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Arctic amplification dominated by temperature feedbacks in contemporary climate models

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Climate change is amplified in the Arctic region. Arctic amplification has been found in past warm[1] and glacial[2] periods, as well as in historical observations[3,4] and climate model experiments[5,6]. Feedback effects associated with temperature, water vapour and clouds have been suggested to contribute to amplified warming in the Arctic, but the surface albedo feedback—the increase in surface absorption of solar radiation when snow and ice retreat—is often cited as the main contributor[7–10]. However, Arctic amplification is also found in models without changes in snow and ice cover[11,12]. Here we analyse climate model simulations from the Coupled Model Intercomparison Project Phase 5 archive to quantify the contributions of the various feedbacks. We find that in the simulations, the largest contribution to Arctic amplification comes from a temperature feedbacks: as the surface warms, more energy is radiated back to space in low latitudes, compared with the Arctic. This effect can be attributed to both the different vertical structure of the warming in high and low latitudes, and a smaller increase in emitted blackbody radiation per unit warming at colder temperatures. We find that the surface albedo feedback is the second main contributor to Arctic amplification and that other contributions are substantially smaller or even oppose Arctic amplification.

A quantitative understanding of the physical mechanisms underlying Arctic amplification is key to developing confidence in and constraining model projections of Arctic climate change, and to focusing research efforts and model–data comparisons on the most important processes. It is well established that Arctic amplification is in part caused by the surface albedo feedback[5,11,13]. Although the Intergovernmental Panel on Climate Change's fourth assessment report stated that it was not clear whether the surface albedo feedback was the main cause of Arctic amplification[14], many recent studies indicate or assume that surface albedo feedback is the main cause[7–10]. However, Arctic amplification does occur in models without surface albedo feedback[11,12] and Arctic amplification in coupled climate models (Fig. 1) has been shown to be primarily caused by feedbacks acting on terrestrial longwave radiation[15]. The latter implies that the surface albedo feedback, which changes the absorption of solar shortwave radiation, can play only a secondary role in causing Arctic amplification. Important contributions to Arctic amplification have been suggested to result from the water vapour feedback caused by the greenhouse effect of additional water vapour[12], the cloud feedback due to changes in the effect of clouds on the Earth's radiative balance[16] and the lapse-rate feedback associated with the vertical structure of warming[5,17]. Changes in atmospheric[18] and oceanic heat transport[6,19,20] are also thought to contribute to Arctic amplification.

The direct impact of rising temperatures on outgoing longwave radiation at the top of atmosphere (TOA; temperature feedback) can be decomposed into a contribution from vertically uniform warming of the surface and troposphere (Planck feedback) and a contribution from tropospheric warming that deviates from the vertically uniform profile (lapse-rate feedback). The lapse-rate feedback connected to the vertical structure of atmospheric warming is known to contribute to stronger Arctic than tropical warming[5,17]. In the tropics, air parcels rising in deep convective clouds create a tight coupling between surface and upper-tropospheric temperatures. In a warming climate, these air parcels release more latent heat, steepening the moist adiabatic lapse rate and thus causing greater warming in the upper troposphere than at the surface. Under this top-heavy warming profile, a smaller increase in surface temperatures is required to offset a given TOA imbalance. In the Arctic, cold dense air close to the surface is hardly mixed with the lighter air aloft, leaving radiation as the primary coupling mechanism. Radiative coupling does not impose a certain lapse rate and surface-based warming remains confined to the lowermost parts of the atmosphere. Under this bottom-heavy warming profile, a larger increase in surface temperatures is required to offset a given TOA imbalance. The lapse-rate feedback is therefore negative in the tropics and positive in the Arctic.

The Planck feedback is generally overlooked as a contributor to Arctic amplification, even though the underlying physics is well established[21]. The longwave radiation (R) emitted by the Earth's surface rises with temperature (T) following $R = \epsilon\sigma T^4$, where ϵ is the surface emissivity close to unity and σ the Stefan–Boltzmann constant. Thus, a given increase in emitted radiation requires a larger temperature increase at colder background temperatures. For example, at 30 °C, an external forcing of 1 W m^{-2} can be balanced by a 0.16 °C warming, whereas at −30 °C a 0.31 °C warming is required to balance the same forcing. As the Arctic is colder than the tropics, the Planck feedback in itself causes Arctic amplification.

