NOTES AND CORRESPONDENCE

A Note on the Effect of Horizontal Momentum Fluxes by Unresolved Synoptic-Scale Eddies in a Low-Resolution Spectral General Circulation Model

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ABSTRACT

Two long-term simulations of a low-resolution spectral general circulation model (Otto-Bliesner *et al.*, 1982) have been made. The single difference between these two runs is that in one (CONTROL) the horizontal flux of momentum by unresolved synoptic eddies is represented by a second-degree, Fickian-type diffusion scheme (down-gradient), whereas in the other (DIFFEX), this flux is zero. The amount of eddy kinetic energy in DIFFEX is found to be significantly larger and more realistic than in CONTROL. Also, the spectral distributions of both eddy kinetic energy and eddy available potential energy in DIFFEX are more realistic than in CONTROL. However, the long-term mean circulations are not statistically different in the two runs.

1. Introduction

Low-resolution general circulation models, which explicitly treat only the largest scales of atmospheric flow, are much cheaper to run than the high-resolution models. Therefore, they are becoming an important tool for climate research. In such low-resolution models, the effect of those synoptic-scale eddies which are not explicitly treated has to be parameterized. One way of dealing with this problem is to parameterize the unresolved heat transport with a down-gradient diffusion formulation; because of a lack of better information, the corresponding transport of momentum (or vorticity) is often parameterized in the same way (McAvaney *et al.*, 1978; Manabe *et al.*, 1979; Otto-Bliesner *et al.*, 1982). The horizontal eddy diffusivity is, typically, either taken as a constant, or written as a function of the deformation (Smagorinsky, 1963) or vorticity (Leith, 1968) of the large-scale horizontal flow. These three specifications give rather similar dissipative effects on the flow at the resolved scales (Holopainen and Nurmi, 1980).

Williamson (1978) found that the eddy kinetic energy of five-day forecasts, made with the National Center for Atmospheric Research Global Circulation Model, increases when the horizontal diffusion is effectively decreased, either by decreasing the diffusion coefficient directly, by decreasing the horizontal grid spacing, or by changing from a second- to fourth-degree form of diffusion. This improvement is related to the decreased damping of the baroclinic scales, providing for an increased decascade of energy to the long waves. The resulting improved amplitude of the long waves also leads to a more accurate advection of the shorter waves. Similarly, Roeckner and Storch (1980) have found that for a specific amount of high wavenumber dissipation needed to produce a realistic spectral slope, a fourth-degree diffusion scheme produces less damping in the resolved scales than second-degree schemes.

Observational studies of the spectral energetics of the atmosphere (e.g., Chen and Wiin-Nielsen, 1978; Lambert, 1981) have shown that there is a fundamental difference between the spectral cascade of kinetic energy and available potential energy. Fig. 1 shows, on the basis of data published by Chen and Wiin-Nielsen, the flux of available potential energy $F_A(n)$, and of kinetic energy $F_K(n)$, across a two-dimensional horizontal wavenumber n, during the Northern Hemisphere winter. These transfers are due to nonlinear wave interactions:

$$F_A(n) = \sum_{\nu=1}^{n} S(\nu), \qquad (1)$$

$$F_K(n) = \sum_{\nu=1}^{n} L(\nu), \qquad (2)$$

where $S(\nu)$ and $L(\nu)$ are, respectively, the gain of available potential energy and kinetic energy at wavenumber ν, due to nonlinear wave interactions. Such in-

