Mean 200-mb Circulation in the Southern Hemisphere Deduced from EOLE Balloon Flights

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ABSTRACT

The EOLE experiment has provided a uniquely consistent and uniform set of 85,000 precise wind data, determined from the essentially horizontal displacements of over 480 constant-level balloons released in the Southern Hemisphere at approximately 200 mb. These data are analyzed here for estimating the climatological aspects of the Southern Hemisphere general circulation, i.e., the mean zonal and mean meridional flow and the standing longitudinal wave patterns. Instantaneous velocities in excess of 100 m sec\(^{-1}\) (200 kt) were indeed observed, but the mean zonal velocity, of the order of 10-30 m sec\(^{-1}\), agrees well with previous observational studies. The mean meridional velocity at 200 mb was estimated for various latitudes throughout the period October 1971-March 1972 with hitherto unknown time resolution, uncovering thereby short-term variations or reversals, particularly during the outbreak of the austral summer season, with typical values of the order of 0.2 m sec\(^{-1}\). The largest contribution to the day-to-day variations of the wind is associated with essentially isotropic transient fluctuations with rms amplitudes of 10-15 m sec\(^{-1}\). Significant standing longitudinal wave patterns are also found, however, with dominant wavenumbers 1 and 4 in temperate latitudes and typically 5 m sec\(^{-1}\) rms amplitude.

1. Introduction

Because of the current emphasis on global meteorology and also because of the intrinsic interest in weather regimes over an essentially oceanic planetary surface, considerable efforts have been devoted to analyzing the available meteorological data and describing the atmospheric circulation in the Southern Hemisphere. Works by van Loon (1965, 1967), van Loon and Jenne (1972) and van Loon et al. (1971) have greatly improved the climatological description of the Southern Hemisphere upper air circulation. It is well known, however, that conventional upper air observations reach a sufficient spatial density only over limited areas of the Southern Hemisphere, i.e., the populated land areas and the fringe of the Antarctic Continent (see, e.g., The Global Experiment in the GARP Publication Series). This is why conventional meteorological observations are often supplemented by subjective analysis and/or theoretical considerations [viz., conservation of atmospheric angular momentum for example (Gilman, 1965)].

Various observational techniques have been suggested (GARP Global Experiment) for filling the data gaps, including the use of superpressure balloons for extended horizontal sounding of the upper air circulation (Lally, 1959; Giles and Angell, 1963). Such horizontal sounding data have been forthcoming at a modest rate for several years from the GHOST program of the National Center for Atmospheric Research (Lally et al., 1966) as well as from the developmental balloon flights by the French Centre National d'Etudes Spatiales, in preparation for the EOLE experiment. Valuable meteorological information about the Southern Hemisphere atmosphere has already been extracted from the constant-level (constant-volume) GHOST balloon flights (Solot and Angell, 1969a,b; Woolridge and Reiter, 1970; Angell, 1972; Solot and Angell, 1973). This paper is a report on the findings from a much larger constant-level flight program, known as the EOLE experiment, conducted also in the Southern Hemisphere, during the period September 1971-December 1972 (Morel, 1973; Morel and Bandeen, 1973). The basic data utilized herein are 100-min average values of the horizontal wind velocity from successive locations of constant-level balloons obtained on successive passages of the special purpose navigation and data collection EOLE satellite\(^1\); 168,000 such geographical fixes were obtained during the course of the program which involved the launching of 480 constant-volume balloons, each tracked around the earth for an average time of 100 days.

2. Wind errors and vertical sampling

How constant is the “constant-level balloon” flight altitude? The concept of horizontal sounding with

\(^1\)The EOLE satellite, also known as Cooperative Application Satellite 1, was fabricated by the French Space Agency C.N.E.S., and launched in space by NASA under an agreement of France and the United States.
essentially unextensible balloons has been discussed many times (see, e.g., Moore et al. 1954; Lally and Rickel, 1967; Morel and Bandeen, 1973), but it is only recently that the development of a miniature radiometer (Levanon, 1969) and the deployment of a large number of constant-level balloons for the EOLE experiment have given the opportunity to really find out the vertical dispersion of such crafts.

