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Published in:
Environmental Research

DOI:
10.1088/2752-5295/acee9e

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2023

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Bintanja, R., Grand Graversen, R., & Kolbe, M. (2023). Regional polar warming linked to poleward moisture transport variability. *Environmental Research*, *2*(4), Article 041003. https://doi.org/10.1088/2752-5295/acee9e

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ENVIRONMENTAL RESEARCH
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To cite this article: Richard Bintanja *et al* 2023 *Environ. Res.: Climate* **2** 041003

IOP Publishing Environ. Res.: Climate 2 (2023) 041003 https://doi.org/10.1088/2752-5295/acee9e

ENVIRONMENTAL RESEARCH
CLIMATE

RECEIVED
23 February 2023

REVISED
12 June 2023

ACCEPTED FOR PUBLICATION
9 August 2023

PUBLISHED
14 September 2023

LETTER

Regional polar warming linked to poleward moisture transport variability

Richard Bintanja[1,2,*], **Rune Grand Graversen**[3,4] **and Marlen Kolbe**[2]

[1] Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
[2] Energy and Sustainability Research Institute Groningen (ESRIG), University of Groningen, Groningen, The Netherlands
[3] Department of Physics and Technology, University of Tromsø, Tromsø, Norway
[4] Norwegian Meteorological Institute, Tromsø, Norway
[*] Author to whom any correspondence should be addressed.

E-mail: richard.bintanja@knmi.nl and r.bintanja@rug.nl

Keywords: regional, polar, moisture, transport, Arctic, warming, Antarctic

Supplementary material for this article is available online

Abstract

Polar warming, ice melt and strong precipitation events are strongly affected by episodic poleward advection of warm and moist air (Woods and Caballero 2016 *J. Clim.* **29** 4473–85; Wille *et al* 2019 *Nat. Geosci.* **12** 911–6), which, in turn, is linked to variability in poleward moisture transport (PMT) (Nash *et al* 2018 *J. Geophys. Res. Atmos.* **123** 6804–21). However, processes governing regional impacts of PMT as well as long-term trends remain largely unknown. Here we use an ensemble of state-of-the-art global climate models in standardized scenario simulations (1850–2100) to show that both the Arctic and the Antarctic exhibit distinct geographical patterns of PMT-related warming. Specifically, years with high PMT experience considerable warming over subarctic Eurasia and West-Antarctica (Raphael *et al* 2016 *Bull. Am. Meteorol. Soc.* **97** 111–21), whereas precipitation is distributed more evenly over the polar regions. The warming patterns indicate preferred routes of atmospheric rivers (Woods and Caballero 2016 *J. Clim.* **29** 4473–85), which may regionally enhance atmospheric moisture content, cloud cover, and downward longwave radiative heating in years with comparatively high PMT (Scott *et al* 2019 *J. Clim.* **32** 665–84). Trend-analyses reveal that the link between PMT-variability and regional precipitation patterns will weaken in both polar regions. Even though uncertainties associated with intermodel differences are considerable, the advection of warm and moist air associated with PMT-variability is likely to increasingly cause mild conditions in both polar regions, which in the Arctic will reinforce sea-ice melt. Similarly, the results suggest that warm years in West-Antarctica disproportionally contribute to ice sheet melt (Trusel *et al* 2015 *Nat. Geosci.* **8** 927–32), enhancing the risk of ice-sheet instabilities causing accelerated and sudden sea-level rise.

1. Introduction

Climate models show that in the Earth's atmosphere, moisture is continuously and increasingly transported towards the polar regions [1, 2], causing elevated polar atmospheric moisture levels and cloud formation. This, in turn, tend to warm the surface and the lower atmosphere by reinforcing downward infrared radiation, thereby contributing to accelerated polar warming [3, 4] (note however that low clouds tend to cool the climate, especially over low-albedo (such as ice-free) surfaces which will occur more often as sea ice melts). Another important consequence concerns enhanced polar precipitation [1], which due to the strong warming increasingly consists of rainfall instead of snowfall [5, 6]. Analyses of climate model simulations reveal that PMT will substantially increase in a warming climate [1, 2]. This is caused primarily by atmospheric moisture increasing mostly at lower latitudes, thereby enhancing meridional humidity gradients [7] (this is opposed to some degree by near-surface polar amplification). Altered atmospheric dynamics may

