LETTER • OPEN ACCESS

Uncertainty in recent near-surface wind speed trends: a global reanalysis intercomparison

View the article online for updates and enhancements.

Environmental Research Letters

LETTER

Uncertainty in recent near-surface wind speed trends: a global reanalysis intercomparison

Verónica Torralba[1,3] [iD], **Francisco J Doblas-Reyes[1,2]** and **Nube Gonzalez-Reviriego[1]**

1.   Earth Sciences Department Barcelona Supercomputing Center (BSC), C/Jordi Girona, 29, 08034 Barcelona, Spain
2.   ICREA, Pg. Lluís Companys, 23, 08010, Barcelona, Spain
3.   Author to whom any correspondence should be addressed.

E-mail: veronica.torralba@bsc.es

Abstract

Reanalysis products have become a tool for wind energy users requiring information about the wind speed long-term variability. These users are sensitive to many aspects of the observational references they employ to estimate the wind resource, such as the mean wind, its seasonality and long-term trends. However, the assessment of the ability of atmospheric reanalyses to reproduce wind speed trends has not been undertaken yet. The wind speed trends have been estimated using the ERA-Interim reanalysis (ERA-I), the second version of the Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) and the Japanese 55-year Reanalysis (JRA-55) for the period 1980–2015. These trends show a strong spatial and seasonal variability with an overall increase of the wind speed over the ocean and a tendency to a decline over land, although important disagreements between the different reanalyses have been found. In particular, the JRA-55 reanalysis produces more intense trends over land than ERA-I and MERRA-2. This can be linked to the negative bias affecting the JRA-55 near-surface wind speeds over land. In all the reanalyses high wind speeds tend to change faster than both low and average wind speeds. The agreement of the wind speed trends at 850 hPa with those found close to the surface suggests that the main driver of the wind speed trends are the changes in large-scale circulation.

1. Introduction

Wind energy has become the most important renewable energy source in the mitigation strategies aimed to reduce climate change impacts on both society and the environment (Solomon *et al* 2007). Nevertheless, this energy source is also susceptible to global change because strong winds from more intense wind storms could lead to safety problems, while a long-term reduction of wind speed can lead to important losses in the wind industry if it is not able to satisfy the electricity supply (Pryor and Barthelmie 2010, Vautard *et al* 2010, Sterl *et al* 2015). Therefore, understanding the uncertainty of climate variability estimates can be useful for an appropriate risk estimation of wind-energy resources and as guidance for the development of policies favouring sustainable adaptation initiatives that avoid poor investment decisions (Fant *et al* 2016).

Observational studies have identified increasing surface wind speeds over the ocean (Young *et al* 2011, Zieger *et al* 2014, Zheng *et al* 2016) and decreasing over land, particularly in northern mid-latitudes (Vautard *et al* 2010, McVicar *et al* 2012, Bichet *et al* 2012). Several drivers have been identified as the origin of these trends: changes in the surface roughness associated with modifications in the land use and vegetation cover (Vautard *et al* 2010, Bichet *et al* 2012, Wu *et al* 2016), aerosol emissions (Guo *et al* 2011, Bichet *et al* 2012) and changes in the large-scale circulation (McVicar *et al* 2012, Azorin-Molina *et al* 2014, 2017, Sušelj *et al* 2010, Dadaser-Celik and Cengiz 2014, Nchaba *et al* 2017). The importance of these factors depends strongly on the region and the dataset selected for the trend evaluation. The characterization of the mean value should be complemented with more detailed information about the trends in the

Table 1. Summary of the main characteristics of the three reanalysis datasets used in the present study.

Name	ERA-I	JRA-55	MERRA-2
Institution	ECMWF	JMA	NASA
Assimilation system	IFS Cy31r2	JMA's operational system (version Dec 2009)	GEOS-5
Assimilation scheme	4D-VAR	4D-VAR	4D-VAR
Horizontal resolution	$0.75° \times 0.75°$	$0.5625° \times 0.5625°$	$0.625° \times 0.5°$
Vertical levels	60 levels (0.1 hPa)	60 levels (0.1 hPa)	72 levels (0.1 hPa)
Time resolution	6 h	6 h	1 h
Period	1979 present	1958 present	1980 present

tails of the wind speed distributions (e.g. 10th and 90th percentiles) (Vose *et al* 2014, Young *et al* 2011).

The main limitation for the assessment of wind speed trends is the unavailability of long enough, homogenous time series of historical data from observational measurements. These data products can also be affected by discontinuities associated with changes in the measuring equipment, its location or in the observing practices (Kaiser-Weiss *et al* 2015, Kirchner-Bossi *et al* 2015), which impacts the data quality. To overcome these limitations global meteorological reanalysis data sets, which are available for long periods and are relatively homogenous, have been recently considered for different wind energy applications (Cannon *et al* 2015, Rose and Apt 2015, Staffell and Pfenninger 2016).

Reanalysis products are the result of the assimilation of observations from different sources into an atmospheric model that generates evenly distributed global data. Changes in the observational type or coverage can produce low-frequency variations and trends in the reanalyses that can be difficult to isolate from the actual climate variability (Simmons *et al* 2014), although special homogenisation techniques to avoid such effects have been developed in the last decades (Auer *et al* 2005). The observations used in the reanalyses are not the only source of uncertainty affecting these products, also there are some errors in the assimilation systems that can have an impact on the quality of the reanalyses (Reichler and Kim 2008). To address the uncertainty inherent in the estimation of long-term trends (Liléo *et al* 2013, Nchaba *et al* 2017, Pescio *et al* 2016) the use of more than one reanalysis has been recommended. A multi-reanalysis approach allows the quantification of the individual reanalysis uncertainty and the identification of robust signals that could be distinguished from artifacts in the observational data sources.

In spite of the potential impact of the long-term variability of wind resources on the wind energy sector, this type of variability has not been fully characterized yet because previous works are only focused on specific regions. As a consequence, for some users it is still difficult to identify the most suitable dataset for their specific needs (Gregow *et al* 2015). This is the case of the wind energy sector, where an intercomparison between different reanalyses at global

scale is not readily available. The characterisation of the limitations of these datasets will facilitate their usability in decision-making processes related with financial and planning decisions, such as the estimation of the long-term economic return of wind-energy farms (Ritter *et al* 2017). In this respect, this study performs a comprehensive evaluation of the long-term trends in wind speed at a global scale using a set of state-of-the-art atmospheric reanalyses. This intercomparison aims to characterize the discrepancies and commonalities in wind-speed trends between datasets.

