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THE PARAMETRIZATION OF THE UPPER OCEAN MIXED LAYER IN COUPLED OCEAN/ATMOSPHERE MODELS

by

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ABSTRACT

In an ocean model suitable for detailed climate studies it is necessary to represent the ocean temperature changes arising from both heat advection and the exchange of heat across the air-sea interface. The relative importance of these two effects in determining the large scale sea-surface temperature field depends upon geographical location. In mid-latitude oceans, away from the boundary regions, local exchanges dominate the upper ocean heat budget so that a simple mixed layer model might be expected to predict the seasonal changes in sea-surface temperature reasonably well.

A number of experiments are described in which a simple mixed layer model is forced with both observed and atmospheric model fluxes. The experiments have a global domain, although particular attention is given to the simulation of the seasonal cycle in middle latitudes. Comparisons between experiments with observed and model fluxes indicate that care should be taken to match the detail of the mixed layer parametrization to the quality of the atmospheric model forcing.

1. INTRODUCTION

In the analysis of numerical experiments using atmospheric general circulation models (AGCMs) with climatologically prescribed sea-surface temperatures (SSTs) and sea-ice extents, little attention has been given to the simulation of the surface fluxes of heat and momentum over the oceans. This is because in such experiments the oceans act as an infinite heat source or sink. In a coupled atmosphere/ocean model the situation is very different since SSTs and sea-ice extents are dependent on the surface forcing. A useful preliminary to a coupled experiment is therefore to look in detail at the fluxes of heat and momentum from AGCM experiments with prescribed SSTs and sea-ice extents.

The major problem in attempting to verify the AGCM simulation of surface fluxes is the lack of sufficiently accurate climatological data sets. This is particularly true over the global oceans where, in many areas, the heat and momentum fluxes across the surface are poorly known due to the lack of data coverage. The existing data sets of global heat budget components (Budyko, 1963, Schutz and Gates, 1971 to 1974, Esbensen and Kushnir, 1981) and momentum flux (Hellerman, 1967, 1983, and Han and Lee, 1981) have allowed modellers to assess the overall patterns simulated by their models. A point is inevitably reached, however, when it becomes impossible to say whether it is the models or the data which are in error. These problems are particularly severe in the southern hemisphere.

A similar problem occurs in the verification of the results from ocean general circulation models (OGCMs). If these models were provided with the best estimates of the surface forcing, how well would they simulate the observed ocean circulation and, most importantly in a coupled model, the spatial and temporal variations of SST? Again a point must be reached at which it is impossible to disentangle errors due to surface forcing from those due to inadequacies in the models.

In a coupled atmosphere/ocean GCM both of the above problems occur together so that, for example, errors in certain aspects of the atmospheric circulation may arise from errors in the SST field which, in turn, may be to some extent a consequence of errors in the surface forcing. The possibilities for getting the wrong answer, or even the right answer for the wrong reasons, are many and the complex interactions are such that it is very difficult to pin-point the source of a particular error.

It is obviously desirable to test both the oceanic and atmospheric components of the coupled system in an uncoupled mode in order to assess the models individually and to ensure that the complexity of the models is suitably matched. With the AGCMs this has been done in experiments with climatologically specified SSTs and sea-ice extents. The results of the various models are well documented.

When testing OGCMs Haney forcing (Haney, 1971) has often been used to parametrize the net surface heat flux via the difference between an effective air temperature and the predicted SST. Such an approach is valuable in assessing the performance of some aspects of the model. However, it can say little about how the SST may be expected to respond in a coupled atmosphere/ocean experiment since the SST is essentially constrained to be close to the effective air temperature. The alternative is to use climatological estimates of the surface heat fluxes. The objection to this approach is that in reality the fluxes will change with the SST. This largely involves a negative feedback via the turbulent heat losses at the sea-surface.

Ultimately, of course, it is necessary to use a coupled ocean/atmosphere model if the important feedback mechanisms are to be effectively represented. However, coupled experiments are expensive in terms of computer resources and the relatively cheap non-interactive tests using both Haney and heat flux forcing can be useful in providing some insight into the behaviour of the coupled system. Most of the experiments reported in this paper are non-interactive in the sense that the surface fluxes do not respond to the SST field. The exception is the last experiment reported using model data, in which the anomalous surface heat flux due to a SST anomaly is assumed to be linearly proportional to the temperature anomaly.

Results of experiments using both observed climatological and modelled surface fluxes to simulate the seasonal cycle of SST in middle latitudes will be discussed. Emphasis is given to temperature changes in middle latitudes for two reasons. Firstly, as indicated in Figure 1, the seasonal range of SST peaks in the middle latitudes of both hemispheres where it is by far the most dominant signal. Secondly, there are good theoretical and observational reasons to expect the open ocean large scale seasonal changes in SST to be determined by the seasonal variations in the heat and mechanical energy fluxes across the sea-surface. (Gill and Niiler, 1973, Barnett, 1981). In fact, the experiments with observed climatological data reported below may be taken as a further indication that this is the case. This means that a simple mixed layer model may well be able to produce a reasonable simulation of the seasonal changes in SST in these regions.

It should be emphasised that it is not being suggested here that a simple mixed layer model provides a suitable representation of the ocean in a global atmosphere/ocean model. This is clearly not the case since advective effects are of primary importance in both the tropics and the regions of large ocean to atmosphere heat exchange associated with the western boundary currents. The mixed layer model is being used rather as a diagnostic tool to assess the sensitivity of the predicted mid-latitude SSTs to the quality of the surface fluxes. If, using modelled fluxes, the seasonal changes in mid-latitude SSTs are predicted to the same accuracy as obtained using observed climatological fluxes (which may themselves provide a fairly poor simulation) then the modelled fluxes are as good as the climatological estimates. As will be shown below, this is not the case and most of the errors in the simulated SST using model fluxes can be directly linked with errors in these fluxes. In fact, the worst errors occur in precisely those regions where a simple mixed layer model should work well.

This paper is organised as follows: Section 2 describes the mixed layer model and Section 3 an experiment using observed climatological surface fluxes. Section 4 describes experiments with surface fluxes derived from an AGCM and conclusions are drawn in Section 5.

2. THE MIXED LAYER MODEL

The mixed layer model used in this study is essentially that of Gill and Turner (1976) as developed by Mitchell (1977a) and Gordon (1984). This bulk model relates changes in the potential energy of a vertical water column to the rate of working by the wind at the sea-surface. The rate of turbulent energy input at the surface is given by the windmixing power

$$W = m_o \rho_w v_*^3 \tag{1}$$

where v_* is the oceanic friction velocity, ρ_w is the density of sea-water and m_o is a scaling factor of order unity. This is decayed exponentially with depth to prevent over-deepening of the winter time mixed layer. W can also be expressed in terms of the local wind speed at some level, so that

$$W = \frac{m_o (\rho_{air} C_L)^{3/2}}{\rho_w^{1/2}} U_L^3 \tag{2}$$

where C_L is the drag coefficient appropriate to a level L in the atmosphere and U_L is the wind speed at that level. ρ_{air} is the density of air. This energy is used to mix the surface heat input throughout the mixed layer. Convection in the model is partly penetrative with 85% of convectively generated turbulent kinetic energy dissipated within the mixed layer. The penetrative short wave flux is represented by a double exponential decay function (Paulson and Simpson, 1977). The effects of salinity on density are not included in the model.

