Angular Momentum Cycle in the Atmosphere–Ocean–Solid Earth System*

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Abstract

Some of the contributions of Victor Paul Starr (1909–76) as a scholar and teacher at the Massachusetts Institute of Technology are described. His work on the atmospheric branch of the earth's angular momentum cycle is emphasized. Certain recent efforts to include the oceanic and solid earth branches of the cycle are discussed.

1. Introduction

The invitation to give the 1988 Victor P. Starr Memorial Lecture has been an unique opportunity for me to express my appreciation for a great scholar and teacher (figure 1).

In the first part of this lecture I will attempt to analyze what it takes to be an inspiring teacher and to arouse the innate curiosity and creativity of a student, using Victor Starr's educational approach as a guide. In the second part, I will look at one aspect of the climatic system that deals with the angular momentum cycle and describe some of the recent progress that has been made in understanding the budget of angular momentum—a topic that was very close to Starr's heart. Then, I will present some thoughts on future challenges in climate research.

2. Victor Starr as a teacher, scholar

Professor Starr was a very inspiring teacher. He evoked in his students both a sense of curiosity and the confidence to undertake basic research. Of course, it is crucial for an incoming student to experience that he or she can do original work. Professor Starr was always accessible to his students. He had great patience and helped his students to overcome their initial trepidations of doing research. He impressed on them the fact that it was not necessary to solve a "big" problem to contribute. In fact, under his guidance a "small" idea or "small" observational fact distilled from the data often proved to be the necessary building block toward solving the "big" problem.

FIG. 1. Victor Paul Starr, 1909–76; scholar and teacher at MIT between 1947 and 1976.

Let me quote from the Massachusetts Institute of Technology (MIT) *Technology Review,* where Newell (1974), on the occasion of Starr's retirement from MIT, describes how Starr used to introduce his students to the main laws of physics on which all our research is based.

> His lectures are deceptively low key: the principles of conservation of energy, angular momentum, and mass as applied to atmospheres and oceans diffuse into one's mind, and one knows his courses with a realization that meteorology is solidly based as a quantitative science. He convinces students, almost imperceptibly, that the constraints set by the conservation principles produce a beautiful degree of order which is always just under the surface of descriptive meteorology. His enthusiasm for always examining the degree to which the real atmosphere and ocean, as observed, obey the basic principles is highly infectious. Theory is never divorced from reality, and both have to be considered simultaneously for the best overall understanding.

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However, there are also other elements of Starr's approach, such as his state of mind, which were always open to new results that do not fit our preconceived notions. He taught his students to let the data speak for themselves, unbiased by the analysis scheme, and to accept nature's solution, and not to force it to fit their ideas of how the system "should" work.

Perhaps this state of mind is similar to what Suzuki (1970) calls "Zen mind, beginner's mind." "If your mind is empty, it is always ready for anything; it is open to everything. In the beginner's mind there are many possibilities; in the expert's mind there are few."

Starr cultivated this open mind in both himself and his students. He had boundless patience with beginning students who could still see many possibilities. He also accepted a great and unusual variety of students and co-workers from many nationalities, disciplines, and backgrounds.

In addition to an open mind, Starr's approach included the element of daring to take risks. Starr worked on problems of almost any scale, ranging from ocean gravity waves to hurricanes, the general circulations of the atmosphere and oceans, other planetary atmospheres, the sun, the solar system, up to the scale of galaxies. He applied, for example, the basic physical constraints of angular momentum balance to many of these systems, arriving at far-reaching, profound conclusions.

I learned from Professor Starr to focus especially on discrepancies between theory and actual data as well as on any unexpected results which will point to either mistakes and biases in our data sample and analysis scheme, or to a new finding that might require modifying or even relinquishing our original notions. Of course, after the original exciting and often provocative results have been obtained, there follows the long, more tedious, but necessary process of taking independent samples and changing the computing and analysis techniques in order to test whether the new findings will stand up under further scrutiny. To my surprise, the results from a well-conducted pilot study usually give basically the correct answer. Further work will tend to confirm the preliminary results, lead to refinements, and also often lead to unexpected extensions and generalizations of the original ideas. Let me give as an example one of Starr's most important findings, the discovery of "negative" viscosity (Starr 1953, 1968) in a great variety of natural systems. Negative viscosity, manifested by a countergradient transfer of momentum from the large-scale eddies to the mean flow, was discovered first in the atmosphere, and later in the oceans, in laboratory models of the general circulation, in Jupiter, and even in the Sun. It is clear that our present knowledge base of the earth's climate system found its firm beginnings in the decades (1950–70) of research at MIT under the direction of Victor Starr (see, e.g., Starr 1954, 1957, 1959, 1963, 1966; Buch 1954; Starr and White 1954; Peixóto 1958, 1960; and Starr and Saltzman 1966).

3. The angular momentum cycle

The angular momentum budget of the earth represents a beautiful and simple example of how the various climatic elements (atmosphere, oceans, and solid earth) work together and are united through a basic physical conservation law, despite enormous differences in their space and time scales and in their masses. Let me begin by recapitulating our first conception of the angular momentum cycle, largely developed by Starr and his co-workers, and then discuss what has been added since.

What is angular momentum? Basically, it is the component of the angular momentum vector that is parallel to the earth's polar axis. In the case of the atmosphere it has two components, one connected with the solid rotation of the earth, the Ω-angular momentum, and the other with the zonal component of the air flow with respect to the rotating earth, the relative angular momentum: $M = M_\Omega + M_r$ (see figure 2). Most of the temporal variability is found in the relative angular momentum.

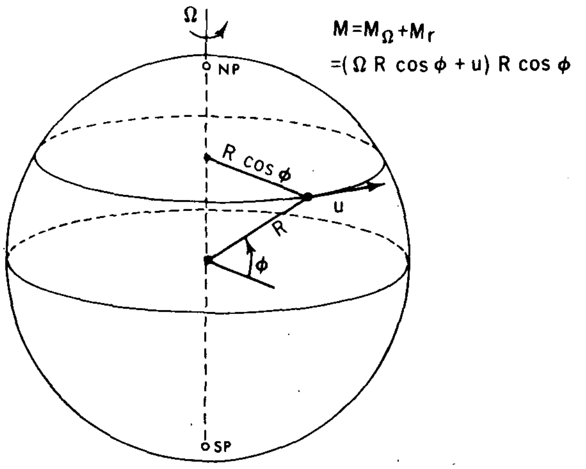

FIG. 2. Schematic diagram of the atmospheric angular momentum around the earth's axis of rotation, $M_{atm} = M_\Omega + M_r$, where $M_\Omega = \Omega R^2 \cos^2\phi$, $M_r = uR\cos\phi$, Ω = angular velocity of the earth, R = mean radius of the earth, ϕ = latitude and u is the eastward (zonal) wind component.

a. *Global atmospheric angular momentum and the length of day*

Considering the earth as a whole, the angular momentum integrated over all the masses of the solid earth, oceans, and atmosphere combined is conserved, assuming external torques (due to the moon and sun) to be negligible at the time scale of months to decades in which we are interested here. Thus, the total angular momentum of the system does not vary with time, and if there would be changes in one component, say the atmosphere, there would have to be compensating changes in the other components so that the total angular momentum is conserved:

$$dM/dt = 0,$$

where

$$M = M_{atm} + M_{oceans} + M_{ice} + M_{crust} + M_{mantle} + M_{core}$$

It has been well known for some time that substantial changes in the relative angular momentum of the global atmosphere are observed to occur at the time scale of days, months, years, decades, and even longer. Recently it has been firmly established that there is a close compensation with the changes of the angular momentum of the solid earth on time scales of days to years and that the oceans and snow and ice do not play an important role in this. These changes in the solid earth are readily observed as changes in the length of day (LOD); for example, an increase in angular momentum of the earth corresponds with a decrease in the LOD.

