The Climatic Effects of the Stratospheric Volcanic Ash①

Qian Yongfu (钱永甫)
Department of Atmospheric Sciences, Nanjing University, Nanjing 210008
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ABSTRACT

The climatic effects of the stratospheric volcanic ash are simulated. The model we used is a primitive equation model with the $P-\sigma$ incorporated coordinate system. The model has 5 layers in the atmosphere and 2 layers in the soil. The volcanic ash is introduced to the first (highest) model layer with a fixed optical thickness of 0.1275. Two comparative numerical experiments with and without the volcanic ash are made. Results show that the effects of the stratospheric volcanic ash on the formations of the mean climatic fields are much smaller than those of the land–sea distribution and the large scale topography. However, it does have contributions to the anomalies of the basic climatic states. The direct effect of the volcanic ash is to increase the temperature in the stratosphere. It can also influence the temperature and the height fields of isobaric surfaces, horizontal and vertical motions, precipitation and the surface climate through dynamic and thermodynamic processes in the atmosphere.

I. INTRODUCTION

The climatic effects of volcanic ashes have been attracting great attentions of climatologists for a long time. Volcanic ashes usually remain in the stratosphere, this is because that these is no deposition induced by the precipitation and the vertical motions are weak in the stratosphere. The horizontal flow is strong in the stratosphere, therefore, volcanic ashes can remain there for a long time, uniformly diffuse to the whole stratosphere and form the ash screen which shields solar radiation, consequently, affects the climate states of the atmosphere and the surface. The temperature changes in this century are dependent on volcanic eruptions to a large extent (see Budyko, 1969). Therefore, the screen index of volcanic ashes is used in long–term weather predictions.

According to the optical and chemical properties of the volcanic ash, it can be divided into two principle kinds. The first kind is the volcanic dust which has forward scattering only and the scattering asymmetric factor is unity. The single scattering albedo of the volcanic dust is 0.974 in the visible band and 0.130 in the infrared band, therefore, the volcanic dust can absorb both the solar and the longwave radiations. The second kind of the volcanic ash is the large amount of SO_2 gases which can melt in water vapour and become particles of sulphuric acid or sulphates in the stratosphere. The single scattering albedo of sulphuric acid or sulphates is 1.0 in the visible band, and 0.01 in the infrared band, therefore, no absorption takes place in the visible band while strong absoption in the infrared band. The asymmetric factor is 0.73. hence the backward scattering exists and attenuates solar radiation reaching the atmosphere and the ground surface (see Wang and Zeng, 1987).

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There have been some studies on the effects of volcanic ashes on termperature. The general results indicate that the stratospheric volcanic ash can result in the increase of the stratospheric temperature by 1–2°C, and the decreases of temperatures in the atmosphere and at the ground surface below the stratosphere to some extent. Some scientists pointed out that the two eruptions of the Philippine volcano in early summer of 1991 might have important climatic effects. According to the observations by the NOAA meteorological satellite in August of 1991, a cloudlike zone composed of volcanic dusts and gases had expanded into an area from 35°S to 35°N, the height of the zone was about 15 miles above sea–level. It is natural for people to ask whether there is some relationship between the flood in the summer of 1991 over the lower reaches of the Yangtze River and the eruptions of the Philippine volcano.

In this paper, a primitive equation model with $P-\sigma$ incorporated vertical coordinate systems is used to simulate the effects of volcanic ashes on the climate and some interesting results are obtained. The regional and the spatial distributions of the climatic effects, the characteristics and the extents of the affected mean climate states are also discussed in some detail.

