THE ROLE OF THE QINGHAI-XIZANG PLATEAU IN FEEDBACK
MECHANISMS AFFECTING THE PLANETARY CIRCULATION

Elmar R. Reiter.

Professor of Atmospheric Science
Colorado State University

and

Ding Yi-Hui

Academia Sinica, Beijing
Visiting Scientist, Colorado State University

MASTER

Abstract

It has been recognized for some time that the Qinghai-Xizang plateau is of great importance in generating planetary long-waves which, in resonance with similar waves induced by the Rocky Mountains, lead to the familiar pattern of quasi-stationary Rossby waves observed on monthly-mean upper level pressure charts. Such waves have also been produced in experiments with fluids in rotating cylinders. The principle of conservation of potential vorticity, in first approximation, accounts for the effects of these large mountain ranges on the formation of planetary waves.

Seasonal forcing of flow patterns also appears to be particularly strong in the Qinghai-Xizang plateau region. It has been pointed out by various authors that the effects of an elevated heating surface, which this plateau represents especially after the snow-melt period of spring, trigger the northward movement of the subtropical high-pressure belt and the development of the summer monsoon, which is then maintained to a large degree by the release of latent heat.

Recent investigations suggest that the Qinghai-Xizang plateau may also be involved in feedback mechanisms which control in an important way the interannual variability of the general circulation of the

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atmosphere. The suggestion by Chen Lieh-Ting merits consideration, according to which snow cover in the plateau region might provide a "memory" for the earth-atmosphere system, by which the summer circulation over China following winters with excessive snow cover differs from that following winters with little snow. From work conducted in the People's Republic of China it appears that these circulation differences leave a measurable impact on the monsoonal weather patterns of most of southern and eastern Asia.

Our own investigations suggest that the "memory" between winter and subsequent summer circulations observed over the Qinghai-Xizang region may be part of a complex system of feedback mechanisms that involves, among other things, circulation characteristics of the southern hemisphere and air-sea interaction. It turns out that years with relatively few typhoons, compared to years with many typhoons, show upper-air circulation changes over the Qinghai-Xizang plateau similar to those observed between summers following snow-poor and snow-rich winters. These circulation changes seem to effect wide areas of the Pacific Ocean, the Indian Ocean, and even Africa. There are indications that the "southern oscillation", which modulates the intensity of the Walker circulation, is involved in the "teleconnections" underlying some of the observed circulation changes. This conclusion raises the suspicion that air-sea interactions, perhaps mainly through sea-surface temperature anomalies in equatorial and maybe also in temperate latitudes, are involved together with the thermal effects of the Xizang plateau, in the observed interannual variability of snow cover in the Qinghai-Xizang region, typhoon frequency, and other general circulation characteristics.

It thus appears that the effects of the Qinghai-Xizang plateau on the interannual variability of the atmospheric circulation over Asia, aptly described in some of the recent literature, are but one important manifestation of a network of feedback mechanisms, ranging from the El Niño problems along the Peruvian coast to droughts in the Sahel region. A better understanding of each of the mechanisms involved will lead us closer to successful long-range forecasting of some of the weather phenomena which have a considerable effect on local and regional economics.

We welcome the opportunity to exchange ideas with our colleagues from the People's Republic of China and to collaborate with them in the search for solutions to these difficult problems involving earth-atmosphere-ocean feedback mechanisms.

1. Introduction: Review of Problems

It has been recognized for some time that the Qinghai-Xizang plateau has an important influence on the seasonal behavior of the atmospheric circulation. The high mountain ranges offer a formidable barrier against the meridional and zonal flow of air masses, hence restrict the movement of fronts in the lower troposphere and of jet streams near tropopause level (Fig. 1) (Ramage, 1952).

Wagner (1931) pointed out that the Indian summer monsoon circulation reaches only to a height of about 5 or 6 km and does not represent the simple consequence of air masses rising in a "chimney effect" over a heated continent. The monsoonal flow patterns are closely tied to the jet-stream behavior which, in turn, is affected by the Qinghai-Xizang plateau.

During winter the westerly jet stream impinging on the mountain ranges tends to split into two branches (Fig. 1). The subtropical branch flows around the southern slopes of the Himalayas while the polar front jet flows around the northern edge of the plateau. Such jet-stream splitting has been observed by several authors (Yeh, 1950; Yeh and Koo, 1956; Yeh, Dao and Li, 1959; Academia Sinica, 1957, 1958a, b). Splitting of the jet stream can be explained from considerations of potential vorticity being conserved in flow over the mountains (Bolin, 1950; Charney and Drazin, 1961; Reiter, 1963, 1969). More about potential-vorticity conservation will be discussed later.

Yin (1949) found that the onset of the Indian summer monsoon is associated with the disappearance of the westerly jet stream south of the Himalayas (see also Yeh, Dao and Li, 1959). An easterly jet stream

takes its place (Koteswaram, 1958) along which travel the rain-producing monsoon disturbances. In September-October the reappearance of westerlies south of the Himalayas signals the sudden retreat of the monsoon (Reiter, 1959; Reiter and Heuberger, 1960; Koteswaram, 1958). Figure 2 gives an illustration of the suddenness with which a westerly jet-stream regime establishes itself south of the Himalayas.

