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The decade of the 1990s over the Atlantic in comparison with longer instrumental and palaeoclimatic records

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The North Atlantic Oscillation (NAO) is the principal mode of variability in surface pressure over the North Atlantic/European sector of the Northern Hemisphere (NH). The mode is particularly dominant during the winter season, explaining part of the surface temperature and precipitation variability over the region. Recent winter values of the NAO during the late 1980s and 1990s have been strongly positive, giving Northern Europe a succession of mild winters. Long instrumental records and palaeoclimatic reconstructions of the NAO indicate several earlier periods of comparable values over the past 500 years. The rise in NAO values from the 1960s to the 1990s, however, does appear unique in the long records. Although the NAO is capable of explaining some of the variability of surface temperature change during the 1990s in the winter season, it cannot explain the warming of the other seasons as the NAO influence is weak and the NAO has been less anomalous in these seasons.

Keywords: Atlantic, climate change, North Atlantic Oscillation, pressure, temperature.

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Introduction

The strong anti-phase relationship between monthly pressure series from Iceland and the Azores was first referred to by Walker (1924) as the North Atlantic Oscillation (NAO). The traditional index has been calculated from the difference between normalized monthly pressures at Ponta Delgada (Azores) and Stykkisholmur (Iceland). These locations were chosen originally as they were the sites with the longest readily available series of pressure observations from the two centres-of-action that represent the phenomenon.

The NAO value is a measure of the westerly wind strength over the North Atlantic and the western half of Europe. Winter values have the strongest influence on surface climate features in the region. Positive values of the NAO, implying stronger westerlies, bring milder weather to Europe, north of about 40°N and vice versa (see Hurrell, 1995 and Osborn *et al.*, 1999). South of 40°N, the relationship is the inverse, particularly over the southern Balkans, Turkey and parts of the Middle East and over southern Spain and northwestern Africa. The NAO also influences the climate over eastern North America, with positive values associated with warmer winters over the southeastern United States and cooler winters over eastern Canada and western Greenland. The four main centres of influence have been extensively studied since Hurrell (1995) and referred to as a quadropole pattern by Slonosky and Yiou (2001). Positive NAO values are also associated with higher amounts of precipitation in Europe north of 45°N and reduced precipitation to the south (Hurrell, 1995).

In this article, several measures of the NAO are compared over as long periods as possible, including two palaeoclimatic reconstructions. Recent changes of the NAO have been unusual, and the anomalous nature of the 1990s with respect to the longer records is discussed. The strength of the relationships between the NAO and surface climate variability of the North Atlantic/European region is then assessed.

Longer records of the NAO

Figure 1 shows several winter (December to February) NAO indicators back to the beginning of instrumental and documentary historical records.

