Climate impacts on vines in the upper Douro valley: Cold air pooling and unprecedented rainfall

Michael G. Sanderson[1], Marta Teixeira[2], Natacha Fontes[2], Sara Silva[2], and António Graça[2]

[1] Met Office, Fitzroy Road, Exeter, EX1 3PB, UK
[2] Sogrape, Rua 5 de Outubro, 4527, 4430-809 Avintes, Portugal

Abstract. Climate is arguably one of the most important factors determining the quality of wine from any given grapevine variety. This study focuses on climate impacts on vines in the upper Douro Valley, which is one of the most important viticultural regions of northern Portugal. Two different phenomena are studied: cold air pooling and unprecedented rainfall totals. Cold-air pools can have several different impacts on viticulture, including timing of budbreak, final grape quality and yields. Cold pools were studied using high time resolution data from two weather stations located in the upper Douro valley. High rainfall during late spring (April to June) can promote growth of the vines but increases the risk of fungal disease. High rainfall during harvest time (August to October) also bears the potential for severe operational disruption and heavy economic losses. The probability of unprecedented rainfall totals in spring and the harvest season over wine-growing regions of northern Portugal has been assessed using an ensemble of decadal hindcasts and three different gridded precipitation datasets. The probability of a precipitation event with unprecedented totals was low (less than 0.04), although such an event would be highly damaging to the vines. A year similar to 1993, when both seasons were exceptionally wet, would be expected to occur, on average, just once in the next 70-80 years in the current climate.

1 Introduction

The quality of wine from any given grapevine variety is determined by the soil, plant material and cultural practices, along with the local climate. These factors are important elements of the concept of terroir [1]. Terroir refers to “an area in which collective knowledge of the interactions between the physical and biological environment (soil, topography, climate, landscape characteristics and biodiversity features) and vitivinicultural practices develops, providing distinctive wine characteristics” [2].

A large diversity of terroirs is present in northern Portugal owing to the different types of soils, climatic variations between vineyards, viticultural management and grapevine varieties. Two aspects of climate which could impact on vine growth and grape quality are cold air pooling and unprecedented rainfall totals. These two phenomena are studied for vineyards located in northern Portugal along the upper Douro valley (Fig. 1). Full descriptions of the data, models used, and results are given elsewhere [3,4]. Here, a summary of the results from these two studies is given.

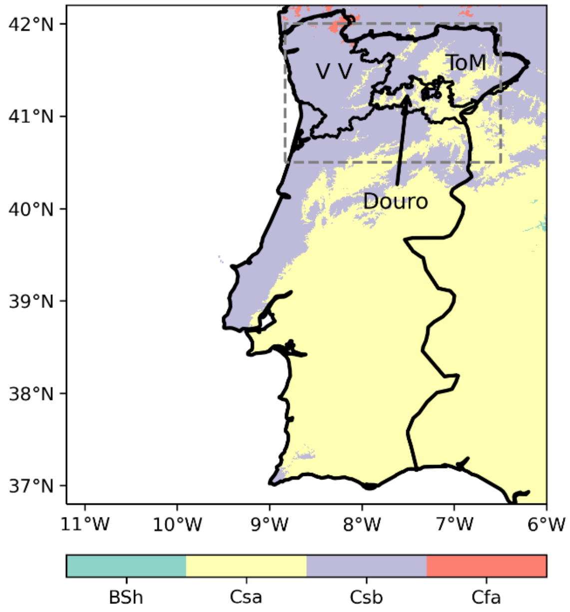

Figure 1. Koeppen climate zones of Portugal. The study areas (box with grey dashed line) are highlighted.

1.1 Cold air pooling

During calm, clear nights, air in contact with the ground becomes cooled via radiative energy loss. This cold air sinks under gravity into valley bottoms and hollows because it is denser than the surrounding air. The air at the valley floor continues to cool via outgoing longwave radiation. The resulting stable stratification prevents the air at the valley floor from mixing with the atmosphere aloft while the surrounding valley sides prevents horizontal movement. Cold air pooling (CAP) occurs where this cooled air collects on the landscape [5].

