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Rephrase

HC3v5 produces correct daily estimates for cloud-free conditions but is mistaking fairly cloudy conditions as cloud-free from time to time.

Thomas et al. (2016a, b) have performed comparisons between hourly and daily HC3v5 estimates and measurements of E performed at a total of 44 Brazilian stations, i.e. at similar latitudes. Performances are fairly similar for both hourly and daily values. One may note that the bias for terrestrial sites is small and closer to 0 than for the PIRATA stations and that the standard deviations are a bit smaller. This may indicate some limitations in the accuracy of the PIRATA measurements.

3.2 The SARAH 2 data set

have you compared it to prev. dataset?

The SARAH-2 estimates correlate very well with the measurements. The correlation coefficient ranges between 0.93 and 0.98 for E and between 0.83 and 0.88 for KT, except at 19s34w (0.63) (Table 2). The bias for E is large and positive (overestimation). It ranges between 11 and 55 W m^{-2} (Table 3) with a tendency to decrease from East to West. This decrease may be related to the increase in KT from East to West as shown in Table 1. The bias varies from site to site with a difference between the maximum and ~~the~~ minimum of 44 W m^{-2}. This indicates a systematic error that is not constant in space, meaning that the actual irradiance field may be spatially distorted ~~by~~ in SARAH-2 and that the actual spatial gradients are not well reproduced. The standard deviation ranges between 62 and 79 W m^{-2}, with a much greater value (118 W m^{-2}) at 19s34w (Table 4). There is no clear relationship between the standard deviation and the frequency of clouds or KT or the geographical location. It may be concluded that the time-series of E are well reproduced though amplitudes of variation in time may be hampered by the large standard deviation of the errors.

As a whole, the SARAH-2 estimates reproduce ~~well~~ the coincident measurements well with small scattering for both E and KT ~~with~~ and an overall overestimation (see e.g. Figs. 2c, 2d). The smallest irradiances are underestimated and the greatest irradiances, i.e. greater than 800 W m^{-2}, exhibit much less overestimation and are more correctly estimated. SARAH-2 shows a tendency to overestimate ~~the actual~~ KT and to underestimate the ~~greatest~~ higher values of KT; it predicts too many cases of cloud-free when cloudy; the opposite case is also true but much less frequently.

but what's relative?

Rephrase

The frequency distributions of SARAH-2 match ~~well that of~~ the measurements of E and differences are very small (see e.g. Fig. 3c). As for KT, there is a tendency to ~~an~~ the underestimation ~~of~~ of frequencies for KT<0.5 and an overestimation around 0.7 (see e.g. Fig. 3d). ?? The monthly means of the estimated E overestimate those of the measurements at all stations, except 19s23w, and for all months at 0n0e and 0n10w, and all months ~~but the~~ except period May-July for 0n23w and 6s10w (see e.g. Fig. 4b). The monthly standard deviations are similar or close for all stations and all months, except an overestimation in January-February at 0n0e and 0n10w.

Rephrase

As for the daily DSIS, the correlation coefficients for daily KT are greater than for hourly KT, greater than 0.90 (0.80 at 19s34w), and similar to those for the daily E. Contrary to the smallest hourly irradiances which are underestimated, the smallest daily irradiances (<300 W m^{-2}) are overestimated; otherwise they are well estimated. In conclusion, HC3v5 produces correct daily estimates for cloud-free conditions but is mistaking fairly cloudy conditions as cloud-free from time to time. Compared to the PIRATA distributions, the frequency distributions of daily E and KT from SARAH-2 are shifted

rephrase

do you mean Sarah

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ensure all figures are referred to somewhere

towards the greatest E and KT, except at 19s23w where the distributions are close. In conclusion, SARAH-2 produces correct daily estimates for cloud-free conditions but is mistaking fairly cloudy conditions as cloud-free from time to time.

