Mean meridional winds estimated from constant level balloon flights in Southern Hemisphere temperate latitudes

By J. K. ANGELL

Air Resources Laboratories, NOAA, Silver Spring, Maryland

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SUMMARY

Temporal and longitudinal variations in mean meridional wind are estimated from GHOST and EOLE constant level balloon flights at 100 and 200 mb in south temperate latitudes during the period 1966/72. At these latitudes there is evidence of about a 0-3 m s⁻¹ poleward flow in winter-spring and equatorward flow in summer-autumn, with the oscillation at 100 mb preceding that at 200 mb by 1 to 2 months. This annual oscillation may reflect a direct circulation between summer and winter hemispheres. At 200 mb in south temperate latitudes there is also evidence for about a 0-1 m s⁻¹ poleward flow during the west wind phase, and equatorward flow during the east wind phase, of the quasi-biennal zonal wind oscillation in the low tropical stratosphere. The significance of this relation has not yet been ascertained. The overall mean equatorward drift of 0-04 m s⁻¹ points up the existence of the Ferrel Cell in the long-term average. A breakdown of the data by longitude shows that the annual variation in zonal-average meridional wind is due to large seasonal variations in meridional wind over the South Atlantic.

1. INTRODUCTION

The National Center for Atmospheric Research has been flying constant level balloons (Project GHOST) in the upper troposphere and lower stratosphere of the Southern Hemisphere since 1966 (Lally et al. 1966). In late 1971 the French released approximately 500 constant level balloons (Project EOLE) for flight at 200 mb (Morel and Bandeen 1973). This paper analyses and combines the meridional winds obtained from the two sets of data. The reader is referred to papers by Solot and Angell (1969a), Kao and Hill (1970), Wooldridge and Reiter (1970) and Angell (1972a) for other discussions of the GHOST data, and to Morel and Necco (1973) for other discussions of the EOLE data.

2. PROCEDURES

The data base for this analysis consists of daily latitudes and longitudes obtained from 32 GHOST flights at 200 mb and 14 GHOST flights at 100 mb during the period April 1966 to February 1971 (Solot 1968, 1972), as well as from 46 of the longest EOLE flights at 200 mb during the period September 1971 to July 1972. The latter data were received from the Goddard Space Flight Center, NASA, in accord with the policy of the EOLE Data Interpretation Group. The GHOST balloons, released from Christchurch, New Zealand (43°S), were positioned by means of the ‘sunseeker’, a device which determines the elevation angle of the sun (Lichfield and Frykman 1966). In temperate latitudes these positions are believed accurate to within 100 km. The average GHOST flight duration was 150 days at 200 mb and 160 days at 100 mb. The EOLE balloons, released from Mendoza (33°S), Neuquen (39°S) and Lago Fagnano (52°S), Argentina, were positioned by means of a special EOLE tracking satellite through successive determination of range, and rate of change of range, between satellite and balloon. The EOLE positions are accurate to within a few kilometers. The average duration of the EOLE flights used herein was 250 days.

Since in a sense we are attempting to relate Lagrangian measurements to Eulerian measurements, it is important to make clear the manner in which the meridional velocities
were evaluated. Throughout this paper it will be implicitly assumed that the meridional displacements of the constant level balloons fairly accurately reflect the meridional displacement of the air itself, but with the realization that there has been some controversy along this line (Solot and Angell 1969b). For the study of temporal variations, the mean meridional velocity has been estimated from the change in latitude along individual balloon trajectories at 10-day intervals and an averaging of the meridional velocities so derived from all the balloons aloft during that 10-day interval. It has been shown by Dyer (1973) and by Webster (1973) that there are inherent dangers in the use of such a procedure (indeed, in the use of most procedures which attempt to relate Lagrangian and Eulerian statistics). To state the most obvious difficulty, if there are variations in zonal wind speed, then biases arise because, in order to obtain a representative zonal-average value, what is required is the meridional velocity at equal intervals of longitude not at equal intervals of time. It is unlikely that in the following the sense of the meridional velocity has been affected through the use of the above procedure, but there is no doubt that the magnitude of the meridional velocity may have been affected thereby, and perhaps seriously so as indicated by Webster.

Finally, it will be noted that the meridional velocity data have been averaged for the entire temperate-latitude band, 30° to 60°S, and consequently if there are systematic differences in the meridional velocity pattern across this band, it is the predominant pattern that is being presented here. This is an unfortunate procedure to have to follow (Schwerdtfeger 1973), but with the relative sparsity of GHOST data it appears necessary in order that useful results are not lost in the high noise level.

