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Copernicus Climate Change Service

Wind uncertainties

Initial assessment

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1. Introduction

This document extends our effort to estimate uncertainties for early upper air measurements, following the methodology introduced in the deliverable C3S_C311_Lot2.2.1.1 (March 2019), with the focus on wind speed and wind direction. The use of observation minus background and observation minus analysis departure statistics, as they are produced by modern dynamic data assimilation systems such as ERA5 (Hersbach et al. 2018), ~~–~~is an efficient alternative way to estimate observations errors, i.e. measurement plus representation error, whenever these are not available from observations. Early observations for sure and most contemporary observations do not supply observation error estimates. Such information can indeed be directly retrieved only in special networks such as the Global Climate Observing System (GCOS, Daan, 2002) Reference Upper-Air Network (GRUAN, Dirksen et al., 2014~~ Citation??)~~), or from the results of radiosonde inter-comparison campaigns (e.g. Yangjiang, Chian, 2010). However, results of such campaigns cannot be easily accessed, and in addition they depend on the types of radiosondes used for the measurements. In contrast, the use of departure statistics for estimating observation errors, according to the method described by Desroziers (2005), is a good general method that is applicable whenever departures are available. In this document we present results of the uncertainty estimation method for wind related observables, namely the wind speed and its decomposition in orthogonal components, and the wind direction.

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2. Data

For this initial version of the uncertainty assessment we use data from the ERA5 observation database (ODB), provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

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~~The rest I would skip. My opinion. ;)~~

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For the following discussion, we will take as an example benchmark for explaining our procedure the Lindenberg observation station (Germany, WMO ID 10393, 2006-2019). It is straightforward to apply this analysis to arbitrary observation stations.

Together with the results presented in this document, we also provide example scripts which allow to reproduce the plots shown.
~~The Lindenberg data is stored in the "data" directory in the form of netCDF files, one for each of the variables of interest:~~
~~- ERA5_1_10393_u.nc and ERA5_1_10393_v.nc for the wind u- and v-components, respectively;~~
~~- ERA5_1_10393_direction.nc and ERA5_1_10393_speed.nc, for the wind direction and speed;~~
~~- ERA5_1_10393_t.nc for the temperature.~~

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We include also the temperature files although the errors estimation for this variable was discussed previously in the C3S_C311_Lot2.2.1.1 (March 2019) deliverable.

The code used to produce the results here presented is available from GitHub at https://github.com/MBlaschek/CEUAS/tree/develop/CEUAS/wind_uncertainty .
~~A brief description of the code and the main workflow will be discussed in Section 5.~~ The repository includes an extended README files with all the relevant information to allow the user to reproduce the results shown in this document.

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During the processing of the ODB files, 16 standard pressure levels are used as a reference for the observations; moreover, all the observations are reported at the 00GMT ~~00Z~~ and 12GMT ~~12Z~~ standard launch times.

3. Method

The statistical framework on which the present analyses is based on, has already been introduced and explained in some details in the previous uncertainty estimation deliverable C3S_C311_Lot2.2.1.1.. We will refer to this procedure throughout this document as Desroziers diagnostics. If ($\mathbf{d}_{\mathbf{O\text{-}B}}$) represents the observation minus background departure and ($\mathbf{d}_{\mathbf{O\text{-}A}}$) represents the observation minus analysis departure, the error covariance matrix **R** can be calculated as:

$$E[\boldsymbol{d}_{\boldsymbol{a}}^{\boldsymbol{o}}(\boldsymbol{d}_{\boldsymbol{b}}^{\boldsymbol{o}})^T] = \boldsymbol{R}$$

Equation 1: Covariance matrix definition

where the expectation value is calculated over an arbitrary time range. The estimation of R is dependent on the temporal intervals. Here we use 1, 2, 6 ~~-~~months and 1 ~~-~~year~~)~~. For each pressure level, the quantities $\mathbf{d}_{\mathbf{O\text{-}B}}$
~~-~~ and $\mathbf{d}_{\mathbf{O\text{-}A}}$ are available~~,~~ and the estimate of the error can be calculated from the time averages.

