DECEMBER 2016: LINKING THE LOWEST ARCTIC SEA-ICE EXTENT ON RECORD WITH THE LOWEST EUROPEAN PRECIPITATION EVENT ON RECORD

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Our study suggests that record-breaking low precipitation over parts of western Europe during December 2016 may have been favored by an unprecedented reduction of Arctic sea ice, likely driven by anthropogenic climate change.

INTRODUCTION. Extreme warm Arctic temperatures during November–December 2016 can only be understood in the context of human influence on climate (Kam et al. 2018; see also Fig. ES1 in the online supplemental information). In the same months, the total Arctic sea ice extent experienced a historical low value with negative anomalies in most of the Arctic, but especially strong in the Barents and Kara Seas (BK; Figs. 1a,c). In addition, a high pressure blocking pattern developed over Europe during December 2016 (Vautard et al. 2017) and caused the total amount of precipitation to be the lowest in the last 116 years (Figs. 1b,d).

Human influence on climate likely includes intensification of precipitation extremes (Min et al. 2011). Furthermore, in the last decade several studies have found causal links between low sea ice cover in late autumn and extreme midlatitude climate anomalies in the following winter. Baroclinic instability generated through enhanced surface heat fluxes due to sea ice reduction promotes planetary wave activity in the troposphere and the troposphere–stratosphere interface that could potentially affect the atmospheric flow, and thus modify midlatitude weather and climate at the surface [see Cohen et al. (2014) and Screen et al. (2018) for a review]. We used three sets of tailored retrospective forecasts to attribute the role of extremely reduced Arctic sea ice conditions (mostly over BK) with regard to the 2016 extremely low precipitation event in Europe.

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DATA AND METHODS. We used observationally based gridded fields of monthly mean sea ice concentration (SIC) for the period 1980–2016 (Cavalieri et al. 1996) and European precipitation for the period 1901–2016 (Haylock et al. 2008; Harris et al. 2014). Sea level pressure for the period 1980–2016 was taken from ERA-Interim (Dee et al. 2011). The BK region (red box in Fig. 1a) was defined as the area within 15°–100°E, 68°–82°N, while Europe (red box in Fig. 1b) was defined as the area within 10°W–30°E, 38°–60°N.

Using the fully coupled climate model EC-Earth3 in forecast mode (i.e., initialized simulations; Doblas-Reyes et al. 2013) with the Autosubmit workflow manager (Manubens-Gil et al. 2016) we simulated the climate of November–December 2016 in three sets of ensemble retrospective predictions, specifically conceived to isolate the preconditioning role of sea ice state. We first produced a set of 100-member forecasts with the observed initial conditions from 1 November 2016 (Forecast16) to describe the baseline skill of the model to predict the 2016 extreme in precipitation. The contribution of sea ice was then assessed by repeating the same experiments, but using sea ice conditions from 1 November 2014, which were chosen due to their closeness to the 1980–2015 climatology in the BK region (Forecast16_Ice14). Previous studies suggest that 100-member ensembles are sufficiently large to separate the atmospheric response to sea ice changes from the noise caused by internal variability (e.g., Screen et al. 2014). For the period 1980–2015, an additional set of 10-member November–December retrospective predictions (Hindcast) was initialized every 1 November with atmospheric, oceanic, and sea ice initial conditions representative of each year to assess the model capability to simulate and predict the mean climate of the period and to establish a baseline to compare the extreme event of 2016 in all forecasts. All model experiments used atmospheric initial conditions adapted from ERA-Interim (Dee et al. 2011), oceanic initial conditions adapted from ORAS4 (Balmaseda et al. 2013), and sea ice conditions from a historical reconstruction using assimilation of SIC from Satellite Application Facility on Ocean and Sea Ice (OSISAF) and the European Space Agency (ESA; http://esa-cci.nersc.no).

