A review of recent Chinese research on convection in the Asian monsoon area

Kesu Zhang
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
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Observational and theoretical studies on effects of convection in the Asian monsoon area are reviewed. The major findings are:

1. The South China Sea is a key area of active tropical convection.
2. Convection in the Asian monsoon area plays an important role in the maintenance of the summer monsoon. The transition of planetary scale convective regions into the southern hemisphere is also intimately related to the winter monsoon activity in east Asia.
3. The vertical transports of momentum and heat by mesoscale convective complexes in southeast China are larger than those computed from synoptic-scale data sets, but comparable with those from squall line cases in the tropics.
4. Convection enhances mesoscale and synoptic-scale motions through cooperative interactions with them.
5. Free and forced mesoscale motions, such as cloud clusters, moist low-level jets and land/sea breezes are typical in the south China monsoon area. These motions are important in forming heavy rainfall events.

Introduction
This paper presents a short summary of recent research on effects of convection in the Asian monsoon area; most of this material was published in Chinese.

China is a mountainous country dominated by the famous Tibetan plateau (Himalaya) in the southwest. China, Japan and South-East Asia all lie in the east Asian monsoon area, and the climate and weather in China are deeply influenced by the variations of the winter and summer monsoon circulations. In recent years, through projects on climate and on mesoscale meteorology conducted in China, much interest there has been drawn to the monsoons, large-scale tropical circulation, convection and mesoscale systems. This paper will summarise some of the recent results relevant to large-scale and mesoscale effects of tropical convection. The review cannot be comprehensive within the limited pages, and will also be of regional character because the west Pacific, South China Sea and Tibetan plateau are the key areas of direct importance to the weather in southern China.

Observational evidence of convective activity
Let us first look at the geographical distribution and seasonal march of convective activity in China and the tropical Pacific.

Figure 1 shows the geographical distribution of the days of severe convection in China based on data collected at 500 surface stations during 1961-70 (Li 1982). A line may be drawn from northeast to southwest of China on this diagram which distinctly separates the rain storm region (> = 50 mm/day) from the hailstorm region. Most of the rain storms occur along the low-level jet related to the Indian and east Asian monsoon in late spring and summer. The hail storms most frequently occur on the Tibetan plateau and in the mountain areas in northern China. The seasonal march of rainstorms and hailstorms is shown in Fig. 2. The severe mesoscale convective activity migrates from southern China to northern China each year starting from April through to September, while the hailstorm activity maximises one month prior to that of the rain storms.

Convection in the tropical Pacific area is studied by cloudiness data from satellite observations (Fan 1985). Figure 3 shows the seasonal march of the monthly mean cloudiness in January, April, July and October. The cloud band in the ITCZ east of 150°E shows less seasonal variations than that west of 150°E. The northern cloud band parallel to the equator stretching across the whole Pacific is maintained steadily between 5°-8°N, while the southern cloud band west of 170°W exhibits a significant seasonal cycle...
Fig. 1 Annual average number of days of (a) hail storms, (b) rain storms, for 1961-1970 (from Li, J. 1982).

Fig. 2 Seasonal changes of upper-level jet, low-level southerly jet, the ridge of the subtropical high over the west Pacific and the corresponding rainfall zone over China. (I) upper subtropical jet at 110°E, (II) low-level southerly jet at 115°E and (III) the ridge of subtropical high. (1) the first northward jump, (2) the second northward jump. (a) South China rain season, (b) the Mei-Yu season in the Yangtze River and Huaile River valleys, (c) north China rain season, (d) autumn rain season in the Yangtze River and Huaile River valleys and (e) South China rain season (from Li, H. 1987).

