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COMPARATIVE ENERGETICS ANALYSIS OF CLIMATE MODELS IN THE WAVENUMBER SPECTRAL DOMAIN

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I. INTRODUCTION

Global-scale atmospheric motion is excited by solar radiation. The driving force of the radiation has a global scale. The solar energy into the atmospheric system will cascade down to smaller scale eddies of high-low pressure systems, and ultimately to the molecular dissipation processes. Analysis of energy transfer among different scales of motion offers a fundamental understanding of the general circulation of the atmosphere. The operational weather prediction models and the state-of-the-art climate models must be formulated to correctly simulate the energy cascade in the wavenumber spectral domain based on the knowledge of the observational analysis.

Present climate models have relatively coarse horizontal and vertical resolutions due to the inevitable restrictions in computing capability. The examination of the influence of the artificial spectral boundary at the truncation wavenumber upon the climatic equilibrium state is an important research subject in the climate modeling effort. As a useful diagnostic tool, spectral energetics analysis has long been performed by a zonal harmonic expansion since the original work by Saltzman (1957; 1970). Kung and Tanaka (1983; 1984) reported the first comprehensive analysis of global energy transformations in the zonal wavenumber domain, using the FGGE observation. In the coarse resolution climate models, the nonlinear energy transfer is forced to terminate at the truncation wavenumber. Hence, the positive and negative values of the nonlinear energy interactions must be re-distributed over the resolvable wavenumbers. Yet, it is not clear how this spectral boundary modifies the spectral energy transfer and how the model's equilibrium is maintained without the accurate energy cascade toward the dissipation range.

The objective of present study is to conduct a sequence of diagnostic energetics analyses of climate model simulations to assess the basic performance of the model atmosphere with respect to the scale interaction and the energy redistribution in the wavenumber domain. Saltzman's spectral energetics diagnosis is carried out in this study for AMIP climate model simulations by the European Center for Medium Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), and Meteorological Research Institute (MRI) at Tsukuba Japan. The energetics analysis results under the AMIP project are compared with the observed atmosphere analyzed by the major operational analysis centers of the ECMWF, JMA and National Meteorological Center

(NMC). In addition, the results are compared with the similar spectral energetics diagnosis for a series of climate model simulations by the NCAR CCM2 in conjunction with the Model Evaluation Consortium for Climate Assessment (MECCA) project.

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 zonal jet stream in the atmosphere.

III. GLOBAL GRIDDED DATA

The primary datasets for the spectral energetics of this study are provided by PCMDI for the ECMWF simulation. We obtained the AMIP run for MRI and JMA directly from these agencies. MRI (new) has a larger gravity wave drag compared with MRI (old). Except for this point, these two are identical. The observed datasets in the real atmosphere for validation are taken from the operational global analyses of NMC, ECMWF, and JMA. In conjunction with this AMIP subproject, a project of MECCA is accomplished and the results are summarized in Hasegawa (1995). The characteristics and the anticipated bias of the climate models are quantified by the comparison with these operational analyses.

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 at 00Z and 12Z. These variables should be given at the longitude-latitude grids over the globe at the mandatory vertical pressure levels. The vertical levels preared for the spectral 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 a period of one full year of the climate model simulations. It is reasonable to analyze a period from 00Z 1 January to 12Z 31 December of the tenth year since most of the AMIP simulations conduct 10 year runs. Only the results from winter means and from January means are presented here.

IV. RESULTS

In general, the energetics characteristics of different operational global analyses (ECMWF, NMC, and JMA) are reasonably consistent with each other, and the discrepancies are relatively small. Comprehensive description of the comparative spectral energetics analysis of operational global analyses is summarized in Ogasawara (1995). Figure 1 illustrates spectral distributions of kinetic energy K_n and available potential energy P_n for JMA, ECMWF, and NMC during the winter of 1988/89. Corresponding zonal-wave interactions M_n, and wave-wave interactions L_n are illustrated also in Fig. 1. The energy levels for these agencies are almost identical for long waves. ECMWF shows slightly higher K_n than the other two datasets at the short waves of wavenumbers grater than 30. The NMC analysis has a model truncation of rhomboidal 40, which is clearly detected by present spectral energetics analysis. Energy transfers by the zonal-wave interactions and wave-wave interactions are large for large-scale motions of wavenumbers less than 20. The magnitude is negligible beyond this wavenumber. According to the results for M_n, we can realize that zonal eddies supply kinetic energy to zonal motion because the values are positive (except for wavenumber 2). In this example of Fig. 1, the contribution is the largest at the wavenumbers 1, 3, and 6. On the other hand, the results of L_n shows two kinds of energy source regions at wavenumbers 2 and 6 (see negative values). The former may correspond to topographic excitation of kinetic energy whereas the latter corresponds to source by synoptic disturbances. These energy source ranges are balanced with energy sink region at wavenumbers 1 and 3-4 (see positive values), where the energy sink is compensated by the wave-wave interactions. The higher wavenumbers have small positive values indicating down-scale cascade of kinetic energy.

