Altimetry and models in the tropical oceans: a review

Altimetry
Oceanic model
Assimilation
Tropical ocean

Altimétrie
Modélisation océanique
Assimilation
Océan tropical

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ABSTRACT

Tropical oceans play a key role in climatic variations. Ocean-atmosphere interactions induce large-scale and low-frequency variations which, due to the specificity of tropical ocean dynamics, are very difficult to observe with traditional *in situ* measurements. During the past twenty years, a variety of numerical models of diverse complexity have contributed much to the description, understanding and prediction of ocean variability in the tropics. However, the capacity of these models to simulate adequately the ocean variability heavily depends on the accuracy of the atmospheric forcings and that of initial conditions. Satellite altimetry provides a unique opportunity to avoid the problem of scarce and non-synoptic *in situ* data coverage for the large-scale low-frequency monitoring of the tropical oceans. Preliminary results have been obtained with Geos 3 and Seasat altimeter data acquired in the late 1970s. The most recent demonstration of such a capacity is the multi-year Geosat mission of the late 1980s. However the use of the sea level variations monitored by Geosat for ocean description is severely limited by the lack of accuracy of the mission dedicated to geodesy. Such a limitation will no longer exist after the launch in 1992 of the Topex-Poseidon satellite which is dedicated to oceanography. Nonetheless these future satellite observations will not alone be sufficient to determine, for example, the oceanic transport of heat involved in climatic variations: it is in the combination of numerical models and altimetry that answers to such a question may lie. Data assimilation into numerical models is a fairly new adventure for oceanographers, the few examples of assimilation of actual altimetric data in the tropics being of very recent date. Different methods have been applied in these examples with different objectives of assimilation, indicating a variety of directions for future research in what is a promising field.

Oceanologica Acta, 1992. **15**, 5, 411-430.

RÉSUMÉ

Une revue de l'altimétrie satellitaire et des modèles dans les océans tropicaux

Le rôle important des océans tropicaux dans l'évolution du climat planétaire est maintenant connu. Ces interactions océan-atmosphère induisent dans les tropiques des variations à basse fréquence et à grande échelle difficiles à observer par les mesures *in situ* traditionnelles. Afin de décrire, comprendre et prédire ces phénomènes, des modèles numériques océaniques ont été développés au cours des vingt dernières années. Cependant, les incertitudes sur les forçages atmosphériques ou sur les conditions initiales de ces modèles limitent sérieusement leur capacité à reproduire la variabilité océanique. L'altimétrie satellitaire fournit une chance unique de pourvoir à l'échantillonnage dispersé et non synoptique des mesures *in situ* dans le suivi à long terme et à grande échelle de l'océan. Des études fondées sur les programmes Geos 3 et Seasat dans les années 1970 ou plus récemment Geosat, à partir de 1985, ont mis en évidence l'aptitude du satellite altimétrique à reproduire les mouvements océaniques. Toutefois, particulièrement pour Geosat, ces études révèlent le manque de précision des missions non spécifiques à l'océanographie. La précision devrait être améliorée lors de la mission altimétrique «océanique» Topex/Poséidon à la mi-1992; ces futures observations ne suffiront probablement pas pour déterminer, par exemple, le flux de chaleur océanique impliqué dans les variations climatiques de la planète. C'est par l'utilisation conjointe des modèles et des données satellitaires que le problème pourra être résolu. Bien que l'assimilation des données océaniques n'ait démarré que depuis peu, les études impliquant différentes méthodes d'assimilation et différents objectifs se révèlent très prometteuses dans les régions tropicales.

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INTRODUCTION

Interest and activity in the tropical domain have always captured the attention of oceanographers. It is now believed that the key to climatic variations lies at least partly in large-scale ocean-atmosphere interactions in the tropics. The tropical ocean dominates oceanic heat transport both in the mean and in annual variations, and is therefore a major component of the climate system. In the Eastern Pacific, for example, periods of anomalous warm waters, the so-called "El Niño" events, are correlated with anomalous winter climate over the mid-latitude areas (Horel and Wallace, 1981). Various scenarios of the El Niño, which is a major climatic occurrence, have been already presented [*i. e.* Rasmusson and Carpenter (1982); Cane and Sarachik (1983)], but a great deal of investigation is being pursued to observe, understand and predict it (Zebiak and Cane, 1987).

Tropical oceans are characterized by a relatively shallow thermocline (about 100 m) separating a warm fluid from a heavier one. Maintained by the permanent easterly tradewinds, the mean thermocline is deeper on the western than on the eastern side of the tropical oceans (by the order of tens of metres). Western boundary currents such as the intermittent New-Guinea current in the Pacific, the Somali current in the Indian Ocean and the North Brazil current in the Atlantic, are transequatorial and can be strong, but the main tropical current system is mostly zonal. Alternative westward and eastward fast zonal currents (of the order of 100 cm/s) exist at the surface, the eastward currents flowing against the trade winds being the "countercurrents". Beneath the thermocline, in all three tropical oceans, there are equatorially confined currents with vertical scales of several hundred metres and speeds of several tens of centimetres per second.

The equatorial ocean, with the vanishing of the Coriolis parameter, responds rapidly and strongly to basinwide wind fluctuations. Linear wave theory has provided a simple framework for discussion of a wide range of equatorial phenomena. In particular, locally-forced wind changes are rapidly communicated eastward by Kelvin waves or westward by long Rossby waves. The travel time of these waves (for the first baroclinic and the first meridional mode) is of the order of 3 and 9 months respectively in the Pacific Ocean, and 1.5 and 4.5 months in the Atlantic and Indian Oceans. However, although linear wave theory is a very fruitful concept in equatorial dynamics, it does not explain all the processes. For example, when the zonal flows are as rapid as the wave phase propagation, processes become nonlinear. Also the zonal shear and vertical shear of the mean currents generate highly non linear instabilities. Furthermore, Sea Surface Temperature (SST) can be affected by three different processes which take place in all three tropical oceans (Cane and Sarachik, 1983), namely: the variation of the heat flux between the atmosphere and the ocean; the advection of heat by oceanic flow; and the variation of the mixed layer depth induced by wind stirring. All these variations, for which the application of the linear wave theory is limited, play a major role in the heat transport and are still under investigation.

Tropical oceans thus have specific features in common. But Philander (1979) suggests that the three tropical oceans may be expected to be quite different for time-dependent motions at the equator, because of their width, their basic stratification and the structures of their wind forcing. Philander and Chao (1991) note that most of the differences between the equatorial Atlantic and Pacific oceanic responses to wind forcing have to be related to the east-west length scale of the winds. In the Pacific, the 15 000 km basin width is substantially larger than the zonal wind scale and this explains why free waves account for a large part of the ocean variability: the adjustment time (determined by the basin width) is larger than the seasonal time scale of the wind and the oceanic response to seasonal forcing is not an equilibrium response. This is not the case for the other two tropical oceans. In the Atlantic Ocean, the narrow size of the basin, compared to the zonal wind scale, induces a basin-wide response mostly in phase with the wind forcing. In the Indian Ocean, the annual reversal of the monsoon winds creates strong annual variations of the Somali current as well as strong semi-annual equatorial fluctuations known as the Wyrtki jet.

annual winds. They find that the semi-annual response of the thermocline in the Eastern part of the ocean is forced by the semi-annual winds in the central part.

Process models: real winds blowing over real basin

Beside process studies, these simple models were also forced by real winds blowing over the tropical oceans, and compared with observations at selected points. Simmons *et al.* (1988) force a non linear reduced-gravity model by observed winds in the northwest Indian Ocean and compare the results with hydrological data rather successfully in the Socotra region during the autumn of 1985. Kindle and Thompson (1989), with a reduced-gravity model forced by Hellerman and Rosenstein's wind (1983), reveal that the 26-day oscillations in the equatorial Indian Ocean are excited by mechanisms significantly different from that believed to be responsible for the 20-30 day oscillations in the equatorial Atlantic and Pacific. They also demonstrate, like Woodberry *et al.* (1989), 50-day oscillations, due to barotropic instabilities of the currents. Woodberry *et al.* (1989) present the large-scale features of the ocean circulation in the entire Indian Ocean north of 25°S (Fig. 1). In the Atlantic, the Focal/Sequal experiment in 1982-1984 leads to the development of models designed to understand the seasonal cycle of the oceanic upper layers. Busalacchi and Picaut (1983), Arnault (1984) and Lévy (1984) demonstrate that the pressure gradients calculated by shallow-water models forced with monthly climatological winds are in good agreement with climatological dynamic height gradients (Merle and Arnault, 1985). In the western basin, the equatorial zonal pressure gradient is, on the other hand, perfectly balanced by the wind stress. More recently, du Penhoat and Gouriou (1987) show the agreement that exists between the dynamic height computed by a linear multimode model and those obtained through hydrological measurements during the Focal/Sequal experiment in 1982-1984. The contrast between 1983 and 1984 is well captured by the model, especially the abnormal flat topography of the sea surface along the equator during the first three months of 1984. This 1984 oceanic anomaly was due to an unusual basin-wide relaxation of the equatorial wind stress, in relation to the Pacific El Niño phenomenon in 1982-1983. This study also points out the importance of the wind-forcing quality, as two different wind data sets produce rather different oceanic signals along the equator. In the Pacific, most existing studies have dwelt on interannual variability due to the importance of the El Niño phenomenon in this ocean, which occurs every three to six years. Busalacchi *et al.* (1983), comparing the pycnocline displacement simulated by a linear shallow-water model with *in situ* measurements, believe that Kelvin and Rossby waves could play a major role during El Niño. Seager *et al.* (1988) run a version of the Zebiak and Cane (1987) half-layer model modified to simulated total SST, forced by Rasmusson and Carpenter's climatology (1982). The cooling obtained in the equatorial eastern Pacific is then underestimated, and the warm pool is rather poorly defined, especially in the northern hemisphere during summer.