Fig. 3 Monthly mean cloudiness (in tenths) for (a) January, (b) April, (c) July and (d) October, in the period February 1965-July 1973.

over the western Pacific Ocean. The seasonal cycle is especially pronounced in the South China Sea, where the ITCZ may reach up to 8°-11°N. Figure 4 shows the time-longitude cross sections of 5-day mean cloud anomalies (4°N-4°S averaged) for 1981-1983. A systematic eastward propagation of low frequency oscillations from the Indian Ocean at a speed of 5 m/s is revealed. Notice that the El Niño event starting from June 1982 was featured by a sudden decrease of cloud amount west of 165°E and an increase east of there. The possible relations between convection.
large-scale circulation, low frequency oscillation and El Niño climate events have attracted increasing interest among Chinese meteorologists in recent years.

**Large-scale effects of convection — contribution to monsoon circulations**

In the past twenty years or so, many papers were published in Chinese about thermal and dynamic effects of the Tibetan plateau on the atmospheric circulation, especially on the formation of Indian and east Asian monsoons. One significant contribution of the convective activity in late spring and early May east of 80°E (from the Bay of Bengal to the South China Sea) and over the Tibetan plateau is to locally heat the atmosphere which results in the onset of the Indian summer monsoon. The monsoon trough in the South China Sea is also related to the seasonal march of convection in the ITCZ.

It is believed that the monsoon, as an important element of the atmospheric circulation, should be studied in terms of comprehensive General Circulation Models (GCMs), rather than being treated as a simple response of the atmosphere to an externally specified thermal forcing. However, even though the latent heat released by convective precipitation cannot be viewed as ‘external’ forcing in the atmospheric systems, the statistical effects of convection on large-scale motions have been widely studied by different ways — heating the atmosphere internally and also externally.

Chen et al. (1983) have made full use of climatological rainfall data provided by the National Meteorological Bureau (1976) and by Jaeger (1976) to directly estimate the atmospheric heat source in South-East Asia by the following formula:

$$Q = R_x - R_o + Sc + LH \quad \ldots \quad 1$$

Here $R_o$ stands for the net radiation observed by satellite at the top of the atmosphere, $R_x$ the radiation at the earth surface, $Sc$ the sensible heat from earth to atmosphere and $LH$ the latent heat. In the tropical area convective precipitation dominates. Therefore, $LH$ mainly represents the thermal effect of convection. Figure 5 shows the calculated heat sources for June, July and August. The significant heat sources are located over the Bay of Bengal (4°C/day) and the South China Sea (3°C/day). Many papers have been published in English concerning the atmospheric heat sources especially for the FGGE year, but no such large heat source centres over the South China Sea were obtained (i.e. Luo and Yanai 1984; He et al. 1987; Wei et al. 1983). By use of the heat source computed by Wei et al. (1983), integration of a three-level primitive equation model (40°S-40°N) does not produce a satisfactory east Asian monsoon pattern. Luo and Zhang (1987) modified Wei et al.’s heat source by including the heating centre at South China Sea for summer monsoon simulation. The results were significantly improved. Figure 6 shows the simulated flow patterns at 850 hPa and 200 hPa. The cross equatorial flows at 40°-50°E and at 105°-120°E, the monsoon trough at South China Sea, the ITCZ in the west Pacific and the subtropical high at 850 hPa are well simulated. The monsoon trough at South China Sea is directly related to the heat source in that region. The simulated 200 hPa flow.
Fig. 5 Monthly averaged heat source distributions in South-East Asia for June, July and August, units in °C/day (from Chen et al. 1983).

The observed monthly mean v-component at the equator in the summer monsoon season of 1979 is given in Fig. 7. The cross equatorial flow at 105°E, 125°E and 150°E are well identified (Liang et al. 1984). The flows at 105°E and 125°E are intimately related to the heat source in the South China Sea in numerical simulations. This heat source is mainly due to convective precipitation.

The two peaks of convective precipitation during summer along 15°N and also in south China are accompanied by successive onsets of the South-East Asian monsoon in early May and the Indian monsoon in June (Fig. 8, from He et al. 1987). The former may be related to the heat source centred over Burma and Thailand in the period of pre-onset of the South-East Asian monsoon. The latter is related to the latent heat source over Bay of Bengal and is also influenced by the mechanical effect of the Tibetan plateau (Chen et al. 1983; Luo and Zhang 1987).