Traditionally, the LOD data are obtained from astronomical measurements, but recently have also been obtained from lunar or satellite laser measurements. A comparison between a 10-yr record of the LOD (dashed curve) and the global-mean angular momentum of the atmosphere (solid curve) is shown in figure 3 from a recent study by Richard Rosen and David Salstein, both former students and coworkers of Victor Starr (Rosen 1988). The two independent datasets confirm the expected relationship at all time scales, except for a slow trend in the LOD data and occasional, still largely unexplained differences. The slow negative decadal trend in LOD is opposite in direction to the expected very long positive trend of about 2 ms/century connected with tidal friction and the earth-moon torque (see figure 4). The decadal trends are thought to be associated with the coupling between the earth's crust and the underlying mantle and core (see figure 5). The occasional discrepancies between the two curves in figure 3 may be caused by the neglected storage of angular momentum in the oceans, ice caps, and snow masses, or may be due to inaccuracies in the determination of M_{atm} and LOD.

Because the changes in the earth's rotation rate are exceedingly small, i.e., changes in the earth's velocity at the equator are on the order of only a few micrometers per second compared to atmospheric velocities on the order of a few meters per second,

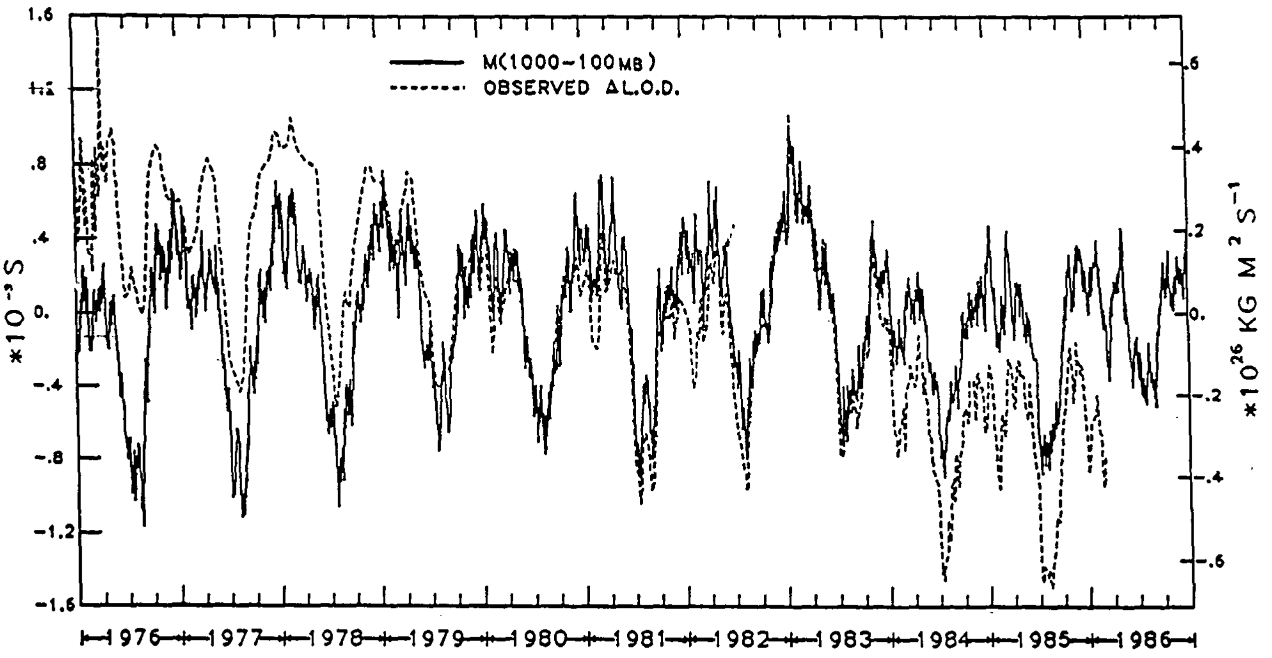

FIG. 3. Time series of daily values of the relative westerly angular momentum M, of the global atmosphere between 1000 and 100 mb based on NMC analyses (solid line), and 3-day means of the length of day (LOD; dashed line) for the years 1976–86. The mean value of each series has been removed, as have solid body tidal terms from LOD (from Rosen 1987).

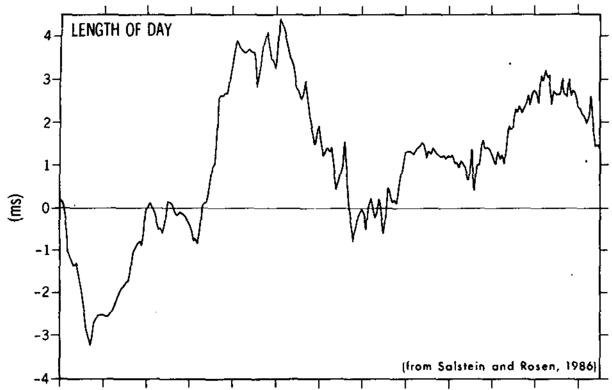

FIG. 4. Time series of semiannual values of LOD during 1860–1985, taken from the work by McCarthy and Babcock (1986). A mean annual signal has been subtracted (from Salstein and Rosen 1986).

