Seasonal Distributions of Mountain Torques during FGGE

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ABSTRACT

Based on surface pressure and terrain height analyses from the National Meteorological Center, mountain torques are calculated for January, April, July and October 1979 during the First GARP Global Experiment. The zonally integrated mountain torques are generally in good agreement with previous studies. For all four months, positive torque exists in the tropical latitudes as well as in the polar and subtropical latitudes of the Northern Hemisphere; negative torque exists in northern middle latitudes and most of the Southern Hemisphere. An exception occurs in July when the mountain torque is negative between 5 and 25°N and positive in the Southern Hemisphere subtropics. Over latitudes where large terrain variation exists such as near 20°S due to the Andes, the estimate obtained in this study is larger in magnitude than that from previous work. The difference is due to the differences in both grid resolution and the particular atmospheric data and topography selected.

The meridional profiles of individual continental mountain torques are examined to illustrate geographical contributions to the net zonal torque. The positive mountain torque in northern high latitudes is due mainly to North America and Greenland. Both North America and Eurasia contribute to the sink of angular momentum in northern middle latitudes and the source in the subtropical latitudes. The negative torque between 5 and 25°N in July is due to the influence of the Indian monsoon trough on Arabia and Africa. The negative mountain torque over South America dominates the positive torque over Africa and Australia in the Southern Hemisphere in January and October.

Although the monthly averaged zonally integrated mountain torque assumes lesser importance when compared to the frictional torque, regional mountain torque at the synoptic time scale is quite large and can have considerable influence on the large scale circulation. Hemispheric torques are in qualitative agreement with previous work. Due to the partial cancellation of hemispheric torques and the variances in mountain torque which can result from different computing methods and grid distribution, no conclusive statement is drawn in regard to the global mountain torques during FGGE.

1. Introduction

The exchange of angular momentum between the earth and the atmosphere takes place through pressure and viscous stresses at the interface. The torque exerted on the atmosphere due to the large scale pressure differential between the east and west faces of the earth's rigid terrain is referred to as the mountain torque. The torque due to viscous stress and the pressure drag on the smaller scale surface irregularities, such as ocean waves, vegetation and small hills, is generally regarded as the surface frictional torque.

Direct computations of the mountain torque have been made using either surface pressure data (e.g., White, 1949: Widger, 1949) or isobaric height data (e.g., Newton, 1971a; Oort and Bowman, 1974). The zonal frictional torque has been estimated using oceanic stress data with the assumption that the average oceanic stress at a given latitude is representative of the net frictional stress averaged over the entire latitude circle (e.g., Newton, 1971b). From the consideration of the conservation of angular momentum an intercomparison can be made between the sum of the zonally integrated mountain and frictional torques and the meridional flux of angular momentum under quasi-steady conditions. In fact, the zonal frictional torque has been estimated as a residual from the other two quantities (Newton, 1971b).

The potential sources of errors and uncertainties in all the methods mentioned above were discussed in detail in a recent paper by Wahr and Oort (1984). In an attempt to assess the quality of the results and determine the extent to which the results are useful, Wahr and Oort reestimated the seasonal and monthly zonal torques with independent data sources and different methods and also compared the seasonal global torque with the length-of-day observations. It was suggested that away from latitudes with steep topography and limited surface observations, the seasonal departures from the annual mean zonal mountain torque can be reasonably well determined from both the surface pressure data and the isobaric height data and that the respective hemispheric and global mountain torques are also in good agreement. Qualitative agreement exists between the meridional angular momentum transport and the sum of mountain torque and frictional torque estimated from the oceanic stress data. The global torque inferred from the angular momentum transport corresponds well with the length-of-day observations in the annual and semiannual time scales.

As a result of the First GARP Global Experiment (FGGE), independent global analyses are now available and offer great opportunities for the study of general circulation. The global balance of the angular momentum was studied in Schaack (1982) where the frictional torque was determined using the residual method with the FGGE analyses prepared by the National Meteorological Center (NMC). While a detailed discussion of the balance will be in a later publication, the purpose of this paper is to present one component of the forcing, mountain torque, computed from the NMC analyses for the four mid-season months during 1979. One objective is to compare the zonal mountain torques during FGGE with previous studies where data used were of different sources. Since most of the previous work was focused upon the zonally integrated values, a second objective is to identify geographical influences on the net zonal mountain torque and its temporal variations.