The model parameter m_o and the e-folding depth for the decay of wind mixing were fixed so that, when the mixed layer depth was of order 20-30 m, the total dissipation in the mixed layer was equivalent to that obtained by Davis et al (1981) using data from the MILE experiment. Although fine tuning of these parameters could have improved the model simulation at a particular location, previous work has shown that it is not possible to choose one set of parameters which give a best fit at all locations (Mitchell, 1977b). With the MILE parameters the modelled seasonal range of

SST at Ocean Weather Station 'PAPA' (50°N, 145°W) was within about 0.5°C of the observed value. The model also produces realistic variations in sub-surface temperatures.

Tests were performed to investigate the sensitivity of the model to both vertical resolution and time step. In these experiments a control integration was run having a uniform 1 m vertical resolution to 200 m and a timestep of one hour. When compared with the control integration, a model with 6 layers in the upper 200 m (centred on 5, 17.5, 32.5, 55, 95 and 160 m i.e. giving greater resolution near to the surface) and a time step of 24 hours, was found to be quite adequate to simulate the seasonal cycle of SST to an accuracy of 1°C. This version of the model was adopted for the experiments to be described later in Section 4.

3. EXPERIMENTS WITH CLIMATOLOGICAL FLUXES

Turbulent and radiative fluxes for this study were taken from the monthly data sets compiled by Esbensen and Kushnir (1981). At the time when these experiments were performed no suitable global data sets of the windmixing power were available. A number of tests were carried out to determine whether existing data sets of monthly mean wind stress (Han and Lee, 1981) and wind speed (Esbensen and Kushnir, 1981) could be used to provide a reasonable estimate of the windmixing over the globe. This was not the case since the cubic dependence of this quantity on the wind speed (see equation (2)) meant that the lack of wind variability in the existing mean data sets led to serious errors when the windmixing power was calculated. Although this can be compensated for locally by introducing an empirical enhancement factor it is not possible to do this globally. Tests with the mixed layer model showed that these errors are not insignificant in the simulation of the seasonal cycle of SST. A global data set of wind-mixing is currently being created and will subsequently be used to force the mixed layer model. Details of the tests referred to above can be found in a recent report by Grahame (1984a).

In the absence of a suitable windmixing data set Grahame (1984b) performed a series of experiments in which the mixed layer depths were specified in various ways. When the daily mean heating at the sea surface is positive and there is insufficient windmixing to redistribute this heat throughout the existing mixed layer, the layer base will establish itself at a shallower depth (h). If the effects of penetrative radiation, decay of mixing energy with depth and heat advection are ignored this is given by the Monin-Obukhov depth (Niiler and Kraus, 1977)

$$h_* = \frac{2W}{\frac{\alpha g}{c} \cdot Q} \tag{3}$$

where W is the windmixing power, Q the net surface heating, α the expansion coefficient of sea-water, g the acceleration due to gravity and c the specific heat capacity of sea-water. The surface temperature, T, increases according to

$$\frac{\partial T}{\partial t} = \frac{Q}{c \rho_w h} \tag{4}$$

In his experiments Grahame (1984b) determined the mixed layer depths during the shallowing season in each hemisphere by interpolation from the Levitus and Oort (1977) hydrographic data set. The net surface heating from the Esbensen and Kushnir (1981) data set was distributed over the mixed layer at each ocean point on a 2.5° by 3.75° latitude longitude grid i.e. the surface temperatures were updated using (4). It is clear from (3) that this procedure is loosely equivalent to specifying a windmixing power. At each point on the grid the seasonal range of SST in this experiment is what one might expect to obtain by running the full mixed layer model described in Section 2 providing the full model reproduces the same time evolution of mixed layer depths as derived from the Levitus and Oort (1977) data set.

Problems arise however when equation (4) is used without modification. For example, in regions of the ocean where there is a net heat loss from the surface over the year the annual mean mixed layer temperature will fall from year to year. In reality this heat loss is compensated for by warm advection due to ocean currents. In the absence of better estimates

Grahame (1984b) approximated the effects of the oceanic heat flux convergence at each grid point by assuming that it leads to a constant heating rate in the mixed layer throughout the year which he derived from the annual mean heat exchange across the surface. This ensured that the annual mean heat content of the water column at each grid point does not change. Thus, when the mixed layer is shallowing (4) was replaced by

$$\frac{\partial T}{\partial t} = \frac{Q}{c\rho_w h} - \frac{\overline{Q}}{c\rho_w \overline{h}} \qquad (5)$$

where $\overline{Q}$ and $\overline{h}$ are the annual mean net surface heating and mixed layer depths respectively. The last term in (5) is the heating rate corresponding to the assumed oceanic heat flux convergence. If the instantaneous mixed layer depth was used in this term rather than the annual mean, then the heating rate would have a spurious seasonal signal associated with the seasonal changes in mixed layer depth. Grahame (1984b) performed a number of experiments in which the annual mean heating was distributed in the vertical in a variety of ways (e.g. over the instantaneous mixed layer, over a 200 m column, etc). It was found that in mid-latitude open ocean regions the details of how the annual mean heating is distributed in the vertical does not fundamentally alter the simulation of the seasonal cycle.

Figure 2 is the difference between the simulated and observed seasonal ranges in SST using the model described by equation (5). As already stated Q and $\overline{Q}$ were taken from Esbensen and Kushnir (1981) and h and $\overline{h}$ from Levitus and Oort (1977). The seasonal range of SST is defined as the monthly mean for August minus the monthly mean for March in the northern hemisphere and the February minus the September value in the southern hemisphere (which leads to the discontinuity in Figures 1 and 2 at the equator). A detailed discussion of the results of this and a number of other experiments can be found in Grahame (1984b). It is evident from Figure 2 that the seasonal range of SST is simulated to within 2°C over much of the world's mid-latitude oceans. This typical accuracy of 2°C should be kept in mind when assessing the simulation of the seasonal cycle of SST using AGCM fluxes.

4. Experiments with modelled fluxes

In the experiments described in this section the fluxes of heat and mechanical energy needed to force the mixed layer model described in Section 2 were extracted from a four year integration of the Meteorological Office 11-layer AGCM. This is a global model, a limited area version of which was used for the GARP Atlantic tropical experiment (Lyne and Rowntree, 1983). It is a primitive equation model using σ (pressure/surface pressure) as a vertical co-ordinate, and a regular $2.5° \times 3.75°$ latitude longitude grid. The seasonal and diurnal variation of solar radiation are represented, and the radiative fluxes are a function of temperature, water vapour, carbon dioxide and ozone concentrations, and prescribed zonally averaged cloudiness. SSTs and sea ice extents are prescribed from climatology, and updated every 5 days.

Fluxes of turbulent and radiative heat at the sea surface and the windmixing power were accumulated every timestep of the atmospheric model and stored on tape once per model day. Subsequently, these fluxes were used to drive the mixed layer model at each grid point.

A number of experiments were performed. In each experiment the temperatures in the upper 200 m of the ocean were initialised using values interpolated from the Levitus and Oort (1977) data set for 'spring'.

