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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 dataset (EMSLP) for 1850–2003 on a 5° latitude by longitude grid is described. This product was produced using 86 continental and island stations distributed over the region 25°–70°N, 70°W–50°E blended with marine data from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS). The EMSLP fields for 1850–80 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. Squared correlations (r^2) indicate that EMSLP generally captures 80%–90% of daily variability represented in an existing historical mean sea level pressure product and over 90% in modern 40-yr European Centre for Medium-Range Weather Forecasts Re-Analyses (ERA-40) 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. It is shown 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.

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1. Introduction

The European Community (EC)-funded European and North Atlantic Daily to Multidecadal Climate Variability Project (EMULATE) 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-yr period would then be assessed with both traditional and new statistical techniques. These variations and trends would 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, therefore, has 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 also be used to study the 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 by longitude grid over the region 25°–70°N, 70°W–50°E (hereafter referred to as the EMULATE region). Daily gridded MSLP fields since 1881 for the Northern Hemisphere north of 15°N are already available (Jackson 1986, hereafter referred to as J86), but are only reliable over western and central Europe (e.g., Germany, Austria, Switzerland, and northern Italy). These fields are improved and extended, using the long station–based European pressure series from earlier EC projects and recently digitized 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-h 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 daily observations, particularly before 1881. During this period, observations are available over only 15% of the EMULATE region. Despite the inclusion of the recently digitized U.S. Maury collection (before 1863; Worley et al. 2005), the marine observations are constrained to the major shipping routes of the time, predominantly between northwest Europe and the Americas and from northwest Europe to around the Cape of Good Hope. Similarly, in remote terrestrial regions such as central Greenland and northern Africa, no station data are 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, our European–North Atlantic mean sea level pressure dataset (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 the understanding of recent events [such as the 2003 summer heat wave in western Europe, the autumn 2000 floods in the United Kingdom (U.K.), and the European floods in Germany, Austria, and the Czech Republic in 2002 (Danube and Elbe rivers)], we expect that this product will be a valuable aid in the further understanding of historical extreme events dating back to the mid-nineteenth 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 (J86), and to improve it while extending the analysis 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 implicitly contain many thousands of station observations. Because of this, we concentrated our efforts on collating and digitizing station data for the period before 1881. The EMSLP fields for 1850–80 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 between stations, all the observations (including the marine and J86 fields) are adjusted to represent the 24-hourly mean. Accordingly, the EMSLP daily fields represent the average pressure over the 24-h period and so are different and indeed smoother than synoptic and 4× daily reanalysis charts.

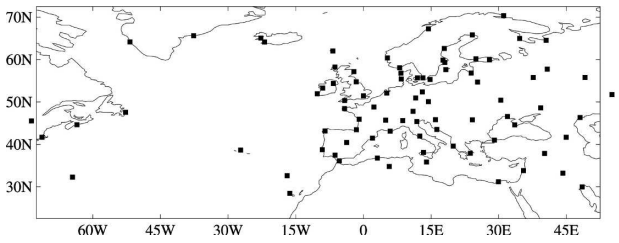


FIG. 1. Distribution of the 86 continental and island stations in EMSLP. Eighty-three station records begin between 1850 and 1880; Tasiilaq, Potsdam, and Tenerife begin after 1880. The years 1850–80 correspond to the period when no J86 fields are available.

a. 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 U.K. stations compiled by earlier EC projects such as Improved understanding of past climatic variability from early daily European instrumental sources (IMPROVE; Camuffo and Jones 2002 and references therein) and Waves and Storms in the North Atlantic (WASA; Schmith et al. 1997), and for the cities of Montreal, Canada (Slonosky 2003); Gibraltar, United Kingdom; De Bilt, Netherlands; Paris, France; Palermo, Italy; and Galway, Ireland (Hickey et al. 2003), by individual efforts (see the acknowledgments). We were able to obtain updates and additional historic data for some WASA stations, extending them back to 1850 and forward to 2003. Considerable material had to be digitized, however, from individual hard copy records from Russian, British, French, and Spanish daily weather records (DWRs), held in the U.K. National Meteorological Archives and Library. These were supplemented by scanned Algerian, French, and U.S. observations on the National Oceanic 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), Greenland, and helped fill gaps in existing records. Data were also digitized from compilations made under the auspices of the U.K. 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 Fig. 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 Table 2. Both the "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/).

QUALITY CONTROL

Most of the 86 station series required some form of quality control and homogenization. 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 millimeters 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," 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°C and to a standard gravity equal to that at 45°N. Some digitized Russian series, however, had been calibrated at 13.33°C (e.g., Lugansk), so additional adjustments had to be made. All pressures were converted to units of hecto Pascals (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, 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 semidiurnal 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 and Lindzen 1970). Over the EMULATE region, the amplitude of both diurnal and semidiurnal oscillation (also referred to as atmospheric tides) is generally <1.0 hPa (Dai and 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 semidiurnal cycle at each station directly. Instead,

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 °W). A source ID is also provided; see Table 2.

Station and source ID	First year	Last year	Lat	Lon	Station and source ID	First year	Last year	Lat	Lon
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	Reykjavík 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	Stykkisholmur 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
Hohenpeissenberg 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

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.

b. Marine data sources

Marine pressure observations were obtained from ICOADS (Worley et al. 2005; Diaz et al. 2002). This dataset combines the Met Office's Marine Data Bank with the previous version of COADS (Woodruff et al. 1987) and also includes several million new observations from the U.S. Maury collection, amongst others. Daily marine gridded MSLP fields were generated using these data for 1850–1997, supplemented with the National Centers for Environmental Prediction (NCEP) Global Telecommunication System (GTS) data for 1998–2003.

SUMMARY OF MARINE GRIDDING PROCEDURE

To quality control and grid the marine observations, we have modified the procedure used in the develop-

TABLE 2. Summary of sources corresponding to source IDs provided in Table 1. A number of the stations used in EMSLP were available as a result of individual efforts; these stations (and the researcher's name) are listed here under miscellaneous sources. Full details of the sources are provided on the EMULATE Web site (www.cru.uea.ac.uk/cru/projects/emulate/).

ID	Source description
1	WASA Project (Schmith et al. 1997)
2	IMPROVE (Camuffo and Jones 2002)
3	U.K. daily weather records (Met Office, 1860–81)
4	French daily weather records (Bureau Central Meteorologique, 1869–81)
5	Spanish daily weather records (Boletin Meteorologico Diario 1875)
6	St. Petersburg yearbooks (Nicolas Central Physical Observatory, 1850–87)
7	Ottoman Empire records (Constantinople Observatoire Imperial, 1870–74: Bulletin, 1869–74)
8	Simultaneous international meteorological observations (Washington Signal Office, 1875–81)
9	Meteorological observations at Bermuda, 1853–54, Halifax, 1854–55, and miscellaneous papers (Board of Trade 1863).
10	Royal Engineers and the Army Medical Department observations (Met 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 yearbooks (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: ADVICE Project (M. Barriendos)
	Bodø: Ø. Nordli
	Cadiz: Real Observatorio de la Armada en San Fernando (Royal Observatory of the Spanish Navy at San Fernando)
	Debilt/Utrecht: Koninklijk Nederlands Meteorologisch Instituut (KNMI) yearbooks (T. Brandsma)
	Durham: Durham University Observatory (D. Lister and N. J. Cox)
	Galway: Hickey et al. (2003)
	Gibraltar: Gibraltar Chronicle and Royal Engineers (M. Rodwell and 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 Palermo (M. Barriendos)
	Paris: Journal des observations météorologiques et magnétiques faites à l'Observatoire de Paris: 1823–62, 1861–72, 1873–80 (M. Barriendos)
	Prague: R. Brazdil
	Reykjavík: P. Jones (http://www.cru.uea.ac.uk/cru/data/nao.htm)*
	Vardø: Ø. Nordli
	Zagreb: Meteorological and Hydrological Service, Gric (L. Srnec)
15	NOAA library scanned images (http://docs.lib.noaa.gov/rescue/data_rescue_home.html)
	Algiers: Bulletin météorologie du gouvernment générale de l'Algérie (1877–81)
	Providence: Caswell (1859)
16	Instituto Nacional de Meteorología (Spanish National Meteorological Office)

* The 1854–80 values for Reykjavík are climatologically derived (see Jones et al. 1997).

ment of the First Hadley Centre Sea Level Pressure dataset (HadSLP1). This historical gridded global monthly MSLP product is described in Basnett and 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 intramonthly variability (see below); the median residual of only those observations that were equal to or less than 3 times this intramonthly value were assigned to 1° latitude by longitude grid boxes. A smoother daily value for each 1° latitude by longitude grid box was then formed by taking the median value of all 1° residuals over a 7° area centered on the 1° × 1° target box. This procedure serves to infill data-sparse or -missing areas and smooth over data-rich areas. For example, if the target box value is missing, but one of the surrounding forty-eight 1° boxes in the 7° area contains an observation, then the target value is replaced with this value.[1] If all grid box values in the 7° degree area contain data, including the target, then the target value will be replaced with the median of all 49 grid box

[1] In the case of an isolated observation, this procedure could result in a block of anomalous values being spread over a 7° × 7° cell.

TABLE 3. List of sources for the Met Office's operational Northern Hemisphere J86 fields up to 2003 (Jackson 1986).

Period	Source
1 Dec 1880–31 Dec 1898	Deutsche Wetterdienst "morning" charts (derived from the "Tagliche Synoptische WetterKarten" covering an area from 80°E to 100°W)
1 Jan 1899–31 Dec 1939	Extended Forecast Division of the U.S. Weather Bureau 1200 UTC charts
1 Jan 1940–31 Dec 1948	Offenbach 0001 UTC charts*
1 Jan 1949–31 Dec 1965	Extended Forecast Division of the U.S. Weather Bureau 1200 UTC charts
1 Jan 1966–20 Aug 1975	U.K. Met Office 0001 UTC charts
21 Aug 1975–31 Dec 2002	U.K. Met Office 0001 UTC model charts
1 Jan 2003–present	NCEP–NCAR reanalysis 6-hourly SLP fields (daily average of 0600 and 1200 UTC charts)

* Recently, G. Compo compared the 1948 NCEP–NCAR reanalysis and Offenbach charts and showed that the Offenbach charts were actually 1200 UTC, not 0001 UTC. We do not know whether this incorrect time stamp is true for all of the Offenbach charts.

values. The 7° area was chosen initially to help combat the sparseness of the available observed data, but it results in considerable smoothing, particularly in well-sampled midlatitude regions. This is considered further in section 4.

