A new globally-complete monthly historical gridded mean sea level pressure data set (HadSLP2): 1850-2004.

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Abstract

We present an upgraded version of the Hadley Centre's monthly historical mean sea level pressure (MSLP) data set (HadSLP2). HadSLP2 covers the period 1850 to date, and is based on numerous terrestrial and marine data compilations. Each terrestrial pressure series used in HadSLP2 under went a series of quality control tests and erroneous or suspect values were corrected where possible or removed. Marine observations from the International Comprehensive Ocean Atmosphere Data Set were quality controlled (assessed against climatology and near neighbours) and then gridded. The final gridded form of HadSLP2 was created by blending together the processed terrestrial and gridded marine MSLP data. MSLP fields were made spatially-complete using Reduced-Space Optimal Interpolation (RSOI). Grid point error estimates were also produced.

HadSLP2 was found to have generally stronger subtropical anticyclones and higher latitude features across the Northern Hemisphere than an earlier product (HadSLP1). During the austral winter, however, it appears that the pressures in the southern Atlantic and Indian Ocean mid-latitude regions are too high; this is seen in comparisons with both HadSLP1 and with ERA 40. Over regions of high altitude, HadSLP2 and ERA-40 showed consistent differences suggestive of potential biases in the reanalysis model, though the region over the Himalayas in HadSLP2 is biased compared to HadSLP1 and improvements are required in this region. Consistent differences were also observed in regions of sparse data, particularly over the higher latitudes of the Southern Ocean and in the south eastern Pacific. Unlike the earlier HadSLP1 product, error estimates are available with HadSLP2 to guide the user in these regions of low confidence.

An evaluation of major phenomena in the climate system using HadSLP2 provided further validation of the data set. Important climatic features/indices such as the North Atlantic Oscillation, Arctic Oscillation, North Pacific Index, Southern Oscillation Index, Trans Polar Index, Antarctic Oscillation, Antarctic Circumpolar Wave, East Asian Summer Monsoon Index and the Siberian High Index have all been resolved in HadSLP2, with extensions back to the mid-19th century.

1. Introduction

The earliest charts and maps of monthly mean sea level pressure (MSLP) over the globe were pioneered by the likes of Buchan (1867,1869,1889), Hildebrandsson (1897) and Teisserenc de Bort (1883,1889). These entirely hand drawn map products were subsequently built on into the twentieth century by other scientists, culminating in the work of Lamb and Johnson (1966) who produced global MSLP charts for the months of January and July back to 1750[1]. In the age of the computer and sophisticated objective analysis techniques, several efforts have been made to develop high quality historical monthly mean sea level pressure (MSLP) data sets covering the Northern and Southern hemispheres and extending to global dimensions (e.g. Trenberth and Paolino, 1980; Jackson, 1986; Jones, 1991; Barnett and Jones, 1992; Jones *et al.*, 1999b; Kaplan *et al.*, 2000; Luterbacher *et al.*, 2002; Smith and Reynolds, 2004; Ansell *et al.*, 2006). Other than reanalysis products (Kalnay *et al.*, 1996; Kistler *et al.*, 2001; Uppala *et al.*, 2005), the major efforts to develop globally-complete MSLP products blending historical terrestrial and marine MSLP data have been made by the Hadley Centre in the UK (Allan *et al.*, 1996; Basnett and Parker, 1997[2])

This paper details the development and evaluation of a new version of the Hadley Centre's globally-complete monthly historical MSLP product (HadSLP2) on a 5^o latitude by longitude grid covering the period from 1850 to 2004, with a near-real-time update version, HadSLP2r, also available. HadSLP2 is the most recent version of the Hadley Centre's historical globally-complete gridded MSLP data products: GMSLP2 and HadSLP1 (Allan *et al.*, 1996; Basnett and Parker, 1997). Its construction involved a major digitisation of hard copy and scanned surface pressure data from historical sources from all over the globe (see Appendix 1 and References). This material was then used to extend, fill gaps in, and produce additional station time series that could be added to existing collations of electronic terrestrial (land and island) surface pressure records. Finally, these terrestrial records were all reduced to MSLP and blended with marine (ship-based) MSLP data from the International Comprehensive Ocean Atmosphere Data Set (ICOADS) (Worley *et al.*, 2005), which combines the Met Office's Marine Data Bank with the previous version of

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[1] April and October charts were never published, but copies are held by the Hadley Centre, Met Office, UK

[2] Principally version 2 of the Global Mean Sea Level Pressure (GMSLP2) gridded monthly data set and HadSLP1 (an updated version of GMSLP2).

COADS (Slutz *et al.*, 1985; Woodruff *et al.*, 1993, 1998). These blended, quality controlled and gridded fields were made spatially-complete by using Reduced-Space Optimal Interpolation (RSOI) (Kaplan *et al.*, 1997, 2000). Grid point error estimates and numbers of observations fields have also been produced. In this regard, HadSLP2 is superior to HadSLP1 and will ultimately be available as interpolated (HadSLP2), uninterpolated (HadSLP2.0), and near-real-time (HadSLP2r) products from http://www.hadobs.org.

2. Data development & sources

Atmospheric pressure data from historical terrestrial and marine sources were collected, collated, digitised, quality controlled and blended together to form the HadSLP2 data set. This undertaking involved a concerted search of data sources held by the UK Met Office Library and Archives, the use of scanned records from various WWW sites (see Appendix 2), and requests to individual meteorological services around the world for specific station series.

The prime sources for global monthly terrestrial (land, island and weather ship) data were the long duration records and/or ongoing climatic data compilations of the US Signal Office (Washington, War Department, 1870; U.S. Signal Office, 1871 – 1889), US International Observations (Washington, Signal Office, 1875-1881, 1881-1883, 1883-1885, 1884-1888), Hildebrandsson (1897), Lockyer (1908, 1909), Reseau Mondial (Air Ministry, Meteorological Office, 1910-1934), World Weather Records (Clayton, 1927, 1934, 1947; U.S. Weather Bureau, 1959; U.S. Environmental Science Services Administration, 1965-1968; NOAA, National Climatic Data Center, 1979-1985, 1987-1994, 1995-1999; 2005; WeatherDisc Associates, 1994), Monthly Climatic Data for the World (Washington, Weather Bureau, 1948-1967; Washington, Environmental Science Services Administration, 1968-1970; Washington, NOAA, EDS: 1971-2004), CLIMAT (World Meteorological Organisation, 1995), the Global Historical Climate Network (GHCN) versions 1 and 2 (Vose *et al.*, 1992; Wuertz per. com., 2002), the GCOS Surface Network (GSN) (http://lwf.ncdc.noaa.gov/oa/climate/gsn/gsnmap.html) and Young (1993). These were augmented by more regional, and various country and colonial records, data from European

Union (EU) funded projects (eg. monthly averages of daily data from IMPROVE (Camuffo & Jones, 2002), ADVICE (Jones *et al.*, 1999b) and monthly averages of daily data from EMULATE (Ansell *et al.*, 2006): see Appendix 2), and various publications by meteorological services throughout the world (see References and Appendix 1 for specific details). In addition, a number of individual station pressure records were provided through various contacts in meteorological services or research institutions world-wide (see Acknowledgements).

As a consequence of this major effort, the number of terrestrial stations used in the construction of HadSLP2 has increased from 718 in HadSLP1 to 2228 in the new version (see Figure 1 for station distribution through time). Of these 2228 stations, 615 have series longer than 100 years, though 275 have less than 20 years of observations. Not surprisingly many are in Europe. Existing HadSLP1 stations were extended to 2004 using CLIMAT records, where available. Particular efforts have concentrated on improving coverage over Antarctica (region of strong trends) and over particularly sparse regions of Africa, South America, Russia and Asia.

Marine observations from the International Comprehensive Ocean Atmosphere Data Set (ICOADS, Worley *et al.* (2005)) were also used in the construction of HadSLP2. ICOADS is a recent blending of the previous version COADS (Woodruff *et al.*, 1993) with the Met Office's Marine Data Bank, and also includes several million newly digitised observations (e.g. US Maury collection and the Japanese Kobe Collection), significantly improving coverage in the 1850-1860s and around the First World War years (Figure 1).

3. Methodology

In order to create globally-complete gridded terrestrial and marine based MSLP fields, a number of steps were required. In section 3a) we describe the quality control procedure adopted for the terrestrial observations, in 3b) our quality control and gridding strategy for the marine observations is outlined, in 3c) we describe how these quality controlled terrestrial observations and gridded marine fields are blended. To create globally-complete fields we employ RSOI, described in section 3d.

a). Quality control – Terrestrial data

Work on developing long, high quality MSLP stations series can be very manually intensive and time consuming (e.g. Madras (Chennai), Allan *et al.*, 2002; Nagasaki, Konnen *et al.*, 2003; Quebec, Slonosky, 2003). Unlike the studies cited above, which have focused on specific individual series, the number of stations requiring quality control in HadSLP2 necessitated a more automated quality control procedure being set up. While the automation procedure cannot compare to individual intense scrutiny, it has enabled us to include a very large number of series.

With this procedure, each station record underwent a series of quality control checks, after initially being corrected for attached temperature and standard gravity (where required), converted to standard units of hPa, and reduced to MSLP.

- Firstly, a check for internal consistency was performed. Each station series was compared to its monthly mean and standard deviations, calculated over the most recent and/or reliable period, in order to remove gross outliers caused by errors in station heights and misprints in data records. Anomalous values that were greater than 4 times the standard deviation were removed.
- A large number of our station series come from multiple sources, with considerable overlapping years. We therefore, secondly, blended sources to create a single MSLP series for each station. When combining the sources, preference was given to those deemed to be more reliable. i.e. had required least quality control hitherto.
- Thirdly, near neighbour checks were performed. Applying a similar technique to multiple qualitative comparisons and adjustments (MCA), described in Slonosky *et al.* (1999), each series was compared to its four nearest neighbours of similar length (to the north, south, east, west), and then flagged and adjusted only if a discontinuity was detected against 3 or more neighbours. This method however relies on having reliable neighbour series of complementary length. Unfortunately these were not always available, and so in these cases the station series was also compared to the nearest grid point value in HadSLP1 (this

check was only available for the period 1871-1998). We note that if all 4 neighbours also contained a discontinuity, no problem would be flagged.

- Fourthly, we check for break points in data series by applying a Kolomogorov-Smirnov (KS) test (Press *et al.,* 1992). Thorne *et al*. (2005) employed a KS test for homogenising radiosonde observations. This technique works by assessing the probability that two populations arise from the same distribution. A seasonal mean difference series is calculated (station 'target' series minus average neighbour series) and the KS test is applied to a time series with a 15 season window on either side of the current point. If a break point is flagged, corrections are then applied. The adjustment is calculated by taking the difference between the neighbour and the target series; this adjustment value is added to the target anomaly values before the break point, to make the series consistent with current data.
- Fifthly, a manual adjustment of break points was considered in cases where suitable neighbour series were not available for the KS test. If metadata information and the series itself indicated obvious break points, manual adjustments were applied. The adjustments were calculated by taking the difference between the mean of the break point period with the mean of a reliable period in the same series, similar to MCA (Slonosky *et al.*, 1999).