rephrase

3.3 The CAMS Radiation Service data set (CRS)

The CRS data set correlates very well with the measurements. The correlation coefficient ranges between 0.93 and 0.97 for E and between 0.82 and 0.88 for KT, except at 19s34w (0.66) (Table 2). The bias for E is large and positive (overestimation) and ranges between 10 and 31 W m^{-2} (Table 3). The overestimation and range of bias are similar to those reported by Thomas et al. (2016a) for 42 stations in Brazil. This decrease (what decrease?) may be related to the increase in KT from East to West shown in Table 1 and is in in agreement with the CAMS validation results quarterly reported by Lefèvre and Wald using terrestrial stations (https://atmosphere.copernicus.eu/validation-supplementary-products). Though it has not been discussed by these authors, one may note ~~in~~ that their reports indicate a tendency of the bias to decrease with an increase ~~of~~ in the mean KT. The tendency is more visible for terrestrial stations where cloud-free conditions are ~~often~~ experienced like the selected PIRATA buoys (rephrase). The bias varies from station to station in the PIRATA network with a difference between the maximum and the minimum bias of 26 W m^{-2}. The systematic error is not constant in space, and as a consequence the actual irradiance field may be spatially distorted by CRS and the actual spatial gradients may not be well reproduced. The standard deviation ranges between 68 and 86 W m^{-2}, with a much greater value (112 W m^{-2}) at 19s34w (Table 4). There is no clear relationship between the standard deviation and the frequency of clouds or KT or the geographical location. It may be concluded that that the time-series of E ~~are~~ is well reproduced though amplitudes of variation in time may be hampered by the large standard deviation of the errors. Coincident measurements are well reproduced by CRS as a whole with small scattering for E ~~with~~ an an overall overestimation (see e.g. Fig. 2e). The smallest irradiances are underestimated and the greatest irradiances, i.e. greater than 800 W m^{-2}, are often correctly estimated. The clearness indices are overestimated as a whole with a noticeable scattering and the greatest KT are underestimated (see e.g. Fig. 2f). CRS predicts too many cases of cloud-free when cloudy; the opposite case is also true but much less frequently. Like HC3v5, CRS makes use of McClear to estimate the DSIS in cloud-free conditions. Though McClear offers accurate estimates, errors are possible in the ~~case~~ of any gross errors in aerosol properties provided by CAMS. Other sources of errors found in cloud-free conditions originate from errors in the assessment of cloud properties (presence, coverage, optical depth).

similar language to prev. sections

The frequency distributions match well that of the measurements of E and differences are very small (see e.g. Fig. 3e). As for KT, all stations exhibit an overestimation of the frequencies around 0.6-0.7. 0n10w and 6s10w show a tendency to underestimate the frequencies for KT<0.6 (see e.g. Fig. 3f). Except 19s23w, there is an overestimation of the monthly means of E for all months except the period May-July during which no bias is observed (see e.g. Fig. 4c). At 19s23w, there is no bias except an overestimation in May-August. The monthly standard deviations are similar or close for all months at 0n23w and 19s34w, and similar or close for the other three stations with an overestimation in October-February.

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As for the daily DSIS, the correlation coefficients for daily KT are greater than for hourly KT, greater than 0.91 (0.81 at 19s34w), and similar to those for the daily E. In conclusion, CRS produces correct daily estimates for cloud-free conditions but is mistaking fairly cloudy conditions as cloud-free from time to time.

3.4 The MERRA-2 re-analysis data set

0.82-0.91 is still quite good

The MERRA-2 estimates do not correlate with the PIRATA measurements: the correlation coefficient ranges between 0.82 and 0.91 for E and between 0.49 and 0.56 for KT (Table 2). The latter coefficients are moderate and mean that at most 31% of the variance contained in the measured clearness indices is explained by MERRA-2. One may note that the correlation coefficients, both in E and KT, exhibit a tendency to increase from East to West. In addition, a dependency was found between the errors and the differences between the true solar time and the mean solar time. MERRA-2 does not account for this difference which is a function of the day in the year as a first approximation (Wald, 2007). This weakens *de facto* the correlation between the two series of data and increases the standard deviation of the errors for both hourly and daily values of E and KT.

where does this come from!

The bias for E ranges between -42 and 23 W m^{-2} (Table 3). It shows a tendency to increase (from negative to positive) from East to West. The dependency of the bias with the solar zenithal angle and other variables is weak, except for the cloud type whose influence is prominent.

can you compare to integ. cloud water/ice instead?