The local temperature change required to offset the radiative imbalance caused by a given forcing or feedback corresponds to that mechanism's warming contribution. We assess individual contributions to Arctic amplification as the difference between contributions to Arctic and tropical warming (Fig. 2). Beyond the simple example quoted above, and accounting for the effects of atmosphere and clouds, the radiative flux change at the surface and TOA associated to a known surface temperature change can be computed from radiative kernels[22]. We here invert the kernel method to compute the local warming contributions of the feedbacks. The contribution of the Planck feedback's spatial structure to the spatial structure of warming is estimated as the difference between the warming response for a globally averaged and for the local Planck feedback (Methods).

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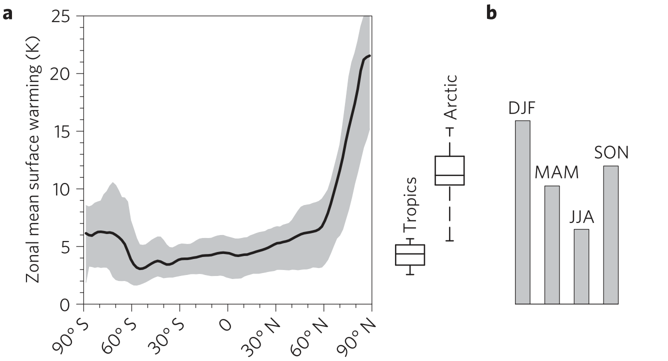

Figure 1 | Arctic amplification in CMIP5 models. a, Zonal mean surface temperature change for the last 30 years of the CMIP5 4 × CO_2 experiment compared with the last 30 years of the control run. Box and whisker plots show the median (lines), 25th to 75th percentiles (boxes) and full spread (whiskers) of temperature change averaged over the tropics (30° S–30° N) and the Arctic (60° N–90° N). **b**, Bars show the intermodel mean warming for different seasons. Intermodel mean warming is 11.2 K in the Arctic and 4.3 K in the tropics. Arctic warming is strongest in winter (15.9 K) and weakest in summer (6.5 K). March–May, MAM; September–November, SON.

Based on a conventional decomposition of feedbacks using TOA fluxes (Fig. 2a), the largest contributor to Arctic amplification is the lapse-rate feedback, followed by the surface albedo and Planck feedbacks. Although in absolute terms, the surface albedo feedback contributes slightly more to Arctic warming, the lapse-rate feedback additionally reduces tropical warming and therefore makes a greater contribution to Arctic amplification, as can be inferred from the distance to the 1:1 line. The water vapour feedback and CO_2 radiative forcing both lead to greater warming in the tropics, opposing Arctic amplification[23,24].

Instead of considering warming and moistening of the atmosphere as separate feedback mechanisms, they can be understood as one feedback caused by warming at constant relative humidity, plus a small feedback accounting for changes in relative humidity[25]. This feedback decomposition assigns only a slightly larger contribution to Arctic amplification to the alternative lapse-rate feedback (Arctic: +3.8 K, tropics: −2.2 K) than to the surface albedo feedback (Arctic: +5.7 K), whereas the effect of the alternative Planck feedback on Arctic amplification is close to zero. In the fixed relative humidity framework, the contributions of the temperature–moisture and the surface albedo feedback to Arctic amplification are thus of roughly equal importance.

Arctic warming is stronger in winter (December–February, DJF) than summer (June–August, JJA; Fig. 1b). The strong winter warming has been linked to the release of heat stored in the ocean and to increases in downwelling longwave radiation[26], but a quantitative understanding of the seasonal cycle of individual feedback mechanisms is lacking. From a TOA perspective, the surface albedo and water vapour feedbacks contribute to stronger summer warming but are outweighed by seasonal heat storage in the ocean and the lapse-rate feedback (Fig. 2b). Seasonal heat storage in the ocean, including latent heat of melting sea ice, mitigates about two-thirds of the summertime effect of surface albedo change. Heat from the ocean is released to the atmosphere in winter, which in combination with the positive lapse-rate feedback causes the well-known pattern of winter-amplified Arctic warming. In summer, when atmospheric stability is much weaker than in winter, the Arctic lapse-rate feedback is actually slightly negative.

