Institute and Faculty of Actuaries

Extension of the Actuaries Climate Index to the UK and Europe

A Feasibility Study

by C. L. Curry*

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Abstract

This report assesses the prospect of extending the Actuaries Climate Index (ACI), originally developed over Canada and the United States, to the United Kingdom and Europe. The definition and underlying methodology of the ACI is reviewed, and we find that no changes are necessary to apply the ACI on the new domain. Regarding the source data for the Index, while each of the previously identified data sources for the ACI are available over the UK and Europe, some gaps are present in certain variables, e.g. extreme precipitation. A newly identified data product, E-OBS-CLIMDEX, specifically developed for climate research and monitoring over Europe, is then examined. While this product provides results over the entire region of interest, the data are interpolated from underlying station measurements, which are spatially heterogeneous. The research literature suggests that where the underlying station density is sparse, E-OBS-CLIMDEX may not give an adequate description of climate extremes. We therefore recommend the UK-European ACI be based on a suitably masked version of E-OBS-CLIMDEX, which only includes the parts of the domain characterized by an acceptably high station density.

Keywords

Climate; climate change; climate indices

Correspondence details

*Correspondence to: IFoA Research & Knowledge, Email: research@actuaries.org.uk

Charles L. Curry, E-mail: curry@solterrasolutions.com

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1. Introduction: Overview of the North American Actuaries Climate Index

The Actuaries Climate Index (ACI) is a retrospective measure of climate change intended for use by actuaries, insurers and their clients, but also for the general public. The index is based upon quality-controlled, periodically updated, publicly available climate data. In its final form, the ACI utilizes information from six distinct climate indicators:

- temperature extremes (high and low)
- heavy precipitation
- drought (as lack of precipitation)
- extreme wind
- sea level

A seventh indicator, soil moisture, was included in an earlier version of the ACI but not retained in the final formulation. A thorough summary of the recent historical behaviour of these indicators, and also their projected future change using state-of-the-art global climate models, was presented in a report sponsored by the major actuarial organizations of Canada and the United States (Solterra Solutions, 2012).

More specifically, the following quantities enter into the definition of the ACI:

TX90p: percentage of days when daily maximum temperature is above the 90th percentile, with the latter determined for the reference period 1961-90;

TN90p: percentage of days when daily minimum (usually nighttime) temperature is above the 90th percentile, with the latter determined for the reference period 1961-90;

TX10p: percentage of days when daily maximum temperature is below the 10th percentile, with the latter determined for the reference period 1961-90;

TN10p: percentage of days when daily minimum (usually nighttime) temperature is below the 10th percentile, with the latter determined for the reference period 1961-90;

R_X: short for *Rx5day*, this is the maximum 5-day precipitation (rain plus snowfall) within a given period (month or calendar year);

D_X: Maximum length of a dry spell, expressed as the maximum number of consecutive dry days (CDD), i.e. days with daily precipitation < 1 mm, in a calendar year;

W_X: percentage of days when the daily mean wind power *WP,* (proportional to the cube of the wind speed), exceeds the 90^{th} percentile of *WP* over the reference period. W_X is analogous to the extreme temperature indices defined above; and

S: Monthly mean sea level at the location of a long-term tide gauge station.

The ACI expresses the change in the above variables in the most recent month/season compared to the reference period of 1961-1990. Specifically, the ACI combines the above indicators as follows:

$$ACI = (1/6)(T90'_{std} - T10'_{std} + R'_{X,std} + D'_{X,std} + W'_{X,std} + f_S S'_{std}),$$

where

$$T90 = (1/2)*(TX90p + TN90p), \qquad T10 = (1/2)*(TX10p + TN10p),$$

are introduced to avoid overweighting the temperature components in the ACI (and to explicitly account for the fact that warm/cold days and warm/cold nights are often correlated).

The notation

$T90'_{std} = \Delta T90/\sigma_{ref}(T90), \ldots$, etc.

indicates the *standardized anomaly*, where the *Δ's* are differences of each indicator from its reference value, as determined over the period of 1961-1990. The quantity σ_{ref} is the standard deviation of the relevant index over the reference period, after removing any linear trend. Note that $T10'_{std}$ enters the formula with a negative sign; this is to account for the fact that the definitions of *T90* and *T10* are oppositely oriented. That is, while the former tracks the frequency of warmer-than-usual temperatures, the latter tracks the frequency of colder-than-normal temperatures. So if we want to the index to reflect changes in warming (either increases or decreases), we need to reverse the sign of *T10* before including it in the ACI.

The factor f_S, $0 < f_S \leq 1$, is included as an adjustment to the sea level contribution, since that variable is important over only a small fraction of the total area of the continent or a particular region. In the gridded representation of the ACI (see below), f_S is defined as the fraction of the number of coastal to total grid points in the region. Finally, note that, due to the simple sum of components each of which has a zero reference period anomaly, the ACI will also exhibit zero change when averaged over the reference period. This property is helpful for placing more recent changes in an historical context.

A recently updated time series of the ACI is shown in Figure 1 below. The definition of the ACI is sufficiently robust that it may be applied over any world region with sufficient observational data. We now look at these data requirements in more detail.