Fig. 5 shows the dependency of the bias and of the correlation coefficient as a function of the cloud type. One observes in Fig. 5a yellow and greenish tones, meaning negative and null bias, for the 'low-level' type (water cloud at low altitude) and 'thin' type (thin ice cloud), and blueish tones, meaning large positive bias for the 'medium-level' (water cloud at medium altitude) and 'high-level' (deep cloud of large vertical extent from low altitude to medium altitude). Fig. 5b shows that the correlation coefficients are similar or very close for all stations (each row is fairly uniformly colored) and that there is a dependency with the cloud type. Though a more detailed study with more cases is necessary, it can be speculated that the medium and high level clouds exhibit more bias and less correlation than the low level clouds. This is consistent with the preliminary findings of Doddy et al. (2017) who looked at the differences between measurements of daily E performed at terrestrial stations in Ireland and MERRA-2 outputs and suggested a systematic link between prevailing cloud structures and errors. A similar dependency of the errors with the mean KT has been reported by Zhao et al. (2013) for MERRA in North America. The bias varies from station to station with a difference between the maximum and the minimum of 65 W m^{-2}. This indicates that the systematic error is not constant in space, meaning that the actual irradiance field in the tropical Atlantic Ocean may be spatially distorted by MERRA-2 and that the actual spatial gradients may not be well reproduced. The standard deviation ranges between 128 and 166 W m^{-2} (Table 4) and exhibits a tendency to decrease with the regional increase in the mean KT (Table 1). Combined with the tendency of the correlation coefficient to increase with the mean KT, i.e. with increasing occurrence of cloud-free conditions, it may be speculated that MERRA-2 is as a whole more accurate in cloud-free conditions that in other conditions. This is in agreement with the findings of Kennedy et al. (2011), Yi et al. (2011), Zib et al. (2012), Zhao et al. (2013) or Boilley and Wald (2015) for MERRA.

Alot of your results are consistent w/ other studies – may it clear what's novel about your study

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The 2D histograms show that the dots for E are fairly well aligned along the 1:1 line with a very large scattering (see e.g. Fig. 2g). One may note a large underestimation of the greatest E. Close examination of randomly selected individual daily profiles of the MERRA-2 DSIS for cloud-free conditions against those from McClear has revealed that hourly means of irradiance are very similar in such conditions. Hence, the MERRA-2 cloud-free DSIS are likely accurate and the underestimation of the greatest E is mostly due to errors in prediction of cloud properties by MERRA-2. This is in agreement with the analysis of the 2D histograms for KT (see e.g. Fig. 2h). The shape of the 2D histogram is not elongated at all with a tendency to overestimate KT and a well-marked underestimation of the greatest KT.

The frequency distributions of measurements are fairly well reproduced for E, with an underestimation of the frequencies for the greatest E (see e.g. Fig. 3g). As for KT, one may note that the actual dynamics of KT is not fully covered by MERRA-2; the greatest values are not represented (see e.g. Fig. 3h). The situation is not the same for all sites. There is an overestimation of frequencies in the range [0.45, 0.65] ([0.6, 0.75] for 19s34w).

There is no systematic deviation in monthly means for all stations; the situation varies from station to station (Fig. 4d). The standard deviation is often underestimated. This is in agreement with the underestimation of the frequencies of the greatest KT.

As for the daily DSIS, the correlation coefficients for daily E are low: from 0.33 to 0.49 (0.81 for 19s34w), and are much less than those for hourly E, more than what is observed for the other data sets (Table 2). As for the daily KT, the coefficients are very low: from 0.36 to 0.47 (0.58 for 19s34w). At most 22% (34% for 10s34w) of the variance contained in the measured daily KT is explained by MERRA-2. There is no regional trend of the correlation coefficients. The 2D histograms have shapes which are not elongated and exhibit very large scattering, in full agreement with the low correlation coefficients. E, respectively KT, is sometimes overestimated but more frequently underestimated, especially the greatest E, respectively KT. Like for hourly values, the results indicates that the actual spatial gradients of daily DSIS are not well reproduced and that the actual field of daily DSIS may be spatially distorted by MERRA-2. This fact is recognized by Koster (2015) whose Figure 4.6 shows the difference between the yearly means of the DSIS between MERRA-2 and CERES (Clouds and the Earth's Radiant Energy System) EBAF (Energy Balanced and Filled) satellite-based observational dataset. In this picture, one may see a noticeable difference between both data sets. It ranges from -20 W m^{-2} in the Gulf of Guinea to 20 W m^{-2} along the Brazilian coast and exhibits structures that are compatible with our findings.

