

Electronic Supplement S2 On the Problem of Homogeneity in Observations and Reanalysis Data

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The analysis of systematic changes derived from environmental and atmospheric data over long time periods is an important scientific task. For an estimation of sudden changes or long-term trends, data homogeneity is a prerequisite as otherwise non-climatic information can lead to wrong interpretations or results. As the number and type of instruments, observational procedures and the surrounding environment change over time, any kinds of necessary corrections or adjustments to different data is usually the rule rather than the exception, especially on longer timescales (Peterson et al. 1998).

Although the issue of data quality and homogenization is not new for the scientific community, public dispute in the post-“climate gate” period has shown that an open discussion and better communication of necessary adjustments and potential impacts on the data is needed. While typical examples with sudden break changes in mean or variance like wind observations (e.g. Lindenberg et al. 2012) can be easily detected, it is very difficult to identify gradual influences of non-climatic effects on observations as in case of “atmospheric stilling” (see below, Vautard et al. 2010). The same is true for urban heat islands (UHI), with the additional difficulty that the UHI effect appeared to be overestimated (Peterson 2003). More recent analysis of the UHI effect on land temperature datasets, which was part of the Berkeley Earth project (www.berkeleyearth.org), shows that this effect is negligible or even slightly negative on larger spatial scales (Wickham et al. 2013). However, for gridded data sets like HadSLP (Allan and Ansell 2006), HadSST (Rayner et al. 2003, 2006) or different reanalysis products (see below), inhomogeneities can be also caused by assimilating different information over time.

The next paragraphs are intended to give a brief and non-conclusive overview of recent studies discussing identified or potential drawbacks for different data sets and variables related to observations including reanalysis products. A main focus is on the analysis of wind data as it provides a very important variable where even small inconsistencies can have important consequences e.g. for coastal planning and protection or the safety and efficiency of on- and offshore infrastructures like wind farms etc.

S2.1 Non-Climatic Signals in Wind Observations

Stations are often installed and observations used to determine the current state of the atmosphere rather than aiming at observing long-term changes. This implies that an improvement of observations has usually higher priority than homogeneity. Typical examples are in-situ wind measurements where station relocations and changes of instruments introduce large inhomogeneities in wind time series (e.g. WASA Group 1998). Even wind observations at coastal and island stations are clearly affected by relocations and changes of the sampling frequency as shown in figure S2.1 for the German Bight in the period 1952-2002 (Lindenberg et al. 2012).

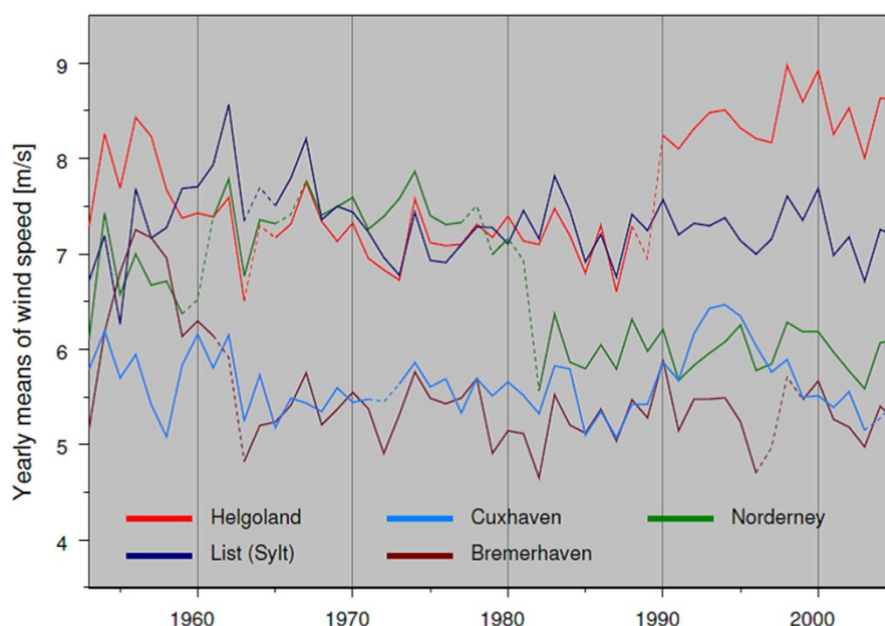


Fig. S2.1 Annual means of wind speed measurements from five synoptic near coastal stations of the German Bight. Shaded lines label years with known station relocations (Lindenberg et al. 2012)