3. ANNUAL VARIATION IN MERIDIONAL WIND

Fig. 1 presents 6-month running averages of the meridional wind (south wind positive) in south temperate latitudes as estimated from GHOST balloon flights at 100 and 200 mb.

![Figure 1](image_url)

Figure 1. Temporal variation in meridional wind (south wind positive) in south temperate latitudes as estimated from 6-month running averages of GHOST-derived velocities at 100 and 200 mb. The number of flights on which the statistics are based is indicated at the top of each diagram.
As shown previously by Solot and Angell (1973), at 200 mb the balloons tend to move
equatorward (northward) during the Southern Hemisphere summer and autumn (December
to May) and poleward during the winter and spring (June to November). Because of the
use of 6-month running averages, the annual variation in meridional wind has been reduced
by nearly half, and the actual amplitude of this oscillation is approximately 0.3 m s$^{-1}$.
The absence of a strong annual oscillation in 1969/70 may be due to the fact that the
meridional velocities were derived from only one balloon trajectory during that time.

A year-by-year comparison with the annual oscillation at 100 mb has not previously
been made. Based on the years 1968/69, the annual oscillation at 100 mb precedes that at
200 mb by about 1½ months (deduced from the phase lag of maximum correlation), with
the amplitude of the oscillation slightly larger at the lower level. Thus, there is the suggestion
that the times of meridional-velocity maxima approach the solstices as one moves higher
into the stratosphere.

In order to give the reader some idea of what this annual variation in meridional velocity
implies from a trajectory point of view, Fig. 2 presents the plot of mean balloon latitude
as a function of time for 8 GHOST flights released between 5 and 15 June, and 6 flights
released between 5 and 15 October 1968. During that year the annual oscillation involved
a latitudinal shift in mean balloon position from about 40°S in winter to 60°S in summer.
Thus, the annual oscillation appears to consist of a swaying back and forth of air parcels
across about half the temperate-latitude zone. The latitudinal dispersion of these balloons
is illustrated by the vertical bars extending 2 standard deviations of the mean either side
of the mean value, and it is seen that the indicated meridional displacement is quite
significant.

![Figure 2](image)

Figure 2. Mean variation of balloon latitude with date for 8 GHOST balloons released between 5 and 15
June and 6 balloons released between 5 and 15 October 1968. The number of 200 mb balloons remaining
aloft is shown by the numbers along the trajectories, while the vertical bars extend 2 standard deviations
of the mean either side of the mean latitude.

Fig. 3 shows the average annual variation in 200 mb meridional wind derived from the
46 EOLE flights during 1971/72 in comparison with that derived from the 32 GHOST
flights during 1966/71. Although the two traces differ in the sense that there is no evidence
from the EOLE data for a mean equatorward drift (the reason for this is given in the next
section), the annual variations in meridional wind are similar, with lagged correlations
indicating that the GHOST-derived oscillation precedes the EOLE-derived oscillation by
only about two weeks. The similarity in the annual variation of meridional wind obtained
from the two sets of data pretty well establishes the reality of the annual variation in
meridional balloon displacement, and presumably the reality of the annual variation in air
parcel displacement as well.
The annual oscillation in meridional velocity derived from the constant level balloon flights at 100 and 200 mb is not inconsistent with the annual variation in meridional velocity deduced from conventional sounding data. For example, Newell et al. (1969), and to some extent Oort and Rasmussen (1970), have shown that in the Southern Hemisphere summer (December to February) the Northern Hemisphere Hadley (direct) Cell tends to straddle the Equator, and the Southern Hemisphere Hadley Cell is practically eliminated owing to its constriction by this strong equatorial cell and the Ferrel (indirect) Cell of south temperate latitudes. What results in essence is a direct circulation between summer and winter hemisphere, and it is this circulation which appears to be responsible for the northward drift indicated by the 100 and 200 mb balloon flights between about November and June. In this connection it is of interest that the maximum northward velocity indicated by the IRLS (Interrogation, Recording and Location System) 50 mb balloon flights in the tropics also occurred in the Southern Hemisphere summer (Angell 1972b), in agreement with Newell et al.'s model of the Northern Hemisphere Hadley Cell straddling the Equator and extending at least to 50 mb at this time.