A useful benchmark to compare the procedure is the result from the WMO inter-comparison campaign performed in Yangjing(2010), and documented in the "Guide to Meteorological Instruments and Methods of Observations (2014)".
In case of upper-wind measurements, errors stem from the combination of three different sources of uncertainties related to the tracking of the horizontal motion of the target, to the determination of

the height of the target, and the difference between the movement of the target and the actual tropospheric motion. ~~The main uncertainty, however, arises from the fact that the scales of observed values and thus of their related uncertainties, for modern instruments, are much smaller than the resolution of numerical weather prediction models. This means that, when comparing observation data and the model state, a representation error is unavoidably introduced. Typical values for the standard deviations of observation/numerical model output (k=2) in mid-latitudes is between 4-6 ms^{-1} in the lower troposphere, and rises up to 4-9 ms^{-1} in the upper troposphere. For comparison, both the random vector error and the systematic bias for GPS wind finding systems do not typically exceed 1 m/s, resulting in an overestimation of the uncertainties due to limitations in the theoretical model outputs. Figure 1 shows the results for the root-mean-squared vector wind differences, that is a combination of wind speed error and wind direction error, (k=1) for different time separations, for 11 pairs of observation, obtained during the Yangjing radiosonde inter-comparison campaign.~~

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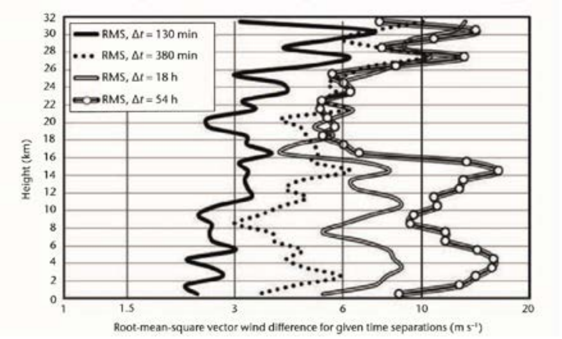

Figure 1 Root-mean-square vector wind differences for different time separations, for 11 pairs of observation, from the WMO Inter-comparison of High Quality Radiosonde System (Yangjiang, Chian, 2010).

The main uncertainty, however, arises from the fact that the scales of observed values and thus of their related uncertainties, for modern instruments, are much smaller than the resolution of numerical weather prediction models. This means that, when comparing observation data and the model state, a representation error is unavoidably introduced. Typical values for the standard deviations of observation/numerical model output (k=2)??? in mid-latitudes is between 4-6 ms^{-1} in the lower troposphere, and rises up to 4-9 ms^{-1} in the upper troposphere. For comparison, both the random vector error and the systematic bias for GPS wind finding systems do not typically exceed 1 ms^{-1}, resulting in an overestimation of the uncertainties due to limitations in the theoretical model outputs. Fig. 1 shows the results for the root-mean-squared vector wind differences, that is a combination of wind speed error and wind direction error, (k=1)??? for different time separations, for 11 pairs of observation, obtained during the Yangjing radiosonde inter-comparison campaign.

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Commented [MB8]: Right? or how would you better describe that measure?

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The odb files provided by the ECMWF include the observed values as well as the departures for the wind u- and v-components. The wind direction and speed value are then calculated from the orthogonal components, as well as the departures needed for the calculation of the Desroziers diagnostics.

3.1 Outlier removal

~~3.1 Outliers Removal~~

Before proceeding to the extraction of the measurement errors, outliers values are removed ~~from the~~from the departure data. This is done to ensure better statistical robustness. The Desroziers diagnostics is indeed sensitive to outlier values, especially when averaging over short time interval, where one single outlier can result in large discrepancies in the error calculation. We use ~~data sets using~~ quartiles statistics in the following way. The 25% and 75% percent quartiles, denoted with q25 and q75 respectively, are computed using the original datasets of the analysis and background departures. An arbitrary ~~cut~~ parameter *cut=*~~*of*~~ *1.5* is then employed to calculate a cut off value:

$$cut\_off = (\mathrm{q75} - \mathrm{q25}) * \mathrm{cut}$$

The values in the data below the lower value q25-cut_off and greater than the upper value q75+cut_off are disregarded when computing the Desroziers averages and errors. For the case of a normal distribution, this means that 0.7% of data are rejected.

The number of outliers found in each dataset depends largely on the pressure levels, and on the time period considered. Generally the number of outliers does not exceed 3% of the wind speed data, in the case of wind speed. For the temperature, the number is slightly higher, especially for departures in the upper troposphere, settling around 10%. The outliers however are still reasonably close to the lower and upper cuts, and the calculation of the Desroziers average is not majorly affected by their inclusion or exclusion.

