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A Note on Korean Monsoon Energetics

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ABSTRACT

The purpose of this note is to demonstrate the role of convective systems in the synoptic-scale circulation as a driving energy source. Energy conversion can be efficiently visualized by the rotational and divergent flow interaction approach. This is also called as the $\psi-\chi$ interaction. In this note the authors present the results of two case studies. Results show that convective heating dominantly leads to the generation of available potential energy, which is next converted into the divergent kinetic energy through the covariance of vertical wind and temperature. The $\psi-\chi$ interaction plays a final role in the transfer of the divergent to the rotational components of kinetic energy that maintain synoptic-scale circulations, such as the Korean monsoon.

Key words: energy transfer, monsoon, synoptic-scale circulation

1. Introduction

This short contribution is intended to describe the importance of convective heating in driving synoptic-scale circulation such as the Korean monsoon. In several energy budget studies (Kung, 1966; Fuelberg and Scoggins, 1978; Vincent and Schlatter, 1979), it was shown that intense convective systems are the main source of meso- to synoptic-scale kinetic energy (KE). In their studies, the decomposition method was employed in available potential energy (APE) and KE computations in which the flow is decomposed into zonal and eddy motions. A set of equations, they used, for the conversion of APE to KE between the zonal and eddy motions and for the nonlinear transfer of energy among the waves was adopted from Lorenz (1955) and Saltzman (1957).

Meanwhile, Chen and Wiin-Nielsen (1976) and Krishnamurti and Ramanathan (1982) presented a different approach for describing APE generation and its transformation into KE. It was the rotational and divergent flow ($\psi-\chi$) interaction framework. There was a special advantage in the use of KEs of the rotational and divergent motions. That is, by casting the basic equations in the framework of rotational and divergent motions, vertical divergent circulations transfer APE directly to the divergent KE. They showed that this $\psi-\chi$ interaction approach is better suited for large thermally driven systems, compared to the conventional decomposition method.

Following this $\psi-\chi$ interaction approach, the authors will explore in this note the impact of the convective systems on the energetics of the Korean monsoon and its relative contribution to the total heating budget. The paper is organized as follows. Section 2 provides a description of mathematical background for the $\psi-\chi$ interaction. Results of energetics are presented in section 3. The final section provides a brief summary and a few concluding remarks.

2. Mathematical Framework

Based on Helmholtz's theorem, the horizontal wind $\mathbf{V}_H$ can be expressed as the sum of rotational and divergent components as follows,

$$\mathbf{V}_H = \mathbf{V}_\psi + \mathbf{V}_\chi, \tag{1}$$

or

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$$\mathbf{V}_H = \mathbf{k}\times\nabla\psi - \nabla\chi \tag{2}$$

where ψ denotes the streamfunction and χ the velocity potential. A list of symbols is provided in Appendix I. The streamfunction and the velocity potential have the following relations with the horizontal wind

$$\nabla\cdot\mathbf{V}_H = -\nabla^2\chi \tag{3}$$

and

$$\mathbf{k}\cdot\left(\nabla\times\mathbf{V}_H\right) = \nabla^2\psi\,. \tag{4}$$

The nergy equations in terms of ψ and χ can be written as follows;

$$\begin{aligned}\frac{\partial}{\partial t}K_\psi &= \nabla\cdot\psi\nabla\frac{\partial\psi}{\partial t} - \psi\nabla\cdot f\nabla\chi - \psi\nabla\chi\cdot\nabla\left(\nabla^2\psi\right)\\ &\quad -\psi\nabla^2\chi\nabla^2\psi + \psi\omega\frac{\partial}{\partial p}\nabla^2\psi + \psi\nabla\omega\cdot\nabla\frac{\partial\psi}{\partial p}\\ &\quad -\psi J\left(\omega,\frac{\partial\chi}{\partial p}\right) + \psi J\left(\psi,\nabla^2\psi + f\right) + D_\psi\,,\end{aligned}\tag{5}$$