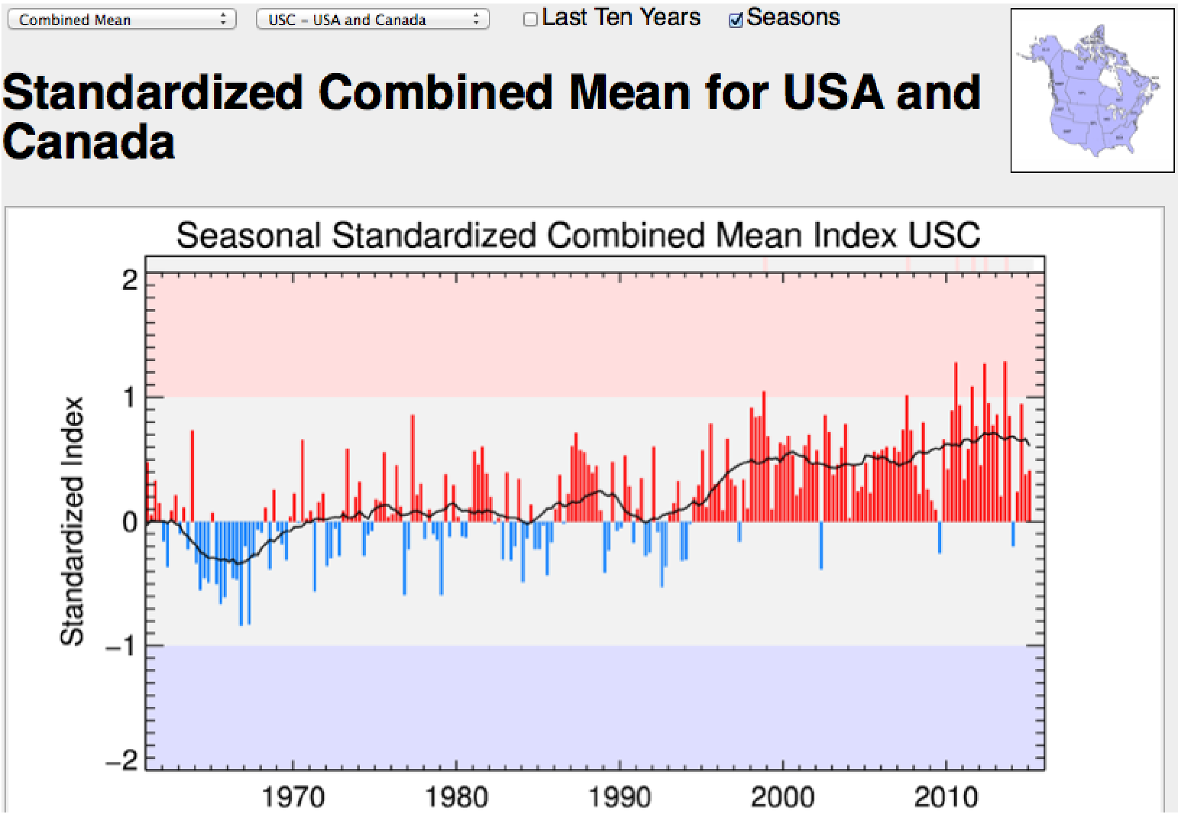


Figure 1. Illustrative time series graph of the ACI over the USA and Canada. Each bar on the graph represents the ACI for a given climatological season, while the black curve is a 5-year trailing mean. Values within the range $-1 < \text{ACI} < +1$ indicate "near-normal" climate variations compared to the reference period, while values outside of that range are considered "above normal" or "below normal" *(Source: ACI prototype webpage, Solterra Solutions Ltd., accessed 11/30/2015).*

2. Data requirements for the ACI

2.1 What type of data do we seek?

In order that the index be both scientifically robust and operational in design, the following properties were sought for the data entering the ACI.

1. *Spatial extent and resolution:* global, ideally, at the highest resolution available and provided on a geographic grid (to ease analysis and future incorporation of socioeconomic data).

2. *Temporal extent and coverage:* from 1960s or earlier to present, to provide long enough base period (~30 yr) for robust statistics. Time resolution of monthly mean or less (daily, ideally), to capture extremes.

3. *Update frequency:* at least seasonally (quarterly).

4. Based on observations, not models.

5. Wide range of variables, beyond just temperature and precipitation.

In most regions of the world, there is no single data product that satisfies all of these criteria. Below we summarize the properties of the most useful ones we have encountered to date.

2.2 Data set descriptions

A. *GHCN-Daily (NOAA)*

http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/index.php?name=data

GHCN-Daily is a land station-based, gridded dataset with global coverage at 3.75° longitude by 2.5° latitude. It is an operationally updated product, with data available from January 1950 up until one month before present (latest to November, 2015).

B. *GHCNDEX*

http://www.climdex.org/gewocs.html

GHCNDEX is a secondary product derived from GHCN-Daily, comprising a collection of 27 distinct indices of climate extremes (known as the CLIMDEX indices), provided on a grid of 2.5° x 2.5° resolution. A full description is available in the paper by Donat, et al. (2013a). The percentile-based extremes in GHCNDEX (see below) are determined for a standard base period of 1961-90, and we adopt the same base period for the ACI as defined in Section 1.

GHCNDEX is updated somewhat less often than GHCN-Daily, usually once every few months. Current data are available from January 1950 to November 2015.

The ACI components *T90, T10,* R_X, and D_X are obtained from GHCNDEX.

C. *HadEX2*

http://www.climdex.org/gewocs.html

HadEX2 is a global gridded data set analogous to GHCNDEX and including many of the same stations, but featuring a larger fraction of quality controlled station data, including those in the ECA&D compilation for Europe (see below). A full description may be found in Donat, et al. (2013b). It is of lower resolution, however (3.75° longitude x 2.5° latitude) and is also not updated regularly—the most recent data available is to the end of 2010.

D. *Reanalysis (NCEP-I/NCEP-II/ERA-40/ERA-Interim, and others)*

http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html

Reanalysis products are global, gridded data sets including many more climate variables than are provided in standard observational data sets. This is made possible by the fact that reanalyses are in fact climate model simulations that are heavily constrained by various types of observations. We obtained surface wind speed data from the NCEP-I reanalysis which, like GHCNDEX, has a horizontal resolution of 2.5° x 2.5°.

The ACI component W_X, which describes the frequency of extreme winds, is derived from the NCEP-I data.

E. *Permanent Service for Mean Sea Level (PSMSL)*

A global repository of monthly mean sea level obtained from tide gauge stations is available at:

http://www.psmsl.org/data/obtaining/

A full description of the data set is given in Holgate, et al. (2013). We obtain data for *S*, the sea level component of the ACI, from PSMSL.

The PSMSL product is of a different character than that of the other index components. It is, of course, restricted to coastal locations. In addition, the various station time series are very heterogeneous, and must be screened for completeness and data quality before being selected for use in the ACI. When combining *S* with the other ACI components, the tide gauge must be located on the spatial grid (2.5° x 2.5°) used for the other components. Finally, since the tide gauges measure *relative* sea level, local land movements (uplift or subsidence) must be similarly quantified if an assessment of absolute sea level change (the climate-only component) is desired. Thus, for the ACI we used predictions of the ICE-5G model of global glacial isostatic adjustment at PSMSL locations by Peltier and collaborators to obtain vertical motions in mm/year:

http://www.atmosp.physics.utoronto.ca/~peltier/data.php

These values were then added to the relative sea level from PSMSL to obtain absolute sea level estimates.

3. The ACI in the European context: Which data set is best?

As they stand, the ACI definition and supply data sets are straightforwardly adapted to the European context. Each of the datasets described above is freely available online, regularly updated (i.e. “operational”), and global in its spatial coverage. Examples of two of the variables entering the ACI are shown over the UK-European domain in Figure 2.