Cold air pools can affect viticulture in several ways. Cold air pooling during spring could be beneficial to wine growers in the upper Douro valley. The lower temperatures within cold pools would delay budburst and partly compensate for the acceleration of the vine growth cycle by high local temperatures during summer. However, cold pools during late spring could be harmful if they are accompanied by frosts which would damage the buds. Cold pools during the ripening and harvest season (August-October) could reduce heat stress of the vines and improve final grape quality by lengthening the maturation period of the growth cycle and by fostering aroma and colour production, both predicted to decrease under climate change [6].

1.2 Unprecedented rainfall

Heavy rainfall can have a variety of impacts on vineyards. Those in the Douro valley are often sited on terraces on steep slopes, and so the soils are prone to erosion by heavy rainfall. High rainfall during late spring (April to June) may increase the risk of fungal disease and disrupt vine phenology, namely blossom and fruit set, which occur during this period as shown in Fig. 2. The total grape must production (green line) from a vineyard in the upper Douro valley is clearly lower in years with very high spring rainfall (purple line, especially 1988, 1993 and 1998. Additionally, the numbers of phytosanitary treat-ments (grey bars) were also larger in years with high spring rainfall. High rainfall during the grape ripening and harvest period (August to October) can also increase the risk of disease and inhibit access of machinery needed to harvest the grapes (data not shown).

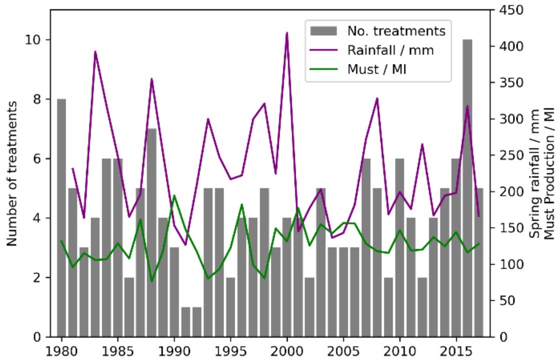

Figure 2. Historical series of total rainfall for late spring (April-June) over northern Portugal (purple line). Very high rainfall totals are seen in 1983, 1988, 1993, 2008 and 2016. Also shown are total grape must production in millions of litres (Ml; green line) and numbers of phytosanitary treatments recommended to control mildew and other fungal infestations (grey bars).

Although projections of climate for Portugal suggest an overall drying trend, the proportion of rainfall from extreme and unprecedented events could increase in the future [7]. The probability of unprecedented rainfall totals over northern Portugal is assessed for two critical periods of vine phenology [8]: budburst and flowering (April to June) and grape maturation and harvest (August to October).

2 Data and methods

2.1 Cold air pooling

Cold air pooling within valleys is controlled by the shape of the valley sides, which is quantified using the topographical amplification factor (TAF). The TAF is a function of the depth, width and cross-sectional area of the valley [5,9]. Higher values of the TAF correspond to narrow and deep valleys. If the valley narrows in the down-valley direction (corresponding to regions where the TAF increases), any flow of cold air down the valley is inhibited, promoting pooling of colder air [9]. Locations where cold pools could form were identified by calculating the TAF along the upper Douro valley using digital elevation data from the Shuttle Radar Topography Mission [9]. Positive and negative trends in the TAF in the down-valley direction were found along different parts of the Douro valley (Fig. 3).

Sogrape Vinhos operates a network of nine weather stations in the upper Douro valley that record a range of weather variables at 15 minute intervals. Their locations are shown by the solid circles in Fig. 3. Three stations are located at Leda where the TAF increases in the down valley direction indicating that cold pools could form there. Therefore, data from two of these stations, located near the valley floor and top of the valley were analysed to identify cold air pools. The weather data were available for 2011-2017.