Preliminary experiments

An experiment in which no account was taken of the annual mean advective heat flux (see equation (5)) produced summer SSTs which were too high (by 5°C or more in places) in both the central North Pacific and the North Atlantic. In both regions the inclusion of the annual mean advective heat flux convergence would have made the simulation worse. These high temperatures were due to the overestimation by the AGCM of the absorbed short wave flux at the surface. This is associated with the use of zonally meaned cloud amounts in the model. A further experiment in which the modelled short wave flux was replaced by the corresponding fields from the Esbensen and Kushnir (1981) data sets (interpolated to daily values) showed a considerable improvement in the simulation of the northern hemisphere summer SSTs. Subsequent experiments with the mixed layer model were therefore carried out with the AGCM short wave flux replaced by the Esbensen and Kushnir (1981) value. In future experiments with the AGCM an interactive cloud scheme will be used in which cloud amounts are predicted within the model, thus allowing longitudinal variations in the modelled short wave flux to be represented.

The annual mean advective heating correction discussed in the previous section was not applied in the above experiments. When using AGCM fluxes a problem arises in the implementation of this correction since the modelled annual mean mixed layer depth is not known in advance. (See equation (5)). In order to circumvent this problem, values of Q were evaluated at each grid point from modelled turbulent and long-wave fluxes and the observed climatological short wave flux. A heat flux equal to Q was then removed at each timestep from the instantaneous modelled mixed layer. The experiment was run for one year and the modelled annual mean mixed layer depths obtained were used as an estimate of h in the calculation of the heating rate

$$\left(\frac{\partial T}{\partial t}\right)_{advection} = \frac{-\overline{Q}}{c\rho_w\overline{h}} \qquad (6)$$

This heating rate was used in all subsequent experiments to represent the annual mean advective heat flux convergence at each location.

Experiment 1

An integration was carried out using daily AGCM fluxes of long wave heating, turbulent heating and windmixing and the Esbensen and Kushnir (1981) short wave flux and with (6) applied to the instantaneous mixed layer. The experiment was run for a period of 4 years and investigates, primarily, the response of the mixed layer model to the above AGCM fluxes.

Figures 3 and 4 show the global distribution of modelled minus observed monthly mean SSTs for March and September respectively. The observed temperatures are from Esbensen and Kushnir (1981) and the modelled values are four year means for these months. Figures 5 and 6 show the corresponding distributions of mixed layer depths. The observed values are from Levitus (1982).

March simulation

Over most of the oceans the modelled March SSTs differ from climatology by less than 2°C (Figure 3). The largest errors occur in the western boundary regions of the northern hemisphere and are probably associated with the simple treatment of the advective heat flux. The model net annual mean heating (Q) is large in these areas and the mixed layer model would not be expected to perform well.

The modelled mixed layer depths in the North Pacific are of the right order but exhibit a larger east-west gradient than appears in the observations (Figure 5). In much of the North Atlantic modelled mixed layer depths are generally too shallow, especially between 20°N and 45°N. A relatively shallow tongue extends across the sub-tropical North Atlantic and leads to the relatively warm modelled SSTs in this region (Figure 3). In the middle latitudes of the southern hemisphere the mixed layer depths are generally too deep. The area in the region of 37°S, 120°W shows simulated SSTs more than 3°C lower than climatology. This is associated with the relatively deep modelled mixed layer depth (about 70 to 80 m whereas the Levitus (1982) data set indicates a shallow mixed layer of about 25 to 50 m). It is also significant that climatological SSTs in this region have a large seasonal range, presumably associated with the shallow summer time mixed layer.

September simulation

In September the northern hemisphere oceans tend to be too cold, by as much as 7°C in the North Pacific (Figure 4). The mixed layer depths are correspondingly too deep (Figure 6), although this cannot account for the large magnitude of the error in the SSTs. The experiment using observed fluxes described earlier also underestimated the summer SSTs in this region, but with the maximum errors occurring somewhat further north (see Figure 2).

One of the major errors in the AGCM integration is a systematic underestimation of the downward long wave flux in the model (Rowntree, 1981). In the areas where SSTs are much too cold the modelled net downward long-wave flux is consistently of order 20-30 Wm^{-2} lower than the estimates given by Esbensen and Kushnir (1981). The effects of this error are to some extent compensated for by the treatment of the annual mean advective heat flux convergence in the model. This puts heat back into the mixed layer so as to ensure that the net change in oceanic heat content at each location is zero over the year. However, this heat flux is applied as a constant heating rate over the whole mixed layer (see equation (6)), not as a surface flux, and no windmixing energy is used to mix the heat throughout the layer. The modelled mixed layer depths are consequently too deep since in reality the instantaneous surface heating is greater and the net annual mean heating is smaller. Greater surface heating means that more windmixing energy must be used to mix the surface heat input throughout the mixed layer and less energy is therefore available for actually deepening the layer.

Mixed layer depths in the Atlantic are also too deep and the SSTs too cold. In the southern hemisphere SSTs are generally simulated to within 1°C of climatology except along the ice edge where differences are larger.

Seasonal range simulation

Figure 7 shows the modelled minus climatological seasonal range of SST. The definition of seasonal range is the same as that used in Section 3. It is evident that over most of the North Pacific and much of the North Atlantic the seasonal range is underestimated. This is associated with the poor simulation of the summer SSTs as discussed above. In the southern hemisphere the simulation is generally better although it is clear that the largest errors tend to occur in those regions where the climatological range is greatest.

A comparison of Figures 2 and 7 shows that the model simulation of seasonal range is considerably worse than that obtained using observed fluxes and mixed layer depths.

Experiment 2

This experiment was identical to Experiment 1 except for the inclusion of a linear feedback term in the surface heat balance. The original purpose of the experiment was to investigate the variability of SST predicted by the mixed layer model when it was forced with daily AGCM fluxes. For this purpose a feedback is essential (Frankignoul and Hasselmann, 1977). The simulated anomalies will not be discussed here but the experiment also produced some interesting features in the mean fields which will be described.

The net heat flux over the ocean is a function of SST and various atmospheric variables such as air temperature, wind speed, cloudiness etc. Denoting the latter collectively by $\underline{x}$, the net surface heating is linearised around the flux obtained with the observed climatological SST, so that

$$Q(T, \underline{x}) \approx Q(T_c, \underline{x}) - \lambda (T - T_c) \qquad (7)$$

where

$$\lambda = \left\langle -\frac{\partial Q}{\partial T}(T, \underline{x}) \right\rangle_{T=T_c} \qquad (8)$$

The angle brackets in (8) represent an ensemble mean over many realisations of the atmospheric variables x. (Frankignoul, 1979). The net heat flux $Q(T_C, \underline{x})$ in (7) is the flux obtained with the climatological SST and is therefore the flux produced in the AGCM simulation. The last term is the anomalous heat flux due to the SST anomaly and is essentially equivalent to a local Haney-type forcing (Gill, 1979). The feedback parameter λ was assigned a globally constant value of 35 $Wm^{-2}K^{-1}$. In reality this parameter should vary with geographical location and the spatial scale of the anomaly so that it decreases to a few $Wm^{-2}K^{-1}$ for changes of SST on a global scale (Bretherton, 1982).

