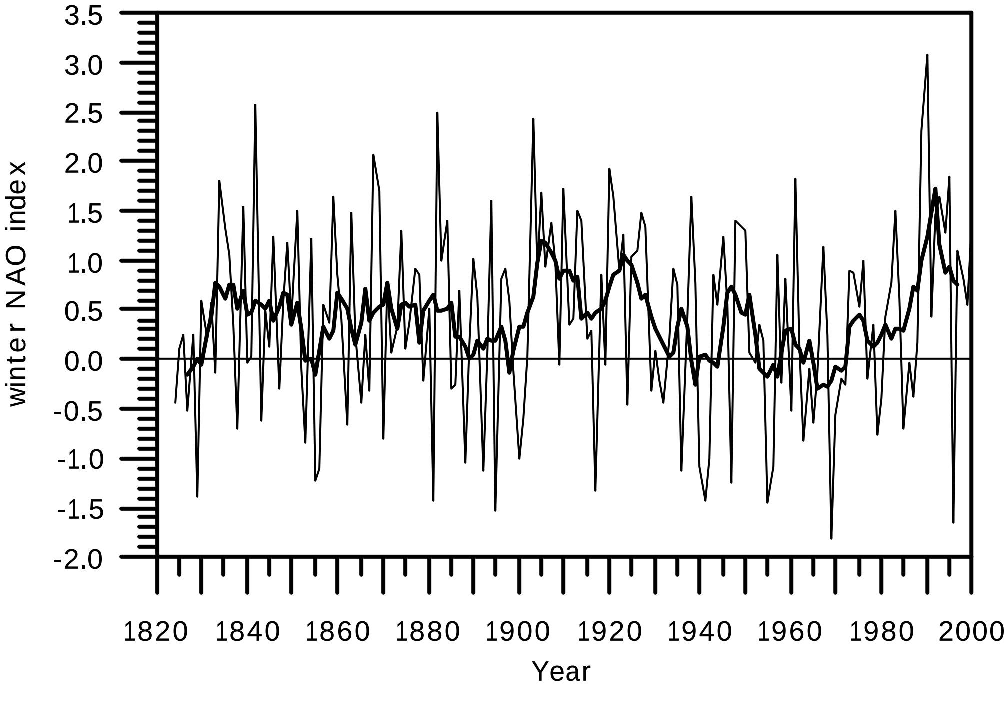
Long-Term Ocean Climate Observations (LOCO)



A proposal for investments in ocean observation capacity

Title:

Long-Term Ocean Climate Observations (LOCO)

Applicants:

Netherlands Institute for Sea Research (NIOZ)

Scientists: dr. H.M. van Aken, dr. J.J.M. van Haren, dr. T. Gerkema, dr. L.R.M. Maas, dr.ir H. Ridderinkhof, prof dr. J.T.F. Zimmerman

Institute for Marine and Atmospheric Research Utrecht (IMAU)

Scientists: prof dr. W.P.M. de Ruijter, dr. P.-J. van Leeuwen, prof. dr. ir. H.A. Dijkstra

Royal Netherlands Meteorological Institute (KNMI)

Scientists: dr. G. Burgers, dr. S.S. Drijfhout, dr. ir. W. Hazeleger

Corresponding scientists:

Dr. H.M. van Aken or dr.ir. H. Ridderinkhof
Netherlands Institute for Sea Research
PO Box 59
1790 AB Texel
email: aken@nioz.nl or rid@nioz.nl

Contents

section page

Executive summary

Scientific and societal interest in issues relating to earth's climate, its variability and climate change is still growing. Much attention is paid to how human activities may influence climate on a global and regional scale. However, many aspects of the climate system, like the driving mechanisms for natural climate variability, are still poorly understood. This hinders reliable future climate predictions, especially on a regional scale. Examples that are of direct relevance to European climate are: the North Atlantic Oscillation (NAO) as a possible major source for interannual climate variability and possible weakening of the Thermo-Haline Circulation (THC) which may drive a substantial climate change over Europe.

Understanding climate variability and the development of climate models with predictive capabilities is the goal of the international programme on Climate Variability and Predictability (CLIVAR), a core programme of the World Climate Research Programme. CLIVAR focuses on the role of the coupled ocean and atmosphere with emphasis on variability, especially within the oceans, on seasonal to centennial time scales. Scientists from different disciplines and nations collaborate under CLIVAR to reach this goal.

Long-term, reliable and consistent observations at a series of critical locations in the world ocean circulation are an important element for the implementation of CLIVAR. This can only be reached by combining the efforts of different nations. This proposal aims to set up some long-term in situ ocean observation experiments and process studies as a Dutch contribution to CLIVAR and other internationally co-ordinated programmes and activities.

To be able to carry out such observations, a national instrumental infrastructure for moored sub-surface measuring systems is required. The proposed measuring systems consist of moorings with current meters, ADCPs (Acoustic Doppler Current Profilers) for velocity profiles and sensors for measuring temperature and salinity. The moorings will be used to obtain long-term observations of the current field and transport of heat and fresh water in some key areas of the global ocean circulation and to perform studies on ocean interior mixing due to internal waves. In order to observe low-frequency variations it is necessary that these moorings are deployed for periods of at least 3 to 7 years, so that also variations due to the NAO and the El-Niño cycle may be covered. Building upon previous WOCE (World Ocean Circulation Experiment) and CLIVAR projects, carried out by Dutch oceanographers, first experiments will be located in three areas: the North-Atlantic ocean (Irminger Sea; where important convection and deep water formation takes place), the Mozambique Channel (tropical-subtropical connection and control of inter-ocean exchange) and east Indonesia (part of the Indonesian Trough-flow). The observations from the moored systems will be used also to study spatial and temporal variability in the internal wave field. Internal waves are considered to be of prime importance for ocean interior mixing and thereby for maintaining the global overturning circulation in the deep sea.

Motivation plan for investments

1. Introduction

The ocean is an important component of the climate system since it stores and redistributes large amounts of heat and fresh water. A well-known example of the ocean's influence on regional climate is the climate in Europe, which, due to the northward heat transport in the North Atlantic is 5 to 10 degrees warmer than the average for its latitude. Changes in the ocean circulation are of great importance for climate variability on time scales of months to decades. A prominent example is the interannual variability associated with the ENSO phenomenon in the equatorial Pacific. Although the role of the oceans in the climate system has been well established, many specific aspects 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 oceans which resolve seasonal to interannual time scales are scarce. The oceanographic community is now in a unique position to accept the challenge of obtaining reliable, comprehensive, and consistent ocean observations. Recent technological advances have expanded our capabilities to observe the oceans. Scientific long-term ocean observing experiments with the new technology are needed at critical locations of the world ocean circulation. This will provide accurate descriptions of the present state of the oceans and the basis for forecasts of climate change. The international programme on Climate Variability and Predictability (CLIVAR) has been initiated under the World Climate Research Programme to obtain, analyse and interpret such long-term ocean observations in order to develop climate models with predictive capabilities.

This proposal aims at the establishment of a national instrumental infrastructure for long-term ocean-climate observations, to be able to carry out some regional experiments which are required for the development of an ocean observation system for CLIVAR and other related global monitoring programmes. The instruments will be used to obtain long-term observations of the current field and transport of heat and fresh water in some critical areas of the global ocean circulation and of processes in the ocean interior providing energy for diapycnal mixing, for example due to internal waves, a key parameter in controlling the large scale circulation. In order to observe low-frequency variations it is necessary that these moorings are deployed for periods of at least 3 to 7 years, so that also variations due to the El-Niño cycle and the North Atlantic Oscillation may be covered. The experiments with moored sub-surface measuring systems build upon previous WOCE (World Ocean Circulation Experiment) and CLIVAR projects, carried out by Dutch oceanographers. It will extend existing time series and/or monitoring programmes and will be carried out in the framework of internationally coordinated research programmes.

Below we first discuss ocean circulation, variability and its importance for the earth's climate in general, followed by a discussion of the methods to obtain long-term in-situ observations. Then we describe the intended set up of experimental regional ocean observing programmes which will use the requested moored instrumentation. Finally we indicate how these observations contribute to international programmes and how international exchange of data and expertise is envisaged.

