The Mean Upper-Air Flow in Southern Hemisphere Temperate Latitudes Determined from Several Years of GHOST Balloon Flights at 200 and 100 mb

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ABSTRACT

Five years of constant-level balloon (GHOST) flights at 200 mb and three years of flights at 100 mb in Southern Hemisphere temperate latitudes furnish information on the mean variation with time of year and longitude of zonal and meridional winds. As found previously from one year of data at 200 mb, there is evidence of a large annual variation in mean meridional wind at these surfaces, with the GHOST balloons moving toward the South Pole at a mean speed exceeding 20 cm sec\(^{-1}\) in the Southern Hemisphere winter and toward the equator at a similar speed in summer. The poleward flow in winter is associated with relatively strong west winds. The semiannual variations in meridional wind are indicated to be out of phase at 200 and 100 mb, with the maximum poleward flow occurring near the equinoxes at 200 mb and near the solstices at 100 mb, implying the existence of meridional circulation cells with flows of opposite sense in the upper troposphere and lower stratosphere. The west wind is strongest over the Indian Ocean and weakest near Cape Horn, and west and south winds are almost out of phase, i.e., standing wavenumber 1 efficiently transports momentum toward the South Pole. The poleward eddy flux of momentum is a maximum in winter and occurs with greatest vigor over the South Atlantic. The meridional convergence of the eddy momentum flux obtained from the GHOST balloons does not come close to counterbalancing the large meridional flux of earth angular momentum associated with the GHOST-derived mean meridional velocities, suggesting either that the derived mean meridional velocities are unrepresentative or that other terms in the momentum equation are of surprisingly large magnitude. This dilemma is discussed, but is not satisfactorily resolved at this time.

1. Introduction

Considerable effort has been devoted in recent years to the study of atmospheric circulation in the Southern Hemisphere. Papers by van Loon (1967b), Taljaard (1967), van Loon and Jenne (1969) and others have greatly enhanced our knowledge of atmospheric processes in this oceanic hemisphere. These analyses have been based on conventional surface and rawinsonde observations. However, a reasonable density of observations, particularly upper air observations, is only realized over populated portions of the Southern Hemisphere. One of the proposed systems for filling in the data gaps is the Global Horizontal Sounding Technique (GHOST) developed by the National Center for Atmospheric Research (NCAR), which involves the flying of constant-volume balloons at various heights in the Southern Hemisphere (Lally et al., 1966).

Analyses of wind data obtained from 200-mb GHOST balloon flights in temperate latitudes of the Southern Hemisphere in 1966–67 have been presented by Solot and Angell (1969a, b), Kao and Hill (1970), Wooldridge and Reiter (1970) and Angell (1972a), based on the data summary of Solot (1968). GHOST balloon flights have been continued at the 200-mb surface through 1970, tripling the amount of data available at this surface, and in addition, quite a few flights have been made at 100 mb (Solot, 1972). The purpose of this paper is to summarize the information on Southern Hemisphere upper-air circulation obtained from this expanded (in space and time) data sample, and in particular to see if this larger sample supports the previous finding of a relatively large annual variation in mean meridional velocity at near-tropopause heights.

2. Procedures

The data analyzed herein were obtained from 16 GHOST balloon flights at 100 mb between September 1967 and October 1970, and 41 balloon flights at 200 mb between April 1966 and February 1971. Most of these flights were launched from Christchurch, New Zealand (43\(^\circ\)). Based on daily latitude and longitude positions
obtained near local noon by means of the "sunseeker" (Lichfield and Frykman, 1966), approximately 5000 24-hr average zonal and meridional winds were obtained at 200 mb and approximately 2000 such winds at 100 mb. Because the great majority of the GHOST positions were within temperate latitudes, the analysis has been restricted to the latitude interval 25S–65S. Within this latitude interval the mean error in GHOST position is estimated to be about 100 km; hence, the mean error in 24-hr average zonal and meridional winds is 1–2 m sec⁻¹.