$$\begin{aligned}\frac{\partial}{\partial t}K_\chi &= \nabla\cdot\chi\nabla\frac{\partial\chi}{\partial t} - \chi\nabla^2\phi + \chi\nabla\cdot f\nabla\psi\\ &\quad +\chi\left(\nabla^2\psi\right)^2 - \chi\nabla^2\left(\nabla\psi\right)^2/2 - \chi\nabla^2\left(\nabla\chi\right)^2/2\\ &\quad +\chi\nabla\psi\cdot\nabla\left(\nabla^2\psi\right) + \chi\omega\frac{\partial}{\partial p}\nabla^2\chi + \chi\nabla\omega\cdot\nabla\frac{\partial\chi}{\partial p}\\ &\quad +\chi J\left(\omega,\frac{\partial\psi}{\partial p}\right) + \chi\nabla^2 J(\psi,\chi) - \chi J(f,\chi)\\ &\quad +\chi J\left(\chi,\nabla^2\psi\right) + D_\chi\,.\end{aligned}\tag{6}$$

After integration over a domain and rearrangement, the equations (5) and (6) can be expressed by,

$$\begin{aligned}\frac{\partial}{\partial t}\overline{\overline{K_\psi}} &= B_\psi + \overline{\overline{f\nabla\psi\cdot\nabla\chi}} + \overline{\overline{\nabla^2\psi\nabla\psi\cdot\nabla\chi}}\\ &\quad + \overline{\overline{\nabla^2\chi\left(\nabla\psi\right)^2/2}} + \overline{\overline{\omega J\left(\psi,\frac{\partial\chi}{\partial p}\right)}} + \overline{\overline{D_\psi}}\,,\end{aligned}\tag{7}$$

$$\begin{aligned}\frac{\partial}{\partial t}\overline{\overline{K_\chi}} &= B_\chi - \overline{\overline{\chi\nabla^2\phi}} - \overline{\overline{f\nabla\psi\cdot\nabla\chi}} - \overline{\overline{\nabla^2\psi\nabla\psi\cdot\nabla\chi}}\\ &\quad - \overline{\overline{\nabla^2\chi\left(\nabla\psi\right)^2/2}} - \overline{\overline{\omega J\left(\psi,\frac{\partial\chi}{\partial p}\right)}} + \overline{\overline{D_\chi}}\,.\end{aligned}\tag{8}$$

Here double overbars mean that

$$\overline{\overline{Q}} = \frac{g^{-1}\iiint Q\,dx\,dy\,dp}{g^{-1}\iiint dx\,dy\,dp} \tag{9}$$

and B_ψ and B_χ represent boundary fluxes. The terms on the right hand side with double overbars are the so-called $\psi-\chi$ interactions. An equation for the time rate of change of available potential energy (APE) over a closed domain can be expressed by the relation,

$$\frac{\partial}{\partial t}\overline{\overline{APE}} = B_{APE} + \overline{\overline{\chi\nabla^2\phi}} + \overline{\overline{G}} + \overline{\overline{D}}_{APE}\,, \tag{10}$$

where B_{APE} and $\overline{\overline{D}}_{APE}$ denote the boundary flux and dissipation terms, respectively. $\overline{\overline{G}}$ represents a generation term, which can be written as $\overline{\overline{G}} = \overline{\overline{H'T'}}$, i.e., the covariance of heating and temperature perturbation. For a closed system, the sum of APE and KEs of rotational and divergent motion is an invariant in the absence of heating friction (Krishnamurti and Ramanathan, 1982).

