A New Approach to the Old Subject of Monsoon

A Comparison between Numerical Simulations of Forced Local Hadley (Anti–Hadley) Circulation in East Asian and Indian Monsoon Regions[1]

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ABSTRACT

Two numerical simulations of forced local Hadley circulation are carried out based on a linear diagnostic equation to provide an insight into the mechanisms of monsoon evolution in different monsoon regions. One simulation is for the zonal mean Hadley circulation over East Asia (from 95°E to 122.5°E), another over India (from 70°E to 85°E).

With the NCEP / NCAR re–analysis data re–processed by Chinese Academy of Science in Beijing, the former simulation displays a dominant anti–Hadley circulation pattern over East Asia at 1200 UTC May 1, 1994. The simulated circulation pattern is consistent well enough with the circulation pattern plotted directly from the data for lack of the radiation information at each level. Although the simulation over India is not as good as that over East Asia, a dominant Hadley circulation pattern is obvious as data show. Further analysis shows that the defective simulation over India is due to the presence of statically unstable condition at some grid points in the lower troposphere. This circumstance slightly violates the hydrodynamic stability criterion required by the elliptic diagnostic equation for the forced circulation.

Since the simulations are reliable enough compared with the given data, the linear equation facilitates a systematic assessment of relative importance of each internally forcing process. The assessment shows that among the internal processes, the horizontal temperature advections account obviously for the Hadley (anti–Hadley) circulation over India (East Asia) at 1200 UTC May 1, 1994 in addition to the process associated with the latent heat releasing. The calculation of latent heat energy is a little bit unreliable due to the unclear cloud physics in the convection processes and the less accurate humidity data. These preliminary results are consistent with the results of previous studies which show that the feature of the seasonal warming in the upper troposphere and the corresponding processes are part of key processes closely related to the evolution of the summer monsoon over East Asia and India.

Key words: Monsoon circulation, Hadley circulation, Forced meridional circulation

1. Introduction

It is well known that one of the distinguishable differences between the summer monsoon

and the winter monsoon is the reversal of lower–layer winds with southwesterly during the Northern summer and northeasterly during the Northern winter. Previous studies (e.g. Chen et al., 1991) show that on the one hand, this seasonal alternation of the lower–layer winds is associated with thermal contrast between continents and their adjacent oceans due to differential heating including radiation, condensation and sensible heat flux from the earth's surface, and also with the large–scale atmospheric heat and moisture transport processes; on the other hand, the inter–annual variation of monsoon is closely related to the global weather variations (Schneider, 1996). These results indicate that monsoon systems as a part of the global circulation interact with many dynamic and thermodynamic systems in the atmosphere. A study of monsoons from circulation point of view enables an overall coverage of these physical processes and provides an insight into the mechanisms of monsoon evolution in different monsoon regions.

The new approach introduced here is designed just for this purpose. The numerical simulations in this study will focus on the Hadley circulations over the monsoon regions for two reasons. 1) The alternation of the summer monsoon and the winter monsoon is characterized by the shift between the southerly component and northerly component of winds. 2). There exists a strong signal of seasonal alternation of Hadley circulation in the meridional planes in the East Asian and Indian monsoon regions (Chen et al., 1991).

In the next section, the major perspectives are reviewed in order to understand the backbone of the diagnostic equation for the local Hadley circulation. Section 3 recalls the main assumption and the final form of the diagnostic equation. Section 4 discusses the data structure used in the numerical simulations. Section 5 briefly reviews the numerical schemes, boundary conditions and the calculation of latent heat energy. Section 6 presents the primary results of numerical simulation and the final section is the summary.

2. The introduction of a stream function for the local meridional circulation

The key to obtain a solvable diagnostic equation for Hadley circulation is the introduction of a stream function. In the derivation of the diagnostic equation for the global–zonal–mean meridional circulation (Garllimore and Johnson, 1981; Wu and Cai, 1994), a stream function is introduced from the global–zonal–mean

$$\overline{(\quad)}^{g\prime} = \frac{1}{2\pi} \int_0^{2\pi} (\quad) d\lambda \tag{1}$$

and formally non–divergent continuity equation

$$\frac{1}{a\cos\varphi} \frac{\overline{\partial(v\cos\varphi)}^{g\prime}}{\partial\varphi} + \frac{\overline{\partial\omega}^{g\prime}}{\partial p} = 0 \tag{2}$$

in isobaric–spherical coordinates without any special efforts. This facility, however, is no longer feasible for the derivation of a diagnostic equation for the local Hadley circulation, since in the original continuity equation in isobaric–spherical coordinates

$$\frac{1}{a\cos\varphi} + \frac{\partial u}{\partial\lambda} + \frac{1}{a\cos\varphi} \frac{\partial(v\cos\varphi)}{\partial\varphi} + \frac{\partial\omega}{\partial p} = 0. \tag{3}$$

the first term cannot be averaged out. In order to introduce a stream function of the local Hadley circulation, a closer look at some characteristics of the Hadley circulation is taken based on the following theorems.

1) Stokes' theorem which states that the circulation around the boundary of any area is equal to the total strength (the integration) of the curl of the velocity (vortex) over that area (Phillips, 1950).

2) The curl of velocity is non—divergent (Phillips, 1950).

3) In a given region, if a vector is non—divergent and continuously differentiable, then it can be represented as a curl of velocity (Phillips, 1950).

4) If a vector function is piecewise differentiable everywhere and vanishes at infinity or outside a finite region, then it can be expressed as the sum of an ir—rotational vector and a non—divergent vector (Phillips, 1950; Weatherburn, 1966).