II. THE MODEL AND THE EXPERIMENTAL SCHEMES

The model used in this paper adopts the $P-\sigma$ incorporated coordinate systems in the vertical. The P–coordinate system is utilized above the 400 hPa level and two layers are there with uniform thickness of 200 hPa. An atmospheric boundary layer with thickness of 50 hPa above the ground surface is of existence and the so–called σ_B coordinate system is used. Between the 400 hPa level and the atmospheric boundary layer there are two layers and σ coordinate system is used. The velocity, temperature, moisture and geopotential height fields are set in the middle of each layer. The staggered grid system is used in the vertical, while non–staggered spherical grid system is used in horizontal directions. In the soil or water there are still two more layers in which the temperature and the soil moisture can be predicted by the use of soil model. The details of the atmospheric model and the soil model can refer to Oian's papers (1985, 1991a), respectively. The model contains 6 kinds of underlying surfaces, that is, the clay pasture, the tropical rainy forest, the desert, the muddy water, the plateau snow cover and the ocean. The model uses a limited area from 5°W eastward to 175°W and from 25°S to 55°N, the grid size is 5° latitudes times 5° longitudes, and the time step is 15 min., an alternative time integration scheme is used with one hour Euler's backward scheme followed by five hours leapfrog schemes. The model has diurnal changes of solar radiation, therefore, the diabatic heating is calculated once an hour and the heating rates are fixed in the hour. The mean climate states are obtained by adding the results in every hour and dividing the sum by the total number of hours.

The volcanic ash is one kind of aerosols, therefore, when the volcanic ash is introduced into the model, the radiation flux density must be computed according to the aerosol parameterization schemes (Qian and Yu, 1991). The volcanic ash we introduced into the model is volcanic dust, its optical parameters have been given in the introduction and the optical thickness is set equal to 0.1275.

Two comparative numerical experiments are made. In the first one there is no volcanic dust in the stratosphere and in the second one the volcanic dust is contained in the first model layer, i. e., between 0–200 hPa, the mean level is equivalent to the 100 hPa level. The initial mean fields for the two experiments are the same zonally averaged monthly mean fields of geopotential height and sea–level pressure in June. After initialization the model surface quantities can be obtained. The initialization scheme is the same as Qian's (1985).

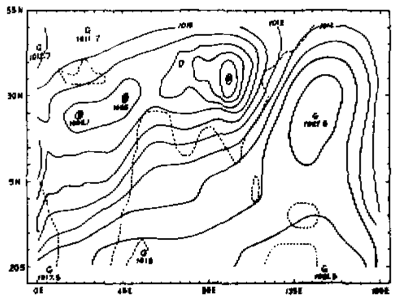

Fig.1. Simulated sea-level pressure (hPa) in CN.

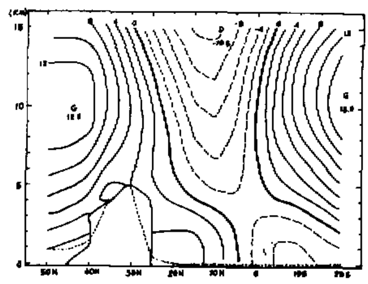

Fig.2. Vertical profile of the u -component along 90°E (m / s) in CN.

The two experiments are both time integrated up to 20 model days and the last 10 day mean results are taken as the climate states which are analysed in detail and compared with each other. Up to the twentieth model day the physical quantities both in the atmosphere and in the soil or water have reached a quasi-equilibrium state.

The first experiment is taken as the control run and designated by CN, the second one as comparative experiment and denoted by BA. The land-sea distribution and the large scale topography are included and the same in both experiments, the highest topography is 5000m. The cloud particles generated in the experiments are treated as aerosols (Qian and Yu, 1991).

III. THE RESULTS AND DISCUSSIONS

1. *The Simulated Results in CN*

The simulated results in CN can be used to judge the capacities of the model for climate modellings. Only when the simulated results are basically in agreement with the observed climate states, the comparative experiment is meaningful.

Fig.1 is the simulated sea-level pressure in CN. It is seen that the high pressure system is located over the oceans and the low pressure system over the land. The distributive pattern of pressure systems is fairly close to the observation (Kuo and Qian, 1982) and in basic agreement with the previous simulations we have obtained (Qian,1990; 1991b). Therefore, the treatment of cloud particles as aerosols does not influence the model capacity.