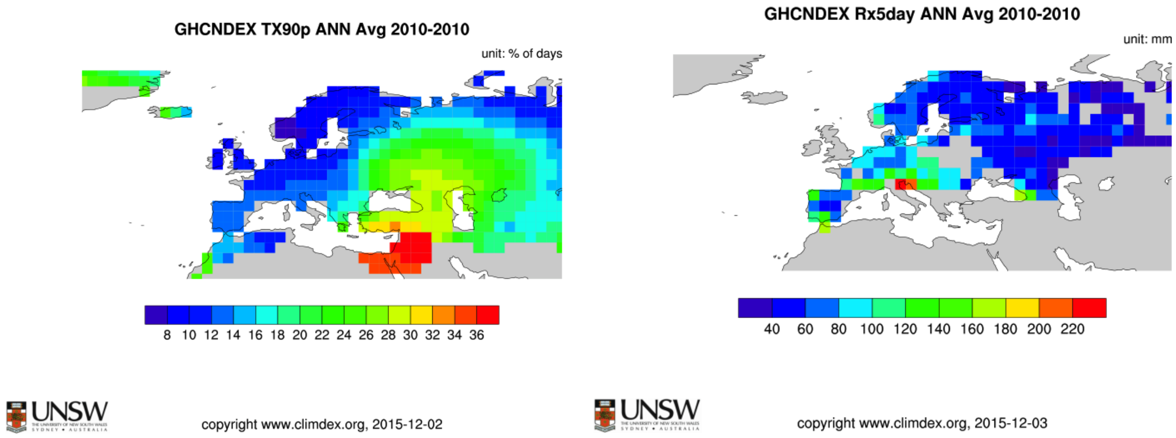


Figure 2. Examples of climate extreme indices over Europe from the GHCNDEX data set. Left: Percentage of warm days, *TX90p,* in 2010 from GHCNDEX. A value of 10% indicates no difference compared to the reference period of 1961-1990. *Right:* Maximum 5-day sum of precipitation, *Rx5day*, in 2010 from GHCNDEX. (*Source:* CLIMDEX project, http://www.climdex.org/view_download.html, accessed 11/30/2015).

Fig. 2 shows that the areal coverage of GHCNDEX over Europe varies according to the variable and time period of interest: generally, the coverage for precipitation variables (e.g., *Rx5day*, *CDD*) is poorer than for temperature variables (*TX90p, TN10p,* etc.). For example, GHCNDEX does not show results for *Rx5day* over the UK for the past five years (2010-2014), and gaps also exist over Poland, Italy, Greece and Turkey. Another obvious limitation is the coarse spatial resolution of this dataset. At 2.5° × 2.5°, the UK is covered by only 6 grid cells (2 of these over Ireland), and incompletely so, due to the ocean mask employed.

Given these shortcomings in GHCNDEX over Europe, it is worth considering still other data sources. Relaxing the requirement of global coverage, we have identified a data compilation specifically tailored to Europe: the ENSEMBLES Observations gridded data set, or E-OBS. This data set is built upon long-term meteorological station data from the European Climate Assessment & Dataset (ECA&D):

http://www.ecad.eu/indicesextremes/index.php

The ECA&D network contains some 2,316 stations, which are variable in their coverage both in time and space (Haylock, et al., 2008; Hofstra, et al., 2009, 2010). The station time series in the database have undergone rigorous quality control and homogeneity testing, although some heterogeneities remain (e.g., breakpoints from splicing series of nearby stations; Hofstra, et al., 2009). Several documents providing a thorough description of the station data, including updating procedure, quality control, and the ECA&D data policy, are available at

http://www.ecad.eu/publications/index.php

The spatial distribution of ECA&D stations with available data for maximum daily temperature during three different 30-year periods is shown in Figure 3.

