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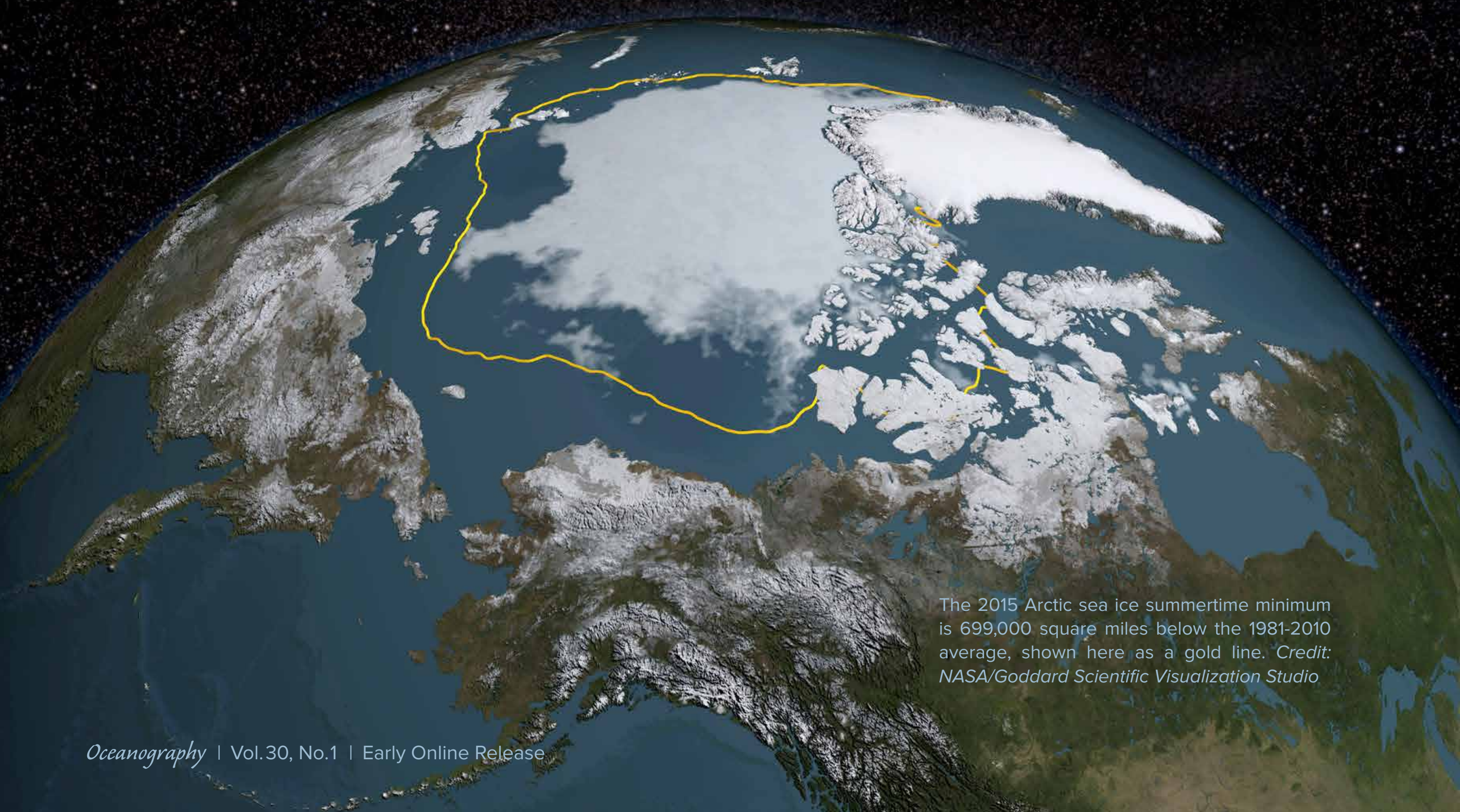
Winter 2015/16

A Turning Point in ENSO-Based Seasonal Forecasts

Winter 2015/16 is likely an inflection point in seasonal forecasting, transitioning from a reliance primarily on tropical ocean variability to also including effects of Arctic Ocean variability.

By Judah Cohen, Karl Pfeiffer, and Jennifer Francis

ABSTRACT. The ocean-atmosphere coupled mode known as the El Niño-Southern Oscillation is considered the dominant mode of global climate variability and is the cornerstone of operational seasonal climate forecasts issued worldwide. Producing accurate seasonal forecasts remains a challenge, but with a record-strong El Niño in the fall and winter of 2015/16, winter seasonal predictions should have been afforded a rare opportunity to showcase forecast accuracy, especially across the North American continent. However, winter 2015/16 forecasts are not noteworthy for their success but rather for their flaws. The inability of the global climate models to predict large-scale climate anomalies likely results from the models' over-sensitivity to tropical forcing. We argue that Arctic influences were also important in causing the observed weather patterns of winter 2015/16, in particular, diminished Arctic sea ice cover, extreme warm Arctic temperatures, and extensive Siberian snow cover. The weak response of the models to Arctic forcing contributed to seasonal forecast errors. To improve seasonal climate forecasts, we recommend complementing the influence of the tropical ocean with contributions from Arctic factors.



