GOCE RESEARCH FOR OCEANOGRAPHY IN THE NETHERLANDS

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ABSTRACT

GOCE-related research in the Netherlands focuses on the dynamics and operation of the thermohaline circulation, the global scale transport of heat and salt (and other water characteristics) by the oceans. This circulation is to a large extend set by several 'choke points' where it displays high sensitivity to changing conditions. The key areas that are addressed are the connection between the Indian and the Atlantic Oceans around South Africa and the separation and extension of western boundary currents like the Gulf Stream and the Kuro-Shio.

INTRODUCTION

The most important missing link in the determination of the absolute velocity field of the ocean circulation is an accurate geoid. TOPEX/POSEIDON and ERS satellite altimeters have been used to determine the geoid for long wavelengths, but for length scales below 1000 km the accuracy is still too small. Large ocean currents like the Gulf Stream, the Kuro-Shio, the Agulhas and the Brazil Current have a strong boundary-layer character. Their characteristic length scales are of the order of tens to one hundred km, so that their time-mean velocity field cannot be determined from altimetry. These large currents transport important quantities of heat, salt and other characteristics of the seawater. The expectation is that the GOCE mission (Gravity Field and Steady State Ocean Circulation Explorer) will provide an accurate geoid on these smaller length scales. From that a time-mean dynamic topography can be derived and thus the absolute velocity field at the ocean surface in those main currents. When the time-mean circulation is known it can be combined with, at that time (2005), about 20 years of time-varying velocity fields from the ongoing altimeter missions (i.e. Geosat, TOPEX/POSEIDON, ERS1 and 2, GFO and JASON). This will provide an enormous extension of the data that can be used to study the interannual and decadal variability of the ocean circulation.

The oceanographic community in the Netherlands is hosted by the NIOZ (Netherlands Institute for research of the sea), IMAU (Institute for Marine and Atmospheric research Utrecht) and KNMI (Royal Dutch Meteorological Institute). Over the past ten years, the IMAU oceanography group has developed extensive expertise in the oceanic interpretation of satellite altimetry data, and the assimilation of these data in numerical ocean models. The data handling is carried out in close cooperation with the DEOS group of the TUD. This expertise can now be extended in the direction as indicated here. At the NIOZ, expertise on sea-going physical oceanography is present to provide the necessary validation of current and other fields. The KNMI has a strong modeling group with applications ranging from mesoscale features to global intermediate complexity models.

The basis for this research is formed by several coherent research projects and programs within the theme 'Ocean Circulation and Climate' conducted at the IMAU, and/or coordinated by IMAU oceanographers. More specifically, this concerns a program in which the exchange between the Indian and the Atlantic Oceans is studied, and a program in which the stability and variability of western boundary currents like the Gulf Stream system is investigated in a fundamental way.

In the following section these project and programs are discussed, and the need for the absolute sea-surface height is highlighted. That is followed by a section on the proposed (and ongoing) research. A summary and conclusions sections closes this abstract.

EMBEDDING IN EXISTING PROGRAMS

The GOCE-related research is strongly embedded in existing oceanographic programs that are discussed below.

Interocean Exchange

The first program is formed by the NOP-program Interbasin Exchange, and the CLIVARNET programs MARE and ACSEX. The NOP-program Interbasin Exchange focuses on the study of dynamical processes that determine the exchange between the Indian and the Atlantic Oceans, and on the impact this exchange could have on the strength of the Atlantic overturning circulation (the "conveyer belt"). This is a theoretical and model-oriented program, which also contains an important component in which the analysis of satellite observations is used to try to determine the large-scale connection between the two oceans. A strong data assimilation component is also present (see Fig.1).

