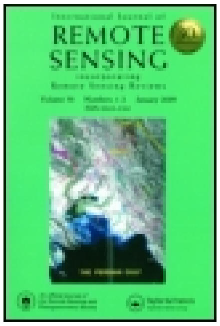

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Ocean modelling studies inspired by the Seasat altimeter

JOHN MARSHALL [a] & PAULA BERRY [a]
[a] Department of Physics, Imperial College, London, SW7 2AZ, England
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Ocean modelling studies inspired by the Seasat altimeter

JOHN MARSHALL and PAULA BERRY

Department of Physics, Imperial College, London SW7 2AZ, England

Abstract. Some recent ocean modelling studies are reviewed which illustrate the ways in which dynamic ocean circulation models can be used to advise on the optimum deployment of, and help analyse the data from, future satellite altimeters for studies of ocean dynamics. At the time of the launch of Seasat the ocean modelling community were unaware of the promise of altimetry. It is a tribute to the enormous success of the Seasat mission that now, ten years on, the modelling community eagerly awaits the launch of a new generation of altimeters.

1. Introduction

Ten years ago when Seasat was launched oceanographers were beginning the process of unravelling the dynamics of the oceans' geostrophic eddy field and its importance in the general circulation of the oceans. Data from concerted *in situ* observing programmes such as MODE (the Mid Ocean Dynamics Experiment—for a review see MODE Group, 1978) were being analysed and the growing availability of super-computers was making possible, for the first time, the modelling of (albeit miniature) ocean gyres at eddy resolving scales (see, for example, Bretherton 1975, Holland 1978).

However, although the altimeter is uniquely suited to monitoring the surface signature of the oceanic eddy field, it would be true to say that dynamical oceanographers did not have much input into the planning of the Seasat mission or the initial analysis of the data. One indication of the success of Seasat is that now, ten years on, as we look forward to imminent altimetric satellite missions—ERS-1 and TOPEX-POSEIDON— the same is not true this time around. The ocean modelling community keenly awaits the launch of the next generation of altimeters. Indeed remotely sensed observations of the oceans' surface are a central component of WOCE (the World Ocean Circulation Experiment) (see Woods 1985).

Although it could be argued that Seasat has not told the oceanographer much about the eddy field that was not known already, it has given us a glimpse of the future potential of altimetry. Altimetry for the oceanographer offers much more than the barometer does to the meteorologist because it provides pressure gradient information at a level where the geostrophic velocities are the largest (perhaps the closest meteorological equivalent would be aircraft observations of 300 mb winds). If the geoid problem can be solved we may look forward to determining the surface signature of the mean circulation as well as monitoring its variability.

Today there is considerable activity in ocean modelling directed at assessing the impact of future altimetric (Seasat-like) missions and particularly investigating how to interface dynamical ocean circulation models with remotely sensed data. Here we report on some recent ocean modelling studies directed specifically at altimetry. Of the many remotely sensed quantities it is the altimetric measurement of the ocean topography which provides information most directly linked to the dynamics of the oceans.

2. The use of models

Ocean models have a role to play in the following areas:

2.1. *Observing system simulation studies*

Designed to optimize the deployment of future altimeters, numerical ocean models can be used to answer questions such as, how important it is to have precise orbit information; whether we need to get the instrument down to centimetre accuracy (as proposed for TOPEX-POSEIDON); if a ten centimetre Seasat-type instrument is suitable for most applications; what the advantages of flying altimeters simultaneously are, or if we need two, three or . . . ; what is the optimum repeat-time strategy required to map synoptically the geostrophic eddy field or to determine its statistics; or what *in situ* measurements complement altimetric measurements of the surface pressure field most effectively, and so on.

As an indication of the guidance such simulation studies can give, experiments with a high resolution eddy-resolving ocean circulation model directed specifically at applications of altimetry as presented in section three.

2.2. *Analysis of data*

Remotely sensed information should not be seen in isolation but only as complementary to *in situ* observations. Each data type has its own error and spatial/temporal sampling characteristics. Perhaps the only way of making sense of such disparate information is to use an ocean circulation model to draw it together in a dynamically consistent way, in much the same manner as meteorologists form their analyses for numerical weather prediction. Although familiar to operational meteorologists the efficacy of this approach in the oceanographic context is still not entirely proven.

