Daily mean sea level pressure reconstructions for the European - North Atlantic region for the period 1850-2003

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Abstract

The development of a daily historical European – North Atlantic mean sea level pressure data set for 1850-2003 on a 5° latitude by longitude grid is described. This product, known as EMSLP, was produced using 86 continental and island stations distributed over the region 70° W - 50° E, 25° – 70° N, blended with marine data from the International Comprehensive Ocean Atmosphere Data Set. The EMSLP fields for 1850-1880 are based purely on the land station data and ship observations. From 1881, the blended land and marine fields are combined with already available daily Northern Hemisphere fields. Complete coverage is obtained by employing Reduced Space Optimal Interpolation. Spatial correlations indicate that EMSLP captures generally 80-90% of daily variability represented in an existing historical MSLP product and over 90% in modern ERA-40 reanalyses over most of the region. A lack of sufficient observations over Greenland and the Middle East, however, has resulted in poorer reconstructions there. Error estimates, produced as part of the reconstruction technique, flag these as regions of low confidence. We show that the EMSLP daily fields and associated error estimates provide a unique opportunity to examine the circulation patterns associated with extreme events across the European – North Atlantic region, such as the 2003 heat wave, in the context of historical events.

1. Introduction.

The European Community (EC)-funded EMULATE (**E**uropean and North Atlantic daily to **MUL**tidecadal clim**ATE** variability) project began in November, 2002. An initial aim of EMULATE was to define characteristic atmospheric circulation patterns over the European and North Atlantic region. Changes in mean amplitudes, variability, persistence and transition regimes of these dominant patterns over a 154 year period would then be assessed with both traditional and new statistical techniques. These variations and trends would then be related to sea surface temperature (SST) patterns over the North Atlantic and worldwide, and to natural and anthropogenic forcing factors, involving various climate model integrations. A final aim was to relate these trends to extremes in temperature and precipitation over Europe.

Previous studies of this nature have been limited by a lack of gridded mean sea level pressure (MSLP) products of sufficient length. Central to EMULATE has, therefore, been the development of daily gridded MSLP fields over Europe and the extratropical North Atlantic, extending back to 1850. These fields will enable us to more fully examine whether relationships between SST and circulation patterns are stationary, and then to more reliably assess the relative importance of anthropogenic factors. They will be also used to study dynamic backgrounds of extreme events and circulation extremes over a well extended period.

Here we present the development of this gridded daily MSLP product on a 5° latitude x longitude grid over the region 70° W - 50° E, 25° – 70° N (hereafter referred to as the EMULATE region). Daily gridded MSLP fields since 1881 for the Northern Hemisphere north of 15° N are already available, but are only reliable over western and Central Europe (e.g. Germany, Austria, Switzerland and Northern Italy). These fields are improved and extended, using long station-based European pressure series from earlier EC projects and recently digitised long station records, particularly over Europe and Russia. Over the ocean we take advantage of the recently released International Comprehensive Ocean-Atmosphere Data Set (ICOADS, Worley *et al.*, 2005; Diaz *et al.*, 2002), using all available observations over the 24 hour period. By blending these sources we are able to produce daily fields from 1850.

The biggest challenge to this work has been the lack of observations, particularly pre 1881. During this period observations are available over only 15% of the EMULATE region. Despite the inclusion of the recently digitised US Maury collection (pre 1863, Worley *et al.*, 2005), the marine observations are constrained to the major shipping routes of the time, predominantly between the UK and Americas and from the UK around Cape Horn. Similarly, in remote terrestrial regions such as central Greenland and Northern Africa no station data is available. In these areas, our fields are based purely on reconstruction. Because of this it is important to be able to constrain analyses in these regions of low-confidence and accordingly EMSLP is available with error estimates to guide the researcher.

Quality control and gridding issues, central to this work, are described in Sections 2 and 3, including the use of interpolation techniques to obtain spatially complete fields. In Section 4 we compare EMSLP to existing analyses and examine its ability to resolve extreme events. In addition to improving understanding of recent events such as the 2003 summer heat wave in Western Europe, the autumn 2000 floods in the United Kingdom (UK) and European floods in Germany, Austria and the Czech Republic in 2002 (Danube and Elbe rivers), we anticipate that this product will be a valuable aid in further understanding of historical extreme events back to the mid-19th century. Conclusions are given in Section 5.

2. Data sources and quality control

Our strategy has been to take advantage of a Northern Hemisphere (north of 15° N) synoptic daily gridded MSLP product available from 1881 to the present (Jackson, 1986, hereafter referred to as J86), and to improve and extend it back to 1850 with the inclusion of new land station and marine pressure observations. The J86 fields are an extremely valuable resource as they are derived from synoptic operational charts and so contain many thousand station observations. Because of this we were able to concentrate our efforts to collate and digitise station data on the period before 1881. The EMSLP fields for 1850-1880 are therefore based purely on a blending of land station data and ship observations; from 1881, the blended land and marine fields are combined with the daily J86 fields.

Because the number and times of observations per day varies markedly across all stations available, all the observations (including the marine and J86 fields) are corrected to represent the 24 hourly mean. Accordingly the EMSLP daily fields represent the average pressure over the 24 hour period and so are different and indeed smoother than synoptic and 4 x daily reanalysis charts.

2.1 Terrestrial data sources

The daily continental and island observations were drawn from a number of sources. Data already in electronic form were obtained for various Italian, Fennoscandian and UK stations compiled by earlier EC projects such as IMPROVE (Camuffo & Jones, 2002) and WASA (Schmith *et al.*, 1997) and individual efforts for Montreal (Slonosky, 2003), Gibraltar (M. Rodwell, D. Wheeler), De Bilt (T. Brandsma), Paris and Palmero (M. Barriendos) and Galway (Hickey *et al.*, 2003). We were able to obtain updates and additional historic data for some WASA stations, extending them back to 1850 and forwards to 2003. Considerable material had to be digitised, however, from individual hard copy records from Russian, British, French and Spanish daily weather records (DWRs), held in the UK National Meteorological Archives and Library. These were supplemented by scanned Algerian, French and United States (US) observations on the National Oceanographic and Atmospheric Administration (NOAA) Library web site (http://docs.lib.noaa.gov/rescue/data_rescue_home.html). Old American 'Bulletin of International Meteorological observations' volumes also provided valuable records for Nuuk (Godthåb) in Greenland and helped fill gaps in existing records. Data were also digitised from compilations made under the auspices of the UK Board of Trade, Royal Engineers and Army Medical Department and from Ottoman Empire records.

In all, 86 continental and island stations over the European - North Atlantic region (see Figure 1 for land station distribution) were selected. A detailed list of the individual station series lengths is provided in Table 1; the corresponding data sources are detailed in Appendix A1. Both 'uncorrected' and quality controlled daily station data series used in the project are available from the EMULATE web site: www.cru.uea.ac.uk/cru/projects/emulate/.

2.1.1 Quality Control

Most of the 86 station series required some form of quality control and homogenisation. Most observations were made with mercury barometers; a number of corrections are necessary for converting these measurements into a true measure of the atmospheric pressure. The reading from a mercury barometer (usually in English inches or millimetres of mercury) is proportional to the length of mercury in a column, balanced against the weight of the entire atmospheric column. The instruments were calibrated at ‘standard conditions’ and so corrections must be applied to account for the thermal expansion of mercury and for the local gravity value. In most cases, the station data had been corrected at source to a standard temperature of 0^{o}C and to a standard gravity equal to that at 45°N. Some digitised Russian series however had been calibrated at 13.33^{o}C (e.g. Lugansk), so additional adjustments had to be made. All pressures were converted to units of hectoPascals (hPa).

When sea level pressures were not available, the station level pressures were corrected to mean sea level. An expression for the reduction of station level pressure to sea level can be obtained by combining the hypsometric equations with the ideal gas equation for air (see Slonosky *et al.*, 2001). This conversion requires the temperature reading. Daily temperature records were not always available and so in these few cases climatological temperature values were employed.

A daily pressure value was obtained for each station by taking the average of all available observations for each day. The number and times of observations per day varied markedly across all 86 stations, however, causing biases because atmospheric pressure has marked semi-diurnal and diurnal variations. This arises from internal gravity waves in the atmosphere, generated by atmospheric solar heating, through the absorption of solar radiation, and upward eddy conduction of heat from the ground (Chapman & Lindzen, 1970). Over the EMULATE region, the amplitude of both diurnal- and semi-diurnal oscillation (also referred to as atmospheric tides) is generally < 1.0 hPa (Dai & Wang, 1999). While this is small compared with daily variability (especially when compared with the tropics) it is important to account for it.

In order for the daily fields to better approximate the 'true' daily mean, each station was corrected for these atmospheric tides. Due to a lack of sufficient sub-daily data however, we were unable to calculate the diurnal- and semi-diurnal cycle at each station directly. Instead, we used the seasonal phase and amplitude gridded fields calculated by Dai and Wang (1999) and interpolated from the nearest grid point. Observation hours for each day of the station series were collated and used to determine the appropriate adjustment required.

2.2 Marine data sources

Marine pressure observations were obtained from ICOADS (Worley *et al.*, 2005; Diaz *et al.*, 2002). This data set combines the Met Office's Marine Data Bank with the previous version of COADS (Woodruff *et al.*, 1993) and also includes several million new observations from the US Maury collection amongst others. Daily marine gridded MSLP fields were generated using these data for 1850-1997, supplemented with National Centers for Environmental Prediction (NCEP) Global Telecommunication System (GTS) data for 1998-2003.

2.2.1 Summary of marine gridding procedure

To quality control and grid the marine observations, we have modified the procedure used in the development of HadSLP1, the Hadley Centre's historical gridded global monthly MSLP product (described in Basnett & Parker, 1997). The quality control and gridding is based on residuals (anomalies), formed by removing a monthly background field (described below) from each ship observation. The residuals were compared to a measure of intra-monthly variability (see below); only those observations that were equal to or less than 3 times this intra-monthly value were gridded on 1^{o} latitude by longitude resolution. A smoother daily value for each 1^{o} latitude by longitude grid box was then formed by taking the median value of all 1^{o} residuals over a 7^{o} area centred on the 1^{o}x1^{o} target box. This procedure serves to infill in data sparse areas and smooth in data rich areas. For example, if the target box value is missing, but one of the surrounding 41 1^{o} boxes in the 7^{o} area contain an observation, then the target value is replaced with this value. If all grid box values in the 7^{o} degree area contain data, including the target, then the target value will be replaced with the median of all 42 grid box values. The 7^{o} area was chosen initially to help combat the sparseness of the available observed data, but it results in considerable smoothing particularly in well sampled mid-latitude regions. This is considered further in Section 4.

We also corrected each observation for the diurnal- and semi-diurnal oscillation, using the Dai and Wang (1999) fields, as with the land data. Considerable effort was also spent exploring and documenting the extent of previously undetected duplicates and a low (anomalously negative) MSLP bias in the early 1850s; these issues are elaborated upon in Appendices A2 and A3. The background fields were added back to the screened, gridded residuals to yield gridded actual values of marine MSLP.

2.3 Gridded data sources

2.3.1 Daily

We have taken advantage of the Met Office's historical (J86) data set (Jackson, 1986), a Northern Hemisphere (north of 15 ^{o}N) synoptic daily MSLP product extending from 1881 to the present on a 5^o latitude by 10^o longitude grid. Until the 1970s, these J86 fields were derived from digitised hand-drawn synoptic charts (see Table 2), including the German Morning charts and US forecast charts. In the 1970s they were replaced with model analysis charts. The J86 product is an extremely valuable resource, as each daily field contains many thousand of station observations that went into the original operational charts each day.

The many changes in source, detailed in Table 2, mean that the J86 fields are, however, subject to heterogeneities, elevation corrections and increasing data availability (see also Jones, 1987; Jones *et al.*, 1999). Potential problems are important over southeastern Europe, the Middle East and parts of the North Atlantic Ocean, particularly before 1940. In order to account for these heteogeneities, the J86 fields were adjusted such that their monthly means agreed with HadSLP1 (described in Section 2.3.2 below). The maximum adjustments were 5-6 hPa. The years 1999-2002 remain uncorrected (HadSLP1 currently extends only to 1998[1]), but potential heteogeneites are more likely before 1975 (see Table 2). Fields were also re-gridded onto a 5^{o}x5^o grid. We applied a correction for the diurnal- and semi-diurnal oscillation using the Dai and Wang (1999) fields and based on analysis times given in Table 2, to make them consistent with the 24 hour 'daily' station and marine data.

Intra-monthly variability fields, introduced in section 2.2.1, were calculated from 4 x 6 hourly NCEP/NCAR (National Center for Atmospheric Research) reanalysis fields (Kalnay *et al.*, 1996)

[1] HadSLP2 (Allan & Ansell, 2005) was not yet available at this time.

2.3.2 Monthly

As described in section 2.2.1, a background field is required for quality-controlling and gridding the marine observations. We have principally relied on HadSLP1 (an updated version of GMSLP2.1f (Basnett & Parker, 1997)), which is a global monthly gridded product, on a 5^o latitude by longitude grid, for 1871-1998. For 1854-1870 we used Kaplan *et al.*'s (2000) optimally interpolated (marine only) fields; a climatological average was used for the period 1850-1854. A land and marine background field is also required when blending the land and marine fields (section 3.1). As Kaplan *et al.*'s (2000) optimally interpolated fields are marine only, a climatological monthly average of 1871-1900 from HadSLP1 was used for the period 1850-1870.