Quality control procedures highlighted a number of issues of concern to long-term global pressure data set development. In many circumstances station series could only be completed by using all available sources, and often no major active repository (e.g. World Weather Records, Monthly Climatic Data for the World, CLIMAT, GSN or GHCN2) held the full station record even up to recent times. In addition, errors and deficiencies in pressure series were detected frequently in all of the major compilations from which data were being drawn. For instance, the quality control applied to MSLP series in the GHCN2 data set was found to have removed a substantial number of real data values which it took to be too extreme. Yet, even with apparently over zealous quality control checks, GHCN2 was still found to have retained a number of what were very obvious erroneous data values and also station time series with distinct changes in data variance over time. These problems were detected during near neighbour checks, and erroneous errors have been corrected where possible. Some data variance problems were resolved by the replacement of affected series by versions from other sources, but others remain. This variance issue will be addressed in the construction of the international pressure data bank (Appendix 3) and will feed into subsequent versions of HadSLP2. Finally, efforts to focus on climatic data series from non-urbanised sites for the detection of anthropogenic climate change have seen the major active data compilations drop many long-term urban records, making updating of pressure data from such locales more difficult. This is likely to have even greater impact on efforts to develop near real-time pressure data compilations.

b). Quality control and gridding – Marine data

Marine observations from ICOADS were quality controlled and gridded using the marine data system (MDS) version 2, developed at the Hadley Centre. MDS has been used to grid sea surface temperature (SST) and surface air temperature observations (see Rayner *et al.*, 2006 Section 2c for a full description). The quality control procedure involves a climatology check, using 5-day (pentad) fields[3], and a near neighbour ‘buddy check’. Unlike the buddy check described in Rayner *et al.* (2006), which utilised neighbouring observations both forwards and backwards in time, the buddy check used here checks only against spatial buddies, not temporal. This is appropriate for MSLP given its rapid variations.

MSLP observations passing these tests were then corrected as appropriate. These corrections included a diurnal cycle correction, using the gridded phase and amplitude fields of Dai and Wang (1999). A correction was also applied for an anomalously low (negative) MSLP bias in the US Maury collection. Both corrections were made using procedures described in Ansell *et al*. (2006). Previously undetected duplicates in the ICOADS database were also removed.

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[3] The pentad climatology was derived from monthly HadSLP1 fields, interpolated to pentad resolution using a cubic spline fit.

Next, data for each pentad were gridded onto a 1° latitude by longitude grid taking the winsorised mean (i.e. trimming the values that exceed a certain threshold: Barnett and Lewis 1994). This served to reduce the influence of any outliers that remained after the quality control procedure (Afifi and Azen, 1979). Monthly averages were then formed and the number of pressure observations in each grid box recorded. The measurement and sampling error for each month and grid box was also calculated as part of the MDS gridding procedure (see Rayner *et al.,* 2006, section 3b). The sampling error is associated with not having enough observations to represent the 'true' grid box MSLP value; it is also known as the representivity error.

The MDS gridding technique differs to that used previously for HadSLP1 and EMSLP (Ansell *et al.,* 2006), in that it no longer contains a smoothing and infilling technique. While this reduces the coverage somewhat, the over smoothing is removed and the subsequent 'number of observation' fields are now more meaningful. The reduction in coverage is compensated by the increase in observations in the ICOADS database.

c). Blending terrestrial and marine MSLP

The final HadSLP2 product was constructed by blending together the quality controlled terrestrial with the gridded marine fields. For each month and in each year from 1850 to 2004, and in each 1° x 1° grid box, the marine grid box value and all terrestrial MSLP observations (if present) were collated. Residuals were formed by subtracting a monthly background field from each terrestrial observation and marine grid box value and then the median value (both land and marine) was selected. This gave greater weight to land observations in coastal regions. All the 1° x 1° median values were then averaged to 5° x 5° grid point values, taking account of their spatial distribution. Absolute pressures were formed by adding back the background field. The background field used here was based on HadSLP1. Prior to 1871, when HadSLP1 begins, we have used a monthly climatology (30 year average from 1871-1900). Post 1998, NCEP-NCAR reanalyses were used as the background field.

The blended land and marine fields were then visually quality controlled; suspect grid box values were deleted or smoothed as appropriate. The coverage prior to reconstruction is shown in Figure 1 for a number of decades. The blended data set, with spatially incomplete fields, is known as HadSLP2.0. It is available on a 5^{o} latitude by longitude grid, covering the period 1850-2004; number of observations and measurement and sampling error gridded fields are also available.

d). Reconstruction

The blended and gridded fields were made spatially-complete by using RSOI (Kaplan *et al.*, 1997, 2000). Ansell *et al.* (2006) applied this technique over the European-North Atlantic region with success; we adopt a similar methodology, working here with monthly fields.

Complete MSLP anomaly fields were reconstructed using the leading 34 Empirical Orthogonal Function (EOF) modes and the measurement and sampling error field. For this error field we followed Ansell *et al.* (2006), in using the 1961-1990 root mean square of 30 combined marine and land fields of measurement and sampling error for given calendar months. For the marine observations the measurement and sampling error for each month was calculated as part of the MDS gridding procedure (see above). In addition we took account of the errors inherent in the ship observations. A value of 0.25 hPa for geographically random one sigma bias was estimated from the differences between synoptic charts and operational model analyses and added vectorially to the sampling error (Ansell *et al.*, 2006). Over land, estimated errors were based on the altitude of the station. Following Ansell *et al.* (2006), an estimate of $h/1500$ was used as the bias associated with the reduction to mean sea level, where h is the altitude of the station (in meters). Again 0.25 hPa was added (vectorially) to the elevation-related bias, to reflect the random bias error. In grid cells with both land and marine data, the errors ascribed were a combination of these land and marine components.

EOFs were calculated over the 1948-2004 epoch, the most recent and reliably observed period, also overlapping with the NCEP-NCAR reanalysis product. The fields used to calculate the EOFs were a Poisson blending (Reynolds, 1988) of the observed anomalies with NCEP-NCAR reanalysis fields, which were firstly interpolated to the HadSLP2 $5^o x 5^o$ grid. EOFs were calculated using a covariance matrix of these monthly (OBS + NCEP) anomalies and applying a fourth-order Shapiro filter (Shapiro, 1971), following Kaplan *et al.* (1997). Kaplan *et al*. (2000) found that it was necessary to re-estimate the signal covariance to obtain more realistic theoretical error estimates (see Appendix in Kaplan *et al.* (2000)). For HADSLP2, plus HadSLP1 and EMSLP (Ansell *et al.*, 2006), it was found however that this step was not required owing, we believe, to the influence of the smooth NCEP-NCAR fields from which the covariance matrix was estimated.

Following Rayner *et al.* (2003), the available 'observations' (as anomalies) were then superimposed on the reconstruction. Grid points were then flagged where the grid point anomaly minus the average of its neighbours was greater than a maximum permitted difference. This maximum permitted value was calculated as the mean anomalous value plus 3 times the standard deviation (based on 1961-1990 monthly averages and standard deviations derived from OBS + NCEP blended fields); those greater than 4 times the standard deviation were not imposed upon the reconstruction. Flagged anomalies and their neighbours were then weighted by the numbers of constituent observations, this gave greater weight to well observed areas. Reconstructed values were treated as being based on one observation. The flagged anomaly was then replaced by the average of the weighted anomalies i.e. the flagged point and its 8 nearest neighbours. This procedure was reiterated two times. Finally, the climatology was added back to yield absolute MSLP values

A final visual quality control was applied enabling suspect grid box values to be smoothed spatially.

4. Validation

The validation of HadSLP2 was performed by using a combination of several existing data sets, including ADVICE (Jones *et al.*, 1999b), the Smith and Reynolds (2004) data set, the Kaplan *et al.* (2000) data set, the ERA-40 reanalysis (Uppala *et al.*, 2005) and HadSLP1, though all of these products do not completely overlap temporally or spatially with HadSLP2. A comparison of the monthly climatologies have shown some improvements in HadSLP2 when compared with HadSLP1, with notably stronger anticyclones in the subtropical high pressure belt and deeper lows to the south of Greenland and in the Norwegian Sea. During the austral winter, however, it appears that the pressures in the southern Atlantic and Indian Ocean mid-latitude regions are too high; this is seen in comparisons with both HadSLP1 and with ERA 40. This will need to be addressed in future products.

Differences between ERA-40 and HadSLP2 are largest over Antarctica, the Himalayas, Greenland, the Khrebet Cherskogo mountains north of Okhotsk in north eastern Russia, and the South African escarpment, all high altitude regions where model estimation of MSLP is likely to be biased. In HadSLP2, pressure time series from high altitude regions were examined and where reduction to MSLP appeared to be questionable we replaced the corrected series by the station pressure anomalies, plus the nearest HadSLP1 grid point climatological value. If left unchecked, erroneous MSLP reductions would be manifest as distinct ‘bulls eyes’ in the final data set. Despite these efforts, some problems are still evident. Comparisons with HadSLP1 indicate that the pressures over the Himalayan and Khrebet Cherskogo mountains are still too high.

The grid point squared correlations (r^2), or coefficient of determination, between HadSLP2 and ERA-40 for February, May, August and November are shown in Figure 2. Generally, these are very high with explained variances largest over the Northern Hemisphere (typically over 90% explained variances over the North Atlantic and Europe) and also in the winter months, because of the greater meteorological signal in this season. Over the Southern Ocean and the African continent, the variance explained is particularly low. The differences between the two climatologies were also large here. This is not surprising, given that the number of observations is very low in both these regions, particularly over the Southern Ocean (see Figure 1). We will show below that sampling errors here are also very high.

Spatial correlations with the Smith and Reynolds (2004), ERA-40 and HadSLP1 products are shown in Figure 3 for the Northern and Southern Hemisphere for the summer and winter months. Following Jones *et al.* (1999b), anomalies were correlated to avoid artificially high correlation co-efficients due to the climatological average spatial distribution of high and low pressures. The correlations with all series in Figure 3 increase with time, as the number of observations increase. They are also more variable in the 19th century. Correlations between HadSLP2 and all three products are generally stronger in the well sampled Northern Hemisphere and particularly in the winter season, when there are stronger anomalies. Correlations pre 1950 in the Southern Hemisphere are the weakest, consistent with the poor sampling here. The number of observations is lower in the winter months in the Southern Hemisphere, resulting in a lower correlation in this season compared to winter in the Northern Hemisphere. Of particular note is the very poor correlation between ERA-40 and HADSLP2 in Figure 3b. A similarly poor correlation is also seen with HadSLP1 and ERA-40 (not shown). We believe this is largely a result of differences over Asia in the winter season (see also Figure 2).

Following Smith and Reynolds (2004), we examine the temporal standard deviation and error estimates for boreal winter (December-February) and austral winter (June-August) months in HadSLP2 during the decades 1851-1860, 1881-1890, 1911-1920, 1941-1950, 1971-1980, 1991-2000 (Figure 4 and Figure 5 respectively). The error estimates in the middle panel are measurement and sampling errors, associated with not having sufficient number of observations to properly represent the ‘true’ grid point MSLP value, as derived in Rayner *et al.* (2006). These fields are not globally-complete, however they are combined (vectorially) with the RSOI (interpolation) error in the right hand side panel. During the first and second World Wars, the number of marine observations is reduced; this is reflected in the middle panel with larger measurement and sampling errors, particularly in the North Atlantic compared to the 1920s (not shown).

