Eddy transports in a greenhouse climate simulation

D.A. Collins*
Centre for Dynamical Meteorology and Oceanography, Monash University, Australia
and
D.J. Karoly
Cooperative Research Centre for Southern Hemisphere Meteorology, Monash University, Australia

(Manuscript received January 1995; revised October 1995)

Control and double CO₂ simulations from a four-level coupled ocean-atmosphere model run at the CSIRO Division of Atmospheric Research are used to investigate the responses of a number of climate parameters to enhanced greenhouse forcing. In particular, changes in important parameters of the atmospheric general circulation are examined, including the eddy transports of heat and momentum. The changes in the mean zonal flow are consistent with the reduced meridional temperature gradient in the enhanced greenhouse simulation. Also, the eddy heat transport is reduced with enhanced greenhouse warming, consistent with a decrease in low-level baroclinicity in middle and high latitudes. However, less obvious results are obtained for the changes in eddy momentum transport and mean meridional flow. The eddy momentum transport remains unchanged or is slightly increased in the greenhouse climate simulations, despite the reduced low-level baroclinicity. Temporal correlations between the eddy momentum transport and the meridional temperature gradient show the temperature gradient to have opposing influences on the eddy momentum transport in the upper and lower troposphere. This may account for the negligible change of the eddy momentum transport in the enhanced greenhouse simulation. Similar correlations between the eddy momentum transport and meridional flow reveal strong correlations which may therefore explain the apparently anomalous behaviour of a reduced Hadley circulation with enhanced greenhouse forcing.

Introduction

Most investigations of greenhouse climate change concentrate on changes in parameters such as mean temperature, precipitation and wind velocities. Few studies have considered changes in the atmospheric general circulation, such as changes in the transports of heat, momentum and moisture by 'eddies' or waves in the atmosphere. These eddy transports provide significant contributions to the global balances of such quantities and arise from small departures from the mean interacting with variations in the wind associated with weather systems or stationary waves. In this investigation, changes in eddy transports are considered in order to achieve an understanding of how the behaviour of these transports might be affected by enhanced greenhouse forcing.

The atmospheric general circulation is defined to be the total of all motions which describe atmospheric flow on a global scale (Holton 1979). Investigations of such flow usually involve climate parameters averaged over time and space. The time-averaged circulation is found to vary greatly with latitude due to the meridional solar heating gradient and latitudinal variations in the

*Corresponding author address: Mr D.A. Collins, National Climate Centre, Bureau of Meteorology, GPO Box 1289K, Melbourne, Vic 3001, Australia.
*Present affiliation: National Climate Centre, Bureau of Meteorology, Melbourne, Australia.
land/sea ratio. Consequently, zonally averaged parameters and meridional transports are used throughout this investigation.

The total time mean, zonal mean meridional transport of a quantity $s$ is given by the sum of two components: a time mean transport by zonal mean values, i.e., by the mean meridional circulation; and a time mean transport by zonal mean departures, i.e., by waves. Symbolically this can be written as:

$$[vs] = [v] [s] + [v^* s^*]$$ ...1

where brackets represent zonal mean, overbars indicate time means and asterisks represent departures from the zonal mean. If $v$ represents the meridional velocity, then the first term on the right-hand side is the meridional transport by the zonal mean meridional circulation and the second term is the total eddy transport. Or, alternatively:

$$[vs] = [v] [s] + [v^*]' [s]' + [v^* s^*] + [v^* s^*]'$$ ...2

where the first term on the right-hand side is the transport associated with time mean zonal mean meridional flow, the second term is the transport associated with time variations of the zonal mean meridional circulation, the third term is the transport associated with time mean zonal variations (standing waves) and the fourth term is the transport associated with time varying zonal variations (transient eddies). The total eddy transport is given by the sum of the standing and transient eddy transports.

