The Zonal Mean Westerlies over the Southern Hemisphere

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(Manuscript received 11 July 1986, in final form 23 December 1986)

ABSTRACT

A brief review and evaluation of various analyses of the Southern Hemisphere westerlies is given along with the presentation of some recent results. Several features characterize the westerlies of the Southern Hemisphere as quite different from those in the Northern Hemisphere and, in the past, these have typically been difficult to reproduce well in general circulation models. They are the double jet structure in winter, the stronger midlatitude tropospheric winds in summer than in winter, and the ensuing much smaller amplitude of the annual cycle which is associated with a maximum of global atmospheric angular momentum in January. New values for the hemispheric angular momentum integrals are larger than previously reported.

Two estimates of the distribution and strength of the southern westerlies that have been widely used are considered to be seriously biased. Factors contributing to discrepancies among different results are large natural variability, missing data and biases in observing systems, and methods of analysis. Over the sparsely observed Southern Hemisphere, the latter is the main reason why biases exist in analyses based only on mean station data, and the absence of imposed dynamical constraints has led to internally inconsistent fields. Even recent estimates of the southern westerlies from global operational analyses should be used judiciously with proper consideration given to reliability and possible biases.

1. Introduction

A challenging problem is to understand how the general circulation of the atmosphere is maintained. This presupposes that we know and can describe the mean atmospheric circulation. Circulation statistics have been compiled in a number of studies but only a few of these have been widely used to validate the simulations of atmospheric general circulation models (GCMs). The perceptions about the performance of such models can be greatly influenced by the "observations" used for comparison.

For the most part, the mean state of the atmosphere is fairly well known. Nevertheless, there are large discrepancies among published statistics on the mean westerlies over the Southern Hemisphere (SH); see Boer et al. (1984b). The purpose of this paper is to evaluate the relevant studies and determine the origin of these discrepancies. Some new results are also presented.

2. Zonal mean westerlies over the Southern Hemisphere

A good description of the global distribution of westerlies at the surface dates back to the first global charts of sea level pressure by Buchan (1869). However, it was not until the IGY during 1957–58 that a comprehensive description of wind over the SH became possible. An excellent review of earlier studies has been given by van Loon (1972).

A very early estimate of the zonal mean winds over the SH for summer was given by Flohn (1950), and this depicted a westerly jet of about 30 m s⁻¹ at 48°S. That was a very creditable effort based on the meager information available then. Other early estimates of the zonal mean winds over the SH are those of Obasi (1963), which were based only on the IGY 1958, and Heathie and Stephenson (1960), both of which are reproduced in Lorenz (1967). In both of these, the strongest westerlies in summer were correctly located near 45°S but with maxima at 200 mb of 25 and 31 m s⁻¹, respectively (see Table 1). In winter, their cross sections revealed the double jet structure with a strong subtropical jet near 30°S at 200 mb of about 35 m s⁻¹ and a strong polar jet near 50°S. The latter extends from the strong surface westerlies into the polar night jet in the stratosphere.

These features were more thoroughly analyzed by van Loon et al. (1971) and reproduced in van Loon (1972). Although he used geostrophic winds, the strength and location of the jets were excellent in view of more recent observations. About the same time, Newell et al. (1972) presented global cross sections of the zonal mean wind [7], and these have been widely used for verifying the results of GCMs (e.g., Washington et al., 1980; Otto-Bliesner et al., 1982; Pitcher et al., 1983). However, the jet was located too close to the equator in summer and had wind speeds about 8

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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TABLE 1. Zonal mean winds reported by various investigators at key locations in the Southern Hemisphere. 1) For summer, the latitude and central speed of the jet are given for months noted. 2) For winter, the speed of subtropical jet near 30°S 200 mb and wind speed in the polar jet at 50°S 500 mb are given in m s\(^{-1}\). The values for the U.K. Met. Of. are from Slingo and Pearson (1987) and for NMC are geostrophic values from Boville and Randel (1986) and Boville (personal communication, 1986).

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Summer jet</th>
<th>Winter jet</th>
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<tr>
<td></td>
<td>Months</td>
<td>Latitude</td>
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<tr>
<td>Heastie and Stephenson (1960)</td>
<td>Jan</td>
<td>45°</td>
</tr>
<tr>
<td>van Loon et al. (1971)</td>
<td>Jan</td>
<td>45°</td>
</tr>
<tr>
<td>Newell et al. (1972)</td>
<td>DJF</td>
<td>40°</td>
</tr>
<tr>
<td>ECMWF (Figs. 1 and 2)</td>
<td>Jan</td>
<td>47°</td>
</tr>
<tr>
<td>NMC</td>
<td>Jan</td>
<td>43°</td>
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m s\(^{-1}\) too light. In winter there was also a bias toward wind speeds that were too low (Table 1).