Surface temperature change can be readily understood through TOA fluxes if the troposphere is essentially well-mixed and changes in the tropospheric temperature profile follow simple physical principles, such as the steepening of the moist adiabat in a warmer climate[24]. These assumptions do not hold in the Arctic, where a positive lapse-rate feedback represents a decoupling between surface and troposphere. The TOA-based feedback decomposition is thus internally consistent, but somewhat unsatisfying from a physical point of view, because the Arctic lapse-rate feedback reflects the breakdown of an assumption of vertical coupling rather than a specific physical mechanism. By analysing feedbacks at the surface in addition to the TOA, we can further understand what causes the surface amplification of Arctic warming reflected in the lapse-rate feedback (Fig. 2c).

At the surface, the temperature feedback can be decomposed into a negative surface warming feedback (longwave radiation emitted from the surface) and a positive atmospheric warming feedback corresponding to the downwelling longwave radiation received by the surface. The largest contribution to Arctic amplification arises from the surface temperature feedback and is due to the smaller increase in longwave emissions per unit of warming at colder temperatures. This nonlinear dependence of blackbody emissions on temperature plays a greater role from a surface than a TOA perspective because the meridional temperature gradient at the surface is larger than that in the troposphere. The atmospheric temperature feedback contributes to Arctic amplification because

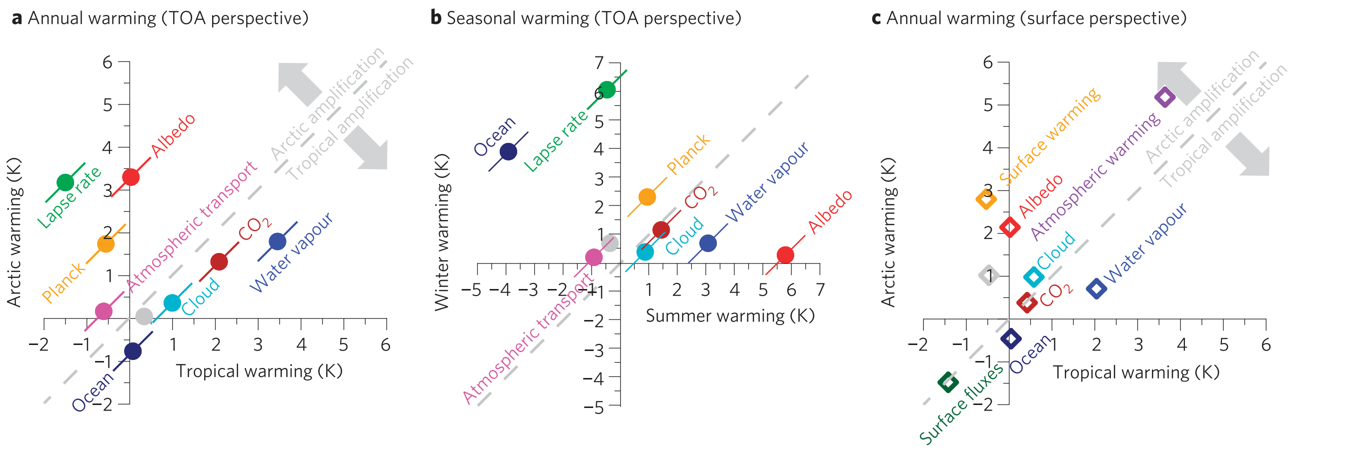

Figure 2 | Warming contributions of individual feedback mechanisms. a, Arctic versus tropical warming from a TOA perspective. **b**, Arctic winter versus summer warming. **c**, Arctic versus tropical warming from a surface perspective. For **a**,**c**, feedbacks above the 1:1 line contribute to Arctic amplification, whereas feedbacks below the line oppose Arctic amplification. Grey is the residual error of the decomposition. 'Ocean' includes the effect of ocean transport changes and ocean heat uptake.