The difference between simulated and observed climatological SST range is shown in Figure 8. Not surprisingly the differences are generally less than those obtained using the model without feedback (Figure 7). Figures 9a and 9b show the mixed layer depths from Experiment 2 for March and September respectively. In March in the North Pacific and sub-tropical North Atlantic the mixed layer depths are generally deeper than those obtained in Experiment 1, whereas they are shallower in the South Pacific. In September the North Pacific depths are shallower and closer to climatology in this experiment and in the southern hemisphere they are deeper. Each of these changes can be understood in terms of the anomalous stabilising or de-stabilising effects of the anomalous heat flux associated with the feedback term.

In general the distribution of mixed layer depths is closer to the Levitus (1982) climatology and, of course, the SSTs are also simulated considerably better than those in Experiment 1. Taken at face value the results of Experiment 2 would give a misleading indication of the ability of the mixed layer model to simulate global SSTs. This illustrates the limitations of using a heat flux forcing which ensures that the SST remains close to its observed climatological value. If the spatial scale-dependence of the feedback parameter λ was introduced as suggested by Bretherton (1982), its value would decrease as the large scale SST differences evident from Experiment 1 started to develop. With this dependence included the simulated SSTs would be a better guide to how the SSTs might respond in a fully coupled integration. The results would, no doubt, exhibit many of the errors found in Experiment 1 but with reduced magnitude. (Ideally, non-local effects should also be taken into account in the manner outlined by Bretherton (1982)).

5. Conclusions

The simulation of the seasonal cycle of SST using fluxes derived from the AGCM must be considered to be rather poor. However, the systematic error in the downward longwave flux at the surface, which was due to inadequacies in the treatment of water vapour absorption and emission in the radiation scheme, has now been corrected. An improvement in the simulation of the SST seasonal cycle is therefore expected in future experiments with the mixed layer model.

The quality of the atmospheric model fluxes is highly dependent on the model in question. For example, previous experiments with the Meteorological Office 5-level AGCM produced much too high summer SSTs in the North Pacific, partly because the summertime windmixing was much too low. The results presented here should not, therefore, necessarily be taken to be applicable to other AGCMs although analogous problems will occur in all models. Using the AGCM fluxes to force the mixed layer model is a useful way to assess the significance of the errors in these fluxes in terms of predicting SSTs. In this context the mixed layer model is a useful diagnostic tool.

Also relevant here is the question as to which upper ocean parametrization should be used in a coupled model. For example, if the AGCM produces a very poor simulation of the global windmixing field, a model with a fixed mixed layer depth may well produce better results than a model which determines the mixed layer depth. The complexity of the ocean model has therefore to be matched to the quality of the fluxes used to force it.

In the near future it is intended to repeat the experiments with climatological heat fluxes but using a global data set of climatological windmixing power to force the full mixed layer model. Simulations of the seasonal cycle will also be performed in which fluxes from an AGCM experiment with improved parametrizations of the downward long wave flux and the surface drag coefficient (see Mitchell, this volume) as well as model predicted surface short wave heating produced by an interactive cloud scheme, will be used. In the longer term the mixed layer model will be embedded into a global version of the Bryan/Semtner model currently being developed for coupling to the atmospheric model.

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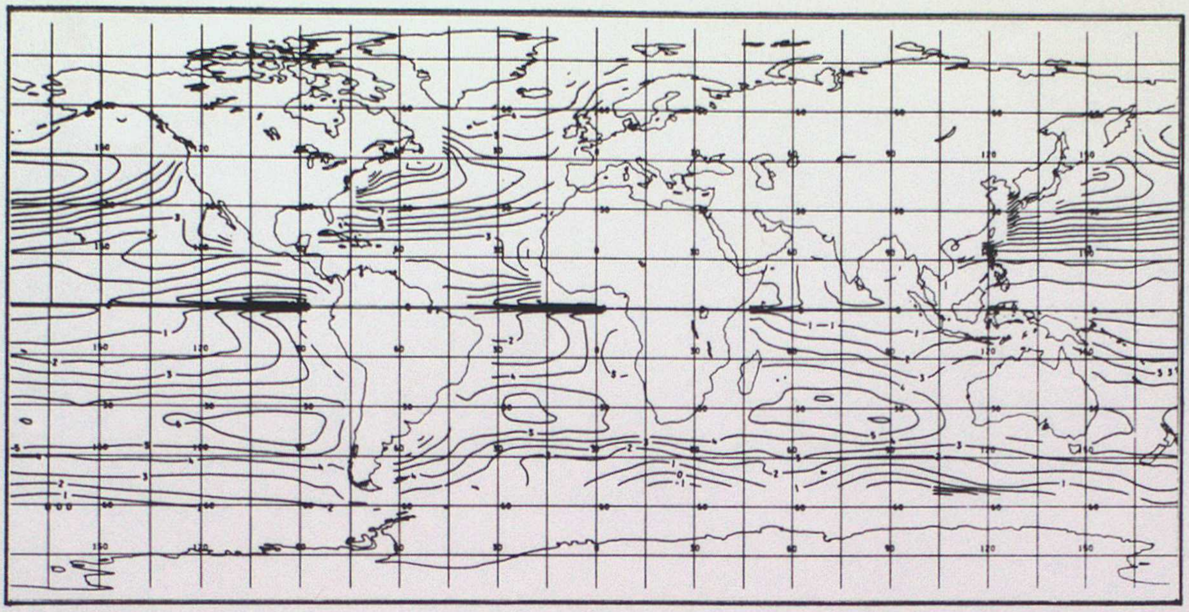

Fig. 1. Seasonal range of SST (°C), defined as the monthly mean for August minus the monthly mean for March in the northern hemisphere and the February value minus the September value in the southern hemisphere.

