OCEAN APPLICATIONS TECHNICAL NOTE 7.

SENSITIVITY OF OCEAN MODELS TO SURFACE FORCING

by

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1. Introduction

Ocean general circulation models are not self contained, they must be passed information about the fluxes of heat, fresh water and momentum across the ocean surface. A challenge for those modelling the ocean is to specify the fluxes. Momentum flux, i.e. the wind stress, is usually specified directly, although the values of the forcing field can come from a wide variety of sources, ranging from analytic idealisations to the simulations of the atmosphere component of an atmosphere model and datasets of observed values. Heat fluxes have been specified in a wider variety of ways, largely because of the great difficulty in deriving reliable estimates of the fluxes over the real ocean. Early models imposed a sea surface temperature (e.g. Bryan, 1969). Others (e.g. Bryan and Lewis, 1979) followed Haney (1971) and relaxed the surface temperature in the model towards a climatological "air" temperature, often using the observed sea surface climatology for want of more detailed information. A further variation on the theme is to use the observed, perhaps climatological, fluxes to drive the model, but to include an additional relaxation towards the observed sea surface temperature using the physical argument that this represents in some way the feedback between the sea surface temperature and the surface fluxes (e.g. Cattle and Gordon, 1988). Creating climatologies of fresh water flux over the ocean is even more difficult than producing those for heat, and modellers are faced with the additional problem that there are no physical justifications for applying a relaxation boundary condition as may be done for heat fluxes. Consequently, modellers are forced to choose between imposing the surface salinity, using flux estimates that are known to have large uncertainties, or to use a relaxation method without a physical justification for doing so.

Ultimately, whichever method is used to derive the fluxes to drive a model, we must know the flux fields from the *real* world. This may be because the fluxes are themselves are used to force the model, or because we need to compare the fluxes that are deduced from the model simulation with reality. Further, we must understand which aspects of the fluxes are important. How accurately must they be specified? What spatial resolution is needed? What temporal resolution do we need? What is the impact of the compromises that have to be made in deriving a flux dataset? To answer all these questions we need to understand the sensitivity of the ocean to variations in the surface fluxes. We are not able to conduct experiments with the real world, so we must understand the sensitivity of ocean models as a proxy.

This paper examines some ocean model integrations that illustrate how they may be sensitive to the surface fluxes, with particular attention to how heat fluxes are represented. Topics covered in the following sections are: how the boundary condition is specified in ocean models; the impact of spatial variability; the impact of temporal variability, and how ocean models respond to differences in the values between different flux estimates. Finally, the conclusions are summarised.

2. Specifying the heat and fresh water boundary conditions

Many ocean models have imposed the surface temperature with some success (e.g. Bryan, 1969). Others, e.g. Cattle and Gordon (1988), have used a relaxation form of the boundary condition based loosely on Haney (1971). Generally, attempts to impose the fluxes alone, without reference to the sea surface temperature, are less successful because they lack feedbacks between the atmosphere and ocean (e.g., for a model of the Indian Ocean, Carrington and Anderson, 1993).

Estimates of fresh water fluxes are less reliable than those of heat, and this has led some modellers to use "mixed" boundary conditions, in which the heat flux is calculated by relaxing the surface temperature to a climatological value, and the surface salinity (or salt flux) is imposed. Inconsistencies that arise from this process can result in instabilities that produce a "thermohaline catastrophe" (as shown by Rahmstorf and Willebrand, 1995, and Power and Kleeman, 1994).

It is not only the heat fluxes that can have a marked impact on the circulation of the ocean in models. Harrison (1991) showed that there was a consensus among the tropical Pacific models then in use that simulations were improved if the Hellerman and Rosenstein (1983) wind stresses were reduced before being applied to the models.

Ji *et al.* (1994) demonstrate the implications of the uncertainties in our knowledge of the fluxes and of how best to apply the fluxes to models. In their seasonal forecasting system the surface fluxes from the atmosphere model that are used to drive the ocean model are modified before they are applied to the ocean; if this is not done large temperature errors soon arise. Although in this case there are large errors that are attributable to the surface flux calculations, it is hard to draw firm conclusions because the ocean model, too, has systematic errors.

3. Spatial variation

Ocean models have grids that range from a few kilometres to many hundreds of kilometres, yet the climatologies of fluxes used to run them are typically on scales of several hundred kilometres. Such climatologies, such as that of Esbensen and Kushnir (1981) can barely represent the presence of the major boundary currents. This causes problems when the climatology is used to drive an ocean model of higher resolution, for the fluxes bear little relationship to the properties of the water in the model. Increasing the resolution of the climatology, e.g. Oberhuber (1988) , goes part of the way to rectifying this weakness, but other factors are important.

How representative can a spatial average be? Consider the Gulf Stream. In any climatology of fluxes this is likely to be represented by a broad region of high latent and sensible heat flux; broad because the temporal variations in the position of the current are translated into a broad, but less extreme, peak by the averaging process.