The corresponding energy spectra and energy interactions are illustrated in Fig. 2 for the AMIP run by ECMWF, JMA, and MRI (old and new). The intercomparison of the energy levels shows noticeable discrepancies among them. JMA indicates higher kinetic energy levels at synoptic scale of wavenumbers less than 10 and lower energy levels at short waves for wavenumbers greater than 20. Accordingly, the spectral slope of JMA is steeper than the other datasets. Zonal-wave and wave-wave interactions are also compared in Fig. 2. Zonal-wave interactions are the largest for JMA and the lowest in MRI. The wave-wave interactions show high positive value at wavenumber 3 for MRI model with reduced gravity wave drag. JMA shows excessively large kinetic energy source at the synoptic waves. It is found that the AMIP model simulations show substantial differences in energetics characteristics which are apparently different from the observed atmosphere.

IV. SUMMARY

First, spectral energy levels of AMIP model simulations are compared for ECMWF, JMA, and MRI with observations. It is found that the spectral slope for JMA is significantly different from the other AMIP run and from observation. The energy level is higher at the synoptic scale and lower at short waves in JMA. The discrepancy in JMA is detected only in the AMIP model simulation, but not for the operational analysis.

Second, the magnitude and direction of the nonlinear zonal-wave and wave-wave interactions are examined for AMIP model atmospheres. Zonal-wave interactions indicate the largest value in JMA and the lowest values in MRI. The wave-wave interactions show high positive value at wavenumber 3 for MRI model with reduced gravity wave drag. JMA shows excessively large kinetic energy source at the synoptic waves which is related to the markedly high eddy kinetic energy. The summary of the present energetics analysis is given as Lorenz energy box diagram in Appendix.

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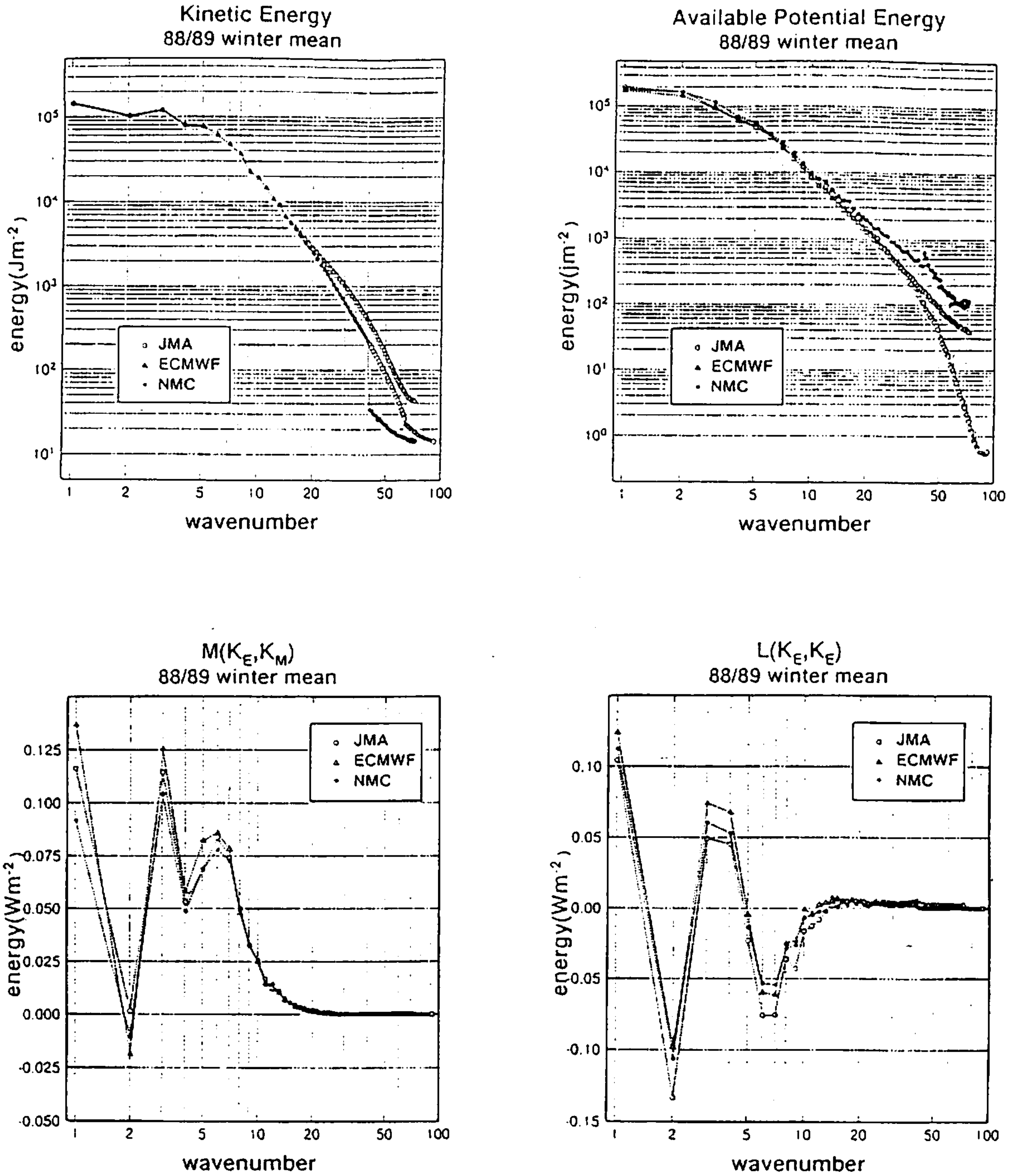