We also corrected each observation for the diurnal and semidiurnal 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 appendixes A and B. The background fields were added back to the screened gridded residuals to yield gridded actual values of marine MSLP.

c. Gridded data sources

1) DAILY

We have taken advantage of the Met Office's historical J86 dataset, a Northern Hemisphere (north of 15°N) synoptic daily MSLP product extending from 1881 to the present on a 5° latitude by 10° longitude grid. Until the 1970s these J86 fields were derived from digitized hand-drawn synoptic charts (see Table 3), including the German Morning charts and U.S. forecast charts. In the 1970s, they were replaced with model analysis charts. The J86 product is an extremely valuable resource, as each daily field implicitly contains many thousands of station observations that went into the original operational charts each day.

The many changes in sources, detailed in Table 3, 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. To account for these heterogeneities, the J86 fields were adjusted such that their monthly means agreed with HadSLP1 [described in section 2c(2) below]. The maximum adjustments were 5–6 hPa. The years 1999–2002 remain uncorrected (HadSLP1 extends only to 1998),[2] but potential heterogeneities are more likely before 1975 (see Table 3). Fields were also regridded onto a 5° × 5° grid. We applied a correction for the diurnal and semidiurnal oscillation using the Dai and Wang (1999) fields and based on analysis times given in Table 3 to make them consistent with the 24-h "daily" station and marine data.

Intramonthly standard deviation fields, introduced in the subsection of 2b, were calculated from the daily four 6-hourly NCEP–National Center for Atmospheric Research (NCAR) reanalysis fields (Kalnay et al. 1996).

2) MONTHLY

As described in the subsection of 2b, a background field is required for quality-controlling and gridding the marine observations. We have principally relied on HadSLP1 [an updated version of the global mean sea level pressure dataset (GMSLP2.1f; Basnett and Parker 1997)], which is a global monthly gridded product, on a 5° latitude by longitude grid for 1871–1998. For 1854–70, we used Kaplan et al.'s (2000) optimally interpolated (marine only) fields. A climatological average was used for the period 1850–54. A land and marine background field is also required when blending the land and marine fields (section 3a). As Kaplan et al.'s (2000) optimally interpolated fields are marine only, a climatological monthly average for 1871–1900 from HadSLP1 was used for the period 1850–70.

For homogeneity checks and validation, a historical gridded product developed as part of the Annual to

[2] HadSLP2 (Allan and Ansell 2006) was not yet available at this time.

Decadal Variability in Climate in Europe Project (ADVICE; Jones et al. 1999) was used. The ADVICE monthly data are available either as 51 individual station series or on a 5° latitude by 10° longitude grid for 1780–1995. Note that ADVICE used monthly averages of J86 data since 1881 and additional monthly fields for 1873–80; accordingly, ADVICE is not independent of EMSLP.

d. Homogenization of land station data

To obtain a long and homogenized series, issues such as change of station location, instrument, and instrument height need to be identified and accounted for. These can be identified in metadata records, but such records are often unavailable.

Potential heterogeneities 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-neighbor comparisons, for example, between Durham and Aberdeen in the United Kingdom, Toulon and Brest in France, Galway, Ireland, Armagh, Northern Ireland, and Gibraltar and Cadiz, Spain. Not all potential heterogeneities 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 homogenization issues more fully, we applied adjustment factors, similar to those applied to the J86 fields [section 2c(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; preference was given to the ADVICE station series where possible). 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 seven terms was applied to the whole monthly adjustment series. This process gives a smooth daily adjustment series, but almost the full daily variability of the station data is still preserved. This homogenization stage is very important, as some of the inhomogeneities found were very large. For example, the London series required adjustments of >7 hPa during 1850. Without these adjustments, EMSLP would be flawed, as the station observations are weighted heavily (see section 3a).

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-h period as the other series. The Canadian stations are 5 h behind central Europe; the easternmost Russian stations are 4 h 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

a. 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 (subsection of 2b). For each day in each month in each year for 1850–2003 and in each $1° \times 1°$ 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 of the $1° \times 1°$ median values were then averaged to $5° \times 5°$ grid point values, taking account of their spatial distribution.

The J86 fields (from 1881 to 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.

b. Interpolation

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 predetermined subset of the empirical orthogonal functions (EOFs) of the spatial covariance matrix. The analysis is constrained to give the 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 the 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 1850–80, the blended land and marine fields have very poor data coverage; 85%–90% of the grid boxes have missing values. To assess how well RSOI would perform with such sparse coverage, we performed verification experiments by subsampling daily NCEP–NCAR reanalysis fields for 1990–2000 to represent the historical sampling of 1850–60. These fields were then reconstructed using RSOI, using EOFs calculated over the period 1951–89 (a relatively well-sampled yet independent period). 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.

PROCEDURE

We now describe how RSOI was applied, detailing first 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° latitude by longitude resolution. The unsmoothed normals were created by taking the climatological 50-yr average for each calendar day of the year. A 50-yr average of 29 February was formed by simulating 29 February in non–leap years by averaging 28 February and 1 March. After the unsmoothed climatology was formed, a binomial (time wise) 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 (Kaplan et al. 2000, their appendix). However, it was found in this study that this step was not required because of, we believe, 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 (1961–90) 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 intrabox standard deviation (calculated from $1° \times 1°$ resolution data within the $5° \times 5°$ 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 intrabox standard deviation 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 neighbors 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 1961–90 daily averages and standard deviations derived from the NCEP–NCAR reanalysis. Flagged anomalies and their neighbors 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, that is, the flagged point and its eight nearest neighbors. Over the 154-yr period, an average of 1.5%

of grid points month^{-1} were initially flagged, with 0.2% remaining after the first weighted average. This procedure was reiterated until data rejections ceased; 90% of these flagged grid points were "corrected" after two iterations. Finally, the climatology was added back to yield absolute values.

4. Assessment of results

To diagnose any potential problems with EMSLP, we have compared the dataset with the monthly ADVICE product (Jones et al. 1999) and with the daily 6-hourly 40-Yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analyses (ERA-40) 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.

a. Climatologies

We compare the EMSLP monthly climatology with the ADVICE gridded product over 1850–1995 in Fig. 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). These results are similar to a recent gridded SLP dataset of Luterbacher et al. (2002) going back to A.D. 1500. One region where differences are prominent is central Spain. Pressures near Madrid in EMSLP are around 1.5 hPa higher during November–January than in the ADVICE grid, whereas from June to August (JJA), 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 2d); 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, Portugal, that are 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, Egypt; and Jerusalem, Israel; records in ADVICE may account for these regional differences in the two products; EMSLP has only limited records for Alexandria, Egypt; and Beirut, Lebanon (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 fields, which are derived from synoptic charts (Table 3), these fields in EMSLP were corrected for the semidiurnal and diurnal cycle. Even though our correction is coarse, the ICOADS observations over the ocean are well sampled throughout the day, and so the daily marine MSLP fields in EMSLP are closer to a 24-h mean than in the original J86 fields. This is supported by the agreement between EMSLP and ERA-40 over the oceans in Fig. 3 (see below).

Comparisons with ERA-40 are shown in Fig. 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 biases in Greenland and Iceland are most prominent during the winter months and are believed to be related to seasonal variations in the estimated air temperatures used in the reduction to mean sea level pressure. This results in fictitious high pressure areas over Greenland and central Iceland during the winter in ERA-40. The lower pressures over Greenland in EMSLP compared with ERA-40 are also evident in comparisons with NCEP–NCAR reanalysis fields (not shown). Models estimate the MSLP there by extrapolating the surface pressure over 2000 m through the ice to sea level, so the result is sensitive to the assumed temperature profile.

Over Europe, the differences are larger than that seen with ADVICE (Fig. 2), and again these are largest in November–February with differences up to 1.5 hPa in eastern Europe. As in Greenland and Iceland, the reduction to sea level during the winter season probably accounts for the differences here between EMSLP and ERA-40. We suspect that differences in the number of observations available to each product, particularly before the late 1970s,[3] may also have had some influence. In North Africa and the Middle East, the differences may be associated with the diurnal cycle correction (see section 4b).

b. Correlations

Spatial correlations and temporal squared correlations were performed to compare EMSLP with the ADVICE and ERA-40 products. Generally, the explained variances are larger in the winter months, because of the greater meteorological signal in this sea-

[3] The input archive for ERA-40 was smaller in the early years (Simmons et al. 2004) than what would have been available to the J86 fields at the time.