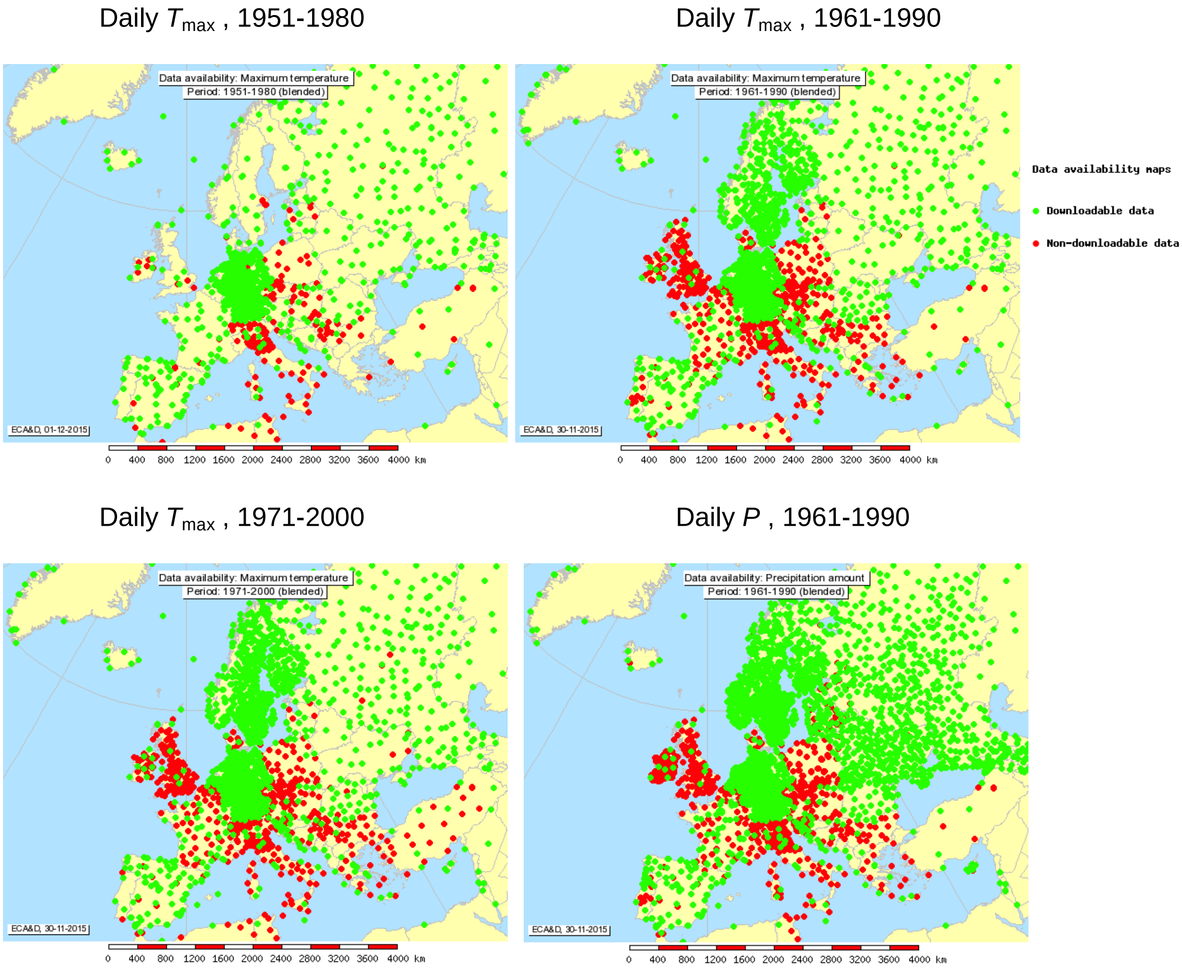


Figure 3. Distribution of measurements from meteorological stations in the ECA&D network underlying the gridded product E-OBS. (*Source:* ECA&D extreme indices website, http://www.ecad.eu/indicesextremes/index.php)

About 75% of the station series are available for direct download from ECA&D; however, according to the E-OBS documentation, “the derived products are made available irrespective of the ‘non-downloadable’/’downloadable’ status of the daily data these products are based on.”

Not surprisingly, the station distribution roughly mirrors population density; however, after 1960, Western Europe and Scandinavia are exceptions in that coverage is more complete than would be expected on the basis of population alone. Note that while the number and coverage of stations with T_{max} measurements increases noticeably from 1951-80 to 1961-90, the difference is not as large for 1971-2000 compared to 1961-90. *This suggests that 1961-90 is an acceptable reference period for calculating subsequent climate anomalies, as done in the ACI*. Fig. 3 also shows the distribution of daily total precipitation data from stations for the 1961-1990 period. Interestingly, there is a much higher number of stations in Eastern Europe and Russia with precipitation records than have measurements for T_{max}.

3.1 The E-OBS data set and its evaluation

Starting from the inhomogeneous station data, methods of spatio-temporal interpolation are used to create the E-OBS gridded product, as described in Haylock, et al. (2008) and Hofstra, New, and McSweeney (2010). In areas with high station density, where several stations might fall within a single “target” grid box of E-OBS (of size 25 or 50 km; see below), this approach gives an accurate rendering of the average climate on that spatial scale. But in areas with more sparse station coverage, stations well outside the target grid box (interpolation radius ~500 km) contribute disproportionately, leading to overly smoothed results. As explained by Cornes and Jones (2013) in their evaluation of E-OBS against reanalysis and the ECA&D stations, “The use of area-averaged data such as E-OBS has the advantage of reducing local noise that is apparent in the station series, although the low density of stations in certain areas, the change in density over time, and also oversmoothing of extreme values by the interpolation technique may limit the ability of the data to depict trends in extreme values [Haylock et al., 2008; Hofstra et al., 2009]. These problems are manifested in data-sparse regions of Europe [Hofstra et al., 2010].”

In light of the above concerns, Hofstra, et al. (2010) went so far as to suggest that only E-OBS grid boxes satisfying a chosen minimum station density criterion might be used for certain applications. For example, one might require that each 25-km grid box include at least one station. Looking back at Fig. 3, this might limit the region of applicability for temperature from 1961-onward to west of ~30 °W and north of ~45 °N, for example. Although it would require some care to keep track of which stations have data over differing time periods, this is an option worth considering for the present project. An illustrative example is shown in Figure 4.

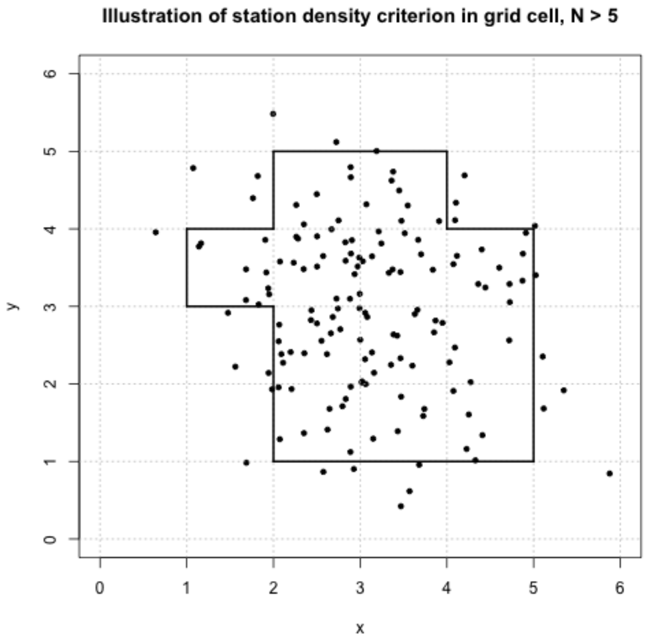


Figure 4. Example of masking gridded data using a critical station density criterion. The black dots represent a hypothetical station distribution, overlaid by a grid representing an interpolated data product. Here the criterion *N > 5* has been applied, meaning that grid cells with fewer than 5 stations are excluded from the final product.

We should first ask the question, however: How well does E-OBS compare against other data sources over various parts of Europe? A few publications have pointed out shortcomings and biases in the product over specific areas (e.g., Hofstra, et al., 2009; Kysely and Plavkova, 2010), usually where a denser station network exists but is not fully included in the ECA&D database (e.g., the UK, Greater Alps, Czech Republic, and central & northern Europe). For the application we have in mind, however, namely using E-OBS to compute the standardized anomalies of temperature and precipitation extremes, the existence of bias is less important than the fidelity of E-OBS with respect to trends and the magnitude of the bias relative to the characteristic standard deviation of a quantity.

