Evaluation of the Global Heating Field in the Atmosphere using the NCEP Reanalysis

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1. INTRODUCTION

Atmospheric diabatic heating is the major driving force of the general circulation of the atmosphere. The terrestrial environment of Monsoon Asia is deeply influenced by the monsoon circulation specific to this area. The intensity of the monsoon circulation, which consists of the annual cycle by definition, varies over the wide range of time spectrum, including intraseasonal, semiannual, biennial, interannual, and interdecadal time scales. The interdecadal variation in the intensity of the monsoon circulation is an important factor in the recent global change study to be pursued.

The intensity of the monsoon circulation, however, is difficult to define. One may define the intensity in terms of a monsoon index such as the total amount of precipitation over India (see Parthasarathy, 1991), since the intensity of the thermal convection induced by the ocean-continent heat contrast has a high correlation with the amount of precipitation. One may define the intensity by the magnitude of divergence at the tropopause level over Tibettern Plato as is directly linked with the intensity of the monsoon thermal convection. The wind shear between 850 and 200 hPa over East Asia or the intensity of the Tibettern high at 200 hPa, or the magnitude of velocity potential over southeast Asia are the candidate of the suitable monsoon index. However, each of these indices has merit and defect as demonstrated by the relatively low time correlation among these indices.

Probably, one of the most fundamental parameters for the monsoon index is the total amount of the diabatic heating over this region. The heat contrast between the Monsoon Asia and surrounding oceans should be the direct driving force of the monsoon circulation. Hence, measuring the diabatic heating over this region and analysis of its interannual variability are the first step to assess the the terrestrial environment of Monsoon Asia.

This study evaluates the diabatic heating field over the globe by means of the residual method with the first law of the thermodynamic equation. We utilized the global reanalysis provide by the National Center for Environmental Prediction (NCEP). The vertical velocity is estimated by a unique method developed in this study based on the 3-D normal mode expansion. The characteristic distributions of the heating field and the annual variation are quantitatively presented.

2. METHOD AND DATA

In this study, the diabatic heating q is evaluated by the residual of the following heat budget equation (refer to Tanaka and Milkovich 1990):

$$\frac{\partial c_pT}{\partial t} = -\mathbf{V}\cdot\nabla c_pT + (\frac{RT}{p} - \frac{\partial c_pT}{\partial p})\omega + q. \quad (1)$$

Here, the left hand side denotes local time change of enthalpy, c_pT, the right hand side represents its advection, adiabatic heating, and diabatic heating. The parenthesis designates static stability parameter in the pressure coordinate. When the vertical p-velocity, ω, is positive, the downward motion causes adiabatic compression to raise temperature under the stable stratification with positive static stability. On the contrary, the upward motion with negative ω causes adiabatic expansion to decrease temperature. Note that all the variables, such as temperature T, pressure p, horizontal wind $\mathbf{V}$, are observed quantity, except for ω and q which are diagnostically evaluated. Therefore, we need to calculate ω first from the observed quantities to obtain q as the residual balance of the equation.

In this study, we have developed a new spectral method to calculate ω by expanding the state variable in 3-D normal mode functions as follows:

$$\mathrm{U}(\lambda,\theta,p,t) = \sum_{nlm} w_{nlm}(t)\mathrm{X}_m\Pi_{nlm}(\lambda,\theta,p), \tag{2}$$

$$w_{nlm}(t) = <\mathrm{U},\mathrm{X}_m^{-1}\Pi_{nlm}> . \tag{3}$$

Here,

$$\mathrm{U} = (u,v,\phi)^T \tag{4}$$

is the state variable vector with horizontal wind velocity u,v and geopotential deviation from the reference state ϕ as functions of longitude λ, latitude θ, pressure p and time t. The 3-D Fourier expansion coefficient w_{nlm} has triple subscripts of zonal, meridional and vertical wavenumbers, respectively. The expansion basis function Π_{nlm} is a tensor product of vertical structure functions G_m and Hough functions. The dimensional factor matrix X_m contains proper scale parameters involving the separation constant of the equivalent depth h_m. The equations (2) and (3) construct a pair of Fourier transforms in the 3-D spectral domain.

Once the expansion coefficient w_{nlm} is obtained, the vertical motion ω may be calculated by the synthesis, corresponding to the inverse transform:

$$\omega = \sum_{nlm} 2\Omega\frac{gh_m p^2}{R\gamma}\frac{dG_m}{dp} w_{nlm} i\sigma_{nlm} Z_{nlm} e^{in\lambda} \tag{5}$$

where Ω is the angular speed of Earth's rotation, g the gravity acceleration, R the gas constant of dry air, γ the static stability parameter, σ_{nlm} the eigenfrequency of Laplace's tidal equation, and Z_{nlm} the geopotential component of the Hough function.