In the first place, the pressurized quasi-constant-volume envelope behaves just like a floater on an agitated stream, constantly bobbing up and down in response to vertical air motions associated with small-scale gravity waves, turbulence or convection (in the tropics). A detailed analysis of these vertical oscillations has been performed by Cadet (1973), indicating a 500-sec period under normal stratospheric stratification. This oscillation period is easily detected by spectral analysis of the balloon vertical or horizontal motions and can also be seen directly on records of balloon flight altitude. It is estimated that the amplitude of the short-period bobbing motion does not generally exceed ±30 m or about ±1 mb at the 200-mb level, but can easily increase to ±100 m when the balloon overflies active convective regions or large orographic obstacles.

In addition to this, although the envelope material has a high tensile strength, a definite expansion does occur when solar radiation warms the helium gas inside and overpressure increases. This expansion of the balloon volume results in a ±100 m diurnal variation of the flight altitude (or rather flight level density) as shown by Fig. 1.

Further, the residual vertical dispersion of the EOLE balloon flight levels, after accounting for the diurnal expansion of the envelope, was still of the order of 100 m (1σ) or about 1% standard deviation about the mean flight level density of 0.328 kg m⁻³ (Fig. 2). This vertical spreading can only be attributed to random errors in the weighting procedure prior to launch and/or an improperly compensated effect of relative humidity variations at the launching site. We may thus conclude that the EOLE balloons have essentially sampled the horizontal air flow within a 300–400 m thick layer centered at the level ρ = 0.328 kg m⁻³ corresponding to 205 mb in the standard atmosphere. Fig. 3 indicates how well the mean density level approximates the 200-mb isobaric surfaces in summer and in winter.

Now, it is well known that the stratospheric air flow exhibits a moderately persistent layered structure with large wind shears on vertical scales of the order of 100–500 m (Sawyer, 1961; Fiedler and Panofsky, 1970; Weinstein et al., 1966). This shear has also been measured by the Laboratoire de Météorologie Dynamique using a specially developed, very sensitive balloon-borne anemometer hanging about 100 m under the carrier balloon (Cadet, 1973). It has been observed in the course of extensive 200-mb stratospheric flights that the 6-hr rms wind shear rarely falls below 0.01 sec⁻¹ (1 m sec⁻¹ per 100 m altitude increment) on any single day, with instantaneous maxima well above 0.05 sec⁻¹. The average of the daily rms wind shear values obtained during this flight series (Southern Hemisphere

![Fig. 1. Diurnal excursion of the flight altitude determined from telemetered ambient pressure and temperature data.](image)

![Fig. 2. Residual dispersion of EOLE balloon flight levels.](image)
winter) was $1.5 \times 10^{-2}$ sec$^{-1}$. Since the instantaneous wind shear and the balloon altitude are independent random parameters, it is estimated that the vertical spreading of the EOLE balloons results in a 1.5 m sec$^{-1}$ standard deviation of the wind vector measurements about the optimum vertical average which would be best applicable to the description of synoptic patterns or the initialization of numerical prediction with general circulation models.

One can point out, on the other hand, that errors suffered from insufficient vertical sampling are compensated for by the near-absence of error resulting from horizontal sampling. Wind determinations are derived from the measured quasi-horizontal displacements of balloons between two successive passages of the EOLE satellite at 100-min intervals, approximately. This time interval can be associated with horizontal distances of 100–200 km for typical lower stratospheric circulation. Thus, the horizontal sounding method associated with satellite tracking results in smoothing out small-scale perturbations and local turbulence with a characteristic horizontal scale less than 100 km. This cutoff is quite appropriate for the purpose of mesoscale and general circulation studies (see Fiedler and Panofsky, 1970).