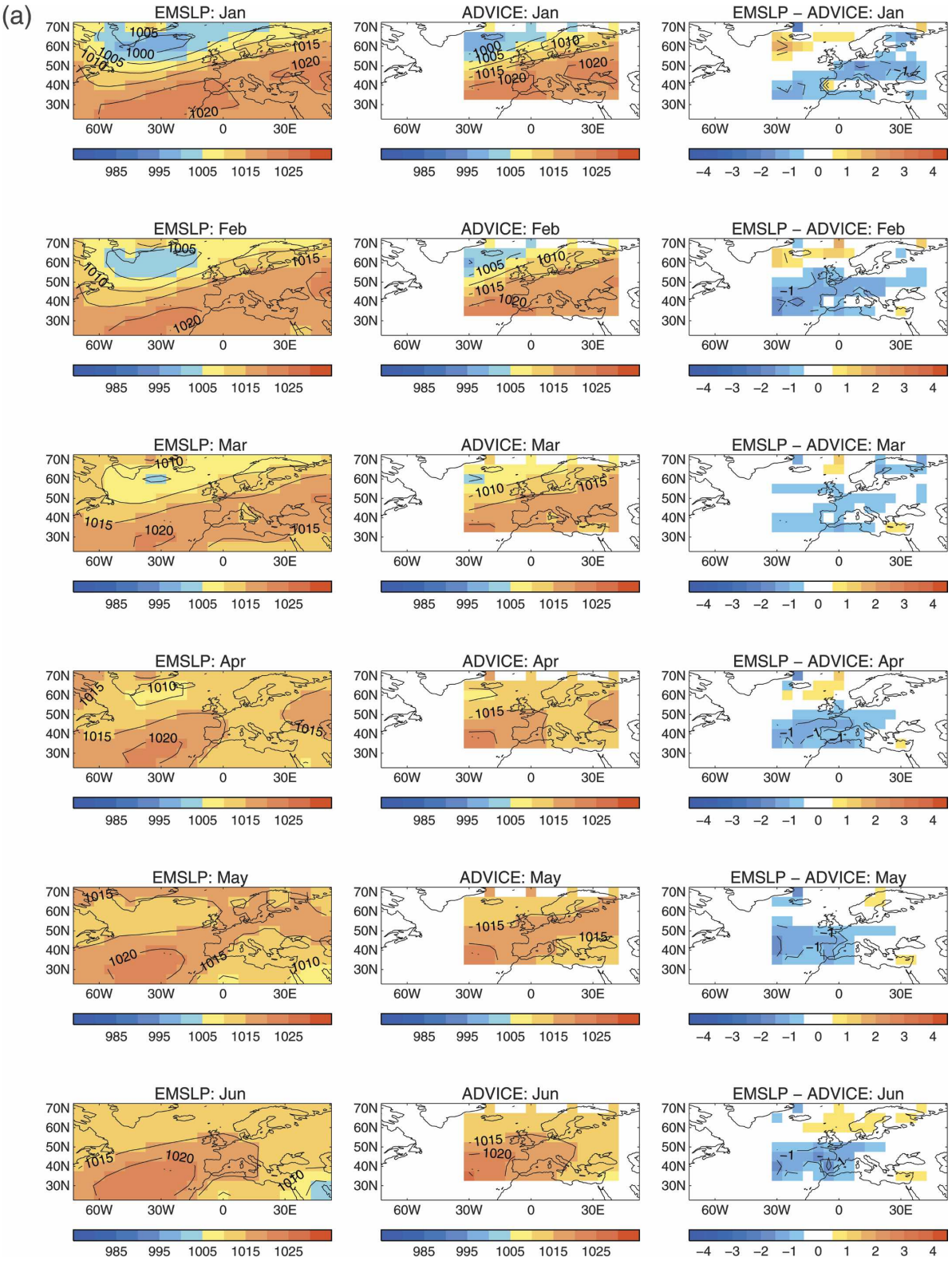


FIG. 2. (a) (top to bottom) January–June monthly normals for (left) EMSLP, (middle) ADVICE, and (right) monthly differences <-0.5 and >0.5 in hPa. Normals are calculated over 1850–1995. To aid the comparison we have interpolated EMSLP to the ADVICE 5° latitude by 10° longitude grid. (b) Same as in (a), except for July–December.

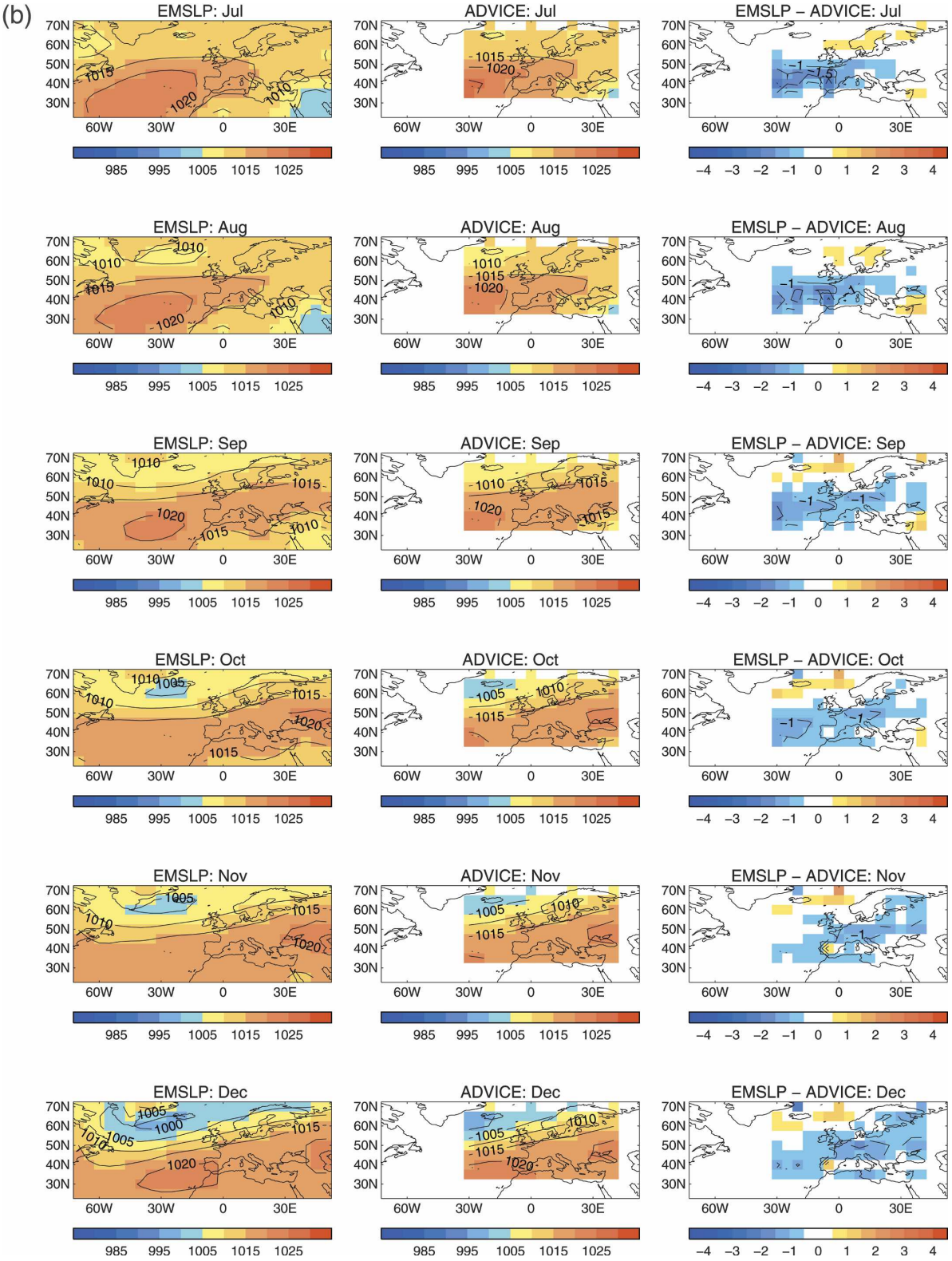


FIG. 2. (*Continued*)

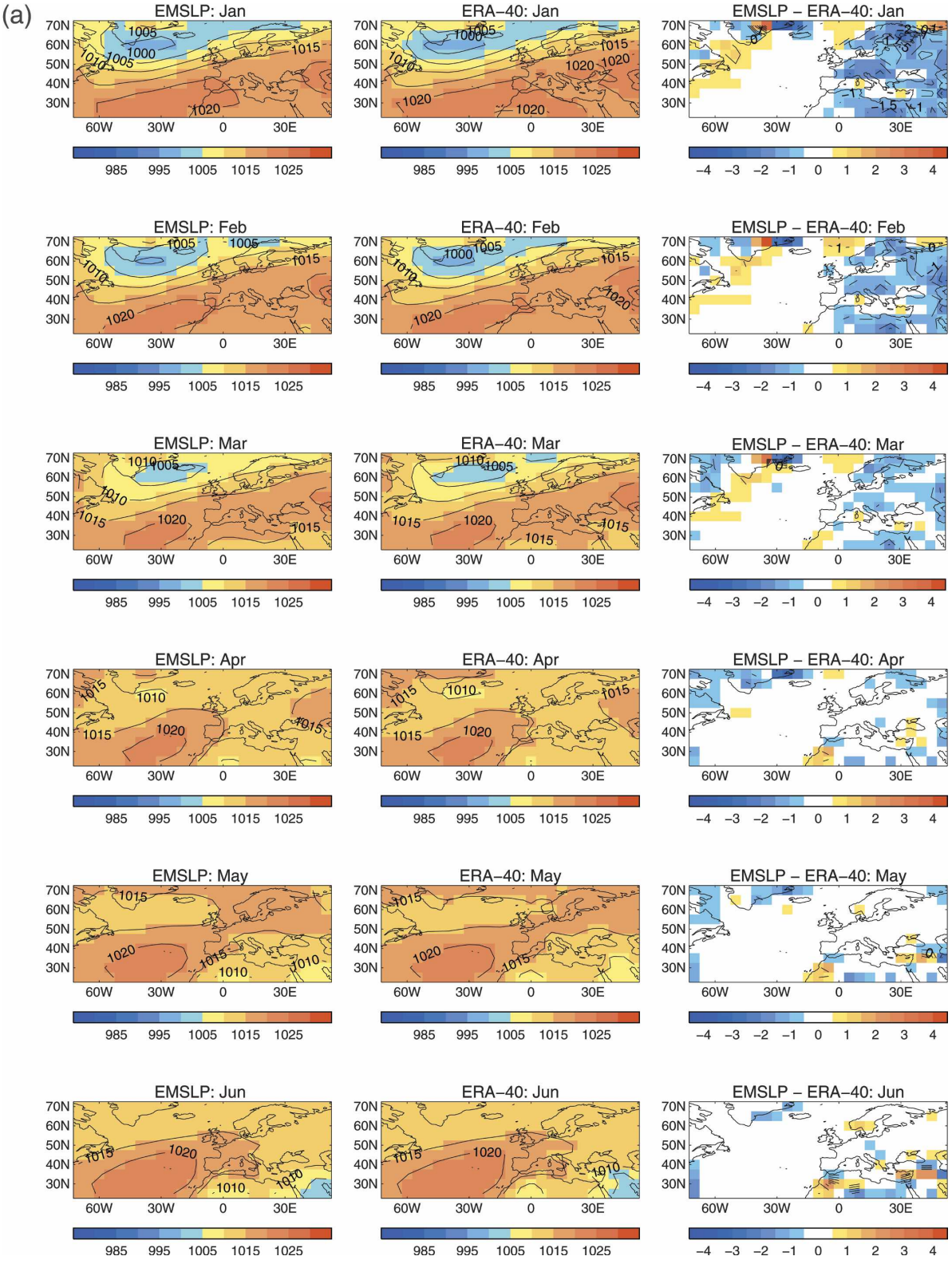


FIG. 3. (a) Same as in Fig. 2a, but for (middle) ERA-40. Normals are calculated over 1959–2001. (b) Same as in (a), but for July–December.

