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Nathalie Huret, F. Duruisseau, A. Andral. On the Accuracy of Stratospheric Meteorological Reanalyses Using Wind Measurements at High Altitude in the Stratosphere. Proceedings of the 22nd ESA Symposium on European Rocket and Balloon Programmes and Related Research, Jun 2015, Noordwijk, Norway. pp.273. insu-03577051

HAL Id: insu-03577051

<https://insu.hal.science/insu-03577051>

Submitted on 16 Feb 2022

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ON THE ACCURACY OF STRATOSPHERIC METEOROLOGICAL REANALYSES USING WIND MEASUREMENTS AT HIGH ALTITUDE IN THE STRATOSPHERE

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ABSTRACT

This study is motivated by the improvement of the knowledge of stratospheric dynamics and the evaluation of the ability of models to represent wind variability in the stratosphere. We deduce from the Zero Pressure Balloons trajectories, operated by CNES during the last decade, zonal and meridional wind to provide a unique database in the altitude range [25–40] km. The collected data are associated with ZBP flights launch during winter and summer in polar region above the Esrange (Sweden) launch base and in equatorial region above the Teresina (Brazil) during easterly and westerly Quasi-biennial Oscillation phase. We performed systematic comparisons between wind measurements and ERA–interim reanalysis from ECMWF (European Centre for Medium-Range Weather Forecasts) and present the vertical profile of biases for both wind component in winter at high latitude. The biases and the standard deviation obtained increase with altitude.

INTRODUCTION

The current computing performances of numerical weather prediction (NWP) and climate research models are providing higher and higher spatial and temporal resolution. For better accuracy the models need to assimilate more and more measurements with better precision. This is possible due to progress in measurement techniques and instrumentation (weather stations, radiosonde balloons, satellites, wind profiler, radar, lidar, etc.). The stratosphere suffers from an obvious lack of measurements. In particular it has been shown that tropospheric weather can be influenced by large scale dynamical structures occurring in the middle atmosphere such as the polar vortex (Baldwin and Dunkerton 2001; Thompson et al. 2001; Charlton et al. 2003; Charron et al. 2012), sudden stratospheric warmings (Sigmond et al. 2013) and the quasi-biennial oscillation (Gerber et al. 2010). Therefore the study and the numerical modelling of the stratosphere is becoming an important issue for NWP centres.

Most of the wind measurements in the troposphere and in the lower stratosphere are performed with radiosondes that are the only *in situ* measurements in the stratosphere but they burst generally below 30 km (around 10 hPa). Others techniques can probe the atmosphere and are expanding as the infrasound technology (Le Pichon et al. 2005) or

lidar measurements. For example new infrastructures aiming to combine these different instrumentations are emerging (ARISE project, <http://arise-project.eu/>).

Zero Pressure Balloon or ZPB (Durry and Hauchecorne 2005; Huret et al. 2006; Wetzel et al. 2013) are the most commonly used for short duration flights (from several hours to a few days). The balloon trajectory is driven by the wind and balloons can be considered as good tracers, if the vertical speed is not too high and if measurements of the balloon location are sufficiently accurate (Alexander et al. 1996). In this paper we use ZPB trajectories in order to retrieve the wind components (zonal i.e. u and meridional i.e. v) and wind speed, and compare them with the ERA-Interim data for studying the ability of ERA-Interim to represent the dynamics of the stratosphere up to 5hPa above Esrange launch base in polar region during winter.

We first describe the method for wind retrieval from balloon trajectory and the methodology developed for comparison with ERA-Interim (Dee et al. 2011). Then we compare results obtained with those obtained by the Hertzog et al. (2004) obtained with Pressure Balloons in the low stratosphere. Then we present and discuss the results obtained as a function of altitude up to 5hPa in winter above Esrange balloon launch base.

1. WIND MEASUREMENTS AND DATA

1.1. ZPB balloon flight profile

Typically the flight duration of ZPB operated by CNES is from 6 hours to few days. Figure 1 shows a typical flight profile (June 9, 2003 in Kiruna, Sweden). The first flight phase just after launch consists in the balloon ascent (1) at typically 5 m s^{-1} up to the ceiling (2). At ceiling the balloon is in equilibrium with the surrounding air thus the pressure level is stable (except for slow variations due thermal effects induced by the diurnal cycle). This equilibrium can be maintained during many hours or even a few days in some occasions. An embedded ballast/valve system allows the control of the vertical speed as observed in Figure 1 for the slow descent phase between 1 m s^{-1} and 5 m s^{-1} . The last phase consists in a rapid descent (the vertical speed can exceed 20 m s^{-1}) of the payload under parachutes down to the ground after balloon-payload separation (4).