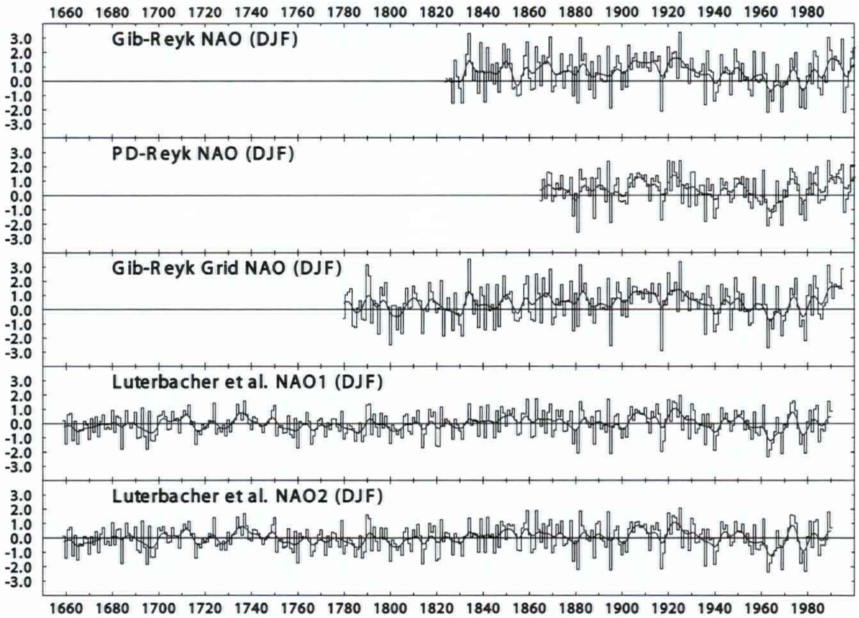

Figure 1. Winter (December to February) times-series of the NAO from long instrumental records (back to 1865, 1821, and 1780) and from documentary-based reconstructions (back to 1659).

The traditional measure uses the Ponta Delgada site in the Azores as the southern node where records began in 1865. For the northern node, Reykjavik has records back to 1821, 25 years earlier than Stykkisholmur (Jones *et al.*, 1997). Hurrell (1995) showed that using a Southwest European location as the southern node, instrumental indices could be extended back further during the winter season. The earliest location in this region is Gibraltar, with records back to 1821 (Jones *et al.*, 1997). Further extension of the NAO to 1780 is possible using the gridded surface pressure reconstructions from Jones *et al.* (1999), which use a network of varying numbers of surface pressure data (including Gibraltar and Reykjavik after 1820).

The final two curves in Figure 1 are two reconstructions of the NAO developed by Luterbacher *et al.* (1999, 2002) using regression analysis. Full details of the methods are given in the two articles. They make use of long pressure series but include additional information from many, even longer, series of monthly temperature averages and precipitation totals and documentary sources. These latter series incorporate information from documentary archives such as diaries, river and Baltic Sea freeze dates and reports of droughts in southern Europe. Rodrigo *et al.* (2001) have recently illustrated the potential for reconstructing the NAO from one such drought series for Andalusia in southern Spain since 1500.

Figure 2 compares the Luterbacher *et al.* (2002) reconstruction with another recent reconstruction by Cook *et al.* (2002). In Figure 2 the winter season is December to March, that used by Cook *et al.* (2002). To enable comparison, the Luterbacher *et al.* (2002) series, which is available monthly, is based on the 4-month average, so is marginally different from that shown in Figure 1. The Cook *et al.* (2002) reconstruction has been developed from natural archives of the past, incorporating several hundred tree-ring chronologies constructed from trees growing in Europe, north Africa, and eastern North America and a few Greenland ice cores. As both reconstructions involve many non-pressure variables (temperature, precipitation, and documentary series in the case of Luterbacher *et al.* (2002) and tree rings and ice cores in the case of Cook *et al.* (2002)), they will also incorporate changes in the influence of the NAO on these indicators as well as changes in the NAO itself (Jones *et al.*, 2001).

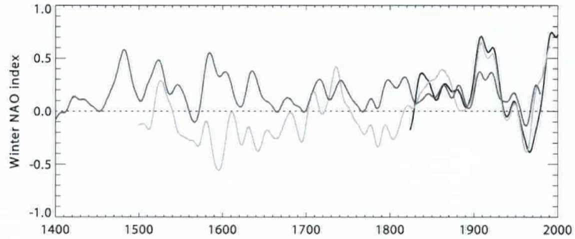

Figure 2. Comparison of two long 'winter' (December to March) reconstructions of the NAO [documentary and instrumental based from Luterbacher *et al.* (2002) (light grey) and from tree rings and ice cores from Cook *et al.* (2002) (dark grey)]. Both series and the observational NAO (black and based on Gibraltar and Reykjavik) have been smoothed with a 30-year Gaussian filter.