2. Ocean circulation, variability and climate

General

Apart from being driven in the end by differential solar radiation, the general circulation of the atmosphere and ocean also actively mitigates the meridional temperature difference of the earth's climate, particularly by transporting heat from the equator to the poles. Any change in this transport must give a climatic response. Although recent estimates (Trenberth and Caron, 2001) indicate that the largest share of this process is taken by the atmosphere, the ocean is certainly not negligible and by its large thermal inertia it is probably more important in driving climate variability on time scales of years or larger.

The mechanisms by which the ocean transports heat (and fresh water) are less well understood than those in the atmosphere, even after such successful international observation programmes as WOCE (World Ocean Circulation Experiment - in situ measurements and satellite observations), TOPEX/POSEIDON (satellite altimetry programme) and CLIVAR (climate variability programme including in situ observations which has just started), the latter being a part of the World Climate Research Programme. There are several reasons for our knowledge of the oceanic part of the global heat transport lagging that of the atmosphere:

- the observational network of the atmosphere is much denser than that of the ocean, even over the oceans themselves, and of much longer duration.

- directly coupled to the former: even if the oceanic network were as dense as that of the atmosphere the ocean requires an observation system at least an order of magnitude finer in order to resolve the meso-scale variability at length scales of several hundred kilometres and time scales of about a year in contrast to the atmosphere where these scales are several thousand kilometres and days to weeks.

- variability in ocean currents is over large areas energetically much larger than the mean, in contrast to the atmosphere where they are at most of equal strength. Both in the atmosphere and ocean the variable part of the circulation contributes appreciably to the meridional heat transport.

- moreover, in the atmosphere the distinction between transport by the mean and by the variable part of the circulation is neatly zonally organised, the former being dominant in the tropics and the latter at mid-latitudes. Such an organisation is much less pronounced in the ocean because of the distribution of the continents, which breaks zonality and gives rise to such phenomena as western boundary-currents, inter-hemispheric transport and inter-basin transport, all of which are lacking in the atmosphere.

- the principal meridional heat transporting mean circulation phenomenon in the atmosphere, the Hadley circulation, centred on the equator, is lacking in the ocean, which has a much more elusive and weaker meridional inter-hemispheric deep-sea circulation with inter-basin connections. The reason for this difference is principally thermodynamic because the atmosphere is heated on its bottom and cooled on its top, whereas the ocean is both cooled and heated on its top. The latter circulation is therefore rather weak and in the end maintained by interior mixing.

- as a consequence of the latter it is of large importance to know which internal mixing mechanisms provide the necessary buoyancy flux in the oceanic interior. A strong candidate is the breaking of internal waves generated by (tidal) flow over the variable depth of the ocean floor or over the steep slopes of the continental margin (Munk and Wunsch, 1998).

- by its large thermal and mechanical inertia the circulation time scale of the ocean is considerably larger than that of the atmosphere. For the latter the radiative forcing time scale is a few months and its frictional decay time scale measures in days. For the ocean relevant thermodynamic and mechanical time scales are much less known but the circulation time scales measure in years for the surface circulation to a thousand years for the deep-sea circulation.

As it are these circulation time-scales that govern the heat-exchange between ocean and atmosphere it may safely be supposed that these scales also are involved in climate variability on the same time scales.

Global ocean circulation

Despite the fact that the global overturning deep-sea circulation, often referred to as the thermohaline circulation (THC), is relatively weak, it is an important part of the world ocean circulation since it connects the different oceans and both hemispheres within the oceans. In the present-day ocean a global THC exists with northern sinking and deep convection in the Atlantic Ocean where North Atlantic Deep Water (NADW) is formed. Part of the NADW is exported to the other basins and a return flow exists at intermediate, thermocline and upper levels. Interior mixing in the deep ocean maintains this circulation. Several critical links and processes exist in this system, such as:

- the North Atlantic where the warm branch of the THC loses large amounts of heat to the atmosphere (Rahmstorf and Ganapolski, 1999) and overturning and NADW production take place.

- inter-ocean exchange, e.g. by warm eddies propagating from the Indian into the Atlantic Ocean (de Ruijter et al., 1999).

- interior mixing by small-scale processes (Munk & Wunsch, 1998, Killworth, 1998).

Interior mixing does not take place uniformly in the ocean, but (as is generally assumed) predominantly near its boundaries (continental slopes) and over rough topography (mid-ocean ridges) (Polzin et al., 1997; Ledwell et al., 2000; Egbert & Ray, 2000; Wunsch, 2000). The importance of this spatial variability for ocean-circulation modelling was recently shown (Marotzke, 1997). Important agents for interior mixing are internal waves, specifically internal tides (Munk and Wunsch, 1998) and (near-)inertial waves. Since internal waves owe their existence to the (vertical) stratification in density, the overall connection between small-scale and large-scale processes becomes manifest: the vertical stratification is maintained by the large-scale (deep) circulation, and in the maintenance of this circulation internal waves play a crucial role in that they produce an effective vertical diffusion.

All three above-mentioned key points are of importance for the strength of the THC while variability in the THC may influence the local ocean processes and climate. For instance, it has been shown with numerical models (Weijer et al., 2001) that the stability and variability of the Atlantic overturning circulation is influenced by the variations of the inter-ocean exchange between the Indian and Atlantic Ocean (and probably also vice versa, De Ruijter et al., 1999). Moreover, model studies indicate that destabilization of the overturning circulation may be led (at time scales of several decades) by changes in the Southern Ocean. In the North Atlantic Ocean changes in the air-sea interaction, governed by the North Atlantic Oscillation, may influence the amount and geographic distribution of heat released into the atmosphere. Reduction or increase of deep convection in the North Atlantic, driven by salinity changes, may be a precursor of, possibly abrupt, change of the overturning circulation. Paleo-data indicate that this has happened in the past, with associated rapid climate changes.

Studies aiming at understanding and, if possible, predicting climate variability at interannual to decadal time scales should therefore include focused programmes on these critical links and processes of the global circulation. Due to the time scales of relevance, these have to involve sustained, long-term, observations.

Over the past decade Dutch oceanographers have been actively involved in research in these critical regions and processes:

-During the WOCE field phase there were strong commitments to the repeat hydrography programme. After the termination of this WOCE field phase bi-annual surveys have been continued under CLIVAR. Between 1991 and 2000 the temperature in the North Atlantic (Iceland Basin) appears to have increased of the order of 1 degree C. This is probably connected to a redistribution of warm Atlantic water, driven by the negative NAO phase in 1996-1997 (Van Aken, 2001, Bersch, 2001).

-In the south-west Indian and south Atlantic Oceans we have been and still are active with the MARE (Mixing of Agulhas Rings Experiment) and ACSEX (Agulhas Current Sources EXperiment) programmes (de Ruijter et al., 2000, 2001). These programmes focus on the inter-ocean exchange: MARE on the spreading and mixing of Indian Ocean waters in the south Atlantic and their impact on the Atlantic overturning, ACSEX focuses on the upstream control of the connection between the two oceans by variability over the Indian Ocean far field, including the connection to variability in the monsoon strength and the Indonesian through-flow.

-Contributions to internal-wave theory and (laboratory) observations include the studies by Maas et al. (1997) on internal-wave attractors, and by Maas (2001) on inertial waves and mean-flow generation. Furthermore, observations were made on internal mixing in the North Sea (Van Haren et al. 1999) and on the effects of internal tidal beams on erosion in Faeroe-Shetland Channel (Van Raaphorst et al., 2001). Recently, scattering of internal tidal beams was studied theoretically (Gerkema, 2001).

The in situ observations of the studies above were of relatively short duration (moorings) or were based on repeated hydrographic surveys with yearly intervals. Presently available technology makes that it is now possible to obtain long-term in situ observations such that also long-term variability in these processes can be studied. Ultimately this, of course combined with ongoing observations and model studies by others, will lead to improved ocean-climate models, and the understanding of the driving forces behind climate variability.

3. Observing ocean variability in situ

The fact that the oceanic circulation has an extremely complex geographical pattern, a small meso-scale fine-structure and a variability in time that easily exceeds decades, presents a formidable observational problem. Although satellites have given a great revolution in time- and space resolution of ocean observation, their use is nonetheless limited to the very surface of the ocean. Yet for most of the transport problems we need information over all depths and for that only in situ measurements, either from a ship, a platform or a moored system, by means of current meters and temperature/salinity sensors remains the only way. In this section we describe these different methods to obtain long-term in-situ ocean observations, illustrated with examples from present and previous Dutch observational programs.

