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Influence of Arctic sea ice on European summer precipitation

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Abstract
The six summers from 2007 to 2012 were all wetter than average over northern Europe. Although none of these individual events are unprecedented in historical records, the sequence of six consecutive wet summers is extraordinary. Composite analysis reveals that observed wet summer months in northern Europe tend to occur when the jet stream is displaced to the south of its climatological position, whereas dry summer months tend to occur when the jet stream is located further north. Highly similar mechanisms are shown to drive simulated precipitation anomalies in an atmospheric model. The model is used to explore the influence of Arctic sea ice on European summer climate, by prescribing different sea ice conditions, but holding other forcings constant. In the simulations, Arctic sea ice loss induces a southward shift of the summer jet stream over Europe and increased northern European precipitation. The simulated precipitation response is relatively small compared to year-to-year variability, but is statistically significant and closely resembles the spatial pattern of precipitation anomalies in recent summers. The results suggest a causal link between observed sea ice anomalies, large-scale atmospheric circulation and increased summer rainfall over northern Europe. Thus, diminished Arctic sea ice may have been a contributing driver of recent wet summers.

Keywords: Arctic sea ice, European climate, Arctic—mid-latitude linkages, precipitation, jet stream, stationary wave

S Online supplementary data available from stacks.iop.org/ERL/8/044015/mmedia

1. Introduction

Northern Europe has experienced a run of wet summers in recent years (figure 1(a)), and repeated occurrences of flooding (e.g. Blackburn *et al* 2008). The six summers (defined here and subsequently as June–July–August, unless stated otherwise) from 2007 to 2012 were all wetter than average (based on anomalies from the 1981–2010 mean). This sequence of six consecutive wet summers is unprecedented over the 34-year period 1979–2012. Summer 2007 was the wettest over northern Europe in this period, and summer 2011 and 2012 were the fifth and sixth wettest, respectively. Positive precipitation anomalies over northern Europe in recent summers have been in contrast to negative precipitation anomalies over Mediterranean Europe and northwest Scandinavia (inset, figure 1(a)).

The long record of precipitation for England and Wales (figure 1(b)) helps place these recent anomalies over northern Europe in a historical context. For England and Wales, summer 2012 was the wettest, and summer 2007 the second wettest, since 1912. The six summers from 2007 to 2012 were all wetter than average, which is the only such sequence of six consecutive wet summers in the record back to 1900, although wet summers also frequently occurred in the late 1950s and late 1920s. The 5-year mean precipitation for 2008–2012 is the highest observed over the 113-year period, and the

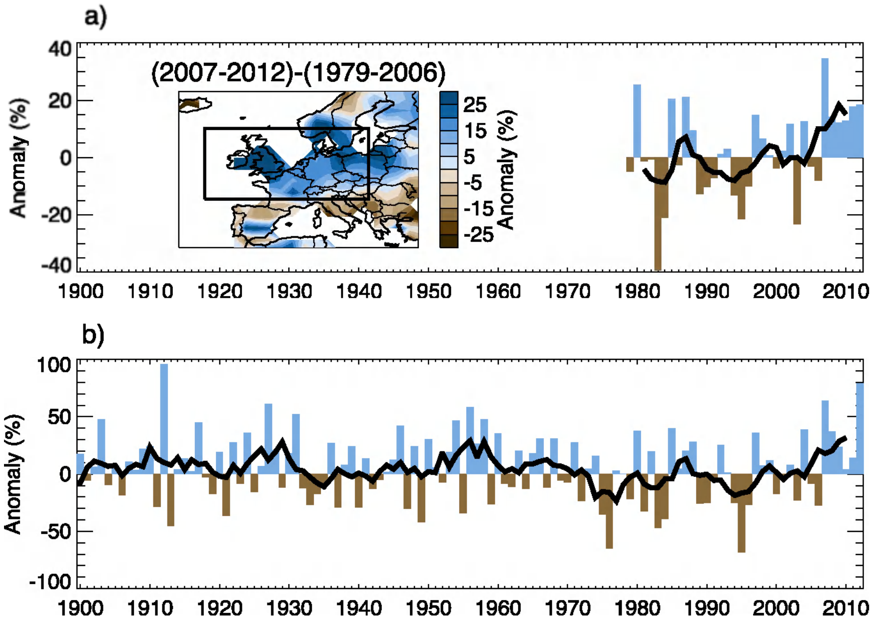

Figure 1. (a) Time-series of observed summer (June–July–August) precipitation anomalies (% from 1981 to 2010 average) averaged over northern Europe (15°W–20°E, 45–60°N; shown by black box on inset map). The inset map shows the precipitation anomalies in the period 2007–2012 relative to the period 1979–2006. (b) Time-series of summer precipitation anomalies (% from 1981 to 2010 average) for England and Wales. The black curves show 5-year running means.