CHARACTERIZING THE EXTREME EVENTS. A breakpoint in sea ice loss (i.e., an accelerated decline) over the BK region took place in the early 2000s (Close et al. 2015). Here we use the 15-yr period 2001–15 as representative of this marked change, not including the extreme autumn–winter of 2016; the 15-yr period 1980–94 is used as baseline for sea ice cover before the dramatic recent sea ice loss. Between the periods 1980–94 and 2001–15 there is a clear shift in the probability distribution of observed sea ice cover in the BK region (Fig. 1c), a shift that has previously been related to anthropogenic climate change (Bindoff et al. 2013). BK SIC in 2016 was the lowest for the period November–December since satellite observations began in 1979 and twice as low as the lowest value in the period 1980–94. The EC-Earth3 hindcasts also exhibit a BK sea ice cover shift between 1980–94 and 2001–15, but less marked than in the observations (Fig. 1c). Indeed, while the observed 2016 SIC remains unlikely but plausible with respect to the 2001–15 hindcasts and Forecast16 distributions, it is virtually impossible when compared to the 1980–94 distribution. Note likewise that the ensemble-mean SIC of Forecast16 lies on the tail of Hindcast 1980–94.

Following the extreme sea ice conditions, December 2016 was characterized by a persistent, abnormally high sea level pressure system centered in northwestern Europe (Fig. 1b) exceeding the December mean (since the early 1900s) by over two standard deviations (Vautard et al. 2017) and leading to reduced humidity transport into Europe from the North Atlantic. As a result, the mean precipitation in Europe was the lowest on record for that month since 1901. Most locations experienced anomalous precipitation well below one standard deviation from the historical mean for December (Fig. 1b). The probability distribution of precipitation barely changed over the observational period (1901–2016). We also compared the same 15-yr periods for precipitation than for sea ice, but we show 1980–2015 due to the lack of long-term trends and higher natural variability (Fig. ES2).

Although EC-Earth3 shows a dry bias in precipitation as compared to observations for the periods 1980–2015 (blue vs gray lines in Fig. 1d), the variability in the model and the observations is practically the same, allowing for a non-bias-corrected analysis of extreme events (Bellprat and Doblas-Reyes 2016). Forecast16 (purple line) displays drier conditions than Hindcast, which supports the ability of the model to broadly simulate, and predict, the occurrence of such events one month in advance. Indeed, the observed spatial features of the anomalous sea level pressure and precipitation in Europe during December 2016 are tightly captured by the model in Forecast16, although with a model tendency to underestimate the observed amplitude (Figs. 1b and 2a). This underestimation is somehow expected in the forecasts, as the reproducibility of the extreme event one month ahead will degrade due to the chaotic nature of the system.

IMPACT OF BARENTS–KARA SEA ICE REDUCTION. Repeating the forecasts with 2014 sea ice (Forecast16_Ice14) initial conditions shifts the mode of the probability density function toward wetter conditions (compared to Forcast16) by about 20%, suggesting that sea ice could have a preconditioning or additive effect on the extreme event in Europe during 2016. Indeed, sea ice initialization from realistic conditions enhanced the anomalous circulation and precipitation spatial patterns in most parts of the continent, except for the southeast area (Figs. 2a,b). To assess the robustness in the mean response to the sea ice initial state we randomly sampled 1000 sub-ensembles of 50 members each from the full 100-member ensemble and computed the mean values of those sub-ensembles for the precipitation and sea level pressure differences between Forecast16 and Forecast16_Ice14 at the gridpoint level. Within the 1000 sub-ensembles there is large agreement (over 80%) on the negative sign of precipitation over most of western Europe (Fig. ES3) and on the positive sign of sea level pressure over most of the continent (Fig. ES4). Note also an important effect of sea ice reduction on western North American precipitation causing a wet south–dry north dipole as seen in