The zonal and meridional wind data for the period of record were first plotted as a function of latitude and time of year, and latitude and longitude. It is apparent from such plots that the balloons tended to float further south in the Southern Hemisphere summer than in the winter. Thus, the resulting data density is not uniform over Southern Hemisphere temperate latitudes, the balloon data being sparse near the tropics in summer and near the polar regions in winter. In addition, because of the launch schedule, there are more data in winter and spring than in summer and fall. However, the data sample is uniform with respect to longitude, and this is the great advantage of the GHOST system; it provides a continuous swath of data around the hemisphere. There is the possibility that this swath of data is not completely representative; for example, the balloons may tend preferentially to follow the meandering jet stream around the hemisphere. With the sparsity of conventional upper-air data in the Southern Hemisphere, it is difficult to determine the extent to which systematic data biases of this sort exist.

In this paper diagrams will be presented showing the mean variation with time of year of zonal and meridional winds in temperate latitudes. The determination of 180-day running averages, and the deviation of 90-day from 180-day running averages, serve to yield crude estimates of annual and semiannual contributions to the
temporal variability. Such estimates are not as exact as those which would be obtained by harmonic analysis, but have the advantage of being readily and obviously presented in diagram form. Of course, the use of such running averages results in approximately a 50\% reduction in the amplitude of the variation. Similar diagrams and procedures indicate the mean variation with longitude of zonal and meridional winds in temperate latitudes as well as the contributions of standing wavenumbers 1 and 2 to the longitudinal variability.

For the purpose of estimating the temporal variation in meridional eddy flux of momentum in temperate latitudes, the daily deviations of zonal and meridional winds from 15-day average values were determined (15 days is the average time required for balloon circumnavigation of the hemisphere), and their mean "eddy" products evaluated for the 15-day intervals. The longitudinal variability of the eddy momentum flux was determined by grouping the individual velocity products (obtained in the above manner) into 15\° longitude bands.

The temporal and longitudinal variations in zonal and meridional winds, and their eddy velocity products, were also determined separately for the latitude intervals 25–45\°S and 45–65\°S, and assumed to apply to latitudes 35\°S and 55\°S. This division of the sample reduces the reliability of the variations and, accordingly, diagrams illustrating these variations are not presented, except indirectly in the case of the meridional convergence of the eddy flux of momentum. However, the derived variation with latitude of the temporal and longitudinal fluctuations is frequently indicated in the text. Also indicated on occasion are the derived phase differences between temporal and longitudinal variations at 100 and 200 mb, as well as the relative magnitudes of the variations at the two surfaces.

3. Temporal variation of zonal and meridional winds

Fig. 1 shows the mean variation with time of year of GHOST-derived zonal and meridional winds at 100 and 200 mb in Southern Hemisphere temperate latitudes, based on the 3–5 years of data. The west wind is stronger at 200 mb than at 100 mb in all months except September, suggesting that only in late winter or early spring does relatively cold air extend as high as the 100-mb surface over Antarctica. The maximum wind speed difference between the two surfaces occurs near the summer solstice and the fall equinox.

Let us examine first the annual variation in zonal wind, as given by the middle diagrams of Fig. 1. The west wind maxima at 100 and 200 mb occur essentially simultaneously toward the end of the Southern Hemisphere winter, in accord with Northern Hemisphere climatology. However, the zonal wind variation is almost twice as large at 100 mb as at 200 mb. Using rawinsonde data, van Loon (1965) found that at 500 mb, at a given latitude, the west wind was actually strongest in summer, although the relatively strong winds extended over a wider latitude band in winter than in summer. Collating these results with the GHOST results, there is the implication that the annual variation in zonal wind, with the west wind maximum near the end of winter, becomes more pronounced with increase in height.