All the winter NAO series indicate relatively unusual conditions during the 1990s, but recent values for individual winters have not been entirely without precedent. Similarly, strongly positive values for individual winters occurred during the early decades of the 20th century and for several earlier periods of one or two decades in earlier centuries. Although recent values have not been entirely unique compared to earlier decades (except on the 30-year time scale of the filtered series), the rise in values over the 30-year period from 1965 to 1995 does stand out.

Relationships with surface variables

Figure 3 shows correlation coefficients between the NAO (the series developed from Ponta Delgada and Reykjavik) and surface temperatures and precipitation totals. The correlations have been calculated for the four climatological seasons, based on data for the 1951–2000 period. Figure 3A shows correlations with temperature and Figure 3B with precipitation. The strongest correlations are as expected in the winter season, but weaker and still significant

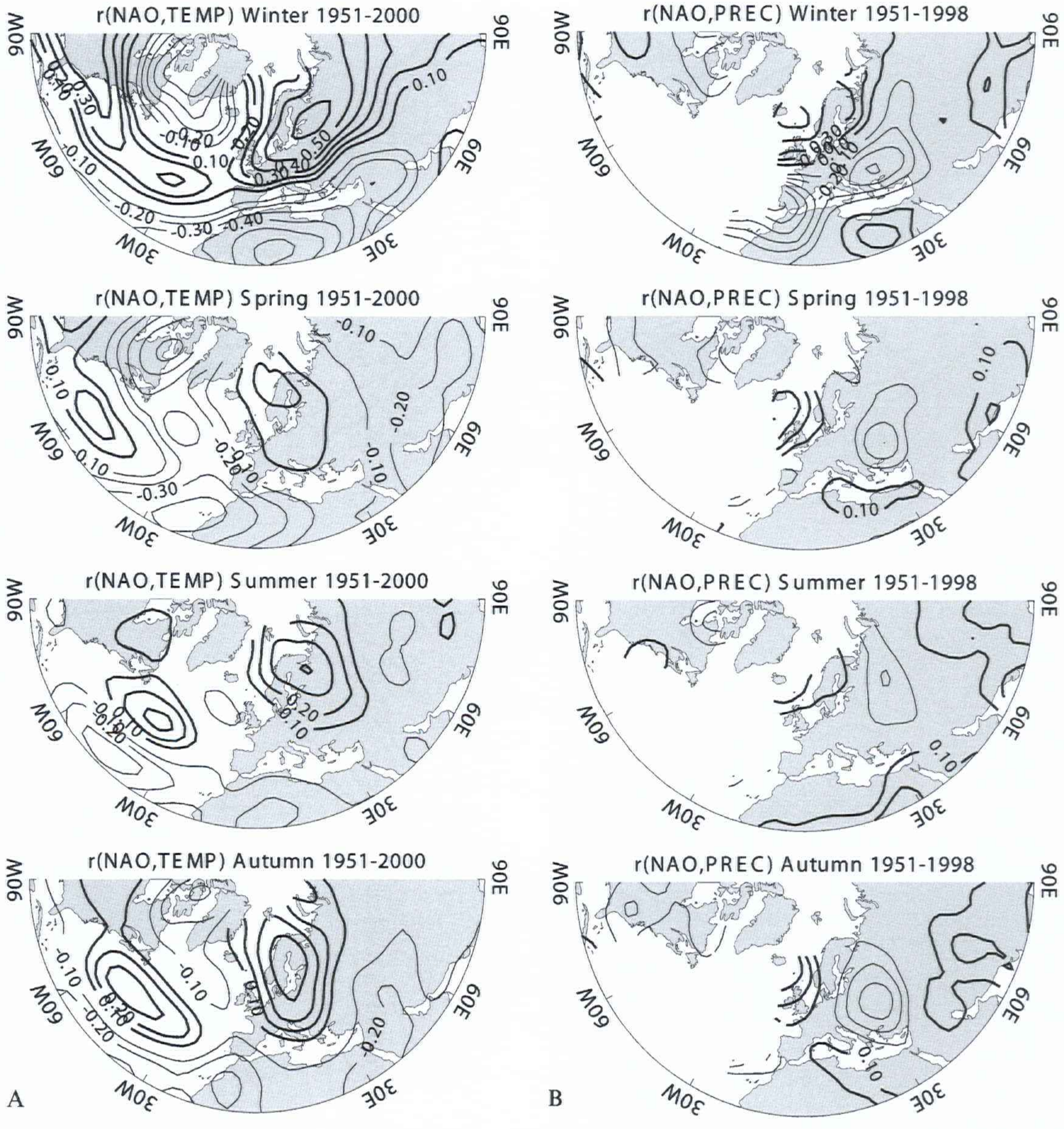

Figure 3. Seasonal correlation maps between surface climate features over the 1951–2000 period and the NAO defined by Ponta Delgada and Reykjavik: (A) temperature and (B) precipitation. In this and subsequent Figures, standard climatological seasons are used. Winter is December to February, Spring is March to May, etc.

correlations are sometimes evident in some areas in the other seasons. Correlations are weakest during the summer season.

Reid *et al.* (2001) and Jones *et al.* (2002) show similar analyses for different periods, illustrating that the strengths of relationships do vary with time. The stronger relationships (those in the key regions of the quadropole pattern), however, tend to maintain similar values through time, but the weaker relationships can be dependent on the time period used in their development. Jones *et al.* (2002) show, in particular, that precipitation/NAO relationships are much more variable with time, reflecting the greater spatial variability of precipitation processes and the greater difficulty of ensuring long homogeneous precipitation series.