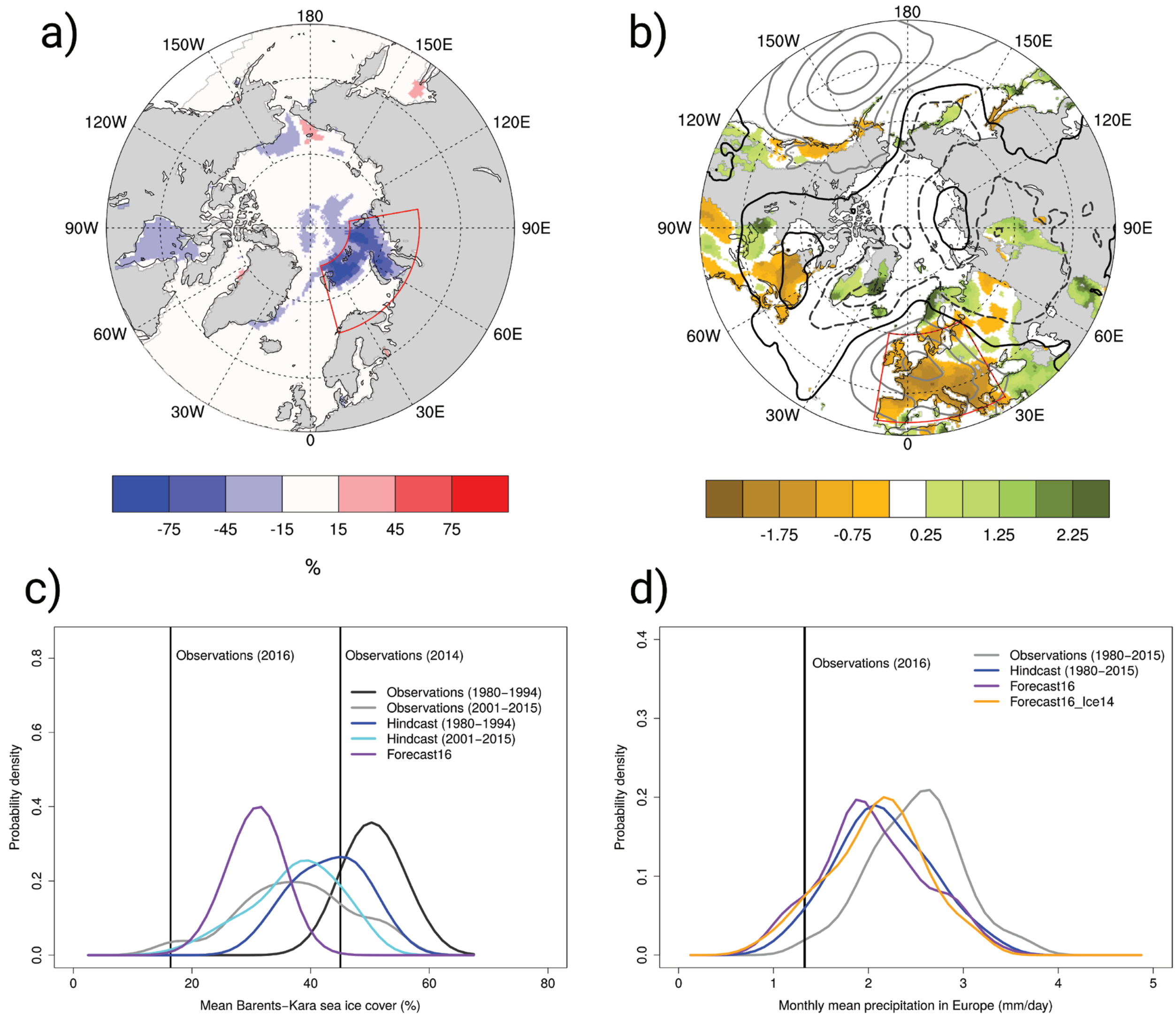

Fig. 1. (a) Observed mean November–December sea ice concentration differences between 2016 and 2014. The red box represents the Barents–Kara region. (b) Observed December 2016 standardized anomalies of total precipitation (colors) and sea level pressure (contours; with 4-hPa intervals, the solid black line is zero and the gray solid and black dashed lines represent positive and negative anomalies, respectively). Regions with mean precipitation below 1 mm day^{-1} were excluded. All anomalies in (b) are computed with respect to the period 1980–2015. (c) Smoothed probability distribution functions (with the Nadaraya–Watson kernel regression in R) of mean November–December Barents–Kara sea ice cover in observations (gray shading) and model experiments (colors). (d) Smoothed probability distribution functions of mean December precipitation in Europe in observations (gray shading) and model experiments (colors).

observations (Fig. 1c). Having a different experimental setup, focusing only on December and having the largest differences in sea ice in BK Seas, could cause somewhat different mean circulation and precipitation responses to sea ice loss in this study than in previous ones (Deser et al. 2016; Hay et al. 2018).

The influence of initial conditions on extremely low precipitation is further explored in Figs. 2c and 2d as an odds ratio. This is defined as the ratio between the probability to be in the lowest quintile, the middle three quintiles (also called the interquintile range), or the upper quintile for each 2016 forecast and the climatological probability of the same three categories in Hindcast (i.e., 20%, 60% and 20%, respectively). Each grid point is attributed to the category with highest odds ratio. The point is drawn in gray if it is attributed to the interquintile range. If the point is attributed to the lower (upper) quintile category, the corresponding odds ratio is plotted as negative (positive). The odds ratio represents how anomalous the probability of a given event is. Comparing Figs. 2c and 2d confirms that Forecast16 captures an increase

