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THE SENSITIVITY OF NUMERICAL SIMULATION TO OROGRAPHY SPECIFICATION IN THE LOW RESOLUTION SPECTRAL MODEL——PART I: THE EFFECTS OF OROGRAPHY ON THE ATMOSPHERIC GENERAL CIRCULATION

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ABSTRACT

In order to identify the sensitivity of the numerical simulation to the orography specification in a low resolution spectral model, two sets of numerical experiments for full-mountain and no-mountain cases are performed. By comparing the results, it is possible to determine the effects of mountains on the atmospheric general circulation.

This is a global, spectral model incorporating the primitive equations sugmented by physical parameterization and mountains, with five equally-spaced sigma levels in the vertical ang a triangular truncation at wavenumber 10 in the horizontal.

Analysis of results supports earlier work by demonstrating that the low resolution global spectral model is capable of simulating the major features of global general circulation and indicates that it is necessary to consider the effects of mouutains on stationary disturbances in the numerical simulation. The simulations show that topography plays an important role in intensifying heat sources for maintenance of disturbances.

All the simulation tests indicate that orography has an important influence on the distribution of heat sources and sinks. It reflects that interaction and interrelation exist between the effects of orography and heat sources and the atmospheric circulhtion via the dynamical processes of atmosphere. This result confirms the view points proposed by Yeh and Zhu (1958), but differs from those by Kasahara and Washington (1971), Manabe and Terpstra (1974).

I. *INTRODUCTION*

In the past two decades, a number of general circulation numerical experiments have been made to identify the influence of orography upon the planetary-scale flow field. The validity of these experiments was supported by the success of the control simulations with realistic orography in simulating the atmospheric general circulation. Special note should be made of the studies by Kasahara and Washington (1971) and Manabe and Terpstra (1974).

Kasahara and Washington (1971) simulated the January climate with and without the earth's orography using the NCAR global circulation model. They discussed the relative importance of the thermal and orographic influences upon the large-scale motions of the atmosphere and concluded that the earth's orography plays a minor role compared to the thermal effect of continentality in determining the major features in the transport mechanism of momentum, water vapor, heat and energy in terms of the zonal mean state. However, they concluded that for the regional aspects of general circulation the effects of orography are significant.

In order to further identify the effects of mountains upon the general circulation of the atmosphere, Manabe and Terpstra (1974) performed a set of numerical experiments using a general circulation model developed at the Geophysical Fluid Dynamic Laboratory of NOAA. The results of the numerical experiments for constant winter conditions indicated that it is necessary to consider the effects of mountains for the successful simulation of the stationary flow field in the atmosphere, particularly in the upper troposphere and stratosphere. In the model troposphere, mountains increase markedly the kinetic energy of stationary disturbances by increasing the stationary component of the eddy conversion of potential energy, whereas mountains decrease such energy of transient disturbance. The sum of stationary and transient eddy kinetic energy is affected little by mountains.

Recently, a set of new simulations have been carried out with and without orography using the two-level GCM at Oregon State University. In general, the results show a smaller orographic effect than that suggested by previous simulations for either January or July.

A review of the preceding studies indicates that there are still questions on the nature of the orographic effects with such effects being dependent upon the specific model and how results are analyzed. Nevertheless the importance of orography on the atmospheric circulation and sensitivity of models to orography is evident.

In this paper we extend the analysis of topographic effects by examining both the statistical significance of the effects and the sensitivity of the simulation to the details of the specification of orography. Furthermore, annual cycle instead of constant season simulations is considered. The low-resolution spectral model is used and basic circulation variables are examined. The full mountain-no mountain comparison parallels that for transports and energetics with this model referenced earlier. The analysis of the case without mountains isolates the overall effect of topography on the circulation which allows a comparison of these results to those found with higher resolution general circulation models. This is summarized in section IV. In section V, we study the effects of topography on the heat sources and sinks. A summary and conclusions follow in section VI.

II. BRIEF DESCRIPTION OF THE MODEL

The low-resolution global spectral model used for this study is described in detail by Otto-Bliesner et al. (1982) and a very brief sketch of the global model is given here.

The sigma coodinate system is used with $\sigma = P/P^*$ where P^* is the surface pressure. Five equally-spaced sigma levels between the surface and top of the atmosphere represent the vertical structure of the model atmosphere (Fig. 1). A rigid top boundary condition, $\dot{\sigma}=0$ at $\sigma=0$, is assumed.