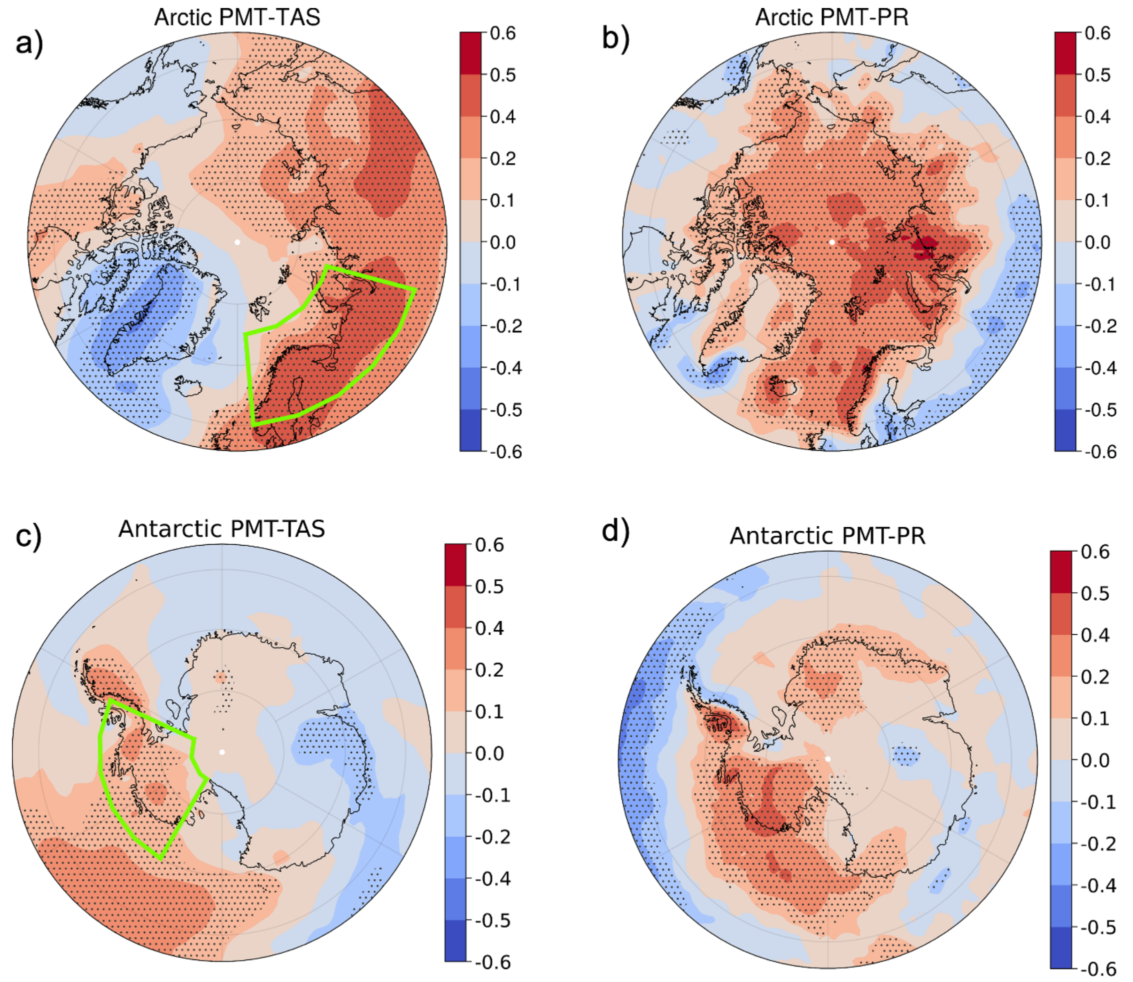

Figure 1. Correlations between interannual PMT at 67.5° N and Arctic (a) temperature and (b) precipitation, and between interannual PMT at 67.5° S and Antarctic (c) temperature and (d) precipitation. Results represent annual means for present-day conditions (1981–2010), CMIP6 model-mean. The 'hotspot' regions denoted by green lines in (a) and (c) are defined to represent areas with relatively high positive correlation between PMT and temperature. Stippled regions indicate where the correlations are significant (see Methods).