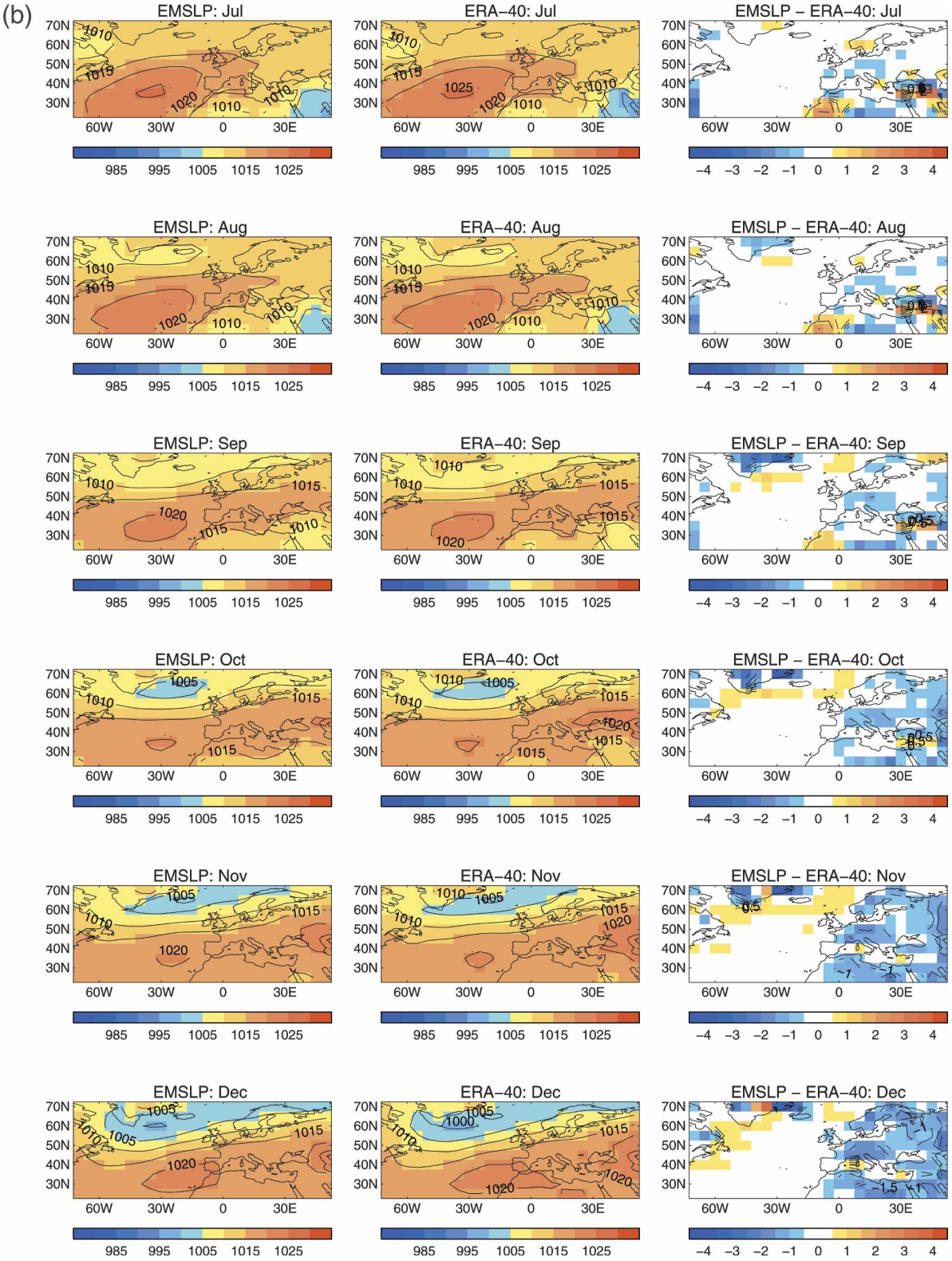


FIG. 3. (*Continued*)

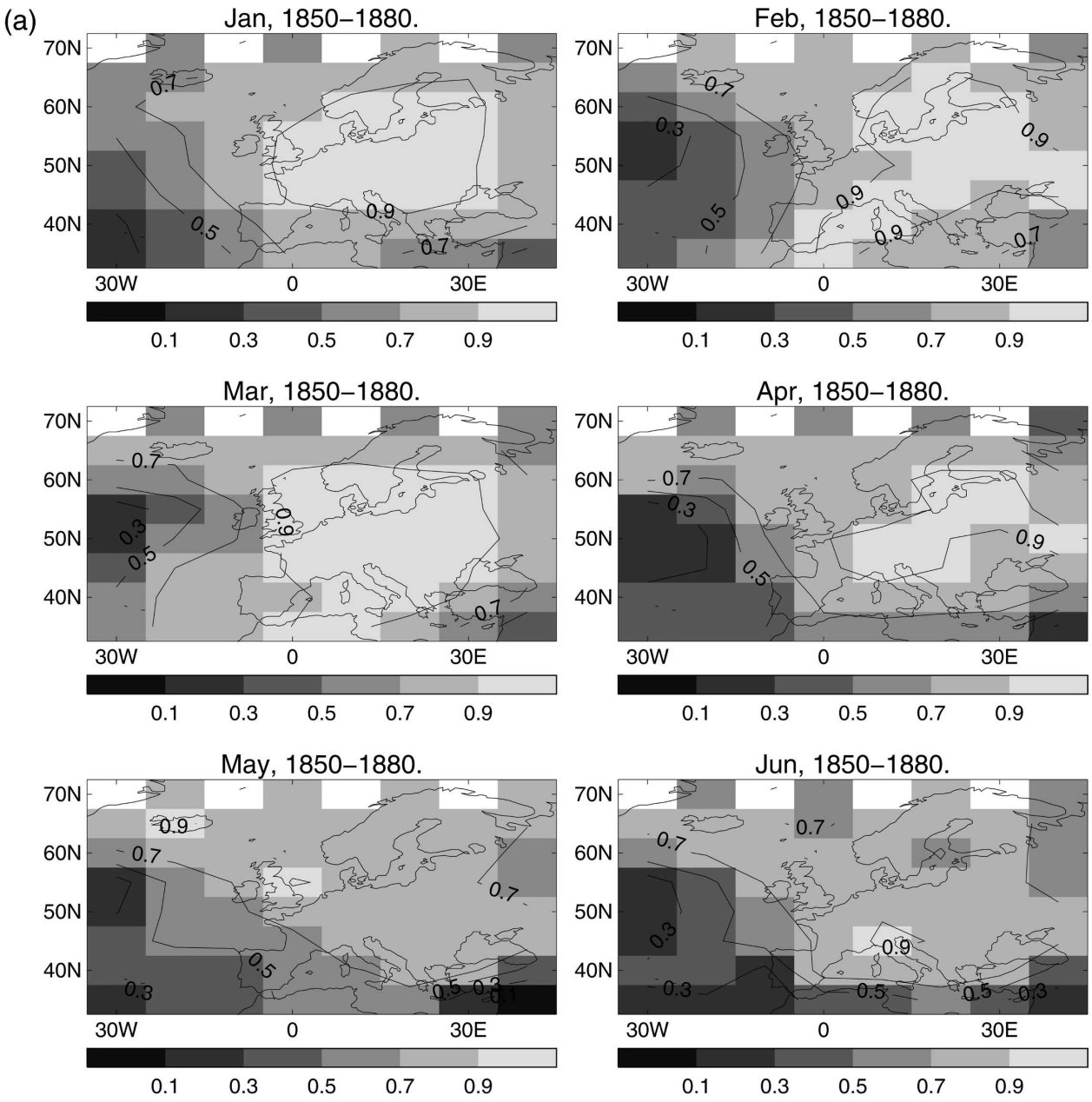


FIG. 4. (a) January–June monthly gridpoint squared correlation (r^2) between EMSLP and ADVICE calculated over 1850–80. (b) Same as in (a), but for July–December.

son. Jones et al. (1999) found a similar result when verifying ADVICE with the Lamb and Johnson (1966) and Kington (1980, 1988) historical analyses.