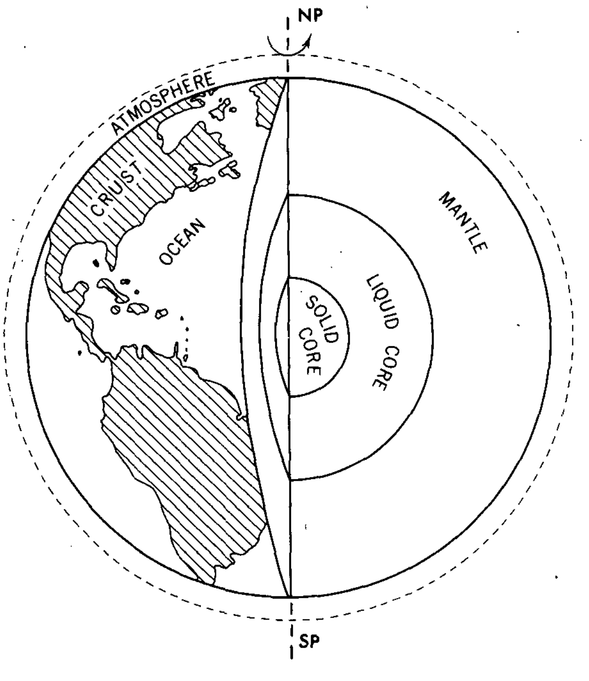

FIG. 5. Schematic diagram of the atmosphere, oceans, crust, mantle, and core of the earth. Note that the vertical scale of the atmosphere (≈20 km) is grossly exaggerated.

the earth cannot noticeably disturb the atmospheric flow. Thus the main point in the comparison shown in figure 3 is to point out the remarkable fact that the atmosphere seems to be pulling and pushing the earth around on time scales of days to years. This tiny, highly turbulent component of the climatic system with a mass of only 10^{-6} of the earth is accelerating or slowing down the giant earth; it seems that the tail of the elephant is driving the elephant around! The interaction is clearly a one-way street: atmosphere → earth. The extension to more regional interactions between the atmosphere and the solid earth will be discussed later.

It may be of interest to quote a sentence from Taylor et al.'s paper (1985) on core-mantle coupling: "It is postulated that through core-mantle coupling, secular (decadal) changes (in the length of day) on the order of 0.5 ms may be driven from *preceding* changes in core rotation."

This sentence suggests a definite direction of forcing: core → mantle → crust. An even more extreme statement connecting changes in the core with climatic changes in the atmosphere is mentioned in Salstein and Rosen's paper (1986): "The hypothesis has also been offered (Courtillot et al. 1982) that the decade changes in LOD originating in the earth's core are responsible for at least some of the changes in climate, by affecting the angular momentum of the atmosphere and hence its circulation."

However it seems inconceivable that the minute changes $[O(10^{-8})]$ in the rotation rate Ω and in the Coriolis force could in any way affect the atmospheric motions, and thereby the general circulation and climate. In fact, the core-mantle forcing could be in the opposite direction so that

$$\text{atmosphere} \rightarrow \text{crust} \rightarrow \text{mantle} \rightarrow \text{core}.$$

It is perhaps a more plausible hypothesis to assume that stochastic or white-noise forcing by the atmosphere would induce the long-period decadal variations in the rotation rate of the earth's core, somewhat like the forcing mechanism proposed by Hasselmann (1976) to explain long-period variations in the oceans.

Next I want to discuss how the transfer of angular momentum occurs at the interface between the atmosphere and the earth's crust. To do this it is instructive to study as an example the normal seasonal cycle in the relative angular momentum of the global atmosphere given in figure 6. The curve shows that the atmosphere rotates faster in northern winter and slower in northern summer due mainly to the strengthening and weakening of the jet streams (superrotation) in the Northern Hemisphere. The derivative of this curve would show the weakening of the westerlies in April–June and strengthening in August–October. There is fair agreement with the observations of the LOD, with differences of about 1 ms in the LOD between January and July (Wahr and Oort 1984)

The variations in the total angular momentum of the atmosphere and those in the LOD must be connected through a net transfer of angular momentum across the earth's surface. This transfer of angular momentum may occur by two processes, namely friction torques over oceans and land, and pressure torques across mountains. We will assume here that the oceans rotate together with the land in solid rotation.

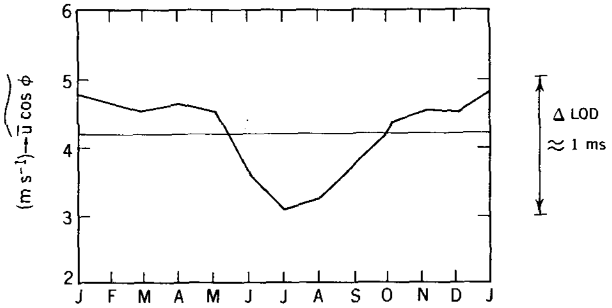

FIG. 6. Normal annual cycle of the global atmospheric angular momentum M_r in terms of the mean zonal velocity, u cosφ, in units of m s^{-1} for the 1963–73 period. The equivalent variation in LOD is shown on the right (in ms).

When the earth is speeding up in the northern spring there must be a net downward transfer of westerly angular momentum by an excess in eastward friction stress and/or by higher pressures on the west side than on the east side of the major mountain ranges (see figure 7, case I). On the other hand, in northern fall there must be a net upward transfer across the earth's surface and/or lower pressures on the west than on the east side of the mountain ranges (see figure 7, case II). Taking the opposite view, i.e., the mountains decelerating or accelerating the atmospheric flow, would lead to a very implausible situation.

In principle, the mountain torque is easy to obtain by measuring the surface pressure on both sides of the mountains (White 1949). However, with a realistic topography of the mountains this becomes a major task and it has been accomplished so far only in a very coarse manner. Over time intervals from days to months the pressure torque seems to dominate the variability in the surface transfer (see, e.g., the general circulation model results reported by Swinbank 1985). Our data given in figure 8 suggest that the large-scale pressure torques can explain an important fraction of the normal annual variation in the required surface torque. Thus it is apparently relatively easy for the atmosphere to transfer locally about 1%–2% of the mass to affect a change, for example, of Δp = 15 mb across a mountain range of 1000 km length and 1 km height, which would be sufficient to lead to the observed seasonal changes in relative angular momentum of the atmosphere. Assuming that the large-scale mountain torque is perhaps the dominant term, we can investigate which mountain ranges are especially important. To do this we will study first some meridional profiles (figure 9). A major imbalance in the northern spring seems to come from the northern midlatitudes, suggesting the influence of the Rocky Mountains, and in northern fall from the latitude belt around 30°N, suggesting the influence of the Himalayas. To some extent, these ideas are confirmed by the global maps for April and October given in figures 10a and 10b. These results hint at how and where the transfer may occur. In summary, we have found evidence of a clear link between the earth and the atmosphere on the time scales up to 1 yr in the direction atmosphere → earth that could occur principally through mountain torques.

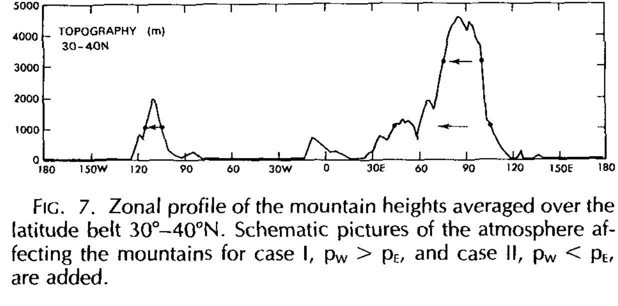

FIG. 7. Zonal profile of the mountain heights averaged over the latitude belt 30°–40°N. Schematic pictures of the atmosphere affecting the mountains for case I, $p_W > p_E$, and case II, $p_W < p_E$, are added.