The basic dynamic and thermodynamic equations of this model consist of the vorticity equation for the vertical component of relative vorticity, horizontal divergence tendency equation, the continuity equation integrated to give surface pressure, the thermodynamic equation for temperature and moisture equation for moisture mixing ratio. Completing the set of equations are the hydrostatic equation and a diagnostic equation for the sigma vertical velocity.

The prognostic and diagnostic model variables are represented in the horizontal as truncated expansions of the surface spherical harmonics. The model is triangularly truncated at wavenumber 10. The model is formulated using the transform method. A semi-implicit time integration (Bourke, 1974) is used in the model to allow a relatively long time step of 90 minutes.

All physical parameterizations are incorporated into the model in grid-point space. They include short wave radiation; long-wave radiation; condensation and convection; the vertical diffusion of momentum, heat and moisture from the surface to the first model level. Also included are horizontal and vertical diffusion parameterizations.

Topography is incorporated spectrally into the model as a lower boundary condition for the geopotential. The specification of topography is discussed in detail in Section III. Other boundary conditions input into the model on the transform grid are sea surface-temperature, sea ice distribution and the surface albedo as a function of latitude and snow limit.

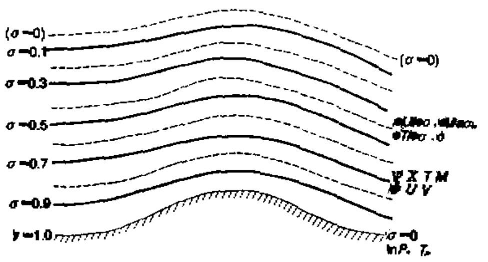


Fig. 1. Vertical grid structure of model. $U=u/\cos\varphi$, $V=v/\cos\varphi$, u and v are zonal and meridional components of wind, respectively; φ, latitude; $\dot{\sigma}$, the vertical velocity in sigma coordinates; Ψ, stream function; X, velocity potential; T, temperature; M, mixing ratio; Φ, geopotential height. The subscript $*$ represents the variables on the surface.

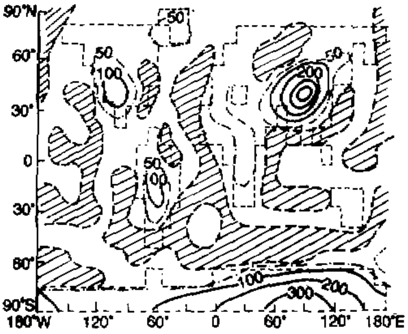


Fig. 2. The distribution of topography in the Case 1. The shaded areas are ripple areas (negative heights). Units: 10 m.

III. THE TEST SCHEMES AND STATISTICAL METHOD

In order to investigate the sensitivity of the global atmospheric circulation to orography, two different models with and without mountains are considered. A detailed description is given as the following:

Case 1, "full" ("unsmoothed") mountain case (control case, Fig. 2, hereinafter referred to as M model). One degree latitude-longitude orography (Jenne, 1975), modified over the Antarctic and Greenland ice caps, is spectrally truncated at wavenumber 10 and incorporated directly into the model. Heights of full mountains are close to the actual heights of mountains and there are many negative height areas (called "ripples") in the model.

Case 2, no mountain case (hereinafter referred to as NM model): All the mountains are removed in the model, that is, we set the heights of the land at mean sea level everywhere. This specification provides model simulations that make it possible to isolate the overall orographic effects, to evaluate the impact of orography and to compare overall performance of this model in terms of topographic effects with higher resolution GCM.

The model with mountains was spun up with perpetual January boundary conditions and forcing starting with an isothermal atmosphere (240 K), no motion or moisture, and a constant sea-level pressure of 1013.25 hPa. The model with mountains was then integrated for six simulated years. The last five years of this run are used for all statistics presented in this study. Then, the model without mountains was run with the same boundary conditions and forcing as the model with mountains for one year and seventy days starting with simulations on October 21, the second simulated year in the model without mountains. The results in the last year of this run compare with the simulations of the third year in the model with mountains.