In order to show the variations of meteorological fields with height and longitude we analysed the vertical profiles of the u -component along 90°E (see Fig.2) and 120°E (figure omitted). The analysis indicates that the vertical structures of the u-component along 90°E and 120°E are the same. There are three wind bands both in the two vertical profiles, that is, the tropical easterly band and two westerly bands on both sides of the former. The axis of the easterlies tilts northward from the lower levels to the upper levels until the upper troposphere where the axis is basically vertical. The maximum cores of the westerlies are both located at the height of 10 km and the core in the winter hemisphere is somewhat stronger. The maximum cores of the easterlies exist in the stratosphere at the height of 15 km and the core in the 90°E profile is stronger than that in the 120°E profile. Therefore, the main body

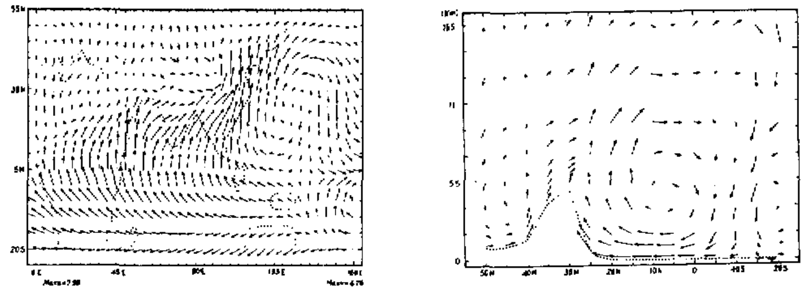

Fig.3. Flow field in boundary layer (a) and meridional circulation along 90°E (b), in CN.

of the South Asian High should be located at 90°E or west to 90°E. Fig.2 is also in agreement with the observations.

Figs.3a and 3b are the velocity field in the boundary layer and the meridional vertical circulation along 90°E, respectively, in CN. From Fig.3a we see that the main properties of the summer monsoon are well simulated, for example, the Somali cross equatorial low–level current, the southwest Indian Monsoon, the north equatorial trough over the African continent, the low pressure circulation over the Tibetan Plateau, the southeast monsoon over East Asia and the high pressure circulation over the western Pacific. Fig.3b shows that there is a clear monsoon circulation at 90°E, the maximum upward motion appears over the south slope of the Plateau near 20°N, and the maximum descending motion is over the area near 15°S, over the Tibetan Plateau there is also ascending motion throughout the whole air column above the Plateau. All those properties are in good agreement with observations.

For brevity, the other simulated fields are omitted. Readers interested in those fields can refer to Qian's another paper (Qian, 1992).

2. *Effects of Stratospheric Volcanic Dusts on Geopotential Heights*

Because of the introduction of volcanic dusts into the first model layer and the absorption of solar radiation by volcanic dusts, the 100 hPa level temperature and geopotential height fields are most influenced. Fig.4a is the height differences of BA from CN at the 100 hPa level (unit: decametre). It is seen that the South Asian High is obviously intensified, especially, over the southeast part of the Mediterranean where the maximum increase of the height is 11m. Therefore, the main body of the High shifts northwestward in BA. According to the relationship between the South Asian High and precipitation it is expected that the rainfall amount over the lower reaches of the Yangtze River in BA would increase when compared with that in CN. Fig.4b is the same as Fig.4a but for the 300 hPa level. We can see that the isobaric surface heights at the 300 hPa level are commonly decreased, but the values of decrease are not large. The maximum decreases are over the North Africa and the coastal regions of East Asia with 6 m and 3 m, respectively. From the 300 hPa level downward to the 850 hPa level, geopotential heights at all isobaric surfaces are decreased, however, the values of decreases become less and less, they are usually less than 3 m.

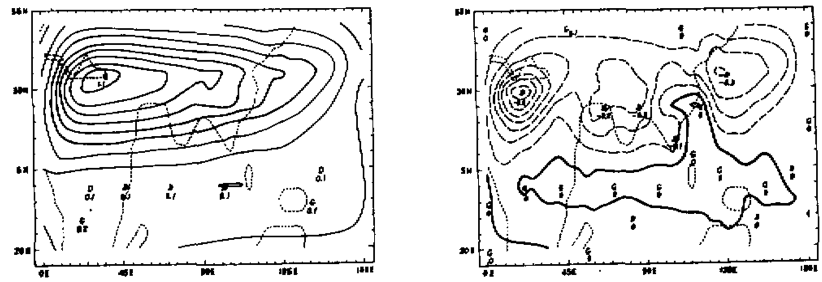

Fig.4. Height differences between BA and CN at the 100 hPa (a) and the 300 hPa (b) levels. unit: decameter.

