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Investigation and quality assessment of the Past Weather Code from the integrated Surface Database

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R J Pope, K M Willett, T J Osborn and P Thorne

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R J Pope[1] (eerjp@leeds.ac.uk), K M Willett[2], T J Osborn[3] and P Thorne[2]

[1]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT
[2]Met Office Hadley Centre, Exeter, EX1 3PB
[3]Climatic Research Unit, University of East Anglia, Norwich, NR4 7TJ

Abstract:

Quantitative SYNOP Code weather variables such as rainfall amount, although of high societal and environmental importance, are frequently subject to recording errors and inhomogeneities resulting in uncertain conclusions. Here we assess the viability of the more qualitative Past Weather Code (PWC) for its use in robust climate analysis in the belief that it is less prone to both random and systematic errors. The Past Weather Code data, from a selection of the National Oceanographic and Atmospheric Administration's Integrated Surface Database (ISD) (4731 sufficiently long stations), is quality assessed by searching for inhomogeneities in station PWC time series, removing the offending stations and averaging the remaining stations into a global gridded dataset. PWCs 6 (Rainfall), 7 (Snowfall) and 9 (Thunderstorms) are found to robustly exhibit seasonal features, e.g. the Indian monsoon and peak Northern Hemispheric winter snowfall. Precipitation responses to the North Atlantic Oscillation are also detected in winter PWC 6 data over Europe.

1. Introduction:

Quantitative SYNOP Code weather variables, e.g. temperature and rainfall (mm), are prone to observing errors, both random and systematic. In the case of rainfall measured by rain gauges, systematic errors arise from calibration error, wind-induced under catch or wetting-evaporation losses (Ciach, 2002). Temperature errors include measurement error, calibration error, solar or wind affected measurements and warming by surrounding urbanisation (Brohan, 2006). While large scale averages mitigate this issue to some extent, uncertainties remain. This is particularly an issue when looking at smaller regions and temporal scales. Furthermore, communication of changes in rainfall in mm can be more complex than simple changes in frequency analysis. Errors linked to instrument changes, station moves, shelter changes, mis-reporting of the correct values and changes in observation time are less likely to impact the homogeneity of the qualitative Past Weather Code (PWC). In theory, such data may be easier to use, easier to communicate basic findings and less prone to both random and systematic errors. However, such theories must be investigated as at present the PWC errors/uncertainties are less well understood.

The PWC is a descriptive measure of the weather, which, combined with other synoptic observations (e.g. temperature, wind speed), forms the World Meteorological Organisation (WMO)'s SYNOP code. The different PWC weather types are shown in Table 1. Weather types 0-3 are classed as "non-significant" (reporting is optional) and 4-9 are "significant" (must be reported), by the WMO.

The PWC is recorded over six and three hourly periods, starting at 0000, 0600, 1200, 1800 for six hourly and including 0300, 0900, 1500, 2100 for three hourly observations (WMO, 1988). As the PWC is hierarchical, only the top two weather types are recorded (W_1, W_2), where W_1 is more significant than W_2. For instance, if PWCs 5, 6 and 9 were observed in a recording period, only 6 and 9 would be recorded as W_2 and W_1 respectively (WMO, 1988). Prior to 1st January 1982 only the most significant weather type was recorded (W) (WMO, 1988; Dai, 2000).

Table 1: World Meteorological Organisation (WMO) Past Weather (W_1W_2) Codes:

Manual Code: 4561

- 0 - Cloud covering half or less of the sky throughout the period
- 1 - Cloud covering more than half the sky during part of the period & half or less for the rest
- 2 - Cloud covering more than half the sky throughout the period
- 3 - Sandstorm, duststorm or blowing snow
- 4 - Fog or ice fog or thick haze
- 5 - Drizzle
- 6 - Rain
- 7 - Snow, or rain and snow mixed
- 8 - Shower(s)
- 9 - Thunderstorm(s) with or without precipitation

Automated Code: 4531

- 0 - No significant weather observed
- 1 - Visibility reduced
- 2 - Blowing phenomenon, visibility reduced
- 3 - Fog
- 4 - Precipitation
- 5 - Drizzle
- 6 - Rain
- 7 - Snow or ice pellets
- 8 - Showers or intermittent precipitation
- 9 - Thunderstorm

Other major changes to the PWC around 1st January 1982, applied to both land and marine weather stations, included optional recording of PWC types 0-3 and the introduction of automated stations that had different weather types for PWCs 0-4. North America has many PWC data gaps as stations there used a different PWC type called PWC24 (FCC 2004). It has different weather types with 13 classifications (PWC has 10), e.g. 01: fog, 10: tornado. The PWC24 should also be recording every hour, while the PWC is recorded at fewer frequency intervals. In this study, only the PWC (W_1) data will be used as W_1 is more significant than W_2.

Investigation into the PWC as a climate data record has been relatively limited to date. Previous studies investigating the PWC data include:

- Dai (2000) used both the Past and Present (another descriptive code more common to the USA) Weather Codes to look at global precipitation patterns. He successfully derived global climatologies (DJF and JJA) of precipitation frequency of occurrence between 1975 and 1997.