The 2015 Arctic sea ice summertime minimum is 699,000 square miles below the 1981-2010 average, shown here as a gold line. *Credit: NASA/Goddard Scientific Visualization Studio*

INTRODUCTION

Sea surface temperatures (SSTs) in the equatorial eastern Pacific generally oscillate between warm and cold phases every two to five years, a phenomenon known as the El Niño-Southern Oscillation (ENSO). The warm phase is known as El Niño and the cold phase as La Niña. Temperature swings in SSTs initiate changes in the overlying tropical atmosphere that influence weather patterns around the globe. ENSO is considered the dominant mode of variability in the global climate system and is universally considered the most influential factor in year-round seasonal climate predictions (Barnston et al., 2012; Hoskins, 2013; Scaife et al., 2014). Predictions based on the record-strong El Niño of 1997/98 resulted in one of the most accurate seasonal forecasts to date, and those predictions are considered a major success story (Barnston et al., 1999; Simon et al., 1999). Climate models have also performed well recently in correctly predicting the streak of record warm global temperatures (Met Office, 2015). So, when statistical and dynamical models predicted that the positive phase of ENSO (El Niño) would reach a near-record high as early as spring 2015, it seemed like another opportunity to produce stellar seasonal forecasts, even at long lead times.

Starting as early as spring 2014, the climate community was anticipating a strong El Niño event based on observations and coupled model forecasts, and the event did finally materialize in the fall and winter of 2015/16. The Niño 3.4 index (the average sea surface temperature in a region along the equator in the Central Pacific) set a new record high temperature of 29.60°C in November 2015, followed by a winter of record-warm months in that region. The El Niño of winter 2015/16 was by all metrics one of the strongest ever observed, along with the events of 1982/83 and 1997/98. The impacts of El Niño on the Northern Hemisphere extratropics are typically strongest across North America (Ropelewski and Halpert, 1987, 1989). Temperatures in the southeastern United States are usually below normal, and temperatures in the northwestern United States, western Canada, Alaska, and to a lesser degree the plains of the northern United States and southern Canada, are above normal (Barnston et al., 1999; Cohen and Jones, 2011). El Niño is also associated with above-normal precipitation from coast to coast across the southern United States, along with below-normal precipitation across the northern United States, especially the Pacific Northwest and the Great Lakes (Ropelewski and Halpert, 1989; Barnston et al., 1999).

Though tropical variability has been considered the dominant predictor for subseasonal-to-seasonal forecasts, more recently the rapidly warming Arctic has also been suggested as a potential source of mid-latitude weather predictability (Furtado et al., 2016). It has also been shown to add skill to long-range predictions in some global climate models (GCMs; Scaife et al., 2014). Over the past two to three decades, the Arctic has undergone the most rapid change relative to other regions across the globe, with an observed warming double to triple that of the global average. While the general atmospheric circulation response to Arctic warming may have been obscured by large natural variability in the past, changes in the Arctic have become sufficiently large and rapid that impacts on mid-latitude weather have become more significant and detectable. Here, we discuss two particular boundary conditions that are expected to force changes in Northern Hemisphere circulation and seasonal weather patterns: variability in Arctic sea ice and Eurasian snow cover.

Observational analyses and model perturbation experiments show that extensive October snow cover in Eurasia, through its effects on surface temperatures and surface-atmosphere energy fluxes, favors a colder surface and strengthened Siberian high-pressure area (Cohen and Rind, 1991; Cohen et al., 2014a; Furtado et al., 2015). Through a chain of physical linkages, this leads to an increased net poleward heat flux and a weakened polar vortex, culminating in an extended period when the Arctic Oscillation (AO) resides predominantly in its negative phase (Cohen and Entekhabi, 1999; Cohen et al., 2007).

The AO is the dominant mode of Northern Hemisphere climate variability, and a negative AO is usually associated with anomalous and persistent weather patterns around the Northern Hemisphere. Typically, these patterns bring below-normal temperatures to the eastern United States and northern Eurasia, including northern Europe and East Asia (Thompson and Wallace, 1998; Cohen and Jones, 2011). A negative AO is also typically related to wet conditions across southern Europe and the Mediterranean, along with dry conditions across northern Europe (Brands et al., 2012).

Recent studies have demonstrated a similar atmospheric response to diminished Arctic sea ice (e.g., Kim et al., 2014; Sun et al., 2015). Several mechanisms have been proposed that link variability in Arctic sea ice with mid-latitude winter weather. Progress in understanding this connection has converged on two key factors: (1) the variability of autumn snow cover in Eurasia, and (2) the variability of sea ice coverage in the Barents-Kara Sea during late fall and early winter. Numerous recent studies based on both observations and model simulations indicate that reduced Barents-Kara sea ice in late fall favors a strengthened and northwestward expansion of the Siberian high, increased poleward heat flux, weakened polar vortex, and ultimately a negative AO (Cohen et al., 2014b, and references therein). Because low Barents-Kara sea ice and high Eurasian snow cover favor northwestward expansion of the Siberian high, this atmospheric pattern increases the probability of driving cold Siberian air southeastward into populous East Asia. However, the influence of Arctic variability on mid-latitude weather remains controversial (McCusker et al., 2016; Shepherd 2016), and the performance of previous forecasts based on Arctic boundary forcings has been mixed (Sullivan, 2015).