Of greater interest is the evidence for a relatively large annual variation in meridional wind at 100 and 200 mb. The implied mean flow toward the South Pole exceeds 20 cm sec\(^{-1}\) in winter (recall the approximate 50\% reduction in amplitude of variation due to the smoothing procedure applied) and in the summer exceeds 20 cm sec\(^{-1}\) toward the equator. The magnitude of the meridional flow is slightly larger at 200 than at 100 mb. A poleward flow in winter in the upper stratosphere and low stratosphere would be in accord with a direct Hadley circulation extending across temperate latitudes, but an equatorward flow in summer at these levels is not obviously related to heat sources and sinks within the hemisphere. Note that in the average for the year there is but weak evidence for an indirect (Ferrell) meridional circulation cell extending into the stratosphere in Southern Hemisphere temperate latitudes, with a year-average mean meridional flow toward the equator of only 1.3 cm sec\(^{-1}\) at 200 mb and 0.6 cm sec\(^{-1}\) at 100 mb.

The correlation between the annual variation in zonal and meridional winds is impressive, −0.98 at 100 mb and −0.87 at 200 mb. The larger negative correlation at 100 mb results from the tendency for the annual variation in meridional wind at 100 mb to precede that at 200 mb by about 30 days. This large negative correlation between annual variation in zonal and meridional winds is an intriguing and perhaps important finding from the GHOST flights. Note that it leads to a poleward transport of momentum if eddy velocities are determined as deviations from time means rather than space means. However, the above evidence for the existence of seasonally large and oppositely-directed mean meridional flows near the tropopause in Southern Hemisphere temperate latitudes has been questioned because 1) there is little evidence for such flows from rawinsonde data in either hemisphere, 2) atmospheric simulation experiments based on the equation of motion do not reproduce them, and 3) such flows lead to very large meridional transports of earth angular momentum.

Because of this lack of agreement with other data and other analyses, one must consider the possibility that the meridional displacements of the GHOST balloons do not reflect mean meridional air motions, but occur, for example, because the balloons become systematically entrained into the jet stream and move meridionally with the jet as it changes latitude with change in season. However, since van Loon (1965) has shown that on the average the Southern Hemisphere jet stream is located nearest the equator during the months May through
October, whereas the GHOST balloons tend to be nearest the equator about June, the entrainment hypothesis is not very convincing. Furthermore, the seasonal meridional balloon displacements at 100 mb are nearly as pronounced as at 200 mb even though there is really no such thing as a jet stream at 100 mb.

Another possible source of bias is to be found in the distribution of balloon losses. Most important in this respect is the observation that the balloons cannot be tracked in polar latitudes in winter because the solar cells provide no power. One can imagine means by which this selective loss of balloons in polar latitudes leads to a bias in derived mean meridional velocity. However, since individual balloons tracked continuously throughout the year show the annual alternation in mean meridional velocity referred to above, the selective loss of balloons does not appear to be a dominant factor in the resultant meridional velocity pattern.

In order to examine this whole question in more detail, Fig. 2 shows the year-to-year variation in GHOST-derived meridional velocity at 200 mb. The tendency for a poleward flow in winter and an equatorward flow in summer is repeated each year, although there are variations in the dates of maximum equatorward and poleward flow and variations in the magnitude of this flow. In particular, the equatorward flow appears to be most pronounced during the transition from odd to even years, implying a possible relation with the quasi-biennial oscillation in the equatorial stratosphere. The repeatability of the annual oscillation in meridional velocity almost ensures that the phenomenon is real, whatever the phenomenon represents. At this time, for want of a better explanation, an alternating meridional air flow would appear the most likely cause for the successive balloon drifts toward high and low latitudes. However, as we shall see in Section 6, this assumption leads to serious problems with the momentum balance.

It may be pointed out here that, in general agreement with the GHOST results at 200 and 100 mb, a maximum northward drift of about 20 cm sec\(^{-1}\) in the Southern Hemisphere summer was also found from satellite tracking of horizontally floating balloons at 50 mb in the tropics (Angell, 1972b). This brings up the possibility that a large-scale Hadley-type circulation exists between summer and winter hemispheres, the upper branch of which extends as low as 200 mb and causes the annual variation in mean meridional drift observed from the GHOST flights. To the writer's knowledge, however, there has been no evidence of such a seasonally-reversible interhemisphere drift from surface wind data.

