. As a result, pole-ward heat transport variations in the upper ocean should be compensated by so called Bjerknes variations in the lower atmosphere. Bjerknes has hypothesized this mechanism for Atlantic air/sea interaction in the mid-latitudes.

The mechanisms for Bjerknes' compensation of heat transport variations through the atmosphere and ocean on decadal time scales has been investigated, using data output from a pre-industrial control run of the Third Hadley Centre Coupled Ocean-Atmosphere General Circulation Model (HadCM3), developed by the Hadley centre, the climate research centre of the Met Office in the UK. By using statistical analysis, Bjerknes compensation (atmospheric heat transport compensating ocean heat transport variations) has been "observed" in these data on decadal time scales at latitudes between 50° and 80°N. Also the magnitude of the maximum compensation rate of this mechanism has been determined, as well as its preferential latitude, in order to estimate its importance and the latitude of maximum response.

The stability of the Atlantic Meridional Overturning Circulation (AMOC) for the pre-industrial climate and a future climate with doubled and quadrupled CO_2 concentrations were investigated, using data from the archive of coupled atmosphere-ocean model output of the Intergovernmental Panel on Climate Change (IPCC). Here no additional model runs were required, while standard simulations with several state-of-the-art coupled climate models were available. Such studies also give insight into the behaviour and quality of climate models, used for the IPCC Fourth Assessment Report (AR4), published in 2007. The AR4 report already had shown that in most, but not all, climate simulations the strength of the AMOC would decrease in response to the increasing amount of greenhouse gases in the atmosphere. The stability of the AMOC and its relation to the oceanic fresh water budget of the Atlantic basin have been determined, searching for specific conditions for an unstable response of the AMOC to relatively small changes in its freshwater forcing.

Subproject 3: Observations on the internal wave climatology in the North Atlantic Ocean (NIOZ). This subproject was divided into 3 work packages:

- W8: The analysis of existing (historical) current meter data from the Atlantic Ocean in order to estimate internal wave characteristics that give rise to vertical mixing and allows the estimate of turbulent mixing coefficients
- W9: Analysis of data from current meters, mounted in internal-wave moorings, deployed in the North Atlantic Ocean as part of the CS1 project.
- W10: Determine the parameterization of vertical turbulent mixing in the ocean, depending on the input of mechanical energy via internal tides and inertial waves.

Despite it being crucial for results from large-scale ocean circulation modelling, our knowledge of the temporal and spatial variability of deep-ocean turbulent diapycnal mixing is very limited. As suggested by Munk and Wunsch in 1998, the Atlantic Meridional Ocean Circulation, itself of prominent importance to European climate, depends strongly on small-scale mixing processes. Processes that supply mechanical energy to drive turbulent mixing in the deep ocean are assumed to be related to internal waves, mainly at tidal frequencies, and to inertial waves, generated by changes in the direct wind forcing at the sea surface. These waves transport mechanical energy from shallower parts of the deep-sea where they will break when encountering irregular and steep topography, generating the irregular turbulent motion that can sustain vertical transport (diffusion) of heat, salt and mass. These processes and the resulting turbulent mixing are required to maintain a horizontal density gradient in the deep ocean, "driving" the deep cold branch of the AMOC. Without turbulent mixing, the ocean will get filled homogeneously with high-density cold water masses, formed by convective mixing in winter at high latitudes, and all deep circulation will stop. A limitation of the available energy for turbulent mixing may lead to unexpected and counter-intuitive responses of the AMOC to changes in climate forcing of the ocean.

The main objective of subproject 3 was to study the spatial (smooth and rough topography) and temporal (summer/winter; but also 'faster' sub-inertial) variations of internal wave motions and their energy distributions in detail in the North-Atlantic Ocean. Hereby the focus was on near-inertial and tidal frequencies, which generally form local maxima in energy spectra of internal waves. However, also the effects of tidal and inertial waves on higher-frequency internal waves were studied. To meet these objectives appropriate historical current meter data from the databases at Oregon State University and NIOZ were analyzed, as well as data sets from current meters, deployed during the CS1 project. The latter data sets were obtained with dedicated deep-ocean internal wave moorings fitted with current meters, obtained from the NWO investment grant. Sites were chosen for these current meters where storms are frequently passing (the Irminger Sea, Bay of Biscay, the Canary Basin, and the near equatorial zone). Every summer the current meter moorings were recovered, serviced, and replaced at another position, in order to extend the coverage over the internal wave observation maximally. The current observations, obtained with the moorings in the Irminger Sea for subproject 1, were also made available for use in subproject 3.

In the Canary Basin the focus was on moorings at the latitude where (diurnal) tidal frequencies match the local inertial wave frequency. In that case a sort of resonance can occur between both types of water motion. Detailed knowledge of the near-inertial response of the ocean is relevant for studies of the entire internal wave band, since at these frequencies vertical current shear (the vertical change in velocity) is largest. Then the vertical length scales associated with vertical current variations are shortest. Shear instability that may lead to the breaking of high-shear internal waves is considered one of the key mechanisms for deep-ocean mixing.

To meet the objective of determining the strength and parameterization of vertical turbulent mixing, data from moored current meters, from a thermistor string that measured the temperature precisely and fast at several levels, and from an acoustic Doppler current profiler (ADCP) were used together. This has led to estimates of internal wave energy variations, shear and stratification, and energy conversion. Certain frequency bands were analyzed specifically, the near-inertial and tidal bands, and their effects on the rest ('background') of the internal wave continuum, also at their non-linear interaction frequencies. Variations in the level of the background and the energy contents and width of any distinguished frequency band have provided information on the varying background conditions, hence climatology of the internal waves in the Ocean. Detailed vertical full-depth profiles of temperature and salinity were recorded, using a CTD during mooring deployment and recovery cruises. Additional micro-structure observations were carried out in the upper 1500 m with a free falling turbulence profiler.

Subproject 4: The influence of the spatial pattern of diapycnal turbulent mixing on the meridional overturning of the North Atlantic Ocean (IMAU). This subproject was divided into 3 work packages:

- W11: Set-up of a numerical general circulation model of North Atlantic Ocean (limited area model) to be used for sensitivity studies within CS1, and to be made available for future climate research.
- W12: Analysis of the influence of different methods of the parameterization of vertical turbulent mixing on the results of simulations with an ocean general circulation model forced with realistic atmospheric data, especially of the influence of the properties of the AMOC. This includes the study of the spatial variation of turbulent mixing on the AMOC.
- W13: A "popular" article for interested non-specialists on the ocean's role in the climate system. This work package should be carried out in cooperation between scientists of the different subprojects.