As a consequence, long-term statistics of wind should be derived from wind and storminess proxies based on more homogeneous pressure observations as suggested by WASA Group (1998) (see Sect. 2.3.3) or from reanalysis data (e.g. Weisse et al. 2005). However, Smits et al. (2005) point to inconsistencies also in NCEP/NCAR reanalysis wind speeds (Sect. S2.2) over the Netherlands in the period 1962–2002 with homogenized wind observations showing a negative trend with in contrast positive trends in the NCEP/NCAR reanalysis data and no trend in geostrophic wind speeds calculated from pressure observations. The decrease in homogenized wind speed observations found by Smits et al. (2005) is corroborated by a recent study showing decreasing wind speeds over almost all regions of the northern hemisphere according to in-situ wind observations in the period 1979–2008 (Vautard et al. 2010). As the decrease of surface wind is not accompanied by a similar decreasing trend of upper level wind measurements at 850 hPa or above (figure S2.2), the authors conclude that the observed “atmospheric stalling” of surface winds is caused by meso- to large-scale changes of surface roughness due to land use changes.

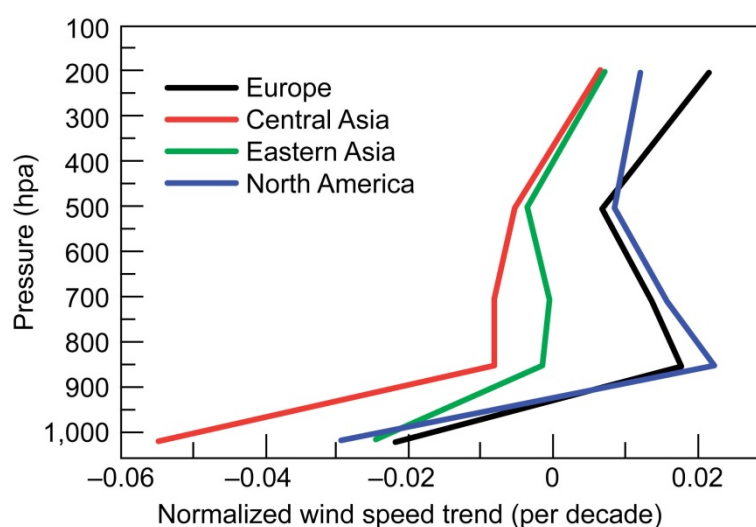


Fig. S2.2 Mean vertical profile of wind speed trends obtained from monthly averaged radiosonde data (850 hPa and above) and closest surface site, averaged over all sites in each region and normalized by mean wind speed at each site (Vautard et al. 2010)

Although the reasons for this large-scale “atmospheric stilling” need to be further evaluated, several modelling studies in the recent decade indicate a local slow-down of wind speeds caused by wind farms with significant local to regional influence on hydro-meteorological variables (e.g. Baidya Roy 2011). Observational evidence for a significant influence of huge wind farms on land surface temperatures is found for Texas, USA, caused by disturbance of the stability of the atmospheric boundary layer in agreement with different modelling studies (Zhou et al. 2012).

The example of “atmospheric stilling” adds to the discussions about potential urban heat island effects of rather slow changes in the environment possibly affecting local measurements even from land use changes on larger spatial scales (Vautard et al. 2010). In contrast to the homogeneity of individual stations, these rather slowly changing non-climatic influences are difficult to detect if the spatial scale of non-climatic influences also affects neighbouring observations as for wind speed observations in case of “atmospheric stilling”. In this case, homogeneous wind observations correctly reflect the local to regional wind conditions but not necessarily variations of the large-scale atmospheric variations. The same is true when observation practices are changed, which usually takes place for all stations of a country at the same time.