In comparison with the vertical sampling error, purely instrumental errors, i.e., navigational errors, are quite insignificant. A detailed comparison of the known location of a fixed platform with positions derived from EOLE data has shown an (unexplained) systematic shift of the order of 500 m and a standard deviation of the order of 1000 m. Larger errors are generally expected for moving platforms, but did not occur to any significant extent in this case, as indicated by the very consistent locations obtained when several range and range-rate measurements were available during a single passage of the spacecraft. It is thus estimated that the rms location error is 2 km, corresponding to a 3-km standard deviation for balloon displacements or a 0.5 m sec$^{-1}$ rms wind vector error.

In consideration of the reasonably large number of wind determinations (over 400 per day during October–November, 1971), it is not expected that a 1.5 m sec$^{-1}$ rms wind vector error would significantly affect the balloon-derived determinations of the transient patterns of the general circulation. This error, mainly attributable to insufficient vertical sampling, will not affect the significance of the balloon-derived estimates of the mean flow velocity or stationary circulation patterns either, because it is much smaller than the day-to-day variability of the wind itself. Random errors, however, are quite significant when the trajectories of neighboring balloons are compared for estimating the horizontal flow divergence or establishing the eddy diffusion rate of a cluster. This problem was discussed in some detail by Morel and Necco (1973).

3. Data coverage

The EOLE data set consists of about 85,000 wind velocity determinations at the 200-mb level (approximately) in the Southern Hemisphere. The data set extends over about one year from September 1971 to August 1972, with a peak density of 500–700 wind observations per day in October–November, 1971, decreasing to only 100 observations per day at the end of the period.

The balloons were released from three launching sites in the Republic of Argentina, ranging from 33S (Mendoza) to 55S (Ushuaía). The launching schedule was, in principle, designed to ensure an homogeneous initial distribution of tracers outside the tropics. Actually, the lateral mixing by large-scale eddies was found to be so strong that balloons were distributed essentially at random, irrespective of their launching site (Morel and Bandeen, 1973). As a result, the balloon population maintained a uniform latitudinal distribution throughout the (spring) launching period. During the summer, however, the increased attrition rate of balloons in the tropics due to high-altitude convective clouds and icing on the one hand, and the thrust of the Hadley circulation toward higher latitudes on the other hand acted to produce a markedly biased latitudinal distribution of balloons. This did not result in an improved data coverage at high latitudes, however, as the polar cap is out of communication range from the EOLE satellite. The polar clustering reversed in the fall but then the remaining number of active balloons had become marginal for general circulation studies.

In addition to this latitude bias, the stationary wave patterns of the general circulation induced a marked longitudinal bias, with a noticeably higher probability of finding balloons over the tropical Pacific (90–180W) and a correspondingly smaller number of tracers at mid-latitudes over the southern Atlantic (Fig. 4). This bias would not be serious in mid-latitudes where
enough data are available to determine monthly averages with good statistical significance. This, however, is not the case in the tropics (10–20°S) where wind data were obtained only over a quarter of the total area. In effect, EOLE balloon soundings were obtained equatorward of 20°S, only where and when the general circulation invaded the tropical zone, with characteristically higher westerly velocity. Thus, mean zonal velocity estimates from the EOLE data are thought to be grossly overestimated in the tropical zone and are not reported here.

Finally, one should remark that the instantaneous distribution of platforms in a Lagrangian sounding system does not by itself give a faithful view of the resulting data coverage because each individual platform can be interrogated and located up to seven times per day (in the latitude range 40–50°S) so that each can provide several independent wind data if only the flow velocity is fast enough to provide enough separation between successive measurements. This situation actually occurred in the EOLE experiment because the satellite orbit was chosen for maximizing the number of interrogations in the latitude range where the mean zonal velocity is the largest. Table 1 shows the resulting latitudinal data distribution obtained during the first 12 months of the EOLE experiment.

**Table 1. Number of wind observations per 5° latitude band per month obtained from the EOLE data.**

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4. Mean zonal velocity

In view of the rapidly changing distribution of the balloons and the existence of fairly sizeable clusters in the early part of the experiment, care had to be taken to offset the possible bias due to non-uniform and not quite random sampling of the velocity field. In order to approach as much as possible the true Eulerian average, and to reduce the weight of individual observations in dense clusters, the following averaging procedure was followed.

