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COMPARATIVE ENERGETICS ANALYSIS OF CLIMATE MODELS WITH HIGH AND LOW RESOLUTIONS

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I. INTRODUCTION

In recent year many scientists have developed and improved climate models and predicted the possible impacts of future climate changes with these models. The central activity in modern climate research is the conduct of numerical simulations with models of one or more components of the climate system. In spite of the many uncertainties associated with such models, they alone afford a scientific means for quantitatively examining the range of future climate changes that may result from anthropogenic activities. It is therefore urgent that the uncertainties of these model projections be quantified in the most systematic and useful manner possible; this was the overall objective of the research plan of the Model Evaluation Consortium for Climate Assessment (MECCA Experiment and Analysis Plan, 1991). The Atmospheric Model Intercomparison Project (AMIP) has started to achieve the similar basic goal following MECCA(Gates, 1992).

For the purpose of conducting regional climate simulations, the methods of nesting a limited area model (LAM) to a large area model (e.g., GCM) have been studied (Giorgi and Mearns, 1991; Kida et al., 1991). The nesting procedure can be implemented in a one-way or a two-way interactive mode. In the former, information from the coarser resolution model is used to drive the higher-resolution submodel, but information from the higher-resolution subregion does not feed back into the lower-resolution domain. In the latter, the exchange of information between the lower-resolution and higher-resolution model components occurs interactively and in both directions. The nested LAM-GCM models are mostly based on the one-way nesting procedure. That is, most of nested LAM-GCM models assume that the up-scale energy transfer of the higher-resolution submodel to the lower-resolution domain can be ignored. This can not be justified unless the magnitude of the scale interactions (i.e., wave-wave interaction) is quantified to be small enough.

The main purpose of this study is to identify characteristic biases in the energy transfer between the atmospheres simulated using climate models with different horizontal resolutions. The effect of the artificial truncation in the wavenumber domain to the energy redistribution of the model atmosphere is argued. The analyses of energy transfer spectra provide some useful information to above studies of nesting a LAM to a GCM.

II. DESCRIPTION OF THE SPECTRAL ENERGETICS

The computational analysis scheme of the standard spectral energetics in the zonal wavenumber domain is based on Saltzman (1957; 1970). Here, the meteorological variables are expanded in zonal harmonics, and the Fourier coefficients are substituted in the governing equations of primitive equations. Since atmospheric kinetic energy and available potential energy are proportional to the wind and temperature variances, the zonal mean energy can be decomposed in contributions from every zonal wavenumber by means of the Parseval's theorem. Energy equations are then constructed for every zonal wavenumber, which describe how the temporal variation of wave energy occurs. The kinetic energy equation represents that the energy variation is caused by its zonal-wave interaction, wave-wave interaction, baroclinic conversion, and energy dissipation. Available potential energy equation is also represented by its zonal-wave interaction, wave-wave interaction, baroclinic conversion, and diabatic heat sources and sinks. Evaluating those energetic terms from the gridded data, the energy spectra and energy transformations can be examined over the wavenumber domain.

Saltzman showed, first, that the atmospheric kinetic energy is generated at the synoptic scale of zonal wavenumbers 6-10 by the synoptic disturbances, and the energy is transferred to both planetary waves and short waves. The energy transfer toward the short waves corresponds to the downscale energy cascade to the dissipation range, whereas the transfer toward the large-scale (up-scale cascade) feeds the energy of the planetary waves and zonal jet stream in the atmosphere.

III. GLOBAL GRIDDED DATA

It is desirable that the models are integrated under the same conditions. The National Center for Atmospheric Research (NCAR) Community Climate Model version 2 (hereafter, CCM2) are integrated under the same conditions, except for the parameters in the cloud parameterization (Hack, et al., 1993; Williamson, 1993). The CCM2 simulations are appropriate for the main purpose of this study. As the climate models with different horizontal spectral resolutions, the CCM2 are analyzed for four types of models using horizontal resolutions of rhomboidal-15 (R15), and triangular-42, -63, and -106 (T42, T63, and T106) resolutions.

Moreover the same analyses are carried out for the observed atmosphere. As the observed atmosphere, the ECMWF (European Center for Medium Weather Forecast) analyses data (TOGA Basic Level III) for 5 years during 1986 through 1990 are used. The discrepancies among the ECMWF, NMC (National Meteorological Center) and JMA (Japanese Meteorological Agency) analyses in the wavenumber domain are reported by Ogasawara (1995), which concludes that the spectral patterns and global energy balances with these analyses resemble each other.