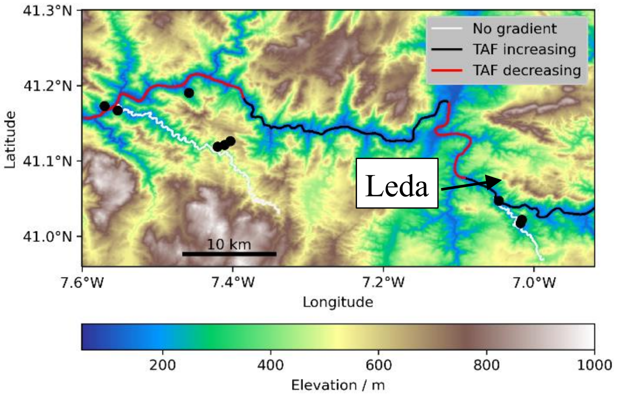

Figure 3. Elevations along the upper Douro valley (in metres) from the SRTM data [10] as shown by the colour bar. The solid circles represent weather stations operated by Sogrape Vinhos. Areas with increasing and decreasing trends in the TAF are indicated by the black and red lines respectively. Leda is located at the lower right of the image, where three weather stations are located.

The cold pool strength is defined as the maximum temperature difference between the two weather stations [3]. It is important to note that cold pools are defined as a temperature difference between two stations, when temperatures at the lower station are colder than those at the upper station. The actual temperatures may not be cold in an absolute sense. In the present study, a cold pool is said to occur when a temperature difference of at least 1 °C occurs one or more times during the night.

2.2 Unprecedented rainfall totals

Two datasets are used to assess the risk of unprecedented rainfall over northern Portugal (area inside the dashed grey line in Fig. 1). Simulated seasonal rainfall totals were taken from the Met Office's decadal climate prediction system DePreSys3 [11]. The forecast model is initialised with atmospheric, oceanic, and sea-ice observational data and current anthropogenic and natural forcings, so that the simulations are representative of current real-world climate. The hindcasts used here were produced from 1980 to 2017, when satellite data are available for model initialisation. The hindcasts begin on the 1st November of each year, corresponding to the start of each viticultural campaign. Forty ensemble members are available for each year, providing 1520 simulations (38 years × 40 members) of spring and harvest time rainfall totals. The five- and nine-month lead times allows the forecasts from the ensemble members to diverge, producing a wide range of plausible extreme rainfall events, some of which will not have been observed [12].

Three gridded datasets (E-OBS [13], Iberia01 [1] and CHIRPS [15]) were used to evaluate seasonal precipitation totals in DePreSys3 and correct any biases. E-OBS and Iberia01 were created by interpolation of surface rain gauge data. Rainfall totals in CHIRPS were derived using a combination of satellite observations of cold cloud temperatures and surface rain gauge data [15].

3 Results

3.1. Cold air pools

Cold air pools were identified on 901 nights when the temperature at the lower station was at least 1°C colder than the upper station one or more times during the night. A comparison of the temporal profiles from both weather stations on these nights led to 67 apparent cold pools being rejected. On a small number of nights warming at the upper station was apparent. On others, temperatures at both stations increased during the night, indicating no cold pooling had occurred. None of the cold pools lasted for more than a day, although a few lasted well into the daytime.

Here, only cold pools observed in late spring (April to June) and late summer (August to October) are studied. Most cold pools had strengths between 1 and 3°C. These pools are weaker than those recorded in other parts of Europe (locations include the Alps and the UK) [3].

The number of cold pools in each season is shown in the upper panel of Fig. 4. The numbers of pools vary considerably, between 5 and 30 in spring and 11 and 33 in summer. Air masses in spring 2011 in the upper Douro Valley were anomalously warm, which is reflected in the small number of cold pools in this year. The data series is too short to estimate any trends.