4. Results

In this section we present the main results of our analysis. In section 4.1 we present the full results of the calculation of the cross-covariance matrices, from which observation errors are calculated. In section 4.2, we present the error time series and distributions for observations at 500 hPa pressure level, comparing the results for different choices of time averaging. In section 4.3 we then compare the results for all the different pressure levels.

4.1 Cross Covariance Matrices

As a starting point, it might be of interest to visualize the cross-covariance matrices~~, most of all for the sake of checking the validity of the procedure. Here w~~. We provide some example for the Lindenberg station, for arbitrary observation days as indicated in Fig. 1. The variables shown are the u- and w- component of the wind, the module of the speed of the wind, and the temperature (as a

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Commented [F11R10]: In principle there is no particular reason to remove outliers rather then deleting data which is obviously wrong, in the sense that they are so unusual that they are likely to be caused by errors in the data takin/writing. So they should not be used. However, if statistics is robust i.e. dataset is large, keeping or removing them produces a small difference, unless their value is extremely different from the average.

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Commented [MB13]: Maybe better say what results are where and how you organized them, rather than this sentence.

Commented [F14R13]: Something along this line?

Commented [MB15]: Really? I would rewrite the whole paragraph. Why do you do this? (about vertical correlation, independence of observations and therefore error estimates) What can be seen? What would indicate errors?

Commented [F16R15]: I think the first thing is that only the diagonal terms are basically important, with some exceptions in the case of the direction. Second, it seems that the values, for all the pressure levels, are similar; this of course the same information as the one you get from the distribution plots for the diagonal terms. If there was a weird "blob" of high correlation values, I would suspect some bugs (either in my code, or in the reading of the data, or in the data itself). This is just a general consideration actually. I would say it was standard for me (in the past) to have such matrices shown, even when the information inside was trivial.

reference, since the estimation of the errors for this variable was the object of the previous report C3S_C311_Lot2.2.1.1).

The values are obtained by computing the product of the analysis departure times the background departure for the standard pressure levels as indicated by the axis labels. Note that usually only the diagonal entries are considered, i.e. one should expect no significant correlation between the measurements at different pressure levels. For these matrices, the value shown is calculated by taking the average over a period of ~~30~~ 365 days following the chose date. Null values, for which no data is available, are neglected in the computation of the average.

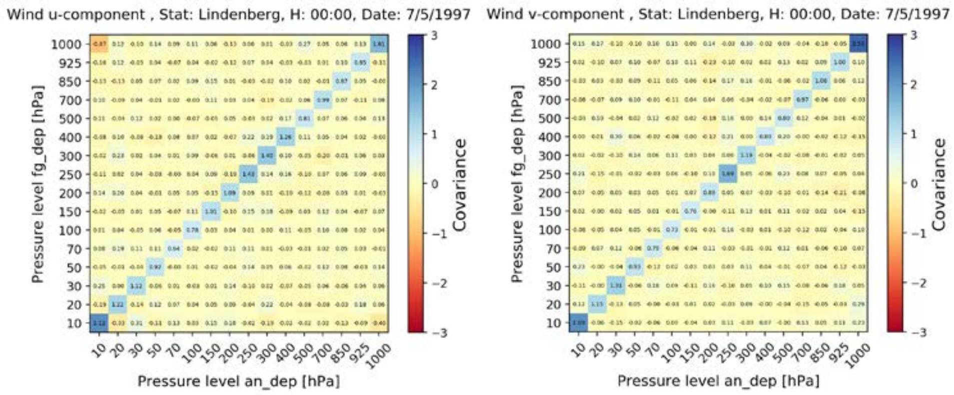

Figure 2 Example of wind u- and v-components correlation matrix, for the day July 5th, 1997, and measurements reported to 00GMT, Lindenberg station.

