Tropical stratospheric zonal winds in ECMWF ERA-40 reanalysis, rocketsonde data, and rawinsonde data

Mark P. Baldwin
Northwest Research Associates, Bellevue, Washington, USA

Lesley J. Gray
Department of Meteorology, University of Reading, Reading, UK

Received 28 December 2004; revised 22 March 2005; accepted 12 April 2005; published 7 May 2005.

[1] ECMWF ERA-40 reanalysis zonal winds are very close to tropical rocketsonde and rawinsonde (radiosonde & radar wind soundings) observations up to 10 hPa. Above 10 hPa differences increase, although the ERA-40 data provide a good representation of tropical winds up to 2–3 hPa. The amplitudes of the quasi-biennial oscillation (QBO) and the semi-annual oscillation (SAO) derived from ERA-40 data match the rawinsonde and rocketsonde observations up to 2–3 hPa. We conclude that zonal-mean ERA-40 equatorial winds could be used, for most purposes, in place of rawinsonde station observations.
Citation: Baldwin, M. P., and L. J. Gray (2005), Tropical stratospheric zonal winds in ECMWF ERA-40 reanalysis, rocketsonde data, and rawinsonde data, *Geophys. Res. Lett.*, *32*, L09806, doi:10.1029/2004GL022328.

1. Introduction

[2] Equatorial stratospheric winds have been measured by rawinsondes at individual stations since the 1950s [*Reed et al.*, 1961; *Naujokat*, 1986]. The rawinsondes continue to provide reliable observations up to 10 hPa (~31 km). Above this level, rocketsonde winds at Kwajalein (8.7°N, 167.7°E) and Ascension (7.9°S, 345.5°E) have provided an incomplete record from ~30 hPa into the lower mesosphere. Frequent rocketsonde observations were made from the mid 1960s to the early 1980s, but no observations have been made since the early 1990s.

[3] In principle, a data assimilation model could use the observations to provide a more complete data record than is available at a single station. Until recently, this approach was limited to a highest pressure level of 10 hPa using NCEP [*Kalnay et al.*, 1996] or ECMWF ERA-15 reanalysis [*Pawson and Fiorino*, 1998]; see www.ecmwf.int/research/era/ERA-15/. Analysis of NCEP data [*Huesmann and Hitchman*, 2001] showed that near 10 hPa the assimilated winds did not capture the amplitude of the observed wind anomalies. The ECMWF ERA-40 reanalysis used a model that extended to 0.1 hPa (~65 km), and provided more accurate winds in the middle stratosphere [*Pascoe et al.*, 2005]. Satellite data (beginning in 1973) and rawinsonde data were assimilated, but rocketsonde data were not. This presents the possibility of validating the ERA-40 data against the rocketsonde data. The purpose of this paper is to validate the ERA-40 equatorial data with rocketsonde and rawinsonde data throughout the stratosphere.

[4] The QBO spans the depth of the stratosphere, from ~100 hPa to at least 1 hPa [*Baldwin et al.*, 2001; *Gray et al.*, 2001a, 2001b]. It is largely zonally symmetric [*Hamilton et al.*, 2004], and the largest QBO amplitude is at the equator near 15 hPa. The QBO is typically defined using monthly-mean rawinsonde wind measurements [*Naujokat*, 1986]. Since the highest reliable rawinsonde level is 10 hPa, there is a detailed record of the QBO in monthly-mean zonal wind, from the 1950s to the present, but only at pressure levels up to 10 hPa.

[5] Rocketsondes provided high-quality data into the mesosphere, but the data record ended more than 10 years ago. Although rocketsonde observations span the upper stratosphere, the stations are far enough from the equator that they do not capture the full amplitude of the QBO [*Baldwin et al.*, 2001, Plate 1]. High Resolution Doppler Imager (HRDI) satellite winds [*Hays et al.*, 1993] have covered the altitude range 30–40 km since 1991, but comparisons with Naujokat winds indicate that the HRDI winds are less accurate than the rocketsonde winds (D. Ortland, personal communication, 2004).