Hydrographic repeat sections

Historically, long-term, regular in-situ observations of the ocean circulation, temperature and salinity were mainly obtained by regular hydrographic surveys. These surveys are mainly restricted to the continental shelf and the nearby deep ocean since the rationale for such monitoring activities generally is related to fisheries research. Fisheries nations like Norway, Iceland, the Faroe, Canada, and Greenland carry out annual to three monthly hydrographic surveys. These activities are coordinated by the International Council for the Exploration of the Sea (ICES) (which publishes annually an ‘Annual ICES Ocean Climate Status Report’). In the last decade similar activities were initiated by repeating WOCE hydrographic sections, such as the (AR7E) section between Greenland and Ireland which is surveyed annually by British, German and Dutch research vessels. What has become clear from these repeat hydrographic sections is that the ocean itself is a highly variable environment, not only because of the presence of meso-scale eddies. Large variability with interannual to decadal time scales has been established (e.g. Sy et al., 1997; Bersch et al., 1999; Bersch, 2001; van Aken, 2001). However, increasing our insight in the driving mechanisms for this variability requires observations with a much higher temporal resolution. These can only be obtained from unmanned platforms like drifting floats or moorings.

Floats and moored systems

In order to fill the gap left by regular surveys with research vessels observations from drifting floats or moored systems can be applied. In the world-wide ARGO programme several thousands of profiling floats will be deployed, to obtain a near global coverage. These floats have the disadvantage that one only can intentionally determine the deployment positions, after which the floats are passively advected away from the deployment site by the currents. Thus, despite the big advantage of having a more or less global coverage, the disadvantage of these floats is that they are unsuitable to obtain long-term observations from a specific location. For such observations moored instrumentation with sensors able to profile salinity, temperature and currents have to be applied.

In the past moorings fitted with current meters and thermistor strings have been used in a variety of Dutch research programs. Most recently such moorings were used in the framework of the WOCE North Atlantic program in the Iceland Basin (van

Aken, 1995) and the Bay of Biscay (van Haren et al., 2001) and in the Mozambique Channel (CLIVAR program) (de Ruijter et al., 2000, Ridderinkhof, 2000) for periods of one to two years. The main purpose of these moorings was to observe low frequency variability in different branches of the world ocean circulation. More process-oriented observational programmes using this type of instrumentation were recently carried in the North Sea (van Haren et al., 1999) and Faeroer-Shetland channel where the focus was on internal wave processes (van Raaphorst et al., 2001). A great logistic advantage of the use of long-term moored instrumentation is that the sampling rate of the instruments (typically one hour) allows both studies on low-frequency (ocean currents) and high frequency processes (internal waves).

Profiling moorings

A recent technical development is the use of moorings with profiling instruments (in stead of instruments at a fixed vertical position). Experiments with such profiling CTD moorings have turned out to be successful, enabling monitoring of the sub-surface hydrography at a very high vertical resolution and at time scales comparable to the time scales of satellite remote sensing. Prototypes of the profilers have been developed by the Advanced Engineering Laboratory of Woods Hole Oceanographic Institution, and have been successfully deployed. A prototype profiled more than one million meters in continuous field operation (~ one profile every two days). Improved profilers are now manufactured commercially. They can be fitted with a CTD, acoustic current meter, and additional chemical and optical sensors. Due to improved low drag coefficient and fairing these profilers will eventually allow up to four million meters profiling over 12 months or more. Whereas the vertical resolution of a profiling CTD mooring is relatively good (O(1 m)), the temporal resolution will be of the order of one profile per day. This will cause aliasing problems if (internal) tides and inertial waves contribute considerable to the total kinetic energy. Then an alternative can be sought in the use of CTD sensors mounted along the mooring cable. Such self-contained CTDs allow sampling rates of 1 sample per two to four minutes for one year of observations. With such instruments tidal and internal wave time scales are well resolved. However the vertical resolution of the profiling CTD is generally superior to that of a series of SeaCATs, mounted along the mooring cable. The actual choice for one of these systems is a trade-off, depending on the monitoring environment and the required temporal and vertical resolution.

4. Proposed long-term ocean-climate observations

The above mentioned technology for moored sub-surface observations is now available to obtain long-term, reliable and consistent observations of the ocean circulation and of the processes that control it. Such observations are needed not only to increase our understanding of ocean variability but also to allow modelling and prediction of climate change and variability. With the proposed establishment of a national instrumental infrastructure for moored sub-surface measuring systems we intend to set up, in international collaboration, some long-term regional ocean observation experiments to obtain 1) observations on (the variability in) the current field and transport of heat and fresh water in some key areas of the world ocean circulation and 2) observations on the temporal and spatial variability of the internal wave field which is of prime importance for (variations in) ocean interior mixing.

Building upon previous WOCE (World Ocean Circulation Experiment) and CLIVAR projects, first experiments are proposed in: the North-Atlantic ocean (Irminger Sea; where important convection and deep water formation takes place), the Mozambique Channel (tropical-subtropical connection and control of inter-ocean exchange) and east Indonesia (part of the Indonesian Through-flow). The proposed sub-surface moorings allow studies on both relatively low frequency (see above) and on high frequency processes. The latter studies will focus specifically on the climatology of the internal wave field. In order to resolve the spatial structure of the internal wave field a specifically designed mooring array will be deployed in these regions for shorter periods.

Below we describe the proposed long-term regional ocean observation programmes in more detail, each with its specific motivation.

The Irminger Sea

As part of the WOCE Hydrographic Programme (WHP) the climatic variations of the hydrography of the North Atlantic Ocean have been monitored since 1990 on a nearly annual basis by research groups from Canada, Germany, the Netherlands, and the UK. After the end of the WHP field phase in 1998 these regular observations have been continued as part of the CLIVAR and VEINS programmes. The WOCE A1 (a.k.a. AR7) A2, and A2' lines are presently surveyed on an annual or bi-annual basis. Several Scandinavian groups are involved in the monitoring of the hydrography of the overflow across the Greenland-Scotland Ridge. Here we propose to deploy three profiling moorings in the Irminger Sea along the A1 WOCE line (Figure 1), initially for a period of five years. The moorings will be fitted with a profiling CTD system and two ADCPs: one down-looking ADCP for the upper 500 m, the other for the lowest 500 m of the water column. The instrumentation on the moorings will record the temperature and salinity structure in the upper 2000 m as well as the sub-surface and near bottom velocity field. By additional self contained CTD sensors in the near bottom layers also the hydrography of the Denmark Strait Overflow Water and the Iceland-Scotland Overflow Water in the deep Irminger Sea will be recorded.

The circulation in the Irminger Sea is part of the larger sub-arctic gyre. Similarly to the Labrador Sea the gyre circulation in the Irminger Sea is organized as a cyclonic sub-gyre with the Irminger Current along the western flanks of the Reykjanes Ridge as eastern boundary, and the narrow southward flowing East-Greenland Current as western boundary current (Lavender et al., 2000). In the centre of the Irminger Sea the isopycnals dome up-wards, producing a pre-conditioning situation for convective mixing. Regularly mixed layer depths of 400 to 800 m are observed in late winter (Pickart, 2000). Continuous monitoring of the upper 2000 m by means of moored instrumentation allows us to determine the annual cycle of hydrographic structure in the sub-gyre, including the convective modification of the Sub-Arctic Mode Water (SAMW) due to the surface heat loss to the atmosphere in winter as well as interannual changes of the convection and SAMW properties. In the Irminger Sea the last convective modification of the SAMW takes place before it enters the Labrador Sea. There the SAMW is ultimately isolated from further atmospheric influence by the convective formation of Labrador Sea Water. This water type is one of the precursors of the North Atlantic Deep Water (NADW), the main contributor to the cold branch of the global THC. Climatic variability of the air-sea heat exchange during the formation of SAMW and of the resulting sea surface

