Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO

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Received 25 July 2011; revised 16 September 2011; accepted 19 September 2011; published 21 October 2011.

[1] Northern Europe was influenced by consecutive episodes of extreme winter weather at the start and end of the 2010 calendar year. A tripole pattern in North Atlantic sea surface temperature anomalies (SSTAs), associated with an exceptionally negative phase of the North Atlantic Oscillation (NAO), characterized both winter periods. This pattern was largely absent at the surface during the 2010 summer season; however, equivalent sub-surface temperature anomalies were preserved within the seasonal thermocline throughout the year. Here, we present evidence for the re-emergence of late-winter 2009/10 SSTAs during the following early winter season of 2010/11. The observed re-emergence contributes toward the winter-to-winter persistence of the anomalous tripole pattern. Considering the active influence of the oceans upon leading modes of atmospheric circulation over seasonal timescales, associated with the memory of large-scale sea surface temperature anomaly patterns, the re-emergence of remnant temperature anomalies may have also contributed toward the persistence of a negative winter NAO, and the recurrence of extreme wintry conditions over the initial 2010/11 winter season. Citation: Taws, S. L., R. Marsh, N. C. Wells, and J. Hirschi (2011), Re-emerging ocean temperature anomalies in late-2010 associated with a repeat negative NAO, Geophys. Res. Lett., 38, L20601, doi:10.1029/2011GL048978.

1. Introduction

[2] Two intervals of severe winter weather affected northern Europe in 2010. First, the period December 2009–February 2010 ranked as the coldest winter for large parts of Western Europe since 1978/79 (see http://www.metoffice.gov.uk/climate/uk/2010/winter.html). It was succeeded by a second extreme cold event during December 2010–January 2011 (hereafter D10J11) when the UK experienced the harshest December in over 100 years (see http://www.metoffice.gov.uk/climate/uk/2011/winter.html). Both episodes endured anomalously heavy snowfall [Seager et al., 2010] and record-breaking negative atmospheric temperature anomalies [Wang et al., 2010].

[3] The winter seasons of 2009/10 and early 2010/11 were also associated with extreme negative phases of the North Atlantic Oscillation [Osborn, 2011] (NAO). Winter 2009/10 coincided with the lowest NAO score (−2.54) since 1825, while December 2010 recorded the lowest (−4.62) monthly (December) score on record since 1825 (Figure S1 in the auxiliary material).1 As the annular modes of climate variability, linked to the NAO, are predicted to trend toward more positive states throughout the 21st Century [Miller et al., 2006], the cold extremes of winter 2009/10 and early winter 2010/11 provide contrary evidence for the unpredictable character of the NAO in a warming climate. Understanding the dynamics responsible for such seasonal climate anomalies is crucial for improving long-range climate prediction. Winter 2009/10 has received much attention [e.g., Jung et al., 2011 and references therein]. The focus of this study is the possible role of the ocean for the secondary extreme event of D10J11.

[4] The re-emergence mechanism [Alexander and Deser, 1995] can enhance the persistence of wintertime sea surface temperature anomalies (SSTAs) beyond traditional timescales (ranging 3–6 months) of sea surface temperature anomaly (SSTA) decay [Frankignoul and Hasselmann, 1977]. Re-emergence is the process whereby ocean temperature anomalies established over a deep winter mixed layer are sequestered beneath the seasonal thermocline in summer and reappear at the surface as the mixed layer deepens during the following winter season [Alexander and Deser, 1995]. The re-emergence of remnant winter SSTAs is important for the seasonal prediction of winter climate over the North Atlantic and Europe [Folland et al., 2006]. While the statistical signature for re-emergence [Alexander and Deser, 1995], and its ubiquity as a global, midlatitude process [Hanawa and Sugimoto, 2004] are well established, evidence for re-emergence of actual SSTA patterns, associated with regional climate variability, is somewhat tenuous. Here, we provide strong evidence for re-emergence of late-winter 2009/10 SSTAs during the subsequent early winter season of 2010/11. We propose that the re-emergence of these remnant anomalies was important for the re-establishment of a North Atlantic SSTA tripole pattern comparable to winter 2009/10, an extreme negative phase of the NAO in December 2010, and the resultant harsh wintry conditions experienced over Northern Europe during D10J11.