With respect to the inconsistencies of wind speeds in the Netherlands (Smits et al. 2005) – decrease in observations, no trends in pressure-based proxies and upward trends in the NCEP/NCAR reanalysis –, pressure-based information such as geostrophic wind speeds might be most reliable in terms of the influence of non-climatic signals. For analysing long-term wind statistics related to atmospheric variability only, Krueger and Von Storch (2011) have demonstrated the high information content of geostrophic wind speeds calculated from pressure observations for open terrain confirming earlier studies based on these quantities (WASA Group 1998; Alexandersson et al. 2000; Wang et al. 2009a, 2011). However, Wang et al. (2014) noticed that also some used historical pressure records contain significant errors (see S2.3).

S2.2 Homogeneity of Gridded Data and Reanalysis Products

Global gridded atmospheric reanalysis products such as NCEP/NCAR (since 1948; Kalnay et al. 1996; Kistler et al. 2001), ECMWF ERA40 (since 1957; Uppala et al. 2005) or shorter products with higher resolution like ERA-Interim (since 1979; Dee et al. 2011) are commonly used for diagnostic studies like assessing climate variability and long-term trends or to force and validate climate models. The underlying idea is to run a forecast model for a short time (e.g. 6 hours) and to (slightly) modify the resulting fields with observations. Different schemes are used to assimilate different kinds of observational data with varying spatial and temporal coverage into state-of-the-art climate models to generate physically consistent atmospheric fields for the state of the atmosphere (Glickman and Zenk 2000). Although “frozen” data assimilation schemes are used to minimize inhomogeneities caused by varying types, numbers, locations and quality of observations, several issues affecting the analysis of long-term variations and trends need to be considered.

The assimilated data may change over time, often consistently over large areas like countries when the type of observations changes (e.g. by replacing manual by electronic measurements) or when a new observing system is introduced (e.g. satellites in late 1978). Several studies have analysed potential inhomogeneities related to these changes. An evaluation of the NCEP/NCAR reanalysis by Kistler et al. (2001) shows that the predictive skill of the model is not constant over time and clearly increases in the first 10 years due to an increased number of stations and improvements of the quality of observations. The degree of realism also varies regionally with considerably lower skills for data sparse regions like the southern hemisphere (e.g. Bromwich et al. 2007). These changes partly also affect long-term trends. Prominent examples of detected spurious trends in reanalysis data are the mass of the atmosphere (Trenberth and Smith 2005), southern hemispheric SLP (Hines et al. 2000), tropospheric humidity in NCEP (Paltridge et al. 2009; Dessler and Davis 2010) or a clear jump in total kinetic energy with the introduction of satellites in ERA40 leading to a significant spurious upward trend (Bengtsson et al. 2004).

Many of these inhomogeneities and spurious trends can be traced back to data-sparse regions. In areas with sufficient observations of good quality, usually good agreement between observations and reanalyses is found, e.g. for extreme temperatures over Europe (Cornes and Jones 2013). Also for the global mean, several studies have found reasonable agreement (Compo et al. 2013; Donat et al. 2014).

Apart from inhomogeneities within reanalysis products, differences also exist between different reanalyses and observations. Comparing the intensification of the winter storm track intensity over the NH in the period 1948-1998 derived from radiosonde observations and NCEP-NCAR, Chang and Fu (2002) find that NCEP might have a systematic bias of lower variance in storm tracks prior to the early 1970s. In more detail, radiosonde data suggests an earlier but weaker intensification from the 1960s to the 1990s compared to NCEP (Harnik and Chang 2003) which coincides with a jump in the skill of the initial conditions in NCEP after the first decade and a change of how the radiosonde data is assimilated into NCEP in 1973 (Kistler et al. 2001). This is in contrast to Wang et al. (2006) who do not find an abrupt change in cyclone activity in the boreal extra-tropics based on a climatology calculated from NCEP and ERA40 in the period 1958-2001. Instead ERA40 shows a systematically stronger cyclone activity over the boreal oceans which is in agreement with results from Chang (2000) for the SH finding a more than 20% higher amplitude in storm tracks in ERA40 compared to NCEP. As less data and almost no radiosondes are assimilated over the sea, it can be concluded that uncertainties for storm track intensities are larger over data-sparse regions like the oceans (Harnik and Chang 2003).