Two particularly useful evaluations in this respect are the papers of Hofstra, et al. (2009) and Cornes and Jones (2013). One encouraging conclusion of Cornes & Jones is that, for trends in temperature extremes over recent decades, E-OBS compares favourably with trends estimated directly from the station data. The comparison for the index of extreme warm temperatures, *TX90p*, is shown in Figure 4 of Cornes and Jones (2013). Their figure shows that both the magnitude and spatial pattern of *TX90p* trends in E-OBS are similar to those obtained from the station network directly. Corresponding results for *TN10p* presented by the same authors show a slight underestimation of the trends in E-OBS compared to the station network, mainly in winter. Nevertheless, the sign of the change is reproduced correctly in each season and the differences are mainly seen in Eastern Europe and Russia, where low station density might preclude the use of E-OBS in any case. Precipitation extremes in E-OBS were evaluated against higher-density station networks in Hofstra et al. (2009), with the authors concluding that "there seem to be significant problems with the underestimation of precipitation extremes" due to over- smoothing of station values via interpolation, except in areas where the station density is quite high. From a practical perspective, this again suggests that masking out areas of low station density (e.g., Russia, the former Soviet republics, Turkey and North Africa) might be a prudent strategy.

Finally, while using a reduced-area version of E-OBS will not allay all concerns identified in the above studies, one must realize that the other gridded data sets described in Sec. 2.2 will have the same issues, likely exacerbated due to the coarser resolution grids they employ. Short of using the ECA&D station network itself—which is not recommended for further development of the UK-European ACI, since socio-economic data would be difficult to integrate—E-OBS is likely to be the best option of those discussed here.

The key properties of the E-OBS data set for the purpose of the development of a UK-European ACI are summarized below.

Temporal coverage: 1950-01-01 to 2015-06-30

Temporal resolution: Daily

Update frequency: Monthly

Spatial coverage: 25°N-75°N, 40°W-75°E.

Spatial resolution: 0.25° or 0.5° (approx.. 25 km or 50 km, true at 60 °N) regular lat-lon grid.

Variables: daily mean temperature, daily minimum temperature *TN*, daily maximum temperature *TX*, daily precipitation sum, and daily averaged sea level pressure.

As for GHCN-Daily, the full suite of CLIMDEX extremes indices has been computed from E-OBS as part of the EUPORIAS (European Provision Of Regional Impacts Assessments on Seasonal and Decadal Timescales) project. These data are freely available from

http://www.ecad.eu/download/ensembles/download_R.php

and are current up to v11 of the E-OBS dataset. The salient properties of E-OBS-CLIMDEX are:

Temporal coverage: 1950-01-01 to 2014-12-16

Temporal resolution: annual, monthly, seasonal

Spatial coverage: 25°N-75°N , 40°W-75°E.

Spatial resolution: 0.25° regular lat-lon grid.

Variables: full set of CLIMDEX indices

At the time of this report, the E-OBS-CLIMDEX indices were updated to October 31, 2015. Figure 5 summarizes the characteristics of E-OBS-CLIMDEX relative to the other options discussed in Sec. 2.2, implying that it is the optimal choice for several of the ACI components in the present application.

One caveat for our specific application is that the E-OBS-CLIMDEX indices *TX90p, TN90p, TX10p,* and *TN10p* are calculated relative to a reference period of 1981-2010 rather than the 1961-1990 period used in GHCNDEX. *Hence, in order to maintain compatibility with the North American ACI, one would need to recalculate these indices relative to the 1961-90 base period (note that the remaining indices comprising the ACI are not sensitive to this choice).* However, this is a one-time exercise: once the new base period percentiles have been determined, only anomalies relative to these percentiles need to be determined on an ongoing basis. The appropriate software to compute the indices relative to any base period and for any input data set has been identified and is freely available (CLIMDEX.PCIC, 2015). Familiarity with the CLIMDEX methodology and also facility with the R programming language would be required to carry out this procedure.

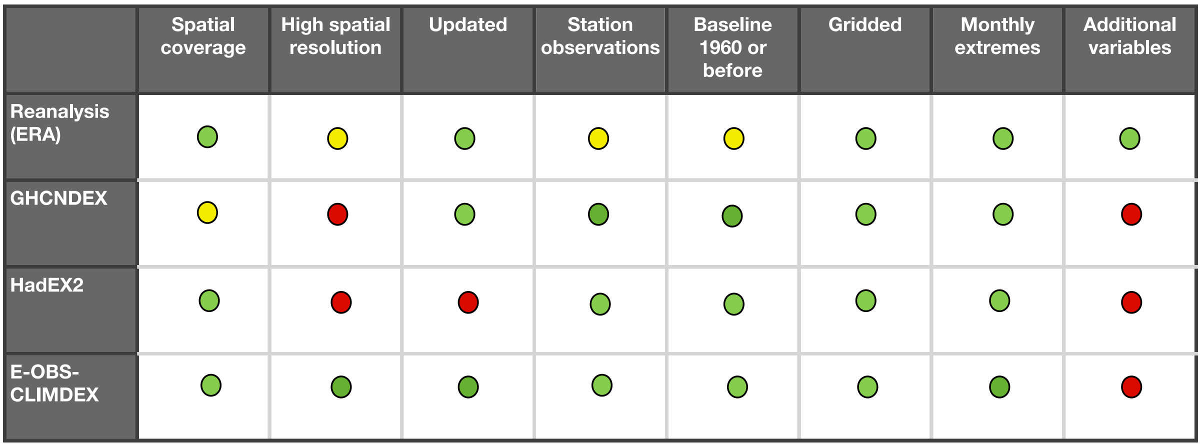


Figure 5. Summary of available data sets with respect to ACI requirements. *Legend: green =* acceptable, *red* = not acceptable, *yellow* = acceptable but not optimal. See Sec.2.1 for a summary of requirements and Secs. 2.2 & 3.1 for a description of the data sets.

3.2 Examples of E-OBS-CLIMDEX data

As an illustration of the type of data available from E-OBS-CLIMDEX, Figures 6 to 9 show a selection of maps obtained from the website,

http://www.ecad.eu/utils/mapserver/eobs_maps_indices_R.php

Results for the year 2010 are shown as an illustration. The following characteristics of these figures are worth noting:

1) The spatial coverage varies according to the climate variable. Temperature data have broader spatial coverage than precipitation, in general. *While the spatial coverage of the underlying ECA&D stations depends upon the time period selected (Fig. 3), the corresponding coverage of E-OBS does not differ greatly from that shown in the maps below.* For example, the spatial extent of the maps for the 1960s is not visibly different from that shown for 2010. However, we must keep in mind that the influence of the interpolation method is larger in earlier decades due to the sparser station distribution, so the results need to be interpreted with caution.

2) Relative to the reference period, 2010 was an unusually warm year in Eastern Europe. There is evidence for this both from *TX90p* (which exceeds 10%; Fig. 6) and *TN10p* (which is less than 10%; Fig. 7). The opposite was true in much of Western Europe, particularly the UK, Scandinavia, and southern France/northern Spain.

