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The sensitivity of the northern hemisphere summer mean meridional circulation to changes in the large scale eddy forcing

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Abstract. A zonally averaged version of the Goddard Laboratory for Atmospheric Sciences (GLAS) climate model is used to study the sensitivity of the northern hemisphere (NH) summer mean meridional circulation to changes in the large scale eddy forcing. A standard solution is obtained by prescribing the latent heating field and climatological horizontal transports of heat and momentum by the eddies. The radiative heating and surface fluxes are calculated by model parameterizations. This standard solution is compared with the results of several sensitivity studies. When the eddy forcing is reduced to 0·5 times or increased to 1·5 times the climatological values, the strength of the Ferrel cells decrease or increase proportionally. It is also seen that such changes in the eddy forcing can influence the strength of the NH Hadley cell significantly. Possible impact of such changes in the large scale eddy forcing on the monsoon circulation via changes in the Hadley circulation is discussed. Sensitivity experiments including only one component of eddy forcing at a time show that the eddy momentum fluxes seem to be more important in maintaining the Ferrel cells than the eddy heat fluxes. In the absence of the eddy heat fluxes, the observed eddy momentum fluxes alone produce subtropical westerly jets which are weaker than those in the standard solution. On the other hand, the observed eddy heat fluxes alone produce subtropical westerly jets which are stronger than those in the standard solution.

Keywords: Symmetric model; eddy transports; sensitivity experiments.

1. Introduction

The observed three cell structure of the zonally averaged time mean circulation (mean meridional circulation, MMC) depends on the distribution of the latent heating, radiative heating, sensible heat flux, transports of heat and momentum by large scale eddies and surface friction. The relative importance of these factors in maintaining the MMC has been studied by many authors (Starr 1948; Rossby and Starr 1949; Palmén 1949; Palmén *et al* 1958; Williams and Davies 1965; Kuo 1956; Saltzman and Vernekar 1971, 1972; Dickinson 1971a, b; Derome and Wiin-Nielsen 1972; Kurihara 1973; Wiin-Nielsen and Fuenzalida 1975; Schneider and Lindzen 1977; Schneider 1977; Taylor 1980; Held and Hou 1980). The aim of the present study is to examine the sensitivity of the MMC to changes in the fluxes of heat and momentum due to the large scale eddies. It is well known that large scale eddy transports of heat and momentum contribute significantly to the maintenance of the middle latitude Ferrel cells. However, the transports of heat and momentum by large scale eddies can also influence the strength of the Hadley circulation in the tropics. In a recent diagnostic study related to the NH winter MMC, Crowford and Sasamori (1981) showed that in the absence of the condensational heating in the tropics, the observed large scale eddy fluxes can maintain

Hadley cells in the tropics with about one-third the observed strength. In this study, we shall examine, in particular, the changes in the northern hemisphere (NH) Hadley circulation due to changes in the large scale eddy forcing. This study was motivated by the fact that, the fluctuations of the large scale eddies in the middle latitude do indeed seem to influence the subseasonal fluctuations of the south Asian summer monsoon. The southwest monsoon shows temporal fluctuations often resulting in long "breaks" in the rainfall. Such long and/or frequent breaks result in a drought situation. It was noted by synoptic meteorologists (e.g. Ramaswamy 1962) that a drastic change in the NH middle latitude circulation from the zonal to the Rossby regime is seen during the onset of a break. The large scale waves in the middle latitude can influence the Hadley circulation in two ways. Firstly, the eddies can influence the tropical circulation through lateral forcing on the northern boundary of the Hadley circulation. Mak (1969) examined this question by introducing stochastic lateral forcing at ±30° latitude in a tropical model. He prescribed the stochastic forcing in terms of second moment eddy statistics. Secondly, the eddies contribute to the heat and momentum budget requirements for maintaining the MMC and hence can influence the Hadley circulation through heat and momentum transports. It is this question that we want to examine in this study.

For the purpose of this study, a zonally symmetric version of the Goddard Laboratory of Atmospheric Sciences (GLAS) climate model was constructed. The zonally symmetric version of the GLAS climate model was obtained by putting all the longitudinal derivatives to zero in the GLAS climate model and contains the same physical parameterizations, resolution and numerical technique as the full climate model. The GLAS climate model has been described and its performance has been discussed by Shukla *et al* (1981). The symmetric version of the GLAS climate model has been discussed in some detail by Goswami *et al* (1984). Briefly, the symmetric model has a 4° latitude grid in the north south direction and nine σ levels in the vertical. For the experiments discussed in the paper, the radiative heating and surface fluxes are calculated using the model parameterizations. The latent heating distribution for these runs is prescribed. We also prescribe the horizontal fluxes of heat and momentum by the large scale eddies as input forcing from observations. The sources for these data are discussed in §2. As discussed in Goswami *et al* (1984), the cloud-radiative feed back has been omitted in these calculations. The lower boundary for all the experiments consists of an all ocean earth. A sea surface temperature distribution corresponding to the NH summer conditions is prescribed. By including the observed global eddy fluxes, a realistic distribution of the latent heating field and calculating the radiative and surface fluxes through model parameterizations, we obtain a control run corresponding to the NH summer condition. Then keeping boundary conditions and latent heating distribution the same, we carried out several sensitivity experiments by changing the observed eddy fluxes. For each run the model was integrated for about 150 days and it was found that the model reached a steady state for each run after about 60 days of integration. The fields presented in this paper were obtained by averaging over the last 60 days of integration in each case.

In §2, we discuss the data used in this study. In §3, the standard solution is presented and compared with observations. The deficiency of the standard solution is also discussed in this section. The results of the sensitivity experiments are presented in §4. The results are summarized and a few remarks are made in §5.

2. Model specifications and data used

The initial condition for all the experiments presented in this study correspond to a resting atmosphere ($u = v = 0$). Climatological distributions of the specific humidity and the temperature field are prescribed initially.