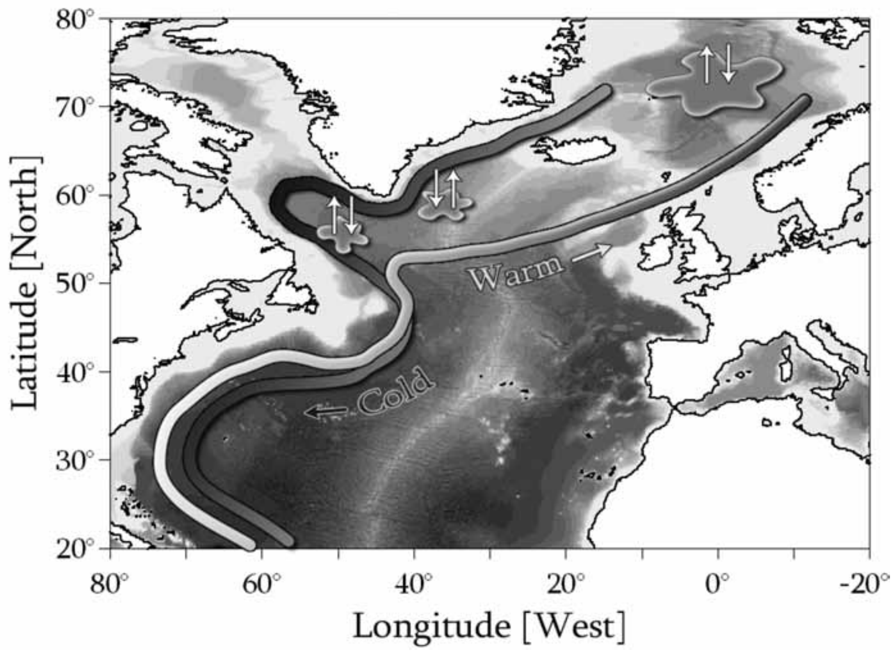
Recent observations have pointed out that diapycnal mixing is highly variable in space. As stated for subproject 3, a main contributor to this locally enhanced mixing is the generation and subsequent breaking of internal waves near steep and/or rough topography. A preliminary study in which the effects of breaking internal waves are incorporated using a parameterization that evolves with the state of the ocean showed a large impact of locally generated turbulent mixing on the density structure of the global ocean and on the simulated strength of the meridional overturning circulation (the AMOC).

So far, comparison studies that aimed at understanding the impacts of diapycnal turbulent mixing on the (overturning) circulation of the ocean have applied spatially varying parameterizations that are independent of the local stratification. That implies that everywhere in the ocean plenty of energy is available to maintain the turbulent mixing, required for the maintenance of the AMOC. However, it has been shown that when the diapycnal mixing coefficient depends on the stratification, consistent with the idea that the mixing is caused by breaking internal waves, the available mechanical energy to support turbulent mixing is a limiting factor for the strength of the AMOC (expressed in volume transport). In such a situation, an increase in the north-south density difference (e.g. between pole and equator) will lead to a decrease in overturning strength, since only a limited amount of energy is available to maintain the required vertical turbulent mass flux. This contrasts the intuitive expectations as well as thermodynamic scaling theory which suggest that the overturning strength will increase with the increase of the south-to-north surface density difference. This result leads to the unexpected outcome that the density of the polar ocean increases because of very cold winters, the AMOC and its heat transport will decrease, which in itself will lead again to colder polar winters. Since nearly all climate models, used for the AR4 IPCC report, predicted a decrease in the strength of the AMOC, but also had a relatively simple parameterization of turbulent mixing, this seemingly esoteric subject has direct relevance for studies dealing with the future of the European climate.

In addition, except for the latter, the comparison studies mentioned above all did neglect the effects of bottom topography. Since the internal waves, responsible for the localization of mixing, are generated near rough topography, it makes little sense to include one and to neglect the other. Last, wind forcing will induce a mixed layer in the upper ocean, and introduce wind-driven gyres that transport water properties in the horizontal plane, contrary to the AMOC, which in principle rotates in a vertical plane. In light of the above, a systematic study was planned, aimed at understanding the impacts of non uniform diapycnal mixing on the ocean circulation of the North Atlantic Ocean. The approach should be two-fold. First sensitivity experiments should be conducted in a highly idealized model set-up to identify the physical mechanisms at work. Idealized bottom topography would be used, and various mixing parameterizations of increasing complexity. Also the influence of wind forcing would be addressed explicitly, by repeating simulations with and without a surface wind stress. After and in conjunction with this, we planned to perform sensitivity experiments using a state-of-the-art high-resolution isopycnic ocean model of the Atlantic Ocean only, with realistic topography and wind forcing. To define the spatially varying diapycnal mixing coefficient Ky, the map for the North Atlantic Ocean that can be constructed from the available observations in subproject 3 should be used. All simulations should be performed with an isopycnic model which is better suited for studies on diapycnal mixing than z-coordinate models. Although in the latter the explicit mixing can easily be made to act mainly along isopycnals, the (often considerable) implicit diffusion associated with the numerical discretization (= numerical diffusion) obscures the physical impacts of a specific mixing parameterization. Therefore one of the challenging technical tasks, to be performed in this subproject was initiating such an isopycnic model for a limited area, and with open boundaries, separating the domain of the model, the Atlantic Ocean, from the rest of the world ocean.

4. Results/Synthesis

The monitoring of the climatic variability in the north-western North Atlantic Ocean, carried out in subproject 1, is a continuation of international efforts to monitor and study this area in the WOCE era (1990-1997), funded in the Netherlands by NWO, and in the later CLIVARNET project, internationally coordinated informally, on a national level coordinated by NWO and funded by NIOZ itself. The LOCO investment subsidy, received in 2003 from NWO, has enabled us to refine the monitoring of the Irminger Sea from annual to daily intervals by the use of the self recording instrumentation, mounted in the profiling moorings. After the end of the CS1 funding period, we have continued the monitoring programme with funding received from the EU as part of the THOR research programme. THOR aims at developing forecast tools to predict and/or analyse changes in the strength of the AMOC and its climatic consequences for Western Europe. The results obtained in CS1 should be judged with the long lasting efforts in mind, needed to maintain a monitoring system to establish the footprint of climatic variability at inter-annual to decadal time scales.



Crude schematic of the North Atlantic Meridional Overturning Circulation. Warm surface water flows northward in the North Atlantic Current system, compensated by a southward flow of cold deep water in the Deep Western Boundary Current. Sites of deep water formation are indicated by the grey patches.