3) According to the *Rx5day* map (Fig. 8), heavy precipitation amounts were smaller in Eastern Europe than in Western Europe. Consistent with this, drought periods were generally longer in Eastern than in Western Europe (Fig. 9).

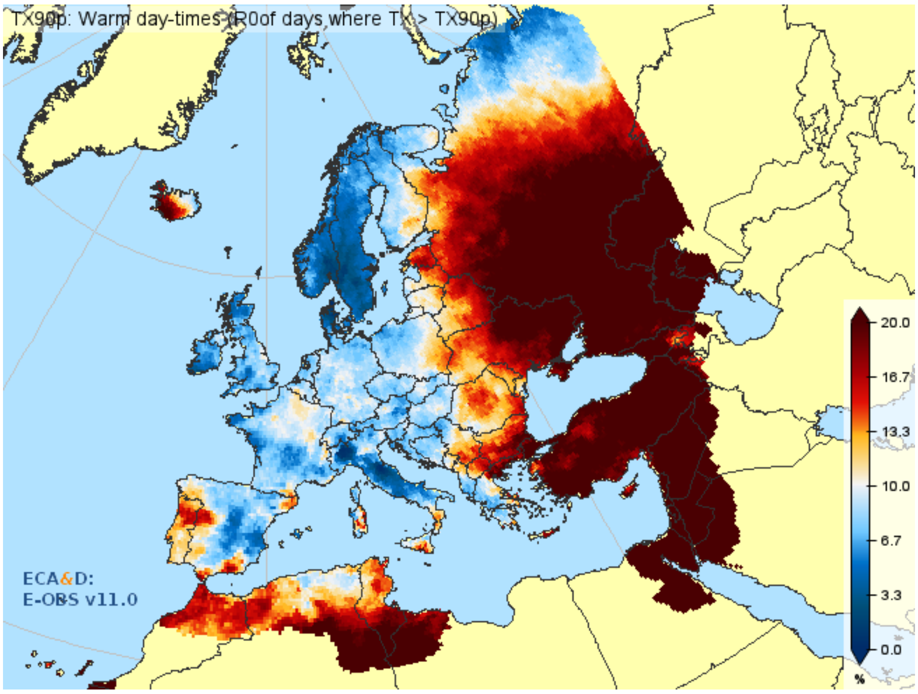


Figure 6. Percentage of warm days, TX90p, in 2010. A value of 10% indicates no difference compared to the reference period of 1981-2010.

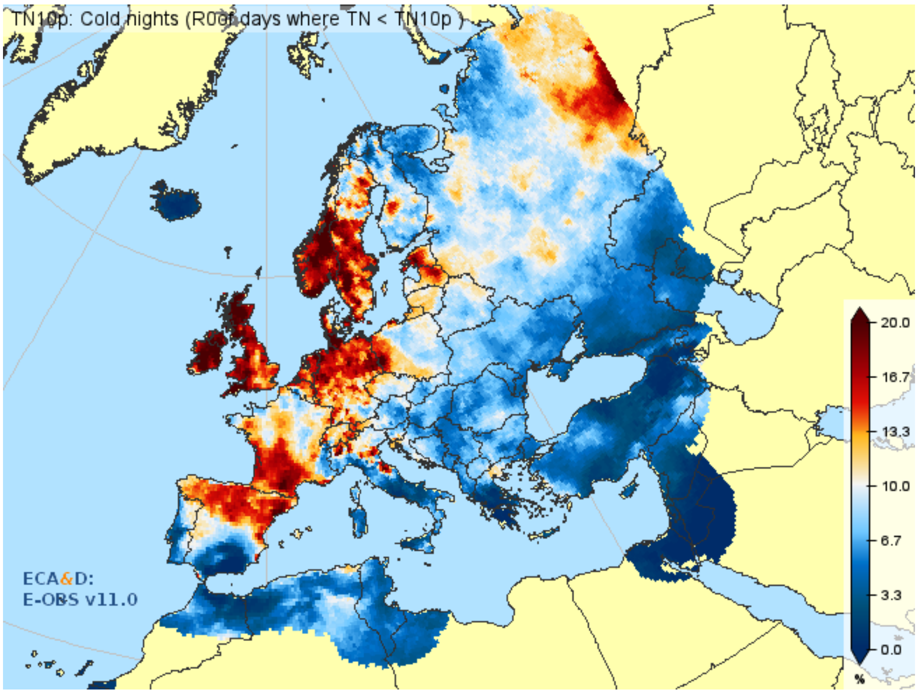


Figure 7. Percentage of cold nights, TN10p, in 2010. A value of 10% indicates no difference compared to the reference period of 1981-2010.

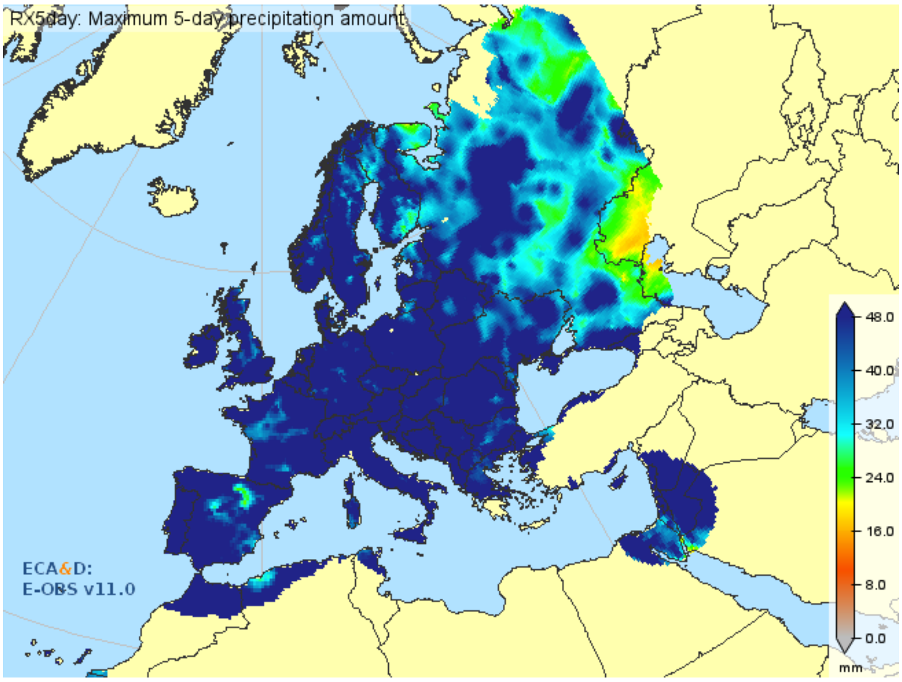


Figure 8. Maximum 5-day precipitation amount (mm), Rx5day, in 2010.