2. Method of computation

The contribution of surface pressure stress to the eastward angular momentum of the atmosphere (τ_p) for an area limited in extent in longitude (λ) and latitude (ϕ) can be written as

$$\tau_p = -\int_\lambda^{\lambda+\Delta\lambda}\int_\phi^{\phi+\Delta\phi} p_s \frac{\partial z_s}{\partial\lambda} r^2 \cos\phi d\phi d\lambda, \qquad (1)$$

where r is the distance from the center of the earth and is approximated by the mean radius of the earth; the subscript s denotes the earth's surface. The convention used here is that a positive (negative) mountain torque transfers eastward (westward) angular momentum from the earth to the atmosphere. Using the chain rule, (1) can be expressed as

$$\tau_p = -\int_\phi^{\phi+\Delta\phi} (p_s z_s)_\lambda^{\lambda+\Delta\lambda} r^2 \cos\phi d\phi + \int_\lambda^{\lambda+\Delta\lambda}\int_\phi^{\phi+\Delta\phi} z_s \frac{\partial p_s}{\partial\lambda} r^2 \cos\phi d\phi d\lambda. \qquad (2)$$

In principle, the second term on the right hand side of (2) is not the mountain torque. However, it is equivalent to the mountain torque when the zonal integration is extended for a complete latitudinal circle (e.g., Oort and Bowman, 1974; Boer, 1982) or if both the east and west integration limits are at points where $z_s = 0$ as first utilized by Hutchings and Thompson (1962). In contrast, the expression in (1) preserves the physical meaning of net torque due to the surface pressure stress acting upon the cross-sectional area of terrain slopes projected on a meridional plane.

Let the overbar denote the arithmetic average along a constant latitudinal circle between λ and $\lambda + \Delta\lambda$ and the prime its deviation:

$$\left.\begin{aligned} \overline{(\ \ )} &= \frac{1}{\Delta\lambda}\int_\lambda^{\lambda+\Delta\lambda} (\ \ ) d\lambda \\ (\ \ )' &= (\ \ ) - \overline{(\ \ )} \end{aligned}\right\}. \qquad (3)$$

Equation (1) can be written as

$$\tau_p = \int_\lambda^{\lambda+\Delta\lambda}\int_\phi^{\phi+\Delta\phi} \left(-\bar{p}_s \overline{\frac{\partial z_s}{\partial\lambda}} - \overline{p_s' \frac{\partial z_s'}{\partial\lambda}}\right) r^2 \cos\phi d\lambda d\phi. \qquad (4)$$

The mountain torque, owing its existence to the pressure differential between the east and west slopes of the earth terrain, is represented by the second term on the right hand side of (4). When considering the mountain torque for a geographical region limited in longitudinal extent, it is probably most unambiguous to have the geographical region bounded by oceans on both east and west sides so that the first term on the right hand side of (4) is zero. If the first term is not zero which is the case when the terrain heights at λ and $\lambda + \Delta\lambda$ are unequal, the magnitude of the second term can often be exceeded by that of the first. The schematic shown in Fig. 1 demonstrates this. For section AC where the cross-sectional area of the upslope (facing east) projected onto a meridional plane is larger than that of the downslope, the mountain torque is most likely to be negative. Positive torque generally exists for section CE where the upslope cross-sectional area is smaller than the downslope one. The effect of pressure differential across earth terrain is thus best isolated when equal net upslope and downslope cross-sectional areas are considered such as for section AE in Fig. 1.

Surface pressure analyses and smoothed terrain height data were obtained from the National Meteorological Center at 2.5° grid resolution in both the latitude and longitude directions. Mountain torques are calculated for January, April, July and October 1979 using the expression in (1). In the results presented below, the continental torques and their

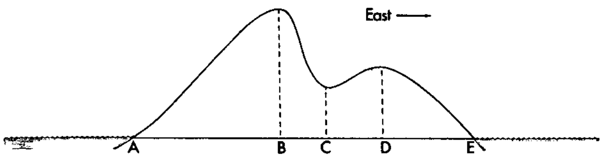

FIG. 1. Schematic showing that unequal meridional cross-sectional areas can lead to ambiguous computation of the mountain torque. In section AC, $[z_s(B) - z_s(A)]$ is greater than $[z_s(B) - z_s(C)]$ and, therefore, evaluation of Eq. (1) most likely results in a negative mountain torque. A positive mountain torque generally exists for section CE where $[z_s(D) - z_s(C)]$ is less than $[z_s(D) - z_s(E)]$. Regional mountain torques should be considered when net upslope and downslope cross-sectional areas are equal, such as section AE where $z_s(A)$ is equal to $z_s(E)$ (see text).

respective meridional distributions will first be examined. Examples of the temporal variation of the continental torques are then given, which is followed by a discussion on the zonal, hemispheric and global mountain torques.