also play a role (e.g. shifts in predominant Rossby wave structure [8] and cyclone pathways [9]), at least regionally. Moreover, PMT exhibits strongly enhanced interannual variability in a warming climate [2], governing polar precipitation variability and the likelihood of warm extremes. PMT-variability is dominated by episodic and regional events of strong moisture transport (also known as atmospheric rivers), and there is evidence that the episodic nature [10] and/or the intensity of PMT will increase [11], thereby potentially reinforcing future trends in extreme polar warming, ice melting, and wettening events [12].

In addition, exceptionally warm events/years will cause disproportionally strong melt of permafrost, snow, sea ice, and land ice, in both polar regions [4]. This suggests that there is a firm link between the occurrence of atmospheric rivers transporting moisture towards the polar regions, enhancement of transport variability, and increased frequency and severity of melt events [13]. Sea ice and snow melt will in turn amplify polar warming through the ice-albedo feedback, especially in the Arctic, whereas land ice melt will contribute to sea level rise. The latter is particularly important in West-Antarctica, where extensive melt events may destabilize the ice sheet, causing ice sheet desintegration and rapid sea level rise [14]. The inherent episodic nature of PMT and atmospheric rivers render future projections of extreme warming and precipitation events quite uncertain, however. Moreover, the spatial patterns and seasonal distributions related to PMT-related warming, including the governing processes, are currently not well known, mainly because of uncertainties in the pathways of moisture transport (which are likely model-dependent). Also, future trends in polar warming/wettening attributable to PMT and atmospheric rivers are underinvestigated, which severely hinders estimates of potential impacts (on e.g. ice melt, sea level).

2. Results

Here we use an ensemble of state-of-the-art global climate models Coupled Model Intercomparison Project, phase 6 (CMIP6) in standardized scenario simulations (historical and SSP5-8.5) [15] to show that in the current climate, interannual variability in PMT is strongly related to specific surface warming patterns in both polar regions (figure 1). In the Arctic, years with high PMT are associated with warming over central Canada and especially over subarctic Eurasia and adjacent parts of the Arctic Ocean. In contrast, such events are associated with cooling in the remainder of the Arctic region, in particular Greenland. This temperature pattern seems to be associated with large-scale Rossby-wave structures, mostly wave 2 since the surface layer pressure correlations exhibit an elliptic shape centered at the North Pole (figure 2(a)). This flow pattern causes transport of heat and moisture northward in the Atlantic sector and cold, dry Arctic air to the south over Greenland (figure 2(a)) causing cold anomalies, especially in winter (supplementary figure 1) [8, 16]. During summer, correlations are generally weaker and even negative (but hardly significant) over virtually the entire Arctic Ocean, which may at least partially be related to the fact that most of the Arctic Ocean is at the melting point, which inhibits warming (supplementary figure 1(c)), and that clouds in summer tend to have a cooling effect.

In winter, the temperature correlation pattern closely resembles the warm Arctic—cold Eurasia dipole signature that is likely associated with the properties and magnitude of the atmospheric jetstream and cyclone activity as dictated by the positive phase of large-scale modes of variability such as the NAO [17] (supplementary figure 1(a)). The NAO-positive phase pattern corresponds to enhanced poleward PMT [18] especially in the Atlantic sector and may as such contribute to reduced sea ice in the Barents-Kara Seas region [19]. Over Eurasia, strong PMT is associated with a predominant west-southwesterly circulation transporting cyclones and relatively warm/moist air into the region (figure 2(a)), with winter surface warming exacerbated by the enhanced greenhouse effect (due to clouds and moisture anomalies) (supplementary figure 2) and possibly by continental surface inversions [13]. A similar dipole warming pattern linked to PMT-variability is found in reanalyses data (supplementary figure 3), showing that current climate models fairly well simulate the atmospheric processes involved in PMT variability. However, multimodel mean correlations are generally a bit lower compared to the reanalyses, which can be attributed to diverging correlation values and patterns between individual models. The relatively low correlations suggest that other mechanisms also contribute to polar temperature and precipitation variability, such as surface evaporation, sea ice processes, lapse-rate and surface inversion mechanisms, which contributions may change differently in future climates (e.g. surface evaporation and surface fluxes will enhance considerably with retreating sea ice).