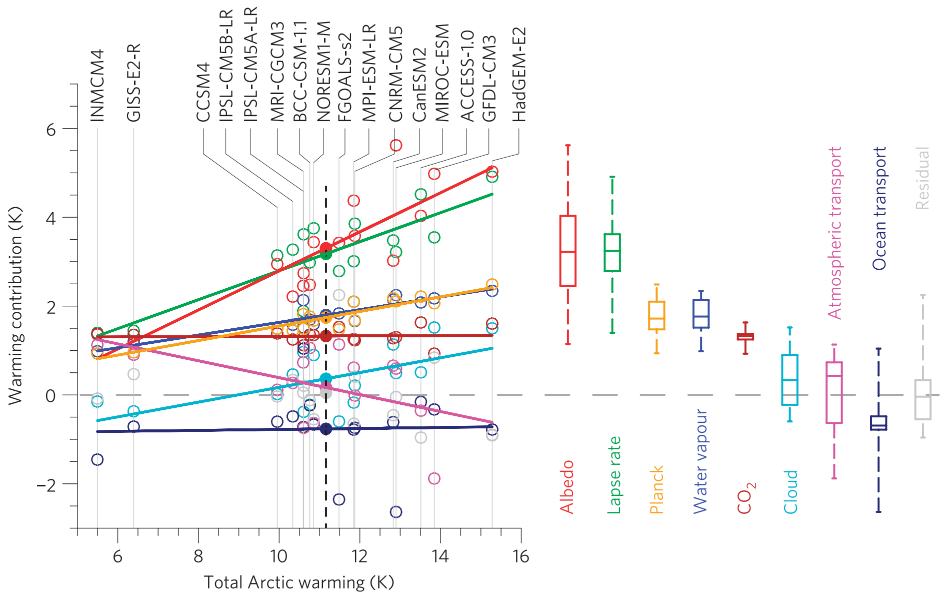

Figure 3 | Intermodel spread of Arctic warming contributions of feedbacks versus total Arctic warming in individual models. Lines are linear regressions of feedback contributions against total Arctic warming. Filled circles on the black vertical line represent the ensemble mean. The right-hand side shows the spread of Arctic warming contributions in the analysed models. Boxes show the median, 25th and 75th percentiles, and whiskers show the full ensemble spread.

the near-surface atmosphere warms more in the Arctic than the tropics. Previous studies decomposing Arctic feedbacks from a surface perspective[10] used a methodology that implicitly includes the spatial structure of the temperature feedback and therefore did not identify the key role of the surface temperature feedback's structure for Arctic amplification.

In the annual mean, cloud feedback opposes Arctic amplification from a TOA perspective, but makes a small contribution to Arctic amplification from a surface perspective. Within the lowest 1–2 km of the Arctic atmosphere, cloud-top temperatures are often similar to surface temperatures[27]. Under these circumstances, low-level clouds hardly affect TOA longwave fluxes because the clouds radiate upwards at roughly the same temperature as the surface, but increase downward longwave radiation and thus warm the surface at the expense of the atmosphere. An increase or thickening of such clouds in a warming climate as predicted by models hardly affects cloud feedback from a TOA perspective, but causes a positive cloud feedback at the surface. Likewise, the water vapour feedback contributes more to summer than winter warming from a TOA perspective, but has a stronger contribution to surface warming in winter than in summer (not shown)[22].

Besides quantifying the different contributions to Arctic amplification in the ensemble mean, it is valuable to understand why models differ in their degree of Arctic amplification[6]. Our analysis shows that intermodel spread in Arctic warming is dominated by the spread in local feedback mechanisms, not meridional transport changes (Fig. 3). Changes in atmospheric heat transport dampen intermodel spread because they are more positive in models with little Arctic warming. This is consistent with results from an energy balance model used to reconstruct warming and transport changes in the Coupled Model Intercomparison Project Phase 3 (CMIP3; ref. 28). In the ensemble mean, atmospheric heat transport does contribute to Arctic amplification by enhancing Arctic and reducing tropical warming (Fig. 2a). Contrary to physical intuition, poleward atmospheric energy transport does not scale with the meridional temperature gradient within individual models, but increases in most models despite a reduction in the Equator-to-pole temperature gradient. Increasing latent energy transports overcompensating the decrease of dry static energy transport have been shown to cause such behaviour of climate models[18,29]. Changes in ocean transport and ocean heat uptake are not correlated with total Arctic warming across different models.

To develop confidence in model projections of future Arctic warming, it is necessary to quantitatively understand the role of different physical mechanisms for Arctic amplification. Contrary to a widespread assumption, temperature feedbacks are the most important contributors to Arctic amplification in contemporary climate models. The surface albedo feedback is the second main contributor, whereas other suggested drivers of Arctic amplification either play minor roles or even oppose Arctic amplification in the ensemble mean.

Methods

Previous studies analysing the role of different feedbacks for Arctic amplification have often diagnosed feedbacks based on TOA and surface fluxes routinely included in climate model output[9,15,26]. These methods provide a precise assessment of longwave and shortwave flux changes, but cannot quantify the temperature changes associated to individual feedback mechanisms. Here, we use and extend the radiative kernel technique[22] to overcome this limitation.

