COMPILATION OF WIND DATA FOR THE UARS REFERENCE ATMOSPHERE PROJECT

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ABSTRACT

The aim of the UARS (Upper Atmosphere Research Satellite) Reference Atmosphere Project (URAP) is to provide a comprehensive zonal mean reference description of the stratosphere using measurements from instruments on board the UARS. A data set has been produced which describes the monthly zonal-mean zonal winds from the surface to the upper mesosphere. Wind measurements from the High Resolution Doppler Imager (HRDI) were combined with results from The Met. Office stratospheric data assimilation system. Balanced winds derived from the URAP temperature data set were used to bridge the gap between the stratospheric winds and HRDI mesospheric winds.

INTRODUCTION

This paper describes the compilation of a monthly wind data set from measurements by the HRDI instrument on board UARS and stratospheric assimilation data from The Met. Office. The initial impetus for the compilation of this data set was the UARS Reference Atmosphere Project (Remedios et al, 2000), which is a compilation of monthly stratospheric data focused on a particular baseline year (April 1992 to March 1993). The data set will also form a part of the SPARC (Stratospheric Processes and their Role in Climate) reference climatology. The data set comprises zonal-mean zonal wind data from the earth's surface to the upper mesosphere every month for a period of about 8 years starting from the launch of UARS. The wind data are stored on a pressure-latitude grid; the pressures are the UARS standard pressure levels (p_i = 1000hPa.$10^{(-i/6)}$, i = 0 to 44) and the latitudes are equally spaced every 4° from 80°S to 80°N.

Wind measurements from HRDI span most of the stratosphere and from the middle mesosphere to the lower thermosphere. In order to obtain as full as possible coverage of the atmosphere, the HRDI measurements have been combined with results from the Met Office stratospheric data assimilation system, which uses a range of meteorological observations to provide wind data for the troposphere and stratosphere. Our wind data set only includes the zonal (westerly) component of the wind and not the meridional (southerly) component. Since the zonal-mean meridional winds are generally closer to zero than the zonal-mean zonal winds, we determined that the meridional winds could not be calculated with sufficient accuracy to be of general use, particularly at higher altitudes.

The HRDI mesospheric measurements do not fully cover the lowest levels of the mesosphere, and the Met Office analyses are also less reliable as they approach their top analysis level, so we have used balanced winds derived from the URAP temperatures (when available) as an additional data source in that region of the atmosphere. Taken together, these data sources provide complete wind fields from the surface to the lower mesosphere. But there are some data gaps in the middle mesosphere and above, particularly at high latitudes. Rather than omitting data where observations or assimilated data are not available, we have provided our best estimates of zonal winds.

In the remainder of this paper, we first briefly describe our main data sources. Next we describe the procedure that we use to construct the merged wind data set, illustrating the procedure for one particular month. Finally, we present some plots of the final zonal-mean winds.

WIND DATA SOURCES

High Resolution Doppler Imager

HRDI (Hays et al, 1993, Ortland et al, 1996, Burrage et al, 1996a) is one of two instruments on UARS which

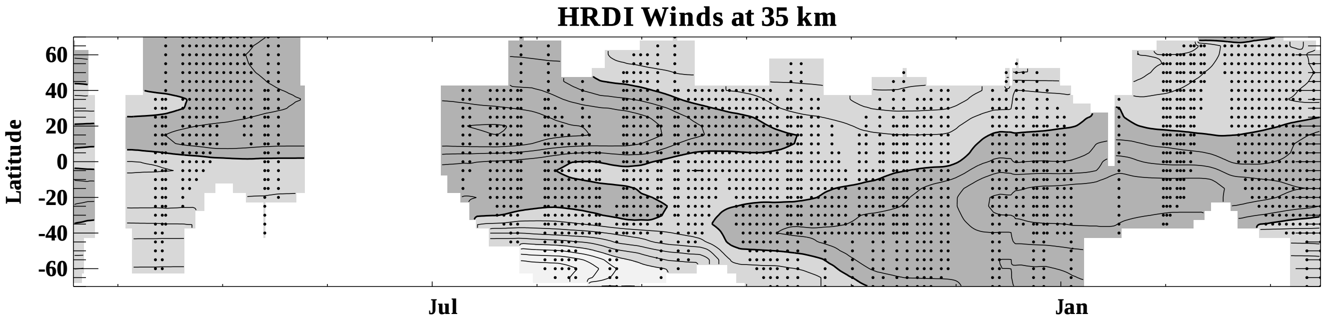

Figure 1. HRDI data at 35 km for the URAP baseline period. The locations of the daily unsmoothed longitudinal averages are indicated by the small dots. The contours show the results of smoothing and interpolating the daily longitudinal averages; the contour interval is 10 ms^{-1} and negative values (easterly winds) are indicated by darker shading.

makes measurements of the wind. HRDI measures wind in the stratosphere, mesosphere and lower thermosphere, while WINDII (Wind Imaging Interferometer) measures winds at higher altitudes, in the upper mesosphere and thermosphere. During the daytime, stratospheric wind measurements are collected by HRDI, using the Doppler shift of O_2 absorption spectra in sunlight that has been scattered into the telescope's field of view. HRDI measures winds in the mesosphere and lower thermosphere (MLT) using the Doppler shift of O_2 emission lines.