The grid point squared correlations (r^2) between ADVICE and EMSLP were calculated for three periods: 1850–80 (Fig. 4), 1881–1940 (Fig. 5), and 1941–95 (not shown). During the mid-nineteenth 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 (Fig. 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 (Fig. 5), the variance explained increases, particularly during summer and over the ocean. The Middle East region, however, remains a region of low explained variance. EMSLP contains no

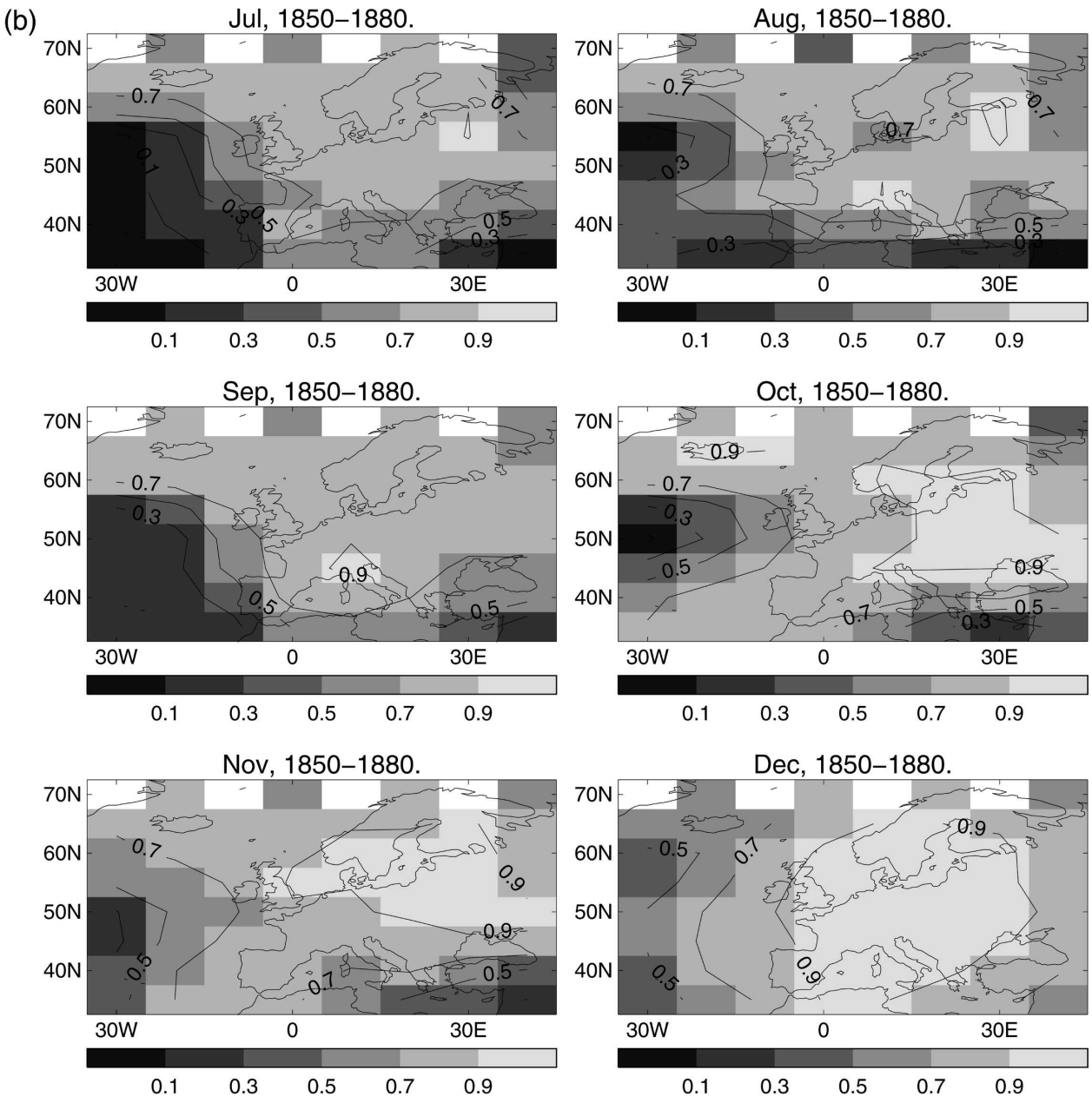


FIG. 4. (*Continued*)

station or J86 observations in this region for 1881–98 and only limited records for Beirut and Alexandria in 1876–81, whereas ADVICE (as noted above) includes data from Cairo and Jerusalem. In the last period examined, 1941–95 (not shown), r^2 values increase slightly.

Given that ADVICE and EMSLP are not strictly independent, we also present the grid point squared correlation (r^2) with ERA-40. These r^2 values are very high, with explained variances over much of the region in excess of 90% (the July–December values are shown in Fig. 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

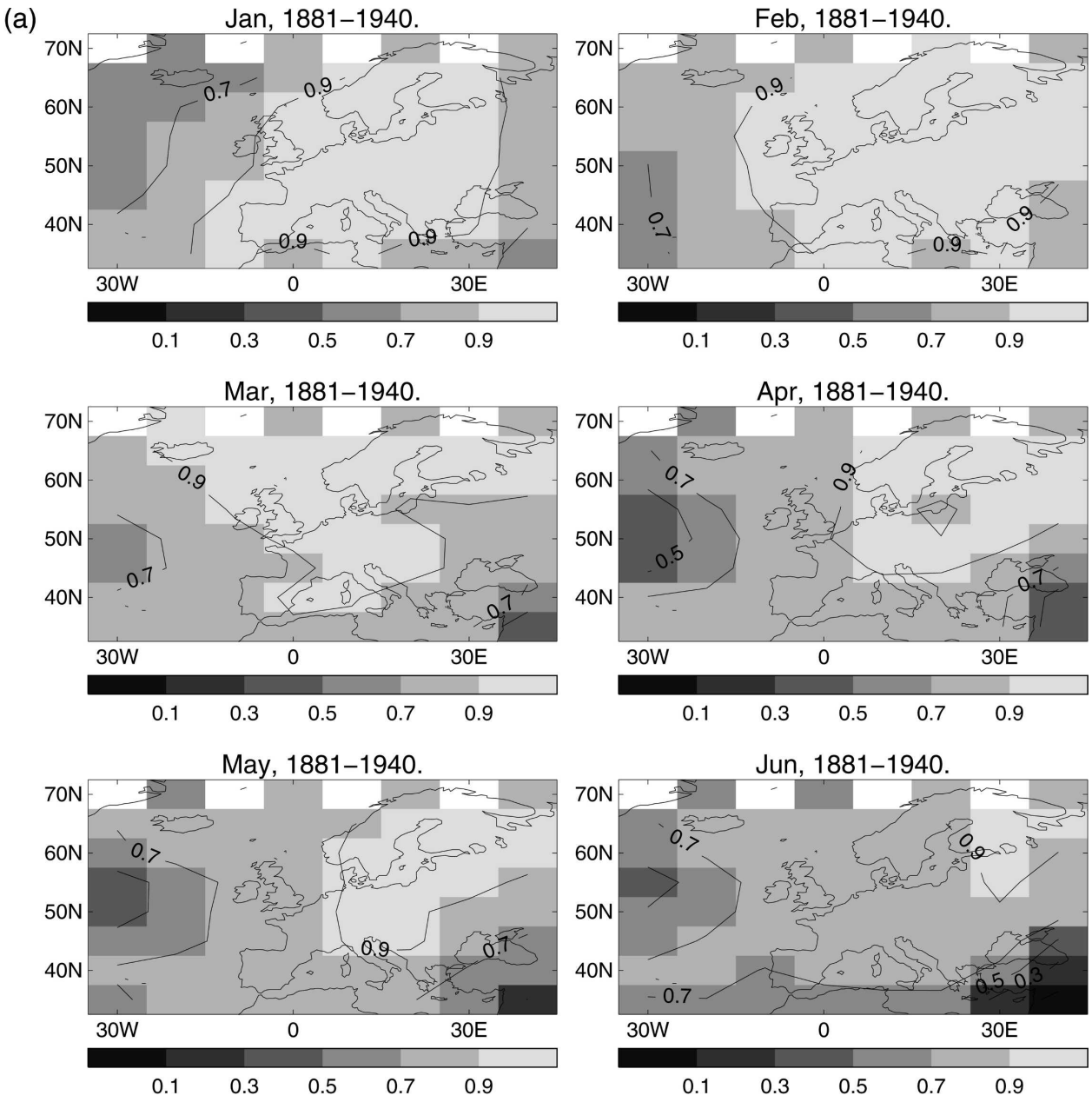


FIG. 5. (a) Same as in Fig. 4, but over 1881–1940.

result of observing times, are expected (as noted above) to be less notable over the marine regions given the good coverage of ship observations throughout the day; r^2 values are indeed high over the ocean. The poorer result 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 coefficients over the common area for 1850–1995 (Fig. 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 normalized anomalies by removing a 1961–90 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 toward the late twentieth century with an increasing number of observations (also plotted in Fig. 7). Owing to the existence of stronger anomalies in winter, corre-