In this regard it is important to discriminate between tropical and mid-latitude processes. As the equator is approached the reduced Coriolis parameter means that vertical stiffness of vortex tubes becomes less, and the geostrophic eddies of middle latitudes turn into waves. Thus TOGA (Tropical Ocean Global Atmosphere, see Gill 1983) models are largely deterministic in nature and offer the prospect of a predictive capability given knowledge of atmospheric forcing function. More than the altimeter, the scatterometer will be crucial in the tropics for it is knowledge of the surface wind–field at high space and time resolution that is the key to predictive capabilities on seasonal time-scales in the tropics.

Dynamical processes in middle latitudes have much more in common with the troposphere, being dominated by geostrophic turbulence. A predictive capability at basin-scale on synoptic, seasonal or climatic time-scales is not a realistic possibility at present but progress has been made in limited areas (a few hundred kilometres square) on time-scales of a week or so; see in particular the review by Robinson (1986) descibing attempts to make predictive forecasts of the position of the Gulf Stream front, its rings and eddies. Hurlburt (1984) also presents a useful review of the potential for ocean prediction and the role of altimeter data. Despite the enormity of the challenge, both in the development of suitable models and sufficiently comprehensive observing systems, there is a growing interest in data assimilation into ocean circulation models. A selection of papers describing work in the field has recently been drawn together and appeared in a special issue of 'Dynamics of Atmospheres and Oceans'. Included is a contribution by Berry and Marshall (1989) in which simulation experiments are described with an eddy-resolving ocean circulation model directed specifically at issues of importance to the next generation of satellite-borne altimeters. In the next section key results of this study are summarized.

3. Simulation studies in support of altimetry.

Detailed studies have begun enquiring into the problem of assimilating single-level data (in particular pressure gradient information at the surface) into a multi-level ocean circulation model. Figure 1 shows two counter-rotating, wind-driven gyres in a two-layer model in which a dynamically unstable frontal region develops (separating subpolar and subtropical gyres) shedding rings and eddies: the model's representation of the separated Gulf Stream. An unstable internal jet flows eastwards parallel to the front. The scale of the eddying motion is set by the Rossby radius of deformation ($\sim$50 km); the eddies have a strong pressure signal and so are associated with pronounced sea-surface slopes. The deviation of the sea-surface from the gravimetric

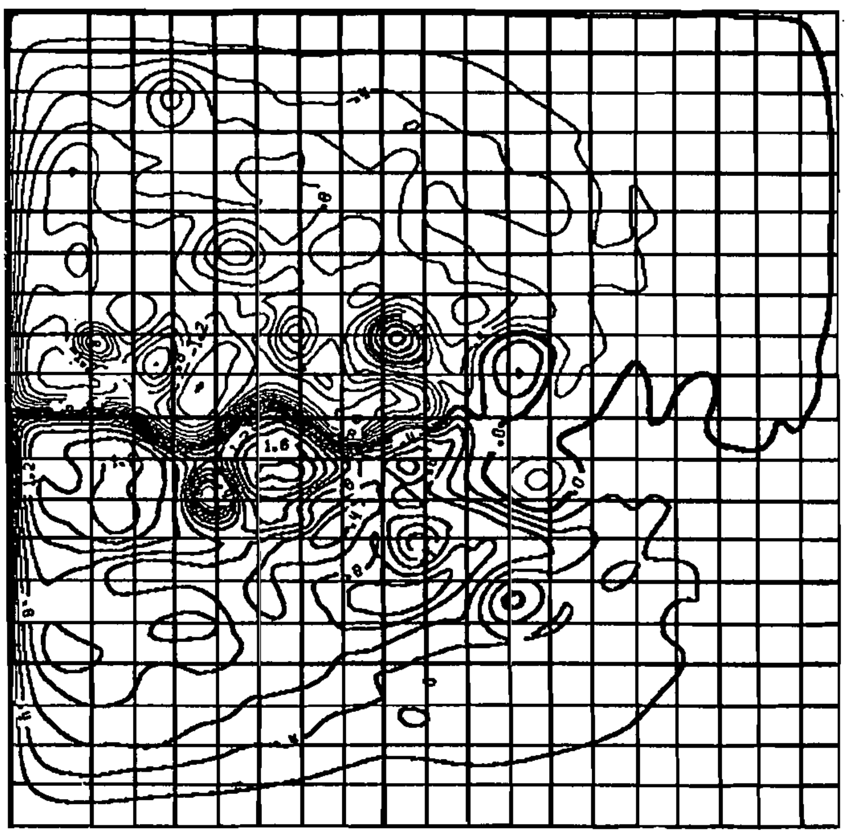

Figure 1. Upper layer streamfunction from a two-layer model 'truth' circulation in a 3000 km square basin driven by a simple wind-stress curl. The simulated Gulf Stream flowing eastward at mid-basin can be seen to be shedding rings and eddies. The contour interval is 5 cm of ocean topography. Simulated tracks from a satellite-borne altimeter flying in a 14 day repeat orbit are superimposed. The satellite lays down the tracks in a regular sequence repeating every 14 days. The spatial and temporal resolution is typical of a satellite in a sun-synchronous repeating orbit with an altitude of 800 km.

