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THE EFFECTS OF THE QINGHAI-XIZANG PLATEAU ON THE MEAN SUMMER CIRCULATION OVER EAST ASIA

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ABSTRACT

Four numerical experiments of simulation have been conducted in this paper by the use of a five-layer primitive equation numerical model with incorporated pressure-sigma vertical coordinate system. The initial fields are taken from the July zonal mean data of many years, while the heat sources and sinks are ideally specified according to the mean heating field over the East Asia calculated from the real data of July, 1979. On the basis of simulated results of temperature and geopotential height patterns we emphatically discuss the effects of the topography and the heating of the Qinghai-Xizang Plateau. From the analyses in this paper, it appears that the heating over the Bengal region makes a larger contribution to the middle and the south branches of the monsoon cell and is also the main cause for the existence of the southerly channel to the east of the Plateau, for the break of the subtropical anticyclone belt below the 500 hPa level and for the formation of the summer Asian anticyclone at the 300 hPa level, while the heating over the Plateau makes a larger contribution to the Plateau monsoon cell and to the anticyclone at the 100 hPa.

I. INTRODUCTION

The dynamic and thermodynamic effects of the Qinghai-Xizang Plateau on the mean atmospheric circulation over East Asia have been investigated by a lot of meteorologists in recent years. More and more numerical experiments about the effects are made with the successful inclusion of large-scale topography in numerical models. Wang et al. has made some experiments about the pure dynamic effects of the Plateau by the use of a two-layer primitive equation model with incorporated p-sigma vertical coordinate system[1]. Recently Kuo and Qian have simulated the development of the July monsoon by the use of a five-layer p-sigma numerical model[2] and obtained some interesting conclusions[3].

In the FGGE period, Chinese meteorologists made surface observations of heat sources and sinks in the Plateau region and obtained many new data, by which Yao et al. calculated the monthly mean heating fields in East Asia[4]. Using the computed heating fields and a two-layer model Wang et al. conducted a few numerical simulations to discuss the thermodynamic effects of the Plateau on the East Asian circulation and got some attractive results[5,6]. However, there is certain limitation because of the low resolution of two-layer model in the vertical direction. Instead we use the five-layer model[2] to make some numerical experiments, taking the many-year averaged July mean zonal fields of meteorological elements as initial inputs and the July mean heating field of 1979 over East Asia as the ideal model diabatic heating forcing. Based on the simulated results we have discussed the effects of the orography and the orographically induced heating of the Plateau on the East Asian mean circulation in July. Especially we have analysed the relative importances of the Plateau heat source and the Bengal heat source to the formation of the circulation properties over these regions.

II. INITIAL FIELDS, HEATING DISTRIBUTION AND DESIGN OF THE NUMERICAL EXPERIMENTS

1. *The Design of the Initial Data and the Ideal Heating Distribution*

The initial data used in the model are zonal mean data of July including the geopotential height fields at the 100 hPa, 300 hPa, 500 hPa and 700 hPa levels and the pressure field at the sea-level surface. The basic data are taken from the climatic mean values on the 5°×5° grid network system prepared by NCAR and reprocessed according to the model domain to get the corresponding zonal mean initial data in that area. By means of those zonal initial data at isobaric levels and the initialization program of the model, all initial values needed in the model can be determined. Fig. 1 shows the initial distributions with latitudes of the geopotential height, the temperature and the wind fields at the 100 hPa, 300 hPa and 500 hPa levels, respectively, after initialization. It is seen from the figure

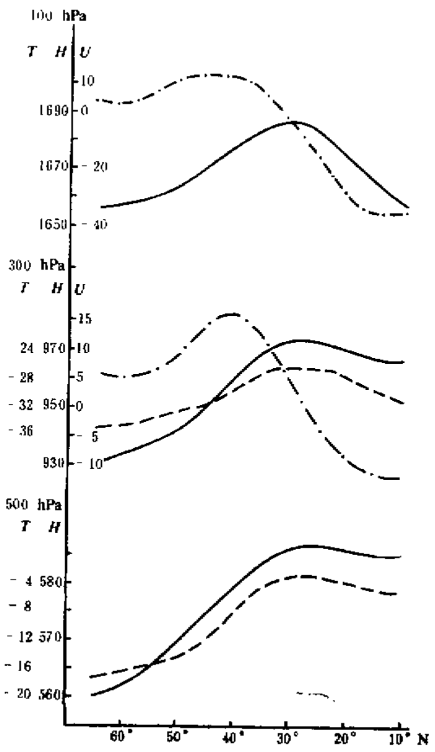


Fig. 1. Meridional profiles of geopotential height in decameter (full lines), temperature in °C (dashed lines), and wind fields in m s⁻¹ (dot dash lines), at 100 hPa, 300 hPa and 500 hPa.

that the jet stream at the 300 hPa level is located about 40°N and the maximum speed is 16 m/s.

The ideal heating field used in the model is taken from Yao et al.[4] and smoothed again. Fig. 2 shows the distribution of the heat sources and sinks in July, 1979. The vertical distribution of the heating or the cooling rates is assumed to follow the regulations: (1) cooling rate is uniform at the lower and the upper layers; (2) latent heating is mainly distributed at the layer near 300 hPa level; and (3) sensitive heating is limited to the low layers near surface.