5-year mean for 2007–2011 is the third highest (1956–1960 is the second highest). Thus, although the recent precipitation anomalies are not without precedent, the recent sequence of consecutive wet summers is extraordinary. An important open question for scientists and decision makers is whether there are climate forcings, either natural or anthropogenic, that are increasing the chances of such events.

Several factors are known to influence European summer precipitation on a wide range of timescales. The summer North Atlantic Oscillation (sNAO), a fluctuation in atmospheric pressure over the North Atlantic, is the principal pattern of interannual atmospheric variability over the North Atlantic-European sector (Folland *et al* 2009). The sNAO exerts a strong influence on northern European rainfall, temperature and cloudiness through changes in the position of the North Atlantic storm track. The positive phase of the sNAO, with a northward shifted storm track, favours drier than average summers over northern Europe and vice versa (Folland *et al* 2009). On decadal to multidecadal timescales, the Atlantic Multidecadal Oscillation (AMO), principally a fluctuation of the North Atlantic sea surface temperature (SST) field, modulates European summer climate (Sutton and Hodson 2005, Knight *et al* 2006, Sutton and Dong 2012). The AMO has been in its warm phase since approximately 1996, with anomalously warm SST in the North Atlantic, which tend to favour wetter than average summers over northern Europe. Between mid-1960s and mid-1990s the AMO was in its cold phase, with anomalously cool North Atlantic SST, favouring drier than average summers over northern Europe. The AMO and sNAO may not be independent, with negative sNAO events more common during the warm phase of the AMO (Folland *et al* 2009).

Another potential driver is the dramatic recent loss of Arctic sea ice (Stroeve *et al* 2011, 2012), which may impact upon mid-latitude weather and climate (Liu *et al* 2012, Petoukhov and Semenov 2010, Overland *et al* 2011, Francis and Vavrus 2012, Screen and Simmonds 2013). Significant declines in sea ice extent have been observed in all months over the satellite era (Stroeve *et al* 2011, 2012). The ice cover has also become thinner (Kwok and Rothrock 2009). Although Arctic sea ice has been in decline for at least three decades, the trends have accelerated in the last decade or so (Comiso *et al* 2008, Comiso 2012). It has been argued that the reduction of Arctic sea ice has become large enough to have an observable impact on the large-scale atmospheric circulation (Francis *et al* 2009, Overland and Wang 2010, Overland *et al* 2011, Francis and Vavrus 2012, Jaiser *et al* 2012). There is a large body of modelling evidence that suggests that Arctic sea ice anomalies influence northern hemisphere atmospheric circulation and weather patterns (Balmaseda *et al* 2010, Strey *et al* 2010, Blüthgen *et al* 2012, Orsolini *et al* 2012, Porter *et al* 2012, Cassano *et al* 2013, Rinke *et al* 2013, Screen *et al* 2013a, 2013b), but there is considerable disagreement between studies as to the sign, spatial extent, timing and magnitude of the impacts, especially in mid-latitudes.

Several studies have suggested that autumn–winter Arctic sea ice anomalies impact winter climate over northern continents (Overland *et al* 2011, Liu *et al* 2012, Tang *et al* 2013). In particular, reduced sea ice in the Barents and Kara Seas is understood to be a driver of extreme cold events over Eurasia (Honda *et al* 2009, Petoukhov and Semenov 2010, Inoue *et al* 2012, Yang and Christensen 2012). Outten and Esau (2012) argue that decreasing Kara Sea ice has been a contributing driver of winter cooling trends across mid-latitude Eurasia from 1989 to 2009. Lim *et al* (2012) show that prescribing realistic Arctic sea ice conditions in an atmospheric model leads to more realistic simulations of winter Eurasian temperature variability, compared to simulations in which climatological sea ice conditions are prescribed.

The potential influence of sea ice anomalies on summer European climate is poorly understood. Overland *et al* (2012) connect recent wet summers in the United Kingdom (UK) to a shift in the early-summer atmospheric circulation since 2007. Specifically, they identify increased ridging over Greenland and an enhanced southward meander in the jet stream leeward of Greenland. Overland *et al* (2012) speculate that this anomalous flow pattern may be driven by reduced spring snow cover over North America and decreased Hudson Bay sea ice, but provide no empirical evidence to support this hypothesis. Wu *et al* (2013) demonstrate significant correlation between winter–spring sea ice anomalies west of Greenland (including the Labrador Sea, Davis Strait, Hudson Bay, Baffin Bay) and Eurasian precipitation anomalies in the following summer. These authors show that decreased winter–spring sea ice is statistically linked to increased summer precipitation over northwest Europe, but are unable to prove causality. This study addresses the question: is it a coincidence that the recent apparent shift towards wet northern European summers has occurred at a time of rapid sea ice loss, or is the reduction of Arctic sea ice exerting an influence on European summer climate?