The results of Oort (1983; see also Oort and Peixoto, 1983) are quite similar to those of Newell et al., but differ substantially from those of other more recent analyses. Swanson and Trenberth (1981) and Trenberth (1984) produced mean profiles based on six years of Australian data. More recent independent results are given in Fig. 1 which shows the \([\bar{u}]\) cross sections for January\(^1\) for four years 1979–82 from ECMWF (European Centre for Medium Range Weather Forecasts) analyses. Corresponding values for winter (June, July and August) are given in Fig. 2. These agree quite well with other recent global cross sections of \([\bar{u}]\) from operational analyses at NMC (the U.S. National Meteorological Center) (Boville and Randel, 1986; Boville, personal communication) and at the U.K. Meteorological Office (Slingo and Pearson, 1987). In addition, there are several other independent analyses of data for the year of the Global Weather Experiment (GWE). A summary is given in Table 1. The effects of the annual cycle are revealed by Swanson and Trenberth (1981). The subtropical jet peaks in July and is present for April–October. At 200 mb, winter (June–August) values of the peak jet are 39 m s\(^{-1}\) compared with the peak July values of 41 m s\(^{-1}\). In summer, December–February values are 31 m s\(^{-1}\) versus January 32 m s\(^{-1}\). Thus differences in Table 1 are mostly not attributable to the months averaged.

There are a number of factors that contribute to the differences found in Table 1. These are (i) natural variability, (ii) missing data and biases in observing systems; and (iii) biases in methods of analysis.

All of the values in Table 1 were based upon different periods of data, and natural variability therefore contributes to some of the discrepancies. Trenberth (1984) estimated the magnitude of this effect at 500 mb and found standard deviations of seasonal mean \([\bar{u}]\) to be 1–2 m s\(^{-1}\). He also showed that during the GWE there were major anomalies in \([\bar{u}]\) in excess of 5 m s\(^{-1}\) at 200 mb. In January 1979, the jet was shifted southwards by 5° latitude to 50°S producing a dipole of anomalies exceeding 5 m s\(^{-1}\). In July, the subtropical jet was analyzed to be weaker than normal, but the polar jet was much stronger than normal. These anomalies are included in the means shown in Figs. 1 and 2.

The second factor of known biases in the observations, often arising because of missing data, is also significant. It seems that winds in the SH subtropical jet during the GWE may have been analyzed to be too weak mainly because of a low bias in satellite cloud motion observations (Pailleux, 1985). Reanalysis of the GWE data by ECMWF (e.g., Uppala, 1986) has produced stronger winds in the SH jet by a few m s\(^{-1}\). Thus the values in Figs. 1 and 2 are probably slightly underestimated. Hollingsworth et al. (1986) have shown how the ECMWF data assimilation system can be used to identify and thus perhaps correct for biases in rawinsonde information. As they note, at individual sta-

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\(^1\) January, rather than summer season December–January–February, results are presented since data are not available for December 1979 and are considered less reliable in December 1978.
tions there are biases due to instrumental errors in winds, and biases in radiosondes which differ from type to type.

Other biases arise from how missing data are handled. In daily analyses, a missing observation is effectively replaced by an estimate based on nearby observations, dynamical constraints, and the model first guess. Typically it is not replaced when monthly mean station data are compiled. A feeling for the extent of this problem can be gained from figures given by LeMarshall et al. (1985), who show for ten years of January 0000 UTC observations received at the World Meteorological Centre in Melbourne, Australia, that an average of 28 (out of 31) daily reports were received from the 41 stations over Australasia. Over Antarctica, the mean number of daily reports from 14 stations drops to 21, and over Africa and South America for 19 and 29 stations, respectively, the average number of daily reports received was only 11. Alternatively, for Africa and South America, only 16 and 9 stations, respectively, reported on more than 15 days during the month, on average. Oort (1983) accepted a station if there were more than ten daily reports in a month. Monthly means based on so few values should not be considered very reliable and can be biased. Van Loon et al. (1971) noted that mean winds were biased low at Marion Island (46½°S, 37½°E) because few ascents could be tracked into the upper troposphere whenever there were strong winds at 500 mb. This bias is one factor influencing the results of Newell et al. and Oort.