Besides differences in data assimilation, dynamics and physical parameterizations of the reanalysis models (e.g. Ulbrich et al. 2009), notable differences between reanalyses are often related to the different resolution. While NCEP has only a horizontal T62 resolution ($\sim 1.9^\circ$ triangular resolution for longitude and latitude), ERA40 has a considerable higher resolution with T106 ($\sim 1.1^\circ$). As a consequence, ERA40 better resolves frontal waves than NCEP which explains a higher number of strong and long-lived cyclones, a higher cyclone intensity and deeper core pressure over the North Atlantic and Europe in the former (Hodges et al. 2003; Trigo 2006; Wang et al. 2006; Löptien et al. 2008; Raible et al. 2008). The largest differences between these reanalyses are found in summer (Löptien et al. 2008) when extratropical cyclones usually are smaller than in winter.

The temporal correlation of the variations of cyclone numbers and their intensity is generally large between reanalyses with a better agreement for the intensities (Raible et al. 2008). These authors also note that the trend analysis of different cyclone characteristics is sensitive to cyclone detection and tracking methods which differ between reanalyses. As different approaches can lead to quite different results (Xia et al. 2012), community efforts have recently been undertaken to compare cyclone detection and tracking algorithms (Neu et al. 2013)

S2.3 Reanalyses Covering the Period Before 1948

With the digitization of a large number of 19th and early 20th century observations, long time series of surface observations have become available (see e.g. Compo et al. 2011). As a consequence, several new reanalysis products have been created which extend the available period back to the beginning of the 20th or even the second half of the 19th century, thus making it possible to investigate events like the 1872 Baltic Sea storm surge (Feuchter et al. 2013), the hot European summer of 1947 (Grütter et al. 2013), the dramatic temperature changes in the Arctic in the 1920s (Brönnimann et al. 2013) or the timing of cold winters with respect to sunspot numbers (Sirocko et al. 2012). Further, there are ongoing efforts to assess the potential of an ensemble of reanalyses (UERRA; www.uerra.eu) and to create a coupled atmosphere-ocean data assimilation system to produce consistent climate reanalyses of the coupled Earth system (ERA-CLIM2; www.ecmwf.int/en/research/projects/era-clim2). All these long-term reanalyses have in common that they can only to a very limited amount draw on upper-air observations, in contrast to the reanalyses from ECMWF or NCEP. Further, over such long periods, it cannot be ruled out that the analyses contain inhomogeneities over time due to changes in observing methods, instrumentation or data density, which need to be addressed.

One of these newly available datasets is 20CR, the 20th century reanalysis (Compo et al. 2011). This dataset uses daily pressure observations and monthly-mean SSTs and sea-ice data only and provides three-dimensional gridded information on the global atmosphere back to 1871. 20CR is based on a modified version of the NCEP/NCAR model, but there are differences in the data assimilation schemes and the assimilated data itself. For data-rich regions like the Northern Hemisphere, 20CR agrees well with the NCEP reanalysis for the common period 1948-2008, even though much less data is assimilated in the former (Compo et al. 2011; Donat et al. 2011). Thus 20CR provides a potentially powerful tool for studying past climate events and extremes (see e.g. Brönnimann and Martius 2013 and the numerous references therein), but a number of criticisms have also been brought up (Ferguson and Villarini 2012; Krueger et al. 2013; Dangendorf et al. 2014; Schenk 2015).

In particular, there is considerable discussion about the consistency of low-frequency variability of storminess in 20CR and other observation-based datasets, and there is currently no consensus to which extent long-term analyses agree with observations of northeast Atlantic storminess (Krueger et al. 2013; Wang et al. 2014). As no reliable wind data exists over this long period, most studies make use of homogeneous pressure observations to derive proxies for storminess or calculate geostrophic wind speeds (Sect. 2.3.2). Based on 20CR, Donat et al. (2011) find positive long-term trends in storminess since 1871 over the NE Atlantic and the North Sea. Krueger et al. (2013, see figure S2.3) show inconsistencies between 20CR and pressure observations (figure S2.3a), which do not show robust long-term trends over the North Atlantic or North Sea (Sect. 2.3.3). A clear improvement in annual and decadal-scale correlations of analog-based storminess reconstructions or geostrophic wind indices by Krueger et al. (2013) with 20CR storminess time series after detrending confirms that the main discrepancy lays in the long-term trend (Schenk 2015).