geoid is $(f/g)\Psi_1$ where f is the Coriolis parameter and g is the acceleration due to gravity and Ψ_1 is the streamfunction for the geostrophic flow in the upper-most layer. Thus in figure 1 the sea-surface drops down by about 1 m moving northwards across the eastward flowing Gulf Stream. The time-scale of the eddying motion is of the order of weeks and months; cut-off warm and cold rings are particularly long-lived. The realism of the eddying motion depicted in figure 1 has been achieved principally as a result of the high spatial resolution of the model (~ 15 km).

The surface pressure field is sampled along selected tracks simulating the spatial and temporal frequency achievable with a radar altimeter in an exactly repeating orbit (the tracks are indicated in figure 1 by the regular criss-crossing black lines). These 'observations' are combined with a first guess provided by an ocean model using objective techniques. The analysis technique used is described in detail in Marshall (1985) or Berry and Marshall (1989). This data assimilation system, model, truth and (simulated) data can be used to explore some of the questions posed above.

3.1. *Repeat-time strategies*

Simulated data, obtained by sampling a time-sequence of truth-fields taken from a model simulation in statistical equilibrium, is assimilated into an identical twin. The 'truth' model is sampled mimicking the spatial and temporal resolution possible with a satellite in an exactly repeating Seasat-type orbit. Typical track separations as a function of repeat-time are given in table 1. The initial state of the assimilating model is chosen to be a linear Stommel solution in the upper layer with no flow beneath, a crude representation of the model's climatology. Figure 2 shows the root mean square error (r.m.s.e.) between the truth and analysis ocean topography as a function of time. For clarity only the upper layer curves are displayed. For each repeat-time the same amount of data (*in toto*) is supplied, only its spatial and temporal frequency differs.

When no data is inserted, curve A, the r.m.s.e. remains fairly steady at 8 cm. This is a useful reference since it is a measure of the variability of the model about climatology. However, it should be remembered that this is a basin-scale measure: the variance is concentrated in the region of the separated jet where it rises to perhaps 50 cmr.m.s.

Assimilation into the model on 10, 14 and 30 day repeat cycles reduces the r.m.s.e. to about one fifth of the variablity about climatology. A useful way of rationalising the trade-off between space and time resolution is to consider the ratio $d/2b$, where d is the track separation and b is the correlation scale of the signal, (see table 1). Our experiments suggest that an optimum sampling strategy would make this ratio $d/2b \sim 1$. Indeed the r.m.s.e. is reduced to a minimum for a repeat-time of fourteen days (curve C in figure 2) implying a track separation of 140 km, almost exactly twice the correlation scale b. Evidently in a 30 day repeat-cycle the satellite over-samples in space ($d/2b = 0{\cdot}4$) at the expense of temporal resolution; the converse is true in a 10 day repeat orbit ($d/2b = 1{\cdot}3$), (see table 1).

Experiments such as these strongly suggest that a repeat-time of somewhere between 10 and 20 days is required to map the geostrophic eddy field. On longer repeat-times the temporal resolution is insufficient; on shorter time-scales the spatial resolution too coarse

3.2. *Impact of random data errors*

Figure 3 demonstrates the insensitivity of the analysis error to reasonable levels of random error in the observations when data is inserted on a 14 day repeat orbit. A

Table 1. Repeat times and track spacings for a satellite in an 800 km orbit.

Repeat time (days)	Track separation at 45° North (km)	$d/2b$
10	200	1·3
14	140	0·9
30	65	0·4

b is the correlation scale (78 km) used in the simulation experiments.

random error of 8 cm (r.m.s.), corresponding to a signal to noise ratio of one, does not cause significant deterioration in the analysis (the objective technique employed to combine data and model is a very efficient smoother). Because of the wealth of *a priori* knowledge being brought to bear (provided by the ocean circulation model) and the smoothing of the random data errors over a correlation scale during the analysis, the error can be brought down to below the random error in the instrument.