- Cacciamani, et al. (1994) used Present and Past Weather Code thunderstorm data to create a climatology of the thunderstorm activity in the Po Valley, Italy.
- Olivier (2002) used PWC 4 data to study the frequency of fog events along the West coast of South Africa, which could be a valuable water resource through fog catching.
- Rydock (2005) used the Present Weather data to investigate the effect of rainfall on structures (e.g. standing walls) by deriving driving rain maps.

This paper attempts to quantify the robustness of the PWC through quality assessment of the data and its ability to reproduce well known global precipitation patterns in spatial and temporal domains. It explores the potential of using the PWC as a complimentary dataset to the more quantitative variables in the SYNOP code and for communication of precipitation changes/patterns to non-scientific audiences.

2. Dataset description:

The PWC (W_1) data comes from the Integrated Surface Database (ISD), which is archived and maintained by the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Centre (NCDC) (Lott, 2004). The ISD includes approximately 30,000 weather stations, with the earliest measurements from 1900. However, the vast majority of stations only have data archived from 1973 onwards. Therefore, this study used stations with sufficient PWC records, between 1973-2008, long enough to derive PWC type climatologies. This resulted in 4731 stations. All observations used have passed the Lott (2004) quality assurance process (Flag=1 in ISD dataset). Further pre-processing steps were taken to eliminate duplicate stations and combine data from multiple sources that appear to be from identical stations based on location and data characteristics.

The sub-daily PWC data were converted to monthly totals of event days for each PWC weather type. An "event day" was defined as a day, which received a reporting during one or more of the sub-daily PWC W_1 observations. For instance, PWCs 4, 5 and 9 may have been recorded in three separated observational periods, results in three event day classifications of Fog, Drizzle and Thunderstorm(s).

The PWC data, which passed the quality assurance (QA) tests, discussed below, were averaged onto a global grid of 5° latitude by 5° longitude resolution to assess large scale features. Given the short spatial scales of the types of weather recorded by PWC, such large grid boxes (>500km^2 in places) may present problems in cases where stations contain missing data. Differences in reporting practices (e.g., time period of PWC report, manual vs automated etc.) may also lead to uncertainties. We hope these are minimised by the QA tests, described in Section 3.

3. Quality Assurance Process/Methodology:

Inhomogeneity is a common problem for assessing long-term features of climate data records. Causes of inhomogeneity include:

- *Manual observer change:* Subjective PWC classification may differ between manual observers over time.

- *WMO Recording Practice Changes:* For instance, the optional recording of PWC weather types 0-3 after 1982 (WMO, 1988; Dai, 2000).
- *Changes in Location/Elevation:* Meteorological conditions will be different between locations altering PWC time series (Jones et al, 1985a & b).
- *Station Automation:* Automatic-manual reporting differences (Dai, 2000) and alteration of the PWC code for automatic stations (WMO, 1988).
- *Station Reporting Changes:* Changes in recording intervals could lead to inconsistent monthly day event totals (O'Loingsigh et al., 2010).

Jones, et al. (1985a & b) describe two possible methods to assess inhomogeneities in station temperature series. Firstly, metadata, where available, can be used to detect sources of station inhomogeneities. Secondly, in the absence of metadata, inconsistencies in difference series of neighbouring stations can be used as a guide to major inhomogeneities. In the absence of digitised metadata, we use the second method. We use the student t-test for inhomogeneity (TTH) to detect stations with PWC inhomogeneities in the multiple weather types. Additionally, we use a missing data threshold (MD) to classify stations as either "Usable" or "Non-Usable".

Following QA testing, data prior to 1986 were discarded as were PWC codes 0-4. Firstly, the WMO 1982 inhomogeneities (optional reporting of PWC 0-3), described by Dai (2000), were commonly found in many stations and resulted in between approximately 300-400 (5-10%) more station quality assurance failures per PWC type in earlier data screenings. Therefore, only data from 1986 onwards were selected, removing the effect from the WMO 1982 changes and the lag time for the new reporting practice guidelines to take effect. Secondly, the lack of metadata meant it was difficult to determine if or when stations had become automated. In Table 1, only PWCs 5-9 are comparable in the codes, so PWCs 0-4 were excluded from further analysis. This assumes that the difference between manual and automated recording of the PWC are negligible.

The missing data (MD) test is used because many of the stations had large periods of missing data. Therefore, a subjective threshold of 5 years continuously missing data meant PWC time series with limited data were removed.

The t-test for inhomogeneity (TTH) is applied to candidate-neighbour composite difference series to detect change points where data samples either side appear to be from significantly different populations.

For each station its 10 nearest neighbouring stations' time series were averaged together and subtracted from it creating a difference series. However, in an attempt to keep climatological precipitation consistency, only the neighbouring stations within 1000km were used in the neighbour average and if fewer than 3 of the neighbours were within this threshold then the station was excluded from further analysis due to the lack validation opportunities. The student t-test was then used on the 60 month sample time series either side of a running point in the difference time series to detect large step changes in the difference time series which could be due to station inhomogeneity. This provides a t-test time series. In cases where the t-test series had 5 years of continuous significant differences at the 99% significance level the station was deemed to be influenced by an inhomogeneity. Shorter periods were trialled but detected inhomogeneities appeared around the time of known large scale natural variability such as ENSO.

