Estimates of the seasonal variation of the general circulation from easily identifiable features

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ABSTRACT

Estimates of the seasonal variation of the zonal wind component and the eddy flux of relative angular momentum in the terrestrial atmosphere were made from the motion of cyclones and anticyclones. It is found that the estimates are in reasonably good agreement with the direct measurements over most latitudes.

Introduction

The author has recently reported (Macdonald, 1966) that the easily identifiable cyclones and anticyclones found on surface weather maps are reasonably accurate tracers of the mean and eddy components of the general circulation. The latitudinal profile of the vertically averaged relative angular velocity, averaged over a year, as determined from the daily displacements of these systems, is in good agreement with the directly measured zonal winds. The best agreement is found when the small cyclones and anticyclones are used as tracers. The average poleward displacement of cyclones is about balanced by the equatorward motion of anticyclones so that the net meridional displacement is small again in agreement with the directly measured meridional winds. In most latitudes, the latitudinal and longitudinal displacement of the systems indicates the presence of an organized horizontal eddy structure in the wind field. The longitudinal and latitudinal displacements of the cyclones and anticyclones are positively correlated and a reasonably accurate estimate of the latitudinal profile of the annual poleward eddy flux of relative angular momentum can be made over most latitudes from the covariance of the displacements. In low latitudes the annual correlation is negative indicating an equatorward transport of momentum which is at variance with the direct measurements reported by Starr & White (1954).

The results reported before are of interest to investigators, such as Ward (1965), who are attempting to determine the general circulation of extra-terrestrial atmosphere from the motion of easily identifiable features. It is also of interest in such investigations to determine whether the well-established annual variation of the mean zonal wind and the angular momentum flux in the terrestrial atmosphere can also be determined from the behavior of the easily identifiable cyclones and anticyclones. It will be shown in this paper that the annual variations of the earth's atmosphere can be estimated from both the monthly averages of the displacements and the number of systems that appear at various latitudes.

Annual variation of the mean zonal wind

The variation of the latitude at which the maximum zonal wind component $[U]$ is found is shown in Fig. 1. The wind component is expressed as the relative angular velocity $[U]/R \cos \theta$ where θ is the latitude and R the mean radius of the earth. Positive values indicate a wind directed toward the east. The solid line is drawn through the latitude where the vertically averaged (surface to 100 mb) directly measured winds reach a maximum in a given month. The averaging was also performed around each latitude belt and over each month of the two-year period from January 1, 1950, through December 31, 1951. The magnitude of the relative angular velocity reaches a maximum in midwinter through early spring over the lower

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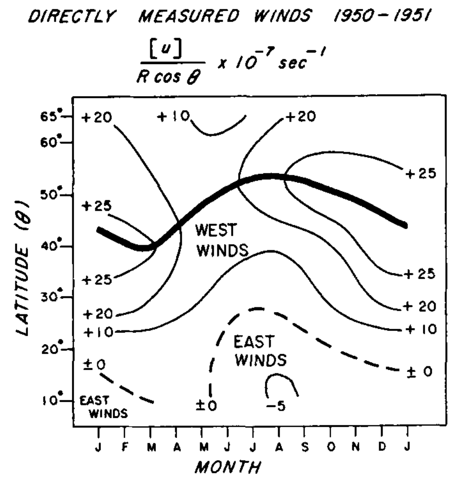

Fig. 1. The annual distribution of the latitudinal profile of the vertically averaged relative angular velocity measured by conventional methods. The averaging was also performed around each latitude belt for each month. The heavy solid line passes through the latitude where the angular velocity reaches a maximum in each month.

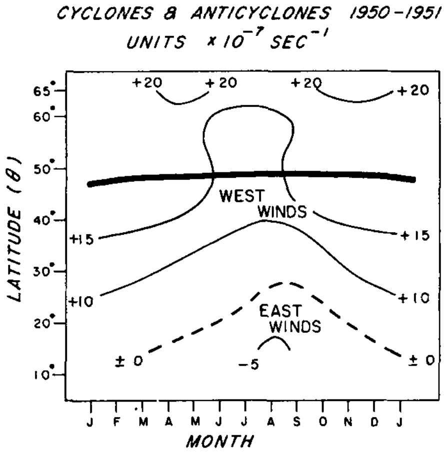

Fig. 2. An estimate of the annual distribution of the latitudinal profile of the relative angular velocity made from the daily displacements of both cyclones and anticyclones. The displacements were averaged around each latitude belt for each month. The heavy solid line passes through the latitude where the angular velocity appears to reach a maximum in each month.

middle latitudes, during late spring and early summer, the latitude at which the strongest winds from the west are found shifts poleward commensurate with the appearance of easterlies in the tropics. The strongest westerlies return to the low latitudes during the fall and early winter as the magnitude of the easterlies gradually decreases. These results, using vertically integrated winds, are very similar to these found by Klein (1958) from wind data at approximately 3 km and 7 km collected over a much longer time.