2. Data and Analysis Methods

2.1. Data Processing

[6] Our approach is to validate ERA-40 data with both rawinsonde data and rocketsonde data at the station locations. The Naujokat rawinsonde data are monthly means of single-station zonal winds at the pressure levels 70, 50, 40, 30, 20, 15, and 10 hPa. These data were taken at Canton Island (2.8°N, 188.3°E, to August 1967), Gan/Maledive Islands (0.7°S, 73.2°E, September 1967 to December 1975), and Singapore (1.4°N, 103.8°E, 1976–present). We calculated monthly means of the ERA-40 data interpolated to the same geographic locations as these stations, and the same pressure levels as the rawinsondes.

[7] Validation of the ERA-40 data against the rocketsonde data is similar, but slightly more involved because the rocketsonde winds were observed at geometric heights, the measurements were more sporadic in time, and the data sometimes have large vertical gaps. These issues necessitated careful processing of the rocketsonde data and examination of every individual sounding for the entire data record.

[8] The rocketsonde data consist of individual vertical profiles on specific dates. The vertical resolution is 2 km in

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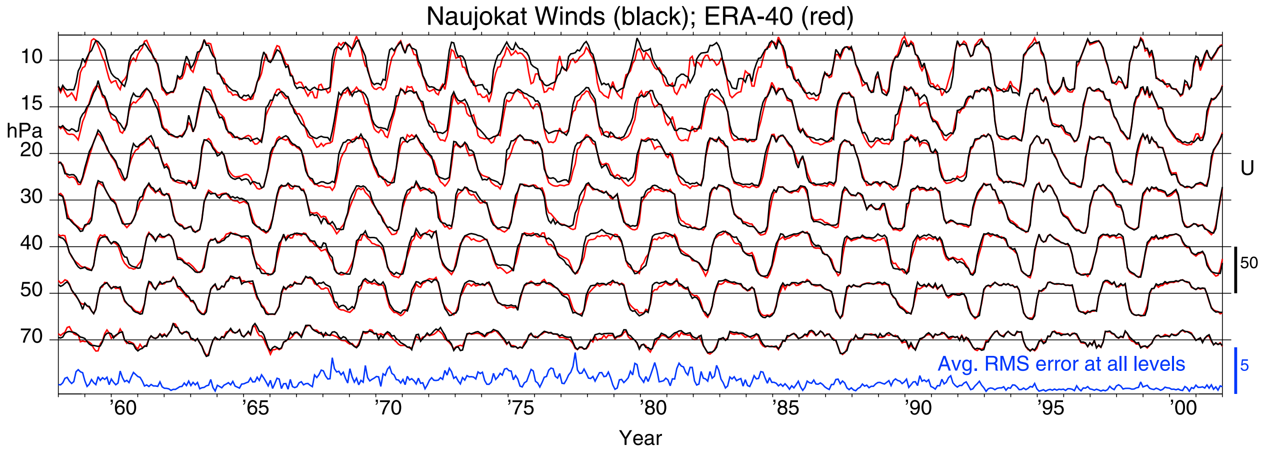

Figure 1. Comparison of zonal wind speed (ms^{-1}) Naujokat rawinsondes (black) and ERA-40 data (red) at the rawinsonde stations. The blue line is the RMS difference between these curves, averaged over all seven levels. The scale is shown at the right edge of the plot.

most cases. To produce monthly means, we retained only those months with at least five soundings. Each sounding was examined, and all data above vertical gaps of more than 5 km were rejected. We used cubic splines to interpolate to the ERA-40 pressure levels. We then used zonal-mean ERA-40 geopotential values to convert from height to pressure (the original rocketsonde data used the US standard atmosphere). The rocketsonde observations began typically near 30 hPa, and extended above 0.1 hPa, the highest level of the ERA-40 data. The rocketsonde data files also contain rawinsonde data (up to ~10 hPa) taken at the same time as the rocket launches. We separated these data to compare rocketsonde and rawinsonde data in the region 10–30 hPa.