With only one exception (see §3.3), for all the experiments presented in this paper, the vertical eddy viscosity coefficient in the middle layer (ν_5) is taken to be approximately 11 $\mathrm{m}^2\,\mathrm{s}^{-1}$. The experiment described in §3.3 is designed to examine the sensitivity of the zonal winds to changes in the vertical eddy viscosity. For this experiment, ν_5 is taken to be 33 $\mathrm{m}^2\,\mathrm{s}^{-1}$. In our model the vertical eddy viscosity varies linearly with pressure.

The observed climatological mean global eddy fluxes for NH summer (June–July–August) used in this study were taken from Oort (1983). This mean was constructed from a 15 year (1958–1972) data set. The eddy fluxes used in this study are $[\overline{u'v'}]$, $[\bar{u}^*\bar{v}^*]$, $[\overline{v'T'}]$ and $[\bar{v}^*\bar{T}^*]$. These fluxes were obtained at intervals of 5° latitude between 80°S and 80°N and on 20 levels in the vertical between 1000 mb and 50 mb. We then interpolated the data to the 9 layers in the vertical and 4° latitude grid of our symmetric model. We employed a linear interpolation scheme using distance weighing (pressure weighing) for the horizontal (vertical) interpolation. These eddy fluxes are shown in figure 1. As there exist large uncertainties in obtaining the vertical fluxes of the large scale eddies from observations, we have not included the vertical transports of heat and momentum by the eddies in this study. We have also neglected variances, $[\overline{v'^2}]$ and $[\overline{u'^2}]$ in the momentum equation. Convergence and divergence of momentum and heat due to the eddies are calculated from the observed fluxes and used in the momentum and thermodynamic equations as time independent forcings. As with most of the other forcing functions, the eddy forcings are also applied to the momentum and the thermodynamic equations only every "physics time step" (i.e. 30 min).

The lower boundary for all the runs is all ocean with fixed sea surface temperature (SST). These runs correspond to the northern hemispheric (NH) summer condition. The SST used for these runs is the same as the one used for the summer runs described in Goswami *et al* (1984). The SST has a maximum at 18°N. The solar declimation is fixed at 15°N. The surface albedo is taken to be 7 % everywhere. The shortwave radiation, the longwave radiation and the boundary fluxes are calculated using the parameterization of the GLAS climate model. However, the latent heating field is not calculated in the model. Instead, we prescribe the latent heating field from the observed zonal mean precipitation distribution for June–July–August. The latent heating field used in this study and the equivalent precipitation distribution (dashed curve) are shown in figure 2a. This latent heating field is similar to the one calculated by Newell *et al* (1974) for the NH summer. As we are interested in only studying the role of the eddy forcing on the MMC, the finer details of the distribution of the latent heating field may not be important for our study.

The reason for prescribing the latent heating field from the observed zonally averaged precipitation distribution instead of calculating the same using the parameterization of the GLAS climate model is the following. The latent heating field calculated by the GLAS climate model depends crucially on the nature of the lower boundary (e.g. whether it is land or ocean). It is not possible to represent the earth's lower boundary in a realistic way in our symmetric model since each grid point represents a 4° latitude belt of either land or ocean. Therefore, we cannot expect to

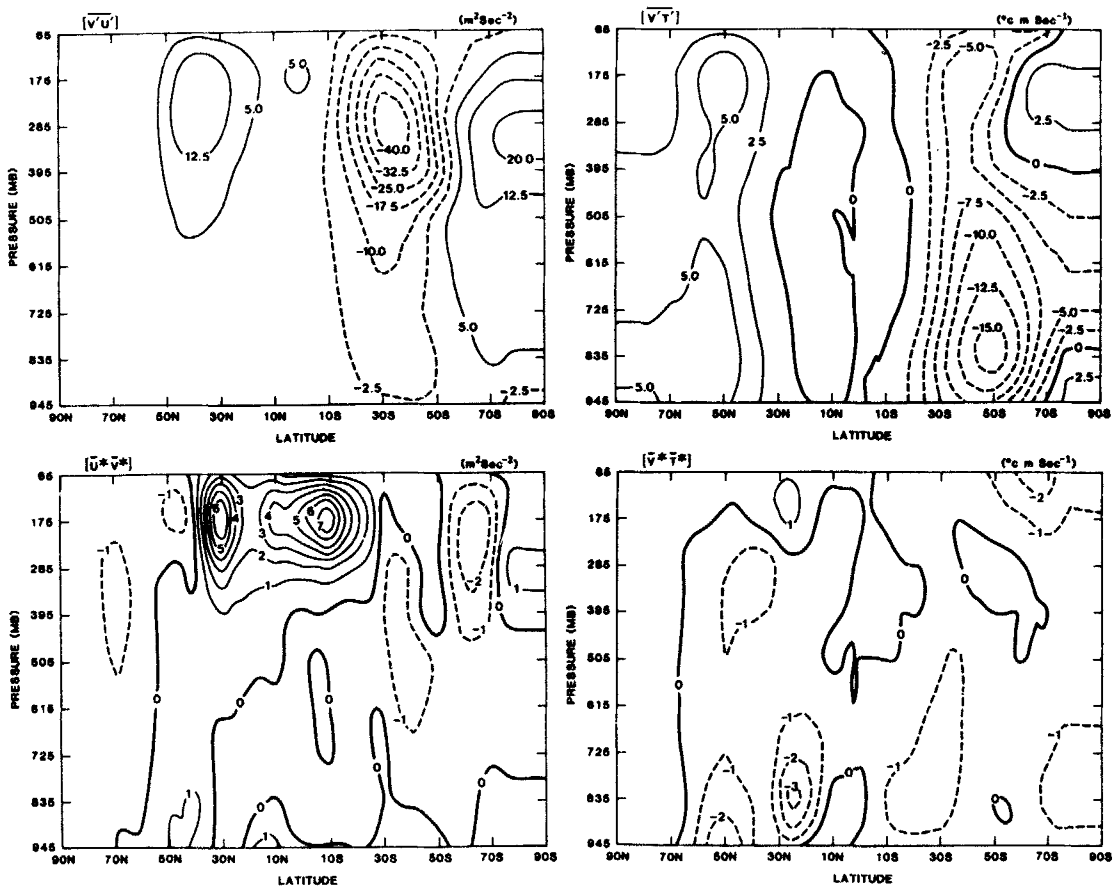

Figure 1. Climatological mean June–July–August transient and stationary eddy fluxes from observation. These eddy fluxes have been obtained from global statistics compiled by Oort (1983) and interpolated to the model grid.