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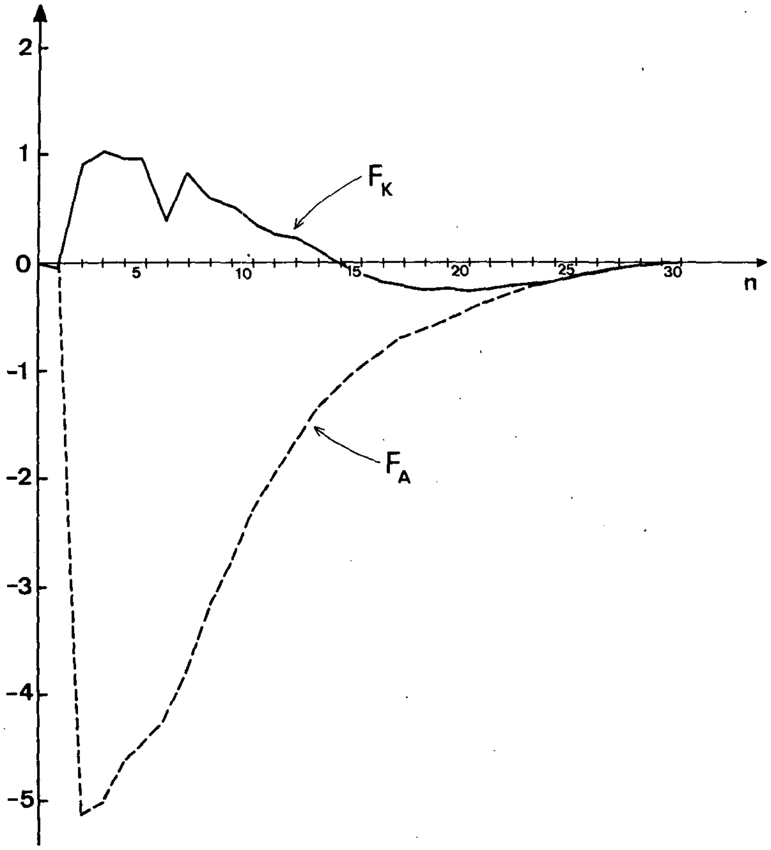

FIG. 1. The observed upscale spectral flux of kinetic energy F_K (solid line), and of available potential energy F_A (dashed line), in the Northern Hemisphere in winter, as a function of two-dimensional horizontal wavenumber n. The curves are calculated from the data of Chen and Wiin-Nielsen (1978). Units: W m^{-2}.

teractions give no net effect, when all the waves are considered together; that is, the F_A and F_K curves asymptote to zero for large n.

Available potential energy cascades toward high wavenumbers throughout the spectrum. The flux of kinetic energy, however, is upscale for scales larger than wavenumber 14. In particular, $F_A(10)$ is less than zero (downscale transfer) and $F_K(10)$ is greater than zero (upscale transfer) with $|F_A(10)|$ considerably larger than $|F_K(10)|$. Thus, in a general circulation model which explicitly treats only flow components with $n \leqslant 10$, the parameterization of the unresolved scales should be designed differently from higher resolution models, in order to agree with these observed facts.

2. The experiment

The low-resolution spectral model of the global atmosphere used in this experiment is that described by Otto-Bliesner *et al.* (1982, hereafter OB). It is a five-layer primitive equation model, which includes orography as well as radiative and convective processes, condensation, and surface transports. Only those horizontal flow components which can be described with the aid of spherical harmonics Y_n^m with the degree $n \leqslant 10$ and $|m| \leqslant n$ are treated explicitly. All the remaining flow components of smaller two-dimensional horizontal scale are either neglected or their effects parameterized.

In OB, the effect of horizontal transport of heat and vorticity by the unresolved eddies is parameterized, using a second-degree, Fickian-type of horizontal diffusion (HD):

$$(\partial T/\partial t)_{\mathrm{HD}} = K_T \nabla^2 T, \tag{3}$$

$$(\partial \zeta/\partial t)_{\mathrm{HD}} = K_\zeta \nabla^2 \zeta, \tag{4}$$

where T is temperature, ζ is vorticity and $K_T = K_\zeta = 5.5 \times 10^5$ m^2 s^{-1}. This parameterization has been successfully used in spectral models with rhomboidal truncation at wavenumber 15, to inhibit spectral blocking (Puri and Bourke, 1974), and is consistent with the previously-mentioned observations for this truncation. In the current model, though, this parameterization implies an implicit downscale spectral transfer of both available potential energy and kinetic energy across wavenumber 10, where the explicitly treated spectral energy transfer is zero due to the truncation. Considering Fig. 1, this situation is clearly in disagreement with the observed behavior of the atmosphere.

No well-proven parameterization scheme exists for the horizontal diffusion of momentum (or vorticity) that would simulate the upscale cascade of kinetic energy. However, a measure of the sensitivity of the model climate to the parameterization of the horizontal momentum fluxes by unresolved synoptic eddies can be obtained by studying differences between two model simulations, one having Fickian-type momentum fluxes, the other not having these fluxes. This is exactly our experiment.