FALL AND WINTER CONDITIONS 2015/16

The expanse of Eurasian snow cover in October 2015 was the fifth highest observed since 1972 and the fourth highest since 1997. Brown and Derksen (2013) argue that satellite-derived October snow cover exhibited a spurious stepwise increase due to methodology in sensing techniques. However, October snow cover was above normal even for the period when inconsistencies due to remote-sensing irregularities are believed to be insignificant. While snow cover was well below the record high, especially in comparison to the coincident El Niño intensity, it was certainly well above normal. Not only was snow cover unusually extensive, but the September 2015 Arctic sea ice extent was the fourth lowest observed, and the November 2015 Barents-Kara sea ice extent was the third lowest since 1979. The high autumn snow cover and low Arctic sea ice were eventually followed by an abnormally weak polar vortex, a sudden stratospheric warming (SSW) event, a negative AO, and cold temperatures across parts of the Northern Hemisphere mid-latitudes during mid-winter, all of which are consistent with the mechanism outlined by Cohen et al. (2014b). A weak polar vortex and negative AO were also found to be favored during El Niño winters (Ineson and Scaife, 2009). The atmospheric behavior in winter 2015/16 over Eurasia is also consistent with the response expected with diminished sea ice conditions, namely a strengthening and northwestward expansion of the Siberian high.

The globe as a whole, meanwhile, set new warm records for every month from May 2015 through mid-2016. The primary contributor to these records was the global ocean: in November 2015, both the Northern and Southern Hemisphere continents and oceans were record warm, and Arctic Ocean temperatures were the third warmest on record. Moreover, the quasi-biennial oscillation (QBO)—a periodic oscillation of the zonal winds in the equatorial stratosphere—was in its westerly phase. The westerly phase is thought to inhibit SSWs, instead favoring strengthened zonal winds of the polar vortex and persistent episodes of the positive AO. Thus, the strong Siberian high, the record weak polar vortex, and below-normal temperatures over parts of Asia defied expectations based on the traditional indicators.

WINTER FORECASTS BASED ON EL NIÑO

The North American Multi-Model Experiment (NMME) website (http://www.cpc.ncep.noaa.gov/products/NMME) provides real-time analyses and forecasts from all the major national modeling centers, including those located in Canada and Europe. Format-consistent data and output from numerous ensemble members from eight North American GCMs are archived. (For further details about NMME models, see Kirtman et al., 2014).

The two dominant influences on model-forecast temperatures during winter 2015/16 were the ever-increasing greenhouse gas concentrations and El Niño (NOAA, 2015). Above-normal temperatures were predicted by all models across much of North America, with the exception of the southeastern United States. The primary influence on precipitation forecasts was El Niño: all models predicted the canonical north-south dipole across the United States typical of strong El Niños. Below-normal precipitation was predicted for the northern tier of states, along with above-normal precipitation across the south (Figure 1). A comparison with the observed precipitation for winter 2015/16, however, indicates a nearly opposite pattern,