Over Antarctica, the temperature response to PMT variability is dominated by strong positive correlations over West-Antarctica and a very small or even slightly negative response elsewhere (figure 1(c)), a pattern that is present in both summer and winter (supplementary figure 4), and also in reanalyses data (supplementary figure 5). Strong surface warming in high-PMT years are linked to a dominant pressure distribution characterized by a high surface pressure over the Amundsen Sea and the adjacent Drake Passage (figure 2(b)) [20, 21], which invokes east-southeastward advection of relatively warm and moist air onto West-Antarctica [22, 23] possibly modulated by El Niño—Southern Oscillation variability [24] and the Southern Annular Mode [25]. Once these air masses reach the Antarctic continent, enhanced moisture levels and cloudiness cause reinforced longwave (greenhouse) warming of the surface, potentially leading to wide-spread surface melt in summer [14]. Years with high PMT have been linked to elevated numbers of atmospheric river occurrences over West-Antarctica [26], thereby contributing disproportionally to surface melt, potentially destabilizing the ice sheet [14]. Variability in PMT through 67.5° S is dynamically focused on the Amundsen Sea—West-Antarctica region, with offshore high pressures directing moisture transports onshore (figure 2(b)), which tend to warm the ice sheet.

PMT not only governs polar surface air temperature patterns but also polar precipitation rates through its effect on atmospheric moisture convergence and cloud formation processes. Over the Arctic, years with high PMT cause Arctic-wide increases in precipitation (figure 1(b)), in sharp contrast to the dipole-patterned temperature response. This disparity likely signals the importance of surface-layer thermodynamic processes amplifying the temperature response over Eurasia while damping it over the Arctic Ocean. Such mechanisms do not affect precipitation rates, which primarily respond to elevated moisture convergence throughout the entire Arctic region [1, 4]. Over Antarctica, however, the precipitation response to PMT appears to mimic the temperature response (figure 1(d)), suggesting that years with strong PMT cause higher precipitation rates mainly over West-Antarctica. This may signal the aforementioned high pressures over the Amundsen Sea and the associated atmospheric river routing towards West-Antarctica as the dominant regional PMT-related mechanism governing surface temperatures as well as the precipitation response through the effect on atmospheric moisture content and clouds [14].