HRDI wind profiles are retrieved on a regular altitude grid extending from 10 to 40 km at 2.5 km intervals in the stratosphere and from 60 to 115 km in the MLT (but the lower altitude limit was reduced to 50 km after 1993). The location of the profiles occur at regular intervals spaced about 4 degrees apart along a tangent point track that lies to one side of the satellite track. As a consequence of the UARS orbital geometry, the latitude of this viewing track ranges from approximately 70° latitude in one hemisphere to 40° latitude in the other hemisphere. For stratospheric observations, the telescope is pointed only to one side of the satellite on any given day. There are some mesosphere observing modes of operation, however, where the satellite pointing alternates sides every other orbit in order to maximize coverage of high latitudes.

As a first step, both the HRDI stratospheric and mesospheric (MLT) profiles are interpolated along the orbit track to the locations where that track crosses the latitude circle of the URAP grid. There are always two such crossings per orbit (except at the turning latitudes): one crossing occurs in the ascending node of the orbit and the other occurs in the descending node. The number of crossings may vary since HRDI observations can only be taken in daylight. It is also worth noting that the orbit track crossing in a given node of the orbit occurs at roughly the same local time for consecutive orbits. This local time actually changes about 20 minutes per day as the orbit precesses. For the next step in the processing, all interpolated profiles at a given latitude crossing on a specific day and at a specific node are averaged. This average is thrown out if the longitudinal locations do not sufficiently sample the full latitude circle. The averages for different nodes but the same latitude are kept separate because they represent data sampled at different local times.

One must take care in interpreting longitudinal averages of satellite observations. The spatial and temporal sampling pattern of observation locations allows the possibility for a family of different wave motions to be aliased (see Salby, 1982). Modes that are aliased with the zonal mean are precisely the migrating tides (e.g. Morton et al, 1993, Burrage et al, 1995). Thus, a longitudinal average of HRDI winds must be interpreted as a superposition of the zonal mean and all tidal components sampled at a specific phase of each tidal oscillation. Since the tidal amplitudes in the stratosphere are smaller than the HRDI measurement errors, it is safe to interpret the HRDI stratospheric wind averages as zonal averages. For the MLT data, however, tidal amplitudes are the same order of magnitude as the zonal mean and interpretation of the longitudinally averaged winds is a problem.

The HRDI mode of operation does note allow for simultaneous measurements of the stratosphere and MLT during a given orbit. For this reason, both the side of the satellite on which observations are made and the region of the atmosphere observed are alternated from either from orbit to orbit or from day to day. This observation strategy has led to strings of days where only stratospheric or only mesospheric measurements are available. As a result, there can be significant data gaps. These data gaps were filled by an interpolation technique that differs between the data sets for the two regions. It was deemed necessary to fill the data gaps so that monthly averages are not biased. These biases may occur as a result of a combination of the sampling pattern and temporal changes in the