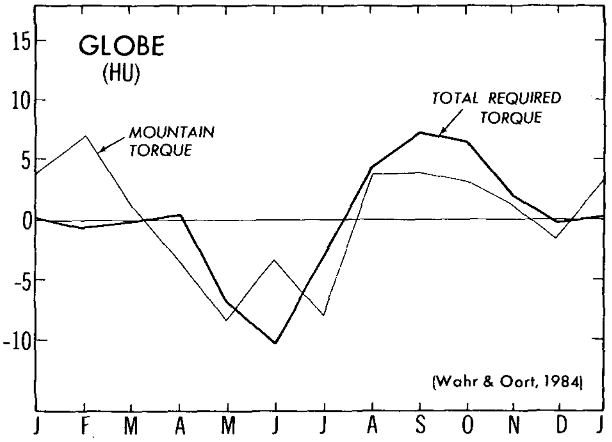

FIG. 8. Normal annual cycle of the required surface torque (thick line) and the large-scale mountain torque (thin line) in Hadley units (1 HU = 10^{18} kg m^2 s^{-2}) integrated over the globe. Only the annual and semiannual components are included in the required torque. The annual mean value of the mountain torque has been removed (from Wahr and Oort 1984).

b. Angular momentum exchange between the tropics and midlatitudes

Let us give a more detailed look at what happens within the various climatic belts of the earth. Figure 11a gives a cross section of the mean zonal circulation in the atmosphere that Professor Starr frequently used when he lectured on the angular momentum cycle. We notice near the surface the familiar westerlies in midlatitudes of both hemispheres, and easterlies in low latitudes. Considering first the land and

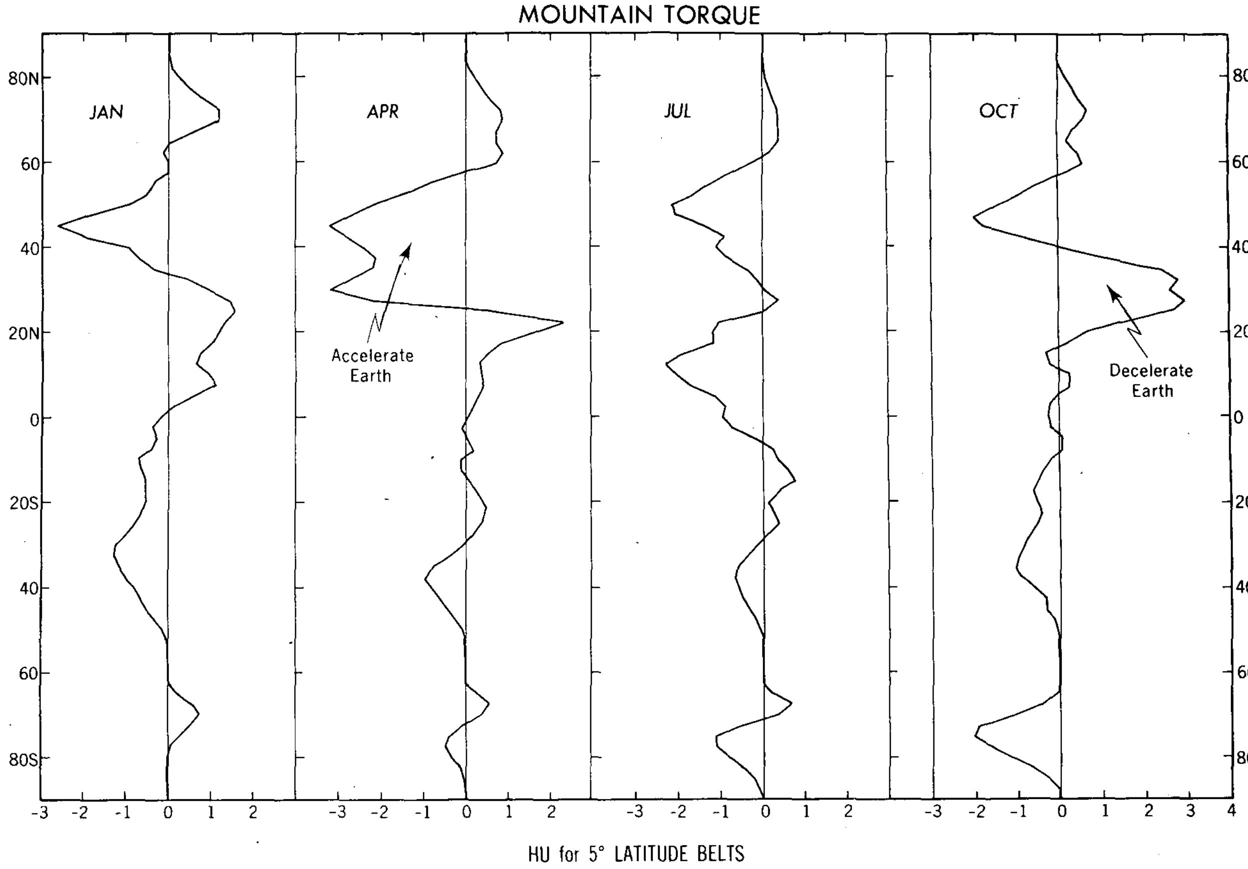

FIG. 9. Meridional profiles of the mountain torque in Hadley units (1 HU = 10^{18} kg m^2 s^{-2}) integrated over 5° latitude belts for January, April, July, and October 1963–73. Global integrals for the four months are −3.2, −9.8, −14.5, and −3.1 HU, respectively, and for the year −6.4 Hu.

oceans rotate to like a solid sphere, friction and mountain drag will tend to slow down both the easterlies and westerlies so that the earth's surface in the tropics will act as a source of westerly (eastward) momentum for the atmosphere and in the midlatitudes as a sink (figure 11b). The angular momentum is carried high into the atmosphere largely by the action of the mean meridional overturnings, as originally pointed out by Lorenz (1967). But at the level of the jet streams the angular momentum is transferred trom low- to midlatitudes through tilted troughs and ridges (SW-NE in the Northern Hemisphere and SE-NW in the Southern Hemisphere) as first suggested on theoretical grounds by Jeffreys (1926) and later identified and documented using observed atmospheric winds by Starr (1948) and his coworkers (figure 12). Of course, under steady conditions (no changes in LOD) the total surface torque integrated over the entire globe must vanish, requiring an approximate balance between the area covered by westerlies and easterlies.