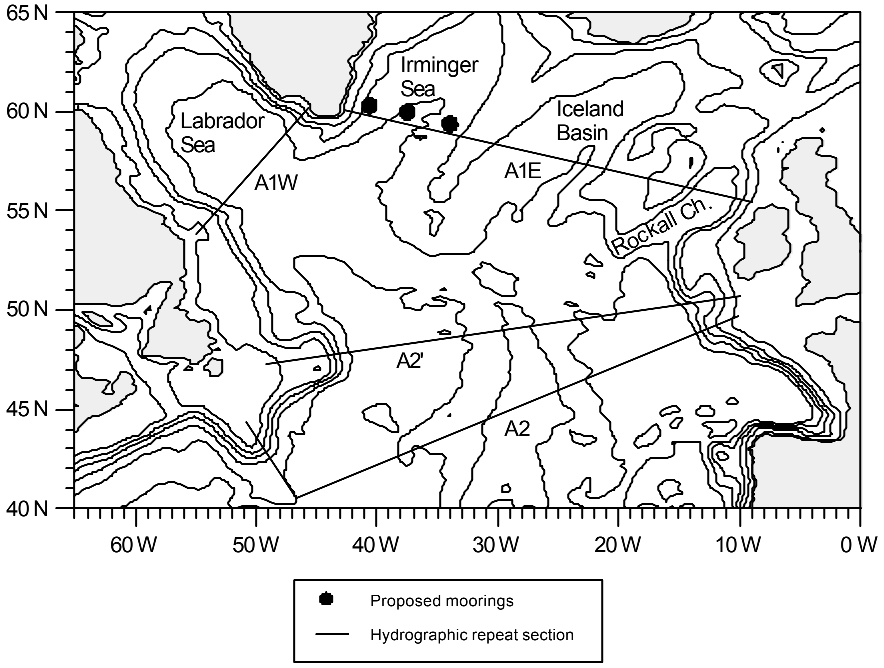


Figure 1, Geography of the North Atlantic Ocean with the proposed mooring positions (black dots) and the regularly surveyed hydrographic repeat sections (straight lines)

temperature is of prime importance for the climate variability in western Europe.

From the horizontal density difference between two adjacent profiling CTD moorings the mean vertical geostrophic velocity shear between these moorings can be determined. With three moorings (one over the Greenland slope, one over the deep centre of the Irminger Sea, and one over the western slope of the Reykjanes Ridge), the strength of the cyclonic circulation and the doming of the isopycnals throughout the year will be estimated. This will allow us to study the relation between pre-conditioning and convective activity.

Analysis of the inter-annual to decadal variability in the Sub-Arctic gyre of the North-Atlantic has shown that the upper 1000 m is strongly influenced by variations in the atmospheric forcing as expressed by the North Atlantic Oscillation (NAO) Index (Hurrell, 1995; Rogers, 1997; Bersch, 2001). The NAO exerts a dominant influence on temperatures, precipitation and storms, fisheries and ecosystems of the north Atlantic Ocean and surrounding continents. The NAO induced changes in the wintertime convection and air-sea heat exchange will lead to a change in the properties, distribution, and flow of SAMW (Dickson et al., 1996; Sy et al., 1997; Bersch et al., 1999; Bersch, 2001). Variations in the sub-arctic gyre circulation due to variations in the wind-stress pattern, related to NAO changes (Eden and Willebrand, 2001) may on short term cause advective variations in the water mass distribution of the upper North Atlantic. The short negative phase of the NAO index in 1996-1997, after a decade of positive values, caused a drastic change in the distribution of the warm and saline Atlantic Water of subtropical origin in the sub-arctic gyre (van Aken, 2000; Bersch, 2001; van Aken 2001). Other climatically important changes in the water mass structure in the sub-arctic gyre are due to the internal ocean dynamics.

Dickson et al (1988) described the "Great Salinity Anomaly" where extremely fresh water of arctic origin was advected around the gyre. Such advective changes in the salinity of the upper ocean may change the static stability of the water column, and influence the depth of wintertime convection and the connected heat release to the atmosphere. With three moorings in different parts of the Irminger sub-gyre we hope to determine the response of the ocean to varying atmospheric forcing in terms of circulation and doming, convective activity and advection into the Irminger Sea of water with different properties.

The regular repeat surveys of the A1 section through the sub-arctic gyre have revealed that large changes in the hydrography and circulation of the gyre occur on annual to decadal time scales (e.g. Sy et al., 1997; Bersch et al., 1999; Bersch, 2001; van Aken, 2001). The seasonal distribution of these annual surveys however shows a strong bias towards the summer season. The winter period when formation of Sub-Arctic Mode Water takes place by convection, driven by the surface heat loss, is not covered at all. The costs of the exploitation of a research vessel are prohibitive for research institutes to cover all seasons. Moored instrumentation with sensors, able to measure profiles of salinity and temperature, now have become commercially available. Moorings fitted with such instruments will fill in the gaps left by annual surveys with research vessels, and strongly enhance our possibilities to describe transient climate changes in the ocean. Groups from the USA maintain such a mooring in the centre of the Labrador Sea, to monitor the convective formation of Labrador Sea Water, additional to the regular observations from OWS Bravo. Groups from Germany and the UK have planned to deploy profiling CTD moorings in the Iceland Basin, while the Irish are considering the deployment of a profiling mooring in the Rockall Channel. With additional hydrographic time series from the Irminger Sea, as proposed here, these observations allow an integrated description of North-Atlantic variability.

The Mozambique Channel

The inter-basin leakage of Indian Ocean water into the South Atlantic is thought to be largely controlled by the inflows into the Agulhas Current on its upstream edge. In the far field this inflow is fed by the South Equatorial Current via two routes, the Mozambique Current and the East Madagascar Current (Stramma & Lutjeharms, 1997). Until very recently, surprisingly little observations had been made of the currents and hydrographic structure in these source regions despite their possible significance for the global ocean circulation.

Recently, the Agulhas Current Sources Experiment (ACSEX) research programme has been initiated to study both the current field in the Mozambique Channel and the current field to the south of Madagascar. In 2000 and 2001 hydrographic cruises were carried out in both areas. Moreover, current meter moorings were deployed at the narrowest width in Mozambique Channel (Figure 2) in order to measure the flow through Mozambique Channel for a period of roughly 1.5 years (de Ruijter et al., 2000, Ridderinkhof, 2000). The results from these recent in-situ observations, combined with other recent studies (Schouten et al., 2001) and our long-term scientific interest in this region (e.g. de Ruijter et al., 1999), motivate us to propose to extend the present set of current meter moorings in Mozambique Channel 1) over a longer period to obtain in-situ observations on long-term variability and 2) to optimise the design of the array of moored instruments based on the information that has been obtained from the present array and 3) to install additional sensors and current meters (ADCPs).

Results from the hydrographic cruise in Mozambique Channel have shown that in this confined part of the Indian ocean which is enclosed by the African continent and Madagascar important branches of the global ocean circulation can be identified and quantified (de Ruijter et al., 2001). In the centre of Mozambique Channel large anti-cyclonic eddies were identified. Roughly estimated, these eddies transport some 10-20 Sv southwards and form an important contribution to the pole-ward transport of heat in the Indian ocean. In addition, studies based on satellite observations (altimetry and infrared), strongly suggest that these eddies interact with the Agulhas current creating a disturbance which deflects the Agulhas current from the continental slope. In turn, this disturbance may trigger the shedding of Agulhas Rings which form an important contribution to the leakage of Indian ocean water into the South Atlantic (Schouten et al., 2001). Thus the eddies originating from Mozambique Channel are a control on the exchange between the Indian and South-Atlantic ocean. Another important finding from this hydrographic cruise was that at greater depths, roughly between 2000 and 2500 m, a north-ward flowing current composed of North Atlantic Deep Water (NADW) was found, with its core hugged against the continental slope of the African continent. This north-ward flowing NADW was found on all hydrographic sections in Mozambique Channel, including the most narrow (and shallow) section where current meter moorings have been deployed, suggesting that an important branch of NADW flows equator-ward through Mozambique Channel. In combination with the southward transport by the eddies of warm thermocline and surface layer waters this may result in a significant meridional heat flux in the channel.

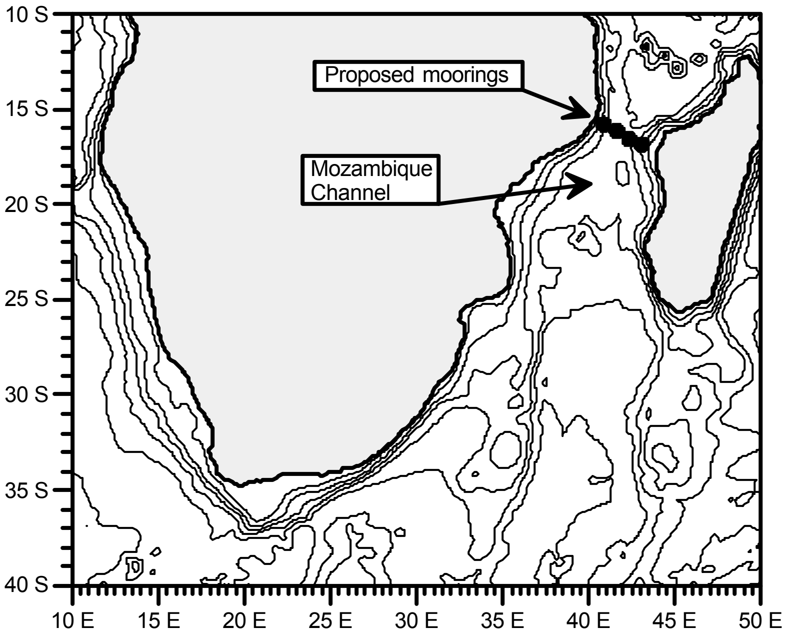


Figure 2. Geography of the Mozambique Channel, and the proposed moorings (black dots).