Standard deviation values are particularly large over the high latitude south eastern Pacific in all epochs shown in Figure 4. This tends to be one of the most data sparse regions during any period in the data set. Nevertheless, high standard deviations in this region have been reduced in HadSLP2 compared to HadSLP1 since 1940s for summer, though they are larger in winter during the 1940s.

The measurement and sampling errors are particularly large in the high southern latitudes, where the number of observations is very low. At times these errors are as large as the pressure signal itself. Based on this we urge caution to be exercised when using HadSLP2 in these regions. In general, such errors are small over the land masses and over well-observed ocean regions, such as the North Atlantic. Generally, our estimates lie between the observational error estimates of Ingleby (2001) of 1 hPa and those of Kent *et al.* (1997) of 2.3 ±0.2 hPa over most of the ocean basins.

5. Applications for climatic research

A number of major features in the climate system that have important environmental, ecological and societal impacts were examined in the HadSLP2 data set. Those detailed in this section were chosen to reflect both global and hemispheric regimes and include the North Atlantic Oscillation (NAO), the Southern Oscillation (a prime measure of the El Niño Southern Oscillation [ENSO] phenomenon), the North Pacific Index (NPI) and the Trans Polar Index (TPI). Several of these climatic phenomena were resolved using the leading modes deduced from principal component or EOF analyses. It was encouraging that many of the lesser modes, down to EOF six, resembled elements of the Eurasian, West Pacific Oscillation, Eastern Atlantic and Eastern Pacific patterns found in a rotated EOF analysis of 700 hPa geopotential heights by Barnston and Livezey (1987).

Additional climatic phenomena (global MSLP trends, the East Asian Monsoon, the Siberian High, the Antarctic Oscillation [AAO], and the Antarctic Circumpolar Wave [ACW]) were also examined following a selective release of the evolving HadSLP2 product to researchers around the world. This release was designed to expose the data set to a range of potential users and test how well the data set resolved distinct climatic features. The range of findings from these appraisals, reported to the authors of this paper, are detailed at the end of this section. These results will be used to improve future versions of the data set.

a). North Atlantic Oscillation (NAO)

The North Atlantic Oscillation (NAO) is a major climatic feature of the Northern Hemisphere, with significant impacts on the North Atlantic-European region. Indices of the NAO are usually calculated as the difference in normalized MSLP between a) either Ponta Delgada in the Azores, or Lisbon in Portugal or Gibraltar and b) Stykkisholmur or Reykjavik in Iceland. The NAO is most frequently analysed in the boreal winter months, though recent studies (Hurrell *et al.,* 2003) have emphasised its importance, on a smaller spatial scale, during the boreal summer. When an NAO index is positive (negative), it is indicative of stronger (weaker) westerlies over the North Atlantic-European middle latitudes. The NAO is thus able to modulate European surface land air and sea surface temperatures, precipitation patterns and storm tracks (Hurrell, 2003).

Station-based NAO indices, however, may not reflect the true nature of the phenomenon, as there is evidence that the nodes of the NAO have shifted spatially over time. Consequently, efforts have been made to develop measures of the NAO derived from EOF analyses of the spatio-temporal patterns of MSLP in the Atlantic-European sector. In fact, the leading EOF of seasonal (December-March) MSLP anomalies over the Atlantic region (20°N-80°N, 90°W-40°E) has been proposed by Hurrell (1995) as being more indicative of the NAO than station-based indices.

Efforts to define important climatic modes over the entire Northern Hemisphere using EOFs and similar techniques have resolved a hemispheric scale annular mode known as the Arctic Oscillation (AO) (Thompson and Wallace, 1998) or Northern Annular Mode (NAM). Controversy continues regarding relationships between the AO and the NAO, so time series of both are plotted and discussed in this section.

Figure 6 shows the winter (December-February) NAO derived from station data (difference of normalized MSLP between Ponta Delgada, Azores and Reykjavik, Iceland) used in HadSLP2 (Figure 6a), the winter NAO deduced as the first EOF in North Atlantic MSLP in HadSLP2 (Figure 6b), and the winter NAM (or AO) defined as the leading EOF in Northern Hemisphere MSLP in HadSLP2 (Figure 6c). An examination of the time series in Figure 6 suggests that despite the above concerns about NAO measurement, the station-based and EOF defined NAO indices from HadSLP2 (Figure a, b 1867-2004) are strongly positively correlated (r=+0.88). The NAM index in

Figure 6c is correlated positively with both NAO indices at r=+0.89 (Figure 6b) for the period 1867-2004 and r=+0.88 for the period 1851-2004) and r=+0.71 (Figure 6a) for the period 1867-2004. The station-based NAO has a noticeably weaker correlation which explains only 50% of the variance. This would seem to be a consequence of the NAM spatial loadings across the North Atlantic sector in EOF 1 (not shown) being concentrated over Iceland-southern Greenland and the Mediterranean, rather than Iceland and the Azores as in the station-based NAO index.

b). North Pacific Index (NPI)

The North Pacific Index (NPI), developed by Trenberth and Hurrell (1994) and derived from MSLP in Trenberth and Paolino (1980), is defined as the area-weighted MSLP from December to March over the region 30°N-65°N, 160°E-140°W. It is available since 1899 (though Trenberth and Hurrell (1994) suggest that it is most reliable after 1924), and provides a strong measure of the intensity of the Aleutian Low. This can be seen if the NPI is compared with the Aleutian Low Pressure Index (ALPI) of Beamish *et al.* (1997) (r=-0.89 for the period 1900-2005). In addition, the NPI also correlates highly and significantly with the Pacific North American (PNA) pattern of Wallace and Gutzler (1981) (r=-0.84 for the period 1950-2002).

Figure 7 shows a comparison of the NPI time series calculated from HadSLP2 (Figure 7a) against the Trenberth and Hurrell (1994) measure of it (Figure 7b) for December-March. These NPI time series are also compared against the ALPI (Figure 7c). What is immediately obvious, is that where the two NPI series coincide temporally (1900-2004) they are extremely similar, and are correlated at r=+0.85. The only major difference between the NPI time series occurs around 1905-1915, and may result from more marine observations being available in HadSLP2. This discrepancy is also evident in comparisons with the ALPI which, as noted earlier, is significantly negatively correlated with both NPI series (r=-0.82 with HadSLP2). In general, the NPI from HadSLP2 shows higher frequency variability in the 19th century than any period in the 20th century. This may result from increased noise owing to data scarcity.

c). Southern Oscillation Index (SOI)

The Southern Oscillation is the atmospheric component of the ENSO phenomenon. After the seasonal cycle and the planetary monsoon system, ENSO accounts for the next major amount of variability in the global climate system. Various indices of the Southern Oscillation have been developed over the years, but all aim to measure fluctuations in atmospheric pressure between the Indo-Australasian and south eastern Pacific regions, by what is essentially a Southern Oscillation Index (SOI) (Allan *et al.,* 1996).

Figure 8a shows the seasonal SOI over the period 1850 to 2004 calculated from the HadSLP2 station data series for Darwin and Tahiti (method after Troup, 1965); Figure 8b is the same index derived using the HadSLP2 grid points closest to Darwin, Australia and Tahiti in the south Pacific, noting the coarse 5 degree spatial resolution. We also plot the Nino 3.4 index in Figure 8c, using HadISST (Rayner *et al.*, 2003). The correlation between the HadSLP2 station series (Figure 8a) and the Allan and Jones station-based series (Allan *et al.* 1996) is r=+0.93. The HadSLP2 station (Figure 8a) and the HadSLP2 grid series (Figure 8b) are correlated at r=+0.97. Correlations with the Nino 3.4 index are r=-0.73 for the HadSLP2 station and r=-0.76 for the HadSLP2 grid series. This difference is likely to indicate the influence of marine observations in the grid based series.

Using a measure for the degree of noise in the SOI (normalized Tahiti plus Darwin MSLP anomalies), Trenberth (1984) and Trenberth and Hoar (1996) raised concerns about the Tahiti MSLP data series prior to the 1930s, and advocated the use of Darwin MSLP anomalies alone as the most reliable long-term measure of the Southern Oscillation (see also plots in Allan *et al,* 1996). This concern led us to examine the early Tahitian records used by various institutions that have calculated the SOI (Australian Bureau of Meteorology (BOM), NCAR and the Hadley Centre). It was found that there were a number of individual monthly MSLP values (many tending towards outliers), and some entire years, when records differed amongst the various holdings. These occurrences were found not just in the pre 1930s period, but also in the 1950s. The greatest differences were between the BOM and the Hadley Centre. There were probably 10-12 individual months with differences of 2-3 hPa between the NCAP and the Hadley Centre Tahiti series, around 1890 (~5 months), 1905 (2-3 months), 1935 (2-3 months) and 1940 (1 month). Such problems may well have resulted from differences between initial telegraphic and final monthly values of MSLP for Tahiti, with incorrect values having been perpetuated in some holdings. As in Allan *et al.* (1996), an examination of the degree of noise in the SOI using a plot of normalized Tahiti plus Darwin MSLP anomalies (not shown) reveals that problems with pre 1930s Tahiti MSLP data have diminished considerably. The only period that stands out as perhaps questionable in the HadSLP2 grid point SOI trace is the earliest decade in the series.

d). Trans Polar Index (TPI)

The Trans Polar Index (TPI) was first proposed by Pittock (1980, 1984) as a measure of the eccentricity of the southern polar vortex and, at low frequencies, is indicative of the phase of wave number one around the Southern Hemisphere. It is usually defined as the normalized pressure difference between Hobart, Tasmania and Stanley in the Falkland Islands. The TPI has been extended and analysed further by Jones *et al.* (1999a), and more recently defined for the austral summer by using a mixture of New Zealand and South American high latitude stations (Villalba *et al.*, 2001).

In Figure 9, TPI's as shown are defined by the normalised austral summer (December-February) MSLP difference between grid points indicative of Hobart and Stanley in HadSLP2 (Figure 9a), the actual Hobart and Stanley station series used in HadSLP2 (Figure 9b), and from Jones *et al.* (1999a) in Figure 9c. The Jones *et al.* station-based TPI (Figure 9c) was found to correlate with the Villalba *et al.* (2001) Summer Trans Polar Index (STPI) at r=+0.62. Not surprisingly, the two station-based TPI series (Figures 9b, c) are very highly correlated (r=+0.94), but these values drop when they are compared with the HadSLP2 grid point TPI which incorporates marine and reconstructed values (r=+0.73 Figures 9a, c; r=+0.72 for Figures 9a, b).

e). Initial evaluations of other climatic features in HadSLP2

Specific work being undertaken by various researchers under a selective release of the evolving HadSLP2 data set includes, global MSLP trends (Gillett *et al.,* 2005) and detection of anthropogenic climate change, evaluations of ENSO influence on Europe (Brönnimann *et al.,* 2006), analyses of the East Asian Summer Monsoon index (updated from Guo *et al.,* 2004), and examinations of the Siberian High (D'Arrigo *et al.,* 2005 checked this index using HadSLP2 and data provided from Panagiotopoulos *et al.,* 2005). The AAO or Southern Annual Mode (SAM) (Jones per. com., 2005 provided additional data to that in Jones and Widmann, 2003 and Marshall, 2003, and recalculated this index using HadSLP2), and the ACW (White *et al.,* 2006) were also examined.