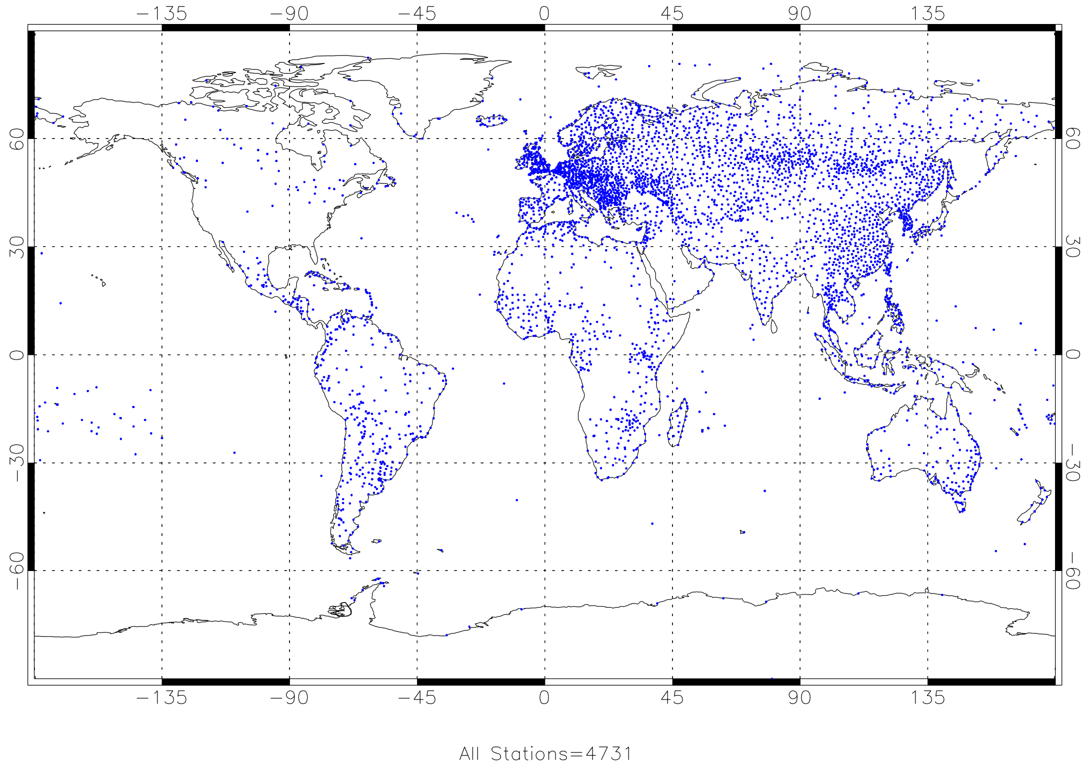

Figure 1: Map of all ISD stations selected for looking at PWC code data. Note that very few US stations are used, because they record a different type of PWC code.