2.2. Comparison of Naujokat Data With ERA-40

[9] Figure 1 shows all the monthly-mean Naujokat and ERA-40 data for the period 1958–2001. The ERA-40 data are in red, and the Naujokat data are overlaid in black. The agreement is best in the 15–50 hPa layer, but the differences are small at all data levels. Overall, the RMS difference between the time series is approximately 2 ms^{-1}. The RMS difference was slightly larger during the 1970s than the 1960s, with a substantial decrease during the 1980s, and consistent values of less than 1 ms^{-1} beginning in 1995. There was no obvious improvement when satellite data were assimilated in ~1973, nor was there a change in 1978, as seen in the NCEP reanalysis [*Huesmann and Hitchman*, 2003]. Since the assimilation model is unchanged through the data record, we speculate that the improvement seen during the 1980s and 1990s was due to more and improved observations. Also, ECMWF assimilated data in several streams, one of which began on 1/1/1995, coincident with a drop in RMS wind errors.

2.3. Comparison of Rocketsonde Data With ERA-40

[10] In Figure 2 we compare the monthly-mean zonal wind climatologies for the rocketsonde data at Ascension and Kwajalein with co-located ERA-40 data. For each data set we used all the available months of data to calculate the climatologies. The ERA-40 data span 1958–2001 (528 months), but at Ascension Island there were 200 months of quality-controlled monthly means during 1965–1983, and at Kwajalein there were 155 months during 1965–1981. Thus, the differences in the climatologies reflect, in part, the different data records. Ascension and Kwajalein are located in different hemispheres on opposite sides of the globe, and so are substantially different, even at the lowest levels.

[11] At Ascension there is good agreement above 10 hPa, even though there were few rawinsonde observations above 10 hPa. The agreement between rocketsonde and ERA-40 data is not as good at Kwajalein. The climatology at Kwajalein changes more rapidly in the vertical, as shown by *Garcia et al.* [1997], and the ERA-40 assimilation model appears not to simulate these changes as well as at Ascension.

[12] Figure 3 compares the rocketsonde data to the ERA-40 data after removal of the seasonal cycle from

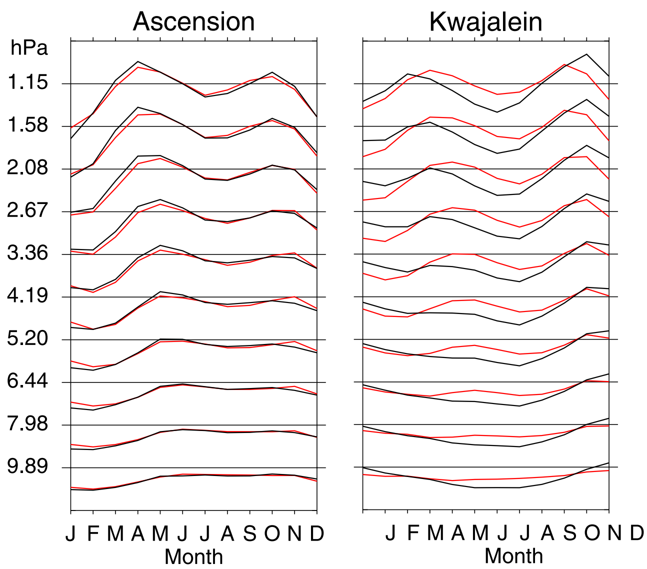

Figure 2. Monthly-mean zonal wind climatologies at Ascension and Kwajalein, using rocketsondes (black) and ERA-40 data (red).

