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Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm

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1. Introduction

- In the winter season of 2015-16, an extraordinary increase in the Arctic surface air temperature (SAT) was observed after an extreme Atlantic windstorm entered the Arctic Circle in late December 2015. This storm, which was named 'Frank' by the U.K. Met Office, recorded a minimum central pressure of 928 hPa on 30 December 2015.
- In particular, the SAT locally increased to the extreme value of approximately 30°C higher than the normal SAT in January over the Eurasian Arctic sector. This event appeared to be super-extreme in the sense that no warming event had developed as rapidly as this event or maintained for such a long period. This case is 'unprecedented' for the available period of modern data and provides an invaluable opportunity to scrutinize a slice of extreme warming in the Arctic.
- In this study, we show that the extreme storm event caused a large heat and moisture intrusion into the Arctic and triggered the subsequent operation of multiple feedback mechanisms, resulting in the record Arctic warming event.

Table S1. Top four extreme Arctic warming events for 58 winter seasons of 1958-2015. Normalized daily PCT is used to define extreme Arctic warming events. The Arctic warming events are identified by the consecutive period during which the normalized PCT exceeds one standard deviation. The extreme Arctic warming events are identified by the consecutive period during which the normalized PCT exceeds two standard deviations.

Rank	Start	End	Duration (days)
1	29 December 2015	6 February 2016	40
2	25 January 2014	17 February 2014	24
3	30 January 2012	20 February 2012	22
4	2 January 1977	20 January 1977	19
	28 November 2007	16 December 2007	