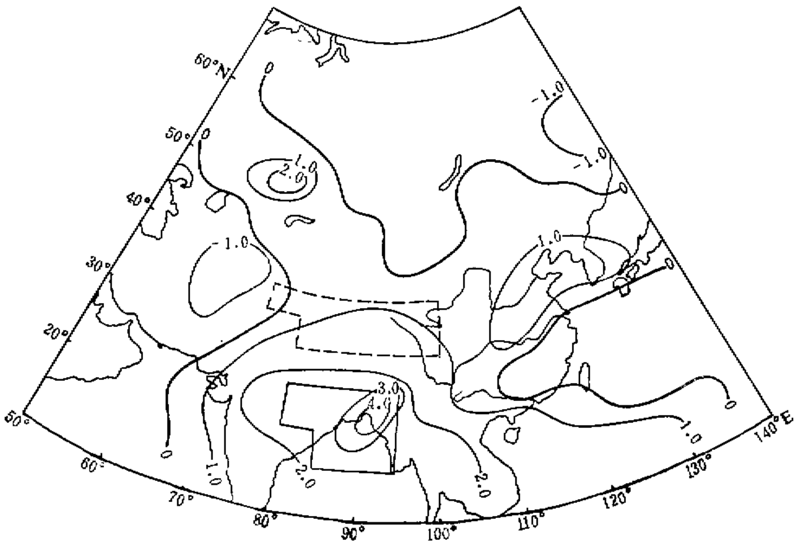


Fig. 2. Idealized heating field in July, 1979 in °C day⁻¹ (full line area: Bengal region; dashed line area: the Plateau).

2. *The Design of Numerical Experiments*

All numerical experiments we have made are time-integrated up to 5 days with a time step of 15 min and with 5° × 5° grid network system. The experimental domain covers the region of 40°—150°E, 10°—65°N. The variables at the north and the south boundaries are treated as fixed and those at the east and the west boundaries as periodic. The topography used in the model is shown in Fig. 3. It is seen from the figure that the average height over most area of the Qinghai-Xizang Plateau is above 3000 m and the maximum is 5000 m, which is close to the real topography in East Asia.

In order to compare the dynamic effect with the thermodynamic effect of the Plateau, two schemes of numerical experiments are designed. The first is called the HN scheme which only includes the topographic factor and no diabatic heating. The second is called the HH scheme which includes both topography and heating. In the second scheme two sub-experimental schemes are designed, one is called the PN subscheme and the other the MN subscheme. The so-called PN subscheme has diabatic heating rate of zero at all points in the area enclosed by the dashed lines in Fig. 2 and the MN subscheme has zero heating rate in the area enclosed by the full lines in the same figure.

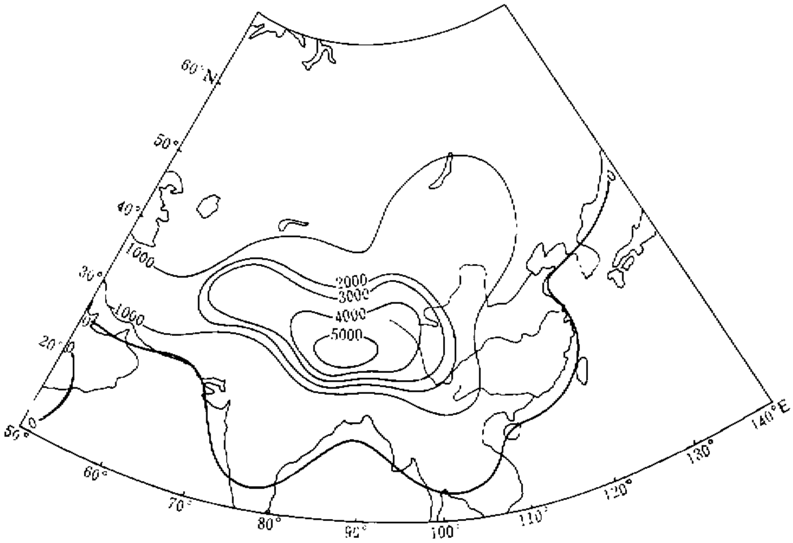


Fig. 3. Smoothed topography used in the model (unit: m).

Therefore, altogether we have four numerical experiments which are called the HN, the HH, the PN and the MN schemes. Comparing the results of these four experiments with the climatic atlas of the July mean we discuss some interesting results in detail below.