A radiative kernel k_i is the change in TOA radiation ΔR_i caused by a small change in the climate variable x_i, for example a one per cent change in surface albedo (dx_i): $k_i = dR/dx_i$. The TOA flux change caused by one feedback in a climate change experiment can be estimated as $\Delta R_i = k_i \cdot \Delta x_i$, where Δx_i is for instance the surface albedo change between the control and perturbed climate. We use this established technique to compute the flux change caused by each feedback and extend the method to convert flux changes into temperature responses associated with each feedback.

The warming response to a TOA flux imbalance is decomposed into three components: a global mean Planck feedback, the local deviation from the global mean Planck feedback and the effect of the lapse-rate feedback, that is, deviations from vertically uniform warming, on surface temperature change:

$$\Delta T = \sum_i \left(\Delta R_i \left(\frac{\overline{dT}}{dR} + \frac{dT'}{dR} + \frac{dT^{LR}}{dR} \right) \right)$$

The warming contribution, for example of the surface albedo feedback, is:

$$\Delta T_a = \Delta R_a \left(\frac{\overline{dT}}{dR} \right)$$

and the contribution of the Planck feedback's deviation from its global mean is:

$$\Delta T_P = \sum_i \left(\Delta R_i \frac{dT'}{dR} \right)$$

The local warming contribution of the lapse-rate feedback is:

$$\Delta T_{\mathrm{LR}} = \sum_i \left(\Delta R_i \frac{\mathrm{d}T}{\mathrm{d}R}^{\mathrm{LR}} \right)$$

The warming response to a unit flux imbalance is the inverse of the vertically integrated temperature kernel, $\mathrm{d}T/\mathrm{d}R = 1/\int k_T\,\mathrm{d}p$, which we obtain by summing over the surface temperature kernel and all levels of the tropospheric temperature kernel. By averaging across latitudes and longitudes, we decompose this into the mean inverted kernel and a local deviation. To obtain the full warming response including the effect of the lapse-rate feedback, each level/is weighted by its warming relative to surface warming when vertically integrating the temperature kernel $\int k_{T,\mathrm{weighted}} = k_{\mathrm{Ts}} + \int (k_{Tl} \cdot (\Delta T_l/\Delta T_s)\,\mathrm{d}p)$.

In the surface-based feedback analysis, the inverted surface temperature kernel alone is used to compute the warming response, whereas atmospheric temperature change is treated as a feedback contributing to the surface flux imbalance. The surface temperature response is separated into a global mean component and the local deviation analogous to the Planck feedback:

$$\Delta T = \sum_i \left(\Delta R_{s,i} \left(\overline{\frac{\mathrm{d}T_s}{\mathrm{d}R_s}} + \frac{\mathrm{d}T_s}{\mathrm{d}R_s}' \right) \right)$$

Atmospheric heat convergence is computed as the difference between TOA and surface fluxes, assuming no storage of heat in the atmosphere on the timescale of the experiment. Changes in oceanic heat convergence and ocean heat uptake, which are non-zero on the timescale considered, are computed as changes in total surface fluxes. To separate tropospheric and stratospheric responses, we assume a tropopause height of 100 hPa in the tropics (30° S–30° N) decreasing linearly with latitude to 300 hPa at the poles. We use surface downward and upward shortwave fluxes to compute the effective albedo. Monthly mean data from the last 30 years of the CMIP5 pre-industrial control and $4 \times CO_2$ runs are averaged into monthly climatologies for the feedback calculations. Radiative kernels were obtained from the MPI-ESM-LR control climate[30]. Using kernels from the $4 \times CO_2$ runs leads to a smaller role of the albedo feedback[30] and using kernels from other models[22] leads to larger residuals but does not qualitatively change the conclusions here.