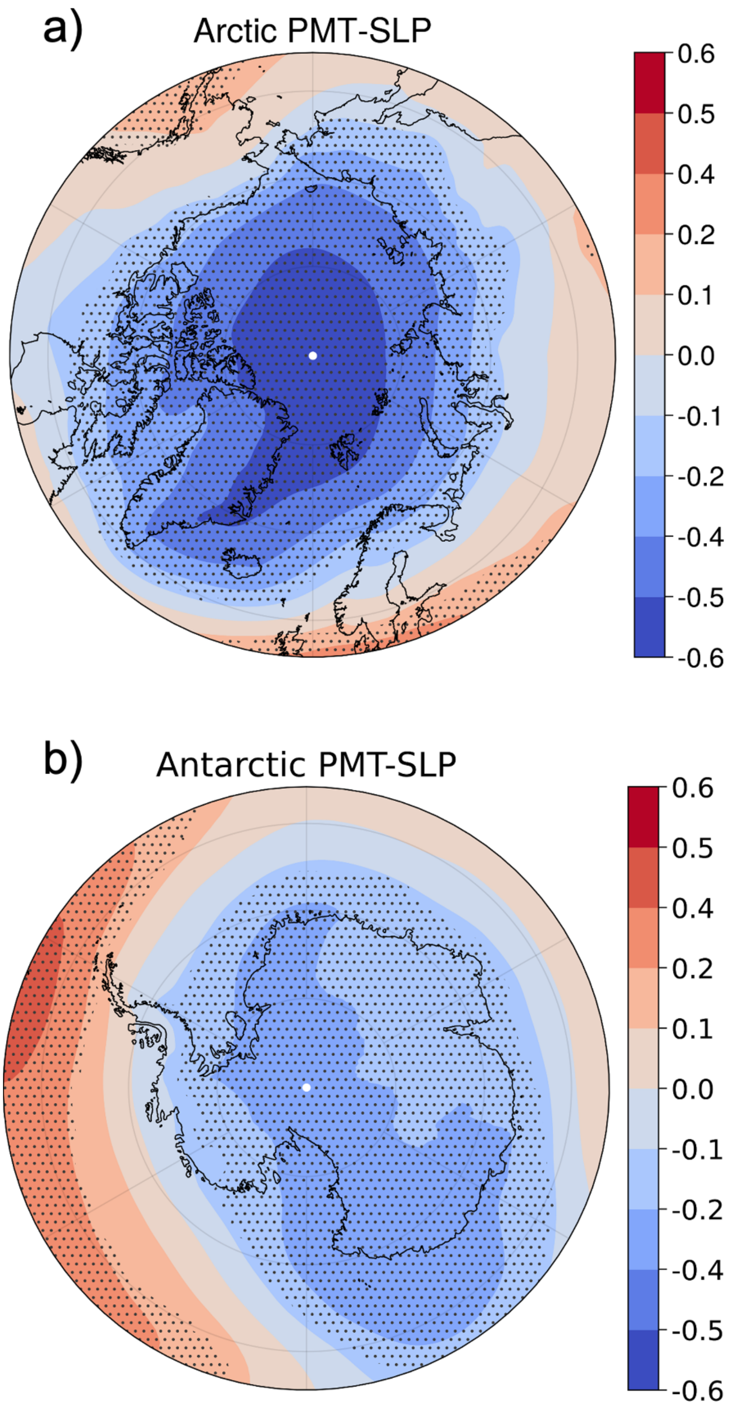

Figure 2. Correlations between (a) interannual PMT at 67.5° N and Arctic sea level pressure, and (b) interannual PMT at 67.5° S and Antarctic sea level pressure. Results represent annual means for present-day conditions (1981–2010), CMIP6 model-mean.

Given the dipole pattern in surface warming linked to interannual variations in PMT (figure 1) in both polar regions, the effect on average polar mean warming will be relatively weak because regions with positive and negative correlations will mostly cancel each other out. We therefore focus on 'hot spot' regions where the PMT-temperature correlations are maximum (subarctic Eurasia, Amundsen Sea and West-Antarctica) to highlight how individual climate models simulate the link between wintertime regional polar warming and PMT (figure 3). Clearly, even though all models exhibit a positive correlation between wintertime PMT and hotspot temperatures (both in the Arctic and the Antarctic), the magnitude of the correlation varies considerably among models. Intermodel differences are a measure of the robustness of the link between PMT and regional polar warming. The finding that all models show hotspot-warming related to positive PMT suggests that the governing processes (e.g. regional moisture advection, longwave warming related to clouds/moisture) are probably well represented, even though for the Arctic the correlations are generally