With these theorems in mind, now let us turn back to Hadley circulation. Since the local Hadley circulation is defined as the circulation in a meridional plane, it is associated with the x—component of vorticity according to the Stokes' theorem. Furthermore, the second and third theorems indicate that the local Hadley circulation represented by a stream function ψ is only associated with the non—divergent part of velocity in the meridional plane. In isobaric—spherical coordinates, that is

$$\frac{1}{a\cos\varphi}\frac{\partial(v_\psi\cos\varphi)}{\partial\varphi}+\frac{\partial\omega_\psi}{\partial p}=0. \tag{4}$$

It is easy to prove that formally the solutions of (4) are

$$v_\psi=-\frac{1}{\cos\varphi}\frac{\partial\psi}{\partial p}, \quad \omega_\psi=\frac{1}{a\cos\varphi}\frac{\partial\psi}{\partial\varphi}. \tag{5}$$

However, (4) is only a part of the original continuity Equation (3). To handle the rest of (3), the above theorem (Phillips, 1950; Weatherburn, 1966) is applied. Normally, a velocity field in the meridional plane is considered piecewise differentiable and vanishes at infinity, so this velocity can be represented as the sum of an ir—rotational vector and a non—divergent vector

$$\vec{v}=\vec{v}_\chi+\vec{v}_\psi, \quad \text{or} \quad v=v_\chi+v_\psi, \quad \omega=\omega_\chi+\omega_\psi. \tag{6}$$

With (4) and (6), the original continuity Equation (3) can be rewritten as

$$\frac{1}{a\cos\varphi}\frac{\partial u}{\partial\lambda}+\frac{1}{a\cos\varphi}\frac{\partial(v_\chi\cos\varphi)}{\partial\varphi}+\frac{\partial\omega_\chi}{\partial p}=0. \tag{7}$$

Up to now, (3) is partitioned into (4) and (7). The quantities v_ψ and ω_ψ in (4) respectively represent the meridional branch and vertical branch of the local Hadley circulation. Since v_χ and ω_χ are eliminated from the candidates of horizontal and vertical branches of the local Hadley circulation respectively, those terms associated with v_χ, ω_χ and u in (7) must be treated as forcing terms and predetermined in the coming diagnostic Equation (15) for the stream function ψ of the local Hadley circulation (Yuan and Wang, 1998). So far, there are two possible ways to determine v_χ and ω_χ. One results from the partitions of u and v into geostrophic and ageostrophic components

$$u=u_g+u_{ag}, \quad v=v_g+v_{ag}. \tag{8}$$

The assumption of constant Coriolis parameter gives

$$\frac{1}{a\cos\varphi}\frac{\partial u_g}{\partial\lambda}+\frac{1}{a\cos\varphi}\frac{\partial(v_g\cos\varphi)}{\partial\varphi}=0. \tag{9}$$

The substitution of (8) and (9) into (3) yields

$$\frac{1}{a\cos\varphi}\frac{\partial u_{ag}}{\partial\lambda} + \frac{1}{a\cos\varphi}\frac{\partial(v_{ag}\cos\varphi)}{\partial\varphi} + \frac{\partial\omega}{\partial p} = 0. \tag{10}$$

Equation (10) indicates that any vertical circulation (either the Hadley circulation or the Walker circulation) is mainly associated with the ageostrophic wind. In other words, v_g, the geostrophic component of horizontal wind does not belong to the horizontal branch of the local Hadley circulation. Since v_χ is also non–indicator of the horizontal branch of the local Hadley circulation, there must exist a relationship between v_χ and v_g. One choice could be

$$v_\chi \approx v_g. \tag{11}$$

To determine the degree of this approximation, reexamine the continuity Equation (7) in terms of (u, v_χ, ω_χ) and (10) in terms of (u_{ag}, v_{ag}, ω) with $f \approx$ constant. If $v_\chi \approx v_g$ is a good approximation then the substitution of $v_\chi \approx v_g$ and its by–product $v_\psi \approx v_{ag}$ into (7) and (10) should lead to an identical form of continuity equation. That is exactly the case since on the one hand, with the application of $v_\chi \approx v_g$ and (9), the continuity Equation (7) becomes

$$\frac{1}{a\cos\varphi}\frac{\partial u_{ag}}{\partial\lambda} + \frac{\partial\omega_\chi}{\partial p} = 0. \tag{12}$$

On the other hand, with $v_\psi \approx v_{ag}$ and the application of (6) and (4), the continuity Equation (10) becomes

$$\frac{1}{a\cos\varphi}\frac{\partial u_{ag}}{\partial\lambda} + \frac{1}{a\cos\varphi}\frac{\partial(v_\psi\cos\varphi)}{\partial\varphi} + \frac{\partial\omega_\psi}{\partial p} + \frac{\partial\omega_\chi}{\partial p} = \frac{1}{a\cos\varphi}\frac{\partial u_{ag}}{\partial\lambda} + \frac{\partial\omega_\chi}{\partial p} = 0.$$

As what we expect, it ends up being the same as (12). Because the only assumption required in above analysis is $f \approx$ constant, it is the only approximation involved in $v_\chi \approx v_g$. With (12), ω_χ can be obtained as

$$\omega_\chi\big|_p = -\int_{p_{\mathrm{TOP}}}^{p}\frac{1}{a\cos\varphi}\Big(\frac{\partial u_{ag}}{\partial\lambda} - \frac{\beta v_g}{f}\Big)dp. \tag{13}$$

with the effect of Coriolis parameter as a function of latitude. Equations (11) and (13) present one of the possible ways to predetermine the forcing factors v_χ and ω_χ.

There is another way to determine v_χ and ω_χ. It starts with the calculation of "observed" x–component of vorticity $(\zeta_x)_{ob}$ with the use of "observed" meridional and vertical motions (v_{ob}, ω_{ob}). Then the Poisson equation $\nabla^2\psi_{ob} = (\zeta_\chi)_{ob}$ can be solved to yield the "observed" stream–function ψ_{ob} associated with the local Hadley circulation (this ψ_{ob} field also serves as the standard solution to test the accuracy of the simulated stream–function ψ field). With the use of (5) and this ψ_{ob} field, $(v_\psi, \omega_\psi)_{ob}$ can be computed, which are the corresponding "observed" horizontal and vertical branches of the local Hadley circulation. Finally, the forcing factors v_χ and ω_χ are predetermined through $v_\chi = v_{ob} - (v_\psi)_{ob}$, $\omega_\chi = \omega_{ob} - (\omega_\psi)_{ob}$.

The second approach is accurate theoretically. Numerically, however, the value of v_χ calculated in this way may be contaminated by the truncation errors, roundoff errors and discretization errors to a higher extent (than the value of $v_\chi \approx v_g$) since a complex Poisson equation in the isobaric–spherical coordinates must be solved numerically in order to get v_χ.

Besides, the vertical branch of the "observed" meridional circulation ω_{ob} would be calculated with many assumptions.

