A NUMERICAL STUDY ON THE MEDIUM–RANGE RESPONSES OF THE ATMOSPHERE TO THE ABNORMAL SOIL MOISTURE*

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ABSTRACT

By employing the improved T42L9 spectral model introduced by NMC (Beijing) from ECMWF and utilizing the FGGE–IIIb data covering the period of 14—19 June 1979, the atmospheric responses to the abnormal soil moisture during the medium–range period have been studied numerically. According to the initial field at 12 GMT 14 June, a five– day numerical experiment under different conditions of the soil moisture has been carried out respectively. The monthly mean climatological soil moisture for June has been used in the control experiment in the initial time and it changes with time according to the moisture budget equation at the land surface. Comparing with the experiments with dry or wet soil, one can conclude that: 1) Source of precipitation over continents in summer consists of the land–surface evaporation and the moisture transfer from oceans. Their intensities are comparable during the medium–range time scale when the soil evaporates its moisture sufficiently. Therefore, the soil moisture can influence the global precipitation and the general circulation significantly; 2) By influencing the thermodynamic difference between land and sea,the soil moisture can change the intensity of monsoon and precipitation distribution; 3) The response of the atmosphere to the abnormal soil moisture has the characteristics of geographical distribution and nonlinear interactions; 4) Human activities on the world can influence the environment greatly.

Key words: soil moisture, surface evaporation, atmospheric response, precipitation, monsoon

I. INTRODUCTION

The observational studies (Rasmussen, 1968; Benton et al., 1953) showed that the convective precipitation draws all of its moisture from the water vapour in the planetary boundary layer in the tropics and in the summer subtropics over North America, and the amount of the water vapour supplied to the boundary layer by surface evapotranspiration is an order of magnitude larger than that supplied by the water vapour transport convergence. This suggests that the surface evapotranspiration is the main determinant of the precipitation in summer over the land.

The surface evapotranspiration consists of two parts, the surface evaporation and the transpiration of plants. The soil moisture is one of the determinants of the land–surface evaporation. The surface evaporation will be lower when the soil becomes drier. Thus, the climatic anomaly (i.e. long–range drought or raining) may cause the abnormal soil moisture. The characteristic time scale at which the moisture of the saturated soil decreases to the critical value by evaporation is 5 to 10 days, and it will be longer if the precipitation is considered. Also, the

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dry–soil can keep dry through evaporation even if it has only intermittent rain.

Plants can capture precipitation during its falling from the air to the ground, then make the water return to the atmosphere from leaves by evaporation rapidly, and enhance the evapotranspiration because of their transpiration. Further, their root systems can bring the water from the deep soil layer to the surface layer and reduce the amount of runoff so that the soil moisture increases. Therefore, the variation of the soil moisture caused by the natural reason or the activity of human beings (i.e. large–scale damage of the vegetation, extensive irrigation or plantation) may influence the weather and climate significantly.

Numerical experiments show that the soil moisture can influence the long–range changes of the general circulation and the climate significantly. For example, Shukla and Mintz (1982) using the GCM of the GLAS ,Walker and Rowntree (1977) using the 11–level limited area model of the British Meteorological Office and Manabe (1975) using the GCM of the GFDL concluded that the atmosphere is sensitive to the soil moisture during the long–range period. However, few people pay attention to the medium–range atmospheric responses to the soil moisture. It is important to know whether the surface processes can influence the medium–range weather processes and their intensities for considering correctly the effects of the land–surface processes on the atmosphere and improving the accuracy of the medium–range weather prediction. Gadd and Keers (1970) found that even in the 18–h prediction for the north–western Europe and the British Isles in August, the results of the evaporation and sensible heat transfer from land and sea surfaces made a noticeable improvement in the predicted rainfall over the land. Utilizing the GFDL model, Miyakoda and Strickler (1981) found that it does not require an extreme change in the soil moisture, in order to produce large changes in the precipitation and circulation field. and that the influence of the land–surface evapotranspiration operates very quickly. In other report, Miyakoda pointed out that sizeable differences in the surface temperature and precipitation appeared with a few days after the supply of the soil moisture change. However, the detailed explanation has not been found.

This paper aims to study the medium–range responses of the atmosphere to the abnormal soil moisture using a GCM.

II. BRIEF DESCRIPTION OF THE T42L9 MODEL

The model used in this paper is the quasi–operational medium–range weather predictional model of the NMC (Beijing) introduced from the ECMWF (hereafter refers to as T42L9 model). The T42L9 model consists of nine levels vertically in the σ–coordinate system. The variables in the horizontal direction are truncated in triangle at wavenumber 42. The semi–implicit scheme is used in time integration. The timestep is 30 minutes. The prediction region is the Northern Hemisphere. One can refer to the technology report written by Baede et al. (1977) for the basic equations of the model and the methods in computation.