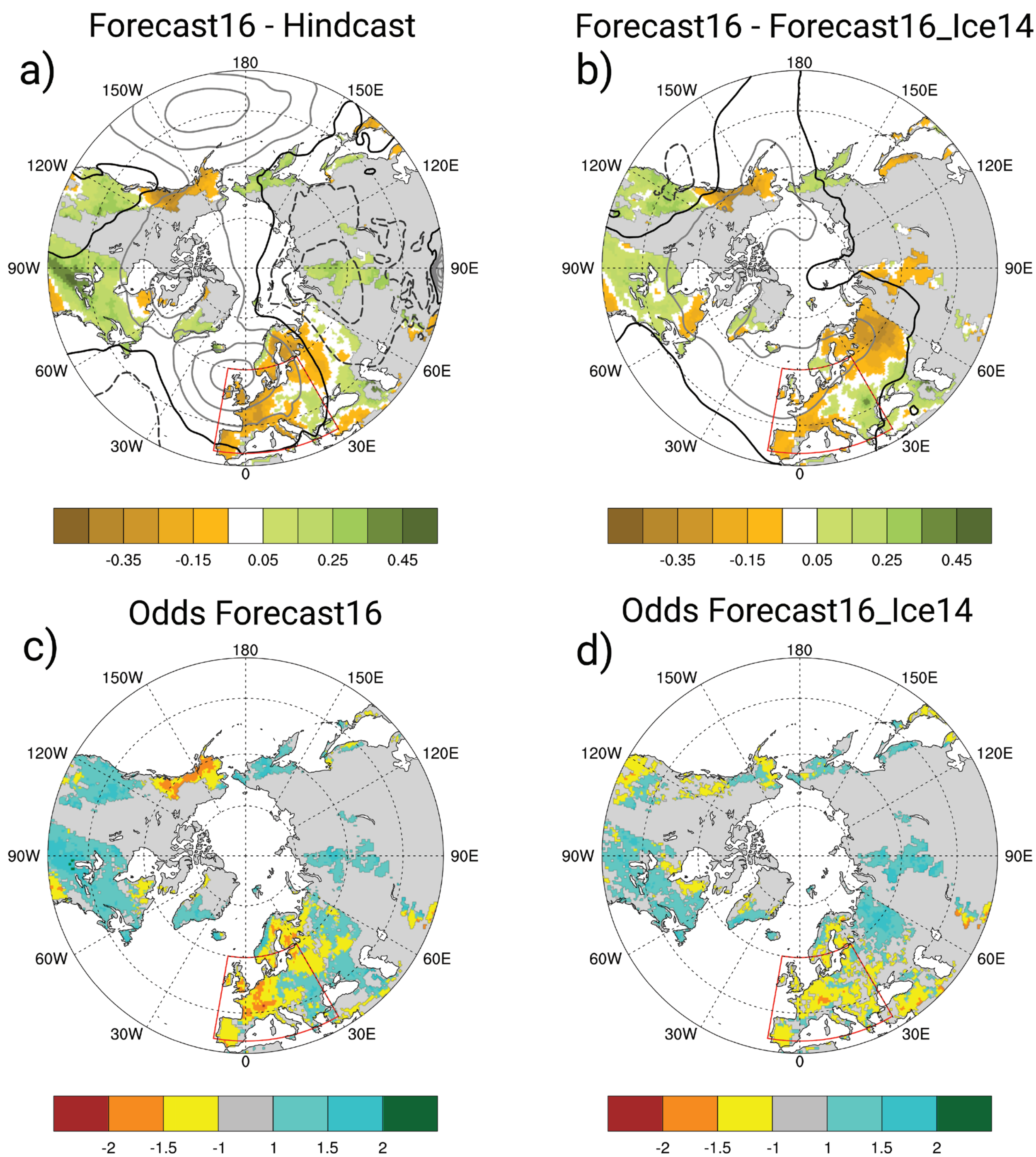

Fig. 2. (a) Mean modeled December 2016 standardized anomalies of total precipitation (colors) and sea level pressure (lines) for all members in Forcast16 (lines every 1 hPa). (b) As in (a), but for Forecast16-Forecast16_Ice14 (lines every 1 hPa). All anomalies in (a) and (b) are computed with respect to 1980–2015. (c) Precipitation odds in Forecast16, which describe the ratio between the probability to be in the lower quintile, the interquintile range, or the upper quintile for the forecast and the probability of the same categories in Hindcast. Each point is attributed to the category with highest odds ratio. The point is gray if attributed to the interquintile range and negative (positive) if attributed to the lower (upper) quintile. (d) As in (c), but for Forecast16_Ice14. Regions with precipitation below 1 mm day^{-1} were excluded in all plots.

in likelihood of extreme dry conditions over western Europe, with many regions showing an increment in the odds of over 1.5. The dry conditions are also present in Forecast16_Ice14, indicating that either the ocean or the atmosphere was important for capturing the event. However, the response in Forecast16_Ice14 is weaker than in Forecast16 in western and northwestern Europe, showing that realistic ice conditions were important to better reproduce the event in these locations.

DISCUSSION AND CONCLUSIONS. EC-Earth3 experiments targeting the low December 2016 precipitation event in Europe indicate that while realistic ocean and atmosphere conditions had a key role in preconditioning and capturing the extremely low precipitation event, initializing the model with actual sea ice conditions increased the likelihood of occurrence over many parts of the continent. The role of internally generated chaotic variability was only indirectly addressed here, by producing and exploring an ensemble of predictions with perturbed initial conditions.

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REFERENCES

Balmaseda, M. A., K. Mogensen, and A. T. Weaver, 2013: Evaluation of the ECMWF ocean reanalysis system ORAS4. *Quart. J. Roy. Meteor. Soc.*, **139**, 1132–1161, https://doi.org/10.1002/qj.2063.

Bellprat, O., and F. Doblas-Reyes, 2016: Attribution of extreme weather and climate events overestimated by unreliable climate simulations. *Geophys. Res. Lett.*, **43**, 2158–2164, https://doi.org/10.1002/2015GL067189.