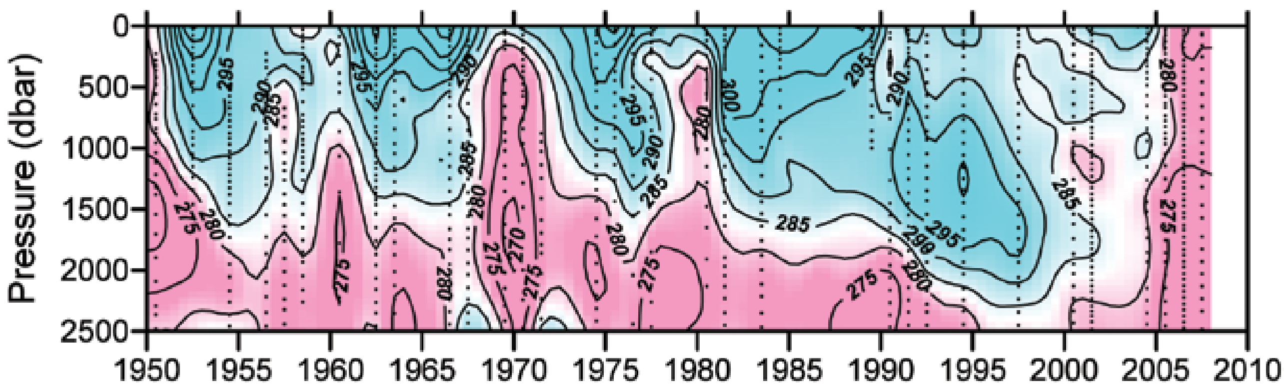
The hydrographic observations, carried out in the Irminger Sea, covered the whole water column, and were continued until the end of the CS1 funding period. That implies that a considerable part of the data analysis will be performed with funding from other sources. Till now, the focus in the data analysis was on the variations in the formation of Labrador Sea Water (LSW), and on processes connected with this formation process. Several papers and a book chapter have been published in cooperation with scientists from Canada, Germany and the UK.

Labrador Sea Water is a principal convectively formed water mass of the sub-polar North Atlantic (SPNA). Using oceanographic data collected along the AR7 line in the Labrador Sea, the Irminger Sea, and the Iceland Basin we could demonstrate striking changes in the SPNA caused by massive LSW production during 1987–1994 and document recent salinification and warming, imminently bringing SPNA to the state last time seen in the late 1960s. Two prominent LSW classes are spreading across

SPNA since the 1980s. The first, record dense, deep, and voluminous, class has been progressively built by intense winter convection through 1987–1994. Once convection weakens, the LSW class became isolated from the upper layer and starts to decay, rapidly losing its volume while retaining the same density, due to isopycnic mixing with the neighbouring warm saline intermediate waters. A similar pattern in temperature, salinity and density was seen in the other basins with different time lags. Even though most of this LSW now has left SPNA, some remnants are still present there. The second, shallower, LSW class strengthened in 2000; over subsequent years its core became slightly thicker and deepens. The anomalous signals acquired by these LSW classes in their formation region arrived in the Irminger and Iceland basins with the characteristic delays of two and five years for deeper LSW and a year and four years for shallower LSW. Analysis of the LSW properties in a 60 year hydrographic time series, reconstructed from the archives, suggested that the main hydrographic signal at LSW levels (~1500 m) was a quasi-periodic temperature signal with a period of about 50 year and a range of 0.7°C. It appears that this "huge" temperature variation can be explained from a large part from variations of the heat flux to the atmosphere. Individual LSW formation events could be identified from variations in the vertical stability, and in the concentration of dissolved oxygen. Convective formation of LSW to 1500 m occurs about every 10 year. The strong LSW class formed in 1987-1994 coincided with the coldest period of the quasi 50 year oscillation, but in other periods newly formed LSW classes could also be recognized as a cold dent in the temperature record, with a deviation of 0.1 to 0.2°C relative to the longer-term trend.

The moored instrumentation has shown that also in the Irminger Sea convection occurs every winter, parallel to the convection in the Labrador Sea. The convection penetrates into the permanent thermocline and forms a cold type of sub-polar Mode Water (SPMW). The properties of SPMW in the Irminger Sea (temperature, salinity, mixing depth) showed considerable changes from year to year, but it also showed the near 50 year temperature variability, related to the long-term variation of the surface heat flux. In cold winters, e.g. the winter of 2008, that convection reached depths of over 1 km, the depth where LSW is found below the SPMW layer. At the levels where LSW was found, the mooring data showed a large day-to-day variability in temperature and salinity. These variations were more or less in phase and compensate each other in density. This is a fingerprint of lateral intrusions, originating from the warm and saline boundary current over the slopes of the Irminger Sea and the Iceland Basin. The lateral mixing of the warm and saline boundary currents with the centres of the Labrador and Irminger Sea forms the mechanism which returns the altered water column after the formation of a new LSW class to its original less oxygenated, more saline, and warmer state, as was observed around 1970.

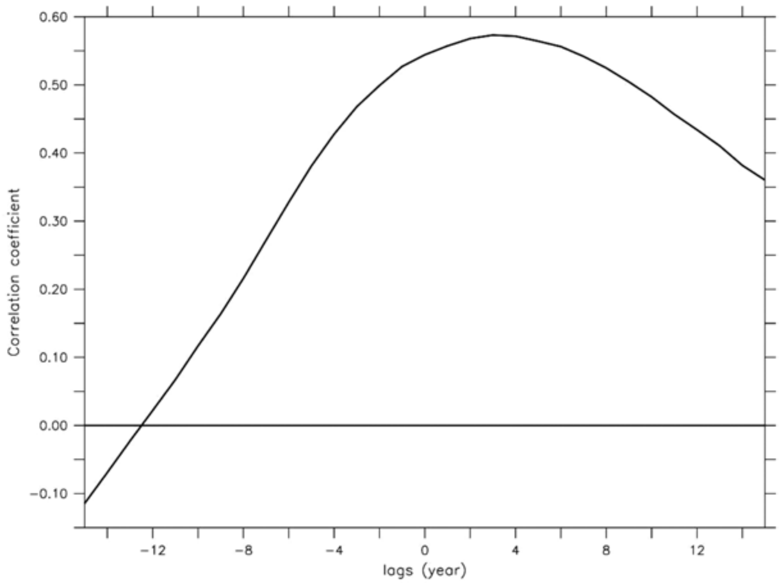
LSW is the shallowest component that contributes to the cold branch of the AMOC. At deeper levels (~2000 to 2500 m) a more saline water mass is found in the Irminger Sea and Labrador Sea. That is the cold water from the Norwegian Sea that flows over the ridges between Iceland and Scotland into the North-eastern Atlantic Ocean, named North-East Atlantic Deep Water (NEADW). From the now available 20 year of observations along the AR7E section, a considerable inter-annual variation in temperature and salinity can be recognized. However, these data still have to be analysed thoroughly before firm conclusions on the character of the variation of NEADW properties can be drawn. Anyway, also this component of the cold branch of the AMOC knows its temporal variability.



The time-pressure plot of the oxygen concentration (mmol/kg) in the central Irminger Sea shows ventilation events (high oxygen) of the intermediate water about every decade. These are caused by deep reaching convective mixing, forced by strong heat fluxes to the atmosphere in successive winters.

