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青藏高原在影响行星环流反馈机制中的作用

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提　要

一些时间以来，人们认为，青藏高原对于产生行星长波具有很大的作用，这种长波与洛矶山脉形成的类似波动发生谐振，一起形成了在高空月平均气压形势图上观测到的熟悉的准静止罗斯贝波型。这种波动在旋转圆筒流体实验中也能产生。作为第一近似位势涡度守恒原理可说明这些大山脉在形成行星波中的作用。

在青藏高原地区，对流型的季节强迫作用是很强的。许多作者指出，在春季融雪之后，高原加热地表的作用特别显著，可启动副热带高压带向北移动和夏季风发展。这些环流以后在很大程度上是靠潜热释放来维持的。

最近研究提出青藏高原也可能被包含在以一种重要方式控制大气环流年际变化的反馈机制中。陈烈庭的看法值得注意，他认为高原上雪盖可能为地—气系统提供一种"存储器"，以此使中国上空的夏季环流在多雪盖冬季后的情况不同于少雪盖冬季后的情况。从中华人民共和国进行的工作看来，这些环流的差异对南亚和东亚大多数地区的季风天气型带来显著的影响。

我们自己的研究提出，这种在青藏高原上观测到的冬季和来年夏季环流之间的"存储器"，可能是包括南半球环流特征和海气关系等在内的复杂反馈机制系统中的一部分。从少台风年和多台风年对比研究表明，它们分别与少雪年和多雪年后的夏季在青藏高原上空的环流变化相似。这些变化似乎影响到太平洋、印度洋甚至非洲的广大区域。有迹象表明，调整沃克环流强部的"南方涛动"与用来说明某些观测到的环流变化的"遥相关"有关系。从这个结论可以推测，由赤道也可能由温带的海温异常所表示的海气相互作用以及西藏高原的热力作用都与青藏高原上观测到的雪盖年际变化、台风频率以及其它环流特征有关系。

近年来论述甚多的有关青藏高原对亚洲上空大气环流年际变化的影响，仅仅是秘鲁海岸的爱厄尼诺问题和萨赫勒地区干旱等大气反馈机制中的一种重要表现。如果我们能深入理解上述各种现象的机制，将会使我们对某些地区的国民经济有显著影响的天气现象作出较为成功的长期预报。

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

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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 (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. 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 jetstream 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 Himalayes signals the sudden retreat of the monsoon (Reiter, 1959; Reiter and Heuberger, 1960; Koteswaram, 1958).

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,

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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. 1 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. 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 signi-