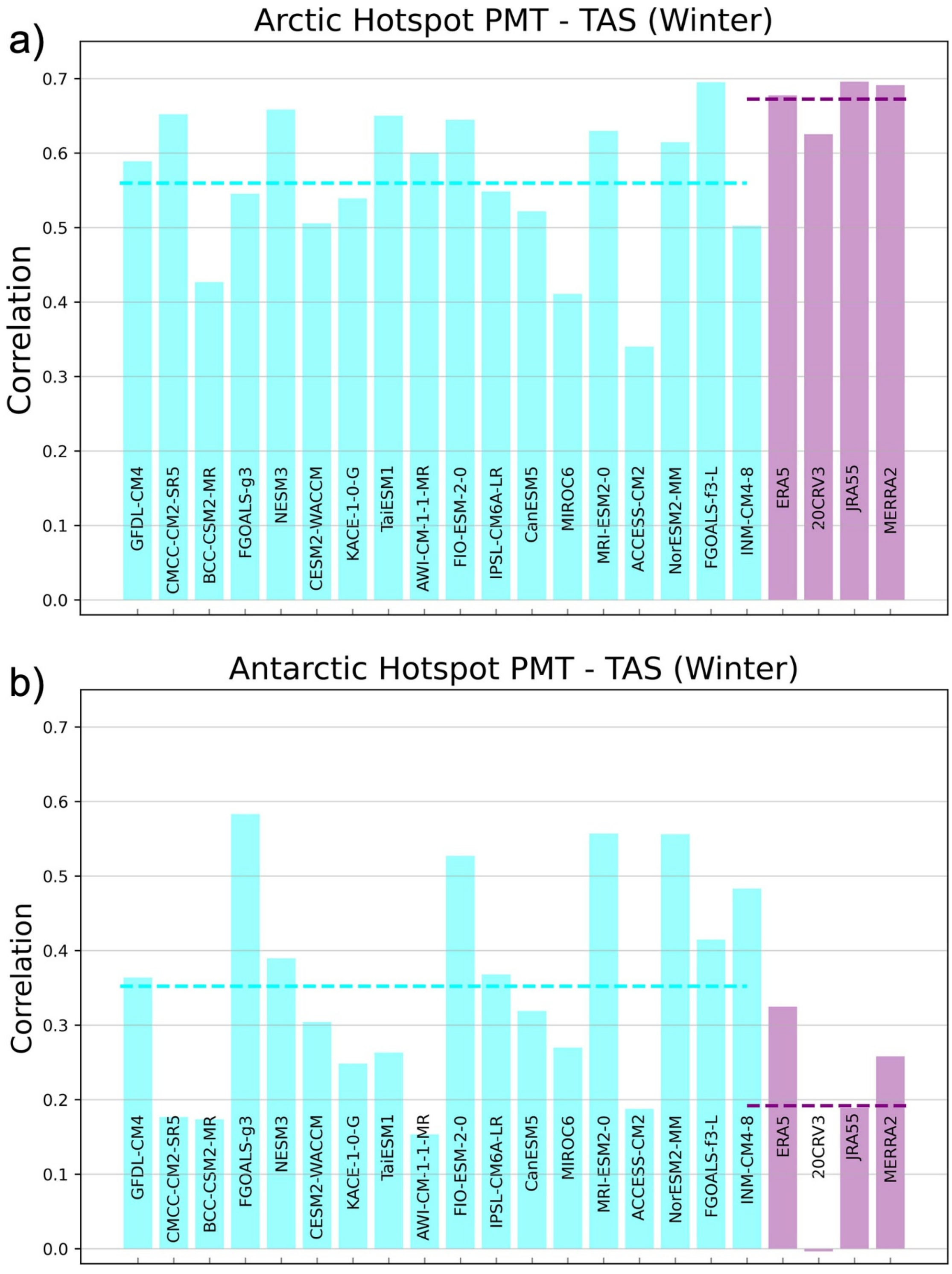

Figure 3. Correlation of (a) interannual PMT at 67.5° N and surface air temperature (DJF mean) in the Arctic hotspot region (see figure 1), and (b) interannual PMT at 67.5° S and surface air temperature (DJF mean) in the Antarctic hotspot region (see figure 1). Blue bars represent CMIP6 models (blue dashed line: model mean), purple bars reanalyses data (purple dashed line: reanalyses mean). Results are for present-day (1981–2010).

weaker compared to the reanalyses. In the Antarctic, the mean of the reanalyses estimates is lower the model-mean, and reanalyses differ widely among themselves. Correlations over Antarctica are generally lower than over the Arctic, stressing the relatively strong link between PMT and Eurasian warming in terms of consistent routing of atmospheric rivers and cyclones following the dominant pressure distribution over the North Atlantic.

