

ASSESSMENT REPORT ON NRP SUBTHEME
"OCEANS AND THE CLIMATE SYSTEM"

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ABSTRACT

This report reviews our present ideas on the physical and biogeochemical role of the oceans in the climate system and gives an assessment of the relevant research in the framework of the NRP and of the related Netherlands research activities.

1. OCEANS AND CLIMATE

1.1 Introduction

The importance of the oceans for the global climate lies both in their role in the transport and accumulation of heat and moisture and in the influence of their biogeochemistry on the composition of the atmosphere. Without any anthropogenic influence the feedbacks in the oceanic system can cause instabilities and "natural" climate variations such as have been deduced from palaeoclimatic evidence. This is reason enough for investigating this system. The actual concern for the anthropogenic influences, however, makes these investigations even more urgent. This task is of a scope that requires concerted international action in the field of ocean observations and ocean modelling, both in physics and in biogeochemistry. The Netherlands effort in those fields, the subject of this review, is to be judged against this background.

The oceans are playing an important role in the climate system, by their physical role in the transport and accumulation of heat, but in addition as the environment

for a number of biogeochemical processes that are acting in the exchange of important greenhouse gases and condensation nuclei (DMS) with the atmosphere. A review of the present opinions with respect to this role of the oceans and a checklist of research needs, composed by an International Meeting of Scientific and Technical Experts, was published by UNESCO (Anon. 1991).

The oceans, in combination with the atmosphere, are transporting the excess of heat received by the earth in the tropical regions to higher latitudes that have a heat deficit. This role can be shown by budget calculations comparing the zonal radiation budget with the meridional transport by the atmosphere, for the direct estimates of the oceanic transport are still less accurate. This meridional transport accounts for about half the transport required for a stable climate (depending on latitude). A recent estimate (Trenberth and Solomon, 1993) is given in the WOCE Science Plan for Ocean Modelling (WOCE International Project Office, 1994).

Although different direct measurements of the oceanic transport still are showing large discrepancies, the finding that the oceanic contribution is important is, in order of magnitude, confirmed by these estimates. However, we need better observations and better models to compute the transport with an accuracy comparable with the atmospheric estimates. It is clear that the oceans must have a significant effect on the distribution of heat over the globe and thus on the global and on the regional climate. For western Europe especially the effect of the oceans on the regional conditions should be noted. Especially for the North Atlantic area the use of coupled ocean-atmosphere models appears to be essential in predicting a possible regional climatic change (Gates et al., 1992).

The rate of climate change under the influence of an increased greenhouse effect is determined by the heat storage of the ocean. This again depends on the vertical exchange processes in the sea. An increase of the downward radiative flux of one or two watts, an amount corresponding with a doubling of the atmospheric CO_2 , reaches a new stationary state after one year if only the upper 10 m of the ocean would be involved. However, this is 10 years for a 100 m thick layer, and if the full depth of the ocean is involved, the equilibrium is only reached after centuries. As the ocean is a strongly layered medium with different vertical exchange processes, we have to do with different short-term and long-term "climatic memories".

In the IPCC reports estimates are given for the exchange of greenhouse gases between ocean and atmosphere. This role appears to be very important for CO_2 . For other greenhouse gases the review given by IPCC (Watson et al., 1990; Watson et al., 1992) indicates that the oceans sometimes act as a "minor source" (methane), sometimes as a "significant, but not dominant source" (N_2O). Yet there are many uncertainties, and better estimates of the different natural greenhouse-gas budgets are necessary before one can make good estimates of the influence of anthropogenic sources.

The same review shows that oceanic DMS (Dimethyl sulphide), produced by algae, is an important item in the atmospheric sulphur budget. As DMS in the marine atmosphere distant from land is supposed to be a major source for cloud

condensation nuclei (CCN) this DMS production by marine organisms deserves attention in climate prognoses.

Changed climatic conditions are likely to cause changes in the contribution of the oceanic sources and sinks of greenhouse gases and DMS, causing feedback processes. Therefore not only improvement of the present budgets but also research of the biogeochemical processes determining the role of the ocean as a source or a sink, and of physico/chemical processes influencing the ocean-atmosphere exchange is necessary.

Although the concern for anthropogenic disturbance of climatic conditions is the main impulse for the present interest in the influence of the oceans on the physical and chemical conditions of the atmosphere, ongoing work cannot be isolated from the more general question of the interactions between ocean and atmosphere and their role on the stability of climate. Palaeoclimatic studies of ice cores show that past "natural" climatic change has been accompanied by changes in the atmospheric composition of greenhouse gases (e.g. Raynaud et al, 1993), pointing to feedback processes that are probably of oceanic origin. Understanding and modelling the physical and biogeochemical systems in the world ocean and their interrelations must be an ultimate goal in the study of past and future climate change. This is a task that will last far into the next century. For the moment most studies concentrate on both systems separately and consequently we too discuss them separately.

Netherlands oceanographers of different disciplines, both in physics and in biogeochemistry, have experience in various studies of this kind. They are able to contribute to the large international programmes going on or planned for the coming years and in fact are doing so already. The NRP programme has enabled this contribution to be strengthened. In the following the main elements of the physical and biogeochemical systems are given first. Then, in the next sections, the international research background for the respective problems is sketched, and the relevant Netherlands activities are reported.

In the following a list is given of the NRP projects within the subtheme "Oceans and the climate system" with the sections where they have been reported (Table 1.1). At the end of the various sections a brief assessment is given of the position of the NRP projects in the national and international research efforts. The activities initiated in the framework of the related "integrated plans" VvA-2 ("The coupled atmosphere-ocean system on time-scales from 0.1 to 100 years"), VvA-3 ("Ocean circulation and climate"), and VvA-9 ("Carbon-balance in the oceanic mixed layer and air-sea exchange") as well as other related oceanic research programmes supported by the Netherlands Science Foundation (NWO) via its subsidiary foundations (SOZ, SRON) have been mentioned when appropriate.

1.2 Ocean physics

In the structure and circulation of the oceans we observe variations that are likely to have their effects on the climate. Such variations may influence local or regional atmospheric conditions, but they also can alter the distribution of heat and moisture on a global scale.

The processes of interaction between atmosphere and oceans should be differentiated according to their temporal and spatial scales. On one side one

encounters the interannual variability of "El Niño" with its influence on regional climate, on the other side the problem of major shifts found in palaeoclimatic studies and the possibility of multiple equilibria of the oceanic circulation, such as the "conveyor belt" that could be "on" and "off" with dramatic consequences for the global climate. In different studies the physics of this variability is investigated.

Although the oceans are much more stable than the atmosphere, changes in properties and circulation do occur. The "El Niño" phenomenon, discussed later, is one example, the recent "Great Salinity Anomaly" in the North Atlantic (Dickson et al., 1988) is another. The subtropical North Atlantic shows a significant increase of temperature since the late fifties (Parilla et al, 1994). Such oceanic variations can have effects on the global or regional climate system, irrespective of any anthropogenic influence. The international scientific community has to establish the sensitivity of the climate for such variations in the atmosphere-ocean system and to assess the risks of interfering with this system, e.g. by an anthropogenic increase of atmospheric CO₂.

The oceans redistribute heat over the globe. This transport of heat takes place at different levels. Although it is difficult to make sharp distinctions, we can discern two patterns. First, the upper layers, that are part of the thermocline in a layer several hundreds of meters deep and that are mainly driven by the wind field. Only to a minor degree is the interaction with the atmosphere determined by the freshwater balance. The interaction may affect regions of the size of an ocean basin and is at time scales up to decades. The transport in the deeper ocean is driven by thermohaline effects (thus by differences in temperature and salinity) and is therefore also determined by the freshwater balance that, however, has a longer reaction time. The interaction may be at time scales of decades and over, and can affect the global ocean.

The TOGA programme is the main oceanographic programme in the World Climate Research Programme that is dealing with the shorter (interannual) time scales (TOGA Scientific Steering Group, 1985). For the longer time scales the WOCE programme deals with the ocean circulation at global scales (WOCE Scientific Steering Group, 1986). Both programmes are important for our understanding the role of the oceans in the climate system: they cover different scales in time and space and the basic physics are different, but they are both contributing to the necessary oceanographic database and to the development of oceanographic modelling.

The transport by the oceans at a global scale and over its full depth means a net surface flow to regions of deep convection (the North Atlantic and around Antarctica) and a deep return flow to areas with (less localised) upward flow. This is the "conveyor belt" that has its place in palaeo-climatic studies (e.g. Broecker, 1987, Broecker, 1991), and that could be "on" and "off", depending on the different equilibrium conditions of the ocean circulation.

Table 1.1
List of projects in NRP subtheme "Oceans and the climate system"

Title	Project leader	Number
Phytoplankton and the oceanic carbon cycle; <i>Emiliania huxleyias</i> a model system	P. Westbroek	850003
VIERS-1 field experiment	W.A. Oost	850005
Variability of the North Atlantic sea surface temperature	A. Kattenberg	850007
CO ₂ exchange between ocean and atmosphere	H.J.W. de Baar	850021
Ocean circulation and climate	W.P.M. de Ruijter	850025
Air Sea exchange of DMS	R. Guicherit	850026
Water/atmosphere exchange of N ₂ O in marine systems	W. Helder	850027
ASGASEX	W.A. Oost	852082
Nonlinear dynamics of the equatorial ocean-atmosphere system.	H.A. Dijkstra	853110
Natural variability in a coupled ocean-atmosphere model	R.J. Haarsma	853134
Mesoscale mixing processes and watermass transformation in the Greenland Sea	H.A. Dijkstra	VvA3-209
Stability of the general ocean circulation	C.B. Vreugdenhil	VvA3-234
The role of mesoscale eddies in the ocean/atmosphere heat exchange and meridional heat transport	W.P.M. de Ruijter	VvA3-244
Distribution, chemical composition and isotopic ratios of dissolved organic carbon in the ocean. Part: dissolved organic carbon	H.J.W. de Baar	VvA9-219
The partial pressure of CO ₂ in sea water as a control on marine biological productivity and calcification	M.J.W. Veldhuis	VvA9-224

In theoretical studies of ocean circulation the possibility of multiple equilibria has been discussed for some decades. An important task now is to discover how and why transitions can occur in practice. But then the actual complexity of the ocean circulation as compared with the simple "conveyor belt" picture becomes an important issue. The suggestion of a transport by one, continuous loop should be amended. The stratification, with the water mainly moving along surfaces of equal density (isopycnic surfaces) and the subdivision of the ocean by continents and oceanic ridges in separate basins causes a layering and segmentation of the transport in many separate loops, each of them linked in a complex way to its neighbours. And the interaction with the atmosphere is along different lines, as discussed above. Oversimplification of this complex system could result in erroneous conclusions with respect to the climate change at time-scales ranging from tens of years to centuries.

The thermohaline processes in the North Atlantic are thought to be critical for the operation of the "conveyor belt". In the North Atlantic the variability of salinity at decadal time-scales has received special attention since the "Great Salinity Anomaly", mentioned above, but also in the Pacific decadal variability is observed (Anon., 1992). Combined with palaeo-climatic data from ice-cores that indicate that the climatic stability during the recent geologic past might be "the exception rather than the rule" (Dansgaard et al., 1993), this stimulates the research in the mechanisms of these decadal-scale ocean variations, especially in the North Atlantic.

In the IPCC analysis the effect of anthropogenic disturbances has been investigated with oceanic models, wherein the ocean circulation is not differing much from the present conditions. These models give indications of the response time of the global and regional climatic indicators, such as temperature, to changing greenhouse gas concentrations. Recently modelling studies have indicated that for certain scenario's of the CO₂ input the thermohaline circulation decreases, and they have shown how this circulation may or may not restore in the long run (Manabe, Stouffer and Spelman, 1994). Still these results give no more than indications. Practice shows that there are many difficulties to overcome before models can attain a predictive quality, and this certainly is the case with long-term climate models.

Improved models should give more insight into the short-term "natural" climate variations, in the longer-term response of the ocean-atmosphere system to anthropogenic forcing, and in the stability of the present climate system. Better models ask for a variety of observations, of process studies and of theoretical and numerical work. The international TOGA and WOCE programs are making a co-ordinated effort aiming at this model-improvement. .

1.3 Biogeochemistry of the Ocean

For different greenhouse gases estimates of the role of the ocean in the global budget have been made. However, the input/output values have considerable error-bars. Better figures are required. But without knowledge of the processes governing the exchange between ocean and atmosphere the actual budget is of limited use: interaction between changes in climate and input/output figures can cause a negative or a positive feedback, both with important consequences.