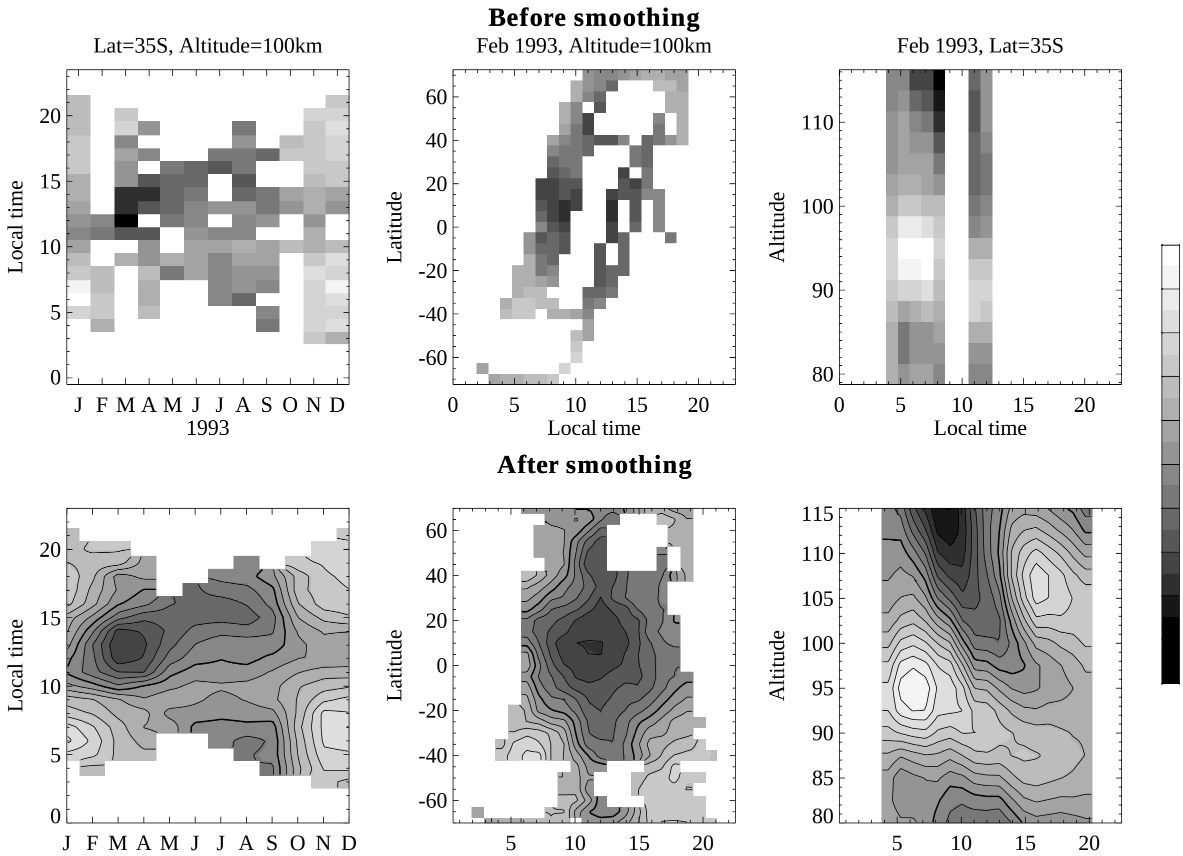

Figure 2. Illustration of the processing of HRDI MLT wind data for February 1993. The top row of plots shows the measured winds, binned by month (in 1993) and local time, latitude and local time, and altitude and local time. The bottom row shows the binned values after smoothing, with a contour interval of 10 ms^{-1}.

daily averages throughout the month.

The processing of the stratospheric winds is illustrated in Fig. 1. The daily stratospheric averages were temporally smoothed and interpolated using a triangular filtering function. The smoothed wind profile derived for a given day and latitude was obtained as a weighted average of all wind profiles at that latitude within 15 days of the given day. The weight was tapered from 1.0 to 0.0 over the 15 day range. If the total weight computed from all available data was less than 1.0, then no smoothed profile is returned.

Because of the local time variability, the MLT wind processing is somewhat more complex. The winds are first binned by month, local time, latitude and altitude, as illustrated in Fig. 2. Ideally, if one had complete local time coverage over the full 24 hour range, then a zonal average at a given latitude and altitude could be obtained by a simple average over the local time bins. However, because of the slow precession of the satellite orbit, it takes about a month to achieve full local time coverage at the equator, and even longer at higher latitudes. Because there are no nighttime measurements and because of the slow precession of the satellite, there are gaps in the local time coverage for each month.

For these reasons, gaps in the local time coverage were filled using a smoothing method. Each bin value was replaced with a weighted average over surrounding bins (adjacent in month and local time), so empty bins were filled if there were sufficient data in the surrounding bins. After the smoothing and interpolation, the monthly means were obtained by simply averaging over the available local time bins for each month, latitude and altitude. There will still be some systematic error to these estimates of the zonal mean zonal winds because of the incomplete local time coverage, but it will have been reduced by filling in this coverage as much as possible.

This smoothing operation is illustrated in the first column of Fig. 2. The remaining columns of the figure illustrate how the smoothing has filled in the picture of the tidal variability for one particular month. The plot in the lower right clearly illustrates the downward phase propagation of the tides. The diurnal tide is predominant in the altitude range 90-100 km, but above this the semi-diurnal tide is predominant.