Flohn (1964) showed that the thermal structure of the atmosphere over India and China during summer contains a warm core over the southern slopes of the Himalayas. It thus appears that the release of latent heat in monsoonal precipitation systems is an important energy source that maintains the upper-tropospheric circulation systems over Asia during summer. The heating of the Qinghai-Xizang plateau during spring, at best, is a triggering mechanism that brings into effect the onset of the monsoon. The maintenance of the monsoon is then largely due to latent-heat release along the foothills of the Himalayas.

In summary, we can ascribe the following effects to the Qinghai-Xizang plateau, hoping to find corroborating evidence for these effects:

- (a) Generation of planetary-scale wave disturbances.
- (b) Thermal effects on the atmosphere and its wave perturbations due to a large-scale elevated heat (cold) source, depending on season.
- (c) Anchoring of precipitation regimes into preferred locations, providing a certain amount of persistence to monsoonal weather regimes.

It is rather difficult to isolate the specific impact of the Qinghai-Xizang plateau from similar effects occurring elsewhere around the hemisphere. Planetary waves are also generated by the American Rocky Mountains. The wave-patterns resulting from both, the Himalayas and the Rocky Mountains, therefore, are expected to fulfill certain

resonance conditions, which will depend on the general nature of the (zonal) mean flow conditions in the atmosphere, hence are a function of time, especially of season. We also have to expect a certain amount of interannual variability in the purely orographically forced planetary wave behavior caused by changes in hemispheric jet stream strength from one year to the next, and changes in the attitude and latitude of impingement of these jet streams on the major mountain ranges. These factors are not so much controlled by topography but by thermodynamic forcing such as large-scale meridional and longitudinal temperature gradients. It has been shown, for instance, by Tucker (1960) that the torque exerted by mountain ranges on the general circulation of the atmosphere has a strong seasonal cycle for the two aforementioned reasons -- even though the mountains remain stationary. This seasonal effect prompts us to the conclusion that a certain interannual variability of mountain torque, and of planetary wave excitation by mountain ranges, should be expected.

Indications of the interannual variability of the mean zonal flow conditions in the atmosphere can be obtained from Fig. 3 which shows departures from the long-term means of monthly values of zonal available potential energy, A_z , averaged over the layer 1000 mb to 100 mb and over the hemispheric area poleward of 20°N . The behavior of A_z provides a measure of the fluctuations in the mean meridional temperature gradient which, in turn, drives geostrophically the mean zonal flow. That flow, however, controls the resonance conditions of orographically generated planetary waves.

Changes in the mean meridional temperature gradient also have a noticeable effect on other parameters characterizing the general circulation of the atmosphere. Korff and Flohn (1969, see Flohn, 1973)

have provided evidence that the position of the subtropical high-pressure belt moves equatorward with increasing meridional temperature gradient (Fig. 4). This observation has been used to argue that cooling trends confined to polar regions might lead to droughts in the regions south of the normal positions of the subtropical anticyclones, the Sahelian drought of the early 1970's being a primary example.

The thermal effects on the atmosphere and its planetary-wave behavior are not restricted to the Qinghai-Xizang plateau, but are experienced where there are significant heat sources and sinks. Moreover, most of these sources are subject to seasonal as well as interannual variability. Chen and Yan (1978) suggested that the interannual variability in the snow-cover of the Qinghai plateau might have an impact on large-scale circulation patterns. Research by Namias (1978), Barnett and Preisendorfer (1978) and Reiter (1978a, b, c; 1979a, b, c, d) points towards an impact of sea-surface temperature (SST) anomalies on large-scale circulation patterns. Kukla and Kukla (1974) investigated the possible effects of interannually varying continental snow cover on general-circulation variability. Charney (1975) developed a model that suggests the existence of a feedback between surface albedo and vertical motions entailing precipitation. From all these diverse pieces of evidence it appears that the possible thermal and albedo-related effects of the Qinghai-Xizang plateau will have to be viewed in the context of other forcing or feedback events elsewhere on the globe.

Similar reasoning holds for the precipitation regimes, monsoonal or otherwise, that appear to be anchored to the Himalayan region. The interannual variability of monsoonal precipitation along the southern slopes of the Himalayas undergoes considerable interannual variability,

so does the snowfall on the Qinghai plateau, as pointed out by Chen and Yan (1978). We have to suspect that other regions of the globe are implicated as well in these variabilities through far reaching feedback mechanisms involving relatively long time scales. It has been known, for instance, since the days of Walker (1924) that the "southern oscillation", i.e. the see-sawing pressure anomalies over the South Pacific and the South-Indian Oceans, relate to the Indian summer monsoon activity. Reiter (1979a) showed that the same southern oscillation is strongly related to the convergence between the North and South Pacific trade-wind systems and the precipitation which falls in the so-called dry region of the Equatorial Pacific, e.g. in the Line Islands region. The implied relationship between the Hadley and Walker circulations has been demonstrated by Chen (1977), Chen and Luo (1979) and Fu (1979). Cornejo-Garrido and Stone (1977) pointed towards the fact, that the Walker circulation in the Pacific appears to be driven by the release of latent heat, in agreement with the trade-wind and precipitation behavior found by Reiter. The suggestion by Fu that the Walker circulation behavior is related to SST anomaly variations is corroborated by the fact that trade-wind convergence, equatorial precipitation (Fig. 5), state of the southern oscillation (Fig. 6) (Berlage, 1966), and SST off the coast of Peru, indicating the occurrence of El Niño events (Fig. 7) all show a close interrelation. It should be regarded as more than coincidence that years with major El Niño occurrences also are characterized by major stratospheric polar-vortex breakdowns in the northern hemisphere (Reiter, 1980). Ding and Reiter (1980a, b) showed that the interannual variability of typhoon frequency in the Pacific is modulated by shifts