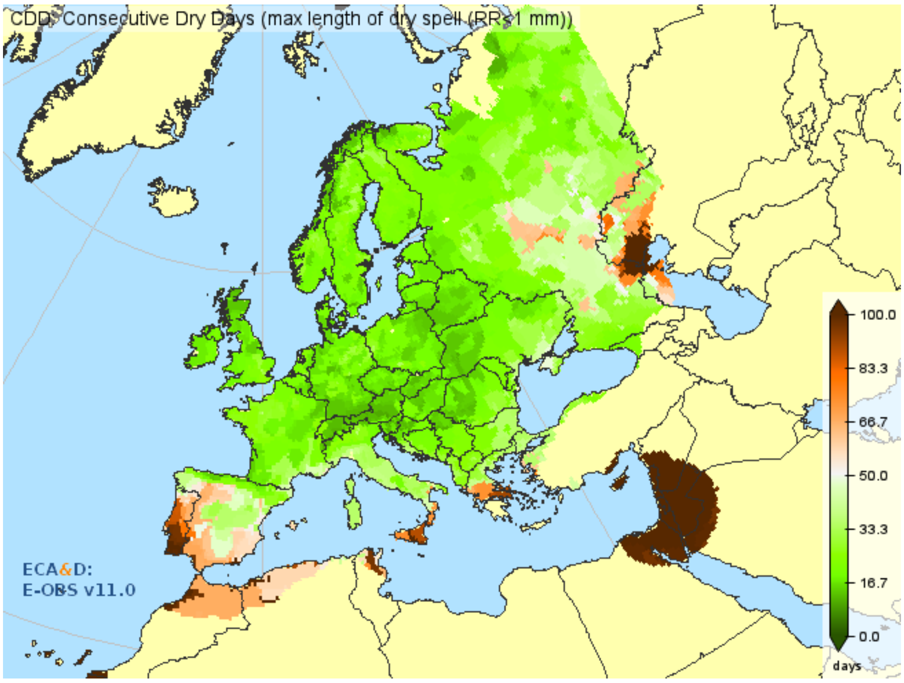
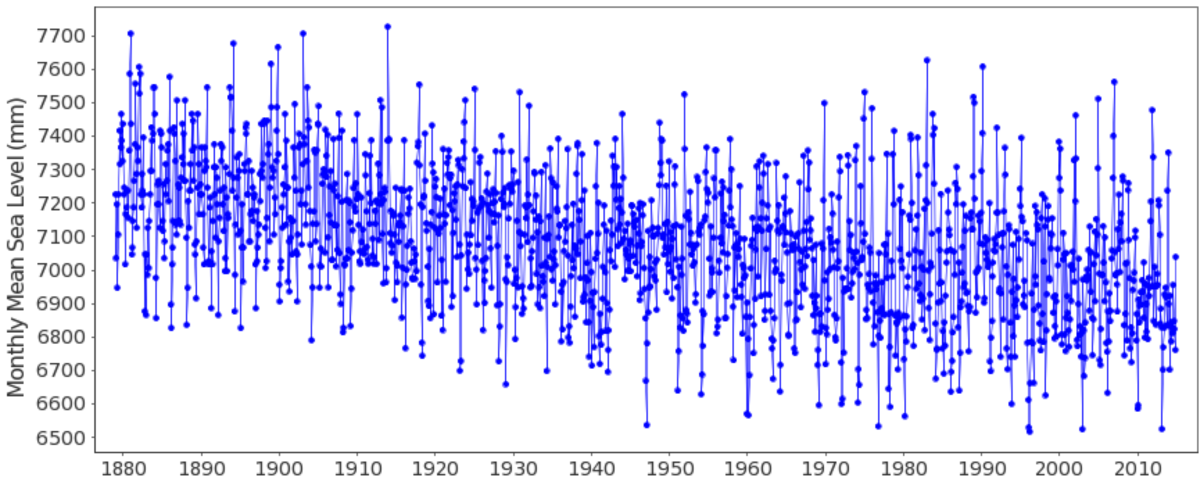


Figure 9. Maximum annual consecutive dry days (days), CDD, in 2010.

3.3 Examples of PSMSL data

An initial application of our quality-control algorithm[1] used to select sea level time series suitable for the ACI yielded 117 stations out of a total of 458 lying within the E-OBS domain from the global data set. (For comparison, only 76 stations were selected over the North American domain). Figure 10 shows two example time series from this subset. The oppositely directed trends seen in relative sea level at the two locations are not atypical; as mentioned in Sec. 2.2, the derivation of *absolute* sea level requires information on local rates of vertical land movement.

Helsinki, Finland



Holyhead, United Kingdom

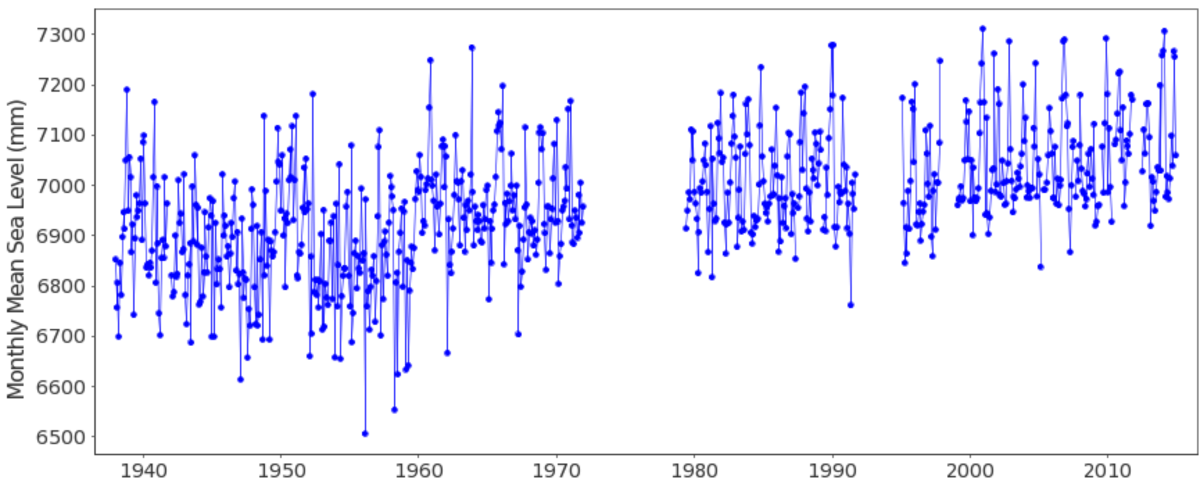


Figure 10. Monthly time series of relative sea level from Helsinki, Finland (1879-2014) and Holyhead, UK (1938-2014). Source: Retrieved 07 Dec 2015 from http://www.psmsl.org/data/obtaining/.