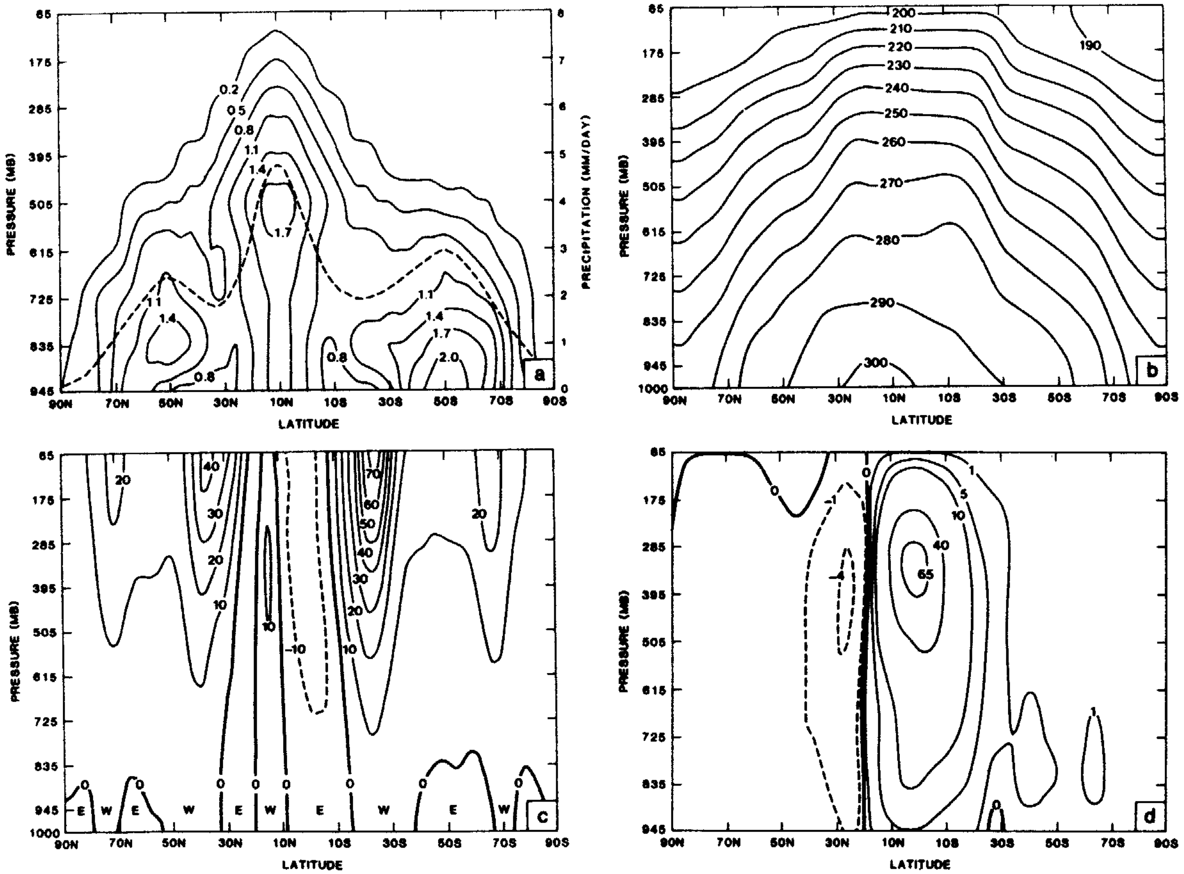

Figure 2. Northern hemisphere summer run without eddies, **a**) prescribed convective heating field, contour deg day^{-1}; **b**) temperature, contour interval 10°K; **c**) zonal wind, contour interval, $10\,\mathrm{ms}^{-1}$; **d**) stream function, contour, $10^{10}\,\mathrm{kgs}^{-1}$.

simulate the observed zonally averaged latent heating field with our symmetric GLAS climate model. In order to study the role of the observed eddy forcing in maintaining the MMC, it is important that we have realistic representation of the other forcing functions. This is why we chose to use the observed latent heating field. As this field is derived from observed precipitation distribution, it implicitly contains the effect of the land-ocean inhomogeneities in the zonal direction in producing the latent heating field. But by prescribing an all ocean lower boundary with fixed SST we imposed a constraint on the sensible heat flux from the lower boundary. The implication of prescribing a fixed SST distribution on the strength of the Hadley cells will be discussed in §3.4.

3. The standard solution

3.1 *Northern hemisphere summer run without eddy fluxes*

We first carried out one integration in which the observed eddy fluxes were not included. The temperature, the zonal wind and the stream function for the steady state for this run are shown in figures 2b-d. The NH westerly jet occurs at about 40°N with maximum westerly winds of about 40 ms^{-1} at the center of the jet. The (southern hemisphere) SH westerly jet occurs at about 26°S with maximum westerly winds of about 70 ms^{-1} at the center of the jet. The surface easterlies appear in tropics between 14°S and 34°N with a westerly region between 6°N and 20°N. Surface easterlies again appear in the high latitudes. Although the westerlies in the subtropical jet stream are much stronger than those observed, the zonal wind distribution has the general characteristics of the observed NH summer mean zonal wind distribution. However, the stream function field shows that in the absence of the eddy fluxes the MMC is quite different from observed. In this case, the MMC has one direct cell in each hemisphere. Only a very weak and shallow Ferrel cell appears in the SH.

3.2 *Northern hemisphere summer run with observed eddy fluxes*

This run is similar to the one described in §3.1, but we now add the large scale eddy fluxes described in §2 as input forcing. The temperature, the zonal winds and the stream function for the steady state for this run are shown in figure 3. We notice that the eddies strengthen the westerlies in the subtropical jet in the NH. In the Southern Hemisphere, the westerly jet occurs at about 26°S with a maximum strength of about 70 ms^{-1}. In the Northern Hemisphere, the westerly jet occurs at about 35°N with a maximum strength of about 50 ms^{-1}. A secondary jet appears in high latitudes in the Southern Hemisphere. In the tropics, surface easterlies appear between 22°S and 34°N with a region of westerlies between 6°N and 18°N. The surface easterlies in the high latitudes also appear in the more or less correct positions.

