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SUPPLEMENTARY INFORMATION

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Reduced European aerosol emissions suppress winter extremes over northern Eurasia

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Contents:

Supplementary Text 1: Recipe for the calculation of local wave activity (LWA)

We illustrate the calculation of LWA using the weather map on 1200 UTC 13 Feb 1983. The calculation is performed for the latitudes of 20N-90N. The detailed calculation procedure is listed below.

1. Choose a latitude of interest, ϕ. Use 50 N as an example here.
2. Determine the corresponding Z_{500} contour such that the equivalent latitude of the contour satisfies $\phi_e = \phi$. The equivalent latitude is obtained from the area from the Z_{500} contour to the North Pole via box counting and converting the area to a hypothetical equivalent latitude such that the contour is zonally symmetric. SI Fig. 7a gives the Z500 contour (solid red) with the equivalent latitude of 50N (dashed red).
3. Compute the eddy term $\hat{z} = z - Z_{500}$. For the calculation at each latitude, only the values between the latitude ϕ and contour Z_{500} will be used. See SI Fig. 7b. Note that z is the actual geopotential height, and ž is the difference between the actual geopotential height and the Z_{500} for the equivalent latitude.
4. The line integral for the southern cyclonic LWA is computed at the longitude λ by box-counting $\hat{z}$ in the southern grid boxes relative to the latitude ϕ_e that satisfy $\hat{z} \leq 0$. Similarly, the northern anticyclonic LWA is calculated for the northern grid boxes satisfying $\hat{z} \geq 0$. LWA at $\phi = 50$N is shown in SI Fig. 7c. This is compared with the product of the zonal amplitude $\hat{z}$ and meridional amplitude $\hat{\phi}$ of a planetary wave described in ref[1], where $\hat{z}$ is the deviation of the geopotential height from the zonal mean, and $\hat{\phi}$ is the meridional displacement of the contour. In the small amplitude limit, LWA=$-0.5a\hat{z}\hat{\phi}$[2], where a is Earth's radius.
5. Repeat steps 1-4 for all the other latitudes. The longitude by latitude map of LWA is shown in SI Fig. 7d.

Supplementary Text 2: Jet Stream Sinuosity Analysis.

The transient sinuosity of the meandering jet stream provides a direct description of the ongoing weather systems in mid-latitudes. The slower but wavier jet stream is generally accompanied by more extreme weather systems, such as low/high pressure and strong frontal systems. The sinuosity of the jet stream is typically defined as the ratio between the length of a trajectory and the length of the shortest straight line between two points. We derive the transient sinuosity of the jet stream (abbreviated as sinuosity hereafter) based on the 6-hourly geopotential height at 500 hPa from the reanalysis data. We first calculate Z500 mean value ($\bar{Z}$) for a mean latitude ($\bar{\phi}$) over a certain latitude zone in NH (20-80° in this study), and then find the contour line of Z in the 2-D map of Z500. The sinuosity is the ratio between the length of the contour line and the length of the latitude circle for $\bar{\phi}$. Such an index was developed to study the jet stream response to global warming[3].

The winter NH mean sinuosity during 1970-2005 shows an essentially insignificant declining trend with a fractional change of about -1.0% per decade and p-value of 0.19 (Supplementary Figure 2). The hemispheric mean similarity between LWA and sinuosity suggests that they are equivalent in characterizing mid-latitude circulations over a large analysis domain.