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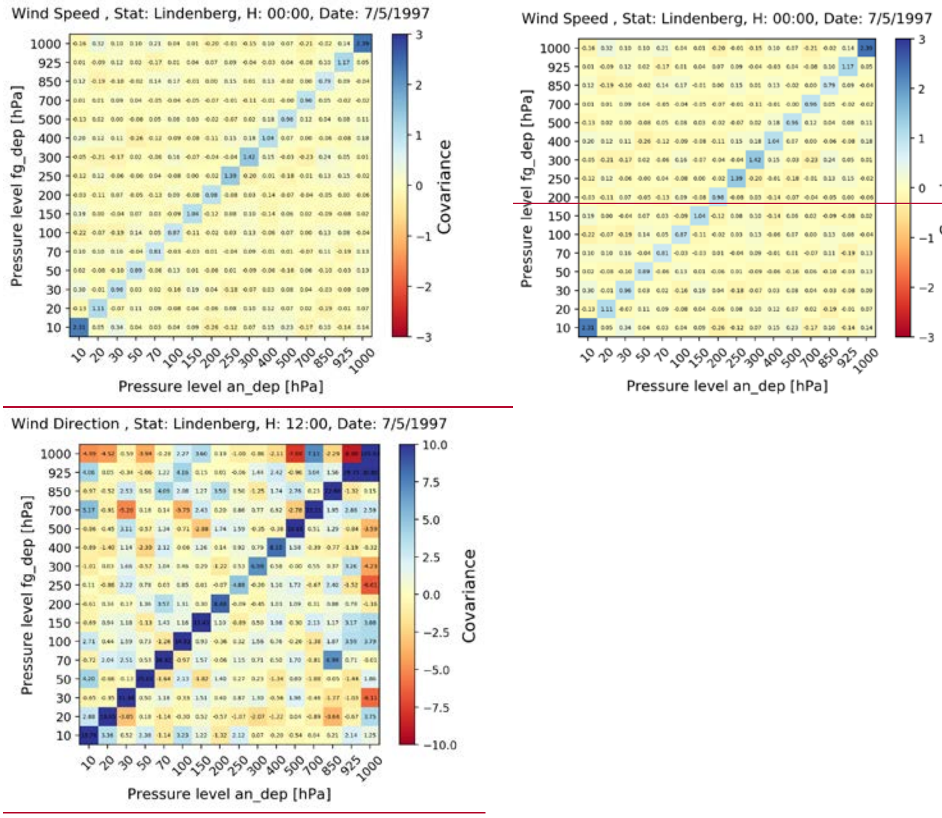
Wind Speed , Stat: Lindenberg, H: 00:00, Date: 7/5/1997

Wind Speed , Stat: Lindenberg, H: 00:00, Date: 7/5/1997

Wind Direction , Stat: Lindenberg, H: 12:00, Date: 7/5/1997

Figure 3 Same as Fig. 2, but for wind speed and direction.

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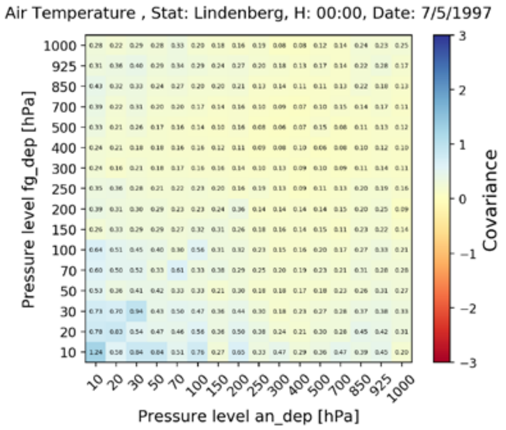

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Figure 4 Same as Fig. 2 and Fig. 3 for the temperature observation.

The correlation matrices are the starting point for the calculation of the uncertainties using Desroziers methods, essentially the square root of the correlations averaged over a time interval. The results for the time series averaged considering different time intervals for the separate wind components are shown in Fig. 5-, while the wind speed and directions are shown in Fig. 6. The selected pressure level is 500 hPa.

Note that the matrices are obtained by evaluating the cross product of the analysis and background departures, hence the presence of negative values. Errors will be calculated by taking the squared root of the absolute of such values. Overall the correlation seems reasonably small; in particular, it is verified that correlations between measurements at different standard pressure levels are negligible, and at the same time the values along the diagonal are effected by larger uncertainties for measurements in the higher atmosphere (lower pressure levels).

The wind direction error correlations are very noisy because of the possibility of vertically strongly changing wind directions, particularly under light wind conditions. Also biases can be large near the surface due to local wind channeling.

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4.2 Distribution and time series of error estimates at the 500 hPa level

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We present here our estimates for the observation errors obtained using Desroziers' method. We start with Fig. 5, which shows the time series of the wind-related variables (u- and v-components, speed, direction) for the whole range of data available (1979-2018) for the Lindenberg station. We chose the 500 hPa standard pressure level. By definition, Desroziers statistics is calculated averaging over a time interval, chosen among the values 1,2,3,6 months and 1 year.