In the equation (10), $\overline{\overline{\chi\nabla^2\phi}}$ represents the conversion of APE into KE of divergent motions. This term can be interpreted as warm-air rising and cold-air sinking within the domain because

$$\overline{\overline{\chi\nabla^2\phi}} = \overline{\overline{\phi\nabla^2\chi}} = -\overline{\overline{\phi\frac{\partial\omega}{\partial p}}} = \overline{\overline{\omega\frac{\partial\phi}{\partial p}}} = -\overline{\overline{\omega\alpha}} = -\overline{\overline{\frac{R}{P}\omega T}}\,. \tag{11}$$

The equations (7), (8) and (10) can be approximated in a closed domain as follows;

$$\frac{\partial}{\partial t}\overline{\overline{K_\psi}} = \left\langle K_\chi\cdot K_\psi\right\rangle + \overline{\overline{D_\psi}}\,, \tag{12}$$

$$\frac{\partial}{\partial t}\overline{\overline{K_\chi}} = \left\langle APE\cdot K_\chi\right\rangle - \left\langle K_\chi\cdot K_\psi\right\rangle + \overline{\overline{D_\chi}}\,, \tag{13}$$

and

$$\frac{\partial}{\partial t}\overline{\overline{APE}} = -\left\langle APE\cdot K_\chi\right\rangle + \overline{\overline{G}} + \overline{\overline{D}}_{APE}\,. \tag{14}$$

Here $\left\langle K_\chi\cdot K_\psi\right\rangle$ denotes $\psi-\chi$ interactions and $\left\langle APE\cdot K_\chi\right\rangle$ the conversion of APE into KE of divergent motions, i.e., $-\overline{\overline{\chi\nabla^2\phi}}$. Without $\psi-\chi$ interactions and dissipation, the KE of the rotational motions $\overline{\overline{K_\psi}}$ is conserved in a closed domain. Therefore, the increase of $\overline{\overline{K_\psi}}$ occurs only via $\psi-\chi$ interactions.

In this framework of energetics, without dissipation, the differential heating defines the generation term $\overline{\overline{G}}$ (i.e., a covariance of heating and temperature) which can enhance the APE. The APE can be released via instabilities and the attendant vertical overturnings, which will produce energy to drive divergent circulations, i.e., APE to K_χ. Finally, the nondivergent circulation will only receive energy from the divergent motions via $\langle K_\chi \cdot K_\psi \rangle$. Thus the $\psi-\chi$ interaction framework is useful for examining the role of total differential heating or convective heating (rainfall system) in the eventual build up of strong circulations.

The physical meanings of each term of the $\psi-\chi$ interactions can be described as follows;

$\overline{\overline{f\nabla\psi\cdot\nabla\chi}}$: The magnitude of this term depends on the orientation of the vectors $\nabla\psi$ and $\nabla\chi$. If over the Northern Hemisphere they are nearly parallel, i.e., $\nabla\psi\cdot\nabla\chi > 0$, then energy exchanges go from the divergent to the nondivergent modes.

$\overline{\overline{\nabla^2\psi\nabla\psi\cdot\nabla\chi}}$: This term also depends on the orientation of the vectors $\nabla\psi$ and $\nabla\chi$. Over regions of cyclonic vorticity over the Northern Hemisphere, energy exchanges from the irrotational to the nondivergent flows occurs, while an opposing argument occurs for the Southern Hemisphere. This converse argument also holds for antiparallel vector, i.e., $\nabla\psi\cdot\nabla\chi < 0$.

$\overline{\overline{\nabla^2\chi(\nabla\psi)^2/2}}$: This term expresses another kind of $\psi-\chi$ interaction where the covariance of the horizontal divergence and the KE of the rotational component is important. At a single point the contribution of this term alone has the form, $\partial/\partial t(\nabla\psi\cdot\nabla\psi/2) = \nabla^2\chi\nabla\psi\cdot\nabla\psi/2$ and leads to an exponential growth of the nondivergent KE wherever the horizontal convergence ($\nabla^2\chi > 0$) is positive.

$\overline{\overline{\omega J(\psi,\partial\chi/\partial p)}}$: Regions of large $\partial\chi/\partial p$ are generally associated with regions of large vertical variations of convergence. Following the streamfunctions, downstream from these regions energy exchange from irrotational to the nondivergent flows can occur if there is general upward motion. The converse holds for the case upstream of these regions.