2. Data and Method

[5] To illustrate the winter-to-winter re-emergence of remnant North Atlantic (5°N–65°N, 80°W–10°E) SSTAs we analyze observations of surface and sub-surface temperature over the period December 2009–March 2011. We use the UK Met Office’s global ocean analysis product ENACT (ENhanced ocean data Assimilation and ClimaTe prediction), version EN3_v2a. ENACT comprises various

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0094-8276/11/2011GL048978

L20601 1 of 6
measurements of surface and sub-surface ocean temperature and salinity, quality controlled (QC) using a comprehensive set of objective procedures developed at the UK Met Office Hadley Centre [see Ingleby and Huddleston, 2007]. The QC data, whose global coverage vastly improved following the advent of the Argo program (see http://wwwargo.ucsd.edu), are subsequently assimilated onto a 1° orthogonal grid, with 42 levels in the vertical. Preliminary evaluation of ENACT suggests it compares favorably with other observational datasets, especially in regions of relatively high sampling density such as the North Atlantic (see http://www.metoffice.gov.uk/publications/HCTN/HCTN_58.pdf).

We directly track the re-emerging signal, through comparison of monthly and seasonally averaged SSTA (0–25 m), and sub-surface temperature anomaly patterns. Sub-surface temperature anomalies (T′) are associated with vertical mixing between the summer and winter mixed layer depth (MLD). The MLD is calculated using a coarse temperature difference criterion of 0.6°C to avoid shallow biases in interpolated data. Monthly temperature anomalies are computed relative to a recent (2000–10) long-term mean.

We further assess the robustness of the re-emergence episode through one-year pattern correlation analyses of North Atlantic SSTAs and T′. Correlations are made between the spatial pattern of SSTAs and T′ in March and each of the subsequent 12 months. The degrees of freedom available for significance testing account for the effects of spatial [Geary, 1954] and temporal self-correlation [Zwiers and von Storch, 1995] within the data. Results are significance tested at 90–95% confidence intervals using the two-tailed t-test.

### 3. Spatial Temperature Anomaly Patterns Over 2010/11

Here, we present strong observation-based evidence for the large-scale re-emergence of late-winter 2009/10 North Atlantic SSTAs during the following early winter season of 2010/11. Figure 1 illustrates spatial analyses of seasonal-mean SSTA and sub-surface temperature anomaly patterns over two successive winter periods, from 2009/10 to 2010/11. Both winter seasons are characterized by an SSTA tripole pattern (Figures 1a and 1e). The large-scale spatial features encompass cold anomalies (of −0.5°C to −1.5°C) in the central North Atlantic, flanked by warm anomalies (ranging 0.1°C to 1°C) to the north and south. The winter 2009/10 tripole pattern persists through spring (Figures 1b and 1g), albeit with slight modification. Specifically, the observed strengthening of positive anomalies (>1.5°C) within the tropical North Atlantic may be attributed to the remote influence of a moderate El Niño episode (see http://www.ncdc.noaa.gov/sotc/global/2010/13) prevailing within the Equatorial Pacific at the same time [Enfield and Mayer, 1997]. A pronounced increase of temperature anomalies in the Labrador basin (>1°C), and along the Gulf Stream, is also apparent at the surface and at depth.

By summer, the 2009/10 winter-forced SSTA pattern is damped, consistent with stochastic atmospheric forcing [Frankignoul and Hasselmann, 1977]. Notably, the cold tongue persisting in the northeast Atlantic (i.e., north of 40°N, east of 40°W), in spring (Figure 1b), is subsequently replaced by positive temperature anomalies (of 0.2°C to 0.6°C) extending southeastward from the Labrador Sea to Western Europe (Figure 1c). Regions of negative SSTAs (−0.5°C to −1.5°C) are still observed throughout midlatitudes, stretching east-southeastward in a narrow band toward north Africa. Further alteration of the SSTA pattern occurs during autumn (Figure 1d), creating a surface anomaly expression that is significantly different from the previous winter. Fundamentally, after two seasons, the surface ocean has lost its memory of past atmospheric forcing.