Once the solutions of the model with and without mountains have been generated, there remains the problem of determining how much of the apparent difference due to orography is actually due to the mountains and how much it is due to the inevitable difference in the statistics of the model's solutions caused by the essentially unpredictable synoptic-scale motions. The technique of the statistical test for the separation of such a climatic signal and the unpredictable noice is used in this study. The standard deviation of interannual variability in monthly means based on the five year simulation in the full mountain case (control case) (Otto-Bliesner et al., 1982) is used as a measure of model variability. Assuming that each year of the five-year annual cycle experiment is equivalent to an independent experiment, differences between other cases and the control are then analyzed according to the t-test (chervin and schneider, 1976) which gives statistical significance at the 5% level if the difference equals 3 standard deviations of natural model variability, and at the 1% level if the difference equals 5 standard deviations.

IV. OVERALL EFFECTS OF OROGRAPHY ON THE GENERAL CIRCULATION OF THE ATMOSPHERE

Comparison of the results of Cases 1 and 2 identifies the overall effects of orography in this low-resolution model. Basic circulation variables (geopotential heights, velocity and temperature) are considered along with moisture, precipitation and diabatic heating. Seasonal (90-day) averages are used, focusing attention on the steady component of the quantities.

1. *Geopotential Height Field*

In northern winter (December-February, hereinafter referred to as "winter"), the Aleutian low, Icelandic low and Siberian high in the Northern Hemisphere and the subtropical highs around 30°S in the Southern Hemisphere are identifiable in Case 1 (the control case) in qualitative agreement with the features of the actual atmosphere. Without topography (Case 2) the Aleutian and Icelandic lows and the Siberian high are weaker than those in Case 1 at 900 hPa and 300 hPa, and the axis line of the ridge responding to Siberian high is from northeast to southwest over Siberia at 300 hPa in Case 2. In contrast, with topography (Case 2) the two troughs and the ridge responding to Icelandic low, Aleutian low and Siberian high, respectively, are more intense and their positions are west of those in Case 2 (compare Fig. 3 (a)—(d)). All of these differences are significant at the 5% level.

The intercomparison between the M and NM models suggests the importance of mountains for maintenance of the Aleutian and Icelandic lows and for the amplitude and position of the Siberian high. The first conclusion is similar to Manabe and Terpstra (1974), who suggested that it is necessary to consider the effects of mountains for the successful simulation of the stationary flow field in the atmosphere. The second result agrees with both Manabe and

Terpstra (1974) and Kasahara and Washington (1971). On the whole, the characteristics of the major stationary disturbances are closely related to orography in the Northern Hemisphere in winter. In the Southern Hemisphere, mountains seem also to intensify the subtropical highs during December–February.

In northern summer, (June–August, hereinafter referenced "summer"), the subtropical highs

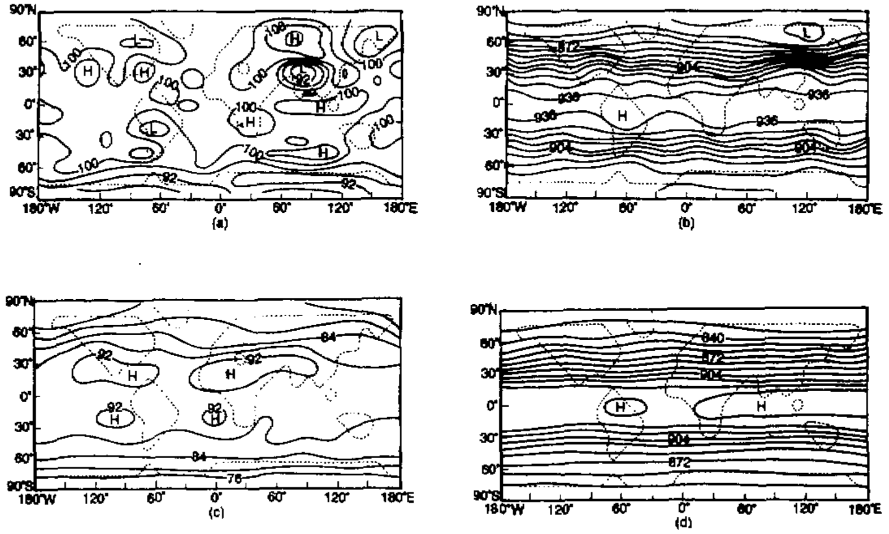


Fig. 3. The simulated time-mean geopotential maps in Northern Hemisphere winter: (a) Case 1 at 900 hPa; (b) no-mountain case, Case 2 at 900 hPa; (c) Case 1 at 300 hPa and (d) Case 2 at 300 hPa. Units:10 m.