In the first place, all available data were distributed between 20 equal-area latitude zones ranging from the equator to 90°S (not 5° latitude intervals as in Table 1) and again separated into 16 longitude intervals, thus producing 320 latitude-longitude boxes of equal area (approximately 800,000 km² or 450 km × 1800 km near 45°S). The instantaneous values of the zonal velocity were first averaged over successive, non-overlapping 5-day intervals, then subjected to a 20-day running average using a filter with a weighting decreasing linearly from the center point, and averaged again over periods of one month. Finally, a zonal average of all 16 monthly mean values in the same latitude zone was performed. The resulting monthly and zonal mean values of the zonal velocity \( \bar{u} \) are given in Table 2, while a better time resolution has been used for drawing the latitude-time cross section of Fig. 5.

In view of the large number of instantaneous observations which go into each of the \( \bar{u} \) estimates in Table 2 (more than 100 in the worst case), random balloon location errors (0.5 m sec\(^{-1}\)) and even vertical sampling errors (1.5 m sec\(^{-1}\)) are quite negligible. Thus, the statistical significance of the mean values \( \bar{u} \) is entirely determined by the spatial and temporal variability of the zonal wind. A rough idea of the variability is given by histograms of the zonal wind data for the months October 1971 and January, April and July 1972 (Fig. 6). Note that the distribution is not quite Gaussian but is definitely skewed toward high velocity values. Wind velocities in excess of 80 m sec\(^{-1}\) were indeed found

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**Table 2. Mean-monthly zonal velocities (m sec\(^{-1}\)) deduced from EOLE balloon flights at 200 mb.**

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(about 1–2% of the observations in winter situations) but have been artificially cut off in data processing.

Now, the spatial variability of the monthly means is characteristic of the standing wave patterns of the general circulation (see Section 6). This variability can be estimated by taking the standard deviation of the 16 monthly means in the same latitude zone as they appear on the next to the last step of the averaging procedure. This deviation is generally of the order of 5 m sec\(^{-1}\), i.e., much less than the zonal mean. A tabulation of the spatial variance associated with standing eddies is given in Table 3 for various latitudes and seasons.

The remaining and largest contribution to the variability of the zonal velocity must be associated then with short-term transient perturbations of the basic flow. The corresponding standard deviations given in Table 4 show remarkably little seasonal variation during the whole period September 1971–August 1972. The table shows fairly high values of the order of 15 m sec\(^{-1}\) in the core of the mid-latitude westerly circulation, dropping off gently to 10 m sec\(^{-1}\) at low and high latitudes. Since most of this temporal variability is associated with quasi-sinusoidal, synoptic-scale perturbations with a period of a few days, it is expected that the confidence limits for monthly Eulerian mean values should be quite narrow, i.e., ±1 m sec\(^{-1}\) approximately.

This view is supported by the excellent agreement of the mean velocity derived from one year of EOLE data with climatological values obtained by other authors, particularly van Loon et al. (1971), from conventional upper air observations. Such agreement would be expected due to the relatively small spatial variability of monthly mean zonal velocities; the inhomogeneous longitudinal distribution of upper air stations in the Southern Hemisphere does not alter drastically the zonal average (Fig. 7). One noticeable difference between the EOLE data and climatological values occurring in the month of October, is associated with the rather quick transition from the winter regime, with maximum zonal velocity in a subtropical jet near 30S, to the summer regime with a polar jet between 40 and 50S. The breakdown of the subtropical jet may result in a bimodal mean zonal velocity profile (quite noticeable in the climatological profile for October) which did occur in November 1971 during the EOLE experiment.