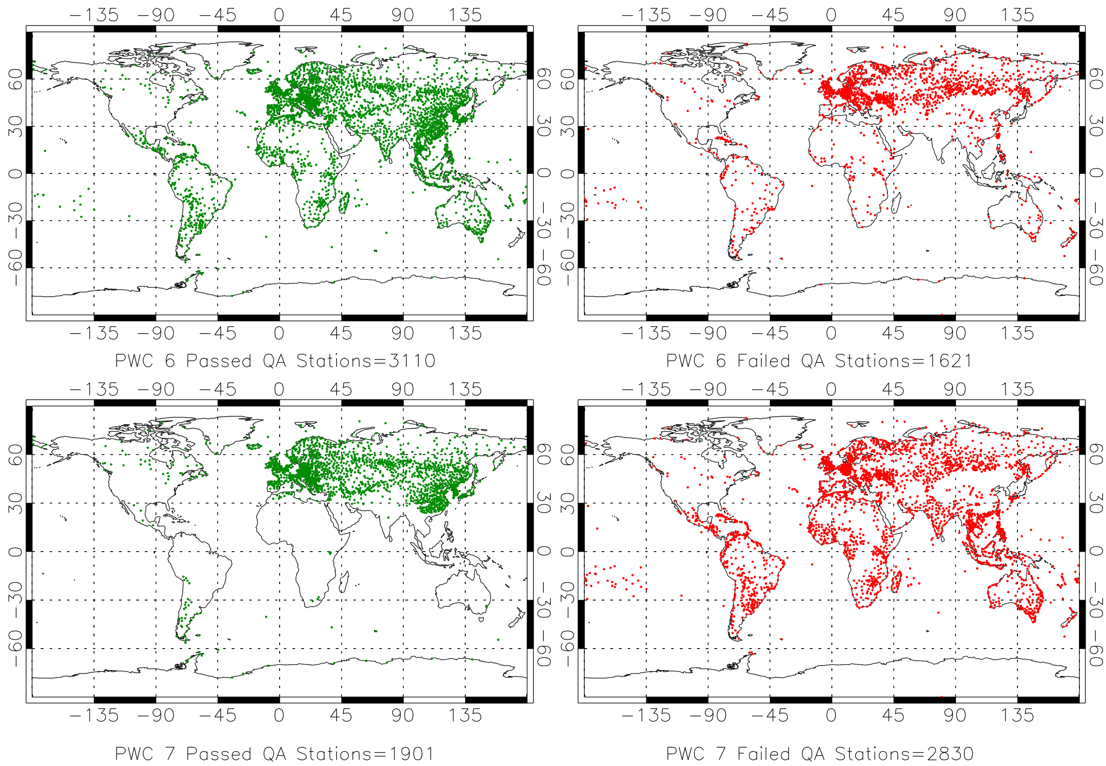

Figure 2: PWC maps of stations which passed (green) and failed (red) the quality assurance process for PWCs 6 (rain) and 7 (snow).

Only PWC types at stations which passed the MD test first and then the TTH test were classed as "Usable" and all others were set to "Non-Usable". Figures 1 and 2 show maps of all the stations and Usable and Non-Usable stations for PWCs 6 (rain) and 7 (snow), respectively. In both cases, stations removals are global in range. For snow, nearly all stations in the tropics are removed. Snow is a low frequency event in these regions and multiple timeseries will be zero because of it, leading to their failure in the QA. As the data are monthly totals, when they are zero, it is difficult to ascertain if it is recording practices (i.e. were any observations taken in the time period- in PWC timeseries it is common to see recorded frequencies for a period followed by zeroes as the station stops recoding) or no weather events. In total, 34.4 % and 59.8 % of stations were removed during the QA tests for PWC 6 and 7, respectively.

4. PWC global and seasonal patterns

The PWC monthly frequencies of days when significant weather occurred during 1986-2007 were seasonally averaged for June-July-August (JJA) and December-January-February (DJF) for each grid box. The season DJF 2008-9 (December 2008, January and February 2009) was omitted due to missing January and February and so for annual consistency the JJA for 2008 was also not included. Figures 3, 4 and 5 show these seasonal means for PWC 6 (rain), 7 (snow) and 9 (thunderstorms), respectively. The PWC 6 signal is noisy but features such as the Indian monsoon are detectable, with 0-5 d month^{-1} where rain occurred in DJF and 15-20 d month^{-1} in JJA. The typical time of the year for the Indian Monsoon spans from June to September. Over continental Europe, DJF rain day frequency is high at 5-15 d month^{-1}, and decreasing in JJA to 0-10 d month^{-1}. Over the UK though, there is little seasonal variability as frequencies range from 15-20 d month^{-1} in both seasons. In northern Asia, DJF rain day frequencies are low typically at 0-2 d month^{-1}. However, in JJA the frequencies range between 0-10 d month^{-1}, especially in eastern Asia. In Southeast Asia, the seasonality is less well defined and the frequency of rain days across seasons is more or less constant at 10-17 d month^{-1}. An African seasonal dipole can be seen, where in DJF the Sahel rain day frequencies range between 0-2 d month^{-1}, while in southern Africa rain day frequencies range between 5-10 d month^{-1}. In JJA, the converse occurs with higher (lower) rain day frequencies in the Sahel (southern Africa).

The hemispheric average annual cycles of monthly totals (Figure 3c) show rain day frequency peaks and troughs that have a lag time of approximately 6 months between hemispheres. The Northern Hemisphere rain day frequency cycle peaks (troughs) in August (February) at approximately 5 d month^{-1} (2 d month^{-1}). The amplitude in the Southern Hemisphere rain day frequency cycle is slightly smaller ranging from 3.5 - 5 d month^{-1} in September and January, respectively.

The analysis of PWC 7 (snow) is mainly restricted to the higher latitudes of the Northern Hemisphere where snowfall is more prominent. In regions where snowfall is very rare, stations may have been removed due to the MD test. The Southern Hemisphere, due to the lower frequencies of stations, has limited coverage of snow day frequency. The seasonal averages over Eurasia nicely highlight the snow day frequency spatial seasonal cycle with higher (lower) frequencies of snow days at 5-20 d month^{-1} (0-2 d month^{-1}), in DJF (JJA).