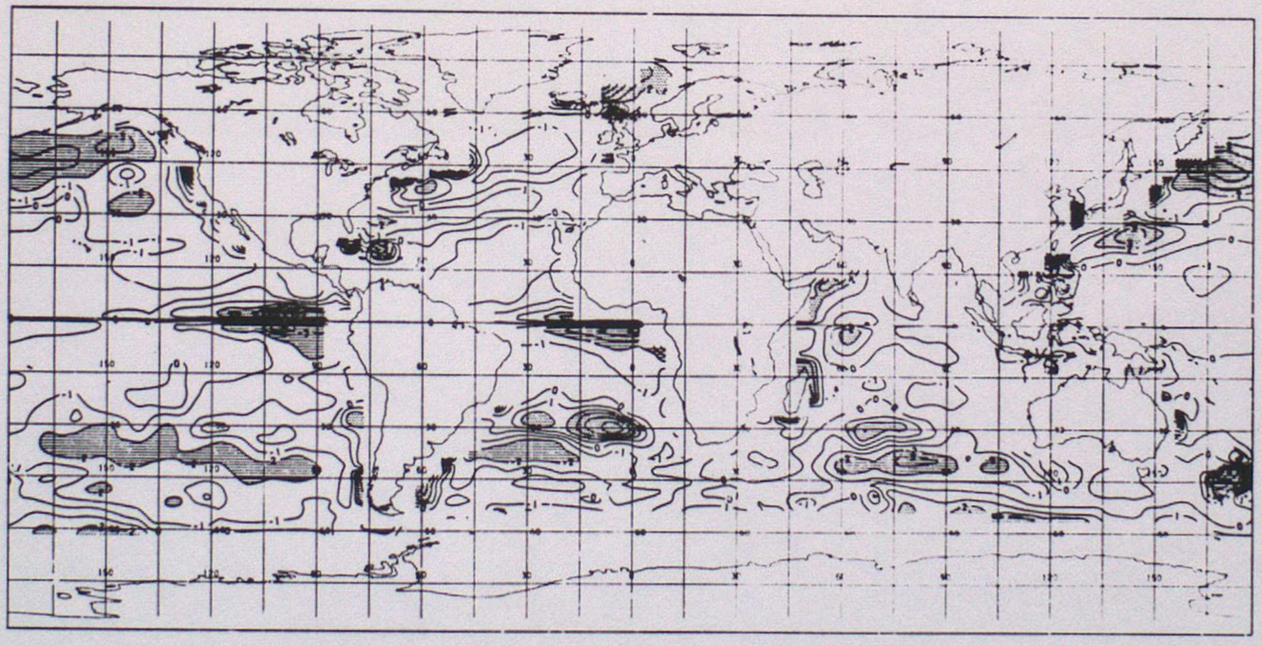

Fig. 2. Difference (°C) between the simulated and observed climatological seasonal ranges of SST. The simulated range was predicted using observed climatological heat fluxes and mixed layer depths, as discussed in section 3. (Hatched areas indicate differences less than −2°C; stippled areas indicate differences greater than 2°C).

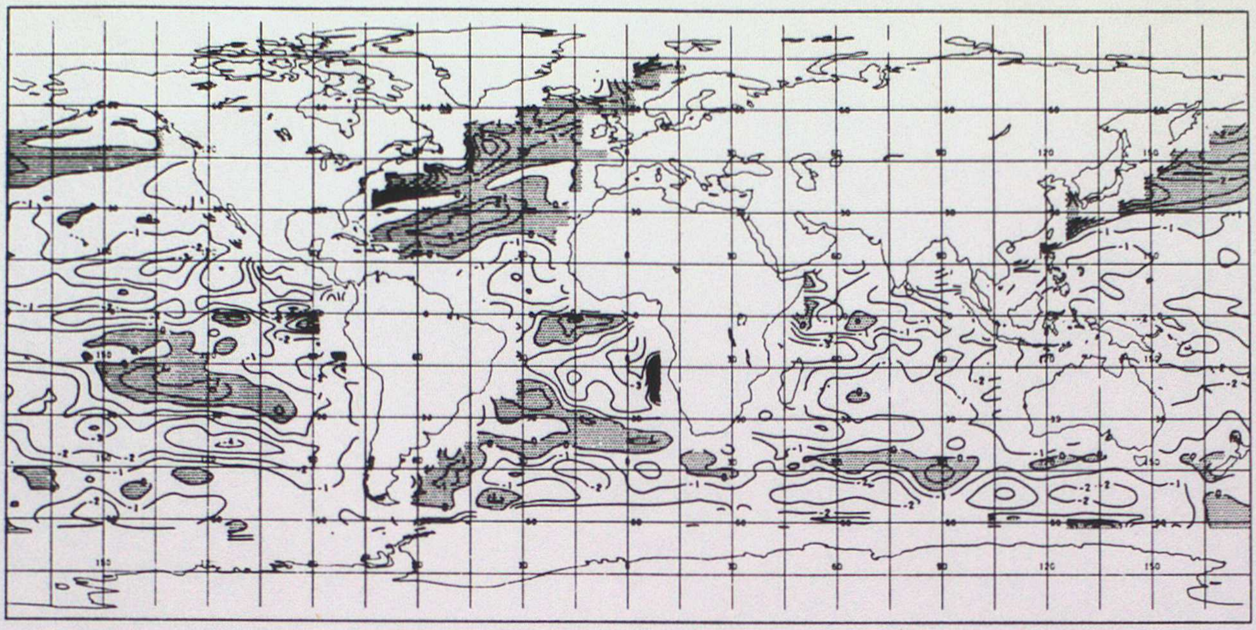

Fig. 3. Difference (°C) between the monthly mean SST for March as predicted by the full mixed layer model and the observed climatological monthly mean value. (Stippled areas indicate differences that are positive).

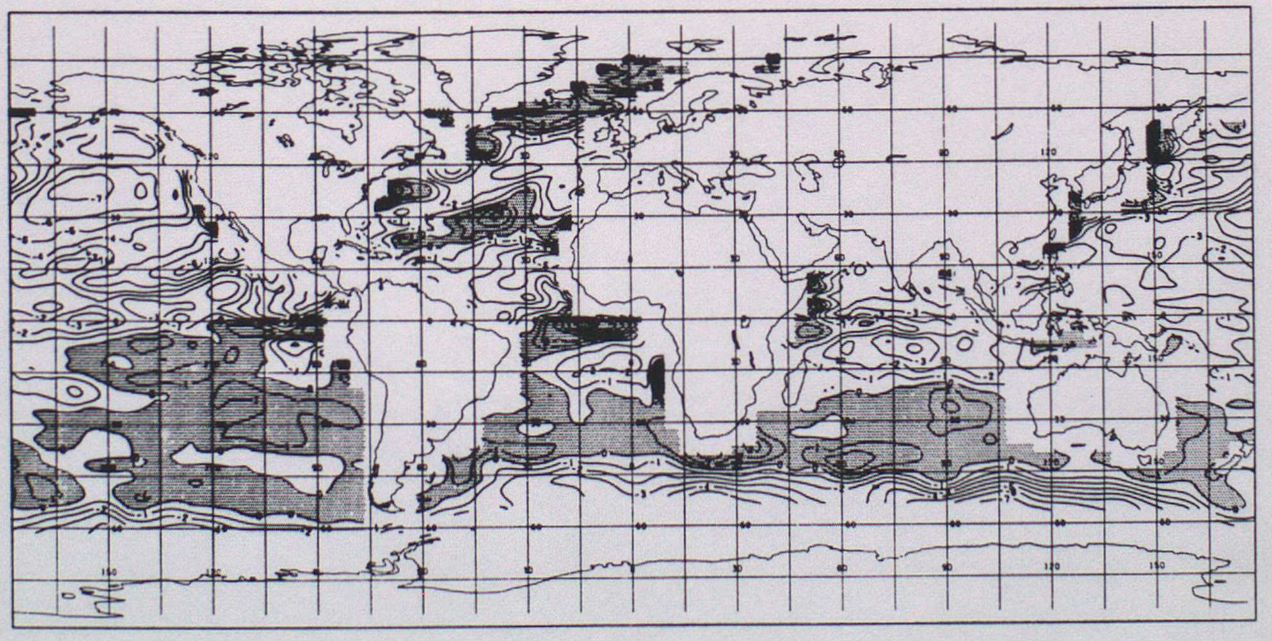

Fig. 4. As Fig. 3 but for September.