The physical processes in the model originate from the GCM of the GFDL, including the turbulent fluxes in the boundary layer, vertical diffusions due to the sub–grid effects, large–scale condensation, convection adjustments and radiation. The convection adjustments consists of dry adiabatic adjustment and moist convection adjustment. The solar radiation at the top of the atmosphere is constant during integration. Absorbing gases in the atmosphere, such as carbon dioxide and ozone, have constant concentrations. Clouds in the model have three kinds, high–, middle– and low–level clouds. The amount of clouds can be calculated by diagnosing the predicted water vapour field according to the method devised by Zheng (1989) in the seven–level global spectral model. In the present model, the surface temperature is calculated from the heat budget equation at the surface, and the sea surface temperature (SST) is replaced by monthly climatological normal. The surface albedo is different between land and seas, so is it between snow–covered and no–snow–covered lands. The depth of snow is also taken as monthly climatological normal. After smoothing, the real orographic height is used. The maximum height of the Qinghai–Xizang Plateau is 5600 m.

An important advance of the T42L9 model made by us is that the climatological water vapour and cloudiness in radiation computation are replaced by the predicted water vapour and the diagnostical cloudiness. This can improve evidently the ability of the model for medium–range prediction. With this method, the T42L9 model has been employed in the numerical study of the dynamic and thermodynamic effects of the Qinghai–Xizang Plateau successfully (Yan and Zheng, 1991).

III. EXPERIMENT RESULTS AND DISCUSSION

1. *Experiment Scheme*

(1) *The initial field of the model*

In this paper, the weather processes during the onset period of the eastern Asian summer monsoon in 1979 are studied. So we used the FGGE–IIIb four–dimension assimulational data at the σ surface and Gauss grid points covering the period of 14—19 June 1979. According to the initial field of 12 GMT 14 June, 5–day numerical prediction experiments were carried out respectively.

(2) *Control experiment*

The control experiment (hereafter refers to as CON) included all the physical processes in the model. The initial soil moisture distribution was taken as monthly climatological normal. Because of the higher ability of the T42L9 model for medium–range weather prediction, the weather processes during the onset period of the summer monsoon in the eastern Asia, and the circulation and precipitation distribution could be simulated successfully (Yan and Zheng, 1991).

In CON, the rate of the surface evaporation is given by the following formula:

$$\beta = \begin{cases} 1, & (\text{sea or snow}-\text{covered land}) \\ 1, & (\text{no}-\text{snow}-\text{covered land, and } W \geqslant W_c) \\ W/W_c, & (\text{no}-\text{snow}-\text{covered land, and } W \leqslant W_c) \end{cases} \quad (1)$$

where W is the soil moisture at the surface, and W_c is the critical soil moisture:

$$W_c = kW_s, \quad (2)$$

where W_s is the maximum moisture storage capacity of the soil, and can be replaced by constant in the model, i.e. $W_c = 15$ cm, k is taken as 0.75.

The soil moisture at the surface is governed by the moisture budget equation:

$$\frac{dW}{dt} = P - \beta E, \quad (3)$$

where P is the rate of precipitation, and E is the rate of the potential evaporation.

(3) *Dry– and wet–soil experiments*

In order to study the influences of the soil, a numerical experiment with consideration of the following two conditions were carried out respectively. One was the dry–soil experiment (hereafter refers to as DRY) in which the rate of the surface evaporation was zero. The other was the wet–soil experiment (hereafter refers to as WET) in which the soil moisture was saturated everywhere and the rate of the surface evaporation was not altered by the supply of the soil moisture, or β was 1 everywhere in the land.

2. *Experiment Results*

due to limited space, only the results for 72 hours are given in the diagrams.

(1) *Precipitation and surface evaporation*

The curves of the precipitation and the surface evaporation averaged over the land for the three experiments are given in Fig.1 against time, showing that the precipitation over the land increases during the whole integration period because it was the onset period of the eastern Asian summer monsoon and thus the large–scale precipitation appeared in India and eastern China. In all the experiments, the water vapour transport convergence exists and increases steadily. Therefore, the precipitation increases constantly not only in DRY but also in WET, as well as in CON. The precipitation exceeds the evaporation over the land significantly in all the experiments. This is partly because that the predicted precipitation in the model is larger than the observational.The difference of precipitation between different experiments is related to the evaporation evidently. Fig.1 suggests that the influence on the precipitation will be significant if the evaporation of the soil becomes larger, and its intensity has equally important contribution in the order of magnitude compared with the water vapour transport convergence from the sea during the medium–range period.