The paper is organized in four sections. Section 2 describes the data and methods used. Section 3 contains the main results and a discussion about the seasonal variability of the wind speed trends and their causes (section 3.1), the characterization of the trends in the 10th and 90th wind speed percentiles (section 3.2) and the reanalyses intercomparison of the wind speed trends (section 3.3). Finally, a summary and conclusions are given in section 4.

2. Data description and methodology

Reanalysis datasets are useful to understand some aspects of the long-term climate variability, particularly in those regions where there are observational limitations. To take into account the constraints of the reanalyses and their potential effects on the long-term near-surface wind speed trends, we compare three different state-of-the-art reanalysis datasets that have been generated by different institutions: ERA-Interim (ERA-I), the Japanese 55-year Reanalysis (JRA-55) and the Modern Era Retrospective Analysis for Research and Applications-2 (MERRA-2). The main specifications of these datasets are summarised in table 1.

ERA-I (Dee *et al* 2011) uses the 4D-VAR approach in the European Centre for Medium-Range Weather Forecast (ECMWF) Integrated Forecast System (IFS) atmospheric model to assimilate observational data of many sources to produce an evenly distributed gridded observational dataset. The data are available as 6 hourly fields produced with a T255 spectral truncation on a reduced Gaussian grid that corresponds to ~$0.75° \times 0.75°$ (a horizontal resolution of 79 km) and 60 vertical levels from the surface up to 0.1 hPa.

JRA-55 (Kobayashi *et al* 2015) is produced by the Japan Meteorological Agency (JMA) operational data assimilation system, which is based on the operational system as of December 2009 with a 4D-VAR scheme. This reanalysis starts in 1958 and provides data with 6 hourly temporal resolution, a T319 spectral truncation (~55 km) and 60 hybrid vertical levels. We have used the spatial resolution of $1.25° \times 1.25°$ instead of the original $0.5625° \times 0.5625°$ resolution in this work because it is the only resolution for which data at 850 hPa level are available.

MERRA-2 (Molod *et al* 2015) is the most recent reanalysis produced by NASA's Global Modelling and Assimilation Office (GMAO). It uses the Goddard Earth Observing System-5 (GEOS-5) atmospheric general circulation model (AGCM) with a 4D-VAR data assimilation scheme. The data are hourly fields produced with a horizontal resolution of $0.625° \times 0.5°$ and 72 sigma vertical levels.

The main limitation of the reanalyses used in the manuscript is their resolution, which results in their inability to represent local processes that are relevant to specific power plants. However, they provide (and for this reason reanalyses are used by the renewable energy research and operations community) an estimate of the wind resource available at regional scales. Particularly, the use of 10 m winds as a proxy for the characteristics of the wind at higher levels is justified because, as it has been recently shown, reanalyses are able to reproduce the 10 m wind speed variability over spatiotemporal scales larger than 300 km and 6 h (Cannon *et al* 2015).

Trends of the wind speed at 10 m provided by reanalysis products can be affected by the different methodologies the reanalyses use to infer 10 m wind speed from the lowest model level (Decker *et al* 2012, Rose and Apt 2016). The ERA-Interim reanalysis uses a modified Monin–Obhukhov scheme to derive the 10 m wind speed with and an aerodynamic roughness length adjusted for orographic drag (ECMWF)[4]. Winds at 10 m in MERRA-2 are interpolated with the Helfand and Schubert scheme (Helfand and Schubert 1995) based on Monin-Obhukhov similarity theory that includes the effects of a viscous sublayer for heat and moisture transport over all surfaces except land (Molod *et al* 2015). In the JRA-55 reanalysis the wind speed at 10 m is estimated with a univariate two-dimensional optimal interpolation process under the assumption of neutral stability from the lowermost level, which is placed too high over regions with trees, reducing the wind speed values in the interpolation from there down to 10 m level (JRA, personal communication). Each reanalysis employs a different methodology for the computation of the 10 m wind speed, but the most important difference is that JRA-55 is considering neutral stability in the surface layer (JRA, personal communication) while the

ERA-Interim and MERRA-2 reanalyses derive the near-surface wind speed using stability-dependent approaches. These different methodologies could lead to differences in the wind speed trends, as it has been previously discussed (Decker *et al* 2012, Rose and Apt 2016, Troccoli *et al* 2012).

To investigate the amount of uncertainty affecting the wind speed trends that can be attributable to the methodologies used to derive 10 m wind speed, we have explored the wind speed trends at the native level of 850 hPa. The wind speed at this level has already been used to investigate the role of the large scale circulation of the wind speed trends (Chen *et al* 2013, Nchaba *et al* 2017, Troccoli *et al* 2012, Vautard *et al* 2010). The limitation for the analysis of wind speed trends at the 850 hPa level is that it is close to the surface, and there are some elevated regions like the Himalayas that are higher that this level. For that reason, a mask has been applied over the elevated regions in those maps corresponding to the trends at 850 hPa which is helpful for the correct interpretation of the trends at this level.

The wind speed used in this study has been computed as the module of the zonal and meridional components of wind speed at each specific level. This computation has been done with 6 hourly for ERA-I and JRA-55 and hourly data for MERRA-2 based on seasonal (3 months) average values throughout the year: December–January–February (DJF), March–April–May (MAM), June–July–August (JJA) and September–October–November (SON). We have evaluated the long-term wind speed trends at the 10 m and 850 hPa levels over the reanalyses common period 1980–2015. In addition, we have explored the trends of the 10th and 90th percentiles within a season. The former wind speed trend estimates the long-term seasonal evolution of wind speed whereas the latter provide information about the distribution tails. The 10th and 90th percentiles have been computed separately for each particular month and year and then averaged over the corresponding seasons.