The surface transfer in the various belts will again occur through friction and mountain torques. In the long-term (annual) mean the friction term is now certainly an important factor (see figure 13). Since most of the earth's surface is taken up by oceans where the surface winds are also strongest, much of the atmospheric angular momentum must be lost to the midlatitude oceans and gained from the low-latitude oceans in the general cycle depicted in figure 11b. How is the cycle closed at the surface (Oort 1985)? Does the return flow of angular momentum from midlatitudes to the tropics take place within the oceans, or does it involve a transfer within the solid earth? If we use typical values of the velocities in the oceans, any possible north-south transport turns out to be much too weak by one or two orders of magnitude. What appears to be happening instead is that the ocean wind stresses (see figure 14) lead to changes in sea level on the two sides of the oceans and to a transfer of the received angular momentum laterally to the continents through a "continental" torque that is very similar to the mountain torque (see figure 15). This hypothesis is confirmed by independent estimates of the sea level from geopotential thickness calculations that are precisely of the right magnitude with ≈50–70 cm differences in sea level between the east and west sides of the continents (figure 16).

Thus we find that all torques are focused onto the continents with the tendency to rotate the continents clockwise in the Northern Hemisphere and counter-

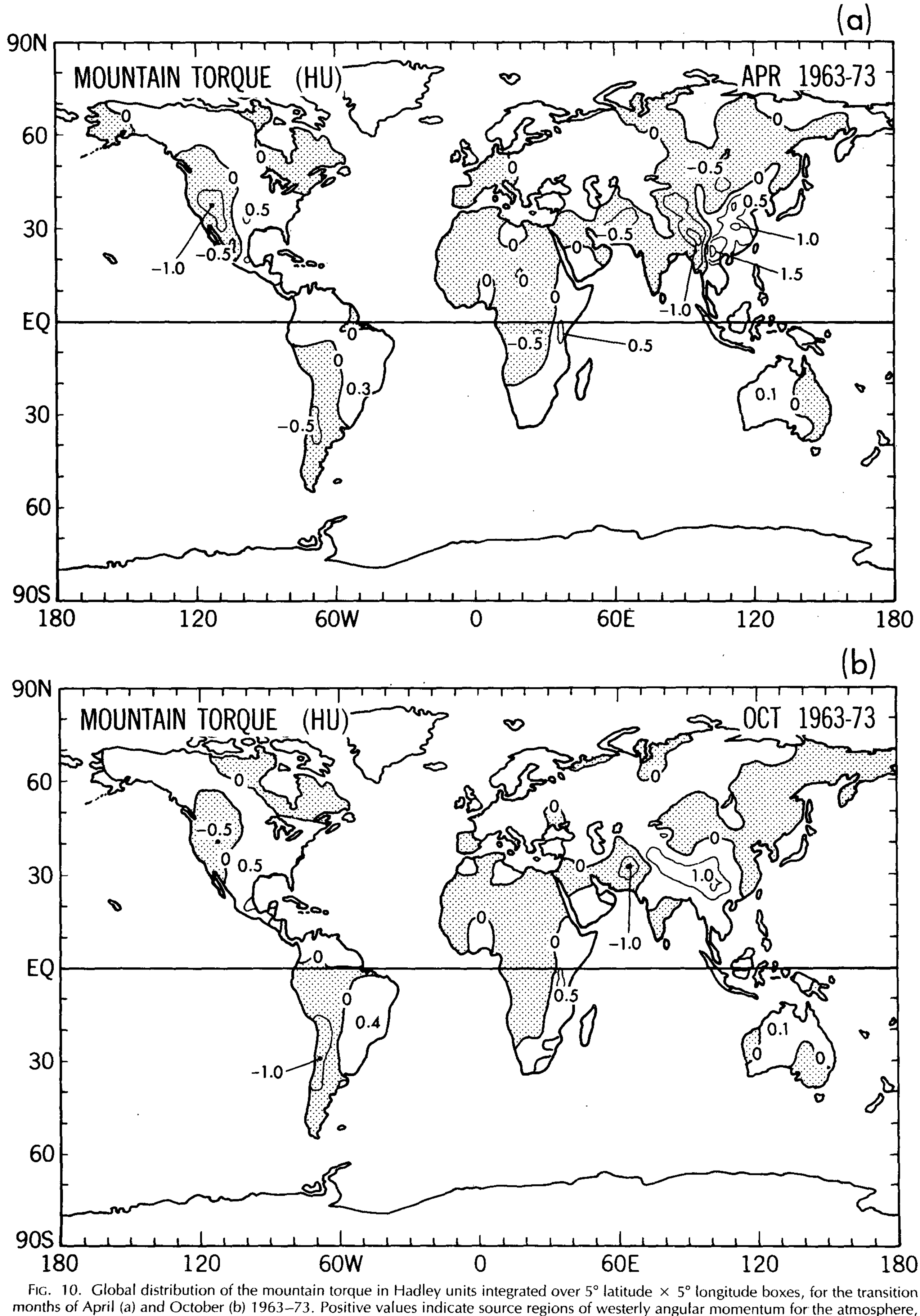

FIG. 10. Global distribution of the mountain torque in Hadley units integrated over 5° latitude × 5° longitude boxes, for the transition months of April (a) and October (b) 1963–73. Positive values indicate source regions of westerly angular momentum for the atmosphere, or a westward torque exerted by the atmosphere on the earth.