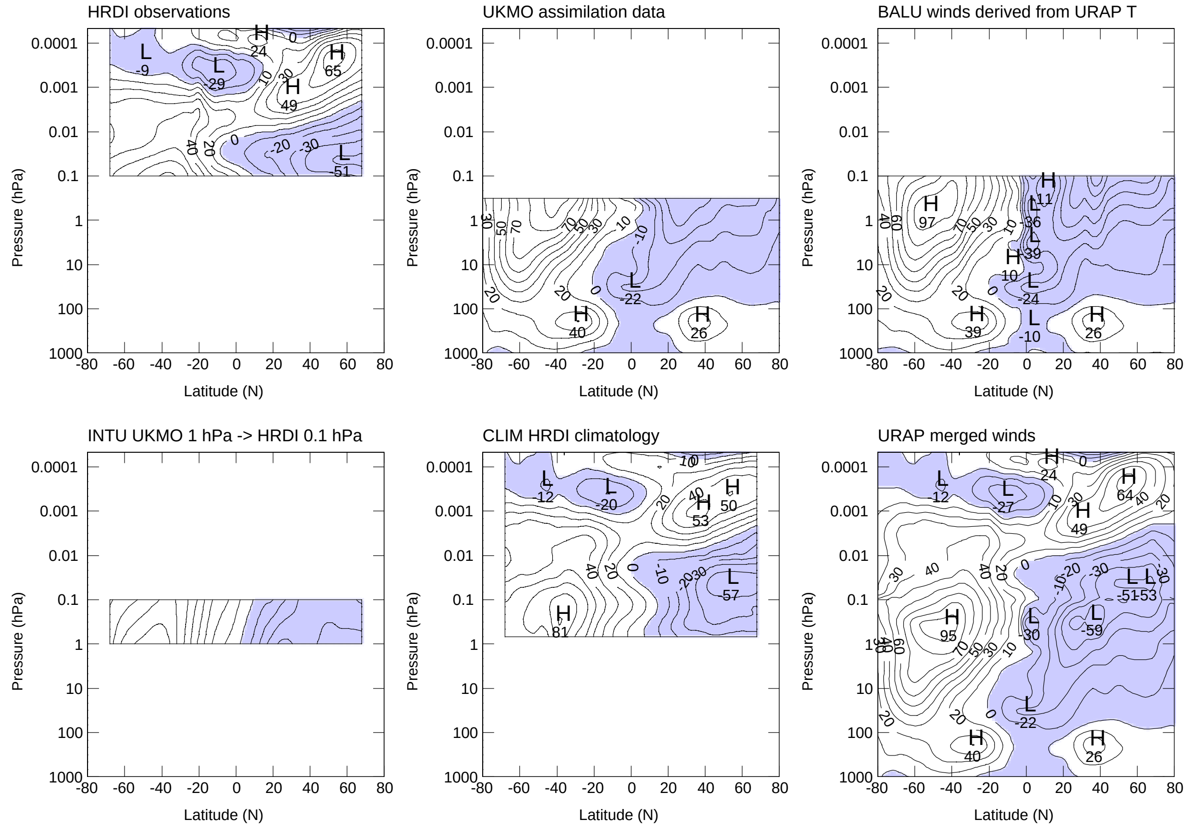

Figure 3. Zonally-averaged winds from each of the available data sources for June 1992: a) HRDI, b) UKMO, c) BALU, d) INTU, e) CLIM, and f) the resulting merged wind data. Wind speeds are shown in ms^{-1}, with negative (easterly) values shaded.

Met Office Stratospheric Assimilation

The Met. Office stratospheric data assimilation system (Swinbank and O'Neill, 1994) has been run daily since October 1991 to produce near real-time global stratospheric analyses at 12 UTC every day. These analyses are supplied to the UARS science team for the validation and interpretation of UARS measurements. The assimilation system is based on the "Analysis Correction" data assimilation system, described by Lorenc et al (1991). It is a modified successive correction method in which observations are repeatedly inserted into the Met Office Unified Model (Cullen, 1993) as it is integrated forward in time. The stratospheric data assimilation system uses a global 42-level configuration of the Unified Model, with a horizontal resolution of 2.5° latitude and 3.75° longitude. The stratospheric analyses are output on the UARS standard levels from 1000 hPa to 0.316 hPa (index range 0 to 21).

For this project, the daily Met Office fields were used to create monthly means at the original horizontal resolution. In turn, those means were used to calculate zonal-mean zonal wind data at the standard URAP latitudes. For brevity, we will refer to the Met Office wind data as UKMO in the remainder of the paper.