For homogeneity checks and validation, a historical gridded product, developed as part of the Annual to Decadal Variability in Climate in Europe (ADVICE) project (Jones *et al.*, 1999) was used. The ADVICE monthly data are available as either 51 individual station series, or on a 5^o latitude by 10^o longitude grid for 1780-1995. Note ADVICE used monthly averages of J86 data since 1881 and additional monthly fields for 1873-1880; accordingly ADVICE is not independent of EMSLP.

2.4 Homogenisation of land station data.

In order to obtain long and homogenised series, issues such as change of station location, instrument and instrument height need to be identified and corrected for. These can be identified in metadata records; but such records are often not available.

Potential heteogeneities can be identified with a standard normal homogeneity test (Alexandersson, 1986). This and similar techniques, described in Slonosky *et al.* (1999), rely on comparisons with 'reference' series that are known to be homogeneous. We made near neighbour comparisons, for example, for Durham and Aberdeen in Britain, Armagh and Galway in Ireland, Toulon and Brest in France and Cadiz and Gibraltar. Not all potential heteogeneities could be identified by this method, however, owing to a lack of suitable nearby reference series. Occasionally the reference series itself was found to contain inhomogeneities (viz. Cadiz). It is also preferable to use records from at least two different observing countries (Slonosky *et al.*, 1999) as methodological changes may have taken place at the same time within individual countries.

To address these homogenisation issues more fully, we applied adjustment factors, similar to those applied to the J86 fields (section 2.3.1). Specifically, the monthly means were calculated for each daily series and compared with a reference value (the corresponding ADVICE monthly station series or an interpolation from the nearest ADVICE or HadSLP1 grid point). The difference in monthly means was then used to adjust the daily SLP values. To avoid jumps in adjustments at the end of each month and year, a binomial filter with 7 terms was applied to the whole adjustment series. This process gives a smooth daily adjustment series, but almost the full daily variability of the station data is still preserved. Preference was given to the ADVICE station series where possible.

For the Canadian stations and those in the far east of the EMULATE region, a final adjustment was required so that their daily average represented the same 24 hour period as the other series. The Canadian stations are 5 hours behind Central Europe, the eastern most Russian 4 hours ahead. As only daily averages were available for these stations, we were forced to interpolate between the preceding (following) day and the actual day for the Canadian (far Russian) stations.

3. Gridding and Reconstruction

3.1 Blending land and marine fields

The quality controlled land station data were blended with the gridded marine fields, using a procedure similar to that employed to grid the marine observations (section 2.2.1). For each day, in each month and in each year for 1850-2003 and in each 1^ox1^o grid box, the marine grid box value and all terrestrial individual MSLP station observations (if present) were collated. Residuals were formed by subtracting a monthly (land and marine) background field from each terrestrial observation and marine grid box value and then the median value (both land and marine) was selected. All the 1^ox1^o median values were then averaged to 5^ox5^o grid point values, taking account of their spatial distribution.

The J86 fields (from 1881-2003) were then combined with these blended (land and marine) 1850-2003 fields using Poisson blending (Reynolds, 1988). Using the blended land and marine observations (anomalous values) as the ground truth, the Laplacian (second derivative) of the 'less reliable' J86 anomalies was used to interpolate between the blended observations and J86 anomalies. For grid boxes with no observations, the J86 value was taken.

3.2 Interpolation

In order to create spatially complete fields, Reduced Space Optimal Interpolation (RSOI) was used (see Kaplan *et al.* (1997) and references therein). The

RSOI technique reconstructs fields by least squares fitting incomplete observed data to yield the amplitudes of a pre determined subset of the Empirical Orthogonal Functions (EOFs) of the spatial covariance matrix. The analysis is constrained to give greatest weight to data with smaller estimated error variance, so that noisy or sparse data are prevented from producing noisy or spurious fields (Kaplan *et al.*, 1997). The series of EOFs is truncated, to remove as much of the noise as possible, while retaining 'true' signals. By construction, therefore, large-scale features of the variable are recovered, which are presumed to be those of greatest climatic importance (Kaplan *et al.*, 2000). A major assumption of this method is that the EOFs describe a set of patterns that occur throughout the reconstruction period.

During the period 1850-1880 the blended land and marine fields have very poor data coverage; 85-90% of the grid boxes have missing values. In order to assess how well RSOI would perform with such sparse coverage, we performed verification experiments by sub-sampling daily NCEP/NCAR reanalysis fields for 1990-2000 to represent the historical sampling of 1850-1860. These fields were then reconstructed using RSOI, using EOFS calculated over the period 1951-1989. The Root Mean Square (RMS) errors for the reconstructed and 'original' daily fields were generally <2.5 hPa, indicating that the technique generally performs very well, even with >85% of the data withheld. Over Greenland and in the far northeast and west of the EMULATE region, RMS errors were as large as 5 hPa, highlighting regions where the technique performs less well.

3.2.1 Procedure

We now describe how RSOI was applied, detailing firstly the calculation of the covariance matrix and error fields.

The most crucial element of RSOI is to obtain a reliable estimate of the spatial covariance matrix (Kaplan *et al.*, 2000). It is desirable to use a relatively long time period of well-sampled fields, so here NCEP/NCAR reanalysis data from 1951-2002 were used. We employed anomalies relative to smoothed daily averages ('normals') for 1951-2000 on 5^{o} latitude by longitude resolution. The unsmoothed normals were created by taking the climatological 50 year average for each calendar day of the year. A 50 year average of February 29th was formed by simulating Feb 29th in non leap years by averaging Feb 28th and March 1st. After the unsmoothed climatology was formed, a binomial (timewise) filter with 21 terms, removing noise under 15 days, was applied at each grid point to yield the smoothed (daily) climatology.

EOFs were calculated for each calendar day over just the EMULATE region using a covariance matrix of MSLP 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 a more realistic estimate of the signal covariance and, by association, more realistic theoretical error estimates (see Appendix in Kaplan *et al.* (2000)). In this study it was found however that this step was not required, due, we believe, to the smooth NCEP/NCAR fields from which the covariance matrix was estimated.

An estimate of the sampling error is also required for RSOI. We used an average (1961-1990) of the combined marine, land and J86 sampling error. For the marine observations the sampling error for each month (after Parker, 1984) was calculated, as part of the marine gridding procedure. This was multiplied by the square-root of the number of days with data to yield the daily error. 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.

Over land, estimated errors were based on the altitude of the station. An estimate of $h/1500$ as the bias associated with the reduction to mean sea level, where h is the altitude of the stations (in meters), was identified by comparing the pressure reduced to sea level and model analyses at a number of high altitude grid points. Again 0.25 hPa was added (vectorially) to the elevation-related bias, to reflect the random bias error. For grid points where the J86 data were used, we based the error on the intra-box variability (calculated from 1°x1° resolution data within the 5°x5° grid box from the NCEP/NCAR reanalysis) divided by the number of observations at that grid point. A sample of historical synoptic charts was used to estimate the number of observations at each grid point. In regions of zero observations (central Greenland and northeast European Russia) the error was set to the intra-box variability at that grid point.

Complete MSLP anomaly fields were reconstructed using the leading 20 EOFs and the error field. Following Rayner *et al.* (2003), the available ‘observations’ (as anomalies) were then superimposed on the reconstruction. Then grid points were 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 daily averages and standard deviations derived from NCEP/NCAR reanalysis). Flagged anomalies and their neighbours were then weighted based on whether they were an observation or reconstruction and on the numbers of constituent observations.

This gave greater weight to well observed areas because 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. Over the 154 year period, an average of 1.5 % of grid points per month were initially flagged, with 0.2 % remaining after the first weighted average. This procedure was reiterated until data rejections ceased; 70% of these flagged grid points were 'corrected' after two iterations. Finally, the climatology was added back to yield absolute values.

4. Assessment / results.

To diagnose any potential problems with EMSLP, we have compared the data set with the monthly ADVICE product (Jones *et al.*, 1999) and 4 x 6 hourly European Centre for Medium-range Weather Forecasts (ECMWF) ERA-40 reanalysis MSLP fields. Both long-term averages and individual events have been examined. Here we highlight issues that may be most relevant to the potential user.

4.1 Climatologies

We compare the EMSLP monthly climatology with the ADVICE gridded product over 1850-1995 in Figure 2. The ADVICE region is only a subset of the EMULATE region, but there is generally excellent agreement between the two products, with differences of the order +/-0.5 hPa (only those values > 0.5 and <-0.5 are plotted). One region where differences are prominent is central Spain. Pressures near Madrid in EMSLP are around 1.5 hPa higher during November-January than the ADVICE grid, whereas from June to August EMSLP pressures are 1.5 hPa lower than in ADVICE. The EMULATE station series are adjusted so that their monthly means are equal to the ADVICE station series (section 2.4); hence the difference between the two products cannot be explained by a discrepancy in the two input series. The coarser ADVICE grid may however account for the differences; the ADVICE grid point for Madrid includes data from Oporto which is not included in EMSLP, because only monthly data are available. Differences between coastal and inland sites are marked in this region, due to thermal pressure systems that develop over the interior.

In the Middle East ADVICE MSLP is lower than EMSLP during most of the year, though particularly during summer.   The inclusion of the monthly Cairo and Jerusalem records in ADVICE may account for these regional differences in the two products; EMSLP has only limited records for Alexandria and Beirut (see Table 1) and for 1881-2003 relies solely on reconstruction and J86 fields here. Differences between the gridded products over the ocean we believe are a result of the inclusion of ICOADS observations in EMSLP and their subsequent impact on the diurnal cycle. While both products are based on J86, which are derived from synoptic charts (Table 2), in EMSLP these fields were corrected for the semi-diurnal and diurnal cycle. Even though our correction is coarse, over the ocean the ICOADS observations are well sampled throughout the day and so the daily marine MSLP fields in EMSLP are closer to a 24 hour mean than the original J86 fields.

Comparisons with ERA-40 are shown in Figure 3; both products are averaged for 1959-2001. Differences over the ocean are very small (<0.5 hPa), except in the Eastern Mediterranean and off the east Greenland coast, north of, and extending into, Iceland. The latter is most prominent during the winter months and is believed to be related to seasonal variations in lapse rates in this region, which influence the reduction to mean sea level pressure. This has found to result in a small, partly fictitious, high pressure area lingering over central Iceland during the winter. Over land differences are larger than that seen with ADVICE (Figure 2) and again these are largest in November through February, with differences up to 1.5 hPa in Eastern Europe. Most differences over land we suspect are due to the superior number of observations available to the ERA-40 product compared to EMSLP. In the Middle East the differences may be associated with the diurnal cycle correction (see section 4.2). The lower pressures over Greenland in EMSLP compared with ERA-40 are also evident in comparisons with NCEP/NCAR reanalysis fields (not shown). We believe this is indicative of the difficulty models have in resolving MSLP here; an estimate is obtained by extrapolating the surface pressure through the ice to sea level.

4.2 Correlations

Spatial and temporal correlations were performed to compare EMSLP with the ADVICE and ERA-40 products. Generally, correlations (and so explained variances) are larger in the winter months, because of the greater meteorological signal in this season. Jones *et al.* (1999) found a similar result when verifying ADVICE with the Lamb and Johnson (1966) and Kington (1980, 1988) historical analyses.

The ADVICE and EMSLP products were correlated at each grid point for three periods; 1850-1880 (Figure 4), 1881-1940 (Figure 5) and 1941-1995 (not shown). During the mid-19th century, over Central Europe in winter (January – February) the variance explained is very high (> 90%), consistent with the quality and amount of data here. This weakens during spring-summer and near the periphery of the region (Figure 4). Over the ocean and the southern regions, differences are also more notable. This is consistent with the inclusion of ICOADS observations in EMSLP and may also reflect the lack of North African station data in ADVICE.

During 1881-1940 (Figure 5), the variance explained increases, particularly during summer and over the ocean. The Middle East region however remains a region of low explained variance. For 1881-1898 EMSLP contains no station nor J86 observations in this region, with only limited records for Beirut and Alexandria in 1876-1881, whereas ADVICE, as noted above, includes data from Cairo and Jerusalem. Correlations strengthen slightly in the last period examined, 1941-1995 (not shown).

Given that ADVICE and EMSLP are not strictly independent, we also present correlations with ERA-40. These correlations are very high, with explained variances over much of the region in excess of 90% (July to December are shown in Figure 6). The exception is in North Africa and the Middle East during April-November. This is most marked in August-September, when the variance explained drops to around 10% in North Africa. The differences may be a result of the diurnal cycle correction being incorrectly applied to the EMSLP product in this area where the true signal is small. Incorrect application could have resulted from unrecorded temporal variations in the times of land station observations used in the J86 fields which were a major input to EMSLP in this area. Differences between the two products, as a result of observing times, are expected to be less notable over the marine regions given, as noted above, the good coverage of ship observations throughout the day. Correlations are indeed high over the ocean. The poor correlation over North Africa may also indicate differences in the number of observations in this region.