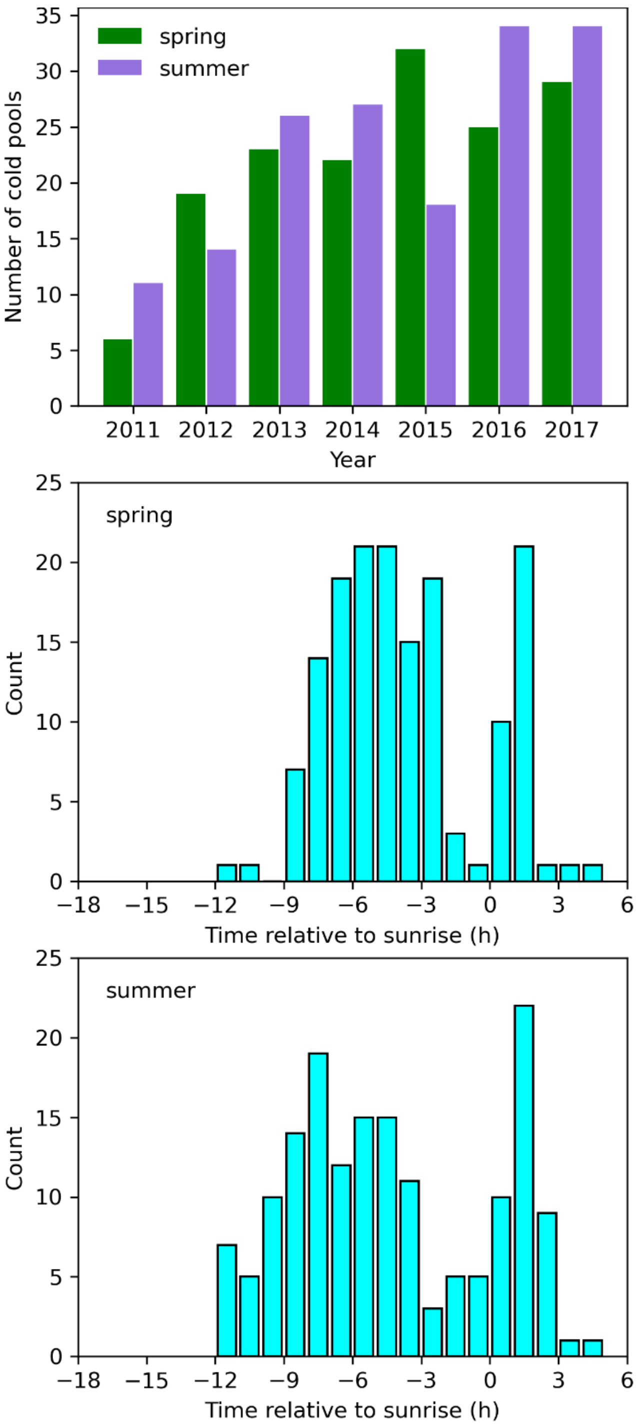

Figure 4. Upper panel: number of cold pools in the upper Douro valley during spring and summer of each year. Middle and lower panels: numbers of cold pools in each hour relative to local sunrise, using the times at which the maximum strengths were recorded, for spring and summer.

The number of cold pools in each hour relative to sunrise is shown for spring and summer in the middle and lower panels of Fig. 4. The hours in which the maximum cold pool strengths are seen are broadly the same in both seasons. During spring, most cold pools reach their maximum strengths between 5 and 7 hours before sunrise. In summer, the distribution is broader, where cold pools reach their maximum strengths between 4 and 9 hours before sunrise. In both spring and summer, a secondary maximum in cold pool numbers is seen 1-2 hours after sunrise, probably due to erosion of the cold pool where the upper station emerges into the boundary layer, but the lower station remains within the cold pool for a longer period. Heating of the valley floor by sunlight and dissolution of the cold pools would be further delayed by the presence of frost or fog [3]. A number of dams were built along the Douro in the 1970s, which has resulted in an increase in the number of cold winter fogs, which become trapped in the valleys [16].