The present spectral energetics diagnosis requires a complete set of atmospheric state variables of u zonal wind speed (m/s), v meridional wind speed (m/s), ω vertical p-velocity (Pa/s), T temperature (K), Z geopotential height (m), RH relative humidity (%) and p_s surface pressure (Pa) for instantaneous time intervals (daily value for CCM2). These variables should be given at the longitude-latitude grids over the globe at the vertical pressure levels for the troposphere and stratosphere. The vertical levels prepared by the existing diagnostic code are: 1000 850 700 500 400 300 250 200 150 100 70 and 50 hPa.

The computation of the nonlinear wave-wave interactions requires considerable amount of CPU time because the nonlinear interactions involve double summations over the whole wavenumbers. Therefore, we analyzed for three month period in summer and winter of the climate model simulations.

IV. MERIDIONAL DISTRIBUTION OF KINETIC ENERGY

Comprehensive description of the spectral energetics analysis of this study is summarized in Hasegawa (1995). Some selected results of the analysis are documented in the following.

Figure 1 illustrates the latitudinal distributions of zonal and eddy kinetic energy with the CCM2 and ECMWF datasets during northern winter. Several discrepancies in K_M and $\overline{u}$ fields between the ECMWF analysis and CCM2 simulations are explained mainly with momentum transfer from eddies to zonal mean field, presented.

Zonal kinetic energy K_M in the CCM2 is significantly overestimated in the SH middle latitude. These larger values of K_M in the simulations are more significant in the winter SH rather than in the summer SH. In the SH middle latitude, the CCM2 simulations, except for T42, represent two-maximum structure of K_M in the winter SH (Fig. 1(b)). These features of the simulated atmosphere are closely related with the insufficient representation of the two westerly cores in the SH. In the SH middle latitude, zonal-wave interaction of K in the CCM2 is significantly larger than in the observation: i.e., the CCM2 circulations transfer much momentum from eddies to zonal mean field and intensify the westerly wind fields. In addition, the minimum value of M in the SH middle latitude is not represented in the CCM2-T42 simulation. The double-jet structure in the winter SH is not, therefore, reproduced in the T42 circulation.

The eddy kinetic energy K_E simulated with the CCM2 is larger than that in the ECMWF analysis in the tropics. This bias results from both large M and C_E near the simulated equator. The CCM2 circulation, moreover, transfers much amount of kinetic energy from zonal mean into eddies ($K_M \rightarrow K_E$) in the winter hemisphere tropics.

V. SPECTRAL DISTRIBUTION OF ENERGY AND TRANSFORMATIONS

Spectral distribution of kinetic and available potential energy during northern winter are presented separately for the ECMWF analysis and each CCM2 simulations in Fig. 2. On the whole, K_n in the CCM2 atmosphere is greater than in the analysis for all wavenumber ranges. K_n in the higher resolution model is larger than in the lower one for the ultra long-wave. K_n in the CCM2 is not improved much by increasing model resolution, except for K_M. P_n simulated with the CCM2 is greater than in the analysis for $n > 20$. In particular, simulated P_n is a few times as large as the observation for $n > 50$. P_n in the simulations for the ultra long- and synoptic waves are improved, but not for the shorter eddies by increasing the resolution.

Spectral distributions of zonal-wave interaction M_n and wave-wave interactions L_n for kinetic energy are compared in Fig. 3 for the simulations and observation in the wavenumber domain. Wave-wave interaction of kinetic energy in the CCM2-R15 circulation is significantly different from those in the analysis and other CCM2 for all wavenumber ranges. The simulated L_n transfers more amount of kinetic energy from the synoptic wave into shorter eddy than in the analysis. The kinetic energy supply by the synoptic disturbance is emphasized in the CCM2, while the simulated L_n for higher wavenumber is reduced and improved with increasing the model resolution.

VI. SUMMARY

The objective of present study is to assess the model's uncertainty associated with the model resolutions with respect to energy transfer. The effect of the artificial truncation in the wavenumber domain to the energy redistribution of the model atmosphere is argued in this study.

The energy flow in the CCM2-R15 simulation, as for both direction and amount, is much different from those in the higher resolution models. It is evidently difficult to employ the R15 model for the studies of nesting a LAM to a GCM, especially with the one-way interactive mode. The improvements from R15 to T42 resolution model are significant. However, the double-jet structure in the winter Southern Hemisphere is not reproduced in T42 model atmosphere at all, while other CCM2 simulations represent it a little. This discrepancy results from the zonal-wave interaction of kinetic energy, M_n, without two maxima in the winter southern middle latitude simulated with the T42 model. The wavenumber-latitudinal distributions of energetics terms in T63 model are similar to those in T106 simulation. The zonal-wave and wave-wave interactions of kinetic and available potential energies in the T106 simulation, however, tend to transfer more energies into higher wavenumber domain than those in the T63 atmosphere. The T106 simulation also has some defects. For example, the generation of eddy kinetic energy simulated with the T106 model is obviously different from those of the observed and other simulated atmosphere. In general, the T63 simulation is comparable to the T106 atmosphere.