Given the potential impact of years with high PMT on surface warming and ice melt (especially under continued polar warming), we have used CMIP6 multimodel trends (historical, SSP5-8.5 scenario) in 30 year moving windows to determine long-term trends in the regressions between PMT and surface warming

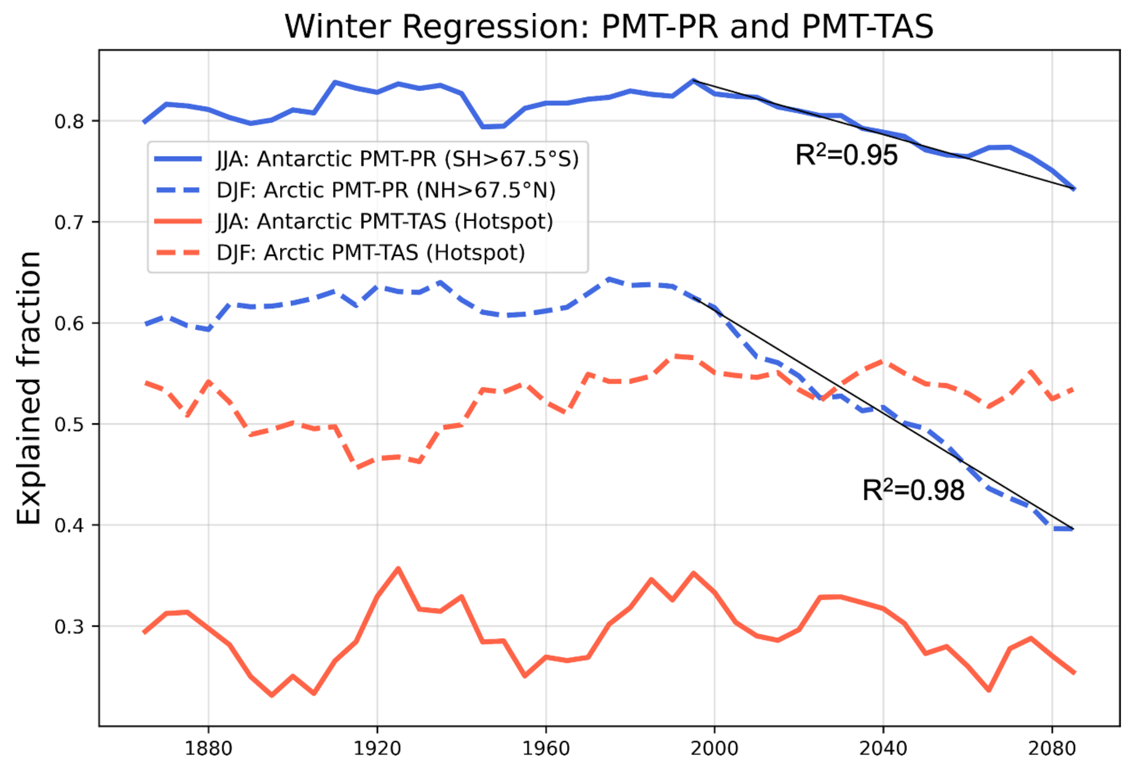

Figure 4. Fraction of hotspot temperature (N or S) and polar (67.5°–90° N or °S) precipitation variability explained by PMT variability over time. Winter (DJF or JJA) data is used in moving 30 year windows. Evaluated as the ratio of regressions between interannual PMT and temperature or precipitation times PMT, and actual temperature/precipitation anomalies. For temperature we used the hotspot regions (see figure 1) as the mean polar tempature signal is quite low due to opposing regional contributions. Black lines indicate linear trend lines from 1995 onwards (Arctic and Antarctic PMT-PR regressions have an R^2 of 0.98 and 0.95, respectively, for a p-value < 0.05). For the Arctic, 2 models did not have a negative trend; all negative trends were significant. For Antarctica, 3 models did not have a negative trend; of all negative trends, 3 were not significant (p-value > 0.05).

(hotspot) and polar mean precipitation (hence ignoring internal polar transports) so as to evaluate the wintertime fraction of temperature/precipitation variations explained by PMT variability (figure 4). While the fraction of polar precipitation explained by PMT is relatively high and constant over the entire period 1870–1995, it significantly decreases after around 1995 for both polar regions. For the Arctic this decrease can likely be attributed to increased importance of surface evaporation as a source for precipitation while sea ice recedes and open water expands [1]. In Antarctica, model results have suggested a future intensification in atmospheric rivers over the Southern Ocean, but also a poleward shift [27], which may reduce the impact of PMT to Antarctica in terms of heat and moisture transports. The importance of PMT variability for future hotspot temperature variations in both the Arctic and Antarctica seems to be fairly constant. This means that future warm years will equally likely be caused by high PMT events. However, since models show that PMT variability will strongly increase [2], this suggests that future PMT-related warming will become more intense. Also, interannual variability is superimposed on rising temperature trends in both polar regions, which likely further reinforces hotspot temperature extremes.