The southward drift at 100 and 200 mb in the Southern Hemisphere winter, less pronounced than the northward drift in summer, is not so obviously in agreement with the model of Newell et al. This model shows the Southern Hemisphere Hadley Cell, at this time of year, nearly straddling the Equator and a relatively shallow Ferrel Cell in south temperate latitudes, resulting in a southward drift in the Southern Hemisphere tropics and essentially no mean meridional velocity at 200 mb in south temperate latitudes. On the basis of the GHOST and EOLE flights we suggest that in winter the Southern Hemisphere Ferrel Cell is even less pronounced than indicated by Newell et al., and that in south temperate latitudes there is in general a weak southward drift at these heights due to the virtual disappearance of this Ferrel Cell and amalgamation of the Southern Hemisphere Hadley Cell and direct Polar Cell, i.e. again basically a direct circulation between summer and winter hemispheres.

The above evidence for the existence of a direct circulation between summer and winter hemispheres is probably one of the more important results derived from these constant level balloon data. It is not clear, however, why the meridional-velocity fluctuation at 100 mb should precede that at 200 mb in the case of such an inter-hemispheric circula-
tion. Note that the satellite-determined stratospheric radiances analysed by Fritz and Soules (1970, 1972), which yield evidence of cooling in the tropics concomitant with warming in polar latitudes, also suggest that the importance of hemispheric-scale meridional motions may heretofore have been underestimated.

In passing, it should be noted that the maximum poleward flow at 100 mb in south temperate latitudes is indicated to occur about 2 months prior to the total-ozone maximum at Macquarie Island (54°S) and about 4 months prior to the total-ozone maximum at Byrd (80°S) and Amundsen–Scott (90°S), suggesting that mean meridional motions, as well as mean vertical motions and meridional and vertical eddy fluxes, play a role in the annual variation in total ozone in south temperate and polar latitudes. The weak point in this argument is that the ozone maximum occurs near 30 mb, not at 100 mb, and we have little proof (only one balloon flight) that the meridional motions are the same at the higher level. Hunt (1969) has indicated, on the basis of a general circulation model, that there is a tendency for counterbalancing effects on ozone concentration due to mean meridional motions and meridional eddy fluxes.

4. QUASI-BIENNIAL VARIATION IN MERIDIONAL WIND

Inasmuch as these constant level balloon data have not previously been analysed from the standpoint of the quasi-biennial oscillation, it seemed desirable to do so here. The solid line in Fig. 4 shows the 12-month running average 200 mb meridional wind determined from GHOST and EOLE constant level balloon flights in south temperate latitudes during the period 1967/71. Apparent is a quasi-biennial type oscillation superimposed on an overall equatorward drift of about 0.04 m s⁻¹, the latter presumably pointing up the existence of the Ferrel Cell in the long term average.

![Figure 4. Comparison between the 12-month running average meridional wind estimated from GHOST and EOLE balloon flights at 200 mb in south temperate latitudes (solid line), and the 12-month running average 50 mb zonal wind at Ascension Island (dashed line). South and west winds are positive.](image)

Plotted for comparison in Fig. 4 is the 12-month running average 50 mb zonal wind at Ascension Island (8°S). While deductions based on short periods of record are no doubt hazardous, there is a quite strong out-of-phase relation (r = −0.78) between the quasi-biennial 50 mb zonal wind oscillation at Ascension and the 12-month running average 200 mb wind in south temperate latitudes, as if the latter did indeed reflect a mid-latitude quasi-biennial oscillation of about 0.1 m s⁻¹ amplitude (the 12-month running mean reduces the amplitude by nearly half). After taking into account the effect on sample size of the running mean, the correlation of −0.78 is significant at the 5 per cent level according to Fisher's Z test. Pittcock (1973) has also recently presented substantive evidence for the extension of the quasi-biennial oscillation into south temperate and south polar latitudes.

Determination of the correlation for various phase lags shows that the quasi-biennial
oscillation in 50 mb zonal wind precedes the quasi-biennial oscillation in meridional wind by 1 month on the average, i.e. the tendency for the meridional wind to lag the zonal wind by about 3 months during 1967/69 is almost balanced by the opposite tendency during 1970/71. Thus, since the quasi-biennial zonal wind oscillation descends at the rate of about 1 kilometer per month (Reed 1965) (and with the observation that, based on the short period of 100 mb record, the quasi-biennial meridional wind oscillations at 100 and 200 mb are almost exactly in phase), we estimate that at 100 mb the quasi-biennial meridional wind oscillation in south temperate latitudes precedes the quasi-biennial zonal wind oscillation in the tropics by approximately 2 months, and with the sense that the maximum equatorward flow slightly precedes the tropical east wind maximum and the maximum (but slight) poleward flow slightly precedes the tropical west wind maximum. Consequently, we suggest here that the reason the EOLE balloons did not undergo an obvious equatorward drift, as did the GHOST balloons in the mean (see Fig. 3), was due to the circumstance that they were released at the time of quasi-biennial west wind maximum in the low tropical stratosphere, and during such a period an appreciable equatorward drift is simply not observed.