For an anthropogenic contribution to the different relevant greenhouse gases it is CO₂ that is considered the most important with respect to its effects (Shine et al, 1990). Now the CO₂ concentration and exchange are strongly influenced by the biogeochemical processes in the oceans. The ocean continuously exchanges CO₂ with the atmosphere, and because the increased anthropogenic input is only partially reflected in an increase of atmospheric CO₂ it is likely that a large part is also taken-up by the oceans. Scenarios for future atmospheric concentrations of greenhouse gases are based upon our understanding of the actual global CO₂ budget as presented by Watson et al. (1990) in the IPCC Report. Adaptations to this budget that are expected from the next IPCC Report still leave open various questions on the oceanic uptake.

IPCC estimates an extra oceanic uptake of 2.0 ± 0.8 GtC/y compared with ocean-atmosphere and atmosphere-ocean fluxes of 90 GtC/y. Other estimates of the redistribution of anthropogenic carbon dioxide result in an imbalance of 1.6 ± 1.4 GtC/y, the "missing sink" (Watson et al, 1990, 1991). In a recent review (Siegenthaler and Sarmiento, 1993) this imbalance has slightly increased: 1.8 ± 1.3 GtC/y. The different suggestions for the cause of this imbalance have to be explored for the development of better CO₂ scenario's. This includes re-assessment of the role of the ocean.

Therefore the available figures of the ocean-atmosphere exchange of CO₂ have to be carefully scrutinized. Independent data are important because present estimates are based essentially upon the same data set. For the important ocean-atmosphere exchange an international programme (JGOFs: Joint Global Ocean Flux Study) has been initiated to tackle this problem over a broad front (Anon. 1990).

Also in the global budgets of some other greenhouse gases the oceans act as a source. Better estimates of this source function for different oceanic environments is important to improve the actual budgets, and thus the concentration scenarios. Moreover, for CO₂, as well as for the other greenhouse gases, the possibility of feedback mechanisms by changed environmental conditions is a serious problem. Changes in ocean temperature, in ocean circulation, and in the meteorological conditions at the sea surface may influence the oceanic sources and sinks of greenhouse gases. Only if the fundamental biogeochemical processes are well understood we can take these feedback mechanisms into account.

The climatic role of DMS production by algae was already mentioned in the introduction. In the report on atmospheric processes of the NRP programme the effects of DMS on the radiation budget are considered. (Guicherit, this volume). In this report the marine aspects of DMS production and its exchange with the atmosphere are discussed together with the other marine research. A problem here, that is shared with some other biogeochemical processes, is the strong influence of short-term blooms as compared with more stationary conditions and the different role of various marine algae in its production.

For better biological detail an organism-centered approach has been advocated as an alternative. The philosophy here is that different processes (carbon cycle, DMS production) are investigated in combination. Because of its important, sometimes

crucial, role in the different processes, and its palaeoclimatic significance the alga *Emiliana huxleyi* has been chosen as a "model" organism in the international "Global Emiliana Modelling Initiative" (GEM) and the related European EHUX programme.

Solutions for the the anthropogenic CO₂ increase have been advocated that in some way or another propose to enhance the storage in the oceans, e.g. by fertilizing the oceans or by deep sea disposal. It is clear that, as long as such technological remedies are popping up, it is necessary to have a broad knowledge of the processes involved. On the basis of present understanding these solutions are considered inefficient or unfeasible (De Baar and Stoll, 1989 and De Baar, 1992).

2. OCEAN PHYSICS AND CLIMATE

2.1 Introduction

Model studies as well as different types of observations (e.g. oceanographic surveys, data from automatic buoys, satellite observations, etc.) are both necessary in the programmes that investigate the main components of the physical system of the oceans and their interaction with the atmosphere. The most important short-term variability is investigated in TOGA (the influence of interannual variations in the tropical oceans - El Niño - on the climate) and the longer-term, global variability (including the role of the deep ocean circulation) in WOCE. The latter has different sub-programmes, aiming at the investigation at different spatial and time scales. Much work still has to be done in the modelling of the oceans alone, with prescribed boundary conditions. This includes the study of different processes that have a crucial role in the system, but that often only can be parameterized. Yet the modelling of ocean-atmosphere exchange is the ultimate goal. But coupled ocean-atmosphere models again have their specific problems.

The international programmes TOGA and WOCE are important steps in the solution of these problems. They also mark a development towards a system of co-ordinated observational systems, generating data that, in combination with data-assimilation models, should be able to give early warnings and predictions of climatic developments.

The basis for our understanding of the physical system is the development of models representing the essentials of the system. Usually one thinks here of numerical models, and only such models can cope with the complexity of the whole system, but they are the result of an integration of many different theoretical and observational studies that have their place in the assessment of the processes involved. Furthermore we need data on the actual and past conditions in the oceans, their structure and circulation for initialization and validation of models. Data-sets from the past often do not attain required accuracy and the distribution of observations over time and place is uneven. Therefore parallel to the modelling effort there is need for a new observational programme that ultimately may develop into an operational observing system.

Most of the physical oceanographic research in the framework of climate change is co-ordinated in the international TOGA and WOCE programmes. Both programmes concentrate on the development of models (stand-alone ocean models

or coupled ocean-atmosphere models), but they require a large effort in the international development of observational strategy and the organization of different process-studies, including the maintenance of quality criteria for the data and the organization of data banks.

For the investigation of interannual variations of climate we need models of only the upper layers of the ocean. This is the approach of TOGA ("Tropical Oceans, Global Atmosphere"). Starting point for TOGA is the observation that the atmosphere, especially at lower latitudes, shows (atmospheric) climatic variations at periods that are usually between 3 to 5 years with no strict regularity: the Southern Oscillation. Later investigations indicated the connection between this phenomenon and oceanic variability in the tropical Pacific, along the Peruvian coast known as the "El Niño" phenomenon, that involves large, multi-annual, variations in sea-surface temperature. This connection is, for instance clear from data shown by the Climate Analysis Centre, Washington, (published by the World Climate Data Programme of WMO, s.d.).

The idea that interaction between certain progressive wave-like processes typical for the tropical oceans and the atmosphere could be responsible for the climate variations led to the ENSO (El Niño - Southern Oscillation) concept. The TOGA programme, expanding this concept, tries to arrive at the predicting of short-term climatic changes on the basis of a combination of oceanic models and oceanic observations (TOGA Scientific Steering Group, 1985). Although the most pronounced climatological effects of ENSO are in the Pacific region, there are indications of effects of ENSO on the European climate as well (Fraedrich, 1994).

However, for longer-term variability that incorporates an increased greenhouse-effect (together with long-term instabilities) we need models for the whole ocean and the complete thermohaline interaction process. In particular simulation and study of time-dependent changes requires that these models are coupled in a realistic way with atmosphere models (Bretherton, Bryan and Woods, 1990). The issue here is not so much prediction at longer time scales, but simulation of climate variation under influence of different external conditions (e.g. an increased greenhouse effect): sensitivity studies. The emphasis is on the development of global or ocean-wide General Circulation Models (GCM's). These GCM's depend on observations for their initialisation and validation, on either historical or new data (temperature-, salinity-, density-distribution, tracers).

The modelling of the oceans that is possible by the development of increased computing power, and the new instrumental possibilities for observation of ocean circulation are equally important for the oceanographic part of climate research. This is the basis for WOCE (World Ocean Circulation Experiment), the international oceanographic programme in the WCRP. This programme has a field phase between 1990 and 1997, contemporary with the period of the new ocean-observing satellites (ERS-1 and TOPEX-POSEIDON). These satellites play an essential role in the WOCE programme are supplementing the many in-situ oceanographic observations made during this period. In the modelling phase of WOCE these data will be indispensable until far into the next century (Koblinsky, Gaspar and Lagerloef, 1992).

The WOCE programme has three "core projects". Core Project 1, the Global Description, aims at the "zeroth order" description of the role of the oceans in the planetary climate system. Core Project 2, the Southern Ocean, concentrates on the formation of Antarctic water masses, and on the connections between the different ocean basins. Core Project 3, the Gyre Dynamics Experiment, focuses on the role of smaller-scale processes (quasi-geostrophic eddies, topographic effects and subduction of water masses) on the circulation of one ocean basin: the North Atlantic. Whereas Core Project 1 is essential for the long-term modelling (say 100 years or more), Core project 3 also is important for the modelling of shorter-term variability (of the order of 10 years).

The development of ocean models is one step in the understanding of the climate system, the coupling of oceanic and atmospheric models is an other one. The physical coupling of the atmosphere and the ocean is by the exchange of heat (sensible and latent, and the balance of long-wave radiation), of moisture (evaporation and precipitation) and momentum (wind stress). Indirectly also the short-wave radiation contributes, because atmospheric conditions determine the radiation reaching the sea surface.

Estimating the heat, moisture and momentum fluxes is done by parameterized relations between bulk properties of the atmospheric boundary layer, and the surface layer of the sea. In these estimates different spatial and temporal scales may be used. The observations over the ocean are scattered in space and time and are often inaccurate. Occasionally this can result in error bars of the fluxes of the order of 100 W/m². Compared with an expected (long-term) greenhouse effect of about 5 W/m² this indicates the urgent need for better estimates. The use of atmospheric general circulation models through the assimilation of surface data appears the best way for better estimates of the the fluxes with the relevant resolution in space and time. Here also the oceanographic satellites are a powerful resource. For estimates of the flux of momentum all over the oceans the scatterometer data from satellites offer new possibilities.

Coupling of ocean and atmosphere models is also a modelling problem. Atmospheric and oceanic models that operate well on their own produce the so-called "climatic drift" when coupled. This is because of inadequacies in the ocean models, because of uncertainties in the fluxes and lack of feedbacks to correct for these. Flux corrections are applied to reduce the climatic drift, but how to do this without predetermining the result is a serious problem.

WOCE and TOGA are not the final programmes in this field. They also are a first step towards a system of oceanic observations and data-assimilation models, comparable to the meteorological system (with differences in spatial and time scales). Within the limits of predictability such a system should be an essential tool for the assessment of natural and anthropogenic climate changes. Experimental predictions of the "El Niño/Southern Oscillation" (ENSO) phenomenon have a moderate skill at lead times of one year.

As to the problem of longer-term climatic trends, that presently are not exceeding the "noise", it has been indicated by McBean (1994) that future predictive models may be able to reduce this "noise".

2.2 Models

Models are being developed for prediction of climate variations at interannual timescales. Models have also been used to assess the consequences of CO₂ forcing, and the possible changes in ocean circulation because of changes in other external factors (occurrence of multiple equilibria). The number of models capable of realistic assessments is limited. However, further development of these models requires various additional modelling exercises, with less elaborate models. The different lines of Netherlands research in this field are referred to in the context of the international efforts.

Models are essential tools for testing hypotheses on the role of the oceans in the climate system. But this asks for a critical attitude towards the quality of these tools. Model solutions can have different structures, depending on their parameterization (e.g. of the exchange with the atmosphere, or of oceanic sub-grid processes). Developing adequate ocean models for different conditions is an important aspect of climate research.

Since the start of the TOGA programme considerable progress has been made in the modelling, understanding and predicting of ENSO. In an evaluation of 1990 it was stated that it was predictable, but the skill of predictions was indicated as "modest" (WMO/IOC Intergovernmental TOGA board, 1990). The official TOGA programme is completed on 31 December 1994, but the development of predictive models is not finished. Short-term modelling furthermore is important in improving modelling skill in general.

Models covering the whole ocean are the objective of WOCE. They have to answer the questions about multiple equilibria and those about the time response of the ocean to anthropogenic disturbances.

In the 1992 IPCC report four coupled ocean-atmosphere models were used to investigate the transient results of increasing CO₂ forcing: GFDL (Geophysical Fluid Dynamics Laboratory, Princeton, USA), MPI (Max-Planck Institute, Hamburg, Germany), NCAR (National Center for Atmospheric Research, Boulder, USA), and UKMO (Meteorological Office, Bracknell, UK). The development of OGCM's (Oceanic General Circulation Models) capable of this type of experiments is a major task and is therefore only done at a few places. However, these models are the result of an extensive international modelling effort, supported by a "family" of intermediate models that concentrate on special regions or special aspects of the ocean circulation.

For instance, a question in the development of ocean models is the role of mesoscale eddies in the ocean. For coarse-grid models the role of these eddies in the horizontal transports has to be parameterized. Also the parameterization of other locally occurring oceanic processes as deep convection is critical. A question that occurs in the coupling of atmospheric and oceanic models is that of the best estimates of the ocean-atmosphere fluxes (of heat, moisture and momentum). The sensitivity of the system for different effects can be explored in intermediate models, sometimes with relatively modest means. Outside the centres where the GCM's are developed important modelling work can be done in these fields.