At this initial stage of coming series of numerical simulations, $v_f \approx v_g$ is adopted and v_{ag} is treated as the "observed" v_ψ. In a future numerical experiment, v_f and corresponding "ob served" v_ω (or ψ_{ob}) will be calculated based on the Poisson equation. It will be an intriguing topic to figure out how large the differences will be between these two fields of v_f and be tween the corresponding simulations and how large the impact will be on the evaluation of the model's ability to simulate the evolution of the local Hadley circulation when the "observed" fields are different.

3. The main assumption and final form of the diagnostic equation for the local Hadley circulation

Like previous studies (Garllimore and Johnson, 1988; Wu and Cai, 1994), a linear diagnostic equation for the meridional circulation is obtained through the use of gradient bal ance assumption

$$u(f + u\frac{\tan\varphi}{a}) = -\frac{1}{a}\frac{\partial\Phi}{\partial\varphi}. \tag{14}$$

A manipulation with this gradient balance equation as well as other primitive dynamic and thermodynamic equations in the isobaric–spherical coordinates leads to the diagnostic equation for the forced meridional circulation in terms of (v, ω). Then the elimination of (v_f, ω_f) from (v, ω) transforms this diagnostic equation into an equation for the local Hadley circulation but with two unknowns v_ψ and ω_ψ. To turn this non–closure equation into a solvable one, these two unknowns are replaced by one unknown ψ with the use of (5), which results in the final form of the diagnostic equation for the stream function ψ of the forced lo cal Hadley circulation (see Yuan and Wang, 1998 for the detail derivation).

$$[\frac{1}{a}\frac{\partial}{\partial\varphi}(A\frac{1}{a}\frac{\partial}{\partial\varphi} + B\frac{\partial}{\partial p}) + \frac{\partial}{\partial p}(B\frac{1}{a}\frac{\partial}{\partial\varphi} + C\frac{\partial}{\partial p})]\psi = F_1. \tag{15}$$

where

$$A = \frac{\sigma_s}{\cos\varphi}, \quad B = \frac{1}{a\cos\varphi}\frac{\partial\alpha}{\partial\varphi}, \quad C = \frac{f_A f_B}{\cos\varphi}.$$

$$f_A = f + 2u\frac{\tan\varphi}{a}, \quad f_B = f - \frac{1}{a\cos\varphi}\frac{\partial(u\cos\varphi)}{\partial\varphi},$$

and F_1 represents forcing terms,
since

$$\sigma_s = \frac{\alpha}{\theta}(-\frac{\partial\theta}{\partial p}). \tag{16}$$

the coefficient A is associated with the static stability, B the degree of baroclinity and C the inertial stability. The classification criterion of partial differential equation $AC - B^2 > 0$ guarantees Equation (15) to be an elliptic equation. In other words, a local circulation must be forced as long as a barotropic atmosphere is static and inertial stable or the atmosphere is hydrodynamic stable. The present numerical scheme is designed for such an elliptic equation. In (15), the given forcing terms are

$$F_1 = \frac{\partial}{\partial p}[f_4(-\frac{1}{a\cos\varphi}\frac{\partial\Phi}{\partial\lambda} + F_\lambda - \frac{u}{a\cos\varphi}\frac{\partial u}{\partial\lambda} + f_B v_\lambda - \frac{\partial u}{\partial p}\omega_\lambda)]$$

$$- \frac{1}{a}\frac{\partial}{\partial\varphi}(\frac{RQ}{pc_p} - \frac{u}{a\cos\varphi}\frac{\partial\alpha}{\partial\lambda} - \frac{v_\lambda}{a}\frac{\partial\alpha}{\partial\varphi} + \sigma_s\omega_\lambda). \tag{17}$$

Similarly, a diagnostic equation for a local–zonal–mean

$$\overline{(\quad)} = \frac{1}{\lambda_2 - \lambda_1}\int_{\lambda_1}^{\lambda_2}(\quad)d\lambda \tag{18}$$

(with $\lambda_1 = 95°E$ and $\lambda_2 = 122.5°E$ over East Asia, $\lambda_1 = 70°E$ and $\lambda_2 = 85°E$ over India) Hadley circulation over a monsoon region can also be derived as

$$[\frac{1}{a}\frac{\partial}{\partial\varphi}(\overline{A}\frac{1}{a}\frac{\partial}{\partial\varphi} + \overline{B}\frac{\partial}{\partial p}) + \frac{\partial}{\partial p}(\overline{B}\frac{1}{a}\frac{\partial}{\partial\varphi} + \overline{C}\frac{\partial}{\partial p})]\overline{\psi} = F_2, \tag{19}$$

where F_2 represents forcing terms.

$$\overline{A} = \frac{\overline{\sigma_s}}{\cos\varphi}, \quad \overline{B} = \frac{1}{a\cos\varphi}\frac{\overline{\partial\alpha}}{\partial\varphi}, \quad \overline{C} = \frac{\overline{f_4}}{f_B}\cos\varphi$$

$$F_2 = \frac{\partial}{\partial p}[\overline{f_4}(-\frac{1}{a\cos\varphi}\frac{\overline{\partial\Phi}}{\partial\lambda} + \overline{F_\lambda} - \frac{\overline{u}}{a\cos\varphi}\frac{\overline{\partial u}}{\partial\lambda} + \overline{f_B v_\lambda} - \overline{\omega_\lambda\frac{\partial u}{\partial p}}$$

$$\text{term 1} \qquad \text{term 2} \qquad \text{term 3} \qquad \text{term 4} \qquad \text{term 5}$$

$$- \overline{\frac{u'}{a\cos\varphi}\frac{\partial u'}{\partial\lambda}} + \overline{f_B v'} - \overline{\omega_\lambda\frac{\partial u'}{\partial p}})]$$

$$\text{term 6} \qquad \text{term 7} \qquad \text{term 8}$$

$$- \frac{1}{a}\frac{\partial}{\partial\varphi}(\overline{\frac{RQ}{pc_p}} - \frac{\overline{u}}{a\cos\varphi}\frac{\overline{\partial\alpha}}{\partial\lambda} - \frac{\overline{v_\lambda}}{a}\frac{\overline{\partial\alpha}}{\partial\varphi} + \overline{\sigma_s\omega_\lambda}$$

$$\text{term 9} \qquad \text{term 10} \qquad \text{term 11} \qquad \text{term 12}$$

$$- \overline{\frac{u'}{a\cos\varphi}\frac{\partial\alpha'}{\partial\tau}} - \overline{\frac{v'}{a}\frac{\partial\alpha'}{\partial\varphi}} + \overline{\sigma'_s\omega'_\lambda}. \tag{20}$$

$$\text{term 13} \qquad \text{term 14} \qquad \text{term 15}$$

The forcing terms in (20) include pressure gradient force (term 1), frictional force (term 2), inertial force (terms 3 and 5) and their eddy modes (terms 6 and 8), "Coriolis" force (term 4) and its eddy mode (term 7), and the forcing associated with diabatic processes (radiation, sensible and latent heating, term 9), horizontal temperature advections (terms 10 and 11) and their eddy modes (terms 13 and 14), adiabatic process (term 12 which is the combined effect of static stability and vertical motion) and its eddy mode (term 15). Since (15) and (19) are linear equations, they can be used to study the separate contribution of each forcing term to the evolution of a local Hadley circulation.