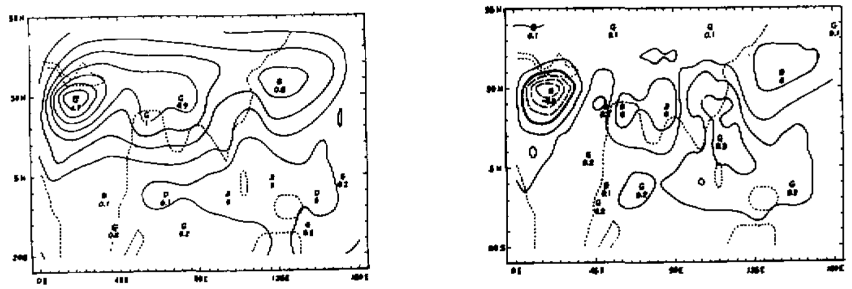

Fig.5. Temperature differences (℃) between BA and CN at the 100 hPa level (a) and the 300 hPa level (b).

3. *Effects of Volcanic Dusts on Temperature*

Fig.5a is the temperature differences (℃) at the 100 hPa level between BA and CN. From Fig.5a it is seen that the temperatures at the 100 hPa level increase in common because of the absorption of solar radiation by the stratospheric volcanic dusts. There are three centres of temperature increases, the first is over the North Africa, the second over the southwest side of the Tibetan Plateau, and the third over the coasts of East Asia, the centre values are 1.7℃, 0.9℃ and 0.8℃, respectively. Over the north part of the Arabian Sea there is also another centre of temperature increase with a value of 1.0℃. By comparison of Fig.5a with Fig.4b, we find that the patterns of the height differences at the 300 hPa level and the temperature differences at the 100 hPa level are very similar, they are negatively correlated with each other. Therefore, the decreases of height at the 300 hPa level are induced by the increases of temperature at the 100 hPa level because the latter makes the lower isobaric surfaces sink. Owing to the hydrostatic relation the isobaric surface heights below the 300 hPa level also decrease to some extent, consequently.

Fig.5b is the temperature differences (℃) at the 300 hPa level. Contrary to Fig.5a, the temperature changes at the 300 hPa level are smaller and in the range of ± 0.3℃. Over the North African desert, the temperature decreases, while over other areas, the temperatures increase. Below the 300 hPa level, the temperatures also increase at isobaric surfaces, however, the values are all very small and less than 0.3℃.

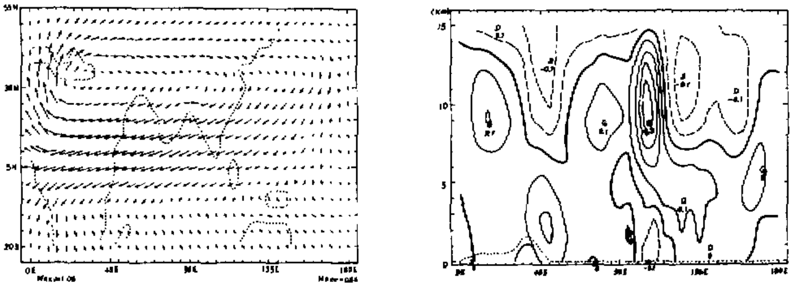

Fig.6. Velocity differences at the 100 hPa level (a) and vertical profile of differential v -components along 5°N (b) between BA and CN (in m / s).