The zonal mean component of baroclinic conversion is small and negative in the CCM2 simulations, while other terms are larger than those in the analysis. In particular, the energetics discrepancies between the CCM2 and analysis are significant in northern summer, which reflect the difficult reproduction of the winter Southern Hemisphere circulation. Because of these biases, the seasonal variations of the energetics terms are insufficient in the CCM2 simulations. Most of above discrepancies between the CCM2 and analysis result from enhanced synoptic waves in the CCM2 simulations. On the whole, the simulated synoptic disturbances tend to transfer much energy from P_M via P_n to K_n, further K_n to K_M. Some of these biases tend to be reduced as increasing the model horizontal resolution.

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References

Gates, W. L., 1992: AMIP: The Atmospheric Modeling Intercomparison Project. *Bull. Ameri. Meteor. Soc.*, 73, 1962-1970.

Giorgi, F. and L. O. Mearns, 1991: Approaches to the simulation of regional climate change: A review. Review of Geophys., 29, 191-216.

Hack, J.J., B.A. Boville, B.P. Briegleb, J.T. Kiehl, P.J. Rasch, and D.L. Williamson, 1993: Description of the NCAR community climate model (CCM2). Technical Report NCAR/TN-328+STR, NCAR.

Hasegawa, A., 1995: Comparative energetics of the climate models with high and low resolutions. Master Thesis, Graduate Program in Geoscience, University of Tsukuba, 119 pp.

Kida, H., T. Koide, H. Sasaki, and M. Chiba, 1991: A new approach for coupling a limited area model to a GCM for regional climate simulations. J. Meteor. Soc. Japan, 69, 723-728.

Ogasasuwara, N., 1995: Comparative study of the spectral energetics of the general circulation with JMA, NMC, and ECMWF global analyses. Grad. Thesis, Natural Science, University of Tsukuba, 54 pp.

Saltzman, B., 1957: Equations governing the energetics of the large scales of atmospheric turbulence in the domain of wavenumber. J. Meteor., 14, 513-523.

Saltzman, B., 1970: Large-scale atmospheric energetics in the wavenumber domain. Rev. Geophys. Space Phys., 8, 289-302.

Williamson, G.S., 1993: CCM2 datasets and circulation statistics. Technical Report NCAR/TN-391+STR, NCAR.

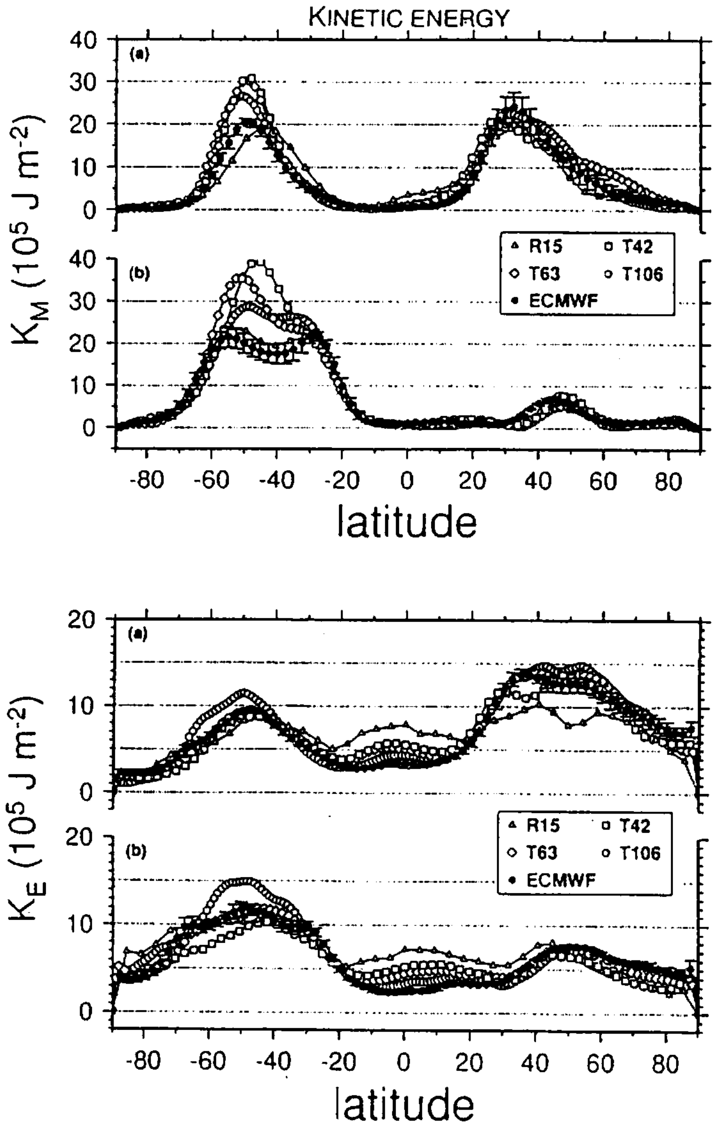

Fig. 1 Latitudinal distribution of zonal kinetic energy K_M and eddy kinetic energy K_E with the CCM2 and ECMWF datasets during (a) northern winter and (b) summer.