2. Arctic warming in January 2016

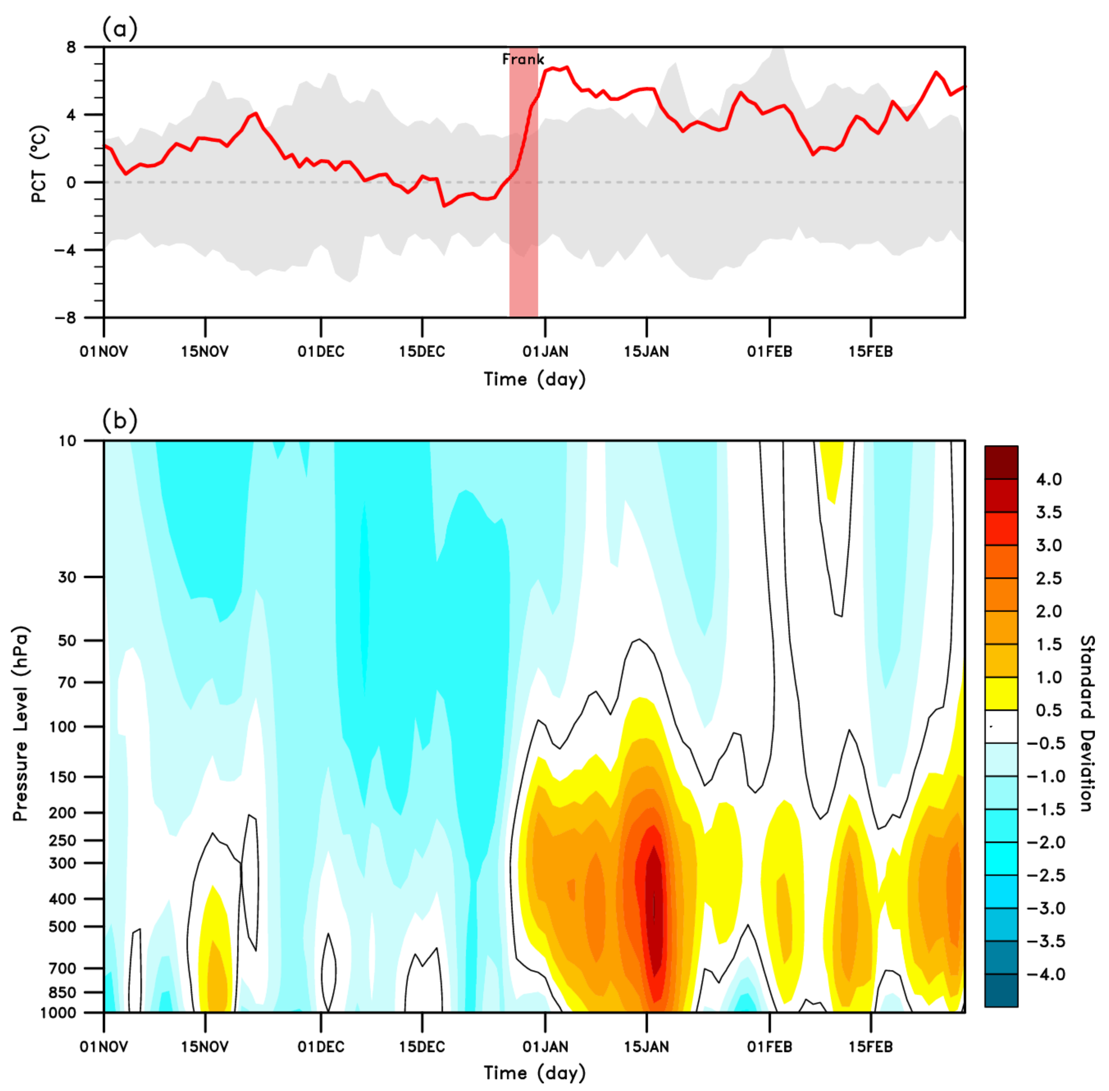
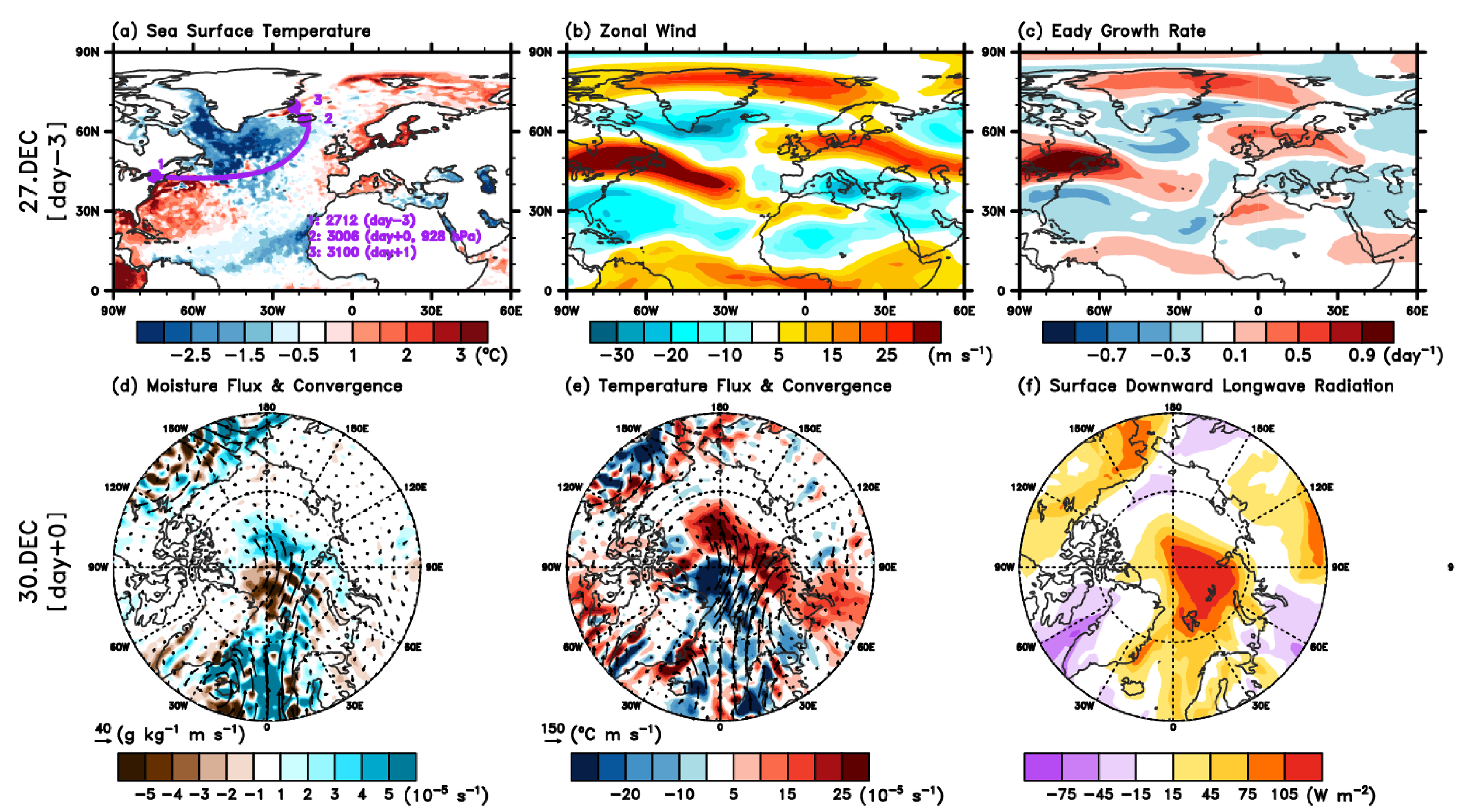