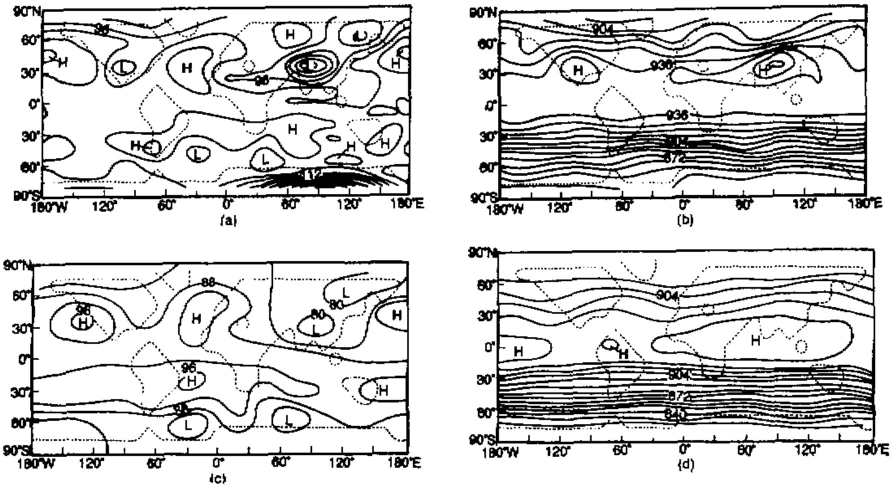


Fig. 4. As in Fig.3, except in Northern Hemisphere summer,

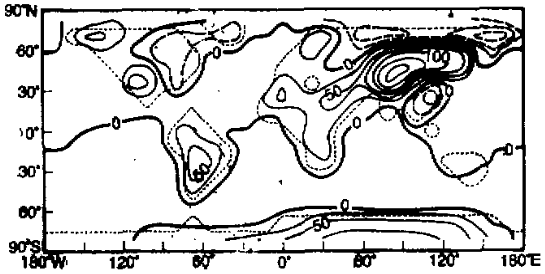


Fig. 5. Simulated surface temperature difference (Case 2 minus Case 1) for the Northern Hemisphere winter. Units: 0.1°C. Solid lines denote positive differences, and dashed lines, negative differences.

at all heights, the monsoonal low in the lower troposphere and the anticyclone in the upper troposphere over the Tibetan Plateau in the control case (Case 1) are simulated (compare Fig. 4(a)—4(c)). Deficiencies are that the geopotential height over southern North America is simulated too low and unrealistic high system exists in the lower troposphere over Antarctica of the Eastern Hemisphere.

Without topography (Case 2) the subtropical highs and South Asia low are weaker and their positions are too far southeast. But the subtropical highs are intensified, South Asia low is deepened when mountains exist (Fig. 4). All these differences between the two models are significant at the 5% level. Therefore, the Tibetan Plateau has an important effect on the intensity and position of South Asian monsoonal circulation but has no influence on its formation (Ni et al., 1985). This result is not perfectly in agreement with Hahn and Manabe's conclusion (1975).

2. *Temperature Field*

Otto-Bliesner et al.' (1982) indicated that the simulated temperature field in the model with full-mountains (Case 1) compared favorably to the observed distribution of temperature in January and July.

The difference in the surface temperature between the full mountain and no mountain simulations (Cases 1 and 2) is shown in Fig. 5. Differences exceed 5°C (and 3 standard deviations of the natural model variability) in the Asian continent, Africa, Andes, Rocky mountains, Iceland and Antarctica. Obviously, surface temperature is lower in the Tibetan Plateau and its downstream region in Case 1 but higher in the north of 60°N and South Asia in Case 1 than those in Case 2. These results are in better agreement with Ghan et al. (1982). Furthermore, the surface temperature in the west of North America is lower but higher in North America and Iceland in Case 1 than those in Case 2. And the surface temperature in the other regions in Case 1 is lower than that in Case 2. These results indicate that topography has an important influence on the global climate.

Comparing the temperature field for northern summer in Case 2 with that in Case 1, it is evident that the effect of mountains is to intensify the warm center maxima over Tibet and the Rocky Mountains in northern summer (June–August).