The mean monthly longitudinal displacements $[\Delta\lambda]$, of the surface cyclones and anticyclones combined for the period of 1950–1951 were computed from the daily displacements in all latitude belts in the same fashion as that described in the author's first report (Macdonald, 1966). The results are shown in Fig. 2. In both Figs. 1 and 2 the seasonal variation of the magnitude of the relative angular velocity in midlatitudes and the change in direction in the tropics are in good agreement. The magnitude of the relative angular velocity in midlatitudes, derived from $[\Delta\lambda]$, is an underestimate by about one-third. However, there is no significant latitudinal shift of the maximum of the angular velocity over the year.

As the author has noted in his previous paper, the total number of cyclones (and anticyclones) that appear in any given month is about the same over the year. But the frequency of occurrence is not the same in each latitude belt over the 12 months. The latitude belt in which the greatest number of cyclones appear shows a pronounced annual variation as can be seen in Fig. 3. The numbers include those cyclones that first appeared on the maps as well as those that migrated into the latitude strip from an adjacent belt, summed over the two years. A system was counted only once no matter how many days it remained in the belt. The solid line is drawn through the latitude where the frequency of cyclones is at a maximum in each month. The shift of the latitude where cyclones appear most often over the year is closely in phase with the meridional shift of the zonal wind component shown in Fig. 1. The number of anticyclones appearing in each latitude belt each month were too few to attach any significance to differences in the frequency of appearance especially in low and high latitudes.

In addition to the meridional profile of the angular velocity in the terrestrial atmosphere, there also exists a profile in the vertical such that the strongest west winds are found some 10 to 12 km above the earth's surface. It is therefore also of interest to determine whether

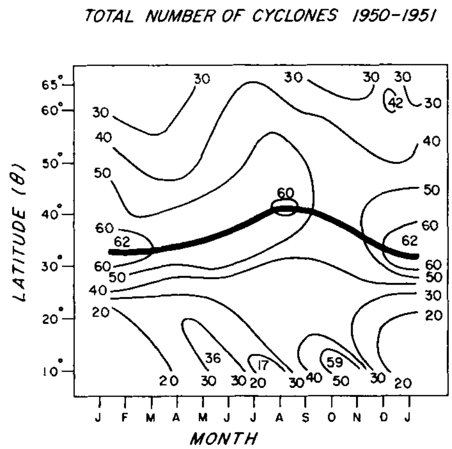

Fig. 3. The annual distribution of the total number of cyclones that appeared in various latitude belts over the 2-year period of 1950–1951. The heavy solid line passes through the latitude where the number of cyclones reaches a maximum in any given month.

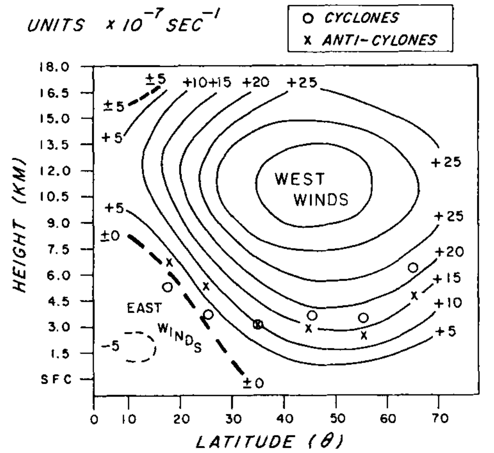

Fig. 4. The isopleths describe the meridional and vertical cross section of the directly measured relative angular velocity averaged over the 2-year period of 1950 and 1951. The circles and crosses show the average daily displacements of cyclones and anticyclones, respectively, averaged over the same time period and around 10° latitude belts.

the longitudinal displacements of cyclones and anticyclones tend to trace out the relative angular velocity at any fixed level in the atmosphere. In Fig. 4 the angular velocity of the cyclones and anticyclones, determined from their longitudinal displacements averaged over a year, is compared with the meridional cross section of the directly measured, angular velocity. The winds and displacements were both averaged around each latitude belt. It can be seen from this figure that cyclones, as compared to anticyclones, are generally displaced at a speed coincidental with the angular velocity found at relatively high altitudes in the middle and high latitudes. However, the longitudinal motion of both systems coincide with the average angular velocity found at different heights at practically all latitudes and only at a small fraction of the maximum wind found at around 10 km in middle latitudes.