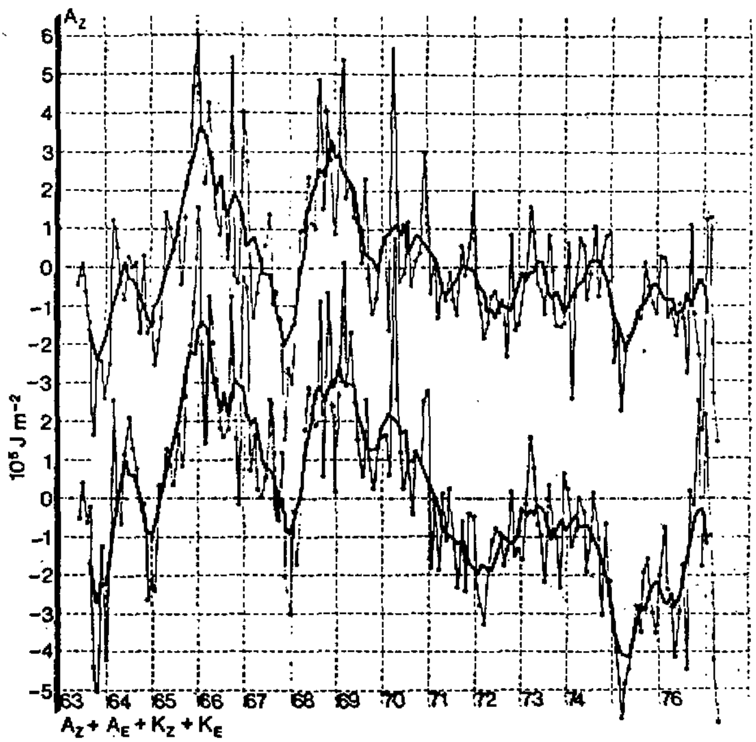

Fig. 1. Departures of monthly mean values of A_Z (upper portion of diagram) and of the sum of zonal available potential energy (A_E), zonal kinetic energy (K_Z) and eddy kinetic energy (K_E) (lower portion of diagram) in 10^5 Jm-2 from their respective long-term monthly mean values. Dots and thin lines 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.)

ficant 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. 2), state of the southern oscillation (Fig. 3) (Berlage, 1966), and SST off the

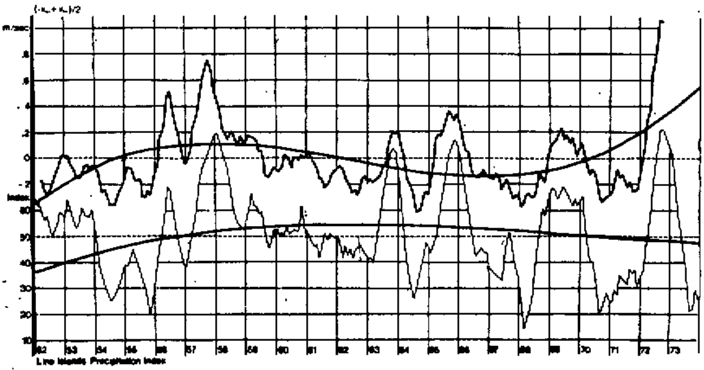

Fig. 2. Mean Pacific trade-wind v-component anomalies $(-v_{N.H.}+v_{S.H.})/2$ (heavy line), and precipitation index for Line Island (thin line). This index is obtained by assigning the value 100 to the largest positive monthly anomaly at the station, and the value 0 to the largest negative anomaly. 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.

coast of Peru, indicating the occurrence of El Niño events (Fig. 4) 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 stratopsheric 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

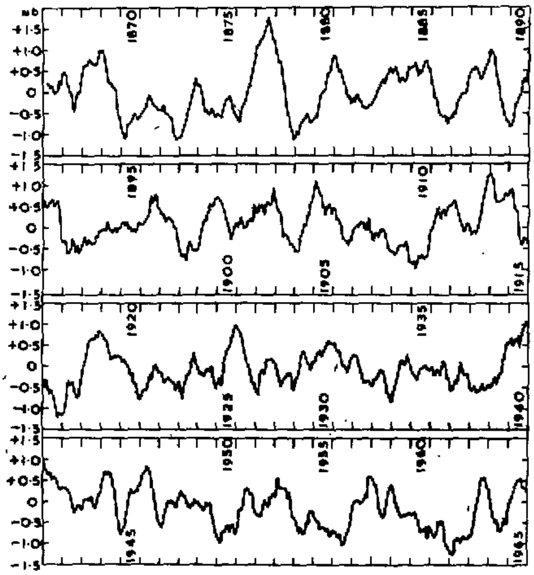

Fig. 3. Southern oscillation, as indicated by surface pressure anomalies at Jakarta, Indonesia. (From Berlage, 1966.)