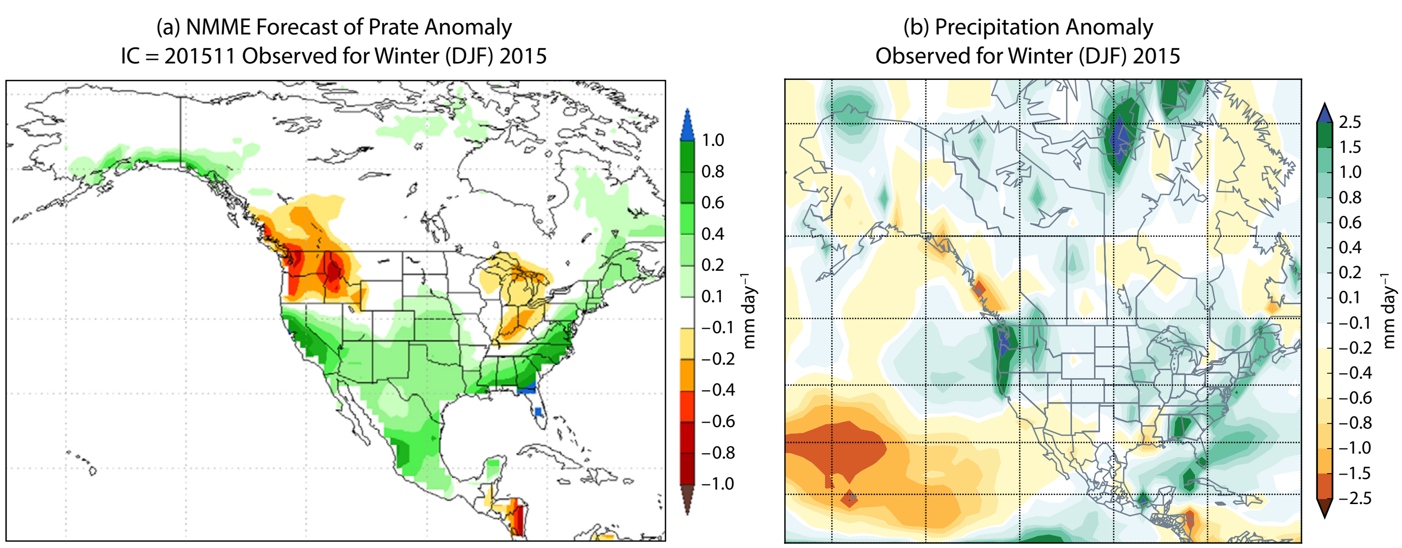


FIGURE 1. Predicted and observed winter precipitation greatly diverge. (a) North American Multi-Model Experiment (NMME) predicted precipitation rate (Prate in mm day^{-1}) for North America from December 2015 through February 2016. (b) Observed average precipitation anomalies (inches) across the United States from December 2015 through February 2016. Please note the difference in color scale.

with above-normal precipitation across the northern United States and below-normal values across much of the south. The only region where the model forecast agrees with observations is along the east coast of the United States, where El Niño typically exerts only a weak influence. Moreover, the largest observed positive anomalies were in the northern United States, in contrast with the model's predicted maximum in the southern states.

Figure 2 provides a comparison of the NMME's ensemble forecasts (109 members) for winter 2015/16 precipitation in Los Angeles and Seattle. It also shows the observed values of precipitation in both cities taken from a gridded data set of merged information from satellites and rain gauges (Janowiak and Xie, 1999). The observed winter precipitation values for both Los Angeles and Seattle clearly lie outside the ensemble spread of the model forecasts. The forecast error for Seattle is particularly noteworthy, with the observed value nearly double the most extreme maximum forecasts from the model simulations. Given that the model spread should have represented all the possible outcomes—encompassing both the forced response from boundary conditions, especially ENSO, and the response due to internally driven variability—values outside the envelope of ensemble members are considered highly improbable. A likely explanation for the disparity is that the models are overly sensitive to tropical forcing and/or they did not account for the large temperature anomalies in high latitudes (see Figure 3). This conclusion is consistent with a study arguing that model parameterizations of tropical convection are inadequate (Stevens and Bony, 2013). It is at odds with another recent study (Eade et al., 2014), however, which concludes that models underrepresent seasonal signals, including those from the tropics, in the winter season. Another possible explanation is that simulated internal variability differs from observed natural variability.

It is well known that seasonal prediction of precipitation is very challenging, and thus forecast skill is low (Saha et al., 2014), but the difference between modeled and observed large-scale patterns in the case of strong El Niño forcing took forecasters by surprise. Clues to the source of prediction error lie in comparing the jet stream configuration during the previous strong El Niño (1997/98) with that of 2015/16. The shading in Figure 4a shows the climatological winter jet structure in the North Pacific along with contours showing the variability associated with ENSO. The atmospheric response to El Niño is a strengthening (weakening) of the jet on the equatorward (poleward) side; the reverse is true for La Niña. The figure also compares the zonal winds at 250 hPa for the winters of 1997/98 (Figure 4b) and 2015/16 (Figure 4c). The jet configuration during the winter of 1997/98 resembles a canonical El Niño pattern, with strengthening equatorward and weakening poleward. In winter 2015/16, however, the reverse pattern is evident, revealing a response more typical of La Niña, including the notable lack of a strong jet across the southern United States. This atypical northward shift of the jet stream was responsible for the poorly predicted precipitation pattern across the United States: dry conditions to the south and a record wet winter in the Pacific Northwest.

ARCTIC INFLUENCE?

The models—as well as human interpretations of model output based on climatological relationships of the past—mistakenly predicted that the record strong El Niño of winter 2015/16 would result in classic El Niño signatures in atmospheric circulation and sensible weather (defined as weather experienced by society). These interpretations failed to consider possible

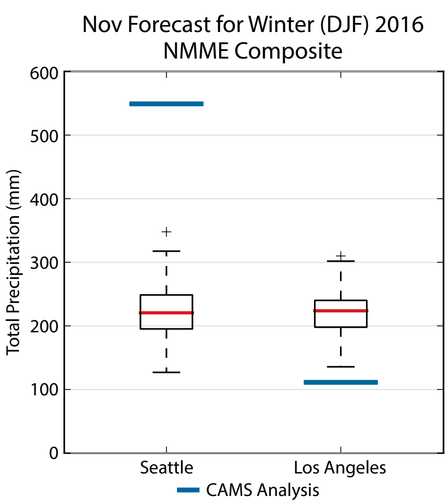


FIGURE 2. Observed precipitation amounts for US West Coast cities lie outside of the model forecast spread as shown by total observed precipitation (mm) for Los Angeles and Seattle from December 2015 through February 2016 (blue solid line), range of operational global climate model forecasts for the ensemble mean (red solid line), 50% of the distribution of the ensembles (box), and 100% of the distribution (whiskers). Outliers beyond ±2.67 sigma are shown as plus signs. Models included in the super ensemble shown are: CMC1-CanCM3, CMC2-CanCM4, COLA-RSMAS-CCSM3, COLA-RSMAS-CCSM4, Cansips, GFDL-CM2p1-aer04, GFDL-CM2p5-FLOR-A06,and GFDL-CM2p5-FLOR-B01.