PMT exhibits strong interannual variations reflective of the episodic nature of the governing processes such as the occurrence of atmospheric rivers [13]. Years with high PMT are likely associated with strong regional warming in Arctic Eurasia and adjacent parts of the Arctic Ocean as well as over West-Antarctica, owing to preferred pathways of relatively warm and moist air, and reinforced by enhanced downward longwave radiation [28] (as well as other mechanisms such as local evaporation and precipitation, surface melt, atmospheric surface layer inversion changes). During such years/episodes, excessive surface melt will occur. With ongoing and accelerated polar warming, extreme warming events will likely continue to contribute disproportionally to melting of snow, sea ice, land ice and permafrost. Over West-Antarctica, the occurrence and magnitude of atmospheric rivers [29], high PMT-related events and onshore advection of warm/moist air will likely cause further widespread warming and surface melt, destabilizing the ice sheet as meltwater may creep into pre-existing crevasses leading to ice shelf break-up [30]. Hence, with ongoing polar warming, it might be expected that years with extreme and widespread surface melt related to PMT-variability and associated atmospheric processes will increasingly contribute to accelerations in sea level rise [31].

3. Methods

In all analyses we used the CMIP6 state-of-the-art global climate models [15], which were forced by historical and standardised future scenarios for the period 1850–2100. Here we use the strong (SSP5-8.5) forcing scenario, for which the combined greenhouse, aerosol and other radiative forcings in the year 2100 totals 8.5 W m^{-2}. We use all models (18) for which data coverage was complete and without obvious errors (other than that no selection of models was made); one ensemble member per model (the first) was used. We define the Arctic (Antarctic) as the region 67.5°–90° N (67.5°–90° S). PMT at 67.5° N (67.5° S) is approximated by means of PMT $= E–P$, in which E and P represent Arctic (Antarctic) mean surface evaporation and total precipitation, respectively [1]. Supplementary figures 6 and 7 show the sensitivity of the results for other definitions of PMT towards the Arctic and Antarctic regions. Changing the meridional boundary of PMT considerably alters the relation between PMT and regional polar climate, in particular for the Antarctic. This can be attributed to the proximity of the high-elevation East-Antarctic mainland to the latitude at which PMT is evaluated, which governs the magnitude of PMT in that sector.

It should be noted that CMIP models tend to overestimate current Antarctic precipitation, but may underestimate future trends in Antarctic precipitation [32]. In figures 1 and 2 (and in supplementary figures 1–7), we chose to show spatial maps of correlations instead of regressions, mainly because regressions are less useful if one of the variables (in our case precipitation) exhibits strong spatial differences (of an order of magnitude or more) over the domain. The main caveat with correlations, however, is its independence on the magnitude of the signals. Correlations were first evaluated per model, then averaged using the a transformation method based on the minimum-variance estimate [33] (we used $k = (9 * \sqrt{2} - 7)/2$). Based on a two-sided Welch's t-test (18 models, 4 reanalyses, 30 year sections), correlations are significantly different from zero at the 99%-level at all stippled regions in the multimodel 2D-plots.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank all climate-modelling groups for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. All data is available in the manuscript or the supplementary file. All climate model output data used in this study are publicly available (CMIP6 portal, renalayses centers). Authors declare no competing interests. All data needed to evaluate the conclusions in the paper are present in the paper and/or the supplementary file. Correspondence and requests for materials should be addressed to R B (richard.bintanja@knmi.nl, r.bintanja@rug.nl). This study is partly funded by The Research Council of Norway (NFR), Project Number 280727.

Author contributions

R B and R G G developed the ideas and methods that led to this paper. M K and R B analysed the climate model results. R B wrote the main paper, with regular input from R G G and M K All authors discussed the results and implications and commented on the manuscript at all stages.

ORCID iD

Richard Bintanja https://orcid.org/0000-0002-0465-5923

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