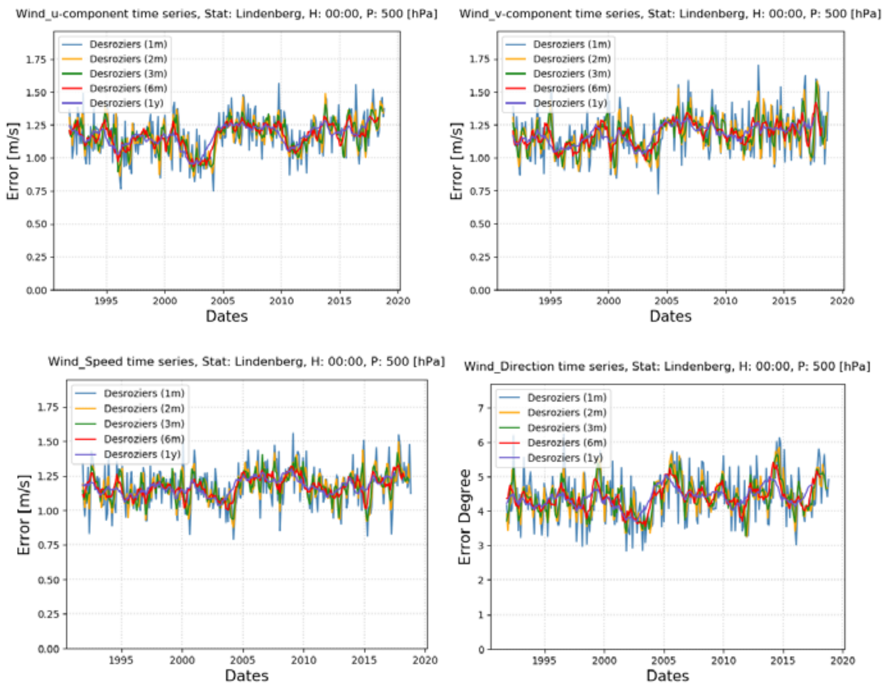

Figure 5 Time series for the error estimates using Desroziers method, averaging over time intervals of 1,2,3,6 months and 1 year, for the u- and v-component of the wind (upper panels), the wind speed (bottom left) and wind direction (bottom right), for 500 hPa standard pressure level.

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For each day in the time series, a running mean is evaluated considering the data of the 1,2,3,6 months and 1 year following the initial date. Outliers in the data were previously removed and not considered in the calculation. In addition, in the case of the wind, data is not always available for all the observation days and pressure levels, so the actual number of measurements considered a fixed time interval is reduced. However, this does not have a great impact in the calculation of the error. In fact the average value of the error is quite stable between 1.1 and 1.2 m~~/~~s^{-1} irrespectively of the time interval considered in the evaluation of the average, while the choice of a longer time results in a smoother distributions of the values. We note also there is no evident trend in the time series, where all the values fluctuates slightly around the median. The same considerations apply also to the estimates of the direction errors, which lies around the 4 degree range.

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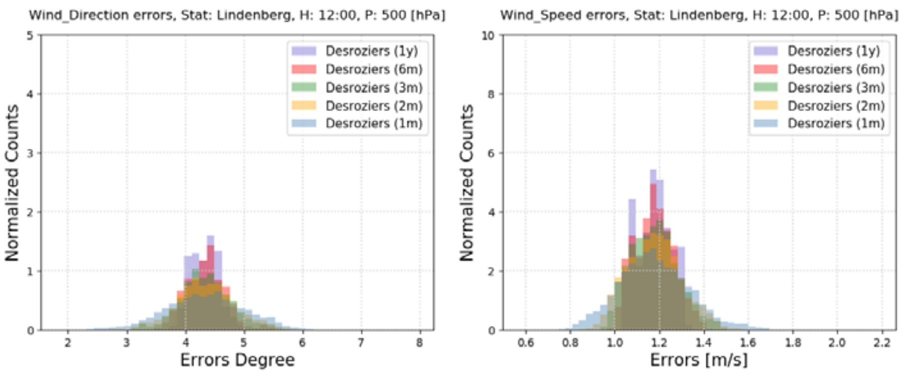

Figure 6 Diagnosed observation error distribution for the wind direction (left) and wind speed (right), for different temporal averages.