The most dramatic change the eddies produce occurs in the stream function field. In this case, the large scale eddy transports result in the observed three cell structure of the zonally averaged circulation. The structures of the Hadley and the Ferrel cells are now close to that of the observed cells in their positions and their latitudinal extents (Oort and Rasmussom 1971; Newell *et al* 1972). The mass fluxes in the Ferrel cells, in this case, are quite realistic while those in the Hadley cells are larger than the mass fluxes obtained

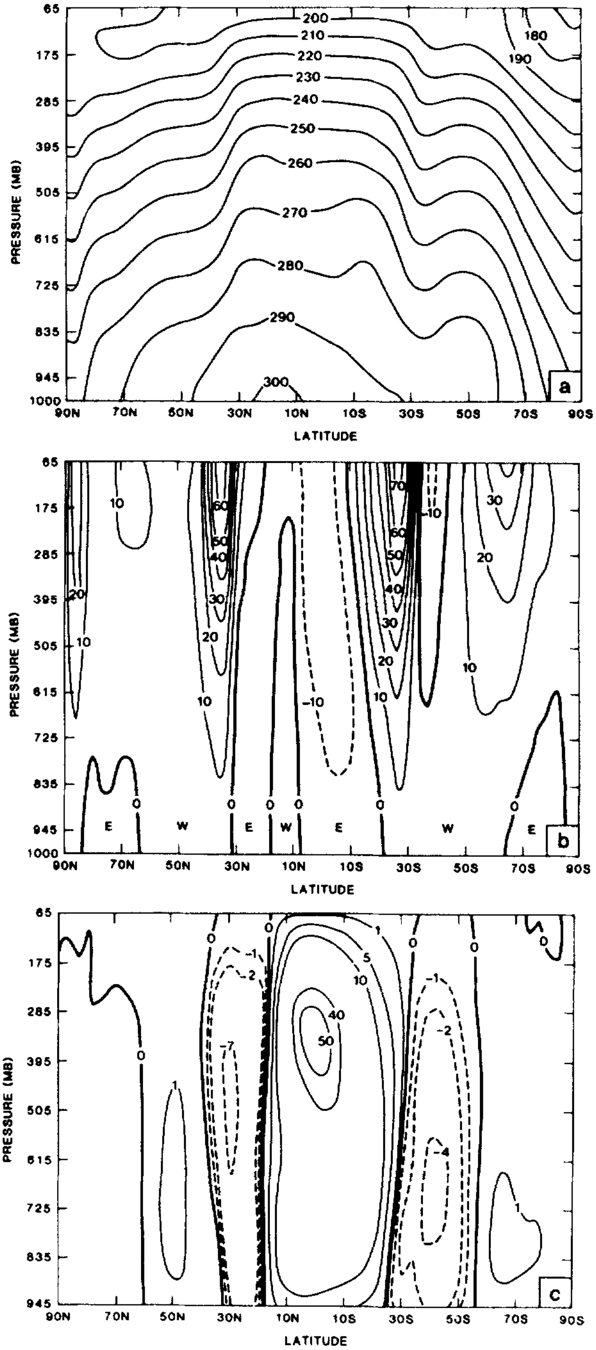

Figure 3. Northern hemisphere summer run with eddies, **a**) temperature, contour interval 10°K; **b**) zonal wind, contour interval 10 ms^{-1}; c) stream function, contour 10^{10} kgs^{-1}.

from observations by about a factor of 2 (Oort and Rasmusson 1971; Newell *et al* 1972). An explanation for obtaining such large mass fluxes in the Hadley cells is given in Goswami *et al* (1984). The gist of this explanation is reproduced in §3.4.

3.3 *NH summer run with observed eddy forcing and large vertical eddy viscosity*

In §3.2, we have shown that the observed eddy forcing together with a realistic distribution of the latent heating field produces a realistic MMC corresponding to the NH summer condition (see figure 3). However, we note from figure 3 that the westerlies in the subtropical jet stream are much larger than those observed. In this section we shall present results of an experiment showing that the strength of the subtropical westerly jet stream depends on the choice of the vertical eddy viscosity in our symmetric model.

We recall that the vertical eddy viscosity coefficient at the middle layer for the experiment described in §3.2 was 11 $m^2 s^{-1}$. We carried out an identical experiment (including the latent heating field and eddy forcing) except that we increased the vertical eddy viscosity coefficient such that ν in the middle layer is 33 $m^2 s^{-1}$. The model was again integrated until it reached a steady state. The temperatures, the zonal winds and the stream function for this steady state are shown in figure 4. We note from figure 4 that the strength of the westerlies in the NH jet is reduced to 30 ms^{-1} in this case as compared to 50 ms^{-1} in the low viscosity case (see figure 3). Similarly, the strength of the westerlies in the SH jet is reduced to 40 ms^{-1} as compared to 70 ms^{-1} in the low viscosity case. It is of interest to note that the zonal wind distribution for the high viscosity case (figure 4) is much closer to the observed zonal winds for the NH summer. The increase in the vertical eddy viscosity increases the strength of the NH Hadley cell by about 25% and decreases the SH Hadley cell by about 10%.

3.4 *Comments on the standard solution*

The behaviour of our model as the vertical eddy viscosity is increased is as predicted by simple model calculations. Held and Hou (1980) showed that if the heat source is fixed and internal viscosity is decreased, the jet stream zonal velocities are increased and sharper meridional jet stream structure is seen. This behaviour is seen in our model solutions also (figures 3 and 4).

There are several features of our standard solution that agree well with the observed mean meridional circulation. Examining the large vertical viscosity solution from our model (figure 4), we note that the position of the subtropical westerly jets correspond well with observations. The intensity ratio between the Hadley and Ferrel cells at the individual maxima is about 10:1 which compares well with the analysis of Newell *et al* (1972). The ratio between the strength of the Hadley cell in the summer hemisphere to the strength of the Hadley cell in the winter hemisphere is about 1:5 which also compare well with observations (Newell *et al* 1972).