Convection also plays an important part in the distribution of heat sources during the winter monsoon season (Ding and Krishnamurti 1986). Figure 9 shows the positions of Siberian highs and the distribution of large-scale heating due to precipitation in stable conditions and of convective heating (computed from a modified Kuo's scheme), which is generated by cold surges related to Siberian highs (located in Box 3). These
calculations are based on once-daily grid-point data (2.5° × 2.5°) at seven pressure levels from ECMWF for 19 cases of Siberian highs during the five winters of 1980-1984. The composite results reveal an interesting feature. As shown in Fig. 10, when the centre of the Siberian high moves from Box 1 (55°N, 95°E) to Box 3 (30°N, 120°E) in Fig. 9(a), the position of the composited divergent centre at 200 hPa shifts from the tropical west Pacific (140°E) to the east Pacific (150°W). It implies a 70° eastward shift of the planetary-scale deep convection. This process is similar to the transition of flow patterns from non-El Niño years to El Niño years.

Statistical effect of convective activity

The statistical effect of convective activity on the vertical transports of heat, moisture and momentum were studied recently (Li 1987) by use of data collected in the special mesoscale field experiment carried out in southeast China during the ‘Mei-Yu’ seasons of 1981-83 (Fig. 11(a)). The average distance between sounding sites is about 90 km and the time interval is six hours. The precipitation was measured hourly. During the convectively-active and non-active periods from 24 to 26 June in 1983, the heat, moisture and momentum budgets were computed. Figures 11(b) and (c) show the vertical distributions of heating rate Q1 and moisture sink Q2 for disturbed and undisturbed periods. The effects of convection are highly dependent on mesoscale systems, which accompany the disturbed periods. The values of Q1 and Q2 here are comparable with those computed for squall lines during GATE (Cheng 1987). Figure 11(d) shows the entrainment parameter, \( \lambda = (1/m) \, \text{dm/dz} \). Comparisons are made for results during the Mei-Yu season in China and Japan (So 1985) and during the GATE experiment (Lord and Arakawa 1980). It is evident that in the disturbed period the
Fig. 10 (a) Anomaly of velocity potential at 200 hPa for Box 1 (Fig. 9). Negative anomaly (convergence) is shaded (unit: $10^5 \text{m}^2\text{s}^{-1}$).
(b) As (a) for Box 2.
(c) As (b) for Box 3.
(from Ding and Krishnamurti 1987).
Fig. 11 (a) The domain and station distribution for the mesoscale field experiment in southeast China in June-July of 1981-1983, • radiosonde station, ○ rainfall station.

(b) Vertical distribution of the apparent heat source in °C/day. Solid lines: disturbed period. Dotted lines: undisturbed period.

(c) Same as (b) except for moisture sink.

(d) Vertical distribution of the entrainment parameter \( \lambda = 1/m \text{dm/dz (km}^{-1}) \) obtained by Lord and Arakawa (1980), So (1985) and Li (1987).

(e) Spectrum of mass flux at cloud base as a function of height of detrainment. Units in hPa/h (from Li 1987).

entainment parameter in China calculated by use of this mesoscale data set is the largest one. Figure 11(e) shows the spectrum of mass flux (hPa/h) at cloud base calculated by solving Niitta's (1975) model. This indicates that during the disturbed period period convection is separated into two categories — high clouds and low clouds. Very little convective cloud detains at the middle troposphere.

Synoptic-scale and mesoscale effects of convection

In order to understand the effects of convection on the synoptic and mesoscale systems, diagnostic and theoretical studies have been carried out. A diagnostic analysis on the formation of the mid-troposphere cyclone over the South China Sea reveals that active convection plays two important roles. One is to transport vorticity upward so that the originally tilted axis of a vortex changes to be vertical. The vorticity tendency caused by large-scale motion and by convection are of the same order of magnitude. The second role is to heat the atmosphere directly by release of latent heat at the mid-troposphere and indirectly by inducing adiabatic descending motion at the upper troposphere (Zhou and Liang 1985).