The mean zonal velocity values derived by Solot and Angell (1969a) from nine GHOST balloon flights at the same level in the Southern Hemisphere, are also plotted in Fig. 7. A serious difference is found equatorward of 30S. This difference may be attributed to the insufficient sampling of low latitudes by the GHOST balloons which have all been released from high latitudes. GHOST balloons would generally enter the tropics

**Table 3.** Spatial variance (m sec\(^{-1}\)) associated with standing eddies, based on three-month Eulerian averages of the zonal and meridional velocities, computed in 16 adjacent longitude intervals in the same 5° latitude band.

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Table 4. Temporal variance (m sec\(^{-1}\)) associated with transient eddies, based on the instantaneous zonal and meridional velocity deviations from the three-month averages. This temporal variance adds (quadratically) to the spatial variance given in Table 3.

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Fig. 7. Latitudinal profile of the 200-mb mean zonal velocity deduced from EOLE data (heavy solid curve) compared with climatological values (dashed curve) given by van Loon et al. (1971) and GHOST flight data (dotted curve) given by Solot and Angell (1969a).

Five Lagrangian vs Eulerian averages

As shall be seen below, the mean meridional velocity of the 200-mb circulation derived from EOLE data is very small indeed, of the order of 10 km day\(^{-1}\). Accordingly, one particular balloon could revolve at least once around the earth while staying generally in the same latitude zone, with an almost constant mean latitude. It is tempting then, to take the time needed to complete

Fig. 8. Mean zonal velocity profile for December estimated from the same EOLE flight data using Eulerian averaging (solid line) and Lagrangian averaging (dashed line).
one revolution as an estimate of the (Lagrangian) mean zonal velocity appropriate to the balloon mean latitude. A Lagrangian mean zonal velocity profile obtained from all balloons flying during the month of December 1971 is shown in Fig. 8 for example. Note that the Lagrangian mean velocity does not exactly tally with the Eulerian average, even in the medium latitude range where the large-scale eddies could be considered stationary with superimposed homogeneous random perturbations. The implication of this for the Lagrangian velocity correlation in large-scale eddies is being presently investigated.

6. Mean meridional velocity

Direct measurements of the mean meridional circulation of the atmosphere generally suffer from large uncertainties since they are relatively small residuals of the order of 0.2 m sec$^{-1}$ left from the time and space averaging of large, fluctuating meridional winds with a temporal variance of 10–15 m sec$^{-1}$ (see Table 4). Indeed, even with ideally uniform observations in space and time, the uncertainty on the monthly Eulerian mean meridional velocity would still have the same order of magnitude (±1 m sec$^{-1}$) as the uncertainty on the mean zonal velocity. This task has nevertheless been undertaken with a large degree of success using several years of observations in the Northern Hemisphere. For a review of these observational studies and recent results, see Oort and Rasmusson (1970). But the Southern Hemisphere upper air network is so far from being adequately dense and uniform that only very sketchy results can be found in earlier observational studies from rawin and pilot balloon observations (Obasi, 1963; Gilman, 1965).

The collection of an extensive set of precise, internally consistent, direct wind measurements with essentially no geographical bias, was a unique opportunity to derive a far more precise determination of the mean meridional circulation at the 200-mb level in the Southern Hemisphere (outside the tropics). Even so, the EOLE wind data could not just be averaged like so many independent point measurements, to produce reliable estimates of the mean meridional velocity, because, while more than 1000 observations per month and per 5° latitude zone were available in the first half-year of the EOLE experiment, the reliability of a standard Eulerian average would still be limited by the natural variability. But the EOLE data are more than just a set of independent discrete measurements: each tracer is identified by a unique code and its trajectory can be tracked continuously for as long a time period as desired. Such trajectories provide the best possible (Lagrangian) average of all scales of motion,
without sampling error. Thus, one need only apply an appropriate smoothing to filter out most of the unwanted fluctuations associated with synoptic-scale transient eddies. This was done by applying a running average over 20 days, with a weighting decreasing linearly from center point, as shown in Fig. 9. The resulting standard deviation of the meridional velocity of the smoothed trajectories (Fig. 10) is thus reduced to \( \sim 1 \text{ m sec}^{-1} \). Now, the same Eulerian averaging procedure as used in the previous section further reduces the variance by a factor of 10, so that the resulting uncertainty on the estimated monthly mean meridional velocity is 0.1 m sec\(^{-1}\) in the latitude range 30-60S, increasing to about 0.2 m sec\(^{-1}\) near the edges of the domain covered by EOLE balloons (20S and 70S).