2. Data and methods

Precipitation observations are derived from two sources: the Global Precipitation Climatology Project (GPCP) data set version 2.2 (Adler *et al* 2003) and the UK Met Office Hadley Centre England and Wales precipitation (HadEWP) data set (Alexander and Jones 2001). The GPCP data set is derived from a combination of *in situ* gauge measurements and satellite observations, and has near-global coverage over the period from 1979 to 2012. HadEWP is based solely on gauge measurements from a network of stations in England and Wales. HadEWP is a single time-series (not a gridded product) covering the period from 1766 to 2012. This study uses data from 1900 to 2012. 300 hPa zonal and meridional winds from the ERA-Interim reanalysis (Dee *et al* 2011), available for the period 1979–2012, are used to diagnose the mean position of the jet stream. Since the reanalysis is constrained by observations, it is considered to provide a realistic depiction of jet stream variability and is used to validate the model output.

Model output is from the UK Met Office Unified Model (Martin *et al* 2011), which is the atmospheric component of the HadGEM and ACCESS coupled models that participated in the fifth Coupled Model Intercomparison Project (CMIP5). This study uses Unified Model version 7.3, which has been previously used to study the atmospheric response to Arctic sea ice loss (Screen *et al* 2012, 2013a, 2013b). Two simulations are analysed, referred to hereafter as the *low ice* and *high ice* runs. In both simulations, the model was prescribed with annually repeating monthly cycles of sea ice concentrations (SICs) and SSTs as boundary conditions. Monthly-mean SICs and SSTs were taken from the Hurrell *et al* (2008) data set, updated to 2009, which is derived from a combination of *in situ* and remotely-sensed observations. All external forcings were held constant. In the *high ice* run, Arctic SICs were representative of observed conditions in 1979. In the *low ice* run, Arctic SICs were representative of observed conditions in 2009. In both runs, SSTs (and Antarctic SICs) were held constant at climatological (1979–2009) values, with the exception of grid-boxes where the SIC differed between the *low ice* and *high ice* runs. In these grid-boxes, SSTs were prescribed in the same manner as SICs (i.e., SSTs representative of observed conditions in 1979 in the *high ice* run, or 2009 in the *low ice* run). This approach captures SST changes directly related to SIC changes, but does not include SST changes outside the sea ice zone (see Screen *et al* 2013a, 2013b for further details and justification). The seasonal-mean SICs in the *low ice* and *high ice* runs, and their differences, are shown in figure 2. In winter and spring, the largest SIC differences are in the Sea of Okhotsk, Hudson Bay, Labrador Sea and Barents Sea. In summer and autumn, they are in the Beaufort, Chukchi, East Siberian and Kara Seas. By design, these differences closely resemble the observed trends in SICs over the period 1979–2009.

Both the *high ice* and *low ice* simulations have been run for 100 years. Since the prescribed surface forcing repeats annually, but the atmospheric initial conditions vary, each year is considered to be an independent ensemble member (atmospheric 'memory' is negligible from year-to-year). Screen *et al* (2013a) showed that a large ensemble (50–60 members or larger) is required to detect the mid-latitude response to Arctic sea ice loss, but that uncertainty due to internal atmospheric variability only marginally decreases as the ensemble is increased beyond around 80 ensemble members. Thus, an ensemble size of 100 is deemed appropriate for this study. The response to Arctic sea ice change is obtained by differencing ensemble means from the *low ice* and *high ice* simulations (*low ice* minus *high ice*). Differences are tested for statistical significance using a two-tailed Student t-test.

3. Results

3.1. Jet stream variability and precipitation

Northern European (defined as 15°W–20°E, 45–60°N) precipitation (NEP) is strongly influenced by the position of the polar jet stream. Figure 3(a) shows 300 hPa zonal winds averaged across the 10% wettest summer months in northern Europe. The composite was formed by considering monthly-mean anomalies for May to August and selecting the 10% of cases ($n = 12$) with largest positive precipitation anomalies, averaged over the region (land grid-boxes only). These are, in order of decreasing NEP: May 1983, July 1988, July 2007, August 1982, June 1980, August 2006, July 2009, May 2007, June 1987, June 2007, August 2010 and August 1992. Wet summer months in northern Europe tend to occur when the jet stream lies over this region (figure 3(a)). Cyclonic systems crossing the Atlantic Ocean are steered by these upper levels winds and when the jet stream is located