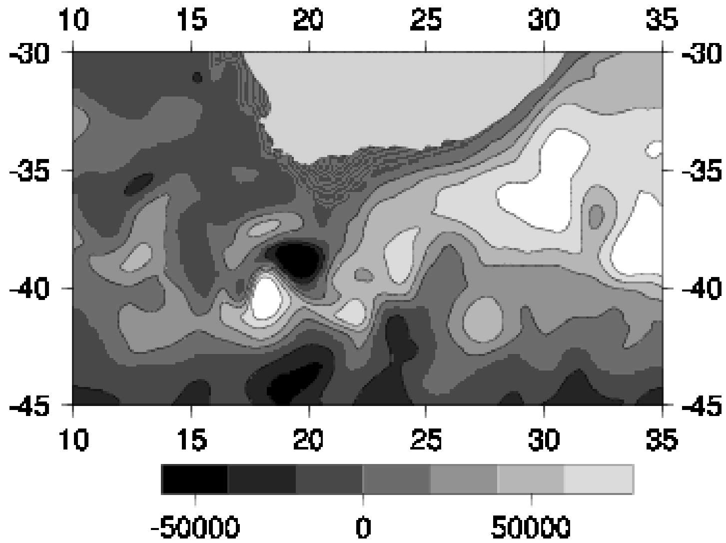

Fig 1 Streamfunction showing the current structure around the southern tip of the African continent. The current flows along the contours. This result is obtained by assimilating altimeter data into a multi-layer model of the ocean, using a new assimilation technique which is superior to the Kalman filter for non linear model dynamics.

MARE, the Mixing of Agulhas Rings Experiment, has recently been granted by NWO in light of the CLIVAR(NET)-program. Partners in MARE are IMAU, KNMI, NIOZ, VUA, Oregon State University (USA) and the University of Cape Town (SA).
ACSEX, the Agulhas Current Sources Experiment, is a further extension of MARE, with, presently, involvement of IMAU, NIOZ, Cape Town University and (presumably) Scripps Institution of Oceanography (U.S.A.).

Each of the above mentioned programs focuses on critical aspects of the variable ocean circulation around South Africa. The exchange between Indian and Atlantic Oceans is established largely by the shedding of enormous Agulhas Rings south of Africa, that migrate into the Atlantic Ocean (see [1] for a review of the Agulhas system). Goal of MARE is to determine what part of those large Agulhas Rings eventually mixes into the Atlantic overturning circulation, how variable that contribution is (at yearly, decadal to millennium time scales), and which physical processes determine that fraction. It comprises a large seagoing component. Three Dutch cruises have been performed in 2000 and 2001 in the Benguela area in the southeast Atlantic Ocean, in which the decay of a large Agulhas Ring is followed in time with *in situ* measurements. (The MARE-1 and 2 cruises have already taken place.) Selection of the ring has been based on satellite altimetry data of the area under study. Altimetry and *in situ* measurements will be assimilated in a high-resolution model of this area. The results will be used to determine e.g. characteristic mixing parameters for this area.

These model parameters, together with the total historical altimetry data set for all Agulhas Rings, will form the basis of budget estimates over the complete area, including time variations of e.g. heat transport.

However, this quantitative study is seriously hampered by the unknown mean sea-surface topography in the area where the Agulhas separates from the continent en where the rings are pinched off. GOCE data will be used to solve this problem as explained below. An interpolated map of satellite altimeter derived time-varying sea-surface topography (i.e. from which the time-mean signal is subtracted to remove the unknown geoid signal) shows a spatial sequence of positive and negative sea-surface height anomalies. In reality the Agulhas Current and the Agulhas Return Current are strongly meandering. Because the time-mean signal is subtracted these meanders cannot be distinguished from rings. Reference [2] and following poapers have used statistical techniques to distinguish the shedding of Agulhas Rings from the other signals, but the number of ring sheddings found in that way seems to contradict with the actual number of Agulhas Rings found downstream in the Atlantic Ocean ([3]). So, without GOCE, we can only roughly estimate ring-related exchanges, not determine the total flow between the two oceans.