The twice daily (0000 and 1200 GMT) NCEP global reanalysis with u, v, ω, T, ϕ are defined at every 2.5 by 2.5 degree grid points over 17 vertical levels from 1000 to 10 hPa. Although ω is provided in the NCEP reanalysis, it is used only for the reference, but not for the heat budget analysis, since the NCEP ω appears to balance with the model's q. Model's q, although it is also provided, is used only for the reference since it is highly model dependent and possibly an artifact of the model product.

3. RESULTS

Figure 1 illustrates global distribution of diabatic heating evaluated by the present normal mode method and averaged for December 1992 to February 1993 (DJF). The values (W m^{-2}) are the vertical mass integral up to 10 hPa. Over Asian continent the diabatic heating indicates negative values of approximately -200 W m^{-2}. Large negative value exceeding -400 W m^{-2} is detected at the Northwest Territory in Canada and the negative values extend to the North America. Characteristic positive values of 200 W m^{-2} are seen over the western North Pacific and North Atlantic Oceans. In the tropics, small scale features dominate, indicating large positive and negative heating fields along the equator. Evidently, ocean is the heat source and continent is the heat sink for the northern winter.

Figure 2 illustrates the global distribution of the diabatic heating averaged for June to August 1993 (JJA). Large heat source is detected over India, exceeding 400 W m^{-2} corresponding to the latent heat release associated with the Indian summer monsoon. The heating area is restricted within a rather small area, extending from northeast to southwest. Large cooling regions are attached along both the eastern and western sides of the major heating area over India. Another large positive value exceeding 200 W m^{-2} is seen over China and Indochina Peninsula. Eastern Pacific is characterized by apparent cooling both in the northern and southern Pacific. In contrast, the western Pacific indicates large positive values, especially over the tropical western Pacific due to the active cumulus convections. Southern Hemisphere Indian Ocean indicates negative values, extending toward southern part of Australia. Those results in Figs 1 and 2 are qualitatively in good agreement with former studies, such as Fortelius (1989) and Schaack and Johnson (1991), although the detail is rather different.

Figure 3 illustrates the difference between the DJF and JJA in Figs. 1 and 2, subtracting the former from the latter. We can notice large positive value over India exceeding 800 W m^{-2} associated with the Indian summer monsoon. The large positive values extend toward wide areas of China and Indochina Peninsula. Positive values of 100 W m^{-2} are located zonally over tropical northern Pacific. Parallel to this, organized negative values are located over the tropical southern Pacific associated with the seasonal excursion of the ITCZ. At the north of 30°N, we can see a clear contrast of negative values over the Pacific. It is interesting to note that the heating field associated with Walker circulation is undetectable. Moreover, the land-ocean heat contrast associated with monsoon is not evident in low-latitudes at the Pacific sector. The land-ocean contrast is clearer at the Indian Ocean sector. The result suggests that Indian monsoon is closely coupled with the seasonal reversal of Hadley circulation instead of the land-ocean heat contrast.

Figure 4 illustrates meridional distributions of the zonal mean diabatic heating for DJF (solid line) and JJA (dashed line) calculated from Figs. 1 and 2. The largest heating in the tropics is associated with the seasonal move of the ITCZ. In DJF, it is located near 10°S showing 75 W m^{-2}, whereas the ITCZ moves to 10°N in JJA indicating a narrow peak of 100 W m^{-2}. Large radiative cooling is seen associated with the subtropical high pressure belt over 20°N in DJF and 20°S in JJA showing the value -75 W m^{-2}. Arctic shows large negative values by the radiative cooling both for DJF and JJA. Interestingly, Antarctic indicates smaller values of the radiative cooling compared with the Arctic.

4. SUMMARY AND DISCUSSION

In this study, global distribution of diabatic heating was analyzed in terms of a residual method of the heat balance equation using the NCEP reanalysis data. The vertical p-velocity ω is computed by means of the 3-D normal mode expansion method. The results of the global distributions of heat source and sink are compared for DJF and JJA in 1993.

The monsoon circulation must be induced, by definition, by the heating contrast between land and ocean, and the heating field must be reversed seasonally. Hadley circulation, on the other hand, is induced by the meridional heat contrast which is also reversed seasonally. In this study we detect the zonally symmetric heating contrast over Pacific and Indian Ocean sectors associated with the ITCZ. The result suggests that the Indian monsoon is induced, to large extent, by Hadley circulation over Indian Ocean. The South Asia is a special area where the two major driving forces of Hadley and monsoon circulations operate simultaneously, reinforcing the circulation with each other so that a strongest convective activity is maintained there.