3. Results and discussion

Pressure differences across mountain ranges result from various factors. Troughs tend to develop on the lee side of mountains in the strong westerly flow of midlatitudes. The seasonal contrast between land and ocean influences the atmospheric thermal structure and therefore the surface pressure distribution near mountains. Passage of weather systems leads to temporal fluctuations in the mountain torque. At a time scale of weeks, mountain torques may also reflect large scale flow patterns, such as blocking.

Monthly averaged mountain torques for January, April, July and October 1979 are shown in Fig. 2 for five geographical regions which are 1) North America and Greenland, 2) South America, 3) Asia, Africa and Europe, 4) Australia and 5) Antarctic. The mountain torques computed by Newton (1971a) for corresponding geographical regions are also included for comparison. North America and Greenland, South America, as well as Europe and Asia north of 41.25°N are each further divided into two parts along lines separating major mountain ranges. Such division illustrates the contributions from the sub-regions to the net continental mountain torque and the seasonal changes. Notice that the cancellation between the adjacent sub-continental regions can be up to two orders of magnitude.

North America and Greenland, as a whole, impart eastward angular momentum to the atmosphere during all four midseason months (Fig. 2). The thermal contrast between North American continental air and the adjacent oceanic air in different seasons is reflected in the meridional profiles of the mountain torque (Fig. 3a). Positive mountain torques occur north of 55°N during January and October and north of 50°N during April. Approximately half of the torque is contributed by Greenland; the influence of the Aleutian low on the western portion of this region is also significant. During July because of the well developed oceanic high pressure system over the North Pacific, the positive torque diminishes and nearly becomes negative at some latitudes in this high latitude portion of North America. Over the middle latitudes of North America negative mountain torques occur roughly between 55°N and 30°N during January, April and October and shift northward during July. These negative torques are most likely due to the occurrence of leeside troughs to the east of the Rocky Mountains. Positive mountain torque is indicated over lower latitudes with only a very small contribution from Central America. For January, April, July and October 1979 the net mountain torques over North America and Greenland are 6.2, 0.5, 1.2 and 1.2 Hadleys (1 Hadley = 10^{18} Kg m^2 s^{-2}), respectively. These values compare qualitatively to Newton's estimates of 8, 2, 3 and 8 Hadleys, with the present value for October being significantly smaller.

As will be discussed later, differences in computing methods and grid resolution and distribution certainly affect the values of mountain torque. However, the differences between the results of this study and

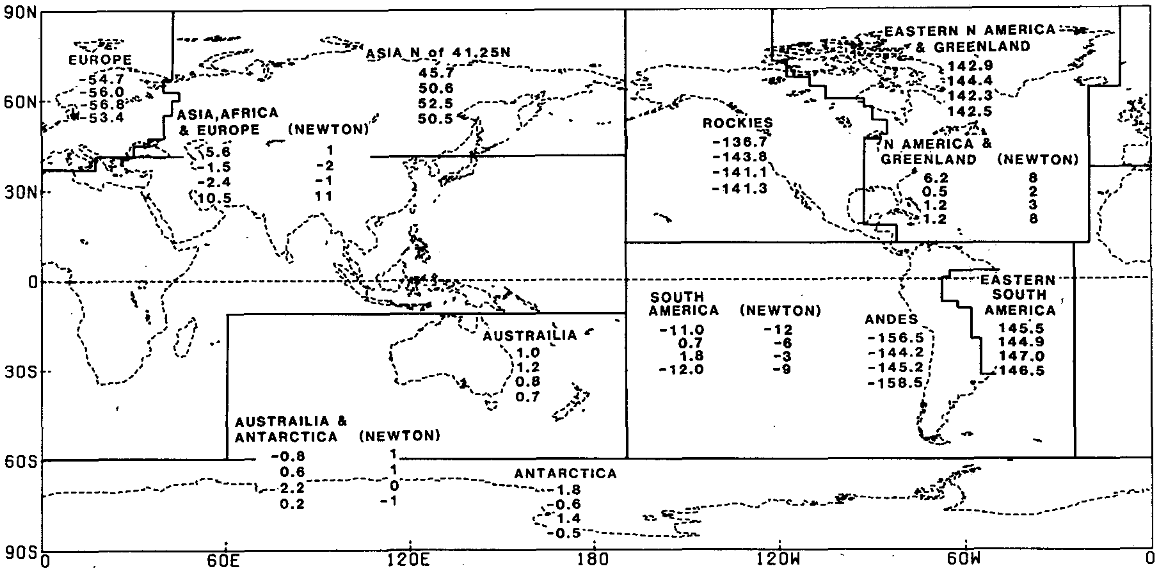

FIG. 2. Mountain torques (units in Hadleys) by geographical regions. The four values in each column, from top down, are for January, April, July and October 1979, respectively. The mountain torques computed by Newton (1971a) for corresponding geographical regions are included for comparison (1 Hadley = 10^{18} kg m^2 s^{-2}).