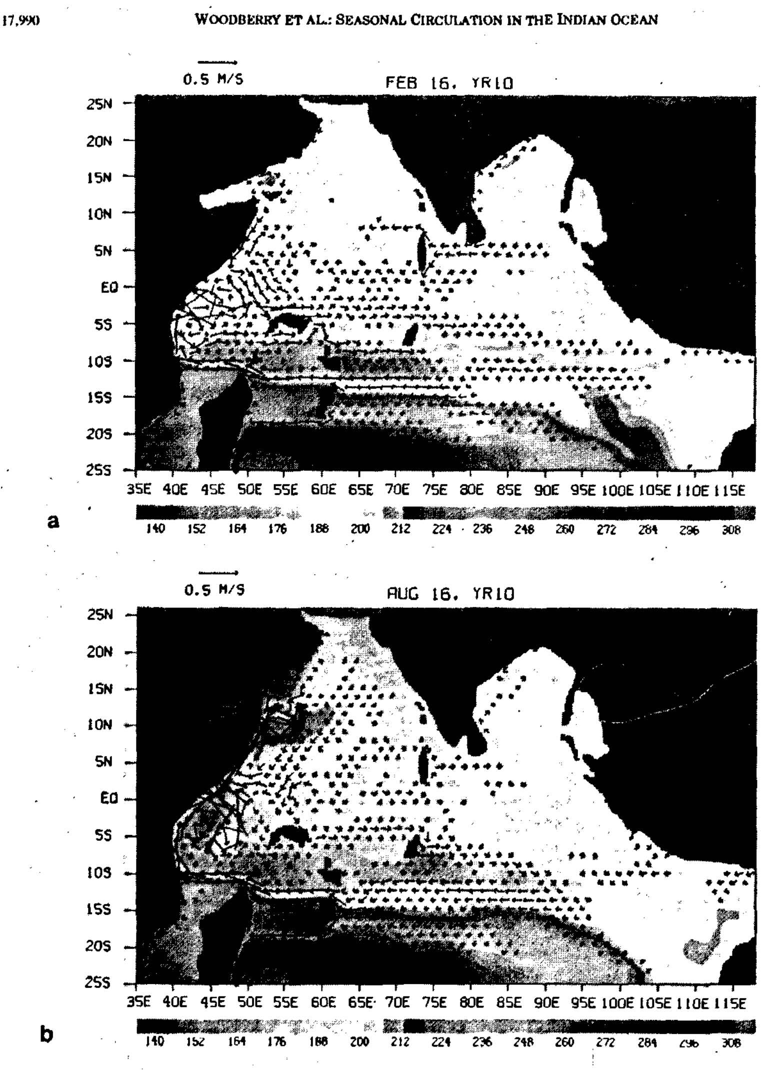

Figure 1

Simulation of surface current and upper layer thickness in the tropical Indian Ocean, from Woodberry et al. *(1989).*

Simulation des courants de surface et de la profondeur de la couche océanique de surface dans l'Océan Indien tropical, d'après Woodberry *et al.* (1989).

Oceanic General Circulation Models (OGCM)

The success of the simple models (shallow-water models, linear multi-mode models...) in representing variations of the thermocline has been quite striking. However, the vertical representation of the ocean is very poor and the predicted currents are at odds with observations. The best attempt to reproduce tropical ocean variability as a whole is certainly obtained by primitive equation models. Even if the Indian Ocean is still poorly investigated using OGCM, this kind of model is now fre-

Traditional *in situ* observations are not sufficient to study the tropical rapid and large-scale variations. Numerical modelling and satellite observations are particularly adequate in this connection.

Because the tropical oceans have a specific dynamic behaviour which can be approached with simple theory as mentioned above, models have been particularly successful in describing and understanding many processes in the tropics. Also, as computer capacity is less and less a limiting factor, more sophisticated models are now available and even used for the prediction of ocean variability. The next part of this paper will review the major steps in the progress of numerical modelling in the tropics, and problems still under investigation will be mentioned.

Among satellite observations, altimetry is a particularly attractive means of monitoring ocean variations, as it can provide sea-level change. In the tropics, sea level can be used as a tracer of the vertical density structure of the ocean, and offers an approximate measure of the heat content of the ocean. For example, as a first approximation, sea level is anticorrelated with thermocline depth. Mean sea level has a slope along the equator which rises from east to west (of the order of a few tens of centimetres over several thousands of kilometres). Mean sea level has also a succession of zonal crests and troughs corresponding to the geostrophic part of the zonal currents and countercurrents described above. Altimetry provides the variation in time of this topography corresponding to the displacement and/or change in intensity of the mean flows. In the third section of this paper, results obtained from existing satellite altimetry are reviewed and perspectives of future altimetric missions are mentioned. In the fourth section, results making simultaneous use of numerical modelling and satellite altimetry are referenced and a state-of-the-art on altimetric data assimilation into numerical models of the tropical oceans is proposed.

THE MODELS

General context

Numerical modelling is a powerful tool for the description and interpretation of basinwide oceanic events which are so difficult to observe with traditional means. To begin with, numerical calculations were mostly focused on specific and/or analytic problems. Then came more sophisticated simulations, together with better computer performance, and part of these simulations are used today in the tropics as descriptive oceanography in a "now-casting" context.

It would be too ambitious to review in this paper all that has been done during the past thirty years in numerical modelling in oceanography. We thus decided to limit ourselves to a review of studies dedicated to the surface layer variability of the tropical oceans (thermocline depth, dynamic height). In particular, we shall not provide details on the coupled atmosphere-ocean models, as the questions addressed by these models are specific to the coupling aspect. In the present section, we shall follow the approach adopted by modellers, starting with simple models focused on an isolated specific aspect, and continuing with complex oceanic general circulation models (OGCM) to provide a more realistic view of the tropical oceans. Finally, we shall examine the problems encountered during these calculations and the perspective offered.

Process models: idealized wind and/or basin geometry

The first type of numerical calculations was designed to understand the basic dynamics of the oceanic forced response, by using idealized winds blowing over simple models. In this approach, a specific oceanic phenomenon is identified and investigated in order to elaborate on physical theory.

The equatorial ocean is characterized by a well marked thermocline separating a warm and light fluid from a colder and heavier one. Most of the simple models used in equatorial oceanography are based on this particularity. For example, in the Indian Ocean, O'Brien and Hurlburt (1974) use a simple, flat-bottom, beta-plane model forced with a uniform eastward wind to demonstrate the kinetics of the equatorial surface jet. Cane (1980), with a two-layer model forced by idealized wind, finds that for westerly and meridional winds, the response of equatorial currents is predominantly local and rapid. He also suggests that the undercurrent that has been observed in the early spring in the Indian Ocean is driven by an eastward pressure force. This pressure gradient is generated by the zonal readjustment of mass induced by the relaxation of the winds at the fall monsoon transition. In the Atlantic, Adamec and O'Brien (1978), following the controversial ideas of Moore *et al.* (1976), use a simple baroclinic model and hypothesize that the upwelling in the Gulf of Guinea is due to a baroclinic Kelvin wave excited in the Western Atlantic by the onset of the southeast trades in May-June. This long wave propagates across the Atlantic to reach the coast, and part of it reflects as coastal waves which upwell the water along the northern shore of the gulf. However, Philander (1979) estimates that the wind field seasonal changes in the Atlantic are of too low a frequency to excite Kelvin waves. Cane and Sarachik (1981) force a linear shallow-water model with periodically varying zonal winds of Gaussian form in the meridional direction and independent of zonal coordinates. The response for parameters characteristic of annual forcing over the tropical Atlantic Ocean shows good agreement with many of the features described by Merle (1980). But more importantly, the calculation demonstrates that the response to periodic forcing differs in fundamental ways from the response to impulsive forcing. Furthermore, it shows that the greater seasonality of the response of the Atlantic *versus* the Pacific could not be attributed to the smaller size or greater memory of the Atlantic but rather to the greater seasonality of the winds over this ocean. It also indicates that the periodic response of the thermocline depends not only on those at the equator, but also on the winds within ten degrees of the equator. In the Pacific, Busalacchi and O'Brien (1980) force a shallow-water model with an approximation to the annual and semi-

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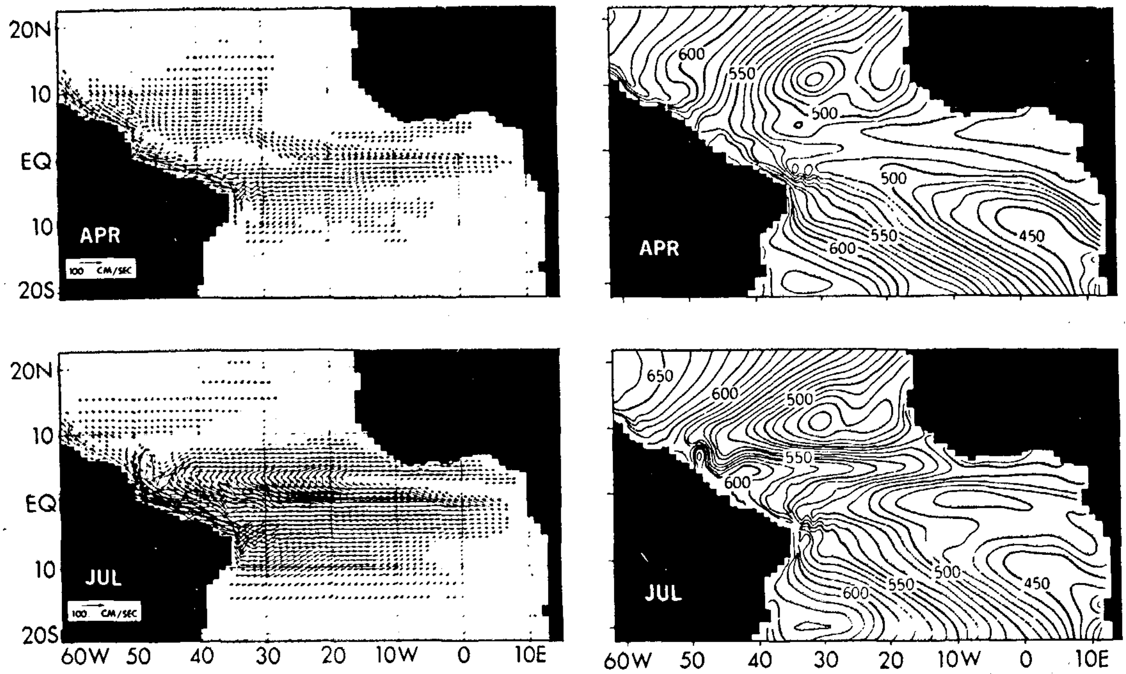


Fig. 3. Maps of surface current vectors and heat storage of the upper ocean (which is defined to be the vertical integral of the temperature from the surface to a depth of 317 m and has units of 10^3 cal cm^{-2}) for April 15 and July 15.

Figure 2

Simulation of surface current and heat storage in the tropical Atlantic Ocean, from Philander and Pacanowski (1986).