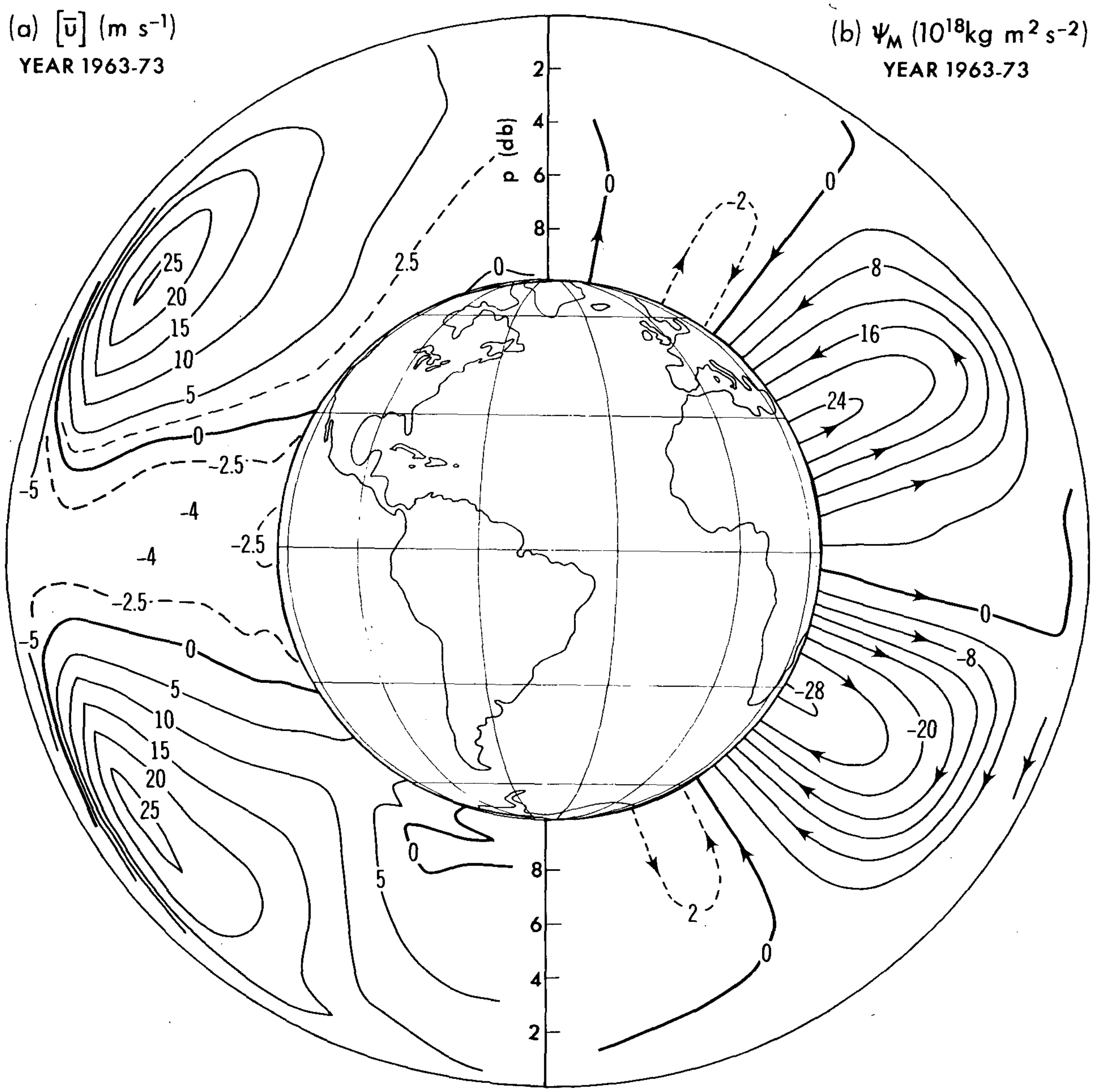

FIG. 11. Cross sections of (a) the mean zonal flow in the atmosphere in units of m s^{-1}, and (b) the streamlines of relative angular momentum in Hadley units, both for annual mean conditions 1963–73 (after Oort and Peixóto 1983). Note that the vertical scale of the atmosphere is grossly exaggerated.

clockwise in the Southern Hemisphere. We should add that similar torques must have been working on the continents throughout the ages. Thus we can speculate about several hypothetical scenarios

1) the continents may actually move slowly under the influence of these torques in a continental drift pattern;
2) the continents are so strongly anchored in the crust that they can withstand this continually acting torque; and
3) the continents may release the stress intermittently by relative internal motions such as those along the San Andreas Fault.

In the last scenario, one would expect the fault lines in the Northern Hemisphere to be preferentially tilted in the SE-NW direction and in the Southern Hemisphere in the SW-NE direction (figure 17). These tilts would be at right angles to the corresponding tilts in the atmosphere (see figure 12). When such motions would occur along the fault lines one might also expect more geological activity, such as earthquakes.

Namias (1988, 1989) has presented some evidence

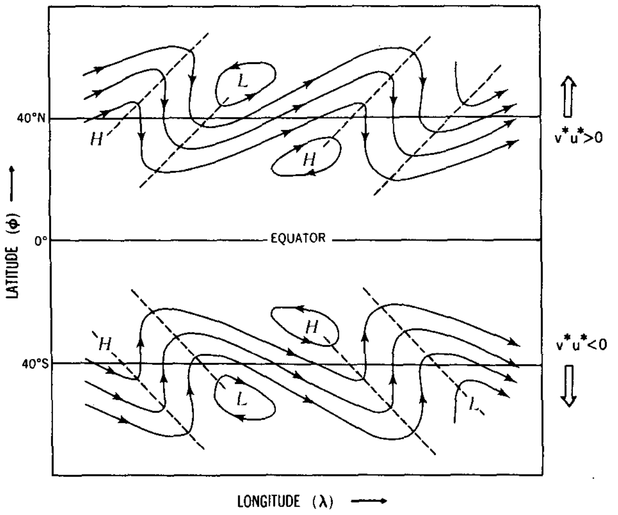

FIG. 12. Schematic diagram of the dominant mechanism of poleward transport of angular momentum by midlatitude waves or eddies. In the Northern Hemisphere the waves are tilted from southwest to northeast leading to a northward transport of relative angular momentum ($v^*u^* > 0$), and in the Southern Hemisphere from southeast to northwest leading to a southward transport of relative angular momentum ($v^*u^* < 0$), where u and v are the eastward and northward components of the wind, respectively, and the asterisks indicate departures from the zonal mean values.

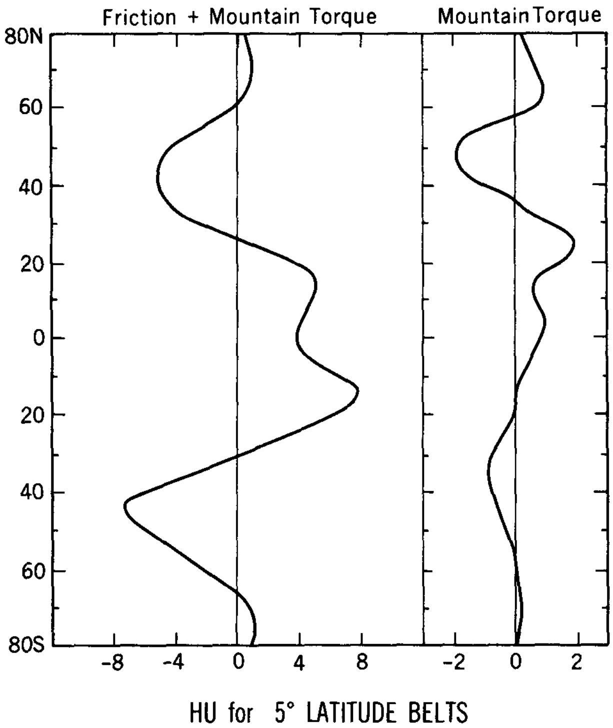

FIG. 13. Meridional profiles of the total surface torque and the mountain torque for annual mean conditions in Hadley units integrated over 5° latitude belts (after Newton 1971).

that certain pressure patterns over the Pacific Ocean and North America (see figure 18) may be correlated with earthquake situations in southern California. Interestingly enough, the earthquake pattern shown by Namias tends to reinforce the usual negative mountain torque over the Rockies. However, from inspection of a limited time series of the pressure torques over southern California from our data, I have not been able to determine a correlation with the earthquake index presented by Namias.

The foregoing is highly speculative and tentative, but the possible implications of a real link between atmospheric, oceanic, and geological processes are so important that they certainly justify further research.