Balanced winds from URAP temperatures

To supplement the two primary data sources, we have used balanced winds (BALU) calculated from a preliminary version of the UARS Reference Atmosphere temperatures. That data set is only available for the URAP baseline period, and over the pressure range 100 hPa to 0.1 hPa. In order to calculate balanced zonal winds, we first needed to calculate zonal-mean geopotential heights. Up to 100 hPa, we have used zonal-mean heights from the UKMO data set. At higher levels, the heights were derived through hydrostatic integration of the URAP temperatures, starting from the UKMO 100 hPa heights. The zonal winds were then calculated using the following balance equation:

$$\frac{\overline{u}^2}{a}\tan\varphi + 2\Omega\overline{u}\sin\varphi + \frac{1}{a}\frac{\partial\overline{\Phi}}{\partial\varphi} = 0, \qquad (1)$$

where Φ is geopotential, φ is latitude, and other symbols have their usual meaning. Values at the equator were evaluated from the curvature expression:

$$\bar{u} + \frac{1}{2\Omega a}\frac{\partial^2 \bar{\Phi}}{\partial \varphi^2} = 0 \quad . \tag{2}$$

CONSTRUCTION OF THE MERGED WIND DATA SET

Our strategy for constructing the wind data set was to merge together HRDI and UKMO monthly zonal-mean westerly wind data, to produce a data set of winds from the surface through the mesosphere. Together, these primary data sources cover most of the domain, except for a gap in the lower mesophere, and high latitudes at higher altitudes. To help fill the lower mesosphere gap during the URAP baseline year, we used the balanced winds (BALU). Another method of filling the gap was to use winds vertically interpolated between UKMO data at 1 hPa and HRDI data at 0.1 hPa; the winds were assumed to vary linearly with log(pressure) over that range. During some months there were insufficient HRDI data to define the zonal-mean winds at some latitudes. In those cases, we used climatological HRDI data, calculated for the 4-year period 1992-1995. At latitudes greater than 72°, there were never any HRDI measurements, so we made the assumption that the zonal winds were proportional to cosφ – equivalent to assuming that the zonal-mean atmosphere rotates as a solid body at high latitudes.

Figure 3 shows cross-sections of the original wind values from the different data sources for one particular month (June 1992). The HRDI data (Fig 3a) cover much of the stratosphere and MLT, but with some large data gaps; it should also be noted that the data counts in the southern hemisphere MLT region were very low. The balanced wind (BALU) data (Fig 3c) are generally similar to the UKMO data (Fig 3b), but they include some unrealistic features at low latitudes, where the balance relationship holds less well. Both the BALU and UKMO data are less reliable at the uppermost levels, near the lid of the UKMO assimilation model, and where the heights derived from the URAP temperatures become less accurate. In the extratropical mesosphere, the HRDI climatology (Fig 3e) is generally quite similar to the June 1992 plot (Fig 3a), confirming that it is reasonable to use climatological values when there are no HRDI data available for a particular month. Figure 3f shows the combined data, demonstrating that our merging procedure produces a coherent and realistic final product.

The merging procedure uses the wind data in the following order of priority:

- HRDI measurements
- Met Office assimilated data (UKMO)
- Balanced winds for the URAP baseline year (BALU)
- Interpolated winds in the lower mesosphere (INTU)
- HRDI climatology (CLIM)
- extrapolated winds at high latitudes (EXTU)

In order to achieve this, we use a “prioritised weighting” approach. We have defined a set of level-dependent weighting factors, shown in Table 1, which reflect where each of the different data sources is available (and in a

Table 1.
Level-Dependent Weighting Factors Used to Construct the Wind Data Set

Level index	Pressure (hPa)	HRDI		UKMO	BALU	INTU	CLIM	EXTU
25-44	0.068-0.000046	1.00		0	0	0	1.00	1.00
24	0.10	0.50	1.00*	0	0.25	1.00	1.00	1.00
23	0.15	0.00	0.75*	0	0.50	1.00	1.00	1.00
22	0.22	0.00	0.50*	0	0.75	1.00	1.00	1.00
21	0.32	0.00	0.25*	0	1.00	1.00	1.00	1.00
20	0.46	0		0.25	1.00	1.00	1.00	1.00
19	0.68	0		0.50	1.00	1.00	1.00	1.00
18	1.0	0		0.75	1.00	1.00	-	-
16-17	2.2-1.5	0.00		1.00	-	-	-	-
15	3.2	0.33		1.00	-	-	-	-
14	4.6	0.67		1.00	-	-	-	-
6-13	100-6.8	1.00		1.00	-	-	-	-
5	146	0.67		1.00	-	-	-	-
4	215	0.33		1.00	-	-	-	-
0-3	1000-316	0		1.00	-	-	-	-