Branscombe and Gutowski (1992) used a primitive-equation, global spectral model to examine the effect of enhanced greenhouse forcing on the life cycles of transient eddies. The model’s surface was zonally uniform and flat and consequently no time-mean stationary eddies were generated. By comparing control and double CO$_2$ simulations of the model it was found that a decreased meridional temperature gradient in the enhanced greenhouse simulation led to reduced eddy kinetic energy and poleward eddy transport of sensible heat, particularly in subtropical regions. Despite the significantly reduced eddy kinetic energy, the eddy moisture transport was found to be increased in the greenhouse simulation due to an increase in the atmospheric moisture content. However, the latitudinal distribution of the eddy moisture transport was found to be shifted poleward due to latitudinal changes in the eddy kinetic energy and consequently precipitation was also shifted poleward in the enhanced greenhouse simulation.

Similarly, Manabe and Wetherald (1980) found the eddy kinetic energy to be decreased in a double CO$_2$ simulation of a general circulation model run at the Geophysical Fluid Dynamics Laboratory (GFDL). This was also attributed to a decrease in the meridional temperature gradient associated with warming at high latitudes. Bates and Meehl (1986) determined the transient eddy variability of extratropical 500 hPa heights to be decreased in a double CO$_2$ simulation of the National Center for Atmospheric Research Community Climate Model. This is also consistent with the results of Branscombe and Gutowski (1992) since the maximum amplitudes achieved by the transient eddies are dependent on the amount of potential energy available. With a weaker meridional temperature gradient in the greenhouse simulation less potential energy is available and hence smaller maximum disturbances are attained by the eddies.

Stephenson and Held (1993) concentrated on the changes in northern hemisphere stationary waves and the associated changes in storm tracks induced by enhanced greenhouse forcing. A reduction in eddy heat transport over the north Atlantic associated with reduced baroclinicity was determined. Another recent study concentrating on northern hemisphere storm tracks by Hall et al. (1994) showed a northward and eastward shift of the storm tracks with greenhouse warming. The northward shift was associated with changes in baroclinicity. The eastward (downstream) intensification was associated with increased diabatic heating in the storm systems and upper-tropospheric baroclinic effects. An increase in eddy kinetic energy was found at upper levels.

The CSIRO4 model

The data used in this investigation were provided by a climate model run at the CSIRO Division of Atmospheric Research and known as the CSIRO4 model (Gordon 1993). Unfortunately, at the time the investigation was begun, data from the higher resolution CSIRO9 model were unavailable (McGregor et al. 1993). The CSIRO4 model consists of an atmospheric general circulation model combined with a “slab” or mixed-layer ocean model. The atmospheric component is a spectral model with R21 horizontal resolution providing a transform grid of 64 points in the east-west direction and 56 points from pole to pole. The vertical resolution is relatively coarse with only four atmospheric sigma levels corresponding to pressure levels of about 900, 650, 350 and 100 hPa. The mixed-layer ocean model includes heat storage within a mixed-layer of fixed depth, enabling the model to be run with a seasonal cycle.
Ocean currents are not directly incorporated in the model but the technique of Q-flux correction is employed to introduce heat flux correction terms between the atmosphere and ocean which allows some of the thermal effects of ocean currents to be included. The model includes parametrisations of most physical processes such as diurnal radiation variations, predicted cloud cover and sea-ice.

A control simulation of the model was undertaken by running it with current observed amounts of atmospheric CO$_2$ until an equilibrium was established. A simulation with double this concentration of CO$_2$ was also run to equilibrium to provide a climate simulation with an enhanced greenhouse effect. Monthly mean, zonal mean data from the equilibrium years 6 to 15 of the control run and years 11 to 20 of the double CO$_2$ simulation were used throughout this investigation. Comparisons between data from these equilibrium simulations provide insight into changes which may be attributed to an enhanced greenhouse effect. Further descriptions of this climate model and the control and double CO$_2$ simulations are presented by Gordon (1993) and Gordon and Hunt (1994).