Fig. 1 Spectral distribution of kinetic energy K_n, available potential energy P_n, zonal-wave interaction M_n and wave-wave interaction L_n of kinetic energy for operation global analyses of JMA, ECMWF, and NMC.

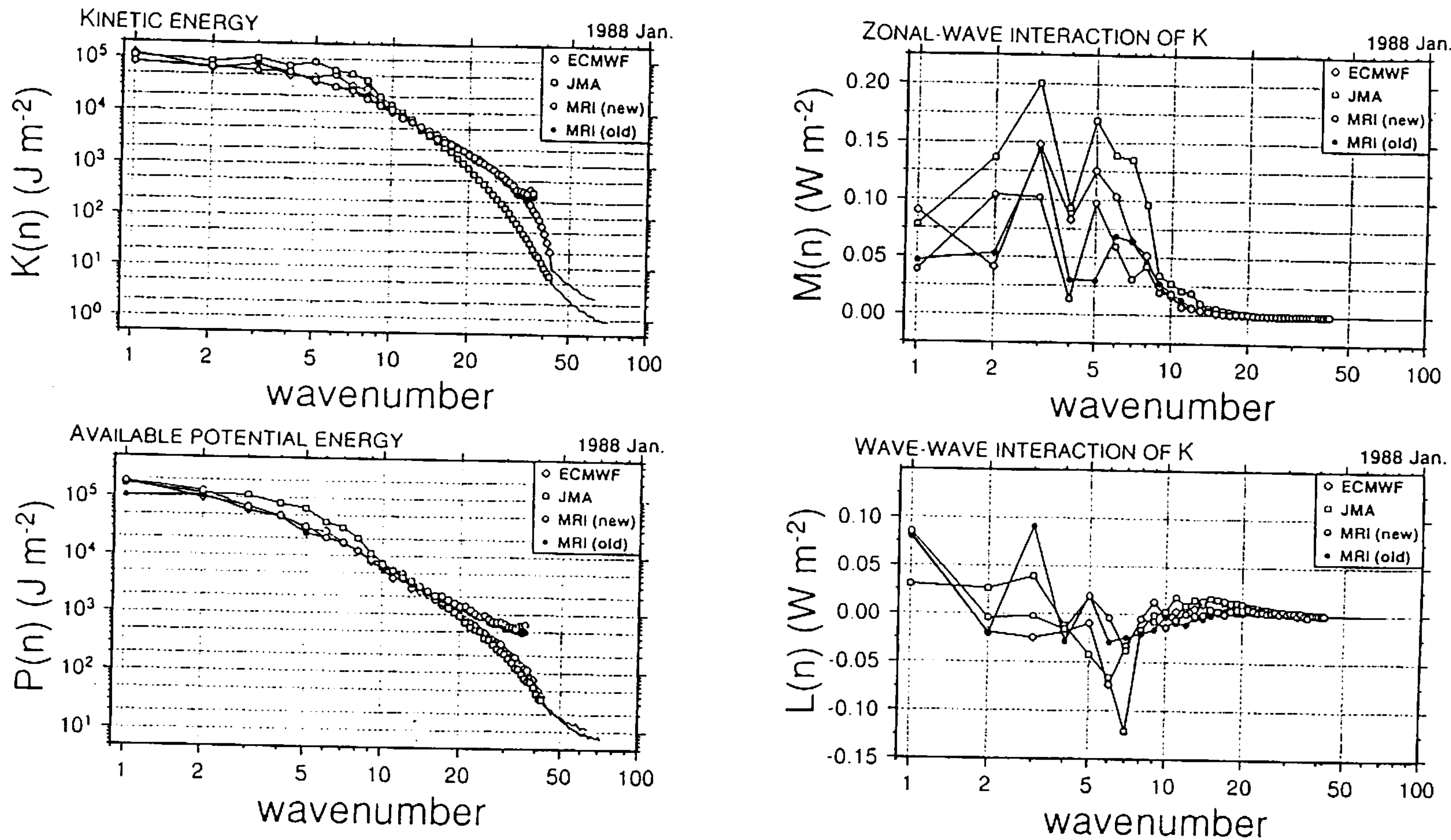

Fig. 2 Spectral distribution of kinetic energy K_n, available potential energy P_n, zonal-wave