Note that instrumental errors proper are much smaller and add negligibly to the uncertainty associated with natural fluctuations.

The observed mean meridional velocities are presented in Table 5 (monthly averages) and are also depicted in Fig. 11 as a time-latitude cross section with the best time resolution compatible with the smoothing operator. One will first notice the fairly large short-term variability of even this smoothed, zonally averaged meridional circulation. These variations are indeed a real effect, measured with very little experimental uncertainty during the period October 1971–March 1972 and are probably a typical feature of the general circulation which would repeat with more or less random phase shifts every year. But the detailed variations

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do certainly not have climatological permanence. The mean values of Table 5, on the other hand, are an attempt to draw a more generally meaningful conclusion regarding the seasonal variation of the mean meridional circulation at 200 mb. From this point of view, three specific situations are clearly distinguishable.

1) The spring period (October–November) with a weak indirect Ferrel circulation restricted to a fairly narrow strip between 25 and 45S and a strong poleward circulation south of 45S. Note that the mean zonal velocity maximum is a subtropical jet lying very nearly at the same latitude as the mean meridional velocity maximum.

2) The late spring period (December) marked by a deep penetration of the direct Hadley circulation as far south as 40S, pushing back both the indirect Ferrel circulation and the mean zonal velocity maximum (polar jet at 45S).

3) The summer period (January–March) characterized by a slow retreat of the Hadley circulation toward the tropics and a corresponding augmentation of the Ferrel circulation.

Note that the mean zonal velocity maximum is never associated with a mean convergence; there is, therefore, no evidence from the EOLE data that balloon tracers should converge toward the mean jet stream latitude.

The December event had a very noticeable effect on the EOLE balloon distribution, as almost all the existing population at that time was pushed toward the polar region. The same effect has been reported by Solot and Angell (1969b, 1973) on the basis of a much smaller, yet similar set of observations with GHOST balloon flights at 200 mb in the Southern Hemisphere during the years 1966–71. This lends substance to the belief that there is indeed a significant ageostrophic equatorward flow at 200 mb during the Southern Hemisphere late summer and autumn, and a well-developed poleward flow south of 40S during the Southern Hemisphere spring. Obasi (1963), analyzing rawin and pilot balloons data collected during the IGY (1958), also found a generally similar behavior, i.e., a typical winter profile like October and a typical summer profile like February. Finally, Fig. 12 shows, in broad outlines, the relation between the mean zonal velocity maximum or mean jet stream, the meridional circulation, and the mean temperature field at 200 mb during the period October 1971–May 1972. The most significant event on this chart is clearly the equatorial outbreak, at the beginning of the austral summer, with simultaneous and nearly equal poleward shifts of the mean zonal jet and the indirect Ferrel circulation, and a general warming of the mid-latitude and polar stratosphere.

7. Standing waves

The existence of a significant standing wave component superimposed on the mean zonal circulation in the Southern Hemisphere has been recognized by several authors from the analysis of fairly limited observational data [e.g., temperature and wind soundings collected during the International Geophysical Year (Van Loon and Jenne, 1972) or GHOST balloon flights (Solot and Angell, 1973)]. The EOLE experiment, on the other hand, provided much denser and more uniform 200-mb wind data than previously
available in the Southern Hemisphere. A study of the standing planetary waves based on the EOLE data yielded a more detailed, but also rather more complicated, picture of the mean circulation than previously indicated.