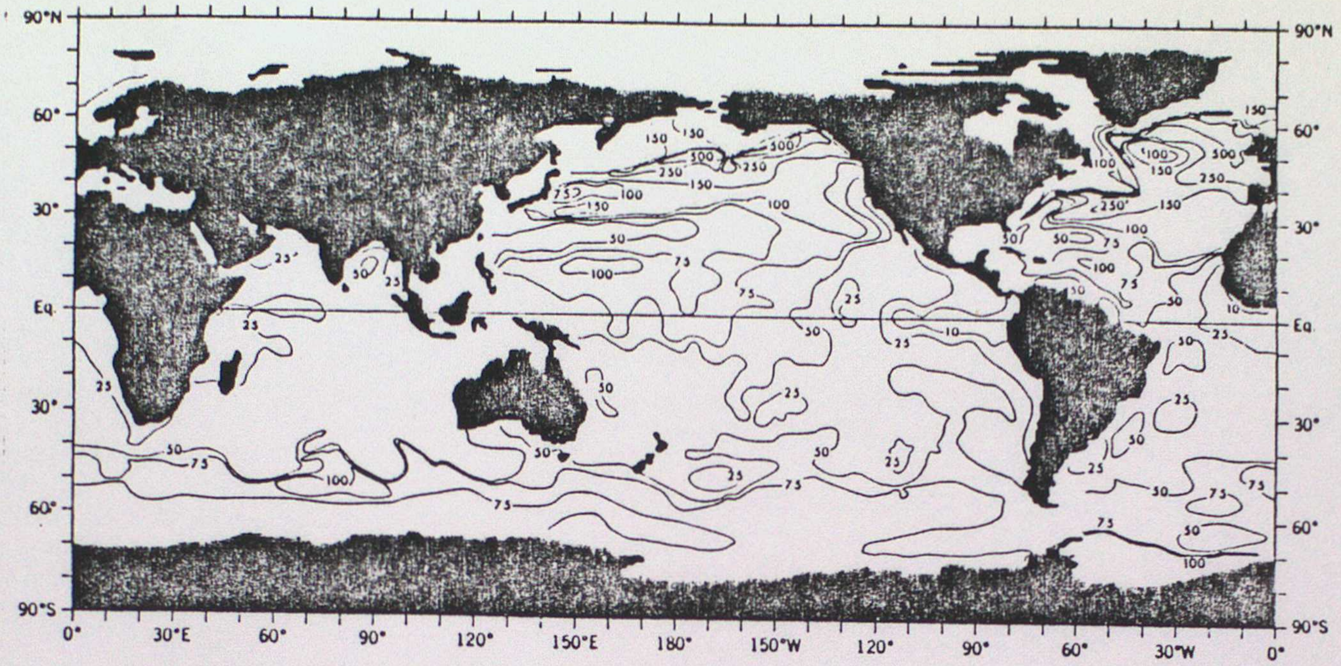

Fig. 5a. Observed climatological distribution of monthly mean mixed layer depths (m) for March (after Levitus, 1982).

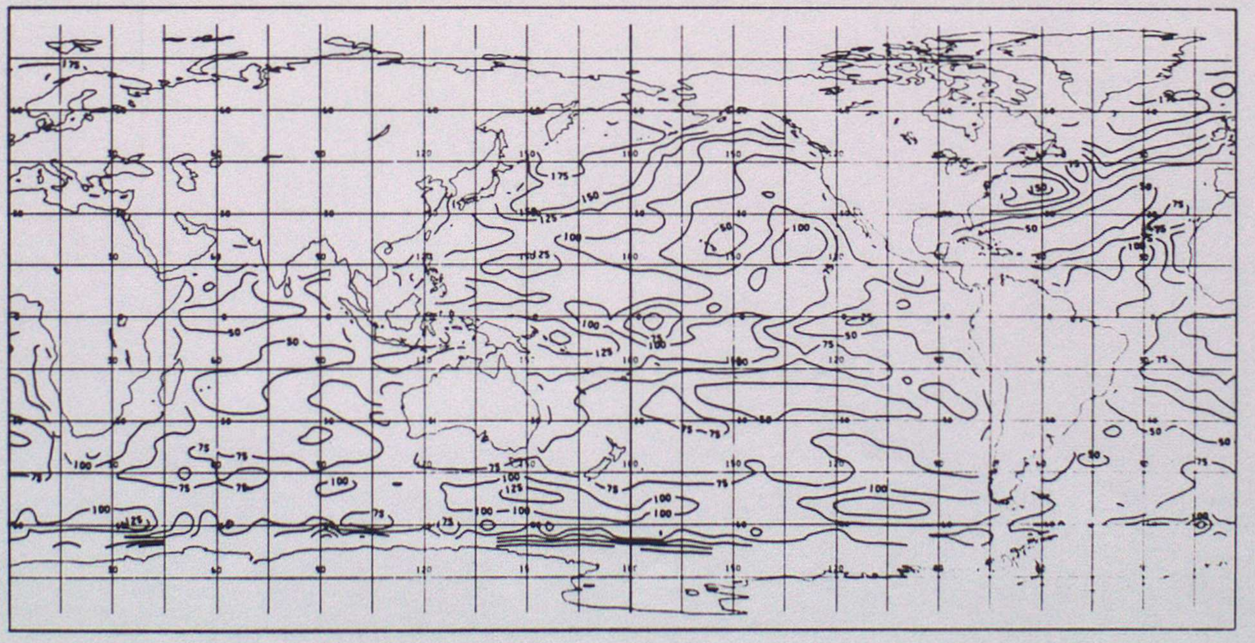

Fig. 5b. Modelled distribution of monthly mean mixed layer depths (m) for March from Experiment 1.

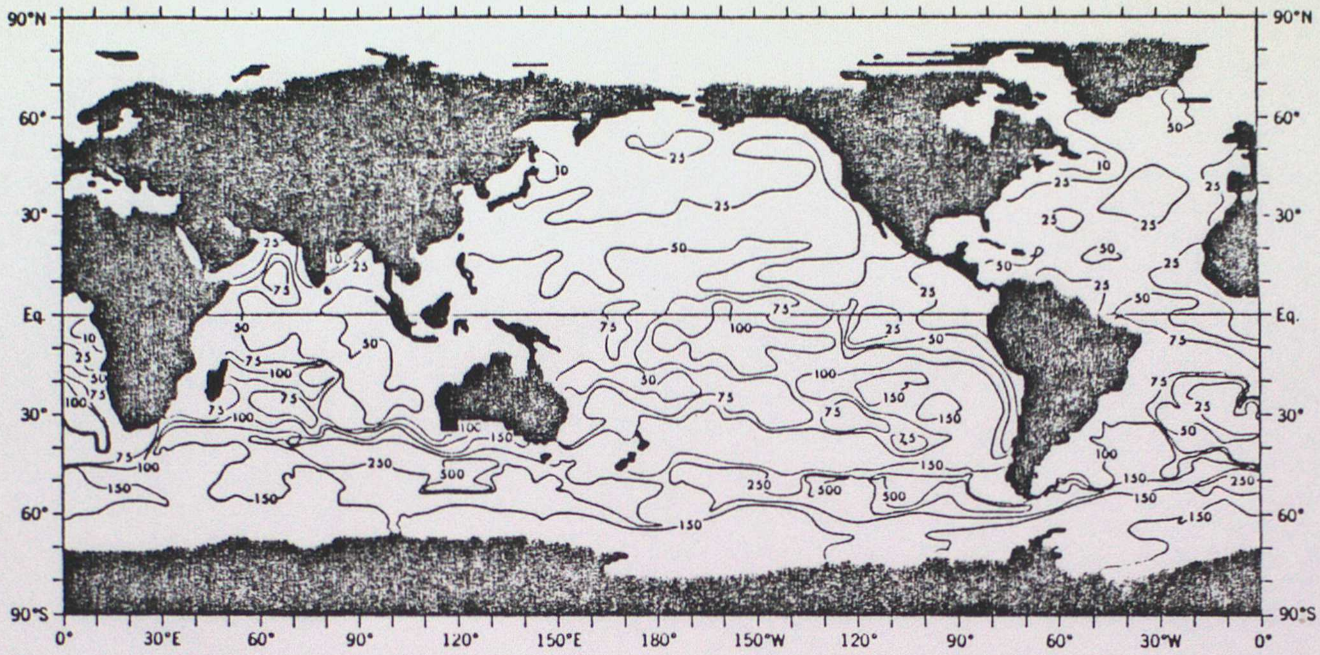

Fig. 6a. Observed climatological distribution of monthly mean mixed layer depths (m) for September (after Levitus, 1982).