However, there are a few features of our standard solution that do not agree well with the observed MMC. Firstly, the zonal winds simulated by the model do not have the closed maxima near 200 mb which is seen in the observations. As a result, the model simulated zonal winds near the upper boundary are stronger than those observed. This is related to the fact that the model simulates much colder temperatures in the upper

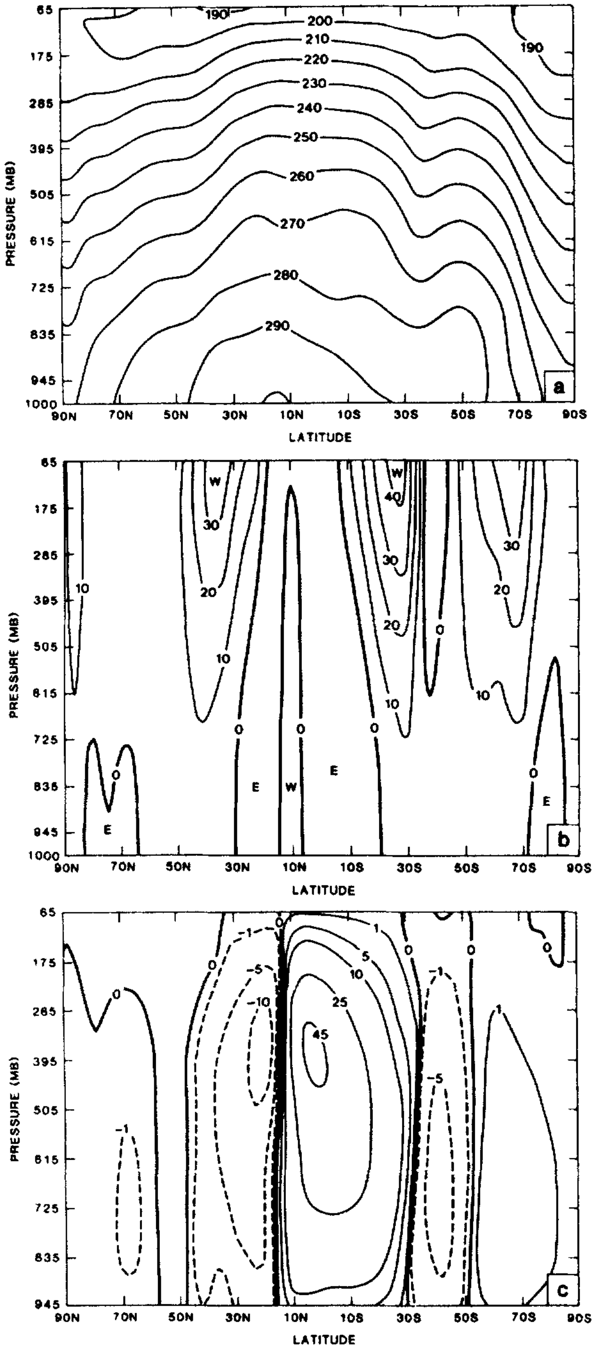

Figure 4. Same as figure 3 but for the run with large vertical eddy viscosity. The coefficient of the vertical eddy viscosity at level 5 for this run is 33 m^2s^{-1} as compared to 11 m^2s^{-1} for the run corresponding to figure 3.

tropospheric polar regions (Shukla *et al* 1981). Another significant feature of our standard solutions is that the meridional mass flux in the Hadley cell is about twice the observed Hadley cell mass flux in summer (Oort and Rasmusson 1971; Newell *et al* 1972). An explanation regarding the large mass flux in our model simulated Hadley circulation is given in Goswami *et al* (1984). This feature apparently results from the neglect of cloud-radiation interaction in the radiative calculations. With the fixed SST distribution at the lower boundary, the removal of the cloud radiation feedback results in larger net outgoing long wave flux at the top of the atmosphere. In terms of Newtonian cooling approximation, it can be shown that, this leads to an effective radiative time constant for our model atmosphere which is about half the radiative time constant of the atmosphere. According to estimates using simple model calculations (Schneider 1977; Held and Hou 1980), the mass flux of the zonally symmetric Hadley cell should be inversely proportional to the radiative time constant. This seems to be the reason why our symmetric version of the GLAS climate model simulates Hadley cells with large mass fluxes.

Since the motivation of the present study is only to examine the sensitivity of the MMC to changes in the eddy forcing, the discrepancies between our standard solution and the observed MMC are not expected to influence our conclusions regarding the sensitivity experiments. We shall only derive qualitative conclusions regarding the role of various components of the eddy forcing on maintaining the MMC by comparing the sensitivity experiments with the standard solution. For this purpose the low internal viscosity run (figure 3) will be taken as the standard solution.

4. Sensitivity of the MMC to eddy forcing

In this section we present results of several sensitivity experiments. These experiments are designed to study the relative role of different eddy components. We shall also examine how the strength of the total eddy forcing affects the MMC. All other conditions for these runs including the prescribed convective heating, and vertical eddy viscosity are the same as described in §3.2.

4.1 *The role of the strength of the eddy forcing*

In order to study the response of the MMC to the strength of the eddy forcing, we carried out two experiments in one of which 0·5 times and in the other 1·5 times the observed eddy fluxes described in §2 are used. The model is integrated in both cases until it reaches a steady state. The stream function and the zonal wind for the steady state corresponding to the weak eddy forcing are shown in figures 5a, b, while those corresponding to the strong eddy forcing are shown in figures 5c, d.