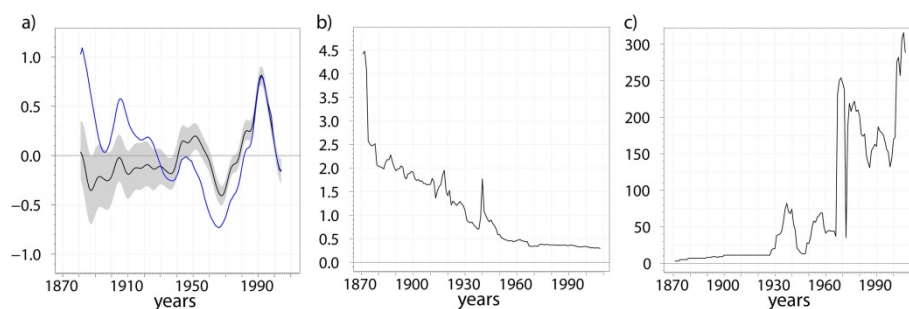


Fig. S2.3a Standardized and lowpass filtered annual 95th percentiles of geostrophic wind speeds over the North Atlantic 1881-2004 derived from observations (blue, updated after Alexandersson et al. 2000) and 20CR (black, ensemble mean) with grey shading for the 20CR ensemble spread (minimum and maximum). **Fig. S2.3b** Yearly mean values of area-averaged 20CR ensemble standard deviation of surface pressure [hPa] over the North Atlantic. **Fig. S2.3c** Number of assimilated station in 20CR over the North Atlantic according to metadata by Compo et al. (2011). Figures from Krueger et al. (2013) ©American Meteorological Society. Used with permission

Applying the same method to station pressure and pressure from 20CR at the closest grid points to these stations, long-term variations of high annual percentiles of geostrophic wind speeds of 20CR seem to deviate from those calculated from observations prior to World War II with 20CR. For the historical period, 20CR shows more than one standard deviation lower storminess for the filtered values around 1888 compared to pressure based observations (figure S2.3a). As the pressure information from observations is also assimilated into 20CR, an explanation could be the changing number of assimilated data (figure S2.3c) which would lead to a larger ensemble spread and a steadily increasing standard deviation for the ensemble pressure going back in time in 20CR (figure S2.3b). Because spurious trends in reanalysis products due to changes in the assimilated data have been reported elsewhere (see S2.2), 20CR should be used with care for long-term trend analyses. We note that the assimilation scheme has the property to remove “unphysical” observations (see also below), the trend of which is not clear. To account for the observational uncertainty in the early 20CR, an ensemble Kalman filter is used. It is, however, not clear in how far this filtering affects the trends.

On the other hand, also observations may be erroneous as they may be affected by changes in observational techniques, relocations, reading and digitization errors etc. Wang et al. (2014) have analysed the WASA pressure observations (Schmith et al. 1998) by first identifying pressure jumps of more than 20 hPa from one observation to the next and then, in order to identify consecutive segments of erroneous values, visual inspection of the time series in question and of neighbouring stations. Figure S2.4 shows the longest such series of very large errors in the pressure data, which is found for Aberdeen for 10 consecutive days.

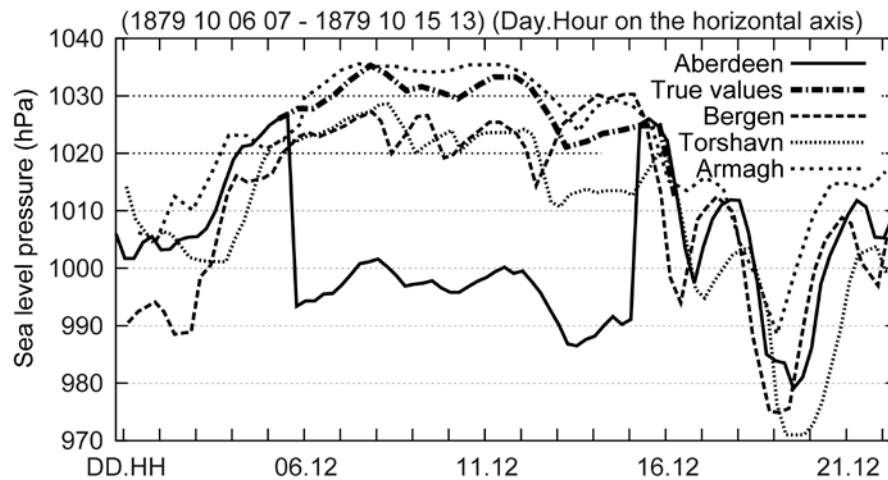


Fig. S2.4 Segments of erroneous SLP values (*full line*) in the Aberdeen data record compared to the corresponding segments from nearby stations (*dashed and dotted lines*) for October 1879. The “True Value” (*original observed hand-written value; dash-dotted line*) has been extracted from the UK Daily Weather Report. Figure from Wang et al. (2014)