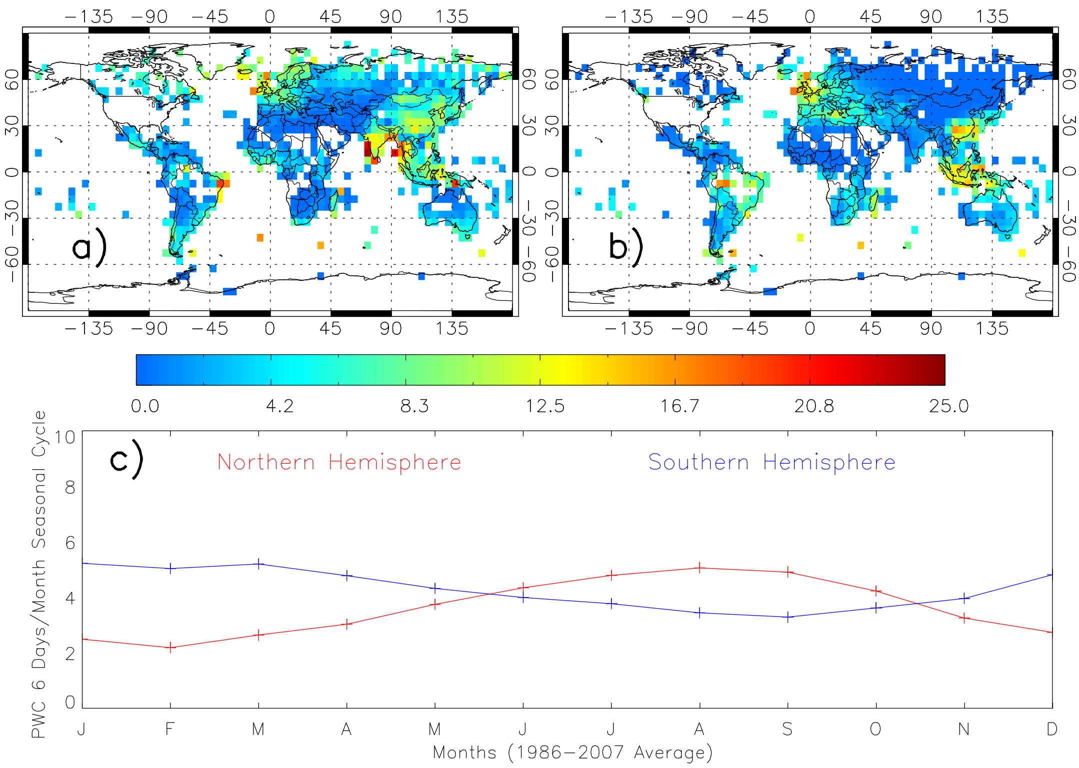

Figure 3: Seasonal maps and hemispheric annual cycles for PWC 6 between 1986-2007: a) JJA, b) DJF and c) hemispheric seasonal cycles (days/month).

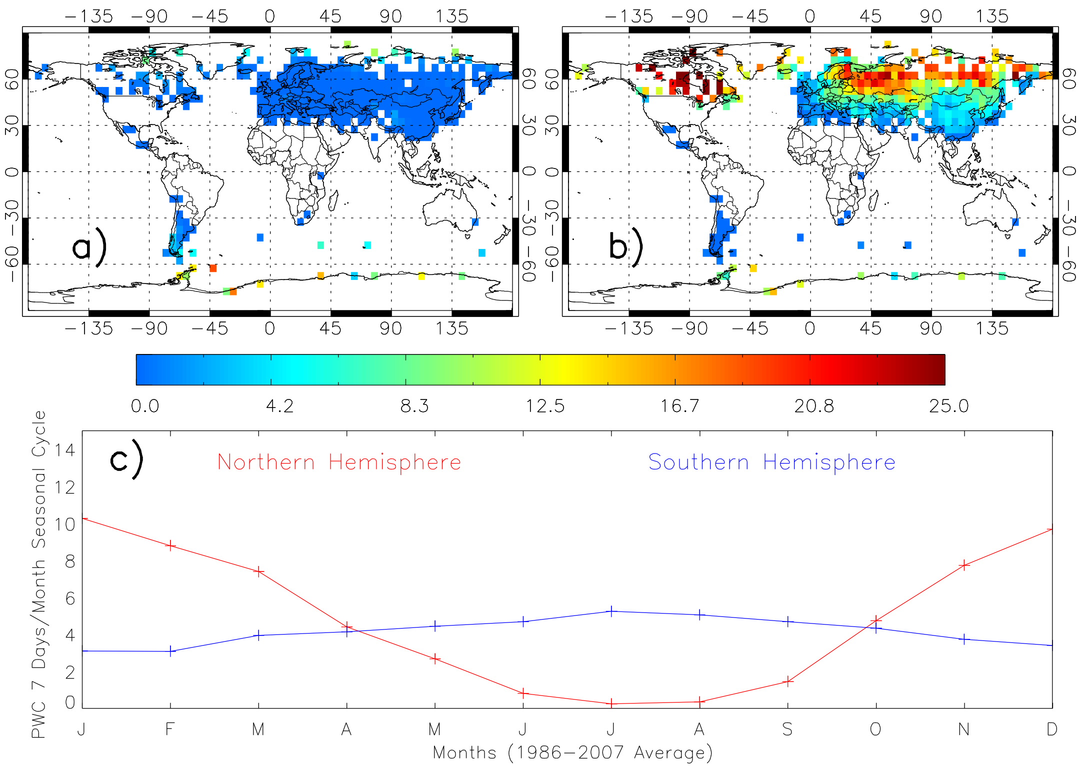

Figure 4: Seasonal maps and hemispheric annual cycles for PWC 7 between 1986-2007: a) JJA, b) DJF and c) hemispheric seasonal cycles (days/month).