The linear trend of these variables has been estimated, at each grid point, from a linear regression whose dependent variable (Y) is the time series of wind speed field and the independent one (X) is time. This model can be expressed as

$$Y = B_0 + B_1 X. \tag{1}$$

The regression coefficient B1 (the slope) indicates the linear rate of change of the wind speed. Positive values correspond to increasing trends whereas negative values denote slowing wind speeds. This linear regression method has been used instead of a more complex technique such as the Theil–Sen Slope estimator (Theil 1950, Sen 1968) since it has been demonstrated that they produce very similar results (Pescio *et al* 2016).

Wind speed shows strong regional gradients, with much higher wind speeds occurring over the oceans than over land, and with large spatial variations over the continents. We have chosen to illustrate the

---

[4] https://www.ecmwf.int/sites/default/files/elibrary/2007/9221-part-iv-physical-processes.pdf.
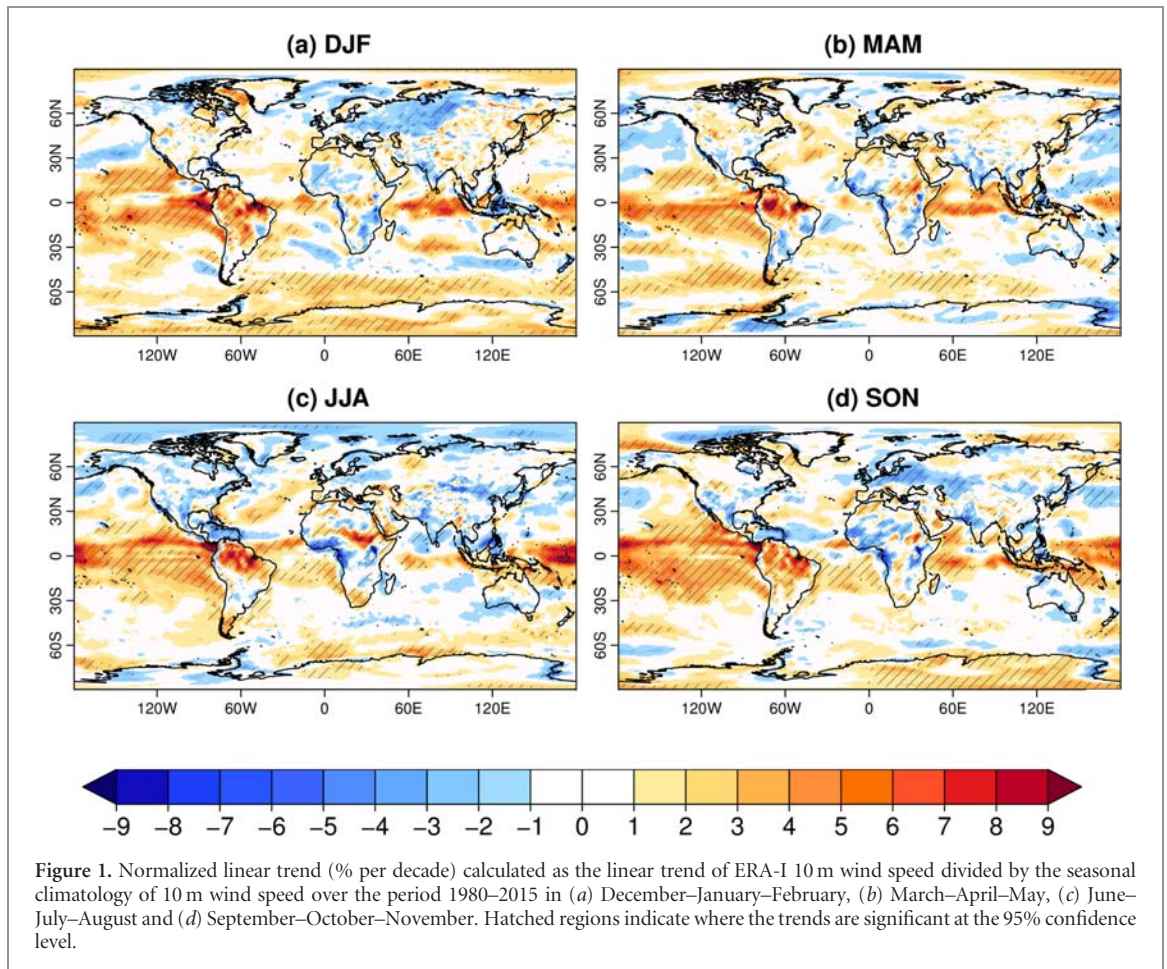
Figure 1. Normalized linear trend (% per decade) calculated as the linear trend of ERA-I 10 m wind speed divided by the seasonal climatology of 10 m wind speed over the period 1980–2015 in (*a*) December–January–February, (*b*) March–April–May, (*c*) June–July–August and (*d*) September–October–November. Hatched regions indicate where the trends are significant at the 95% confidence level.

long-term wind speed decrease or increase in relative terms to describe in a simple way the changes that take place in both areas with high and low wind speed. The linear trend has been normalized by the climatological mean wind speed and expressed as a percent of change per decade in every grid point. Although the values of the trends in % per decade could be affected by the biases of the mean wind speed, the results of the trends in m s^{-1} per decade (not shown) are consistent, indicating that the biases are not playing an important role. A *t*-test has been applied to assess if the trends are significantly different from zero at the 95% confidence level.

3. Results

3.1. Wind speed trends as a function of the season
The near-surface wind speed trends in the period 1980–2015 of the ERA-I reanalysis are illustrated in figure 1 for each season. The results estimated for JRA-55 and MERRA-2 (figures S1 and S2) lead to similar conclusions to those described for ERA-I, although the JRA-55 trends tend to be systematically larger, particularly over land. The spatial patterns of the ERA-Interim wind speed trends show a strong seasonal variability (figure 1). Globally, positive trends appear over the oceans, particularly in the tropical regions.

These positive trends are caused by the strengthening of the Walker circulation attributed largely to climate change (L'Heureux *et al* 2013, England *et al* 2014). However, in the North Pacific and subtropical North Atlantic a significant negative trend is observed, for the Atlantic in JJA and SON only (panels 1(*c*) and (*d*)). The global increase in wind speed over the oceans, which is much more noticeable in the tropical Pacific than in other basins, is in agreement with the results described by different authors (Young *et al* 2011, Zheng *et al* 2016) using satellite altimeter measurements and wind data from cross-calibrated multi-platform ocean surface wind velocity product for meteorological and oceanographic applications (Atlas *et al* 2011).