3.2 Unprecedented rainfall

3.2.1 Evaluation of rainfall in the decadal hindcasts

The rainfall totals from DePreSys3 for each season (i.e., late spring, April to June, and late summer, August to October) were compared with those from the three gridded datasets (E-OBS, Iberia01 and CHIRPS). A full description of the evaluation is given elsewhere [4]; only a summary is provided here.

Seasonal rainfall totals over Spain and Portugal from DePreSys3 were compared with totals from the three gridded datasets. DePreSys3 reproduced the spatial pattern, with higher rainfall totals over northern Spain and Portugal, and smaller totals over the south of both countries [4].

Next, time series of rainfall totals over northern Portugal were calculated for each season from DePreSys3 and the three gridded datasets. If the ensemble mean precipitation from DePreSys3 is correlated with the observations, the modelled rainfall extremes would be tied to the initial conditions, which could mean a full range of possible climatic states would not be sampled. For late spring, Pearson correlation coefficients (R) between the ensemble mean precipitation and the three gridded datasets were 0.12 or smaller, and the corresponding *p*-values were about 0.5 or larger, indicating no correlation. For summer, the correlation coefficients were larger and the *p*-values were in the range 0.01-0.08, indicating some correlation. The hindcasts for spring are therefore independent of the initial conditions, whereas the hindcasts for late summer represent events that follow the slowly evolving climatic state [4].

3.2.2 Fidelity of the decadal hindcasts

The fidelity of the DePreSys3 hindcasts is assessed further over the study area of northern Portugal (Fig. 1). A key requirement is that the distribution of rainfall in the model ensemble members and observations should be indistinguishable [12]. Using the rainfall time series for each season (see Sect. 3.2.1), 10,000 proxy time series were sampled by bootstrapping with replacement from the modelled rainfall series. If the mean, standard deviation, skewness and kurtosis from the observations are within the central 95% of the model bootstraps, the modelled and observed rainfall totals are considered to be indistinguishable [12]. An example of the modelled distribution and observed precipitation totals is shown in Fig. 5.

For both spring and harvest time, the standard deviation, skewness and kurtosis from all three observed datasets (Iberia01, E-OBS and CHIRPS) lie within this percentile range. Biases were found in the mean precipitation totals. A dry bias for summer was found when comparing modelled precipitation totals with CHIRPS and Iberia01. Conversely, when comparing modelled precipitation totals with E-OBS, a wet bias was found for spring, whereas the summer rainfall totals were in good agreement.

The bias in the modelled precipitation totals was corrected as follows. The difference between the ensemble mean and the observations was calculated, and then this difference was added to each of the hindcast ensemble members. This approach corrects the bias in the mean of the modelled rainfall totals but has no effect on the other characteristics of the rainfall distribution. All the observed metrics now lie within the central 95% of the model distributions; therefore, the model is statistically indistinguishable from the observations [12].

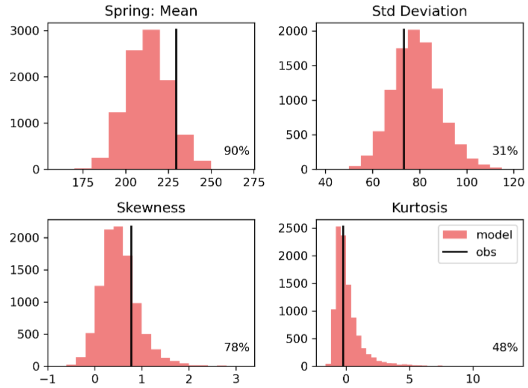

Figure 5. The distributions of the mean, standard deviation, skewness and kurtosis of the sampled modelled precipitation data (light red) compared with the observed values from CHIRPS (black vertical lines) for late spring (April to June). The vertical scales indicate the number of values in each of the histogram bins. The percentile of the observed value in the sampled model distribution is shown at the lower right of each panel.