Acknowledgments

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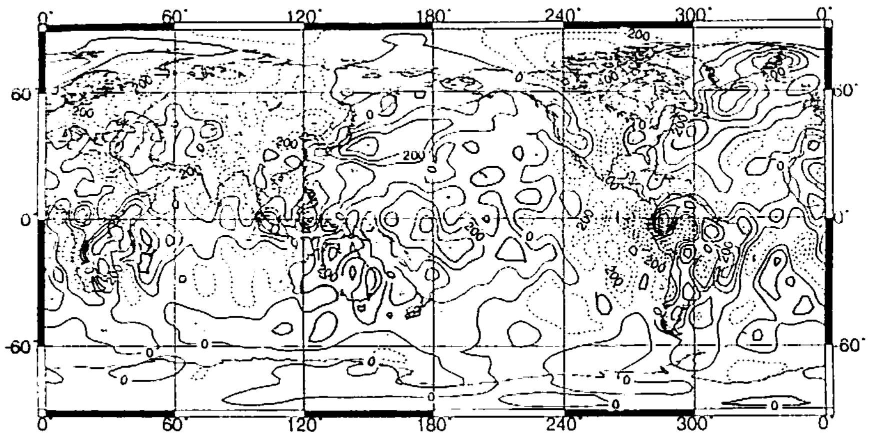

Fig. 1 Global distribution of diabatic heating for December 1992 to February 1993 (DJF).

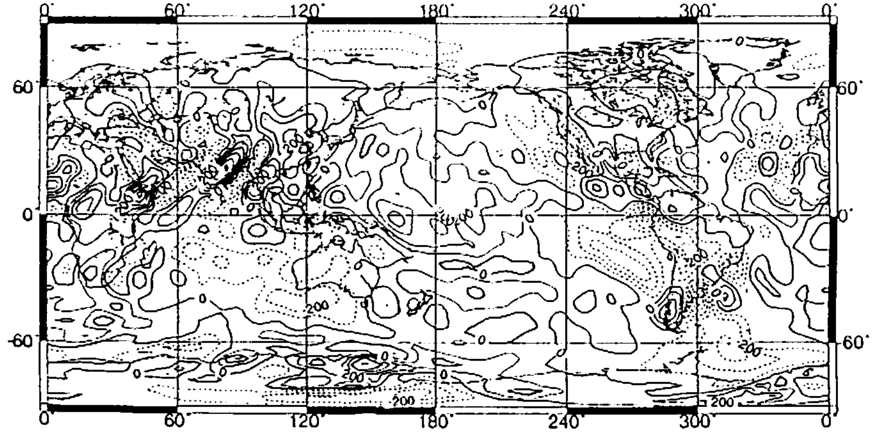

Fig. 2 Global distribution of diabatic heating for June to August 1993 (JJA).

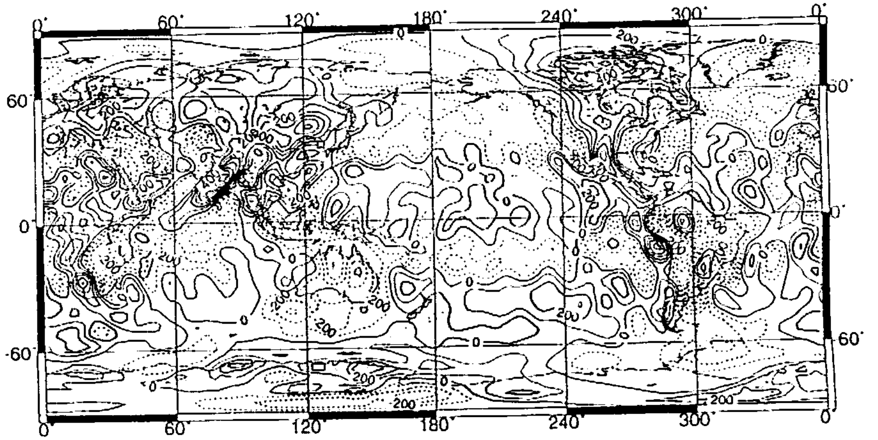

Fig. 3 Difference between the DJF and JJA (JJA-DJF). Units are W m^{-2}.

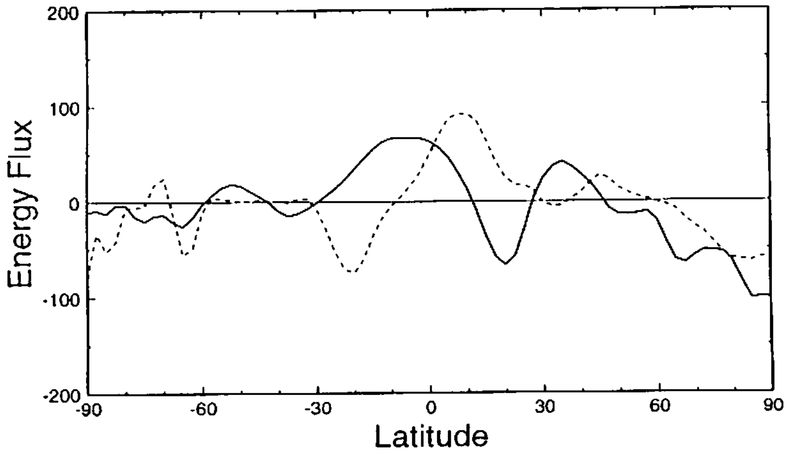

Fig. 4 Meridional distributions of the zonal mean diabatic heating (W m^{-2}) for DJF (solid line) and JJA (dashed line).