The main factor, however, responsible for the differences seen in Table 1 is the method of analyzing the data. The analyses of Obasi, Newell et al., and Oort were based on station data with no use of dynamical constraints such as the geostrophic relation. This can lead to unacceptable discrepancies in regions of sparse data. Oort's values are biased low by 5-10 m s\(^{-1}\) in the zonal mean and the bias exceeds 15 m s\(^{-1}\) locally (Trenberth, 1982; Oort, 1983). Since geopotential heights at 40° and 70°S are reasonably well constrained by observations over Antarctica and the subtropical continents, the geostrophic wind can be used as a check.

At 200 mb in January, from 40°–60°S, the mean geostrophic wind computed from Oort's mean geopotential fields are stronger than the mean wind, as analyzed, by 6.4 m s\(^{-1}\) or 28%. Thus Oort's own analyses are internally inconsistent, with the analyzed wind speeds biased low.

The more recent results from global analyses produced subsequent to the Global Weather Experiment have tended to converge (Table 1), but they are nevertheless subject to some shortcomings over the Southern Hemisphere. Biases in observing systems affect analyses at all centers unless the bias is known and corrected for, and this capability is becoming developed in modern data assimilation systems (e.g., Hollingsworth et al., 1986). The previously mentioned bias in satellite cloud motion vectors is one such factor. Another is the tendency for horizontal temperature gradients inferred from TIROS-N soundings to be systematically too weak (Schlatter, 1981). These factors indicate that even recent estimates of the southern westerlies may be biased low. On the other hand, "model bias" can become significant in daily analyses in areas of sparse observations. For the ECMWF analyses, an indication of the direction of the model bias is given by the systematic error in 10-day forecasts (Arpe and Klinker, 1986). In the SH in both seasons by day 10, the error is predominantly barotropic and westerlies are too weak by ~2 m s\(^{-1}\) from 20°–35°S but slightly too strong (~1 m s\(^{-1}\)) from 40°–60°S. The subtropical jet tends to shift upwards. The impact of model bias on the zonal westerlies in the analyses is thus likely to be very small, although the impact on other quantities, especially second moment statistics, could be significant.

At NMC there are other problems. Trenberth and Christy (1985) showed prior to 1982 that the circumpolar trough was analyzed to be 3 to 7 mb shallower in NMC than in Australian analyses. Moreover, during the winter of 1983, an anticyclone was analyzed over Antarctica in the troposphere, resulting in easterlies of ~10 m s\(^{-1}\) at 300 mb near 80°S (Boville, personal communication, 1986). This is in sharp disagreement with other operational analyses and is evidently spurious. Thus results from operational analyses must also be assessed and used prudently.

3. Related results

Although the flow in the SH is more zonally symmetric than in the Northern Hemisphere (NH), there are substantial asymmetries that are particularly evident in the winds. Figure 3 illustrates the 4-year means at 200 mb. In January, the jet is located at 45–50°S at all longitudes and varies in strength from 37 to 25 m s\(^{-1}\). There is less zonal symmetry in winter. A double jet structure is pronounced in the New Zealand sector. The mean westerlies exceed 50 m s\(^{-1}\) from the west coast of Australia to the date line but with minimum
values of less than 15 m s\(^{-1}\) at 200 mb over the South Island of New Zealand.

The vertical mean of the winds (Fig. 4) has been computed by making use of the 4-year mean of the computed surface pressure as the lower boundary at each grid point for the appropriate season, and with 100 mb as the uppermost level, taken to represent the layer from 150–50 mb. Oort and Peixoto (1983) present vertical mean profiles for the surface ~25-mb-level based on the information in Oort (1983). They show maxima of only 15 m s\(^{-1}\) at 30–45\(\degree\)S in winter and 14 m s\(^{-1}\) from 45–50\(\degree\)S in summer. In contrast, the values given in Fig. 4 are 30–40% larger.

The well-established (van Loon, 1972) but little-known fact that the zonal mean winds are stronger in summer than in winter is well demonstrated in Fig. 4. This is less apparent at 200 mb (Fig. 3) than at lower levels. At 500 mb the winds are at their maximum over the southern Indian Ocean and are locally stronger in summer (Trenberth, 1982). Strongest vertical mean winds in winter over the SH are nearly the same as in the NH (19.8 versus 20.6 m s\(^{-1}\)). However, in summer, whereas maximum values exceed 20 m s\(^{-1}\) (maximum = 20.8 m s\(^{-1}\) at 47\(\degree\)S) in the SH (Fig. 4), the maximum vertical mean in the NH is only 10.2 m s\(^{-1}\).