Gulev (1994) has discussed how variations within a grid square influence the flux calculations. The author reminds us that the fluxes are strongly non-linear, and that variations in the atmospheric wind and temperature are correlated. Forming a climatology by calculating fluxes from individual observations and then averaging the resulting fluxes to form an average over an area automatically takes this into account. In a numerical model, either for weather forecasting of climate simulations, the main variables (wind, moisture, temperature) are considered to be representative of the values over the area of a grid square (in a spectral model they are often assumed to be representative of some geographical area that is used for calculating the "physics"of the model). In this case the considerations of Gulev (1994) become very significant, for then the values of the transfer and drag coefficients should depend on the grid spacing to parametrize the sub-grid scale variability that is absent from the model. Although this might make a noticeable difference to the fluxes calculated by the model, the amount by which the coefficients must be enhanced is likely to depend on the synoptic situation; translating this into the context of flux climatologies means that the enhancement is likely to vary regionally, or more correctly to vary according to the local climatology. This poses a problem for climate change studies, in which the climatology of the model must be allowed to evolve unfettered.

4. Temporal variation

Investigating sensitivity of ocean models to the frequency of updating the surface fluxes is simpler that studying that to the spatial resolution. This is because it is possible to define sets of fluxes based on a high sampling rate and then degrade the time resolution by averaging. An example of such a study, for the North Atlantic, was reported by Foreman and Alves at a workshop held at ECMWF in 1991. This study used fluxes by an NWP (numerical weather prediction) system and considered the impact on an ocean model of averaging the fluxes to remove a particular band of timescales. They found that the circulation in their numerical model differed markedly between integrations in which the surface fluxes were updated using estimates every three hours and when monthly averages were used, particularly in the Labrador Sea, the difference in the mixed layer characteristics in these runs being much greater than between the run with monthly forcing and the climatology. This study had been unable to distinguish between the importance of diurnal and synoptic variations in the fluxes. Stanev *et al.* (1995) performed a similar study using fluxes that were derived from winds, humidity and temperature from twice daily US National Meteorological Center analyses. By filtering the analyses using different time filters they were able to show that, in their model of the Black Sea, the formation of the deep waters was affected by the frequency of the forcing and thus to the atmospheric synoptic variability. This suggested that the main effect seen by Foreman and Alves was the result of synoptic changes rather than to the diurnal cycle.

Both the above integrations used surface fluxes from NWP centres. Another source of surface flux estimates that is able to produce high time resolution is an integration of a coupled ocean-atmosphere model. Fluxes from such a model cannot be considered to be as accurate as those from an NWP system, but they do represent a convenient and internally consistent set of fluxes for performing sensitivity studies. To see if there would be an impact from diurnal variations in fluxes, two coupled model integrations were run. Each started from the same conditions, and each ran for one year. The difference between the two runs is that in one the atmosphere and ocean models were coupled every six hours, and in the other coupling occurred once a day. The average of the fluxes from the six hour coupling run is not the same as that from the daily coupling because the atmosphere was able to respond in different ways in the two integrations. Thus, this comparison might be expected to show more sensitivity to the frequency of updating fluxes than runs using NWP fluxes. Like, the earlier experiment by Foreman and Alves, these runs showed differences in the mixed layer depths at high latitudes although, perhaps because the coupled model produces shallower mixed layers than the earlier runs did, the amplitude of changes in the coupled run was smaller. Interestingly, both experiments showed shallower mixed layer depths in the run with diurnal forcing. There were also differences of up to 2°C in the temperature of the upper Pacific between the two coupled runs.

There is thus strong circumstantial evidence that it is important to represent the synoptic variability of fluxes in an ocean model, although a more systematic investigation is needed to determine the relative importance of seasonal, synoptic and diurnal variations.

5. Accuracy

Requirements for the accuracy of surface flux climatologies have been expressed in general terms, for example the WOCE goal of 10 W m^{-2} for 10° squares (WCRP, 1988). Few experiments have been performed to determine the response of models to errors in the surface flux estimates, perhaps because the likely errors are hard to determine and any response is as likely to be as indicative of problems in the ocean model as of sensitivity to the fluxes.

Perhaps most work on this topic has concentrated on sensitivity to the wind stress, prompted by the TOGA experiment. Many studies have shown that the tropical circulation is largely driven by the wind stress, and ocean modellers typically optimise their use of the stresses in some way, e.g. by modifying climatological estimates (Harrison, 1991, describes how the Hellerman and Rosenstein, 1983, stresses have been shown to be too strong in the tropics), or by modifying the stresses derived from a numerical model (Ji *et al.*, 1994).