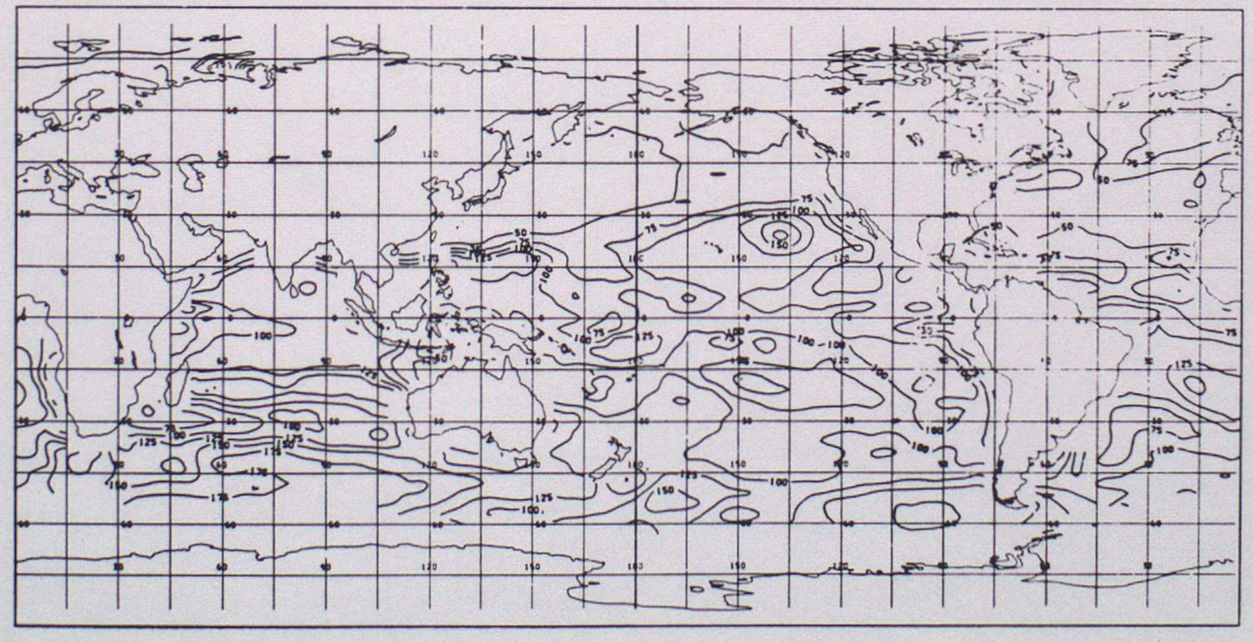

Fig. 6b. Modelled distribution of monthly mean mixed layer depths (m) for September from Experiment 1.

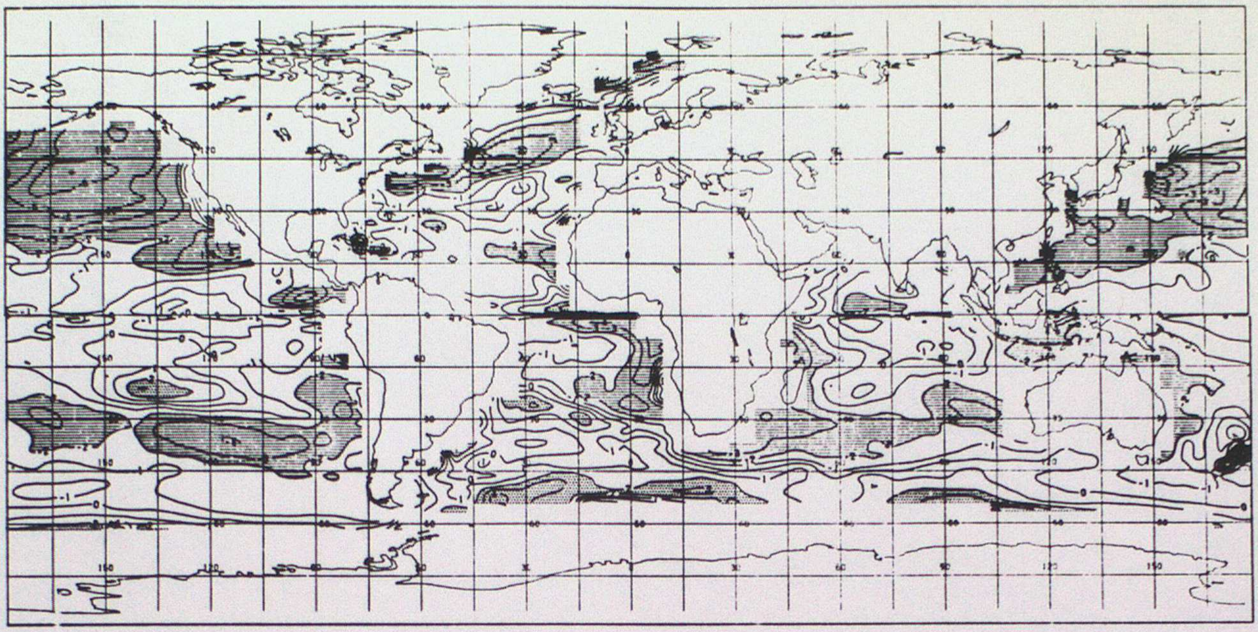

Fig. 7. Difference (°C) between simulated and observed climatological seasonal ranges of SST. The simulated range was predicted using AGCM heat and windmixing fluxes to force the full mixed layer model. (Shading as in Fig. 2).