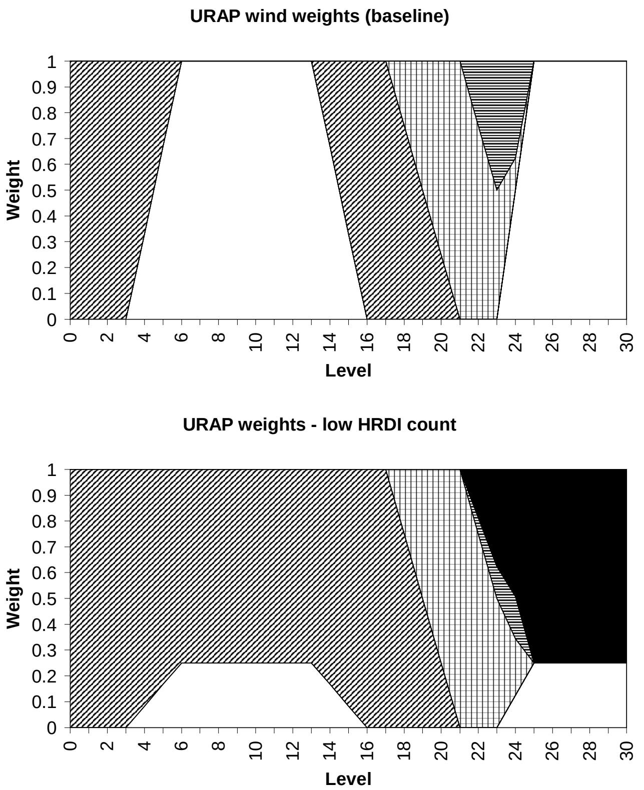

Figure 4. Weights used for each of the data sources as a function of level index: a) during the URAP baseline year, assuming a high HRDI data count; b) after the baseline year; c) during the baseline year, but assuming a HRDI data count of just 2. The weights of different data sources are indicated by shading: HRDI - unshaded; UKMO - diagonal shading; BALU - square shading; INTU - horizontal shading; CLIM - solid black.

rough sense, their accuracy). In general, each data source is available for a restricted range of levels and the weighting factors are reduced over the lowermost and uppermost few levels, to improve the blending of data from different sources. The first data source (HRDI) is given the weight (w_1) shown in the first column in the table, and the remainder of the weight is divided between the remaining data sources. (But the HRDI weighting is reduced if the data counts are low, as will be explained later.) The next data source (UKMO) is then allocated the tabulated fraction (w_2) of the remaining weight, i.e. it is given the weight $(1-w_1).w_2$, and the remaining weight is allocated to the third and subsequent data sources, and so on. If any data source has a weighting factor of 1, none of the subsequent data sources are used. This procedure ensures that the better data sources are given preference, when they are available. Since the last possible data source is always given a weighting factor of 1, the individual weights always add up to 1.

As mentioned above, the weighting of the HRDI data (w_1) is reduced if the HRDI counts are low. In the stratosphere, the count is the number of unsmoothed days' data contributing to each latitude/level bin for a particular month. In the MLT, the count is the number of local time bins used (before smoothing). In both cases, if the data count is less than 8, the HRDI weighting is reduced linearly with the count value. This weighting was found to be necessary to reduce artifacts in the data set which resulted when the HRDI measurements did not adequately sample the atmosphere. In a similar manner, the INTU data were weighted according to the HRDI data count at 0.1 hPa. Furthermore, the lower mesospheric HRDI winds were less accurate early in the UARS mission since they were somewhat degraded by aerosol from Mt. Pinatubo, and also because the operating mode of the instrument was improved as the mission progressed. To reflect these changes, and to make best use of data when the BALU data became unavailable, the HRDI weights were altered from April 93 (after the end of the URAP baseline year), in order to use HRDI mesopheric data from lower altitudes. The weights used for the latter part of the period are indicated with asterisks in Table 1. Since the BALU data exhibited some unrealistic features at low latitudes, consideration was given to reducing the BALU weighting close to the equator. However, test calculations showed that change had only a small impact, so the latitude-dependent weighting was omitted.

Figure 4 illustrates the weights assigned to the different data sources as circumstances vary. Figure 4a show the level-dependent weights for the baseline period, assuming that the HRDI data counts are at least 8. Figure 4b is