Following Jones *et al.* (1999), we compared ADVICE and EMSLP by calculating spatial correlation co-efficients over the common area for 1850-1995 (Figure 7). Jones *et al.* (1999) note that anomalies should be used to avoid artificially high correlations due to the climatological average spatial distribution of high and low pressure over the European – North-Atlantic region. To give equal weight to the less variable lower latitudes and the more variable higher latitudes, we formed normalised anomalies by removing a 1961-1990 average and dividing by the standard deviation, also calculated over this period. As expected correlations are sometimes poor during the early period, but gradually improve towards the late 20th century with increasing number of observations (also plotted in Figure 7). Owing to the existence of stronger anomalies in winter, correlations are stronger during the winter season, generally around 0.8, but correlations are particularly poor in June, August and September. This result suggests that greater caution may be needed when using EMSLP to study summer phenomena over this region. Interannual variations are also quite prominent in Figure 7, often associated with the variability in the number of observations used in the data set and in ICOADS in particular.

4.3 Regional comparisons

Sub-regional comparisons have also been made and have revealed that there is a tendency for highs (lows) in the EMSLP series to be not ‘high’ (‘deep’) enough. This tendency can be clearly seen in Figure 8, where the EMSLP pressures are plotted against the corresponding ADVICE pressures for the same 31 year period. A straight line representing EMSLP = ADVICE values is also plotted. We suspect that this is a consequence of the ‘smoothing’ and ‘in-filling’ procedure, applied when gridding the marine observations (section 2.2.1). It may also be partly due to the application of RSOI, which tends to produce damped fields, despite our attempts to reduce this by blending back in the observations (section 2.3.1). A similar relationship to that seen in Figure 8 is evident during 1881-1920, 1921-1960 and 1961-2000 (not shown), indicating that it is a persistent feature of the EMSLP product. We have also seen this dampening when comparing the nearest grid point value from EMSLP with the original station series. A monthly analysis of extreme events (not shown) indicated the flattening appears not to have a major impact on these timescales.

In Figure 9 we plot the winter NAO using EMSLP and the monthly HadSLP2 product (Allan & Ansell, 2005), taking the grid point nearest to Ponta Delgada in the Azores minus the grid point nearest Reykjavik in Iceland. Seasonal averages are formed for each year and the differences standardised by removing a 1961-1990 mean. Also plotted is a station based index using data from Azores and Reykjavik (data available from http://www.cru.uea.ac.uk/cru/data/nao.htm). All three series compare well; the correlation coefficient for EMSLP and HadSLP is 0.97 and is 0.98 for EMSLP and the station series. There is a lot of interannual variability evident in the NAO series, and encouragingly, despite the smoothing described above, EMSLP has the correct magnitude. This may be a result of the influence of the Icelandic and limited Azores station data on EMSLP.

4.4 Variability

A general feature of least-squares objective analyses is a reduction in variance and this is evident in the EMSLP reconstructed fields. It is most prominent in the data-sparse regions, e.g. northwest Greenland and northeast European Russia, in the far northeast of the EMULATE region. We plot daily variability within the summer season by calculating the standard deviation of all June-July-August daily fields for each of the 10 decades of the data set (1850-1950) in Figure 10. For the first 3 decades the variability off the west Greenland coast and Newfoundland is lower than during the rest of the period. This region and period correspond to locations with virtually no observations before blending with the J86 fields in 1881.

During 1875-1880 we have very sporadic records from Nuuk (64.16^{o}N, 51.75^{o}W). In 1894 the Tasiilaq (Ammasalik) record (65.60^{o}N, 37.63^{o}W) begins. Nuuk and Tasiilaq are the only two Greenland stations included in the dataset, beside those implicit in the J86 product. Complete monthly data are available for Nuuk from 1866, but we were unable to locate the complete daily records. The inclusion of the Nuuk station in 1875, resulted in an increase of variability on the coast. It is also much higher over central Greenland during this decade.

Over much of Europe and the subtropical Atlantic Ocean, where coverage is better, less marked changes are observed. However, over most of the central and northwest Atlantic, the variability is lower in the 1860s than in the earlier decade, particularly off Newfoundland. While the number of marine observations is consistently lower during 1850-1880 than subsequently, they did not increase steadily over this 30 year period. In fact the 1860s were a relatively data poor period, owing to the American Civil War and a general decline in the Maury collection (changes in the number of observations is shown in Figure 7). This may account for the greater reduction in variability during this period compared with the slightly more data-rich period of 1850-1860.

There is little that can be done to adjust the low variance, however error estimates produced with the RSOI solution can be used to place error bars. Indeed very large errors and uncertainty are associated with the period before 1881 near northwest Greenland. The errors decrease in 1875 with the inclusion of the Nuuk observations.

4.5 Extreme events

Recent extreme climate events such as the 2003 heat wave in Europe (Beniston, 2004; Fink *et al.*, 2004; Schär *et al.*, 2004, Luterbacher *et al.*, 2004, Stott *et al.*, 2004) which significantly affect human health (Kovats *et al.*, 2004; Koppe *et al.*, 2004; Stéphan *et al.*, 2005) have led climatologists to question whether such events are unprecedented in the historical record. EMSLP provides a unique opportunity to explore the circulation patterns associated with both daily and sub- monthly extreme events back to the mid-19th century.

Following Burt (2004), we are now able to plot the atmospheric circulation conditions associated with the extreme UK heat waves of June 1859, July 1868, July 1881, August 1911, July 1923 and August 2003 using EMSLP. In Figure 11 we plot the anomalous MSLP field for the days corresponding to the highest temperatures of the summer, equal to or exceeding 35^{o}C. The years 1859, 1911 and 2003 were also anomalously warm summers over Central Europe (e.g. Pfister, 1999; Luterbacher *et al.*, 2004). Anomalously high pressure centred over or near southern Scandinavia is a common feature in all 6 events (weakly in July 1868), resulting in anomalous southeasterly flow bringing hot continental air into the UK. Much of Central Europe is dominated by high pressure associated with these events (Figure 11).

This circulation pattern and anomalous flow has been identified previously by Maryon *et al.* (1982) in a cluster analysis of summer (July-August) 15-day average MSLP fields for the Northern Hemisphere. A similar analysis of both daily and 5 day fields with EMSLP and model analyses, as part of EMULATE, has revealed a similar circulation type.

EMSLP also enables us to examine the circulation patterns associated with recent UK floods, such as in autumn 2000, in the context of historical events. The three wettest Octobers in England and Wales during 1766-2003 were 1903, 2000 and 1987 (Jones & Conway, 1997, Alexander & Jones, 2000). Using UK Daily Weather Records and a chronology of British Hydrological events (see http://www.dundee.ac.uk/geography/cbhe/), we have selected days associated with flooding in the UK for each of these extreme months, in addition to three 19th century flooding events: 1882, 1870 and 1872. These three were the 8th, 13th and 21st wettest Octobers respectively. The anomalous circulation conditions are plotted in Figure 12. While all events are dominated by anomalously low pressure over the UK, arguably of more interest are the differences in the Nordic region and over northwest Russia. Anomalously high pressure dominates this region in 2000, 1882 and 1872, whereas during 1870, 1903 and 1987 negative pressures extending into Norway and parts of Sweden are prominent. EMSLP is now being used to examine circulation changes associated with changes in extreme storms over the UK (Alexander, personal comm.).

5. Conclusions

We have described the development of a daily gridded European – North Atlantic MSLP data set for 1850-2003 on a 5^o latitude by longitude grid, produced with 86 continental and island station records and ship observations from the ICOADS database. The EMSLP fields for 1850-1880 are based purely on the land station data and ship observations. From 1881, the blended land and marine fields are combined with already available daily J86 fields. Comparisons with historical products, such as ADVICE (Jones *et al.*,1999) and recent analyses, such as ERA-40, indicate that EMSLP is able to reproduce climatological features well and explain over 90% of the variance over much of the EMULATE region.

Three main issues, however, have been highlighted. First, smoothing applied during the gridding and quality control procedure has ‘flattened’ the daily fields. Nevertheless the seasonal NAO index calculated from EMSLP appears to have the correct magnitude (Figure 9) and the flattening appears not to have a major impact on a monthly analysis of extreme events (not shown).

Second, during the data sparse period of 1850-1880, the variance to the far east and far west of the EMULATE region is notably lower than after 1880. This is a consequence of the RSOI procedure and data sparseness. While it is difficult to correct this problem, error estimates produced with the OI solution can be employed to flag unreliable values. This result highlights the need to digitise the millions of observations that are still available in ship log books held in the UK National Archives at Kew, London, the National Maritime Museum in Greenwich, London and land station records available in daily weather record volumes held by the Met Office Archives.

Third, again during the data sparse period noted above, the pressures over Greenland appear to be too high in winter. We suggest this is due to the use of NCEP/NCAR reanalysis data in the reconstruction of the MSLP fields. It is not a direct result of the high pressure bias over Greenland in NCEP/NCAR reanalysis in winter, because the reconstruction of EMSLP uses the covariance matrix of NCEP MSLP anomalies. Rather, we argue that this bias is due to the NCEP fields being too variable over Greenland (seen in comparisons with ERA-40 (not shown)), resulting in slightly positive MSLP anomalies, via the covariance matrix, over the high altitude northwest Atlantic in this period, yielding strong positive MSLP anomalies over Greenland.

Despite these issues, we believe EMSLP is suitable to characterise circulation patterns over the European – North Atlantic region. We were able to examine the anomalous conditions during the recent 2003 heat wave in Europe (Figure 11) and recent flooding events (Figure 12) in the context of historical events. Using EMSLP, the next stage of EMULATE will be to fully examine whether relationships between SST and circulation patterns are stationary. EMSLP, its associated error estimates and number of observation fields will be freely available from November 2005 from www.cru.uea.ac.uk/cru/projects/emulate/.

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Appendix

A1: List of sources corresponding to stations ID provided in Table 1.

ID	Source description
1	WASA project (Schmith et al, 1997)
2	IMPROVE (Camuffo & Jones, 2002)
3	UK daily weather records (UK Met Office archives)
4.	French Daily weather records (UK Met Office archives)
5	Boletin Meteorologico Diario (Spanish daily weather records – UK Met Office archives)
6	St Petersburg year books (Nicolas Central Physical Observatory, 1850-1887)
7.	Ottoman Empire Records (Constantinople Observatoire Imperial, 1870-1874: Bulletin, 1869-1874
8.	Simultaneous international meteorological observations (Washington Signal Office, 1875-1881)
9.	Meteorological observations at Bermuda, 1853-4, Halifax, 1854-5 & miscellaneous papers. (Board of Trade, 1863).
10.	Royal Engineers and the Army Medical Department observations (Meteorological Office, 1890)
11.	Six-and Three-hourly Meteorological observations from 223 U.S.S.R. Stations (Razuvaev et al 1998)
12.	Environment Canada
13.	Austrian Year books (Zentralanstalt für Meteorologie und Geodynamik, 1854-1984)
14.	Miscellaneous data sources: Armagh : Armagh Observatory records (A. García-Suárez) Athens : Athens Observatory records (D. Founda, M. Petrakis, E. Xoplaki) Barcelona : M. Barriendos ADVICE project Bodø: Ø. Nordli Cadiz: Real Observatorio de la Armada en San Fernando (Royal Observatory of the Spanish Navy at San Fernando, Cadiz, Spain). Debilt/Utrecht : Koninklijk Nederlands Meteorologisch Instituut (KNMI) year books (T. Brandsma) Durham: Durham University Observatory (D. Lister & N. Cox) Galway: (Hickey et al 2003) Gibraltar: Gibraltar Chronicle & Royal Engineers (M. Rodwell & D. Wheeler) Hohenpeissenberg: German Weather Service (DWD) Jena: F. Gerstengarbe Madrid: El Noticioso Newspaper, Rico Sinobas Paper, Rico Sinobas Manuscript, La Gaceta Newspaper, Real Observatorio Astronomico de Madrid. Montreal: Observations by Dr. Smallwood, Dr. Sunderland, Dr. Hall near McGill Observatory, Montreal (V. Slonosky) Palermo: Astronomical Observatory Palerm (M. Barriendos) Paris: Journal des observations meteorologiques et magnetiques faites a l'Observatoire de Paris', 1823-1862, 1861-1872, 1873-1880 (M. Barriendos) Prague: R. Brazdil Reykjavik: P. Jones (http://www.cru.uea.ac.uk/cru/data/nao.htm)[2] Vardø: Ø. Nordli Zagreb: Meteorological and Hydrological Service, Gric, Zagreb (L. Srnec)
15.	NOAA library scanned images (http://docs.lib.noaa.gov/rescue/data_rescue_home.html) Algiers: Bulletin météorology du government générale de l'Algérie (1877,1878,1879,1880,1881) Providence: Caswell (1859)
16.	Instituto Nacional de Meteorología (Spanish National Meteorological Office)

[2] *The 1854-1880 values for Reykjavik are climatologically derived (see Jones et al., 1997).*

A2. Undetected duplicates.

We were advised (Gil Compo, personal communication 2003) that there were a number of undetected (and hence unflagged) duplicates in the ICOADS data base. These arose because in some cases, the gravity correction has been applied in reverse to the MSLP data obtained from one particular deck of data (deck 156). Another deck (193) contained many data at the same position (within +/- .1°) as the deck 156 data and with identical values for SST, air temperature, etc., but different pressures by twice the gravity correction. This only happened in certain months and so may be the result of the error of one particular digitiser. This is a relatively easy problem to correct when there are coincident data from deck 193 with which to compare the deck 156 data, and a fix was developed to exclude the erroneous data from deck 156. However, there are many areas for which there are deck 156 data, but no deck 193 data; and deck 156 carries on after 1938 when deck 193 ends. These non-duplicate deck 156 data have been compared with other neighbouring (but not coincident) values from other decks (e.g. 207, 116, 155, 110) during the 1940s and no evidence of undetected duplicates was found. This is consistent with the belief that this problem does not persist beyond 1938 (S. Woodruff, personal communication, 2003).