in subtropical and tropical pressure systems similar to the ones observed by Chen and Yan (1978) that characterize the variability of snowfall in the Qinghai plateau, as well as the interannual variability of polar-vortex behavior.

Thus we have mounting evidence that:

(a) The effects of the Qinghai-Xizang plateau on the circulation patterns of the atmosphere undergo considerable interannual variability;

(b) These effects are tied to a complex network of "teleconnections" involving atmospheric circulation characteristics in high and low latitudes, even in the southern hemisphere, and also suggesting feedback mechanisms with the oceans;

(c) Some of these teleconnections persist over time scales of several months, leading to seasonal anomalies in certain meteorological parameters, such as temperature, precipitation and tropical cyclone activity. We suspect that these persistent features in anomaly patterns involve not only regional forcing effects (such as albedo changes due to variations in the snowcover of the Qinghai plateau) but feedback mechanisms of much larger, perhaps hemispheric or even global scale. The same suspicion prompts us to the admission, that any effects that the Qinghai-Xizang plateau has on atmospheric structure and circulation, will not remain confined locally or even regionally, but will have hemispheric, perhaps even global reverberations. Therefore, the Qinghai region and its meteorology becomes an important concern for global climate research.

2. Theoretical Approaches

In trying to find an explanation for the observed distortions in the large-scale atmospheric flow which are seemingly produced by large mountain ranges, a number of theories have been advanced. A recent summary by Smith (1979) provides an excellent overview of this theoretical work. Charney and Drazin (1961) used vertically integrated quasi-geostrophic flow, subjected to numerous restrictions, such as stationarity of the perturbations, and background zonal winds constant with height. In spite of these simplifications, Charney and Eliassen (1949) and Bolin (1950) were able to reproduce a number of features in their model calculations that are actually observed in midlatitude flow patterns downstream from mountain ranges, such as the troughs to the east of the Rocky Mountains and of the Qinghai-Xizang plateau (Fig. 8).

In these earlier theories the shape of the mountains was chosen as

$$h(x,y) = h_m \cos \lambda y \cos kx \quad (1)$$

The distance between the bounding latitudes, at which the orographic effects were assumed to vanish, is π/λ . The inverse of the longitudinal scale of the mountains, k , must be chosen so that it fits with an integer number, n , of waves with length, λ , into the circumference of a latitude circle, $L = 2\pi a \cos \phi$ (a = earth's radius, ϕ = latitude). The condition for k , therefore, is

$$n\left(\frac{2\pi}{k}\right) = n\lambda = L \quad (2)$$

which is quite restrictive.

From the above-mentioned theory a stream function, $\bar{\psi}$, can be derived which describes the quasi-geostrophic mean tropospheric flow conditions around the hemisphere as a function of x and y

$$\bar{\psi}(x,y) = \left[\frac{f h_m / H}{k^2 + \ell^2 - \beta/U} \right] \cos \ell y \cos kx$$

(3)

The curves of constant values of $\bar{\psi}$ can be interpreted as streamlines of this highly simplified and idealized flow. ($f = 2 \Omega \sin \phi$, Coriolis parameter; Ω = earth's angular velocity; h_m mean height of the mountains; $H = \frac{1}{\rho_0} \int_0^\infty \rho(z) dz$ is the scale height of the atmosphere, i.e. the height of an atmosphere with constant density ρ_0 as observed at the surface, and with the same mass as the real atmosphere; β = change of the Coriolis parameter with latitude, approximated as being constant.)

The interesting conclusion emerges from Eqn. (3) that for mountains with relatively small longitudinal and meridional scales

$$k^2 + \ell^2 > \beta/U$$

(4)

Under such conditions, according to Eqn. (3), the amplitude expression in brackets will be positive, meaning that the streamlines will be displaced northward over regions of high ground and southward over regions with low ground. Planetary "long" waves are formed.

If however, the horizontal scale of the mountains is so large that

$$k^2 + \ell^2 < \beta/U$$

(5)

the inverse displacement of streamlines occurs, and "ultralong" planetary waves are formed (Fig. 9). Winter conditions in Asia seem to favor the formation of such ultralong waves, as the subtropical jet stream forms a trough in flowing around the southern edge of the Qinghai-Xizang plateau.

Near

$$\beta/U = k^2 + \ell^2$$

(6)

the amplitude in Eqn. (3) should become exceedingly large, representing a standing Rossby wave.