Over land a strong positive trend in Northern South America, and an overall negative trend, which is more visible over Europe, India and western Africa, are found (figure 1). Over western North America positive and significant trends are noticeable in boreal spring (panel 1(*b*)). The negative and significant wind speed trend over Europe is more accused in both DJF and SON (panels 1(*a*) and (*d*)). This negative trend has been already identified in different observational sources and even climate simulations and it has been attributed to several factors: changes in the surface roughness related to the recent increase in vegetation cover in such area, variability of aerosol emissions, or changes in the atmospheric circulation (Vautard *et al* 2010,
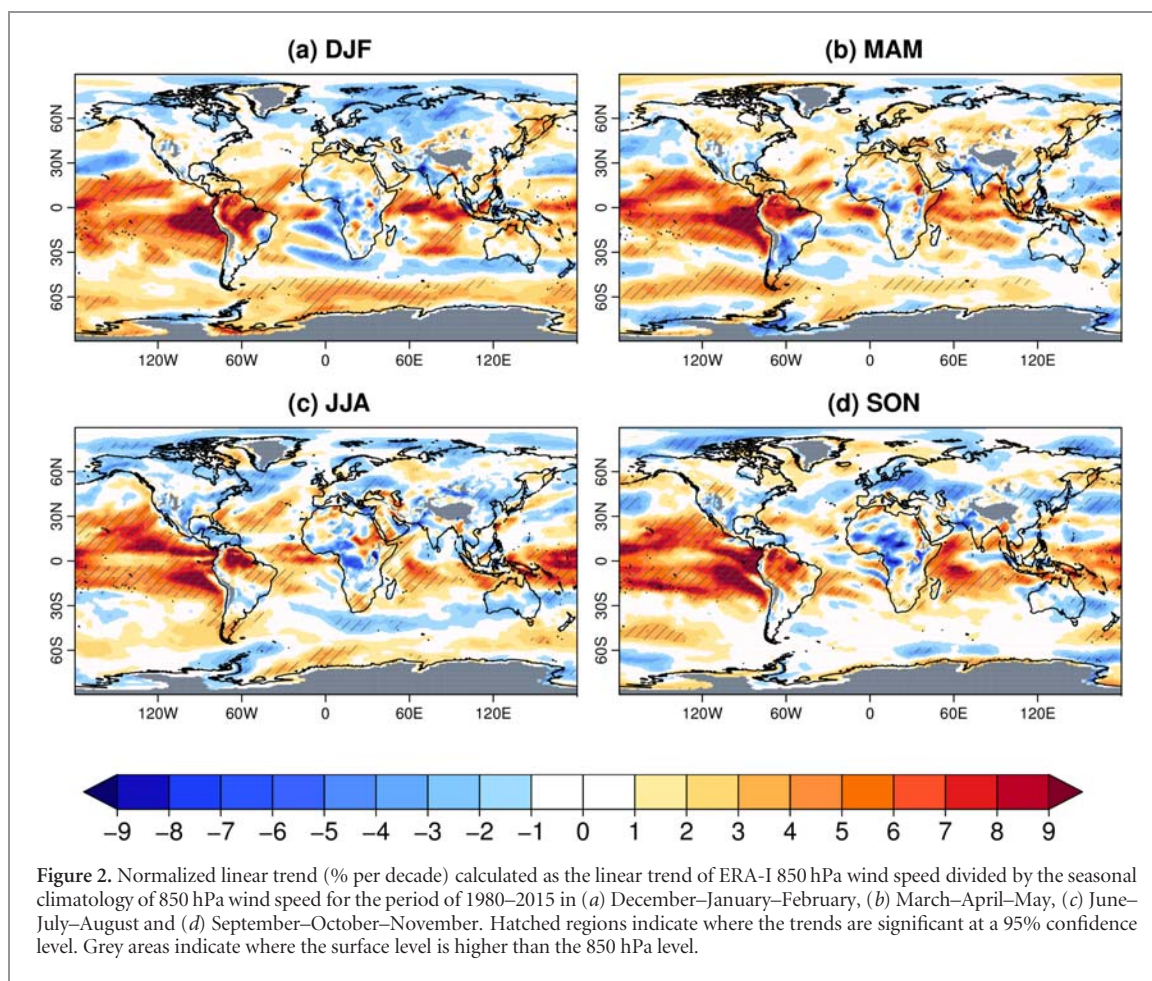
Figure 2. Normalized linear trend (% per decade) calculated as the linear trend of ERA-I 850 hPa wind speed divided by the seasonal climatology of 850 hPa wind speed for the period of 1980–2015 in (*a*) December–January–February, (*b*) March–April–May, (*c*) June–July–August and (*d*) September–October–November. Hatched regions indicate where the trends are significant at a 95% confidence level. Grey areas indicate where the surface level is higher than the 850 hPa level.