3. Results of Energetics

Intense convective systems are usually considered as a source of synoptic-scale KE (Vincent and Schlatter, 1979). The importance of the precipitation systems in energetics can be visualized by the aforementioned $\psi-\chi$ interactions.

Two $\psi-\chi$ interaction experiments are carried out in the present study. The experiment date is 12Z 27 June 1994 when there were a strong Korean monsoon and intense rainfall systems over western India and north of the Bay of Bengal. The initial data are obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. The data set of temperature, geopotential height, vertical velocity, and horizontal winds at 1000, 800, 700, 500, 300, 200, and 100 hPa levels were obtained from a history tape after a one-day forecast of the Florida State University Global Spectral Model (FSUGSM) at a resolution of T126. Meanwhile, heating rates and rainfall rates were produced by one time step model integration from the history tape. The data obtained have been interpolated to a 1° by 1° grid before calculating each term of the $\psi-\chi$ interactions, which are composed of a generation term of APE, a conversion term of the APE to the KE of divergent flows, K_χ, and a conversion term of K_χ to the KE of rotational flows, K_ψ.

a. Korean monsoon

The first experiment is performed over the Korean monsoon region extending from 90°E to 170°E and 0 to 50°N. In this closed domain, the sum of APE, K_χ, and K_ψ is conserved in the absence of heating and friction. The 850 and 200 hPa streamlines with the rainfall rate are shown in Fig. 1 (a) and (b), respectively. A strong high pressure system is located over the southern sea of Korea at both levels, which plays a crucial role to maintain the Korean monsoon. This pattern of flows is almost the same as that of the Indian monsoon studied by Krishnamurti and Ramanathan (1982).

The origin of the prominent KE of rotational flows, K_ψ, can be tracked as follows.Total fields of heating are constructed by condensation, radiative processes, and surface fluxes at each model grid. Among the various types of heating, heating by condensation is the largest