Theoretical studies consider the effects of convection in terms of parametrisation of cumulus heating and momentum mixing by both mechanistic and numerical models. The formulation of wave-CISK and cumulus momentum mixing (CMM) may overestimate the effects of convection because observational evidence and numerical experiments show a time-lag of convection to the pre-existing mesoscale forcing. The mechanistic model for CISK (Charney and Eliassen 1964) and CMM (Schneider and Lindzen 1976) theories have been applied to Symmetric Instability Theory, not only for synoptic-scale disturbances within the monsoon trough and for typhoons, but also at mesoscales for low-level jets and mesoscale cloud bands. The formulation of the model is as follows (Zhang 1987):

\[
Du + wU_r - \zeta_0 v + \partial p/\partial x = F \\
\varepsilon Dv + fU + \partial p/\partial y = 0 \\
\lambda Dw - \theta + \partial p/\partial z = 0 \\
D\theta - M^2 w + N \omega w = \tilde{H} \\
\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0
\]

where

\[
D = \delta \partial t + U \delta \partial x, \quad (u, v, w, \theta) = \bar{p} (u', v', w', \theta' - \bar{\theta}), \\
N^2 \equiv \frac{\varepsilon}{\theta} \frac{\partial}{\partial z}, \quad M^2 \equiv \frac{\varepsilon}{\theta} \frac{\partial}{\partial y} = fU, \quad F = \frac{\partial}{\partial z} M_c (U-U_r), \\
\zeta_0 = f\Upsilon_v, \quad \tilde{H} = Q_c G(z) N^2 w
\]

\( \lambda \) and \( \varepsilon = 0 \) or 1 indicate, respectively, whether the model is hydrostatic and geostrophic or not. \( U \) represents the basic flow, \( \theta_c \) a constant potential temperature, \( \tilde{H} \) the heating rate, \( M_c \) the vertical mass flux, and \( U_c \) the horizontal velocity in a cloud.

At mesoscales (\( \lambda = \varepsilon = 1 \)) we are seeking ageostrophic modes which may be of potential importance in triggering and organising convections. Figure 12(a) indicates that a basic flow \( U(y,z) \) is more symmetrically unstable along the right flank of the jet core and at low latitudes because of the smaller absolute vorticity of \( \zeta_0 \). Figure 12(b) shows the instability spectrum of the ageostrophic symmetric modes with and without cumulus heating (wave-CISK) and cumulus momentum mixing (CMM). The effects of convection significantly enhance the growth rate and also extend the instability spectrum to the larger scales. Figure 12(c) shows the distribution of spectral points for pure and parametrised symmetric modes. Convection drives the pure growing SI-mode, which should otherwise be stationary, to propagate in the directions being perpendicular to the basic flow.

At synoptic scales hydrostatic and geostrophic balances are assumed (\( \lambda = \varepsilon = 0 \)). CISK and CMM theories are applied for the typhoon and monsoon trough. The axi-symmetric typhoon
model in p-coordinates (U = 0) is adopted using Mak’s (1981) formulation for heating (Li 1983)

\[ Q = c_p \varepsilon \eta(p) \left( M_\text{r} \frac{1}{r} \frac{\partial v_\text{r}}{\partial \tau} + N_1 \frac{1}{r} \frac{\partial v_\text{r}}{\partial \tau} \right) = Q_\text{c} + Q_\text{e} \]

where \( \eta(p) \) is the heating function, and \( r \) is the radial co-ordinate, \( \varepsilon \), \( N_1 \) are coefficients, \( * \) indicates a certain reference level and \( B \) the bottom of the model. \( Q_\text{c} \) and \( Q_\text{e} \) are cumulus heating rates generated by CMM and Ekman pumping, respectively. Figure 13 shows the growth rates obtained in a 15-level model. CMM-CISK gives a scale selection between 500-1000 km. Ekman pumping alone produces more weakly growing disturbances.