The approximate semiannual variations in zonal and meridional winds are indicated in the bottom diagrams of Fig. 1. At 200 mb the zonal and meridional wind variations are clearly out of phase, but at 100 mb the variations tend to be in phase. This difference is due to a 180\(^\circ\) (90-day) phase shift of the meridional wind between 200 and 100 mb. As shown in detail in Fig. 3, at 200 mb the meridional flow is indicated to be equatorward near the solstices and poleward near the equinoxes whereas at 100 mb the flow is indicated to be poleward near the solstices and equatorward near the equinoxes, resulting in a temporal correlation of \(-0.68\) between the flows at the two surfaces. When confirmed, we propose that this semiannual alternation in meridional wind be denoted the GHOST oscillation in honor of its method of discovery. Such an alternation suggests the existence of meridional circulation cells with oppositely-directed meridional flows in upper troposphere and lower stratosphere. The physical significance of such a semiannual oscillation is not clear to us, although it must be intimately linked with the relatively large semiannual wind, pressure and temperature oscillations in the Southern Hemisphere (van Loon, 1967a). To be specific, the observation that at mid-tropospheric levels of the Southern Hemisphere the temperature contrast between middle and high latitudes reaches a maximum near the time of the equinoxes would seem to be in accord with the GHOST evidence for poleward flow at 200 mb (and presumably at lower levels) and equatorward flow at 100 mb at these times of year, since such a meridional flow implies upward motion in polar regions and downward motion in the subtropics, which would,
if the flow is adiabatic, lead to an enhanced meridional temperature gradient in mid-latitudes.

Examining the data in the separate latitude bands, we find that at 200 mb the semiannual variations in zonal wind at 35 and 55S are nearly out of phase, and in such a sense as to be in agreement with the findings of van Loon (1967b) that the maximum west winds occur near the equinoxes poleward of 45S and near the solstices equatorward of 45S. However, this change in phase with latitude does not show up in the GHOST data at 100 mb, so that the phenomenon may not extend far into the stratosphere. The GHOST data also suggest that the annual variation in zonal wind is greater at 35S than at 55S, but that the annual variation in meridional wind is greater at 55S.

The surprising strength of the semiannual oscillation in the Southern Hemisphere has been pointed out by van Loon (1967a). Based on GHOST-derived averages across the whole Southern Hemisphere temperate-latitude band, the semiannual variation in zonal and meridional wind is about two-thirds the annual variation, three times the ratio observed in Northern Hemisphere temperate latitudes (Solot and Angell, 1969a, b).

4. Longitudinal variation of zonal and meridional winds

Fig. 4 shows the mean variation with longitude of GHOST-derived zonal and meridional winds at 100 and 200 mb in Southern Hemisphere temperate latitudes, based on the 3–5 years of data. We examine first the contribution of standing wavenumber 1 to the longitudinal variability, as given by the middle diagrams of Fig. 4. At 200 mb the west wind is a maximum over the Indian Ocean [in agreement with van Loon's (1964) findings at the surface and at 500 mb] and a minimum near Cape Horn and the Andes Mountains. Thus, standing wavenumber 1 may be orographically forced. At 200 mb the zonal and meridional winds are almost
exactly out of phase (correlation of $-0.96$), with maximum flow toward the South Pole over the Indian Ocean and toward the equator near Cape Horn (70W). Apparently, at this surface, standing wavenumber 1 represents a very efficient mechanism for the poleward transport of angular momentum. At 100 mb the out-of-phase relation between zonal and meridional wind is not so pronounced (correlation of $-0.78$), the maximum poleward flow occurring near the Greenwich meridian.