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

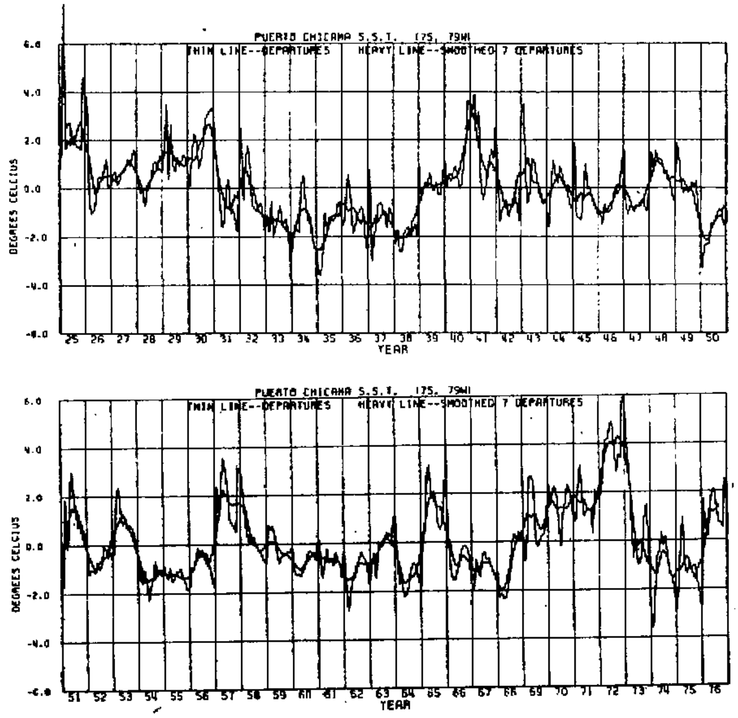

Fig. 4. Monthly anomalies of sea-surface temperature (°C) from the long-term (52-year) mean (thin lines) and 7-month running-mean values of SST anomalies (slightly heavier lines).

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 quasigeostrophic 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 actualy 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.

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

$$h(x, y) = h_m \cos ly \cos kx \tag{1}$$

The distance between the bounding latitudes, at which the orographic effects were assumed to vanish, is π/l. 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

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

which is quite restrictive.

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

$$\Psi(x, y) = \left[\frac{fh_m/H}{k^2+l^2-\beta/U}\right]\cos ly \cos kx \text{ for } -\frac{\pi}{2} < ly < \frac{\pi}{2} \tag{3}$$

The curves of constant values of Ψ 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; 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

$$k^2+l^2 > \beta/U \tag{4}$$

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

$$k^2+l^2 < \beta/U \tag{5}$$

the inverse displacement of streamlines occurs, and "ultralong" planetary waves are formed (Fig. 5). 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

$$\beta/U = k^2+l^2 \tag{6}$$

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

A Fourier decomposition of the actual topography of the earth 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.

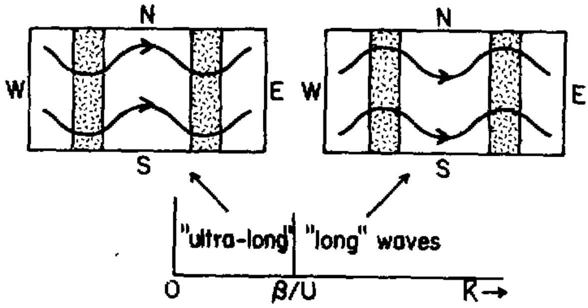

Fig. 5. The orographic perturbations to a westerly wind according to the vertically integrated model. For $\bar{k}^2 = k^2 + l^2 > \beta/U$, the pressure disturbance and meridional streamline displacement are in phase with the orographic height (so-called long-wave behavior). For longer waves ($\bar{k}^2 < \beta/U$) 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.)

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). Th esimple 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.

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 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 circulation 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 I may serve as an example.

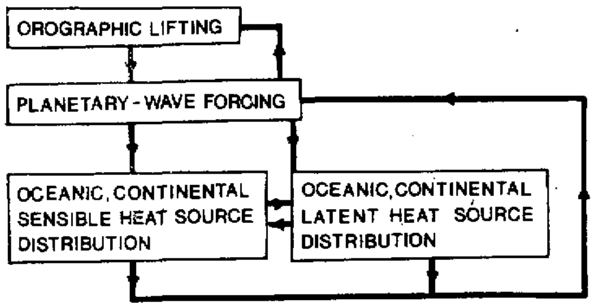

Fig. 6. Schematic diagram of feedback between orographically forced planetary waves, latent and sensible heat sources over continents and oceans.

In Fig. 6 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. 6. For the same reason, much of the evidence presented in the next chapter is circumstantial at best be continued.