Newton's also reflect the particular atmospheric pressure distribution during FGGE. Take October 1979 as an example. A comparison of the mean sea level pressure distributions from the NMC analyses and climatic information (Schutz and Gates, 1974) shows that the central pressures of the Aleutian and Icelandic lows and the pressure over the continental U.S. during October 1979 are lower than the climatic means. Since the positive continental torque during this month is a net result of the positive contributions from north of 55°N and south of 30°N and the negative contribution in between (Fig. 3a), it is difficult to pinpoint a particular feature to explain the contrast between 1.2 Hadleys of this study and 8 Hadleys of Newton's for October without examining the meridional profiles from climatic data. The effect of differences in atmospheric pressure distributions should be kept in mind in the rest of the discussion.

South America serves as an angular momentum sink during January and October and a small source during April and July (Fig. 2). The seasonal variation is largely a reflection of changes in the pressure distribution in the region of the Andes, since the seasonal variation of mountain torque over the eastern Brazilian highlands is relatively small compared to that of the Andes. The mountain torque is mostly positive in the tropical section between 10°N and 10°S, becoming negative south of 15°S (Fig. 3b). This transfer of westward angular momentum from earth to atmosphere is largest during January and October when the subtropical high pressure system over the South Pacific is well developed. The respective net continental mountain torques in January and October are −11 and −12 Hadleys, as compared to −12 and −9 Hadleys from Newton. The South Pacific high pressure system is substantially weaker during April and is replaced by an oceanic trough during July, resulting in a large decrease in the magnitude of the negative torque south of 15°S. For South America as a whole, net torques in April and July are 0.7 and 1.8 Hadleys, respectively, which contrast with Newton's −6 and −3 Hadleys.

Due to the consideration of equal cross-sectional areas of the upslope and downslope discussed earlier, it is perhaps most reasonable to examine meridional profiles of mountain torque for Asia, Europe and Africa as one landmass (Fig. 3c). A transfer of westward angular momentum is observed north of approximately 40°N for all mid-season months. During January and October, a transfer of eastward angular momentum occurs south of 40°N with the maximum occurring between 40°N and 20°N. This transfer is associated with the southward extension of the Sibe-