According to the conventional point of view, when the stratospheric volcanic dusts which can absorb short wave solar radiation are introduced at the 100 hPa level, the temperatures of the atmosphere below that level should dectease. However, our experimental results show that the temperatures mainly increase except for some regions over the North Africa where temperature decreases at the 300 hPa level. Such discrepancies between the conventional point and our experimental results are easy to explain. As we know, many studies on the climatic effects of aerosols use one–dimensional models, and in one–dimensional models the only cause which makes the temperature change is the heating or cooling effect of radiation, the most important factor is the absorption amount of solar radiation. We have used a one–dimensional model to simulate the climatic effects of aerosols and the results show that the temperature changes have close relations with the height, the optical thickness of the aerosols and the surface albedos (see Qian, et al., 1992). However, in a three–dimensional model, the dynamic effects are also included besides the thermal effects, therefore, the case is much more complex. We have pointed out such situations in a previous paper (see Qian et al., 1991).

4. *Effects of Volcanic Dusts on Flow Fields*

Fig.6a is the velocity differences (m / s) between BA and CN at the 100 hPa level. It is seen that the anticyclonic circulation increases, which is in consistence with the height differences at that level; The pattern of the differential circulation is similar to that of the flow field at the 100 hPa level in CN. The axis of the differential flow circulation is located near 32.5°N, the westerly winds north to the axis, strengthen and the easterly winds south to the axis, increase. Over the west part of the North Africa and the Mediterranean, the southerly winds strengthen, while over the western Pacific, the northerly winds increase. Those variations in the flow field can be also seen in the vertical profiles of the u -and the v -components. Fig.6b is the vertical profile of differential v -components along 5°N. We can clearly see that the northerly components at high levels increase. However, in the upper troposphere from 6 km to 14 km the northerly winds increase in some places and decrease in other places. By comparison of Fig.6b with the vertical profile of v -components along 5°N in CN (not shown), we find that the Somali lows–level cross–equatorial current at 50°E strengthens and so does the northerly current above it. Therefore, the vertical meridional circulation here is increased. At 105°E, the case is just reverse. In other regions such as Africa, the Pacific and at 80°E, meridional circulations are decreased, but not strongly.

From above analysis, we can see that the stratospheric volcanic dusts have larger influences on the flow field at the 100 hPa level, however, the pattern of the influence is simpler. The influences on the cross–equatorial currents and the vertical meridional circulations are more complex. The volcanic dust has the strengthening effect on the Somali lower–level current, while it has the weakening effect on the current at 105°E. However, generally speaking, the effects on the wind speeds are not obvious, the maximum difference of the wind speed at the 100 hPa level is about 1–2 m / s.

5. *Effects of Volcanic Dusts on Meridional Vertical Circulations*

The variations of meridional circulations can be seen from the vertical profile of v –components along 5°N, though it is not the direct indicator of the variations. Therefore, we select the differential meridional circulations along 90°E and 120°E to analyse the effects of the volcanic dusts. From the profile along 90°E (not shown), we see that below 5.5 km the differential meridional circulation has the same direction as that shown in Fig.3b for CN, so the convergence to the Plateau at lower levels increases in BA, especially on the south slope of the Plateau where the ascending motions are obviously strengthened. However, above 5.5 km, the directions of the differential circulation are opposite to the meridional circulation itself in some places, especially over the Tibetan Plateau and its vicinities, where the upward motions are weakened. We know that the vertical motion has close and direct relationship with the heating field, therefore, the above discovery shows that the heat source near the ground surface of the Tibetan Plateau increases, while that in the upper atmosphere decreases.

Fig.7 is the differential meridional circulation along 120°E. It is seen that the upward motion near 25°N increases. By comparison of it with the meridional circulation along 120°E in CN (not shown), it is found that the monsoon circulation along 120°E is intensified in BA.

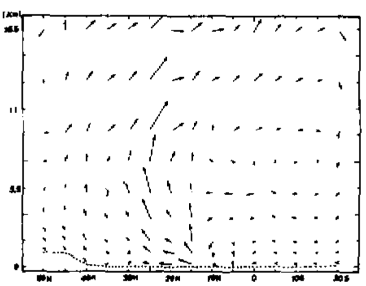

Fig.7. Differential meridional circulation along 120°E between BA and CN.