III. DISCUSSION OF THE EXPERIMENTAL RESULTS

1. *Temperature and Geopotential Height Fields*

(1) *Comparison between the dynamic and the heating effects of the Plateau*

The comparison between experimental results of the HH and HN schemes at 100 hPa (Fig. 4), 500 hPa (Fig. 5) and 700 hPa (figure omitted) indicates four basic facts. (a) The disturbances resulting from the dynamic effect of the Plateau in the temperature and the geopotential height fields have a typical flowing-round pattern in the low and the middle troposphere, such as the weak ridge to the north and the shallow trough to the south of the Plateau at the 500 hPa and 700 hPa levels. (b) The effect of the East Asian heat source results in the Qinghai-Xizang anticyclone at the 100 hPa level with the core at 85°E, 35°N, and the height of 1684 decameters and the corresponding so-called south Asian high at the 300 hPa level. The heating effect also makes the troughs to the south of the Plateau at the 500 hPa and 700 hPa levels deepen apparently with a matching warm centre of −4°C at the 500 hPa level. A weak high pressure belt exists near 35°N at the 700 hPa

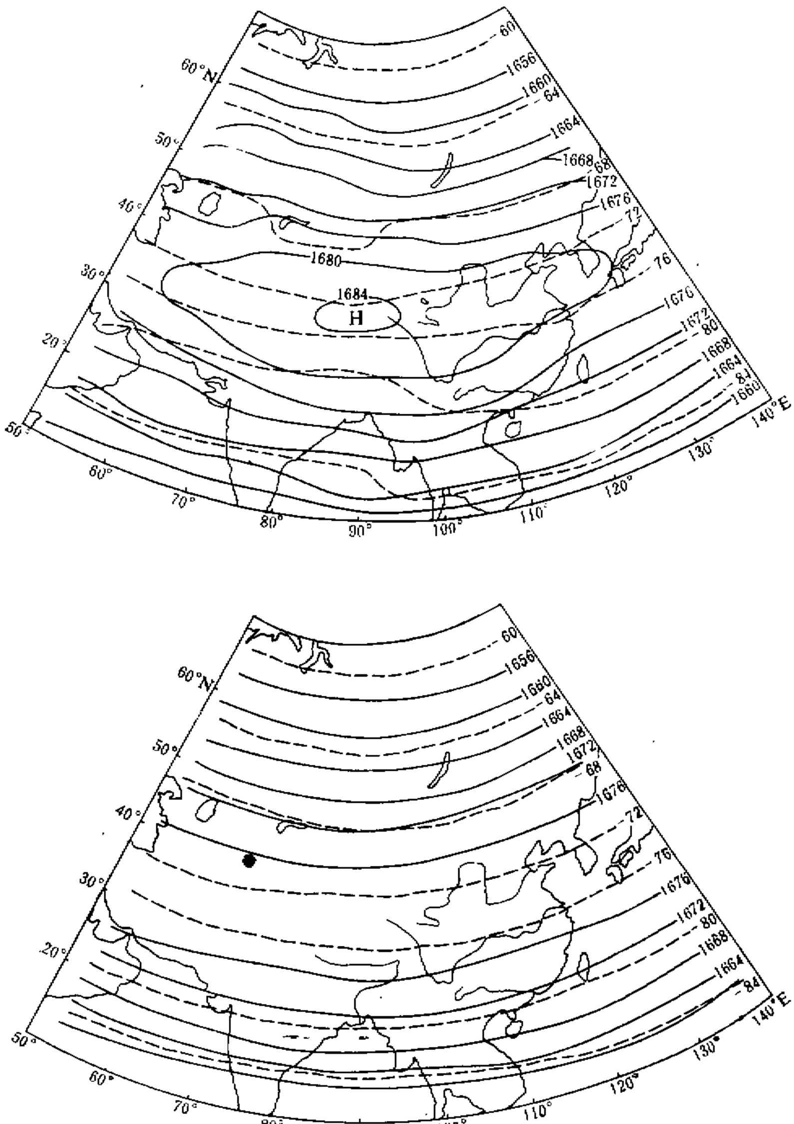
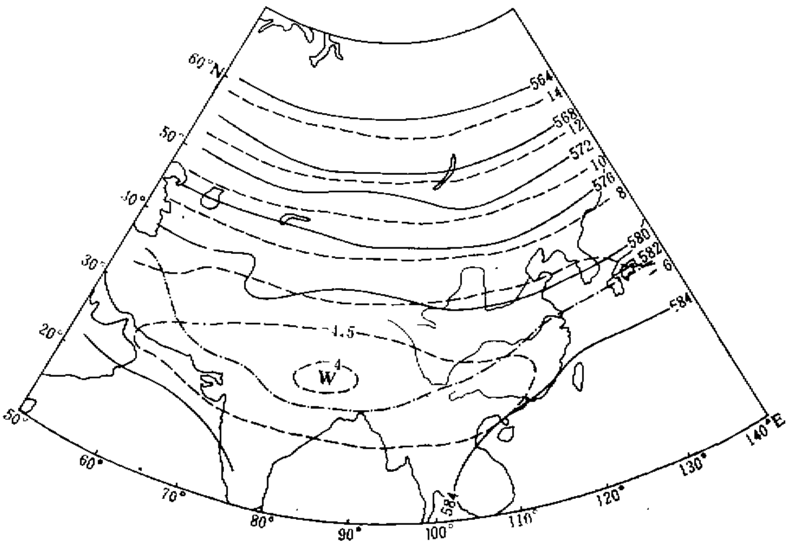