A Fourier decomposition of the actual topography of the earth (see e.g. Fig. 8) will force "ultralong" as well as "long" planetary waves which, according to linear theory, will be superimposed over each other, giving a rather complex atmospheric wave pattern. Since the condition of Eqn. (2) strongly restricts the waves that are allowed to form, it is unlikely that the resonance wave of Eqn. (6) will actually be excited. The flow will, however, be dominated by waves that approach this resonance condition.

Equation (3) not only contains forcing effects of the mountains, but admits the possibility of heat sources and sinks to act similar to mountain ranges by forcing a vertical motion pattern, such as for instance evident in the Walker and Hadley circulations over the Pacific, to be discussed later. Even though we have to assume that these motion patterns are weaker than those forced by high mountain ranges, the atmospheric response may be sizeable if the resonance conditions of Eqn. (6) are approached.

Continental and oceanic heat sources undergo considerable interannual variability, as will be demonstrated in the next chapter. If these heat source distributions can act to force long and ultralong planetary waves, as described by Eqn. (3) we have to anticipate strong interannual variability in the behavior of these wave patterns as well. Together with the orographic forcing component, in some years the resonance condition in Eqn. (6) will be more closely approached than in others, leading to interannual variabilities in the amplitudes, phase angles, and also in the stationarity aspects of such waves, even though the mountains themselves remain immobile.

More sophisticated planetary wave theories can be advanced (see e.g. Smith, 1979). The simple foregoing discussion suffices, however, to demonstrate the sensibility of certain planetary wave patterns to the combination of orographic and (variable) thermal forcing. This sensitivity presumably is the major cause of changes in the general circulation from one year to the next -- even over the major mountain regions of the northern hemisphere.

The theory sketched out briefly relies essentially on the quasi-geostrophic vorticity equation

$$\frac{d}{dt}(q + f) = -f \nabla_H \cdot \vec{v} \quad (7)$$

and the continuity equation

$$\bar{\rho} \nabla_H \cdot \vec{v} + \frac{\partial(\bar{\rho}w)}{\partial z} = 0 \quad (8)$$

[q = relative vorticity, f = Coriolis parameter, $\vec{v}$ = horizontal wind vector, w = vertical wind velocity component, $\bar{\rho}$ mean (constant) density of atmosphere, $\nabla_H = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y})$]. The vertical velocity distribution is forced by the flow over the mountains, so that

$$w_0 = u_0 \left(\frac{\partial h}{\partial x} \right)$$

(u_0 = zonal wind component on surface, h = height of mountain).

We can envision that thermal effects of continental and oceanic surface temperature distributions will also induce vertical circulation systems in meridional and zonal planes, hence can have an impact on harmonic solutions to Eqns. (7) and (8) as provided by Eqn. (3). In a rather crude sense, the global distribution of heat sources and sinks is envisioned to provide harmonic components of certain wave numbers and amplitudes to Eqn. (1) which, in turn, will influence the formation of long and ultra-long planetary waves and their possible resonant behavior as expressed by Eqn. (6).

One might scrutinize (zonal) Walker and (meridional) Hadley circulation cells over various regions of the globe as preliminary indicators of vertical circulations forced by surface heat source and sink distributions. One has to be careful, however, with the conclusions drawn from such an approach. Regional Walker and Hadley circulations are strongly influenced by the superposition of planetary wave patterns over that particular region, hence the heat source distribution, especially over the ocean, might be the consequence of, rather than the cause for, planetary wave patterns and their associated anomalies in Walker and Hadley circulations. The best interpretation that we can offer at this time is, that a feedback exists between planetary waves and oceanic (and perhaps also continental) heat source distributions (Reiter, 1979d; Middleton, 1980). This feedback can be assumed to be strong when Walker and Hadley circulations run faster than normal or have assumed anomalous positions and when the associated planetary wave patterns are relatively stationary. Weak feedback, most likely, is associated with less stationary, rather mobile planetary-wave patterns, hence with less well-expressed mean zonal and meridional circulation cells. A complicating factor arises from the fact that internal heat sources in the atmosphere, such as the release of latent heat, can contribute significant perturbations to the planetary-wave patterns. The Indian monsoon precipitation, mentioned in Chapter 1 may serve as an example.

In Fig. 10 the envisioned feedback mechanisms, indicated by closed loops in the path ways of lines with arrows, are sketched schematically. Unfortunately, our meteorological data base is all but plentiful. Therefore we cannot yet provide a quantitative model as a counterpart to

Fig. 10. For the same reason, much of the evidence presented in the next chapter is circumstantial at best.

3. Observational Evidence.

Figure 11 shows the Line Island precipitation index from 1910 to 1975. This index was computed and combined for the precipitation stations of Fanning Island, Washington Island and Christmas Island. It is defined by assigning the value of 100 to the wettest in a long series of months, say January, and the value 0 to the driest month in the same series. The interval between the wettest and driest month of January is thus divided into 100 units. The procedure is repeated for the other months of the year (Solot, 1950). This procedure eliminates the seasonal cycle and gives equal weight to dry and wet stations, as well as dry and wet seasons.

Similar data are shown for Nauru (Fig. 12) which lies much farther to the west. (Data courtesy of H. Flohn.) The agreement between the two sets of curves is demonstrated by the lag-correlation analysis of Fig. 13. There is also reasonable agreement with sea-surface temperature anomalies at Puerto Chicama (Fig. 7), as demonstrated by the lag correlations shown in Fig. 14.