The WOCE Numerical Experimentation Group (WOCE International Project Office, 1994) has developed a strategy for ocean modelling. This group concludes that for the further development of ocean models one should:

1. Encourage greater support for the development of small-scale process models. Areas of particular importance are the oceanic mixed layer, air-sea fluxes, deep convection, bottom water formation, overflows between ocean basins and mixing within the ocean.
2. Continue encouraging high-resolution studies of the ocean. It should be emphasised that what is required of these studies are models with the highest possible realism. Such studies will need the fastest of modern array processor computers.
3. Encourage the development of more accurate fully coupled models, the validation of such models using the high resolution models and the small scale process models, and the use of such models to study the circulation of the ocean, its variability and effect on climate change.

In addition the group draws conclusions as to the strategy with respect to data assimilation and the setting-up of operational oceanographic analysis and forecast centres. Here models will have an important role (Smith, 1991).

Work on ocean models in the framework of NRP and in related Netherlands programmes is directed at (1) the modelling of short-term coupled ocean-atmosphere models, at (2) the study of the role of different parameterizations for the model solutions of long-term stability of the thermohaline ocean circulation and (3) at the development of small-scale process models that should form fundamental building blocks for the final large-scale models. In the following these activities and the perspectives and results are reported.

Short-term modelling

This point in the first place addresses not the possible anthropogenic climate change, but the natural variability at interannual to decadal time scales. The question whether it is possible to predict short-term (interannual) climatic change is of direct interest for society. The adequate coupling of atmosphere and ocean is crucial for this short-term modelling. In most models a flux correction is applied to suppress so-called climatic drift. Much work is being done to investigate the influence of the various coupling procedures. It is clear that a flux correction easily may limit the applicability of such coupled models to variability studies. In Neelin and Dijkstra (1994) it is shown that multiple equilibria can be produced by coupled models as artefact of the flux correction.

An objective of TOGA is to develop operational predictive models. However, notwithstanding the progress in modelling the El Niño phenomenon, the fundamental reasons for its irregularity still are under dispute, and the reliability of predictions over longer periods only can be improved if this point is clarified. For the study of these problems there is place for relatively simple analytical models, parallel to the "brute force" numerical models (e.g. the El Niño results reported in Science 264: 70-74 from the numerical model of Jin et al., 1994, and the analytical model of Tziperman et al., 1994).

In the NRP/VvA project NRP project 853110 "Nonlinear dynamics of the equatorial ocean-atmosphere system" (H.A. Dijkstra, Institute for Marine and Atmospheric Research, Utrecht - IMAU) this point is tackled by such a parallel approach with a combination of such models. The aim is to determine the role of nonlinear wave structures in the interannual variability. The results could be a starting point of a systematic validation of certain components of a predictive GCM.

In a number of interconnected modelling projects the KNMI, especially in co-operation with the Max Planck Institute of Hamburg contributes to the modelling of short-term variations. In Germany the interest in short-term modelling led to a concentrated effort for developing a coupled ocean-atmosphere high-resolution model for climate predictions over 1 year. This model has been developed by the Max-Planck Institute in co-operation with the Netherlands KNMI and the ECMWF (European Centre for Medium-Range Weather Forecasts/Forecasting). (Latif et al., 1994, Stockdale et al., 1994). Although this modelling is not specifically directed to the TOGA region but to a more general applicability, the KNMI contribution to this project is directed to the modelling of the tropical Pacific Ocean in relation to the TOGA programme. Parallel to this in the NRP project "Variability of North Atlantic Sea Surface Temperature" of Kattenberg (NRP project 850007) the aim is to find adequate procedures to incorporate the mixed layer in an (existing) North Atlantic model (Kattenberg, 1993). This work is further discussed below in Section 2.1.

At longer time-scales variability in the thermohaline processes becomes important. It was shown by Lenderink and Haarsma (1994) that regions can be identified in a simplified N.Atlantic circulation model in which unstable conditions prevail where deep convection may, or may not, occur. So this work in some respects is comparable at basin-scale with the modelling of the large-scale multiple equilibria that may determine the operation of the global "conveyor belt", and it may operate on decadal or centennial time scales. However, it is not about a conveyor belt being "on" or "off", but about the intensity and the regional extension of the deep circulation. The NRP/VvA project NRP project 853134 "Natural variability in a coupled ocean-atmosphere model" (R.J. Haarsma, Royal Netherlands Meteorological Institute - KNMI - De Bilt) continues this work by coupling the ocean model with an atmospheric model for the hydrological cycle and a sea-ice model. The aim is to investigate the natural variability of this system in the range of 10 to 100 years.

Long-term modelling

For long-term modelling the whole ocean and the whole range of interacting processes should be taken into account. The number of Global General Circulation Models capable of this is small. But developing the scientific background, necessary for improving these models is an international task. One activity is the development of small scale process models to be discussed later. An other approach is the development of less elaborate models, with a higher degree of parameterization. These models should be capable of highlighting particular aspects of the modelling of the circulation.

In certain respects the VvA-2 project "Natural variability in a coupled ocean-atmosphere model" discussed above belongs to this category, but this considers more the shorter time-scales. In the VvA-3 project "Stability of the general ocean circulation" (C.B. Vreugdenhil), originally initiated as a part of NRP project 850025 "Ocean circulation and climate" (W.P.M. De Ruijter, Institute for Marine and Atmospheric research, Utrecht - IMAU) a simplified - initially 2-d meridional - model of the ocean circulation is being developed for this type of studies. This model, as the more complex models, shows multiple equilibria. By analysing the structure of the equilibrium model-solutions for different parameterizations in a systematic way the sensitivity for these parameterizations is being investigated. This, for instance, refers to the role of convective adjustment (Section 2.1) and of the atmosphere-ocean coupling. The results thus obtained have to be tested finally in more realistic, 3-d models.

Process models

Mixed layer models. The oceanic mixed layer is an important factor in linking atmospheric and oceanic models. The mixed layer is formed either by convection (during cooling) or by turbulent mixing (by wind stress and current shear). The applicability of the different existing theoretical models appears to be restricted, and the parameterization of the mixing in the usual GCM's is still unsatisfactory. This is one of the problems in the development of coupled ocean-atmosphere models.

In the NRP project 850007 "Variability of North Atlantic Sea Surface Temperatures" (A. Kattenberg, Royal Netherlands Meteorological Institute, KNMI, De Bilt), an explicit Mixed Layer Model was developed. This model was combined with the MPI North Atlantic model, and its performance was tested (Sterl and Kattenberg, 1993, 1994). An improved representation of the sea surface temperatures was found, especially under conditions of wind stirring. However, in the MPI model convection is not treated adequately, and this cannot be cured by the combination with the mixed-layer model. This leads to the conclusion that our understanding of convective processes and their modelling has to be improved. Yet outside the convective regions, in the (sub-)tropics, the introduction of the mixed-layer model shows a more realistic modelling result (6).

A further result is the reduction of errors in the heat flux, and this can improve the sensitivity for climate drift.

Deep convection. Is a small-scale process that yet forms an important link in the global thermohaline circulation of the oceans and therefore should be represented accurately in the climate models. In the North Atlantic the Greenland Sea and the Labrador Sea are important locations for deep convection. Deep convection results from extreme cooling events at high latitudes. To penetrate down to the ocean bottom the water mass formed should (in-situ) exceed the densities at that depth, depending on its thermodynamic properties as determined by the acquired temperature and salinity.

Observations have shown that, before the deep convection starts, a series of processes of different scales are contributing to the preconditioning of the water in the upper layers for a deep convective event (Schott, Visbeck and Send, 1994). An

important stage is the formation of "chimneys" of some 100 meters deep and with diameters of the order of 100 km. These chimneys again are thought to be the result of the formation of smaller-scale (order 100 meters) convective "plumes" (Marshall, Whitehead and Yates, 1994). In this small-scale process the formation of ice and the resulting brine ejection appear to be important.

A problem is that small-scale processes cannot be observed directly in the sea. Conjectures, made on the basis of physical reasoning and founded on tests in laboratory models and by numerical experiments, should finally result in a picture of the process of convection as a whole and a parameterization of this process in GCM's.

In the VvA-3 project "Mesoscale mixing processes and water mass transformation in the Greenland Sea" (H.A. Dijkstra, Institute for Marine and Atmospheric Research, Utrecht-IMAU) the aim is to contribute to a further understanding of the succession of processes. It concentrates on the role of preconditioning by freezing (Dijkstra and Molemaker, 1994, Dijkstra and Kranenborg, 1995) and on the role of differential diffusion of heat and salt (salt-fingering and the formation of "staircases") in competition with plume-formation, and their consequences for the appropriate parametrization of the convective process.

Eddies. In many respects eddies in the ocean are comparable with depressions in the atmosphere. Atmospheric transport of heat and moisture is strongly dependent on the contribution by mid-latitude depressions, and it is therefore probable that, *mutatis mutandis*, this also is the case for the oceanic eddies. However, their size is about one tenth of that of the atmospheric depressions, estimating their effect by measurements is difficult and a model that explicitly takes them into account (eddy-resolving) is very demanding in computing power. The study of the role of eddies therefore is important for the development of oceanic climate models. Their effect is on the circulation pattern and on the transport of heat (and other properties). This role also appears to be different for different ocean regions (e.g. Gill, 1983).

The incorporation of the role of eddies in GCM's by adequate parameterization, is a major task for further ocean modelling. Such a parametrization should consist of the eddy-transport of heat, salt, (potential) vorticity and momentum, and the eddy-induced changes in mean-flow transport of these quantities. A recent parameterization (Danabasoglu, McWilliams and Gent, 1994, Neelin and Marotzke, 1994) accounts for eddy-transport of heat and salt by linear eddies, which is believed to occur along isopycnals with the constraint of no density transport, while at the same time the isopycnal slope is reduced. This parameterization has been shown to improve steady state modelling. However, it does not account for the transport of isolated eddies (rings) and the transport of vorticity and momentum by eddies. Therefore it should be considered only as a first step towards a complete parameterization.

The question investigated in the VvA-3 project "The role of mesoscale eddies in the ocean/atmosphere heat exchange and the meridional heat transport" (W.P.M. De Ruijter, Institute for Marine and Atmospheric Research, Utrecht - IMAU, and G.J. Komen, Royal Netherlands Meteorological Institute - KNMI- De Bilt) is directed to the role of eddies on the heat transport and the consequences for the

parametrization. The exchange with the atmosphere on eddy-scale appears an essential element and is explored in this study. This work extends earlier studies by Drijfhout (1990, 1992, 1994). In the VvA-3 study the role of eddies in a combined isopycnic/mixed-layer model is investigated.

Circumpolar current. The "conveyor belt" scheme of the ocean circulation shows that the Atlantic has to receive surface water from the Indian and Pacific Oceans, that is returned at greater depths. From the Indian Ocean the Atlantic receives water transported by the Agulhas rings, discussed later (Section 2.2). From the Pacific the transport is via the Drake Passage by the Circumpolar Current. The physics of this current have been described by Nowlin and Klinck (1986). By connecting the different (Atlantic, Pacific and Indian) ocean basins it is a critical link in the global circulation. Its study is a central element in the WOCE Core Project 2.

Different models of the Southern Ocean and the Circumpolar Current exist. Eddies play an important role in the dynamic balance. One of the programmes in NRP project 850025 "Ocean circulation and climate" (W.P.M. De Ruijter, Institute for Marine and Atmospheric research, Utrecht - IMAU) is investigating the dynamical balance of the Circumpolar Current and its relation to the Drake Passage transport in an eddy-resolving numerical model. (For the numerical methodology used: see Walsteijn, s.d.). The sensitivity of the current for stratification and windforcing and their role for different sectors of the current are investigated in this model. It appears that there are important variations at timescales of several years.

Assessment

Different reasons can be given for a strengthening of Netherlands ocean modelling effort by the NRP programme. Development of a separate national global general circulation model cannot be the objective: it would be inefficient and unrealistic. Association with one or more of the groups that develop such a model is a more promising option. Further possibilities are those contributing to the international modelling effort, e.g. along the lines of the WOCE modelling strategy (WOCE International Project Office, 1994), or a critical analysis of the modelling premisses.

We note that the NRP project 850007 is done in association with the German MPI modelling development, and that it also is contributing to the mixed layer modelling (especially important for developments at interannual time-scales). The modelling efforts started in NRP project 850025 are more contributing to the last two options mentioned above.

The work in NRP project 850007 has already given interesting results, and in the combination with the MPI modelling has the promise of at least a better understanding of the interannual climate variations in the North Atlantic area. The work on TOGA can be considered as a useful exercise for an area with strong interannual signals. In addition: there are indications that the El Niño phenomenon has certain climatic effects at a global scale (e.g. McPhaden, 1994).

Part of the modelling activities in NRP project 850025 had a late start. They are continued in the VvA-3 programme. Published results are only available on the

model development. A critical systematic analysis of certain modelling approaches is certainly important. The modelling of the Antarctic Circumpolar Current fits with other activities undertaken in the framework of this NRP project project (see below).