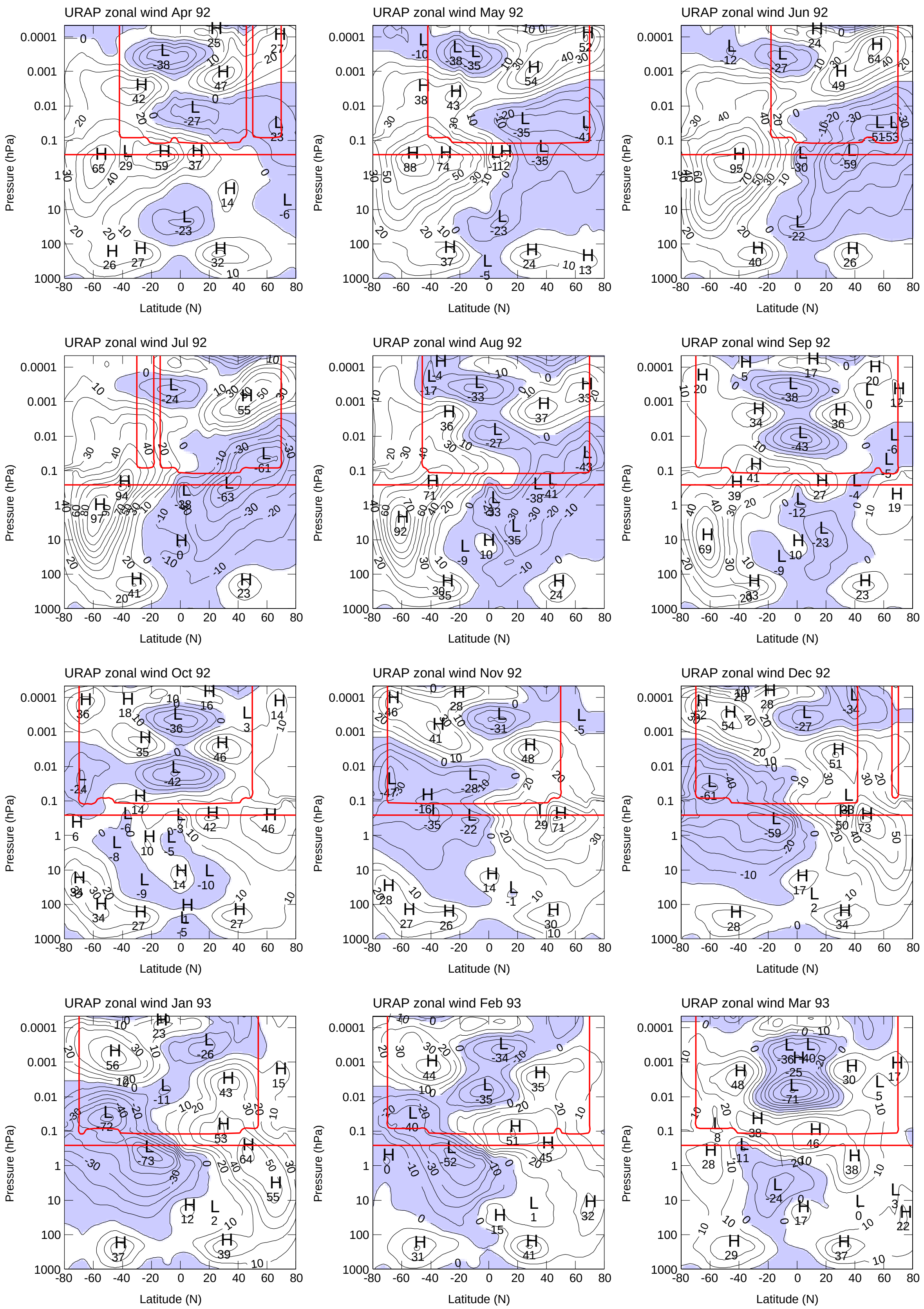

Figure 5. Zonal-mean zonal wind cross-sections for each month in the URAP baseline year, April 1992 to March 1993. The additional lines show where the values are mainly derived from interpolated or climatogical data (see text).