In summary, there seems to be an undeniable link between the atmosphere and the solid earth, two basic components of the climatic system, in the sense that the earth follows the atmosphere, presumably mainly through east-west atmospheric pressure torques across the mountains and through east-west ocean pressure torques across the continental shelves. However, there is still considerable uncertainty and need for further research regarding whether differential motions may be set up in the earth through regional pressure torque anomalies.

4. Discussion

I would like to conclude with some general thoughts on where we are in our science:

1. We have a fairly good description and understanding of how the climate engine works, i.e., how angular momentum, water, and energy are cycled through the various components of the climate system.
2. In the last three decades we have developed very powerful new tools, such as general circulation models, to simulate and analyze the earth's climate system from first principles. There is surprising, steady progress being made in this field.
3. We have learned much about the predictability of the climate system (especially the atmosphere) and about the sensitivity of the system to internal and external perturbations.

What lies ahead? To draw an analogy with the situation in physics in the early 1950s, we seem to be proceeding from the prenuclear to the nuclear age in meteorology and oceanography. Our research is be-

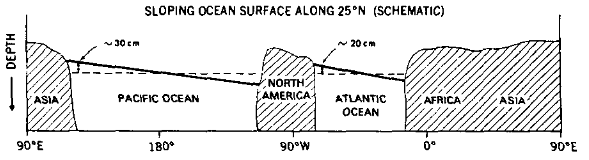

FIG. 15. Schematic diagram of the east-west sloping of sea level along the 25° latitude circle (from Oort 1985).

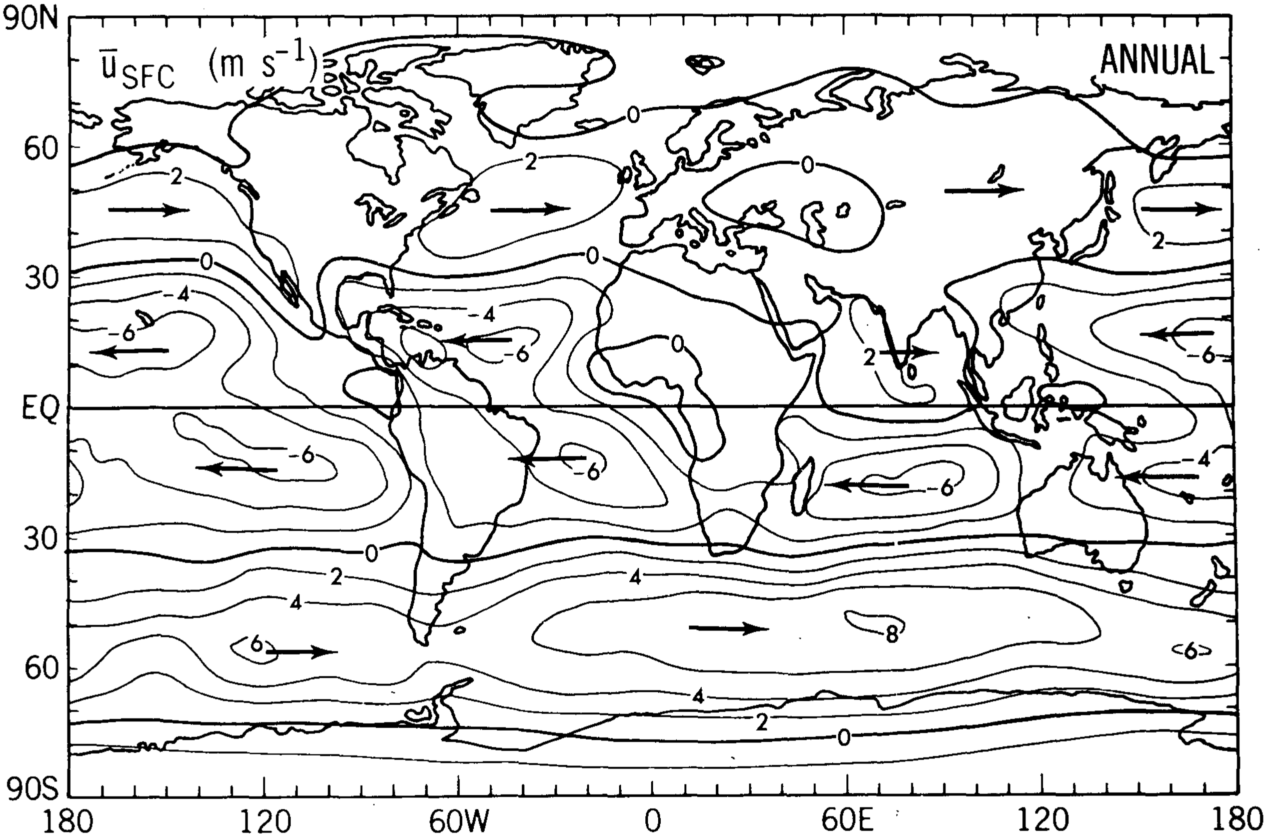

FIG. 14. Global distribution of zonal wind component u at the surface for annual mean conditions in units of m s⁻¹.