ACSEX, the Agulhas Current Sources Experiment, is closely related to MARE. Immediately after the MARE cruises an *in situ* measurement program has been carried out in the ocean area around Madagascar, focusing on the, relatively unknown, inflow of the Agulhas Current. The NIOZ oceanography group has anchored a series of moorings in the Mozambique Channel to quantify the time varying transport in the channel for one year. Recent Analysis of TOPEX/POSEIDON and ERS observations, in combination with the first results from the *in situ* measurements from the first ACSEX cruise, shows that the variability at the ocean surface is related to the regular formation of large anticyclonic rings north in the Mozambique Channel. These rings subsequently move towards the Agulhas retroflection area, where they seem to trigger the shedding of an Agulhas Ring. As part of ACSEX three cruises have been conducted in the area around Madagascar to obtain snapshots of the regional hydrography and, in particular, investigate the structure of the sea surface height anomalies. Altimetry has had a steering role to determine the cruise tracks.

The formation process of the rings in the Mozambique Channel is unclear. It might be related to an instability of the South Equatorial Current, but that current shows little variability, so presently its structure is difficult to determine from altimetry alone. The mean sea-surface topography provided by GOCE will shed more light on these flows, and thus on the formation of the rings.

Also the South East Madagascar Current seems to produce rings that move towards the Agulhas area. Variability of the sea-surface height directly east of the Agulhas Current is so large that determining the real character of the anomalies from altimetry is presently virtually impossible. This large variability is not understood, and is also not present in state-of-the-art ocean models. It has been hypothesized that the variability might be related to the Madagascar Ridge, that extends southward from the island. It can also be related to retroflection and eddy shedding of the East Madagascar Current itself, but little is known about that current after separation from the coast south of Madagascar. Again, GOCE can shed light on what are eddies, what are meanders of the mean flow, and, more specifically, what is the nature of the large-scale anomalies southwest of Madagascar.

Multiple equilibria of western boundary currents.

The second program, in which the stability and variability of the Gulf Stream is under study, is part of the NWO-PIONIER program "Stability and temporal variability of the climate system: towards a regime diagram of the coupled ocean/atmosphere/sea-ice system." (Pionier: Dijkstra). In this project a systematic approach is used to study the stability of the global ocean circulation and the physical origin of the variability. Questions addressed are: What is the evolution of perturbations on the present global ocean circulation, and what are the physical mechanisms that induce the oscillatory behavior on interannual and decadal time scales? What is the importance of feedbacks between ocean, atmosphere, and sea ice on the spatial pattern of the mean ocean circulation, and how do these feedback processes influence the stability and temporal variability of that mean state? To this end, the dynamical behavior of the coupled system is analyzed quantatively in an hierarchy of models of increasing complexity. The results will lead to successive regime diagrams. On the basis of these diagrams hypotheses will be posed on the stability and evolution of perturbations in the system. Calculation of specific trajectories in General Circulation Models (GCM's) will be used to test these hypotheses. The aim is to reach eventually a full classification of western boundary currents regarding the origin of their variability, an example of which is given in [4].

As part of this project the Gulf Stream system is investigated (see [5] and [6]). The variability of the Gulf Stream is strongly coupled to low frequency climate variability over Western Europe, i.e. on interannual, decadal and centennial time scales. Results from models with increasing complexity suggest that the separation of the Gulf Stream from the American continental shelf and its subsequent trajectory in the Atlantic Ocean can run along two, or more, mean paths (under the same external forcing). An example from an analysis of the state-of-the-art model POCM is presented in Fig.2. These different mean paths are accompanied by strongly different meridional heat transport. Transitions between these trajectories are potential prototype phenomena to clarify different climate states in the recent past, like the Little Ice Age.

Presently altimetry observations are used in this project for optimal parameter estimation in the idealized models and, if possible, to test if the theoretically obtained dynamical behavior is realistic. To monitor the occurrence of the regime shifts between different equilibrium states of the Gulf Stream we need observations of the mean path of the Gulf Stream for quite a long period of time. However, even a relatively short period of observations of the absolute velocity field (over the complete North Atlantic Basin) can give an indication of the present Gulf Stream regime. In this way a bridge can be established with the model results. GOCE observations will be used to give the correct data set.