Bichet *et al* 2012, McVicar *et al* 2012, Sterl *et al* 2015). A non-uniform behaviour of the trends over Asia in most seasons and regions has been observed, although a declining wind speed appears in the Indian subcontinent all year round.
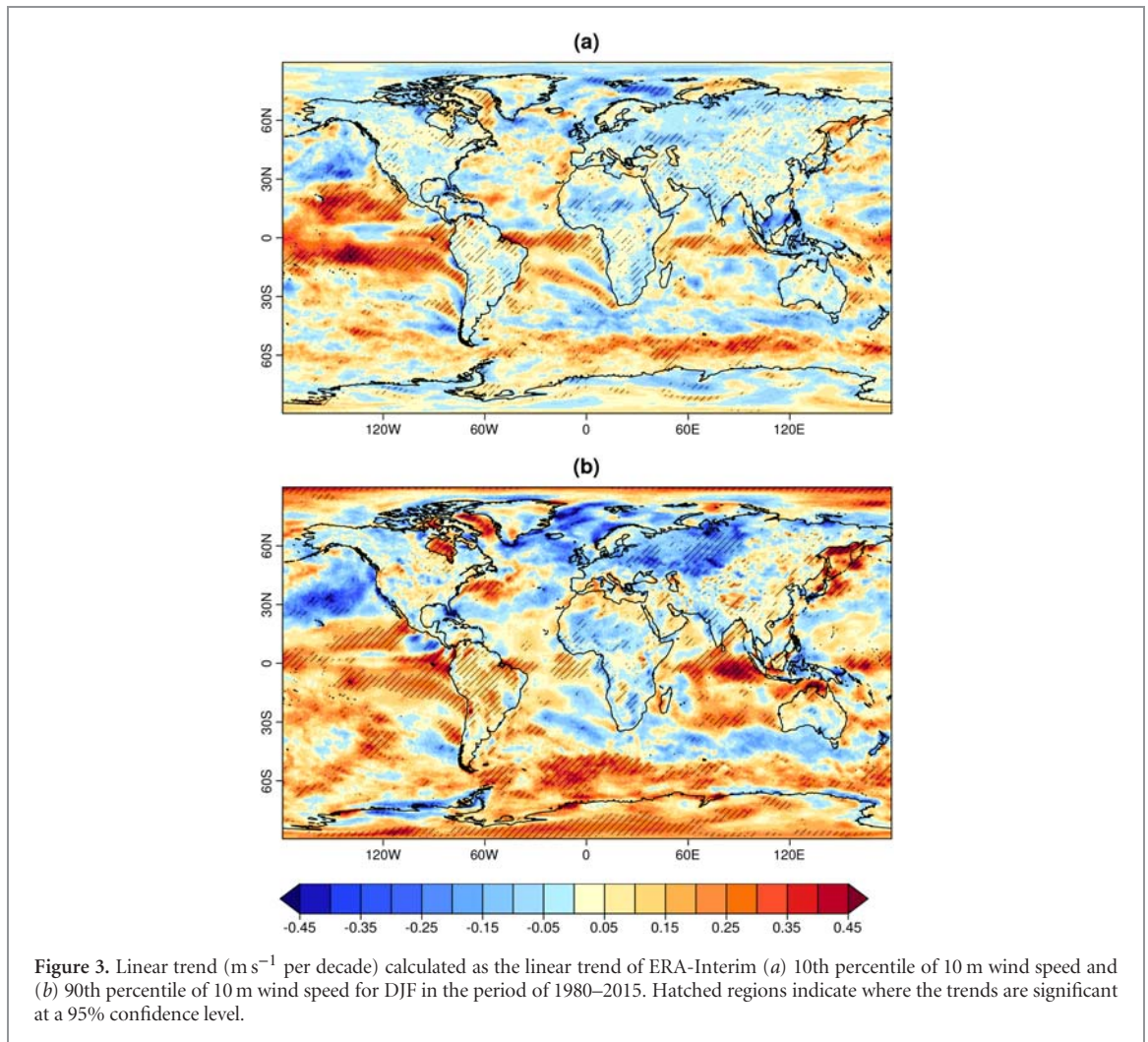
An increase of wind speed is found in several continental areas, such as the northern part of South America (panel (*b*)), which displays the highest positive wind speed trends inland for the four seasons. Over western North America positive and significant trends are noticeable in boreal spring (panel (*b*)), but change their sign in JJA (figure 1(*c*)). A non-uniform behaviour of the trends over Asia in most seasons and regions has been observed, although a declining wind speed appears in India all year round.

To identify if the trends displayed by the reanalyses can be due to changes in the atmospheric circulation or to other forcings like changes in the aerosols or the roughness length, we have also analysed the seasonal trends of the wind speed at 850 hPa for the ERA-I reanalysis (figure 2). The corresponding results for JRA-55 and MERRA-2 are included in the supplementary material (figures S3 and S4 available at stacks.iop.org/ERL/12/114019/mmedia). There is a strong similarity between the trends in both levels, although they tend to be stronger at 850 hPa, particularly over the ocean. The tropical Pacific and the Indian oceans display positive wind speed trends at 850 hPa

in all seasons, while the tropical Atlantic shows higher positive wind speed trends mainly in DJF (figure 2(*a*)) and MAM (figure 2(*b*)) relative to the 10 m trends in the same region and season (figures 1(*a*) and (*b*), respectively). Substantial differences in the trends between the 850 hPa and 10 m levels are only observed in two regions over land, namely Northern South America where positive trends are stronger at 850 hPa than at 10 m, and Central Africa where the positive trends at 10 m become negative at 850 hPa in most seasons. The agreement among the trends found at the two levels analysed illustrates the link between the trends in near-surface wind speed and the atmospheric circulation and allows attributing a large part of the near-surface trends to changes in the large-scale circulation.