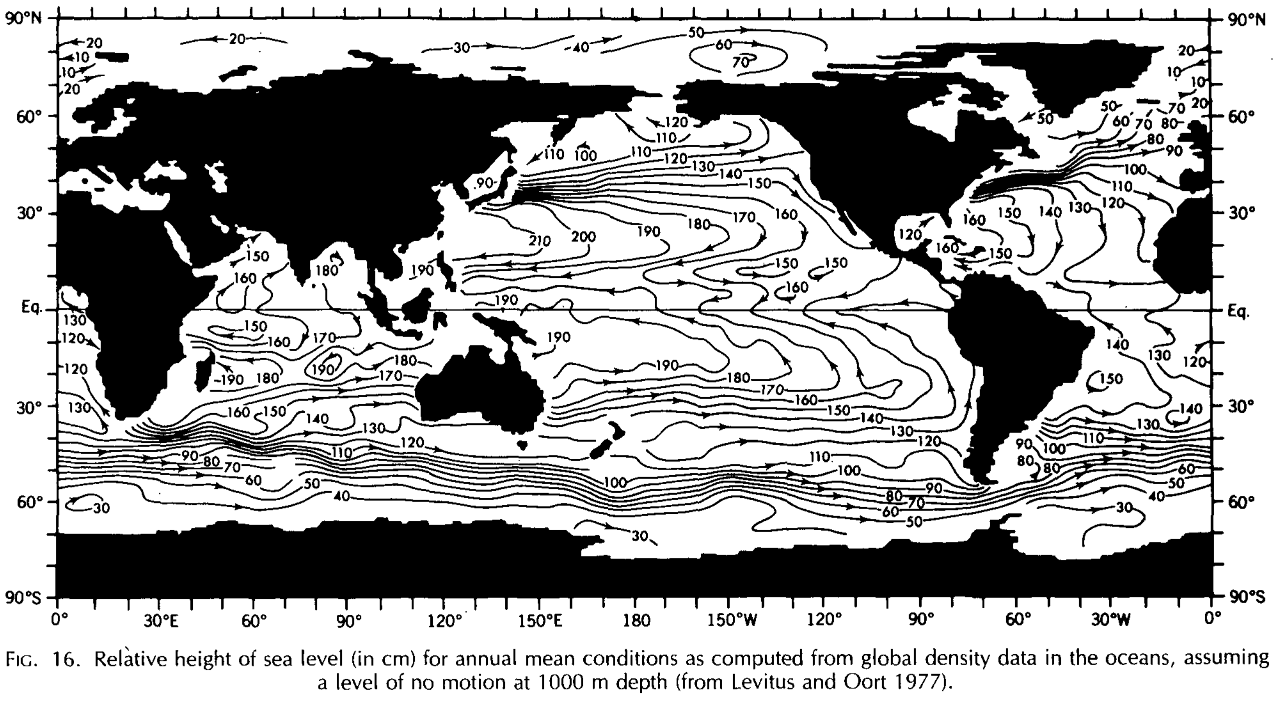

FIG. 16. Relative height of sea level (in cm) for annual mean conditions as computed from global density data in the oceans, assuming a level of no motion at 1000 m depth (from Levitus and Oort 1977).

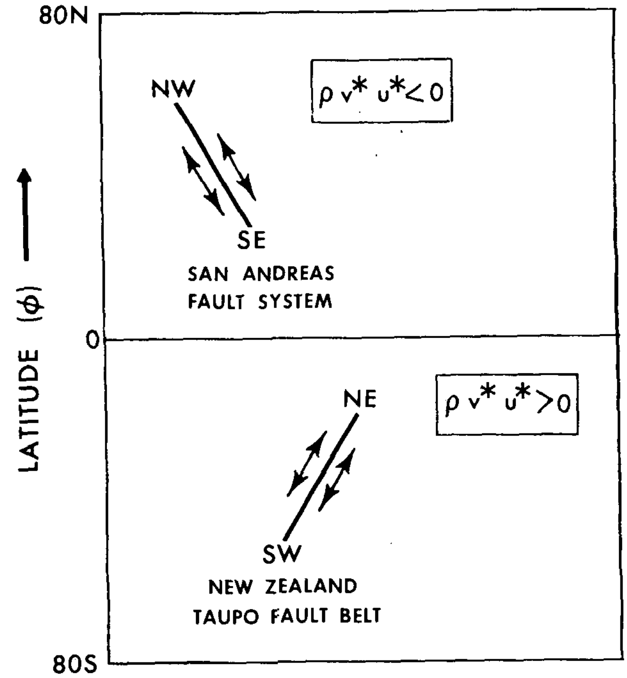

FIG. 17. Two examples of typical fault systems in the continental land masses that could lead to SE-NW mass shifts ($v^*u^* < 0$) in the Northern Hemisphere and SW-NE shifts ($v^*u^* > 0$) in the Southern Hemisphere, occasionally relieving the atmosphere-ocean torques imposed on the continents (after Oort 1985).

coming more and more relevant and applicable to everyday life. Also, we are finding that the climate may be changing, perhaps due to our actions. There is the temptation to do nothing and to let human pollution of the atmosphere and oceans continue unchecked. However, there is also the dangerous temptation to try to "improve" nature, and to modify the climate regionally or even globally. We are faced with a great challenge to find the middle road, and to stop the deterioration of the environment without further upsetting the natural balance.

What I see as our main task as environmental scientists is to provide the general public with information on the actual state of the earth. We need to show both what has happened in the past and what is happening now with the earth's climate on a regional and global scale and, where possible, to give early warnings of impending changes in the climate, with which we will have to learn to live. In meteorology we have a great tradition of cooperation in exchanging data internationally and in organizing global field projects. By continuing and expanding this work in the future we can also give an excellent example for peaceful cooperation in other disciplines.

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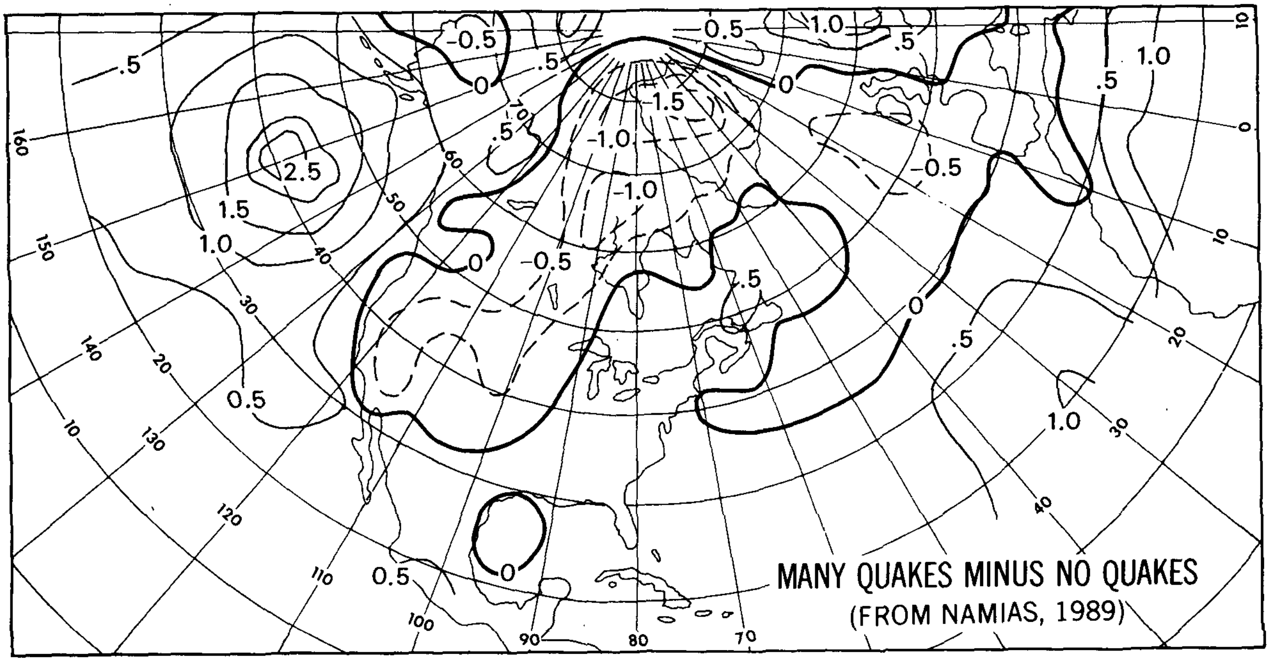

FIG. 18. Map of the difference in mean sea level pressure for summers with many earthquakes (more than 5 with magnitude > 4.5 on Richter scale) and no earthquakes in southern California (from Namias 1989).

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