Supplementary Text 3: LWA correlation with climate oscillation indices

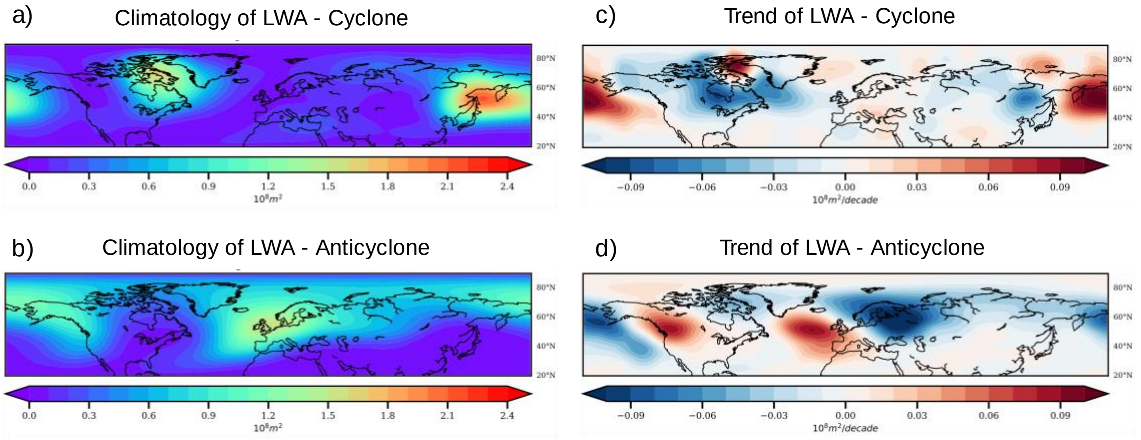
By individually correlating the time series of seasonal Northern Hemisphere mean LWA with six climate oscillation indices, we are able to identify those that explain the weather extreme variability on the interannual time scale. The Arctic Oscillation (AO, or NAM) and the North Atlantic Oscillation (NAO) are the two most pronounced climate variabilities exhibiting close relationships with LWA over Northern Hemisphere mid-latitudes, with correlation coefficients about −0.83 and −0.66, respectively. The anti-correlations agree with previous studies that analyzed those relationships in different time periods[4]. The PDO exhibits a much weaker correlation with LWA, with a coefficient of +0.33. The Stratospheric variability (Strato.), El Niño-Southern Oscillation (ENSO), and Quasi-Biennial Oscillation (QBO) play even smaller roles in the year-to-year variability of LWA, with the coefficients < 0.1.

1 Screen, J. A. & Simmonds, I. Exploring links between Arctic amplification and mid-latitude weather, *Geophys. Res. Lett.*, **40**(5), 959–964, doi:10.1002/grl.50174 (2013).

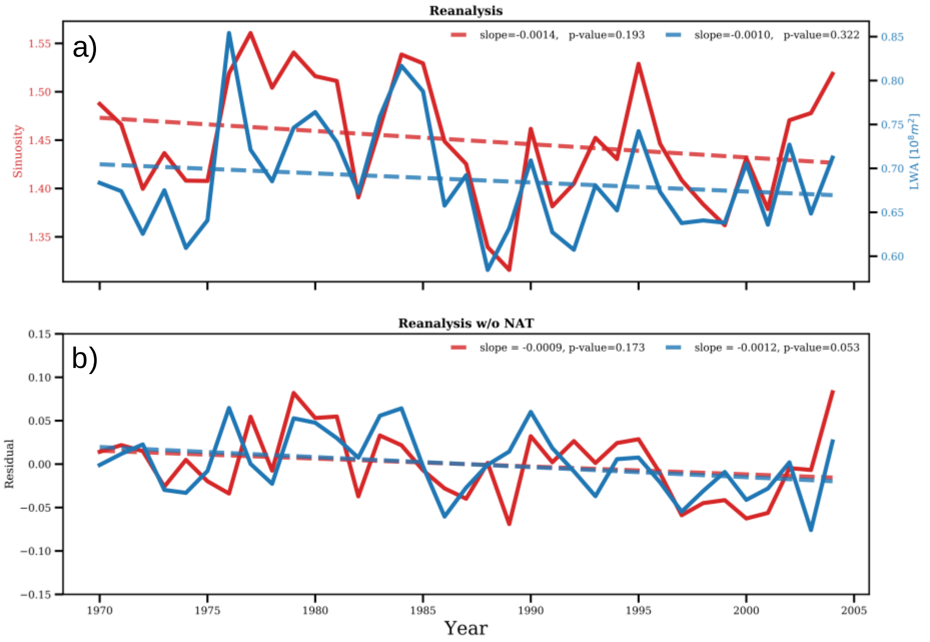
2 Chen, G., Lu, J., Burrows, D. A. & Leung, L. R. Local finite-amplitude wave activity as an objective diagnostic of midlatitude extreme weather, *Geophys. Res. Lett.*, **42**(24), 10,952-10,960, doi:10.1002/2015GL066959 (2015).

3 Cattiaux, J., Peings, Y., Saint-Martin, D., Trou-Kechout, N. & Vavrus, S. J. Sinuosity of midlatitude atmospheric flow in a warming world. *Geophys. Res. Lett.* **43**, 8259-8268, doi:10.1002/2016gl070309 (2016).