interaction M_n and wave-wave interaction L_n of kinetic energy for AMIP simulations of ECMWF, JMA, and MRI (old and new).

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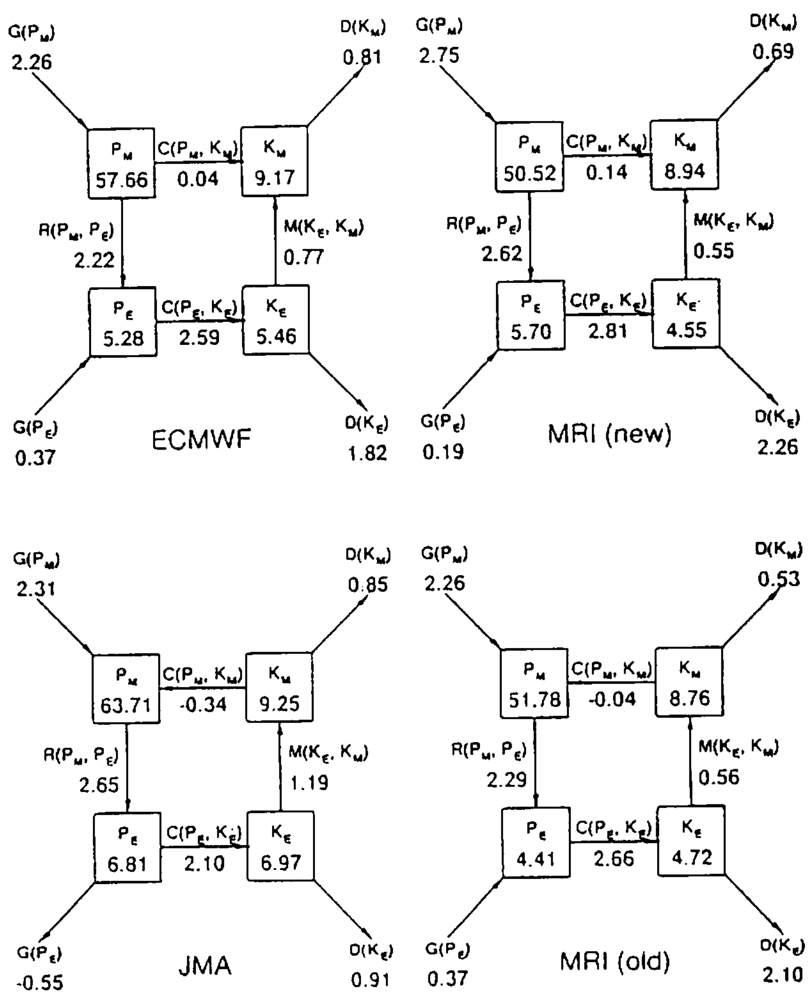

Appendix Lorenz energy box diagrams for ECMWF, JMA, MRI(new), and MRI(old). Units are $10^5 Jm^{-2}$ for energy and Wm^{-2} for transformations.