Although the vertical mean westerlies are stronger in summer from ~40\(\degree\)–50\(\degree\)S, the meridional extent of the strong winds increases in winter so that the total angular momentum becomes larger. The hemispheric and global mean integrals of the relative angular momentum in the atmosphere, given by \(M = \mu a \cos \phi\), have been computed. Results are given in Table 2 along with Oort and Peixoto’s (1983) values for comparison. The latter should be larger, since their integrals are from \(p_t\) to 25 mb versus the current integrals from \(p_t\) to 50 mb (also our values of \(p_t\) are smaller). However, this is not the case and, instead, the Oort and Peixoto values are seen to be considerable underestimates in both hemispheres and in both seasons.

### Table 2. Hemispheric and global integrals of the relative angular momentum \(M\) for January and for June, July and August in \(10^{25}\) kg m\(^2\) s\(^{-1}\). Oort and Peixoto (1983) values are in parenthesis.

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<tr>
<th></th>
<th>January</th>
<th>JJA</th>
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<tbody>
<tr>
<td>NH</td>
<td>11.15 (9.6)</td>
<td>1.06 (0.2)</td>
</tr>
<tr>
<td>SH</td>
<td>6.46 (4.8)</td>
<td>11.54 (9.5)</td>
</tr>
<tr>
<td>Globe</td>
<td>17.61 (14.4)</td>
<td>12.60 (9.7)</td>
</tr>
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</table>

Fig. 3. Mean westerly wind component at 200 mb for 1979–1982 from ECMWF analyses, in m s\(^{-1}\). (a) January; (b) June–August.

Fig. 4. Vertical mean of the winds for 1979–82 in m s\(^{-1}\). For January (solid) and June–August (dashed).
These results show clearly the much larger annual cycle in the NH and reveal that the angular momentum of the atmosphere is actually larger in winter over the SH than in the NH. With proper inclusion of the stratospheric jet, the difference would be even more pronounced. Also of note is how much the global atmospheric angular momentum increases during January. More detailed information on variations in the hemispheric and global means, including daily time series, have been given in Rosen and Salstein (1983, 1985). Their values were integrated from 1000 mb to 100 or 1 mb. It is worth noting when we perform the integration with \( p = 1000 \) mb, that although there are marked differences in the vertical integral at individual latitudes, the hemispheric mean values are nearly the same as given in Table 2 in both seasons.

4. Discussion

It appears that the speed of the zonal mean jets in the SH exceeds 30 m s\(^{-1}\) in summer and 40 m s\(^{-1}\) in winter, but with large interannual fluctuations of several m s\(^{-1}\) possible. In retrospect, the van Loon et al. (1971) estimates were excellent and have stood the test of time. However, the Newell et al. profiles have been much more widely used for comparisons with GCM results. Since many GCMs in the past also underestimated the strength of the tropospheric southern westerlies (e.g., McAvaney et al., 1978; Gilchrist, 1979; Otto-Bliesner et al., 1982; Pithier et al., 1983; Hansen et al., 1983; but with also some notable exceptions as in Boer et al., 1984b), a misleading impression was often obtained about the quality of the simulation. Alternatively, as higher resolution GCMs have been introduced, the strength of the southern westerlies has generally increased, but with corresponding exaggeration in the strength of the Northern Hemisphere westerlies (Manabe et al., 1979). The solution to this quandary apparently lies in the introduction of enhanced orographic drag through either envelope orography (Palmer and Mansfield, 1986) or gravity wave drag (Boer et al., 1984a); see also Slingo and Pearson (1987) for a more complete discussion.

Oort's (1983) recent results have tended to reinforce the previous misconceptions. The discrepancies and shortcomings of his analyses were discussed at some length in Oort (1983) after being noted by Trenberth (1982), but the statistics have subsequently been used in momentum and kinetic energy budgets (Oort and Peixoto, 1983; Wahr and Oort, 1984) uncritically. Also, statistics derived from daily analyses, especially second moment statistics such as covariances, can be distorted by model bias. The message is that no observational results, including those here, should be used without due consideration of reliability and possible biases.

In this paper, we have presented some mean fields and focussed the discussion on aspects that differ greatly between the hemispheres, but which have typically not been well-reproduced in GCMs. These are the double jet structure in the SH in winter and the stronger tropospheric winds in summer than winter, so that there are marked differences between the annual cycles in the two hemispheres.

Acknowledgments. I wish to thank Byron Boville for providing me with his updated results using NMC data and Richard Rosen for comments.

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