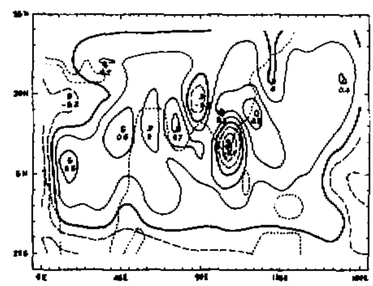

Fig.8. Changes of vertical motions (mm / s) at the 300 hPa level.

6. *Effects of Volcanic Dusts on Vertical Motions*

Changes in vertical motions are closely related to changes of horizontal flow fields. From Fig.6a we find that the anticyclone at the 100 hPa level is increased, though the variations of the divergence and convergence fields are different from place to place. Usually the enhancement of divergence at the 100 hPa level results in the increase of the upward motion and that of convergence results in the increase of the downward motion or the decrease of the upward motion. Fig.8 is the differences of the vertical motion at the 300 hPa level. We see that the inclusion of the volcanic dusts results in remarkable changes of the upper level vertical motions. Over the Indo–China Peninsula and the Tibetan Plateau there are two areas with decreased upward motions and the centre values are–0.7 and –0.3 mm / s, respectively over the Yangtze River Valley, especially, over the area from the low reaches of the Yangtze River to the East China Sea, the Indian Peninsula and the central Africa, there are areas with increased upward motions and the centre values are in the range of 0.5–0.8 mm / s. In later paragraph we will indicate that those areas with decreased or increased upward motions are basically correspondent with the areas with decreased or increased precipitation, respectively. From the changes of the boundary vertical motions (not shown), we find that the upward motion over the Tibetan Plateau is increased by a maximam value of 0.8 mm / s. The changes in other places are very small. Therefore, the effects of the stratospheric volcanic dusts decrease downward.

7. *Effects of Volcanic Dusts on Surface Temperature and Moisture*

Fig.9 is the differences of surface temperature between BA and CN. From the differences we can see that the changes of surface temperature induced by the volcanic dusts are not uniform. The changes over the ocean are small and in the order of 0.1℃. Over the most areas of the Eurasian continent and North Africa, the temperature increases with maximum value of 0.4℃, while in Somali and the Arabian Peninsula, the temperature decreases, the maximum decrease is –0.3℃, over India, China and the northeast part of Asia, the temperature decreases, too. The changes of the surface moisture are positive or negative and related to that of the surface temperature. Generally speaking, the surface moisture decreases in the areas with increasing surface temperature and vice versa, such a correspondence is evident. The values of surface moisture changes are very small and within ±2%.

The above analysis indicates that the effects of the stratospheric volcanic dusts on the surface climate are not very obvious. This conclusion is not in agreement with that in the case of one–dimensional model.

8. *Effects of Volcanic Dusts on Precipitation*

Now, we are going to discuss the problem in which we are most interested, that is, the effects of the volcanic dust on precipitation. Figs.10a, b are the differences of total precipitation amount (a) and cumulus rainfall (b), respectively. It is seen that the two distributive patterns of the differences are very correspondent to each other. Therefore, we can conclude that the changes of total precipitation are mainly due to the changes of cumulus rainfall and the effects of the stratospheric volcanic dust on the summer precipitation come to reality through its effects on the cumulus convective precipitation. From the effects of the volcanic dust on the temperature, it has been seen that the temperature increases at upper levels are larger than that at lower levels, therefore, the convective stability of the atmosphere should increase. However, when the conditional convective instability is not destroyed, the amount of the cumulus precipitation mainly depends on the convergence of moisture and the moisture flux at the bottom of the unstable layer. Therefore, the convergence or divergence can also be inferred from the changes and distributions of the convective precipitation.

Figs.10a, b both indicate that the regions with increased or decreased precipitation are distributed in wave form with west to east orientation. Over the west part of North Africa the precipitation decreases, over the East Somali, it increases, over the Arabian Sea it decreases, over India it increases, over the Bay of Bengal, the south side of the Tibetan Plateau and the Indo–China Peninsula it decreases, over the South China, especially over the area from the Huaihe River Valley to the South China Sea it increases again, over the Northeast China and the East China Sea it decreases, and so on. The most obvious changes of precipitation are located in the tropical areas. Though we do not know the real changes of precipitation in the whole monsoonal region in the summer of 1991, the precipitation over the Huaihe River and the Yangtze River Valley does increase. That is to say that the volcanic dusts from the eruption of the Philippine volcano do influence the summer precipitation of China. Of course, the simulated changes of precipitation are far smaller than the observed ones because of the coarse resolutions of the model we used.