Also the NRP projects 853110 and 853134 have been initiated recently. Earlier work on these subjects is promising.

The different modelling projects strengthen the existing Netherlands experience in the field. They follow different lines, but are sufficiently connected to warrant a good overall contribution to the international modelling efforts.

2.3 Ocean observations

In spite of the available oceanographic data the modelling of the role of the ocean in climate change requires a new, high-quality global data set. The WOCE programme is designed to generate this set, and also to provide a basis for long-term monitoring of the ocean and its interaction with the atmosphere. Netherlands observational programmes in the North Atlantic are contributing to the WOCE in-situ data set. Some of these programmes can also provide support for the biogeochemical observations discussed in Section 3.

Furthermore Netherlands efforts in the processing and analysis of altimeter data from ERS-1 and TOPEX-POSEIDON not only contribute to the application of altimetry techniques to oceanography, but also provide information on the actual developments in the southern Oceans.

Direct observations of changes in the ocean require long series of regular data of critical oceanographic parameters. Such observations have a warning function that something is going-on (e.g. the "Great Salinity Anomaly"). Regular observations improve the predictive capability of models by data assimilation. Existing data programmes are only partially useable for these purposes. The number of long-term oceanographic data-series from one location is small, and most are from non-representative coastal seas. Also ocean data sets are needed for initialisation and validating of ocean models. At present the available oceanographic data (those stored in data centres and screened) that are our source of information are not adequate. The Levitus data set (Levitus, 1982) is often used, but it has not the quality that is needed in many cases. The WOCE hydrographic programme has the purpose to create a better and more "synoptic" data-set of the actual conditions and to support the development of a more permanent observational system (GOOS: Global Ocean Observing System, and GCOS: Global Climate Observing System). Also TOGA is generating a contribution to such a system. Efforts are now underway to set-up an adequate system for this purpose on an international basis. (Ocean Observing System Development Panel, 1993).

The scientific background of the WOCE observational programme, edited by the WOCE International Planning Office (1988), formulates in detail the different components in the different "Core Projects". The whole programme is the most extensive observational effort in oceanography and with the available means it only can be accomplished within a number of years: between 1990 and 1997. It also has been agreed that programmes in the framework of WOCE can support JGOFS activities and vice-versa, by offering facilities for observations. It also is

clear that the detailed WOCE observations offer a physical framework for different biogeochemical studies.

In view of the variability of less than 10 years a programme of repeated sections, fixed stations and regular XBT programmes is planned to resolve these time scales. In addition the satellite data are used. The altimetry of the sea-surface is particularly important in this respect. The observations from the ERS-1 and TOPEX-POSEIDON satellites form an essential contribution to the WOCE programme. They provide a high-density (space and time) picture of oceanic variability that, together with the in-situ observations gives a fairly complete picture of the ocean circulation. The accuracy expected from these satellites is adequate for the identification of the main oceanographic processes. Earlier (Geosat) data already show the potential of these observations in regions with strong sea-level signals.

Different programmes in the framework of WOCE Core Project 3 in the North Atlantic have a Netherlands contribution. As to altimetric observations from satellites, this is being stimulated by the Netherlands Space Research Foundation (SRON). This contributes to a fruitful co-operation between experts in satellite altimetry and oceanographers from Delft and Utrecht Universities, and it has resulted in application of these techniques from Geosat, and, more recently, ERS-1 and TOPEX-POSEIDON (see Haagmans, Naeije and Feron, 1993) to oceanographic studies of the Southern Oceans (WOCE Core Project 2).

The Southern Ocean

The planning of the Southern Ocean programme of WOCE (Core Project 2) started in 1987 (Anon., 1987). The observations should be directed to the Antarctic Circumpolar Current, including interbasin exchange, the meridional transport, including that in and out of the Southern Ocean, and the ocean-atmosphere fluxes. Especially for this area, with its vastness and difficult environmental conditions, satellite data are very important.

The exchange between the Indian and the Atlantic Oceans south of Africa appears to be an involved process. The dynamics of the Agulhas Current, that runs westward south of the Cape, are important in this connection. Most of the transported water retroflects eastward, but large rings shedded from the current transport water to the south Atlantic. Estimates of this transport, its variability and understanding the dynamics of the shedding process are necessary elements in the modelling of the global circulation.

As one of the sub-projects in the programme (NRP project 850025) "Ocean Circulation and Climate" (W.P.M. de Ruijter, Institute for Marine and Atmospheric Research, Utrecht - IMAU) an analysis was started of satellite data from the Agulhas retroflection, for a better description of the meso-scale processes occurring. Originally working with Geosat data techniques have been developed that allow to extract the characteristic spatial and temporal scales of the currents in this region. The large warm eddies that are formed in the Agulhas retroflection area and their movement to the northwest can be observed (Feron, 1992). This results in a better description of the ring shedding process (Feron, De Ruijter and

Oskam, 1992). The analysis of the altimetric data applied was compared with results from the FRAM model (Feron, 1993, 1994a, 1994b).

A further phase of the programme is to investigate the relation between the formation of the rings and other variations of the Agulhas system (De Ruijter, Van Leeuwen and Lutjeharms, (submitted), Van Leeuwen and De Ruijter, (submitted). For this continued work the new results from the ERS-1 and TOPEX-POSSEIDON missions are available. The higher accuracy and higher resolution of these data enlarges the possibilities of satellite altimetry for this work.

The North Atlantic

For the oceanographic changes in the Atlantic the WOCE Core-project 3 ("Gyre dynamics") provides the framework. An important aspect here is the interannual variability. At basin-scale the circulation in the North Atlantic is composed of a Sub-Tropical (anticyclonic) and Sub-Polar (cyclonic) Gyre. In the Sub-Tropical Gyre water that has exchanged properties with the atmosphere is subducted in the permanent thermocline, to be transported as "18° Water" and "Sub-Polar Mode Water" over periods of several years around the Sargasso Sea until surfacing again in the extension of the Gulf Stream, when the cycle may be repeated, or crossing-over to the Sub-Polar Gyre takes place. In the Sub-Polar Gyre the water is gradually conditioned by cooling until deep convection is realised.

Recent provisional results of this part of WOCE show that there is a warming of the upper 3000 m over the past 35 years, and cooling below 3000 m in the subtropics (Parilla et al, 1994), while marked variations in the conditioning in the Sub-Polar Gyre have been found by Read and Gould, 1992. It is clear that such changes at decadal time-scales have to be modelled adequately before one can hope to predict climate changes over such periods.

In the deeper parts of the North Atlantic deep water masses flow southward as part of the long time-scale ("conveyor belt") circulation.

Regular observations of the variability of the oceanic structure between Europe and the Antilles (Sub-Tropical Gyre) have been made since 1991 in the VvA-3 project "Repeated XBT sections and analysis of variable meso-scale structures in the N. Atlantic in the framework of WOCE" (L. Otto, Netherlands Institute for Sea Research - NIOZ - Texel). This is a co-operative programme of the Royal Netherlands Navy and the Netherlands Institute of Sea Research (NIOZ).

These observations can be used to estimate the variability in the subduction and in the transport by a branch of the Sub-Tropical Gyre (Azores Current), and provide information on the structure of the Mediterranean outflow (De Bruin et al, 1992).

In the "DUTCH-WARP" programme financed by the former SOZ ("Stichting Onderzoek der Zee" or Marine Sciences Foundation) observations have been made to describe and quantify the circulation in the eastern part of the Sub-Polar Gyre, where the main transport to areas of deep convection takes place. In this framework also drifters have been released (Otto, Van Aken and de Koster, 1992), and this part of the programme is continued as the VvA-3 project "Determination

of the current field and the diffusivity in the NE Atlantic with ARGOS drifters in the framework of WOCE". As a result the picture of the circulation and of the eddy kinetic energy in this part of the Sub-Polar Gyre is improved (Otto and Van Aken, submitted).

As part of the "DUTCH-WARP" programme also the deep circulation and especially the overflow from the Norwegian Sea across the Scotland-Faroe-Iceland Ridges was observed. This overflow is an important element in the deep return branch of the "conveyor belt" circulation. Both long-term current measurements (Van Aken, 1993) and hydrographic analysis (Van Aken, submitted) are used to evaluate this circulation and its variability (De Boer, van Aken and Van Bennekom, 1991, De Boer, 1993).

Assessment

Next to the various modelling activities reported above, good ocean data are necessary. Therefore a substantial support from the Netherlands to the programme of WOCE observations is important for international research. Although not incorporated in the NRP-1 programme, such a contribution to WOCE is partly being made via the VvA-3 programme. As the WOCE programme and subsequent observational or monitoring programmes need contributions from many countries, a continued Netherlands contribution in the framework of NRP and/or VvA certainly has its place. This also supplements the biogeochemical programmes in the oceans.

For the past period the NRP support in NRP project 850025 to application of satellite altimetry to the observation of the Agulhas retroflexion has resulted a number of publications that give valuable oceanographic information. Moreover the development of experience in oceanographic applications of satellite altimetry is important for future monitoring of the oceans in relation to the Global Climate Observing System.

It is desirable to consider a further focussing of the observational programmes (including regional JGOFS programmes, see below) to areas of common interest. Application of altimetry to the eastern North Atlantic now appears to be possible with the higher-accuracy satellites, and the southern oceans are of special interest to JGOFS. Also in view of the modelling activities in the North Atlantic and the Southern Oceans this could result in an effective exchange of experience and ideas between Netherlands oceanographers.

2.4 Ocean-atmosphere interaction

Our limited knowledge of the exchange between ocean and atmosphere is a problem for climate studies. Higher-quality observations are necessary and a better understanding of the physics of the exchange processes. Satellite data are becoming more important for estimating global ocean-atmosphere exchange.

A "stand-alone" ocean model (such as are found in long-term modelling) is constrained by prescribed conditions at the ocean-atmosphere interface. If realistic values of the wind stress and of the fluxes of moisture and heat can be given, the model performs according to its inherent quality. However, the estimate of the wind stress and the fluxes of moisture and heat is still a major problem, because of the wide range of spatial and temporal scales involved, and the

inadequacy of observations. The first task is therefore to improve these estimates. In WOCE accuracies of 10 W/m² are sought in estimates of the mean heat flux components, averaged over monthly and longer time-scales, of 1 mm/d in evaporation and precipitation and of 10% or at least 0.01 Pa in surface stress (WOCE International Planning Office, 1988). This has to be accomplished by optimizing the regular meteorological observations. Application of satellite data that are matched with in-situ data, and data-assimilation procedures are further ways of improvement.

For estimates of the water budget direct observations over the oceans are too inaccurate to be used. Only indirect estimates are available. For a comparatively well-known area such as the North Atlantic estimates of the total evaporation minus precipitation differ by several times the Amazon run-off (Schmitt and Bryan, 1991).

Satellite data are translated into physical quantities with algorithms that formulate the relation between observed values and the values sought-for. These algorithms as a rule are derived from process-models based upon micro-meteorological observations. In this way small-scale local studies are important for obtaining reliable large-scale global results.

The availability of good facilities to study air-sea interaction processes (observation platform, flume) and the experience in modelling air-sea interaction is a basis for Netherlands contributions to these problems. The different programmes in this field are discussed below. It is logical that the field programmes also incorporate observations of the chemical fluxes. The physical observations are also needed for the interpretation of the chemical fluxes (see Section 3.1).

Small-scale interaction

The VIERS-1 programme that aims at developing algorithms for obtaining wind stress data from scatterometer observations has been running since the eighties. It is a joint programme of a number of Dutch and foreign institutes in the course of which a number of field experiments have been conducted at the open sea research platform "Meetpost Noordwijk".

In connection with this programme a NRP programme (NRP project 850005) "VIERS-1 (Preparation Interpretation ERS-1) field experiment". (W.A. Oost, Royal Netherlands Meteorological Institute - KNMI - De Bilt) was performed in which, besides the fluxes of momentum, sensible heat and water vapor, also the flux of carbon dioxide was measured, using the eddy-correlation technique. The CO₂ flux measurements by eddy-correlation are difficult to make, but valuable experience was obtained and this resulted in the subsequent ASGASEX experiment (further discussed in Section 3.3).

The other observations result in a set of data of the relevant physical parameters under a variety of conditions.

An important aspect of the project is that the flow-distortion by the Noorwijk platform has been carefully studied. This has resulted in the characteristics of this distortion being well-known, which adds to the value of this platform among the few facilities for all kinds of flux measurements by eddy-correlation techniques. (Oost, 1994, Oost et al., 1994)

Large-scale observations

The assessment of large-scale fluxes between ocean and atmosphere (necessary for using coupled models), remains a considerable problem, as the necessary meteorological and oceanographic data cannot be obtained in the conventional way. The distribution in time and place of observing in-situ platforms never will be adequate to obtain the necessary resolution in space and time. Only remote-sensing data, combined in data-assimilation schemes with large-scale numerical models have, in principle, this capability.