In the first place, one must realize that the definition of "transient" and "standing" eddies is somewhat arbitrary, to the extent that it depends upon the choice of one particular time filter or averaging period, consistent with our subjective idea of persistence. The standing wave contribution is just the residual left after the specified time filtering; the longer the averaging period, the smaller the residual. Now a large fraction of the variability of meteorological quantities is associated with traveling perturbations and periods of the order of 2–20 days, while a definite spectral gap exists between periods of 1 month to 1 year (Vinnichenko, 1970, Fiedler and Panofsky, 1970). On the other hand, the basic zonal circulation itself may vary quite noticeably in the course of 1–2 months, and very
definitely so from winter to summer. This change of
general circulation patterns is clearly seen on the mean
monthly 200-mb streamfunction maps for October 1971
(Fig. 13a), January 1972 (Fig. 13b), April 1972 (Fig.
13c) and July 1972 (Fig. 13d) for example. The winter
regime is characterized by a strong zonal flow and
relatively little waviness, while the summer regime has
a typically slower zonal flow and pronounced perturba-
tions over the tropical Pacific. In principle, then, one
would want to define the standing (stationary) waves
of the general circulation with the shortest averaging
period consistent with effective smoothing of the
traveling disturbances. Experimentation with various
running averages has shown that truly stationary dis-
turbances of the general circulation can only be deter-
mined over periods of 3 months or more. Accordingly,
we have restricted our study to two 3-month periods
with good coverage of EOLE wind data. Fig. 14 shows
the isopleths of the mean meridional and the mean
zonal velocities $\bar{u}$, $\bar{v}$ during the period December 1971–
February 1972, typical of the austral summer regime.
Fig. 15 shows the same data for a typical winter period,

One can readily appreciate from Figs. 14 and 15 that
no simple pattern emerges. A transition from the sub-
tropical circulation to a high-latitude or polar circula-
tion seems to occur near 35 or 40°S in both seasons. The most striking stationary feature of the subtropical circulation (25S), then, is the positive anomaly of both the mean zonal velocity u and mean meridional velocity v in the central Pacific. Note that the u anomaly, particularly, is still faintly noticeable at 35°S but completely reversed at 45°S, thus indicating a displacement of the zonal velocity maximum (jet core) from mid-latitudes in the Atlantic toward the tropics in the Pacific. Wavenumbers 1 and 3-4 are prominent at high latitudes for both the u and v anomalies, with virtually the same amplitude and phase in summer as in winter.

8. Conclusions

The emphasis in this paper has been placed on the climatological aspects of the Southern Hemisphere general circulation during the period September 1971–August 1972 when a significant number of EOLE balloons were aloft. This is the first step of our EOLE data analysis program, including also, and successively, the study of traveling disturbances, momentum and energy transfer by the large-scale transient eddies, and two-dimensional turbulence at 200 mb.

The results presented here agree generally with many previous climatological studies of the Southern Hemisphere, based on conventional soundings. They also confirm the findings of the GHOST horizontal sounding program with regard to the temperate latitude (40–70°S) 200-mb circulation, while covering a wider latitude range and providing a much improved resolution both in space and time. The EOLE data do support, for example, the finding of a general alternation of the mean meridional flow in temperate latitudes with a definite 0.2 m sec⁻¹ poleward mean velocity in late winter (October 1971) and a corresponding equatorward velocity during the summer; yet the EOLE data also show a similar but reversed alternation of the mean meridional velocity at lower latitudes, between 20 and 40°S. The remarkable anticorrelation of the mean zonal velocity anomalies at 25 and 45°S is yet another example of the different character of the subtropical circulation on one hand, and the temperate or rather polar circulation on the other. Although definite conclusions regarding planetary atmosphere dynamics cannot rigorously be drawn from a purely climatological study, one is tempted to correlate the changing character of the standing eddies and mean meridional flow at 40°S with the geographical distribution of land masses in the Southern Hemisphere. In this context of general circulation studies, the Southern Hemisphere is not quite a quasi-uniform, marine planet as sometimes proposed in the literature—only the temperature zone from 45–65°S can be so described.

Acknowledgments. The EOLE experiment has been made possible by the devoted effort of many, in the Centre National d’Etudes Spatiales and also in the Laboratoire de Météorologie Dynamique. Their invaluable contribution is gladly acknowledged by the authors.

REFERENCES