In contrast, the summer and autumn spatial patterns of T′ show strong similarity to the anomaly pictures described for winter 2009/10, throughout much of the North Atlantic (Figures 1h and 1i). The SSTA signal for winter 2009/10 persists beneath the seasonal thermocline, isolated from SSTA decay by air-sea interaction. Notwithstanding slight spatial variation and minor changes to the magnitude of the remnant T′ over the intervening summer months (averaging ±0.9°C), presumably through advection and mixing within the ocean interior, the sub-surface anomaly pattern subsequently re-emerges (during late-autumn to early winter) back into the surface layer as the mixed layer deepens into the following winter season (Figure 1j). Coincident with this re-emergence of remnant temperature anomalies back into the mixed layer, is the restoration of a SSTA tripole pattern at the surface during winter 2010/11 (Figure 1e).

The pattern of SSTAs for winter 2010/11 does not fully replicate that of the preceding 2009/10 winter. Positive SSTAs are more pronounced at high latitudes (>1.5°C within the Labrador/Irminger Sea basins), while anomalies in the tropics exhibit slight cooling (up to −1°C). Negative temperature anomalies are also stronger (by −0.5°C) in the western subtropical Atlantic (20°N–40°N, 60°W–80°W) during winter 2010/11. The remote influences of a moderate-to-strong La Niña, developing within the Equatorial Pacific during mid-2010, may have contributed toward the reduced strength of positive SSTAs apparent in the tropical Atlantic [Enfield and Mayer, 1997]. Furthermore, most of the above mentioned discrepancies originate in regions where re-emergence is less likely to operate, since the annual mixed layer cycle is too shallow [Timlin et al., 2002]. The SSTAs present in these regions will likely reflect a passive response to contemporary atmospheric forcing rather than entrainment of a sub-surface ocean signal. It is within extratropical provinces of the North Atlantic, where re-emergence typically occurs [Hanawa and Sugimoto, 2004], that the large-scale anomaly patterns bear the greatest similarity from one winter to the next.

### 4. Observed Re-emergence of Sub-surface Temperature Anomalies

Further evidence of the vertical structure, magnitude and exact timing of the re-emergence episode can be obtained through regional depth-time analyses. Figure 2 illustrates the evolution (over 0–800 m) of temperature anomalies through 2010 and into early 2011, as a spatial average throughout the extratropical northeast Atlantic (35°N–60°N, 45°W–10°E - purple box in Figure 1e), one of the regions strongly conducive to re-emergence [Timlin et al., 2002]. Negative anomalies (−0.5°C) develop within the mixed layer during February-April 2010. These anomalies are subsequently capped by a pronounced surface
warming (of 0.2°C to 0.4°C) over the summer and early autumn (May–September 2010). Conversely, beneath the seasonal thermocline (remote from air-sea interaction), the large volume of negative temperature anomalies (ranging from −0.2°C to −0.5°C) established during the recent late-winter, persists over a depth range of ∼35–370 m throughout the intermediate milder period. From October to December of 2010, negative temperature anomalies (−0.2°C to −0.3°C) are re-established at the surface. The recurrence of these cold temperature patterns appears to be linked, via re-emergence of the remnant T' preserved beneath the seasonal thermocline, to the negative SSTAs first established in late-winter of 2009/10. By January 2011, the strength of the negative SSTAs have declined (to −0.1°C to −0.2°C), reflecting integration of the remnant oceanic signal with contemporary atmospheric-driven temperature anomalies for the present (2010/11) winter season. [13] Additional depth-time analyses also reveal a re-emergence signature within the central extratropical (25°N–45°N, 65°W–30°W) North Atlantic (not shown). In this region, T' propagate downstream and re-emerge at locations remote from where they formed during the previous winter (Figures S2 and S3). This conforms with earlier work establishing an important influence from advection upon re-emerging temperature anomalies in the

Figure 1. North Atlantic SSTA and sub-surface temperature anomaly patterns for (a, f) winter (December–February) 2009/10, (b, g) spring (March–May) 2010, (c, h) summer (June–August) 2010, (d, i) autumn (September–November) 2010, and (e, j) winter 2010/11.
vicinity of the North Atlantic Current [DeCoëtlogon and Frankignoul, 2003].