It is perhaps premature to comment on the possible significance of the above relationship since some will undoubtedly believe that the data record is not of sufficient length to confirm its existence. Accepting for the moment the relation suggested by Fig. 4, the question arises as to whether the tropical quasi-biennial zonal wind oscillation is influencing the meridional flow in south temperate latitudes, or vice versa. If equatorward and poleward moving air parcels in temperate latitudes conserve their absolute angular momentum, then east winds will develop in the former case and west winds in the latter case, but the extent to which this could influence the zonal wind in the tropics is not clear and in any event the phase lag should be about one-quarter of the quasi-biennial cycle (7 months) rather than the 2 months indicated above. At this point we leave the above relation as something to be noted and considered, but, so far unexplained.

Again in passing it should be emphasized that the quasi-biennial maximum in total ozone in south temperate and polar latitudes tends to follow the quasi-biennial maximum in poleward velocity in south temperate latitudes by about one-quarter cycle, suggesting that even on this scale total-ozone fluctuations are affected by mean meridional motions as well as by mean vertical motions and meridional and vertical eddy fluxes.

5. Longitudinal variation in meridional wind

The bottom diagram of Fig. 5 shows the variation with longitude of the annual mean meridional wind in south temperate latitudes, as determined by evaluation of GHOST and EOLE 200 mb meridional velocities on a daily basis. The mean equatorward flow exceeds 0·2 m s\(^{-1}\) to the east (lee) of the Andes Mountains, while a smaller equatorward drift is found over the South Indian Ocean. Over South Africa and Australia the mean flow is toward the pole. The letter R denotes the mean ridge positions found by van Loon and Jenne (1972) from analyses of conventional sounding data. There is good agreement between the two sets of data, except in the South Pacific (150°W) where the constant level balloon data do not clearly delineate a mean poleward flow.

The top diagram of Fig. 5 shows the variation of 200 mb meridional wind with longitude and month based on data for the years 1966/72. This diagram is of particular interest in pointing up the fact that the annual variation in zonally-averaged meridional wind noted earlier (poleward flow in winter–spring, equatorward flow in summer–autumn) is due almost entirely to the large seasonal variation in meridional wind over the South Atlantic. Thus, in the Southern Hemisphere winter there is indicated to be a mean poleward flow of about 0·4 m s\(^{-1}\) over the South Atlantic, in contrast to a mean equatorward flow
of about 0.6 m s\(^{-1}\) in summer. This alternation to some extent reflects the seasonal shift in wave number one associated with the winter–summer difference in heating experienced by the relatively large temperate-latitude land mass of South America (resulting in the formation of a mean 200 mb ridge over the continent in summer and a trough in winter), but the important point is that the meridional drift over the South Atlantic apparently is not compensated at other longitudes so that there exists in the zonal average a meridional velocity of the same sense as noted over the South Atlantic. The varied Southern Hemisphere data of Pittock (1973) may prove useful in examining the possible reasons for, and significance of, this lack of compensation.

6. CONCLUSION

With the assumption that the GHOST and EOLE constant level balloon flights at 100 and 200 mb yield representative meridional velocity statistics, it is shown that in south temperate latitudes there exists:

(i) Approximately a 0.3 m s\(^{-1}\) poleward flow in winter–spring and equatorward flow
in summer–autumn at 100 and 200 mb, which flow may reflect a direct circulation between hemispheres. This alternating flow, if it extends to higher altitudes, may contribute to the annual variation in total ozone in south temperate and polar latitudes.

(ii) Approximately a 0.1 m s\(^{-1}\) poleward flow at 200 mb during the west wind phase, and equatorward flow during the east wind phase, of the quasi-biennial zonal wind oscillation in the low tropical stratosphere, providing evidence for an extension of the quasi-biennial oscillation into temperate latitudes and, more generally, providing evidence of an intimate link between the mean flows in the two climatic zones.

(iii) An overall equatorward drift of about 0.04 m s\(^{-1}\) at 200 mb, pointing up the existence of the Ferrel (indirect) circulation in the long-term average.

(iv) A seasonal variation of about 1.0 m s\(^{-1}\) in mean meridional wind over the South Atlantic at 200 mb, which variation is not completely compensated at other longitudes and is therefore responsible for the zonal-average annual variation noted in (i).

Because of the useful and intriguing results obtained from the GHOST and EOLE flights, it is believed most desirable to continue the GHOST flight program in order that further information can be obtained on the temporal and longitudinal variability of that notoriously evanescent parameter, the mean meridional velocity.

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