A two-level slab-symmetric model with constant wind shear \( U_z \) (Mc = 0) produces a slowly propagating Ekman-CISK mode which may be related to the observed moving monsoon troughs and 30-50 day oscillation (Li 1985).

The above-mentioned mechanistic models are only able to interpret the effects of convection qualitatively. In numerical models the effects of convection are more carefully considered. Hu and Wei (1986) used a five-level primitive model developed by Zhou et al. (1987) in a limited area (91-122°E, 15-28°N, \( dx = dy = 100 \text{km} \)) to simulate the development of a low-level jet by including cumulus friction

\[ F = \frac{1}{\rho} \frac{\partial}{\partial z} \left( \text{Mc} (\nabla \cdot V) C \right) \]

in the momentum equation. The vertical mass influx is estimated by Anthes’ formulation (1977)

\[ M_c(p) = M_b \left( \frac{p}{p_b} \right)^{-RT} \frac{\mu}{\beta} \]

where \( \mu \) is entrainment rate and \( b \) denotes the cloud bottom. The time integration was started from the initial field at 0000 UTC, 24 April 1983. The difference between the predicted maximum wind speeds at the core of the low-level jet with and without cumulus friction is about 5 m/s at 700 hPa and 850 hPa. The predicted low-level jet agrees more favourably with the observations in both strength and location when the model includes cumulus momentum mixing.

Cumulus heating is also considered in numerical models for heavy rainfall prediction. Zhang and Yan (1981) compared two convective adjustment procedures and Kuo’s parametrisation. They concluded that the latent heat release is essential for the development of meso-cyclone which brought about heavy precipitations. In
operational numerical predictions in summer of 1986 and 1987 at Wuhan, the convective parametrisation procedure usually increases precipitation by 10-20 per cent and therefore has improved the heavy rainfall prediction (Zhou et al. 1987).

Free and forced mesoscale systems and their dynamics

In recent years mesoscale systems which are relevant to heavy rainfall, hailstorms and strong winds have attracted increasing attention among Chinese meteorologists. This section will deal only with those mesoscale systems which occur south of 30°N — a region more influenced by tropical systems.

Organised cloud clusters, usually accompanied by heavy rain storms, are often found in south China. Li and Wang (1986) analysed a heavy rainfall event related to a low-level jet. Figure 14(a) shows the distribution of precipitation in six hours (0200-0800 LST, 13 July 1980). Two centres of rainfall along the coast are clearly identified. The occurrence of rain storms are preceded by intensification of the southwesterly low-level jet. Figure 14(b) shows the vertical structure of winds along the core of the low-level jet at 2000 LST, 12 July, which feature three centres of strong winds. As they propagated along the low-level jet, they caused severe convective rain storms.

Sun (1979) analysed another case which shows the relationship between the pulses of precipitation and wind speed of the low-level jet (Fig. 15). The kernels of strong winds propagate along the low-level jet and are accompanied by rain storms (Fig. 15(a)). Wind speed was measured at the top of Jiu Xian mountain (in Fujian province, about 1644 m in altitude). Figure 15(b) shows a close relation between super-geostrophy of the low-level jets and the six-hourly precipitation. This observational evidence of mesoscale perturbations may be related to inertial gravity waves generated by one of many possible mechanisms such as topography, convection upstream, geostrophic adjustment of an unbalanced low-level jet, instability and nonlinear advective processes.

Zhang (1988) found that a baroclinic basic flow of small Richardson number may be unstable against ageostrophic mesoscale perturbations. The linear governing equation for a characteristic wave of complex speed c and complex amplitude W(z) is:

\[ \frac{d^2 W}{dz^2} - \frac{(fU_z + M^2)c}{(U-C)[f^2-k^2(U-C)^2]} \frac{dw}{dz} - \frac{k^2[N^2-\lambda k^2(U-C)-U_g(U-C)]}{[f^2-k^2(U-C)^2]} W = 0 \]
The growth rates are computed by a matrix method from a version of Eqn 6 in three variables \((\zeta, u, \theta)\), with upper and lower boundary conditions \(W = 0\), which is further discretised in the vertical in 20-levels, for \(Ri = 0.625, 6.25\) and 25 \((N^2 = 10^{-2} s^{-2}, 10^{-3} s^{-2} \text{ and } 4 \times 10^{-4} s^{-2})\) for a linear wind profile \(U = 0-40 \text{ m/s in } z = 0-10 \text{ km}\), respectively. Significant instability spectrum is obtained at mesoscales (Fig. 16(a)). At higher vertical resolution the Eady modes (right branch of curves in Fig. 16(a)) do not change, but the mesoscale instability (left branch) increases. The structure of a slowly propagating, growing mode is shown in Fig. 16(b), which corresponds to an isolated spectral point \(\bigcirc\) (indicated in Fig. 16(c)). Notice that there is a 'continuous' spectrum of growing, neutral and damped modes propagating at a speed between \(U\)-min and \(U\)-max. These modes may be of potential importance in interpreting those mesoscale perturbations which propagate along the jet stream.

The sea-breeze along the coast of the South China Sea may also be typical as a forced mesoscale system (Zhu et al. 1982). Figures 17(a) and (b) show the surface wind distributions at 0300 and 1700 (local time) in May 1978. The wind speed of the land breeze from the mainland to the South China Sea is about 1 m/s, while the stronger sea-breeze may reach 1.5-2.5 m/s, occasionally. Figure 17(c) shows how the rainfall is modulated by the sea-breeze in a heavy rain process occurring at Lufeng (in Guangdong province) from 28 to 31 May 1977. The precipitation intensifies periodically from midnight to morning which is in accordance with the variation of divergence forced by the sea-breeze along the coast of the South China Sea.

**Summary**

Convective activity and mesoscale systems in south China are intimately related to the tropical large-scale circulation in South-East Asia and especially to the east Asian monsoon and Indian monsoon. The southwesterly Indian monsoon brings abundant precipitation to south China in June. However, before the Indian monsoon sets in, there are earlier rainfalls in late April and early May in south China brought by the southwesterlies in South-East Asia which may be related to the sensible heating centre over Burma, Thailand and the east Tibetan plateau in April and May. The noticeable heating centres, mainly due to convective precipitation over the Bay of Bengal and South China Sea, are demonstrated by numerical simulations to be essential to the formation and maintenance of the Indian monsoon and east Asian monsoon. In particular, the active monsoon trough over the South China Sea, and the cross equatorial flows at 40°-50°E and at 105°E, are mainly forced by this convection.

Convection also significantly influences and cooperates with synoptic and mesoscale systems. Vertical transports of latent heat and vorticity by convection enhance the development of the mid-tropospheric cyclones over the South China Sea. The vertical transports of momentum and heat by convection in convectively disturbed periods over southeast China are comparable with those of squall-line cases in the GATE.
Fig. 17 The surface winds and the corresponding divergence field at (a) 0300 (local time), (b) 17 (local time) in May 1978 along the coast of the South China Sea. Full bar: 0.2 m/s, short bar: 0.1 m/s, flag: 1 m/s (unit: 10^5 s^-1), (c) time variation of precipitation at Lufeng (point *) during the period of a heavy rainfall event, 28-31 May 1977 (from Zhu et al. 1982).

experiment. Theoretical analyses show that the positive feedback of convective heating promotes the development of typhoons, the monsoon trough, low-level jets, and mesoscale rain bands through the mechanism of Symmetric Instability at synoptic and mesoscales. The ageostrophic mesoscale instability of transverse modes may serve as a mechanism to trigger and organise convective cloud clusters along the moist low-level jets which are frequently observed in the summer monsoon system.

The winter monsoon, featured by the Siberian high and cold surges, also generates tropical convection and related convective heating patterns, which then change the large-scale pattern of velocity potential in the tropics. The convection-generated flow pattern will in turn influence higher latitudes by propagation of planetary waves. In order to clarify the relation between large-scale motion and convection in the tropics, more extensive observational and numerical experiments are required in the future.

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