Fig.2 shows the geographic distribution of the surface evaporation. It can be found that the higher evaporation regions are mostly on the sea, among which the intensive evaporation in the Bay of Bangal and the western Pacific is the important source of moisture for the monsoon rain in India and eastern China. The difference between WET (or DRY) and CON is given in Fig.2b

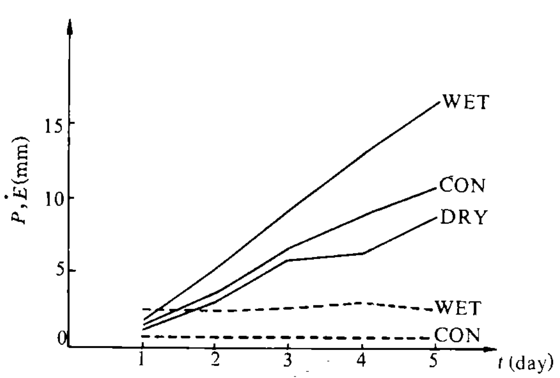

Fig.1. Precipitation (P) and evaporation (E) averaged over the land.

------evaporation,—— precipitation.

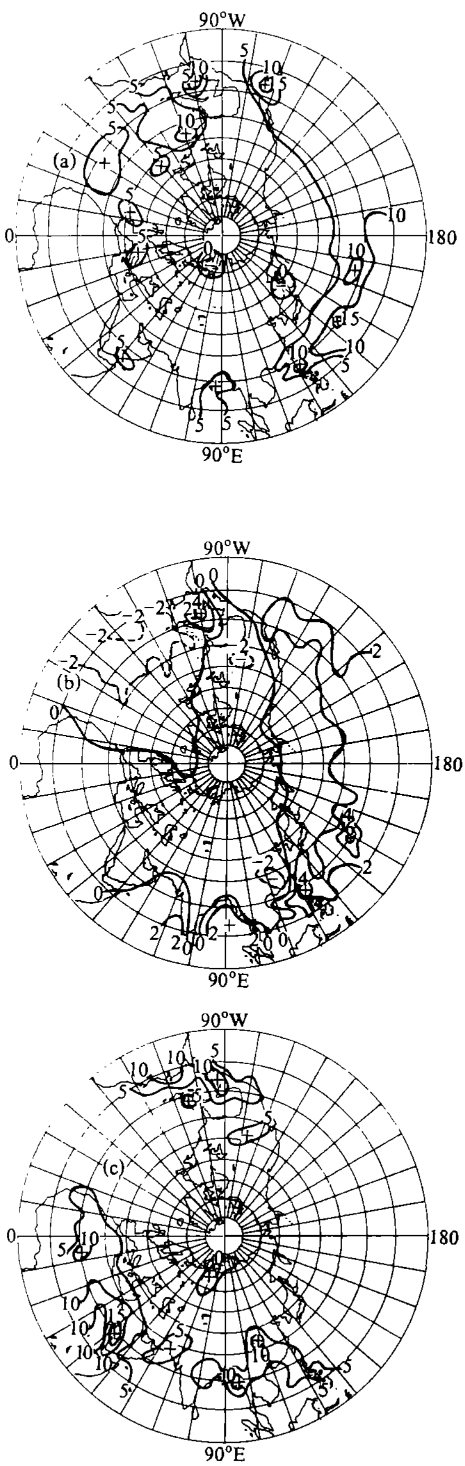

Fig. 2. Surface evaporation for 3rd day: (a) CON;(b) DRY–CON; (c) WET–CON (unit: mm / d).