The fact that there is no systematic trend in monthly means and standard deviation may indicate that the spatial distortion occurs at various temporal scales. This is supported by the findings of Bengulescu et al. (2017). These authors performed a comparison between several data sets, among which HC3v5 and MERRA-2, and in situ measurements made at Vienna (Austria) and Kishinev (Moldova). They reported a very high correlation coefficient between MERRA-2 and in situ measurements (0.97 and 0.97 respectively) and showed that this high correlation was mostly due to the very high correlation coefficient between MERRA-2 and in situ measurements at the yearly period (0.99 in both stations), i.e. MERRA-2 reproduces well the seasonal variability. For any period less than 1 year, the correlation coefficient is only moderate and is

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less than 0.8, i.e. less than 64% of the variance of the estimates, indicating that MERRA-2 does not reproduce the variability observed in measurements for these periods.

3.5 The ERA-5 re-analysis data set

The ERA-5 estimates do not correlate with the measurements as well as the satellite-derived data sets: the correlation coefficient ranges between 0.88 and 0.93 for *E* and between 0.57 and 0.64 for *KT* (Table 2). The latter coefficients are moderate and mean that at most 41% of the variance contained in the measured clearness indices is explained by ERA-5. The standard deviation of errors ranges between 112 and 141 W m^{-2} (Table 4). The standard deviation exhibits a clear decreasing trend from East to West.

The bias for *E* ranges between -10 and 25 W m^{-2} (Table 3) and exhibits a regional tendency to decrease in absolute values and to rephrase tend to underestimation with increasing mean *KT* (Table 1). However, such a complex behavior can only be speculated given the small number of sites. The bias varies from site to site with a difference between the maximum and the minimum of 35 W m^{-2}. This indicates that the systematic error ~~that~~ is not constant in space. The actual irradiance field in the tropical Atlantic Ocean may be spatially distorted by ERA-5 and the actual spatial gradients may not be well reproduced. This is further supported by the strong dependency of the bias with the cloud type. Fig. 5 shows the dependency of the bias (Fig. 5c) and of the correlation coefficient (Fig. 5d) as a function of the cloud type. The medium and high level clouds exhibit more bias and less correlation than the low level clouds.

The 2D histograms show that the dots for *E* are aligned along the 1:1 line with a large scattering (see e.g. Fig. 2i). One may note a large underestimation of the greatest *E*, i.e. greater than 800 W m^{-2}. We may speculate from these 2D histograms that the DSIS for cloud-free conditions is underestimated. This is supported by the analysis of the 2D histograms for *KT* whose shapes are not elongated ~~at~~ all with a tendency to overestimation for *KT*<0.6 and a well-marked underestimation for *KT*>0.6 (see e.g. Fig. 2j). This has yet to be confirmed as ERA-5 does ~~is~~ not providing estimates of the DSIS for cloud-free conditions contrary to MERRA-2.

The frequency distributions of measurements are fairly well reproduced for *E*, with an underestimation of the frequencies for the greatest *E* (see e.g. Fig. 3i). As for *KT*, one may note that the actual dynamics of *KT* is not fully covered by ERA-5; the smallest and greatest values are not represented (see e.g. Fig. 3j). There is an underestimation of frequencies for all values of *KT*, except an overestimation in the range [0.45, 0.65] for all stations.

There is no systematic deviation in monthly means for all stations; the situation varies from station to station (see e.g. Fig. 4e). The standard deviation is often underestimated. This is in agreement with the underestimation of the frequencies of the greatest *KT* (see e.g. Fig. 3j).

As for the daily DSIS, the correlation coefficients for daily *E* are low: from 0.48 to 0.65 (0.87 for 19s34w), and expectedly are less than those for hourly *E*. The correlation coefficients for the daily *KT* are low: from 0.37 to 0.60 (0.71 for 19s34w). At most 36% (50% for 10s34w) of the variance contained in the measured daily *KT* is explained. Except 19s34w, the 2D

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Make it clear why you discuss daily & hourly

histograms have shapes which are not elongated and look more like discs, and exhibit large scattering, in full agreement with the low correlation coefficients.