The observations along the AR7E section also show the presence of a very cold (<1.5°C) core of water over the lower continental slope off Greenland. That is Denmark Strait Overflow Water (DSOW), the water mass from the northern Iceland and Greenland Seas that spills over the shallow (~650 m) sill in Denmark Strait between Greenland and Iceland into the Irminger Sea. This water type is the coldest and densest contributor to the cold southward branch of the AMOC. The 20 year of annual AR7E observations have shown that also this water type shows relatively large inter-annual variations in its temperature and salinity, only partly compensating each other in density. The use of self-recording instrumentation, mounted near the sea bottom in the moorings in the Irminger Sea has revealed that the irregular appearance of the inter-annual variability is an artefact of the 1/year sampling frequency. Since we sampled at a much higher rate, it appeared that the variation in temperature and density mainly occurs as a saw tooth curve with annual frequency, with the low density peaks in summer. Changes in salinity of the DSOW were more or less orthogonal to the saw tooth changes in temperature, and were not correlated with density changes. With both moorings, on the eastern and western side of the Irminger Basin, near coherent but irregular swings in salinity were observed with a characteristic time scale of about 1.5 year. It was concluded that these salinity variations were likely connected with the supply side of this water type; water mass changes at, or north of Denmark Strait.

The subproject on modelling studies of heat transport variations in the ocean and atmosphere (subproject 2) was run according to schedule. The mechanisms for Bjerknes compensation of heat transport variations through the atmosphere and ocean on decadal time scales were investigated, using data output from a pre-industrial control run of the Third Hadley Centre Coupled Ocean–Atmosphere General Circulation Model (HadCM3). This control run was chosen to evade the problems, connected with the influence of anthropogenic induced transient changes of climate characteristics on the meridional heat transport. Contrary to a re-analysis or hindcast, the model run was not intended to reproduce the historical climate development, but it should reproduce similar climate statistics as the historical reality (average, variance, and higher order norms). It already has been shown that Bjerknes compensation occurs with characteristic decadal time scales in a long pre-industrial control run of HadCM3. This result was elaborated on by performing lead/lag correlations of the atmospheric and oceanic heat transports. By using statistical analysis, Bjerknes compensation was observed on decadal time scales at latitudes between 50° and 80°N. A maximum compensation rate of ~55% appeared to occur at 70°N. At this latitude, the correlation rate peaks when the ocean leads the atmosphere by one year. The mechanisms by which Bjerknes compensation occurs at this latitude were also investigated. Anomalies in oceanic heat transport appeared to be associated with variations in the strength of the AMOC. The associated sea surface temperature (SST) anomalies were in general too weak to assert a significant impact on the atmosphere. At 70°N, however, such SST anomalies were a prelude to the transition from sea ice coverage to open water after which the associated changes in heat exchanged with the atmosphere are strong enough to force an atmospheric response. Because of the presence of a strong AMOC component in the Atlantic Ocean, this interaction was confined to the region where the northeast Atlantic and Arctic Oceans connect. The atmospheric response to increased (decreased) heating from below is a decreased (increased) pole-ward temperature gradient; leading to a decreased (increased) heat transport by baroclinic eddies. The anomalous thermal low that is set up by heating from the ocean is associated with anomalous advection of cold air from the Greenland landmass.

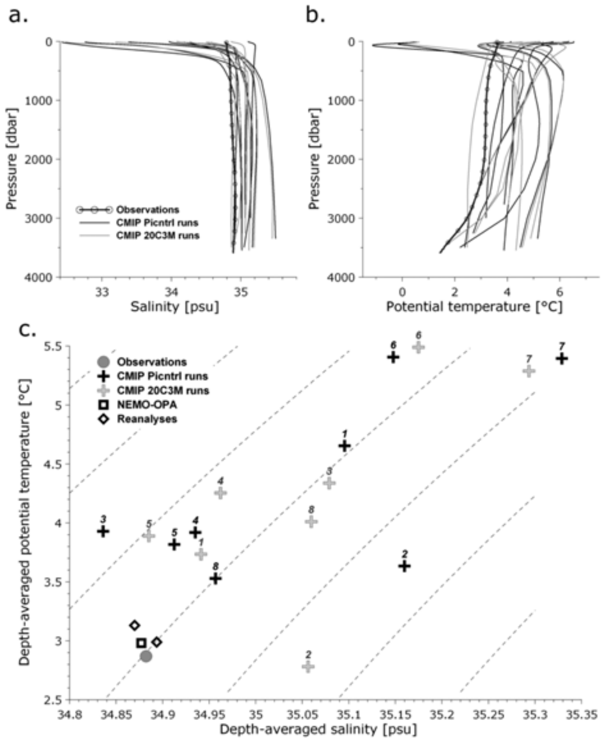


The correlation of the ocean heat transport at 70°N with the integrated flux of the ocean into the atmosphere in an area bounded by 70°W, 40°E, 60°N, and 80°N. One can see that the ocean heat transport at 70°N leads by approximately 3 yr.

Climate not only exists as an averaged state, the natural variability with its own statistics is also part of climate, and may change with "climate change". One can therefore question whether the natural climate variability will change because of greenhouse gas driven climate change. To study this, the response of the internal variability of the AMOC to enhanced atmospheric greenhouse gas concentrations has been studied. As "data" the simulations from an ensemble of climate change scenario runs, used for the IPCC AR4 report, were available. In the model, enhanced greenhouse forcing resulted in a weaker and shallower AMOC with reduced internal variability. At the same time at 55°N between 0 and 1,000 m depth the overturning rate increased as a result of a change in the area of convection. In a warmer world, new regions of deepwater formation develop further north due to the pole-ward retreat of the sea-ice boundary. The dominant pattern of internal AMOC-variability consists of a monopole centred around 35°N. Due to anthropogenic warming this monopole shifts pole-ward. The shift is associated with a stronger relation between MOC-variations and heat flux variations over the sub-polar gyre. The "old" convective sites (e.g. the Labrador Sea) become marginal for convective mixing. Therefore convection becomes more irregular, which leads to enhanced heat flux variability. In new convective sites heat flux variations initially are related to sea-ice variations. When the sea-ice coverage further decreases they become associated with (irregular) deepwater formation. Both processes act to tighten the relation between sub-polar surface heat flux variability and MOC-variability, resulting in a pole-ward shift of the latter. Overall this may lead to a more variable climate in Europe.

The analysis of the freshwater budget and its influence on the meridional heat flux sustained by the AMOC could not be completely finished, due to the premature departure of the assigned postDoc, but is continued after CcSP CS1 with alternative funding. The main result was that an abrupt shut-down of the AMOC has a large climate impact on Western Europe. Paleoclimatic proxy data on the last glacial cycle do show evidence of such abrupt collapses of the AMOC. The absence of rapid climate changes after the Younger Dryas suggests that the AMOC has resided in a more stable regime over the last 10.000 years. However, an intensified hydrological cycle, due to global warming, might destabilize the deep ocean circulation again. In contrast, climate models in future scenario runs do not show a shut-down of the deep ocean circulation. By applying a new diagnostic that has been shown to measure the stability of the deep ocean circulation in simpler climate models, we found a robust signal in data output from state-of-the-art climate models from the IPCC model data archive, that indicates a shift of the AMOC towards a reduced stability due to global warming. The diagnostic was based on the net freshwater transport by the AMOC into the Atlantic basin. We also found that the deep ocean circulation for the present climate is biased towards a too stable equilibrium in all models, as compared to observations. This bias prevented the MOC from a shut-down in climate scenario runs for the future. As a result the collapse of the MOC in the near future is therefore more likely to occur than the scenario simulations with current state-of-the-art climate models predict.