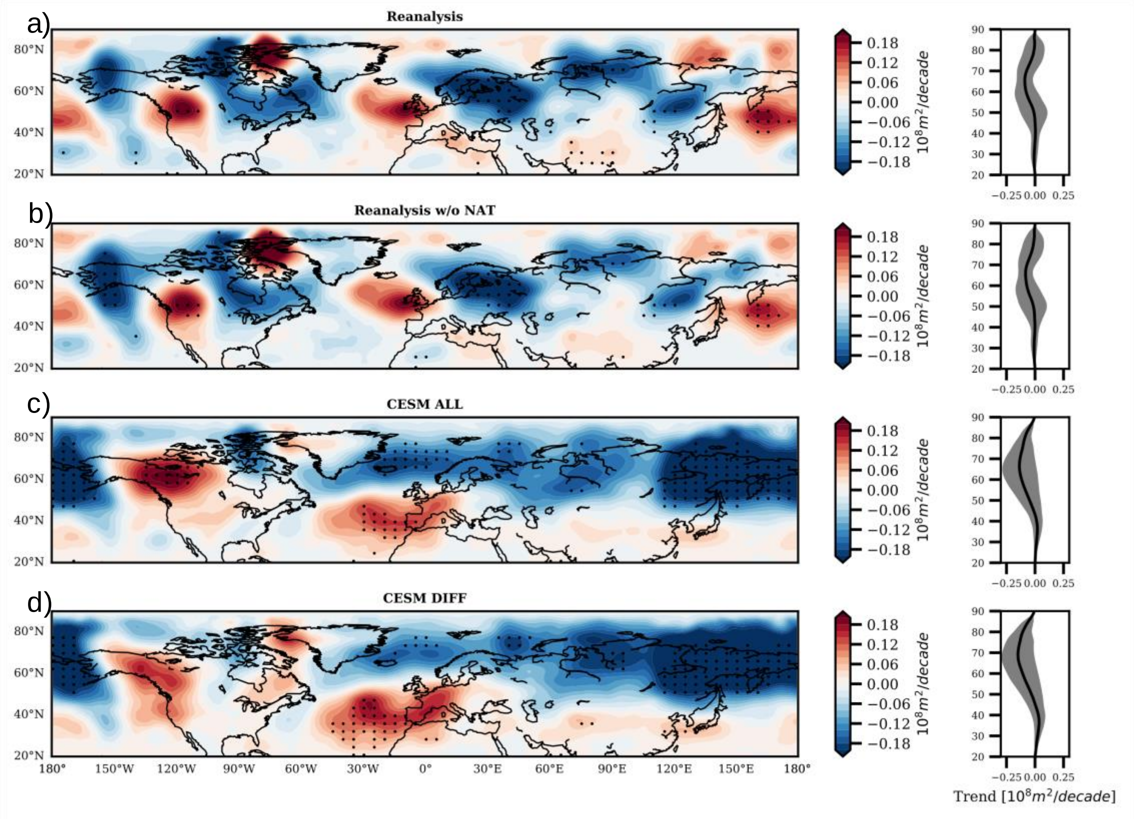
4 Liu, J. P., Curry, J. A., Wang, H. J., Song, M. R. & Horton, R. M. Impact of declining Arctic sea ice on winter snowfall. Proc. Nat. Acad. Sci. U.S.A. 109, 4074-4079, doi:10.1073/pnas.1114910109 (2012).