[1] The quality criteria are: 1) 30 or more years of semi-continuous data prior to 1990; 2) the fraction of missing values over the entire time series is < 1/3.

3.4 Other considerations

Although the North American ACI is calculated on a 2.5° x 2.5° grid, the results are presented as regional averages over 12 zones spanning Canada, the contiguous United States, and Alaska. The regions were chosen according to both climatic coherence (e.g., U.S. Southwestern Pacific, a temperate but arid climate) and political boundaries (to facilitate incorporation of socioeconomic data in a subsequent version of the index incorporating climate impacts and/or risk). Similarly, it may be desirable to define sub-regions of the UK-European domain for the final presentation of the Index. Figure 11 shows a regional classification based entirely on climate, as an illustrative example.

4. Concluding assessment of the prospects for the development of a European ACI

Based on the information reviewed above, we can say that the prospects for constructing an analogue to the Canada-US ACI over the European region are promising. No changes to the formulation of the index are required; rather, the main challenge is to select the optimal gridded dataset for the temperature and precipitation-related extremes that enter into four of the six ACI components. The E-OBS-CLIMDEX gridded product appears to be the most suitable basis for these components. However, due to concerns with this product in areas where the underlying station data are sparsely distributed, it may be desirable to exclude these areas from the ACI. As illustrated in Section 3, overlaying the ECA&D station distribution onto the E-OBS grid would allow data-sparse regions to be excluded from the ACI in a straightforward manner. Finally, since E-OBS-CLIMDEX is based on a 1981-2010 base period, it will be necessary to recalculate the various percentile thresholds for the 1961-90 base period, in order to allow ready comparison of the UK-European ACI with the Canada-US ACI.

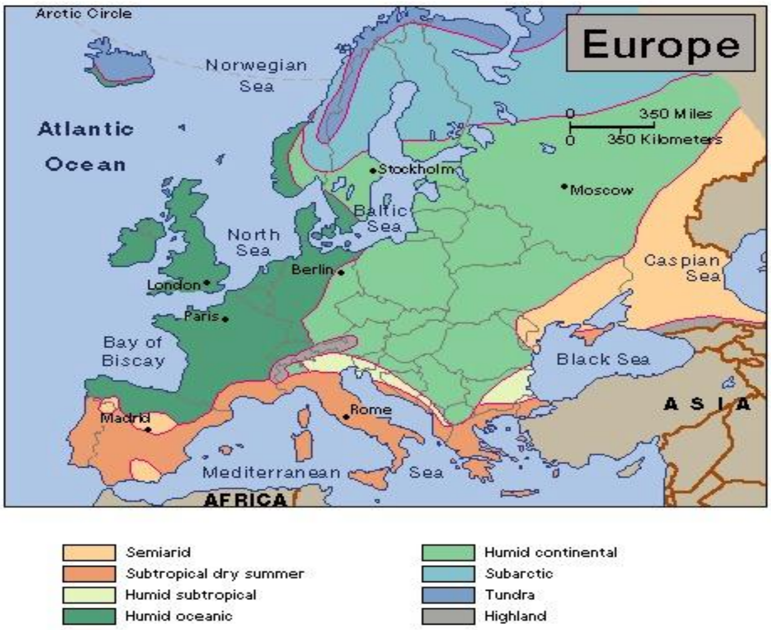


Figure 11. A climate classification scheme for Europe.Source: https://sites.google.com/a/masdstudent.org/europe-s-world-geography/climate

References

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Glossary of Terms and Acronyms

CLIMDEX: A set of 27 index definitions used to characterize the statistical properties of any source of climate data, produced through the coordination of the joint WMO CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI).

ECA&D: European Climate Assessment & Dataset. Science-based operational service, with contributions from 66 meteorological and hydrological services, observatories and universities from across Europe and the Mediterranean. Provider of daily, quality controlled datasets of key meteorological variables.

E-OBS: Gridded data set based upon ECA&D daily climate variables.

GHCN: Global Historical Climate Network, a compendium of data collected from many thousands of meteorological stations worldwide.Two versions are publicly available: GHCN-Monthly and GHCN-Daily.

GHCNDEX: Global data set containing the CLIMDEX indices constructed from GHCN-Daily, interpolated onto a grid of equally spaced latitude and longitude.

HadEX, HadEX2: Global data sets containing the CLIMDEX indices constructed from many thousands of meteorological stations worldwide, Hosted by the UK Met Office Hadley Centre for Climate Change.

PSMSL: Permanent Service for Mean Sea Level.

Reanalysis: Reanalysis products are global, gridded data sets including many more climate variables than are provided in standard observational data sets. This is made possible by the fact that reanalyses are in fact climate model simulations that are heavily constrained by various types of observations: e.g., land-based, ocean-based, balloon-borne, aircraft, and satellite.

standardized anomaly: The difference between a quantity and its average value over a reference period, divided by the standard deviation of the quantity over the reference period.

Institute and Faculty of Actuaries

London

7th Floor · Holborn Gate · 326-330 High Holborn · London · WC1V 7PP
Tel: +44 (0) 20 7632 2100 · Fax: +44 (0) 20 7632 2111

Edinburgh

Level 2 · Exchange Crescent · 7 Conference Square · Edinburgh · EH3 8RA
Tel: +44 (0) 131 240 1300 · Fax: +44 (0) 131 240 1313

Oxford

1st Floor · Park Central · 40/41 Park End Street · Oxford · OX1 1JD
Tel: +44 (0) 1865 268 200 · Fax: +44 (0) 1865 268 211

Beijing

6/F · Tower 2 · Prosper Centre · 5 Guanghua Road · Chaoyang District · Beijing China 100020
Tel: +86 (10) 8573 1000 · Fax: +86 (10) 8573 1100

Hong Kong

2202 Tower Two · Lippo Centre · 89 Queensway · Hong Kong
Tel: +11 (0) 852 2147 9418 · Fax: +11 (0) 852 2147 2497

www.actuaries.org.uk