Simulation des courants de surface et du contenu de chaleur dans l'Océan Atlantique tropical, d'après Philander and Pacanowski (1986).

quently used in the tropical oceans. After some preliminary studies (Philander and Pacanowski, 1980; 1981; Fig. 2), recent years have been dedicated to such models. In the Atlantic Ocean, Richardson and Philander (1987) compare GFDL three-dimensional model results with shipdrift data, on a climatological basis, and find small differences: for example, simulated currents present an annual signal amplitude that is too strong in the western part of the basin compared to shipdrifts. Philander and Chao (1991) note that the Atlantic/Pacific differences for the oceanic response to wind forcing is mostly due to the wind zonal scale compared with the basin width, and not merely to the latter as previously supposed by Philander (1979). Like du Penhoat and Gouriou (1987), Morlière *et al.* (1989 *a*) and Reverdin *et al.* (1991), using the LODYC OGCM, insist on the importance of wind forcing during 1982-1984, by showing that an upwelling signal can be deeply reduced using different wind forcings. A detailed evaluation of the WOCE model - forced with climatological wind - has also been conducted recently by Schott and Boning (1991), with emphasis on the importance of wind forcing and vertical friction on the western Atlantic currents. Still with reference to the current system in the Atlantic, we may also mention an interesting way of comparing model results and data: Morlière and Duchêne (1991) use a statistical test to conclude that the differences observed between climatological shipdrifts and LODYC OGCM results could not be attributed solely to uncertainties in connection with the data (winds, shipdrifts), and that the LODYC model used in this study nevertheless gives better results than the GFDL model run by Philander and Pacanowski (1986). In the tropical Pacific, a high-resolution version of the Bryan/Cox model has been run by Gordon and Corry (1991), using either climatological forcings (Hellerman and Rosenstein, 1983) or averages over a four-year integration of the United Kingdom Meteorological Office atmospheric GCM (Slingo *et al.*, 1989). The temperature at 155°W as computed from the model, or from XBT profiles from the Tahiti-Hawaii shuttle, shows two major differences: a lack of doming near 10°N and a more diffuse thermal structure in the equatorial region in the model. Most of these differences are also attributed by the authors to surface forcing functions. Comparison of their model with those run by Philander *et al.* (1987) also demonstrates the importance of spatial and vertical resolution.

Coupled oceanic-atmospheric models

As stated in the introduction, it is not our intention in this review to deal with coupled modelling, which requires a closer integration of assimilation, in the place of what is at present carried out separately for the atmosphere and the ocean. For a more complete review of this question, readers are referred, for example, to Meehl (1990) and McCreary and Anderson (1991).

The term "coupled model" has multiple meanings in the hierarchy of formulations developed to study various aspects of the coupled ocean-atmosphere climate system.

Non-dynamic ocean representations that have been used in coupled models include a "swamp" ocean (SST) or a simple mixed-layer ocean (Manabe *et al.*, 1975). The rapid increase of computer power has allowed longer runs with more complicated models. Furthermore, better understanding of observed phenomena (El Niño-Southern Oscillation, for example) has provided insight into the modelling of the coupled system. Then, several classes of models can qualify as coupled general circulation models. In the first, simplified continental outlines are specified (Manabe and Bryan, 1969). The second class of models uses some type of atmospheric GCM coupled to a limited ocean dynamic domain. These can include very simple coupled models of one ocean basin, as well as global atmospheric GCM coupled to a tropical Pacific Ocean model, for example, with climatological boundary conditions specified elsewhere (Zebiak and Cane, 1987; Latif *et al.*, 1988; Schopf and Suarez, 1988; Philander *et al.*, 1989...). The final class of coupled models comprises a global atmospheric GCM coupled to a global ocean GCM with some type of sea-ice formulations (Sperber *et al.*, 1987; Washington and Meehl, 1989; Manabe *et al.* 1990).

Given the prospects of increased computing power and faster, computationally more efficient models, we are at the threshold of a new era of coupled ocean-atmosphere modelling. As our understanding of the observed coupled climate system continues to improve, and models and computers become more sophisticated, coupled modelling can address problems involving atmospheric chemistry processes, detailed interactions with the biosphere, and climate sensitivity that is dependent on a more accurately modelled cryosphere (Meehl, 1990).

Limitations and perspectives of oceanic modelling

The attempt to simulate ocean variability by forcing ocean models with real winds and verifying the model response by comparing with oceanic data, brings observations and theory into an intimacy rare in oceanography, and provides a continuing arena for testing our understanding of dynamic and thermodynamic processes. Models constitute a powerful tool both to understand and to provide a global description in space and time of all the parameters needed for climate studies. The specific dynamics of the tropical upper ocean lead to affordable requirements for model resolution. Therefore it is not surprising that the tropical models have been the first to be developed in a now-casting context (Leetma and Ji, 1989; Morlière *et al.*, 1989b).

But, due to the uncertainties in the parameterization of the models, in the model forcings, in the boundary and initial conditions and in the mean climatological state, a great deal of work remains to be done in order adequately to simulate the entire ocean circulation in the tropics.

Blumenthal and Cane (1989) note that the determination of model parameters is a universal modelling problem. No ocean model, not even the most elaborate GCM, can include a complete representation of all ocean physics. Even if all the fundamental physics and computational dynamics are understood, it is still necessary to include the influence of subgrid scale processes on the larger scales which are retained. Attempts to do so rely on the assumption that these processes can be parameterized. A successful parameterization correctly represents the influence of the processes addressed on the scales retained in the model. In their paper, Blumenthal and Cane (1989) study the SST evolution which involves ocean dynamics and thermodynamics and surface heat flux representations. They first optimize the model parameters using a procedure which explicitly takes account of the uncertainties in the available data. The model/data discrepancies remaining after the parameters have been optimally chosen are analyzed to determine wether the present form of the model is adequate for simulating SST evolution. Their results show that while the physics included in the model are adequate to simulate SST in the Pacific, this is not the case for the Atlantic, because the poorly modelled coastal regions have a stronger impact on the circulation than the "open" ocean in the Atlantic. More recently, the development in the LODYC OGCM numerical code of a sophisticated parameterization in the mixed layer depth (TKE code) has greatly improved the simulation of all the variables of the model (Blanke and Delecluse, 1992). Studies on the numerical scheme related to the diffusion are also in progress (Marti *et al.*, 1992).

Nevertheless, the best numerical code will always suffer from uncertainty in the forcings, the boundary and initial conditions and in the mean state. The importance of wind forcing has been mentioned in this review and in various studies. Oceanographers have often complained about wind forcing inaccuracy, showing that different wind fields could induce different oceanic phenomena (du Penhoat and Gouriou, 1987; Morlière *et al.*, 1989 *a*). At present, wind data are issued from numerical atmospheric GCM and/or conventional observed data. Special attention will be paid in coming years to satellite winds, with the ERS1 scatterometer mission, for example. Previous studies comparing *in situ* and satellite winds demonstrate the ability of remote-sensed data to reproduce accurately atmospheric features (Etcheto and Banege, 1991). It is to be hoped that the combination of *in situ* measurements, remote-sensed data and AGCM simulations will provide winds of good quality, with adequate time and space resolution to force our models.

More controversial is the problem of atmospheric fluxes involved in OGCM. These fluxes are at the moment known with sometimes a 100 % relative error. Their importance for numerical simulations has also been thrown into relief, especially when SST is considered. For instance, Gent (1991) uses a reduced-gravity model of the upper equatorial ocean to study the heat budget in the western Pacific Ocean. He finds that the annual mean net heating of the ocean surface in this region is between 0 and 20 W m^{-2}. This is considerably less than the estimates given in climatic atlases which vary from about 30 W m^{-2} (Esbensen and Kushnir, 1981) to about 50 W m^{-2} (Weare *et al.*, 1981) and about 70 W m^{-2} (Reed, 1985). Liu and Niiler (1990) also demonstrate the great sensitivity of the latent heat flux to the air humidity approximations used in ocean circulation models. These fluxes are difficult to measure from space. Nonetheless, methods to compute ocean surface heat, momentum and water fluxes using satellite data are being developed and improved. Data systems such as ISCCP (International Cloud Climatology Project), Wetnet, GPCP (Global Precipitation Climatology Project) and SRB (Surface Radiation Budget), and projects such as GEWEX (Global Energy and Water Cycle Experiment) and EOS (Earth Observing System) are being investigated to address those questions. An example of thermal forcing derived from satellite data over the tropical Pacific is given in Liu and Gautier (1990).

In addition to the accuracy of the forcings, model simulations are dependent on boundary initial conditions which are often at least as poorly known as forcings. Lateral rather than bottom boundaries have a strong influence on the surface circulation. *A priori*, the shape of the eastern and western boundaries is important for ocean wave reflection. It is shown by du Penhoat and Cane (1991) that this is not crucial in the Western Pacific. On the other hand, the assumptions made on the boundary between the Indian and the Pacific Oceans are determinant for the simulations of the circulation in the Indian Ocean: this can be seen by comparing shallow-water models of the Indian Ocean which have open boundaries (Woodberry *et al.*, 1989), closed boundaries (Périgaud and Delecluse, 1991), or connection with the Pacific Ocean (Kindle *et al.*, 1989). Similarly, the southern boundary condition has a key role in the mean state balance between the northern and the southern basins in the Indian Ocean. This can be evidenced by comparing the previous simulations, which are derived from boundaries ranging from 40° to 25°S, with different conditions. In the Atlantic Ocean, Busalacchi and Blanc (1989) show that the large-scale interior solutions of a shallow-water model forced by idealized winds and a realistic Atlantic cycle are relatively insensitive to the choice of boundary conditions. However, the mere existence of certain western boundary features such as coastally trapped jets, is strongly dependent on the choice of boundaries under mean and seasonal equilibrium conditions. In particular, only those solutions with an open western boundary are able to simulate the continuous North Brazil current during spring and the eastward veering of this current in the North Equatorial countercurrent in autumn. This problem of boundary conditions is also encountered with OGCM in the Indian Ocean; and in the tropical Pacific and Atlantic Oceans, the northern and southern boundaries are generally relaxed to Levitus climatology. However, altimetry is *a priori* an efficient way to constraint sea-level variability at these boundaries.

Similarly, models suffer from the lack of good initial conditions. The use of altimetry is a partial solution which constrains the sea level state relative to the mean climatological state. The question of the accuracy of the mean state is indeed crucial. De Mey (pers. comm., 1992) has shown that assimilation of altimetric sea level variations permits improvement of the estimate of the mean circulation in the mid-latitudes. This has not yet been demonstrated in the tropics.

ALTIMETRIC DATA

What is altimetry ?

First, let us briefly review how altimetry can be used by oceanographers. The altimeter measures the distance from the spacecraft to the ocean, the orbit of the spacecraft being determined by independent ground tracking. Thus, the difference between the altimeter measurement and the orbit primarily indicates large permanent undulations of the geoid. The difference also contains the oceanic circulation which corresponds to a signal of much weaker amplitude. As the time-invariant geoid is generally not known with a good accuracy for oceanographic studies, attention is paid only to the oceanic variability by subtracting to the altimetric data a mean value representative of both the unknown geoid and the mean oceanic circulation (Bernstein *et al.*, 1982). This time-varying part of the altimetric signal is derived from the difference between two altimeter measurements at the same point, either using along-track data if the mission is an exact repeat mission (parts of the Seasat and Geosat missions), or at the crossover points between ascending and descending tracks.

Along-track and/or crossover differences not only contain the oceanic variations. They are polluted by a variety of time-dependent signals which are "errors" for oceanographers (orbit ephemeris, ionospheric and tropospheric corrections, tide signals, sea state bias...). We shall examine later which, among these errors, are the most crucial for tropical studies.