3.2. Trends of the seasonal 10th and 90th percentiles

The characterization of the high-frequency wind speed seasonal distribution tails can provide extra information about the long-term changes in the frequency of unusual events and in the shape of the wind speed distribution. The trends of the 10th and 90th percentiles for ERA-I have been illustrated in figure 3 for DJF (other seasons are shown in figure S5). The analysis has also been done for the other two reanalyses considered in this study, JRA-55 and MERRA-2 (figures S6 and S7, respectively), leading to similar conclusions.
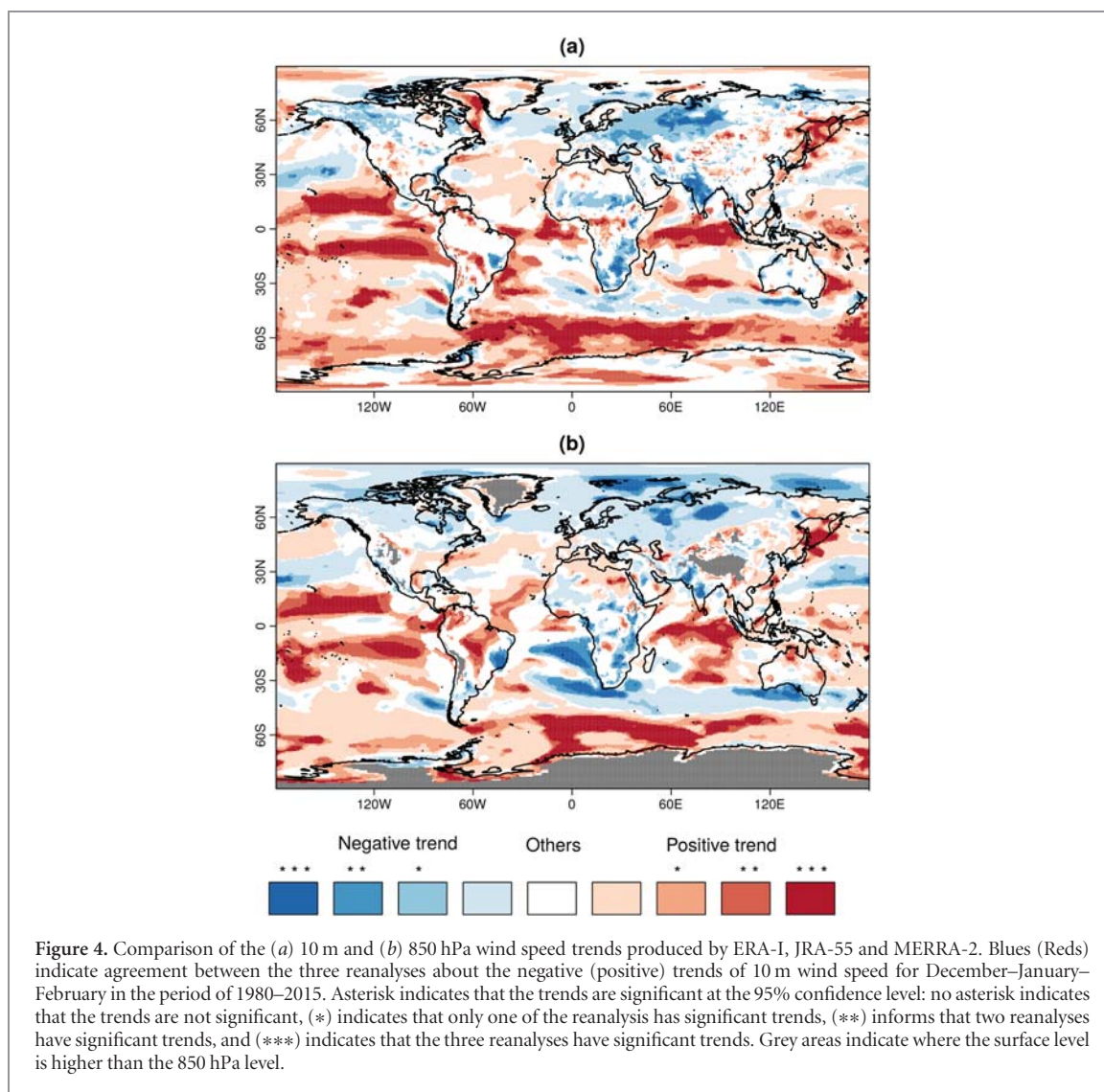
Figure 3. Linear trend (m s^{-1} per decade) calculated as the linear trend of ERA-Interim (*a*) 10th percentile of 10 m wind speed and (*b*) 90th percentile of 10 m wind speed for DJF in the period of 1980–2015. Hatched regions indicate where the trends are significant at a 95% confidence level.

Positive trends are observed for both 10th and 90th percentiles (figures 3(*a*) and (*b*)) over the oceans, which are stronger over the tropics than the extratropics. This is consistent with previous results (Young *et al* 2011, 2012) and with the trends for the mean wind (figure 1(*a*)). The tropical Pacific displays higher wind speed trends for the 10th percentile than for the 90th percentile, suggesting a change in the skewness of the whole distribution. The central North Pacific shows a decreasing trend of the 10th percentile that is less intense than for the 90th percentile.

Positive and significant trends over the Indian ocean are much more intense for the 90th percentile than for the 10th percentile, which evidences that high wind speeds increase faster than low wind speeds over that basin. Some differences are found in the spatial pattern of the trends for each index over the Atlantic basin, although both indices show positive and significant trends over the tropical Atlantic. By contrast, the structure is different between the two indices over the western North Atlantic, where trends for the 90th percentile are stronger than for the 10th percentile. These differences appear for other seasons too (figure S5) and suggest changes in the structure of the wind speed

distribution. A similar behaviour is found in the Western North Pacific, the Sea of Okhotsk and around Japan.

The most obvious differences between the trends obtained with the two percentiles over land appear in South America, central United States, Eastern Europe and Western Asia. In South America, the 90th percentiles shows positive trends, similar to those found in the mean wind speed for that region (figure 1(*a*)). However, the increasing trend of the 10th percentile is weaker than the widespread increasing trend of the 90th percentile. The trends of Central United States in DJF have different sign for both percentiles, but generally they are not statistically significant. The increase in the 90th percentile of wind speed in the reanalysis where real observations show decrease has been previously identified (Pryor and Barthelmie 2010) and attributed to the limitations of the reanalyses, which tend to underestimate the long-term variability of wind speed in that region. The decreasing wind speed previously discussed for the trends of the mean wind speed in Europe and northwest Asia are also found for both percentile indices. Particularly, the trends of the 90th percentile of the wind speed show a stronger decrease

Figure 4. Comparison of the (*a*) 10 m and (*b*) 850 hPa wind speed trends produced by ERA-I, JRA-55 and MERRA-2. Blues (Reds) indicate agreement between the three reanalyses about the negative (positive) trends of 10 m wind speed for December–January–February in the period of 1980–2015. Asterisk indicates that the trends are significant at the 95% confidence level: no asterisk indicates that the trends are not significant, (∗) indicates that only one of the reanalysis has significant trends, (∗∗) informs that two reanalyses have significant trends, and (∗∗∗) indicates that the three reanalyses have significant trends. Grey areas indicate where the surface level is higher than the 850 hPa level.

than the 10th percentile. The resulting change in the climatological distribution is particularly relevant for the strong wind-energy industry in the region.

3.3. Reanalysis intercomparison

The discrepancies and similarities of the wind speed trends from each reanalysis in DJF (other seasons) are summarized in figure 4 (figure S8). Coloured regions correspond to those locations where the reanalyses agree in the increasing or decreasing long-term behaviour of the wind speed over the last 36 years. Note that the magnitude of the ERA-I, JRA-55 and MERRA-2 trends has been displayed in figure 1, figure S1 and S2 respectively.

A positive and significant increase of the 10 m wind speeds in boreal winter is reproduced by the three reanalyses over the tropical oceans (figure 4(*a*)). These positive wind speed trends displayed by the reanalyses could be linked to the changes in the global circulation, in particular the recent strengthening of the Walker circulation (L'Heureux *et al* 2013, England *et al* 2014).