5. The Statistical Signature for Re-emergence

[14] The statistical signature of re-emergence is characterized with a pattern correlation function. In Figures 3a and 3b we correlate SSTA and sub-surface temperature anomaly patterns in March 2010 with equivalent anomalies in subsequent months through March 2011. Re-emergence extends the persistence of remnant SSTAs; an e-folding timescale of 9–11 months is observed for winter 2009/10 North Atlantic SSTAs (Figure 3a), compared to the maximum 6-month memory period predicted by stochastic SSTA

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Figure 2. Evolution of temperature anomalies (contour interval of 0.1°C) and MLD (thick black line) in the northeast Atlantic from January 2010 to January 2011. The vertical axis is non-linear.

Figure 3. One-year pattern correlation function for (a) North Atlantic SSTAs and (b) North Atlantic sub-surface temperature anomalies (T'), from March 2010 to March 2011. The dot-dot-dash (dashed) black line illustrates the 95% (90%) significance level. (c) As Figure 3a for each March-to-March 12 month period ranging from 2000/01 to 2009/10 (blue lines), the annual period spanning March 2010 to March 2011 (red line), and an 11-year (2000–10) average (green line).
Figure 4. Monthly time series of the NAO index from December 2009 to March 2011. The index is based on the difference in normalized sea level pressure between Gibraltar, UK and Stykkishólmur/Reykjavík, Iceland. The green asterisks highlight the timing of the late-2010 re-emergence episode.

decay theory [Frankignoul and Hasselmann, 1977]. Initially, the SSTA pattern correlation remains high (>0.75) from March–May, signifying strong preservation of the late-winter anomaly pattern throughout spring. Thereafter, correlations decrease with further lag and become non-significant (<90%) after 4 to 5 months. The SSTA pattern correlation reaches a minimum value (0.19) in September/October 2010, prior to increasing to a secondary (significant) maximum (0.64) in the following winter (January 2011). The occurrence of this secondary maximum coincides with the re-emergence of negative temperature anomalies back into the surface mixed layer, from beneath the seasonal thermocline. In contrast, the pattern correlation function for $T'$ remains significant (>95%) throughout the 12 month analysis period (Figure 3b). A minimum coefficient (0.33 to 0.36) is obtained in November–December 2010, coincident with the re-emergence of anomalous temperature signals preserved at depth, back into the surface mixed layer, with increasing SSTA correlations observed thereafter (Figure 3a). Analogous with the surface expression, a secondary peak in the sub-surface pattern correlation (of ~0.5) is observed in January 2011, decreasing afterwards for the remainder of the winter season. Both analyses invoke a greater influence of SSTA re-emergence upon the resulting early winter climate (November–December), compared to the later half of the season (January–February). Correlations associated with the re-emerging SSTA pattern decrease over subsequent winter months due to progressive mixing (and modification) of the re-entrained temperature anomalies by air–sea interaction.

[15] Supplementary pattern correlation analyses between the $T'$ in summer (Figure 1h) and the SSTAs for the preceding (Figure 1a) and subsequent (Figure 1e) winter seasons strengthen the above assertion. Correlation values of 0.64 and 0.62 respectively demonstrate a stronger statistical relationship than the equivalent calculations (of 0.37 and 0.56) for both winter SSTA patterns and the intervening summer SSTAs (Figure 1c). The higher correlation between summer SSTAs and the surface anomaly expression for winter 2010/11 (relative to winter 2009/10) suggests a degree of persistence associated with the summer SSTAs into the following winter season, contributing (alongside re-emergence) toward the large-scale SSTA patterns observed thereafter.