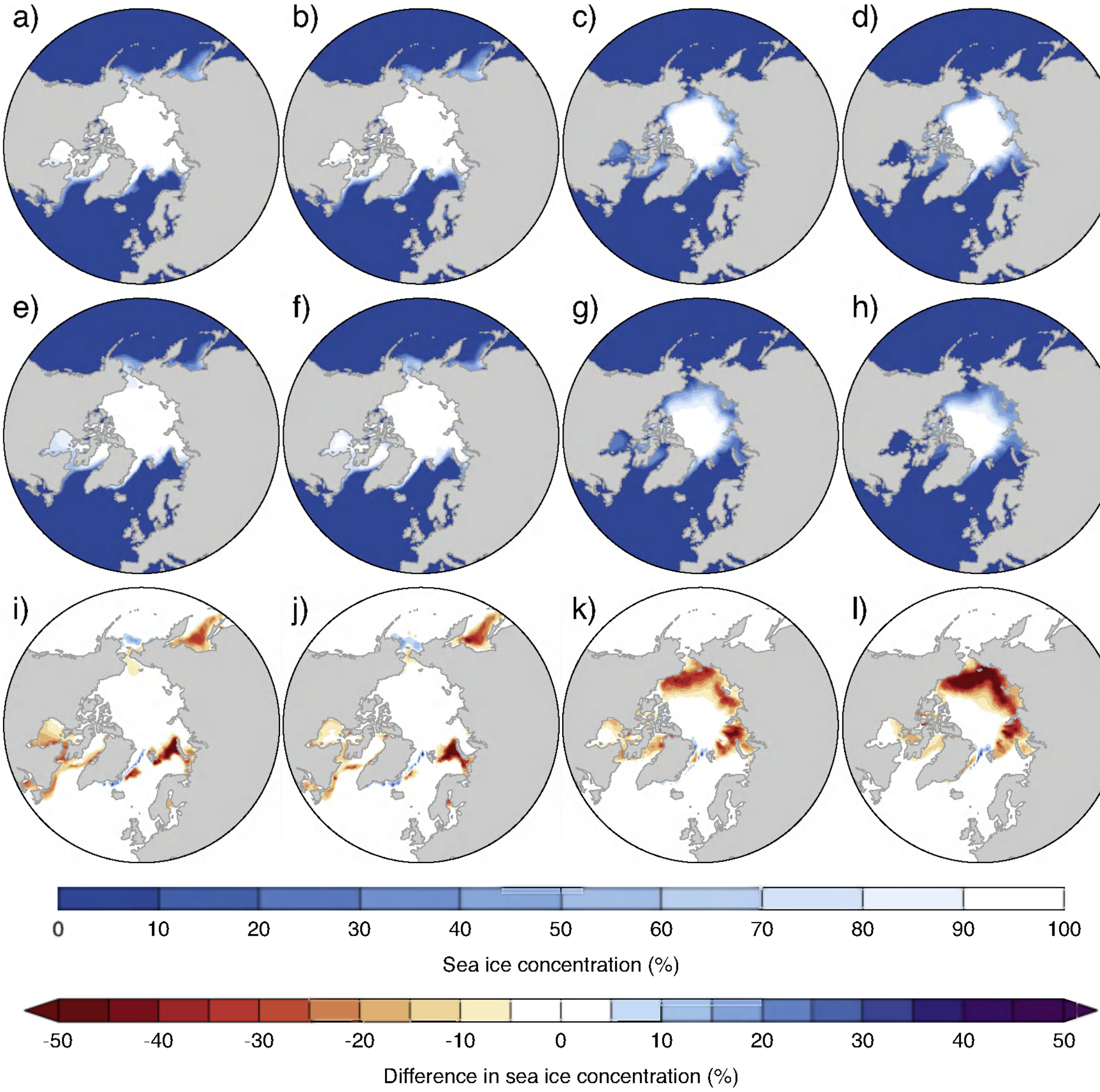

Figure 2. (a)–(d) Sea ice concentrations (%) in the *high ice* run for winter (December–January–February), spring (March–April–May), summer (June–July–August) and autumn (September–October–November), respectively. (e)–(h) As (a)–(d), but for the *low ice* run. (i)–(l) Sea ice concentration differences (%) between the *low ice* and *high ice* runs (*low ice* minus *high ice*) for the four seasons, respectively. Note the inverse colour scale.

over northern Europe, more storms track over the region bringing increased NEP. Conversely during the 10% driest summer months (defined as above but for the largest negative precipitation anomalies; July 1983, August 2003, May 1989, August 1995, June 2006, May 1990, July 2006, August 1991, August 1983, June 1996, May 1998 and May 1980), the jet stream is found in a more northerly location, tracking between Scotland and Iceland (figure 3(b)). This configuration of the jet stream steers storms away from northern Europe and is associated with reduced summer NEP. The link between summer NEP and location of the jet stream, often described in terms of the sNAO, is well known (e.g., Folland *et al* 2009).

A similar association between NEP and the jet stream is found in the model and can be seen by comparing the 300 hPa zonal winds during the 10% ($n = 40$) simulated wettest summer months over northern Europe (figure 3(c)) and the 10% simulated driest summer months (figure 3(d)). Here output from the *high ice* run is shown, but almost identical results are found using the *low ice* run (supplementary figure 1, available at stacks.iop.org/ERL/8/044015/mmedia). Thus, in both the observations and model, there is a southward shift of the jet stream over Europe in wet summer months compared to dry summer months (figures 3(e) and (f)). The good agreement between observations and simulations provides confidence that the main processes driving observed NEP variability are faithfully reproduced in the model.