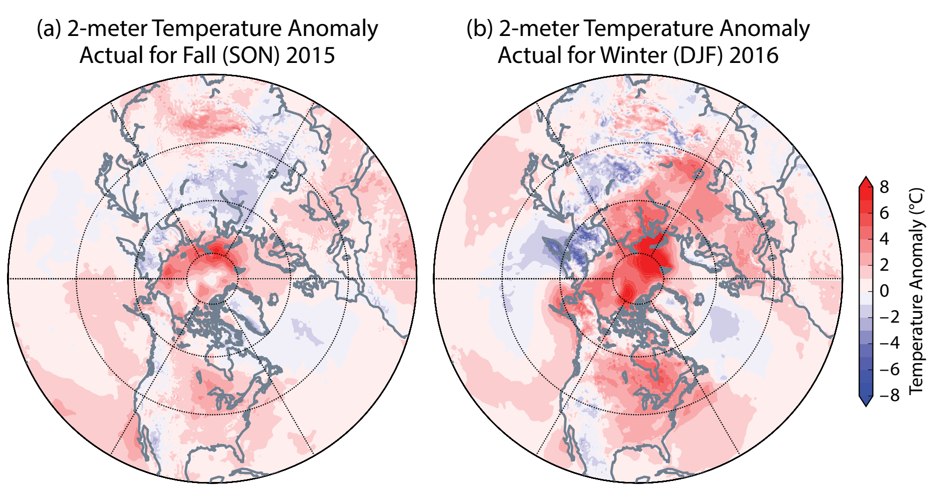


FIGURE 3. Surface temperatures exhibit amplified Arctic warming: observed near-surface temperature anomalies (°C; shading) for (a) September, October, and November 2015, and (b) for December, January, and February 2016.

influences from newly emerged boundary forcings, such as those in the Arctic. For example, during the early part of the winter, the polar vortex was exceptionally strong (see Figure 5a). When the polar vortex is strong, the jet stream is displaced farther northward. Furthermore, during weak and strong polar vortex events, the atmosphere tends to be barotropic, with the jets in both the stratosphere and troposphere aligned (Matthewman et al., 2009). A strong polar vortex is a plausible explanation for the poleward-displaced jet stream during winter 2015/16, despite a record strong El Niño that favors just the opposite response.

Two of the proposed Arctic boundary influences on weather patterns in lower latitudes are changes in Arctic sea ice coverage (Honda et al., 2009; Overland et al., 2011; Vihma, 2014) and in Eurasian snow cover (Cohen and Entekhabi, 1999; Cohen et al., 2007; Allen and Zender, 2011). The atmospheric response most closely associated with these factors is variability in the strength of the Siberian high (Cohen et al., 2014a). As noted previously, Arctic sea ice extent was well below normal and Eurasian snow cover was above normal in fall 2015, both of which favor a lagged response of a northwestward expansion of the Siberian high (Cohen et al., 2014a). In Figure 6 we present both the observed sea level pressure (SLP) anomalies and the predicted SLP anomalies produced by the NMME suite of models for winter 2015/16. The figure also includes a region (45°N–70°N, 40°E–85°E; box in Figure 6a and 6b) that indicates the region where an expansion of the Siberian high is expected following above-normal Eurasian snow cover (Cohen et al., 2014a) and below-normal sea ice in fall (Honda et al., 2009). However, variability in the Siberian high is not exclusively sensitive to Arctic boundary forcings, and certainly other factors can influence Siberian high variability and possibly remote boundary forcings. Observations indicate a northwestward expansion of the Siberian high inside the box, but models forecasted below-normal SLPs in the box and no northwestward expansion of the high. Similar to Figure 2, we also show the ensemble spread of the NMME forecasts for the maximum SLP anomaly inside the box compared with observed values. The observed value is greater than the predicted value and lies outside of the spread of the model forecasts, with the exception of one extreme member out of a total ensemble of 20. This suggests that, in contrast to tropical forcing, the models are insufficiently sensitive to Arctic

