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PERSPECTIVE

A Paradigm Shift of Compound Extremes over Polar Ice Sheets

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The paradigm of compound extremes shifts from hot-dry spells over ex-polar lands to warm-wet extremes over polar ice sheets. This warm-wet synchrony is likely driven by intrusions of warm-moist air from lower latitudes, and under global warming, its net effect could destabilize the polar ice sheets and accelerate global sea level rise.

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Introduction

Compound extremes pose major threats to the well-being of socioeconomic and ecological systems. Among them, compound hot-dry extremes have received the most attention since they are responsible for 40% of global disaster-related deaths, and their associated risks have been increasing [1]. Here, we present observational evidence indicating distinct characteristics of the most representative compound extremes occurring over the polar ice sheets in Antarctica and Greenland, where warm-wet extremes prevail, in contrast to mid-latitudes.

Compound Warm-Wet Extreme Events over Polar Ice Sheets

In February 2022, an intense atmospheric river impacted the Antarctic Peninsula and produced a record-breaking extreme warm event (EWE), record-high surface melting, and anomalous precipitation including rain [2]. Just one month later, in March 2022, a record high warming event hit the eastern Antarctic plateau, where Dome C (75.1°S, 123.39°E; 3,233 m above sea level) observed a staggering increase of 49 °C in just 4 d [3]. The peak temperature reading of −9.4 °C surpassed the March climatology by an astonishing 44 °C [4]. This remarkable warming was accompanied by a strong atmospheric river event resulting in an extreme precipitation event (EPE) over East Antarctica upon the interaction between the atmospheric river and the continent where March precipitation exceeded 300% above the average [4]. In January 2016, the transport of warm-moist air from lower latitudes to West Antarctica caused the rapid onset of a long-lasting warming episode that potentially contributed to ice sheet mass loss [5]. Over Greenland, on 14 August 2021, rain fell at its peak for the first time on record. At the same time, above-freezing temperatures were observed at the Summit station (72.58°S, 38.46°W; 3,216 m above sea level) for the third time in a decade. This concurrent EWE–EPE event was also associated with warm-moist air intrusions from lower latitudes [6]. These findings indicate that the mechanisms responsible for EWEs and EPEs in polar regions are interconnected. We analyze the global pattern of the concurrent likelihood of EWEs and EPEs and reveal a paradigm shift of compound extremes, transitioning from predominantly hot-dry conditions (such as heat waves and droughts) across most ex-polar lands (i.e., 60°N to 60°S) to warm-wet conditions over the polar ice sheets.

We examine warm-wet synchrony worldwide for the period from 1979 to 2021. Synchrony is quantified by the ratio of the number of compound warm-wet extreme days (when EWE and EPE co-occur) relative to the total number of extreme precipitation days. In this study, EWEs are defined as days surpassing the 90th percentile of daily temperature anomalies based on the 1979–2008 climatology, and EPEs are defined as days exceeding the 90th percentile of daily precipitation on wet days (precipitation > 0.02 mm/d). Globally, warm-wet synchrony at the 90th percentile is approximately 20%, with most regions exhibiting values less than 25% (Fig. 1A). The region that exhibits the most striking warm-wet synchrony is Antarctica, where the average synchrony is greater than 50% across the entire plateau (Fig. 1B). In the region of Wilkes Land, up to 70% of EPEs are accompanied by EWEs. The peak value of the warm-wet synchrony could be attributed to the frequent intrusion of quasi-stationary warm and moist air masses into the Antarctic Plateau due to the highest blocking frequencies to the north between 150°E and 180°E [7]. Figure 1D shows the degree of synchrony separately for the Antarctic coastal (blue bars) and inland regions (red bars). High synchrony is mainly found across inland regions, indicating that the likelihood of occurrence of these compound extremes increases with surface elevation. The region exhibiting the second-highest synchrony is Greenland (Fig. 1C), averaging 28.3% across the territory. The greatest synchrony is observed over the central Greenland plateau, exceeding 50% at the 90th percentile level.

Driving Mechanisms of the Paradigm Shift

Here, the distinct paradigm shift of compound extremes over polar ice sheets further emphasizes the need for a better understanding of its driving mechanisms. The relevant discussions in the literature are fragmented and limited. It is well accepted that compound hot-dry extremes over ex-polar lands result from active land–atmosphere interactions. Specifically, a mid-tropospheric ridge initiates descending motions, creating clear-sky conditions downstream. The resultant excessive shortwave heating of the land surface depletes soil moisture through enhanced evaporation. A dryer land heats more quickly, and the associated excessive sensible heating warms the air above and further strengthens the existing mid-tropospheric ridge, establishing a positive feedback during an extreme hot-dry event [8]. The presence of a self-maintained thermal ridge through active land–atmosphere interactions further insulates the region from intrusions of precipitation-producing synoptic disturbances and thus exacerbates the existing dry conditions.