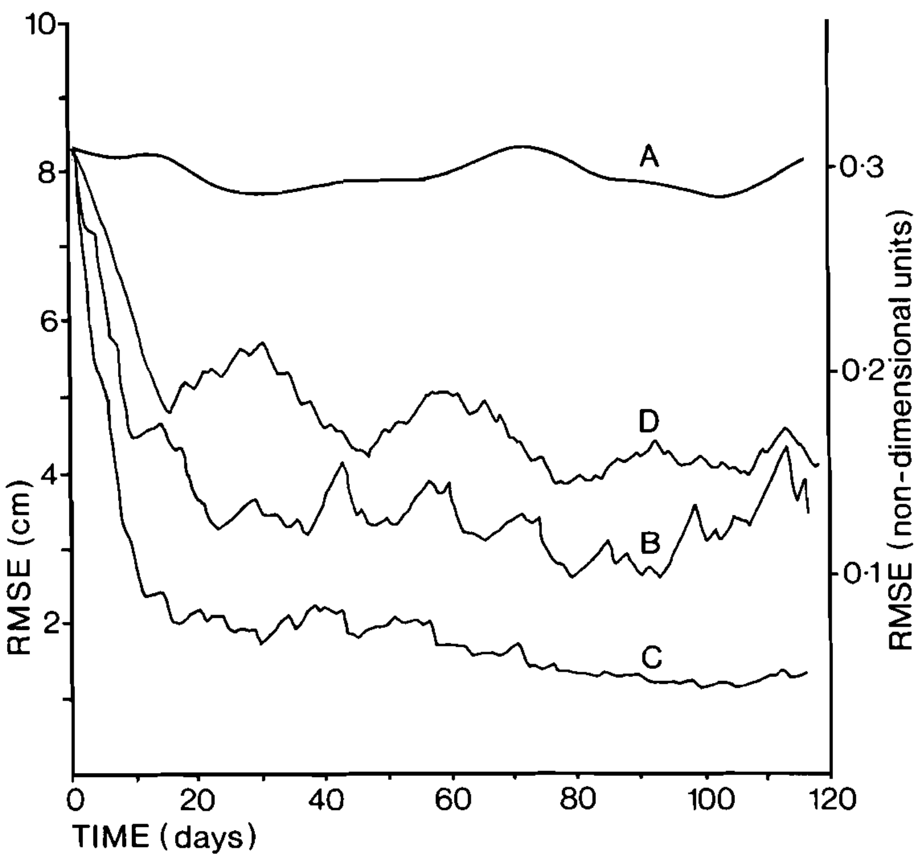

Figure 2. Root mean square error as a function of time between the truth and analysis ocean topography from a two-layer model assimilating perfect surface pressure data on various repeat-time strategies. del is initialized using a Stommel solution in the upper layer with no flow beneath. Curve A, no data assimilated; Curve B, data assimilated from a 10 day repeat orbit; Curve C, data assimilated from a 14 day repeat orbit; Curve D, data assimilated from a 30 day repeat orbit. Curve A is a measure of the variability of the model about climatology.