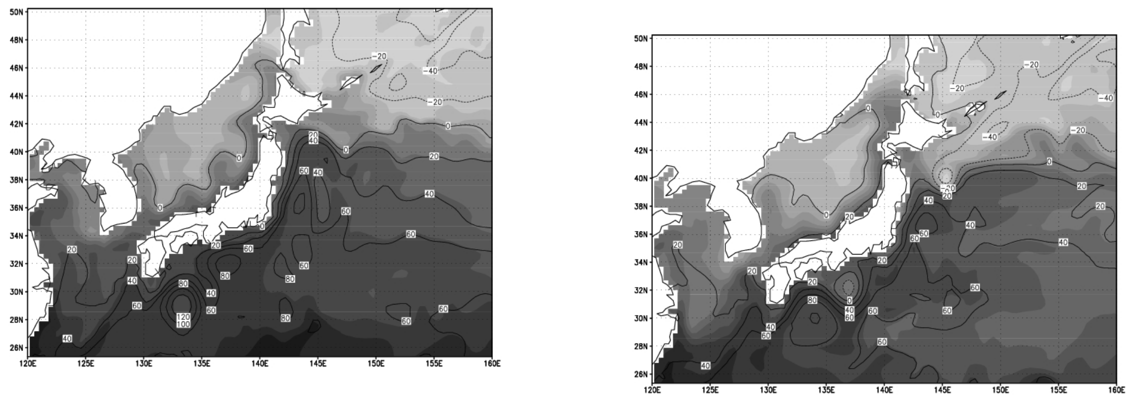

Fig. 2 Two mean states of the Kuro-Shio in which the model stays for several years in the state-of-the-art ocean model POCM. The Gulf Stream has two similar states, showing either the correct separation from the continent, or the overshoot state. (Courtesy Maurice Schmeits).

Concluding

An absolute description of the circulation and transports in these highly variable key areas in the World Ocean circulation is hampered by the lack of an accurate geoid. When that is determined from GOCE data, it will dramatically improve the accuracy of our estimations and descriptions resulting from the above mentioned programs.

RESEARCH

The GOCE-related research is to quantify the expected improvements in the determination of the mean circulation in the above mentioned ocean regions, on the basis of dedicated model and data assimilation studies. Once GOCE is available we plan to use it to determine for the first time the mean ocean circulation of (at least) the South Atlantic and South Indian Ocean current systems, focussing on their connection. As GOCE will only give us the mean *surface* circulation, it will be combined with the in-situ data from the MARE cruises (and historical data from, e.g. the World Ocean

Circulation Experiment archives) to estimate the 3-dimensional current structure. In combination with the in-situ observations of the buoyancy field we will be able to estimate inter ocean heat and salt fluxes and meridional overturning transports in the South Indian and South Atlantic Oceans. The approach will be by data assimilation, as explained below.

The model we will use is MICOM, the Miami Isopycnic Coordinate Ocean Model. This model will be run in eddy-resolving mode with a horizontal grid spacing of 25 km or less, to optimally use the altimeter and GOCE measurements. Instead of using the z-coordinate in the vertical the model uses density. Because the subsurface flows in the ocean predominantly flow along isosurfaces of density (isopycnals) spurious mixing across isopycnals is absent. This is of vital importance for the above mentioned programs that try to make budget analyses of the mixing in the real ocean.

The data assimilation method we will use is a so-called ensemble smoother (see [7], [8] and [9]). In a smoother an optimal model state in space *and time* of the system under study is sought given the observations, the model dynamics, the model initial condition, and their uncertainties. So, it differs from standard inversions in that also the time dimension is taken into account. Advantages are for instance that not only mean transports can be determined, but also their variation with time. The latter is of vital importance for our understanding of the operation of the climate system. Because the model dynamics are nonlinear, the problem is best formulated in a probabilistic way. Data assimilation then becomes the combination of the probability densities of the model evolution and the observations to generate the posterior probability density. This density contains all information present in the model and in the observations ([7]). In an *ensemble* smoother an ensemble of perturbed model initial states is propagated in time. The evolution of the ensemble describes the probability density of the model evolution. The probability density of the observations is assumed to be known, for instance a Gaussian. In [8] the assumption is made that the probability density of the model is Gaussian too, as in the Kalman filter and extensions thereon, leading to a very efficient scheme. Presently tests are being conducted to get around this assumption, while still keeping the scheme efficient. A first example in given in Fig. 1. Major advantage of ensemble methods is that no backward integrations have to be performed to propagate information from the data back in time. Methods that use backward integrations, so-called adjoint methods, still face serious consistency problems, or are extremely complicated.