Bindoff, N. L., and Coauthors, 2013: Detection and attribution of climate change: From global to regional. *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge University Press, 867–952.

Cavalieri, D., C. Parkinson, P. Gloersen, and H. Zwally, 1996: Sea ice concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS passive microwave data, version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center, accessed April 2018, https://doi.org/10.5067/8GQ8LZQVL0VL.

Close, S., M.-N. Houssais, and C. Herbaut, 2015: Regional dependence in the timing of onset of rapid decline in Arctic sea ice concentration. *J. Geophys. Res. Oceans*, **120**, 8077–8098, https://doi.org/10.1002/2015JC011187.

Cohen, J., and Coauthors, 2014: Recent Arctic amplification and extreme mid-latitude weather. *Nat. Geosci.*, **7**, 627–637, https://doi.org/10.1038/ngeo2234.

Dee, D. P., and Coauthors, 2011: The ERA-Interim Reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, https://doi.org/10.1002/qj.828.

Deser, C., and Coauthors, 2016: Does ocean coupling matter for the northern extratropical response to projected Arctic sea ice loss? *Geophys. Res. Lett.*, **43**, 2149–2157, https://doi.org/10.1002/2016GL067792.

Doblas-Reyes, F., and Coauthors, 2013: Initialized near-term regional climate change prediction. *Nat. Commun.*, **4**, 1715, https://doi.org/10.1038/ncomms2704.

Harris, I., P. Jones, T. Osborn, and D. Lister, 2014: Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 dataset. *Int. J. Climatol.*, **34**, 623–642, https://doi.org/10.1002/joc.3711.

Hay, S., P. J. Kushner, R. Blackport, and K. E. McCusker, 2018: On the relative robustness of the climate response to high-latitude and low-latitude warming. *Geophys. Res. Lett.*, **45**, 6232–6241, https://doi.org/10.1029/2018GL077294.

Haylock, M., N. Hofstra, A. Klein Tank, E. Klok, P. Jones, and M. New, 2008: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. *J. Geophys. Res.*, **113**, D20119, https://doi.org/10.1029/2008JD010201.

Kam, J., T. R. Knutson, F. Zeng, and A. T. Wittenberg, 2017: CMIP5 model-based assessment of anthropogenic influence on highly anomalous Arctic warmth during November–December 2016 [in "Explaining Extreme Events of 2016 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **99** (1), S34–S38, https://doi.org/10.1175/BAMS-D-17-0115.1.

Manubens-Gil, D., J. Vegas-Regidor, C. Prodhomme, O. Mula-Valls, and F. J. Doblas-Reyes, 2016: Seamless management of ensemble climate prediction experiments on HPC platforms. *2016 IEEE Conf. on High Performance Computing & Simulation (HPCS)*, Innsbruck, Austria, IEEE, https://doi.org/10.1109/HPCSim.2016.7568429.

Min, S.-K., X. Zhang, F. W. Zwiers, and G. C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470**, 378, https://doi.org/10.1038/nature09763.

Screen, J. A., C. Deser, I. Simmonds, and R. Tomas, 2014: Atmospheric impacts of Arctic sea-ice loss, 1979–2009: Separating forced change from atmospheric internal variability. *Climate Dyn.*, **43**, 333–344, https://doi.org/10.1007/s00382-013-1830-9.

——, and Coauthors, 2018: Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models. *Nat. Geosci.*, **11**, 155–163, https://doi.org/10.1038/s41561-018-0059-y.

Vautard, R., A. Colette, E. Van Meijgaard, F. Meleux, G. Jan, F. O. Oldenborgh, I. Tobin, and P. Yiou, 2017: Attribution of wintertime anticyclonic stagnation contributing to air pollution in western Europe [in "Explaining Extreme Events of 2016 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **99** (1), S70–S75, https://doi.org/10.1175/BAMS-D-17-0113.1.