Figure 1. Observed anomalies of SAT and normalized geopotential height over the polar cap: (a) Polar cap (north of 65°N) SAT anomalies (PCT; red line) and (b) normalized polar cap geopotential height anomalies (PCH; shading) at 32 pressure levels from 1 November 2015 to 28 February 2016. In (a), the range of historical daily SAT anomalies are shaded using the data from 1979-80 to 2014-15 and the transparent red bar indicates the lifetime of Storm Frank. The black solid lines in (b) show zero anomalies.

Table 1. List of the top five strongest windstorms that occurred in the North Atlantic during the winter seasons of 1979-2015.

Rank	Name	Date	Minimum central pressure (hPa)
1	Braer	11 January 1993	913
2	Noname	15 December 1986	916
3	Dirk	24 December 2013	927
4	Frank	30 December 2015	928
5	Vivian	26 February 1990	940

3. Storm Frank and changes in Arctic circulation



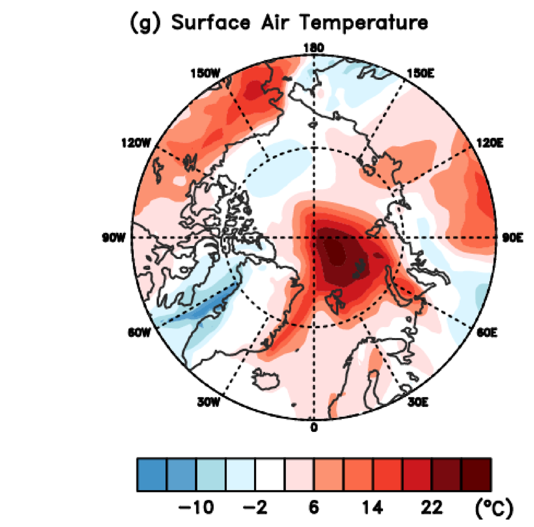


Figure 2. Anomalous atmospheric and SST conditions for the initial date (day -3) and the peak date (day 0) of Storm Frank: (a) SST (shading) and storm trajectory (purple line), (b) 300-hPa zonal wind, (c) Eady growth rate between 200 and 850 hPa, (d) 850-hPa moisture flux (arrows) and its convergence (shading), (e) 850-hPa temperature flux (arrows) and its convergence (shading), (f) surface downward longwave radiation (downward positive), and (g) SAT.