Preliminary results from the current meter moorings, which were recently serviced after a period of one year, confirmed the results from the hydrographic survey in that large anti-cyclonic eddies dominate the (low-frequency) current field (Ridderinkhof, 2001). Four such eddies passed through the mooring array during the period of observations. Moreover, the high-frequency part of the current meter data clearly show that in this area (internal) tidal currents form an important part of the total kinetic energy. Presently these observations are studied in more detail; both with respect to the low frequency (eddy induced) variations and with respect to the high frequency variations due to internal tidal waves. The latter study is motivated also by the specific geometry of this ocean basin where the sloping sides are relatively close together so that 'geometric focussing' of reflecting internal waves may occur, a mechanism which may give rise to localised increased diapycnal mixing (Maas et al., 1997).

We propose that the new design of a mooring array in Mozambique Channel consists of 5 moorings (to cover the entire channel at its narrowest width with a distance of roughly 50 km between adjacent moorings). Each mooring consists of 2 ADCPs (top + bottom), 3 current meters and 5 CTD sensors so that both the spatial structure of the eddies and of the undercurrent and their properties (temperature, salinity) are observed. Such a spatial distribution will minimise the under sampling of our present observations drastically. The present array of current meter moorings has a few shortcomings, both due to a lack of instrumentation and due to the design which was based on very few previous observations. For instance: we assumed that a boundary current (the 'Mozambique Current') would be dominant for the southward transport through the Channel. Therefore, both available ADCPs were used on moorings close to the continental shelf (where at least one of these instruments did not observe the passing of eddies in the centre of the Channel). Moreover, we had only one current meter in the region where NADW was found during the hydrographic surveys and no temperature/salinity sensors with high enough accuracy to observe variations in these parameters accurately.

These moorings should be deployed for a period of 5 years such that also year to year variability is observed. A study based on satellite-altimetry data suggests that there can be considerable variability in the (number of) eddies that are formed in Mozambique Channel. Moreover, there appears to be a strong correlation between these 'Mozambique eddies' and the number of Agulhas Rings that are shed of from the Agulhas current into the South-Atlantic ocean (Schouten et al., 2001). Long-term in-situ observations are needed to substantiate (or reject) these suggestions. Nothing is known on (variability in) the northward flow of NADW at greater depths, except that this flow seems to be a northward extension of the 'Agulhas Undercurrent' (Beal & Bryden, 1997). Extending the time series (with more current observations at greater depths, see before) would give quantitative insight in the temporal variability of this flow.

Strait Lifamatola through-flow

NIOZ has been invited to participate in an international long-term (3 years) observational effort to determine the complete Indonesian through-flow and its variability in a comprehensive way (ARLINDO monitoring phase). This through-flow forms an important link in the THC. The measurements (led by prof. A.L. Gordon from LDEO, USA) will be carried out in co-operation with groups from the USA, Indonesia, Singapore, Japan, and Australia, which all plan to measure the transport through several passages in both the northern and southern boundaries of the east Indonesian seas. The minimum time, required for such a monitoring programme is three years. Given the experience, built up during the Snellius 2 expedition, NIOZ was asked to supply a mooring for the measurement of the transport across the sill in Strait Lifamatola (Figure 3), with emphasis on the through-flow of deep Pacific water. In this mooring ADCPs should record the water velocity in both the lowest and upper 500 m of the water column, where large vertical shears are expected. In between the ADCPs 3 current meters should be mounted, with SEACAT CTD's. The sampling rate of the ADCP's and current meters (once every 30 minutes) will resolve most of the IWB energy.

The Indonesian through-flow is assumed to form an important link for this inter-ocean exchange, and determines strongly the hydrography of the upper southern Indian Ocean (A.L. Gordon, pers. comm.). Most of the through-flow of thermocline water from the Pacific Ocean to the East-Indonesian Seas takes place through Makassar Strait ($O(10\ 10^{6} m{\cdot}s^{-1})$) whereas some additional transport may follow a course through the Halmaheira Sea ($O(1\ 10^{6} m{\cdot}s^{-1})$) (Cresswell and Luick, 2001; Gordon et al., 1999). For both passages a time series of current meter observations of at least one year has been recorded. Although the time series for Makassar Strait covers a period of only 19 months, Gordon et al. (1999) suggest a significant correlation of the Indonesian through-flow with the ENSO index, which may be a cause of indications of large interannual changes in through-flow. Lifamatola Strait forms the only deep connection between the Pacific Ocean and the Banda Sea system which allows deep water (to about 2 km) from the Pacific Ocean to enter the East-Indonesian seas. For this passage only two short time series of current measurements exist (Broecker et al., 1986; van Aken et al. 1988). The reported transports through Lifamatola Strait differ by a factor of 2.4. No representative annual mean transport estimate for Lifamatola Strait exists, let alone any information on possible seasonal and inter-annual variability. The proposed observations in Strait Lifamatola will give insight in the "mean" transport, its variability on seasonal and inter-annual time scales, and possible connections with the ENSO variability.

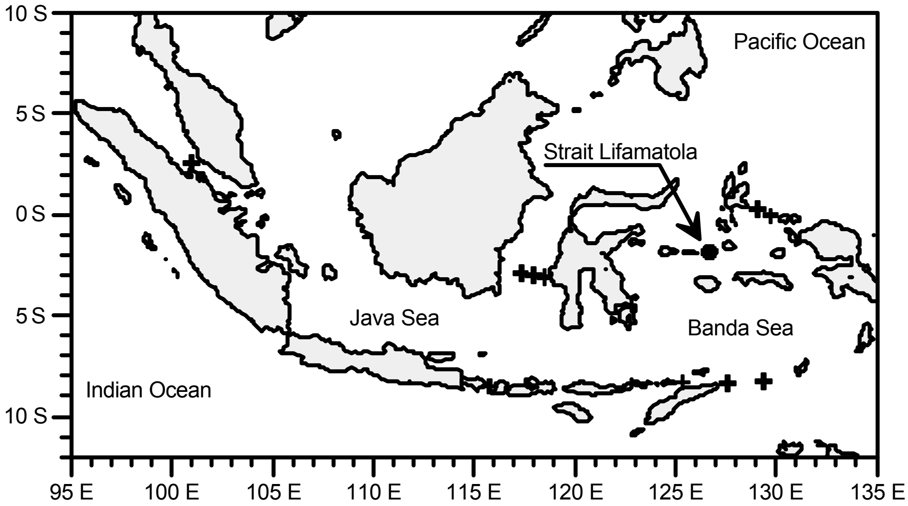


Figure 3 Geography of the Indonesian archipelago with the approximate positions of moorings, to be used for the long term observation of the Indonesian through-flow (crosses). The proposed mooring in Strait Lifamatola is indicated with a black dot.

Ffield and Gordon (1992) have described that in the Indonesian through-flow the water from the warm THC branch is strongly modified due to intensive mixing. The diffusion coefficient in the thermocline, needed to simulate this mixing is an order of magnitude larger than the canonical value for the thermocline diffusion. Van Aken et al. (1988) came to a similar conclusion for the deep through-flow of the Banda Sea via Lifamatola Strait. The enhanced diapycnal mixing in the Banda Sea maintains the density gradient along the path of the THC in eastern Indonesia which is the driving factor for this circulation. From time series of CTD-casts, sea surface temperature, and current observations Ffield and Gordon (1996) have deduced that (internal) tides are a main cause for the enhanced diapycnal mixing during the Indonesian through-flow of the THC. This opens the possibility of modification the deep THC in eastern Indonesia with several beat time scales of the tides. Van Aken et al. (1988) reported strong variations of character of the internal tides, from mainly diurnal to mainly semi-diurnal. The internal wave signal, which also will be measured with the Lifamatola mooring, will supply information on the variability of the internal wave field on time scales up to 3 years.