There is a major difference between the two models at 100 hPa in both winter and summer. The model with mountains (Case 1) fails to produce the cold tropics and the warm poles at 100 hPa in winter, and cold tropics and south pole and warm north pole regions in summer. Kasahara and Washington (1971) indicated that the winter deficiency is due to the upper boundary condition where the suppresion of vertical motion vanishes at the top boundary and prevents adiabatic cooling in the upper troposphere in the tropics. The summer time shortcoming can be attributed to the lack of solar heating absorbed by ozone in the troposphere. But it is noteworthy that the model without mountains is able to produce the cold tropics and the warm poles with the warmest middle-latitudes of the Northern Hemisphere in winter, the cold air occupied over low latitudes and the equatorial region and its warmest over poles at 100 hPa in summer. The difference in sign between the M and NM errors at 100 hPa makes it difficult to explain the shortcoming in the M model in terms of the upper boundary conditions alone.

3. *Zonal Wind*

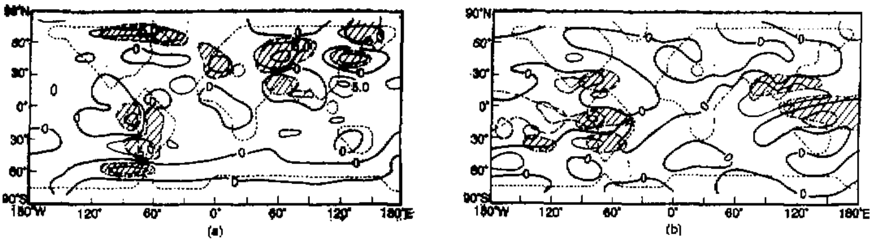
The simulation with full mountains by Otto-Bliesner et al. (1982) showed that the main features of the zonal wind distribution of the model (Case 1) in January and July agree reasonably well with the observations.

The difference between the zonal wind in the Case 2 and Case 1 at 900 hPa in northern winter (Fig. 6(a)) exceeds 5 m/s (and 3 standard deviations) over Asia, North America, South America and Iceland; whereas, at 300 hPa the major differences are over the zone around 30° N, South America and tropical Pacific (Fig. 6(b)). The presence of mountains causes the intensity of the jet stream over the southern side of the Tibetan Plateau to be significantly weakened and the jet over its northern side to be intensified with its position being shifted northward from about 30° N (Case 2) to 45° N (Case 1). In the Southern Hemisphere topography intensifies the easterly and westerly jets over South America. The local maximum of zonal flow on the eastern side of the lee trough of the Rocky Mountains is not significantly changed by the effect of mountains.

In northern summer, the presence of mountains significantly weakens the westerly and easterly jets over Asia continent and the neighboring Pacific and intensify them over North America and southern South America (see Fig. 6(c) and (d)). However, the inclusion of mountains significantly weakens the intensity of the zonal wind over central South America and Antarctica in the upper troposphere, in agreement with Mechoso's experiment (1981).

4. *Meridional Wind*

The 5-year simulation in the case 1 (Otto-Bliesner et al., 1982) shows that the model captures the general character of the observed meridional Hadley circulations in all the four seasons, but underestimates their intensity.



(a) (b)

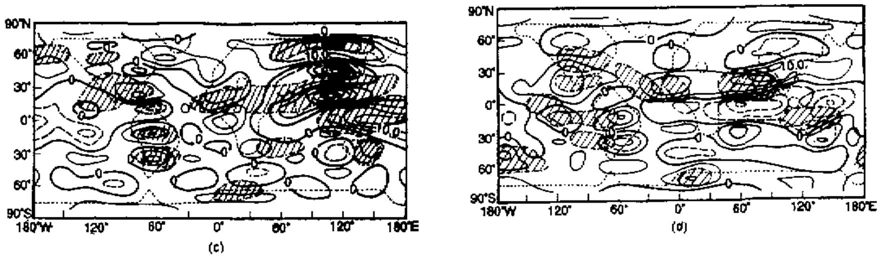


Fig. 6. Simulated zonal wind difference maps (Case 2 minus case 1). Contour intervals are 5 m/s. Solid lines are for positive differences; and dashed lines for negative differences. Statistically, significant areas at the 5% level are shaded. (a) 900 hPa for northern winter; (d) 300 hPa for northern winter; (c) 900 hPa for northern summer and (d) 300 hPa for northern summer.