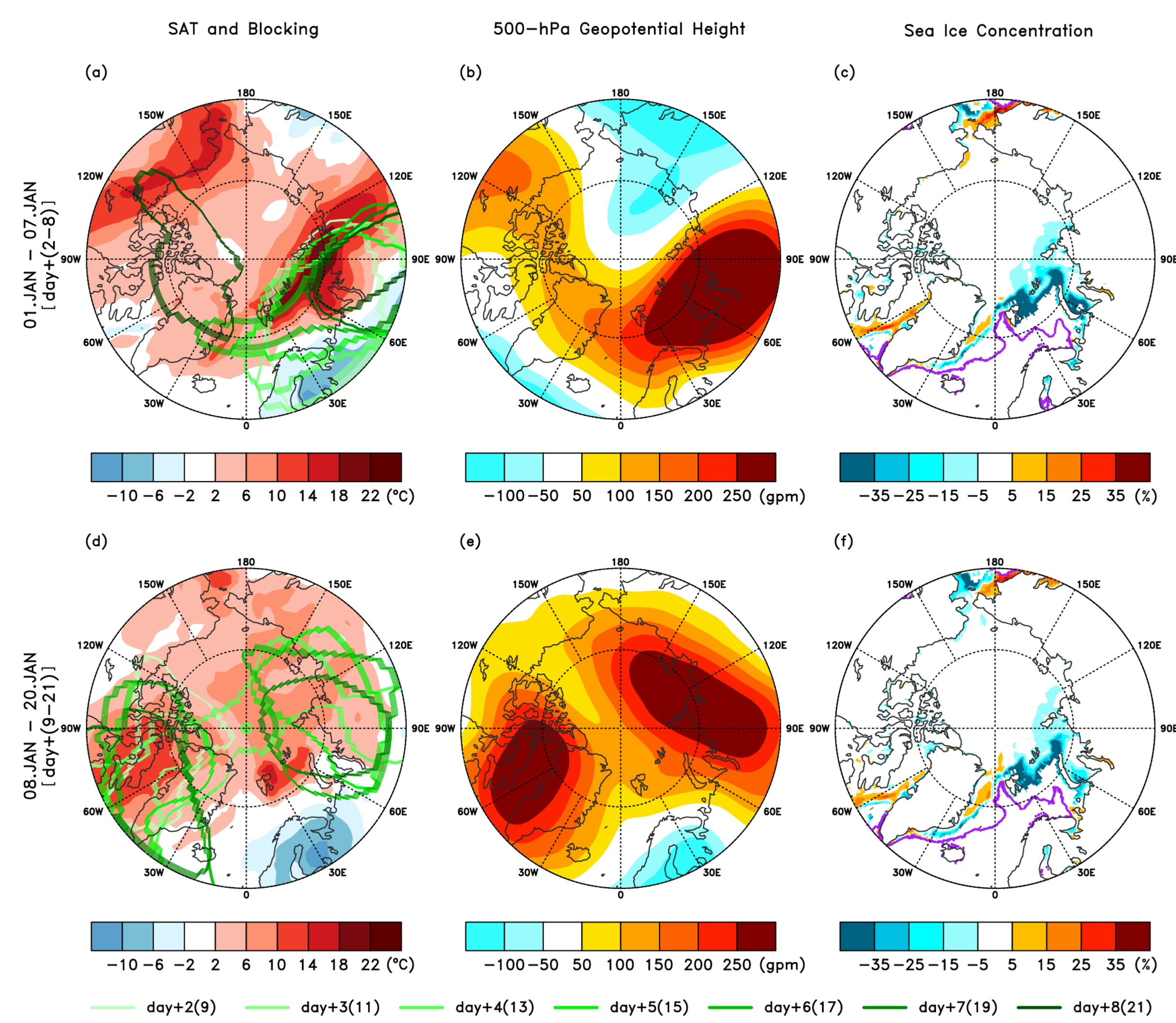


Figure 3. Atmospheric and sea ice responses after the termination of Storm Frank: (a, d) averaged SAT anomalies (shading) and individual blocking areas (coloured closed curves), (b, e) averaged 500-hPa geopotential height anomalies, and (c, f) sea ice concentration anomalies. Upper rows and lower rows contain the first seven days (1-7 January) and the next 13 days (8-20 January), respectively. In (a) and (d), the coloured curves denote the timing of the blocking event with brighter colours for earlier dates and darker colours for later dates. In (c) and (f), the purple coloured lines depict climatological sea ice edge boundaries (sea ice concentration of 15%). As with previous figures, 30 December is defined as day 0.