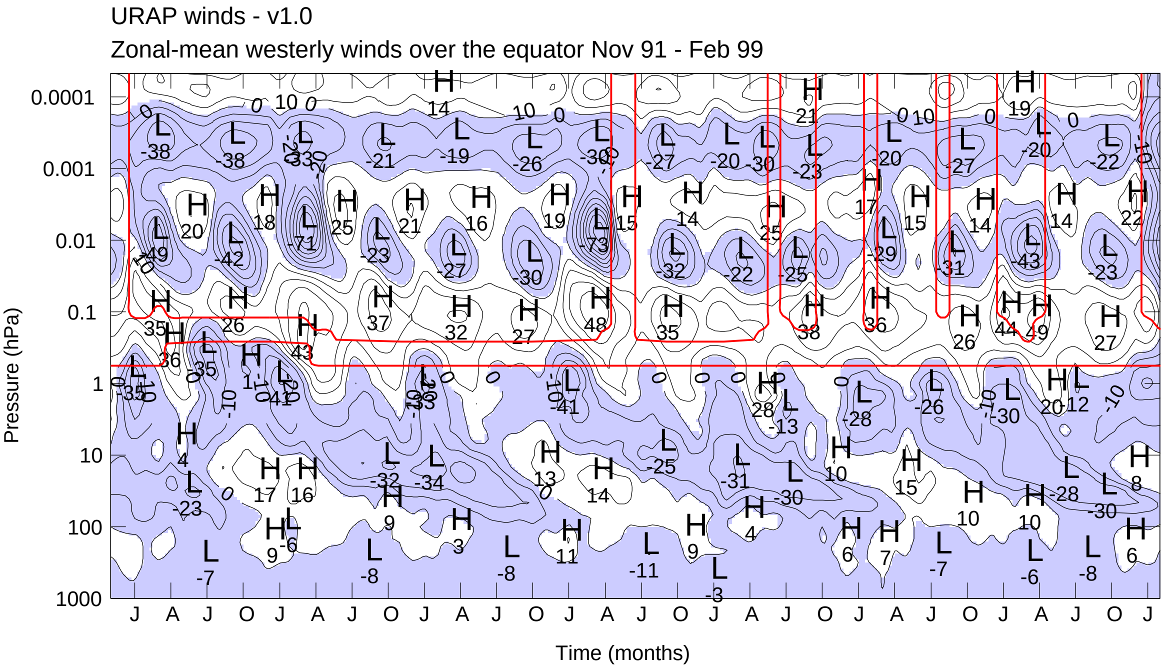

Figure 6. Time series of zonal-mean westerly winds over the equator, from November 1991 to February 1999. The tick marks along the x-axis mark each January, April, July and October. The additional lines show where the values are mainly derived from interpolated or climatogical data.

calculated assuming a HRDI data count of 2 at all levels; note the increased use of UKMO in the stratosphere and the HRDI climatology in the mesosphere. Figure 4c shows the weights after the baseline period, when BALU data are not available and HRDI mesospheric data is used at lower altitudes. In the latter case the winds in the lower mesosphere come primarily from the interpolated data (INTU), rather than the balanced winds (BALU).

The URAP constituent data sets include a flag to indicate where the data are less reliable (indicated by setting the mixing ratios to negative values). In order to give a similar indication of the reliability of the merged wind data set, we needed to indicate where the final value of the wind is derived mainly from the primary data sources (HRDI or UKMO), and where final value is mainly interpolated data or climatology. In order to derive an indicator of reliability, we added together the weight assigned to HRDI, the weight for UKMO and 0.5 times the weight for BALU (since the latter is derived indirectly from observations too). Where this reliability index is less than 0.5, we have added 10000 to the merged wind values.

RESULTS

Figure 5 shows cross-sections of the merged wind data for each of the months in the URAP baseline year, from April 1992 to March 1993. The regions where the wind values are less reliable have been delineated using the criteria described above The cross-sections clearly show the annual cycle of winds throughout the middle and lower atmosphere. In mid-winter, in both hemispheres, the polar night jets peak near the stratopause. Above the jet level there is a marked equatorward tilt, so that the strongest westerlies are in the subtropics in the mesosphere. Conversely the easterly jets are tilted towards the summer poles. Generally speaking, there are westerly jets in both hemispheres at the mesopause (altitude about 90 km, or approximately 0.003 hPa). Near the equinoxes, they are quite symmetric, but in the solstice seasons the jet in the summer hemisphere extends upwards and polewards. Over the equator there are easterly jets in both the mesosphere and lower thermosphere at the equinoxes, but again these become less symmetric at the solstices. The mid-mesospheric variations between easterlies at the equinoxes and weak winds at the solstices constitute the mesospheric SAO. As discussed by Fleming et al (1996), there are some significant differences between the HRDI MLT wind measurements and previous wind data sets, particularly those derived from the medium frequency (MF) radar observations.

The variations of wind over the equator from the full data set are shown in Figure 6. In addition to the mesospheric SAO, a stratopause SAO can also be seen, although it probably would have been captured better had it not been for the gap in the HRDI measurements. At lower altitudes the stratospheric QBO can also be clearly seen.

There is some evidence that the meospheric wind variations are modulated by the stratospheric QBO (see also Burrage et al, 1996b). For example, there are strong easterlies in NH Spring 1993 and 1995, with weak SAO easterlies in between. This pattern is less clear during the latter part of the period, since the HRDI data coverage is poorer.

CONCLUSIONS

As part of the UARS Reference Atmosphere Project, a data set has been constructed showing the variation of zonal wind with altitude and pressure for much of the period of the UARS mission. The data set is being made available to the scientific community through both the URAP web-site and the SPARC Data Centre. The scope of the present paper is limited to a description of the compilation of the UARS Reference Atmosphere wind data set. We hope that it will constitute a useful resource for future scientific investigations, complementing the other URAP data.

Acknowledgements

We thank John Gille and John Remedios for the provision of the URAP temperature data set before it was publicly available. Much of this work was carried out while RS was a visiting fellow at the Data Assimilation Office, funded by NASA through USRA contract NAS5-98181.

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