A3. Correcting for the low MSLP bias in US Maury Observations

The 1850s decade in the ICOADS data is dominated by anomalously low MSLP over much of the global ocean. This signal is strongest in midlatitude regions. Such a large and coherent signal was not seen during any other decade and was not supported by land-based data. It was first reported by Todd Mitchell in 2002 at a workshop in Boulder, USA, on the use of Historical Marine Climate Data (Diaz et al, 2002), and remains an unresolved problem within the ICOADS pressure community.

During 1850-1855 the only data source was deck 701 (the US Maury collection). After 1855, observations from the Netherlands deck 193 begin and the low bias is less prominent. Because the EMULATE project required fields to start in 1850, it was not possible to simply ignore the US Maury observations.

The marine gridding procedure works with residuals, by removing a reference monthly background field value based on 1850-2003 from each observation (section 2.2.1). The deck 701 observations are anomalously negative compared with these background fields, but if we create residuals by removing a background based on just the biased deck 701 observations, the residuals are smaller in magnitude. So a deck 701 monthly background climatology was created by averaging deck 701 gridded fields only for 1850-1860. The gridding and quality control procedure was re-run, using now two reference monthly background fields: the 'normal' monthly 1850-2003 background and the deck 701 monthly climatology. If an observation was from deck 701, the 701 climatology was removed; the 'normal' monthly background field was removed from all other observations. After the daily median residual was formed on the $1^{o}x1^{o}$ degree grid, the 'normal' monthly background value was added back.

By incorporating this procedure, a marked reduction in the low MSLP bias was observed. When comparing the 1850-1860 decade to a 1961-1990 climatology, the MSLP over the North Atlantic region remained anomalously low, though this signal was weaker than was observed in an earlier, uncorrected, version of the EMSLP dataset. Our procedure will have removed any real multi-annual climate anomaly during 1850-1855, but comparisons with land-based data support our treatment of the marine data.

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Figure Captions

Figure 1: Distribution of the 86 continental and island stations in EMSLP. 83 station records begin between 1850 and 1880; Ammasalik, Potsdam and Tenerife begin after 1880. 1850-1880 corresponds to the period when no J86 fields are available.

Figure 2a: January - June monthly normals for EMSLP (left panel) and ADVICE (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1850-1995. To aid comparison we have interpolated EMSLP to the ADVICE 5^o latitude by 10^o longitude grid.

Figure 2b: July - December monthly normals for EMSLP (left panel) and ADVICE (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1850-1995. To aid comparison we have interpolated EMSLP to the ADVICE 5^o latitude by 10^o longitude grid.

Figure 3a: January - June monthly normals for EMSLP (left panel) and ERA-40 (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1959-2001.

Figure 3b: July - December monthly normals for EMSLP (left panel) and ERA-40 (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1959-2001.

Figure 4a: January - June monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1850-1880.

Figure 4b: July - December monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1850-1880.

Figure 5a: January - June monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1881-1940.

Figure 5b: July - December monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1881-1940.

Figure 6: July - December monthly grid point correlations (r^2) between EMSLP and ERA-40 calculated over 1959-2001.

Figure 7: Time series of spatial correlations for January-December for EMSLP and ADVICE. Correlations (solid line) are plotted for 1850-2003 with scale on the left-hand-axis. Also plotted is the average number of observations in each grid box for each month (dashed line), with scale on the right-hand-axis.

Figure 8: Monthly EMSLP MSLP (y-axis) versus ADVICE MSLP (x-axis) at 45 ^{o}N , 10 ^{o}E, for 1850-1880 (crosses). A straight line representing monthly EMSLP = ADVICE is also shown.

Figure 9: The winter (DJF) North Atlantic Oscillation from 1850-2003 from EMSLP (red), and HadSLP2 (blue) gridded products. The winter NAO is calculated by taking the difference between the grid point closest to Ponta Delgada and that closest to Reykjavik. The 1961-1990 mean series value is then removed from each value. Also plotted is a station based index from 1866-2003 (green), using data from Reykjavik

and Ponta Delgada. Differences between the two station series are formed and the 1961-1990 average is also removed. Correlation coefficients are also given.

Figure 10: Daily variability observed within the summer season (JJA) in each decade (from 1850-1949) in EMSLP. Contours are in hPa.

Figure 11: MSLP anomalies for 6 heat wave events over the United Kingdom. The MSLP average anomaly is plotted for the hottest days, where 35^{o}C or more was reached (after Burt, 2004). Anomalies are formed by removing a 1961-1990 climatological average; contours are in 2 hPa.

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Figures

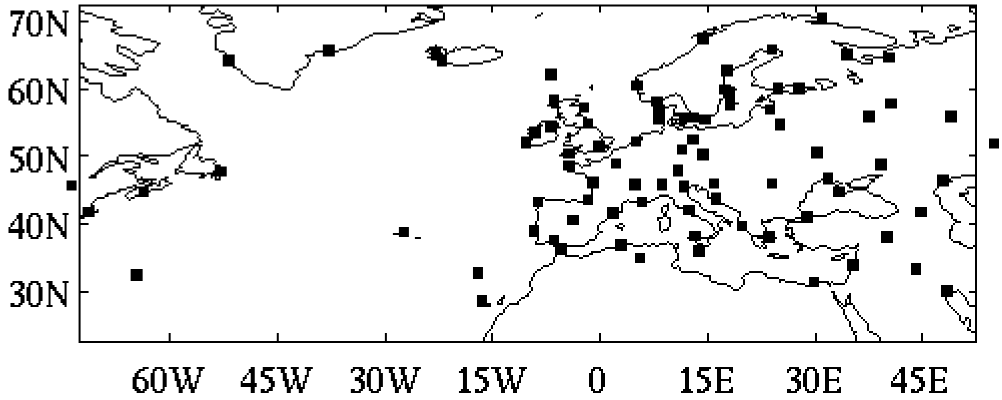


Figure 1: Distribution of the 86 continental and island stations in EMSLP. 83 station records begin between 1850 and 1880; Ammasalik, Potsdam and Tenerife begin after 1880. 1850-1880 corresponds to the period when no J86 fields are available.

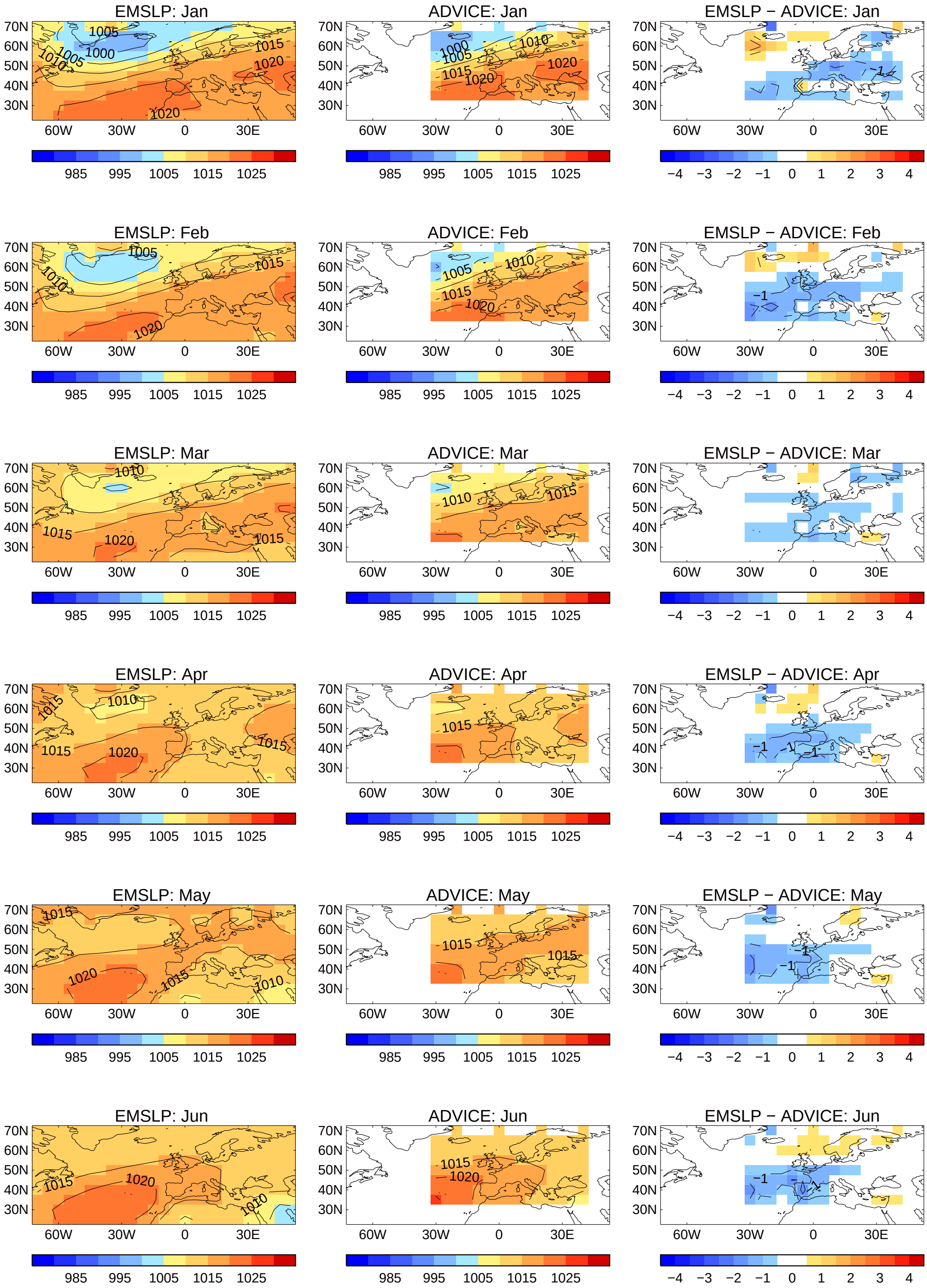


Figure 2a: January - June monthly normals for EMSLP (left panel) and ADVICE (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1850-1995. To aid comparison we have interpolated EMSLP to the ADVICE 5^{o} latitude by 10^{o} longitude grid.

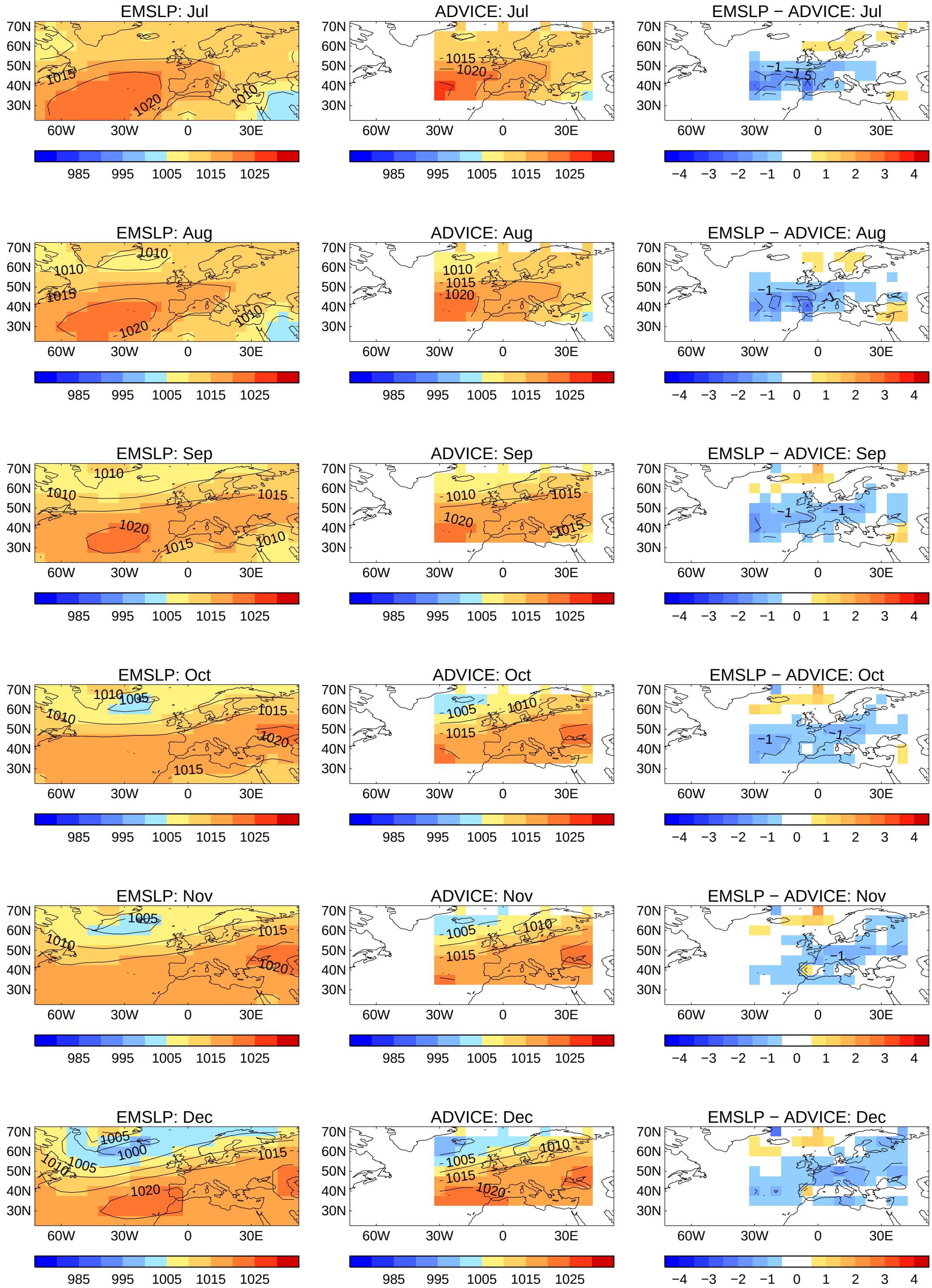


Figure 2b: July - December monthly normals for EMSLP (left panel) and ADVICE (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1850-1995. To aid comparison we have interpolated EMSLP to the ADVICE 5° latitude by 10° longitude grid.