Another important question is related to the general reliability of the climate models, used for the simulation of climate scenarios. When such models are not able to reproduce the present climate with its averages and variations, it will be hard to rely on such models for the important decisions on the costly measures, needed to reduce global warming, or on the large investments required for adaptation in a complex society like the Dutch. To be able to judge the quality of the models a systematic comparison between observations and simulations is required. Because of the work carried out in subproject 1, data and know-how were present within CS1 for such an exercise, while climate simulation products were collected for subproject 2. The performance of coupled climate models (CCMs) in simulating the hydrographic structure and variability of the north-western North Atlantic Ocean, in particular the Labrador and Irminger Seas, could be assessed. This sea area plays an important role in the AMOC, and in the heat release from the ocean to the atmosphere. Hydrographic properties of the pre-industrial run of eight CCMs used in the IPCC AR4 report were compared with observations from the WOCE AR7 section from the Irminger Sea and the Labrador Sea. The mean and standard deviation of 20 yr of simulated data were compared in three layers of the water column, representing the surface waters, intermediate waters, and deep waters.



Vertical profiles of (a) salinity and (b) potential temperature from the observations and simulations in the Labrador Sea. The preindustrial model runs are drawn in black; the twentieth-century runs are drawn in gray. (c) The depth-averaged potential temperature and salinity for the observations, models, and reanalyses in the Labrador Sea. The numbers next to the symbols represent different climate models. Dashed lines of equal density anomaly are drawn at 0.1 kg m^{-3} intervals.

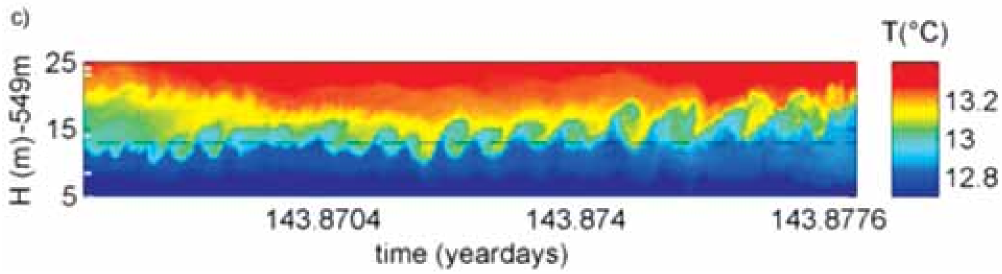
Two models simulated an extremely cold and fresh surface layer with model biases of salinity and temperature down to, respectively, 1.7 psu and 4.0°C, much larger than the observed ranges of variability. The intermediate and deep layers of the ocean in the climate simulations were generally too warm and saline, with biases up to 0.7 psu and 2.9°C. An analysis of the maximum mixed layer depth has shown that the low surface salinity is related to a convective regime restricted to the upper 500 dbar. Thus, intermediate water formed by convection in the model was partly replaced by warmer water from the south. Model biases seemed to be caused by the coupling to the atmospheric component of the CCM. Model drift during long spin-up periods allowed the initially small biases in water mass characteristics to become significant. Biases that developed in the control run were carried over to the twentieth-century climate scenario runs, which were initialized from these pre-industrial control runs.

The observations on the internal wave climatology in the North Atlantic Ocean, carried out in subproject 3, continued until the end of the CS1 funding period. That implies that the data analysis will continue after the end of the CcSP programme, and will require alternative funding. However, the data analysis and interpretation were as lively a part of the subproject as was the data collection and instrumental development, since already many current meter data, available at the data centre of the Oregon State University or coming from previous NIOZ project were available for analysis. The geographic variation of the distribution of internal wave energy in the open ocean was investigated at the dominant inertial and semidiurnal tidal frequencies using historic current observations from the North Atlantic Ocean, around mid-latitudes. Wave kinetic energy may be focused in space because of the existence of topographic attractors. Emphasis was also on possible energy variations due to major topography changes between the eastern (Canary) and western (Hatteras, Sohm) basins, thereby crossing the Mid-Atlantic Ridge (MAR). While in open basins on both sides of the MAR semidiurnal kinetic energy dropped in magnitude by some 50% between latitudes from 20°N to 28°N, in agreement with satellite derived elevation data, an even larger longitudinal dependence was observed. West of the MAR, semidiurnal energy was up to 30 times less than east of it. Inertial kinetic energy is either decreasing (by a factor of 2 to 4) westward or more or less independent of longitude. This contrasted strongly the westward intensified near-surface inertial energy fluxes previously reported. The latter fluxes also did not show an increase (by a factor of 5 to 10) for latitudes from 25°N to 30°N, as observed here for inertial energy in both basins. West of the MAR, the internal wave background level for frequencies up to sixth cycles per day was much less, by a factor of 3 to 10, at tidal-inertial interaction frequencies than east of MAR. No significant atmospheric or large-scale vorticity influence or seasonal variations therein was found on inertial energy content across the basin. As no individual peaks were observed at frequencies K1, O1 and M1, S1, direct diurnal tidal forcing and sub-harmonic resonance must be accompanied by nonlinear interactions in possibly enhancing inertial energy at the critical diurnal latitude.

Around latitudes near 30°N/S where the above mentioned diurnal tidal frequencies equal the local inertial frequency, f, several mechanisms can enhance shear at f due to a reduction in vertical scales of the internal diurnal tides. This would imply locally enhanced deep-ocean mixing. Here, 1.5 years of acoustic Doppler current profiler (ADCP) observations from the Canary Basin revealed that the largest kinetic energy is found at semi-diurnal tides, but also showed a complete absence of semi-diurnal shear. Instead, shear is peaking at slightly sub-inertial frequencies, and the typical vertical scale at the inertial frequency is an order of magnitude smaller than at semi-diurnal frequencies. However, the f-band is broader than the spectral peaks of the deterministic tidal frequencies and the smallest vertical scales, organizing shear in thin layers, are found at the lower inertio-gravity wave limit. Hence, besides possibly sub-harmonic resonance, other mechanisms must be involved in enhancing f-shear and wave to turbulence conversion, including non-linear harmonic interactions and wave trapping at the critical latitude's pole-ward shift. Similar results on the frequency dependence of the magnitude of the vertical shear and wave to turbulence conversion was found in a data set from the Bay of Biscay.