Comparing the results of the weak eddy forcing case (figures 5a, b) with figure 3 we note that the reduced strength of the eddy forcing reduces the core strength of the NH subtropical westerly jet from 60 ms^{-1} to 50 ms^{-1}. The tropical easterlies and SH subtropical westerly jet strength do not get affected appreciably by the reduction in the total eddy forcing. Moreover, we note that the easterly jet in the middle latitude seen in the standard solution (figure 3), is not seen in the reduced eddy forcing case. Thus the origin of the easterly jet may be traced to the heat and momentum transports by the

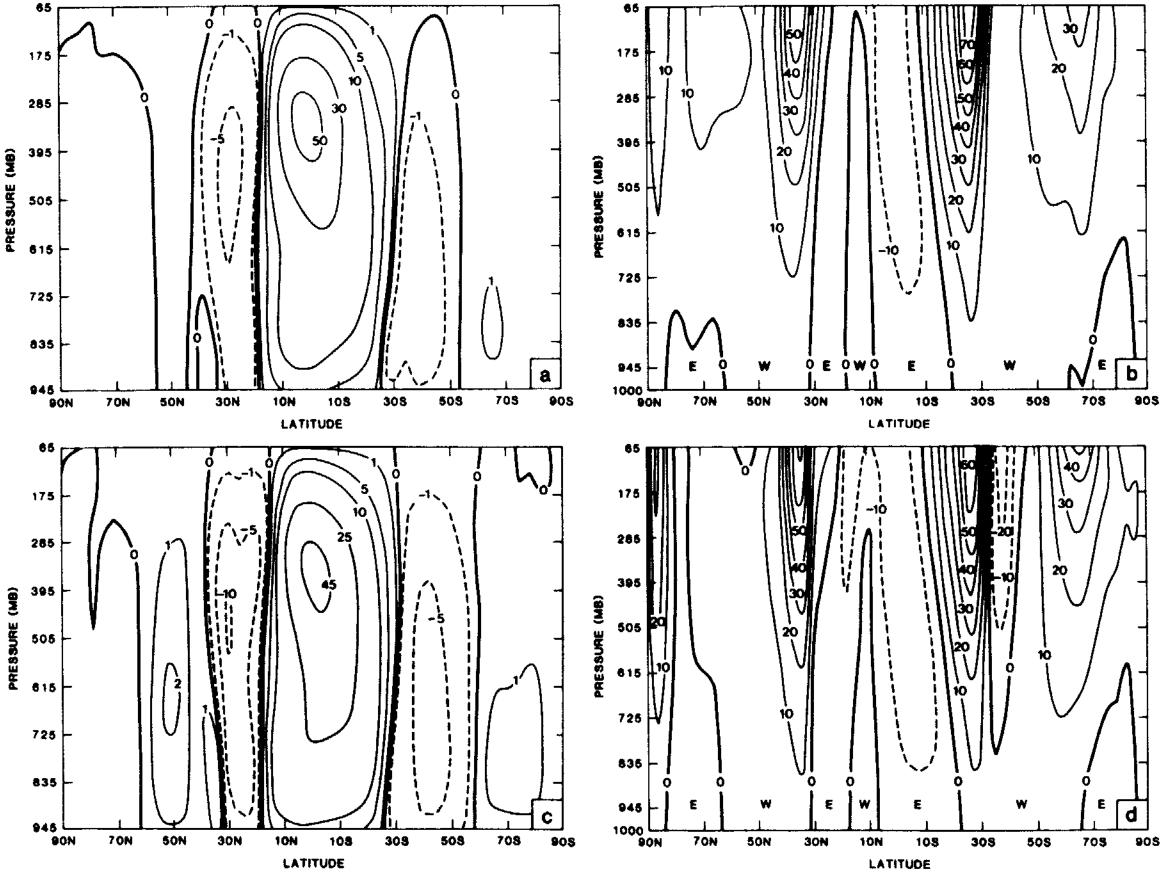

Figure 5. **a**) Stream function, contours $10^{10}\,\mathrm{kgs}^{-1}$, **b**) zonal wind, contours $10\,\mathrm{ms}^{-1}$ for a run with 0·5 times the observed eddy forcing. **c** and **d** represent stream function and zonal wind for a run with 1·5 times the observed eddy forcing.

large scale eddies. Comparing figures 5d and 5b, we note that the increase in the eddy forcing increases the strength of the NH westerly jet while it reduces the strength of the SH westerly jet.

Comparing the stream function fields for the reduced and increased eddy forcing cases (figures 5a, c) with the standard case (figure 3c) we note the following points. The decrease in the eddy forcing decreases the strength of the NH Ferrel cell by about a factor of 2 while that of the SH Ferrel cell is decreased by about a factor of 3. The decrease in the eddy forcing decreases the strength of the NH Hadley cell by about 30 % while it does not change the strength of the SH Hadley cell appreciably. Similarly, the increase in the eddy forcing increases the strength of the NH Ferrel cell by a factor of 2 but it increases the strength of the SH Ferrel cell only by about 25 %. The increase in the eddy forcing increases the strength of the NH Hadley cell by about 40 % while it reduces the strength of the SH Hadley cell by about 10 %.

4.2 *The role of eddy heat flux forcing only*

In this run we introduced only the observed eddy heat fluxes namely $[\overline{v'T'}]$ and $[\bar{v}^*\bar{T}^*]$ as input forcing and omitted the eddy momentum fluxes. The stream function and the zonal wind for the steady state for this run are shown in figure 6. The stream function field shows that the eddy heat flux alone cannot maintain the NH Ferrel cell. The strength of the SH Ferrel cell is also reduced by about a factor of 2 as compared to the standard solution (figure 3). The strength of the NH Hadley cell is reduced by about 30 %. Moreover, the westerly winds at the SH subtropical jet in this case are increased to 90 ms^{-1} as compared to 70 ms^{-1} in the case of the standard solution (figure 3).

4.3 *The role of eddy momentum flux forcing only*

This run is similar to the run described in §4.2. In this run we included only the observed eddy momentum fluxes, $[\overline{u'v'}]$ and $[\bar{u}^*\bar{v}^*]$ and neglected the eddy heat fluxes. The stream function and the zonal winds for the steady state obtained from this run are shown in figure 7. We note from the stream function field that the eddy momentum forcing alone can maintain the Ferrel cells in both hemispheres. The mass fluxes in the Ferrel cells in both hemispheres are smaller than those in the full eddy forcing case (figure 3). The strength of the NH Hadley cell is reduced by about 30 % in this case while the SH Hadley cell is maintained at the same strength as in the standard solution.

We also note that the eddy momentum forcing alone maintains much weaker westerly jets in both hemispheres. In this case the maximum westerly winds in the subtropical westerly jets are about 40 ms^{-1} in both hemispheres as compared to 60 ms^{-1} in the NH and 70 ms^{-1} in the SH in the full eddy forcing case.