Altimetric missions

Five generations of altimeters have been launched since 1973: Skylab in 1973, Geos 3 in 1975, Seasat in 1978, Geosat in 1985 and ERS1 in 1991. The accuracy ranges from about one metre for the first missions to several centimetres for the most recent. Only Geos 3, Seasat and Geosat have been useful for oceanography; Skylab was not accurate enough, and ERS1 has been launched only recently. Geos 3 was launched - not on an exact repeat orbit - in April 1975 and delivered data until December 1978, but with large gaps in time and space depending on the location and the availability of ground stations. The high frequency noise for Geos 3 was estimated at about 30 cm (Agreen, 1982). Seasat had a better altimeter (about 7 cm accuracy), but worked from 7 July 1978 to 10 October 1978 with only 24 days of exact repeat mission (3-day period). The Geosat mission lasted 54 months, from March 1985 till September 1989. The first 18 months constituted a classified geodetic mission and only crossover differences were released to the oceanographic community (Cheney *et al.*, 1987). The exact repeat mission began in November 1986 with a 17.05 day period. Therefore, Geosat, with its long series and its 4 cm accuracy, provides oceanographers a unique opportunity to address the low-frequency variability of the oceans.

Errors and corrections

As mentioned earlier, altimetric raw data involve different signals, which for oceanographers look like "pollution" and must therefore be eliminated. Moreover, in the tropics, where the amplitude of the oceanic signal is not too large (10 cm) in comparison, for example, with the Gulf Stream and the Kurushio or the Aghulas current high variability regions (over 30 cm), the signal to noise ratio is small, and specific attention must be paid to the elimination of these errors.

Several corrections do not appear to play a key role for tropical regions. Sea state bias, for example, is usually small in tropical regions. Small-scale ionospheric variations are concentrated in equatorial regions, but they are *a priori* decorrelated from the seasonal oceanic signal. Large-scale variations (due principally to solar radiation, which was minimal in 1975-1977) are probably well reduced by polynomial adjustment. Due to satellite aliasing, the M2 tidal signal can also affect the annual signal variations (Jacobs *et al.*, 1992; Périgaud and Zlotnicki, 1992, this issue). But most disturbing are the errors associated with the troposphere (especially for the wet component), the orbit ephemeris uncertainty and the orbit error removal process.

Seasat, but not Geosat, had a radiometer on board to provide simultaneous water vapour information. For Geosat, the water vapour content was first corrected using either the FNOC model or SMMR data climatology (Cheney *et al.*, 1987). More recently, new corrections have become available (SSMI since July 1987 or TOVS data), and studies emphasize the wide range of variability (spatial and temporal) of the tropospheric corrections in the tropics (Emery *et al.*, 1990; Monaldo, 1990; Jourdan *et al.*, 1991).

Orbit uncertainty is also a dominant problem in the tropics. Because orbit error has a long wavelength (the dominant error is at one cycle per revolution of the satellite), it is particularly crucial for large-scale studies, which represent, as we shall see, the major part of tropical investigations. The Seasat PGSS4 orbit accuracy was about 70 cm, and the best orbit released for the first two years of the Geosat exact repeat mission has a 40 cm accuracy (GEMT2). Classical methods of orbit error reduction (by polynomial fit over long arcs) do not separate the orbit and the oceanic signal in a large scale context, and a severe reduction of orbit error also reduces the oceanic signal.

However, even with these various limitations, altimetry has proved to be a powerful means of obtaining a global view of oceanic variability in the tropics. As noted previously, long wavelength errors, such as the orbit error, add to the difficulty of studying large-scale variability in the tropics. Thus, we try to divide this "altimetric" review into "mesoscale" and "large-scale" components, even if these concepts are sometimes difficult to separate in the tropics.

Mesoscale variability and local comparisons

Because of the short duration of the mission, most oceanographic studies using Seasat data relate to mesoscale investigations, in particular in the highly energetic and narrow western boundary currents. Indeed, the Seasat special issue of the *Journal of Geophysical Research* (1982) does not contain any paper specially dedicated to tropical studies. However, the originality of the tropical oceans stands out among the global results on mesoscale activity. For example, Cheney *et al.* (1983) compute global maps of mesoscale variability from Seasat, showing a mean value around 6 cm for tropical oceans, which is lower than anywhere else in the world. Fu (1983) shows that the Seasat along-track spectrum is significatively different between high energetic regions (k^{-5} spectrum) and low energetic areas (k^{-1} spectrum).

A few years later, Seasat studies specifically devoted to the tropical regions appeared, with comparisons between altimetric data and "conventional" *in situ* measurements. In the Indian Ocean, for example, Périgaud and Minster (1988) find a good agreement between altimetric results and dynamic height derived from merchant ship expendable bathythermographs (XBT). Combining XBT, crossover and alongtrack differences, these authors map the variability of the great whirl in the Somali current.

Thanks to the long duration of Geosat, these preliminary works have been pursued and the oceanic variability assessed with better reliability. Zlotnicki *et al.* (1989) compare Geosat global mesoscale variability maps with those of Cheney *et al.* (1983), and show that the use of Geosat longest data series increases mean values. Studying the seasonality of this variability, they find that although the strongest changes occur in mid-latitude western boundary currents, variability in the tropics presents a zonal pattern of a 6 to 9 cm rms amplitude which is larger than in the eastern mid-latitude basins. As for Seasat, the first tropical experiments have been conducted to assess Geosat accuracy by comparing local (in time or in space) altimetric and *in situ* measurements. Cheney *et al.* (1989) find that the rms differences between Geosat crossover time series and sea-level tide-gauge anomalies at fourteen stations in the tropical Pacific is about 4 cm and the correlation is 0.7. Taï *et al.* (1989) compare Geosat data with dynamic height derived from XBTs and also with Pacific island sea-level data. Overall, the three fields show statistically significant correlation with one another, with better agreement in the northern hemisphere. At island sea-level stations, altimetry generally correlates better with tide-gauges (0.64) than with the XBT-derived dynamic height (0.46). Still in the Pacific Ocean, Périgaud (1990), comparing Geosat and tide-gauge energy spectra, finds little sign of aliasing due to the satellite sampling. Only part of the highest frequency energy is missed by the 17-day repeat satellite and not fully recovered by the space-time analysis of adjacent descending and ascending arcs. Another local comparison in the Pacific is done by Picaut *et al.* (1990). They use the meridional second-order derivative of the along-track altimetric sea level differences to determine the geostrophic equatorial zonal current variability. They demonstrate the ability of their original approach by showing a good agreement between their altimetric results and currentmeter observations along the equator, at 165°E, 140°W, 110°W (respective correlations of 0.83, 0.85 and 0.51; mean rms difference of 23 cm/s). In the Atlantic, Carton and Katz (1990) find a good correlation between monthly sea level and six inverted echo sounders in the northwestern tropical Atlantic. Arnault *et al.* (1992) organize in October 1988 the *Aramis 1* campaign, to compare the along-track altimetric signal with dynamic height computed from XBT temperature profiles and salinity samplings. North of 5°S, the correlation between the two signals is about 0.9, with a mean rms difference of 3.5 cm.

All these comparisons are highly conducive to confidence in the results derived from altimetry in the tropical oceans. But limitations need to be kept in mind. Wyrtki and Mitchum (1990) show that interannual altimetric sea level changes are dubious unless benchmarked by tide-gauge data. Furthermore, in all these local comparisons, assumptions have to be made to match the time and space resolution of the satellite with *in situ* measurements. Identification, from altimetry, of oceanic processes could lead to great confidence in altimetric results. Hansen and Maul (1991), using Geosat data together with drifting buoys, XBTs and hydrological samples, describe anticyclonic eddies that occur off the Pacific coast of central America. They interpret their formation as a result of potential vorticity conservation when the North Equatorial CounterCurrent (NECC) turns northward upon approaching the coast during its autumnal maximum.

But perhaps the most astonishing results regarding the identification of expected tropical processes have been obtained with large-scale studies.

Large-scale investigations

Although more difficult to obtain due to the possible pollution of the altimetric signal by long-wavelength error, results on large-scale variations appeared with the early Geos 3 and Seasat. Using crossover analysis of Seasat data in the Indian Ocean, Périgaud *et al.* (1986) find an adequate averaging to detect sea-level slope variations along the equator which present some consistency with climatology. A most promising approach for large-scale low-frequency studies is demonstrated by Ménard (1988) in the Atlantic. He combines Geos 3 and Seasat altimetric data with a reference mean sea surface and shows that the mean seasonal cycle obtained is in rather good agreement with the climatological 0/500 dbar dynamic topography (Merle and Arnault, 1985). In the Pacific, Malardé *et al.* (1987) derive from Seasat a 1 000 km zonal wavelike structure, with an amplitude of 15-20 cm, moving westward along 4.5°N at about 40 km per day. Its occurrence is consistent with surface temperature front undulations observed by Legeckis (1977).

As remarked before, due to its unmatched spatial and temporal coverage, Geosat significantly improves our learning of large-scale processes from altimetry. The last two Atlantic and Pacific studies mentioned above were pursued using Geosat by Arnault *et al.* (1990) and Périgaud (1990). Following Ménard (1988), Arnault *et al.* (1990) find consistency between monthly Geosat sea-level anomaly maps over the tropical Atlantic from November 1986 to November 1987 and the climatological large-scale signal of the dynamic height. The agreement is particularly good in the NECC region. Périgaud (1990) derives an energy spectrum of oceanic variations with frequencies lower than twenty days from two years of Geosat over the entire tropical Pacific. The energy peak is found along 5°N in the 28-40 day period and 1 000-2 000 km wavelength with a 35 km per day westward propagation. These waves, generated by barotropic instability of the surface westward South Equatorial Current (SEC) and the eastward NECC (Philander, 1978; Cox, 1980), seasonally oscillates as the SEC/NECC shear does.

Altimetric observations have also been dynamically interpreted, in particular from analysis of contemporaneous wind fluctuations. This was all the more convincing with Geosat as the satellite flew during the highly contrasted 1986-1987 El Niño and 1988 La Niña events. With the early

Fig. 2. (**A**) Altimeter-derived sea level time series at 13 locations (8° intervals between 166°E and 98°W) along the equator, April 1985 through April 1987. Sea level was computed in the same manner as in Fig. 1A. Horizontal lines indicate zero mean values for the first 12 months (April 1985 through April 1986) with 20-cm offset between pairs of series. (**B**) Histogram along the *x*-axis indicating the time intervals during which westerly wind bursts were persistently observed in the far western equatorial Pacific. The histogram was constructed by summing the number of days for which analyzed westerly winds greater than 5 knots were found in each 5° by 5° box in the region 0° to 5°S, 130°E to 170°E (*19*).