Experience in wave-modelling has given an important contribution to the development of data-assimilation techniques for estimating the momentum flux at a global scale from satellite (scatterometer) data. In a joint programme with the ECMWF (European Centre for Medium-Range Weather Forecasts), supported by the Netherlands Remote Sensing programme (BCRS), this has already resulted in good-quality wind-stress fields over the oceans. (Janssen, 1994). In the VvA-2 project "Assimilation of wind and wave data to produce global flux fields" this approach is being developed further.

Assessment

The NRP project 850005 is a limited project, mainly a precursor of the ASGASEX project (Section 3.1). The work on small-scale physical exchange is part of a long series of similar experiments that in different ways have contributed to understanding the interaction processes close to the sea surface. Adequate parameterization of these exchange processes depends on good-quality observations of the small-scale processes just above the sea surface under a variety of meteorological conditions. Because of the technical problems connected with the study of air-sea exchange processes expertise is restricted to a few groups. The facilities in the Netherlands are an important factor for maintaining this expertise. Support of the use of the Noordwijk platform for solving the different air-sea interaction problems in the field of climate research is a recommendable course.

3. BIOGEOCHEMISTRY OF THE OCEANS

3.1 Introduction

Reducing the error-bars in the global CO₂ budget needs a co-ordinated oceanographic research programme. In JGOFS such an effort is undertaken at international level. Also the role of the ocean in the production of N₂O and DMS is believed to be important. The expectation that complex biogeochemical interactions with physical conditions can be an important factor that regulates climatic change makes a better understanding of the biogeochemical system necessary. An approach at such a better understanding for one (model) organism (*Emilianya huxleyi*) is undertaken in the GEM.

The oceans are an important reservoir for CO₂ that can act as a source or a sink for the atmosphere. The budget is evaluated in terms of the carbon flows and storage. Different fluxes and reservoirs can be defined in this budget. The exchange of carbon (as CO₂) is with the surface layer, and between the surface layer and the

deeper parts of the ocean direct transport of dissolved inorganic carbon takes place by a localised process of deep convection downward and a more ocean-wide process of upward movement across the permanent thermocline. In addition, however, biogeochemical processes play a role ("the biological carbon pump") by the production of organic carbon (dissolved and particulate) and of particulate calcium carbonate. The downward transport of dissolved organic carbon appears negligible compared with that of the inorganic carbon. However, the biological processes are important by their production of particulate material. This particulate carbon sinks down, the organic carbon to be remineralised in the deep ocean, the calcium carbonate to be partly dissolved, but partly deposited on the ocean floor. These processes should have their place in models of the carbon cycle.

Estimates of the uptake of carbon by the oceans of the increasing CO₂ burden recently have been reviewed by Siegenthaler and Sarmiento (1993). Using more or less complex box models with their mutual exchanges (recently also GCM models) and suitable tracers (radiocarbon) estimates of the net oceanic uptake of carbon result in about 2 GtC/y. However, the error bars of these estimates are comparatively large. They depend on the models for the global carbon cycle discussed above.

Improvements can come from better and possibly more detailed models and from better constraints, such as regional differences in ocean/atmosphere fluxes. Presently the estimates of these fluxes rely on a restricted data-set for the CO₂ partial pressure difference atmosphere/water and there is much activity to improve this by the present programme of observations. Also observations of the atmospheric oxygen content can give additional means to constrain seasonal models (Keeling and Shertz, 1992). These models should form the starting point for longer-term budgets.

Once a model is obtained, it is possible to estimate the development of the atmospheric CO₂ concentration with time for different scenarios, as done in the IPCC report (Watson et al., 1990). A further application is to investigate the possibility of feedbacks. This asks for more details in the parameterization.

For instance, a long-term gas exchange coefficient, relating the flux and the partial pressure difference may be wrong for changed climatic conditions. To assess this, one has to turn to the basic micrometeorological processes, that presently give values for the exchange coefficient differing considerably from the coefficient presently used. Although the difference between short-term and long-term values may offer (partly) an explanation for this, a further investigation of this problem appears appropriate.

For the scenario-studies the role of biota on the carbon budget is not explicitly taken into account. It is assumed that changes in different marine biota do not critically depend on changed carbon concentrations, but rather on nutrients (nitrogen, phosphorus and silicium), light and the physical environment (although this assumption remains under critical scrutiny). However, this being so, the changes in climate may result in changes in biota and this can result in feedbacks that could be important, also because in a biological system different opposing feedback mechanisms could occur.

The task to solve the most important problems of the biogeochemical role of the oceans in the climate system is considerable. JGOFS (Joint Global Ocean Flux Study) is the main programme to solve these problems by an international approach.

JGOFS has the goals (Anon., 1990):

1. To determine and understand the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.
2. To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

For this JGOFS is concerned with the development of models and with an observational programme, consisting of a mixture of global surveys and process studies, measurements of fluxes between atmosphere and ocean, with benthic sediments, and between the oceans and coastal regions. In addition palaeoceanographic studies have to contribute to the understanding of the carbon cycle in the geologic past. Netherlands scientists have been involved in JGOFS right from the beginning (De Baar et al., 1989).

The relation between the carbon cycle in the oceans and the production of biogenic products closely links the different biogeochemical studies for N_2O and DMS with the JGOFS programme.

A complicating factor is that the uptake of CO_2 and the production of other greenhouse gases and DMS are the result of concurring biogeochemical processes and that the mutual relation between these processes can be fairly different for different organisms. This indicates that there are limitations to large-scale modelling that is not taking into account such idiosyncrasies. Therefore another, in principle complementary approach is that of the Global *Emiliana* Modelling Initiative (GEM) a co-operative programme of different scientists involved in studies of the pelagic alga *Emiliana huxleyi*. GEM concentrates on the biogeochemical role of this one significant organism, with the objective to evaluate its present and past climatic relations and its role in the different chemical budgets.

The GEM research strategy is that of process studies and modelling at different scales, from the biomolecular to the global level (Westbroek et al., 1993)

3.2 Chemical exchange ocean-atmosphere

The chemical exchange between ocean and atmosphere is driven by the partial pressure difference of the gases near the sea surface and in the atmosphere. For assessment of the chemical fluxes more data are needed on a world-wide scale, but it is also important that the exchange processes are better understood. The data, as constraint on the modelling of variations of atmospheric greenhouse gases, can give better estimates of the oceanic fluxes.

Direct (micrometeorological) measurement of the exchange of chemicals between ocean and atmosphere is difficult, and certainly not feasible as a routine observation. The estimates of chemical fluxes depend on parameterizations. From

the difference of partial pressure, near the sea surface and in the overlaying atmosphere, D_p , the flux is estimated, using a transfer velocity K_g . This parameter appears to depend on the wind speed, and on the specific mass of the gas exchanged, expressed in a Schmidt number. Two often used parameterizations are those of Liss and Merlivat (1986) and of Wanninkhof (1992). The uncertainty in these parameterizations is about a factor 2.

There are considerable discrepancies between large-scale fluxes of CO_2 based on geochemical modelling and estimates of fluxes from the few direct measurements. (Broecker et al., 1985; Smith and Jones, 1986; Wesely, 1986). This brings to the questions whether some of the implicit assumptions in the models are applicable, and about the accuracy and generalisation of direct measurements, and illustrates the need for systematic measurements of $\Delta p\text{CO}_2$ and for reliable values of K_g .

In the programme (NRP project T 850021) "CO₂ exchange ocean/atmosphere" (H.J.W. De Baar, Netherlands Institute for Sea Research - NIOZ- Texel), later in VvA-9 continued as "Carbon budget in the oceanic mixed layer and air/sea exchange" measurements are made on transects across the (South) Atlantic and Antarctic waters. They constitute an important amplification of the existing datasets. Together with other data these observations can improve the estimate of the exchange of CO_2 over those sea areas (Bakker and De Baar, 1992). First results indicate that these areas are an important sink for CO_2 .

The methodology for measuring the partial pressure (equilibrator system) is important also for the measurement of partial pressure of other greenhouse gases (see Section 3.2).

The parameter K_g stands for a complex exchange process in which meteorological conditions (especially the wind) and the state of the sea play their role. In fact the problems that are encountered in estimating the fluxes of heat, moisture and momentum, discussed in Section 2.3, all are met again in estimating the chemical fluxes. The value of K_g for different gases and its dependence on the external conditions are therefore still under dispute.

For other greenhouse gases the problems are the same. For the N_2O emission from the sea (see "Water-atmosphere exchange of N_2O in marine systems, NRP project 850027) the estimates are also based on $\Delta p\text{N}_2\text{O}$ measurements and a K_g parameter. The dependence of this parameter on the wind is a critical factor in upwelling areas where N_2O concentrations are high and winds are strong.

For DMS flux measurements were made in enclosures, in the framework of the NRP project "Formation and air/sea exchange of DMS from marine sources" (NRP project 850026). These measurements indicate agreement with theoretical values of the fluxes for lower wind speeds, but larger fluxes than theoretical at stronger winds.

The flux-measuring programme (NRP project 852082) "ASGASEX" = Air Sea GAS EXchange (W.A. Oost, Royal Netherlands Meteorological Institute, KNMI, De Bilt) is designed to improve the parameterization as described above. In the Dutch research platform "Meetpost Noordwijk" facilities are available for

micrometeorological flux observations, and they serve not only to investigate the physical (see Section 2.3), but also the chemical fluxes. Different research groups from various countries are working together, performing measurements of a broad scale of micrometeorological and oceanographic measurements.

Via the eddy-correlation technique measurements are made of the CO₂ fluxes. A large difficulty here is the accurate measurement of the fluctuating CO₂ signal.

Comparison of estimates from the ocean-atmosphere pressure difference with the results of the eddy-correlation measurements indicates that the thickness of the layer over which the pressure difference $\Delta p\text{CO}_2$ (and on which the K_g parameter is applied) is rather critical. A similar point is the evaluation of the skin effect discussed by Robertson and Watson (1992).

Another micrometeorological method is to measure the gradient of gas concentration in the layer of air directly above the water. Combination with the projects NRP 850021 and NRP project 850027 (for CO₂ and N₂O respectively, see above and Section 3.2) gives the possibility to apply this method and to compare different estimates. Also for DMS, be it not on occasion of ASGASEX the gradient method was attempted.

Assessment

Systematic collecting of $\Delta p\text{CO}_2$ data in the framework of JGOFS is an important point in the evaluation of the greenhouse-gas problem, and the NRP project 850021 forms a direct contribution to this effort. Results of this project are interesting in highlighting the importance of the southern ocean in the CO₂ budget.

For future modelling it will become important to obtain better insight in the physics of the exchange processes, but accurate data are difficult to obtain. By supporting the ASGASEX measurements (NRP project 852082) NRP contributes to developing techniques for direct flux measurements, using facilities that are very suitable for this purpose. The co-ordination with the projects for CO₂ and N₂O (NRP project 850021 and NRP project 850027) provides a basis for valuable results. In case of further exchange measurements also co-ordination with possible future DMS exchange studies is to be considered.

3.3 Greenhouse gases and DMS

The role of the oceans as a sink of anthropogenic CO₂ is one of the most important issues in the oceanographic climate research. The JGOFS programme that focuses on this problem from the beginning received substantial Netherlands support. The role of biological systems (especially of the "biological pumps") is studied in JGOFS by exploring different "biogeochemical provinces" in the ocean.

Biological processes also are responsible for the role of the oceans as a source of N₂O and DMS. No special international programmes have been organised for these items. But the N₂O programme is closely linked with JGOFS, while for the DMS research at national level a programme has been organised within NRP that covers most aspects of its production.

The CO₂ system

At short terms only the uptake of excess CO₂ in the upper layers of the ocean is significant. But over longer periods the transport of excess of dissolved carbon to sub-surface layers becomes important. This transport, by convection and by the action of the marine biota that act as a carbon pump transferring particulate carbon to deeper waters cannot be neglected in a balanced approach also considering other possible variations and long-term feed-backs.

The role of the biological "pumps" is an important JGOFS issue. Various factors: nutrient concentrations, light, water stratification and zooplankton grazing are the classical agents regulating these pumps (although further studies on other factors as availability of iron, concentration of CO₂ still are required). These factors again, including nutrient concentration, are determined by physical processes (e.g. upwelling, watermasses, etc.). In JGOFS different "biogeochemical provinces" are defined that primarily depend on the physical forcing functions. It will be clear that one of the possible feedback mechanisms is a shifting of these provinces. Therefore process studies are planned for these different provinces on which models are to be based of the shorter-term developments. At the other hand remote sensing has to expand the local and regional results to global scales, together with a programme of large-scale surveys from ships of opportunity, from fixed stations and by joining WOCE campaigns, etc. Furthermore a benthic programme should link the JGOFS results with palaeo-oceanographic work. Right from the beginning the Netherlands have played an active role in JGOFS. Since the start of the NRP and VvA programmes additional work in the framework of JGOFS has been supported.