From an analysis of December-February MSLP in the NCEP-NCAR and ERA-40 reanalyses, HadSLP2.0 (uninterpolated variant of the data set), and eight coupled climate models over the period 1955-2005, Gillett *et al.* (2005) have shown that the spatial pattern of global MSLP trends is similar for the reanalyses products and the observed HadSLP2.0 data set. Simulated MSLP trends in the coupled models are well represented over the Southern, but not the Northern, Hemisphere in both the reanalysis products and HadSLP2.0. They suggested that the simulated MSLP response to external forcing is either underestimated in the Northern Hemisphere or the internal variability in the models is too small. However Scaife *et al.* (2005) have been able to simulate the observed trend in the NAO between 1965 and 1995, when observed trends in the lower stratosphere were imposed. The lack of data in the Southern Hemisphere and the large errors in this region, suggest we need to be cautious in interpreting the trends here.

An examination of ENSO influences on Europe by Brönnimann *et al.* (2006) has compared and contrasted January 1940 to February 1942 MSLP anomalies from HadSLP2, GMSLP2 and NCAR. During this period, there is broad agreement between the data sets over the common domain of the Northern Hemisphere (not shown). This is most evident in the GMSLP2 and NCAR data fields, which is not surprising given that the latter was used in the construction of the former. Across the Northern Hemisphere, HadSLP2 resolves high latitude positive MSLP anomalies that are strongest over Scandinavia and the adjacent Norwegian Sea while there is no extension of major positive MSLP anomalies across to Greenland as in GMSLP2 and NCAR.

The AAO or SAM is the main mode of extratropical circulation in the Southern Hemisphere, and is indicative of the exchange of mass between mid- and high latitudes (Thompson and Wallace, 2000). The AAO has been defined as the first EOF of MSLP for the domain 20^{o}S-80^{o}S, while the AAO index (AAOI) has been calculated recently using MSLP station data and EOF analyses of Southern Hemisphere MSLP. The AAOI describes the strength of the zonal circulation around Antarctica, in which a positive (negative) index represents strengthened (weakened) circumpolar zonal flow. Marshall (2003) utilised normalised monthly station data to construct zonal MSLP at 40°S and 65°S and derived a measure of the SAM from the difference between these zonal means, while Jones and Widmann (2003) calculated an AAOI by multiple regression of NCEP-NCAR reanalysis data against the first EOF of November-January MSLP station data over the Southern Hemisphere. An examination of the spatial pattern of the AAO in HadSLP1, HadSLP2 and the ERA40 reanalysis in the 1958-98 epoch (not shown) reveals the expected differences in spatial structure between seasons in all three data sets (J. Jones per. com., 2005). Consensus amongst the data sets and the reanalysis product is greatest during the austral spring (September-November). Investigations of the AAOI calculated from various station data (many from stations in the HadSLP data bank), the HadSLP1 and HadSLP2 data sets and the ERA40 reanalysis (Jones and Widmann, 2003; J. Jones per. com., 2005) reveal that all of the AAOI measures are in good agreement in the post 1950 period, are reasonably well aligned prior to the 1920s, but are most divergent during the 1920s-1950s epoch (not shown). In fact, during the latter period the AAOI in both HadSLP1 and HadSLP2 appears to be much more negative than the station-based measures of the index. Hence, they appear to be largely influenced by the grid points with reconstructed MSLP, particularly for the 1920-1950s epoch. Work is continuing to examine the influence of the period chosen to calculate the EOFs used in the reconstruction (section 3d). An AAOI based on a reconstruction created with EOFS calculated over the shorter 1978-2004 epoch, was more similar to the station based index than the HadSLP2 AAOI. We were reluctant to use this reconstruction beyond testing however, as the short period over which the EOFS were calculated would mean we would not sample adequately longer time-scale variability.

An East Asian Summer Monsoon index was developed by Guo *et al.* (2004) using GMSLP2 up to 1950 then the NCAR-NCEP reanalysis. This index is the sum of the MSLP difference between longitudes of 110°E and 160°E at successive 5° latitudes from 20°N to 50°N in the boreal summer (June-August). We compare the Guo *et al.* (2004) GMSLP2-based index (1873-1950) with corresponding values from HadSLP2. Similar features are seen in both indices (not shown), but there also differences between them. The most prominent difference is found in the late 19th and early 20th centuries, with the index derived from HadSLP2 showing a significantly stronger and more extensive period of low values (weaker summer monsoon) around 1885-1910. This is not surprising given that considerably more coastal marine and Chinese terrestrial data has gone into HadSLP2 than were available for GMSLP2. The extension of the summer monsoon index back to 1850 in HadSLP2 produces an overall time series which displays a higher degree of variability in the 19th than in the 20th century. This new East Asian Summer Monsoon index is to be reproduced in the Intergovernmental Panel on Climate Change (IPCC) Working Group (WG) 1 Fourth Assessment Report (Zhai, per. com., 2005).

The Siberian High or anticyclone is a quasi-stationary and semi-permanent feature of the climate system, with major implications for the climate of Eurasia (D’Arrigo *et al.*, 2005; Panagiotopoulos *et al.*, 2005), particularly the monsoon systems of the region. It is most dominant during the boreal winter. An index of Siberian High (SHI) has been defined by the above studies as the average December-February MSLP over the region 40°N-65°N, 80°E-120°E. In Panagiotopoulos *et al.* (2005), the feature was investigated using three gridded MSLP sources (Trenberth and Paolino, 1980; CRU, University of East Anglia [http://www.cru.uea.ac.uk/cru/data/pressure.htm]; and GMSLP2) plus various station data series. D’Arrigo *et al.* (2005) used only the gridded Trenberth and Paolino (1980) and GMSLP2 data sets (correlated at r=+0.89 for 1900-1994) to construct a SHI. Comparisons between the index generated using GMSLP2 and HadSLP1 with those using HadSLP1 and HadSLP2 data sets indicate that they are strongly positively correlated in the common period from 1872-1994 (r=+0.93 and r=+0.93). This is to be expected, given that the SHI's in GMSLP2, HadSLP1 and HadSLP2 were created with almost the same station series. The only difference is that in HadSLP2 they have been extended back in time and the bulk of the station data gaps noted in Panagiotopoulos *et al.* (2005) filled. Of particular interest is the recent downward trend in all SHI's since 1978 (D'Arrigo *et al.,* 2005; Panagiotopoulos *et al.,* 2005), a feature that is also seen in the East Asian Summer Monsoon Index.

The Antarctic Circumpolar Wave (ACW) is an eastward propagating coupled wave in co-varying oceanic and atmospheric parameters that travels around the Southern Ocean taking about eight years to make one circuit of the globe (White and Peterson, 1996). Detection and analyses of the ACW has entailed an assortment of sophisticated signal detection techniques including Complex and Extended EOFs, Complex Singular-Value-Decomposition (SVD) phase sequences and Multi-Taper-Method-SVD (MTM-SVD). White *et al*. (2006) have produced an analysis of the ACW using HadSLP2 in combination with high quality historical SST data. The results of this work reveal a distinct ACW signal near 17-yr period in MSLP anomalies propagating eastward across the Pacific sector of the Southern Ocean at 50°S from 1870 to the present. However, any eastward propagation of the 3.6-yr period ACW signal in MSLP along 50°S is clear only from 1950 to the present, and before then both eastward and westward propagation is indicated.

6. Conclusion and discussion

Development of the HadSLP2 data set has required prolonged investment in data archaeology and treatment. This has been necessary in order to construct a database of terrestrial and marine pressure adequate to the task of analyses of climate worldwide. Processing and quality control of these data to form the final gridded HadSLP2 set has been particularly intensive. Overall, the HadSLP2 effort demonstrates what is needed in order to produce a modern high quality, high resolution, historical gridded globally-complete data set for just one climatic variable. HadSLP2 brings MSLP into the same realms of sophistication and quality that has been achieved with surface land air and sea surface temperature and precipitation data products.

Assessing and validating HadSLP2 is an ongoing process, and provides the basis for future upgrades and versions of this data set. In this paper, the results of our own appraisals and testing of HadSLP2 have been supplemented by those undertaken by a number of researchers/groups. The result is that HadSLP2 has not only been validated against a number of existing observational MSLP and reanalysis products, but it has been tested for how well it can resolve important climatic indices and phenomena in time and space.

Over the Northern Hemisphere, HadSLP2 has been particularly valuable as a means of generating indices and/or spatial fields that are able to resolve the NAO, AO and NPI back to 1850. It is the best MSLP data set available for historical studies investigating large-scale circulation phenomena that span terrestrial and oceanic regimes, and is ideal for exploring NAO and AO relationships, and for examinations of circulation variability over the North Pacific - especially those related to the Aleutian Low. Specific Northern Hemisphere climatic indices are also well resolved, and their series can be extended back in time using HadSLP2. Historical indices of the East Asian Summer Monsoon and the Siberian High (SHI), generated by averaging or differencing MSLP observations, have both been improved and extended when generated using HadSLP2 data. The SHI calculated from HadSLP2 also relates well to the palaeo-reconstruction of the index by D’Arrigo *et al.* (2005).

In the tropical-subtropical domain, HadSLP2 has been found to produce an SOI which naturally integrates terrestrial and marine observations into a basic index of the ENSO phenomenon. The study of Brönnimann *et al*, (2006) has also highlighted the strengths of HadSLP2 in an evaluation of ENSO influence into the higher latitudes of the Northern Hemisphere using the data set in conjunction with NCAR data and the old GMSLP2 data set.

Across the Southern Hemisphere, all historical climatic data sets, including HadSLP2, are affected by regions of sparse data, especially over Antarctica, the high latitudes of the Southern Ocean and in the south eastern Pacific Ocean. However the error estimates provided with HadSLP2 can be used to guide analyses of major features of the mid- to high latitude Southern Hemisphere climate, such as the TPI, AAO and ACW. Indeed, the large errors here indicate caution is needed in interpreting results in this region. In comparison with measurements of the TPI from other data sets, the HadSLP2 index version appears to be strongly influenced by the reconstructed MSLP grid points, which are not included in simple two station difference indices (Hobart minus Stanley). Efforts to resolve the AAO and the ACW in HadSLP2 are at a preliminary stage, but early results indicate strong coherence in the AAOI amongst station-based, HadSLP1, HadSLP2 and ERA-40 reanalysis measures of it during the post 1950 and pre 1920 period, but significant differences between them in the 1920s-1950s epoch. More work is needed to quantify the nature of the ACW in HadSLP2 but, like the AAO, is likely to indicate the important influence of the marine MSLP data going into the data set and interpolation techniques.

From a global perspective, Gillett *et al.* (2005) have shown that boreal summer MSLP trends in NCEP-NCAR and ERA-40 reanalysis, HadSLP2.0, and eight coupled climate models during the period 1955-2005 are most coherent over the Southern Hemisphere. In the Northern Hemisphere, trends in boreal winter MSLP in the NCEP-NCAR and ERA-40 reanalysis and HadSLP2.0 show very similar spatial characteristics, but these are not found in the coupled climate model MSLP fields.