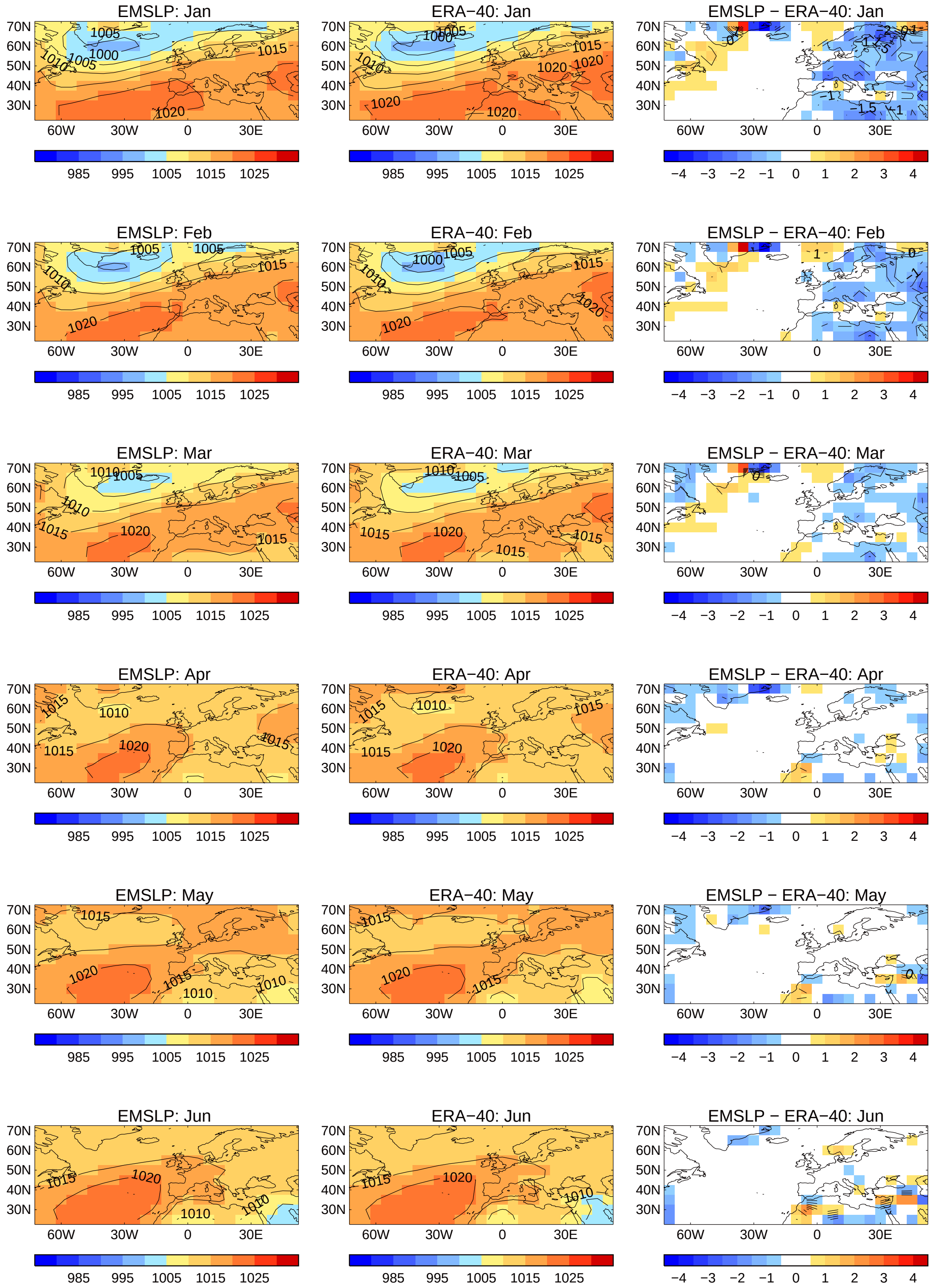


Figure 3a: January - June monthly normals for EMSLP (left panel) and ERA-40 (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1959-2001.

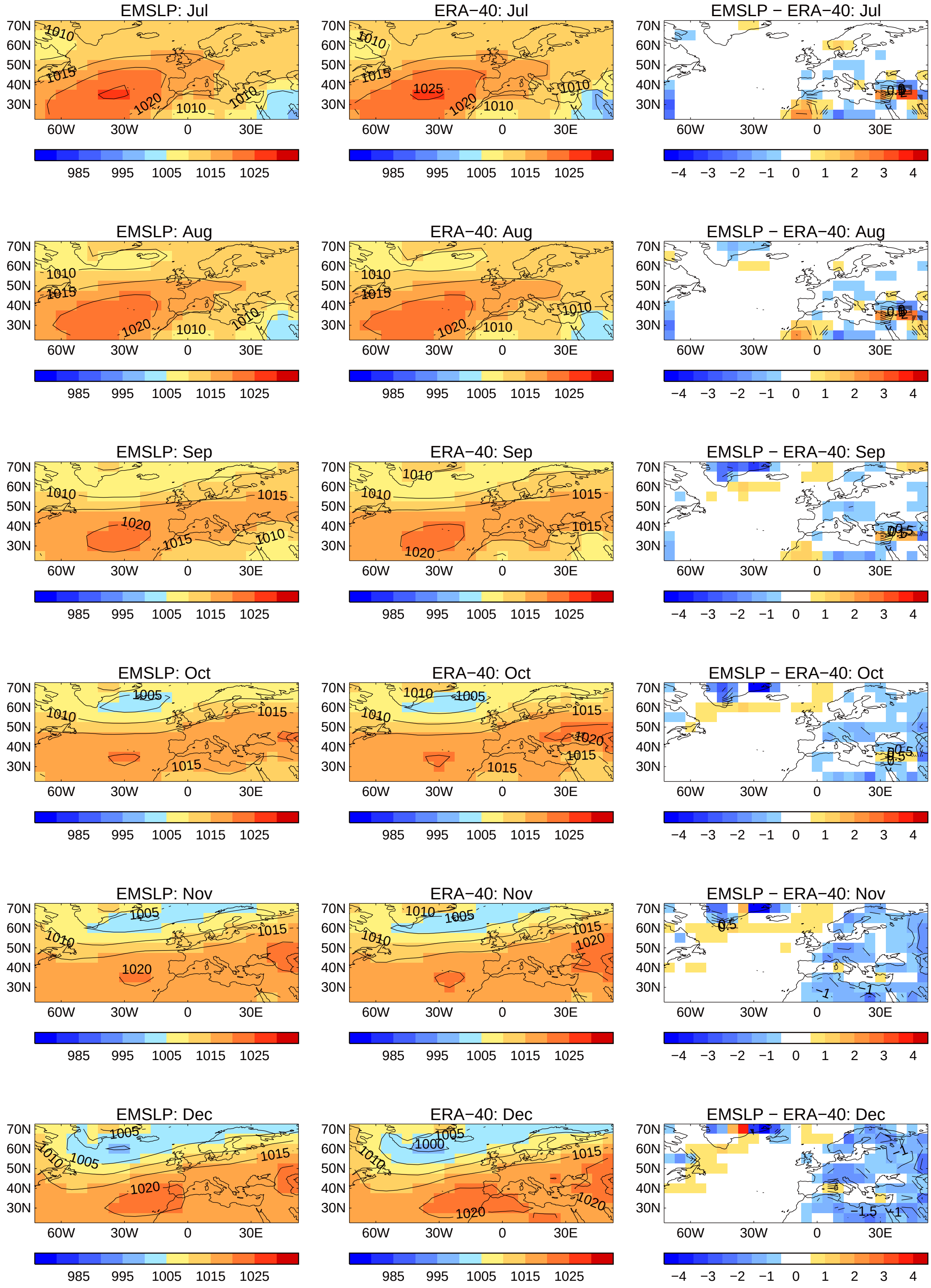


Figure 3b: July - December monthly normals for EMSLP (left panel) and ERA-40 (middle panel) and monthly differences < -0.5 and > 0.5 (right panel) in hPa. Normals are calculated over 1959-2001.

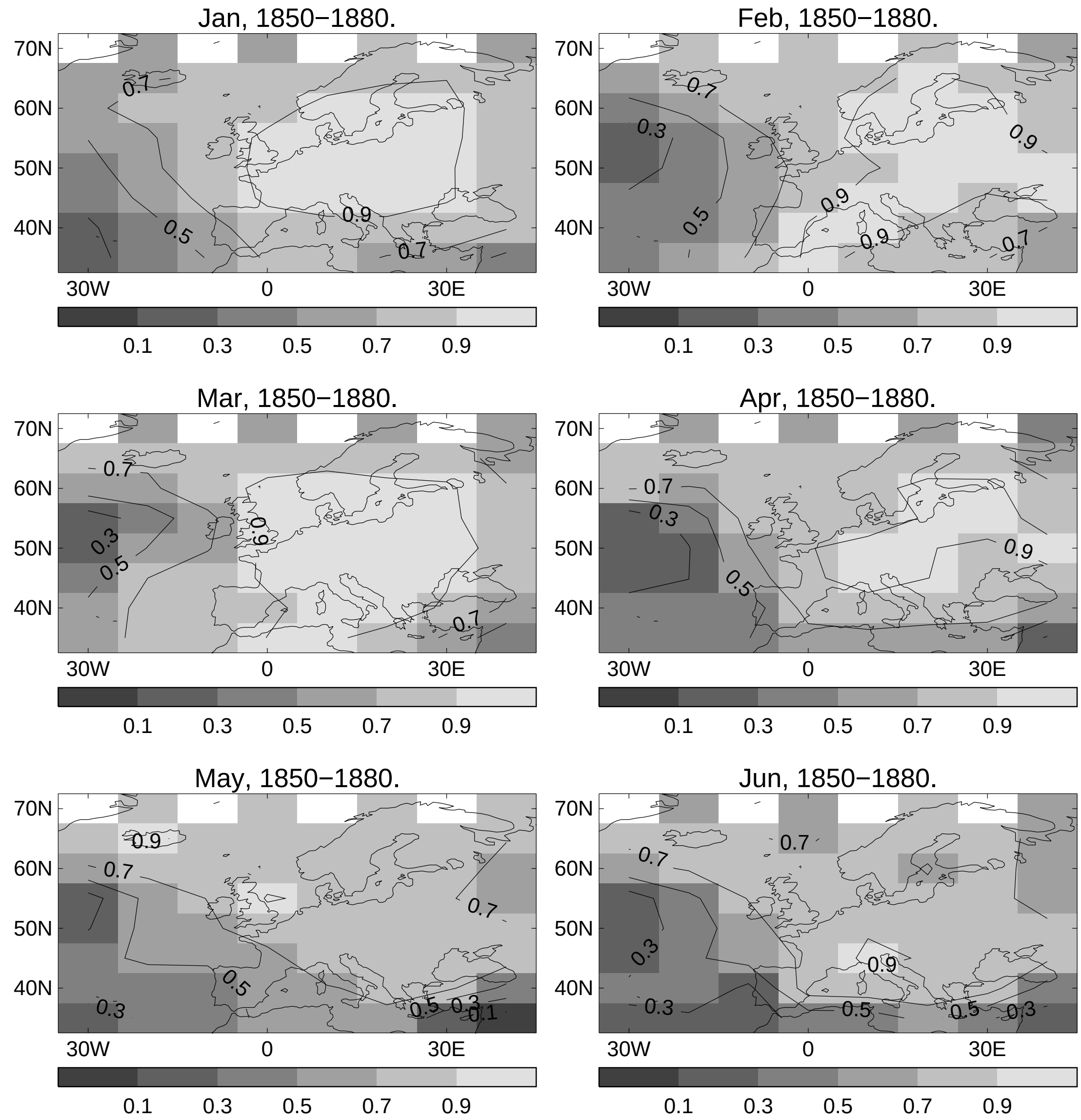


Figure 4a: January - June monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1850-1880.