The Netherlands VvA-9 programme ("Carbon budget in the oceanic mixed layer and air/sea exchange") is now the core of the Netherlands participation in JGOFS. Yet a brief survey over the JGOFS participation should not be limited to NRP and VvA alone.

In 1989 the first North Atlantic Pilot Study took place, and since a programme started in the Southern Oceans and in the Indian Ocean. These programmes were supported by the Marine Science Foundation (SOZ) of that time. Below they are discussed below separately.

The regular observations of CO₂ partial pressure in the South Atlantic that now are part of the VvA programme (but that started as NRP project 850021) have already been discussed in Section 3.3. Their contribution to an assessment of the role of the southern oceans to the global carbon budget is an important element of the JGOFS implementation.

Process studies aim at the evaluation of parameters that are required in models for the biogeochemical state of the ocean. We note that within the *Emiliania huxleyi* project of Section 3.3 (NRP project 850003) a number of studies is made that are directly relevant as JGOFS process studies. Two of the four processes of transport of carbon from the surface waters to the deep sea, the processes of settling of particulate organic matter (1) and of calcium carbonate (2) are being investigated in the *E. huxleyi* project. To the study of the downward transport by the ocean circulation of dissolved CO₂ (3) and organic carbon (4) by the ocean circulation contributions are made in the VvA-9 programme.

Actual observations made with sediment traps at different levels (Van Hinte and co-workers) produce figures of the fluxes of particulate carbon (1 and 2) and of the transformation processes in- and outside the euphotic zone. Sediment cores relate the actual fluxes with conditions in the geologic past.

Special attention is given to the transport of dissolved organic carbon in the VvA-9 programme "Distribution, chemical composition and isotopic ratios of dissolved organic carbon in the ocean". The methodology for the concentration measurements of organic carbon has been investigated by De Baar et al. (1993). The values for dissolved organic carbon and dissolved organic nitrogen appear to be much higher than previously measured. For the organic carbon found in oceanic sediments an important question is their provenance: are they of marine or terrestrial origin. In the framework of this VvA programme this is investigated by means of certain biomarkers.

Also in the framework of the VvA-9 programme a study is undertaken on "The partial pressure of CO₂ in seawater as a control on marine biological productivity and calcification". This study investigates in how far the principle that in the sea (in contrast to conditions on land) CO₂ partial pressure should be unimportant in regulating the phytoplankton growth (see above) is to be amended. Also this programme is directly related to the *E. huxleyi* project (Section 3.3) because of the opposing effects by photosynthesis and calcification on the CO₂ partial pressure accompanying *E. huxleyi* blooms.

The JGOFS North Atlantic studies. The international JGOFS Pilot Study in 1989 had as scientific objective the understanding of the evolution in time of the spring bloom: the mechanisms for its generation, maintenance and decay. The main part was by multiple-ship (Canada, FRG, Netherlands, UK, USA) observations along a 20°W section between March and October. An important aspect of the North Atlantic is the transport of water to the source areas for deep convection, and thus for transport of dissolved carbon to the deep ocean. Also during the DUTCH-WARP programme (see Section 2.2) additional observations were made that resulted in estimates of the transport of dissolved inorganic carbon in the Iceland Basin. Plans for future North Atlantic JGOFS programmes are being considered.

The Netherlands participation to this programme, with support from the SOZ (Marine Science Foundation) of that time, has resulted in a number of publications (De Baar et al., 1993, Veldhuis, Kraay and Gieskes, 1992, Stoll et al., 1993, Stoll, 1994).

The JGOFS Indian Ocean studies. The northwest Indian Ocean is a biogeochemically important area because of the strong seasonal monsoon variations. In the framework of the Netherlands Indian Ocean Expedition with the RV Tyro of 1992/93 (organized by the SOZ-Marine Science Foundation) a number of exploratory studies was made for the JGOFS studies that are planned from 1994 onwards.

In Section 3.2 results of N₂O and methane observations from this programme are discussed.

The JGOFS Southern Ocean studies. This programme started in 1992 with cruises of the RV Polarstern (FRG) and Discovery and James Clarke Ross (both UK) to be followed in 1993 by cruises of the RV Marion Dufresne (France). Netherlands scientists participate in these expeditions, with the objective to quantify the spring plankton bloom. This work continues earlier work in the framework of the EPOS (European Polarstern Study) of 1988 (Lancelot et al., 1991, Lancelot, Veth and Mathot, 1991).

Recently it was found that dissolved iron is crucial in developing plankton blooms in Antarctic waters and thus cause CO₂ undersaturation of surface waters (De Baar et al., 1995).

Other greenhouse gases

The study of the production of other greenhouse gases by marine biota logically is closely connected with the JGOFS programme. Estimates of the oceanic input as a rule are based on the principles discussed in Section 3.1. The available data are subject to improvements of the parametrization of the sea-atmosphere exchange. The most important oceanic contribution of the other greenhouse gases (excluding water vapour) is nitrous oxide. In the IPCC report (Watson et al., 1990) an estimate is given of the oceanic input of 1.4 - 2.6 Tg N per year, on the basis of an estimated gas exchange coefficient and available data of the difference in partial pressure near the sea surface and in the atmosphere. But we note that regional and temporal variability in the oceanic concentrations make an estimate difficult. Two microbiological processes produce N₂O in the open oceans: nitrification by oxidation of ammonium in an aerobic environment, and denitrification by reduction of nitrate and nitrite in an anaerobic environment.

The former conditions occur in large parts of the oceans, but most intensively in upwelling regions, the latter occur only in special, often restricted regions. Upwelling and the occurrence of anaerobic conditions in the ocean are very sensitive to climatic variations. This indicates the possibility of feedback between N₂O input from the oceans and climate change.

Improving our estimates of present production and our insight in possible feedback mechanisms asks for the study of N₂O production in different environments. In the NRP project 850027 programme "Water/atmosphere exchange of N₂O in marine systems" (W. Helder, NIOZ) observations of N₂O are made together with other relevant oceanographic observations (hydrographic structure, oxygen concentration) in different marine environments. These include the Somali basin (upwelling region) and the northern Arabian Sea (low-oxygen conditions), both in the Indian Ocean, and in different locations in the North Sea and Netherlands coastal waters.

Earlier findings that indicate the NW Indian Ocean as a significant source of N₂O (Law and Owens, 1990) could be confirmed. Upwelling waters were found to be important sources.

Coastal waters (Scheldt estuary) can be an important source in local N₂O budgets. The input into the atmosphere from the North Sea does not differ from the global average.

Parallel to the N₂O observations observations of methane are made. According to IPCC estimates (Watson et al, l.c.) the oceans "are thought to be a minor source of atmospheric CH₄. However, the estimated flux of CH₄ from the oceans is based on a limited data set, taken in the late sixties/early seventies when the atmospheric concentration of CH₄ was about 20% lower. There are inadequate recent data from either the open oceans or coastal waters to reduce the uncertainty in these estimates". For this reason the newer CH₄ data give an opportunity to check the IPCC estimates.

DMS

The role of oceanic-produced DMS in the climate system is that it is a source of cloud condensation nuclei (CCN) and so may influence the cloudiness. This especially holds for conditions over the oceans: the atmospheric lifetime of most sulfur compounds is limited, and over the oceans the role of other sources of CCN is less important. The different aspects of changes in the concentration of CCN on the formation of clouds and on climate are discussed elsewhere (See: Guicherit, Assessment Report subtheme "Atmospheric processes & UV-B radiation", this volume). Here we discuss the production of DMS in surface waters by marine plankton, its exchange with the atmosphere, and the question whether these processes can be at the basis of a feedback mechanism as suggested by Charlson et al., 1987).

Estimates of the input of DMS (as Tg S per year) is 10 - 50 (Table A1.10 in Watson et al., 1992). Because of the large variations of concentration of DMS in place and time these estimates are rather uncertain. The concentrations in the ocean are related to the variable biological activity, and the process of formation depends on the dominant phytoplankton species and on the chemical transformations in the water. This means strong variations of DMS production in time. Also the relationship between dissolved DMS and chlorophyll concentration is not unique, and the possibility to make concentration estimates of DMS in water by means of remote sensing of chlorophyll still has its uncertainties. If by future RS methods it might be possible to discriminate between various organisms, and when we have gained further understanding of their production of DMS, this might change.

The production of DMS by different algae and at different stages of their growth cycle is a first step in the assessment of their role in the process. A review of this subject has appeared by Liss, Malin and Turner (1993).

In the project "Formation and air/sea exchange of DMS from marine sources" of Guicherit (NRP project 850026) the objectives are to assess (1) the processes and rates of production of DMS and its precursor DMSP, and (2) the processes of their degradation and transformation in the water column and by sediments, and (3) to estimate the fluxes to the atmosphere (Guicherit, 1993). This project is also assessed in the framework of the subtheme "The Climate System".

The work is being done in cultures, boxcosms and enclosures, but also field measurements are made to be compared with production models. As *Emiliania huxleyi* is an important producer of DMS there is a link with the work described in Section 3.3. However, the work also is directed to *Phaeocystis*, also an important producer of DMS, and frequently blooming in Dutch coastal waters. As both

organisms play a different role in the carbon fixation and concurrent DMS production, their climatological significance is expected to be different.

As the project has shown, only a fraction of the in-situ production of DMS(P) enters the atmosphere, in fact less than thought before. The production is mainly during blooms and in view of the rather short atmospheric lifetime of sulfur compounds, DMS presently might be more a factor of regional than of global climatic significance. However, in the conclusions of the assessment for "The Atmosphere" it is suggested that: "... minor changes in the bacterial and phytoplankton population density or composition could have pronounced effects on the global S budget, with all of its consequences". There appear to be reasons for further study of the DMS problem in the context of climate change.

Assessment

The different projects in this group (NRP project 850021, NRP project 850027 and NRP project 850026) are closely connected, and also results of the *E.huxleyi* project (NRP project 850003) can be considered against the background of the study of the systems of carbon and DMS in the sea. They contribute in different ways to the Netherlands JGOFS participation.

The methodology for measuring the concentrations of dissolved gases in (sea)water with the equilibrator technique could be implemented via NRP project 850021 and NRP project 850027 and is available now for continued work. Combination of the different programmes resulted in common data sets, important for the study of the different systems.

The work in NRP project 850027 produced new data for the study of the production of N₂O by different marine environments. Values for the transport of particulate carbon to the deep sea are being obtained in NRP project 850003 as the result of the *E.huxleyi* programme, but they are of direct relevance to JGOFS.

Apart from the judgements given for NRP project 850026 in the assessment report by Guicherit, we may state that here the study of the DMS system from its production at microbiological level to its role in the formation of cloud condensation nuclei has brought together quite different research groups.

3.4 The phytoplankton system

Studying the biogeochemical interaction with climate of one organism is an approach that is different from the JGOFS approach, although in actual research there is a considerable overlap. In an international group of investigators *E.huxleyi* was chosen as the object of this approach (Global Emiliania Modelling Initiative). This organism is important both for the CO₂ exchange and for DMS production.

The biochemical investigation of the role of the oceans in the budget of CO₂ and some other greenhouse gases and as a source for DMS primarily is of interest in an evaluation of the present-day conditions and in the assessment of their development for reduction policies. But also these investigations will provide more insight in the possibility of feedback mechanisms that can be expected and that, judging from palaeoclimatological evidence, appear to have acted in the past.

The JGOFS approach, as described above, is to establish global values and global relations by considering large-scale biogeochemical provinces. To what extent the critical feedback mechanisms thus can be described adequately remains a question that only can be answered in the long run.

A different approach is an organism-centered approach. The NRP-supported project 850003 "Phytoplankton and the oceanic carbon cycle; *Emiliana huxleyi* as a model system" (Westbroek) takes this approach. The philosophy is that by considering separate phytoplanktonic organisms that play an important role in the biochemical transformations the interactions can be evaluated better. This philosophy is tested on the coccolithophore *Emiliana huxleyi* in the co-ordinated studies of the GEM ("Global *E.huxleyi* Modelling Initiative"). This organism contributes significantly to the biological pump by producing coccoliths, small calcium carbonate shells that during blooms can occur in huge quantities that can be observed on remote-sensing images. At the other side it is an important producer of DMS (Westbroek, 1992, Westbroek et al., 1993).