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4.3 Dependence of observation error on pressure

In the following we give an estimate of the variation of the errors as a function of the standard pressure levels, focusing on temperature and wind speed only. In Fig. 7 we take as an example the Desroziers means averaged over 2 months, and analyze the distribution of the error estimates.

As expected, both the shape of the distribution and the median depend on the pressure level considered, i.e. for lower pressures the average error estimate~~s~~ is larger of approximately a factor 2 compared to the values in the mid and lower troposphere. At the same time, the distribution spreads over a larger interval, while results are very narrow for larger pressure values~~. This reflects the higher level of accuracy of the measurement for lower elevations.~~ It is anyhow interesting to note that the smallest median values are found for intermediate elevations, between the 250 and 500 hPa pressure levels.

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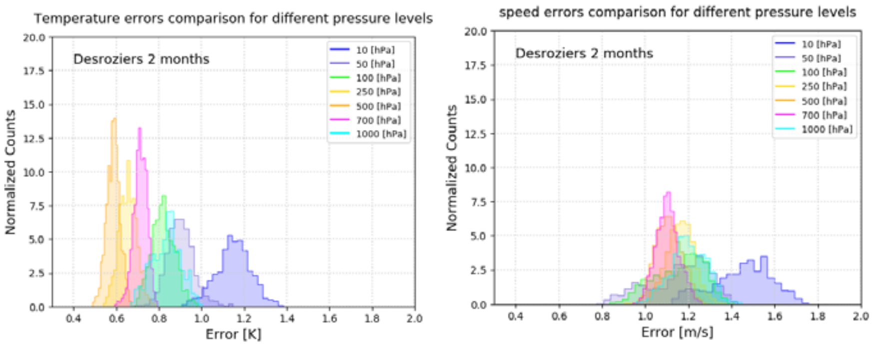

Figure 7 Distribution of the errors for the temperature (left) and speed (right) for different pressure levels. The Desroziers average was calculated using a time interval of 2 months.

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For further analysis, we extracted the mean value and standard deviation for the distributions of the errors, for which some examples were shown in Fig. 7~~,~~. ~~were fitted with an arbitrary Gaussian distribution to extract the mean vale and the standard deviation.~~ The complete set of results for all the pressure levels, considering the wind related variables, are shown in Fig. 8. The blue and red lines refer respectively to the errors obtained assuming 1-~~-~~month and ~~1 year~~1-year time averaging. Observation at 00GMT and at 12GMT are plotted with solid and dashed lines respectively. We note that this is a similar representation of the rms error reported in the diagonals of the matrices of Fig~~ure~~. 1, with the difference in the units of the elevation. We find similar values for the estimated error, or more precisely for the mean value of the error assuming a Gaussian distribution, and find a similar vertical distribution with increased error values for higher elevations. The errors show little dependency on the observation hours, with noticeable differences only at low elevations. Finally, the choice of the two extreme values for the time averaging in the Desroziers departure does not affect the mean value of the errors, but it is evident that the choice of the longer time interval reduces the standard deviation of the distribution.

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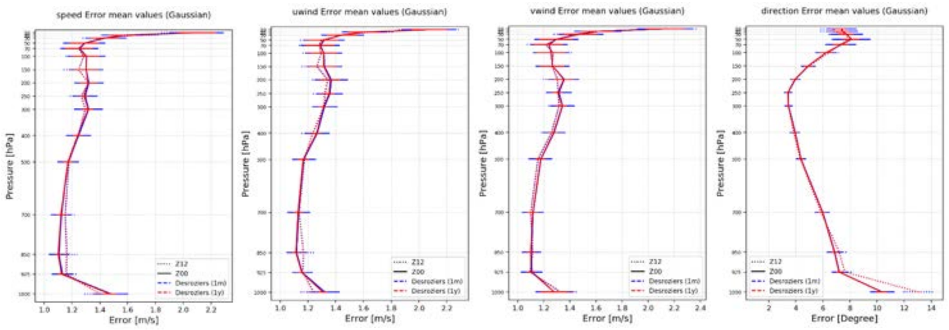

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Figure 8 Error mean values and standard deviation, ~~calculated assuming a Gaussian distribution,~~ for the wind speed, u- and v-component, and direction. The blue and red lines show the values obtained assuming a time interval of 1 month and 1 year respectively when applying the Desroziers method. Dotted lines show the results for 00GMT observations, and solid lines refer to 12GMT observations.