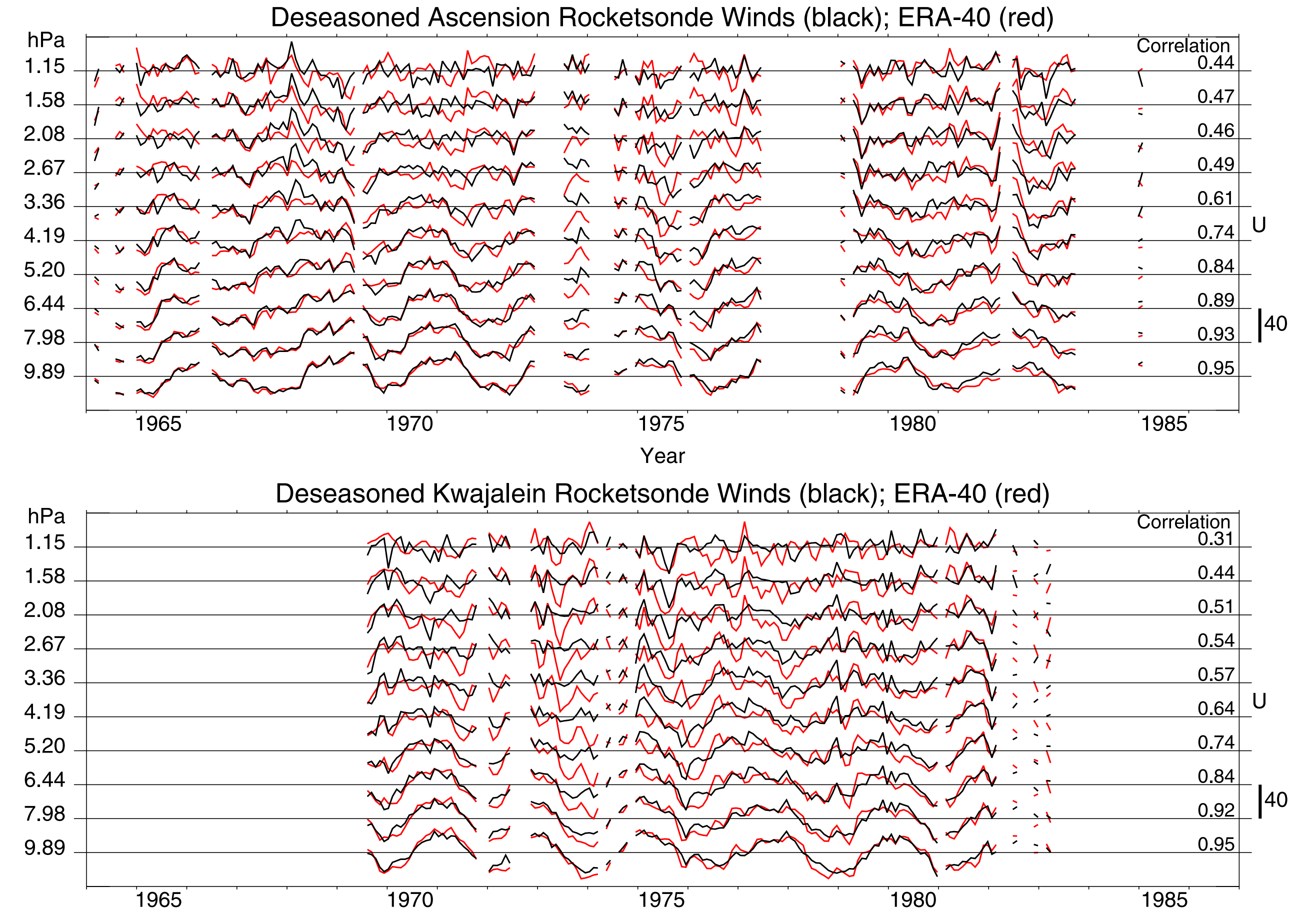

Figure 3. Comparison of rocketsonde winds (black) with ERA-40 data (red). The seasonal cycle has been removed.

Figure 2. This is a more difficult test of the ERA-40 data than a comparison of the total wind (not shown). Below 10 hPa correlations exceed 0.95. Prior to the availability of satellite data, there were few data assimilated above ~10 hPa, so the comparison in Figure 3 can be viewed as a test of the assimilation model. The more recent ERA-40 data do not appear to be substantially better than the pre-satellite data.

2.4. Amplitude of the QBO and SAO

[13] We estimated the amplitude of the equatorial QBO as a function of pressure in all the data sets. Spectral filtering (e.g., bandpassing periods of 20–40 months) could not be used because the rocketsonde data have gaps, so we used the following procedure for all data. We defined "the QBO" as the equatorial zonal wind in the range 10–70 hPa, after removal of the seasonal cycle. We assume that any zonal wind time series, u, off the equator or outside 70–10 hPa, may be written as:

$$u = q + \varepsilon$$

where q is the part of u due to the QBO and ε is random "noise". We choose u_e as the single equatorial QBO series in the range 10–70 hPa that is best correlated with u, so that

$$\mathrm{Cov}(u_e, u) = \mathrm{Cov}(u_e, q)$$

This is equivalent to

$$r(u_e, u)\sigma_{u_e}\sigma_u = r(u_e, q)\sigma_{u_e}\sigma_q$$

where r is a correlation coefficient and σ is a standard deviation. It then follows that