The above appraisals and assessments demonstrate that HadSLP2 is the current state-of-the-art monthly historical gridded MSLP data set. This has been enhanced by the availability of error estimates and uninterpolated (HadSLP2.0) and near-real-time (HadSLP2r) products. Future planned improvements to HadSLP2 include work on the southern midlatitude region, which will involve using supplementary ICOADS data (e.g. Japanese Whaling and Russian R/V data (see Worley *et al.*, 2005)). It may also involve changes to the marine gridding procedure and the re-imposing of observations onto the reconstruction. We also plan examinations using EOFs calculated over different epochs in the reconstruction and to improve our land quality control procedure. As detailed in Appendix 3, efforts are now underway to develop a truly international pressure data bank which will hold not only all of the individual station series used in products such as HadSLP2, but will be set up to develop and extend temporally all available pressure records.

Appendix 1: Data archaeology and hard copy sources

Region	**Sources**
Alaska	US Coast and Geodetic Survey, 1879; Henry, 1900
Antarctica	Jones and Limbert, 1987; Jones and Wigley, 1988; Jones and Reid, 2001
Australia	Russell, 1871-1886, 1904, 1905, 1906; Ellery, 1873-1891; Todd, 1879-1910; Government Meteorological Observer, 1885; Post and Telegraph Department, 1889-1896; Cooke, 1901; Griffiths, 1910; Hunt, 1910-1913, 1911, 1914, 1916, 1918, 1929; Warren, 1940, 1948; Watt, 1936; Bureau of Meteorology, 1945-1953, 1954-1956;
Austro-Hungarian Empire	Zentralanstalt fur Meteorologie und Geodynamik [ZAMG], 1854-1984
British Empire & colonies	Glaisher, 1850; 1851; 1851-1877; 1858; 1901; 1902; Meteorological Office, 1860-1881; 1878-1939; 1890, 1904; 1915; 1922-1947; Straits Settlements, 1861-1866, 1870-1911; Indian Meteorological Department, 1875-1890, 1891-1922, 1923-1950; Purser, 1875; Committee of the British Association on the Climatology of Africa, 1892-1901; Ravenstein, 1894; Ravenstein *et al.*, 1894; 1895, 1896, 1897, 1898, 1899a,b; Eliot, 1903; Cairo, Survey Department, Public Works Department, 1902-1905; Cairo, Survey Department, 1915; The Meteorological Magazine, 1923-1940; Weather Bureau, 1942-1951; Walter, 1948; Rhodesia and Nyasaland Meteorological Service, 1951; Department of Meteorological Services, 1952; Air Ministry, Meteorological Office, 1957
Canada	Toronto, Meteorological Service. (Dominion of Canada.), 1877-1915, 1878-1918, 1917-1971; Slonosky and Graham, 2005
Dutch East Indies/Indonesia	van Bemmelen, 1913; Berlage, 1939, 1940, 1941, 1943; Boerema, 1939, 1941
Estonia	Weihrauch, K. and Oettingen, A. von, 1892; Dorpat (Jourieff), Imperial University, 1916
Europe	Koninklijk Nederlands Meteorologisch Instituut [KNMI], 1854-1864, 1866-1894, 1871, 1877; Hann, 1887; Angot, 1906 ; Gorczynski, 1917 ; Jones *et al.*, 1999b ; Schmith *et al.*, 1997; Tuomenvirta *et al.*, 2001; Camuffo and Jones, 2002 ; Ansell *et al.*, 2006 ; European Climate Assessment & Data set Project [ECA&D] http://eca.knmi.nl/
France & colonies	Bureau Central Meteorologique, 1869-1881 ; 1880-1913 ; 1926 ; Angot, 1906 ; Dakar, Afrique Occidentale Francaise. Service Meteorologique, 1959
German colonial/missionary	Deutsche Seewarte, 1887-1922; Heidke, 1913
Global compilations	Washington, War Department, 1870; U.S. Signal Office, 187 – 188 ; Washington, Signal Office, 1875-1881, 1881-1883, 1883-1885, 1884-1888; Greely, 1890; Hildebrandsson, 1897; Lockyer 1908, 1909; Air Ministry, Meteorological Office, 1910-1934; Clayton, 1927, 1934, 1947; Washington, Weather Bureau, 1948-1967; U.S. Weather Bureau, 1892-1910; 1959; U.S. Environmental Science Services Administration, 1965-

	1968; Washington, Environmental Science Services Administration, 1968-1970; Washington, NOAA, EDS: 1971-2004; NOAA, National Climatic Data Center, 1979-1985, 1987-1994, 1995-1999; 2005; Vose *et al.*, 1992; Young, 1993: WeatherDisc Associates, 1994; GCOS Surface Network (GSN) (http://lwf.ncdc.noaa.gov/oa/climate/gsn/gsnmap.html)
Indian Ocean Islands	Male, Maldives, Meteorological Centre, 1980
Ireland	Hickey *et al.*, 2003
Japan, Korea, China & Taiwan	Shanghai, Inspectorate General of Customs, 1877-1905; Central Meteorological Observatory, 1954; Tao *et al.*, 1997
New Zealand & offshore islands	Fouhy *et al*, 1992
Ottoman Empire	Constantinople, Observatoire Imperial, 1870-1874 ; 1889-1897
Pacific Ocean Islands	Henry, 1925 ; Watt, 1940 ; Collen, 1992
Panama	Abbot, 1899 a,b,c, 1900, 1903, 1904
Philippines	Observatorio Meteorologico del Atenes Municipal de Manila Bajo la Direccion de la Compania de Jesus, 1873
Portugal & colonies	Servico Meteorologico Nacional, 1915-1951; Observatorio Do Infante D Luiz, 1942
Russia/Russian Empire	Nicolas Central Physical Observatory, 1850-1887 ; 1888-1894 ; 1895-1897 ; 1898-1912 ; de Tillo, 1890; Razuvaev *et al.*, 1998; Polyakov *et al.*, 2003
South America	Santiago, Oficina Meteorologica de Chile (Instituto Central Meteorologico y Geofisico de Chile.), 1873-1884, 1886, 1900-1911, 1912-1970; Mossman, 1923; La Paz, Servicio Meteorologico de Bolivia 1946-1978; San Jose, Costa Rica, Servicio Meteorologico Nacional., 1971-1978
Southern Hemisphere	Jones, 1991
Spain	Boletin Meteorologico Diario, 1875
West Indies	Meteorological Office, 1890; Alexander, 1899, 1900, 1901; Kimball, 1901
Various assorted series/sources	Board of Trade 1861, 1863; U.S. Signal Office, 1872-1891, 1892-1910; Berlage, 1957, 1966; Allan *et al.*, 1991; Peterson and Griffiths, 1996, 1997; Griffiths and Peterson, 1997; Page *et al.*, 2004

Appendix 2: World Wide Web (WWW) sources of pressure data

Climate Database Modernization Program (CDMP)
http://www.ncdc.noaa.gov/oa/climate/cdmp/cdmp.html

EMULATE Mean Sea Level Pressure (EMSLP) data set
www.hadobs.org or http://www.cru.uea.ac.uk/cru/projects/emulate/

NOAA Central Library, Climate Data Imaging Project
http://docs.lib.noaa.gov/rescue/data_rescue_home.html

GCOS Surface Network (GSN)
http://lwf.ncdc.noaa.gov/oa/climate/gsn/gsnmap.html

World Weather Records (WWR)
http://dss.ucar.edu/data sets/ds570.0/data/

Monthly Climatic Data for the World (MCDW)
http://www7.ncdc.noaa.gov/SerialPublications/MCDWPubs?action=getpublication

British Antarctic Survey (BAS)
http://www.antarctica.ac.uk/met/READER/surface/stationpt.html

Russian Antarctic Expedition/Project Antarctica
http://south.aari.nw.ru/default_en.html

Jacka Southern Hemisphere high latitude data
http://www.antcrc.utas.edu.au/~jacka/pressure.html

European Climate Assessment & Data set Project (ECA&D)
http://eca.knmi.nl/

Appendix 3: International pressure data bank

The development of the HadSLP2 data sets is now linked closely with the WMO AOPC/OOPC Surface Pressure Working Group initiative to develop an international pressure data bank. This repository, which will be generally accessible on the WWW, will hold not only gridded MSLP data sets but also the individual terrestrial and marine (station level and MSLP) observations which were used to construct the various gridded MSLP data sets. A step towards this end will be a link to the individual terrestrial MSLP data sets held by the Hadley Centre (after checks that all data sources are willing to release their data in this way) on the AOPC/OOPC Surface Pressure Working Group WWW site (http://www.cdc.noaa.gov/Pressure). This site will seek to encourage researchers and meteorological services around the world to check the terrestrial station and MSLP holdings and, if possible, to provide data which correct, extend and fill gaps in any series held. This will produce a two-way link with researchers and meteorological services which can only benefit all parties and lead to wider availability of high quality and quantity pressure data.

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Figure Captions

Figure 1: Distribution of the continental and island stations in HadSLP2 (red squares) together with the number of marine MSLP data at each grid point for the decades 1851-1860, 1881-1890, 1911-1920,1941-1950, 1971-1980, 1991-2000. The red squares indicate the location of the stations, not the number of observations. Many of the land station record 3 times per day, giving over 10,800 observations per decade at the single station site. Such sampling for the marine observations is only seen in the North Atlantic.

Figure 2: Monthly grid point squared correlations (r^2) between HadSLP2 and ERA-40 calculated over 1959-2001 for a) February, b) May, c) August, d) November. Contours are 0.2.

Figure 3: Times series of global field correlations for a) January and b) July for the Northern Hemisphere and c) January and d) July for the Southern Hemisphere for HadSLP2 and ERA-40 (dotted line: 1959-2002), HadSLP2 and S&R (Smith and Reynolds, 2004) (solid line 1854-1997), HadSLP2 and HadSLP1 (dashed line: 1871-1998). The S&R product is predominately a marine only data set, with some coastal stations included.

Figure 4: Temporal standard deviation and error estimates for boreal winter (December-February) months in HadSLP2 for the decades 1851-1860, 1881-1890, 1911-1920, 1941-1950, 1971-1980 and 1991-2000. Left hand side panel: standard deviation fields, with contours 1 hPa. Middle panel: measurement and sampling error estimates (after Rayner *et al.*, 2006) in hPa. Right hand panel: measurement and sampling error combined with the error in the reconstruction (after Kaplan *et al.*, 2000) in hPa.

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Figure 7: Time series of the North Pacific Index (NPI) (sea level pressure during December-March averaged over the North Pacific 30°N-65°N, 160°E-140°W) from a) HadSLP2, b) after Trenberth and Hurrell (1994). The ALPI from Beamish *et al,* (1997) is plotted in c). All series are expressed as normalised departures from the long-term mean. The bars give the wintertime series and the thick curve is a low pass filter, removing variability at less than 7 years.