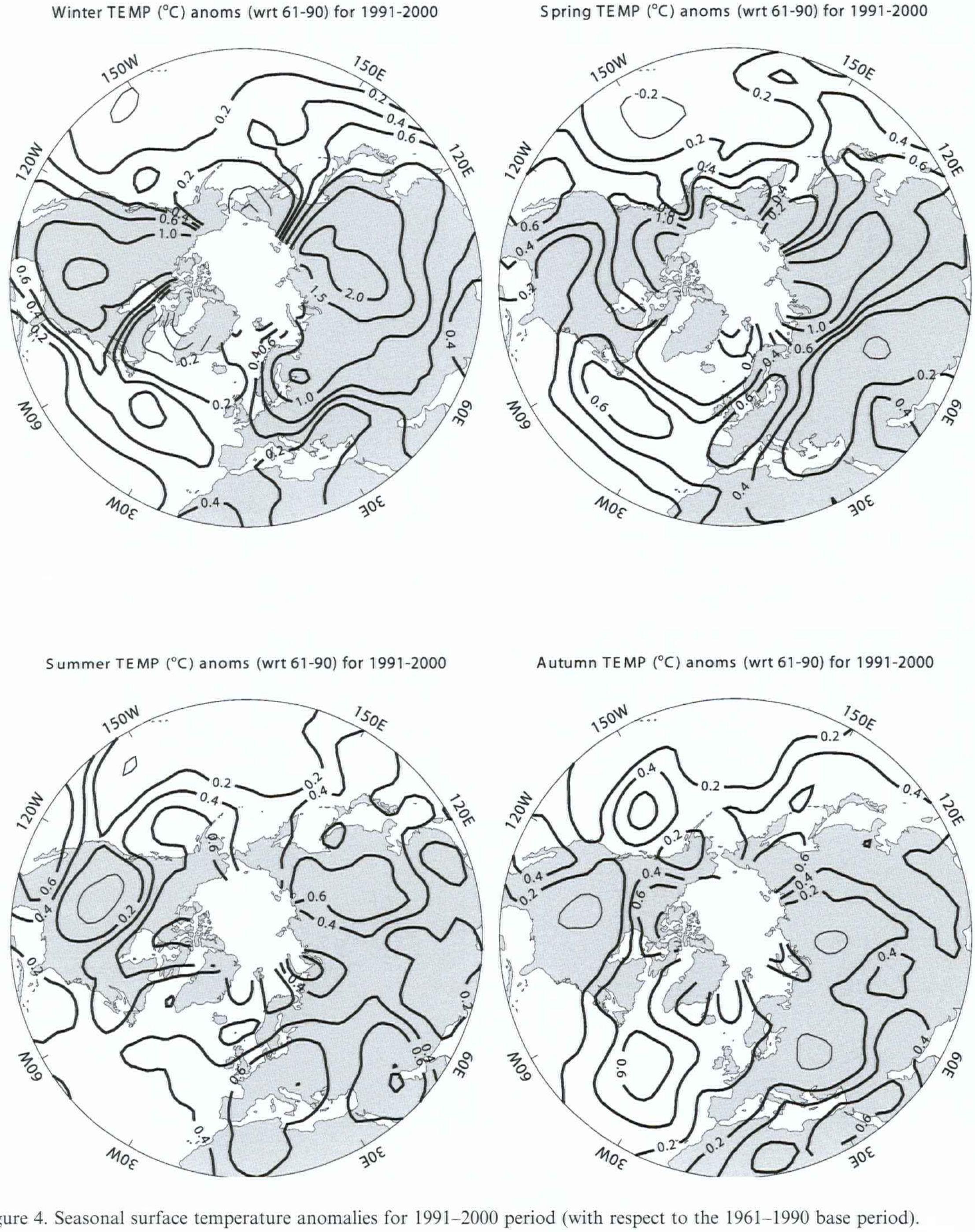

Figure 4. Seasonal surface temperature anomalies for 1991–2000 period (with respect to the 1961–1990 base period).

The 1990s in comparison to earlier decades

Figure 4 shows seasonal temperature anomalies for the 1991–2000 period, with respect to the 1961–1990 period, for the whole NH north of 20°N. For all seasons, most of the analysed area indicates warmer conditions than during the 1961–1990 period. Figure 5 shows similar maps for seasonal pressures, again expressed as anomalies from the 1961–1990. As average pressure across this region would be expected to be conserved, the maps reveal regions during 1991–2000, which experienced higher and lower pressures compared to 1961–1990. The most striking season is winter, where lower pressures