$$\sigma_q = \sigma_u r(u_e, u)$$

if it is assumed that q, the QBO contribution to u, is perfectly correlated with the QBO in the equatorial series u_e, that is, if $r(u_e, q) = 1$. Thus, if $r \equiv r(u_e, u)$, then $\sigma_u r$ is, under these assumptions, the estimate of the standard deviation of the part of u due to the QBO, and $2\sqrt{2}\sigma_u r$ is its peak-to-peak amplitude. We calculated $2\sqrt{2}\sigma$ for the equatorial QBO, and found it to be a close measure of the peak-to peak amplitude of the QBO, even though the QBO time series is not sinusoidal.

[14] Figure 4 shows the QBO amplitude using ERA-40 data, rocketsonde data, and rawinsondes at the Naujokat equatorial stations, Ascension and Kwajalein. As we would expect from Figure 1, agreement between the Naujokat data (dotted black) and equatorial ERA-40 data (solid black) is very close, with a peak QBO amplitude near 15 hPa of ~55 ms^{-1}. At Ascension and Kwajalein there is good agreement between the rocketsonde data and rawinsonde data in the region of overlap (~10–35 hPa). Up to 3–4 hPa

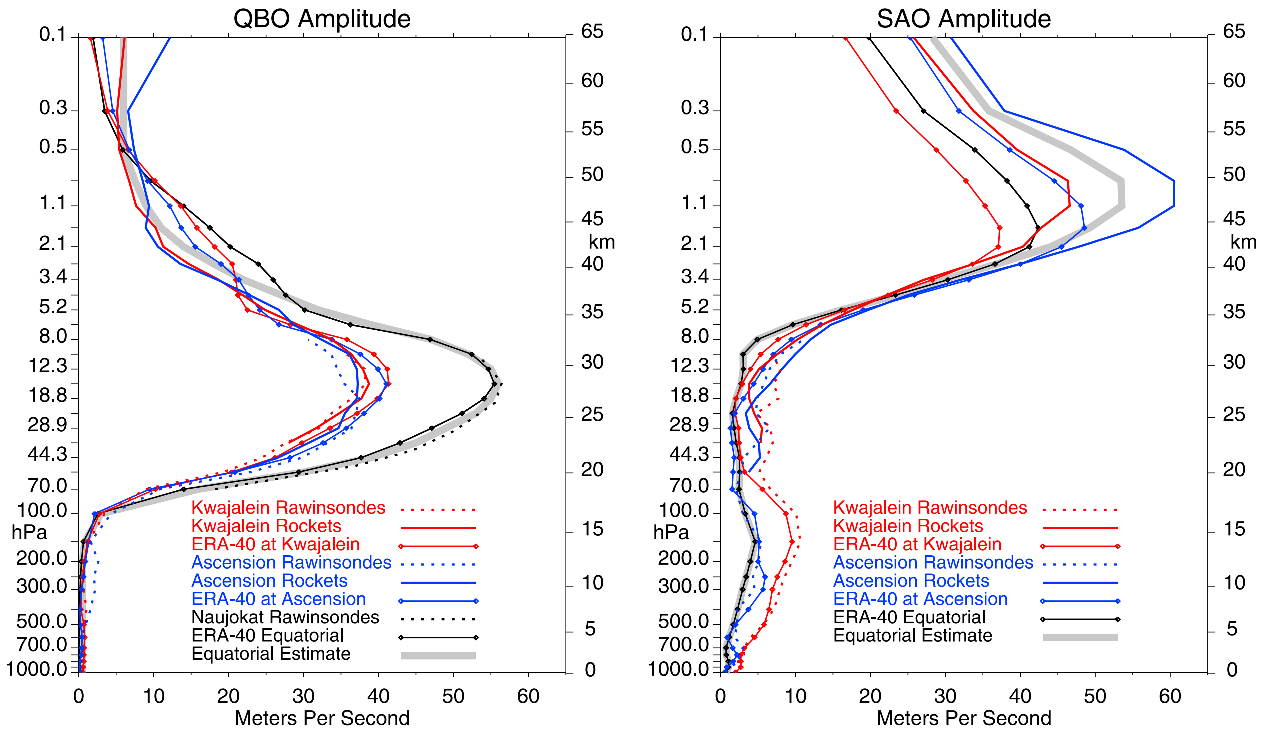

Figure 4. Comparison of the amplitude of the QBO and SAO in zonal winds estimated using rawinsondes, rocketsondes, and ERA-40 data. The thick gray curve is a subjective estimate of the equatorial amplitude based on all the available data.

there is close agreement among all the data sources at both stations.