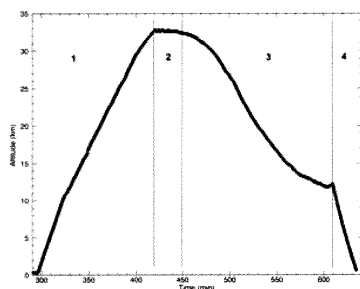


Figure 1. Example of balloon flight profile (June 9, 2003 in Kiruna, Sweden) phase 1: ascent; phase 2: ceiling; phase 3: slow descent; phase 4: descent under parachutes.

In our study the ascent, the ceiling (with undersampling of 15 minutes) and the slow descent are used to deduce u and v from the balloon trajectory. The last phase cannot be used due to the very high vertical speed during descent.

1.2. Wind retrieval

For each ZPB flight the available data is derived from the GPS (Global Positioning System) position (longitude, latitude, altitude) of the balloon. The measured pressure and surrounding air temperature are also available as a function time. The time step of the recorded data is 10 s. The accuracy of the balloon location by GPS is better than 10 m in the horizontal and around 15 m in the vertical. As a consequence the precision of both zonal and meridional component are 0.1 m s^{-1} . The accuracy of the surrounding air temperature measurements is around 2°C (Pt100 temperature probe) and the pressure uncertainty is about 0.5 hPa (capacitive transducer probe). The pressure sensor is sufficiently accurate in the troposphere but not enough for pressures below 10 hPa. For example the altitude derived from the pressure measurements present an error higher than several hundred meters at 10 hPa. Hence we use the GPS altitude as the vertical coordinate and the wind components (u and v) are calculated from the latitude, longitude, altitude and time provided by the GPS. We use a centered difference using two points separated 100 s. This allows us to filter high frequencies generated by pendulum oscillations. The flight chain is between 100 m and 200 m long and then (considering a simple gravity pendulum in the small-angle approximation) the oscillation period is between 20 s and 30 s. In this study we assume that the balloon is a perfect passive tracer. Note that if the balloon is not a perfect tracer (aerodynamic effects) then the calculated wind is underestimated.

By using the derived vertical speed we have identified the different phases The added value of this dataset is that a lot of wind measurements are available up to 43 km in the stratosphere, while studies using meteorological radiosondes are

limited to measurements below 30 km (Houchi et al. 2010; Moffat-Griffin et al. 2011 for example) because the balloon burts.

1.3 ECMWF ERA-interim data

Because we need model results coming from the same “stable” model during the last decade to perform model/measurement comparisons we use ERA-Interim reanalyses (Dee et al. 2011). We use the ERA-Interim wind data, pressure, temperature and geopotential height on pressure levels (37 levels) with a horizontal resolution of $0.75^{\circ}\times 0.75^{\circ}$ in latitude and longitude and a time step of 6 hours. ERA-Interim wind data are spatio-temporally interpolated for each balloon wind measurement. The interpolation is performed considering 3 points in latitude, 3 points in longitude, 2 levels in pressure and 3 time steps. A quadratic interpolation is performed in the horizontal and time variables whereas the vertical interpolation is linear. Note that, for the vertical interpolation, we use the altitude derived from the GPS because of the large uncertainties in balloon pressure measurements at high altitude. Thus we can calculate the zonal (u) and the meridional wind (v) components, the temperature and the pressure from ERA-Interim for each balloon point of measurement.

1.4. Method

In order to study the vertical evolution of wind biases as a function pressure, different pressures bins centered on a mean pressure varying from 100 hPa to 10 hPa every 5 hPa are considered. Tests have been made considering four half-widths with at 100 hPa: 5 hPa, 10 hPa, 30 hPa, 100 hPa. The width of the pressure bins follows a logarithmic variation as a function of the mean pressure considered (figure 2a).

Figure 2b show the vertical evolution of the number of points in each bin. They are respectively roughly 500, 1000, 2500 and 6500. The too small numbers of points of measurements inside the two intervals with small width (black and blue) do not allow us to perform statistical analysis.

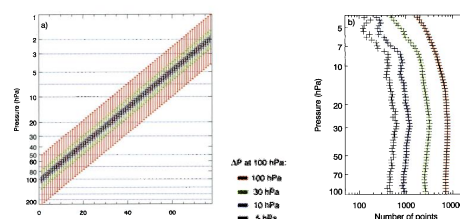


Figure 2: a) Pressure intervals considered with bins of different half-widths given at 100 hPa : black for 5 hPa, blue for 10 hPa, green for 30 hPa and red for 100 hPa. b) Number of points in each pressure intervals as a function of pressure.