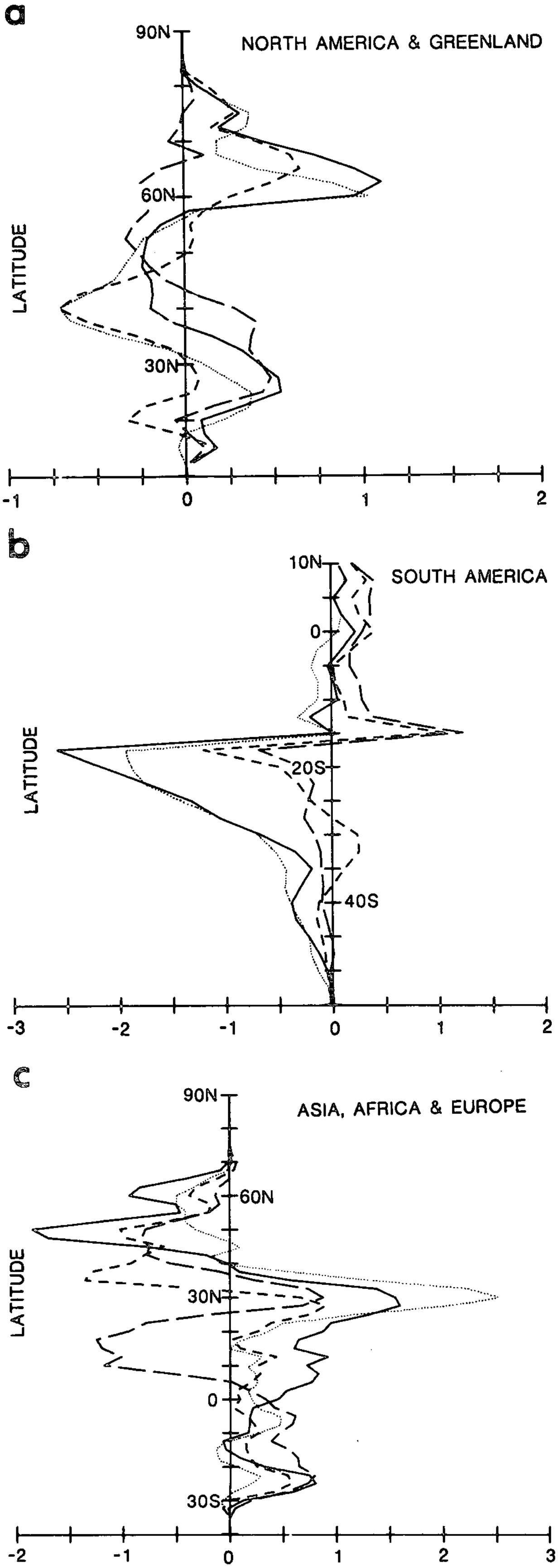

FIG. 3. Meridional profiles of the mountain torque per 2.5° latitudinal zone (units in Hadleys) for (a) North America and Greenland, (b) South America, and (c) Asia, Europe and Africa. The solid line denotes January, short-dashed line April, long-dashed line July and dotted line October.

rian high to the east of Tibet. The negative mountain torque between 25 and 5°N during July can be attributed to two factors: one is the weakening of the high pressure over southern China and the other is the development of the Indian monsoon trough, occurring respectively on the east and west sides of the mountain complex in southeast Asia. Although there is a partial cancellation of the effects on the mountain torque over the eastern region of China and India, the development of the Indian monsoon trough causes a large increase in the negative contribution from the western region of Arabia and Africa, particularly south of 25°N, resulting in negative mountain torque between 25 and 5°N in the Eastern Hemisphere during July. The positive mountain torques during all four months south of 10°N are mainly due to the presence of Africa. The larger value in July corresponds to the more intense Mascarene high during the summer monsoon (Krishnamurti and Bhalme, 1976). Total mountain torques for Asia, Europe and Africa during the four midseason months are 5.6, −1.5, −2.4 and 10.5 Hadleys, respectively, which compares well with Newton's values of 1, −2, −1 and 11 Hadleys.

Australia provides a positive mountain torque for all midseason months, although its magnitude is relatively small. Combined with Antarctica, net mountain torques are −0.8, 0.6, 2.2 and 0.2 Hadleys. These values compare with Newton's estimates of 1, 1, 0 and −1 Hadleys.

Discussion so far has been on monthly averaged mountain torques. It has been shown in previous studies (e.g., Newton, 1971a; Wahr and Oort, 1984) and will be reconfirmed later in Fig. 6 that the zonally integrated monthly or seasonal mountain torques are dominated by the frictional torques at most latitudes. It should be noted, however, that while the frictional torque exhibits more of a steady nature, the regional mountain torque at individual time periods can often be much larger than its monthly or seasonal averages and have considerable influence on the temporal evolution of large scale circulations. This point was also emphasized recently by Swinbank (1984) where the time rate of change of the global angular momentum was shown to correspond mostly with the fluctuations in the mountain torque with the frictional torque displaying a minor effect.

Shown in Fig. 4 are some examples of the temporal variation of the continental mountain torques calculated at 0000 GMT and 1200 GMT for selected months. During January the mountain torque of South America (dotted line in Fig. 4a) remains mostly negative. The mountain torque of North America and Greenland in April (Fig. 4b) fluctuates between opposite signs with magnitudes nearly one order larger than the monthly averaged values (Fig. 2). Fluctuations on the order of several days reflect the passage of synoptic weather systems. However, the mountain torques of the Western and Eastern Hemispheres north of 40°N (solid and dashed lines in Fig. 4a, respectively) during January show variations on a longer time scale. In a study on atmospheric blocking, Källen (1982) examined the mountain torques during January–March 1979 for the Eastern and Western Hemispheres north of 30°N. His results showed that the negative torque over Eurasia between 1 and 18 January 1979 (also see Fig. 4a) was associated with a well developed 500 mb ridge in the North Pacific; the negative or small positive torque over the Western Hemisphere between 18 January and 9 February was associated with an Atlantic blocking situation.