4. Model simulation results

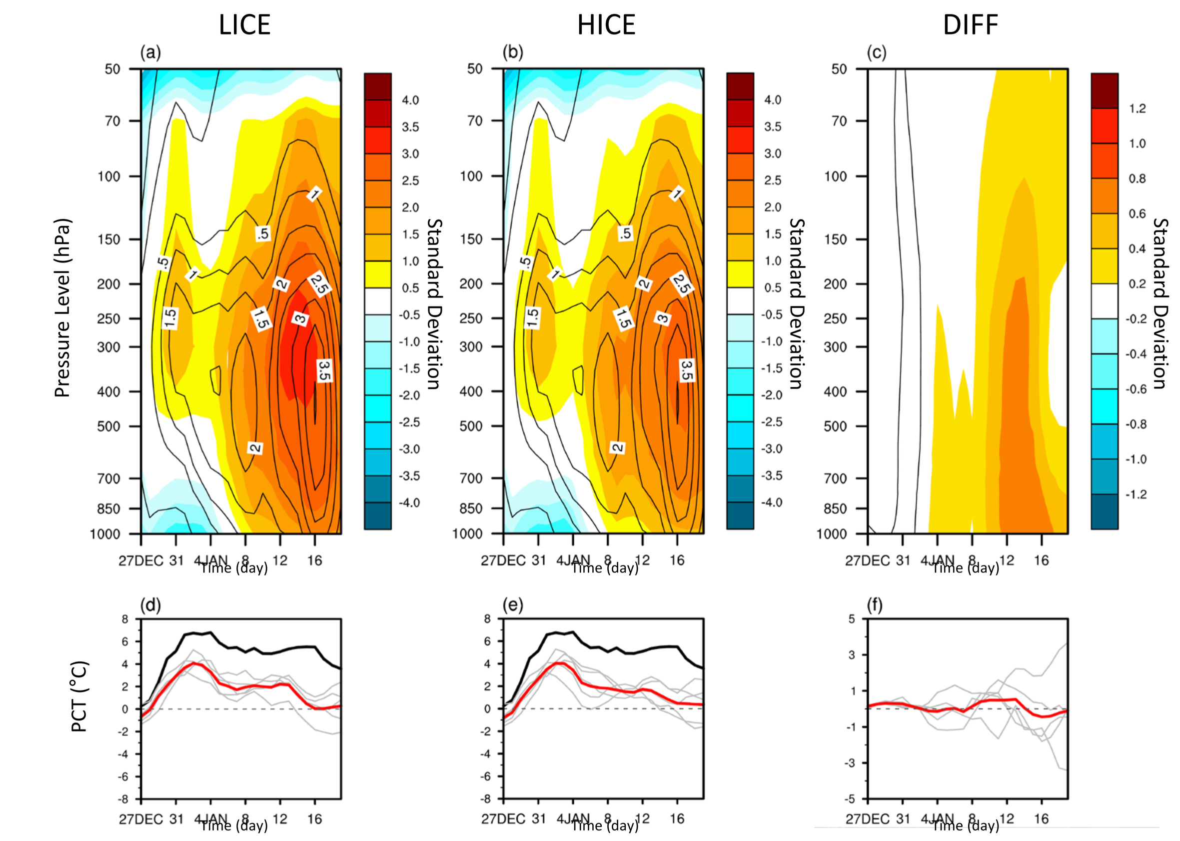


Figure 4. Model-simulated PCH and PCT: Ensemble mean of (a, b) the normalized polar cap geopotential height anomalies (shading) and (d, e) the polar cap SAT anomalies (red line) from 27 December 2015 through 23 January 2016 from the Polar WRF ensemble experiments. The corresponding variables from the JRA55 data are overlaid with black contours for the geopotential height anomalies and a black line for the polar cap SAT anomalies. The geopotential height anomalies in (a) and (b) are normalized by the standard deviation for the period of 1981-2010. The left column and middle column correspond to a low sea ice condition (LICE) and a high sea ice condition (HICE), respectively, and the right column (c, f) contains their differences (LICE minus HICE). The black solid lines in (c) show the zero anomalies. The gray lines for the bottom panels indicate the results from individual ensemble members.

5. Discussion

- Although this single event cannot be directly linked to the concept of Arctic amplification, this extremely anomalous event in the Arctic may have lingering effects on slow-varying sea ice and ocean, which may contribute to Arctic amplification of a recent warming trend. Yet, it is not known whether this event is an archetype of what has been happening recently under the Arctic warming trend. We should investigate whether triggering a pulse of Arctic warming by an intense synoptic storm that enters the Arctic and the subsequent development of planetary-scale blocking flows, as in this case, have contributed to Arctic warming. This advanced topic on a climatic time scale requires additional investigation.

6. Data and definitions of key variables

- The meteorological variables are obtained from the Japanese 55-year Reanalysis data. The high-resolution National Oceanic and Atmospheric Administration (NOAA) optimum interpolation SST version 2 dataset (OISST v2) is used for the sea ice cover and SST. These datasets are used for both the observational analyses and the lower boundary conditions of the model experiments. The period of the main analyses for the 2015-16 winter event encompasses 1 November 2015 to 28 February 2016. The anomalies are calculated based on the 30-yr climatology for the period of 1981-2010. The National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis (FNL) data are obtained to initialize the model and prescribe the lateral boundary condition.
- The Arctic warming event is quantitatively measured using the PCT, which is defined as the SAT anomaly averaged inside the Arctic Circle (north of 65°N). An indicator of large-scale weather regimes is defined by the PCH, which is obtained by averaging geopotential height anomalies over the area north of 65°N and normalizing the averaged anomaly by the standard deviation for each of the pressure levels. By definition, it is negatively correlated with the NAM.
- To investigate the sensitivity of Arctic warming to the sea ice conditions, two sets of ensemble numerical experiments are performed using the Polar Weather Research and Forecast model (WRF) with a 36 km horizontal resolution.
- Please refer to Kim et al. (*Accepted in Scientific Reports on 1 December 2016*) for detailed specifications of the model experimental design and blocking detection algorithm.