Data from the simulations were archived such that zonally averaged fields are available for each month of simulated time. Decadal mean, zonal mean fields were produced from this data for two seasons; southern hemisphere winter and summer. Generally only changes during the southern hemisphere winter are shown, as changes during the summer are similar. A preliminary understanding of the ability of the CSIRO4 climate model to simulate the present-day atmospheric circulation was determined by comparing the zonal mean wind velocities and eddy transports from the control simulation with appropriate observed statistics. The observational data used were decadal mean statistics based on the daily analyses of the atmospheric circulation by the European Centre for Medium Range Weather Forecasts (ECMWF) during the years 1979 to 1989 (Hoskins et al. 1989). Unfortunately, only total eddy transport data were available from the CSIRO4 model, i.e., no individual transient or stationary eddy transports. However, for all seasons in the southern hemisphere and from June to August in the northern hemisphere, standing eddy fluxes are relatively small and the total eddy flux is predominantly due to transient eddies (van Loon and Kidson 1993). Therefore, throughout this investigation, the total eddy transports given by the model were often used as approximations of the transient eddies during the June/July/August season, particularly for comparisons with the observed transient eddies. No observational plots are formally presented here.

**Greenhouse responses of the climate**

The decadal June/July/August mean, zonal mean atmospheric temperature field for the equilibrium control simulation (Fig. 1(a)) shows the expected results of higher temperatures in the northern hemisphere tropics and gradually decreasing temperatures with height in the troposphere. Figure 1(b) displays the difference between the equilibrium control and double CO$_2$ simulations for the same season. The temperature difference field shows warming in the troposphere of around 4°C and cooling in the stratosphere. The stratospheric cooling and tropospheric warming is observed across all latitudes with maximum warming occurring in the tropics and at the winter pole; a similar response to the double CO$_2$ simulations of other mixed-layer ocean climate models (Houghton et al. 1990).

The decadal June/July/August mean, zonal mean zonal wind from the control simulation is

![Fig. 1 June/July/August mean, zonal mean (a) temperature [T] for control simulation and (b) temperature difference $\Delta$[T] between control and double CO$_2$ simulations. Contour intervals are (a) 10 K and (b) 2.0 K.](image-url)
shown in Fig. 2(a). Considering the limited resolution of the climate model, this plot qualitatively compares well with the ECMWF observed zonal winds for the same season (not shown). The zonal wind from the control simulation shows a double jet structure in the southern hemisphere and a weaker northern hemisphere summer jet. The maximum strength of the simulated zonal winds in the southern hemisphere is about 35 m/s, similar to the observed maximum of about 37 m/s. However, the strength of the simulated northern hemisphere jet is about 11 m/s, much weaker than the observed 20 m/s. Generally, other climate parameters are simulated with similar degrees of accuracy (Gordon and Hunt 1994).

The difference between control and double CO₂ simulations of the zonal wind during the southern hemisphere winter (Fig. 2(b)) shows an increase in zonal winds in the upper troposphere at latitude 20°S and a decrease at around 60°S, suggesting that enhanced greenhouse forcing may lead to an equatorward shift of the southern hemisphere jet. The stippling in the anomaly field represents significant differences at the 5% level and is determined with a t-test using the interannual variability of the seasonal mean, zonal mean values in the control and double CO₂ simulations. Using this t-test the changes in zonal wind are generally significant. The reduced vertical gradient of zonal winds at high latitudes is consistent with the reduction of the meridional temperature gradient in the lower troposphere, as expected from the thermal wind balance. The studies by Hall et al. (1994) and Stephenson and Held (1993) also found the changes in zonal mean zonal wind to be consistent with the temperature changes in their model experiments. However, these changes are somewhat different to the zonal flow changes in the CSIRO4 model, with reduced zonal flow on the equatorward side of the subtropical jet and increased zonal flow on the poleward side of the subtropical jet.