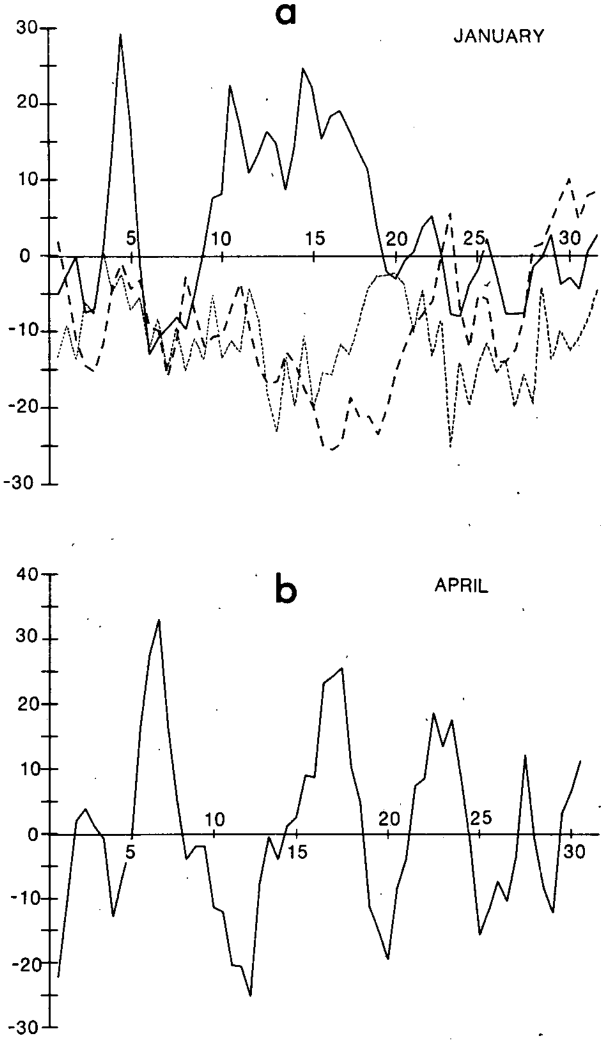

FIG. 4. Mountain torques (units in Hadleys) computed at 0000 and 1200 GMT for (a) January and (b) April. In (a), the solid and dashed lines are for the Western and Eastern hemispheres north of 40°N, respectively, and the dotted line is for South America. The solid line in (b) is for North America and Greenland.

Figure 5 shows the zonally integrated mountain torques in combination with Newton's (1971a) results and the five-year mean torques by Oort and Bowman (1974). All three profiles are in good agreement,

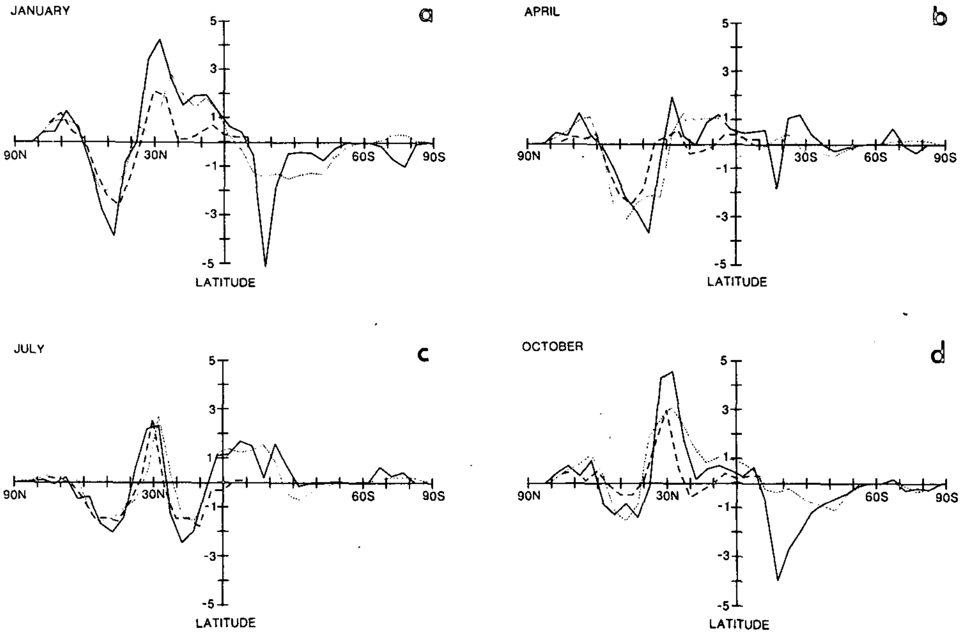

FIG. 5. Zonally integrated mountain torque for 5° latitudinal belts (solid line, units in Hadleys) for (a) January, (b) April, (c) July, and (d) October 1979. The dotted lines represent those computed by Newton (1971a) and the dashed lines by Oort and Bowman (1974).