3.2.3 Unprecedented precipitation events

Time series of modelled and observed rainfall totals (from CHIRPS) are shown in Fig. 6. The shaded region represents the minimum and maximum precipitation from the decadal hindcasts in each year. The observed precipitation series is shown by the solid black line. the dashed line indicates the maximum of the observations. Unprecedented precipitation events occur when the modelled precipitation totals exceed the highest observed values.

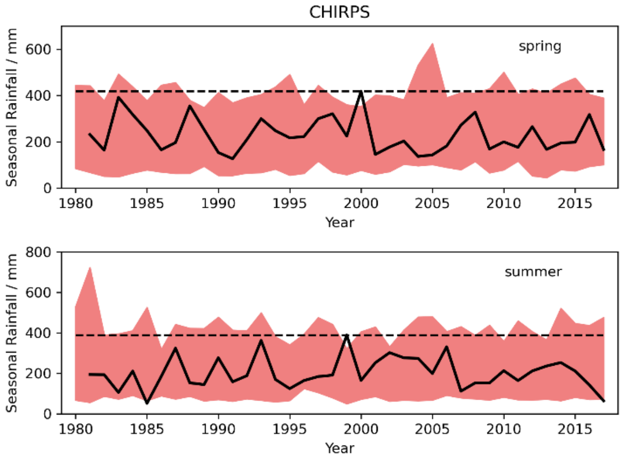

Figure 6. Seasonal rainfall totals for spring (April to June) and summer (April to October) in northern Portugal from 1980 to 2017. The shaded areas represent rainfall totals from the bias-corrected hindcasts. The solid black lines show observed rainfall totals from CHIRPS [15], and the dashed black lines indicate the highest observed values. Unprecedented rainfall totals are apparent when the modelled rainfall totals lie above the dashed line in each panel.

Trends in the numbers and magnitudes of the unprecedented rainfall events in the hindcasts were calculated using linear regression. Most of the trends were small and close to zero and none was significant at the 5% level.

It is assumed that the unprecedented events occur with probability P, which can be estimated as the number of events divided by the sample size [17]. A binomial approach is used to estimate the 'counting uncertainty' in these probabilities, using P as the binomial probability of success. The 95% confidence ranges in these probabilities were estimated using Wilson score intervals [18].

The probabilities together with the maximum precipitation totals from each of the observed datasets (Max Obs) and the number of modelled values above this total (N above) are summarised in Table 1. The range of probabilities calculated reflect the different datasets used to correct biases in the mean of the modelled precipitation totals.

Table 1. Probabilities of unprecedented rainfall from the decadal hindcasts. The 95% confidence intervals in the probabilities are shown in brackets.

	CHIRPS	**Iberia01**	**E-OBS**
Spring			
Max Obs	418	456	319
N above	20	7	41
Probability (95% CI)	0.013 (0.008, 0.020)	0.005 (0.002, 0.009)	0.027 (0.020, 0.036)
Summer			
Max Obs	389	460	384
N above	56	13	43
Probability (95% CI)	0.037 (0.028, 0.047)	0.009 (0.005, 0.015)	0.028 (0.021, 0.038)

The probability of an unprecedented rainfall event in either season is less than 0.04. Considering the 95% confidence intervals of the probabilities, an unprecedented rainfall event might be expected, on average, once in the next 20-100 years.

In 1993, both the late spring and late summer were exceptionally wet over northern Portugal. Years similar to 1993 were searched for in the hindcasts, using thresholds of 300 mm and 360 mm for either season. These thresholds were based on the observed rainfall totals for 1993. A year similar to 1993 reoccurring in the present climate would be expected to occur, on average, once in the next 70-80 years in the current climate. Although the probability of another year like 1993 is low, it would have a high impact on wine production, via erosion of soils and terraces, damage to the vines and reduced grape yields.