It is interesting to note from figures 3, 6 and 7 that the eddy heat transports tend to strengthen the westerly jets but cannot maintain the observed Ferrel cells. On the other hand, the eddy momentum transports tend to reduce the strength of the westerly jets and can maintain fairly strong Ferrel cells.

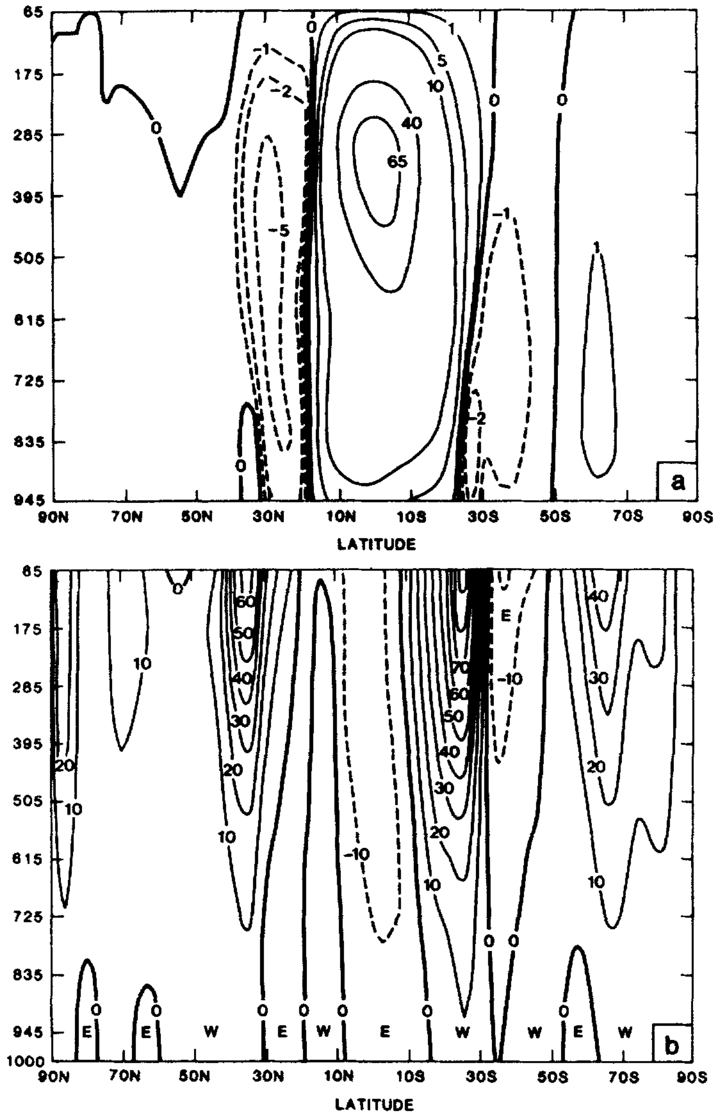

Figure 6. Summer run with eddy heat forcing only, a) stream function, b) zonal wind. Units are the same as in figure 3.

4.4 *The role of the stationary eddies*

In order to examine the role of the standing eddies in maintaining the MMC, we conducted one experiment in which we introduced only the transient eddy fluxes $[\overline{u'v'}]$ and $[\overline{v'T'}]$ and neglected the stationary eddy fluxes. The stream function and the zonal winds for the steady state obtained for this run are shown in figure 8. We note that in the

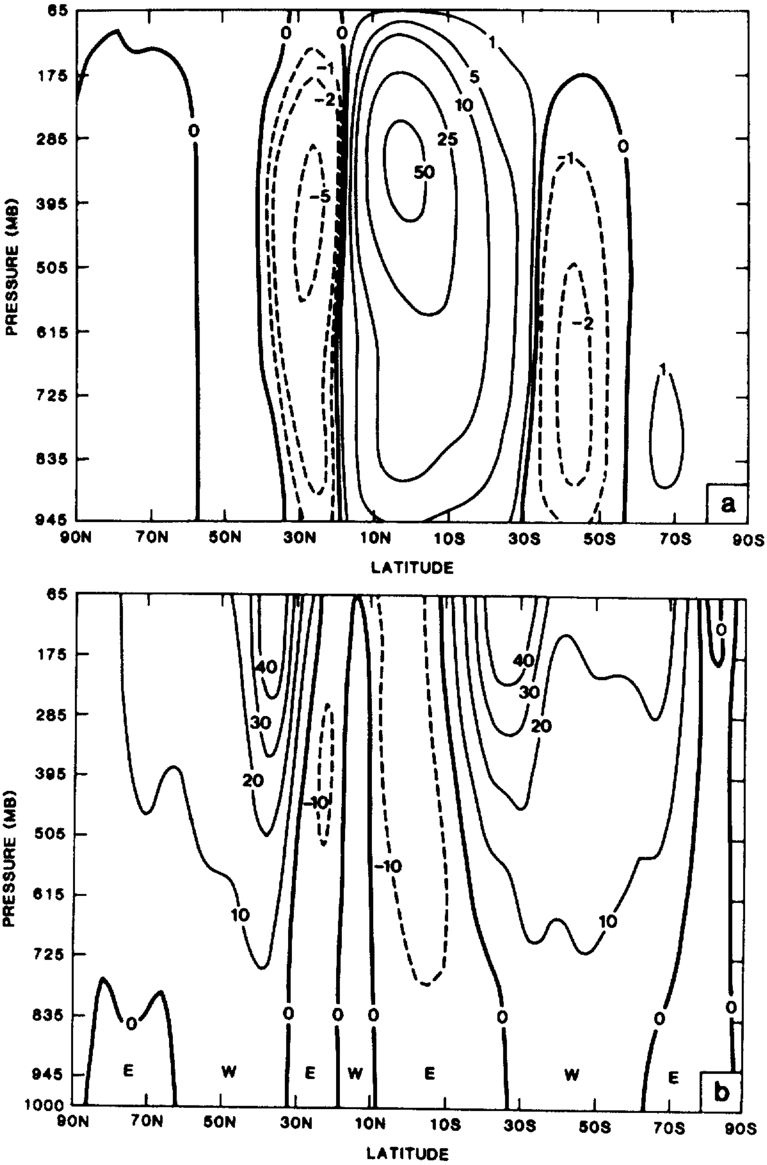

Figure 7. Summer run with eddy momentum forcing only, **a**) stream function, **b**) zonal wind. Units are the same as in figure 3.

absence of the stationary eddies, the NH westerly jet strength is reduced but the SH westerly jet is maintained at the same strength as in the case of the standard solution. In this case, Ferrel cells are maintained in both hemispheres but with reduced strength. The NH Hadley cell is also maintained with a reduced strength but the SH Hadley cell is maintained at the same strength as in the standard solution.