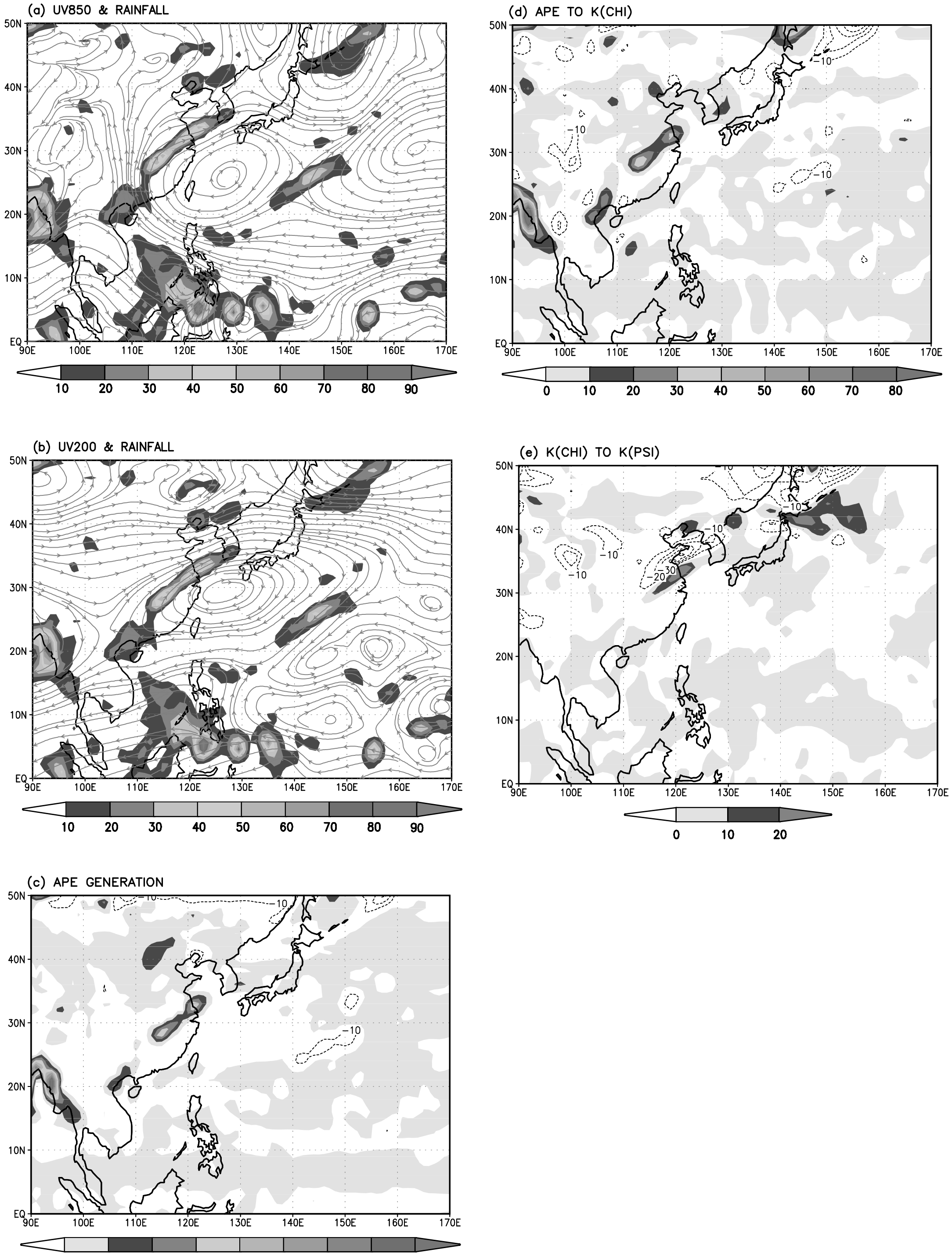

Fig. 1. The energetics of the Korean monsoon at 12Z June 27 1994, dashed lines denote negative values, (a) the 850 hPa streamline and rainfall rate (mm/day), (b) the 200 hPa streamline and rainfall rate (mm/day), (c) the generation of available potential energy (W/m^2), (d) the energy exchange from available potential to kinetic energy of divergent flows (APE to K_χ), and (e) the energy exchange from the irrotational to the nondivergent component (K_χ to K_ψ).

one. It contributes the most to the total heating, that is, most of heating generated is generally related to the precipitation systems. This total heating and temperature covariance produces the APE (Fig. 1 (c)). The locations of the APE generation have a tendency to coincide with regions of rainfall except in a few places. These exceptions are primarily due to the contribution of the temperature perturbation. Two strong APE generation regions are located in the northwestern part of the high pressure system which is related to the Korean monsoon and north of Bay of Bengal (This region will be discussed in the second experiment). Meanwhile, most values of the APE generation rate are within 0 to 10 W/m^2. This APE will in turn be converted into the KE of divergent flows, K_χ, via vertical overturnings due to instabilities (Fig. 1 (d)). The regions of energy transformation from the APE to K_χ coincide with those of the APE generation, which implies that the APE will be converted into K_χ immediately after its generation. Finally, the K_χ will be converted to the KE of the nondivergent circulation, K_ψ, via the $\psi-\chi$ interaction, which is shown in Fig. 1 (e). As mentioned before, the orientation of the vectors $\nabla\psi$ and $\nabla\chi$ generally determines the magnitude of the $\psi-\chi$ interaction term. Although the magnitude of the energy exchange rate is much smaller than others at this moment (the rest of K_χ will be released at a later time), it is evident that the energy exchange from K_χ to K_ψ occurs in the region of the Korean monsoon and assists at maintaining it. The strong negative values might be related to the existence of the jet stream. In summary, total differential heating or convective heating (rainfall system) is the origin of development of strong Korean monsoon circulations.