~~5. Code Usage and Reproducibility~~

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~~The code used to produce the results heredocumented in the present deliverable presented is available on GitHub at~~

~~https://github.com/MBlaschek/CEUAS/tree/develop/CEUAS/wind_uncertainty .~~

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~~In the following description we will refer to scripts that are currently being developed for the complete analysis of the XXXX datasets and will be made available in the future according to the xxx deliverable. However, the analysis presented here is self-consistent and does not depend on any of~~

~~such external script, unless the user wishes to extend the capability of the scripts presented here to handle a different input dataset or to add further functionalities.~~

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~~To allow for easy reproducibility, the user will find the netCDF files ready in the GitHub repository, while in general, for other observation stations, the user will have to run separately the odb converter and extract himself/herself the necessary netCDF files.~~

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~~The treatment of the variables connected to the wind measurements follows two separate procedures. For the u and v wind components, the procedure is straightforward and the code implementation basically follows what has been presented already in the initial assessment of the uncertainties of the temperature and humidity. In fact, in the ERA5_1 database files the information of the first guess (fg) and analysis (an) departures are already available, and the Desroziers method can be applied straightforwardly.~~

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~~However, the primary observables of the wind are the values of the direction and of the speed, it is of interesting to come back to these primary observables. This can be done using the u and v components and their analysis and first guess departures values, from which one can extract the values of the observed speed and direction as well as first guess and analysis departures. These values will be used to estimate the observation errors with the Desrozier method, in the same fashion as for the other variables (u,v wind component, temperature).~~

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~~The main step of the uncertainty assessment requires the evaluation of these data from the netCDF files for the u and v components, by running the script~~

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~~extract_speed_direction_netCDF.py~~

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~~the files "ERA5_1_10393_speed.nc" and "ERA5_1_10393_direction.nc" are produced in the "data" directory, containing the observed values of the wind speed and direction and the departures as~~

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~~explained above. Note that, to avoid redundancy, since the data is extracted from the netCDF files and not from the original odb files, in addition only the datum information is stored in these files, since the rest can be easily retrieved in the u and v components netCDF files.~~

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~~Then, the script~~

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~~extract_covariance.py [-f True]~~

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~~is called. This produces a dictionary containing the covariance matrices for the wind u and v components, and speed and directions. The data is stored in a python dictionary, saved in a numpy filed called "covariance_matrices.npy".~~

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~~The script first looks for the numpy file, defined in the variable cov_file and specified by the user; if the script finds the file, it will terminates. Otherwise, if the file is not found, the script will proceede to the creation of the file. The creation of the file can be forced by passing the optional argument [-f True] when calling the script. Note that the numpy file contains all the covariance matrices for all the possible combination of pressure levels, making it quite sizable (around few hundreds of MB for the Lindenberg station), possibly requiring a few minutes for the creation of the file. If created, the new file will be stored in the current working directory.~~

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~~Once the numpy file is available, calling the script~~

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~~analyse_covariance.py~~

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~~will perform the analysis and produce the results, including the ones presented in this document, inside the "results" directory.~~

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~~6.~~5. Conclusions

We presented the first estimate of observation errors of the wind related variables (u- and v-components, speed and directions) using the departure statistics methods developed by Desroziers et al. ????. This method makes use of the ERA5 reanalysis and forecast departures information to estimate observation errors, that include the representation uncertainties related to the employed model. Since this errors estimation is based on reanalysis departure, it includes the related representation error. By making use of more accurate and up-to-date reanalysis, the estimated error will decrease. It will also possible to use alternative reanalyses which go further back in time, such as the JRA-55, and extracts observation errors which are otherwise not available.

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This work extends the previous study of the estimations of the error for air temperature and humidity. We found that the typical order of magnitude of the error standard deviation of the wind speed, as well as the projection onto its orthogonal components, is of order of 1.1-1.5 m~~/~~s^{-1}, depending on the pressure level considered, while the uncertainty related to the directions is of order 4-8 degree.

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Finally, we made all the scripts and input data available on GitHub available at https://github.com/MBlaschek/CEUAS/tree/develop/CEUAS/wind_uncertainty. The format of the input files needed, that are available as an example for the Lindenberg station, follows the standard netCDF convention. The README file contains the instructions to allow the user to reproduce the statistical analysis and the results here presented.

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~~7.~~6. References

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~~8.~~7. Introduction