Fig. 4. 5-day 100 hPa HH(a,top) and HN(b,bottom) geopotential height ($\Delta Z=40$ m) and temperature ($\Delta t=4°C$).

level. All these features are very resemble to the real climatic ones[2]. (c) The pure dynamic effect of the Plateau does not result in the break of the subtropical high belts at both the 500 hPa and 700 hPa levels while heating effect does. (d) The locations of the troughs and ridges, north of 30°N at the 300 hPa level and north of 40°N at the 500 hPa level, are



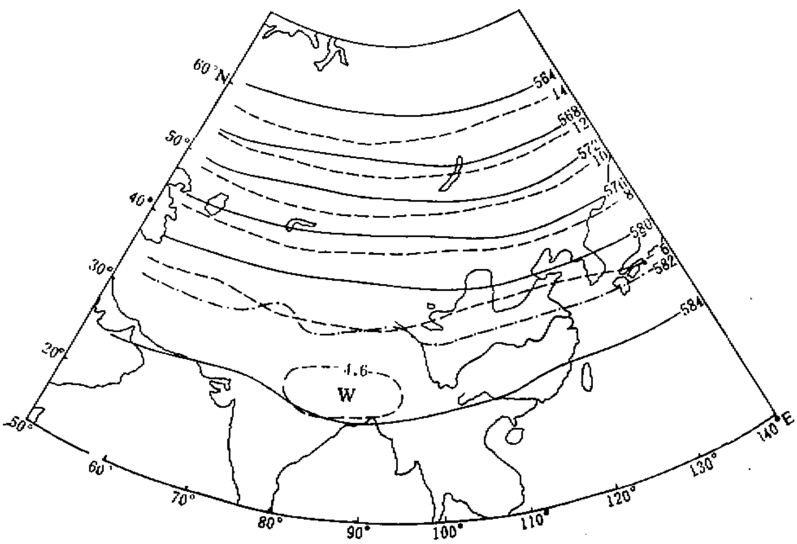


Fig. 5. As in Fig. 4. except for 500 hPa

very similar in both HH and HN experiments, the only difference being the intensity. It indicates that the pure dynamic effect of the topography over East Asia produces an important impact on the formations of the mean ridges and troughs while the heating effect makes large contributions to their intensities.

(2) *The comparison between heating effects over the Bengal and the Plateau areas*

From the above discussion we find that either the formations of the anticyclones at the 100 hPa and 300 hPa levels or the deepening of the troughs over and to the south of the Plateau are all related to the heating sources in East Asia. However, the relative importances of the heat sources over the Plateau and the Bengal areas are still in lack of knowledge. Here we discuss this.

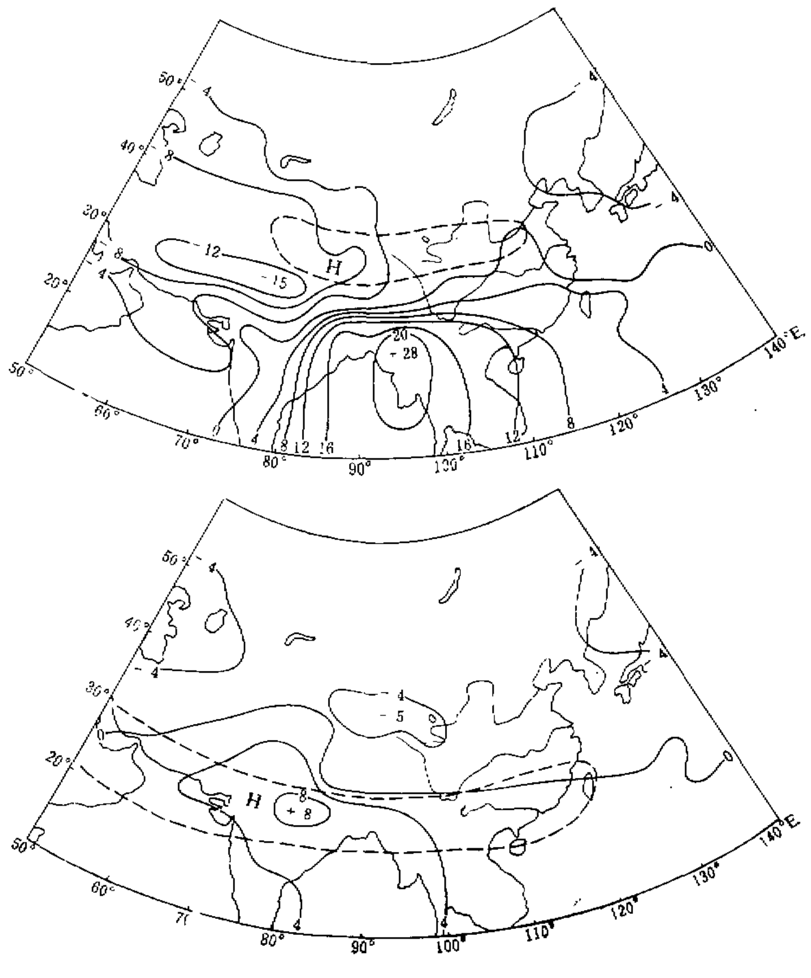


Fig. 6. 100 hPa (a,top) and 300 hPa (b,bottom) ΔH_{PN-MN} distribution (unit: dkm).