With the CS1 subsidy also the construction of a high-resolution thermistor string was funded. Accurate (<1 mK) temperature sensors were tightly moored for 1.5 year at ~1450 m in the open Canary Basin while sampling the temperature field at 1 Hz. The sensors were in an area where regular thermohaline and density steps occur. We have investigated the variability of internal waves in such a "staircase" environment. The waves moved layers of persistent temperature gradients for particular temperatures vertically. The frequency spectra of the temperature, and more clearly those of inferred vertical currents, showed an internal wave band that extends from slightly sub-inertial frequencies to a transition frequency, higher than the buoyancy frequency N computed over large vertical scales (~100 m). The extension of the internal wave band beyond the traditional bounds was probably due to small-scale vertical layering. Isothermal smoothing revealed details of coherent vertical internal waves and incoherent motions.

Also with a thermistor string sampling at 1 Hz between 0.5 and 50 m above the sloping side of Great Meteor Seamount detailed overturning was observed. While previously reported frontal bores of 40 m amplitude can form with vigorous near-bottom motions and sediment re-suspension at the beginning of the up-slope phase of larger tidal carrier waves, the down-slope phase presented was more "permanently" turbulent away from the bottom. This turbulence was inferred from high-resolution space-time series of the temperature. This revealed ubiquitous finger-like structures during the clear-water tidal phase, with low amounts of acoustic scatterers in the water column. The high-frequency finger-like motions were observed simultaneously with local mode-2 near near-inertial motion with an overall high shear. These motions coincided with large temperature variations, 5 to 10 m vertical amplitudes, and occasionally developed Kelvin-Helmholtz billows. The typical (Eulerian) period of these firstly observed deep-ocean billows amounted to about 50 s. These results have been published in scientific journals and even attracted the attention of the New York Times, which published a summary of the results in its 19 April 2010 issue and stressed the beauty of the observations.



Example of temperature variations during 15 minutes. All data points are included from the 1-Hz sampled thermistors. The vertical coordinate gives the distance to the bottom at 549 m. The curly structures in the temperature distribution show Kelvin Helmholz instabilities, where energy of internal waves is converted to turbulent energy.

The generation and propagation of internal tides in the ocean was also studied with an isopycnic three-dimensional ocean model, MICOM. The response of a uniformly stratified sea in a channel, which is forced by a barotropic tide on its open boundary, was considered. The tide progressed into the channel and forced internal tides over a continental slope at the other end. In a series of four experiments it was shown how the cross-channel geometry affects the propagation and trapping of internal tides. In particular it was found that a cross-channel bottom slope constrains the penetration of the internal tidal energy. Most internal waves refracted toward a cross-channel plane where they were trapped. The exception was formed by edge waves that carry part of the energy away from the continental slope. In the case of rotation near the continental slope, the Poincaré waves that arose in the absence of a cross-channel slope no longer bore the characteristics of a wave attractor predicted by 2D theory, but were almost completely arrested.

Internal-tide energy fluxes were determined halfway over the southern slope of Great Meteor Seamount (Canary Basin), using data from combined CTD/LADCP yoyoing, covering the whole water column. The strongest signal is semi-diurnal and is concentrated in the upper few hundred meters of the water column. It was argued that a commonly applied condition used to determine these profiles was in fact invalid over sloping bottoms. The vertically integrated energy flux could be established unambiguously; the observed results were compared with the outcome of a numerical internal-tide generation model. For the semi-diurnal internal tide, the vertically integrated flux, found in the model, corresponded well to the observed one. The observed diurnal signal appeared to be largely of non-tidal origin.

The least successful of the subprojects of CS1 was subproject 4, studying the influence of the spatial pattern of diapycnal mixing on the meridional overturning. In this part of the programme serious problems were experienced with the setup of a stable isopycnic Ocean General Circulation Model of the Atlantic Ocean (MICOM). By successively simplifying the topographic structure of the ocean basin until a rectangular flat-bottomed basin was used, it was possible to show that the cause of the problems probably was connected with the numerical schemes used in the models of the MICOM family. Especially the coupling of the barotropic and the baroclinic modes in these models lead to an artificially enhanced vertical diffusive transport which renders the resulting overturning circulation unstable. With a model, displaying such strong numerical diffusion effects, no improvement in performance can be expected from a more realistic turbulence parameterization. The turbulent transport, to be studied with these models, will be overwhelmed by the artefact of numerical diffusion. In order to generalize these findings it was decided to switch to a more up-to-date hybrid isopycnic-sigma-pressure (generalized) coordinate Ocean General Circulation Model, HYCOM, for which it was expected that the above mentioned algorithm driven diffusive heat and mass transports would be absent. However, the results with HYCOM were disappointing too. HYCOM is an offspring of MICOM and partly uses similar diffusion algorithms. No stable state of the ocean could be achieved either in the HYCOM runs. Apparently, the isopycnic and related hybrid model families especially developed to solve problems with their hidden numerical diffusion which occur in grid point or z-coordinate models show similar problems. The PostDoc, working for subproject 4, had to leave the research because he had reached the end of the funding period before the problems with the models could be solved. However, it is questionable whether that is possible, also for the more advanced HYCOM model. But one can at least conclude that diffusive mixing and transport, which is essential for the maintenance of the global and the Atlantic meridional overturning circulation, is probably ill presented in most, if not all, climate models. What the consequences of this failure are for the quality of climate predictions and scenarios still has to be established, but some care should be taken when interpreting modelling results.

5. Discussion and conclusions

Original ideas, formulated in the textbooks from the 1960s and 1970s and hardly replaced in more recent literature, assumed that the ocean currents and water masses were reasonably steady. For example, characteristic velocities should be 10 ± 1 cm/s. With the increase in record length and accuracy, allowed by continuous monitoring programmes, it has turned out that characteristic current velocities are more like 1 ± 10 cm/s. One of the challenges, encountered in monitoring programmes is to understand the ± 10 cm/s ocean variability. Similarly the formation and existence of the “permanent” water masses in the world ocean also turns out to be quite variable, with variations in the locus and spread of the water mass characteristics in parameter (T-S) space and in physical space. The CS1 monitoring efforts in the Irminger Sea have confirmed that also in this ocean area, variability is a dominant feature of the ocean’s characteristics. At all depth levels an unexpected large variability was encountered; of the Sub-Polar Mode Water in the near surface layers, of the Labrador Sea Water at intermediate levels of the North-East Atlantic Deep Water at deep levels, and of the Denmark Strait Overflow Water in the bottom layers. By the combination of near continuous monitoring with moored instruments and annual surveys of the AR7E line it was shown that the hydrographic variability takes place at a large range of time scales, day to day variability linked to tides and intrusions were observed, as well as meso-scale eddies and the seasonal cycle. At inter-annual time scales the formation, spreading and decay of new classes of water types has been followed, while at multi-decadal time scales large changes of the intermediate water masses were observed. It is likely that the length of the record of historic hydrographic data determines the longest (multi-decadal) timescale of variability, and that longer record will reveal processes that dominate variability at even lower frequencies. For part of the observed variability the cause of the variability could be identified. The thickness and temperature of the mode water is mainly determined by the local air-sea interaction over the Irminger Sea. The Labrador Sea Water reflects the atmospheric forcing of the Labrador Sea as well as the advection it intermediate levels. The causes of the hydrographic changes, observed at deeper levels, are not known, but are likely located near the overflow sites on the Greenland-Scotland Ridge. Apparently all water masses, involved in the cold branch of the AMOC show strong changes. It is not known yet, what the consequences of this hydrographic variability are for the strength of the AMOC, the related meridional heat transport, and the North Atlantic climate.