[15] The amplitude of the QBO peaks near the equator, but above 10 hPa there are no equatorial observations. We can use differences between the ERA40 data and the rocketsonde data, together with the equatorial ERA40 data, to estimate the equatorial amplitude of the QBO above 10 hPa. The gray curve shows the (subjective) estimate of the QBO amplitude, which is derived from the ERA-40 equatorial data, but adjusted based on the differences between the ERA-40 and rocketsonde data. We note that at Ascension and Kwajalein the ERA-40 data overestimate the QBO amplitude by ~50% over the pressure range 1–3 hPa.

[16] We estimated the amplitude of the SAO from Figure 2. As is clear in Figure 2 (as well as in work by *Dunkerton and Delisi* [1997] and *Garcia et al.* [1997]), the two SAO peaks may not be separated by six months. We therefore removed a single annual harmonic from Figure 2, and defined the SAO amplitude as $2\sqrt{2}\sigma$, where σ is the standard deviation of the time series after removing the annual harmonic.

[17] Figure 4 shows close agreement in the amplitude of the SAO at all three locations, up to ~2–3 hPa, with the stratospheric SAO somewhat larger at Ascension. The Naujokat data suggest that at 10 hPa the SAO at the equator is smaller than off the equator. From 3 to 5 hPa, rocketsondes and ERA-40 agree well, but above 3 hPa the ERA-40 data have too small an SAO amplitude at both stations. The equatorial ERA-40 SAO amplitude is very close to the average of the two rocketsonde stations. Near the stratopause (~1.15 hPa), the ERA-40 SAO underestimates the rocketsonde SAO by ~25%.

[18] For both the QBO and SAO, the ERA-40 data appear to be very good up to 2–3 hPa. From 2 to 0.8 hPa, the ERA-40 data show a QBO that is ~50% too large and an SAO that is ~25% too small.

3. Conclusions

[19] The zonal mean equatorial ERA-40 wind is very close to the Naujokat data from 1958–2001, and could be used in place of it. This would have several advantages, including higher vertical resolution and higher time resolution. The useful vertical domain is 1000 to near 1 hPa instead of 70 to 10 hPa. Data are available at all latitudes and longitudes, instead of at selected stations, allowing an estimate of the zonal-mean to be made. Comparisons with rocketsonde data suggest that the ERA-40 data are reliable up to 2–3 hPa, and can be used for some purposes up to ~1 hPa.

[20] At Kwajalein and Ascension, the agreement between deseasoned rocketsonde and ERA-40 data is very good at 9.89 hPa, but it deteriorates with height. By 3.36 hPa there are large differences, and by 1.15 hPa the monthly anomalies do not match very well (the correlations are 0.31 and 0.44). This suggests caution in using ERA-40 data above 2–3 hPa.

[21] We see little evidence that equatorial winds improved in the ERA-40 data when satellite data were assimilated. However, we do see improvements in the 1980s and 1990s at the equator from 70 to 10 hPa. In the upper stratosphere at the rocketsonde stations, we do not discern any improvement from the pre-satellite era to the 1980s.

[22] **Acknowledgments.** We thank two anonymous reviewers for suggested improvements to this paper. MPB was funded by NSF (under the US CLIVAR program), by NOAA's Office of Global Programs, and

NASA's SR&T Program for Geospace Sciences, Living With a Star Program, and Oceans, Ice, & Climate Program.

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M. P. Baldwin, Northwest Research Associates, Bellevue, WA 98007, USA. (mark@nwra.com)

L. J. Gray, Department of Meteorology, University of Reading, Earley Gate, P. O. Box 243, Reading RG6 6BB, UK. (lesley@met.reading.ac.uk)