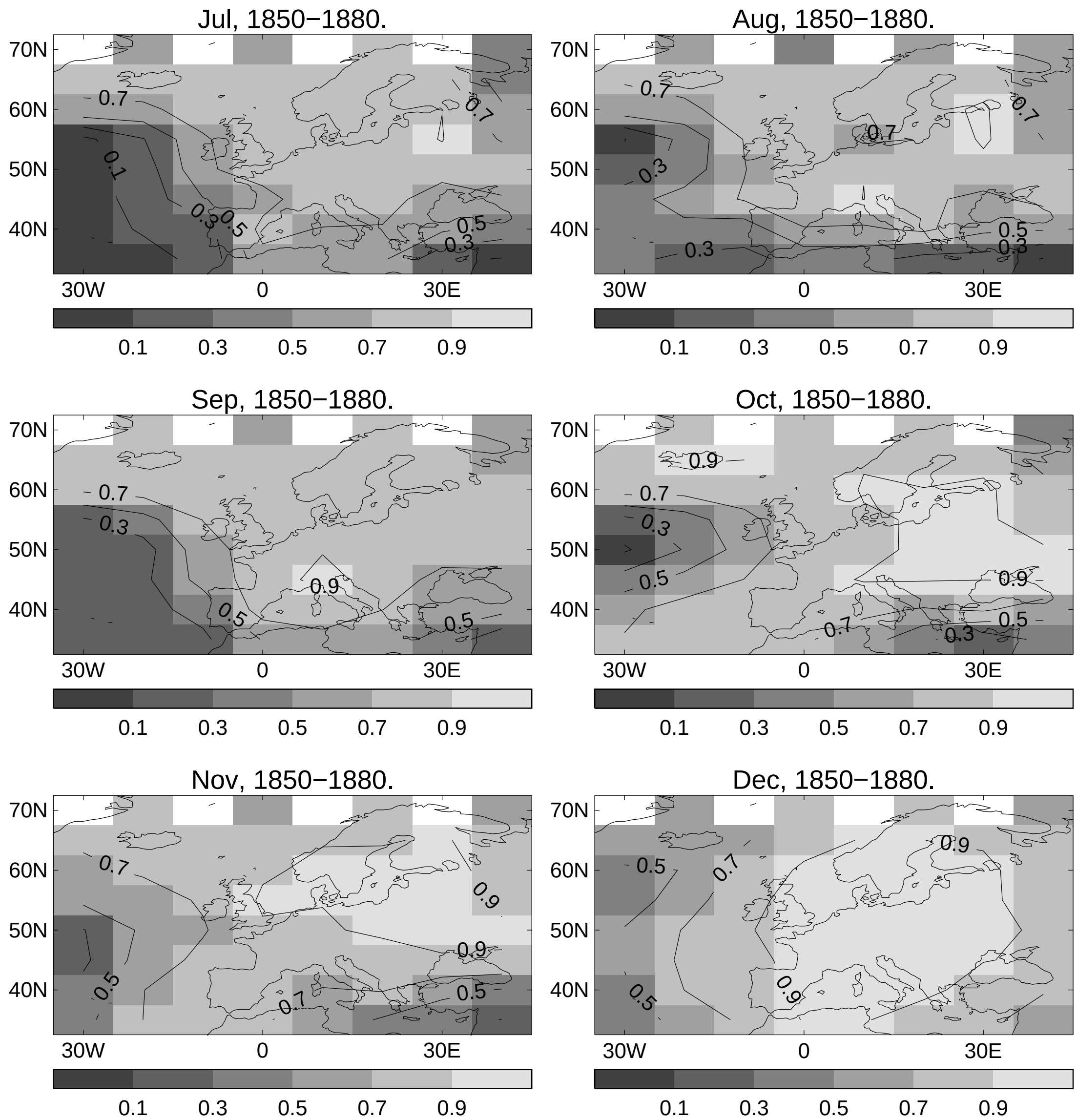


Figure 4b: July - December monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1850-1880.

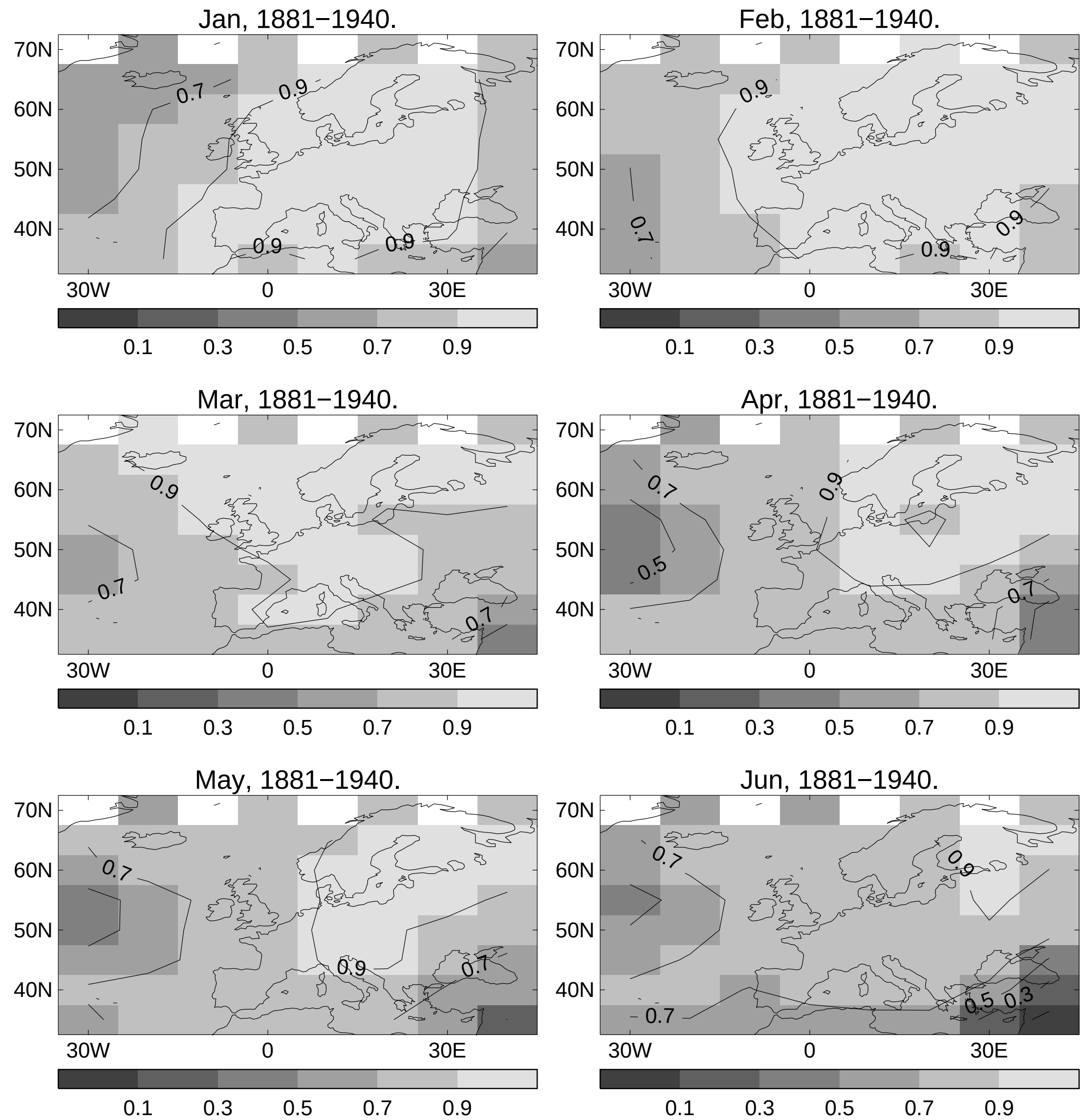


Figure 5a: January - June monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1881-1940.

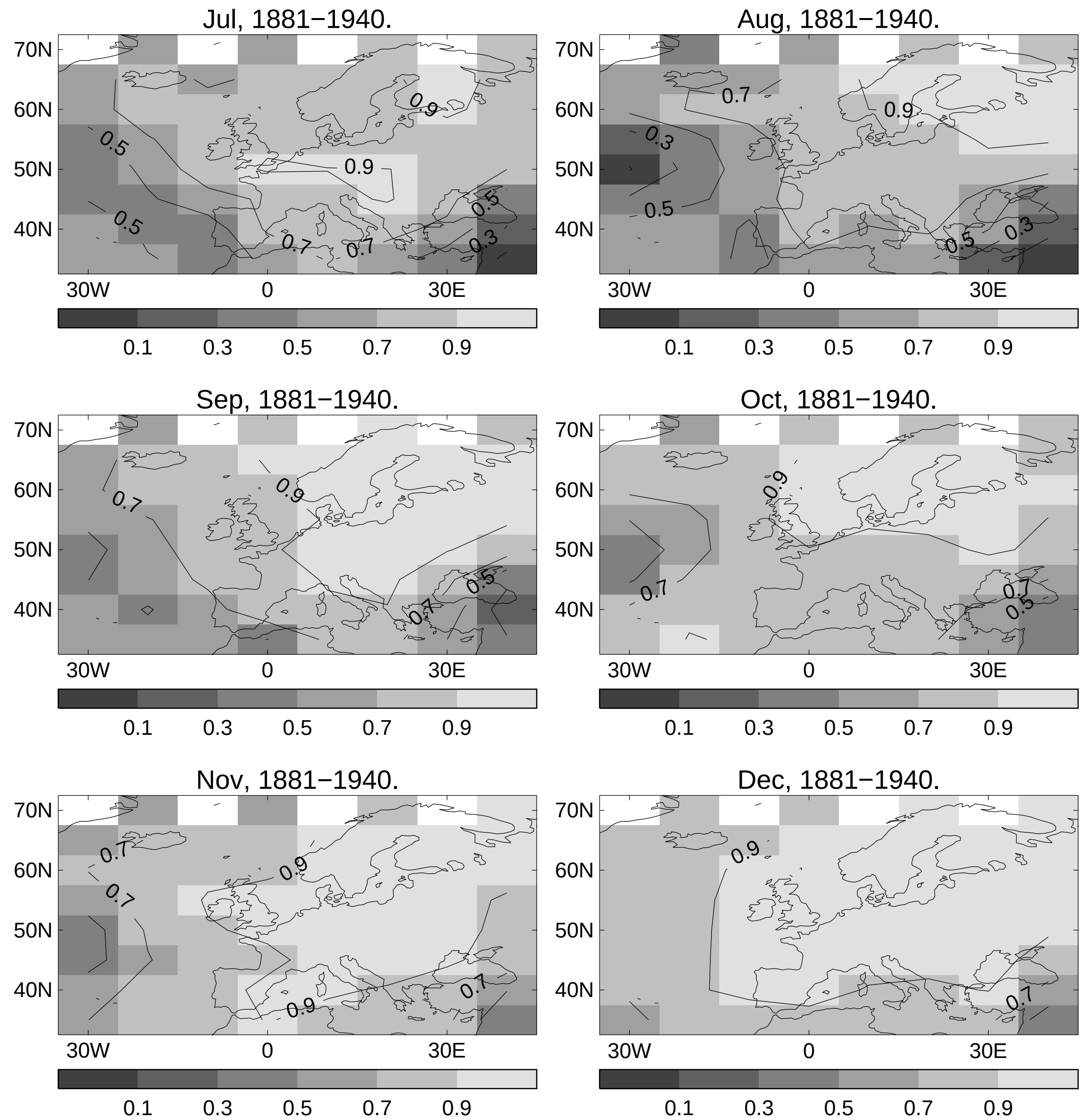


Figure 5b: July - December monthly grid point correlations (r^2) between EMSLP and ADVICE calculated over 1881-1940.

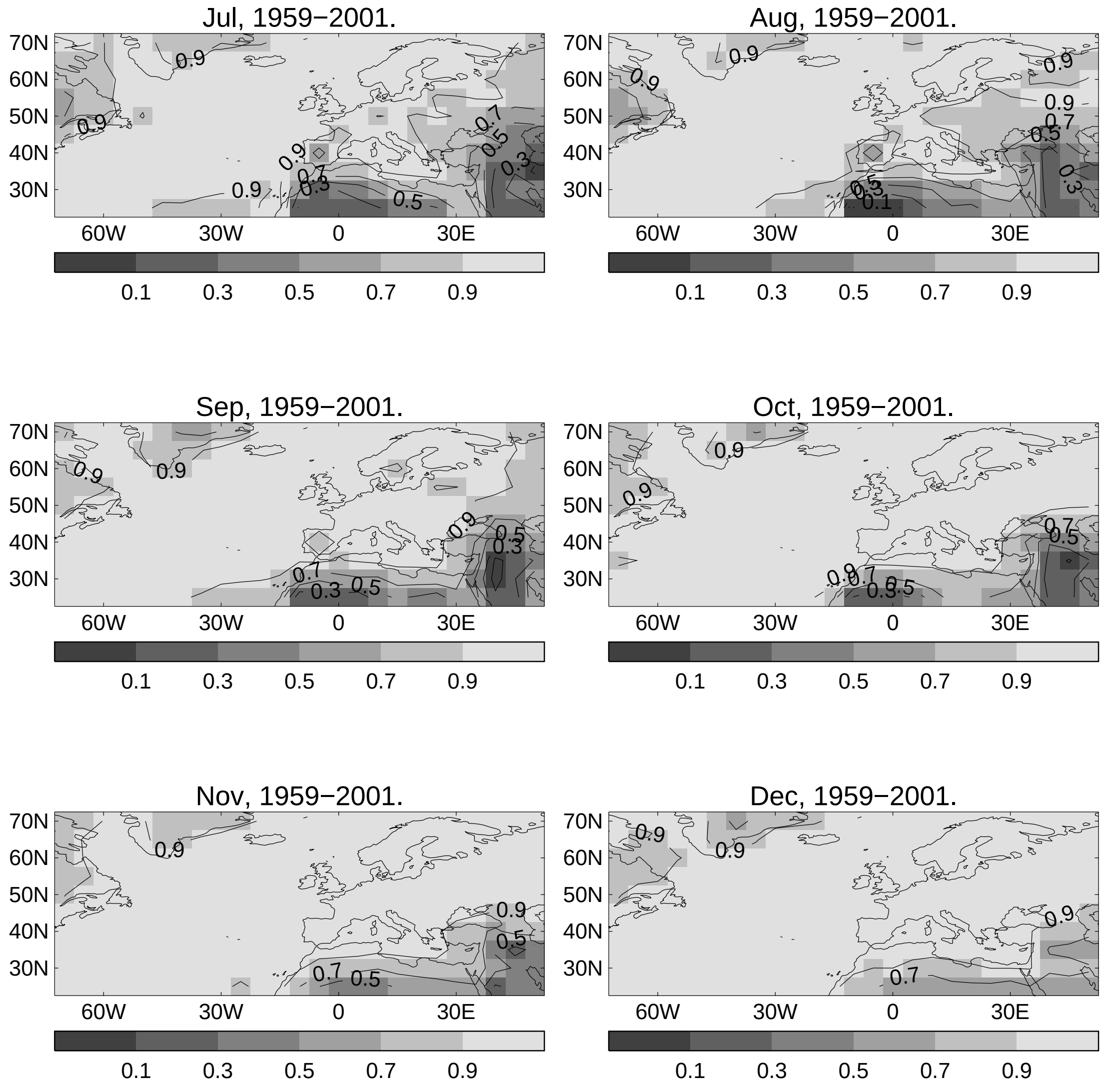


Figure 6: July - December monthly grid point correlations (r^2) between EMSLP and ERA-40 calculated over 1959-2001.