The southward shift of the jet stream over Europe, in wet summer months compared to dry summer months, is part of a large-scale wave disturbance in mid-latitudes, which is clearly manifest in the 300 hPa meridional winds (figure 4(a)). Anomalous southward transport (negative anomalies as the meridional wind is defined as positive in the northward direction) is found over the central Pacific, western North America and east Atlantic, with anomalous northward transport over the eastern Pacific, eastern North America and Eastern Europe. This anomalous wave pattern, in wet summer months compared to dry summer months, is also identified in the model (figure 4(b)), albeit with some minor

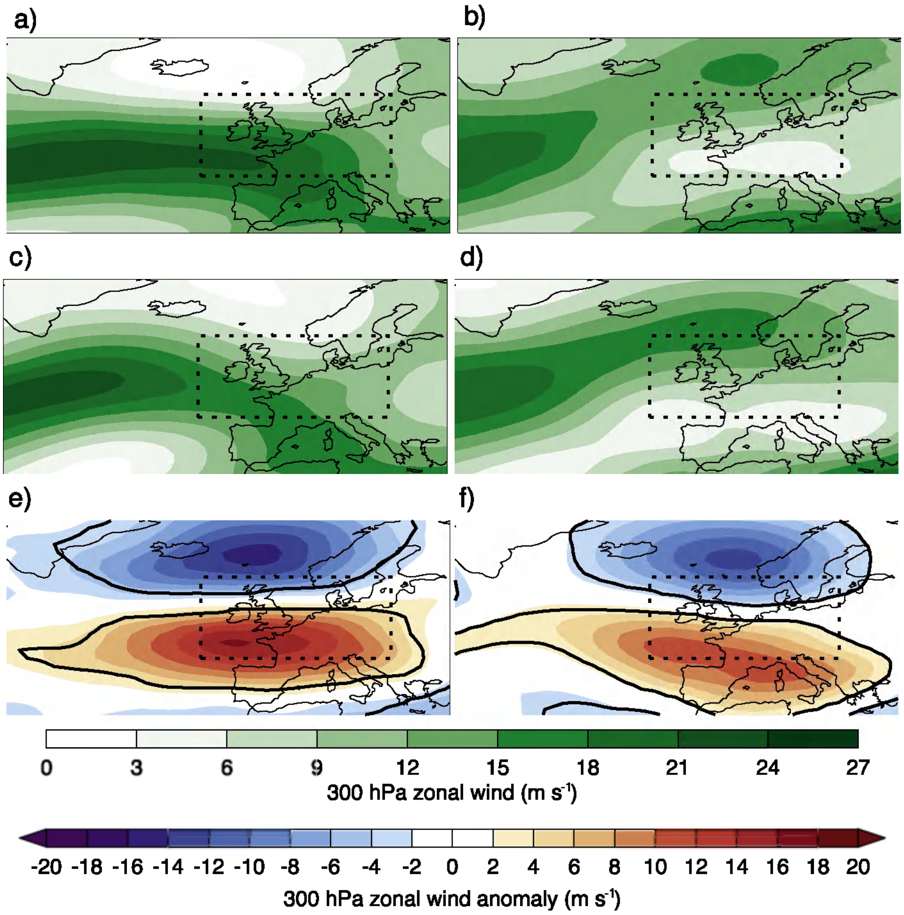

Figure 3. (a) Observed 300 hPa zonal wind (m s^{-1}) averaged over the 10% wettest summer months over northern Europe (15°W–20°E, 45–60°N; shown by dashed box). (b) As (a), but for the 10% driest summer months over northern Europe. ((c), (d)) As ((a), (b)), but for the simulations. ((e), (f)) Differences between (a) and (b), and between (c) and (d), respectively. Black contours show the $p = 0.1$ statistical significance level.