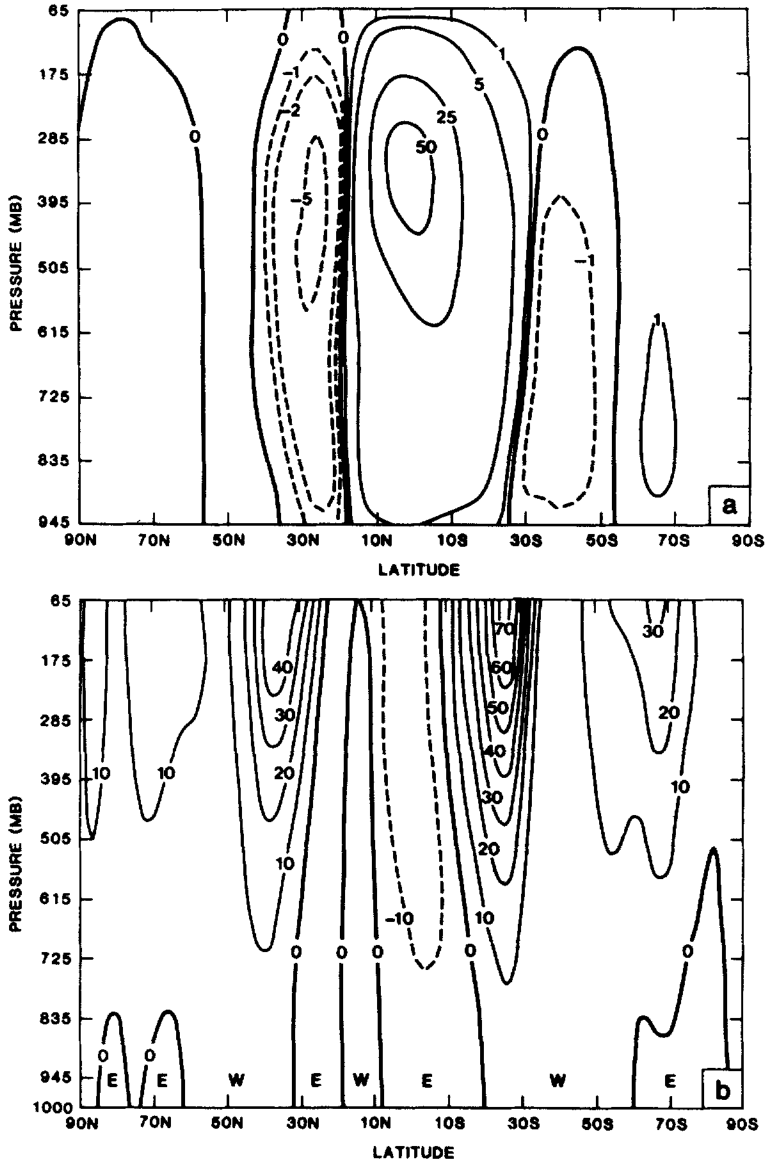

Figure 8. Summer run with transient eddy forcing only, **a)** stream function, **b)** zonal wind. Units are the same as in figure 3.

5. Conclusions and discussion

The role played by the large scale eddy activity in maintaining the mean meridional circulation in general and the Hadley circulation in particular is studied using a zonally averaged model.

When the eddy forcing consisting of climatological horizontal fluxes of heat and momentum by the transient and the stationary eddies is reduced to 0·5 times or increased to 1·5 times its climatological values, the strength of the Ferrel cells decrease or increase proportionally. This result is as expected since the Ferrel cells are essentially driven by the eddy forcing. However, we also note that the changes in the eddy forcing can influence the strength of the NH Hadley cell significantly. In the case when the eddy forcing is reduced to 0·5 times the climatological values, the strength of the NH Hadley cell reduces to about 30% while it is increased by about 40% when the eddy forcing is increased to 1·5 times. This result is in agreement with the results of Crawford and Sasamori (1981) in which they showed that even in the absence of the condensational heating, the eddy forcing could maintain Hadley cells in the tropics at about a third of its observed strength. Sensitivity experiments with respect to various components of the eddy forcing show that the eddy momentum fluxes seem to be more important in maintaining the Ferrel cells as compared to the eddy heat fluxes. Moreover, the eddy momentum fluxes tend to decrease the strength of the subtropical westerly jets while the eddy heat fluxes tend to increase them.

Thus, the results of this preliminary study indicate that the changes in the large scale eddies can indeed influence the monsoon circulation via changes in the strength of the NH Hadley cell. However, we must be cautious in drawing quantitative conclusions regarding the influence of the eddies on the monsoon circulation based on these results. This is because the monsoon circulation is actually a regional, reverse Hadley circulation anomaly, roughly between 40°E and 120°E embedded in the global Hadley circulation. Thus, diabatic heating field and eddy fluxes averaged over this region may be more important in maintaining the monsoon circulation. The latent heating field and the eddy fluxes used in this study were derived by zonally averaging the observed fields over an entire latitude circle. Thus, these forcing functions may not be representative forcing functions for the monsoon circulation. Therefore, it may be more meaningful to obtain latent heating field and eddy fluxes by averaging the observed fields between say, 40°E and 120°E and use these forcing functions in a zonally averaged model. We are currently engaged in deriving these regionally averaged forcing functions. In a later study, we shall examine the sensitivity of the monsoon circulation using such forcing functions.

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