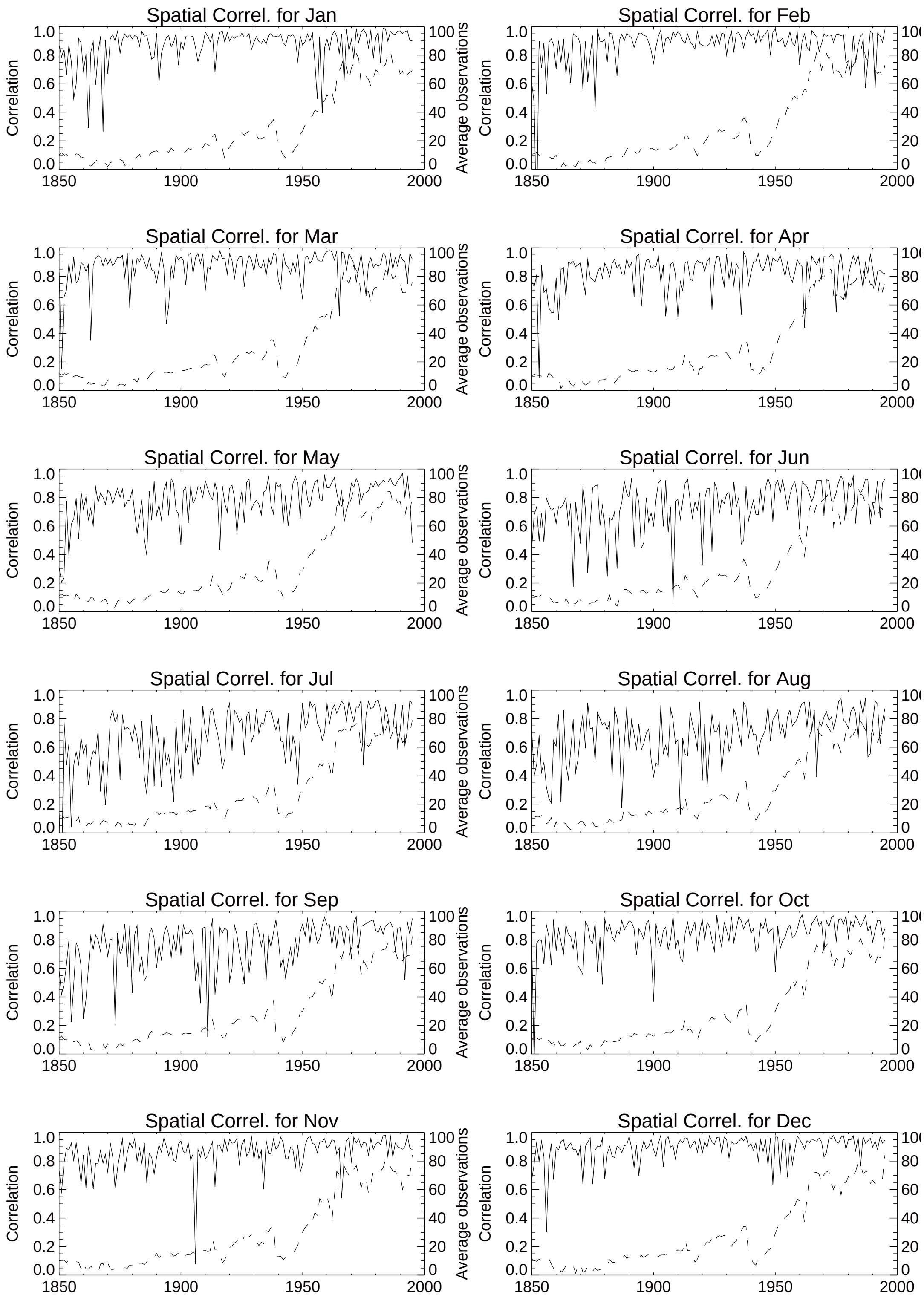


Figure 7: Time series of spatial correlations for January-December for EMSLP and ADVICE. Correlations (solid line) are plotted for 1850-2003 with scale on the left-hand-axis. Also plotted is the average number of observations in each grid box for each month (dashed line), with scale on the right-hand-axis.

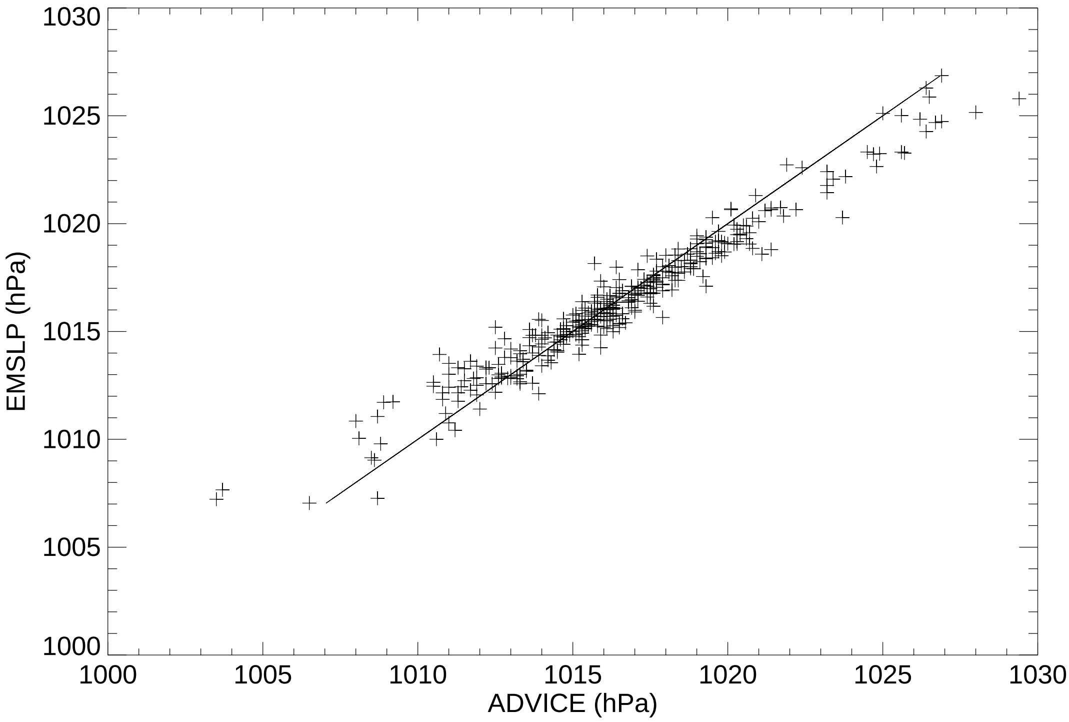


Figure 8: Monthly EMSLP MSLP (y-axis) versus ADVICE MSLP (x-axis) at 45 ^{o}N , 10 ^{o}E, for 1850-1880 (crosses). A straight line representing monthly EMSLP = ADVICE is also shown.

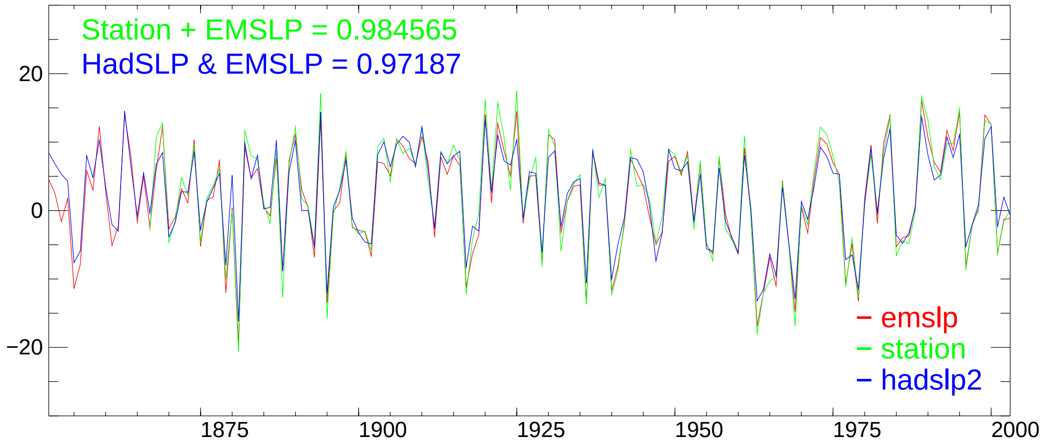
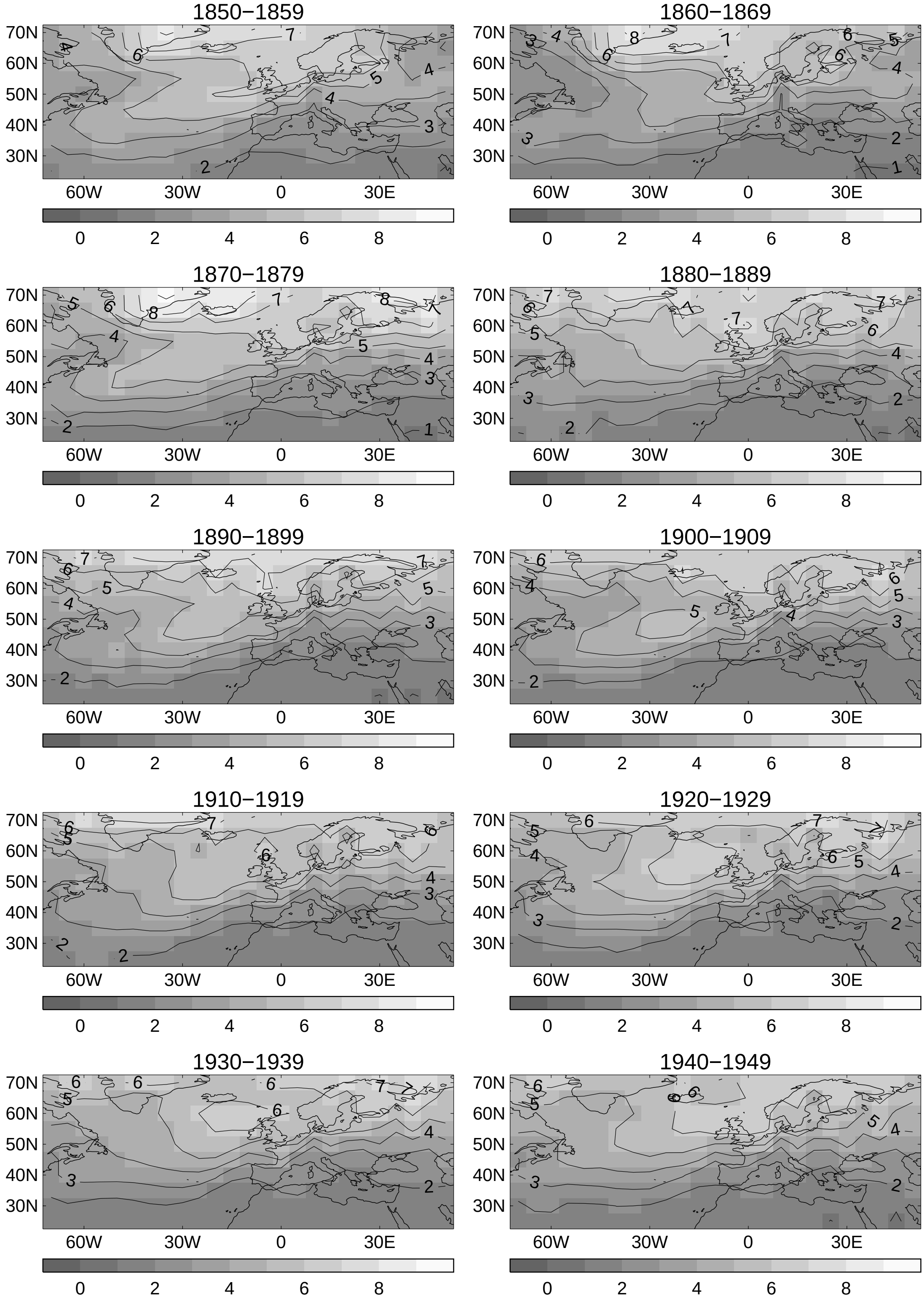


Figure 9: The winter (DJF) North Atlantic Oscillation from 1850-2003 from EMSLP (red), and HadSLP2 (blue) gridded products. The winter NAO is calculated by taking the difference between the grid point closest to Ponta Delgada and that closest to Reykjavik. The 1961-1990 mean series value is then removed from each value. Also plotted is a station based index from 1866-2003 (green), using data from Reykjavik and Ponta Delgada. Differences between the two station series are formed and the 1961-1990 average is also removed. Correlation coefficients are also given.