The zonal mean meridional velocity from the control simulation (Fig. 3(a)) also compares well with the observational data during the southern hemisphere winter. The simulated zonal mean meridional circulation displays a strong Hadley circulation in the tropics and reversed Ferrel cells in the mid-latitudes of both hemispheres. The strength of the simulated meridional circulation is similar to that of ECMWF analyses (not shown). The difference between control and double CO₂ simulations of the meridional winds is shown in Fig. 3(b) and suggests that enhanced greenhouse forcing may result in a significant decrease in meridional wind speeds at the equator during the southern hemisphere winter, i.e., a reduced Hadley circulation. This is somewhat surprising.
considering that enhanced greenhouse forcing results in increased tropical precipitation associated with general warming of the troposphere. This might be expected to produce a stronger Hadley circulation.

Differences between control and double CO₂ simulations of the eddy transports are also considered for both the summer and winter seasons. Unfortunately the control simulations of eddy heat and momentum transports do not compare as favourably with the observed statistics. The control simulation of eddy heat transport correctly displays a poleward heat transport in both hemispheres (Figs 4(a) and 5(a)). However, the strength of this transport is significantly greater than the ECMWF analyses, with the climate model displaying a maximum of about 40 K m/s at 65°S and the observational data showing a maximum of only 18 K m/s at 50°S (not shown). The control simulation of eddy momentum flux (Figs 6(a) and 7(a)) is qualitatively similar to the ECMWF analyses but about 30% weaker. Many other climate models also have the problem of an eddy heat flux that is too strong and an eddy momentum flux that is too weak (Boer et al. 1991).

By comparing Figs 4(b) and 5(b) to Figs 4(a) and 5(a) respectively, it is evident that the poleward eddy heat transport is significantly decreased by an enhanced greenhouse effect for both summer and winter seasons. This is consistent with the decrease in lower tropospheric meridional temperature gradient associated with enhanced polar warming (Fig. 1(b)). The energy of the eddy transports is provided by the potential energy of the meridional temperature gradient through the process of baroclinic instability (Held 1993). Just as the meridional temperature gradient is decreased, so too is the energy of the eddy transports, resulting in decreased eddy heat transport. This is consistent with the eddy responses determined by Branscome and Gutowski (1992).

Comparing the changes in eddy momentum transport (Figs 6(b) and 7(b)) with the eddy momentum transports of the control simulation (Figs 6(a) and 7(a)) reveals that enhanced greenhouse forcing results in slightly reduced eddy momentum flux in the summer hemisphere and slightly increased eddy momentum flux in the winter hemisphere, particularly during the December/January/February season. This is

Fig. 4 June/July/August mean, zonal mean (a) eddy heat transport \([v^*T^*]\) for control simulation and (b) eddy heat transport difference \(\Delta[v^*T^*]\) between control and double CO₂ simulations. Contour intervals are (a) 5.0 K m/s and (b) 2.0 K m/s.

Fig. 5 As in Fig. 4, but for December/January/February mean.
surprising considering the significantly reduced eddy heat transport. The responses of the two eddy transports to enhanced greenhouse forcing might be expected to be similar since the energy of both transports is provided by baroclinic instability. The change in eddy heat transport appears to be consistent with reduced baroclinicity whereas the change in eddy momentum transport does not. However, these responses are not necessarily incompatible if the influences of the meridional temperature gradient at different levels of the troposphere are considered.

The change in zonal mean atmospheric temperature (Fig. 1(b)) shows that the meridional temperature gradient has different greenhouse responses at various levels of the atmosphere. The enhanced warming at the winter pole results in a reduced meridional temperature gradient in the lower troposphere of the winter hemisphere whereas the amplified warming in the tropics results in increased meridional temperature gradient in the upper troposphere at some latitudes. The effects of these differing responses on the eddy transports are not well understood. Held (1993) suggested that the differing responses of the upper and lower tropospheric temperature gradients may have competing effects on the eddy transports and that, due to linear instability theory, changes in the lower tropospheric temperature gradient should be dominant over changes in the upper tropospheric gradient. This is probably the case for the eddy heat transport but the eddy momentum transports may also be significantly influenced by upper tropospheric temperature gradients since these transports are greatest near the tropopause (Figs 6(a) and 7(a)). Also, upper tropospheric conditions determine how easily disturbances are able to radiate away from their source region.