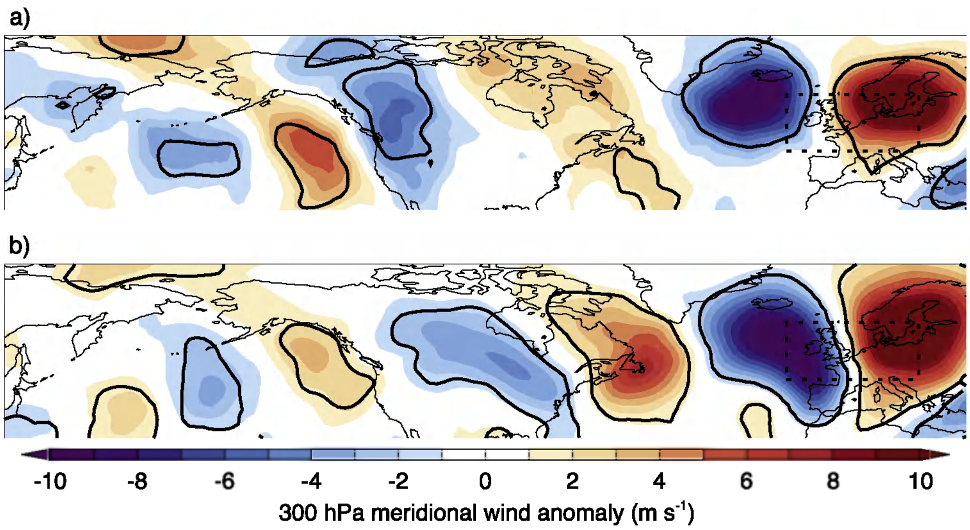

Figure 4. (a) Observed 300 hPa meridional wind anomalies (m s^{-1}) during the 10% wettest summer months over northern Europe (15°W–20°E, 45–60°N; shown by dashed box) relative to the 10% driest summer months over northern Europe. The black contours show the $p = 0.1$ statistical significance level. (b) As (a), but for the simulations.

differences. Thus in both the observations and model, summer NEP anomalies appear to be associated with large-scale disturbances in the mid-latitude jet stream that are strongest in, but are not confined to, the Atlantic-European sector.

3.2. Influence of Arctic sea ice loss

Figure 5(a) shows the differences in May–June 300 hPa zonal wind between the *low ice* and *high ice* runs. In

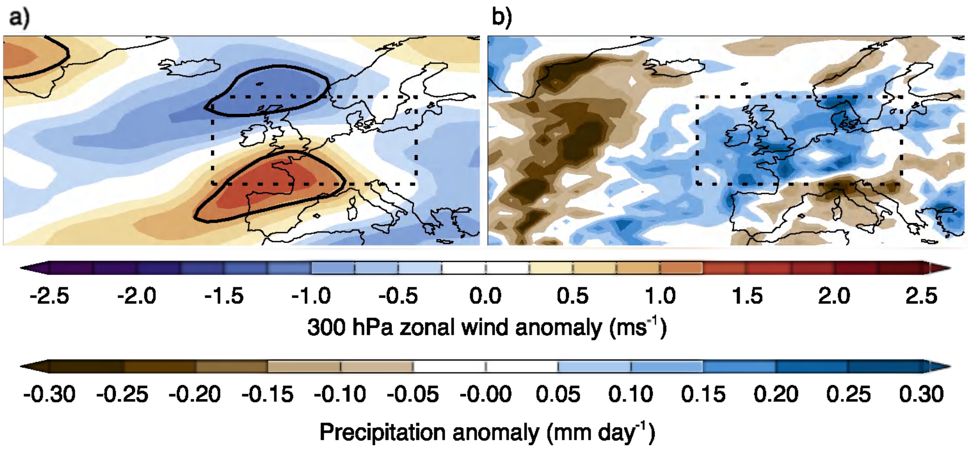

Figure 5. (a) Simulated May–June 300 hPa zonal wind anomalies (m s^{-1}) in the *low ice* run relative to the *high ice* run. The black contours show the $p = 0.1$ statistical significance level. (b) As (a), but for precipitation anomalies (mm d^{-1}). For clarity, local statistical significance is not plotted in (b), but the precipitation anomaly averaged over northern Europe (15°W–20°E, 45–60°N; shown by dashed box) is statistically significant at the $p = 0.1$ (and $p = 0.05$) level.

the simulations, Arctic sea ice loss causes a southward shift in the mean location of the jet stream over Europe. Associated with this southward shift of the jet stream, the simulations show increased NEP (figure 5(b)). The simulated precipitation anomalies in response to sea ice loss display a very similar spatial pattern to the observed anomalies in recent summers (cf figures 5(b) and 1(a)), with increased precipitation over northern Europe but decreased precipitation over Mediterranean Europe and northwest Scandinavia. This suggests a contributing role for Arctic sea ice loss in driving recent NEP anomalies, at least in early summer. The simulated precipitation anomalies also bear close resemblance to those associated with the warm phase of the AMO (Sutton and Dong 2012). It has been argued that a portion of the observed Arctic sea ice decline is attributable to the shift in the AMO towards its warm phase since the mid-1990s (Day *et al* 2012). Thus, changes in the AMO, sea ice and NEP may be interconnected. Simulated 300 hPa zonal wind and precipitation responses to Arctic sea ice loss in July–August are different to those in May–June. In July–August, a southward shift of jet stream is simulated farther east and is associated with increased precipitation over central Eastern Europe (supplementary figure 2, available at stacks.iop.org/ERL/8/044015/mmedia). The simulated July–August precipitation response bears weaker resemblance to the observed anomalies than does the simulated May–June response. However, a statistically significant increase in NEP is simulated in both May–June and July–August.

The simulated May–June 300 hPa meridional wind response (figure 6(a)), *low ice* minus *high ice*, displays a wave-train structure, with anomalous southward transport over the central Pacific, central North America and east Atlantic, and anomalous northward transport over the eastern Pacific, eastern North America and eastern Europe. This wave train closely resembles the anomalies identified previously during wet summer months in northern Europe (figure 4). Thus, the large-scale atmospheric circulation anomalies associated with increased May–June NEP in response to Arctic sea ice loss appear to be similar to those that drive month-to-month variability in summer NEP.