Figure 8: Seasonal Troup Southern Oscillation Index (SOI) calculated from a) HadSLP2 station data for Darwin and Tahiti (after Troup, 1965) and b) HadSLP2 grid point data. The Nino 3.4 index from HadISST (Rayner *et al.*, 2003) is plotted in c). The SOI indices are calculated by creating monthly anomalies of both series with respect to a 1933-1992 average. The Tahiti minus Darwin difference is then formed. This is then normalised by dividing by the standard deviation of the

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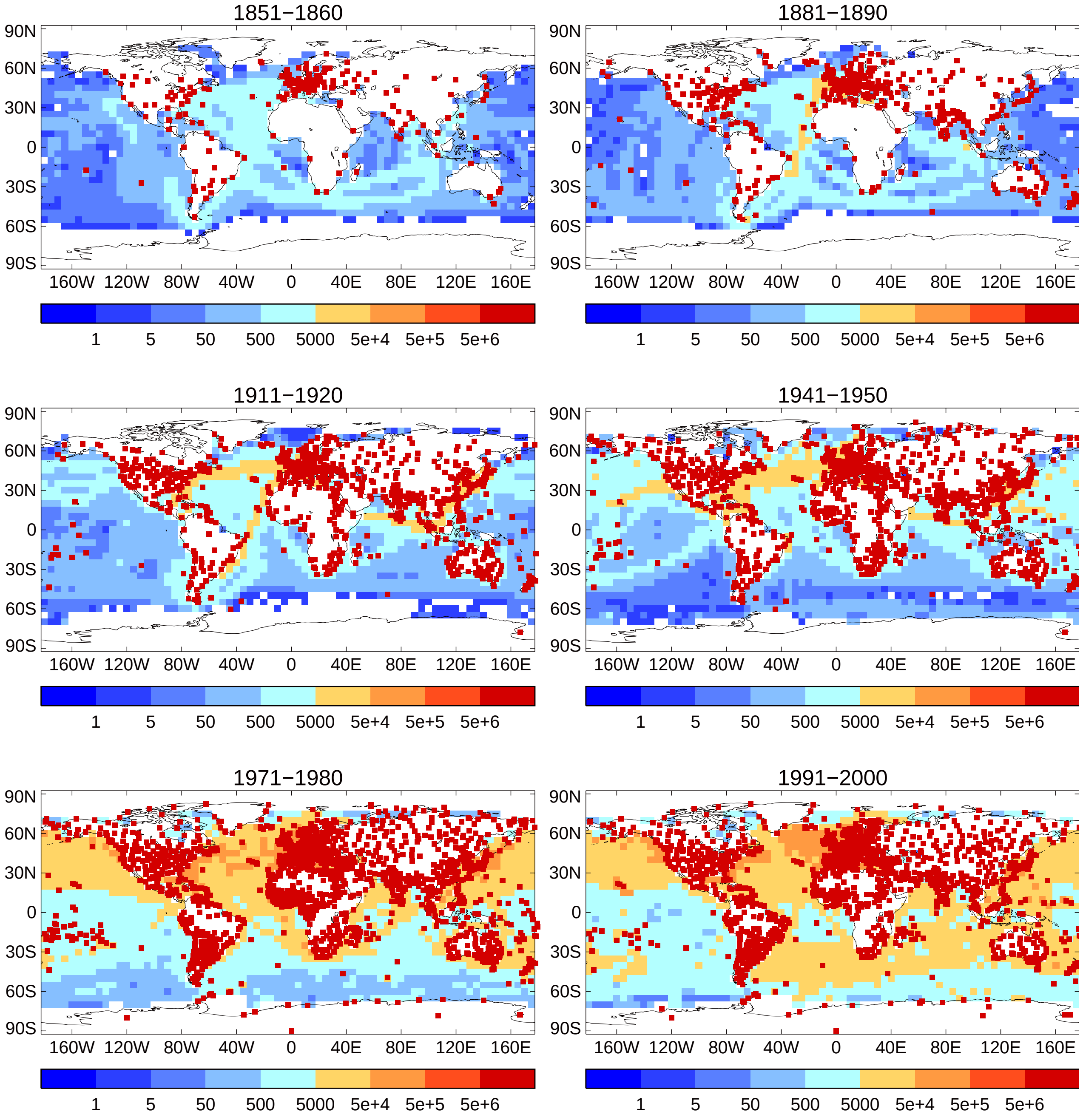

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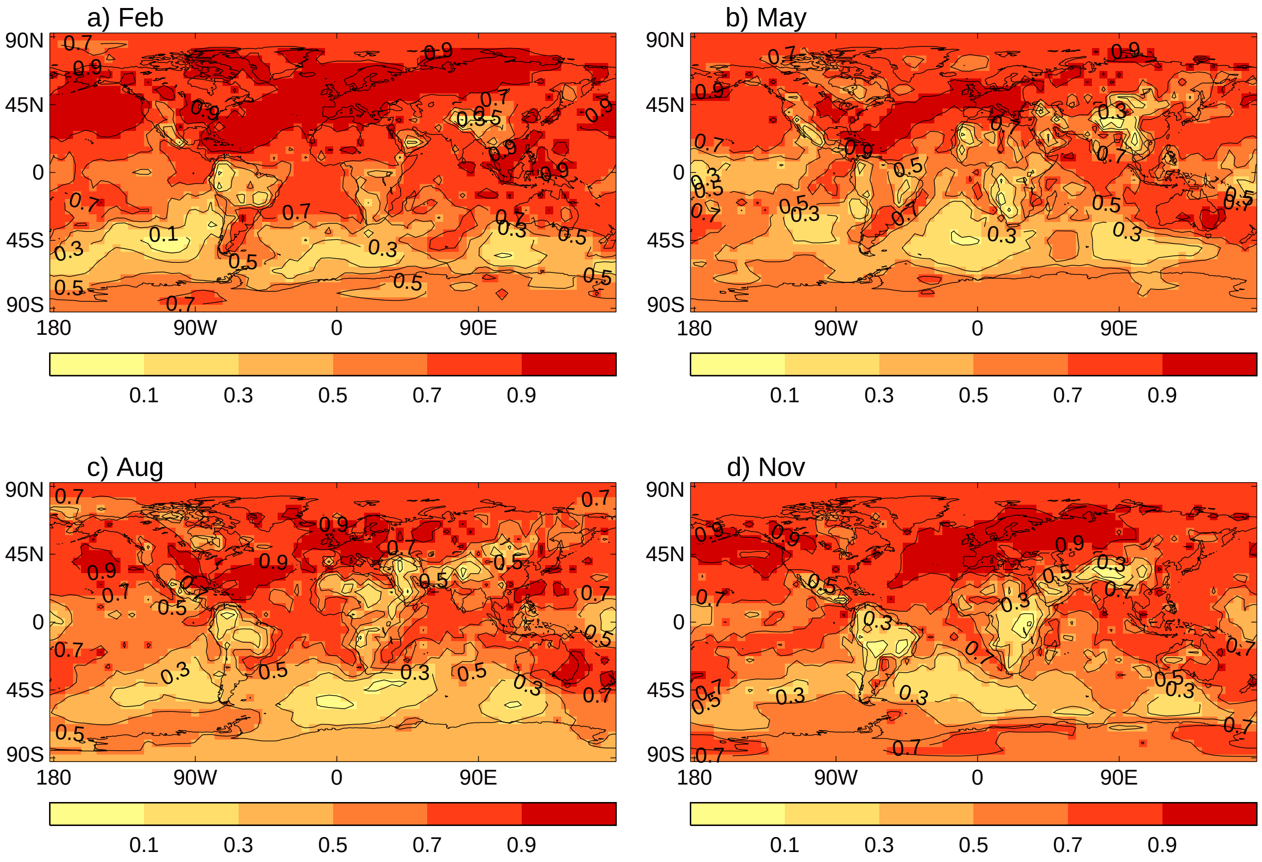

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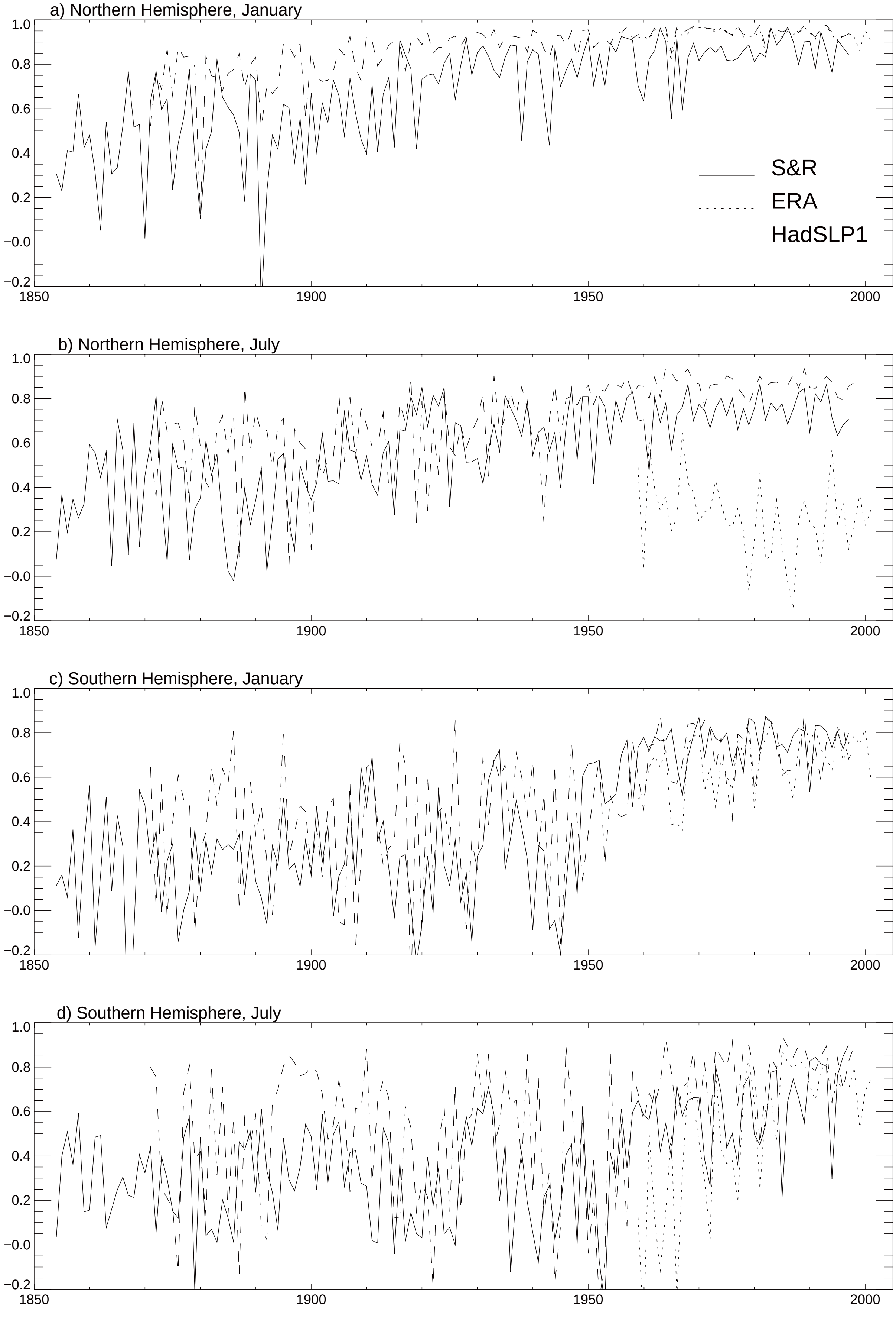
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b) Northern Hemisphere, July