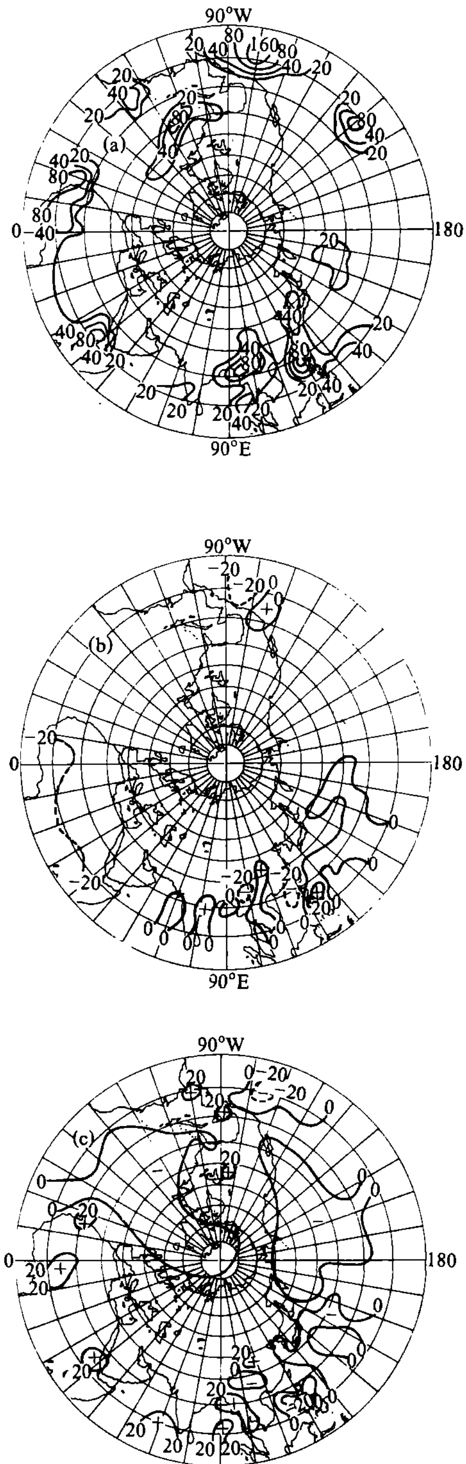

Fig. 3. As in Fig.2, but for precipitation.

(or 2c). In DRY, the evaporation is less than that in CON over almost the land, especially over westsouthern and southern China and over the south of North America. However, the sea–surface evaporation in the Bay of Bangal, the South China Sea, the western Pacific and the Caribbean Sea is larger obviously. This is because the wind speed in the surface layer of the atmosphere over the above–mentioned areas raises significantly (figure omitted). In WET, the evaporation increases over all of the land, and there are several maxima centered over the southeast of Eurasia, the centre of northern Africa, the south of North America and the central America.

The predicted precipitation distribution in CON (Fig.3a) shows that the main rain regions are located over the area from the Indochina Peninsula to the south of the Qinghai–Xizang Plateau and over the coastal and equatorial area of Africa. The intensive rain belt over the south periphery of the Qinghai–Xizang Plateau is contributed by the onset of the summer monsoon. In DRY (Fig.3b), the precipitation decreases over almost Eurasia and North America with the averaged amount over the land of 0.8 mm / d , especially over the equatorial area of Africa. The detailed analysis shows that the change of precipitation is close to zero over the inner Africa. This is because that there is arid region and it can hardly rain. However, there are some areas over which precipitation increases in southern Asia, the Indochina Peninsula , the east of the Qinghai–Xizang Plateau, and the coastal area of Mexico. This suggests that the monsoon rain can increase over certain coastal area of monsoon region when the soil is drier. In WET (Fig.3c), the precipitation increases over all the land. The positive centres are in the Indochina Peninsula, the centre of North America and the Central America. The amount of the increase averaged over the land is 2.6 mm / d. Further, the precipitation decreases over all seas except the western Pacific in DRY, and also decreases over both the Pacific and Atlantic in WET.

(2)*Cloudiness*

In the T42L9 model, the amount of the high–, middle– and low–level clouds is considered in radiation computation. Table 1 lists the daily amount of the three levels and the total clouds averaged over the land. One can find that the total cloudiness increases steadily during the integration,and the precipitation as well. The amounts of the high– and middle–level clouds in

Table 1. Cloudiness Averaged over the Land

Integration Time (h)		0	24	48	72	96	120
High clouds	CON	0.25	0.41	0.43	0.48	0.53	0.54
	DRY	0.25	0.41	0.42	0.48	0.52	0.53
	WET	0.25	0.41	0.43	0.48	0.52	0.54
Middle clouds	CON	0.29	0.40	0.41	0.40	0.42	0.45
	DRY	0.29	0.40	0.41	0.40	0.42	0.44
	WET	0.29	0.40	0.40	0.41	0.41	0.42
Low clouds	CON	0.09	0.39	0.52	0.53	0.53	0.53
	DRY	0.09	0.33	0.42	0.48	0.49	0.48
	WET	0.09	0.74	0.87	0.85	0.81	0.80
Total	CON	0.37	0.61	0.67	0.67	0.69	0.70
	DRY	0.37	0.59	0.62	0.66	0.67	0.69
	WET	0.37	0.80	0.89	0.89	0.86	0.87

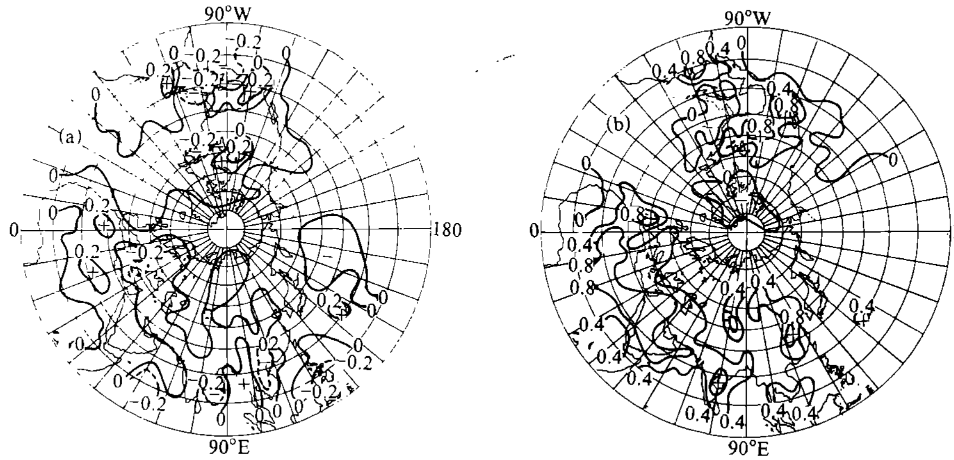

Fig. 4. Total cloudiness for 72 h integration: (a) DRY−CON; (b) WET−CON.