Then the histograms of differences between u and v from ERA-interim data and u and v from our measurements are calculated for the green and red pressure interval thereafter SPI and LPI (Small Pressure Interval and Large Pressure Interval). Statistics properties are deduced for each pressure intervals: bias (mean value of the difference between Era-interim and measurements), the standard deviation, the skewness and the kurtosis. We also verify that the bias obtained in each pressure interval is statistically relevant verifying that the standard error $\frac{\sigma}{\sqrt{n}}$ is lower than the bias.

2. RESULTS

2.1 In the low stratosphere above Esrange

In this section we focus on the comparison of the biases we obtained with those of the study of Hertzog et al. (2004) (H2004 thereafter). H2004 compared wind components deduced from sixlong duration pressure balloon flights which occurred inside the polar vortex in 2002. They compare their wind measurements with ECMWF analyses with an horizontal resolution of $0.5^{\circ} \times 0.5$. They used two types of balloon to combine two pressure ranges : [85.1; 82.8] hPa and [64.7; 58.6] hPa. For comparison with H2004 we have to be careful to select similar geophysical conditions (i.e. inside the polar vortex). To select data inside the polar vortex the temporal evolution of potential vorticity from ERA-Interim above Kiruna from 2000 to 2011 have been analysed. For example figure 3 presents the time evolution of the Lait potential vorticity or Lait-PV (Lait, 1994) normalized at 380 K, above Kiruna from 1 February up to 31 March 2000. The reported black vertical bars identify the range of the pressure for each ZPB flight in that period.

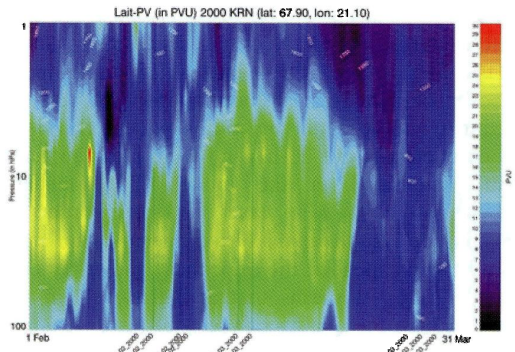


Figure 3. Lait potential vorticity normalized at 380 K as a function of pressure derived from ERA-Interim above Kiruna (67.9°N, 21.1°E) between February and March 2000. Each flight is associated to one vertical black bar and the top of each corresponds to the ceiling reached by the flight.

It appears that flights on 16, 22, and 23 February, and those on 25, 27 and 29 March 2000 took place

in air masses with low values of Lait-PV, i.e. are not occurring inside the polar vortex, whereas the 3 flights on 18 February, 1 and 3 March are inside the polar vortex from 100 hPa up to the ceiling with large Lait-PV values. Thus only the data from these latter flights are relevant (same geophysical conditions) for comparison with the study of H2004. Then 33 ZPB flights trajectories are used from 2001 to 2011. The statistical parameters obtained are resumed in table 1 as well as those of H2004.

Table 1. Statistics of ECMWF ERA-Interim minus ZPB balloon observations and results of Hertzog et al. (2004).

	Zonal component (m s ⁻¹)		Meridional component (m s ⁻¹)	
	H2004	this study	H2004	this study
Bias	-0.1	-0.09	0.1	0.03
Standard deviation	2.3	2.53	2.2	2.23
sweekness	0.1	0.24	0.0	-0.17
kurtosis	0.0	1.29	0.1	0.80

Zonal wind biases for both components are similar to those of H2004. We find slightly higher values of standard deviation, probably because we have less number of points (2340) compare to the 11000 points of H2004. However the standard error is lower than the biases calculated, then our results are statistically significant.

2.2 Above Esrange during winter

The figure 4 presents the vertical profiles of biases obtained for SPI (green) and LPI (red) intervals in winter considering the 49 ZPB flights of the period from 2000 to 2011 for both wind components. Standard deviations are reported. Whatever the pressure interval considered the zonal component present very small bias lower than 0.1 m s⁻¹ in the low levels (below 20 hPa). Above the bias slightly increase to attain 1.5 m s⁻¹ at 5 hPa. For the meridional component the biases remain very low for all altitudes. The standard deviations which are only 3 m s⁻¹ and roughly constant between 100 hPa and 50 hPa, increase above, with a value of 4 m s⁻¹ at 5 hpa for the zonal component and 5 m s⁻¹ for the meridional. This can be explained by the low numbers of wind data assimilated by the model (Dee et al., 2011) at these altitudes because only few radiosonds attain 30 hPa and no in-situ measurements exists at high level.

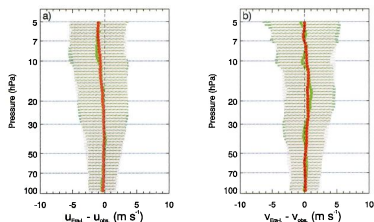


Figure 4. *u* (a) and *v* (b) biases and standard deviations calculated from December to March in polar region (49 ZPB flights from 2000 to 2011) for SPI (green) and LPI (red) pressure intervals.