From the agreement between the convergence of the Pacific trade winds and Line Island precipitation (Fig. 5) we are encouraged to conclude that during precipitation surges in the equatorial Pacific the Hadley circulation is stronger than normal in its surface component, namely the equatorward flow in the trade-wind region. A numerical general circulation model (GCM) experiment by Julian and Chervin (1978) suggested that another manifestation of the Hadley cell intensity, namely the strength of the subtropical jet stream over the Mexican Pacific coast, increases at the same time.

The Walker circulation, which represents the wind anomalies (Fig. 15) associated with the much larger southern oscillation of surface pressures (Fig. 16) indicates a rising branch over the equatorial East Pacific when waters are warm there, as they are during El Niño and heavy precipitation surges. Sinking motions are enhanced over Port Darwin and Djakarta during such periods (see Fig. 16, but compare also Figs. 6 and 7 with each other).

Our own investigations showed similar shifts in the equatorial Walker circulation associated with SST anomalies in the eastern North Pacific north of the equator (Figs. 17 and 18). Such an association would indicate a connection between El-Niño related SST changes in the Humboldt and South Equatorial currents with SST changes in the California and North Equatorial currents. Furthermore, important teleconnections between South and North Pacific regions would be indicated through the actions of the equatorial Walker circulation and the Hadley cells in that region. Such interhemispheric relationships, therefore, are not confined to the cross-equatorial monsoon flow over the Indian Ocean.

A negative correlation between equatorial Pacific precipitation surges and rainfall during the Indian summer monsoon becomes apparent from Fig. 15.

A negative correlation between snow accumulation over the Himalayas during winter and the subsequent monsoon rainfall has been noted by Walker (1923) (see WMO-ICSU, 1975). In agreement with this, Chen and Yan (1978) report that with abnormally high and long-lasting snow cover

over the Qinghai-Xizang plateau the establishment of the summer heat low and the upper tropospheric anticyclone appears to be delayed and weakened. The advance of the ITCZ trough from the Bay of Bengal into northern India is delayed accordingly, leading to a late commencement of the monsoon season. The tropical easterly jet stream over India during such years is found to the south of its normal position, so is the West Pacific subtropical high which, furthermore, extends farther to the west than normal. All these indicators mentioned by Chen and Yan (1978) point towards a Walker circulation as depicted in the lower portion of Fig. 15, indicative of a warm equatorial East Pacific. As shown by Figs. 17 and 18, such a Walker circulation also favors above-normal frequency of typhoon generation during the summer months (see Table 1) (Ding and Reiter, 1980a). This particular teleconnection is again in excellent agreement with statements by Chen and Yan (1978) pertaining to an increase of summer rainfall in Southern China subsequent to snow-rich winters in the Qinghai province. After all, typhoons contribute significantly to rainfall in southern China.

In line with what has been said in Chapter 2 we should not expect a perfect and consistent year-by-year match in the afore-mentioned teleconnections because of the complex responses of planetary waves to orographic and thermal forcing. With what little data we have, we attempted to match the anomalous number of days with snow cover at Heihe Station (dashed line in Fig. 19) with the Line Island precipitation index (Fig. 20). A time lag of the order of one year, with snow at Heihe leading precipitation in the equatorial Pacific, seems to yield the best match of peaks in the two sets of curves, with a notable exception in 1972/73. This time lag is quite bothersome because we cannot

think of a physical mechanism, especially for a continental region, that would provide for such a long "memory".

We have attempted another crude comparison, by superimposing the (inverse of the) Heihe snow-cover day anomalies over SST anomalies in the Atlantic, this time without a time lag (Fig. 21). Again, there is a hint of a correspondence in the two sets of curves. Rowntree (1976) has commented on possible European weather pattern responses to Atlantic SST anomalies in the tropics. The SST anomalies shown in Fig. 21 were observed at higher latitudes than Rowntree's and most likely are indicators of interaction between the ocean and atmospheric flow patterns, similar to those found over the Pacific (Reiter, 1978a, b, c, 1979a, b, c, d). We do not yet have positive proof of this hypothesis, but we are encouraged to speculate that Atlantic SST anomalies might affect planetary wave patterns even over the Asian continent. These SST anomalies might provide the "memory" affecting the correlation between snow cover on the Qinghai-Xizang plateau and the atmospheric circulation patterns over China during the subsequent summer.

Even though we have not yet attempted to quantify planetary-wave adjustments to the interannual variability of heat sources and sinks over oceans and continents, preliminary indications are that such adjustments may be significant. How else could one explain the large interannual variability in planetary-wave characteristics, unless one assumed random processes to dominate the long-term behavior of the atmosphere?