The meridional heat transport, responsible for the moderate West European climate, is supported by atmosphere and the ocean circulation. For the heat transport by the ocean and its variations, the AMOC plays an important role. Variations in the atmospheric climate may induce changes in the forcing of the AMOC, what may lead to changes in the oceanic temperature distribution. At the sea surface such temperature changes may induce an alteration of the atmospheric circulation which in its turn may lead to a change in the atmospheric forcing of the AMOC, etc. Such feedback loops, which can determine the character of the natural climate variability in Western Europe, can be studied by means of state of the art coupled climate models. The changing SST, related to variations in the AMOC, has a limited magnitude and therefore influences the atmospheric circulation only in a limited degree. Therefore the Bjerknes compensation, whereby the atmosphere compensates the changes in oceanic heat transport, is not complete. Only at high latitudes, where the changing heat transport alters the distribution of sea ice, and therefore the heat exchange between ocean and atmosphere, shows the Bjerknes compensation a maximum. Model simulations of climate scenarios in a world with enhanced greenhouse gas concentrations show stronger natural climate variability, related to variations of the AMOC. Also here the changing sea ice coverage plays an important role, allowing a large region of convective water mass formation driving a weaker and shallower AMOC. However, a systematic study of the stability characteristics of the AMOC in coupled climate models has shown that the AMOC, and therefore also the West European climate has a considerable bias to too much stability. One can expect that the future west European climate will be more variable than suggested by climate scenario simulations.

By combination of long-term time series of hydrographic data from subproject 1 with climate scenario simulations, use in subproject 2, we were able to study the ability of the coupled climate models to simulate climatic reality in the ocean. Both the simulated stratification of the temperature and of the salinity in the Irminger Sea and the Labrador Sea showed systematic differences with the observations. The characteristic of the convective mixing in the models was apparently wrong, reflected by a relatively fresh surface layer which suppressed further convective formation of intermediate Labrador Sea Water that was replaced by more saline, warmer water with a southern origin. As this water mass is one of the contributors to the cold branch of the AMOC, conclusions of climate scenario studies on the strength of the AMOC should be treated with care. The erroneous sub-surface temperatures in climate models will also have consequences for the predicted sea level rise.

The monitoring of the internal wave climatology has confirmed that the magnitude of the mechanical energy connected with internal tidal waves and with inertial waves varies strongly in space. Such changes were also observed for the higher-frequency background internal wave field. The changes can have the characters of a large-scale west to east gradient, of enhanced energy and shear levels near steep and irregular mid-ocean ridges, or of enhanced energy levels near critical latitudes, where the inertial frequency equals the frequency of specific tidal bands. These spatial changes in the energy levels of the internal wave band are likely reflected in spatial differences in the conversion of internal wave energy to turbulent energy. The resulting differences in turbulent mixing in the ocean will have consequences for the large-scale deep upwelling, and therefore on the strength and spatial structure of the cold, deep branch of the AMOC. A combination of high-frequency measurements of the temperature stratification with a thermistor string and current measurements showed bore-like breaking internal waves in more detail. On these bores occasionally Kelvin-Helmholz billows were observed to develop, the classical mechanism to drive turbulence in a shear flow. This was the first time such structures were observed in the deep-sea. By means of a numerical model, 2-dimensional theoretical aspects of internal wave propagation in 3-dimensional space were studied. Most waves showed a trapping mechanism, corresponding to 2-dimensional theory, but also other systematic differences can be encountered.

The Miami Isopycnic Coordinate Ocean Model (MICOM) is a regional ocean model, and was used to study the influence of spatially varying turbulent mixing on the structure of the AMOC. MICOM is an isopycnic-coordinate oceanic circulation model formulated with the aim of simulating thermodynamically and mechanically driven flow in realistic basins. However, it was not possible to get the MICOM model stable in order to study effects of the turbulence parameterization, because of too large numerical diffusion, although this model had been chosen since it was expected to have much lower numerical diffusion than standard grid point models and its ability to simulate restricted ocean basins with open boundaries. The hybrid HYCOM model, embedded in MICOMs development effort, failed in the same way as MICOM. Simplified versions of the Miami model have been used for 15 years in a number of process studies. While large-scale applications of the fully configured model now include simulations of individual basin circulations and of the global ocean. The advantage of using density surfaces as a coordinate is evident since the eddy mixing in the ocean is mainly along neutral surfaces, or approximately surfaces of constant density. The cross isopycnal mixing is orders of magnitude lower and can in most model experiments be neglected. However, for long term climate simulations where diapycnal mixing is also important apparently the small but finite numerical diffusion can have serious consequences in the heat tendency of the isopycnal layers, making the whole model unstable. The Dutch climate community should reconsider the use of the popular MICOM model where long-term integrations of turbulent diffusion effects are needed.

6. List of publications, resulting from the CS1 efforts

PhD thesis

De Jong M.F. (2010) Hydrographic variability of the Irminger Sea. PhD Thesis, Utrecht University, pp. 208, ISBN: 978-90-393-5425-4.

peer reviewed journals

De Jong, M.F., S.S. Drijfhout, W. Hazeleger, H.M. van Aken, and C.A. Severijns (2009) Simulations of hydrographic properties in the north waestern North Atlantic in coupled climate models. Journal of Climate, 22(7), 1767-1786, DOI: 10.1175/2008JCLI2448.1.

Drijfhout, S.S. and L.R.M. Maas (2007) Impact of channel geometry and rotation on the trapping of internal tides. Journal of Physical Oceanography, 37, 2740 - 2763.

Drijfhout, S.S. and W. Hazeleger (2007) Detecting Atlantic MOC changes in an ensemble of climate change simulations. Journal of Climate, 20, 8, 1571-1582, doi:10.1175/JCLI4104.1.

Drijfhout, S.S., W. Hazeleger, F. Selten and R. Haarsma, (2008) Future changes in internal Atlantic Meridional Overturning Circulation variability. Climate Dynamics, 30, 4, 407-419, doi:10.1007/s00382-007-0297-y.