Internal wave climatology

It is clear from the above (see section 2) that not only low-frequency currents are important for studies on variability of ocean circulation, but also high-frequency motions (faster than once per day) due to internal waves. Internal wave mixing is thought to be the key in maintaining the general ocean circulation (Munk and Wunsch, 1998), induced about half by tidal motions and half by atmospheric (wind) induced inertial motions. As waves do not mix, non-linear interaction between internal waves is assumed to transfer energy to smaller scales, eventual leading to wave breaking, and mixing. Near-inertial internal waves are considered to be important because of their strong shear (van Haren et al., 1999), tidal motions because of persistent generation and focusing in basins (Gerkema, 2001), and motions at both frequencies because of their occurrence in groups (Thorpe, 1999). Recent observations over the abyssal plain in the Bay of Biscay suggest that non-linear interaction between internal waves occurs not only in topographically-dominated areas, but, due to the presence of strong, deep-ocean near-inertial motions, also well away from sloping boundaries (van Haren et al., 2001). This means that near-inertial motions too can play an important role in mixing.

To study in more detail the climatological mean of spatial and temporal variability of internal-wave intensity, being a measure for deep-ocean mixing, for different types of basins (above sloping topography and far away from boundaries in deep-ocean basins), we propose to use 2 sets of 4 moorings. The first set of these moorings will be located for medium-long periods (typically 1 to 1½ years) near the sites in the Irminger Basin and the Mozambique Channel to study specific processes like internal wave focusing (Maas et al., 1997) and effects of convection; and the second set at mid-latitudes in the North Atlantic Ocean. Together these sites are exemplary for most internal wave occurrences.

Per set of moorings we require one 75 kHz acoustic Doppler current profiler (ADCP) enhancing vertical resolution, so that 8 m shear (relevant for mixing induced by shear instability) is resolved. All moorings will be equally equipped with 4-5 current meters, adapted for long-term monitoring whilst sampling relatively fast, at about once/10 min to resolve most of high-frequency internal wave motions in the deep ocean (where the buoyancy period is typically 20-30 min). To resolve relevant horizontal length scales moorings will be spaced 5-20 km at each location, so that with other moorings at the sites length scales between 5-200 km are resolved and we will be capable of identifying wave propagation directions. The former distance is the closest logistically possible, which is about twice the mooring line length. The spatial distribution of instrumentation in the vertical and horizontal will be adjusted for specific needs listed below.

The first set of 4 moorings will be used to temporarily raise the spatial resolution of instrumental coverage for specific internal wave studies at each of the sites listed above, each during one deployment period (1 to 1½ years). In the Mozambique Channel they need to cover beams of enhanced (tidal) internal wave energy, typically several hundreds of meters vertically. Horizontal resolution of 5-10 km is sufficient to resolve typical variability of internal wave motions in such a narrow basin, with effects of focusing and amplification at critical bottom slopes (van Raaphorst et al., 2001; Gerkema, 2001). In the wider Irminger Sea, horizontal distances can be larger above the sloping sides because of wider basin dimensions. Of particular interest are strong variations in vertical density stratification occurring in the centre of the basin. There, deep convection (local process) and advection of Labrador Sea water may modify the internal wave background. This requires higher vertical spatial resolution, with IWB-moorings very near to undulating-CTD-moorings measuring background stratification variations in great (vertical) detail.

As a complement to the types of regions covered by the first set, we propose to study the internal-wave climatology also at locations representative of the important (because extensive) `open-ocean’ regions at mid-latitudes. Therefore, the second set of 4 moorings will be deployed in the eastern North-Atlantic Ocean, around the 20ºW meridian. This set will be deployed in a deep basin halfway between continental slopes and the Mid-Atlantic Ridge near 30ºN (to monitor deterministic inertial motions generation at diurnal tidal frequencies) and near 45ºN (stochastic near-inertial motions generation, many storms passing (Alford, 2001). They will also be located once at a position above rough topography (nearby Mid-Atlantic Ridge), where mixing due to internal waves is known to be relatively strong (see section 2); the measurements we propose to make will provide estimates of the long-term variability of their intensity. At these sites current meters should be distributed evenly spaced, so that also inertial motions can be monitored across a large range in the vertical to establish their downward and equator- or pole-ward propagation direction (Garrett, 2001). Inertial motions may become trapped near the bottom close to their critical latitude, focusing their energy which may lead to enhanced mixing (Maas, 2001).

Our proposed internal wave study will complement previous NIOZ studies (Bay of Biscay, Faeroe-Shetland and Mozambique Channel) and other studies (like the HOME-project; led by Scripps Oceanographic Institution, USA) by being dedicated to different internal wave forcing mechanisms in deep-ocean basins, and by addressing its long-term variability in intensity both due to as well as leading to changes in ambient stratification and current fields.

5. International framework

The importance of sustained long-term ocean observations for a better understanding of climate variability has long been recognised internationally.

Different international scientific programmes promote the development of this type of observations. Our proposal contributes most to the implementation of CLIVAR, a programme of the World Climate Research Program. Below we first indicate how we contribute to CLIVAR. Then we discuss how the data from the North Atlantic ocean will be used to contribute to the publication of the ‘Annual Ocean Climate Status Report’ by the ICES. This is followed by an overview of related observational programmes in the North Atlantic and Indian Ocean in which we indicate how our proposed observations will be combined with other activities to obtain integrated in situ ocean observations. Finally the relation to some other international programs and organisations is described.

CLIVAR

Our proposed observations are explicitly mentioned in the CLIVAR Initial Implementation Plan (1998), under the sub theme CLIVAR DecCen (in which decadal to centennial climate variability is studied).

The North Atlantic region is mentioned under the principal research areas North Atlantic Oscillation and Atlantic Thermohaline Circulation (p. 162). More specifically: it is recommended that long-term profiling moorings are deployed as part of a ‘NAO array’ (p. 178) and that ‘spatial variability in deep diapycnal mixing’ is studied since it ‘may affect the thermohaline transport on longer time scales’ (p. 225).

Also the south-west Indian Ocean region has been singled out as requiring special research attention. Under the rubric of Focused Research Projects for Pacific and Indian Ocean decadal variability (p. 253) it is stated that: 'Conditions in the Mozambique and East Madagascar Current regions also appear to be linked to southern African rainfall and to the advection of Indonesian through-flow water towards the South Atlantic, but these currents are so under-explored that the first order of business must be to provide a basic description'.

Thus the proposed observations contribute directly to the goals of CLIVAR and can be seen as a Dutch contribution to this programme. Presently CLIVAR is establishing implementation panels that deal with each ocean basin (dr. John Gould, pers. comm.).

ICES Climate Status Report

The data from the North Atlantic Ocean also will be sent to the data centre of the International Council for the Exploration of the Seas (ICES) in Copenhagen for international exchange. The ICES, through the observational efforts of its member states, through the efforts of its oceanographic data centre, and through the co-ordinating role of its committees and working groups, effectively maintains a regional Ocean Observing System for the North Atlantic Ocean and adjacent seas since the early 20-th century. The ICES Working Group on Oceanic Hydrography (WGOH) will use the mooring data from the Irminger Sea, among others, for the publication of the "Annual ICES Ocean Climate Status Report". Together with similar, planned mooring data from the Iceland Basin (Prof. Meincke, Institut für Meereskunde Hamburg; Dr. Pollard, Southampton Oceanography Centre) and Rockall Channel (Dr. White, University College Galway), and annual hydrographic surveys data from American, Canadian, Icelandic, British, German, Norwegian, Danish, French and

Spanish institutes, as well as satellite altimetry, it will allow a precise description of the annual and inter-annual changes in the northern North Atlantic Ocean. The annual reports produced by the WGOH are used for environmental and fisheries assessment. They also constitute a near "on line" climate description. Via the international contacts of the ICES data centre the data will also become available for the World Oceanographic Data Centre.