4. Data processing

In this numerical simulation, the original data are the $2.5° \times 2.5°$ NCEP / NCAR reanalyzed data which again have been processed by the Institute of Atmospheric Physics, Chinese Academy of Science in Beijing. To run the simulation model of the local Hadley circulation, a simple linear scheme is used to interpolate the 15–data–level wind, potential height and temperature, 13–data–level ω, and 8–data–level humidity to the 19 levels (from

1000 hPa to 50 hPa) in the local Hadley circulation model (Wang and Yuan, 2000). The Lorentz's convention (Lorentz, 1955) is extended to determine the values of a property at the model levels under and near the earth' s surface (i.e. they are equal to the corresponding values at the earth' s surface). Since the radiation information is not available within the troposphere, the radiation processes are excluded in the present numerical simulations.

5. Numerical schemes, boundary conditions and the calculation of latent heating rate

To solve the elliptic equation (15) or (19) numerically, the second order centered differencing scheme is applied to both horizontal and vertical derivatives. Then the difference elliptic equation is solved through the use of successive–over–relaxation (SOR) iteration method (Strikwerda, 1989; Wang and Yuan, 2000).

The northern boundary (at 52.5°N) and southern boundary (at 5°N) of considered domains are treated as opened boundaries in order to include boundary effects such as cross–equatorial flow. With $v_\psi \approx v_{ag}$ and Equation 5, the values of stream function ψ of meridional circulation at the northern boundary and the southern boundary are calculated based on the local–zonal mean of the ageostrophic component of meridional wind. At the top boundary (50 hPa), the vertical motion is assumed to be zero. Therefore, ψ is constant (e.g. zero) at 50 hPa due to (5). On the earth' s surface, the assumption

$$\omega_s \approx - \rho g w \approx - \rho g (\frac{u_{10u}}{a\cos\varphi} \frac{\partial z}{\partial \lambda} + \frac{v_{10u}}{a} \frac{\partial z}{\partial \varphi})$$ (21)

is taken into account, which implies that $\partial \psi / \partial \varphi$ is not equal to zero according to (5), i.e. the stream line will follow the earth's surface. Since radiation data are not available at each model level, the diabatic process associated with radiation is excluded in this simulation. As for the latent heating rate, the calculated is based on the specific humidity equation

$$Q_L = - L(\frac{\partial q}{\partial t} + \frac{u}{a\cos\varphi} \frac{\partial q}{\partial \lambda} + \frac{v}{a} \frac{\partial q}{\partial \varphi} + \omega \frac{\partial q}{\partial p})$$ (22)

without considering the cloud physics in the convection processes.

6. Results of numerical simulations and discussion

Two major steps are taken in this numerical study dealing with the diagnostic Equation (19). Step one is testing capability of the numerical model to simulate the forced local Hadley circulation. A schedule for this purpose is given here for clarification. 1) With all 15 forcing terms (or 17 internal forcing processes since Q in term 9 of Equation (19) includes latent heat releasing, sensible and latent heat flux processes) and opened boundary conditions, a simulated stream function ψ for a local zonal mean Hadley circulation is produced through running the model built on (19). 2) With this stream function ψ, the simulated horizontal branch of the local Hadley circulation v_ψ is calculated based on the relation given by Equation (5). 3) This simulated v_ψ is then compared with the " observed" horizontal branch of the local Hadley circulation $(v_\psi)_{ob} \approx v_{ag}$.

Step two is exploring the main mechanisms responsible for forcing the local Hadley circulation with the benefit of the linearity of the diagnostic Equation (19). For this purpose, 17 simulations will be carried out for those 17 internal forcing processes respectively with closed lateral boundary conditions. All the simulations are performed with the same data set of 1200

UTC May 1, 1994 when the weather patterns were notably different over East Asia and India
(Fig. 1). According to Fig. 1a, at 850 hPa over East Asia, there existed a low and warm system
around 24°N. This pattern favored a warm temperature advection in this region. On the con-
trary, over India, 850-hPa cold temperature advection influenced most of the northern India
due to a cold trough to the north of India. The differences between the weather patterns over
East Asia and India also existed at 500 hPa (Fig. 1b). Another reason for selecting the data set
of 1200 UTC May 1, 1994 is that in the meridional plane, the local-zonal-mean meridional
wind component (the sum of ageostrophic and geostrophic modes) already consisted of
southerly component (positive value) in the lower layers over East Asia (Fig. 2a) while north-
erly component (negative value) still dominated the lower layers over India (Fig. 2b).