The eddy moisture flux is increased with enhanced greenhouse forcing (not shown). This is consistent with the results of Branscombe and Gutowski (1992) and appears to be due to an increase in atmospheric moisture content associated with general tropospheric warming. This increase in atmospheric moisture content may also have two competing effects on the eddy transports of heat and momentum (Held 1993). With greater atmospheric moisture, more latent heat is released in the atmosphere which directly
enhances the eddy energy. However, the meridional temperature gradient is determined by the balance between the poleward transport of energy by the eddies and the meridional heating gradient. With increased eddy moisture transport the poleward transport of latent heat increases and therefore smaller eddies are required to maintain the same temperature gradient. These potentially conflicting influences may also complicate the responses of the eddy heat and momentum transports.

Temporal correlations with eddy transports

Using a technique similar to that of van Loon and Kidson (1993), temporal correlations between the eddy transports and the meridional temperature gradients in the upper and lower troposphere were determined to investigate their relative influences on the transports. Only temporal correlations during winter in the mid-latitudes of the southern hemisphere were considered since the greenhouse responses of the zonal mean temperature show major changes in the general circulation in this region and season. Also, the greenhouse responses of the eddy heat and momentum transports appear to differ most during this season.

Time-series were determined for the eddy transports and meridional temperature gradients from the 10 years of June, July and August means at spatial points between the latitudes 20°S and 70°S. Correlations were then determined between the time-series of eddy transport values at each spatial point between 20°S and 70°S and the time-series of meridional temperature gradient values at every other point in the same interval. This was done at an upper tropospheric level (σ = 0.35) and a lower tropospheric level (σ = 0.9). Only temporal correlations from the double CO₂ climate simulation are shown as the results from the control simulation are generally similar.

Figures 8(a) and (b) show correlations between the eddy heat transport and the meridional temperature gradient at the σ = 0.35 and σ = 0.9 levels respectively. The horizontal axis is the latitude of the meridional temperature gradient time-series and the vertical axis is the latitude of the compared eddy heat transport time-series. Consequently, the leading diagonal represents correlations between spatially corresponding time-series. It is evident that there are generally larger values and more uniform patterns of correlation at the σ = 0.9 atmospheric level than at the σ = 0.35 level. This reinforces the suggestion made by Held (1993) that the eddy heat transport is in fact more influenced by the lower tropospheric meridional temperature gradient than the upper tropospheric gradient. The large values of correlation at the σ = 0.9 level indicate that the time variations of the terms are similar. These correlation values are generally negative due to the terms having opposite variations in this region. Therefore, a significant decrease in the lower tropospheric temperature gradient with enhanced greenhouse forcing results in a decrease in the magnitude of poleward eddy heat transport. Since eddy heat transport is negative in this region (Fig. 4(a)), a decrease in magnitude results in a positive change with enhanced greenhouse forcing (Fig. 4(b)).
Fig. 9  Ten-year June/July/August correlations between eddy momentum transport at the 0.35 sigma level and meridional temperature gradient at the (a) 0.35 and (b) 0.9 sigma levels of the double CO₂ simulation.

(a) [u* v*] and \( \partial[T]/\partial y \) correlated at \( \sigma = 0.35 \)

(b) [u* v*] and \( \partial[T]/\partial y \) correlated at \( \sigma = 0.35/0.9 \)

Fig. 10  As in Fig. 9, but for correlations between eddy momentum transport and meridional velocity.

(a) [u* v*] and \( v \) correlated at \( \sigma = 0.35 \)

(b) [u* v*] and \( v \) correlated at \( \sigma = 0.35/0.9 \)

Similar comparisons were made between the eddy momentum transport and the meridional temperature gradient. Since eddy momentum transport is weak at the \( \sigma = 0.9 \) level (Fig. 6(a)), the transport at the \( \sigma = 0.35 \) level was used for correlations with the temperature gradient at both the \( \sigma = 0.35 \) and \( \sigma = 0.9 \) levels in Fig. 9. By comparing Figs 9(a) and (b) it is evident that the magnitudes of the correlations with the temperature gradients at the two levels are similar. This supports the hypothesis made by Held (1993) that the eddy momentum transport is influenced by both the upper and lower tropospheric meridional temperature gradients.