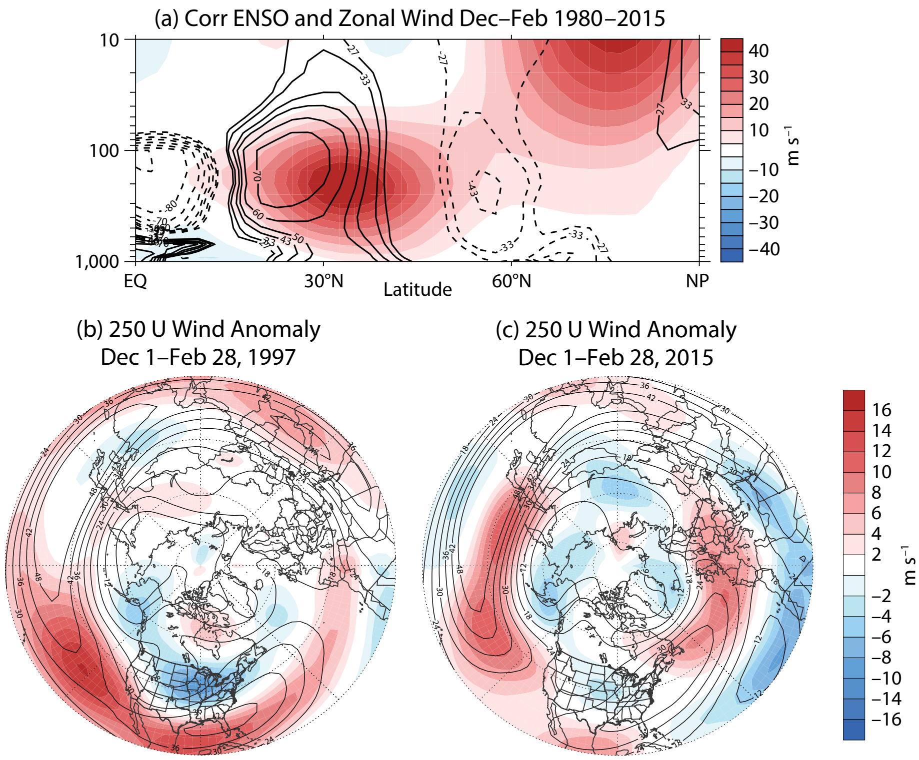


FIGURE 4. (a) Climatological winter jet structure (zonal-mean zonal wind in m s^{-1}, shading) along with the variability associated with the El Niño-Southern Oscillation (ENSO) (correlation ×100 of zonal-mean zonal wind and DJF Niño 3.4 index; contours) in the North Pacific sector for winters 1979/80–2014/15. First, second, and third contours represent 90%, 95%, and 99% statistical significance, respectively (figure adapted from Cohen, 2016). (b) Mean zonal wind at 250 hPa (m s^{-1}; contours) and zonal wind anomalies (m s^{-1}; shading) over the Northern Hemisphere for December 1997 through February 1998. (c) Same as (b) except observed values for December 2015 through February 2016.

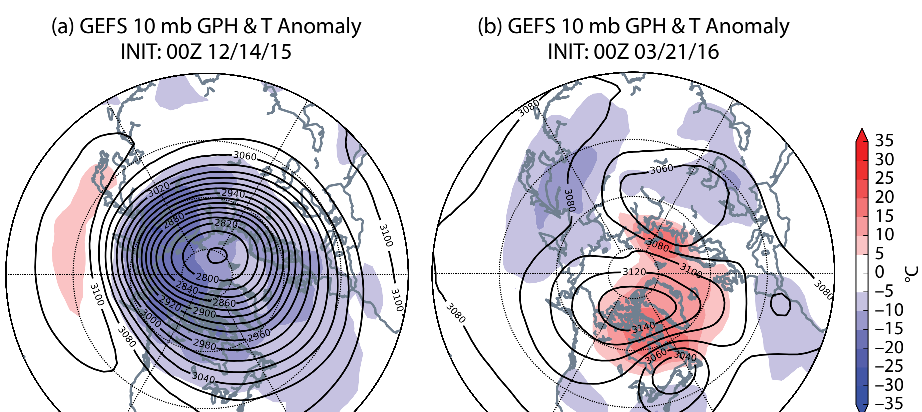


FIGURE 5. The polar vortex begins winter record strong (a) but ends record weak (b), as illustrated by geopotential heights at 10 hPa (decameters; contours) and temperature anomalies (°C; shading) on (a) December 14, 2015 and (b) March 21, 2016. In the free atmosphere, geopotential heights are strongly related to temperatures.

forcing. Other model-based studies found an insensitivity to Arctic forcings such as sea ice and snow cover (Hardiman et al., 2008; McCusker et al., 2016), so it remains an open question whether the models are deficient in simulating the atmospheric response to Arctic forcings.