Other North Atlantic programmes

Prof. Meincke (University of Hamburg) has planned, as part of the German CLIVAR efforts, a continuation of the regular surveys of the A1E section in co-ordination with NIOZ and BSH (Hamburg). He also plans to deploy profiling moorings in the Iceland Basin. The BSH in Hamburg (Dr. Kolltermann) will survey bi-annually the A2 section as well as a A2' section, in between A1E and A2. In the nearby Labrador Sea an international consortium of research groups from the US, Canada, and Germany carry out the Labrador Sea Deep Convection Experiment. Part of that experiment is the use of a profiling CTD mooring in the Labrador Sea (OWS. Bravo). The continuation of the observations at OWS Bravo as well as a profiling mooring near station S off Bermuda (BOTS) are a part of the planned US CLIVAR programme. Temporarily two such moorings have been deployed in the Irminger Sea (Dr. Pickart, WHOI). Further co-operation with Dr. Pickart on the monitoring of convection in the Irminger Sea, and pooling of instrumentation, is in progress. At the university of Kiel (Prof. Schott) a special research programme "Dynamics of thermohaline circulation variability" focuses on the elucidation of the role and importance of air-sea interaction variability on interannual to decadal time scales. The observations in this programme are directed mainly to the formation of Labrador sea water and the deep circulation and mixing of overflow water from Denmark Strait and the Iceland-Scotland Ridge. The British "Rapid Climate Change" programme forms part of the UK CLIVAR involvement. By the use of a series of profiling moorings it will be attempted to monitor the strength of the THC at 25ºN, far from the sources of the cold branch of the THC. In the German CLIVAR programme MOVE (Dr. Send) a similar mooring section fixed with self-contained CTD's at 16ºN will also monitor the integral strength of the THC. Co-operation and data sharing with especially the groups involved in observations in the Labrador sea, Irminger Sea, and Iceland Basin is envisaged, when our proposal is granted.

The Indian Ocean

The proposed mooring observations in the Mozambique Channel are a follow-up of ACSEX (Agulhas Current Sources Experiment), a joint Dutch-South African programme involving the group of Prof Lutjeharms from the University of Cape Town and our groups. With these observations we will continue our collaboration with the South Africans. Proposals by US scientists have recently been funded by the National Science Foundation for long-term moored observations in the south-west Indian Ocean, in particular to observe the variability of the Agulhas Undercurrent (Dr Beal of Scripps Institution of Oceanography), and in the south-east Atlantic to observe the leakage of Indian Ocean water into the Atlantic (Dr Byrne, Univ. of Maine). If our proposal is granted, we will combine our observational programme in the Mozambique Channel with these US programmes to obtain a coherent picture of the time varying transports in the south-west Indian and south-east Atlantic Oceans. To discuss this co-operation both US scientists have recently attended the Inter-ocean Exchange Workshop at Utrecht University, which was embedded in the Climate Conference 2001, organized by IMAU and the Netherlands Centre for Climate Research.

Warm THC water enters at the other end of the Indian Ocean via the Indonesian through-flow. The ARLINDO program is a joint oceanographic research endeavour initiated by Indonesia and the United States, designed to study the through-flow and mixing of waters within the Indonesian seas. Variations of that through-flow most probably propagate across the Indian Ocean into the Mozambique Channel and subsequently around South Africa. In the ARLINDO circulation experiment the through-flow through Makassar Strait has been monitored for about 1½ year. In most other Indonesian passages to the Pacific Ocean, reliable long-term transport observations are lacking, while in the passages to the Indian Ocean such observations are absent. During the ARLINDO monitoring phase, which will last until 2007, an effort will be made by an international group, chaired by Prof. A.L. Gordon (LDEO) to monitor for at least 3 years the through-flow through both the southern and northern east Indonesian passages. If granted, NIOZ will participate in this ARLINDO monitoring experiment.

Relation to other international programmes and organisations

The device of a permanent system for ocean observations is one of the goals of GOOS (Global Ocean Observing System) and its European component, EUROGOOS. In the framework of permanent monitoring systems with direct links to operational forecasts, as is envisaged by GOOS, our observations serve as pilot studies. Similarly, the data will contribute to the overall goal of integrated (ocean, land, atmosphere) observational programmes like IGOS (Integrated Global Observing Strategy) and, on a European level, GMES (Global Monitoring for Environment and Security).

A recent initiative amongst oceanographic institutions is POGO (Partnership for Observations of the Global Ocean). POGO is an international network of major oceanographic institutions, established to promote and foster the integration and implementation of global oceanographic activities, particularly in situ observations. Directors meet regularly in an informal setting to review their programs and to plan co-operation. NIOZ participates in POGO and our planned activities have been discussed in a recent POGO meeting. The recently developed European Marine Science Plan among others focuses on the major importance of in situ observations in the North Atlantic Ocean to further our understanding of climate change in Europe. It is foreseen that in the next EU Framework (FP6) centres of excellence in marine sciences will collaborate intensively in this field. If granted the research proposed will be an important Dutch contribution to this European key research area.

6. Data policy

The CLIVAR data management structure is still under construction, and no guidelines on submission and exchange are operational yet. That implies that the data from the proposed observational experiments should be identified explicitly as

CLIVAR data at the national and international data archive level, in order to allow future data exchange. Awaiting official CLIVAR guidelines, the International CLIVAR Project Office and appropriate regional CLIVAR working groups will be informed on the availability of the data.

All data will be submitted to the NIOZ Data Management Group (DMG) for archival and national distribution. Additionally they are reported to the appropriate international data centres (WDCA for the Indian Ocean data, ICES for the North Atlantic data) and the CLIVAR community, to allow international exchange of data. The data also will be published in international scientific journals.

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National importance

The proposed studies will form a major Dutch contribution to the international WCRP programme CLIVAR. The ultimate goal of CLIVAR is to better understand and predict climate change and variability both on a global and a regional scale. This will include model studies in which observations like ours will be used for model improvement and thereby for better predictions of future climate change, globally and in Europe. This is of great importance since climate change will especially affect a low lying and crowded country like the Netherlands. For instance, policy regarding land-use and coastal defence may have to be adapted. This is recognised not only within the scientific community but also within different departments of the Dutch government. A recent example is an initiative of the ministry for Economic Affairs which intends to fund (substantial parts of) a multi-disciplinary research programme on climate change (ICES/KIS-3). Similarly, the theme ‘Climate Variability’ is a prioritised research theme of the Council for Earth and Life Sciences of the Netherlands Organisation for Scientific Research (NWO). This illustrates that there is a wide scientific community active in climate research. Since the proposed long-term ocean-climate observations will be carried out in the framework of international programmes, it will facilitate the access to other (international) observational and model studies. This will support Dutch climate research in general.

The three applicants of this proposal represent the entire Dutch community of physical oceanographers who are active in ocean research. Over the past decades these groups have acted more or less separately in which ocean studies by NIOZ were mainly based on theory and in-situ observations and studies by IMAU and KNMI were mainly based on theory and on numerical models in combination with satellite-altimetry data. Since a few years, these groups collaborate strongly in a number of research programs (MARE and ACSEX) which have both ocean-going and modelling components. The present proposal for investments in equipment for long-term ocean-climate observations will stimulate further long-term collaboration between these groups. It is foreseen that combined modelling-observational studies will be initiated in which the observations obtained with these measuring systems will play a prominent role.

Moreover, the in situ observations will be coordinated with ocean observations from space, in particular from satellite altimetry and the GOCE gravity mission which is planned to be launched in 2005. The proponents are actively involved in the research coupled to these missions. The in situ observations will be used for interpretation of these satellite data.

Societal significance

Modern society is sensitive to climate variations, by its effects on safety (e.g. floods, severe storms) and agriculture (e.g. droughts or excess precipitation, length of the growing season). In order to support the way society deals with the effect of climate variations and climate change, a good understanding of climate variability and reliable climate forecasts are required.

The most important and direct societal impact of the proposed long term ocean-climate observations will lie in the realm of better understanding the role of the ocean in climate, climate variability and climate change. The observations will form a direct contribution to the set up of a global observational data base which is urgently needed to test climate models and a variety of hypotheses on the role of the ocean in climate variability.

The observations in the North-Atlantic ocean are of direct importance for a better understanding of the role of the ocean for the climate in Western Europe. Especially issues related to climate variability will be addressed like the role of the ocean in the NAO induced variability. Moreover, different ocean-climate models suggest that due to ‘global warming’ the strength of the THC will be reduced drastically in the coming decades leading to a colder climate in Western Europe. Our observations will be used to monitor parts of this THC variability such that, combined with long-term observations by others, these model projections may be validated. Another important issue concerns the possible climate driven variations in the marine ecosystem, which may lead to variability in commercially exploited fish stocks. These data will contribute to increased insight in such relations.