c) Southern Hemisphere, January

d) Southern Hemisphere, July

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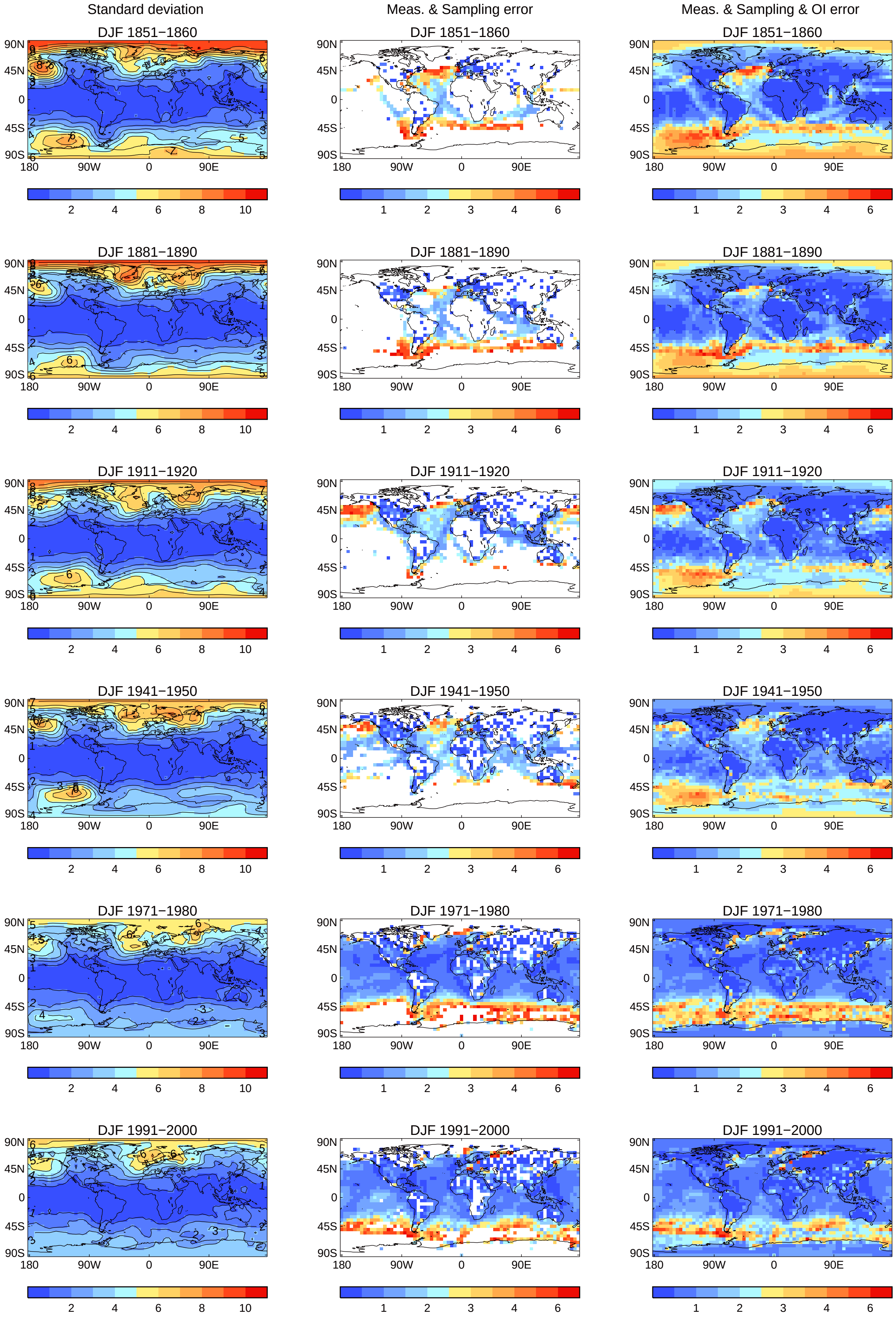

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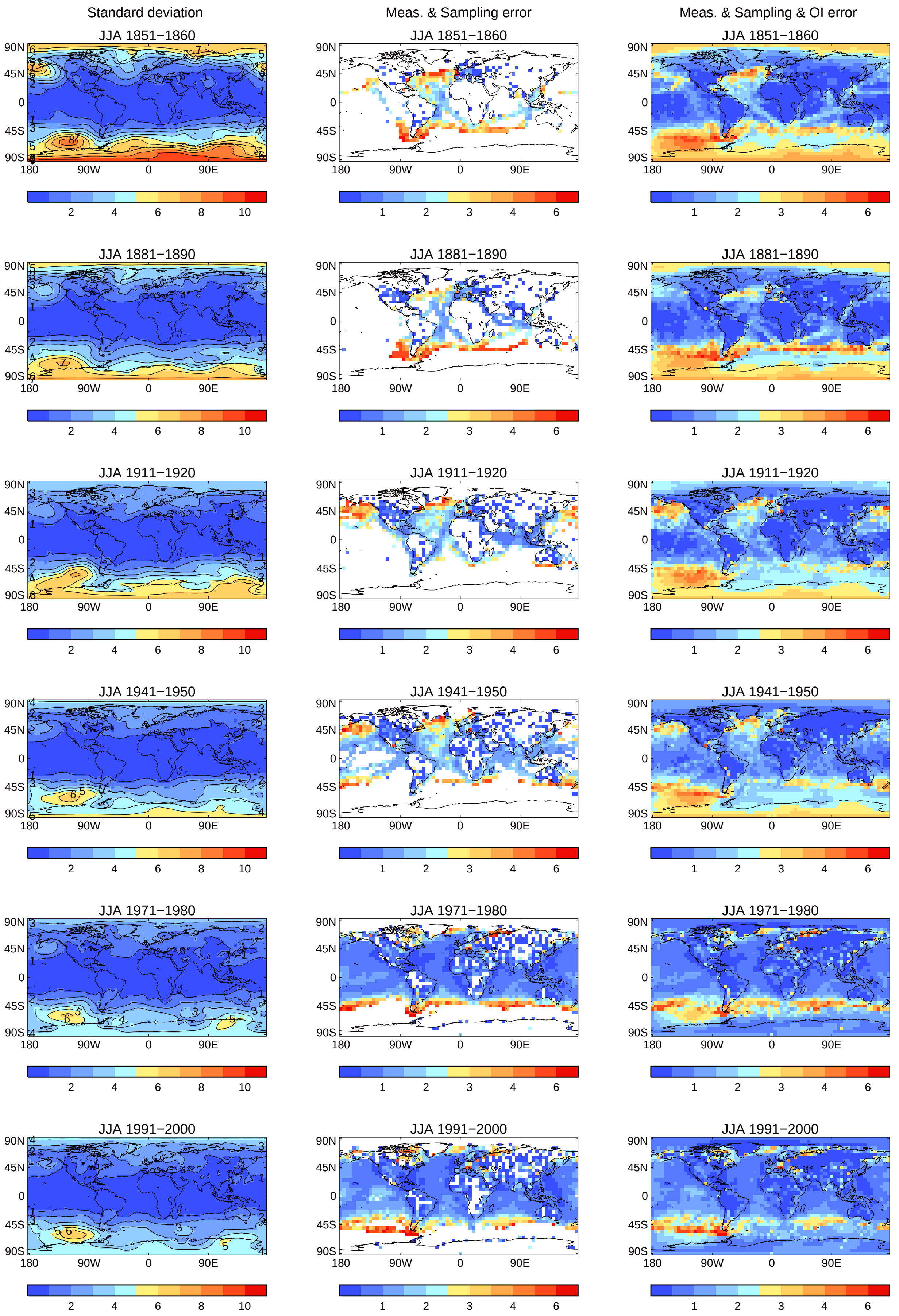

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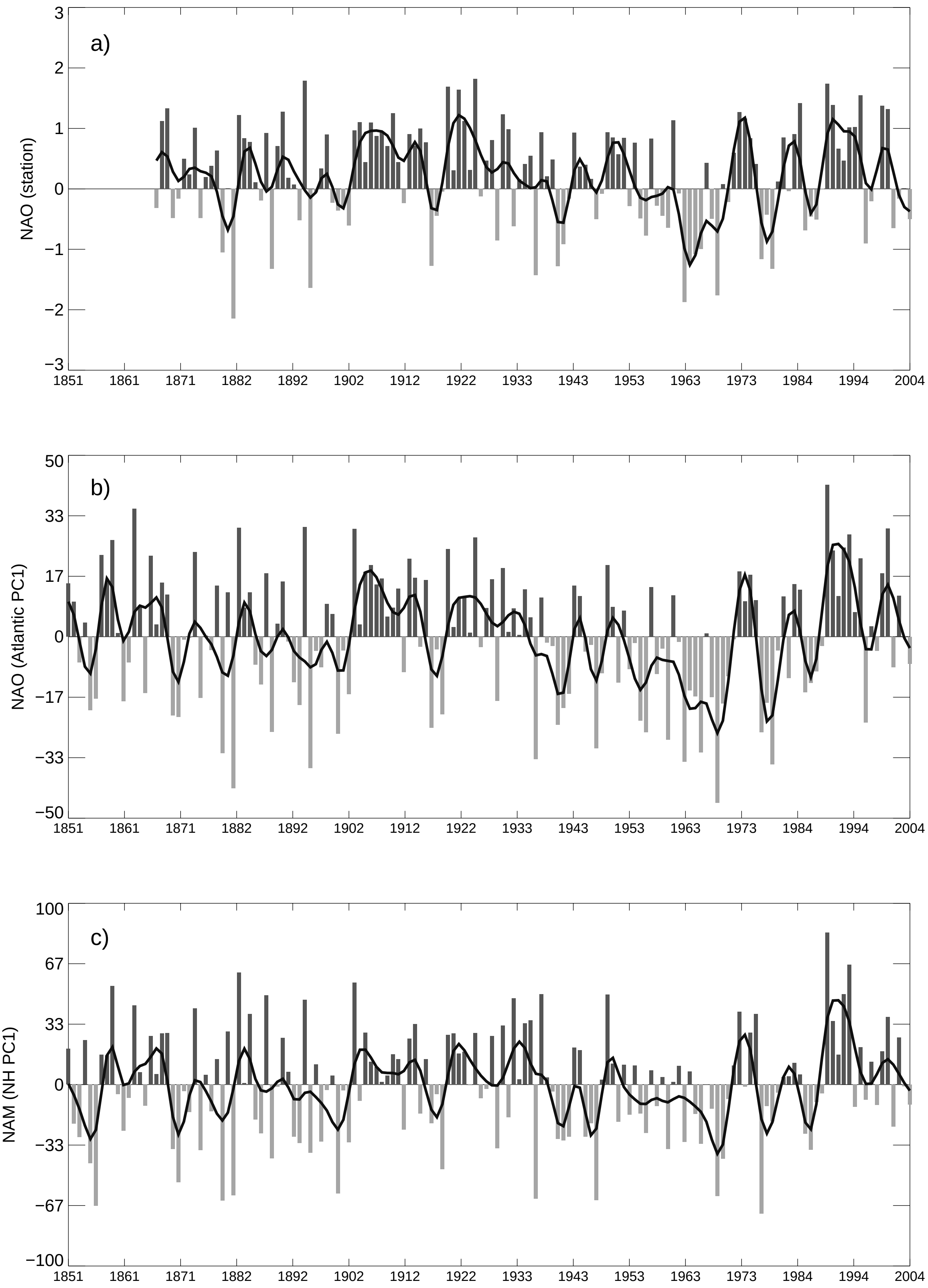