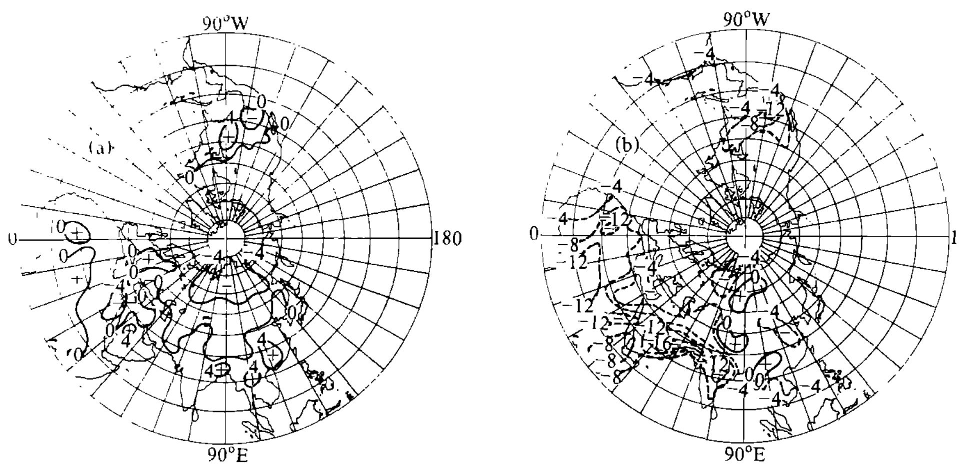

Fig. 5. Surface temperature for 72 h integration: (a) DRY−CON; (b) WET−CON (unit: °C).

DRY and WET are closed to those in CON, but the amount of the low–level cloud is much different.This suggests that the change in the surface evaporation has a negligible influence at high– and middle–levels during the medium–range period. However, the effect on the low–level cloud is noticeable, and the influence of the surface evaporation on the total cloudiness should be realized by changing the low–level cloudiness .

Further, the geographic distribution of the difference of the total cloudiness for 72 hours between DRY or WET and CON is given in Fig.4. In DRY, the total cloudiness decreases over Eurasia and North America by and large, particularly over the east of North America, East Asia and the Mediterranean Sea, and increases over the southeast of the Qinghai–Xizang Plateau and Mexico, and the precipitation as well. Although there is no rain over the northern Africa in both DRY and CON, there are two increase centres of the total cloudiness in DRY which are contributed by the increase of the high–level cloudiness according to the detailed analysis (figure omitted).In contrast, the total cloudiness decreases over both the Pacific and

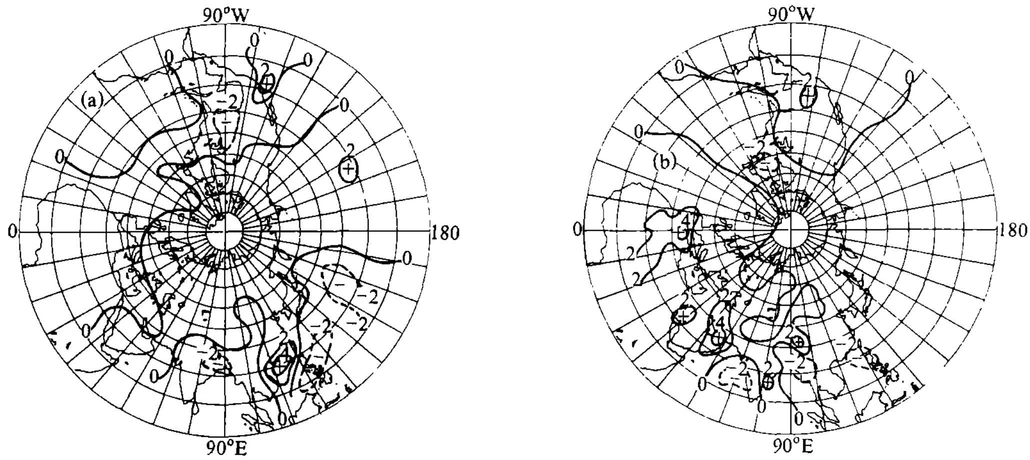

Fig. 6. Surface pressure (a) DRY−CON; (b) WET−CON (unit: hPa).