In a preliminary attempt to relate the activity of planetary wave numbers 1, 2, 3 and 4 to typhoon activity over the Pacific, we show in Fig. 22 the time sections of 500-mb height anomalies at 30°N for two

years with many typhoons (1967, 1972) and two years with few typhoons (1969, 1975). It becomes evident from these diagrams that the suppression of typhoon activity in the Pacific is associated with a strong and stable ridge near the date line. During the two years with many typhoons shown here the mid-Pacific trough is weak and is interrupted several times. The Atlantic ridge appears to be more stable than the Pacific ridge in the two examples shown here. It appears, that the relative westward shift of the equatorial Walker circulation during years with few typhoons (Fig. 17) is matched by a westward migration of the East Pacific long-wave trough. A coupling of SST anomalies, low latitude Walker circulation and planetary long waves, therefore, seems to be suggested by observational evidence.

Also shown in Fig. 22 are time-sections for the years 1962 and 1968 which, according to Fig. 19, were characterized by excessive snow cover in the Qinghai region and, according to Fig. 21, by relatively cold SST in the central North Atlantic. These two sections should be compared with the time sections for 1967 and 1972. During these years little snow prevailed on the Qinghai-Xizang plateau and the central North Atlantic was relatively warm. During the early part of 1967 and 1972 a strong and persistent planetary long-wave ridge covered the Atlantic warm-water region, indicative, perhaps, of blocking anticyclonic activity in that longitude sector. On the other hand, during the early part of 1968, with above-normal snow in Qinghai, the high pressure ridge near 120° - 110° W (Rocky-Mountain region) appeared to be more dominant. From Fig. 23 we find that relatively warm SST's prevailed off the coast of California during the winter of 1967/68, more so than during the winters of 1966/67 and 1971/72. The Qinghai-Xizang region (80° E) shows relatively more cyclonic (trough) activity during January 1962 and 1968 than

during the same month in 1967 and 1972. Moreover, relatively strong troughs prevailed during the early part of 1967 and 1972 over central and eastern Europe, downstream from the Atlantic blocking high, suggesting a planetary wave pattern of considerable amplitude west of the Qinghai region, and prevailing southwest winds aloft in the region between 30°E and 60°E . In the early part of the snow-rich years 1962 and 1968, on the other hand, the European trough was weak. During February and March anticyclonic conditions extended well into southeastern Europe. Figure 22 suggests that a zonal to northwesterly flow component by long planetary waves was the dominant feature of the 1967/68 winter along the western border of the Qinghai region.

We thus have preliminary evidence that SST anomalies in the Atlantic and Pacific oceans can interact in a significant way with planetary long-wave patterns, as postulated in Chapter 2. Furthermore, snow-cover characteristics on the Qinghai-Xizang plateau appear to respond to planetary long-wave characteristics. The albedo and atmospheric energy-budget modifications by a snow-covered plateau might conceivably produce an important feedback process with planetary-wave behavior. It might be more than coincidence that in March/April 1967 and 1972, following a snow-poor winter in the Qinghai region, anticyclonic conditions were established rapidly in the Asian sector (Fig. 22), whereas in April 1962 and 1968, following a snow-rich winter, relatively cyclonic conditions prevail in the same longitude sector. We, therefore, find ourselves in agreement with the important work conducted by several of our Chinese colleagues (Chen and Yan, 1978).

4. Discussions and Conclusions

In the foregoing chapters we have presented a rather simplistic theoretical outline of possible interactions of orographically forced planetary waves with hemispheric heat-source distributions. We envision that such interactions are enforced by vertical circulation anomalies in zonal and meridional planes, as evident from analyses of typical Walker and Hadley circulation patterns. Preliminary analyses of data in the Pacific region suggest that these circulation patterns seem to interact with sea-surface temperature (SST) anomalies.

Previous research on SST anomaly generation (for references see Reiter, 1979d) points towards an interaction between atmosphere and ocean, rather than a simple cause-effect relationship. Relatively long time scales are involved in the coherence patterns of Pacific SST anomalies, as described by Middleton (1980). Thus, the possibility of a long-term "memory" acting in the ocean-atmosphere system has to be considered in an explanation of the observed interannual variability of the atmosphere. Similar conditions of air-sea interaction have to be expected to exist in the Atlantic longitude sector.

If we allow for air-sea interaction processes to provide a linkage between SST anomalies and Walker as well as Hadley circulations in vertical planes, we will have to test the efficacy of various physical processes by which energy -- mostly in the form of sensible and latent heat -- can be passed between ocean and atmosphere. Such tests are most expeditiously conducted by coupled numerical ocean-atmosphere general circulation models, because the noise present in the observational data from the real world sometimes makes it difficult to judge the sensitivity of the general circulation system to external forcing. Numerical

investigations of this sort are presently in progress at various institutions in the United States, but are still a long way from providing us with definite conclusions on the precise functioning of the ocean-atmosphere-continent system.

The Walker and Hadley circulations may well be linked to SST anomaly patterns, as suggested by evidence presented in Chapter 3. These circulations do not stand by themselves, however, but are an integral part of the quasi-stationary planetary long-wave pattern. As such, these circulations become links in far-reaching "teleconnections", which provide seemingly significant correlations between weather patterns and anomalies over distant parts of the globe.