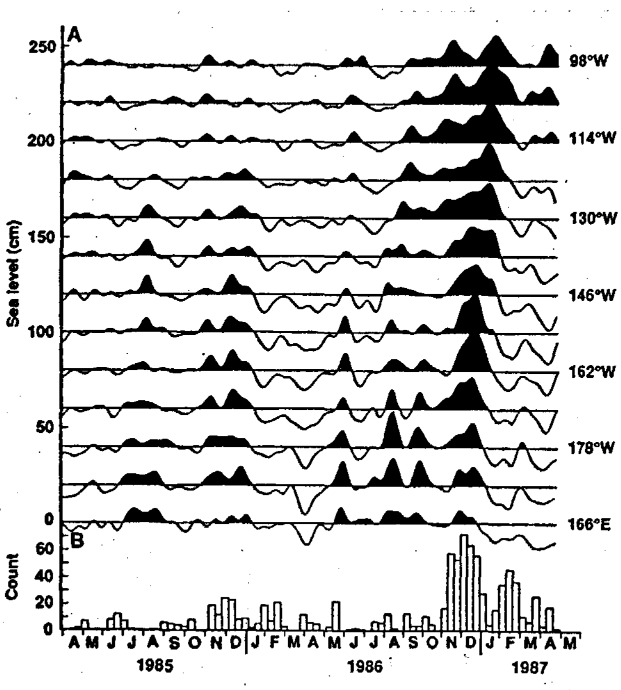


Figure 3

Observations of Geosat sea level time-series in the tropical Pacific Ocean, from Miller et al. *(1988).*

Observation du niveau de la mer par le satellite altimétrique Geosat dans l'Océan Pacifique tropical, d'après Miller *et al.* (1988).

geodetic Geosat mission, Miller *et al.* (1986), using cross-over analysis, demonstrate for the first time the propagation of an equatorial wavelike pattern, moving eastward at a speed of 3 m/s, between May and June 1986. Later, Miller *et al.* (1988) detail this analysis of eastward propagating anomalies along the equator associated with the 86-87 El Niño (Fig. 3). Both positive and negative anomalies of 10-centimetre amplitude and a 2 to 4-week time scale propagate across the Pacific with phase speeds of 2.4 to 2.8 m/s, suggesting downwelling and upwelling Kelvin waves. The positive anomaly (downwelling Kelvin wave) seem to be related to outbursts of westerlies in the western Pacific in May 1986. Delcroix *et al.* (1991) go further in the interpretation of these propagating anomalies in terms of equatorial waves. They correlate the generation of the equatorial downwelling Kelvin wave in December 1986 with a strong westerly wind anomaly occuring west of the dateline. Its phase speed (2.28 to 2.82 m/s) and meridional structure are characteristic of a first baroclinic mode. Equatorial upwelling Kelvin waves are then detected in January 1987 propagating all along the equator, and in June 1987, propagating from the western to the central Pacific. A first meridional mode equatorial upwelling Rossby wave crossing the entire Pacific from March 1987 to September 1987 is also identified at 4°N and 4°S. The phase speed (1.02 m/s) is characteristic of the first baroclinic mode and roughly corresponds to the theoritical c/3 (m = 1) phase speed. The authors suggest that these Rossby waves could be partly due to a reflection of the January 1987 Kelvin wave. The consequences of these waves on the zonal currents are very important as the major equatorial currents are weakened by an amplitude similar to their mean annual velocity values. In the Atlantic, the large-scale latitudinal meandering of the core of the NECC is also strongly related to the wind stress curl obtained from satellite data (Arnault *et al.*, 1991 *a*). The NECC core reaches its northernmost position during boreal summer, as does the wind stress curl. An unusual southward position of the current is detected during 1988, one year after the Pacific El Niño, as was already the case in 1984 after the 1982-1983 El Niño. Therefore, interannual events can also occur in the Atlantic following a Pacific El Niño.

Furthermore, the demonstration that the altimetric variations are wind-driven has been made by comparison with numerical model simulations. In the Indian Ocean, Périgaud and Delecluse (1991) compare Geosat data with a non-linear shallow-water model forced by observed winds from 1985 to 1989 (Fig. 4). Good agreement is found for the annual, the semi-annual and the interannual variations for sea level. Surprisingly, the strongest annual variations occur over a large region in the southern tropical Indian Ocean along the SEC. They propagate westward and poleward, and are free propagating Rossby waves radiating away from the eastern boundary. The semi-annual variations are concentrated on both sides of the equator and are identified as Kelvin and Rossby equatorial waves generated by the semi-annual reversal of the zonal wind stress in the central basin. The strongest interannual variations between 1985 and 1989 are found in the southern tropical Indian Ocean with a maximum basin-wide upwelling in winter 1987 as opposed to a maximum downwelling in winter 1988. In the tropical Atlantic, Arnault *et al.* (1991 *b*) compare Geosat data with the results of two models forced by monthly 1986-1988 winds: one is a simple linear vertical mode-model, and the other is the LODYC OGCM (Fig. 5). They evidence the agreement on the low-frequency variability of the tropical Atlantic between the OGCM and Geosat. Interannual features such as the appearance of warm waters in the Gulf of Guinea in spring 1988 are evi-

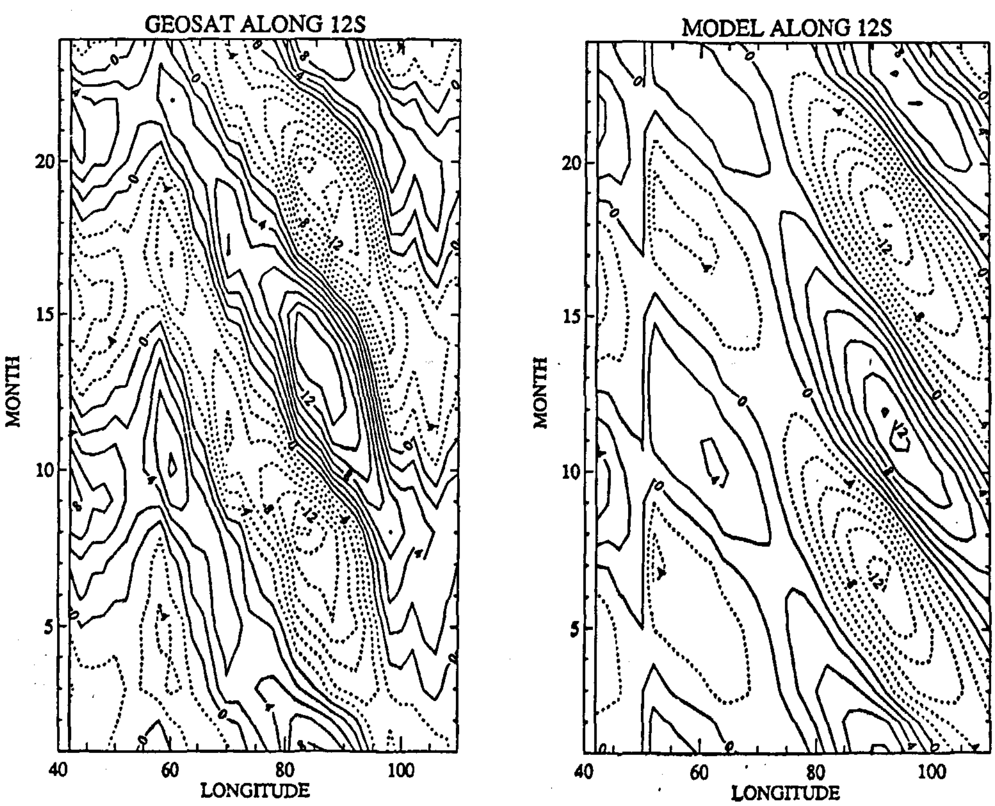


Figure 4

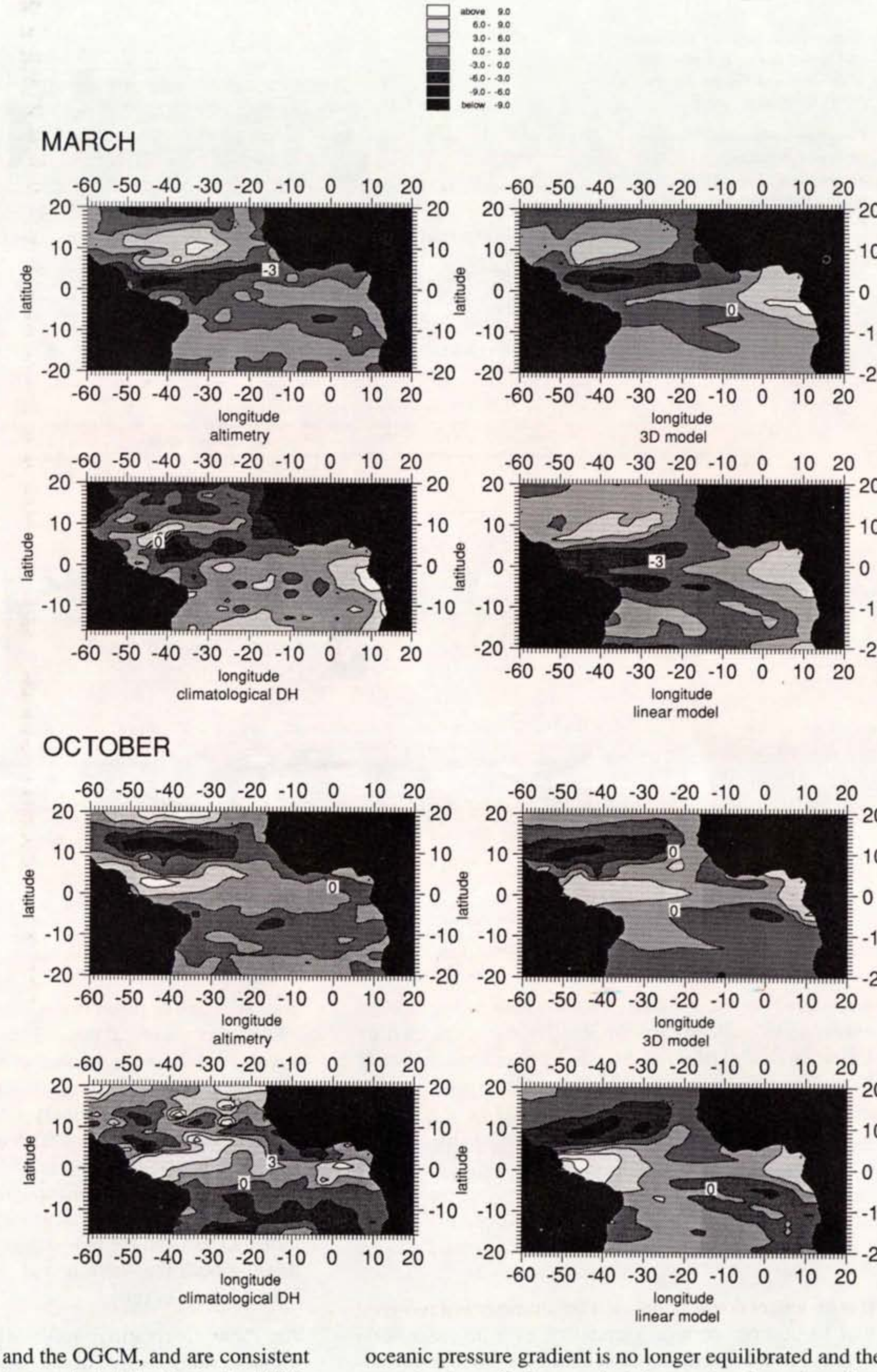
Comparison between Geosat and model sea-level variations in the tropical Indian Ocean, from Périgaud and Delecluse (1991).