At the surface, the simulations show reduced sea level pressure (SLP) along the north Pacific storm track, elevated SLP over central north America, reduced SLP over eastern North America, increased SLP over the north Atlantic and lowered SLP over Europe (figure 6(b)). The low-pressure anomaly over northern Europe likely reflects more storms tracking over this region, and it is this increase in storms that leads to enhanced NEP. The spatial extent of the simulated precipitation increases closely matches the region of statistically significant SLP decreases (cf figures 5(b) and 6(b)). It is worth noting that the simulations show enhanced ridging over the north Atlantic and Greenland, which suggests a role for sea ice loss in driving recent increases in Greenland blocking during June (Hanna *et al* 2012, 2013). In turn, Greenland blocking is known to induce downstream summer NEP anomalies. However, further work is required to elucidate possible links between sea ice loss and Greenland blocking. This simulated wave-train response in mid-latitudes is manifest throughout the troposphere (figure 6(c)) and there is evidence of a westward tilt with altitude, which is characteristic of extratropical stationary waves (Holton 2004). The mid-latitude stationary wave response from the Pacific to Europe is not simulated in July–August (supplementary figure 3, available at stacks.iop.org/ERL/8/044015/mmedia). Instead, the simulated July–August response is confined to eastern Europe and the Pacific.

3.3. Possible mechanisms

An interesting feature in figure 6(b) is the reduction of SLP in the north Pacific, suggesting a strengthened Pacific storm track. Whilst in reality the Pacific storm track is influenced by multiple drivers, including the Pacific Decadal Oscillation, the strengthening of the storm track in these simulations can be attributed to sea ice alone. Previous studies have shown that sea ice anomalies in the Sea of Okhotsk affect cyclogenesis in this region, and have a downstream effect on the Pacific

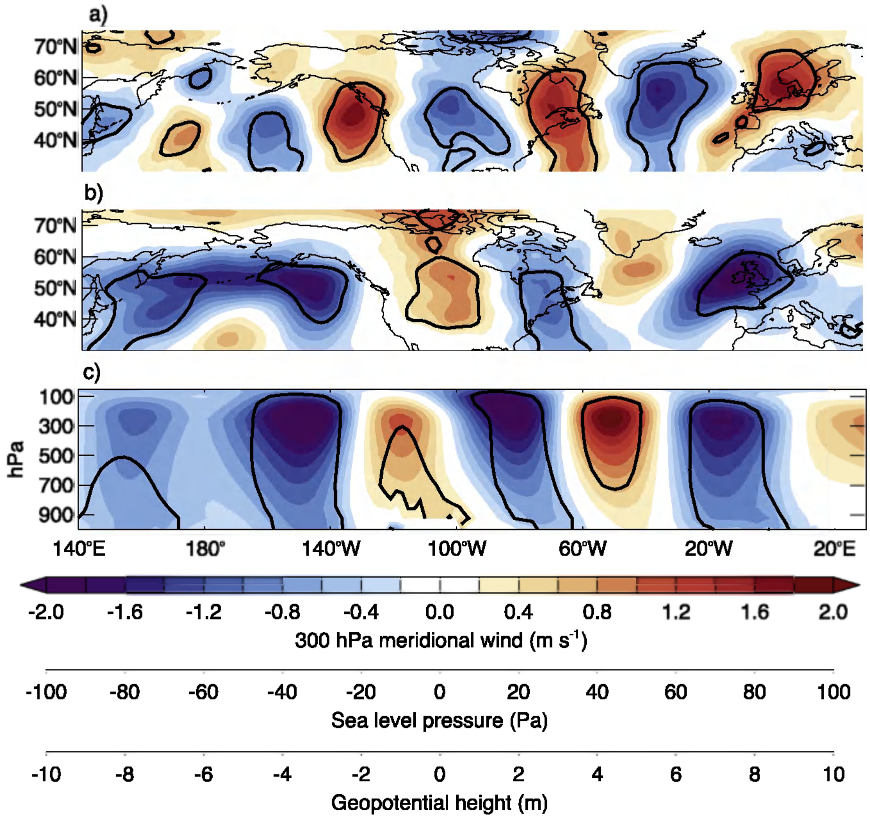

Figure 6. (a) Simulated May–June 300 hPa meridional wind anomalies (m s^{-1}) in the *low ice* run relative to the *high ice* run. The black contours show the $p = 0.1$ statistical significance level. (b) As (a), but for sea level pressure anomalies (Pa). (c) Altitude–longitude cross-section of simulated May–June geopotential height anomalies (m), in the *low ice* run relative to the *high ice* run, averaged over latitudes 30–65°N.