The programme consists of studies of the biochemistry at cellular level, experiments in the laboratory and in enclosures, and open-ocean studies. Remote sensing and geological observations add a global and palaeoclimatological dimension. The study aims at modelling of the system at various integration levels (cellular, population, global levels). By the choice of *E. huxleyi* an organism is selected that has a wide distribution and has existed for a long geological period. Results of the programme therefore are applicable not only under actual, but also under palaeoclimatological conditions. Further palaeoclimatic implications of this work come from the discovery that long-chain alkenones found in marine sediments and that are likely to come from *E. huxleyi*, reflect the growth temperature of the organism.

This programme and the studies of the CO₂ system and of the DMS production are interlinked: coccolithophores rank high as DMS producers. Results of this programme can be considered, together with other results, in the relevant earlier Sections 3.2 and 3.2. The organism-centered approach discussed here should reveal the important interconnections between different parts of the carbon budget, the DMS production, and possible other relevant factors.

Emiliana huxleyi is chosen to represent calcifying plankton in general. These organisms have their typical role in climate-related processes. Furthermore they are special in that their growth may be limited by the inorganic C supply in the surface waters.

Blooms of *E. huxleyi* can be observed by remote sensing, and appear to have mainly an effect on a regional scale, compared with standing-stock estimates (Brown and Yoder, 1994). They exhibit a special succession in the various carbon fluxes. Their net effect is likely to be strongly non-linear. How to parameterize the standing-stock and bloom effects further can be clarified by the *E. huxleyi* project. The production of DMS and the carbon cycle are biologically related. For typical organisms this relation has to be established.

Summarizing: The effect of these studies is twofold: First the dynamism of this system can be better understood. Also the methodology of this approach probably can be applied to similar studies of other crucial organisms. The biological detail obtained in this way can result in better parameterization of the more general biogeochemical models.

Assessment

A separate assessment of the NRP project 850003 should consider the success of the underlying concept, that is: studying the different interactions of one

organism with its environment. At this moment this is not possible. Immediate questions, such as: "how accurate are our present views of the carbon budget in the oceans?", are only addressed indirectly. But specific results obtained in this project, are contributing to JGOFS (such as the data on downward transport of particulate carbon, have been mentioned under Section 3.2). At the other hand, in VvA-9 work of direct relevance to this project (see above) is continued as a JGOFS activity.

The organism-centered approach is important for focussing on complex interactions that may receive less attention when more immediate goals as the budgets of greenhouse gases are the issue. The choice of coccolithophores for this approach also provides a link with palaeoclimatic studies.

4. CONCLUSIONS

The review given above describes the role of the oceans in the problem of climatic change, the international appreciation concerning the most important scientific issues and the Netherlands activities in these fields, with emphasis on the projects supported by the Dutch National Research Program on Global Air Pollution and Climate Change (NRP).

The Netherlands oceanographic research that is discussed here addresses selected areas from a large scientific and societal problem. Scientifically, integration of the results takes place at three levels: first there is the integration at the level of the specific subject, the physical or biogeochemical processes, and the methodology of model development. Then there is the integration at modelling level: observations, processes and modelling methodology converge in model-simulations of climatic change. This is the aim of the large research projects as TOGA, WOCE and JGOFS. Finally the results of different simulations are integrated at IPCC level to obtain a scientifically broadly accepted opinion on the climatic change problem.

In this review the emphasis is on the description of the different NRP projects in relation to the rest of the Netherlands and international research of the role of the oceans in climate. The quality of this work only can be judged in very general terms. Individual principal scientists have to report their results separately in the appropriate scientific communities. Firm conclusions concerning the ultimate contribution of specific oceanographic NRP projects to a better understanding of the climate problem cannot be given at this place.

The importance for climate research of a strong international oceanographic research effort is evident. Netherlands oceanographers contribute in different fields and are supported by different sources in this effort. The NRP projects that have been evaluated here form a substantial part of this. Many of them have not yet been finished: either the final scientific reporting has to be done, or the project has not yet been concluded and is continued in another form.

In the NRP evaluation by SPA/HCG (1992) critical remarks are made on the co-ordination within this theme. It has to be said that the theme "water" is a heterogeneous one. There is certainly co-ordination at project level. JGOFS

observations have been made at WOCE cruises and vice-versa. The ASGASEX programme offers facilities for investigators of the ocean-atmosphere exchange of CO₂ and N₂O. The studies of the CO₂ budget, the work on *E.huxleyi* and on DMS production to some extent are intermingled. But generally the level of interaction between biogeochemistry and physics is low. Unless there is an explicit wish for more interaction, the need for future combined programming of both sectors can be questioned. Further internal co-ordination within the sectors "physics" and "biogeochemistry" can, however, be profitable.

The above review is not dealing with the IMAGE model, that is being developed in NRP as a tool for integrated assessment of climate change. We note, however, that also in the IMAGE 2.0 effort a modelling of the coupled ocean and atmospheric energy balances is undertaken (Anon., 1993). For the ocean physics a "quasi 2-D" model is applied. In the IMAGE model an attempt is made to evaluate the effect of various, mainly biogeochemical, processes on the storage of anthropogenic carbon (Klepper et al., 1993).

These results suggest that over one century predictions of atmospheric CO₂ concentrations can be made without consideration of complex biogeochemical feedbacks. Question is how serious one has to take such ideas, considering the large efforts within and outside NRP to understand better the climatic role of the oceanic system. It is clear that the application of the oceanographic module of IMAGE could gain from exchange of ideas and results with the research groups working in the field, and that this could give weight to future judgements made on the basis of IMAGE.

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6. REFERENCES

- Anon., 1987. WOCE Core Project 2 Planning Meeting. The Southern Ocean Bremerhaven, F.R.G., may 1986. WMO/TD 181 (WOCE Report 09/87), 53 pp.
- Anon., 1990. The Joint Global Ocean Flux Study, JGOFS, Science plan. JGOFS rep. 5. SCOR, 61 pp.
- Anon., 1991. The oceans and climate: A guide to present needs. IOC Technical Series 38. UNESCO 1991. 39 pp.
- Anon., 1992. Oceanic interdecadal climate variability. IOC Technical Series 40. UNESCO 1992. 40 pp.
- Anon., 1993. Report International Review Meeting IMAGE 2.0. Dutch National Research Programme on Global Air Pollution and Climate Change. Rep. 00-09.
- Bakker, D., and H.J.W. De Baar, 1992. Exchange of CO₂ between the oceans and the atmosphere. *Change* 10: 3-4.

- Bretherton, F.P., K. Bryan and J.D. Woods, 1990. Time-dependent greenhouse-gas-induced climate change. In: Houghton, J.T. G.J. Jenkins and J.J. Ephraums, eds.). *Climate Change. The IPCC Scientific Assessment*. Cambridge Univ. Press, Cambridge, p. 173-194.
- Broecker, W.S., J.R. Ledwell, T. Takahashi, R. Weiss, L. Merlivat, L. Memery, T-H. Peng, B. Jahne, K.O. Münnich, 1986. Isotopic versus micrometeorologic ocean CO₂ fluxes: a serious conflict. *J. Geophys. Res.* 91: 10517-10527.
- Broecker, W.S., 1987. Unpleasant surprises in the greenhouse? *Nature* 328: 123-126.
- Broecker, W.S., 1991. The great ocean conveyor. *Oceanography* 4: 79-89.
- Brown, C.W., and J.A. Yoder, 1994. Coccolithophorid blooms in the global ocean. *J. Geophys. Res.* 99: 7467-7482.
- Charlson, R.J., J.E. Lovelock, M.O. Andreae and S.G. Warren, 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature* 326: 655-661.
- Danabasoglu, G., J.C. McWilliams and P.R. Gent, 1994. The role of mesoscale tracer transports in the global ocean circulation. *Science* 264: 1123-1126.
- Dansgaard, W., S.J. Johnsen, H.B. Clausen, D. Dahl-Jensen, N.S. Gundestrup, C.U. Hammer, G.S. Hvldberg, J.P. Steffensen, A.E. Sveinbjörnsdottir, J. Jouzel and G. Bond, 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364: 218-220.
- De Baar, H.J.W., H.G. Fransz, G.M. Ganssen, W.W.C. Gieskes, W.G. Mook, J.H. Stel, 1989. Towards a Joint Global Ocean Flux Study: Rationale and objectives. In: Ayala-Castañares, A., W. Wooster and A. Yáñez-Arancibia, eds., *Oceanography 1988*. UNAM Press, México D.F., 11: 34.
- De Baar, H.J.W., and M.H.C. Stoll, 1989. Storage of CarbonDioxide in the Oceans. In: P.A. Okken, S.J. Zwart, S. Zwerfer, eds. *Climate and Energy: the feasibility of controlling CO₂ emissions* Kluwer Ac.Publ., Dordrecht, p. 143-177.
- De Baar, H.J.W., 1992. Options for enhancing the storage of Carbon Dioxide in the oceans: a review. *Energy Convers. Mgmt.*, p. 635-642.
- De Baar, H.J.W., C. Brussaard, J. Hegeman, J. Schijf and M.H.C. Stoll, 1993. Sea-trials of three different methods for measuring non-volatile dissolved organic carbon in seawater during the JGOFS North Atlantic pilot study. *Marine Chemistry* 41: 145-152.
- De Baar, H.J.W., J.T.M. De Jong, D.C.E. Bakker, B.M. Löscher, C. Veth, U. Bathmann and V. Smetacek, 1995. Iron is essential for plankton blooms and carbon dioxide drawdown in the Southern Ocean, *Nature* (in press).
- De Boer, C.J., H.M. Van Aken and A.J. Van Bennekom, 1991. Hydrographic variability of the overflow water in the Iceland Basin. *ICES C.M.1991/C*: 13, 11 pp.
- De Boer, C.J., 1993. Water mass distribution in the Iceland Basin calculated with an optimal parameter analysis. *ICES C.M.1993/C*: 16, 18 pp.
- De Bruin, T. F., R.X. De Koster, S. Ober and L. Otto, 1992. Netherlands XBT programme along the WOCE AX-5 section. NIOZ Data-report 1992-3, 40 pp.
- De Ruijter, W.P.M., P.J. Van Leeuwen and J.R.E. Lutjeharms, submitted. Triggering mechanisms for Natal Pulses in the Agulhas Current. *Subm.to J.Geophys.Res.*
- Dickson, R.R., J. Meincke, S.A. Malmberg and A.J. Lee, 1988. The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982. *Prog. Oceanogr.*, 20: 103-151.

- Drijfhout, S.S., 1990. Ring genesis and the related transport of heat, momentum and vorticity: A parameter study. *J. Phys. Oceanogr.* 20: 1645-1665.
- Drijfhout, S.S., 1992. Ring genesis and the related heat transport. Part II: A model comparison. *J. Phys. Oceanogr.* 22: 268-285.
- Drijfhout, S.S., 1994. Heat transport by mesoscale eddies in an ocean circulation model. *J. Phys. Oceanogr.* 24: 353-369.
- Dijkstra, H.A., and M.J. Molemaker, 1994. Double diffusive and direct instabilities below growing sea-ice. *Int. J. Heat Mass Transfer*, 37: 2547-2559
- Dijkstra, H.A., and E.J. Kranenborg, 1995. The structure of (linearly) stable double diffusive flow patterns in a laterally heated stratified liquid. *Phys. Fluids* (in press).
- Feron, R.C.V., 1992. Satellite altimetry: its use for monitoring the ocean. *Change* 11: 6-7.
- Feron, R.C.V., W.P.M. De Ruijter and D. Oskam, 1992. Ring shedding in the Agulhas Current system. *J. Geophys. Res.* 97: 9467-9477
- Feron, R.C.V., 1993. Comparing the UK Fine Resolution Antarctic Model (FRAM) with 3-years of Geosat altimeter data. In: R. Rummel and F. Sanso eds. *Satellite altimetry in geodesy and oceanography*. Springer Verlag : 467-479.
- Feron, R.C.V., 1994. Eddies and mean flow in the ocean. Applications of satellite altimetry. Thesis, Univ. Utrecht. 126 pp.
- Feron, R.C.V., 1995. The Southern Ocean western boundary currents: comparison of FRAM-model results with Geosat-altimeter data. Accepted in: *J. Geophys. Res.*
- Fraedrich, K., 1994. An ENSO impact on Europe? A review. *Tellus* 46A, 541: 541-552.
- Gates, W.L., P.R. Rowntree and Q-C. Zeng, 1990. Validation of climate models. In: Houghton, J.T., G.J. Jenkins and J.J. Ephraums, eds. *Climate Change. The IPCC Scientific Assessment*. Cambridge Univ. Press, Cambridge, 1990: 93-130.
- Gates, W.L., J.F.B. Mitchell, G.J. Boer, U. Cubasch and V.P. Meleshenko, 1992. Climate modelling, climate prediction and model validation. In: J.T. Houghton, B.A. Callander and S.K. Varney, eds. *Climate Change 1992. The supplementary report to the IPCC Scientific Assessment*. Cambridge Univ. Press, Cambridge, 1992: 97-134.
- Gill, A.E., 1983. Eddies in relation to climate. In: Robinson, A.R. ed. *Eddies in marine science* Springer-Verlag, p. 441-445.
- Guicherit, R., 1993. Ocean dimethylsulphide (DMS) and climate. *Change* 16: 7-9.
- Haagmans, R., M.C. Naeije, and R.C.V. Feron, 1993. TOPEX/POSEIDON and ERS-1: New dimension in satellite altimetry, part 1 & 2. *Geodetical Info Magazine* 5, nov-dec. 1993.
- Janssen, P.A.E.M., 1994. Results with a coupled wind wave model. ECMWF Technical Report 71, 60 pp.
- Jin, F.F., J.D. Neelin, M. Ghil, 1994. El Niño on the devil's staircase: annual sub-harmonic steps to chaos. *Science* 264: 70-72.
- Kattenberg, A., 1993. The upper layer of the ocean. *Change* 14: 18-19.
- Keeling, R.F., and S.R. Shertz, 1992. Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle. *Nature* 358: 723-727.