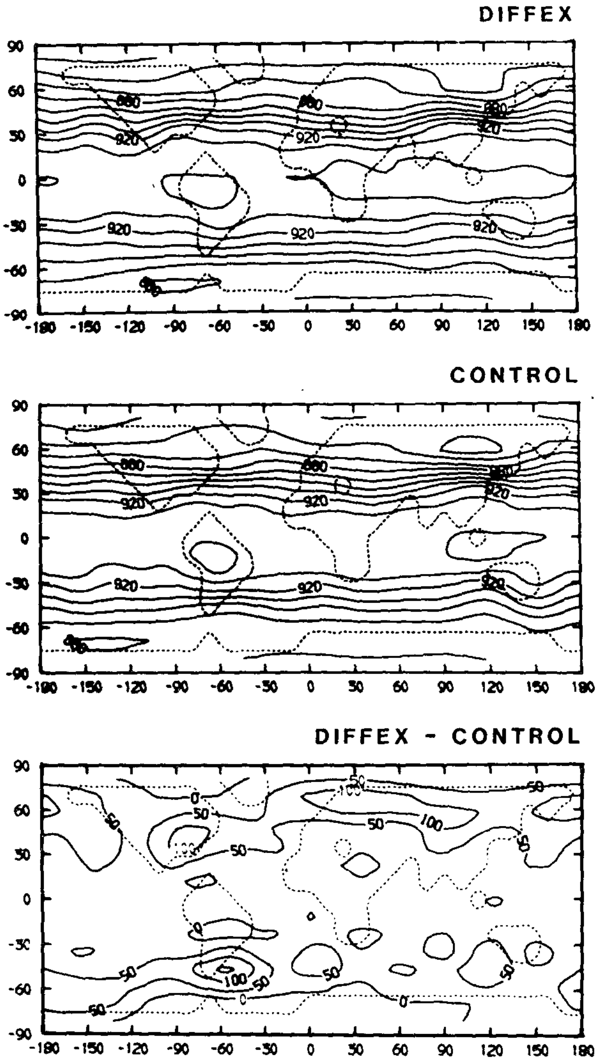

FIG. 2. Global distribution of the 180-day mean 300 mb geopotential height in DIFFEX and CONTROL (dam) and the difference DIFFEX − CONTROL (m). Contour interval is 10 dam in DIFFEX and CONTROL and 50 m in DIFFEX − CONTROL.

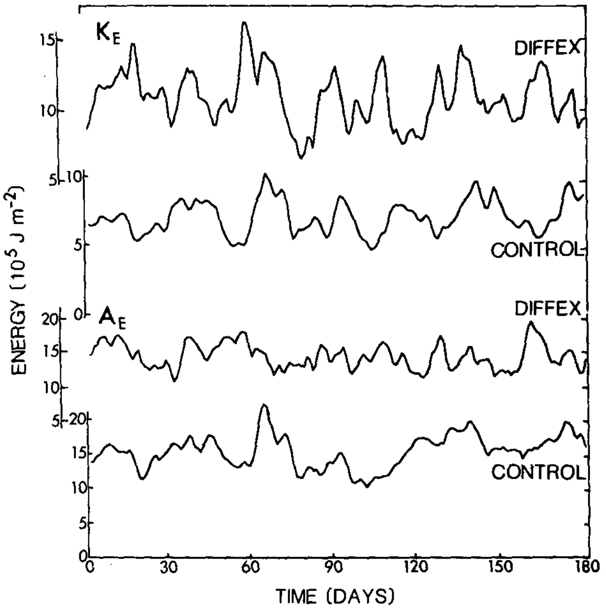

FIG. 3. Available potential energy and kinetic energy in eddies as a function of time in the Northern extratropics in CONTROL and in DIFFEX. Data averaged as in Table 1. Units: 10^5 J m^{-2}.