b. Convective heating vs. total heating

In order to investigate the impacts of convective heating and total heating on energetics, respectively, another experiment is carried out over the global tropics, i.e., 30°S to 30°N, at the same time as the first experiment (12Z 27 June 1994). Even though calculations are made over the global tropics, one part of the tropics is selected, where the strong energy exchanges are detected. The 850 and 200 hPa streamlines with the rainfall rates are shown in Fig. 2 (a) and (b), respectively, over 60°E to 120°E and 0 to 30°N. Although there exist no strong KE of nondivergent circulation, unlike the first case, two intensive rainfall systems can be found over the western India and north of the Bay of Bengal.

The generation of the APE by convective heating and by total heating are depicted in Fig. 2 (c) and (d), respectively. It is clear from this figure that the convective heating contributes the most to the total heating. The small differences between them are due to the inclusion of the radiative processes and surface heat fluxes in the total heating. Therefore, one can confidently say that most of the APE originates from the precipitation system, i.e., convective heating. Fig. 2 (e) and (f) represent the energy exchanges from APE to K_χ and from K_χ to K_ψ, respectively. The energy exchanges utilizing the total heating are not shown in the figure because the transformation of both the APE by convection and total heating to K_χ produce similar results. The physical interpretation of the energy transformation from the APE to K_χ is similar to the Korean monsoon case. However, there are no strong $\psi-\chi$ interactions over the domain in this case (Fig. 2 (f)). The rest of the energy produced by convective heating might be transported to the middle-latitude and used to maintain synoptic systems there.

4. Conclusion

The crucial role of convective systems in the maintenance of synoptic-scale circulation (Korean monsoon) was discussed based on the $\psi-\chi$ interaction framework. This approach provided a better definition of energetics and helped us to understand overall energy circulations.

Convective heating turned out to be the origin of development of strong Korean monsoon circulations. It was illustrated that the context of rotational and divergent motions provides a link between the heat sources, sinks, and the eventual maintenance. The differential heating first generated the APE, which was in turn converted into the divergent KE via ascent of relatively warmer air and descent of relatively colder air. Finally it was passed on to the rotational KE through the nonlinear ($\psi-\chi$) interactions between the divergent and the rotational motions, resulting in the maintenance of the Korean monsoon. The orientation of the $\nabla\psi$ and $\nabla\chi$ isopleths played a major role in determining

