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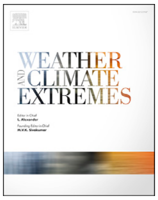

Drivers of 2016 record Arctic warmth assessed using climate simulations subjected to Factual and Counterfactual forcing

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ABSTRACT

A suite of historical atmospheric model simulations is described that uses a hierarchy of global boundary forcings designed to inform research on the detection and attribution of weather and climate-related extremes. In addition to experiments forced by actual variations in sea surface temperature, sea ice concentration, and atmospheric chemical composition (so-called Factual experiments); additional (Counterfactual) experiments are conducted in which the boundary forcings are adjusted by removing estimates of long-term climate change. A third suite of experiments are identical to the Factual runs except that sea ice concentrations are set to climatological conditions (Clim-Polar experiments). These were used to investigate the cause for extremely warm Arctic surface temperature during 2016.

Much of the magnitude of surface temperature anomalies averaged poleward of 65°N in 2016 (3.2 ± 0.6 °C above a 1980–89 reference) is shown to have been forced by observed global boundary conditions. The Factual experiments reveal that at least three quarters of the magnitude of 2016 annual mean Arctic warmth was forced, with considerable sensitivity to assumptions of sea ice thickness change. Results also indicate that 30–40% of the overall forced Arctic warming signal in 2016 originated from drivers outside of the Arctic. Despite such remote effects, the experiments reveal that the extreme magnitude of the 2016 Arctic warmth could not have occurred without consideration of the Arctic sea ice loss. We find a near-zero probability for Arctic surface temperature to be as warm as occurred in 2016 under late-19th century boundary conditions, and also under 2016 boundary conditions that do not include the depleted Arctic sea ice. Results from the atmospheric model experiments are reconciled with coupled climate model simulations which lead to a conclusion that about 60% of the 2016 Arctic warmth was likely attributable to human-induced climate change.

1. Introduction

NOAA's Arctic Report (Overland et al., 2016a) indicated that the annual surface air temperature anomaly in 2016 for land areas north of 60°N far exceeded the highest in the observational record since 1900. Further, the 2016 anomaly was double the magnitude during just the prior year. In this study, a set of historical climate model simulations are introduced that contribute to the Climate of the Twentieth Century Detection and Attribution Project (Folland et al., 2014). These simulations are used to determine the drivers of extreme Arctic warmth in 2016.

Record setting Arctic warmth in 2016 did not come entirely as a surprise. A prolonged warming of annual Arctic surface temperatures has been observed since the late 1970s (Overland et al., 2016a), despite appreciable superposed intrinsic decadal variability (e.g. Polyakov et al., 2002). The recent Arctic warming has occurred in tandem with temperature rises in middle and lower latitudes, suggesting that it is part of an overall global warming pattern (e.g. Serreze and Francis, 2006). Most of the Arctic warming since 1979 has occurred during fall and winter, with observational studies (e.g. Screen and Simmonds, 2010) and climate model experiments (e.g. Screen et al., 2013a, b; Perlwitz et al., 2015) indicating sea ice loss to have been a major driver. Given that 2016 Arctic sea ice extent was itself near a record low,[1] boundary conditions were conducive for high Arctic surface temperatures.

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[1] Record low monthly extents were set in January, February, April, May, June, October, and November. http://nsidc.org/arcticseaicenews/2017/01/low-sea-ice-extent-continues-in-both-poles/.

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Lest the impression be that extreme Arctic warmth was unavoidable and that the record-setting conditions in 2016 could have been readily anticipated, several lines of evidence also indicate an appreciable random, unforced contribution. For instance, multi-model simulations of the Coupled Model Intercomparison Project (CMIP5) were used to examine how global warming contributed to the remarkable November–December 2016 warmth near the North Pole (van Oldenborgh et al., 2017). Results indicated that the magnitude of warmth was an extreme condition relative to the global warming signal itself, and as such was a low probability outcome in 2016. Likewise, Kim et al. (2017) examined impacts of intense Storm Frank during January 2016 when daily Arctic surface temperatures were as much as 30 °C above average, revealing the importance of weather-driven heat and moisture transports.

Quantifying the effects of various drivers is central to explaining how extreme Arctic warmth can arise, to understanding why it happened in 2016 specifically, and to better anticipating future occurrences of extreme Arctic events. In this study we first pose the question whether the magnitude of the observed annual surface air temperature anomalies averaged poleward of 65°N were reconcilable with boundary forcing during 2016 alone using a unique set of atmospheric model simulations. Our modeling approach should be distinguished from a purely CMIP5 approach (e.g. van Oldenborgh et al., 2017) in so far as the particular observed ocean and sea ice conditions of 2016 are treated as forcings in the model experiments used herein. We then inquire about the character of the boundary forcing by using a set of experiments driven by realistic and idealized representations of global boundary conditions. Among various questions these experiments address, one focuses upon whether the extreme warmth arose mostly from drivers within or outside of the Arctic. We also explore the extent to which the extreme articulation of 2016 Arctic warmth may have resulted from an appreciable impetus provided by purely random variability. It is apparent from synoptic analysis of Arctic weather conditions in 2016 (e.g. Kim et al., 2017; Overland and Wang, 2016) that weather driving was important, and that such weather driving likely affected the sea ice boundary conditions. Thus, consistent with estimates that about 40% of Arctic sea ice loss since 1979 is due to internal atmospheric variability (Ding et al., 2017), estimates of the random component of 2016 warmth must address such internal coupled feedbacks. Our analysis therefore also examines coupled model simulations that span the same historical record as our atmospheric simulations, and which involve large ensembles to facilitate diagnosis of the magnitude for internal coupled noise.