Comparaison entre les niveaux de la mer provenant du satellite altimétrique Geosat et d'un modèle numérique dans l'Océan Indien tropical, d'après Périgaud et Delécluse (1991).

Figure 5

Comparison between Geosat and model sea-level variations in the tropical Atlantic Ocean, from Arnault et al. *(1991* b*).*

Comparaison entre les niveaux de la mer provenant du satellite altimétrique Geosat et d'un modèle numérique dans l'Océan Atlantique tropical, d'après Arnault *et al.* (1991 *b*).



denced both by Geosat and the OGCM, and are consistent with the response of the tropical Atlantic to the 1986-1987 Pacific El Niño. The interpretation could be the following: warm water extension all along the equator in the Pacific, between April and September 1983/1987, displaces the atmospheric Walker cell. As a result, trade winds intensify over the Atlantic and thus, the pressure gradient force. In January 1984/1988, when things return to normal in the Pacific, the Atlantic winds weaken, the oceanic pressure gradient is no longer equilibrated and the warm waters piled up against the western boundary flow back eastward in the Gulf of Guinea. In the Pacific, Cheney *et al.* (1989) compared Geosat observed sea level variations with OGCM simulations in 1985-1986 (Fig. 6), while du Penhoat *et al.* (1992, this issue) compare Geosat results with simulations from a shallow-water model forced by climatological winds and observed winds simultaneous with Geosat. They determine the repartition bet-

Figure 6

Comparison between Geosat and model sea-level variations in the tropical Pacific Ocean, from Cheney et al. *(1989).*

Comparaison entre les niveaux de la mer provenant du satellite altimétrique Geosat et d'un modèle numérique dans l'Océan Pacifique tropical, d'après Cheney *et al.* (1989).

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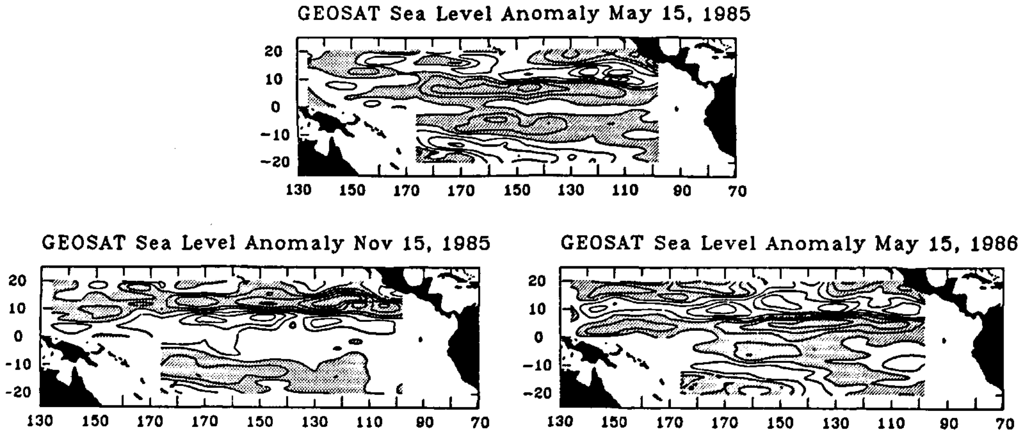


Fig. 11. Sea level anomaly based on Geosat altimetry. Three maps are shown at 6-month intervals to illustrate the dominant annual signal seen by the altimeter; May and November represent the peak signal along the equator. Maps are constructed from independent time series, each determined using all altimeter data in an 8° × 1° area. Anomalies represent departures from a 1-year mean, April 1985-1986. Contours are at 4-cm intervals; areas with negative values are shaded.

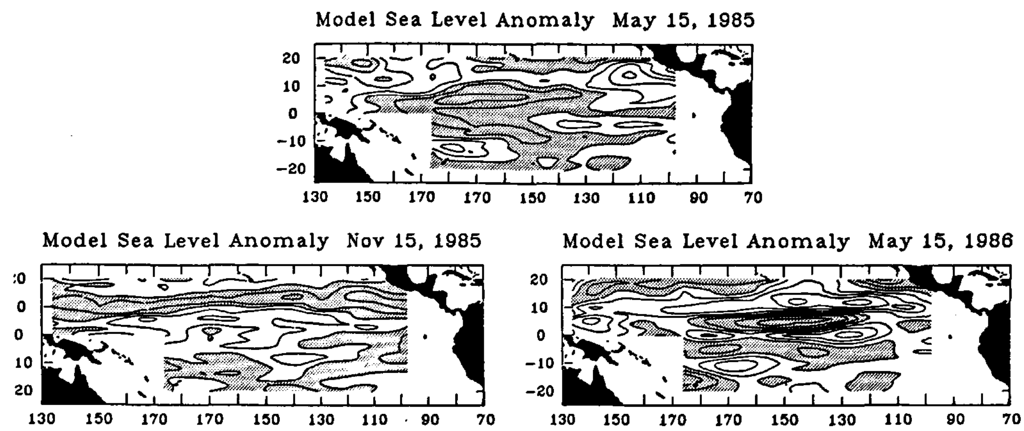


Fig. 12. Sea level anomaly computed from an ocean general circulation model driven by winds (A. Leetmaa and M. Ji, personal communication, 1988). The three maps correspond in time to the Geosat maps in Figure 11 and are plotted using the same conventions (4-cm intervals, negative shaded). For the 1-year period April 1985 to March 1986, rms agreement with Geosat is approximately 4 cm.

ween wind-forced and reflected waves during the El Niño event, and conclude that the Rossby wave detected by Delcroix *et al.* (1991) in March 1987 is mostly locally wind-forced rather than Kelvin wave reflection.

Thus, important results have been brought by altimetry in the tropical regions. We shall now analyse the limitations of the present data and the perspectives offered with the next altimetric missions.

Limitation and perspectives

It is no longer doubted that satellite altimetry is a powerful tool to observe oceanic variability, even in large-scale events. For the first time, oceanic features - such as equatorial waves - have been observed on a basinwide scale. However, today's available altimetric data come from non-dedicated satellite missions. Obviously, use of Geos 3 data is limited by the poor accuracy of its altimeter and the inhomogeneity and discontinuity of its coverage. Use of Seasat is limited by the short duration of the mission. Use of Geosat is limited by the lack of good tropospheric corrections. Furthermore, all three missions suffer from the poor accuracy of their orbit ephemeris. Different studies in all three oceans reveal that orbit is the more important error source for large-scale studies, even after the best improvement of orbit computation performed for Geosat and Seasat (40 cm accuracy). Nonetheless, large-scale seasonal and interannual variations have been detected and successfully interpreted from altimetry. In addition, these observations bring new results which oceanographers had not yet identified, such as the strong annual variations of the SEC in the Indian Ocean and the importance of the interannual variations in both the Atlantic and Indian Oceans during El Niño-La Niña events.

Are these observations accurate enough, however, to be useful to study the role of the ocean in climate, to quantify mass and heat transport of the ocean ? The answer to this question remains to be given. A promising future is on the way with the dedicated Topex/Poseidon mission, launched in mid-1992, with much better tracking and on-board radiometer. But even with existing altimetric data, it is worth pursuing the effort to extract as much information as possible. For example, ongoing research consists in interpreting the systematic difference between all observations together *versus* all simulations together. The best approach to this kind of problem lies in the assimilation of altimetric data into numerical models.

MERGING THE INFORMATION

Introduction

As we have seen, observations and simulations alike present limitations. The following question is addressed: what is the optimal estimate compatible with both observations and models, given their specific errors ? To provide an answer to this question is the purpose of data assimilation in numerical oceanic models. Indeed, given the complexity of the problem, different methods, which are first briefly recalled here, have been developed. Data assimilation in oceanography is fairly recent and methods applied to models of the tropical ocean and altimetric data are few. As mentioned in the first section of this paper, equatorial dynamics is specific, giving rise to specific problems in data assimilation. In particular, the sea level cannot be directly used as in mid-latitudes to constrain the stream function. As explained by Crépon (pers. comm.), in the tropics, it is rather related to the vertical density structure. Also a small amplitude of sea level variation corresponds to a large velocity of geostrophic current. Thus, errors in sea level can give rise to large erroneous current fluctuations. *Via* free waves (Kelvin and Rossby waves...), the information can be spread rapidly over large areas of the oceans. Furthermore, whereas mid-latitudes have no free waves for intermediate frequencies (between 2 and 100 day^{-1}), all frequencies are covered without discontinuity in the tropics *via* the mixed Rossby gravity waves. This is why spurious waves can be generated during assimilation in the tropics. Some of these aspects have been examined in connection with the assimilation of conventional or simulated data, and are reviewed here. Then data assimilation studies of conventional data done for hindcast estimates are described. Finally studies using actual altimetric data are examined.

The methods

A detailed review of data assimilation can be found for example in Talagrand (1981) and Ghil and Malanotte-Rizzoli (1991). A special issue on data assimilation is also published in *Dynamics of Atmospheres and Oceans* (vol. 13, n° 3-4, June 1989). Up to now, oceanographers have used different methods which are either suboptimal or optimal. This qualification does not mean that one method is better than the other one, but rather corresponds to different objectives. To simplify, one may say that the suboptimal method consists in using observations in a model to drive simulations and/or predictions closer to reality - a practical objective which carries high potential to face the major caveats of modelling as previously described (*e. g.* boundary, initial conditions, mean state...). This approach is numerically easy to handle and has been applied to sophisticated models. The optimal approach, on the other hand, consists in combining observations and simulations in order to estimate the best fit (given the specific errors of data and models). The results are derived from the complete minimization in space and time of the difference between the data and model variables. Results show how much variance of the data can be explained by a model (which for example can be an isolated process far from the complex reality). Then, the objective is not necessarily to obtain an estimate as close as reality. It is rather to establish rigorously the best estimate compatible with data, model and their respective errors. In addition, the optimal approach can be used to improve simulations via estimations of model parameters, forcing, boundaries and/or initial conditions. The optimal approach can help to provide the best estimate of those unknowns.