Atlantic in DRY. In WET, the total cloudiness increases over all the Northern Hemisphere, especially over the land. The area over which the amount of the increase exceeds 0.8 covers eastern China, the Indian Peninsula, the northern Africa and the coastal region of the Mediterranean Sea , the south of North America and the northern coastal region of South America. It also increases a little over seas, except the west of the North Atlantic.

(3) *Surface temperature*

It can be seen that in DRY the surface temperature raises significantly in the southern Europe, the northern Africa, the eastern Asia and the subcontinent of the southern Asia with the maximum range of 4—7°C, which is contributed by the reduction of the latent heat flux from the surface and the increase of the solar radiation due to the decrease of the cloudiness, except the northern Eurasia and the north of North America. In WET, the surface temperature decreases in almost the land, especially in the south of North America and the northern Africa and from the Arabian Peninsula to the Indian Peninsula with the magnitude exceeding −12°C, because of the increase of the latent heat flux and the reduction of the solar radiation due to the increase of cloudiness.

(4) *Surface pressure*

It is clear that there are subtropical high over both the Pacific and Atlantic, and a thermal low over the Qinghai−Xizang Plateau and a weaker low over the south of North America according to the simulated surface pressure field by CON. This is the typical distribution determined by the heating field in summer. The difference of the surface pressure between DRY (WET) and CON for 72 hours is given in Fig.6a (6b). In DRY, despite of the increase over the northern Europe, the surface pressure is lower over North America, the northern Africa and the subcontinent of South Asia. The maxima are located at the south flank of the Qinghai−Xizang Plateau and the east of North America with the intensity of −2 to −3 hPa. Except the western Pacific, the surface pressure is higher over both the Pacific and Atlantic.There is a maximum of 5 hPa centered over the South China Sea. Another positive centre is over the sea to the east of

Mexico. When the surface pressure is lower over the land, the vertical ascending motion must be greater. This can produce the stronger sinking motion through the response of the vertical circulation. The sinking motion enhances the anticyclonic circulation in these regions and causes the corresponding rise in surface pressure. This kind of change can enlarge the difference of the surface pressure between the land and ocean. In contrast, the surface pressure is higher over the northern Africa, North America and the most part of Eurasia in WET. It exceeds 4 hPa over the coastal area of the northern Africa and the Arabian Peninsula. There are also centres of 2 hPa over the west coast of Mexico, the East African Plateau and the Qinghai–Xizang Plateau. Meanwhile, the surface pressure is lower over the Pacific and Atlantic Oceans and East Asia. This indicates that both thermal low and subtropical high are weaker in WET.

(5) *Vertical meridional circulation*

The profile of the meridional circulation averaged between 15 and 30°E for 72 hours in CON is shown in Fig.7a. It can be found that there is sinking motion over the greater part of the continent of North Africa, except the ascending motion at the lower troposphere near the equator. The strongest sinking motion is located near 10°N. However, the profile averaged between 85°E and 100°E (Fig.8a) is much different compared with the former pattern. The ascending motion prevails over all the area to the north of the equator, and its strongest region is between 25 and 30°N. Figs.7b and 7c and Figs.8b and 8c are the profile of the meridional circulation of DRY and WET over the two regions respectively. In DRY, the circulation pattern over the northern Africa has not changed on the whole, but the ascending motion is stronger slightly.This is because that the sensible heat transport is not enough to compensate the radiation cooling at the surface layer of the atmosphere, and the thermal balance must be maintained by the adiabatic warming of the dynamic descent of the air. In WET, the ascending motion is

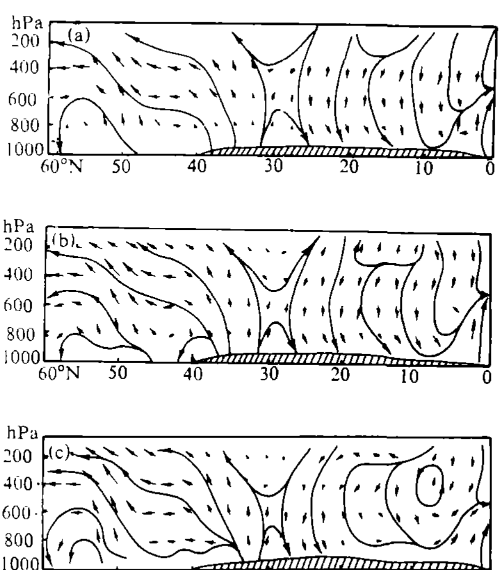

Fig. 7. The profile of the meridional circulation averaged between 15°E and 30°E for 72 h integration:(a) CON; (b) DRY; (c) WET.