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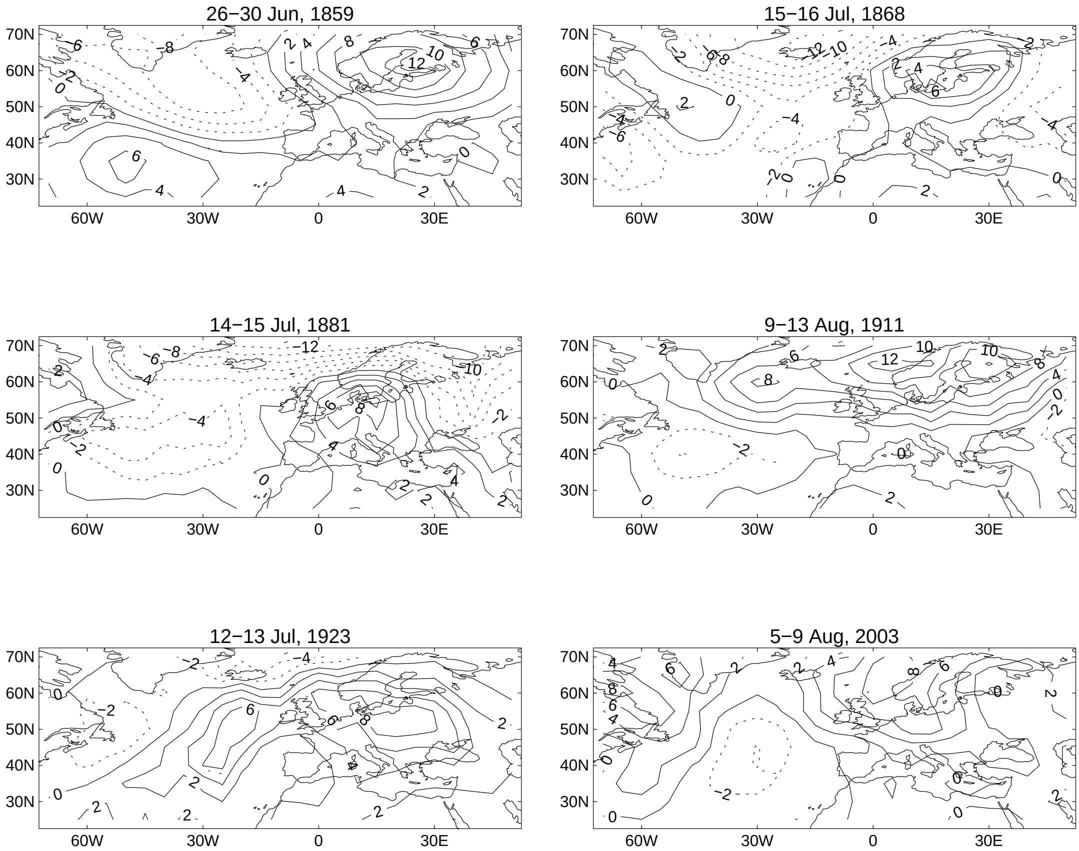

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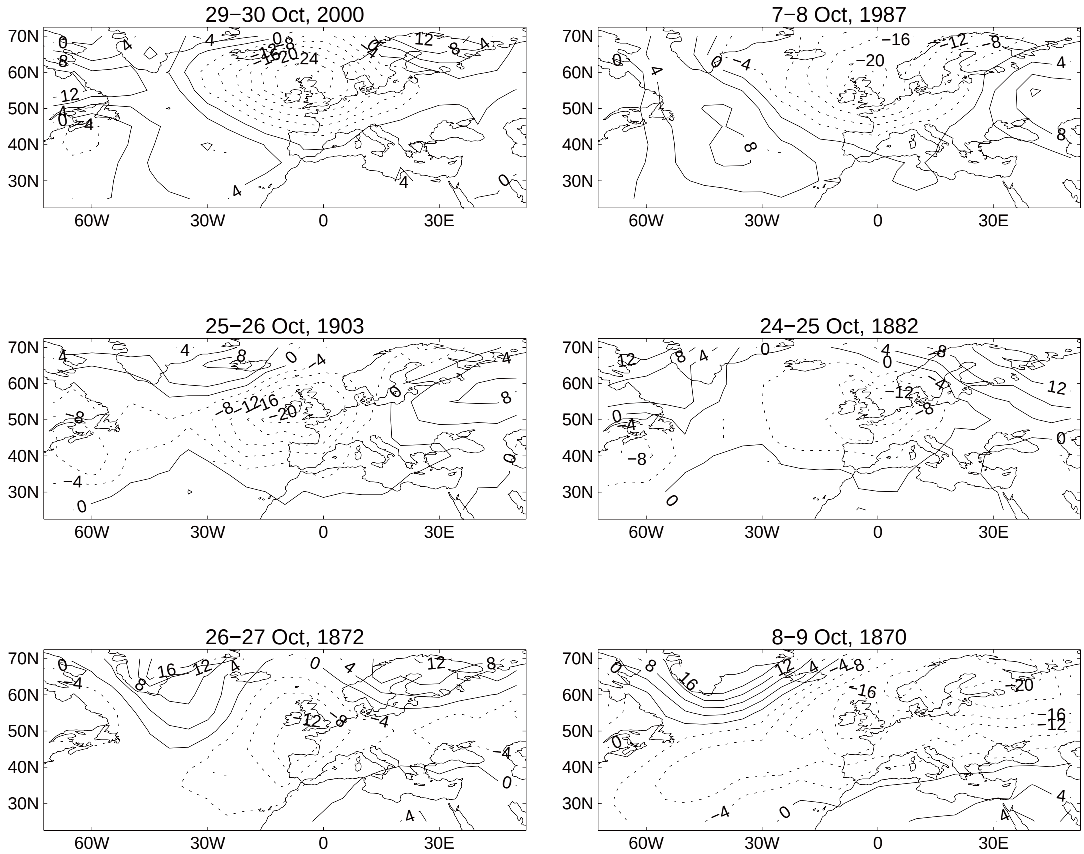

Figure 12: MSLP anomalies for 6 flooding events over the United Kingdom. Days were selected in each case from daily station totals, available in the UK Daily Weather Records held in the UK Meteorological Library and with reference to historical flooding events available from the Chronology of British Hydrological Events (http://www.dundee.ac.uk/geography/cbhe/). Anomalies are formed by removing a 1961-1990 climatological average; contours are in 4 hPa.

Tables

Table 1: List of 86 pressure sites used in EMSLP. The start and end year of the record is given, as well as the latitude and longitude in decimal degrees (negative longitudes are degrees west). A source ID is also provide; see table A1 in the appendix.

Station & source ID	First year	Last year	lat	Long	Station & source ID	First year	Last year	lat	long
Aberdeen 1,3	1861	1995	57.16	-2.10	London 3,4	1850	1881	51.46	0
Alexandria 13	1876	1881	31.20	29.95	Lugansk 6	1850	1880	48.60	39.30
Algiers 4,15	1872	1881	36.76	3.10	Lund 1	1864	2001	55.70	13.20
Tasiilaq 1	1894	1995	65.60	-37.63	Lyon 4	1869	1881	45.72	4.95
Angra (de Heroismo) 4	1871	1878	38.66	-27.22	Madrid 14,16	1853	1880	40.45	-3.71
Archangel 6,11	1866	2000	64.55	40.53	Malta 4,10	1852	1880	35.83	14.00
Armagh 14	1850	2001	54.35	-6.65	Milan 2,4	1763	1998	45.61	8.73
Astrakhan 6,11	1850	2000	46.35	48.03	Montreal 14	1850	1873	45.53	-73.60
Athens 14	1850	1880	37.90	23.73	Moscow 6,11	1850	2000	55.76	37.66
Baghdad 7,4	1869	1876	33.23	44.23	Nikolayev 6	1850	1880	46.58	31.95
Barcelona 14,16	1850	2002	41.50	2.01	Nordby 1	1874	2002	55.43	8.40
Beirut 7,13	1874	1881	33.82	35.48	Oksøy fyr 1	1870	2002	58.07	8.05
Bergen 1	1868	2002	60.38	5.33	Orenburg 6	1850	1876	51.75	55.10
Bermuda 10	1852	1880	32.28	-64.50	Padua 2	1766	1997	45.40	11.85
Biarritz 3,4	1860	1880	43.46	-1.53	Palermo 4,14	1851	1880	38.13	13.33
Biskra 4,15	1878	1881	34.80	5.73	Paris 14, 4	1851	1880	48.81	2.33
Bodø 1,14	1868	1994	67.26	14.43	Plymouth 3	1861	1881	50.35	-4.15
Brest 3,4	1861	1881	48.45	-4.16	Potsdam 1	1893	1993	52.38	13.06
Cadiz 2,14	1786	2002	37.46	-6.28	Prague 14	1850	1880	50.08	14.42
Corfu 10,13	1852	1880	39.61	19.91	Providence 15	1850	1860	41.68	-71.25
De Bilt 14	1850	2001	52.10	5.18	Reykjavik 14	1820	2001	64.13	-21.90
Diyarbakir 4,7	1869	1876	37.88	40.18	Riga 6,11	1850	1990	56.81	23.89
Durham 14	1850	1881	54.76	-1.58	Rochefort 3,4	1862	1881	45.93	-0.93
Fao 4,7	1869	1876	29.98	48.50	Rome 4	1869	1881	41.95	12.50
Funchal 4	1871	1881	32.63	-16.90	Scutari 10	1866	1880	41.00	29.05
Galway 3,14	1850	1880	53.28	-9.02	Sevastopol 6,11	1850	1990	44.61	33.55
Gibraltar 4, 14	1850	2002	36.10	-5.35	Sibiu 4	1878	1881	45.80	24.15
Nuuk (Godthåb) 8	1875	1880	64.16	-51.75	St Johns 10,12	1852	1876	47.56	-52.70
Gothenburg 1	1860	2002	55.70	11.98	Stockholm 1	1756	1998	59.33	18.05
Halifax 9,12	1850	1875	44.63	-63.50	Stornoway 3,4	1872	1881	58.22	-6.32
Hammerodde 1	1874	1995	55.30	14.78	St Petersburg 6,11	1850	2000	59.93	27.96
Haparanda 1	1860	2002	65.82	24.13	Stykkis-holmur 1	1874	2003	65.08	-22.73
Harnosand 1	1860	1995	62.61	17.93	Tenerife 16	1901	2002	28.47	-16.32
Helsinki 1	1844	2001	60.17	24.95	Tbilisi 6,11	1850	1990	41.68	44.95
Hohen-peissenberg 14	1850	2002	47.80	11.02	Tórshavn 1	1874	2002	62.02	-6.77
Jena 14	1850	2000	50.93	11.58	Toulon 3,4	1868	1881	43.10	5.93
Kazan 6,11	1850	2000	55.78	49.13	Uppsala 1	1722	1998	59.86	17.63
Kem 6	1866	1880	64.95	34.65	Valentia 1,3,4	1861	1995	51.93	-10.25
Kiev 6,11	1850	1990	50.40	30.45	Vardø 14	1861	2003	70.36	31.10
Kostroma 6	1850	1880	57.73	40.78	Vestervig 1	1874	1995	56.77	8.32
La Coruna 3,16,5	1865	2002	43.16	-8.50	Visby 1	1860	2002	57.63	18.28
Lesina (Split) 4,13	1869	1881	43.53	16.30	Wilna 6,11	1850	1990	54.68	25.30
Lisbon 4	1869	1881	38.77	-9.13	Zagreb 14	1862	2000	45.82	15.98

Table 2: List of sources for Met Office's operational Northern Hemisphere J86 fields up to 2003 (Jackson, 1986).

Period	Source
01/12/1880-31/12/1898	Deutsche Wetterdienst '**morning**' charts (derived from the 'Tagliche Synoptische WetterKarten' covering an area from 80^{o}E to 100^{o}W).
01/01/1899-31/12/1939	Extended Forecast Division of the US Weather Bureau **1200Z** charts
01/01/1940-31/12/1948	Offenbach **0001Z** charts[3].
01/01/1949-31/12/1965	Extended Forecast Division of the US Weather Bureau **1200Z** charts
01/01/1966-20/08/1975	United Kingdom Met Office (UKMO) **0001Z** charts
21/08/1975-31/12/2002	UKMO **0001Z** model charts
1/1/2003 - to date	NCEP/NCAR reanalysis 6 hourly SLP fields (daily average of **0600Z** and **1200Z** charts)

[3] Recently Gil Compo compared the 1948 NCEP/NCAR reanalysis and Offenbach charts and showed that the Offenbach charts were actually 1200Z, not 0001Z. We do not know whether this incorrect time stamp is true for all of the Offenbach charts.