The contribution of standing wavenumber 2 to the longitudinal variability at 200 and 100 mb is given in the bottom diagram of Fig. 4. At both surfaces, but particularly at 100 mb, west wind maxima are located just to the east of Cape Horn and to the west of Australia. At 200 mb there exists a mean equatorward flow to the east of Cape Horn, i.e., to the lee of the Andes Mountains. This presumably reflects the influence of the Andes in anchoring standing wavenumber 2. However, this anchoring tendency does not appear to extend to 100 mb.

The difference in phase of the standing waves between 35 and 55S indicates a wave tilt with latitude (northwest-southeast) which, in agreement with the northeast-southwest tilt customarily found in the Northern Hemisphere, is associated with a poleward eddy flux of momentum. In the case of both wavenumbers 1 and 2 (for both zonal and meridional winds) the waves tilt westward with height, as would be expected in a baroclinic atmosphere with cold air near the poles.
Recently, van Loon and Jenne (1972) presented the mean locations of standing waves in Southern Hemisphere temperate latitudes based on daily 500-mb maps for the International Geophysical Year (IGY) and mean monthly maps for other surfaces between sea level and 100 mb. They find in all months a well-defined wave-number 3 pattern with ridge lines near the continents, i.e., at about 45E, 75W and 165E. The dashed line at upper left in Fig. 4 shows that, based on the GHOST data at 200 mb, the maximum meridional flow occurs near 85E, 45W and 135W. Since in the case of wave-number 3 there should be a 30° longitude difference between the ridge line and the location of the maximum meridional flow, in two of the three cases there is good agreement between the GHOST results and those obtained from conventional data.

At 500 mb, van Loon and Jenne also find that the ridge line of wavenumber 1 varies greatly with latitude, being located in the eastern Atlantic at 30S and in the eastern Pacific at 60S. This makes difficult a comparison with the GHOST results which apply to the whole temperate-latitude band. For wavenumber 1, GHOST data indicate a mean ridge position near the International Date Line, suggesting that the GHOST trajectories are dominated by the ridge location in subpolar latitudes.

5. Temporal and longitudinal variation of meridional eddy momentum flux

The diagrams at left in Fig. 5 show the variation with time of year of GHOST-derived zonal-meridional eddy velocity covariance at 100 and 200 mb in Southern Hemisphere temperate latitudes. As is well known, the zonal-meridional eddy velocity covariance is proportional to the meridional eddy flux of relative (westerly) angular momentum. Large negative values in the diagrams signify a large eddy flux of westerly momentum toward the South Pole.

The annual variation in meridional eddy momentum flux is given by the middle diagram at left in Fig. 5. At both 100 and 200 mb the poleward eddy momentum flux is a maximum in late winter and a minimum in late summer, but with the flux maxima and minima occurring about two months later at 100 mb than at 200 mb. Basically, the poleward eddy momentum flux is large when the west wind is strong (compare with Fig. 1). In the case of the semiannual variation (bottom left diagram), poleward flux maxima occur in general near the equinoxes, but about one month earlier at 100 mb than 200 mb.

The diagrams at right in Fig. 5 show the variation with longitude of the GHOST-derived meridional eddy momentum flux at 100 and 200 mb in Southern Hemisphere temperate latitudes. At both surfaces there is a marked tendency for the maximum poleward eddy momentum flux to occur over the South Atlantic. The flux variation with longitude is dominated by wave-number 1, with no obvious contribution from wave-number 2. The minimum in the poleward eddy flux of momentum in the New Zealand area suggests that developing (diverted) troughs are common in this region.