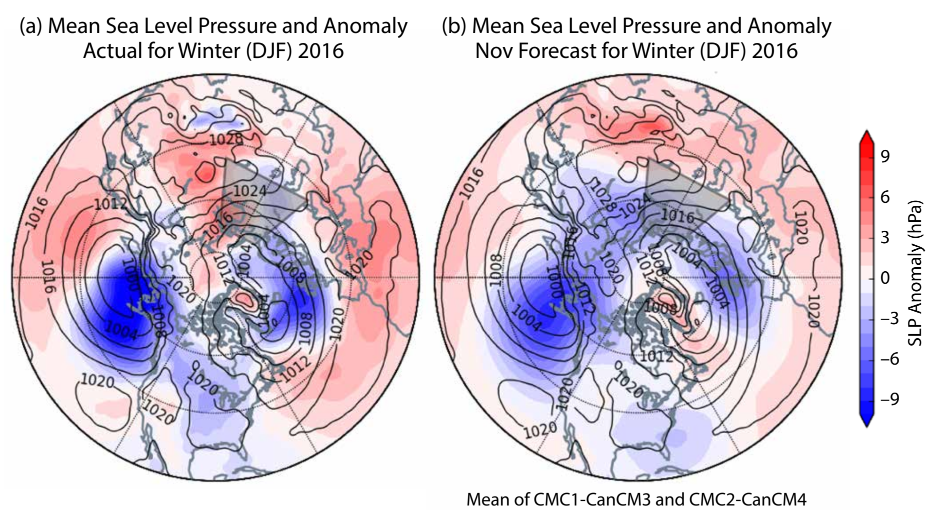
Another important atmospheric response attributed to amplified Arctic warming is a weakened polar vortex during middle to late winter (Cohen et al., 2014b; Kim et al., 2014). The weakened polar vortex is caused by increased poleward heat and equatorward momentum transport related to increased upward vertical wave activity flux (WAFz) and is associated with a stronger Siberian high (Cohen et al., 2007; Jaiser et al., 2012). The winter began with an anomalously strong polar vortex (Figure 5a, contours). However, poleward heat transport was anomalously strong throughout the winter of 2015/16 (not shown), which eventually culminated in a polar vortex split and a record weak stratospheric polar vortex (Figure 5b, contours). The weak polar vortex allowed cold Arctic air to plunge southward and warm mid-latitude air to flow northward, coupled with adiabatic warming due to descending air, resulting in record stratospheric warmth (Figure 5b, shading). The persistent poleward heat transport related to increased WAFz pulses resulted in two SSWs, one in February and another in March. The latter SSW was so strong that it caused a record weak polar vortex, measured as the strength of the zonal wind at 60°N and 10 hPa (not shown).

The combination of active poleward heat transport and two SSWs maintained a predominantly above-normal polar cap geopotential height anomalies (PCH) for the first five months of 2016. Cohen et al. (2013) demonstrated that positive PCH values often coincide with a variety of extreme weather events throughout the mid-latitudes. In Figure 7 we present the analogous figure for PCH and extreme events during January–May 2016. In the 2013 paper we argued that the simultaneous occurrence of positive PCH episodes and extreme mid-latitude weather events strongly suggested a link between the two. As Figure 7 indicates, high PCH episodes in 2016 were also coincident with a variety of extreme weather events across the Northern Hemisphere, from record snowfalls and cold-air outbreaks (in the eastern United States and East Asia) to flooding and unusual Greenland melt.

CONCLUSION

Producing accurate seasonal forecasts carries many challenges; unfortunately, erroneous model forecasts are still more common than accurate ones, especially in conditions of weak forcing (Hoskins, 2013). Swings in SSTs associated with ENSO elicit responses in the overlying tropical atmosphere that affect the large-scale circulation around the globe. Understanding and capitalizing on this relationship has driven progress in model development as well as seasonal forecasting. When it became clear in fall 2015 that a record strong El Niño event was underway with unprecedented warm ocean temperatures, forecasters expected an excellent opportunity to showcase decades of climate research and climate modeling efforts with an accurate winter forecast. Though some aspects of the forecast were successful—such as the overall warm temperature pattern hemispherically, as we demonstrated above—there were also obvious shortcomings, especially across the United States. This surprising "blown" forecast in the face of strong tropical forcing offers an opportunity to the climate and long-range forecast communities to re-examine the relative roles of tropical variability and other emerging factors in seasonal weather forecasts and numerical model simulations.

As Figure 2 demonstrates, the observed winter precipitation values for both Los Angeles and Seattle lie outside the ensemble spread of the forecasts generated by the NMME group of GCMs. The



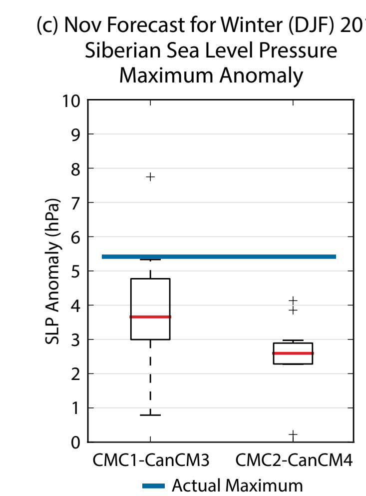


FIGURE 6. Arctic-forced response of strong Siberian high not predicted by forecast models. (a) Observed climatological mean sea level pressure (SLP) (1981–2010; contours) and SLP anomalies (shading) in hPa for the Northern Hemisphere from December 2015 through February 2016. (b) Same as (a) but from NMME forecasts. (c) Observed maximum SLP anomaly (hPa) in the region bounded by 45°N–70°N and 40°E–85°E (gray boxes in panels a and b) for December 2015 through February 2016 (solid blue line). Also shown are the ranges of NMME forecasts for the ensemble mean (red solid line), 50% of the distribution of the ensembles (box), and 100% of the distribution (whiskers). Outliers beyond ±2.67 sigma are shown as plus signs. Models included in the super ensemble shown are CMC1-CanCM3 and CMC2–CanCM4.