By comparison of Fig.9 with Figs.10a, b, we find that the direct causes of the changes of the surface temperature and moisture are the changes in precipitation, instead of the direct effects of volcanic dusts on the absorption and scattering of the solar radiation, because the areas where the surface temperature increases and the surface moisture decreases are the same areas where the precipitation decreases and vice versa.

By comparison of Fig.8 with Figs.10a, b, we also find that the areas where the precipitation increases (decreases) are basically coincident with the areas where the upward motion increases (decreases). It means that the changes of precipitation mainly depend on the changes of the vertical motion, while the latter is controlled by the convergence and divergence of the flow fields at the lower and the upper levels and the vertical distributions of the divergence fields.

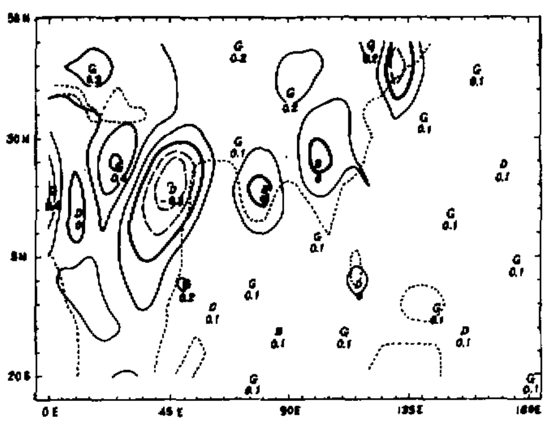

Fig.9. Differences of surface temperature (℃) between BA and CN.

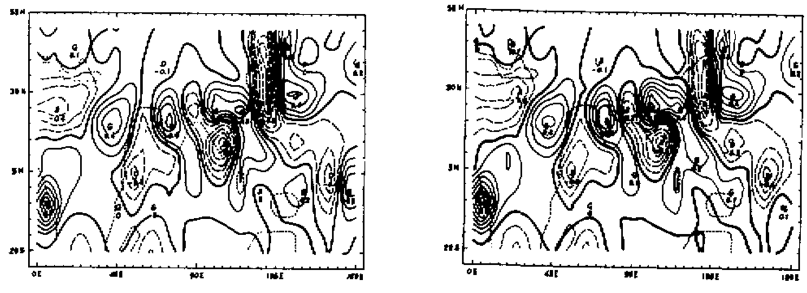

Fig.10. Differences of total precipitation (a) and cumulus rainfall(b) between BA and CN (in mm / day).

9. *Discussions ofthe Mechanism ofthe Effects ofVolcanic Dusts on the Climate*

According to the above analyses, we may find the mechanism through which the volcanic dusts influence the climate changes. The basic mechanism can be described as followins:

At first, because of the absorption of the stratospheric volcanic dusts, the heating effect of the short wave radiation at the 100 hPa level is enhanced, consequently, the temperature at the level increases, the geopotential heights increase too, which the geopotential heights below the 300 hPa level decrease. The changes in the geopotential height field of the 100 hPa isobaric surface induce the changes of the flow field at the same level through the dynamic relation between the height and the flow. Secondly because of the continuity of the fluid, the changes in the 100 hPa level flow field would result in the changes of the distributions of flow fields in the whole atmosphere which, consequently, induce variations of the divergence and convergence distributions. The vertical motions and the cumulus convective precipitation change, and so does the distribution of the released latent heat due to convective condensation. The temperatures at the isobaric surfaces are altered again. The above processes constitute a cycle and many times of alternations reach a quasi-equilibrium climate state.

It is seem from the above discussion that the direct effect of the volcanic dusts is the heating effect on the atmospheric layer at the 100 hPa level, the other effects are all indirect.