These two steps are taken in the following two numerical studies. One is for East Asia,
another for India.
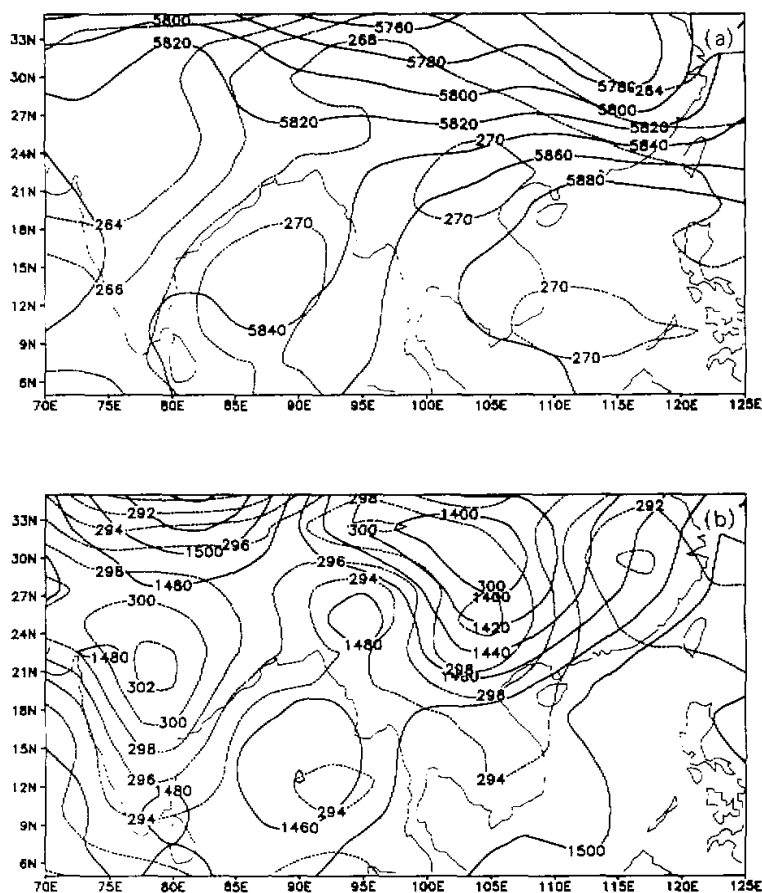
Fig. 1. The distributions of geopotential height (solid in gpm) and temperature (dashed in K) over
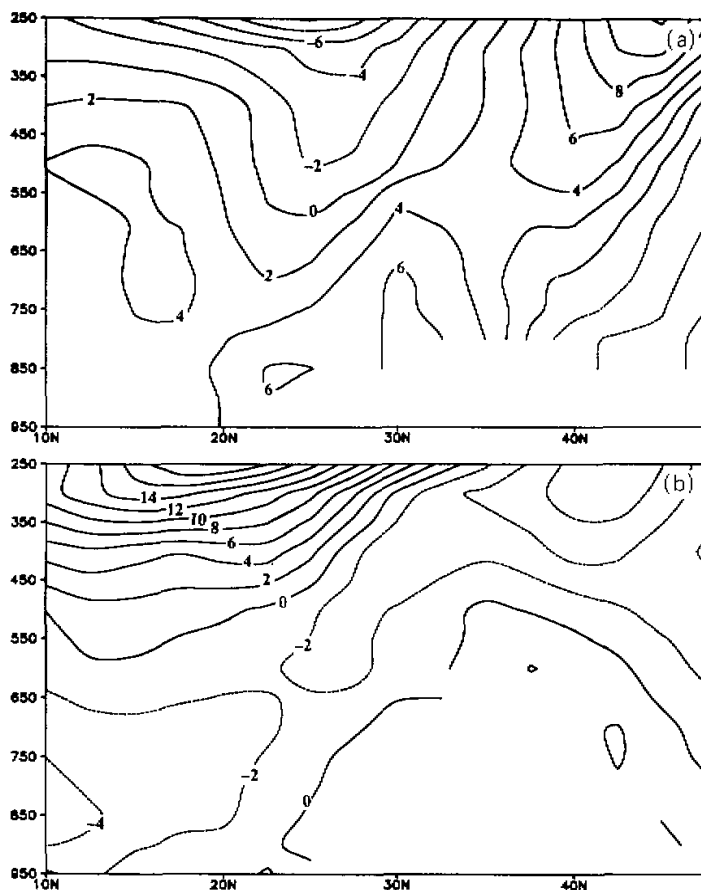India and East Asia at 1200 UTC May 1, 1994. (a) at 500 hPa. (b) at 850 hPa.

Fig. 2. "Observed" local–zonal–mean meridional wind (the sum of ageostrophic and geostrophic modes in m s^{-1} at 1200 UTC May 1, 1994 with positive value for southerly component and negative value for northerly component. (a) In the East Asian meridional plane (an average over 95–122.5°E) and (b) in the Indian meridional plane (an average over 70–85°E).

6.1 The simulation over East Asia

Taking all physical processes into account except the radiation, the forced Hadley circulation is simulated over East Asia. The distribution of simulated horizontal branch of the local–zonal–mean Hadley circulation (Fig. 3) is astoundingly similar to that of the "observed" one (Fig. 4). Figure 3 shows a quite convincing result although there are some "noisy" structures near the earth's surface. To figure out the cause of the "noisy" structure, a simulation is carried out with all the forcing terms but not the forcing related to latent heating. The result of this special simulation is presented in Fig. 5. The removal of the "noise" in Fig. 5 implies that the calculation of the latent heating rate is somewhat unreliable for two reasons. One is the absence of cloud physics in the convection processes, another is the less accurate humidity data. However, the price for the absence of latent heating processes is the southward and

downward shifting of the southerly wind center in the tropical region. Thus, the thermal forc-
ing associated with latent heat releasing plays an important role in the evolution of the local
Hadley circulation.

These numerical simulations demonstrate that the present model is capable of simulating
the local–zonal–mean Hadley circulation at 1200 UTC May 1, 1994 over East Asia. There-
fore, an advantage of the linearity of the diagnostic equation is taken to estimate the relative
importance of each internal forcing. This is accomplished by keeping only one forcing term in
the equation and then running the model with closed lateral boundaries. For instance, to in-
vestigate the role of pressure gradient force, keep term 1, eliminate term 2 to term 15 and then
run the model with southern and northern boundaries closed. The corresponding result shows
a beautiful anti–Hadley–circulation (Fig. 6a) with a maximal southerly wind greater than 2
ms^{-1} in the East Asian meridional plane (Fig. 6b). Consistent with the common sense, this re-
sult also agrees very well with the theory (Yuan and Wang, 1998). The theory points out that
if pressure increases with the increase of longitude in lower atmosphere and decreases with
longitude in upper atmosphere, then the meridional circulation in response to this pressure
distribution will come out to be an anti–Hadley circulation. Although the pressure gradient
force has a big contribution (bigger than that made by any other forcing except for Coriolis
force) to the southerly wind in this case, pressure gradient force and Coriolis force cancel each
other out. Therefore, these two forces are no longer considered in the following comparison
among the internal forcing terms.