The hemispheric average annual cycle of snow day frequency (Figure 4c) shows the Northern Hemispheric annual cycle peaking in January and December at 10 d month^{-1}, and troughs in July below 1 d month^{-1}. The Southern Hemispheric annual cycle is less pronounced, similar to rainfall, probably due to the limited station coverage especially in the higher latitudes, but ranges from approximately 3 d month^{-1} in summer (December-January-February) and peaks in winter (July-August) at close to 6 d month^{-1}.

The seasonality of PWC 9 (thunderstorms) is well defined between hemispheres and season. In the hemispheric summer season, greater surface heating and convection increases thunderstorm frequencies. In the DJF, the Northern Hemisphere winter has 0-1 d month^{-1} of thunderstorms, while in the Southern Hemisphere thunderstorm events range from 5-12 d month^{-1}. In JJA, the Southern Hemisphere winter experiences 0-1 d month^{-1} of thunderstorms, but the Northern Hemisphere mid-latitudes and sub-tropics range from 0-5 d month^{-1} and 5-15 d month^{-1}, respectively. The annual cycle shows similar signals with peak (trough) Northern Hemispheric thunderstorm activity, approximately 4 d month^{-1} (under 1 d month^{-1}), in JJA (DJF). The opposite occurs in the Southern Hemisphere, but with similar magnitudes for the respective seasons (i.e. winter summer).

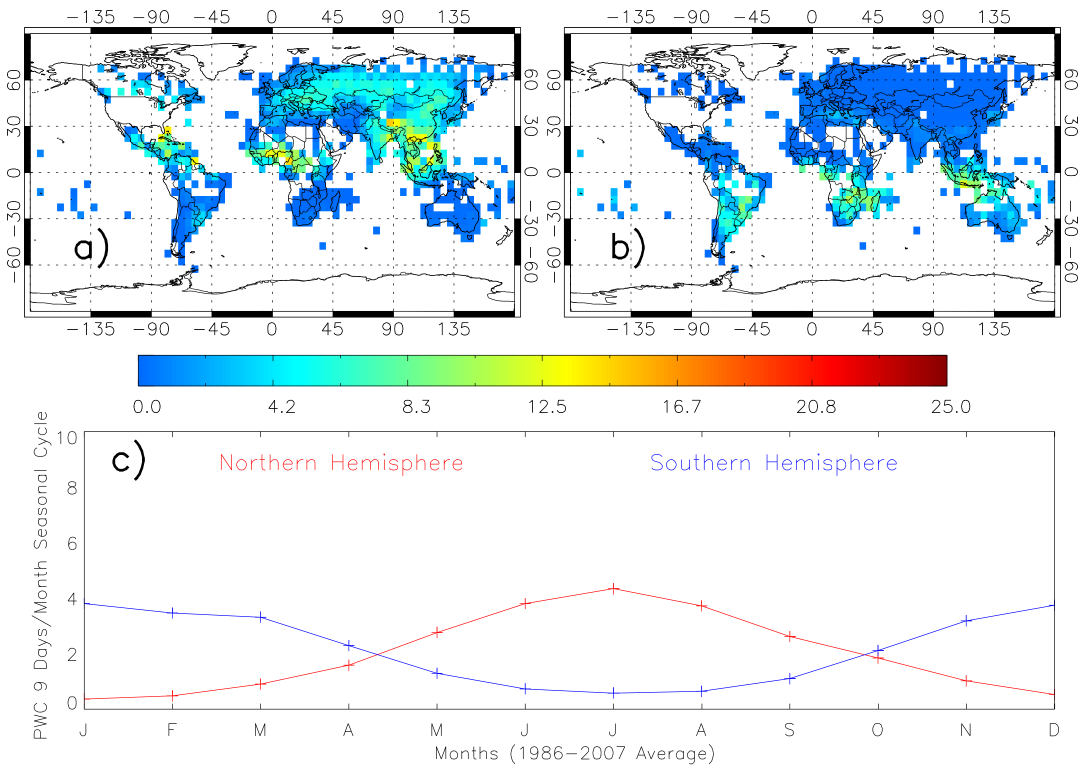

Figure 5: Seasonal maps and hemispheric annual cycles for PWC 9 between 1986-2007: a) JJA, b) DJF and c) hemispheric seasonal cycles (days/month).

5. The detectability of the North Atlantic Oscillation in PWC data

The North Atlantic Oscillation (NAO), described more fully in Osborn (2006), is an atmospheric phenomenon affecting weather patterns over western Europe, most prominent in the winter. It is expressed through the pressure gradient between the climatological Icelandic Low and Azores High pressure systems and it influences the entry of North Atlantic storm tracks in to Europe.

During a NAO positive phase, the winter pressure gradient between the Icelandic Low and the Azores High is stronger than average. This results in milder and wetter conditions in north western Europe by directing the majority of winter storms north-east. Southern Europe and the Mediterranean have a drier winter than average. In the negative phase of the NAO, when the pressure gradient is weaker than normal, the converse applies.