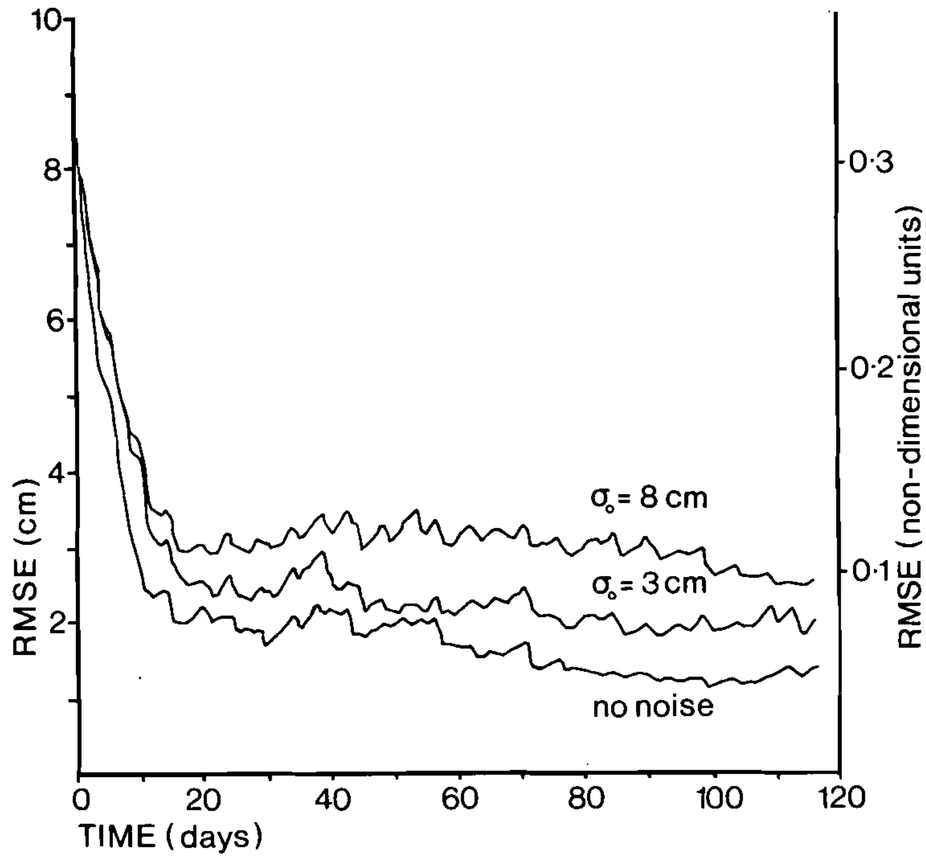

Figure 3. Error curves for the ocean topography obtained by assimilating data with various levels of random noise on a 14 day repeat into the two-layer model initialised as in figure 2.

Our simulation studies indicate an insensitivity to (reasonable) levels (of random) noise suggesting that a Seasat-type 10 cm altimeter is sufficient (provided, of course, that it is adequately tracked).

3.3. *Inferring the deep circulation using models*

Given that altimetry can only provide information about the surface of the ocean, the question arises as to how we might make use of models to help us infer the deeper flow. In fact consideration of the r.m.s.e. in the bottom layer of our two-layer integration (figure 4), shows that assimilation of data into the model at the surface over a period of one hundred days or so, leads to a marked reduction in the error levels in the deeper layer. It should be emphasized that no vertical extrapolation procedures are employed; rather the lower layer is allowed to evolve dynamically in response to forcing by the vertical velocity at the interface.

It is not difficult to see how, in this two-layer integration, information gets down into the lower layer. Energetic eddies in the upper layer (i.e., in and above the main thermocline) drive the deep flow through undulations of the interface spinning up, through vortex stretching, motion beneath. The eddies act like plungers rippling the interface on scales of 100–200 km, exciting Rossby waves in the lower layer. The altimeter provides the model with information about the position of fronts, rings and eddies in the upper layer and so the spatial and temporal pattern of the vertical velocity field at the inerface between the layers can be very readily inferred. The bottom layer of the model is very deep (4 km) and so the waves excited here by the interfacial eddy plungers are essentially linear. In fact, as shown in Berry and Marshall (1989), the lower-layer error field decays like a damped Rossby wave with a (scale independent) *e*-folding time set by the Ekman spin-down rate. So it is the level of explicit dissipation in the model that determines how rapidly the errors in the initial state fall in figure 4.

We should be very wary, however, of this rather optimistic result. Experiments with models having more than two layers (for example three-layer experiments presented in Berry and Marshall, 1989) show that our ability to infer the deep flow from altimetric data alone, even in very idealized wind-driven calculations, is severely compromised. There is usually some error reduction in the abyssal gyres but the simple mechanism described above is no longer appropriate; non-linear processes in intermediate layers inhibit the linear excitation of Rossby modes in the deep layers. The clear message is, not surprisingly, that altimetric data alone is insufficient to constrain a baroclinic eddy resolving, basin-scale model and must be augmented with *in situ* measurements.