The observations in the Mozambique Channel are of direct importance for a better understanding of the climate on the African continent. It has been suggested that the ocean region in the Mozambique Channel has substantial impacts on the rainfall of southern Africa. By properly observing the oceanic heat transport of the region it is hoped that predictability of continental rainfall will be substantially improved.

The examples above illustrate the importance of the proposed observations for assessing regional climate variability. However, many studies have suggested that there are also global connections. An example is the inter ocean exchange between the Indian and South-Atlantic ocean which may affect the THC in the North Atlantic Ocean thereby influencing the climate in Europe. Such studies are based on numerical model simulations in which many underlying simplifications and assumptions may influence the results. Our data and data analyses will contribute to a further improvement of these global models which ultimately will lead to better predictions on climate change. This has obvious and far reaching societal implications. The emerging successes of El Niño forecasts demonstrate the possibility and importance of climate forecasts world-wide.

Financial budget

The available mooring instrumentation at NIOZ mainly consists of current meters (presently some 20) and ADCP's (2), with acoustic releases and buoyancy units. The proposed long term observation experiments with moored instrumentation are expected to last for 5 years, requesting a permanent use of the mooring instruments. Given the presently available mooring equipment, this will interfere strongly with the instrument availability for shorter term research projects. Moreover, at present instruments to measure temperature and salinity, with an accuracy required for climate studies, are not available at NIOZ. Therefore we propose funding for the purchase of mooring equipment and sensors dedicated to carry out the observations described above.

Table 1 presents the prices of the different mooring elements in which we assume that a representative mooring has a total length of 2000 m. Prices are per instrument and include battery packages for the first period of observations. The last column gives the estimated costs of servicing the moorings. This includes new battery packages for the instruments and new mooring material (cables etc.).

Mooring element	Price per unit (Euro)	Service costs (Euro)
ADCP + foam float	71.000	410
Current meter	11.300	370
Temperature-salinity sensor	5.900	150
Profiling CTD	77.500	400
Floatation	8.000	
ARGOS beacon	3.850	950 per year
Mooring cable	2.100	2.100
Acoustic releases	27.300	600
Other mooring material (weights etc.)	2.700	2.700

Table 1. Costs of sub-surface mooring elements

Based on Table 1. the required material budget for the different projects is:

Irminger Sea

Three moorings are proposed for the Irminger Sea (one in the center, one on each side) to measure ocean currents + convection/water mass transformation. This requires an autonomous profiler resulting in a daily vertical profile of S, T and U. Near the top and bottom an ADCP measures ocean currents directly. Near the bottom one additional CTD sensor is required.

Initial costs per mooring (in Euro): 77.500 (profiler) + 142.000 (2 ADCP's) + 5.900 (1 CTD sensor) + 43.950 (releases, floatation, mooring cable etc) = Euro 269.350.

Total initial costs (3 moorings): Euro 808.050.

These moorings are serviced each year. Total service costs: Euro 23.160 per year

Mozambique Channel and Lifamatola strait in the Indian Ocean

Five moorings are required across the narrow section of the Mozambique Channel and one in Lifamatola strait to measure the variations of the ocean currents and transports. The design of these moorings is the same. Each mooring consists of 2 ADCP's (top + bottom), 3 current meters, 5 CTD sensors.

Initial costs per mooring (in Euro): 142.000 (2 ADCP's) + 33.900 (3 current meters) + 29.500 (5 CTD) + 43.950 (releases,floatation, mooring cable etc.) = Euro 249.350.

Total initial costs (6 moorings): Euro 1496.100 .

These moorings are serviced each 1.5 year, service costs are Euro 54.180 per service, i.e. Euro 36.120 per year.

Moorings for internal wave studies

In order to study internal wave variability and propagation directions the relevant meridional horizontal length scales varying between 5 – 200 km need to be resolved. This requires a set of moorings which are deployed at relatively short distances. Given the range of locations mentioned above we need 2 sets of 4 moorings each, observing simultaneously, with 5 current meters in each mooring. One of these moorings has an ADCP to extend measurements by some 500 m towards the surface and to resolve smaller shear scales.

Initial cost per mooring (in Euro): 56.500 (current meters) + 43.950 (releases, floatation, mooring cable etc.). Per site we require one ADCP (Euro 71.000).

Total initial costs (2 sites, each 4 moorings): Euro 945.600 .

These moorings are serviced each year, service costs are Euro 66.420 per year.

Table 2. presents an overview of the estimated material budget for the proposed long-term observations. For completeness we also added the estimated costs of ship time. For the North Atlantic Ocean we require roughly 4 weeks ship time per year (yearly service of the profiling moorings + replacement of internal wave moorings + bi-annual survey of the WOCE repeat section). The moorings in Mozambique Channel require roughly 3 weeks ship time per 1.5 year (i.e. 2 weeks per year for the financial overview in Table 2). For deployment and servicing of the moorings in Lifamatola strait ship time is provided by US funds. For simplicity we combined the costs for the Irminger Sea and the internal wave studies under ‘North Atlantic’ and for Mozambique Channel and Lifamotala strait under ‘Indian Ocean’. One day of ship time is estimated to cost Euro 10.000.

Region	*Initial costs (Euro)*		*Service costs per year (Euro)*	
	Moorings	*Ship time*	*Moorings*	*Ship time*
North Atlantic	1.753.650	280.000	89.580	280.000
Indian ocean	1.496.100	210.000	36.120	140.000
Total	3.249.750	490.000	125.700	420.000

Table 2. Initial and service costs (per year)of the long term ocean climate observations

Funding requested

Based on the above, Table 3 presents the total budget needed to carry out the proposed observations. For the exploitation costs, it is assumed that all observations cover a period of 5 years. Personnel costs include 3 technicians and 1 scientist (see exploitation). Hence, the total budget for the project during 5 years is Euro 7.218.250.

	Initial costs (Euro)	*Exploitation costs (Euro)*
Moorings	3.249.750	628.500
Ship time	490.000	2.100.000
Personnel		750.000
Total	**3.739.750**	**3.478.500**

Table 3. Total costs of the 5 year ocean observations

We request funding for the initial costs of the instrumentation (purchase and first deployment) amounting to Euro 3.739.750. This is 52% of the total project budget.

Exploitation

Moorings

It is proposed that the instruments will form part of the national pool of instruments for seagoing research at NIOZ. NIOZ supervises this pool as part of its mission to support and facilitate seagoing research in the Netherlands. We propose that part of the yearly budget that is available for this task, carried out by NIOZ-MRF (Marine Research Facilities), will be allocated for the service costs of the moorings.

Personnel

Maintenance and servicing of these instruments will be done by technicians at NIOZ who have ample experience in this type of work. Data management will be done by the NIOZ data management group. We expect that in total the assistance of 3 full time technicians (roughly 2.5 for technical assistance and 0.5 for data management) is needed. NIOZ scientists will supervise all logistic and technical aspects of the projects. We estimate that the time required is equivalent to allocating 1 full time scientist to these tasks. These tasks will be carried out by NIOZ personnel.

Ship time

It is obvious that ship time is needed for the deployment and regularly servicing (at least every 1.5 years) of these moored systems. The amount listed in the financial budget (Tables 2 and 3) gives the estimated maximum amount which is needed if all ship time has to be rented (except for the mooring in one of the Indonesian straits for which ship time will be made available as part of the ARLINDO programme). In reality, for both regions it is expected that the actual amount needed will be less by combining the proposed ‘mooring activities’ with other seagoing programmes. Below we indicate some of these possibilities.

For the servicing of the moorings in the North Atlantic ocean an obvious option is the use of the Dutch RV Pelagia. Other options result from combining our seagoing activities with those from other (foreign) institutes (e.g. from Germany, UK or USA).

For the servicing of moorings in Mozambique Channel 3 weeks ship time per 1.5 year are needed, assuming that transit to and from the region takes one week. This can be done by hiring a vessel in South Africa. However, similar to the North Atlantic ocean, there may be possibilities to combine our activities with those from other (European) research institutes. For example: our present array of moorings in Mozambique Channel will be recovered by joining a cruise with the British ‘RV Charles Darwin’.

Through our international contacts the options of combining seagoing activities for servicing the moorings will be actively explored. Therefore we expect that the actual funds needed for ship time for servicing, for which we will apply through the regular channels, will be significantly less than those listed in Table 3.