especially in terms of the latitudinal belts of eastward or westward angular momentum transfer. A positive torque exists north of 60°N in all midseason months with the exception of the much diminished magnitude and the negative torque occurring near 60°N in July. A comparison of the meridional profiles for North America and Greenland and Eurasia (Figs. 3a and 3c) shows that this high latitude zonal mountain torque mainly comes from North America. Both Eurasia and North America contribute to the angular momentum sink in the northern middle latitudes with the former giving the larger contribution. For January, April andOctober, positive mountain torques exist in the Northern Hemisphere tropical latitudes. The sink of angular momentum occurring in July between approximately 5°N and 25°N is a reflection of the negative torque from the same latitudes of the Eurasia sector (Fig. 3c). In the Southern Hemisphere, Africa and Australia generally impart eastward angular momentum to the atmosphere for all seasons although the magnitude is small (see Fig. 3c for Africa). The transfer of westward angular momentum by South America between 15 and 50°S is large in January and October (Fig. 3b), accounting for the net zonal sink. The negative torque by South America is particularly weak in July, giving rise to net positive zonal mountain torque north of 30°S.

The largest difference between the profiles of this study and those of Newton occurs near 20°S. A 5° latitudinal interval was used in the analyses by Newton (1971a), whereas all results presented here are obtained from 2.5° grid analyses. In a preliminary investigation, similar computations were performed for two grid arrangements of 5° resolution determined by selecting alternating grid points from the 2.5° grid along each latitude. The zonally integrated mountain torques were similar to that from the 2.5° resolution over most latitudes except near 25–35°N and 10–25°S where large terrain variations exist. In one case the zonally integrated torque near 20°S in January is approximately 1.5 Hadleys less than that shown in Fig. 5a, suggesting that a smoother terrain can result in a smaller mountain torque. Despite the difference in magnitude, the meridional profiles from the two 5° resolution calculations resembles the profiles from 2.5° resolutions more than Newton's results. Therefore, the differences in meridional profiles between this study and Newton's (1971a) as shown in Fig. 5 are due to the differences in the grid resolution and distribution (Wahr and Oort, 1984) as well as the particular atmospheric data and topography selected (Oort and Bowman, 1974).

Recently Núñez (1983) estimated the mountain torque due to the Andes in January and July for 0.5° latitude belts from 24 to 50°S using the method of Hutchings and Thompson (1962). The pressure difference across the mountain range was assumed to be constant with height and its value was approximated by the climatological mean sea level pressure difference. The magnitude of his results is greater than the meridional profiles of the mountain torque over South America shown in Fig. 3b by up to 1.5 Hadleys. This is due to an over-estimation of the pressure differential along mountain slopes by the mean sea level pressure difference. However, the latitudinal variation with the large negative mountain torque near 20°S and a continual decrease in magnitude southward is very similar to those shown between 15 and 50°S in Figs. 5a and 5d. The large negative mountain torque across South America during January and October 1979 (Figs. 3b, 5a and 5d) may be realistic.

Table 1 summarizes the mountain torque for the two hemispheres and the globe. The Northern Hemisphere tends to gain and the Southern Hemisphere to lose angular momentum from the surface pressure stress in January and October. The reverse appears to be true in April and July. The magnitudes of the hemispheric torques from this study are quite compatible with Newton's (1971a) results except for the Southern Hemisphere during October. Both are in good qualitative agreement with the monthly hemispheric mountain torques computed by Wahr and Oort (1984). Wahr and Oort noted that due to partial cancellation of the contributions from the two hemispheres, the global mountain torque is not as well determined as the hemispheric ones, although it appears to be roughly in phase with the monthly variation of the torque in the Northern Hemisphere. The differences among their estimates of the global mountain torque with various data sources and computing methods were up to several Hadleys. In view of this, it is not particularly fruitful to compare the global mountain torques computed for 1979 in this study and those of Newton derived from mean analyses of several years.

The monthly frictional torque for January and July 1979 computed using the residual method in Schaack (1982) is reproduced in Fig. 6. Results from the NMC FGGE analyses are in agreement with those from previous investigations in that the mountain torque assumes a lesser but not negligible contribution to the monthly and zonally averaged angular momentum balance.