There exists a variety of suboptimal methods, but only two different optimal ones. The suboptimal methods consist in assimilating data by regular updating, after suboptimal analysis (Cressman, 1959; Bratseth, 1986), after objective analysis (Bretherton *et al.*, 1986;De Mey and Robinson, 1987) or variational methods (Provost, 1983; Bourles *et al.*, 1991), or nudging (Verron, 1990). The optimal approach is either Kalman filter (and smoother) or adjoint. Kalman filter (Miller, 1986; Gaspar and Wunsch, 1989) computes the error covariance matrix of the forecasted field at each time step. This requires detailed knowledge of model and data errors, and its numerical cost is usually expensive. The Kalman filter and smoother computes the same minimization of the difference between model and data at each time step, but the integration is performed backward in time so that future data also contribute to the estimate at a given moment. The adjoint approach performs the same minimization once over the whole time when data are available for assimilation. Instead of each time step, the global minimization is iterated until convergence is reached. The adjoint approach with the weak constraint also permits the introduction of model error into the minimization, so that Kalman filter and smoother or adjoint method applied on the same data, same model, with the same model and data errors give identical best fitted estimates.

Assimilation of conventional or simulated data in tropical models

Up to now, there have been few attempts to assimilate real altimetric data in the tropics. Most studies have made use of "conventional" data sets or "idealized" data.

In the Indian Ocean, Moore *et al.* (1987) regularly update a linear reduced gravity model and a non-linear twelve-level OGCM, with simulated (generated from the same model) temperature data and velocity data. They find that, for this twin experiment, initializing either model with temperature data is better than velocity. However, for the simple model, increasing the diffusion and decreasing the eddy viscosity inverse the results as the energy distribution is changed (kinetic energy being greater than potential energy). They also assimilate data from the TOGA Indian Ocean XBT network using a successive correction and interpolation scheme. For the layer model, the errors fall to zero after a couple of months, whereas for the OGCM there is little reduction of the error because the analysis scheme is not able to resolve the small-scale structures of the model. This highlights the problem of assimilating data with short length scales, particularly near the boundaries. Cooper (1988) follows on this study to investigate the effect of neglecting salinity on models. His results show that providing only temperature or only salinity data produces larger errors on the velocity fields than using no data at all! In the Pacific Ocean, Moore (1989) uses a reduced-gravity model to assimilate XBTs data from the ship-of-opportunity network following the data interpolation procedure of Moore *et al.* (1987). Initializing the model with observations in the Western Pacific generates a shock larger than in the Eastern Pacific. Attempts to suppress these waves cause greater damage on the model first-guess fields than if they are left unchecked. Moore and Anderson (1989) add that, away from the equator, in the Western and Central Pacific, the structure of any isotherm in the thermocline can be retained for up to twelve months. In the Eastern Pacific, the improvement from data assimilation is lost more quickly because it is not balanced by the forcing. They also note that the planetary waves excited by the assimilation on a time-scale of a month degrade the solution in the east, and eventually propagate westward and degrade the solution there, too. They conclude that the data retention period of the model will therefore be a function of the model stratification and the forcing fields used. Miller and Cane (1989) apply a Kalman filter to a two-vertical mode, five-meridional mode linear wind-driven model to assimilate tide-gauge data in the tropical Pacific. They assume that the model errors are dominated by the errors in the wind stresses. The resulting maps of sea level exhibit fine structures absent from the original model outputs. The error estimates suggest that there is a reduction of the error by the filter by about 1 cm in the equatorial wave guide which is a great deal, bearing in mind that only five data points were assimilated. The few independent verification points available are also consistent with this estimate. Also in the Pacific, the adjoint technique is used in a shallow-water model of the tropical Pacific by Smedstad (1989). Then, the sea level zonal distribution, between 1979 and 1984, is in good agreement during El Niño year, but the converse for non-El Niño year. Long and Thacker (1989) also use a simple long-wave low-frequency model of the tropical Pacific to assimilate simulated data with the adjoint method. They evidence a good recovery with full density surface and subsurface data, as well as with only subsurface data. Finally, Sheinbaum and Anderson (1990 *a*, *b*) use a variational method based on the adjoint technique to assimilate XBT data. The model is a linear reduced gravity model. The XBT data contain large-scale information that corrects the model first guess. However, due either to error in forcing or model deficiency, the model is not capable of fitting the data in the eastern basin. But it is noteworthy that no spurious waves are generated with this technique as opposed to the Moore and Anderson's case (1989).

Operational hindcasting context

In an operational hindcasting context, Leetmaa and Ji (1989) mention that until forcing fields are improved, accurate simulations will require the use of data assimilation. The GFDL OGCM they use, give excessively cool SST in the eastern Pacific and too warm SST in the western ocean. Therefore, first experiments were carried out to gain experience in the assimilation of thermal data. A monthly global SST field (Reynolds, 1988) is used together with XBT data to correct the model. They are assimilated by first objectively mapping the difference between the mid-month model fields and XBT observations. This difference field is then used to correct the model subsurface thermal structure, mixed layer depths are determined, and mixed layer temperatures are forced equal to the monthly global field. The model is then stepped forward another month using the forcing fields, and the assimilation is repeated at the mid-point of each successive month. Hayes *et al.* (1989) analyse the results of the assimilated run by comparing the simulated currents with mooring data which were not taken into account in the procedure. The inclusion of thermal observations generally improves agreement between simulated and observed time series. This improvement was largely due to reduction in the mean offsets of SST and thermocline depth. Data assimilation did little to improve the month-to-month differences in thermocline depth. In addition, south of the equator in the Eastern Pacific, relatively large and systematic intramonth SST deviations occur. These deviations correspond to an erroneous heat flux of about 80 W m^{-2} and the dynamics is inadequate to evacuate excess heat introduced by the corrected terms. But it is interesting to note that although no velocity data was assimilated, the improved model thermal structure leads to improved velocity simulation. In the Atlantic, another OGCM (from LODYC) is run operationally by Morlière *et al.* (1989 *a*). Morlière *et al.* (1989 *b*) assimilate temperature on an operational basis during 1984. The method of assimilation is similar to those of Leetma and Ji (1989): from the observed data, an analysed temperature field is produced using successive corrections (Cressman, 1959) and the simulated temperature field as guess field. The difference between the analysed and the simulated temperature fields is then introduced as a corrective term in the heat equation of the model. The authors find that, after assimilation, the thermocline is stengthened, and low-frequency variability near the equator is close to the observed one, resulting in a more realistic zonal slope of the thermocline. The current structure, although it still differs noticeably from the observations, is more realistic, with stronger near-surface countercurrents and a faster equatorial undercurrent. Carton and Hackert (1990) begin a four-dimensional data assimilation procedure on the GFDL OGCM in the Atlantic, with a first guess of the three-dimensional fields of temperature, salinity and possibly velocity. These first guesses may be provided either by a climatological data set or by numerical simulation. The first guess temperature fields are then corrected by a series of updating steps carried out on the fifteenth of each month of the analysis. The corrected fields become that month's analysis of the state of the ocean, and may also be used as initial conditions for a numerical integration providing the first guess fields for the following month's analysis. Then, the amplitude of the seasonal changes in the meridional thermal gradient is doubled at 38°W, bringing the analysis closer to the observations. The zonal gradient along the equator is increased, as the month-to-month variability. Here again, assimilation also improves some features of the velocity field, such as the depth of the undercurrent core or the strength of the NECC. Finally, Derber and Rosati (1989) assimilate temperature data in a coupled GCM. A statistical interpolation (Gandin, 1963) provides corrective fields which are introduced at every time step in the model. Large-scale features in the SST are consistent with those presented by independent observations, and subsurface fields are more realistic. Furthermore, the information contained is shown to be retained in the solution after the assimilation procedure is terminated.

Real altimetric data assimilation

As stated earlier, there are few studies using real altimetric data for assimilation in tropical models. Due to the satellite sampling, data can be assimilated along-track one track at a time, along-track several tracks at a time, or from a gridded field. The last option could be seen as redundant with the problem addressed, however the "one-track assimilation" gives poor constraint in space and the assimilation of several tracks presents the problem of the determination of the observation error covariance as the errors are far from being Gaussian.

In the Indian Ocean, Périgaud et Delecluse (1989) use Seasat data to initialize the linear or non-linear versions of a reduced gravity model. An optimal analysis of Seasat data provides maps of oceanic variability, and successive corrections compute the difference between the simulated height and the data. This difference is directly introduced in the model, and the model is run from these new initial conditions of sea level. This reinitialization improves agreement between model and observations for the non-linear version, but not for the linear, as the impact of this data assimilation lasts less than a week for the linear model. In the Atlantic, Bourles *et al.* (1991) use a variational approach (Provost, 1983) to regularly update a three-vertical-modes model forced by monthly wind stresses (Fig. 7). The altimetric data were previously monthly-gridded using an objective analysis (De Mey and Robinson, 1987), and then projected on the vertical modes of the model using the variational method. This analysis consists in a global minimization of a cost function over the entire basin. Data have been assimilated during 1987 and effective improvement of the simulation can be observed. In the Gulf of Guinea, where altimetric data are suspect, the dynamics of the model helps in reproducing the upwelling signal; and near the boundaries, when the dynamics of the model is poor, assimilation provides results in better agreement with data. However, strong anomalies along the coasts of Brazil and Guyana observed from Geosat are not reproduced by the simulation, due to the larger length scales used in the smoothing constraint. Two months after the last assimilation, in February 1988, the forecast remains strongly improved out of the equatorial band, essentially in the northern hemisphere. This work