3.6 About the differences in spatial support of the buoy and the grid cell of the data sets

One may object that the size of the grid cell is inappropriate for the comparison with a single buoy because surface measurements are for a single point in space, whereas the estimated irradiances are for the area of a pixel (typically 5 km) or a grid cell (typically 50 km). Cloud properties may vary within the grid cell and large random errors are unavoidable at hourly time steps. Using monthly averages is a means to ?? reduce the errors caused by the problem (see e.g. Zhao et al., 2013). One may believe that this mismatch in spatial support of information may explain the performances of the re-analyses presented here. However, it can be argued that there is no orographic effect in the Atlantic Ocean and there is no strong systematic gradient in irradiance over short distances corresponding to the hourly time step. Hence, the irradiance field is fairly homogeneous at sub-meso-scale and this should mitigate the effects of the differences in spatial support of the buoy and the grid cell. In addition, one may note that the drawbacks reported above are also observed at daily scale. Finally, the work of Boilley and Wald (2015) can be mentioned. These authors compared the satellite-derived HelioClim-1 data set to PIRATA measurements. HelioClim-1 is fairly similar to the re-analyses with regard to the spatial support of information because it is made of estimates of the DSIS made on 5 km pixels spaced by 25 km in both latitude and longitude (Lefèvre et al., 2007, 2014), and a spatial bi-linear interpolation was performed to create the time-series at PIRATA locations. Though the period is not the same than presently as HelioClim-1 covers the period 1985-2005, one may compare the correlation coefficients reported by these authors that range between 0.82 and 0.88 for daily E and from 0.79 to 0.88 for daily KT for HelioClim-1, and are much greater than those obtained for the re-analyses both in the work of Boilley and Wald and here (Table 2). These findings of Boilley and Wald support the argument that differences in spatial support of information cannot be the only reason for the bad performances of the re-analyses.

?? rephrase

If it's cloud free, rather than cloudy, should overestimate

Conclusions

It was found that the re-analyses MERRA-2 and ERA-5 often report cloud-free conditions while actual conditions are cloudy, yielding an underestimation of surface irradiance, and reciprocally, actual cloudless conditions as cloudy, yielding an overestimation. These alternating underestimations and overestimations compensate each other with a small bias as a result masking some deficiencies in properly modelling cloud properties. These conclusions are similar to those already reported regarding meteorological re-analyses as a whole (Wild, 2008). The estimates from MERRA-2 or ERA-5 poorly correlate with the clearness indices at station; a large part of the variability in the optical state of the atmosphere is not captured by the MERRA-2 or ERA-5 re-analyses. It is recommended not to use them in studies of the variability in time of the surface irradiance in the tropical Atlantic Ocean when it is necessary to reproduce actual measurements.

elaborate on

The bias varies noticeably with the calendar month, which means that MERRA-2 or ERA-5 cannot be used confidently at monthly scale. The re-analyses exhibit small bias when compared to PIRATA measurements over one or more years. Hence, one may use them to follow changes in yearly values of irradiance at one location. However, caution must be taken as Zhao et al. (2013) reported correlation coefficients between yearly means of MERRA and observations ranging from 0.50 (moderate anti-correlation) to 0.95 (high correlation) at several sites in North America.

Another striking feature is the variability of the bias and other performance indicators within this ocean area which is fairly homogeneous for the irradiance and clearness index. Accordingly, an additional recommendation on re-analyses is not to use them to study the irradiance spatial field at whatever time scale: the performances strongly vary from one location to another, especially for MERRA-2, which means that the field of surface irradiance is spatially distorted, even at yearly scale.

The present results bring more evidence on the qualities and limitations of MERRA-2 and ERA-5. These re-analyses may be used in studies of the tropical Atlantic Ocean with proper understanding of the limitations and uncertainties. Zhao et al. (2013) proposed an empirical relationship for correcting the bias observed between MERRA estimates and measurements of monthly averages of irradiance performed at several sites in North America taking into account the dependency between the bias and KT and surface elevation. The bias and the root mean square error were reduced but at the expenses of an increase in standard deviation of errors. Jones et al. (2017) have tested several methods for adjusting ERA-Interim estimates of E onto HC3v5. They found that when compared to measurements of daily irradiance performed at 55 terrestrial stations in Europe, the bias was reduced for 10 stations and similar for the others and that the other indicators (standard deviation of errors, root mean square error, correlation coefficient, median of errors…) were unchanged. Though the works were performed for MERRA or ERA-Interim, it is speculated that similar conclusions would be reached when applied to MERRA-2 or ERA-5, given the similarities between these re-analyses.