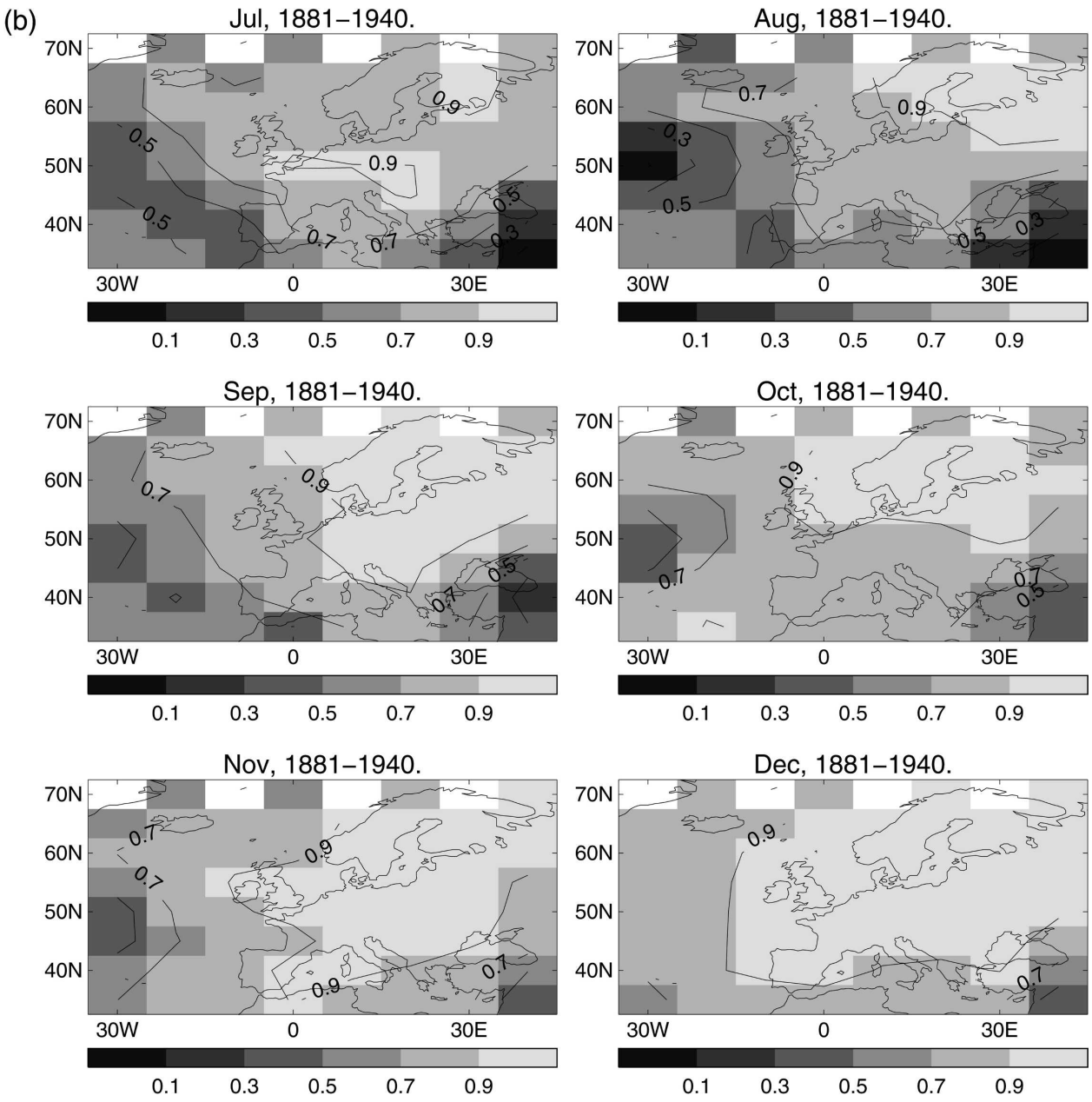


FIG. 5. (*Continued*)

lations are stronger during the winter season, generally around 0.8, but correlations are particularly poor in June, August, and September. The climatic conditions in Europe in summer are mainly influenced by regional-scale processes and are more sensitive to local forcing related to insolation distributions and the high sensitivity to local lower-boundary conditions such as soil moisture; these features are hard to resolve with the available station data (Luterbacher et al. 2000). 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 Fig. 7, often associated with the variability in the number of observations used in the dataset and in ICOADS in particular.

c. Regional comparisons

Subregional comparisons have also been made and have revealed that there is a tendency for highs (lows) in the EMSLP series to not be "high" ("deep") enough. This tendency can be clearly seen in Fig. 8, where the

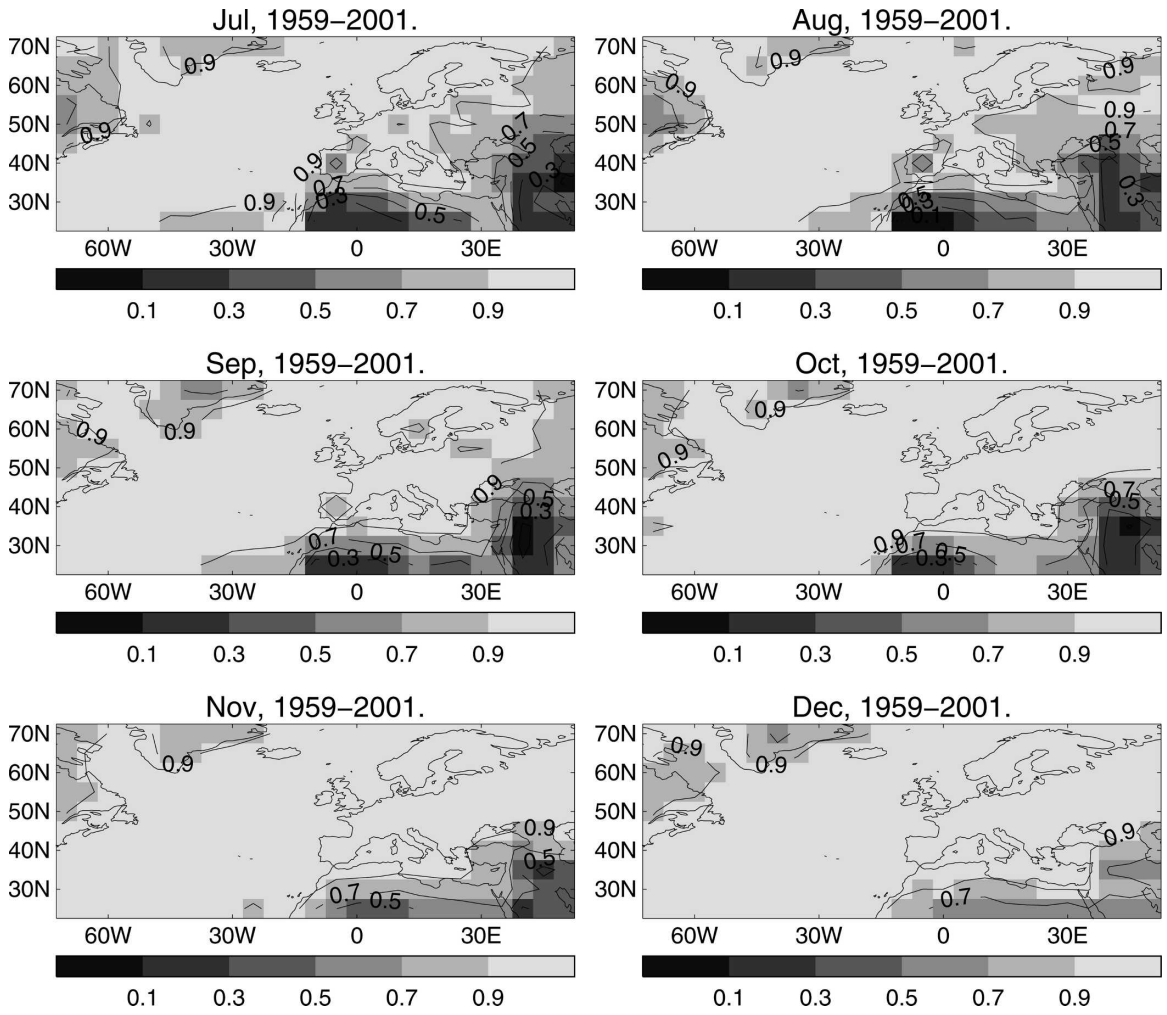


FIG. 6. Same as in Fig. 4b, but between EMSLP and ERA-40 over 1959–2001.

EMSLP pressures are plotted against the corresponding ADVICE pressures for the same 31-yr 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 (subsection of 2b). 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 (subsection of 3b). A similar relationship to that seen in Fig. 8 is evident during 1881–1920, 1921–60, 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 that the flattening appears not to have a major impact on these time scales.

In Fig. 9 we plot the winter North Atlantic Oscillation (NAO) using EMSLP and the monthly HadSLP2 product (Allan and Ansell 2006), taking the grid point nearest to Ponta Delgada in the Azores minus the grid point nearest Reykjavík, Iceland. Seasonal averages are formed for each year and the differences are standardized by removing a 1961–90 mean. Also plotted is a station-based index using data from the Azores and Reykjavík (data available online at http://www.cru.uea.ac.uk/cru/data/nao.htm). All three series compare well; the correlation coefficient for EMSLP and HadSLP2 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.