If a linkage of Walker and Hadley circulation anomalies, hence of planetary wave patterns, to SST anomalies can be surmised from observational evidence, continental surface heat budget and atmospheric temperature anomalies should be coupled to similar adjustments in planetary wave patterns. Convincing evidence to that effect has been presented by our Chinese colleagues (op. cit.). Again, we will have to take recourse to numerical or laboratory model experiments to be able to separate orographic perturbations from thermal forcing. We are easily convinced, however, that the Qinghai-Xizang plateau is a unique region on our globe, in which thermal forcing superimposed upon orographic forcing, can achieve large interannual variability that will not remain unnoticed in other parts of the northern hemisphere, and perhaps even of the globe. For this reason, a detailed investigation of the atmospheric heat budget over the plateau and over adjacent upstream and downstream regions is strongly advocated.

In spite of the prominent effect of the Qinghai-Xizang plateau on atmospheric circulation patterns and their variability, we cannot afford

to isolate these effects from other forcing effects, notably of air-sea interaction. Planetary wave patterns, by virtue of their dynamics and their resonance capabilities, are sensitive to all forms of forcing, and not only to orographically generated perturbations alone. Figure 21 has provided an interesting, albeit not conclusive, glimpse of an interplay between oceanic and continental interaction with the atmosphere.

The main results of our study can be summarized as follows:

(a) Long and ultra-long planetary waves in the atmosphere are forced not only by the large mountain ranges but also by heat sources and sinks.

(b) Interannual variability in these long-wave patterns, hence in seasonal and regional weather anomalies, can be produced by changes in the heat-source distribution, notably by shifts in SST anomaly patterns and by changes in the albedo characteristics of the Qinghai-Xizang plateau.

(c) Planetary-wave adjustments are not confined to a limited region but produce "teleconnections" between weather anomalies over distant parts of the globe. Snow cover in the Qinghai region seems to be linked to SST anomalies over the central North Atlantic, blocking activity in that region, and trough intensity over Europe. In agreement with earlier conclusions by Chinese scientists, the development of an anticyclone over Tibet during spring seasons following snow-rich winters appears to be delayed and weakened. Shifts in long-wave patterns also affect the Pacific longitude sector and are directly reflected in the typhoon activity.

(d) Pacific typhoon frequency is also modulated by SST anomalies in tropical and subtropical regions of the East Pacific. Walker and Hadley circulations appear to be linked to these SST anomalies as well.

(e) Shifts in Walker and Hadley circulations are reflected in phase shifts of the long and ultra-long planetary waves. A feedback mechanism between these waves and SST anomalies is indicated. Inter-annual variability of planetary wave characteristics appears to be the cause of snowfall variability on the Qinghai-Xizang plateau which, in turn, also can exercise a feedback effect on planetary waves. Thus a complex pattern of interactions between continents and mountain ranges, oceans, and the atmosphere evolves.

(f) These interactions are by no means fully explained by our study but have to remain the target of further exploration using observational data, laboratory experiments and numerical modelling approaches.

(g) The Qinghai-Xizang plateau not only is a forceful source of perturbations affecting the global atmospheric circulation; its meteorological characteristics also respond to forcing processes that occur elsewhere on the globe. The high plateau, thus, symbolizes the rôle of the Middle Empire (中國) in history: for millennia it has provided global civilization with an inexhaustible source of culture, yet it has not shunned impulses for advancement that came from outside its borders.

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Fig. 1. Frequency of jet streams at the 500-mb level (1949 and 1950) and topographic cross section along 80°E. (Ramage, 1952 in Jet Stream Meteorology, Reiter, 1963.)

Fig. 2. Time section of the New Delhi rawin, September and October, 1954. Solid lines indicate the division between easterly and westerly components of flow. Wind speeds >40, 60, 80, 100 are marked by different hatching. (Reiter and Heuberger, 1960.)

Fig. 3. Departures of monthly mean values of A_z (upper portion of diagram) and of the sum of zonal available potential energy (A_E), zonal kinetic energy (K_z) and eddy kinetic energy (K_E) (lower portion of diagram) in 10^5 J m^{-2} from their respective long-term monthly mean values. Dots and thin lines represent actual monthly mean values, heavy lines were obtained by application of a seven-month running-mean filter. Vertical coordinate lines indicate the month of January of each year. (Reiter, 1979d.)

Fig. 4. Correlation between geographic latitude (ϕ_s) of the subtropical high-pressure belt and the mean tropospheric (300-700 mb) temperature gradient between equator and pole (after Korff and Flohn, 1969, from Flohn, 1973).

Fig. 5. Mean Pacific trade-wind v-component anomalies $(-v_{N.H.} + v_{S.H.})/2$ (heavy line), and precipitation index for Line Island (thin line). This index is obtained by assigning the value 100 to the largest positive monthly anomaly at the station, and the value 0 to the largest negative anomaly. The remainder of the anomalies are distributed according to their percentile between 0 and 100. This procedure gives equal weight to dry and wet stations and to dry and wet seasons. Seven-month smoothing was applied to both curves. The heavy smooth lines represent a least-squares, third-order polynomial fit.

Fig. 6. Southern oscillation, as indicated by surface pressure anomalies at Jakarta, Indonesia. (From Berlage, 1966.)

Fig. 7. Monthly anomalies of sea-surface temperature ($^{\circ}\text{C}$) from the long-term (52-year) mean (thin lines) and 7-month running-mean values of SST anomalies (slightly heavier lines).