As shown in Fig. 6, ΔH_{PN-MN} are the distributions of geopotential height differences between the PN and MN schemes at the 100 hPa and 300 hPa levels. It is seen that the Plateau heat source is of greater importance to the 100 hPa anticyclone while the Bengal heat source makes more contribution to the 300 hPa anticyclone. Another interesting fact is that the 100 hPa anticyclone comes to appear near 35°N at the interface line between the easterlies and the westerlies at the 100 hPa level, for the 300 hPa anticyclone it is also true at the 300 hPa level near 25°N. The latitudes of the interface lines and the heat source centers overlap either over the Plateau or over the Bengal region. Therefore the suitable background circulation is the necessary condition for anticyclonic genesis while the heating effect is a trigger mechanism. Similar analyses of ΔH_{PN-MN} at the 500 hPa level show that the PN scheme has a greater influence on the monsoon trough than the MN one, and that the break of the subtropical high belt is induced by the Bengal heat source.

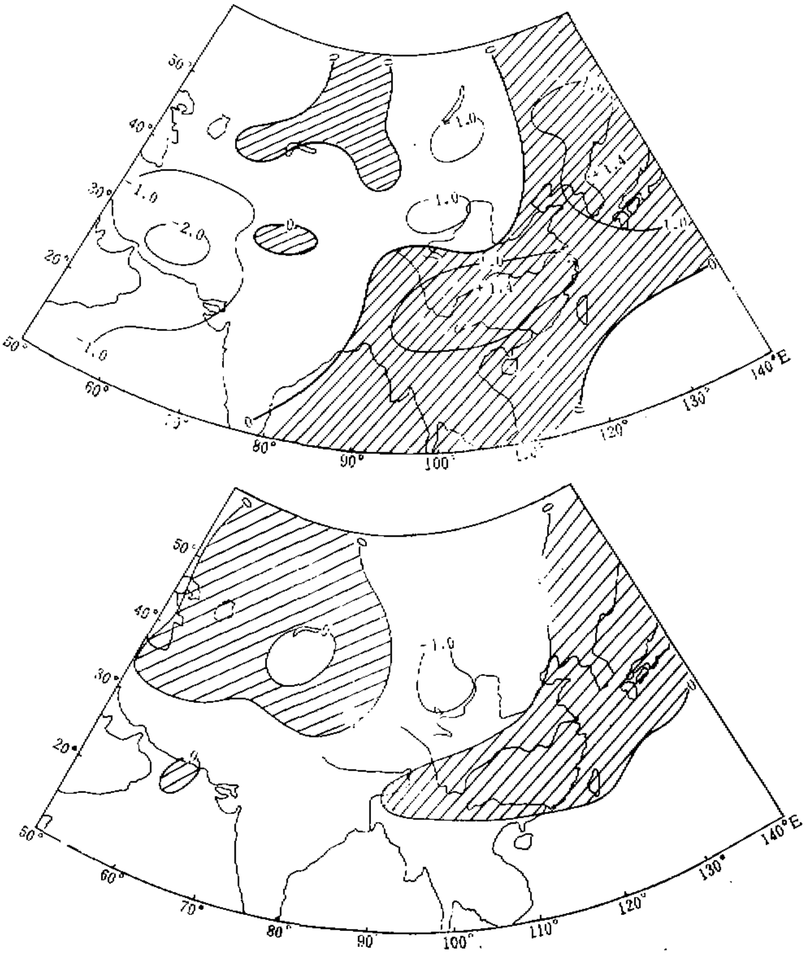


Fig. 7. HH(a,top) and HN(b,bottom) v-component at p_r* surface (unit:m/s).

2. *Flow Fields*

In this part the horizontal flow fields at the 100 hPa, 300 hPa levels and at p^*_3 ($\sigma=0.25$), p^*_7($\sigma=0.75$) and p^*_s ($\sigma_B=0.5$) surfaces and the vertical circulations along longitudinal and meridional circles over East Asia are discussed in detail.

(1) *The comparison between the dynamic and the thermodynamic effects of the Plateau*

i) Horizontal flow patterns

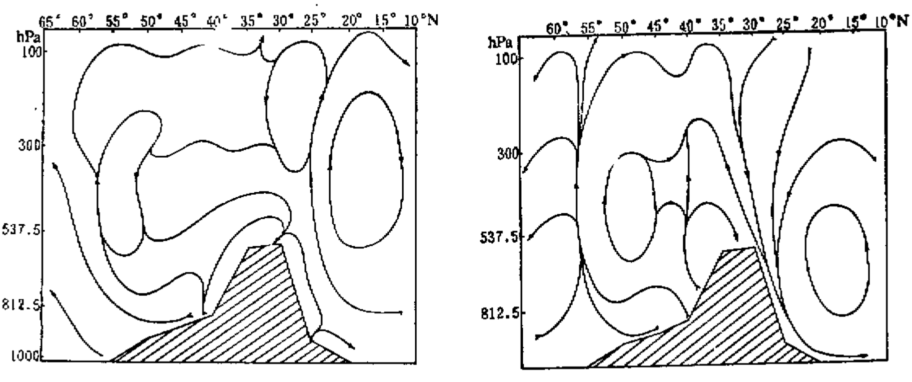
The southerly components over the areas south and east to the Plateau coming from the Bay of Bengal and the South China Sea form an important water vapor channel there and result in the precipitation in East China and the Plateau.