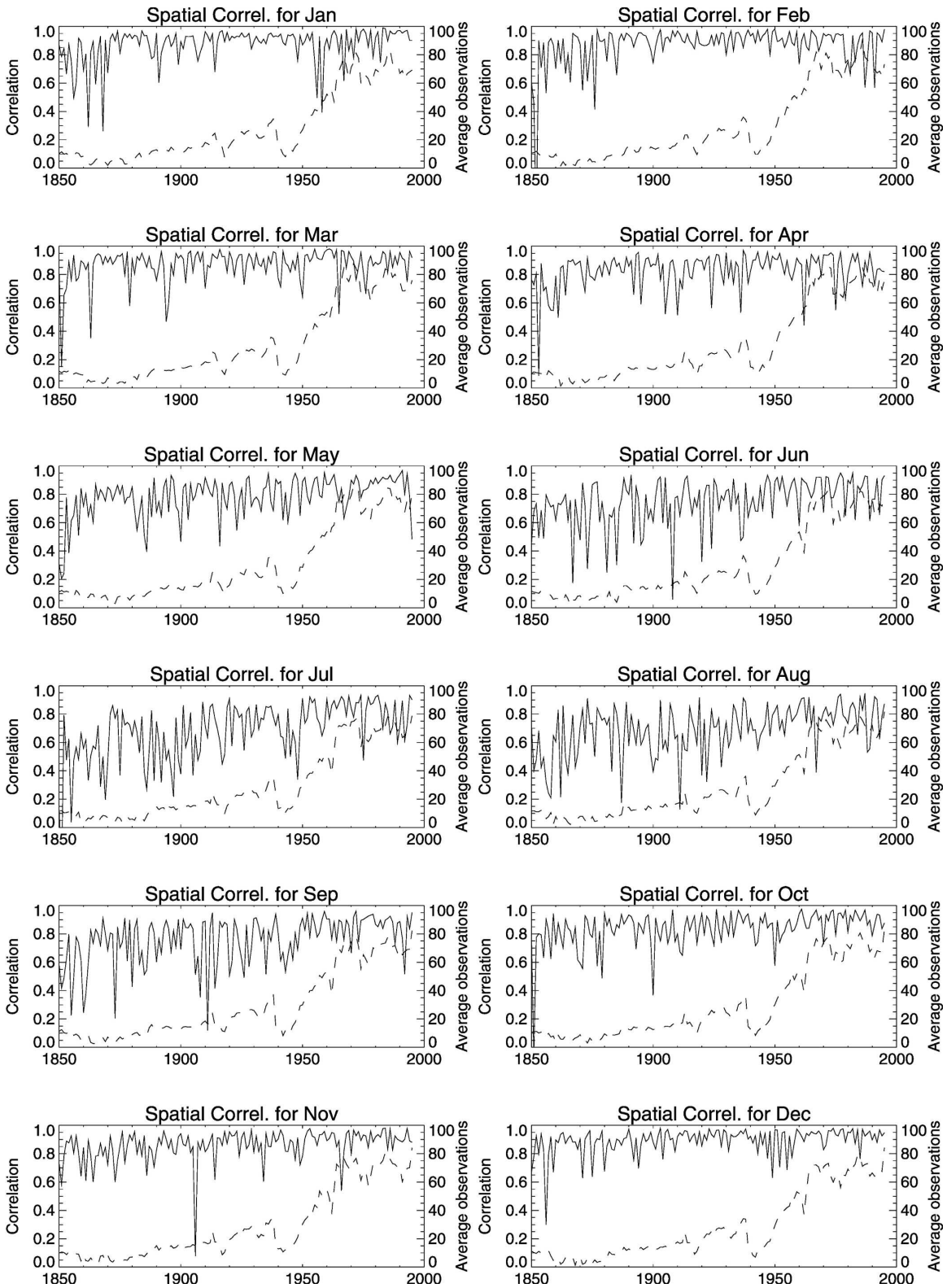


FIG. 7. Time series of spatial correlations for January–December between EMSLP and ADVICE. Correlation coefficients (solid line) are plotted for 1850–2003 with the scale on the left-hand axis. Also plotted is the average number of observations in each grid box for each month (dashed line) with the scale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

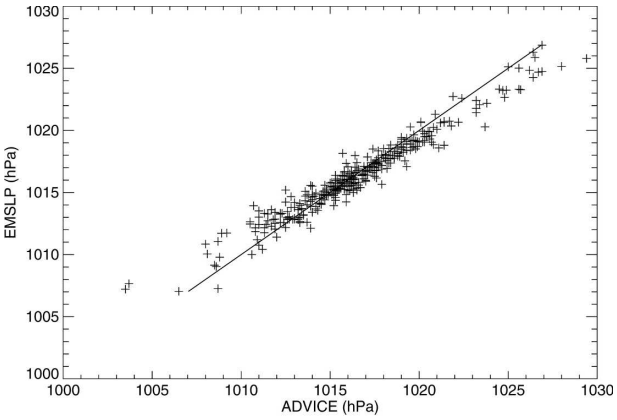


FIG. 8. Monthly EMSLP MSLP (y axis) vs ADVICE MSLP (x axis) at 45°N, 10°E for 1850–80. A straight line representing monthly EMSLP = ADVICE is also shown.

d. 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 JJA daily fields for each of the 10 decades of the dataset (1850–1950) in Fig. 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 1875–80, we have very sporadic records from Nuuk (64.16°N, 51.75°W). In 1894, the Tasiilaq (Ammasalik), Greenland, record (65.60°N, 37.63°W) begins. Nuuk and Tasiilaq are the only two Greenland stations included in the dataset, besides 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 1850–80 than subsequently, they did not increase steadily over this 30-yr 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 are shown in Fig. 7). This may account for the greater reduction in variability during this period compared with the slightly more data-rich period of 1850–60.

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.

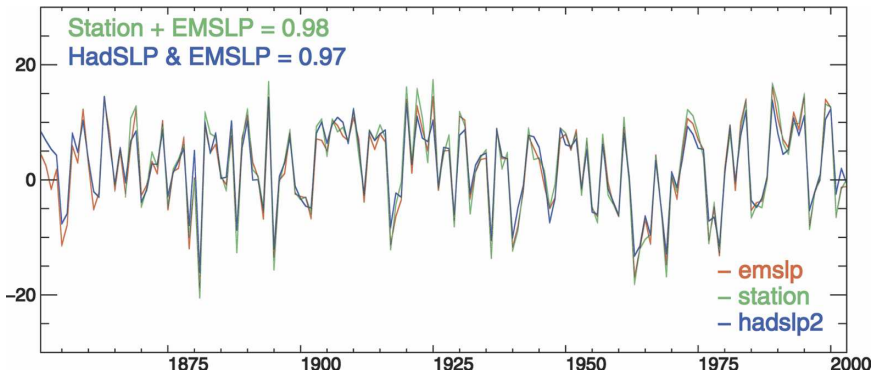


FIG. 9. The winter (December–February) NAO for 1850–2003 from EMSLP (red) and HadSLP2 (blue) gridded products. The winter NAO is calculated by taking the difference between the grid point closest to Ponta Delgada and that closest to Reykjavík. The 1961–90 mean series value is then removed from each value. Also plotted is a station-based index from 1866–2003 (green), using data from Reykjavík and Ponta Delgada. Differences between the two station series are formed and the 1961–90 average is also removed. Correlation coefficients are also given.

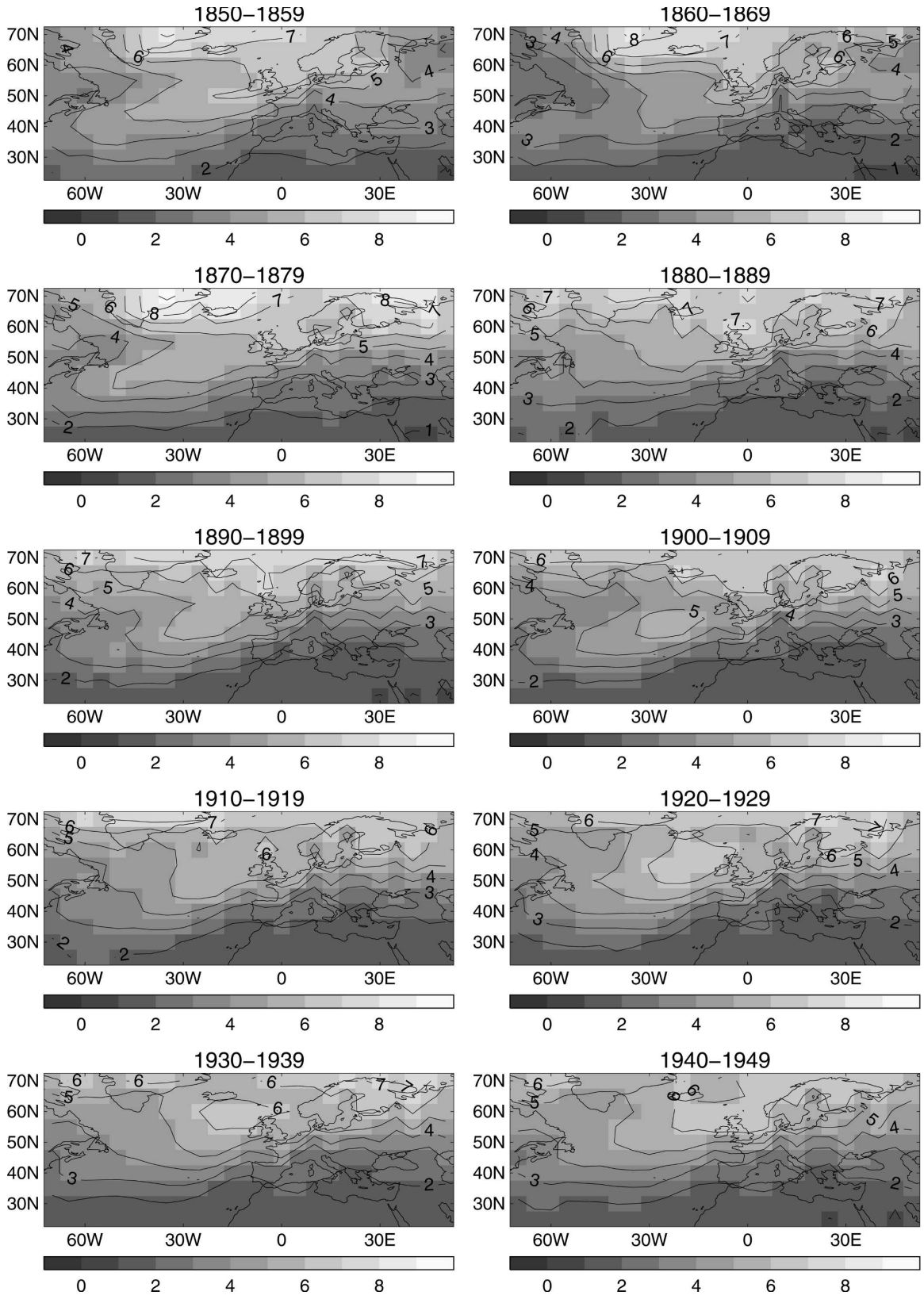


FIG. 10. Daily variability observed within the summer season (JJA) in each decade (from 1850–1949) in EMSLP. Contours are in hPa.