The investigation of other individual internal force is done in the same way as that of
pressure gradient force. The results show that the very well organized anti–Hadley meridional
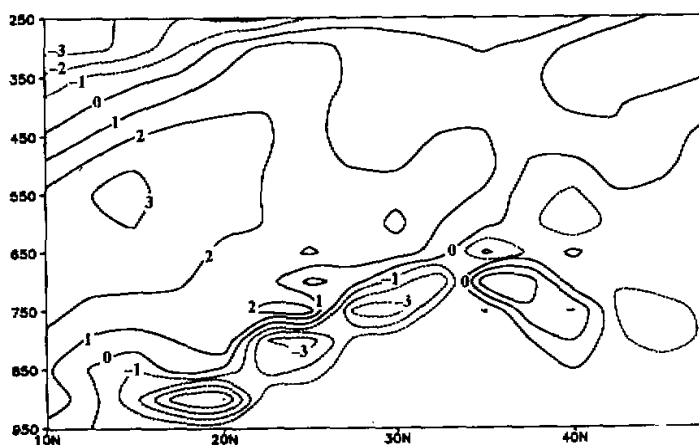

Fig. 3. Simulated horizontal branch (m s^{-1}) of local–zonal–mean (95–122.5°E) Hadley circulation
at 1200 UTC May 1, 1994 with positive value for southerly component and negative value for
northerly component in the East Asian meridional plane. This simulation takes all the forcing pro-
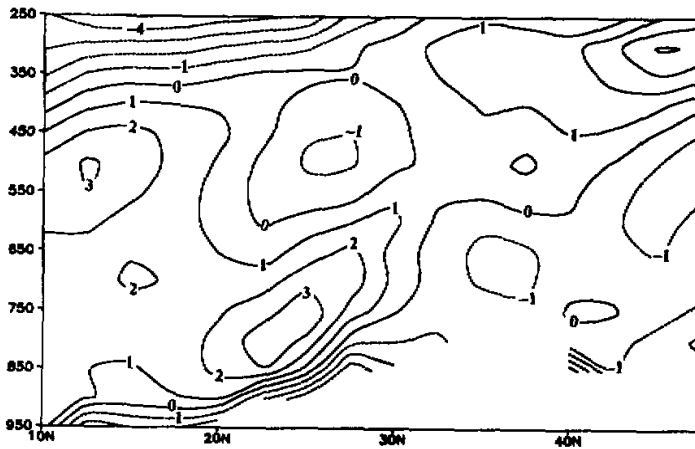cesses into account.

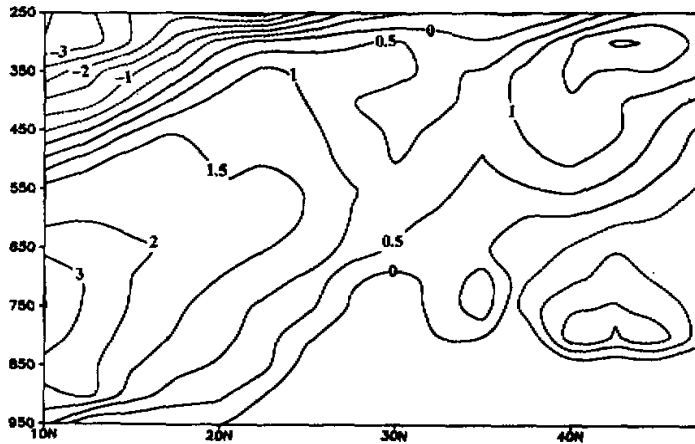Fig. 4. The same as Fig. 3 except for "observed" ageostrophic meridional wind (m s^{-1}).

Fig. 5. The same as Fig. 3 except for that the simulation eliminates latent heat releasing process.

wind pattern with a maximal southerly wind of 1 ms^{-1} is produced by the process associated with the mean mode of u–component temperature advection (term 10). The corresponding circulation is shown in Fig. 7. The contribution from the mean mode of adiabatic process (term 12) ranks the second. The third is the process associated with the mean mode of meridional momentum advection (or v component internal force).

Finally, a simulation is completed including term 10 to term 15 – the combined impacts of mean and eddy modes of horizontal temperature advection as well as adiabatic process (Fig. 8). This simulation reveals that the mean and eddy modes of horizontal temperature advection as well as adiabatic process together also play an important role in the establish-

ment of anti–Hadley circulation over East Asia at 1200UTC May 1, 1994. These mechanisms can be further understood through an investigation from synoptic point of view. The synoptic situation at 1200UTC May 1, 1994 indicated the presence of warm temperature advection in the region to the north of the South China Sea from lower to upper troposphere (Fig. 1). This is a favorable synoptic situation for the formation of anti–Hadley circulation according to both theory and common sense. Previous theory (Yuan and Wang, 1998) concludes that if the distribution of temperature advection is characterized by the increase of warm temperature advection with latitude, then the northern part of domain will warm up in contrast with the southern part of domain. In response to this thermal process, the direct circulation will appear as an anti–Hadley circulation.
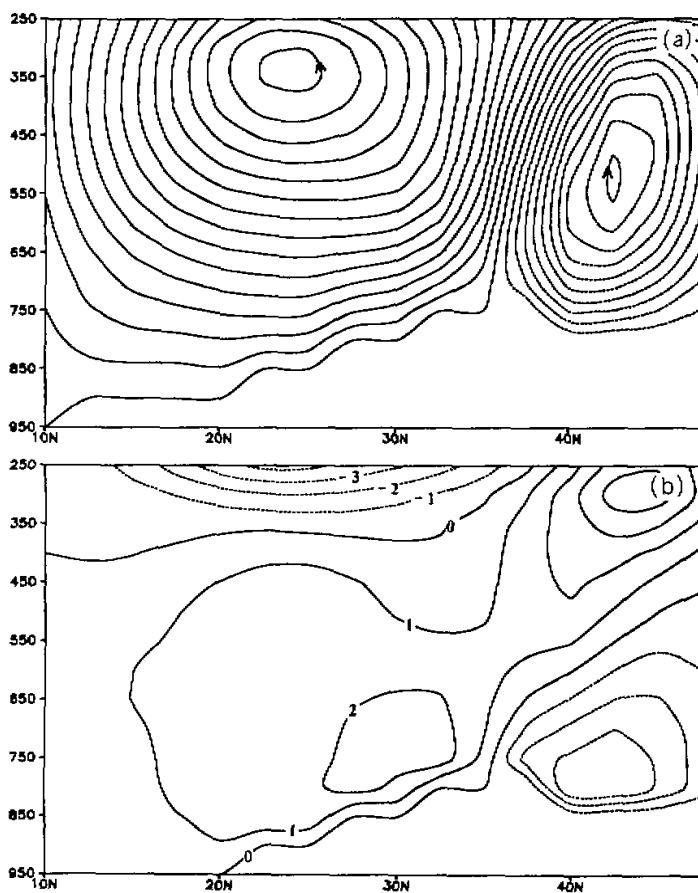