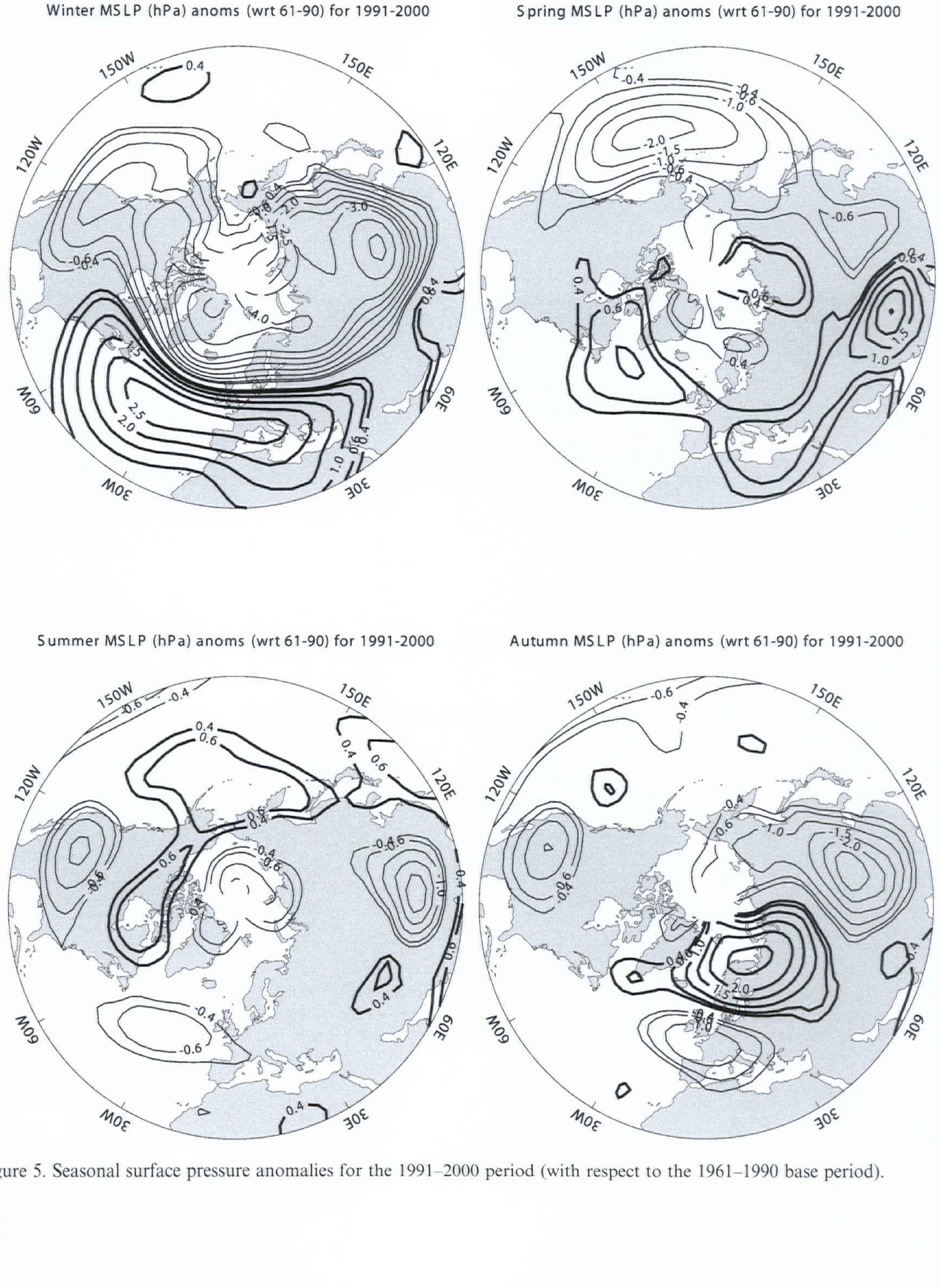

Figure 5. Seasonal surface pressure anomalies for the 1991–2000 period (with respect to the 1961–1990 base period).