storm track and Aleutian Low. Mesquita *et al* (2011) show that above-average ice cover suppresses cyclogenesis and weakens the Pacific storm track, and vice versa. In the *low ice* simulation, reduced winter and spring SICs in the Sea of Okhotsk (relative to the *high ice* run; figure 2) may increase cyclogenesis and therefore, strengthen the Pacific storm track. Indeed, simulated SLP shows increased variance on timescales of 1–10 days over the Sea of Okhotsk and north Pacific, supporting the notion of enhanced storm activity (supplementary figure 4, available at stacks.iop.org/ERL/8/044015/mmedia). Honda *et al* (1996, 1999) present idealized model simulations to demonstrate that sea ice anomalies in the Sea of Okhotsk induce a stationary wave-train response with downstream effects in the Atlantic-European sector. Other authors have shown that sea ice anomalies in proximity to the climatological storm tracks and their associated baroclinic zones (as is the case for the Sea of Okhotsk) are more effective at influencing the mid-latitude jet stream, than are sea ice anomalies distant from the climatological storm track (e.g. Kidson *et al* 2011). Thus, prescribed losses of ice in the Sea of Okhotsk may be partially responsible for driving the wave-train response seen in figure 6.

Prescribed losses of sea ice in Hudson Bay and the Labrador Sea may also be a factor in driving the simulated NEP response. Using reanalysis data, Wu *et al* (2013) show that reduced winter–spring sea ice in these regions is correlated with an anomalous atmospheric wave train in the following summer. This mid-latitude wave train shares many common features with that shown in this study (figure 6), including reduced geopotential heights over Europe and increased NEP. Wu *et al* (2013) propose that spring sea ice anomalies averaged over an area encompassing Hudson Bay, the Labrador Sea, Davis Strait and Baffin Bay, is a potential precursor for summer atmospheric circulation patterns and corresponding rainfall anomalies over Eurasia.

Sea ice is also reduced in the Barents Sea in the *low ice* versus *high ice* run (figure 2). Reduced autumn and/or winter sea ice in the Barents Sea has been shown to strengthen the Siberian High and drive cold winters over Eurasia (Honda *et al* 2009, Petoukhov and Semenov 2010, Inoue *et al* 2012, Zhang *et al* 2012, Lim *et al* 2012, Tang *et al* 2013). However, it is unclear what influence Barents Sea ice has on summer European climate.

Sea ice conditions vary in all seasons and in many geographical regions between the *low ice* and *high ice* runs (figure 2). From these simulations alone, it is impossible to confidently attribute the NEP response to sea ice changes in any specific location (and/or season). Indeed, the simulated NEP changes may be an integrated (and potentially non-linear) combination of responses to sea ice anomalies in multiple locations (and/or seasons). Future work will investigate whether summer NEP is especially sensitive, or insensitive, to sea ice anomalies in specific ocean regions and seasons.

4. Discussion and conclusions

This study has provided evidence of a causal link between observed Arctic sea ice changes, the large-scale atmospheric circulation and increased summer NEP. The simulated NEP response is relatively small compared to simulated year-to-year variability. For example, the difference (*low ice* minus *high ice*) in summer NEP is 0.12 mm d^{-1} compared to a standard deviation of 0.47 mm d^{-1} (*high ice*). This means that whilst low sea ice coverage increases the risk of wet summers, other factors can easily negate this influence and lead to dry summers during depleted ice conditions, or wet summers during extensive ice conditions. This is consistent with the broader view that mid-latitude responses to past Arctic sea ice loss are, in general, small compared to internal variability (Hopsch *et al* 2012, Screen *et al* 2013a, 2013b). However, the simulated summer NEP response is statistically significant ($p = 0.05$) in the large ensemble presented here. The simulated response equates to a 4% increase in summer NEP relative to the observed climatology. By comparison, the observed (linear) change in NEP from 1979 to 2009 is 11% (recall that the prescribed forcing is representative of sea ice trends over this period). Thus, based on the magnitude of the NEP response in these simulations, observed sea ice trends could explain approximately one third of the observed trend in summer NEP from 1979 to 2009.

It is worth noting that these simulations should not be expected to mimic reality, for a number of reasons. Firstly, many factors other than sea ice are known to influence summer NEP, for example Atlantic Ocean SSTs (e.g., the AMO; Sutton and Hodson 2005, Knight *et al* 2006, Sutton and Dong 2012) and the El Niño–Southern Oscillation (Folland *et al* 2009), which are not accounted for in the simulations. Secondly, the observed NEP changes may be partly related to internal atmospheric variability and not to any particular forcing. Thirdly, the simulated NEP response may be underestimated due to the lack of ocean feedback. For example, stationary waves may be reinforced by SST anomalies, which are induced by the wave train itself (Honda *et al* 1996, Wu *et al* 2013). Lastly, there may be deficiencies in the model physics. The evidence presented is drawn from a single model and it remains to be seen if other models show similar linkages. Nevertheless, the results suggest that Arctic sea ice changes exert an influence on NEP and thus, large observed reductions in Arctic sea ice may have been a contributing factor to recent summer precipitation anomalies.

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