Fig. 6. The same as Fig. 3 except for (a) simulated stream function of local–zonal–mean–Hadley circulation and (b) the corresponding horizontal branch (m s^{-1}). This simulation only takes the pressure gradient force into account.
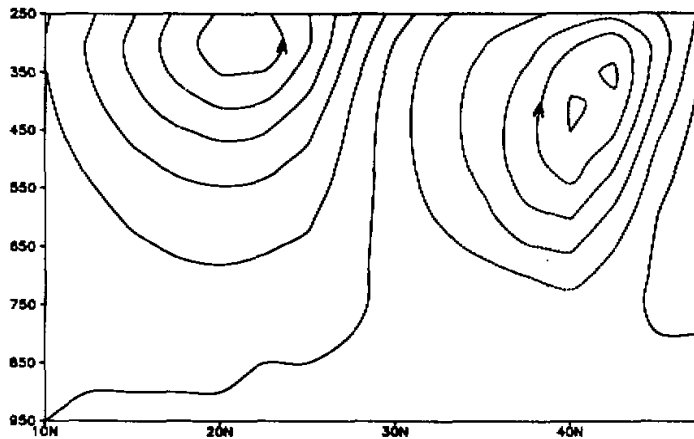
Fig. 7. The same as Fig. 6a except for that the simulation only takes the mean mode of u-compo-
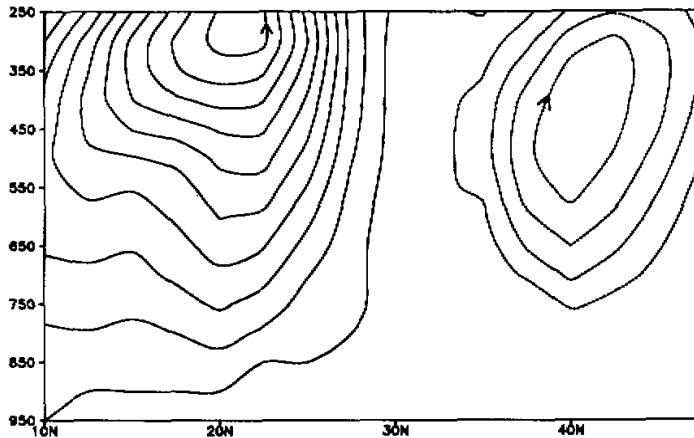nent temperature advection into account.

Fig. 8. The same as Fig. 7 except for that the simulation takes mean and eddy modes of horizontal
temperature advection and adiabatic heating (term 10 to term 15) into account.

6.2 The simulation over India

At 1200UTC 1 May 1994, the cross-section of "observed" v_g displayed a Hadley-circu-
lation pattern above 850 hPa over India (Fig. 9). The simulated result without considering the
effect of latent heating process (Fig. 10) only catches part of the characters of Fig. 9. If the ef-
fect of latent heating process is taken into account, the simulation is somehow worse especial-
ly in the boundary layer partly for the same reasons mentioned in the East Asian monsoon
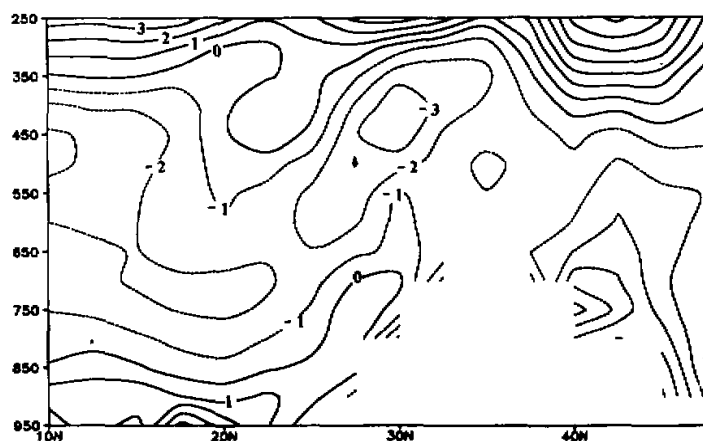case. However, the crucial reason may be the presence of a shallow statically unstable layer

Fig. 9. " Observed" local–zonal–mean (70–85°E) ageostrophic meridional wind (m s⁻¹) at 1200
UTC May 1, 1994 in the Indian meridional plane with positive value for southerly component and
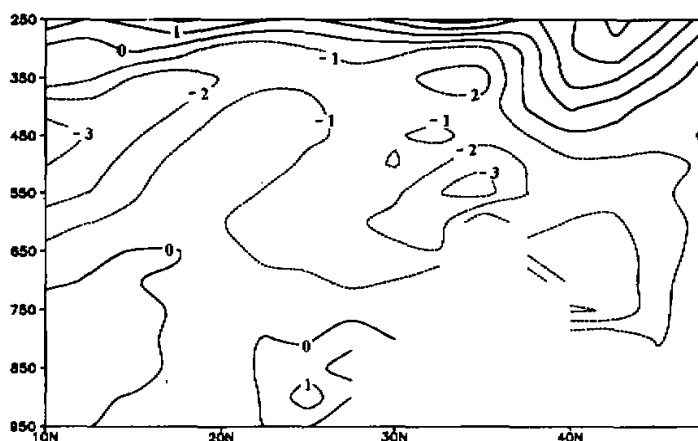negative value for northerly component.

Fig. 10. The same as Fig. 9 except for simulated horizontal brach (m s⁻¹) of Hadley circulation.
This simulation eliminates latent heat releasing process without the adjustment.

$(A < 0)$ over India (Fig. 11) since $AC - B^2 < 0$ in this shallow layer slightly violates the criterion $AC - B^2 > 0$ required for the elliptic equation (see Section 3) and is somewhat beyond the model' s ability. Although in the present case, this shallow statically unstable layer does not lead to the divergence SOR iteration, in an extreme case, the SOR iteration will not converge if the hydrodynamic stability criterion $AC - B^2 > 0$ is highly violated. One likely way to fix the divergence problem is that as long as $AC - B^2 < 0$ takes place, coefficients A, B, and C may be respectively adjusted to A^*, B^* and C^* of the minimal positive $A^* C^* - (B^*)^2$.