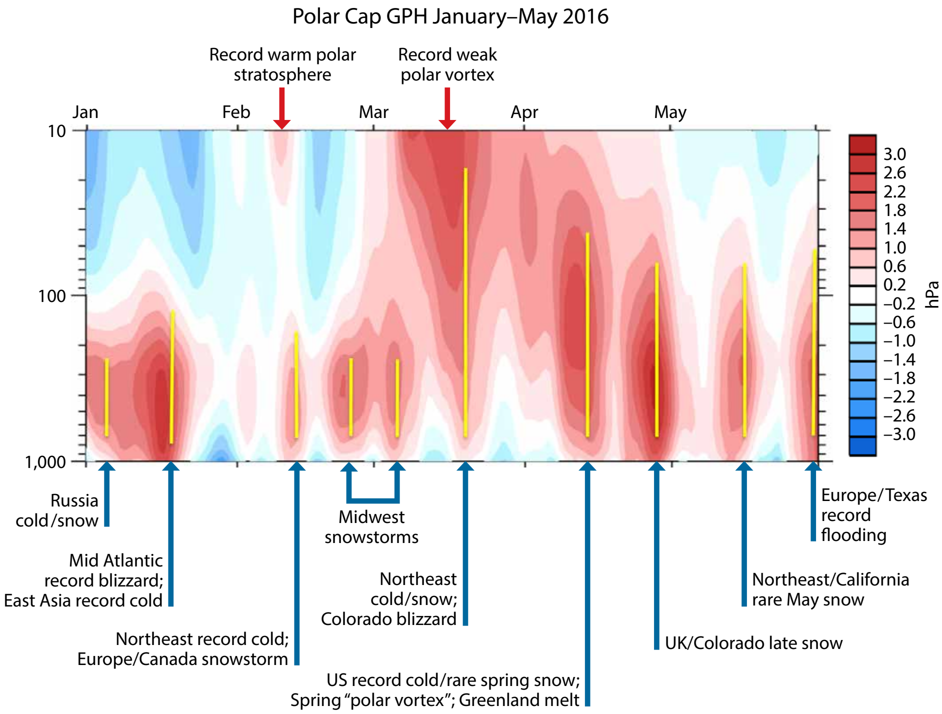


FIGURE 7. Extreme weather events coincided with enhanced Arctic warming as indicated by anomalies of daily standardized polar cap (60°N–90°N) geopotential height (GPH) from January 1, 2016, through May 31, 2016. Anomalously high heights (corresponding with warm temperatures) are shaded in red. Blue arrows denote extreme weather events across the Northern Hemisphere, while the red arrows show the dates of two sudden stratospheric warmings. Yellow bars highlight the alignment of pulses in the polar cap GPH with an extreme event.

forecast error for Seattle is particularly noteworthy, as the observed value is nearly double the most extreme maximum forecasts from each of the models. Given that the model spread should have represented all the possible outcomes, encompassing both the forced response from boundary conditions, especially ENSO, and the response due to internally driven variability, values outside the envelope of ensembles should have been considered highly improbable if not impossible, yet the observed values did occur outside of the model envelope of all possible outcomes.

The shortcomings of the winter forecast have important and far-reaching implications not only for these specific cities but also for climate science in general. The tropics have long been considered the primary source of global atmospheric variability. The most plausible explanation for the low forecast skill, however, is that the models are overly sensitive to tropical forcing and/or that they are insensitive to climate variability at high latitudes, including related impacts of the strong polar vortex in early winter and the weak polar vortex in late winter. As some regions are more conspicuously impacted by climate change than others, shifts in the fundamental energy balance and dynamics of the system are inevitable. The relative importance of particular forcing mechanisms is likely also shifting (Feldstein and Lee, 2014; Cohen, 2016), which challenges traditional theories of relationships among various aspects of the climate system. The role of the rapidly warming Arctic is one of these factors, in particular its influence on large-scale circulation patterns in the Northern Hemisphere. This topic has been the target of a flurry of recent research, accompanied by intense media attention and controversy within the community of atmospheric dynamists (e.g., Kintisch, 2014; Palmer, 2014; Wallace et al., 2014; Gramling, 2015; Overland et al., 2016; Shepherd 2016). The main support for the argument that the tropics dominate atmospheric variability derives from model simulations that perturb tropical SSTs. Other model experiments that do target the Arctic's influence on the mid-latitude atmosphere are inconclusive, but whether the uncertainty stems from inadequacies in model physics, inappropriate metrics, experimental design, or obfuscation owing to complex nonlinear interactions is unknown. Some models already initialize and include ice dynamics (MacLachlan et al., 2015). However, to date, improved seasonal forecast skill due to correct initialization of Arctic boundary forcings such as sea ice in GCMs has yet to be demonstrated.

Comparison of model forecasts with observations of precipitation during winter 2015/16 points to models generally underrepresenting the importance of profound Arctic changes relative to tropical influences on mid-latitude weather. Furthermore, our analysis suggests that natural variability as simulated by numerical models can markedly differ from that of the real atmosphere at times. For example, model forecasts for winter 2015/16 demonstrated that the divide between simulations and the real world is surprisingly large.

There is much still to learn about ocean-atmosphere coupling, particularly in the era of human-induced climate change. Lessons learned from the 2015/16 winter, characterized by a record strong El Niño in combination with a record warm Arctic, suggest that the balance between tropical and Arctic influences on mid-latitude weather patterns needs to be reevaluated with rigor in both modeling and observational studies.

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