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References

1. Barron, E. J. A warm, equable cretaceous: The nature of the problem. *Earth-Sci. Rev.* **19,** 305–338 (1983).
2. Dahl-Jensen, D. *et al.* Past temperatures directly from the greenland ice sheet. *Science* **282,** 268–271 (1998).
3. Chapman, W. L. & Walsh, J. E. Recent variations of sea ice and air temperature in high latitudes. *Bull. Am. Meteorol. Soc.* **74,** 33–47 (1993).
4. Bekryaev, R. V., Polyakov, I. V. & Alexeev, V. A. Role of polar amplification in long-term surface air temperature variations and modern arctic warming. *J. Clim.* **23,** 3888–3906 (2010).
5. Manabe, S. & Wetherald, R. The effects of doubling the CO_2 concentration on the climate of a general circulation model. *J. Atmos. Sci.* **32,** 3–15 (1975).
6. Holland, M. & Bitz, C. Polar amplification of climate change in coupled models. *Clim. Dynam.* **21,** 221–232 (2003).
7. Serreze, M. C. & Francis, J. A. The arctic amplification debate. *Climatic Change* **76,** 241–264 (2006).
8. Screen, J. A. & Simmonds, I. The central role of diminishing sea ice in recent arctic temperature amplification. *Nature* **464,** 1334–1337 (2010).
9. Crook, J. A., Forster, P. M. & Stuber, N. Spatial patterns of modeled climate feedback and contributions to temperature response and polar amplification. *J. Clim.* **24,** 3575–3592 (2011).
10. Taylor, P. C. *et al.* A decomposition of feedback contributions to polar warming amplification. *J. Clim.* **26,** 7023–7043 (2013).
11. Hall, A. The role of surface albedo feedback in climate. *J. Clim.* **17,** 1550–1568 (2004).
12. Graversen, R. G. & Wang, M. Polar amplification in a coupled climate model with locked albedo. *Clim. Dynam.* **33,** 629–643 (2009).
13. Arrhenius, S. On the influence of carbonic acid in the air upon the temperature of the ground. *London, Edinburgh, Dublin Phil. Mag. J. Sci.* **41,** 237–276 (1896).
14. IPCC. *Climate Change 2007: The Physical Science Basis* (Cambridge Univ. Press, 2007) .
15. Winton, M. Amplified Arctic climate change: What does surface albedo feedback have to do with it? *Geophys. Res. Lett.* **33,** L03701 (2006).
16. Vavrus, S. The impact of cloud feedbacks on Arctic climate under greenhouse forcing. *J. Clim.* **17,** 603–615 (2004).
17. Bintanja, R., van der Linden, E. & Hazeleger, W. Boundary layer stability and Arctic climate change: A feedback study using EC-Earth. *Clim. Dynam.* **39,** 2659–2673 (2012).
18. Manabe, S. & Wetherald, R. T. On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. *J. Atmos. Sci.* **37,** 99–118 (1980).
19. Khodri, M. *et al.* Simulating the amplification of orbital forcing by ocean feedbacks in the last glaciation. *Nature* **410,** 570–574 (2001).
20. Spielhagen, R. F. *et al.* Enhanced modern heat transfer to the arctic by warm atlantic water. *Science* **331,** 450–453 (2011).
21. Planck, M. Ueber das gesetz der energieverteilung im normalspectrum. *Ann. Phys.* **309,** 553–563 (1901).
22. Soden, B. *et al.* Quantifying climate feedbacks using radiative kernels. *J. Clim.* **21,** 3504–3520 (2008).
23. Zhang, M., Hack, J., Kiehl, J. & Cess, R. Diagnostic study of climate feedback processes in atmospheric general circulation models. *J. Geophys. Res.* **99,** 5525–5537 (1994).
24. Hansen, J., Sato, M. & Ruedy, R. Radiative forcing and climate response. *J. Geophys. Res.: Atm.* **102,** 6831–6864 (1997).
25. Held, I. & Shell, K. Using relative humidity as a state variable in climate feedback analysis. *J. Clim.* **25,** 2578–2582 (2012).
26. Bintanja, R. & van der Linden, E. The changing seasonal climate in the arctic. *Sci. Rep.* **3,** 1556 (2013).
27. Serreze, M., Schnell, R. & Kahl, J. Low-level temperature inversions of the Eurasian Arctic and comparisons with Soviet drifting station data. *J. Clim.* **5,** 615–629 (1992).
28. Hwang, Y-T., Frierson, D. M. & Kay, J. E. Coupling between arctic feedbacks and changes in poleward energy transport. *Geophys. Res. Lett.* **38,** L17704 (2011).
29. Held, I. M. & Soden, B. J. Robust responses of the hydrological cycle to global warming. *J. Clim.* **19,** 5686–5699 (2006).
30. Block, K. & Mauritsen, T. Forcing and Feedback in the MPI-ESM-LR coupled model under abruptly quadrupled CO_2. *J. Adv. Model. Earth Syst.* **5,** 1–16 (2013).

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Author contributions

T.M. developed the ideas that led to this paper. F.P. developed the inverted kernel method, analysed the model data and wrote the main paper with comments and input from T.M.

Additional information

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Competing financial interests

The authors declare no competing financial interests.