Except for the bias, the three satellite-derived data sets exhibit better performance indicators than the two re-analyses. All three overestimate the irradiance. Assuming that PIRATA achieve the "moderate quality" pyranometer measurements defined by WMO (2008, rev. 2012), one may ask if these data sets are compliant with "moderate quality" if one may remove the bias. Defined as the 95% probability (P95), the relative uncertainty for "moderate quality" should not exceed 20%. The total uncertainty takes into account the uncertainty of PIRATA and the uncertainty of the estimates. It can be expressed in a first approximation as the quadratic sum of both uncertainties. As a consequence, the total relative uncertainty should not exceed 28% (P95), or 14% (P66) if the estimates were of "moderate" quality. The standard deviations (P66) for each data set reported in Table 3 are below 14%. It can be concluded that to a first approximation, the three satellite-derived data sets can be considered of moderate quality if bias can be removed.

One may note several similarities in performances between HC3v5 and SARAH-2. It is speculated that this is partly due to the fact that they exploit the same method, Heliosat-2, though the implementation differs.

The three satellite-derived data sets are appropriate to study the dynamics of the downward solar irradiance at the surface of the tropical Atlantic Ocean. Their performances are fairly similar. The CRS exhibit the lowest biases. When the study of the irradiance field is at stake, one should prefer HC3v5 as the bias is fairly similar from one location to the other which means that the actual spatial gradients are well reproduced.

Other data sets are available that cover the tropical Atlantic Ocean and must be assessed against the PIRATA measurements to gain knowledge on their limitations and confidence in their use. Examples are the satellite-derived OSI-SAF (www.osi-saf.org) or the Japanese 55-year re-analysis (JRA 55, Kang et al., 2015; Kobayashi et al., 2015).

The findings reported here are similar to those already published. This demonstrates a posteriori that the PIRATA measurements may be used for the validation of models and data sets. However, some uncertainties remain: It is striking that all satellite-based data records show their lowest correlation at the same buoy location, i.e. 19s34w. While the different levels and variability of surface irradiance in this location might impact the quality of the satellite-based data sets, a reduced data quality of the buoy data (despite the quality control applied) might also have an impact on the presented evaluation. Studies like these when multiple data records are considered can help to identify problem in surface reference measurements (Urraca et al., 2017). The PIRATA network is a unique and valuable means to study and monitor the surface irradiance in the tropical Atlantic Ocean and deserves support for operations to further enrich the data records.

Data availability

PIRATA measurements performed every 2 min were downloaded from the web site (www.pmel.noaa.gov/tao/drupal/disdel/) of the National Oceanic and Atmospheric Administration (NOAA) of the U.S.A. The authors acknowledge the help of the GTMBA Project Office of NOAA/PMEL in getting the data and the PIRATA team for servicing the network and freely providing the data.

Time-series of HelioClim-3v5 data were downloaded from the SoDa Service web site (www.soda-pro.com) managed by the company Transvalor. Data are available to anyone for free for years 2004-2006 as a GEOSS Data-CORE (GEOSS Data Collection of Open Resources for Everyone) and for a charge for the most recent years with the amount depending on requests and requester. The time-series used in this article are available for free in CSV format by request to Mireille Lefèvre.

Time-series of SARAH-2 data were extracted from the gridded data sets available at https://doi.org/10.5676/EUM_SAF_CM/SARAH/V002.

Time-series of CAMS Radiation Service data were downloaded from the SoDa Service web site (www.soda-pro.com).

Time-series of cloud classification were downloaded from the SoDa Service web site (www.soda-pro.com).

MERRA-2 times-series were extracted from the gridded data sets available at https://goldsmr4.gesdisc.eosdis.nasa.gov/data/MERRA2/.

ERA-5 times-series were extracted from the gridded data sets available at http://apps.ecmwf.int/data-catalogues/era5/?class=ea&stream=enda&expver=1.

Author contribution

All authors contributed equally to this work.

Competing interests

The authors declare no competing interests.

Disclaimer

N/A

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