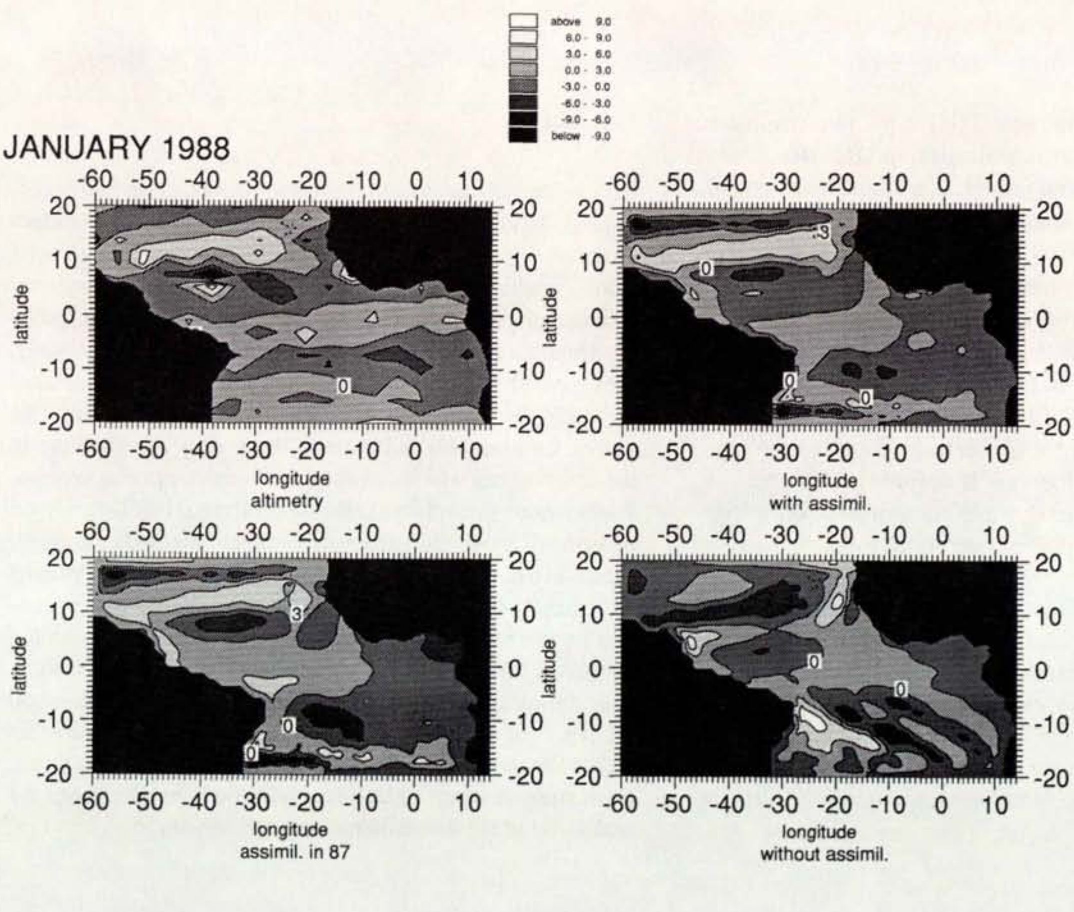


Figure 7

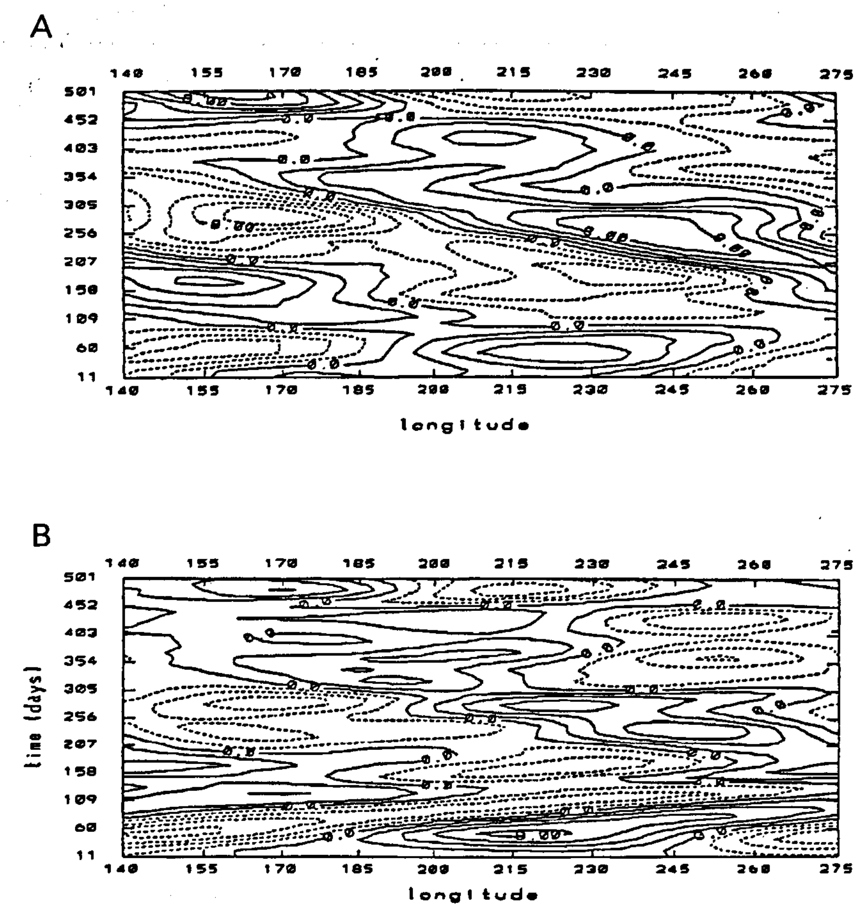
Assimilation of Geosat sea-level variations into a three-vertical-modes linear model by variational approach, from Bourles et al. *(1992).*

Assimilation, par la méthode variationnelle, des niveaux de la mer provenant du satellite altimétrique Geosat, dans un modèle numérique en ondes libres équatoriales, d'après Bourles *et al.* (1992).

Figure 8

Assimilation of Geosat sea-level variations into a model of free equatorial waves by Kalman filter, from Fu et al. *(1991).*

Assimilation, par filtre de Kalman, des niveaux de la mer provenant du satellite altimétrique Geosat, dans un modèle numérique en ondes libres équatoriales, d'après Fu *et al.* (1991).



Time-longitude plots of the sea level anomalies represented by the four-wave model solutions at (a) 4°N* and (b) the equator.

has been carried out more recently over the two complete years of the Geosat exact repeat mission (Bourles *et al.*, 1992, this issue). The same model, in a simplified version reduced to one mode, is also used to apply a Kalman filtering (Gourdeau *et al.*, 1992, this issue). In the Pacific Ocean, Fu *et al.* (1991) also investigate assimilation through Kalman filtering using a first baroclinic free Kelvin and Rossby wave model (Fig. 8). The Geosat data are introduced one track at a time, and the Kalman filter is used to estimate the amplitude and phase of the waves. The model error covariance is determined so that the performance of the model forecast is optimized. The results show that, among the fourty wave components, only four have significant amplitudes: the two longest Kelvin waves, and the two longest Rossby waves which are clearly the response of the model to data main features such as 1986-1987 El Niño event. The results show that 23 % of the variance contained in the oceanic part of the observed signal can be explained by these four free waves. In this example, the model was not supposed to be close to reality. More recently, Fu *et al.* (pers. comm., 1992) have applied the same approach to wind-driven equatorial waves.

Summary

For clarity, data assimilation methods can be classified according to: "optimal" and "suboptimal" approaches. The former (Kalman filter, adjoint method....) fully answers the questions from a mathematical point of view: they provide the optimal estimate given the model, the observations and their respective errors. As these optimal approaches are numerically heavy, they have up to now been applied to simple models. Optimal methods can resolve a specific phenomenon (linear free waves, for example) and quantify the amount of variability in the observations which can account for this particular process. Furthermore, unexplained observed variance can be analysed in terms of model deficiency. Suboptimal methods (nudging, successive corrections...) trigger the simulation to observation by regularly merging both. The main objective is then to correct for errors in simulation resulting from inadequate initial condition, forcing or diffusion terms or the numerical scheme. This merging can be performed on sophisticated numerical models such as OGCM. However, there is no general mathematical control of the merging in these suboptimal methods. Each study is a particular case and little is known about the sensitivity of the results to method deficiencies.

CONCLUSIONS AND DISCUSSION

To conclude, satellite data and numerical models have provided oceanographers with a uniquely powerful means of learning about tropical ocean large-scale dynamics. However, the use of altimetric data is limited by orbit uncertainty and errors in the tidal or in the wet tropospheric corrections. The Topex/Poseidon satellite, launched this year, was designed for a mission dedicated to oceanography (Stewart *et al.*, 1986). In particular, its orbit accuracy is expected to be far better than that of any previous altimetric satellite. All the major error sources have been eliminated *via* adequate engineering devices or will be controlled *via* adequate scientific analysis prepared by the Science Working Team (*see* SWT reports from 1989, 1990, 1991). It is thus most likely that Topex/Poseidon data will provide for five years sea-level variations with an exceptionally good accuracy. The analysis of those exceptional data is also most likely to provide evidence for other sources of error which have not yet been carefully examined (such as low-frequency orbit errors, other tidal components...). This is thus a new area for altimetry which will start this year. In addition, other altimetric satellites are flying or will be launched during and - it is hoped - after the Topex/Poseidon mission [ERS1, ERS2, Geosat follow-on,... (Koblinski *et al.*, 1992)]. Those missions will probably not have the accuracy of Topex/Poseidon, but the combination of the different altimetric missions is a promising approach for monitoring sea-level variations over at least a decade, with the adequate resolution in time and space, and - it is also to be hoped - the adequate accuracy to be able to monitor the large-scale low-frequency variations of sea level.

Nonetheless, this is only part of what is needed to describe, understand and predict overall oceanic variability and its role on climate changes. Numerical models offer another approach, but the use of models is limited by several factors. First, forcings are far from being accurate enough. Up to now, winds (either observed from ship or simulated by atmospheric models) are desperately inaccurate. They will perhaps be better monitored when satellite scatterometry becomes operational. It is greatly to be regretted that the NSCAT mission was cancelled in 1989 and will hardly be contemporaneous with Topex/Poseidon. This mission is definitely crucially needed to fulfill WOCE objectives, especially in the tropics where the circulation is so directly related to the winds. Thermodynamic forcing is also a great unknown. Up to now, climatological data and empirical formulae have been used. For the future, missions to investigate the radiative budget and water fluxes at the air-sea interface are being developed. Models also suffer from the inaccuracy of parameterization (diffusion in particular). Modellers are analyzing and improving this process by testing different numerical schemes. Finally, there is also the problem of boundary and initial conditions. Altimetry can obviously constrain those conditions. But in point of fact, the combination of altimetry and model *via* assimilation techniques can bring much more.

The assimilation of data has been already well approached by oceanographers, either with cheap (in a numerical sense) suboptimal methods (nudging...) in complex models (OCGM) or with expensive optimal methods (Kalman...) in simple process models. Up to now, the objectives of these two approaches have been viewed differently. Assimilation with cheap suboptimal methods in complex models is an attempt to drive the simulations closer to reality. These methods tend to be used for impact studies or hindcasts. Assimilation with expensive optimal methods in simple process models is the only way to estimate the best fit between data and model, given their errors. In addition, the optimal method permits the estimation of model parameters, forcings, and boundary or initial conditions. So if the same data, model and errors were assimilated with either approach, the optimal approach would give not only better results (the best fit) but also consistency. Hence, work is being done to reduce the cost of optimal approaches in order to be able to apply them on more sophisticated models and come closer to reality.

Nonetheless, the optimal approach, besides being expensive, also requires model and data error description. A lot of work has been done in estimating appropriate data errors for altimetry. A great deal remains to be done in order to estimate model errors. So the optimal approach still needs to demonstrate its success in handling the complexity of models and in estimating the adequate model errors. Meanwhile, suboptimal methods provide a very efficient way of confronting the major limitations present in modelling. It is to be hoped that they will be as successful in oceanography as in meteorology for hindcast purposes.

Acknowledgements

Sabine Arnault is supported by ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération). The research described in this paper was partly carried out by the Programme National de Télédétection Spatiale and partly supported at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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