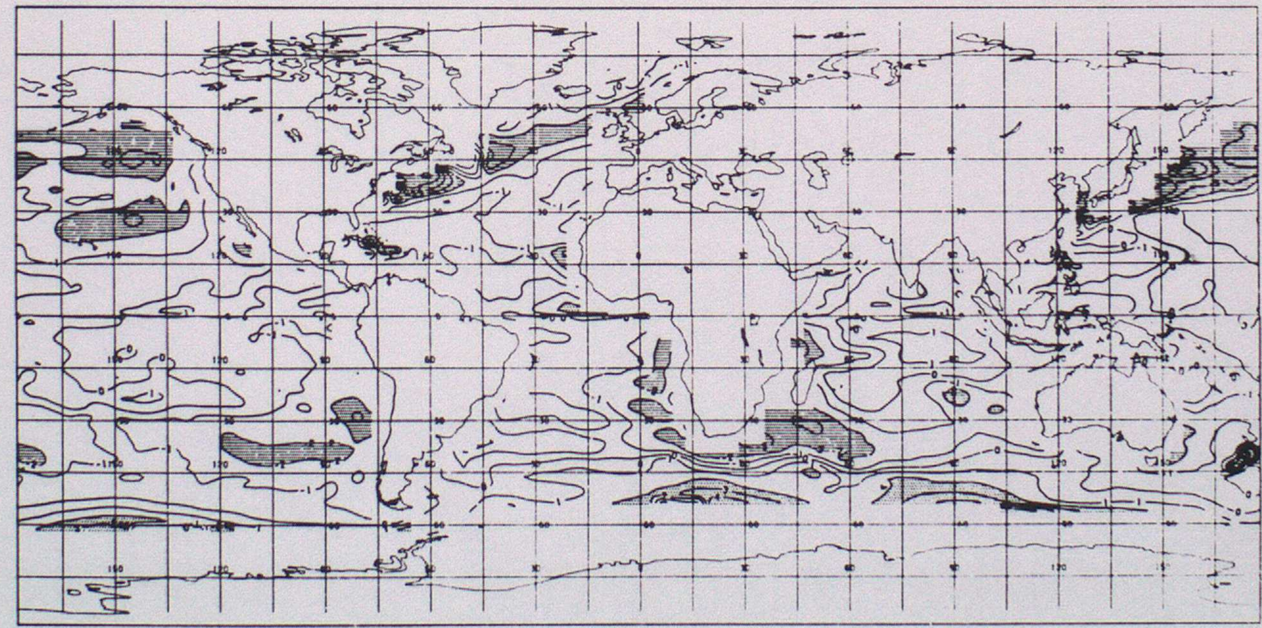

Fig. 8. As Fig. 7 but using the model with a linear feedback term.

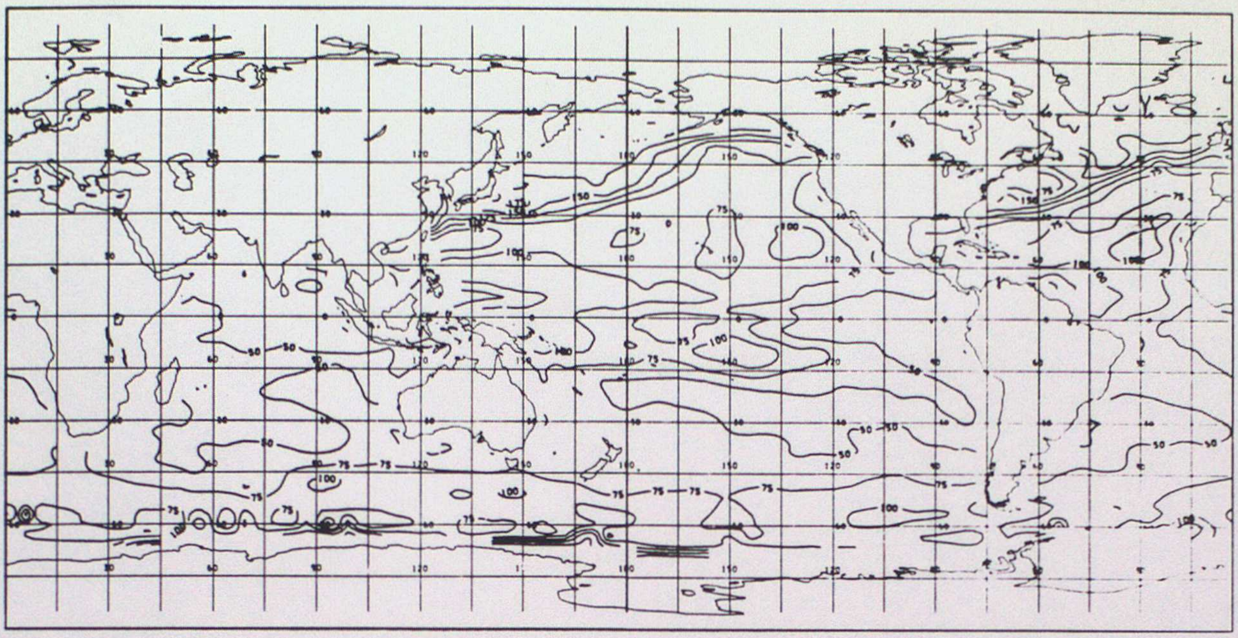

Fig. 9a. Modelled distribution of monthly mean mixed layer depth (m) for March from Experiment 2.

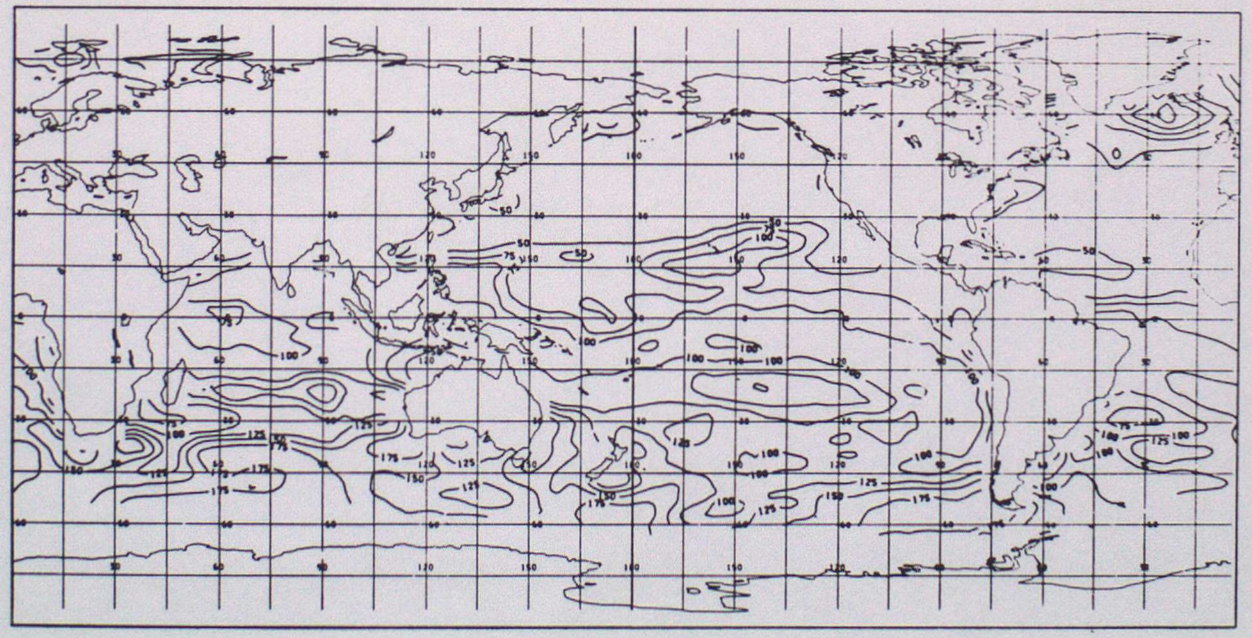

Fig. 9b. As Fig. 9a but for September.