4. Conclusions

The following general conclusions can be drawn from simulation studies such as those presented in §3:

(*a*) Observations of the surface pressure field on space and time scales possible with a single satellite-borne radar altimeter provide strong constraints on multi-level, eddy resolving ocean circulation models, both at the surface and in deeper layers

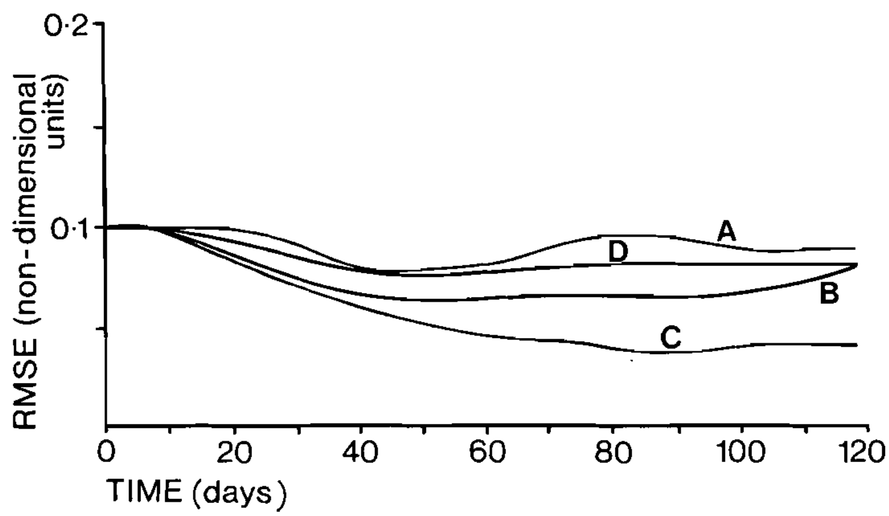

Figure 4. Lower layer r.m.s.e. curves for the two-layer integration corresponding to figure 2. Altimetric data supplied at the surface evidently does have a beneficial impact on the deep layer. Errors in the initial conditions decay as damped Rossby waves decaying on Ekman spin-down time-scales.

(*b*) The skill of the surface analysis is a strong function of the spatial and temporal frequency of the altimetric observations, and is only weakly dependent on the random error in the instrument (for reasonable levels of noise). For synoptic mapping in middle-latitudes on basin scales, an orbit repeat time of about 15 days is found to be optimum. We believe that this is a rather robust conclusion and is not a consequence of the type of ocean model used in our simulation studies. Simulation experiments in which data is assimilated from several altimeters flying simultaneously suggest that it is highly desirable to synchronize future altimetric missions to ensure that they fly contemporaneously.

(*c*) The dynamical mechanism by which information at the surface is extrapolated vertically, constraining abyssal flows, can be readily understood in two-layer models in which the deep flow is a superposition of damped linear Rossby waves forced by vortex stretching at the interface between the layers. However, in more realistic models, where many shallow layers are required to represent the upper levels of the wind-driven gyre, the ability of the model to spin up sub-surface flows from information at the surface alone is severely compromised.

Finally it should be stressed that altimetric, and indeed all remotely-sensed data, should not be considered in isolation but only as component parts of the observing network. *In situ* measurements are of the utmost importance, not only in the verification of remote sensors, but more directly because it is only *in situ* measurements that give direct information about sub-surface flows. Future simulation studies should assess the impact of altimetry used in conjunction with both complementary observations (for example, velocity measurements at thermocline depth from neutrally buoyant floats) and other remotely sensed data (for example, sea-surface temperature and ocean colour sensors).

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References

Berry, P. J. and Marshall, J. C., 1989, Ocean modelling studies in support of altimetry. *Dynamics of Atmosphere and Oceans*, **13**, 269–300.

Bretherton, F. P., 1975, Recent developments in dynamical oceanography. *Quarterly Journal of Royal Meteorological Society*, **101**, 705–721.

Gill, A. E., (editor), 1983, Tropical Ocean—Global Atmosphere (TOGA) programme report. World Climate Program Report, World Meteorological Organisation, Geneva.

Holland, W. R., 1978, The role of mesoscale eddies in the general circulation of the ocean: numerical experiments with a quasi-geostrophic model. *Journal of Physical Oceanography*, **8**, 363–392.

Hurlburt, H. E., 1984, The potential for ocean prediction and the role of altimeter data. *Marine Geodosy*, **8**, 17–66.

Marshall, J. C., 1985, Determining the ocean circulation and improving the geoid from satellite altimetry. *Journal of Physical Oceanography*, **15**, 330–349.

MODE Group, 1978, The mid-ocean dynamics experiment. *Deep Sea Research*, **25**, 859–910.

Robinson, A. R., 1986, Data assimilation, mesoscale dynamics and dynamical forecasting. In *Advanced physical oceanographic numerical modelling*, edited by J. J. O'Brien (Holland: Reidel Press).

Woods, J. D., 1985, The world ocean circulation experiment. *Nature*, **314**, 501–511.