6. GHOST-derived velocities and the momentum balance

The momentum equation provides one possible way of gauging the representativeness of the GHOST-derived mean meridional velocity. Neglecting dissipation, the rate of change of zonal wind (∂u/∂t) in a latitude ring may be expressed by

$$\frac{\partial u}{\partial t} = -\frac{\partial}{\partial y}(u'w') + Vf + V\left(\frac{u}{a}\tan\varphi\frac{\partial w}{\partial y}\right)$$

where the first term on the right indicates the effect on the zonal wind within the ring of the convergence of the meridional eddy momentum flux, and the second term the effect caused by meridional advection of earth angular momentum (f is the Coriolis parameter). The third term on the right indicates the influence on the zonal wind due to advection of a latitudinally varying zonal wind by the mean meridional velocity plus a contribution due to convergence of the meridians (a is earth radius, \(\varphi\) latitude). This term is generally in phase with the previous term but is usually one order smaller in magnitude and will not be considered separately here. The last two terms represent, respectively, the effect on the zonal wind of the convergence of the vertical eddy flux of momentum and the effect due to vertical advection of a wind field varying in strength with height. These last two terms cannot be considered directly in a quantitative fashion because the GHOST balloons yield no information on vertical velocity.

Fig. 6 shows the variation with time of year of GHOST-derived zonal wind acceleration, poleward transport of earth angular momentum, and eddy momentum flux convergence at 100 and 200 mb in Southern Hemisphere temperate latitudes. Since the Coriolis parameter is negative in the Southern Hemisphere, the poleward transport of earth angular momentum is of opposite sign to the meridional velocity in Fig. 1, i.e., a mean poleward (negative) flow leads to an increase in west wind and is plotted as a positive contribution to the momentum balance. The eddy momentum flux convergence has been determined from the difference in meridional eddy momentum flux in latitude bands 25-45S and 45-65S, and applied to the latitude interval 35-55S. Because of the division of the sample, the estimate of eddy flux convergence is not as reliable as the estimate of eddy flux itself, especially since we are determining the relatively small difference...
between quite large quantities. Convergence of the poleward eddy momentum flux leads to an increase in west wind, and is also plotted as positive in Fig. 6. Rather surprisingly, the eddy flux convergence of momentum is indicated to be larger in summer than in winter, nearly the opposite of the annual variation in flux itself. The reason for the relatively small annual variation in zonal wind in the Southern Hemisphere (in comparison with the Northern Hemisphere) may be related to this observation that the meridional convergence of the eddy momentum flux is a maximum in the summer in the Southern Hemisphere.

The correlation coefficients plotted in Fig. 6 show that the correlation between poleward transport of earth angular momentum and the eddy-flux convergence of relative angular momentum is usually quite strongly negative. Accordingly, these two terms tend to counterbalance one another, suggesting that the mean meri-
dional velocities are established to counteract an over-
vigorouse convergence of eddy momentum flux, or vice
versa. However, it is also obvious that the indicated
magnitudes of the temporal variations of the two terms
are not at all compatible. We know that the eddy flux of
momentum, and hence the flux convergence of momentum, has been badly underestimated because of
the use of once-a-day GHOST positions to determine
velocity. This underestimate probably exceeds a factor
of 2, but it would be surprising if it exceeded a factor
of 4, and even a factor of 4 would not yield a temporal
variation for this term comparable to that found for the
term expressing the transport of earth angular momen-
tum. Thus, the two terms in the momentum equation
which, based on geostrophic scale analysis, might
reasonably be expected to balance each other, do not
do so, and we are left with the possibility that either the
GHOST-derived mean meridional velocities are un-
representative or that other terms in the momentum
equation are of surprisingly large magnitude.

In the latter event, the only two terms really available
to compensate the GHOST-derived meridional flux of
earth angular momentum are the two terms involving
the vertical velocity. Unfortunately, from the GHOST
data alone there is no way to even estimate the con-
vergence of the vertical eddy flux of momentum. In any
case, the vertical advection of a wind field varying in
strength with height would seem a more likely candidate
to balance the indicated meridional flux of earth angular
momentum because the two terms are similar in form.
The difficulty here is that near-tropopause heights
the vertical wind shear is not large, and hence the
derived vertical velocity has to be unseemly large to
effect a balance. To be specific, with the assumption
that the GHOST-derived wind shear between 200 and
100 mb applies to the surfaces of 200 and 100 mb, then
in order to balance the momentum equation one would
have to hypothesize near the tropopause in temperate latitudes a mean sinking motion of 5–10 cm sec\(^{-1}\) in the
Southern Hemisphere spring and a rising motion of
nearly 5 cm sec\(^{-1}\) in the autumn. While the derived
descending motion in spring would be qualitatively in
accord with the evidence for a downward transport of
radioactive debris (List and Telegadas, 1969) and ozone
(Dütsch, 1970) at this time of year, such vertical motions seem too large, both on the basis of continuity and of the radiative warming and cooling required to
balance the resultant adiabatic cooling and warming.