Over land the reanalyses show a robust negative trend over Eurasia, India, the Sahel and Southern Africa. Wind increases are not robust and show patchy patterns. The decreasing wind speeds in South Africa have already been noticed in reanalysis products and been attributed to the changes in the large-scale circulation (Nchaba *et al* 2017). Although the trends in the Northern Hemisphere continents have been described in section 3.1 for the ERA-I reanalysis, the agreement between the three reanalysis indicates that some of the mechanisms proposed previously as potential drivers of the wind speed trends, such as changes in land use or aerosol concentrations, can not be the only explanation of the negative trends because they are dealt with in different ways by each reanalysis. An alternative explanation of the decreasing trends might lie in changes in the large-scale circulation. If the large-scale circulation played a role, similar trends would be observed in the free troposphere. This is illustrated in figure 4(*b*), where the agreement of the 850 hPa wind speed trends among the different reanalyses is displayed. Over land, there are many regions (e.g. Europe, South Africa,

India) where the three reanalyses provide similar results at both levels. The main differences between the trends in the two levels (figures 4(*a*) and (*b*)) are for the negative trend in the South Atlantic at 850 hPa.

The discrepancies among the reanalyses products are particularly strong between JRA-55 on one side and ERA-I and MERRA-2 on the other. The large trend generally found for the JRA-55 reanalysis over land (figure S2) has been suggested to be attributable to deficiencies in deriving wind speed for that particular reanalysis (Japanese Meteorological Agency, personal communication). In the JRA-55 data assimilation system the regions where the vegetation type is categorized as trees shows a negative near-surface wind speed bias. This bias appears due to the lowermost atmospheric level, where land surface processes occur, being placed too high over regions with trees, reducing considerably the wind speed in the interpolation from there down to the altitude of 10 m. This negative wind speed bias is corrected with the assimilation of observed wind speed. Nevertheless, changes in the availability of observations can have an impact on the data used for the correction, resulting in large differences in wind speed trends. This important information is typically not reported in the reanalysis documentation available to wind energy users, who might misuse the reanalysis data to characterize long-term variability of wind speed. The trends of wind speed at 850 hPa for JRA-55 and MERRA-2 (figures S4 and S5) show that the JRA-55 trends at 850 hPa are similar in magnitude to those of both ERA-I and MERRA-2, supporting the hypothesis that the overestimation of the JRA-55 trends is a feature due to the treatment of the winds near the surface.

Figure 4 also shows that there are several regions (e.g. Northern South America or Australia) where the three reanalyses do not agree in the sign of the trends in winter. Among the uncertainty sources that can produce such discrepancies we can consider the different ways in which low-level wind speeds are derived, the observational sources included, or the corrections for the instrumental drifts that can generate inconsistencies in the observations. The former source of uncertainty can affect the wind speeds at 10 m (figure 4(*a*)), but for the trends at 850 hPa level these differences in the trends reproduced by the reanalyses that can not be attributable to the techniques each reanalysis use for the interpolation of 10 m wind speeds because the 850 hPa are not derived, therefore the other two sources of uncertainty could be the responsible of the discrepancies among the trends at this level.

4. Conclusions

Observational studies of wind speed indicate the existence of trends. The causes of these trends are not fully understood, but their characterisation and the identification of their drivers can be helpful for the wind energy decision making, such as the financial and planning decisions of the wind farms. To address this need, this paper provides an intercomparison method to describe the uncertainty in long-term trends from different observational-based references. Given that atmospheric reanalyses are global in scope and cover long periods, wind speed trends in the last 36 years have been estimated using data from three of the most reputable reanalyses available: ERA-I, JRA-55 and MERRA-2.

High seasonal variability in the ERA-I wind speed trends at 10 m and 850 hPa has been observed globally. Europe is a particularly interesting example of this seasonal variability because it shows more accused declining of the wind speed in DJF and SON, which is when the wind resource tends to be stronger, than in other seasons. There are several factors that can potentially lead to the wind speed trends described in observational studies, the robust trends found in the reanalysis products should be partly attributed to changes in the large-scale circulation. We have also characterized the trends in the 10 m wind speed distribution tails, finding that the high wind speeds, which have been analysed with the 90th percentile of the six-hourly wind speed over the season, show more intense trends than those of both the 10th percentile and the mean wind speed. This intense trends of the 90th percentile are also observed for the high frequency maximum wind speeds in a season that is a high frequency index helpful for the wind energy user (figure S9). This result suggests that higher wind speeds are changing faster than lower values, an expected result for a skewed and bounded (wind speeds are positively defined) variable. However, some regions show stronger trends for the 10th than for the 90th percentile.

The intercomparison of the 10 m wind speed trends between the three reanalyses shows agreement in many regions. These trends may be caused by changes in the large-scale circulation, as suggested by the similar trends found at both 10 m and 850 hPa levels, since other possible factors such as the time changes in land use or aerosols are not considered or dealt with differently in these reanalysis. Despite many regions agreeing in the trends, important differences have also been found. For example over Northern South America the three reanalyses show differences in both the intensity and sign of the trends in all seasons. Among the differences, it is important to note that JRA-55 produces more intense near-surface wind speed trends over land than ERA-I and MERRA-2. This is due to the wind speeds from that reanalysis having a negative bias that is not fully corrected in the data-assimilation process. This is a limitation that has not been reported before in the literature, but that could have an important impact for the wind energy users as they evaluate the long-term wind speed variability using reanalysis data.

In this paper only wind speeds at two levels (10 m and 850 hPa) have been selected because they are the only two available levels relevant for the wind industry in the three datasets. Typical turbine heights

range from 25 to 100 m (Staffell and Green 2014), but MERRA-2 is the only reanalysis that provides wind speeds at these heights (50 m). We have performed the analysis of the trends at 50 m, and we have obtained very similar results to the 10 m wind speeds with only some differences over Northern South America and central Africa (figure S10). Taking into account these results, we can assume that the trends for 10 m wind speed showed in the manuscript should be similar to those trends at turbine heights.