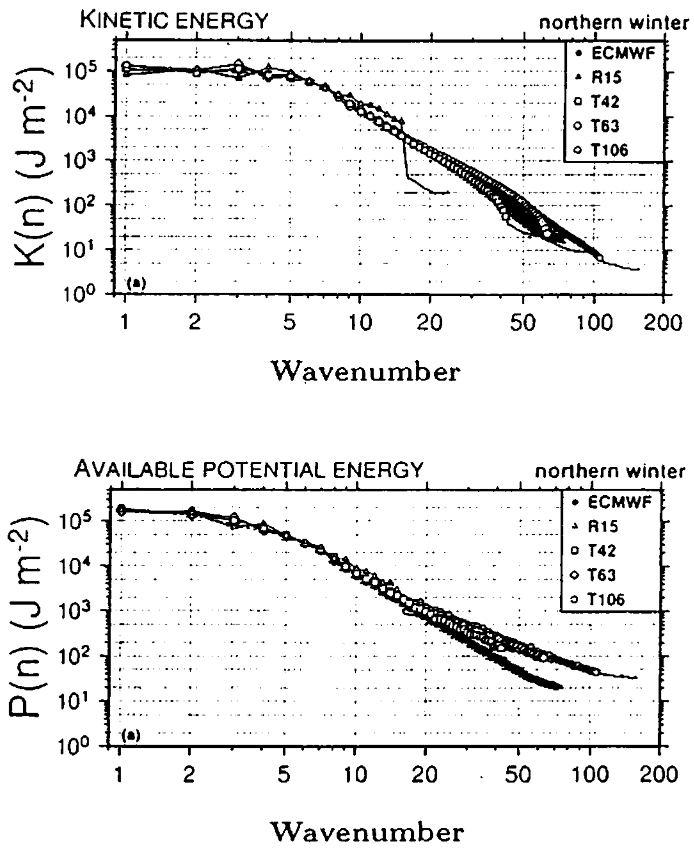

Fig. 2 Spectral distribution of kinetic energy K_n and available potential energy P_n with the CCM2 and ECMWF datasets during northern winter.

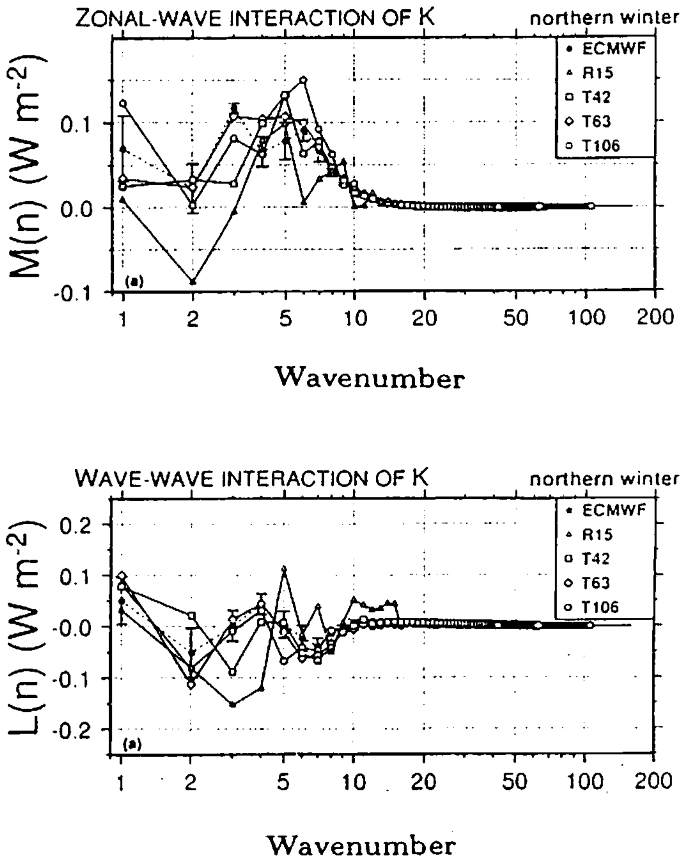

Fig. 3 Spectral distribution of zonal-wave interaction M_n and wave-wave interaction L_n for kinetic energy with the CCM2 and ECMWF datasets during northern winter