However, corresponding correlations in the two plots generally have opposite signs suggesting that the meridional temperature gradients of the two levels may have competing effects on the eddy momentum transports. Figure 9(b) tends to suggest that the reduced meridional temperature gradient of the enhanced greenhouse simulation results in increased eddy momentum transport at high latitudes and reduced eddy momentum transport at low latitudes. This would lead to increased momentum flux convergence, as observed in the greenhouse simulation.

The meridional wind velocity was also correlated with the eddy momentum transport to determine whether the apparently inconsistent greenhouse response of the Hadley circulation is related to the unexpected response of the eddy momentum flux. Figures 10(a) and (b) show the
correlation plots between the eddy momentum transport at the $\sigma = 0.35$ level and the meridional wind velocity at the $\sigma = 0.35$ and $\sigma = 0.9$ levels. Large correlation values and uniform patterns are observed in both plots indicating that the behaviour of the meridional velocity is closely related to the eddy momentum transport. The plots are qualitatively similar but show opposite signs for corresponding correlations due to the opposing directions of meridional flow at the two levels. Since the meridional wind velocity and eddy momentum transport are closely related across all latitudes (Fig. 10), the minimal greenhouse response of the eddy momentum transport is consistent with the lack of significant change in the zonal mean meridional velocity.

Conclusions

Generally the zonal mean differences between control and double CO$_2$ simulations of a number of climate variables are consistent with simple dynamical relationships. In particular, the decrease in lower tropospheric meridional temperature gradient associated with polar warming is consistent with the reduced poleward eddy heat transport and an equatorward shift of the southern hemisphere jet producing a reduction in the vertical gradient of zonal winds at high latitudes. However, two apparent inconsistencies exist. These are the minimal change in eddy momentum transport despite a significant decrease in eddy heat transport and a decrease in the Hadley circulation during the southern hemisphere winter even though the atmospheric moisture content has increased in the enhanced greenhouse simulation.

By considering the relative influences of the upper and lower tropospheric meridional temperature gradients on the heat and momentum transports, these apparently inconsistent responses are found to be quite feasible. The eddy heat transport is found to be more influenced by the lower tropospheric temperature gradient so as this gradient decreases with greenhouse warming so too does the poleward eddy heat transport. However, the meridional temperature gradients of the upper and lower troposphere appear to have opposing influences on the eddy momentum transport. This suggests that the energy of the eddy momentum transport may be complicated by other processes resulting in the greenhouse response of this transport. Further investigations of the relationships between terms of the heat and momentum budget equations may reveal the greatest influences on the eddy transports and consequently provide a more complete explanation for their greenhouse responses. The meridional velocity is found to be closely related to the eddy momentum transport so the lack of significant change of the eddy momentum transport may explain the apparently inconsistent response of the Hadley circulation to enhanced greenhouse forcing.

It is important to recognise that the limited vertical resolution in the CSIRO4 model may have affected these results and therefore they may not be applicable to other models or to the real climate. However, the reduction of the eddy heat transport in the enhanced greenhouse simulation has been determined in other models (Branscombe and Gutowski 1992; Stephenson and Held 1993; Hall et al. 1994) and there appear to be no other reports of eddy momentum changes in such simulations. Hall et al. (1994) have noted the differing effects of the reduced low-level baroclinicity and increased upper level temperature gradient on the transient eddies in their greenhouse simulation, which are consistent with the results here. Further studies of the eddy heat, momentum and moisture transports in enhanced greenhouse climate simulations may help to better understand important changes in the atmospheric general circulation.

Acknowledgments

This study was supported by a grant from the National Greenhouse Advisory Committee. We are grateful to Hal Gordon and Barrie Hunt of the CSIRO Division of Atmospheric Research for allowing access to their climate model data.

References