- Klepper, O., B.J. De Haan, P. Saager and M.S. Krol, 1993. Oceanic uptake of anthropogenic CO₂: mechanisms and modelling. RIVM report 481507004. 48 pp.
- Koblinsky, C.J., P.Gaspar and G. Lagerloef, 1992. The future of spaceborne altimetry. Oceans and climate change. A long-term strategy. Joint Oceanogr. Inst. Incorporated, Washington D.C., 75 pp.
- Lancelot, C., G. Billen, C. Veth, S. Becquevort and S. Mathot, 1991. Modelling carbon cycling through phytoplankton and microbes in the Scotia-Weddell Sea area during ice retreat. *Marine Chemistry* 35: 305-324.
- Lancelot, C., C. Veth and S. Mathot, 1991. Modelling ice-edge phytoplankton bloom in the Scotia-Weddell sea sector of the Southern Ocean during spring 1988. *J. Marine Systems* 2: 333-346.
- Latif, M., T. Stockdale, J-O. Wolff, G. Burgers, E. Maier-Reimer, M.M. Junge, K. Arpe, L. Bengtsson, 1994. Climatology and variability in the ECHO coupled GCM. *Tellus* 46A: 351-366
- Law, C.S., and N.J.P. Owens, 1990. Significant flux of atmospheric nitrous oxide from the northwest Indian Ocean. *Nature* 346: 826-828.
- Lenderink, G., and R.J. Haarsma, 1994. Variability and multiple equilibria of the thermohaline circulation associated with deep-water formation. *J. Phys. Oc.* 24: 1480-1493.
- Levitus, S., 1982. Climatological atlas of the world ocean. NOAA Prof. paper 13, 173 pp.
- Liss, P.S., and L. Merlivat, 1986. Air-sea gas exchange rates: Introduction and synthesis. In: P. Buat-Ménard, ed. *The role of air-sea exchange in geochemical cycling*, p. 113-127.
- Liss, P.S., G. Malin and S.M. Turner, 1993. Production of DMS by marine phytoplankton. In: G. Restelli and G. Angeletti, eds. *Dimethylsulphide: Oceans, Atmosphere, and climate* ECSC, EEC, EAEC, 1993: 1-14
- Manabe, S., R.J. Stouffer and M.J. Spelman, 1994. Response of a coupled ocean-atmosphere model to increasing atmospheric carbon dioxide. *Ambio* 23: 44-49.
- Marshall, J., J.A. Whitehead and T. Yates, 1994. Laboratory and numerical experiments in oceanic convection. In: Manalotte-Rizzoli and Robinson eds. *Ocean processes in climate dynamics: Global and Mediterranean examples*. Kluwer Ac. Publ. 1994: 173-201.
- McBean, G.A., 1994. Global change models - A physical perspective. *Ambio* 23: 13-18.
- McPhaden, M.J., 1994. The eleven-year El Niño? *Nature* 370: 326.
- Neelin and Dijkstra, 1995. Coupled ocean-atmosphere interaction and the tropical climatology. Part I: The dangers of flux-correction. Part II : Why the cold tongue is in the east. *J. Climate* (in press).
- Neelin, J.D., and J. Marotzke, 1994. Representing ocean eddies in climate models. *Science* 264: 1099-1100.
- Nowlin, W.D., jr. and J.M. Klinck, 1986. The physics of the Antarctic Circumpolar Current. *Rev. Geophysics* 24: 469-491.
- Ocean Observing Development Panel, 1993. Interim design for the ocean component of a Global Climate Observing System. Dept. Oceanogr. Texas A&M Univ. 105 pp.
- Oost, W.A., C.W. Fairall, J.B. Edson, S.D. Smith, R.J. Anderson, J.A.B. Wills, K.B. Katsaros and J. DeCosmo, 1994. Flow distortion calculations and their

- application in HEXMAX. Proc. 5th conf. on Meteorology and Oceanography in the coastal zone. *J. Atmospheric and Oceanic Technology* 11: 366-386.
- Oost, W.A., 1994. Errors in eddy correlation measurements of momentum fluxes and their correction. *J. of Marine Systems*, 4: 171-181.
- Otto, L., H.M. Van Aken and R.X. de Koster, 1992. Use of drifters in the "DUTCH-WARP" programme, 1990 and 1991. Programme description and preliminary results. NIOZ Data-report 1992-2, 12 pp.
- Otto, L., and H.M. Van Aken, submitted. Surface circulation in the North-East Atlantic as observed with drifters. Subm. to *Progress in Oceanography*.
- Parilla, G., A. Lavín, H. Bryden, M. García and R. Millard, 1994. Rising temperatures in the subtropical North Atlantic over the past 35 years. *Nature* 369: 48-51.
- Raynaud, D., J. Jouzel, J.M. Barnola, J. Chappellaz, R.J. Delmas, C. Lorius., 1993. The ice record of greenhouse gases. *Science* 259: 926-259.
- Read, J.F., and W.J. Gould, 1992. Cooling and freshening of the subpolar North Atlantic Ocean since the 1960s. *Nature* 360: 55-57.
- Schmitt, R. and K. Bryan, 1991. Mysteries of the ocean water budget. Annex IV to Committee on Climatic Changes and the Ocean (CCCO), 12th session Woods Hole, June 1991, 17 pp.
- Schott, F., M. Visbeck and U. Send, 1994. Open ocean deep convection, Mediterranean and Greenland Seas. In: Manalotte-Rizzoli and Robinson eds. *Ocean processes in climate dynamics: Global and Mediterranean examples*. Kluwer Ac. Publ. 1994: 203-225.
- Shine, K.P., R.G. Derwent, D.J. Wuebbles and J.J. Morcrette, 1990. Radiative forcing of climate. In: J.T. Houghton, G.J. Jenkins and J.J. Ephraums, eds. *Climate Change. The IPCC Scientific Assessment*. Cambridge Univ. Press, Cambridge, 1990: 41-68.
- Siegenthaler, U., and J.L. Sarmiento, 1993. Atmospheric carbon dioxide and the ocean. *Nature* 365: 119-125.
- Smith, N., 1991. The role of models in an Ocean Observing System. OOSDP Background Report 1. Joint CCCO-JSC, 85 pp.
- Smith, S.D., and E.P. Jones, 1986. Isotopic and micrometeorological ocean CO₂ fluxes: different time and space scales. *J. Geophys. Res.* 91: 10529-10532.
- SPA and HCG, 1992. Evaluation of the technical emphasis, policy relevance and management performance of the Dutch National Research Program on Global Air Pollution and Climate Change. Washington and Amsterdam 66 pp.
- Sterl, A., and A. Kattenberg, 1993. Study of North Atlantic SST evolution with a coupled OGCM-Mixed Layer model. In: G.J. Boer ed. *Research activities in atmospheric and oceanic modelling WMO-TD 533*: 838-839.
- Sterl, A. and A. Kattenberg, 1994. Embedding a mixed layer model into an OGCM of the Atlantic: the importance of surface mixing for heatflux and temperature. *J. Geophys. Res.* 99: 14139-14157.
- Stockdale, T., M. Latif, G. Burgers, J-O. Wolff, 1994. Some sensitivities of a coupled ocean-atmosphere GCM. *Tellus*, 46A: 367-380
- Stoll, M.H.C., J.W. Rommets and H.J.W. De Baar, 1993. Effect of selected calculation routines and dissociation constants on the determination of total carbon dioxide in seawater. *Deep-Sea Res. I* 40: 1307-1322.
- Stoll, M.H.C., 1994. Inorganic carbon behaviour in the North Atlantic Ocean. Thesis, Univ.Groningen. 193 pp.

- TOGA Scientific Steering Group, 1985. Scientific plan for the Tropical Ocean and Global Atmosphere Programme. WMO/TD 64, 146 pp.
- Trenberth, K.E. and A. Solomon, 1993. A new look at atmospheric and oceanic poleward heat transports. In: Fourth Int. Conf. on Southern Hemisphere meteorology and oceanography. Hobart, Australia. Am.Met.Soc.Boston USA.
- Tziperman, E., L.Stone, M.A. Cane, H. Jarosh, 1994. El Niño chaos: overlapping of resonances between the seasonal cycle and the Pacific ocean-atmosphere oscillator. *Science* 264: 72-74.
- Van Aken, H.M., 1993. Current measurements in the Iceland Basin. ICES C.M.1993/C: 11, 13 pp.
- Van Aken, H.M., (submitted) Hydrographic variability in the bottom layer of the Iceland Basin. Subm. to *J. Phys. Oc.*
- Van Leeuwen, P.J., and W.P.M. De Ruijter, submitted. Natal pulses and the formation of Agulhas rings. Subm.to *J. Geophys. Res.*
- Veldhuis, M.J.W., G.W. Kraay and W.W.C. Gieskes, 1992. Growth and fluorescence characteristics of ultraplankton on a north-south transect in the eastern North Atlantic. *Deep-Sea Res.* 40: 609-626.
- Walsteijn, F.H., 1994. Oceans and climate: robust numerical methods for 2D turbulence. *J. Comput. Phys.* 114: 129-145. Also: Dutch Nat.Res. Progr. on Global Air Pollution and Climate Change. Report 001/project 850025. 34 pp.
- Wanninkhof, R., 1992. Relationship between wind speed and gas exchange over the ocean. *J.Geophys. Res.* 97: 7373-7382.
- Watson, R.T., H. Rodhe, H. Oeschger and U. Siegenthaler, 1990. Greenhouse gases and aerosols. J.T. Houghton, G.J. Jenkins and J.J. Ephraums, eds. The IPCC Scientific Assessment. Cambridge Univ. Press, Cambridge, 1990 : 1-40.
- Watson, R.T., L.G. Meira Filho, E. Sanhueza and A. Janetos 1992. Sources and sinks. In: J.T. Houghton, B.A. Callander and S.K. Varney, eds. Climate Change 1992. The supplementary report to the IPCC Scientific Assessment. Cambridge Univ. Press, Cambridge, 1992: 25-46.
- Wesely, M.L., 1986. Response to "Isotopic versus micrometeorologic ocean CO₂ fluxes: a serious conflict" by W. Broecker et al.. *J. Geophys. Res.* 91: 10533-10535.
- Westbroek, P., 1992. Global Emiliana modelling initiative (GEM), an international programme to study the role of life in the global climate. *Change* 9: 8-10.
- Westbroek, P., C.W. Brown, J. v. Bleijswijk, C. Brownlee, G.J. Brummer, M. Conte, J. Egge, E. Fernández, R. Jordan, M. Knappertsbusch, J. Stefels, M. Veldhuis, P. v.d.Wal, J. Young, 1993. A model system approach to biological climate forcing. The example of *Emiliana huxleyi*. *Global and Planetary Change*, 8: 27-46.
- World Climate Data Programme, s.d. Climate System Monitoring. The Global Climate System. A critical review of the climate system during 1982-1984. Unofficial Report.
- WOCE International Planning Office, 1988. World Ocean Circulation Experiment, Implementation Plan. Vol.1 Detailed Requirements, Vol.2 Scientific Background. WMO/TD 242 & 243 (WOCE Report 20/88 & 21/88).
- WOCE International Project Office, 1994. WOCE Strategy for Ocean Modelling. WOCE NEG Science Plan for Ocean Modelling 1993. WOCE Report 112/94, 35pp.
- WOCE Scientific Steering Group, 1986. Scientific Plan for the World Ocean Circulation Experiment. WMO/TD 122 (WOCE Report 06/86), 83 pp.