Dickson, et al. (2000) reproduces the conditions described by Osborn (2006|), by calculating the positive-negative phase precipitation differences in the NAO record (1947-96). They found positive differences of 1.5-2.4 mm in northern Europe and negative differences of -1.5 to -2.4 mm in southern Europe (Iberia). Hurrell (1995) found similar patterns looking at moisture transport, with peak moisture transport of 200 $kgm^{-1}s^{-1}$ (1979-93), transported into northern (southern) Europe in the positive (negative) NAO phases, respectively.

Here, the PWC has been used to detect the winter patterns of the NAO. The monthly resolution winter NAO Index was obtained from the Climatic Research Unit (CRU- http://www.cru.uea.ac.uk/). The index is the normalised (standard deviation) monthly mean pressure difference between the Azores/Gibraltan and Icelandic weather stations (Jones et al. 1997).

Northern Hemisphere winter months (DJF) were averaged for all months with a positive phase NAO index value and separately for all negative phase NAO months, for each PWC weather type. The PWC data were only included when the NAO index series was greater (lower) than +/-1 standard deviation, following Hurrell (1995) and Dickson, et al. (2000).This resulted in 29 and 14 NAO positive and negative phase months, respectively, between 1986-2007.

The NAO phase averages of PWC 6 (rain) (Figures 6a and b) reproduce the expected higher rainfall frequencies over northern (southern) Europe in the NAO positive (negative) phases. Differencing the grid boxes between each phase (Figure 7a) highlights this rain day frequency dipole with positive differences of over 5 d $month^{-1}$ over the UK and between 1-5 d $month^{-1}$ over northern Europe. In southern Europe/Mediterranean there are negative differences of -1 to -5 d $month^{-1}$ and < -5 d $month^{-1}$ in Iberia. The black polygons represent significant differences between the two phase averages at the 95% significant level, using the student t-test (as the series are not continuous the effect of temporal correlation is not a factor).

The PWC 7 (snow) (Figures 6c & d) NAO phase averages have similar snow day frequencies of 0-4 d $month^{-1}$ in southern and western Europe, while the maximum frequencies are over 16 d $month^{-1}$ in northern Russia and Scandinavia. The NAO winter signal in the difference between the two phases (Figure 7b) reveals significant differences in NAO phase snow day frequency for some regions. There are significantly higher snow day frequencies in the positive phase over Scandinavia (1-5 d $month^{-1}$), Iceland (over 10 d $month^{-1}$) and northern Russia (~3 d $month^{-1}$) and significantly lower snow day frequencies over east and central Europe (3-5 ~d $month^{-1}$).We have been unable to find supporting literature describing European-wide patterns. Most studies consider impacts of the NAO on sub-regional (e.g. Eastern Europe: Bednorz (2004)) snow cover or reported studies related to US snowfall. Hartley (1999) found that snowfall is negatively correlated with the winter NAO in the north-east US. Over western and central Europe, we find that snowfall is more frequent in the NAO negative phase. However, over Russia, snowfall frequency and the NAO are positively correlated.