It is easy to find from the v-component diagrams at the p^*_s and the lower surfaces that the horizontal convergent flow patterns over the area east to the Plateau are well simulated both in the HH and the HN experiments at 90°—115°E along 30°N, but the southerlies in the two schemes are very different from each other. Fig. 7a and 7b give the results of the two schemes at p^*_7 surface. It is evident that the intensities of the southerlies are very different. Besides, the southerlies in the HN scheme are formed by the flowing-round flows at the east wing of the Plateau, having no relations to the oceans, while those in the HH scheme dominate over the area from the Bay of Bengal to the South China Sea, with an extension up to 35°N and form a very strong southerly channel connected with the oceans.

From above we may conclude that the strengthening and northward extension of the southerlies over the southeast part of the Plateau and over East China are greatly affected by the heating fields.

ii) Meridional circulations

We assume that the meridional circulation profile along 90°E be representative for the Plateau area. Fig. 8a and 8b show those profiles in the HH and the HN schemes, respectively.



(a) (b)

Fig. 8. The meridional vertical circulations along 90°E based on HH scheme (a) and HN scheme (b).
(The vertical velocity is magnified by 400 times)

We can see from the profiles that a remarkable difference exists at the low latitudes. In the HN scheme there is a Hadley cell with the maximum downward motion at the south slope of the Plateau and subsidence predominates over the Plateau. To the contrary, in the HH scheme there is a well-developed monsoon cell south of 25°N with the maximum upward