The impact of the discrepancies of the wind speed trends in different reanalysis can lead to inconsistencies in the evaluation of long-term wind power estimations that use these sources of data. This paper offers an atlas for both researchers and users to assess their vulnerability to this source of uncertainty. For that reason, these results are also disseminated among those who need to estimate wind power and its uncertainty. They could allow wind energy users to develop alternative strategies for the estimation of the future wind energy resources variability, and to assess the potential of climate predictions to produce more accurate and reliable information than the estimations of the future wind speed variability based on retrospective approaches alone.

Acknowledgments

ORCID iDS

Verónica Torralba ⓘ https://orcid.org/0000-0002-8941-1548

References

Atlas R, Hoffman R N, Ardizzone J, Leidner S M, Jusem J C, Smith D K and Gombos D 2011 *Bull. Am. Meteorol. Soc.* **92** 157–74

Auer I *et al* 2005 *Int. J. Climatol.* **25** 139–66

Azorin-Molina C, Vicente-Serrano S M, Mcvicar T R, Jerez S, Sanchez-Lorenzo A, López-Moreno J I, Revuelto J, Trigo R M, Lopez-Bustins J A and Espírito-Santo F 2014 *J. Clim.* **27** 3692–712

Azorin-Molina C, Vicente-Serrano S M, Mcvicar T R, Revuelto J, Jerez S and López-Moreno J I 2017 *Int. J. Climatol.* **37** 480–92

Bichet A, Wild M, Folini D and Schär C 2012 *Geophys. Res. Lett.* **39** 11

Cannon D J, Brayshaw D J, Methven J, Coker P J and Lenaghan D 2015 *Renew. Energy* **75** 767–78

Chen L, Li D and Pryor S 2013 *Int. J. Climatol.* **33** 2579–90

Dadaser-Celik F and Cengiz E 2014 *Int. J. Climatol.* **34** 1913–27

Decker M, Brunke M A, Wang Z, Sakaguchi K, Zeng X and Bosilovich M G 2012 *J. Clim.* **25** 1916–44

Dee D P *et al* 2011 *Q. J. R. Meteorolog. Soc.* **137** 553–97

England M H, McGregor S, Spence P, Meehl G A, Timmermann A, Cai W, Gupta A S, McPhaden M J, Purich A and Santoso A 2014 *Nat. Clim. Change* **4** 222–7

Fant C, Gunturu B and Schlosser A 2016 *Appl. Energy* **161** 565–73

Gregow H, Poli P, Mäkelä H M, Jylhä K, Kaiser-Weiss A K, Obregon A, Tan D G H, Kekki S and Kaspar F 2015 *Adv. Sci. Res.* **12** 63–7

Guo H, Xu M and Hu Q 2011 *Int. J. Climatol.* **31** 349–58

Helfand H M and Schubert S D 1995 *J. Clim.* **8** 784–806

Kaiser-Weiss A K, Kaspar F, Heene V, Borsche M, Tan D G H, Poli P, Obregon A and Gregow H 2015 *Adv. Sci. Res.* **12** 187–98

Kirchner-Bossi N, García-Herrera R, Prieto L and Trigo R M 2015 *Int. J. Climatol.* **35** 2635–46

Kobayashi S *et al* 2015 *J. Meteorolog. Soc. Japan Ser. II* **93** 5–48

L'Heureux M L, Lee S and Lyon B 2013 *Nat. Clim. Change* **3** 571–6

Liléo S, Berge E, Undheim O, Klinkert R and Bredesen R E 2013 *Elforsk Report* **13** 18

McVicar T R *et al* 2012 *J. Hydrol.* **416** 182–205

Molod A, Takacs L, Suarez M and Bacmeister J 2015 *Geosci. Model Dev.* **8** 1339–56

Nchaba T, Mpholo M and Lennard C 2017 *Int. J. Climatol.* **37** 2850–62

Pescio A E, Martin P B and Dragani W C 2016 *Int. J. Climatol.* **36** 501–7

Pryor S C and Barthelmie R J 2010 *Renew. Sust. Energy Rev.* **14** 430–7

Reichler T and Kim J 2008 *J. Geophys. Res.-Atmos.* **113** D5

Ritter M *et al* 2017 *Appl. Energy* **185** 1087–99

Rose S and Apt J 2015 *Renew. Energy* **83** 963–9

Rose S and Apt J 2016 *Renew. Energy* **94** 157–65

Sen P K 1968 *J. Am. Stat. Assoc.* **63** 1379–89

Simmons A J, Poli P, Dee D P, Berrisford P, Hersbach H, Kobayashi S and Peubey C 2014 *Q. J. R. Meteorolog. Soc.* **140** 329–53

Solomon S, Qin D, Manning M, Marquis M, Averyt K, Tignor M, Miller H L and Zhenlin C 2007 *Climate Change 2007 The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC* vol 4 (Cambridge: Cambridge University Press) p 996

Staffell I and Green R 2014 *Renew. Energy* **66** 775–86

Staffell I and Pfenninger S 2016 *Energy* **114** 1224–39

Sterl A, Bakker A M R, Van Den Brink H W, Haarsma R, Stepek A, Wijnant I L and De Winter R C 2015 *Environ. Res. Lett.* **10** 35004

Sušelj K, Sood A and Heinemann D 2010 *Theor. Appl. Climatol.* **99** 403–19

Theil H 1950 *Series A Mathematical Sciences* (Proceedings of the Koninklijke Nederlandse Akademie Wetenschappen) pp 345–81

Troccoli A, Muller K, Coppin P, Davy R, Russell C and Hirsch A L 2012 *J. Clim.* **25** 170–83

Vautard R, Cattiaux J, Yiou P, Thépaut J N and Ciais P 2010 *Nat. Geosci.* **3** 756–61

Vose R S *et al* 2014 *Bull. Am. Meteorol. Soc.* **95** 377–86

Wu J, Zha J and Zhao D 2016 *Clim. Dyn.* **46** 847–63

Young I R, Vinoth J, Zieger S and Babanin A V 2012 *J. Geophys. Res. Oceans* **117** 1–13

Young I R, Zieger S and Babanin A V 2011 *Science* **332** 451–5

Zheng C W, Pan J and Li C Y 2016 *Ocean Coast. Manage.* **129** 15–24

Zieger S, Babanin A V and Young I R 2014 *Deep-Sea Res. Pt. I. Oceanogr. Res. Pap.* **86** 56–67