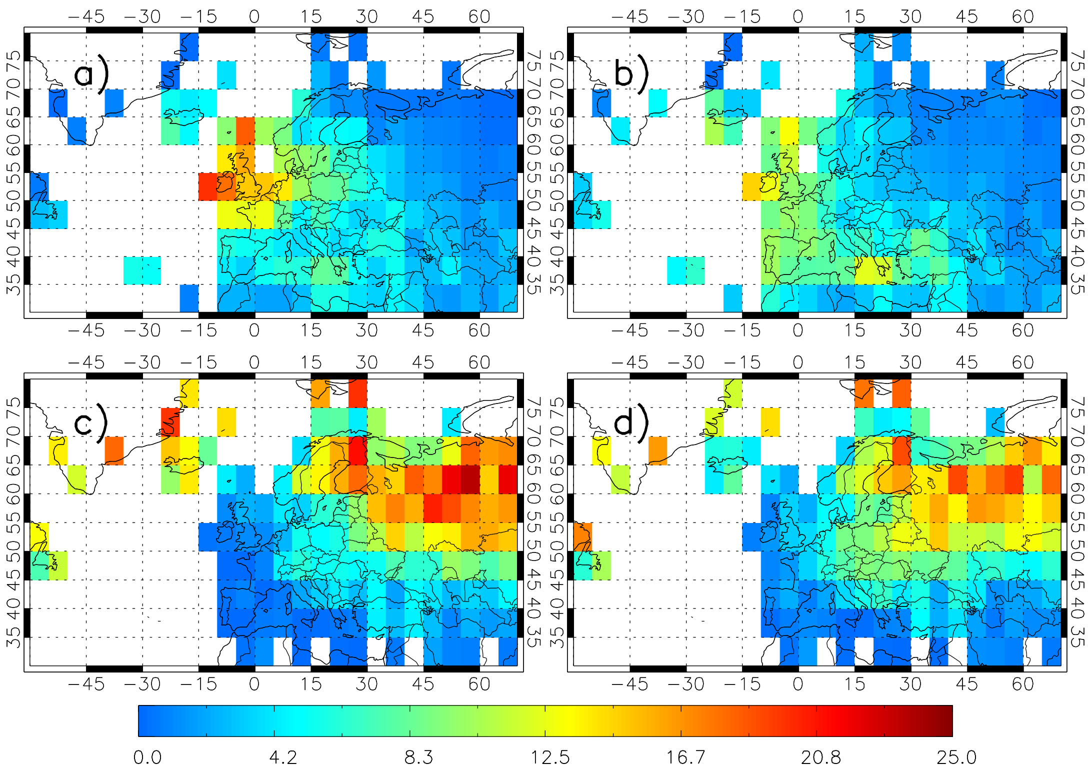

Figure 6: NAO composites of PWCs 6 and 7 between 1986-2007: a) PWC 6 NAO + composite, b) PWC 6 NAO – composite, c) PWC 7 NAO + composite and d) PWC 7 NAO – composite.

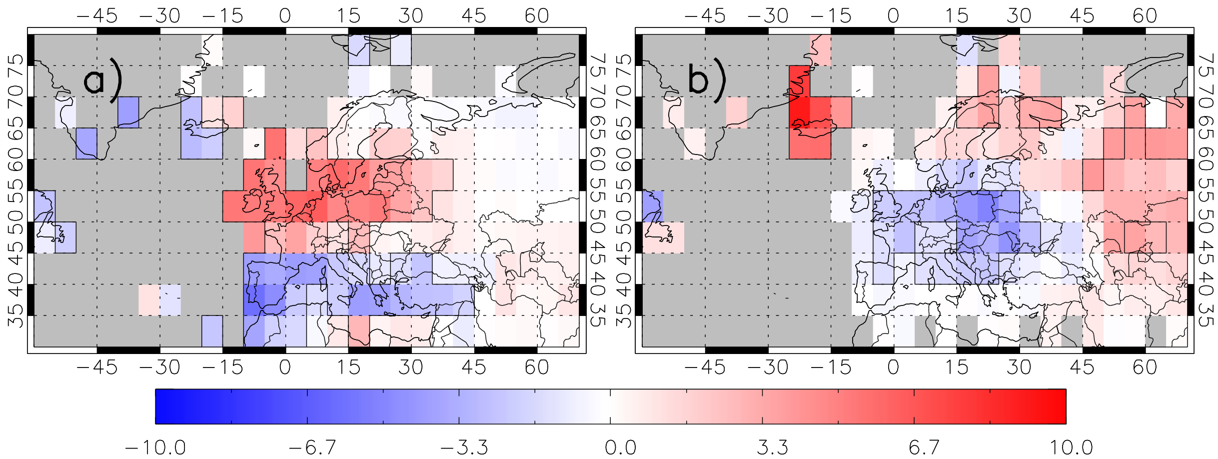

Figure 7: NAO positive – NAO negative composites for PWCs 6 and 7 between 1986-2007: a) PWC 6 NAO difference composite and b) PWC 7 NAO difference composite.

6. Discussion and Conclusion:

After applying quality assurance tests on the 4731 PWC stations, a reasonable number of stations were identified as being of sufficient length and quality for climate analysis: for PWC 5-9 (drizzle, rain, snow, showers and thunderstorms) this resulted in 2297, 3110, 1901, 2617 and 3030 stations , respectively. The Indian Monsoon is apparent in the JJA seasonal averages for PWCs 6 and 9. The Northern Hemispheric winter spread and summer retreat of snowfall days, and the seasonal hemispheric peak thunderstorm frequencies coinciding with summer induced surface/ boundary layer convection, are also apparent.

The phase of the winter NAO is apparent in PWC 6 (rain) where for example the positive phase increases (reduces) days with liquid precipitation (PWCs 5 and 8 too) over northern (southern) Europe, respectively. The winter NAO phase signal is also apparent in PWC 7 (snowfall) with the positive (negative) phase showing higher (lower) snow day frequency over Scandinavia, Iceland and northern Russia and lower (higher) snow day frequency over east and central Europe. These results go beyond the previous work which has focused on snow cover rather than snowfall frequency.

The detectability of these features shows the value of climate data records of frequency of drizzle, rain, snow, showers and thunderstorms. In many instances the concept of event day frequency may be easier to use than quantitative measures/units because it is less prone to recording and reporting errors or systematic changes of the observing system. Additionally, lightning damage claims could be verified by a local weather station PWC 9 (thunderstorm) event record, though lightning is now automatically and accurately detected using arrival time differences (ATD) between electromagnetic signals reaching a network of detectors. Furthermore, change in event day frequency may be more intuitive to some for communicating changes than mm yr^{-1} or percentage increases as it can be interpreted as how often one needs to use an umbrella or whether an investment in a tumble drier is necessary. While quantitative assessments will still be essential for issues such as flood management and irrigation, there is value in maintaining a PWC record for as many stations as possible.

These data are available in raw form from the NOAA NCDC website (http://www.ncdc.noaa.gov/oa/climate/isd/index.php) or for a subset of stations with long records as part of the HadISD dataset (Dunn et al. 2012; www.metoffice.gov.uk/hadobs/hadisd).

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