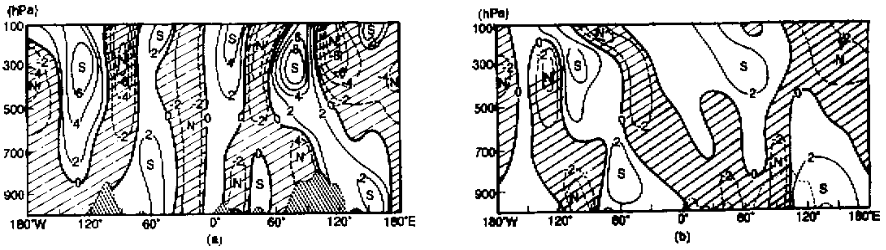


Fig. 7. Latitude-height distribution of the time-mean meridional wind (m s^{-1}) along the 45°N latitude circle: (a) Case 1 for northern summer and (b) Case 2 for northern summer.

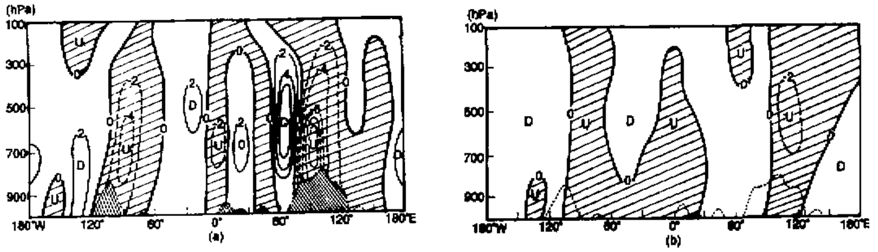


Fig. 8. Latitude-height distribution of the time-mean vertical motion (10^{-4}hPa/s) along the N45° latitude circle: (a) Case 1 for northern summer and (b) Case 2 for northern summer.

In order to depict the effects of orography on the meridional wind, a comparison was made of the longitude-height distributions of the time-mean meridional wind along the 45°N latitude circle for Cases 1 and 2 for northern winter (figure omitted). The mountains clearly have an influence on the distribution of the meridional wind, and shift the phases of the stationary disturbances half of a wavelength, particularly in the upper troposphere and stratosphere in agreement with Manabe and Terpstra's experiments (1974). However, it is noteworthy that the distribution of the meridional wind associated with the Aleutian and Icelandic lows and the meridional wind corresponding to Siberian high are weaker in Case 2 than in Case 1.

In the northern summer, the distribution of meridional wind corresponding to the ridge in middle and upper troposphere and the trough in the lower troposphere over both the Rocky

Mountains and Tibet is present in both cases. However, their positions are shifted and the magnitudes of meridional wind are intensified by mountains (Fig. 7(a), (b)).

These results suggest that mountains play a significant role both in the distribution of the meridional wind consistent with the maintenance of Aleutian and Icelandic lows and in the intensification of Siberian high in northern winter. The formation of the South Asian monsoon is dependent not on Tibet but on the general temperature contrast between the sea and land. A statistical test shows that all these effects of orography are significant at the 5% level.

5. *Vertical Motion*

The longitude-height distributions of the winter time-mean vertical velocity along the 45°N latitude circle in Cases 1 and 2, respectively, show that the strong upward motion over Tibet and Rocky Mountains in Case 1 and the downward and upward motion in Case 2, exist over the western and eastern Tibet respectively, and downward motion dominates over Rocky Mountains. The magnitudes of vertical motion with topography present are larger (figure omitted).

In northern summer, Tibet and the Rocky Mountains still play an important role in the distribution and intensification of vertical motion (see Fig. 8(a) and (b)).

The difference between the vertical motions at 900 hPa and 300 hPa in both cases in northern winter and summer exceeds 0.05×10^{-4} hPa/s over Tibet and Rocky Mountains, which is significant at the 5% level.

6. *Precipitation*

The major simulated precipitation area in northern winter and summer in Case 1 are in basic agreement with observations (Otto-Bliesner et al., 1982).

The difference between precipitation in Cases 1 and 2 exceeds 0.4 cm/d (and 3 standard deviations) in southern Asia, the North Indian Ocean, the Western Pacific, North America, the Mexico Gulf, the North Atlantic and South America in both northern winter and summer (figure omitted). The presence of mountains tends to increase precipitation. However, mountains decrease precipitation in the Indo-China Peninsula and North American Basin in northern summer and in the subcontinent of South Asia in northern winter.