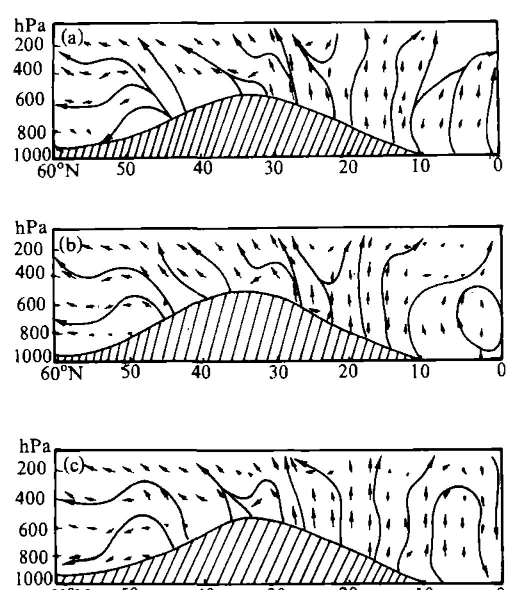

Fig.8. AS in Fig.7, but for between 85°E and 100°E.

stronger near 5°N over the northern Africa, and the clear Hadley cell appears. In the southern Asia, the upward motion changes to the downward motion at the equator in DRY, and the ascending motion at 20°N is stronger, so that the closed counter circulation occurs. This means that the monsoon circulation is stronger. It is due to the reinforcement of the heat low over the southern Asia which must be accompanied by the stronger convergence from the sea to

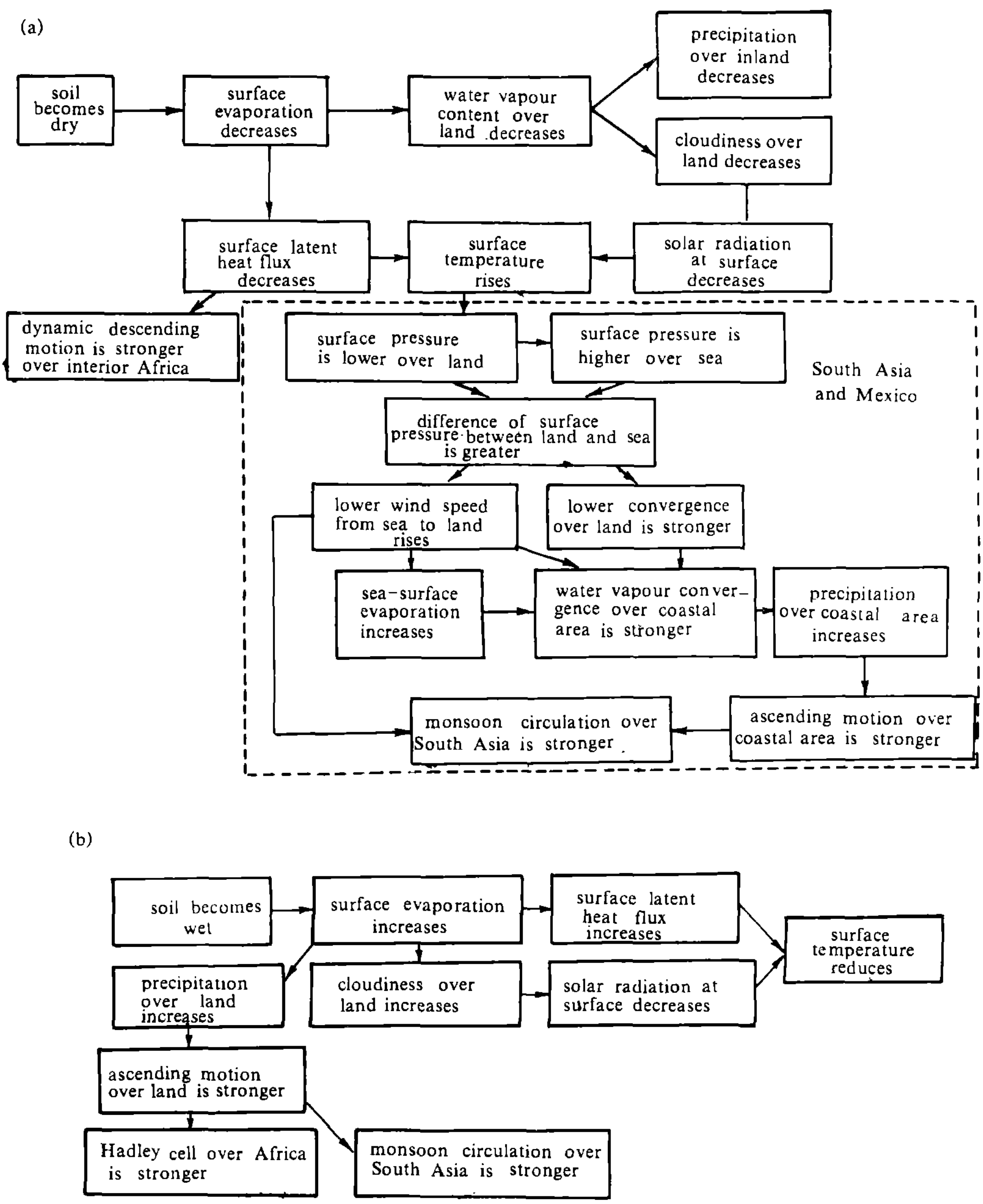

Fig. 9. Schematic illustration of the mechanism for the medium-range responses of the atmosphere to the abnormal soil moisture.