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4 Summary

Two different weather events of interest to wine companies, cold air pools and unprecedented rainfall totals, have been studied over northern Portugal. Cold air pools could moderate vine growth and final grape quality. Cold pools were identified in the upper Douro valley using data from two weather stations located near the valley floor and top of the valley. These cold pools were generally weaker than those observed in other parts of Europe. Cold pools were observed in late spring, when the vines begin to flower, and late summer when the grapes would be harvested. Most cold pools reached their maximum strength around 6 hours before sunrise.

A large ensemble of decadal hindcasts has been used to estimate the probability of unprecedented rainfall events over northern Portugal in the current climate. The large ensemble of model simulations, with nearly-two orders of magnitude more data than the observational record, allows the probability and return periods of extreme monthly rainfall to be estimated robustly. Unprecedented rainfall totals are possible over northern Portugal under the current climate in both late spring and late summer. The probability of such events in both seasons was less than 0.04. An unprecedented rainfall event might be expected, on average, just once in each season over the next 20-100 years. Another year similar to 1993, with very high rainfall in both spring and summer, is also low, and might occur, on average, once in the next 70-80 years in the current climate. Nevertheless, a year similar to 1993 could have high negative impacts on the area, via erosion of the terraces and loss of vines.

References

1. J. Gladstones. *Wine, terroir and climate change* (Wakefield Press, Kent Town, Australia, 2011)
2. OIV. *Resolution OIV/VITI 333/2010* (2010)
3. M. Sanderson, M. Teixeira, and A. Graça. J. Appl. Meteorol. Climatol. **61,** 1893-1904 (2022)
4. M.G. Sanderson, M. Teixeira, N. Fontes, S. Silva, and A. Graça. Clim. Serv. **30**, 100363 (2023)
5. J.D. Lundquist, N. Pepin, and C. Rochford, J. Geophys. Res. **113**, D22107 (2008)
6. X. Venios, E. Korkas, A. Nisiotou, and G. Banilas. Plants **9**, 1754 (2020)
7. J. Martins, H. Fraga, A. Fonseca, and J.A. Santos. Agronomy **11**, 990 (2021)
8. H. Fraga, A.I. García de Cortázar, A.C. Malheiro, J. Moutinho-Pereira, and J.A. Santos. OENO One **51**, 61-69 (2017)
9. C.D. Whiteman, *Atmospheric Processes over Complex Terrain*, Meteor. Monogr. Amer. Meteor. Soc. **45**, 5-42 (1990)
10. A. Jarvis, H.I. Reuter, A. Nelson, and E. Guevara, *Holefilled seamless SRTM data V4.* International Centre for Tropical Agriculture, CGIAR, accessed 26 November 2008, https://srtm.csi.cgiar.org.
11. N. Dunstone, D. Smith, A. Scaife, L. Hermanson, R. Eade, N. Robinson, M. Andrews, and J. Knight. Nature Geosci. **9**, 809-814 (2016)
12. V. Thompson, N. Dunstone, A. Scaife, D. Smith, J. Slingo, S. Brown, and S. Belcher. Nat. Commun. **8**, 107 (2017)
13. R. Cornes, G. van der Schrier, E.J.M. van den Besselaar, and P.D. Jones. J. Geophys. Res. Atmos. **123**, 9391-9409 (2018)
14. S. Herrera, R.M. Cardoso, P.M. Soares, F. Espírito-Santo, P. Viterbo, and J. M. Gutiérrez. Earth Syst. Sci. Data **11**, 1947-1956 (2019)
15. C. Funk, P. Peterson, M. Landsfeld, D. Pedreros, J. Verdin, S. Shukla, G. Husak, J. Rowland, L. Harrison, A. Hoell, and J. Michaelsen. Sci. Data **2**, 150066 (2015)
16. R. Mayson. *Port and the Douro* (4th Ed. Infinite Ideas Ltd, 2019)
17. C.K. Kent, E. Pope, V. Thompson, K. Lewis, A.A. Scaife, and N. Dunstone. Environ. Res. Lett. **12**, 054012 (2017)
18. E.B. Wilson. J. Am. Stat. Assoc. **22**, 209-212 (1927)