The maxima of precipitation in Case 1 are larger than those in Case 2 and their distributions of Case 1 are much less zonal than those of Case 2.

In Case 2, the heavy precipitation areas in the south of North America, the west of Atlantic and Tibet decrease or disappear. These results indicate that mountains play a very significant role in the intensification of monsoonal precipitation as well as in the heavy precipitation in the south of northern America and the west of Atlantic in summer.

V. THE EFFECTS OF TOPGROAPHY ON HEAT SOURCES AND SINKS

Represented in Fig. 9 is the difference between the sensible heat in Case 2 and Case 1. Fig. 9a shows that in winter, with topography the intensity of heat sinks in the continents of North America and Asia is weakened, but sensible heat in the northern Pacific and Tibetan area is obviously weaker in Case 1 than in Case 2, while sensible heat is greatly increased in the North-western Pacific. Note that the intensity of sensible heat in the northern Atlantic is stronger in Case 2 than in Case 1. Comparing Fig. 10(a) with Fig. 10(b), it shows that in winter, the latent heat in the North-western Pacific is weak but there are strong latent heat areas in the northern Atlantic and the southeast of Asia continent in Case 1, respectively. But in Case 2, the latent heat in the same areas as Case 1 is much weaker than in Case 1. These results

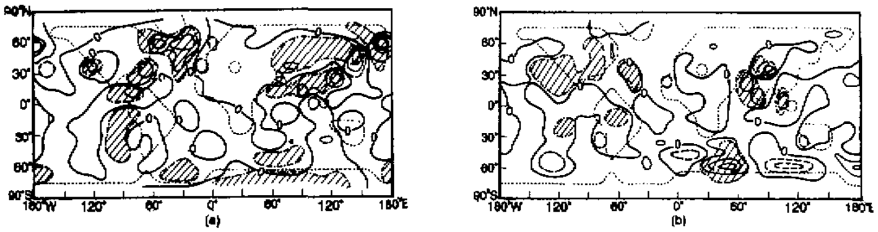


Fig. 9. (a) Sensible heat difference (Case 2 minus Case 1) in northern winter.
(b) sensible heat difference in northern summer.
Solid line, positive difference; dashed line, negative difference; contour intervals, 20 W/m^2; shaded areas, significant areas at the 5% level.

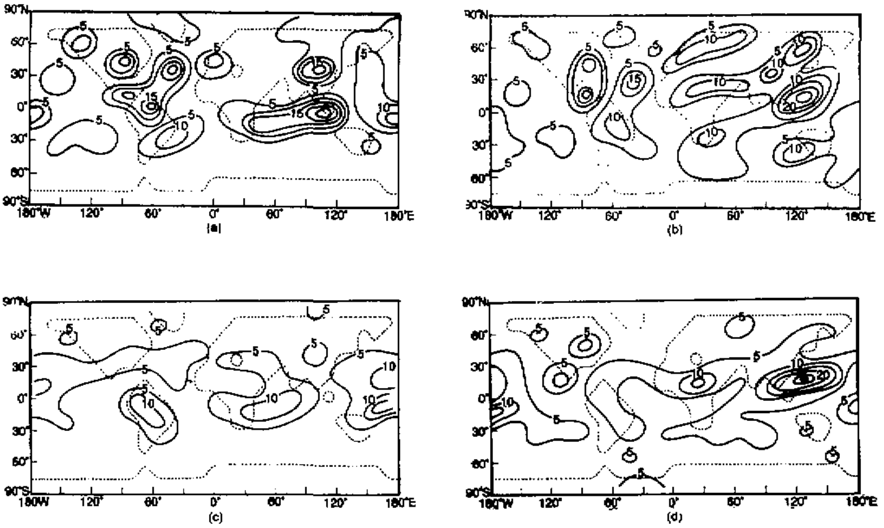


Fig. 10. Distribution of simulated latent heat. Contour intervals, 50 W/m^2. Units: 10 W/m^2. (a) Case 1 for northern winter; (b) Case 2 for northern winter; (c) Case 1 for northern summer and (d) Case 2 for northern summer.

suggest that the effects of topography on the two major heat sources corresponding to the Icelandic and Aleutian lows in the Northern Hemisphere in winter are evident: one is in the Northwestern Pacific and the southeast of Asia continent, and the other in the North Atlantic. Due to the presence of mountains, the sensible heat north of the first heat source area, and the latent heat south of this heat source area and in the second heat source area are increased, but the sensible heat in the second heat source area decreased. Furthermore, we emphasize the significance of the intensified Icelandic low with latent heat and the Aleutian low with sensible heat in winter when mountains are included.