The meridional bias component presents larger standard deviation than the zonal bias at high altitude. The *u* biases at high altitude (in the pressure range [10; 5] hPa) are relatively small compare to the *u* mean value ($\sim 40\text{ m s}^{-1}$) and do not exceed 7%. The *v* biases are relatively slightly larger and can reach 11% at 17 hPa. Regarding now the biases on the wind speed and the wind direction (figure 5a and 5b), it appears that the model underestimate the wind speed in the whole profile. The absolute differences between ERA-Interim and the measurements in the pressure range [100; 20] hPa never exceed 1 m s^{-1} . This shows that ERA-Interim reanalyses are robust in the low stratosphere. Several previous studies assess also of the quality of the ECMWF model in the low stratosphere (Hertzog et al. 2004, Hertzog et al. 2006; Knudsen et al. 2006; Christensen et al. 2007; Boccara et al. 2008; Houchi et al. 2010).

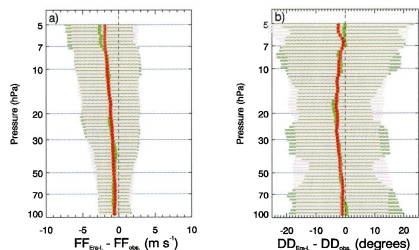


Figure 5. Wind speed (a) and wind direction (b) biases and standard deviations calculated from December to March in polar region (49 ZPB flights from 2000 to 2011) for SPI (green) and LPI (red) pressure intervals.

ERA-Interim reanalyses encounters some difficulties to represent winds at higher altitudes above 20 hPa. The wind speed biases (figure 5a) increase almost linearly to attain -2 m s^{-1} at 5 hPa. The Era-interim reanalysis underestimate the wind above 20 hPa. The wind direction biases can be considered as zero for the polar winter conditions but with a standard deviation between 12° and 23° . The polar vortex moves over pole and can be temporally perturbed due to sudden stratospheric warnings (SSW) which induce a reversal of the

zonal circulation starting at high altitude. Perturbations due to SSWs come from the stratopause and higher levels and propagate downward. Then because most of the ZBP attain 40 km of altitude, their trajectories are witness of such perturbations in the wind circulation. This could explain the increase in the wind speed and the wind direction biases and also the high value of standard deviations for polar winter conditions at high level. It is important to notice that this standard deviation at 5 hPa have the same order of magnitude than the globally root mean square error on the wind speed at the tropopause shown by Dee et al (2011).

3.CONCLUSION

We have retrieved the wind profile in the stratosphere using actual ZPB trajectories. This dataset provides *in situ* measurements in the mid-stratosphere up to 2 hPa at different locations over many years. This dataset has been used to assess the ERA-Interim reanalyses through a methodology designed to study the wind biases as a function of pressure. The implemented methodology (selecting geophysical conditions, testing several values for the width of the pressure bins, checking the number of points and calculate the standard error on the biases) allows us to get information on the accuracy of Era-interim to represent wind up to 40 km. The results obtained in the low stratosphere are in good agreement with H2004 for *u* and *v* components. ERA-interim slightly underestimate the wind speed in the low levels. Biases obtained with ZPB compare to reanalyses on one hand and with BP compare to ECMWF analyses (H2004) give similar results in the low stratosphere in polar vortex conditions. This confirms the quality of ERA-interim reanalyses in the low stratosphere in polar region during winter. ERA-Interim reanalyses encounters some difficulties to represent winds at higher altitudes above 20 hPa.This altitude corresponds to the altitude widely attain by radiosondings and as a consequence above 20 hPa no wind measurements are assimilated in the model. The standard deviations at 5 hPa have the same order of magnitude than the globally root mean square error on the wind speed at the tropopause shown by Dee et al (2011). It means that at high levels in the stratosphere the quality of the wind data is not so good and have to be improved.

ACKNOWLEDMENTS

This study has been initiated by the DEDALE working group of Centre National d’EtudesSpatiales (CNES), including links with the CSTB committee (<http://www.lmd.polytechnique.fr/cstb/>), INSU/CNRS, CNES and the ARISE project. We thank particularly Claude Camy-Peyret from IPSL. This study has been funded by the French Research

Minister, Ecole Doctorale (EMSTU) of the Université d'Orléans, the Region Centre, the Labex VOLTAIRE (ANR-10-LABX-100-01) and by SPARC/WMO (<http://www.sparc-climate.org/>). We thank the CNES balloon direction for providing the balloon trajectory files and Institut Pierre Simon Laplace (IPSL) for access to the ERA-Interim data. We thank all members of the CNES balloon launching team for their commitment during campaigns in the last decade.

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