Further inspection (see Appendix in Wang et al. 2014) suggests that this error (and most of the other identified errors) has been introduced during the digitization of the original paper records. As the errors are usually on the order of tens of hPa, it is very probable that the original data values (in inches, 1 inch = 25.4 mm) were misread (29 instead of 30 in. or vice versa). Of course, this has a notable effect on the calculated geostrophic wind speeds. Most errors are found in the time series of Aberdeen (146; 98 of them in 1879) and Tórshavn, but errors have also been found for Valentia, De Bilt and Vestervig. Apparently, none of these errors had been corrected in the WASA Group (1998) dataset or subsequent publications. The 20CR quality control system, however, rejected 143 of the 146 erroneous values for Aberdeen.

However, correcting for inconsistent pressure values does not considerably reduce the discrepancy between observations and 20CR before around 1920 (Wang et al. 2014, see figure S2.5). Owing to problems in both, historical pressure data and long-term trends in reanalysis products over data-sparse regions, no consensus on the existence of long-term trends in storminess has been achieved so far. Pressure-independent storminess information like surge records for the North Sea since 1843 (Dangendorf et al. 2014) or wind observations from Denmark since 1860 (Clemmensen et al. 2014), analog-based storminess (Schenk 2015) and many others (Feser et al. 2015; Sect. 2.3.2) corroborate pressure-based indices which show comparably high storm levels in the 1870s to 1880s as at the end of the 20th century.

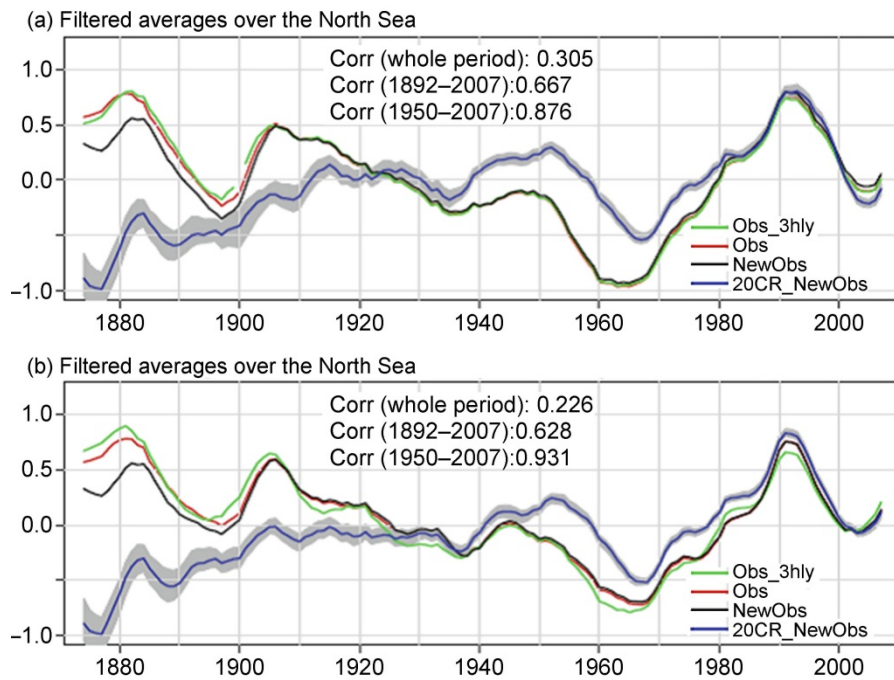


Fig. S2.5 Comparison of old (*green, red*) and new corrected (*black*) filtered averaged of geostrophic wind indices after removing the digitization error in Aberdeen (see text). (From Wang et al. 2014, figure 4)

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