Comparing distribution of heat sources and sinks in Case 2 in winter with those in Case 1, we can also see that topography significantly increases the sensible heat in the Siberian region although the increase amount is small. But the effect of topography on latent heat is statistically not significant. It is likely that the intensification of the Siberian high is not due to the thermal effect but to the dynamical effect of mountains, that is, the cold air is piled up over the northern Asia due to the block of the Tibetan Plateau.

In summer, mountains obviously increase sensible and latent heat in the Tibetan Plateau (see Fig. 9(b)). Fig. 9(b) and Fig. 10(c) show that, in Case 1, there is a strong summer heat source consisting of heating areas with sensible and latent heat in the Tibetan Plateau and with latent heat in North Africa, the southeast of Asian continent and the Pacific Ocean, and another heat source is in North America and Mexico Gulf. Apparently, there is also a close correspondence between these two heat sources and South Asian high in the upper troposphere and subtropical high in North America. However, the position, intensity and extent of these two heat sources are changed in Case 2; especially, sensible and latent heat centers disappear in the Tibetan Plateau. These results indicate that, in northern summer, the heat sources in the Tibetan region, northern Africa, North America and Mexico Gulf are intensified with the existence of mountains, and the heat sources thus intensified are very important for the intensification and position of the warm-anticyclone over the Tibetan Plateau, as well as of the ridge over Rocky Mountains; especially note that the center of South Asian high is just located at the center of sensible and latent heat in the Tibetan Plateau.

The simulations mentioned above clearly show that topography has an apparent influence on the intensity, distribution and characteristics of heat sources and sinks. This is because that, once the disturbances forced by topography are formed, it would exert effects on the distribution of heat sources and sinks. However, the heat sources and sinks have an influence on westerly and atmospheric circulation via the dynamical process of the atmosphere immediately. These results suggest that the interaction and interrelation between the effects of topography, heat sources and atmospheric circulation exist via the dynamical process of atmosphere, and that topography plays an important role in this process. All these results confirm the view points held by Yeh and Zhu (1958), but differ from those by Kasahara and Washington (1971), who concluded that orography plays a minor role compared to the thermal effect of continentality in determining the major features of atmospheric general circulation.

VI. CONCLUSIONS

In order to investigate the sensitivity of the low-resolution spectral model for global atmospheric circulation to orography, simulation tests with and without mountains have been performed. A comparison of the general circulation experiments with and without mountains has shown that the low-resolution global spectral model is able to simulate as well the effect of mountains on stationary disturbances as Manabe and Terpstra's (1974) and Kasahara and Washington's (1971) experiments with higher-resolution general circulation grid models. Our simulation suggests the importance of mountains for the maintenance of the Aleutian and Icelandic lows, and for determining the intensity and position of Siberian high in northern winter. The first conclusion is similar to Manabe and Terpstra (1974), who suggested that mountains are necessary for the successful simulation of the stationary flow field in the atmosphere. The second conclusion is consistent with both Manabe and Terpstra (1974) and Kasahara and Washington (1971). It appears that, in the Southern Hemisphere, mountains intensify the subtropical highs during December-February. In northern summer, the subtropical highs are intensified, while South Asia low is deepened, and their positions are in better agreement with observations when mountains exist in the Northern Hemisphere.

Simulations further suggest that, in winter, sensible heat is important for Icelandic low and latent heat for Alutian low, but the intensified Siberian high is due mainly to the dynamical effect of orography, whereas in summer, the increased sensible heat and latent heat in the

Tibetan Plateau and the latent heat in North America are important for maintenance of Southern Asian monsoon and the ridge over Rocky Mountains, respectively, when mountains are in volved.

Simulation tests also indicate that interaction and interrelation exist among the effect of orography, that of heat sources, and atmospheric circulation, via the dynamical process of atmosphere. Obviously, the effect of orography on the distribution of heat sources and sinks reflects the interaction and interrelation between them, and orography plays an important role in this process. These results confirm the view points held by Yeh and Zhu (1958), but differ from Kasahara and Washington (1971), who concluded that orography plays a minor role compared to the thermal effect of continentality in determining the major features of atmospheric general circulation.

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