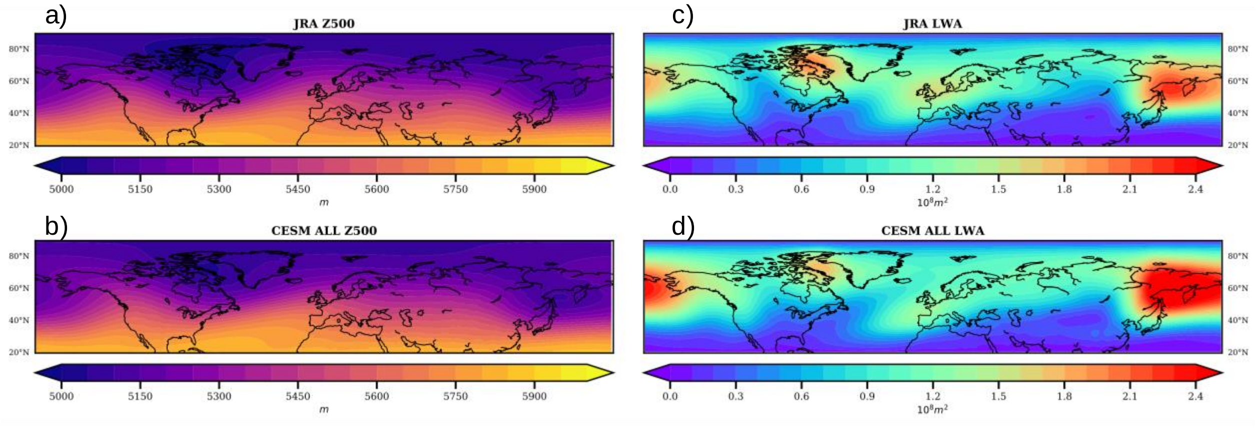
Supplementary Figure 1. Climatology and trends (1970-2005) of cyclonic and anticyclonic wave activities based on JRA-55.



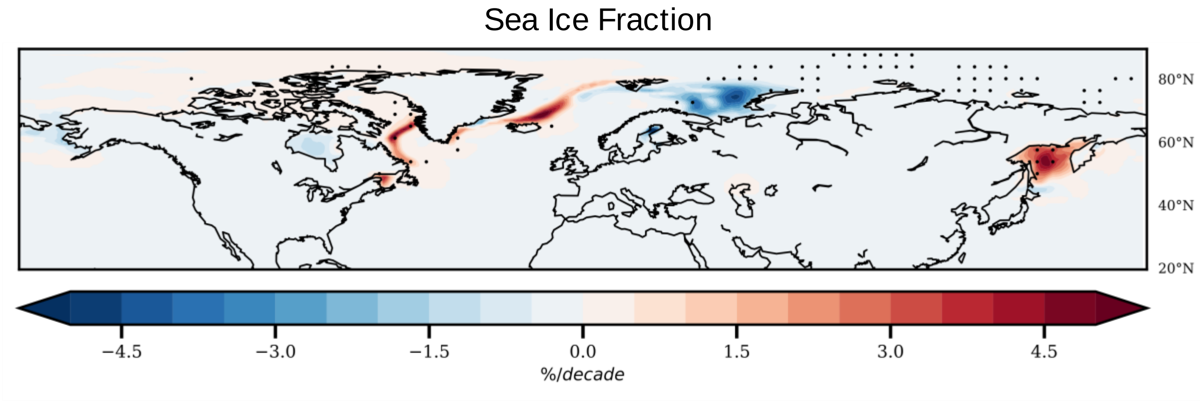
Supplementary Figure 2. Northern Hemispheric trends of jet stream sinuosity and local wave activity (LWA) during 1970-2005 based on JRA55 Reanalysis. The bottom panel shows the results with removal of natural variability (NAT) by the multivariate linear regression method.



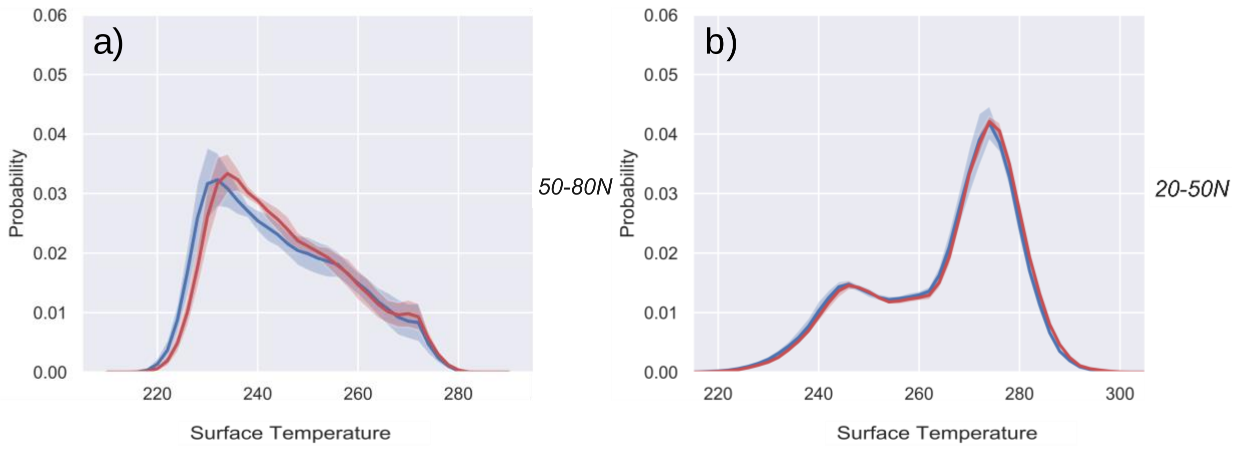
Supplementary Figure 3. Same with Figure 1 but for top 10% LWA during each season. They indicate the extreme LWA cases and strongest cyclonic/anticyclonic events