However, the results with the adjustments may not be much better or could be worse than those in the slight violation case since the adjustment may upset the balances of the atmospheric systems (Fig. 12). Figure 12 shows the simulated v_ψ field with the adjustment, which is almost identical with Fig. 10 (the simulated v_ψ field without the adjustment) except for a few small scale structures in the boundary layer.

Despite the simulations over India suffer from the limitation of the model, the estimation of the contribution made by each internal forcing process may still provide some information in terms of relative importance. Like the East Asian case, the latent heat process is obviously important but the result is not so reliable. Different from the simulated results over East Asia, the very well organized pattern of the local–zonal–mean Hadley circulation with a maximal northerly wind of 1.2 m s^{-1} in lower atmosphere is produced by the process associated with the mean mode of v–component temperature advection (term 11) (Fig. 13) instead of u–component of temperature advection. A synoptic explanation is provided by Fig. 1 which shows that due to a relatively deep trough over India, cold temperature advection was prevailing over India at 850 hPa and 500 hPa levels. These synoptic situations were just opposite to those over East Asia. To the Hadley–circulation pattern, the contribution from the mean mode of u–component of momentum advection ranks the second in the region between 10°N and 27°N. The rest processes produce either opposite or rather unorganized patterns.

7. Summary

A linear–second–order partial differential equation for a forced local–zonal–mean Hadley circulation is successfully, to some extent, applied to the numerical simulations of the circulation in the East Asian and Indian monsoon regions based on 1200 UTC 1 May 1994 NCEP / NCAR reanalysis data set. With the benefit of the linearity of this diagnostic equation, the investigation of the contribution made by each dynamic and thermodynamic process reveals the relatively important mechanisms responsible for the different characters of monsoon circulation over East Asia and India. The results show that besides the latent heating
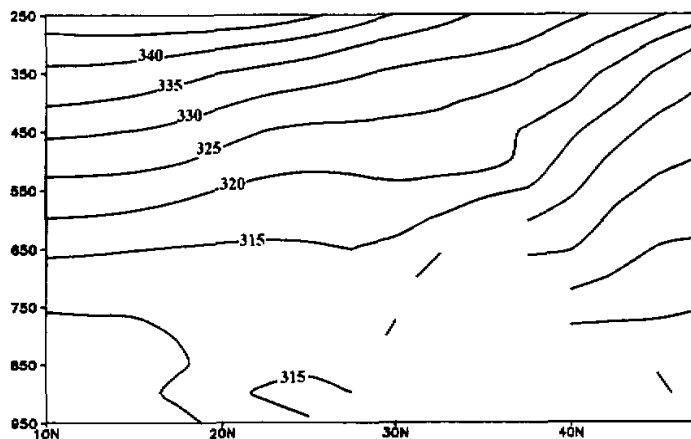

Fig. 11. Meridional cross–section of local–zonal–mean potential temperature (in K) at 1200 UTC May 1, 1994 over India (70–85°E).
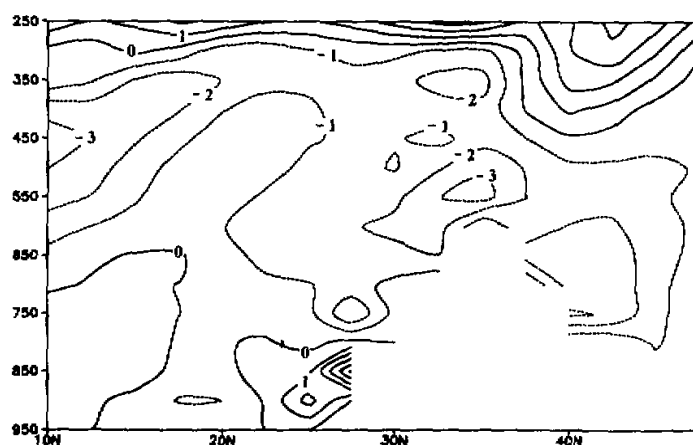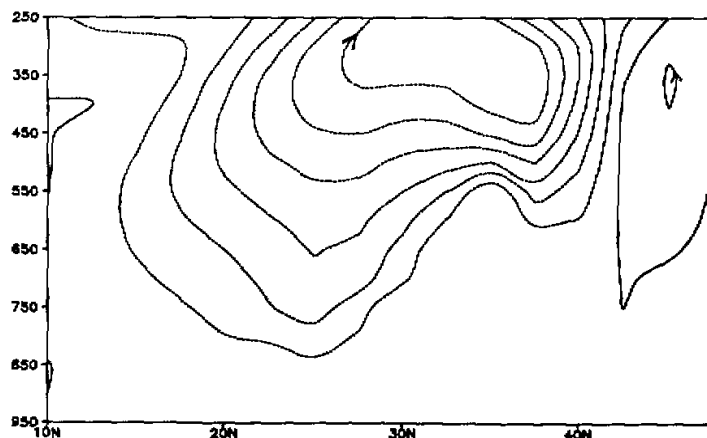
Fig. 12. The same as Fig. 10 except with the adjustment.

Fig. 13. The simulated stream function of local–zonal–mean Hadley circulation with the adjust-
ment. This simulation only takes the mean mode of v–component temperature advection into ac-
count.

processes, the increase of warm (cold) temperature advection with latitude in the East Asian
(Indian) region is also one of the key factors responsible for the formation of anti–Hadley
(Hadley) circulation in the region at 1200 UTC May 1, 1994. These preliminary results are
consistent with the seasonal averaged results by He and Jian (1998) and Jian and He (2000): 1)
The evolution of the East Asian summer monsoon is closely related to the seasonal warming
in the East Asian region bounded by 10°N and 30°N. This seasonal warming is mainly due to
the warm temperature advection and latent heating processes. 2) Compared with the East
Asian monsoon, the delay of the Indian monsoon is associated with the cold temperature

advection affecting the Indian region bounded by $10°N$ and $30°N$.

Since the radiation information within the troposphere is absent from the NCEP / NCAR reanalysis data, those processes associated with radiation are temporarily excluded in present numerical simulations, so does the cloud physics. Next effort of this study will focus on collecting radiation and cloud physics information and improving the calculation of latent heat energy.

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