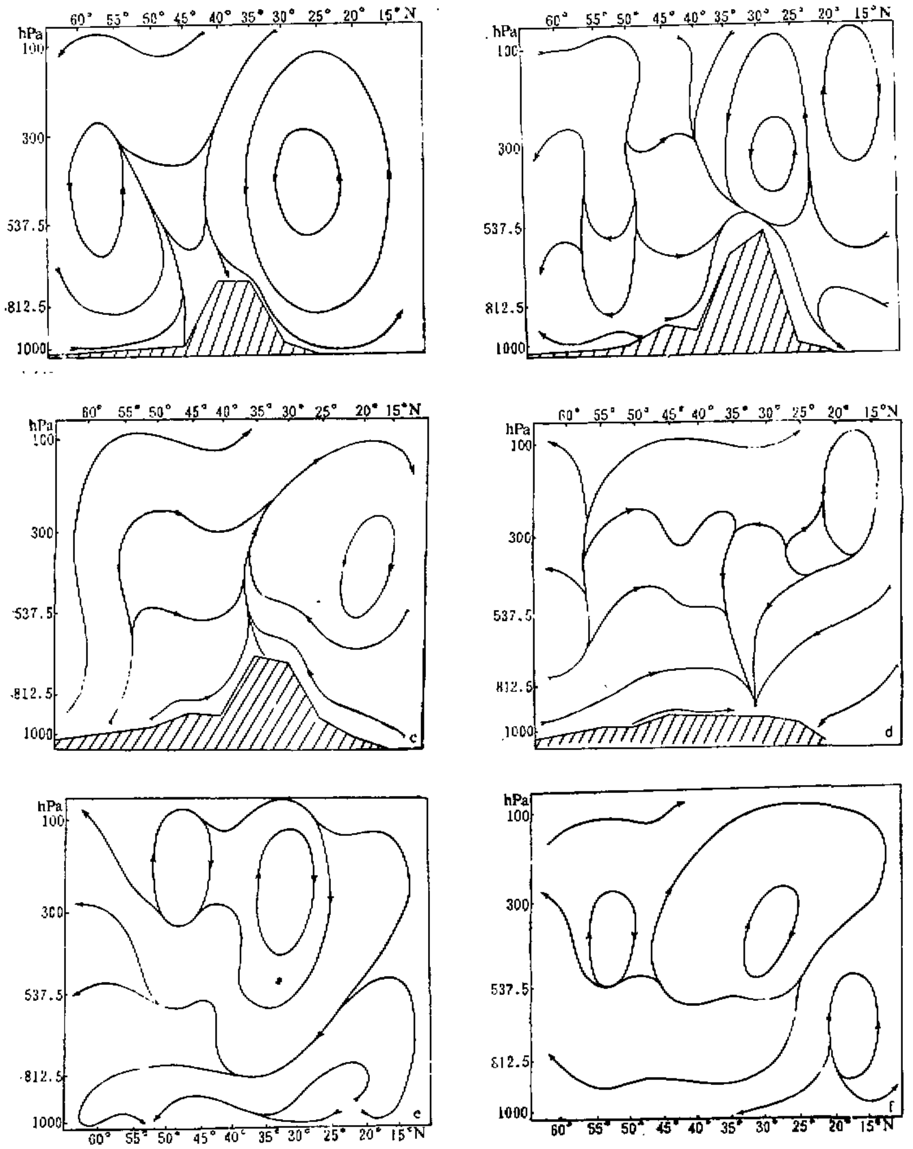


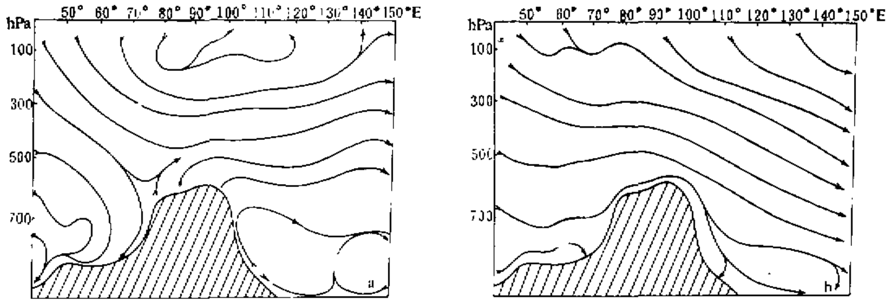
Fig. 9. The meridional vertical circulations along 70° E (a, top left), 85° E(b, top right), 100° E(c) 105° E(d), 120° E(e), 130° E(f). (The vertical velocity is magnified by 400 times)

motion at 20°—25°N. A more detailed analysis indicates that below the 300 hPa level over the Plateau there are a branch of upward motion near 40°—35°N and a weak subsidence at about 30°N, forming a small monsoon cell, which is defined as the Plateau monsoon cell. It is separated from the strong monsoon circulation to the south of the cell by the subsidence at 30°N. This Plateau monsoon cell, of course, remains to be further verified with much smaller grid systems.

The monsoon circulations are the main features of the summer atmospheric circulations over the East Asian monsoon region and, therefore, we discuss them in detail. In order to do this we draw a meridional vertical profile every 5° from 40°E to 150°E. From these profiles we have found quite a few interesting phenomena. Here we only show some representative and typical profiles of the HH scheme with the consideration of saving spaces. Figs. 9a—9f are the meridional profiles from the HH scheme along 70°E, 85°E, 100°E, 105°E, 120°E and 130°E, respectively. Three interface lines separating different climatic regions from one another are in existence at the low and the middle latitudes in our experimental domain. One of the three lines is along 80°E, to the west of which there is a Hadley cell dominating which extends from the west to the east and the north with the maximum intensity at 70°E and shrinks gradually to the east. The monsoon cell initially occurs at the 10 km aloft near 80°E and extends downward from the west to the east, occupying the whole troposphere at 90°E. The second separating line is along 90°E and between 80°—90°E there is a weak Plateau monsoon cell apart from the Indian monsoon cell to its south on the south of the Plateau. At 95°E the two monsoon cells merge into a strong monsoon circulation with the maximum intensity at 100°E and upward motion extending to 40°N. The third line is along 105°E and is also the separating one between the India-Plateau monsoon cell and the subtropical monsoon cell. At 105°E the monsoon cell decreases and shrinks suddenly, and a new monsoon cell which is defined as subtropical monsoon cell appears at 110°N and is very much alike to that obtained by Yin et al. from the real data. The subtropical monsoon cell does not occupy the whole troposphere as the India-Plateau cell does, only appearing aloft. Its rising branch is located at about 35°N to the north of the subtropical high and its descending branch connects into the Pacific subtropical high at the 500 hPa level. Below the monsoon cell there is an ill-developed Hadley cell which is not completely simulated because of the limitation of the model domain. A further study of the cell needs new experiments with larger model domain. No monsoon cells appear at low latitudes in the HN scheme and a Hadley cell dominates all along. The above discussion tells the truth that the vertical monsoon cells and their spatial variations are evidently related to heat sources.

(iii) Longitudinal circulations

Figs. 10a and 10b are the vertical profiles along 35°N of the HH and the HN schemes respectively. It can be seen that the two schemes get very different simulations. The heating effect results in stationary descending motion in the west of the Plateau and maintains the Iranian high there evidently. There is a constant upward draft east of 80°E over the Plateau, the lower part of the draft exists on the east of the Plateau with a compensative downward draft in the Pacific subtropical high, while the upper part of the upward draft keeps rising after flowing over the Plateau with a compensative downward branch at a remote area. The above characteristics are similar to those obtained by Yeh et al[4]. The exact location of downward motion is unknown in our experiment because of the model



(a) (b)

Fig. 10. The longitudinal vertical circulations along 35°N from the HH scheme (a) and HN scheme (b).
(The vertical velocity is magnified by 700 times)

boundaries. All the above-mentioned motions are related to the heating effect because the HN scheme does not show such properties.

(2) *Comparison of the heating effect over the Bengal region with that over the Plateau*

From the vertical profiles of the v components in the PN and the MN schemes below the p_s^* surface along 95°E and 110°E (not shown) we can see that either the intensity or the area of the southerlies is higher or wider in the HN scheme. It proves that the heating over the Bay of Bengal makes more contribution to the south-west monsoon than that over the Plateau.