We describe in Section 2 our suite of atmospheric model simulations that employ boundary forcings representative of 2016 conditions for a factual (observed) and counterfactual (absent long-term climate change) world. The rationale is to create an experimental dataset, routinely updated and made available to the broader scientific community, that can be used to isolate contributions of specific drivers to observed climate variability and extreme events. The experimental methods involve large ensemble simulations for each configuration of boundary forcing, thereby permitting diagnosis of contributions by various drivers and also by internal atmospheric variability. A feature of the experimental suite is that in addition to runs forced by the actual variations in sea surface temperature, sea ice concentration, and atmospheric chemical composition (the standard Atmospheric Model Intercomparison Project (AMIP) configuration); additional experiments are conducted in which the boundary forcings are adjusted by removing plausible estimates of the effects of long-term climate change. Section 2 describes how these counterfactual boundary conditions were constructed and addresses implications of various simplifying assumptions.

The application of these experiments toward an attribution of the 2016 extreme Arctic warmth is presented in Section 3. It is demonstrated that roughly three quarters of the magnitude of 2016 annual mean Arctic warmth was likely a forced signal owing to the particular global ocean boundary conditions. Of this forced signal, about 30–40% likely arose from drivers outside of the Arctic, while Arctic sea ice loss accounted for 60–70% with estimates sensitive to assumptions of sea ice thickness change. The Discussion section compares results on the drivers of 2016 Arctic warmth drawn from our atmospheric model experiments with results using transient coupled climate model simulations.

2. Observed data and model experiments

2.1. Observations

Near-surface air temperatures are based on five reanalysis products — NCEP/NCAR (R1; Kalnay et al., 1996), ERA-Interim (Dee et al., 2011), NASA-MERRA-2 (Gelaro et al., 2017), and two versions of JRA-55 analyses that involve different treatments of the near-surface air temperature (Kobayashi et al., 2015). The common period for these products is 1980–2016. Annual surface air temperatures are area-averaged for the region 65°N-90°N, and anomalies are calculated with respect to each product's 1980-89 mean.

Two sea surface temperature (SST) data sets are used to investigate long-term change since 1880. We use the NOAA Extended Reconstructed Sea Surface Temperature v3 (ERSSTv3) (Smith et al., 2008), results from which are compared to the Hadley Center Global Sea Ice and Sea Surface Temperature v1 (HadISSTv1) data (Rayner et al., 2003).

2.2. Atmospheric model and experiments

The atmospheric model used in support of the Climate of the 20th Century Detection and Attribution Product is the European Center for Medium Range Weather Forecast/Hamburg (ECHAM5) model (Roeckner et al., 2003). The model is run at a spectral resolution of T159 (~85 km horizontal resolution) and 31 vertical levels having a model top at about 1 hPa.

In its standard AMIP configuration (hereafter, Factual experiment), ECHAM5 is forced by specifying observed monthly variations in SST and sea ice concentration as derived from Hurrell et al. (2008). Greenhouse gases (GHGs) vary according to the observed concentrations and their extension after 2005 assuming Representative Concentration Pathway 6.0 (RCP6.0) (Meinshausen et al., 2011). Monthly evolving tropospheric and stratospheric ozone also vary based on Cionni et al. (2011). Aerosol concentrations do not vary interannually in ECHAM5, and a specified repeating seasonal cycle is derived from an aerosol model described in Tanre et al. (1984). The experiments are from January 1979–December 2016. A 30-member ensemble of simulations is generated in which each member experiences identical time evolving boundary forcings, but is begun from different atmospheric initial states in January 1979.

Two additional parallel experiments are performed in which the boundary and external forcings are modified. In one suite (hereafter, Counterfactual experiment), the model is forced with monthly varying boundary conditions that retain the interannual and decadal variability as occurring in the Factual experiment, but in which the long-term trends in the boundary forcings have been removed. For external radiative forcing in these Counterfactual experiments, GHG and ozone concentrations are simply set to their 1880 values. For the SSTs, an approximation of 1880 conditions is generated by removing a 1880–2011 linear SST trend from the monthly variability. Sea ice concentrations are set to a 1979–1989 climatological mean globally, a period that mostly precedes the time of substantial decline in Arctic sea ice that culminated in the near-record low concentrations during 2016. In the second suite (hereafter, Clim-Polar experiment), all boundary conditions and external radiative forcings are identical to those specified in the Factual runs, except that global sea ice concentrations are set to a 1979–1989 climatological mean. Each suite spans 1979–2016 and includes 30-member ensembles. Table 1 summarizes these three sets of experiments and their specified boundary forcings.

When diagnosing the 2016 Arctic extreme warmth, the model spread is represented by the 95% confidence bound across 30 members of simulations based on student's t-test. The contribution from the drivers