The annual variation of the eddy flux of angular momentum

The magnitude of the directly measured poleward flux of the vertically integrated relative angular momentum by the horizontal eddy exchange process reaches a maximum in lower middle latitudes in the three winter months. The minimum occurs in summer as can be seen in Fig. 5. The eddy flux calculated from the covariance of the displacements of both cyclones and anticyclones is shown in Fig. 6 for the three winter (dash line) and three summer (solid line) months. In these computations, it is assumed that the systems reflect the vertically integrated motion of the total atmospheric mass of 1000 gm/cm². The shape of the meridional profiles of the transports over the low and

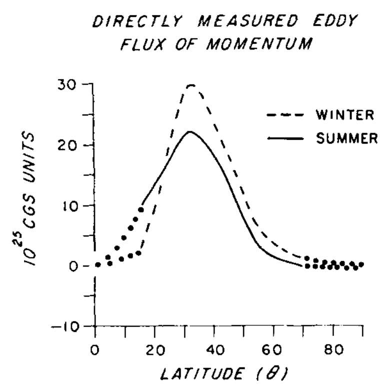

Fig. 5. Direct measurements of the meridional profile of the poleward flux of the vertically integrated relative angular momentum by the horizontal eddy exchange process during the winter and summer. Here v is the northward component of the wind velocity and u the zonal west wind component. The momentum flux is determined from $[u' v']\, 2\pi R^2 \cos^2\theta$ where R is the earth's mean radius.

middle latitudes is very similar in both seasons with the maximum flux occurring in winter in lower middle latitudes. The magnitude of the estimated flux is within a factor of 2 of that measured directly except near 50° N where the measurements differ in sign but in both instances the flux is small.

The annual momentum flux in the tropical regions, estimated by the author in the earlier paper, had shown an equatorward transport that was at variance with the direct measurements. This disagreement was produced by the seasonal bias in the appearance of the cyclones which comprise most of the data for the daily displacements. The bias can be seen from an examination of Table 1 where seasonal correlations of the latitudinal and longitudinal displacements, $r(\Delta\lambda, \Delta\theta)$, of cyclones and anticyclones in the 10° to 20° latitude belt are displayed. In the table, N indicates the number of pairs of $\Delta\lambda$ and $\Delta\theta$ used to compute the correlations and covariances. The asterisks denote those correlations significant at or above the 95% confidence level. Well over 50% of the cyclones appeared during the late summer (August) and the three fall months when the correlations were negative. The correlation excluding these four months was positive.

Table 1. *Latitude belt 10°–20°N*

	Spring (MAM)	Summer (JJA)	Fall (SON)	Winter (DJF)
Cyclones				
N	287	201	380	123
Cov($\Delta\lambda$, $\Delta\theta$)	.06	−1.37	−3.34	1.94
$r(\Delta\lambda, \Delta\theta)$	.01	−.13	−.24*	.26*
Anticyclones				
N	43	12	13	23
Cov($\Delta\lambda$, $\Delta\theta$)	1.67	1.19	−2.77	.90
$r(\Delta\lambda, \Delta\theta)$	.68*	.41	−.40	.78*
Cyclones and Anticyclones				
N	330	213	393	146
Cov($\Delta\lambda$, $\Delta\theta$)	.86	−.09	−3.06	1.42
$r(\Delta\lambda, \Delta\theta)$	.14*	−.01	−.30*	.33*

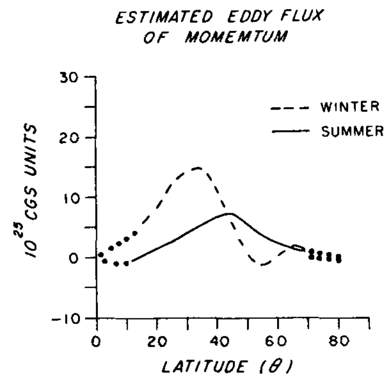

Fig. 6. An estimate of the meridional profile of the poleward flux of the vertically integrated relative angular momentum made from the displacements of both cyclones and anticyclones. Here $\Delta\theta$ is the northward displacement while $\Delta\lambda$ is considered positive for a displacement toward the west. The momentum flux was estimated from $[\Delta\theta' \; \Delta\lambda'] \, 2\pi \, R^2 \cos^2\theta$.

Summary

From the results described here and those reported earlier, it is apparent that the daily displacements of the easily identifiable surface cyclones and anticyclones can be used to obtain reasonable estimates of certain characteristics of the general circulation of the terrestrial atmosphere. The estimates of the mean and eddy wind components are in general within a factor of two of that measured directly. The displacements of the systems can also be used to deduce the average latitudinal profile and the annual variation of the magnitude of the relative angular velocity. An analysis of the displacements does not reveal the annual oscillation of the latitude where the maximum winds are found. An extra-terrestrial observer attempting to detect such a variation would have to be clever enough to surmise that the frequency with which the bright (cloud filled) cyclones appear at various distances from the equator corresponds to the annual latitudinal oscillation of the maximum angular velocity.

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ОЦЕНКИ СЕЗОННЫХ ИЗМЕНЕНИЙ ОБЩЕЙ ЦИРКУЛЯЦИИ ПО ЛЕГКО ИДЕНТИФИЦИРУЕМЫМ ПРИЗНАКАМ

Были проведены оценки сезонных изменений зональной компоненты ветра и турбулентного потока относительного углового момента для земной атмосферы на основе анализа движений циклонов и антициклонов. Обнаружено, что для большинства широт оценки достаточно хорошо согласуются с результатами непосредственных измерений.