Thus, we are left in the unsatisfactory position of not
being able to prove that the GHOST-derived mean
meridional velocities are unrepresentative, and yet also
not being able, reasonably, to balance the momentum
equation if they are representative. At this point we
would like to steer an intermediate course, and state our
belief that an annual variation in mean meridional
velocity does exist in Southern Hemisphere temperate
latitudes, but that its magnitude has been overestimated
by the GHOST balloons. A possible reason for such an
overestimation lies in the difference between mean
values of quantities determined from Eulerian and
Lagrangian data, as brought out in an enlightening
fashion by Dyer (1973).

7. Conclusion

Constant-level balloons furnish useful information
for atmospheric circulation studies because they provide
a continuous swath of data around the hemisphere. In a
data-sparse hemisphere such as the Southern Hemi-
sphere the flying of such balloons is one way of obtaining
fairly realistic estimates of the longitudinal variation
of zonal and meridional winds and meridional eddy
momentum flux. As a corollary, from such balloon
flights one would hope to obtain reasonably reliable
estimates of parameters notoriously difficult to measure,
such as the mean meridional velocity around the
hemisphere.

One of the interesting possibilities raised by the
analysis of the GHOST data is that a Hadley-type
circulation exists between the summer and winter
hemispheres. This is suggested by the GHOST-derived
evidence at 100 and 200 mb for a more than 20 cm sec\(^{-1}\) flow toward the South Pole in the Southern Hemisphere
winter, and a flow of equal magnitude toward the
equator in summer. However, consideration of the
momentum equation suggests that the magnitude of
this mean meridional flow has been overestimated,
possibly because of difficulties in relating Lagrangian
mean values to the more customary Eulerian mean
values. Certainly, the large-scale French ÉOLE experi-
ment, involving the satellite positioning of hundreds of
constant-level balloons at 200 mb in the Southern
Hemisphere in 1971–72 (Morel, 1969), should have as
one of its main aims the confirming of this alternating
meridional flow derived from 3–5 years of GHOST
balloon flights.

Another possibly significant finding is the indicated
out-of-phase relation between semiannual variations in
meridional flow at 100 and 200 mb, which implies the
existence of meridional circulation cells of alternating
sense centered near the tropopause in Southern Hemi-
sphere temperate latitudes. Such meridional circulation
cells would have to be intimately related to the rela-
tively large semiannual zonal wind, temperature and
pressure oscillations found in this hemisphere. When
confirmed, this alternation in meridional wind could
well be designated the GHOST oscillation in honor of
its method of discovery.

The emphasis in this paper, and in other similar
papers, has been on the climatological aspects of the
Southern Hemisphere flow. This emphasis on clima-
tology has almost been necessitated by the once-a-day
positioning, which pretty much eliminates use of the
balloons for what might be called synoptic investiga-
tions. If balloon positioning were accomplished by
synchronous satellite so that accurate 2-hr positions
could be obtained as in the old transosonde program (Angell, 1962), a whole spectrum of circulation details would be open to investigation. Despite the undoubted success of remote sensing from satellites (Wark, 1970), it is likely that in the future in situ measurements of wind will still be required in order to obtain estimates of the ageostrophic wind and its relation to the mass field. Tracking of cloud elements and constant-level balloons by synchronous satellites appears the most feasible way of obtaining such data.

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