the subcontinent and the increased south flow. Also, the precipitation contributed by the monsoon in the southern Asia increases because of the water vapour convergence, and consequently the ascending motion is stronger there. In WET, the change of the monsoon circulation over the southern Asia is similar to that in DRY. Although the surface pressure field is unfavourable to strengthening of the monsoon circulation, the precipitation increases greatly due to the increase of the surface evaporation over the land, leading to strong release of the latent heat which enhances the ascending motion and reinforces the monsoon circulation.

3. *Discussion*

Based on the above experiment results, Fig.9 summarizes the mechanism of the medium–range responses of the atmosphere to the abnormal soil moisture.

The difference between land and sea is one of the determinants which drive the general circulation of the atmosphere. The main differences of the physical characteristics between land and sea include: 1) difference of thermal capacity. In the T42L9 model, the land–surface temperature is calculated from the heat budget equation, but the sea surface temperature is constant. This implies that the thermal capacity of land or sea is zero or infinity. 2) difference of the surface roughness. The land–surface roughness is greater than that of the sea surface. 3) difference of the surface albedo. In general, the land–surface albedo is higher than that of the sea surface, except the sea–ice region. 4) difference of the rate of the surface evaporation. β is 1 everywhere over the sea, while it is between 0 and 1 over the land. In our experiments, only the fourth characteristic or the rate of the surface evaporation is changed. In DRY, β is zero over the land so that the difference between land and sea reaches maximum. However, there is no difference between land and sea in WET. Under the above hypothesis of the thermal capacity, these two kinds of extreme conditions can change the difference of heating between land and sea immediately and make the circulation change significantly within a short–range period. In fact, there is a lag of the response of the surface temperature to the rate of the surface evaporation due to the thermal capacity of the soil. Thus, the real response time may be somewhat longer than that in the model. In other words, the response characteristic of the model atmosphere is closely related to the parameterization scheme of the physical processes.

The experiment results show that there is obvious geographic distribution of the atmosphere responses to the soil moisture. At first, the responses at the lower latitude are greater than that at the higher latitude. Secondly, there is extensive changes over some coastal regions in the tropics or subtropics (i.e.the Bay of Bangal or the Gulf of Mexico) compared with the interior continent or oceans. The primary cause is the higher surface temperature thus the larger potential evaporation, about an order of magnitude at the lower latitude more than that at the higher latitude. When the rate of the surface evaporation changes, the amount of change of the evaporation there will be greater. The local response can produce the evident changes at the lower latitude. Along the coastline at the lower latitude and in its neighbouring area, the above changes can enlarge the spatial variability of the surface physical characteristics much greatly (than that in the coastal area at the higher latitude or the interior continents or oceans), so that the changes of the circulation are more obvious. In addition, it can be found that the contribution of the dry–soil to the precipitation turns out contrary to that of the wet–soil over the interior land but both of them can increase the precipitation over the monsoon region of South Asia, by comparing the experiment results of the dry–soil and wet–soil cases. This is because the soil moisture not only influences the land–surface evaporation directly but also influences the water vapour convergence in the atmosphere indirectly. Therefore, there are complex nonlinear interactions between the atmosphere and the soil moisture.

our experiment results also imply that the global activity of human beings can affect the environment greatly. The global drying of the soil due to the large–scale deforestation or over–cultivation or over–grazing would result in further less rainfall over the arid region in the interior land and much more rainfall over some coastal monsoon regions. Further, the decrease of the precipitation over the arid region would accelerate the exhaust of the vegetation, and the soil and water loss would be more serious in pluvial regions because of the damage of the vegetation and the increase of precipitation, so that the environment would be worse. In contrast, the increase of the soil moisture due to the global irrigation and plantation would reduce the degree of aridity in the interior land, thus the environment would be improved.

Finally, because of the soil moisture can influence the atmosphere during medium–range period, it must be important to utilize the real–time data of the soil moisture for raising the accuracy of the medium–range weather prediction. This is a further research way in future.

IV. CONCLUSIONS

In the light of the above discussions, the four conclusions can be drawn as described in ABSTRACT.

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