Starting from 1 January of the second year of a five-year simulation (see OB), and keeping the external conditions constant (perpetual January), two 180-day runs of the model were made. In the first run (CONTROL), the model was used in its basic version (with $K_T = K_\zeta = 5.5 \times 10^5$ m^2 s^{-1}); the second run (referred to as DIFFEX) was exactly the same as CONTROL, except for having $K_\zeta = 0$. (Note that DIFFEX is not inviscid, since surface stress and internal vertical friction are still included.)

The noise level of the model can be estimated from the five Januarys generated during the original five-year seasonal cycle experiment (OB), if each year of the five-year experiment is considered an independent experiment. These statistics allow an evaluation of the significance of differences between the simulations (*t*-test; see Chervin and Schneider, 1976).

Fig. 2 shows the 180-day mean geopotential heights at 300 mb from CONTROL and DIFFEX, and the difference between the two experiments. Except for the dissimilar gradients near the tip of South America, the differences between these two time-mean fields are not statistically significant at the 1% level. However, after an initial period of adjustment, the amount of kinetic energy in the eddies in the northern extratropics reaches a new equilibrium value in DIFFEX that is considerably larger than in CONTROL (Fig. 3). The difference in the eddy kinetic energy between DIFFEX and CONTROL is statistically significant at the 1% level. On the basis of observational estimates by Tomatsu (1979), the amount of eddy kinetic energy is also more realistic in DIFFEX than in CONTROL (Table 1). As the amount of zonal kinetic en-

TABLE 1. The mean amounts of eddy available potential energy A_E, eddy kinetic energy K_E, and zonal kinetic energy K_Z, for the northern extratropics in CONTROL, DIFFEX and observed (Tomatsu, 1979). The model statistics are 180-day means for the region from 23.21 to 81.11°N and the surface to 100 mb. The observed data are for December through February for the region from 25 to 75°N and 925 to 100 mb. Units: 10^5 J m^{-2}.

	CONTROL	DIFFEX	Observed
A_E	15.3	13.8	11.5
K_E	6.9	10.5	11.6
K_Z	9.0	8.9	8.9

ergy does not statistically vary in the two simulations, both being comparable to observed, the ratio of zonal to eddy kinetic energy is improved in DIFFEX. Also, the magnitude of eddy available potential energy improves in DIFFEX.

The spectral distribution of available potential energy at northern extratropical latitudes is similar in the two simulations (Fig. 4). The kinetic energy in the long waves is significantly improved from CONTROL to DIFFEX, but is still underestimated compared to observed. This deficiency may be related to the resolution of the model. Past studies (e.g., Puri and Bourke, 1974) seem to indicate that addition of degrees of freedom to a model improves the energy content of the long waves, through barotropic redistribution of the energy.

3. Discussion

In this note, we have considered only the effect of horizontal momentum fluxes by unresolved eddies on the large-scale flow. In the real atmosphere, the internal vertical exchange of momentum, which occurs for example in connection with clear-air turbulence, most likely affects, to some extent, the dissipation and the spectral distribution of the kinetic energy of the large-scale flow; unfortunately we have very little quantitative information on this effect. In DIFFEX, the internal dissipation due to vertical exchange processes was found to be negligible compared with that due to surface stress (boundary-layer dissipation).

That the level of eddy kinetic energy increases when the horizontal diffusion is decreased, is to be expected on the basis of the model results of Williamson (1978) and Haidvogel and Held (1980). The fact that the time-mean circulation does not change, while the eddy kinetic energy increases considerably from CONTROL to DIFFEX, may at first appear