However, a comparison of meridional profiles every 5° in the PN scheme with those in the MN scheme shows that they are very similar to the west of 75°E and to the east of 110°E and that the main differences are in existence between 80°—105°E. Although a monsoon cell exists at 80°E in the PN scheme, small Plateau monsoon cell is unable to develop because of lack of heating over the Plateau. Its upward branch can only reach 30°N as the northernmost latitude and is not as much strong as that in the HH scheme. The 90°E separating line of climatology disappears. Although a weak Plateau monsoon cell appears between 90°—100°E over the Plateau region in the MN scheme, a Hadley cell stationarily dominates over the south Plateau from 80°E to 105°E and the subtropical monsoon cell does not appear until 110°E. The above discussion indicates that the monsoon cell to the south of the Plateau in the whole troposphere is mainly controlled by the heating over Bengal and the Plateau monsoon cell by the heating over the Plateau.

The longitudinal vertical circulations along 35°N in the PN and the MN schemes have no substantial differences from those in the HH scheme. In fact, they are completely similar in the west of the Plateau. Slight differences among them exist over the Plateau and its east part. Because of zero heating rate over the Plateau in the PN experiment upward drafts over this area are reduced significantly, however, the two upward drafts to the east of the Plateau are both stronger than in the MN experiment. Therefore they are mainly controlled by the heat source over the Bengal region.

Fig. 11 shows the vertical circulation along 25°N. It is found that the Bengal heat source not only results in the rising motion over this region, but also strengthens the descending motion over west India. Therefore the heating effect over Bengal enhances transport of water vapor in its east part and contributes to the formation of downward draft over the dry area in west India.

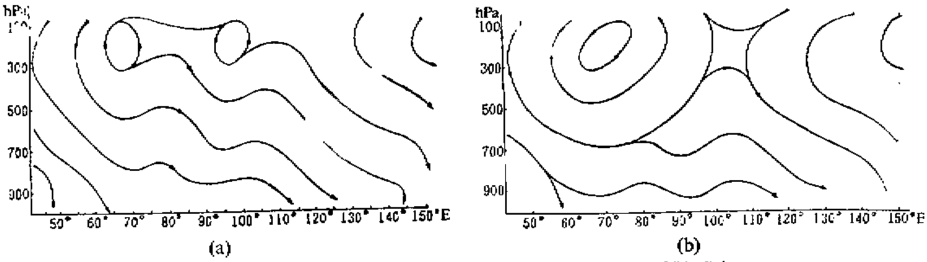


Fig. 11. As in 10 a,b except for 25°N and MN(a), PN(b) Schemes.

IV. CONCLUSIONS

From the discussion in the previous section we have obtained the following conclusions.

(1) The pure dynamic effect of topograph in East Asia results in weak disturbances in the form of flowing-round patterns at the low and mid troposphere and the disturbances are more evident north of 40°N than in the low latitudes and decrease upward. The strong anticyclone with warm core in the upper troposphere and the lower stratosphere, the break of subtropical high belt at the 500 hPa level and the monsoon trough are all attributed to the heat field over East Asia.

(2) The formation of the Qinghai-Xizang High at the 100 hPa level is mainly affected by the Plateau heat source while by the Bengal heat source at the 300 hPa level. The break of subtropical high belt below the 500 hPa level, the formation of monsoon trough to the south of the Plateau are mainly controlled by the Bengal heat source.

(3) Many key properties of the summer monsoon circulations can not be simulated in the experiment only with pure dynamic effect. The pure dynamic effect can produce the convergent line located at the middle part of the Plateau and to its east, but the southerlies in the south of the line are not connected with oceans. After heating effect is taken into consideration, the southerlies are then connected with oceans and form a very strong channel. Besides, the pure dynamic effect can only simulate the Hadley cells in the low latitudes from 55°E to 145°E, the special monsoon cells exist only when heating effect is taken into consideration. They appear from 80°E to the east boundary of the model and can be divided into two groups by the meridian at 105°E. The west group consists of the India-Plateau monsoon cells while the east one of subtropical monsoon cells. The former occupies the whole troposphere south of 35°N and reaches the maximum intensity at 100°E, the latter exists in the mid and upper troposphere with the centre drifted to north.

(4) The heating effect over the Bengal region on flow patterns is obviously different from that over the Plateau. The formations of some monsoon circulation systems in the low latitudes, such as the southerly channel, the monsoon cell in the south of the Plateau and the two upward drafts to the east of the Plateau at 35°N are all mainly controlled by the Bengal heat source, while the Plateau monsoon is controlled mainly by the Plateau heat source. The Bengal heat source also makes contribution to the downward motion over the droughty area of west India at 25°N.

The interaction mechanism among the east-Asian topography, the heating fields and the background circulations is very complicated. Our experiments can not completely reveal the mechanism, however, even such simple experiments we made have obtained quite a lot of inspirations about the dynamic and the heating effects over the east Asian area.

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