Actual surface flux estimates will have errors in all components, and the methods of deriving the surface fluxes are likely to mean that there are relationships between the errors in the individual flux components. Therefore, in addition to understanding the ocean response to errors in individual surface fluxes, the impact of errors in the combined flux datasets needs to be found. One way of achieving this is to compare the surface fluxes from different weather forecasting centres and use them to drive an ocean model. Figure 1 compares

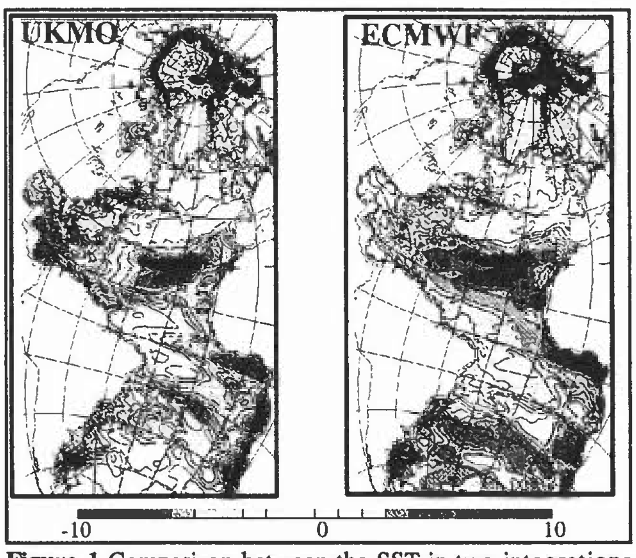

Figure 1 Comparison between the SST in two integrations of an Atlantic ocean model when driven by fluxes from different NWP centres. Each run was for one year, and the SST differences from a run with climatological forcing are shown. Left, Met. Office fluxes; Right: ECMWF fluxes.

sea surface temperatures from two ocean model simulations after one year of integration driven by monthly mean surface fluxes from the ECMWF and Met. Office operational forecast suites (all heat flux, fresh water and momentum fluxes were taken from the NWP models, and there was no relaxation towards reference sea surface temperatures). Differences from a control run using climatological fluxes are shown. There are clear differences between the two simulations, even after only a year. For example, in the Gulf of Mexico the run using Met. Office (UKMO) fluxes was up to 6°C warmer than the ECMWF run, while at 30°S the ECMWF run was warmer by up to 6°C. In both these areas the heating in the model integration is consistent with the differences in the heat fluxes applied to the model, i.e. a largely direct response. In the region of the Gulf Stream the two runs differed by about 4°C, and the time evolution of the response suggests that differences in the circulation may be as important as direct heating in that region. When the results of the NYC and ECMWF reanalysis projects become available it will be interesting to see how ocean models respond to their surface fluxes. This will help us to understand how important the differences between the surface fluxes are for the evolution of ocean circulation.

6. Summary

Specifying the requirements for the representativeness and accuracy of surface fluxes is a precursor to designing an experiment to measure them, or a project to derive the fluxes from existing sources. Ocean models provide one way of setting limits on the accuracy that is needed, although the models themselves cannot be assumed to be a faithful proxy for the real ocean.

Ocean modellers are calling into question some of the conventional ways of specifying the upper ocean boundary condition. Models with mixed boundary conditions, in which heat fluxes are specified and the surface salinity is relaxed to observed values, have been shown to exhibit physical instabilities that are an artefact of the forcing mechanism. This places greater emphasis on the use of surface fluxes for developing ocean models.

It has been clear for some time that the ocean responds to surface fluxes in an non-linear way. Using annual mean fluxes to drive an ocean model soon leads to significant problems in the formation of deep water, problems that could be reduced by using monthly forcing. Recently it has been demonstrated that, especially at high latitudes, monthly means may be inadequate for driving an ocean model, and that ocean models are sensitive to synoptic atmospheric disturbances. Although details of the structure of the upper ocean are sensitive to the diurnal cycle, the present generation of ocean models are not sufficiently sensitive to this to allow justify using such high frequency forcing to drive the models.

As the resolution of ocean models increases, the spatial resolution of available surface flux climatologies will be increasingly inadequate. Purely increasing the resolution of the climatology itself may not be a satisfactory approach. There be too few observations to define the climatology with enough accuracy. Further, on small space scales the fluxes may depend more on the position of the ocean features (for example the Gulf Stream) than on geographic position, making climatological averages difficult to define.

It is becoming clearer that the ocean circulation can be sensitive to the details of the synoptic behaviour of the fluxes. It is not only the effect of the events on the mean state that is of importance, but the correlation between different flux components that can have an influence, e.g. strong winds and rapid cooling of the ocean in a cold outbreak.

Therefore, surface flux datasets to be used for running ocean models are in future likely to be asked to specify how the climatology varies on short space and time scales so that synoptic events can be represented in the climatology. This is one stage further than Oberhuber's (1988) study that specified how the heat flux responded to variations in sea surface temperature. This will be a major challenge to those developing the climatologies, and will blur the distinction between climatologies and models.

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