Fig. 8. The tropographic profile (bottom) and the observed (solid line) and computed (dotted line) 500-mb heights at 45°N (top). (After Charney & Eliassen, 1949). Mean zonal wind is chosen at 17° longitude/day and the north-south distance between bounding latitudes is 33°. (From Smith, *Advances in Geophysics*, Vol. 21, 1979.)

Fig. 9. The orographic perturbations to a westerly wind according to the vertically integrated model.

For $\bar{k}^2 = k^2 + l^2 > \beta/U$, the pressure disturbance and meridional streamline displacement are in phase with the orographic height (so-called long-wave behavior). For longer waves

($\bar{k}^2 < \beta/U$) there is southward displacement and low pressure over the mountain regions (so-called ultralong wave behavior). (Smith, 1979, in *Advances in Geophysics*, Vol. 21, 1979.)

Fig. 10. Schematic diagram of feedback between orographically forced planetary waves, latent and sensible heat sources over continents and oceans.

Fig. 12. Precipitation index for Nauru for the years 1892 (= -8) to 1972. Thin lines indicate monthly values, heavier lines stand for a 7-month running average. (Data courtesy H. Flohn.)

Fig. 11. Line Island precipitation index for the years 1910 to 1975. Dots indicate monthly values, the heavy line stands for a 7-month running average. (Data from Meisner, 1976.)

Fig. 13. Lag correlations between monthly precipitation index values for Line Island and Nauru. Dots indicate correlations obtained from individual monthly values, the solid curves give correlations between 7-month smoothed data sets.

Fig. 14. Lag correlations between monthly anomalies of sea surface temperature (SST) for Puerto Chicama and precipitation index for Nauru (upper panel) and Line Islands (lower panel).

Fig. 15. Schematic representation of the Walker Circulation. The top panel applies with normal cold water off the South American coast. The wind arrows denote actual average departures from normal of the zonal winds at 200 and 850 mb (or 700 mb) for Cocos Island, Port Darwin, Canton Island and Lima, Peru. The departures from normal are in meters per second. The bottom panel indicates the composite anomalies during the El Niño warm water months. (Julian and Chervin, 1978.)

Fig. 16. Schematic map (after Berlage, 1966) showing isopleths of correlation of monthly mean station pressure with that of Djakarta, Indonesia (Dj). Other localities shown are Coco Island (CO), Port Darwin (D), Nauru (N), Ocean Island (O), Palmyra (P), Christmas Island (X), Fanning (F), Malden Island (M), Apia, Samoa (A), Tahiti (T), Easter Island (E), Puerto Chicama (PC), Lima (L) and Santiago (S). (From Julian and Chervin (1978).)

Fig. 17a. The equatorial Walker circulation over the Pacific ocean, averaged over the latitude band 5°S to 5°N . Upper panel is for 1975, a year with few typhoons. Lower panel is for 1972, a year with many typhoons.

Fig. 17b. Similar to Fig. 17a, except for 1969 and 1967.

Fig. 18. Sea-surface temperature anomaly (SSTA) patterns for (a) summer of 1975; (b) summer of 1972; (c) summer of 1969; (d) summer of 1967; (e) spring of 1975; (f) spring of 1972; (g) spring of 1969; (h) spring of 1967. Dashed lines denote negative anomalies, thin solid lines denote positive anomalies, and slightly thicker lines are zero-isolines of SSTA.

Fig. 13 (continued)

Fig. 18 (continued)

Fig. 19. The interannual variability in the anomaly of the number of days with snow cover (%) over the Tibetan plateau (averaged for 3 regions with much snow cover) and at Heihe Station. Years are indicated for each January of respective winter season. (Chen and Yan, 1978.)

Fig. 20. Percent anomaly of days with snow cover at Heihe Station (dashed line with years marked near dots) and Line Islands precipitation index (thin line: monthly values; slightly heavier line: 7-month running mean).

Fig. 21. Percent anomaly of days with snow cover at Heihe Station (dashed line and dots plotted in the corresponding winter season) and Atlantic sea-surface temperature anomalies at 40°N 40°W , showing monthly data (thin line) and 7-month running means (slightly heavier line).

Fig. 22. Time section of 500 mb-heights, truncated after planetary-wave number 4, at 30°N. Abscissa is marked for every 10° of longitude; each dash along the ordinate corresponds to a five-day period. Months are labelled on the right side of each diagram. The year is given on top of each diagram. Isolines are drawn at intervals of 50 m of geopotential height. Low-pressure anomalies are shaded.

Fig. 22 (continued)

Fig. 22 (continued)

Fig. 22 (continued)

Fig. 22 (continued)

Fig. 22 (continued)

Fig. 23. Filtered time series (cut-off period ca. 15 months) of the trade wind convergence $(-v_{N.H.} + v_{S.H.})/2$ in m/sec in the West Pacific (5°N - 19°N , 1°S - 15°S ; west of 160°W), the full Pacific (same latitude bands), and the East Pacific (same latitude bands, east of 160°W); filtered series of the Line Islands precipitation Index expressed as ranging from -50 (dry) to +50 (wet), and of SST anomalies ($^{\circ}\text{C}$) at various grid points as indicated. Years are plotted along the abscissa. (Filter design and computations by J. Middleton.)