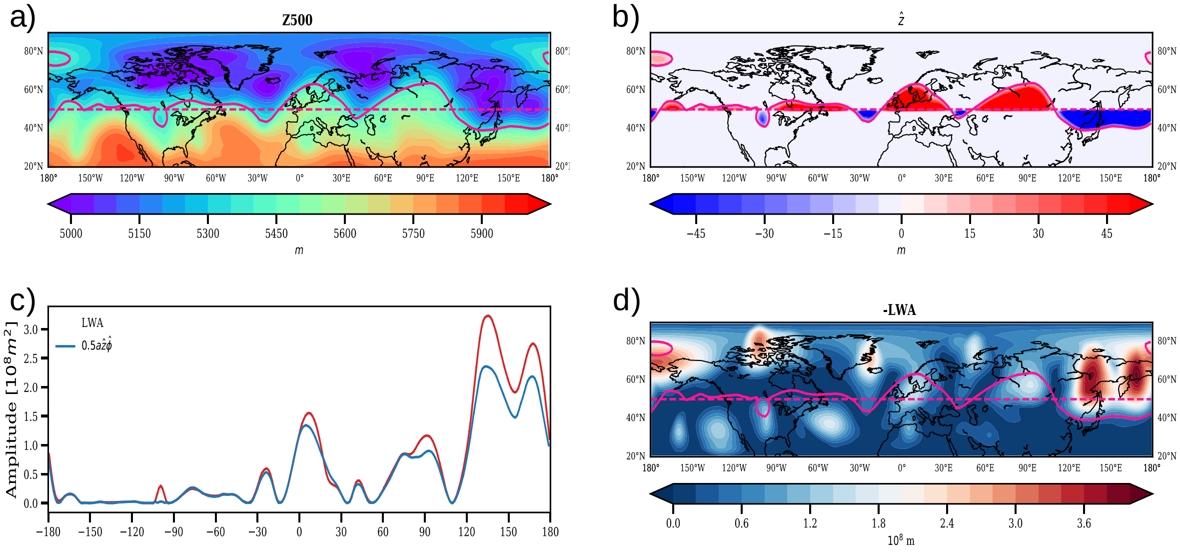
Supplementary Figure 4. Comparison of climatological geopotential height at 500 hPa (Z500) and local wave activity (LWA) between JRA-55 and the CESM all forcing experiment.



Supplementary Figure 5. CESM model simulated trends of sea ice fraction.



Supplementary Figure 6. CESM simulated Probability Distribution Function (PDF) of wintertime $T_{\min}$ averaged over two periods, 1970-1975 (blue) and 2000-2005 (red), under the all-but-aerosol forcing scenario. The shades in the PDFs denote the spread (1-σ) among different years in each period.



SI Figure 7. (a) Z_{500} as a function of longitude and latitude. (b) The eddy term $\hat{z}$ plotted between the latitude 50N and the contour with the equivalent latitude $\phi_e = 50$N. (c) LWA at 50N as a function of longitude (red). The product of the zonal amplitude $\hat{z}$ and meridional amplitude $\hat{\phi}$ of a planetary wave (blue). In the small amplitude limit, |LWA|=$0.5a\hat{z}\hat{\phi}$. (d) -LWA as a function of longitude and latitude. In (a), (b) and (d), the contour with the equivalent latitude $\phi_e = 50$N is shown in solid red, and the latitude 50N is in dashed red.