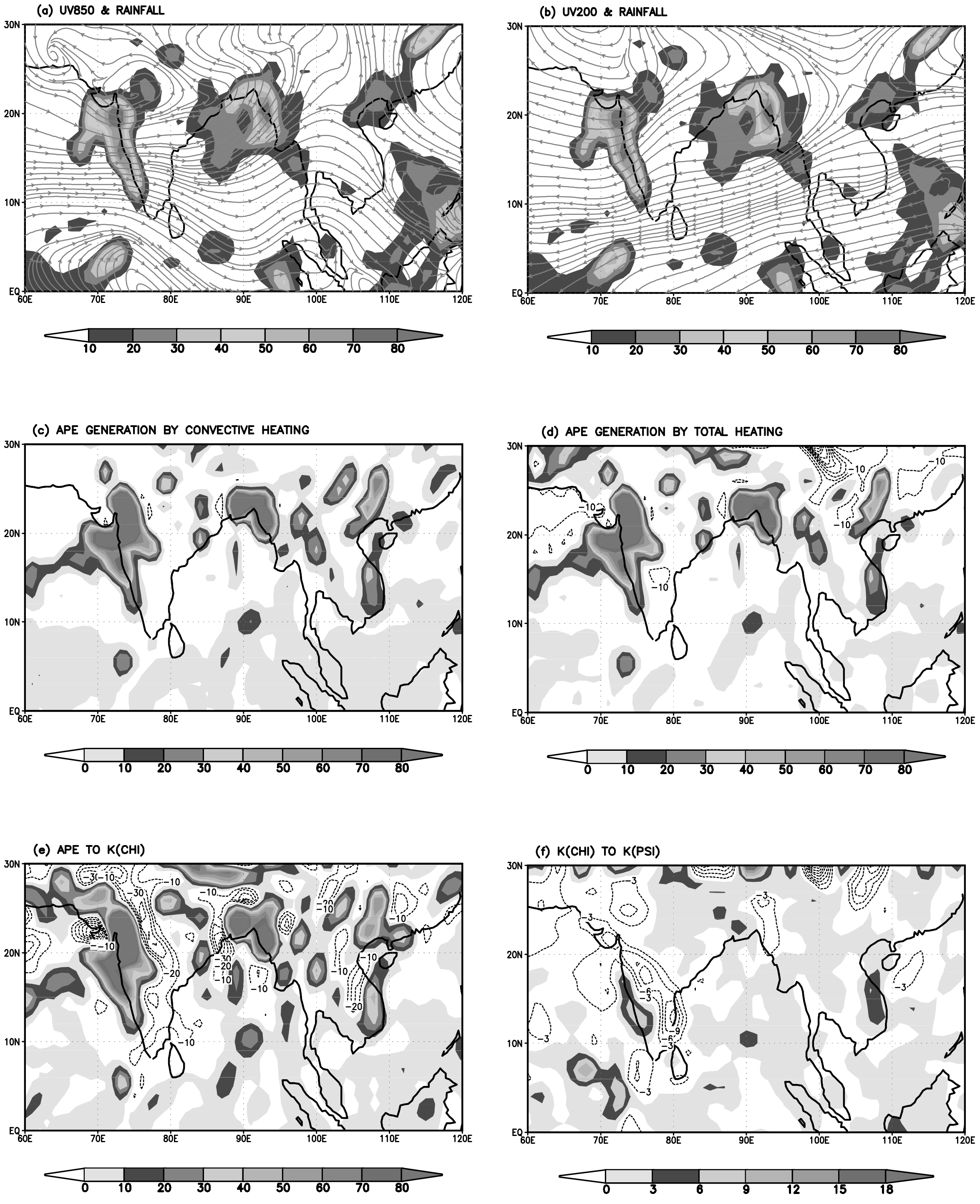

Fig. 2. The energetics over the India at 12Z June 27 1994, dashed lines denote negative values, (a) the 850 hPa streamline and rainfall rate (mm/day), (b) the 200 hPa streamline and rainfall rate (mm/day), (c) the generation of available potential energy (W/m^2) due to convective heating, (d) the generation of available potential energy (W/m^2) due to total heating, (e) the energy exchange from available potential to kinetic energy of divergent flows (APE to K_χ), and (f) the energy exchange from the irrotational to the nondivergent component (K_χ to K_ψ).

the transfer of divergent KE into rotational KE of the monsoon.

The scope of this study is fairly limited. A detailed diagnosis of the monsoon lifecycle from the onset to decay stages is required in order to obtain a better understanding of the energetics of Korean monsoon system. A more systematic approach is needed in the computation of resolving relative contribution of radiative heating, large scale condensation, convective heating, and eddy diffusion to the total heating budget to some degree of completeness. However, this note provides at least a milestone how to assess the fundamental Korean monsoon energetics.

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APPENDIX

A list of symbols

B	Boundary fluxes
D	Dissipation of energy
f	Coriolis parameter
g	Acceleration due to gravity
G	Energy generation
H	Heating
J	Jacobian operator
$\mathbf{k}$	Vertical unit vector
K	Kinetic energy
K_ψ	Kinetic energy of streamfunction
K_χ	Kinetic energy of velocity potential
p	Pressure
R	Gas constant for dry air
$\mathbf{V}_H$	Horizontal wind vector
t	Time
T	Temperature
α	Specific volume for dry air
ϕ	Geopotential height
ω	Vertical wind component
χ	Velocity potential
ψ	Streamfunction
∇	Horizontal gradient operator

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