[16] To further highlight the significance of the SSTA pattern correlation obtained during 2010, the corresponding signals for the years 2000–10, and the 11-year average of these individual one-year functions, are shown (Figure 3c). Notwithstanding the large interannual variability that accompanies North Atlantic climate, pattern correlation analyses for years preceding 2010 (blue lines), and the decadally-averaged signal (green line) typify stochastic SSTA decay [Frankignoul and Hasselmann, 1977]. Correlations decrease continuously toward near-zero values with increasing time lag. In contrast, the result for 2010 (red line) is significantly different from the overall mean (green line), particularly over the later months (December–March). The secondary peak in correlation apparent in late 2010 is not observed in previous years, suggesting that 2010 provides a relatively unique occurrence (since 2000) for winter-to-winter re-emergence of North Atlantic SSTAs.

6. Anticipated Effects of Re-emergence on the Winter Atmospheric Circulation

[17] In the present study, we reveal strong evidence for the re-emergence of SSTAs established in late-winter 2009/10 during the following October to December, throughout most of the extratropical North Atlantic. The 2010 re-emergence was proceeded by the recurrence of extreme winter weather over Northern Europe during DJ10J11. Although other factors controlling the early 2010/11 winter atmospheric circulation, such as changes in sea-ice concentration [Petoukhov and Semenov, 2010], soil moisture memory [Koster et al., 2000], ENSO and stratospheric dynamics [Ineson and Scaife, 2009], anomalous autumnal snow cover over Eurasia [Cohen et al., 2010], and direct radiative forcing effects [Jung et al., 2011], cannot be neglected, an active influence of the ocean, through the re-emergence of remnant (winter 2009/10) SSTAs, may also be important.

[18] Re-emerging temperature anomalies can contribute toward the winter-to-winter persistence of the same SSTA tripole pattern within the North Atlantic, as vertical mixing re-entains well-preserved sub-thermocline anomaly patterns back into a deepening winter mixed layer [Watanabe and Kimoto, 2000; Timlin et al., 2002]. The resulting tripole signal may then project upon the overlying atmospheric circulation (i.e., 500 hPa geopotential height variability) via transient eddy fluxes, reinstating the previous winter’s phase of the NAO [Rodwell and Folland, 2002]. This concept is supported through the model-based experiments of Cassou et al. [2007], who directly quantified a significant winter atmospheric response to re-emerging remnant ocean temperature anomalies in the North Atlantic. Further evidence is acquired from the time series of the monthly NAO index between December 2009 and March 2011 illustrated in Figure 4. NAO indices portrayed a decrease back to negative values (of ~2.01 to ~2.38), in August/September 2010, following a period of gradual increase (to a positive score of 0.06) during the previous February to July. The re-emergence of previous (2009/10) winter SSTAs (from October to December) may have facilitated the move toward more extreme negative NAO values (~2.41 to ~4.62) over the
later quartile of the 2010 calendar year. Thus, it is unlikely that re-emergence triggered the initial switch back to a negative NAO environment throughout the North Atlantic; however its occurrence may have provided a stimulus for a more extreme atmospheric response. The harsh weather patterns experienced over northern Europe in D10J11 were in turn associated with the NAO in an extreme negative phase [Visbeck et al., 2001].

[19] Future work should quantitatively investigate the direct influence of the re-emerging temperature anomalies on the early 2010/11 winter atmospheric circulation response. It would also be also be worthwhile, from a dynamical perspective, to investigate (and understand) the key processes responsible for the remarkable transition toward a warmer winter climate regime over the second half of the 2010/11 winter season. The remarkable events of winter 2009/10 and 2010/11 further emphasize the challenges for climate research to improve the quality (and societal perception) of long-range seasonal forecasts.

[20] Acknowledgments. We thank the UK Met Office for access to the ENACT dataset, and Tim Osborn (University of East Anglia) for the NAO index data. Sarah Taws was funded by a NERC Quota Studentship, the ENACT dataset, and Tim Osborn (University of East Anglia) for the

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