The existing data-assimilation system has to be modified for the area under study, and to involve GOCE data. After completion of the model data-assimilation system we will perform a series of numerical 'twin' experiments to investigate the impact of the GOCE data. Starting point will be an eddy-resolving, multi-layer, time integration of the circulation of the Ocean region around South Africa. The parameter ranges will be identified in the field program of MARE. From this run we will extract 'synthetical' in situ data as well as sea-surface height data along the WOCE-hydrographic sections and the TOPEX/ERS/JASON-altimeter ground tracks. Then the initial conditions as well as model parameters and forcing fields are changed. The synthetical data are now used in data assimilation experiments to try to reproduce the original time integration. Two basic experiments are performed: one in which the mean sea-surface height is not known, and one in which it is known. We will vary the accuracy of the mean sea-surface height data and determine the impact, not only on the surface flows and transports, but also in the deeper ocean. So, we will not only be able to make a quantitative comparison in the upper ocean, but also in the deeper ocean. Because we will use a smoother, not only the time mean state over a few years can be studied, but also variations thereof.

We expect an enormous benefit of the GOCE-data for the data-assimilation system. As said above, we not only adapt the upper ocean with the mean sea surface topography, but also the rest of the water column, all the way to the bottom. To combine altimeter data with a model one has to provide a mean sea surface some way. A wrong mean can give rise to completely wrong interpretations of how the circulation works, what physical processes are important, and what the impact of the Agulhas Rings is on the global thermohaline circulation. Reference [10] and [11] have tried to estimate the mean signal from the time varying part with a method of increasing complexity, but the resulting mean flow remains an estimate with relatively large error bars. The accuracy that GOCE will provide can never be obtained with these methods.

For the southwest Indian Ocean, the ACSEX area, and specifically the Mozambique Channel, the ocean around Madagascar and the bordering Agulhas and Agulhas Return Current, we will have to develop and test a data assimilation system first. An important constraint will be the transport measurements in the Mozambique Channel, that are collected with the current meter moorings of the NIOZ. Further activities will run along the same lines as suggested for the South Atlantic Ocean.

If the system runs well, this would lead to a full and detailed quantification of the circulation and transports between the Indian and the Atlantic Ocean, the mean as well as the variations thereof for a period of almost 20 years. The close connection with the MARE, NOP and ACSEX programs (and through it also with CLIVARNET and the international CLIVAR programs) guarantees that it is at the same time coupled to process-oriented and impact studies.

When the GOCE data are available they will also be used for the study of the multiple equilibria of the Gulf Stream. We will be able to perform an estimation of the parameters that are associated to dissipative processes of the North Atlantic circulation. We propose to do this with inverse techniques. Estimated values are crucial in connection with the present model resolutions to determine if multiple equilibria of the Gulf Stream could really exist. This would provide important information to infer to what extend (fast) regime switches are responsible for climate variations over Europe. The PIONIER environment guarantees also here a direct incorporation in the relevant national and international research programs.

SUMMARY AND CONCLUSIONS

The GOCE-related research for oceanography is embedded in several existing programs. These programs focus on the interocean exchnage south of South Africa and on the dynamics of western boundary currents like the Gulf Stream. The combination in *in situ* observations, numerical models and satellite derived measurements, using data assimilation, will provide the optimal use of GOCE data in the future. Furthermore, the embedding in the existing programs ensures that the expertise for those areas where GOCE-data will be used is fully available.

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