Gerkema, T., and H. van Haren (2007) Internal tides and energy fluxes over Great Meteor Seamount. Ocean Science, 3, 441-449.

van Aken, H.M., H. van Haren and L.R.M. Maas (2007) The high-resolution vertical structure of internal tides and near-inertial waves measured with an ADCP over the continental slope in the Bay of Biscay. Deep-Sea Research I, 54, 533-556.

van Aken, H.M., M.F. de Jong, and I. Yashayaev (2011) Decadal and multi-decadal variability of Labrador Sea Water in the north-western North Atlantic Ocean derived from tracer distributions: heat budget, ventilation, and advection. Deep-Sea Research I, accepted for publication.

van der Swaluw, E., S.S. Drijfhout and W. Hazeleger (2007) Bjerknes compensation at high Northern latitudes: The ocean forcing the atmosphere Journal of Climate, 20, 24, 6023-6032, doi:10.1175/2007JCLI1562.1.

van Haren, and H; Millot, C (2009) Slantwise convection: A candidate for homogenization of deep newly formed dense waters. Geophysical Research Letters: 36, L12604.

van Haren, H (2009) High-frequency vertical current observations in stratified seas. Continental Shelf Research: 29. 1251-1263.

van Haren, H (2009) Using high sampling-rate ADCP for observing vigorous processes above sloping [deep] ocean bottoms. Journal of Marine Systems: 77, 418-427.

van Haren, H. (2007) Longitudinal and topographic variations in North Atlantic tidal and inertial energy around latitudes 30±10°N. Journal of Geophysical Research. 112, C10020, doi:10.1029/2007JC004193.

van Haren, H. (2007) Monthly periodicity in acoustic reflections and vertical motions in the deep ocean. Geophysical Research Letters, 34, L12603, doi: 1029/2007GL029947.

van Haren, H. (2007) Self regulation of deep-ocean internal wave continuum: Observations on related near-inertial shear and high-frequency vertical motions. Geophysical Research Letters, 35, L04606, doi:10.2007GL032697.

van Haren, H. (2008) Abrupt transitions between gyroscopic and internal gravity waves: the mid-latitude case. Journal of Fluid Mechanics, 598, 67-80.

van Haren, H. (2008) Self-regulation of deep-ocean internal wave continuum: Observations on related near-inertial shear and high-frequency vertical motions. Geophysical Research Letters, 35(4) L04606, DOI: 10.1029/2007GL032697.

Van Haren, H; and Gostiaux, L (2009) High-resolution open-ocean temperature spectra. Journal of Geophysical Research-Oceans: 114, C05005.

Van Haren, H; and Gostiaux, L (2010) A deep-ocean Kelvin-Helmholtz billow train. Geophysical Research Letters, 37, L03605, doi:10.1029/2009GL041890.

van Haren, H; Laan, M; Buijsman, DJ, et al. (2009) NIOZ3: Independent Temperature Sensors Sampling Yearlong Data at a Rate of 1 Hz. IEEE Journal Of Oceanic Engineering: 34, 315-322.

Yashayaev, I., H. M. van Aken, N. P. Holliday, and M. Bersch (2007), Transformation of the Labrador Sea Water in the subpolar North Atlantic, Geophysical Research Letters, doi:10.1029/2007GL0318.

Yashayaev, I., M. Bersch, and H.M. van Aken (2007) Spreading of the Labrador Sea Water to the Irminger and Iceland basins. Geophysical Research Letters, 34, L10602, doi:10.1029/2006gl028999

book chapters

Yashayaev, N. P. Holliday, M. Bersch I., and H. M. van Aken (2008) The history of Labrador Sea Water: Production, Spreading, Transformation and Loss. In: Arctic-Subarctic Ocean Fluxes, R.R. Dickson, J. Meincke, and P. Rhines (Eds.) Springer, ISBN 978-1-4020-6773-0, pp. 569-612.

poster presentations

De Jong, M.F. and H.M. van Aken, Five years of daily observations from the Irminger Basin, 23 oktober 2008, BBOS symposium, Texel, the Netherlands.

De Jong, M.F., S.S. Drijfhout, W. Hazeleger, H.M. van Aken, and C.A. Severijns, Simulations of hydrographic properties in Coupled Climate Models, 14 april 2008, EGU Wenen.

Drijfhout, S.S., Future changes in internal MOC-variability. Poster: North Atlantic Subpolar Gyre Workshop, 19/3/2007-21/3/2007 CLIVAR, Kiel, Germany.

E. van der Swaluw, S.S. Drijfhout and W. Hazeleger, Poster presentation: Analyses of modeled heat transport variability in a coupled climate model. Climate changes spatial planning, 12-13 September 2007, The Hague, The Netherlands.

Swaluw, E. van der, S. Drijfhout and W. Hazeleger, Bjerknes compensation at high Northern latitudes: the ocean forcing the atmosphere Poster: Rapid Climate Change, 24/10/2006-27/10/2006, Birmingham, United Kingdom.

Swaluw, E. van der, S.S. Drijfhout and S.L. Weber, Is the stability of the Atlantic MOC changed by global warming? Poster: EGU General Assembly, 15/4/2007-20/4/2007, Vienna, Austria.

outreach papers

Drijfhout, S.S. (2008) Veranderingen in de Warme Golfstroom, Meteorologisch Informatiebulletin Maritiem, 2008, Jan., 6-12.

Drijfhout, S.S., (2008) Changes in the Atlantic Meridional Overturning Circulation, KNMI Biennial Report 2005-2006.

Van Aken, H. and F. de Jong, (2008) De toestand van de noordelijke Noord-Atlantische Oceaan. Geografie, nov./dec. 2008, 8-11.

van Aken, H.M. (2008) De Atlantische Oceaan, de Golfstroom en ons klimaat. GEA, 41(4), 106-110.

Climate changes Spatial Planning

Climate change is one of the major environmental issues of this century. The Netherlands are expected to face climate change impacts on all land- and water related sectors. Therefore water management and spatial planning have to take climate change into account. The research programme 'Climate changes Spatial Planning', that ran from 2004 to 2011, aimed to create applied knowledge to support society to take the right decisions and measures to reduce the adverse impacts of climate change. It focused on enhancing joint learning between scientists and practitioners in the fields of spatial planning, nature, agriculture, and water- and flood risk management. Under the programme five themes were developed: climate scenarios; mitigation; adaptation; integration and communication. Of all scientific research projects synthesis reports were produced. This report is part of the Climate scenarios series.

Climate scenarios

The projects in this field are designed to obtain high quality climate information and scenarios relevant for the Netherlands. The projects both focus on an improved monitoring and modelling of regional climate variability, and at the construction of tailored climate change scenarios suitable for exploring spatial adaptation options, such as flood retention areas or coastal defense. In all fields special attention is devoted to extreme climate conditions. The climate scenarios are designed and developed jointly with a number of key stakeholders.

Programme Office Climate changes Spatial Planning

c/o VU University Amsterdam, FALW
De Boelelaan 1085
1081 HV Amsterdam
The Netherlands
T +31 20 598 7318
office@klimaatvoorruimte.nl

c/o Alterra, Wageningen UR
P.O. Box 47
6700 AA Wageningen
The Netherlands
T +31 317 48 6540
info@klimaatvoorruimte.nl

www.climatechangesspatialplanning.nl