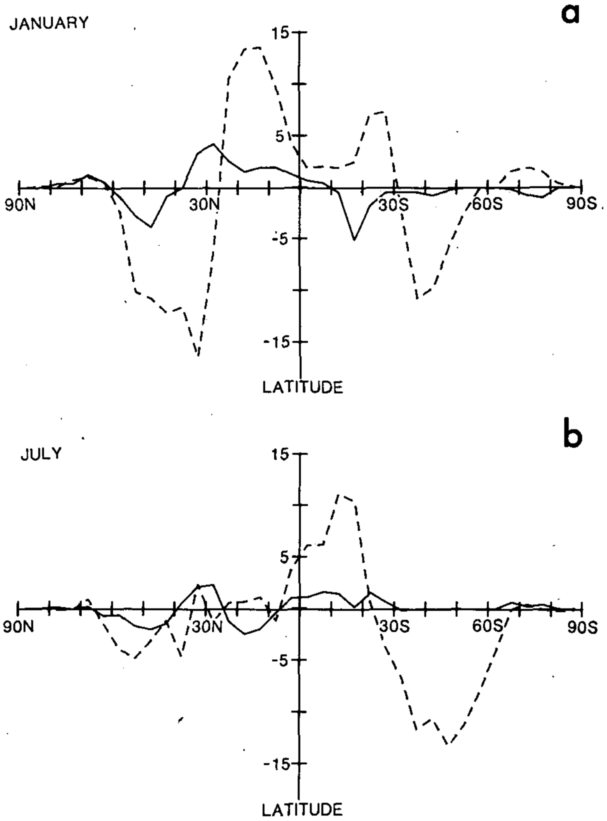

FIG. 6. Zonally integrated mountain torque (solid) and frictional torque (dashed; Schaack, 1982) for 5° latitudinal belts for (a) January and (b) July 1979 (units in Hadleys).

TABLE 1. Hemispheric and global mountain torques (units in Hadleys) from this study and Newton (1971).

	January	April	July	October
Northern Hemisphere	11	−3	−6	10
Southern Hemisphere	−11	2	8	−12
Global atmosphere	0	−1	2	−2
(Newton 1971)				
Northern Hemisphere	8	−5	−4	14
Southern Hemisphere	−10	−1	4	−4
Global atmosphere	−2	−6	0	10

4. Summary

The contribution of surface pressure stress to global angular momentum balance is examined for January, April, July and October 1979 using the NMC FGGE IIIa surface pressure and terrain height analyses. While a full discussion of the angular momentum balance is contained in Schaack (1982), one of the objectives of this study is to compare the zonally integrated and continental mountain torques computed using the FGGE IIIa analyses with previous work conducted with different data sources. Computational procedure places emphasis on preserving the physical meaning of surface pressure stress acting on the cross-sectional area of terrain slopes projected on a meridional plane. Therefore, one is able to illustrate geographical influences on the zonally integrated mountain torque and its seasonal variations.

Zonally integrated mountain torques are generally in good agreement with Newton (1971) and Oort and Bowman (1974), especially in terms of latitudinal belts of eastward and westward angular momentum transfer. Positive mountain torque exists at high latitudes, roughly north of 60°N, in the Northern Hemisphere during January, April and October and becomes nearly zero during July. The influence mainly comes from the North America and Greenland sector, since weak negative torque occurs between 70°N and 60°N in the Eurasia sector. Negative mountain torques over the middle latitude sections of both North America and Eurasia give rise to a net sink of angular momentum between approximately 60°N and 35°N in all four months; the contribution from Eurasia is somewhat larger than that from North America. The subtropical latitudes in the Northern Hemisphere and the tropics generally experience positive mountain torque with a maximum near 30°N during all seasons except during July when a negative torque exists between roughly 25 and 5°N. Although North America has a positive contribution to the source of angular momentum just mentioned, the contribution from Asia and Africa is larger. The weakening of high pressure over southern China and the development of the monsoon trough over northern India during July results in some cancellation of their effects on the mountain torque over China and India. However, the effect of the development of Indian monsoon trough on the Arabian and African sector leads to a net negative mountain torque between 25 and 5°N. Over most latitudes in the Southern Hemisphere, the mountain torque is negative in January and October, positive in July and is relatively small in April. Africa and Australia provide mostly positive torque of small magnitude which is dominated by the sink of angular momentum from South America in January and October.

The largest disagreement in the zonally integrated mountain torque between this study and Newton (1971a) occurs near 20°S where large terrain variation exists. It is partly due to the difference in horizontal resolution (2.5° used in this study as compared to 5° used by Newton), and partly due to the particular atmospheric data and topography used.

The monthly averaged and zonally integrated mountain torque is generally smaller in magnitude compared to the frictional one. However, within the synoptic time scale, sources and sinks of angular momentum by regional mountain torque can be one order of magnitude larger than the zonally integrated values and should have considerable influence on the large-scale circulation.

The Northern Hemisphere tends to gain and the Southern Hemisphere to lose angular momentum through surface pressure stress in January and October; the gain and loss reverse in April and July. Since grid resolution, topography and the particular atmospheric data used all directly affect the estimation of the mountain torque, net global mountain torque is a sensitive quantity and no conclusive statements can be made with the current method of computation.

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