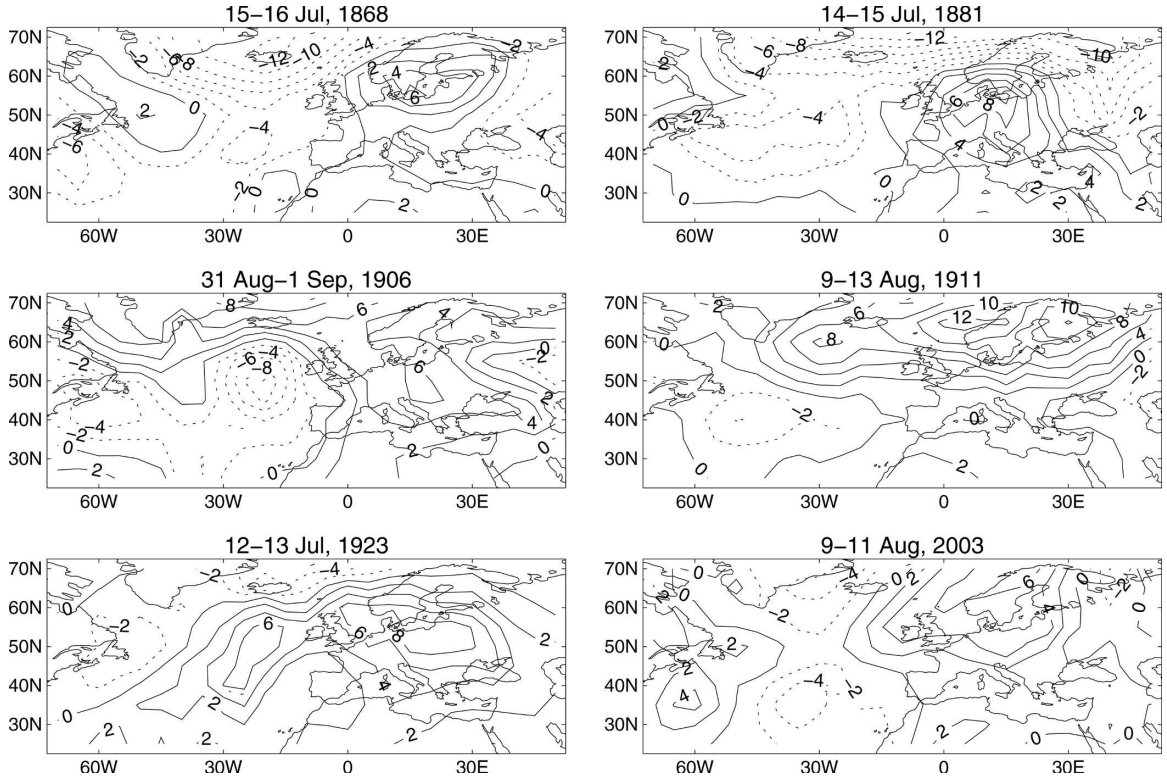


FIG. 11. MSLP anomalies for six heat wave events over the United Kingdom. The MSLP average anomaly is plotted for the hottest days, where 35°C or more was reached (after Burt 2004). Anomalies are formed by removing a 1961–90 climatological average; contours are in 2 hPa.

e. Extreme events

Recent extreme climate events such as the 2003 heat wave in Europe (Trigo et al. 2005; Fink et al. 2004; Schär et al. 2004; Luterbacher et al. 2004; Stott et al. 2004) that 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 submonthly extreme events back to the mid-nineteenth century.

Following Burt (2004), we are now able to plot the atmospheric circulation conditions associated with the extreme U.K. heat waves of July 1868, July 1881, August–September 1906, August 1911, July 1923, and August 2003 using EMSLP. In Fig. 11, we plot the anomalous MSLP field for the days corresponding to the highest temperatures of the summer, equal to or exceeding 35°C. The years 1911 and 2003 were also anomalously warm summers over central Europe (e.g., Pfister 1999; Luterbacher et al. 2004). Anomalously high pressure centered over or near southern Scandinavia is a common feature in all six events, resulting in anomalous southeasterly flow bringing hot continental air into the United Kingdom. Much of central Europe is dominated by high pressure associated with these events (Fig. 11).

This circulation pattern and anomalous flow has been identified previously by Maryon et al. (1982) in a cluster analysis of summer (JA) 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 U.K. floods, such as in autumn 2000, in the context of historical events. The three wettest Octobers in the United Kingdom and Wales during 1766–2003 were in 1903, 2000, and 1987 (Jones and Conway 1997; Alexander and Jones 2001). Using U.K. daily weather records and a chronology of British hydrological events (see online at http://www.dundee.ac.uk/geography/cbhe/), we have selected days associated with flooding in the United Kingdom for each of these extreme months, in addition to 3 nineteenth-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 Fig. 12. While all events are domi-

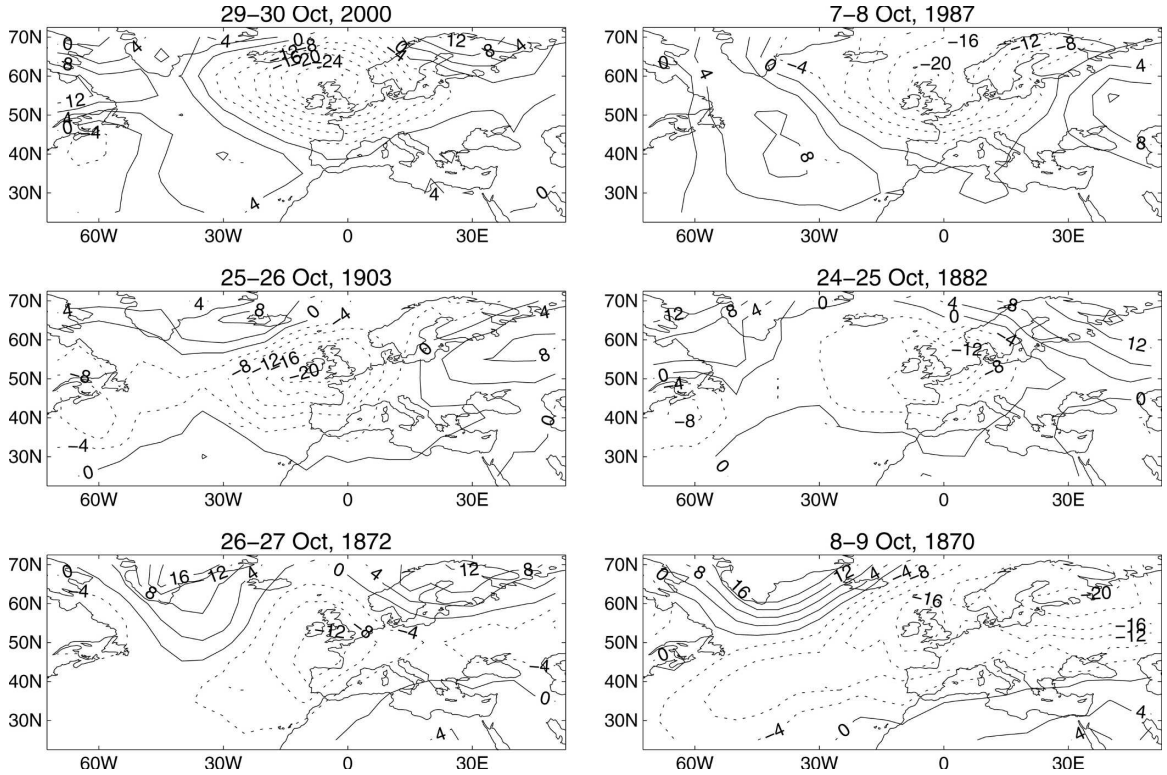


FIG. 12. MSLP anomalies for six flooding events over the United Kingdom. Days were selected in each case from daily station totals, available in the U.K. DWRs held in the U.K. Meteorological Library and with reference to historical flooding events are available from the Chronology of British Hydrological Events (http://www.dundee.ac.uk/geography/cbhe/). Anomalies are formed by removing a 1961–90 climatological average; contours are in 4 hPa.

nated by anomalously low pressure over the United Kingdom, 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 United Kingdom (L. V. Alexander 2005, personal communication).

5. Conclusions

We have described the development of a daily gridded European–North Atlantic MSLP dataset for 1850–2003 on a 5° latitude by longitude grid, produced with 86 continental and island station records and ship observations from the ICOADS database. The EMSLP fields for 1850–80 are based purely on the land station data and ship observations. From 1881, the blended land and marine fields are combined with already available adjusted daily J86 fields, using a technique that reduces the effect of any remaining heterogeneities in these fields. Thus, EMSLP provides 154 yr of homogenized pressure fields. Comparisons with other 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 (Fig. 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 1850–80, 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 digitize the millions of observations that are still available from ship logbooks held in the U.K. National

Archives in Kew and the National Maritime Museum in Greenwich, and land station records available in daily weather record volumes held in 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 that 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 the 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 for characterizing circulation patterns over the European–North Atlantic region. While the existing J86 fields, derived from synoptic hand-drawn charts, provide greater detail than EMSLP, they contain heterogeneities (see Jones 1987), arising in particular from changes in source (detailed in Table 3). As a result, EMSLP, being homogenized, is more suitable for extended analyses back to the nineteenth century. For more recent (post 1970) analyses of synoptic events or cyclone tracking studies, we suggest that reanalysis products would be more suitable. However, we were able to examine the anomalous conditions during the recent 2003 heat wave in Europe (Fig. 11) and recent flooding events (Fig. 12) in a historical context.

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 online after November 2005 (www.cru.uea.ac.uk/cru/projects/emulate/).

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APPENDIX A

Undetected Duplicates

We were advised (G. Compo 2003, personal communication) that there were a number of undetected (and hence unflagged) duplicates in the ICOADS database. 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 $\pm -0.1°$) as the deck 156 data and with identical values for SST, air temperature, etc., but with pressures different by twice the gravity correction. This only happened in certain months and so this may be the result of the error of one particular digitizer. 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 nonduplicate deck 156 data have been compared with other neighboring (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 2003, personal communication).

APPENDIX B

Correcting for the Low MSLP Bias in U.S. 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 on the use of historical marine climate data (Diaz et al. 2002), and remains an unresolved problem within the ICOADS pressure community. During 1850–55, the only data source was deck 701 (the U.S.

Maury collection). After 1855, observations from the Netherlands deck 193 begin and the low bias is less prominent. Because EMULATE required fields to start in 1850, it was not possible to simply ignore the U.S. Maury observations.

The marine gridding procedure works with residuals by removing a reference monthly background field value based on 1850–2003 from each observation (see the subsection of 2b). 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 for only 1850–60. The gridding and quality control procedure was rerun, now using 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 $1° \times 1°$ 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 1850–60 decade to a 1961–90 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 multiannual climate anomaly during 1850–55, but comparisons with land-based data support our treatment of the marine data.

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