However, there is one question which has not been answered so far. The question is why the uniformly distributed volcanic dusts in the stratosphere can result in climatic effects with regional properties of distribution. As we know that the volcanic dusts absorb not only the direct solar radiation downward, but also the reflected radiation from the surface and the cloud tops, the reflected radiation, however, is evidently not uniform and depends on the physical properties of the underlying surface, the height and the thickness of the could layer. The surface albedo of the deserts is the highest, that of the oceans the lowest, and that of other land surfaces is in between. The surface albedo of the Plateau snow cover is even larger than that of the deserts, however, the area is small and the influence is also small. If we look back at Fig.5a, we would believe this.

IV. CONCLUSIONS

The simulated results in this paper indicate that the stratospheric volcanic dusts have direct effects on the absorptions of the direct radiation, as well as the reflected radiations from underlying surfaces and clouds, the stratosphere, therefore, obtains supplementary short wave radiative heating and the temperature at the 100 hPa increases, the maximum increment of temperature is about 1.7℃, which is in agreement with the results of previous studies. The heights of the 100 hPa level increase due to the increase of temperature and that of the lower isobaric surfaces decrease, however, the temperatures at lower levels increase by small values of 0.3℃ or so. The temperatures over the North African deserts at the 300 hPa level decrease, the minimum of the temperature change is −0.3℃. The changes in geopotential heights result in the changes of flow fields at the 100 hPa level and other levels of the atmosphere. The anticyclonic circulation at the 100 hPa level strengthens, while the lower level flow fields change a little. Along 5°N, only the vertical circulation at 50°E intensifies and those at other longitudes weaken to some extent. Over the Tibetan Plateau, the upward motion increases in the lower layers and decreases at the upper levels, however, the meridional monsoon circulation along 120°E increases. The changes of vertical motions are dependent on that of the flow fields. The areas with increasing or decreasing upward motions at the 300 hPa level are in good correspondence with the areas of increased or decreased precipitation. The effect of volcanic dusts on precipitation is also evident, the inclusion of the stratospheric volcanic ashes might induce the increase of precipitation over the Huaihe and Yangtzt River Valley which is in good agreement with the case of the 1991 summer when the precipitation over the areas in question was largely increased. The changes of the surface temperature and moisture are mainly influenced by the changes of precipitation, they are in good correspondence with each other.

From the mechanism discussions we can see that the only direct effect of volcanic dusts is their effect on the temperature at the 100 hPa level, changes of other meteorological fields are resulted from the adjustments due to the interior dynamic and thermodynamic processes, therefore, the effects are indirect.

REFERENCES

Budyko, M. I. (1969), The effect of solar radiation on the climate of the earth, *Tellus*, **21** (5):611–619.

Kuo, H. L. and Y. F. Qian (1982), Numerical simulations of the development of mean monsoon circulation in July, *Mon. Wea. Rev*, **110:** 1879–1897.

Qian, Y. F. (1985), A five-layer primitive equation model with topography, Plateau Meteorology, **4** (2): (suppl.), 1–28.

Qian, Y. F. (1991), Numerical simulations of temperature and moisture changes in land-air coupled system, *Acta Meteor. Sinica*, **49:** 538–547.

Qian, Y. F. and Y. Yu (1991), A preliminary study of cloud and aerosol effects on temperature, *J. Nanjing Institute of Meteorology*, **14:** 10–19.

Qian, Y. F. (1991b), Numerical experiments of the effects of initial desert moisture on the climate change, *Adv. Atmos. Sci.*, **8:** 459–470.

Qian, Y. F., Y. Qian and Y. Yu (1992), Numerical modelling of the effects of clouds and aerosols on temperatures in a soil-air coupled model, *J. Tropical Meteorology*, **8(2):** 105–114.

Qian, Y. F. (1992), Simulated properties of the climate in the summer monsoon area, CEG / IVth ISC, Beijing, July 20–25.

Wang, M. X. and Q. C. Zeng (1987), Variations of the atmospheric trace gases and their climatic effects, *Progress Report on Climate Studies, The Chinese Committee on Climate Studies*, Beijing, 71–76.