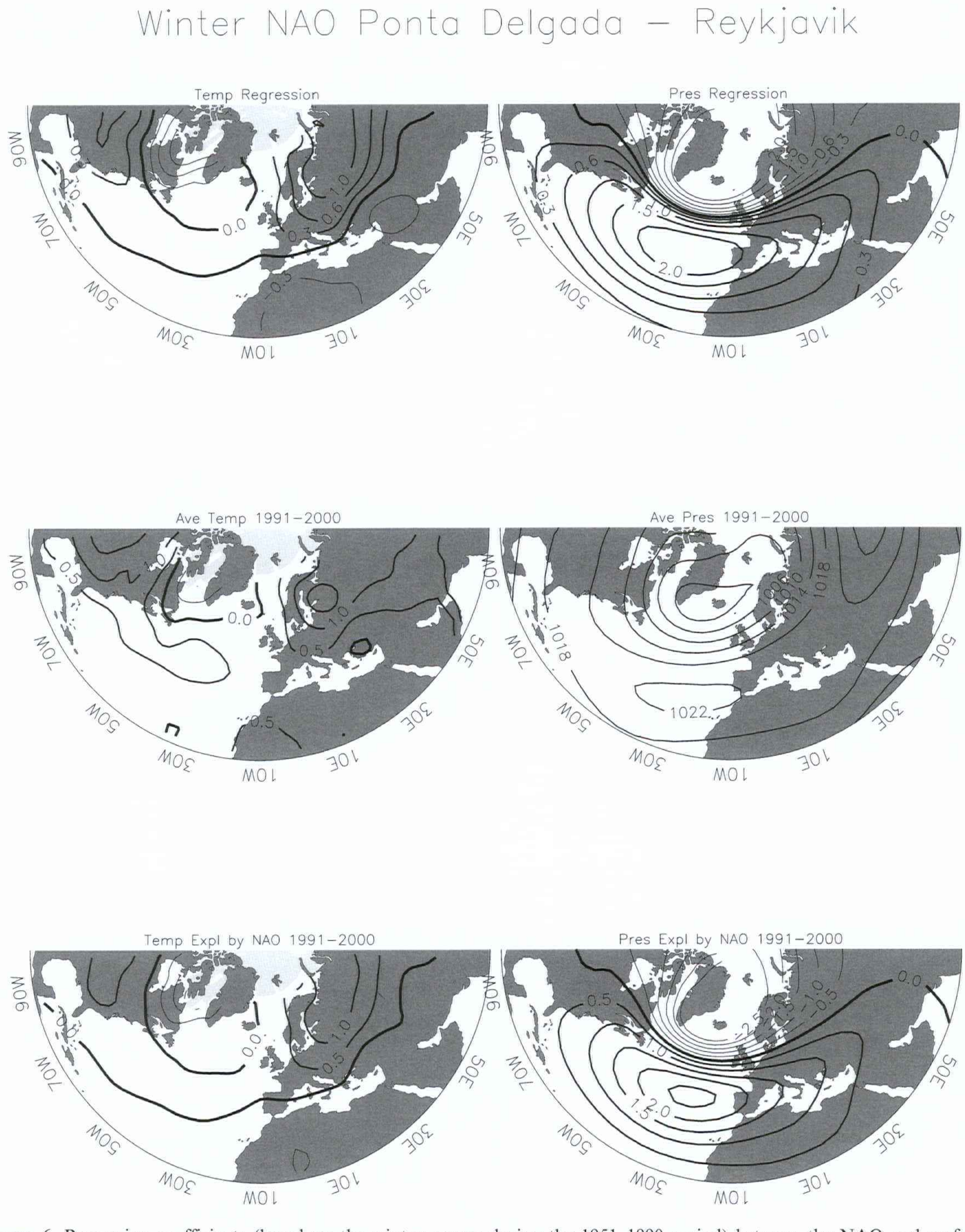

Figure 6. Regression coefficients (based on the winter season during the 1951–1990 period) between the NAO and surface temperature/pressure fields (top pair); temperature and pressure anomalies for 1991–2000 (middle pair) and the amount of temperature and pressure change explained by the regression during 1991–2000 (lower pair).

during 1991–2000 were evident over the Arctic region, northern Asia, and all of western North America. Pressures were higher over the southern North Atlantic and much of southern Eurasia.

Finally, Figure 6 illustrates for the winter season how much of the mean change of temperature and pressure during 1991–2000 can be explained by the NAO. Regression relationships for winter were derived between the Ponta Delgada–Reykjavik NAO and the temperature and pressure fields for the 1951–1990 period and then used to estimate the expected change in temperature and pressure for the 1991–2000 period. The NAO explains a significant fraction of the change, particularly over the expected areas of Europe, North Africa, and eastern North America. Similar analyses for the other three seasons (not shown) indicate that few of the changes can be explained by NAO variability, principally because the NAO has been less anomalous in these seasons and its influence is considerably weaker.

Conclusions

Recent individual winter NAO values during the 1990s have not been anomalous compared to longer records, although they appear unprecedented at the 30-year time scale. The rapid shift from negative values in the 1960s to the strongly positive values in the 1990s appears to have been unique. In the winter season the NAO explains a significant fraction of the change in climate over the greater North Atlantic region during the 1990s. The weaker influence of the NAO in the other seasons and its less anomalous behaviour mean that hardly any changes that have occurred in the 1990s can be significantly explained by the NAO.

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