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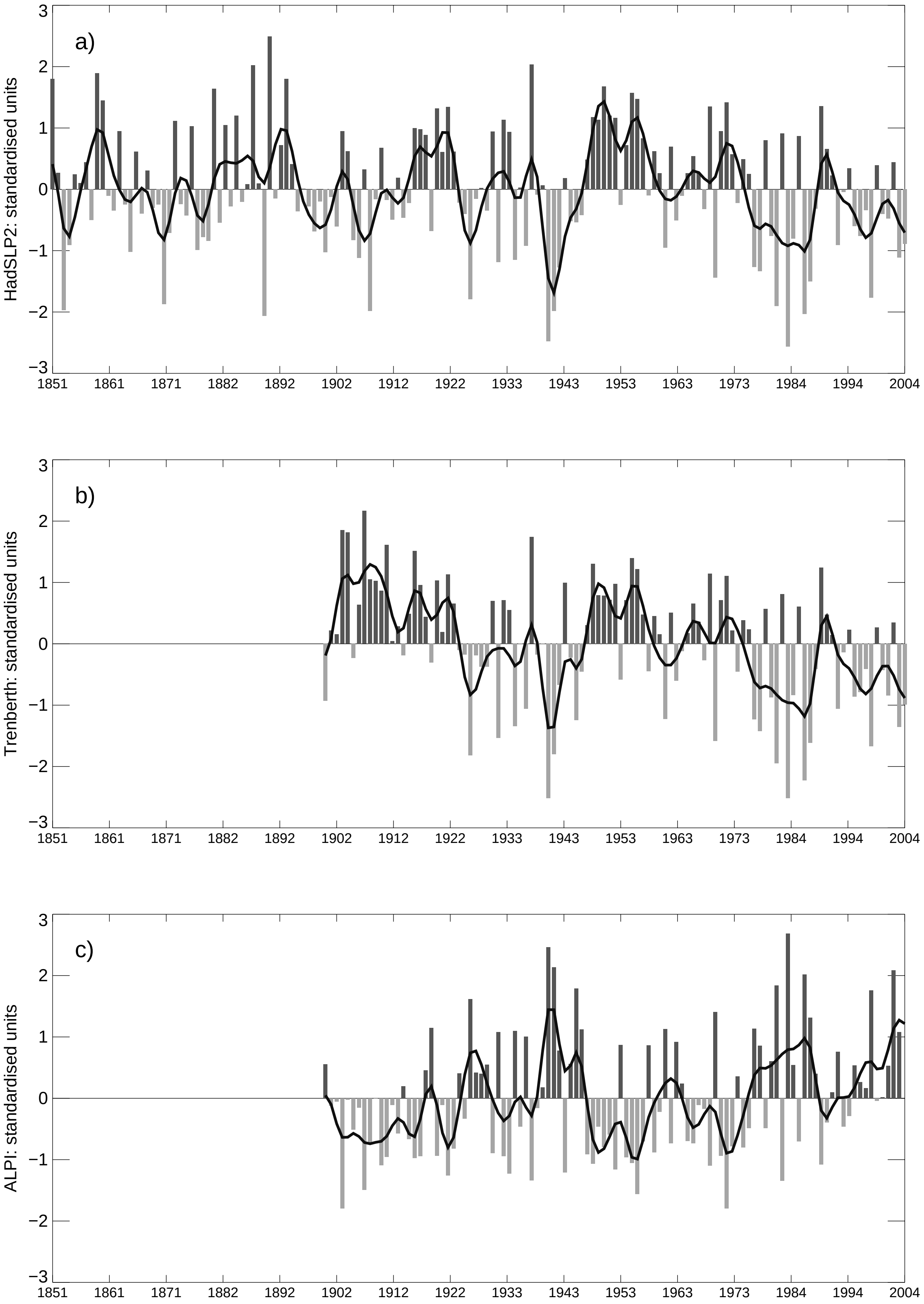

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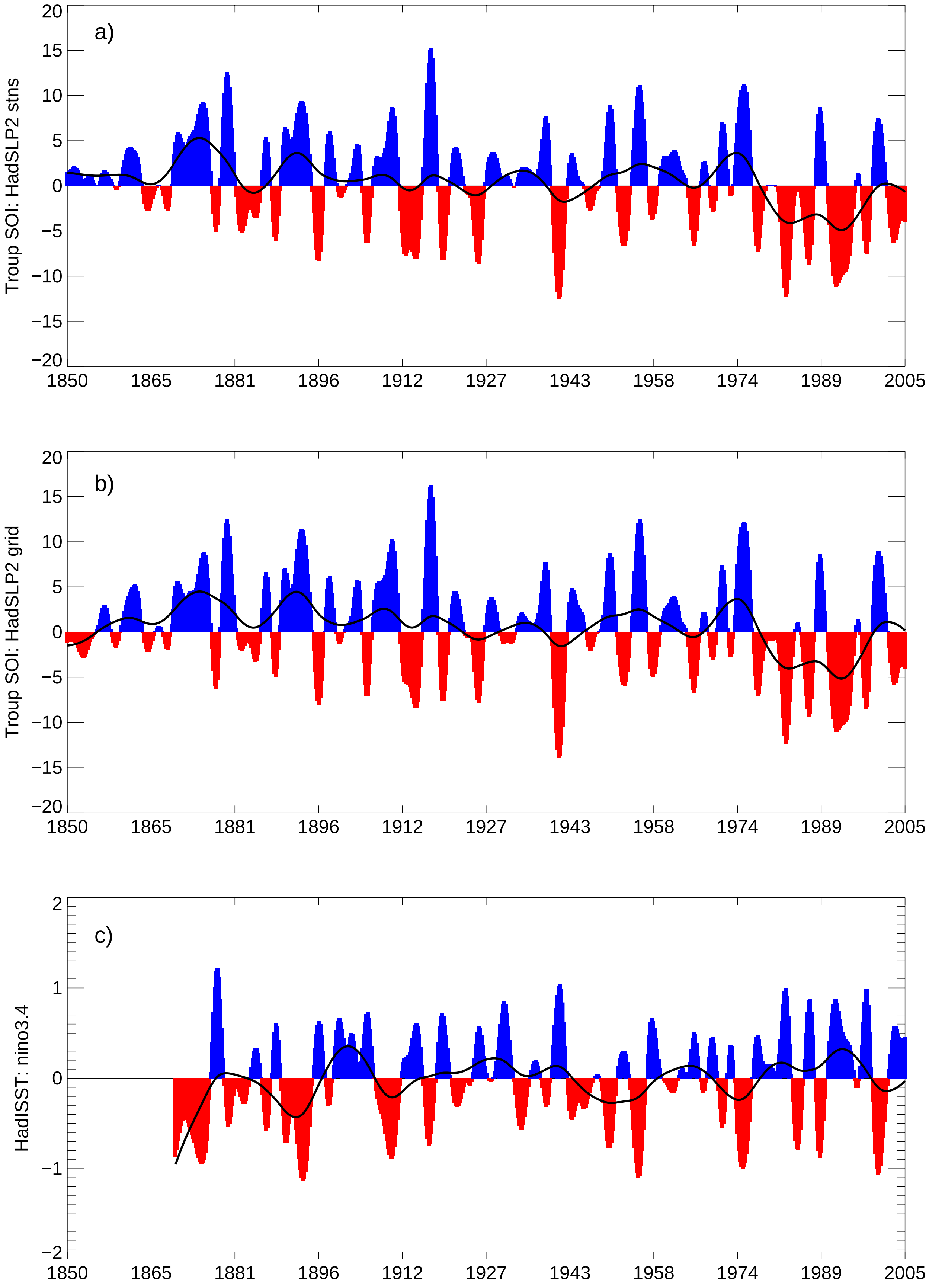

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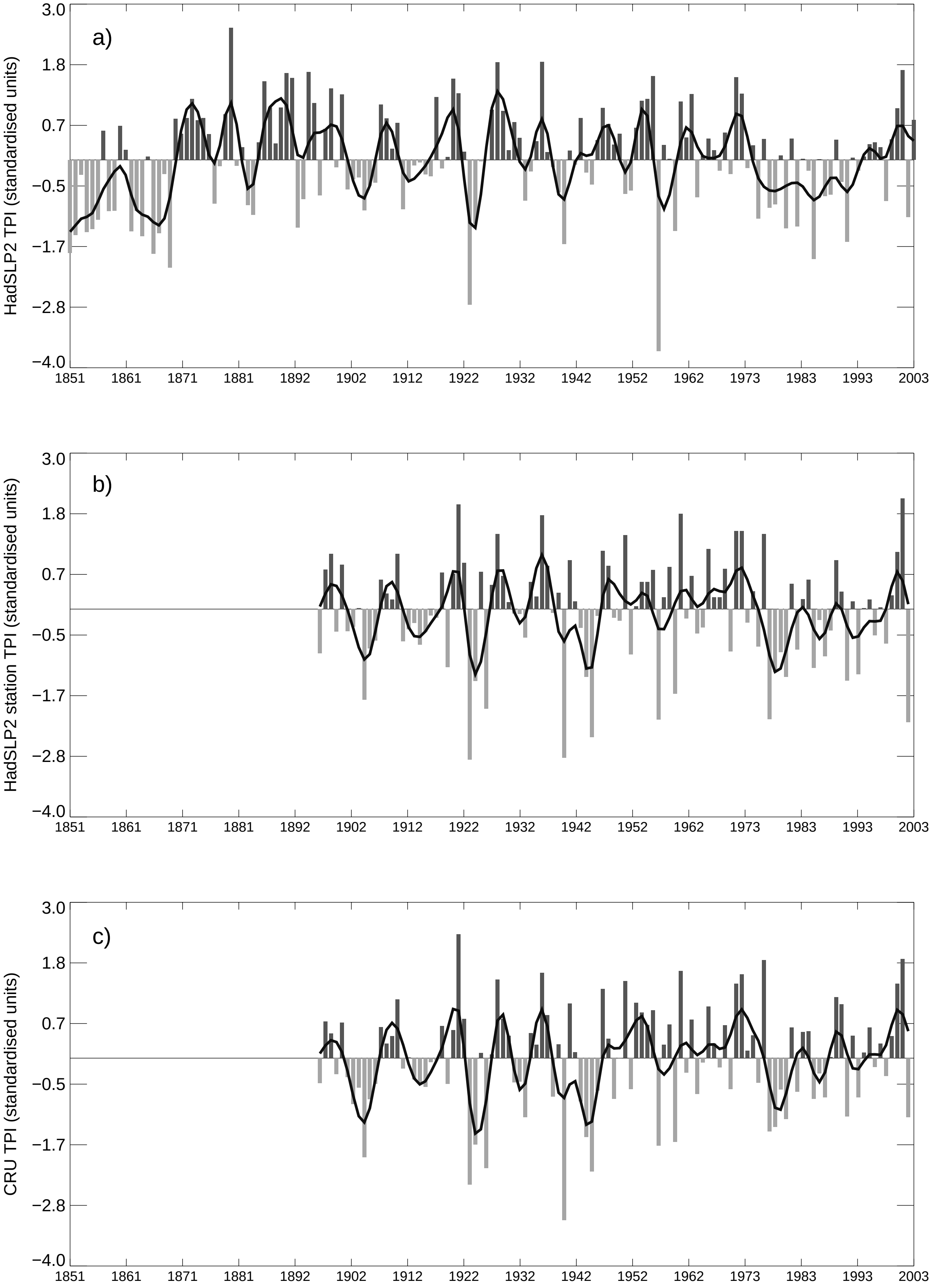

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