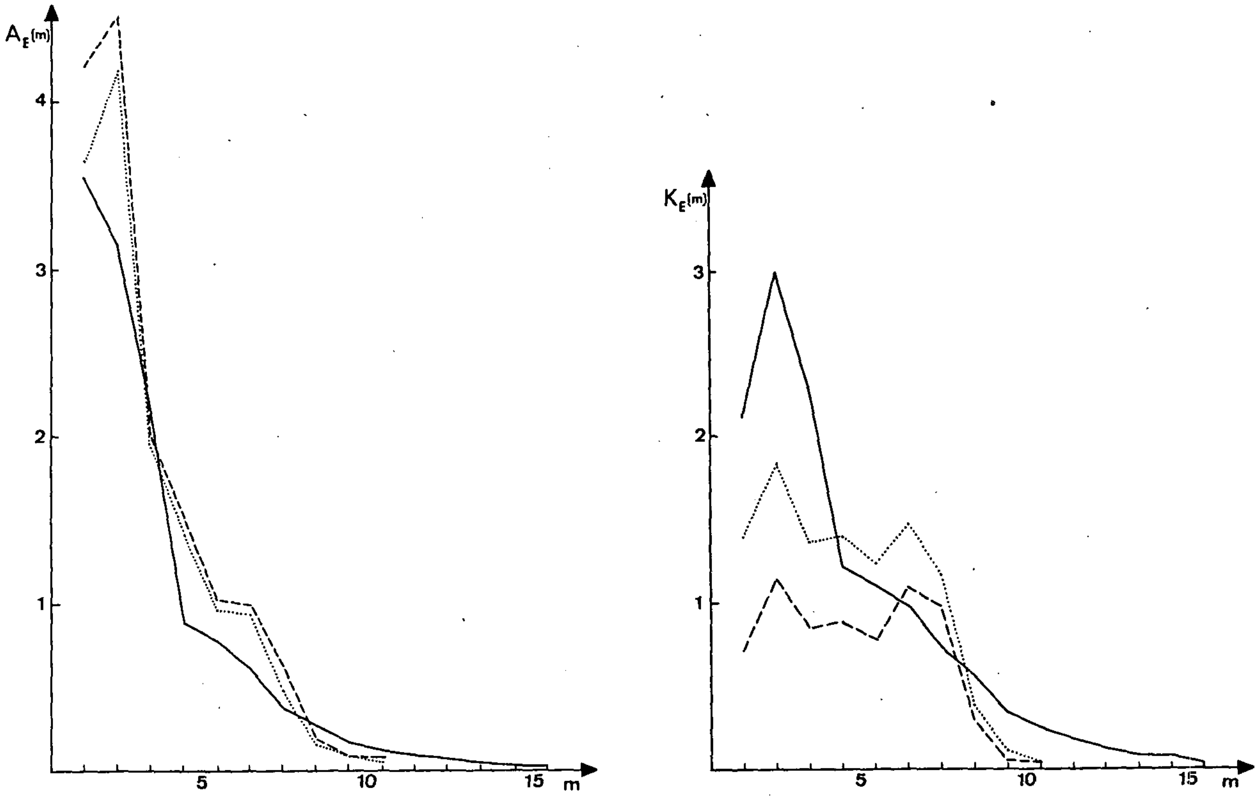

FIG. 4. Available potential energy (left) and kinetic energy (right) in eddies as a function of the zonal wavenumber m in the Northern extratropics in CONTROL (dashed line), DIFFEX (dotted line) and according to the observational study by Tomatsu (1979) (solid line). Data averaged as in Table 1. Units: 10^5 J m^{-2}.

unusual. It becomes more understandable, however, in light of recent observational studies (e.g., Holopainen, 1982) which indicate that the effect of transient eddies on the time-mean flow is, to a large extent, determined by the horizontal heat transfer by these eddies. Hence, if the increase of eddy kinetic energy (from CONTROL to DIFFEX) takes place mainly in the barotropic flow component, which does not have any effect on the heat transfer, the effect of the transient eddies on the time-mean flow can be practically the same in two runs. Under such conditions, the eddy kinetic energy may increase while the time-mean flow remains unchanged. That primarily the kinetic energy of the barotropic flow component is increased from CONTROL to DIFFEX, is indicated by the results in Fig. 4, showing that at wavenumbers 1 and 2, the kinetic energy increases, while the available potential energy, which is related to the horizontal temperature differences and, thus, to the baroclinic component of the kinetic energy, actually decreases.

Our experiment has given some indication of the sensitivity of a model climate to the parameterization of the horizontal momentum fluxes by the unresolved synoptic-scale eddies. In the current study, a second-order diffusion scheme was used. A fourth-order scheme, being more scale-selective, might improve the results. On the basis of Fig. 1, it is also clear that a down-gradient diffusion scheme might be more appropriate in models truncated at wavenumbers $\geqslant 15$, because for these wavenumbers, $F_K < 0$. However, the problem of parameterizing the "negative viscosity" phenomena of the atmospheric large-scale circulation still remains unsolved.

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