Over the ice sheets in Antarctica and Greenland, the active land–atmosphere interactions discussed above are largely muted because of a nearly complete seal-off of surface turbulent heat fluxes, limiting the supply of moisture and heat from the surface to the atmosphere. As a result of these muted land–atmosphere interactions and the coldness of the ice surface, high-pressure systems over polar ice sheets tend to be shallow, and the shallowness of the high-pressure systems over the polar ice sheets translates into much weaker downward air motions and weaker adiabatic warming in the atmospheric layer above the ice. Therefore, compared to ex-polar land surfaces, high-pressure systems are not as effective at creating warm events over the ice sheets.

Due to the lack of efficient local feedback processes, EWEs over Antarctica and Greenland are mostly "externally" driven by intruding lower latitude moist air through long-range advective transport [9,10]. These warm-moist air intrusions are possible due to traveling synoptic low-pressure systems and, sometimes blocking highs, originating in the corresponding mid-latitude

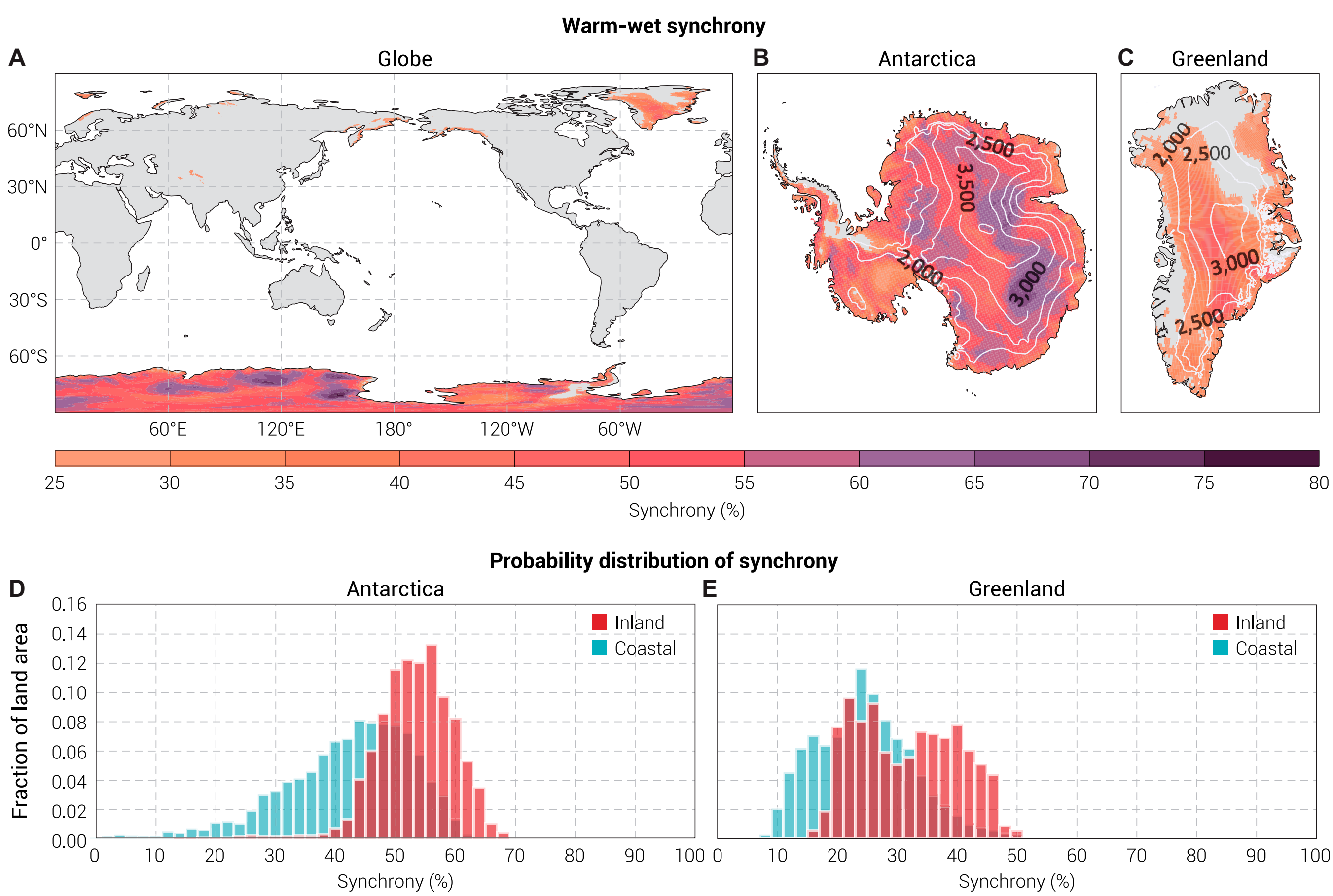

Fig. 1. (A to C) The warm–wet synchrony (ratio of compound warm–wet extreme days to total extreme precipitation days, in percentage) during 1979–2021 over (A) the globe, (B) Antarctica, and (C) Greenland, respectively. Contours in (B) and (C) represent the surface elevation (in meters). (D and E) Probability distributions of synchrony over inland (red bar, elevations exceeding 2,000 m) and coastal (blue bar, elevations lower than 2,000 m) regions of (D) Antarctica and (E) Greenland, respectively. Data for synchrony analysis are sourced from 2 main datasets: the ECMWF ERA5 reanalysis, which provides global temperature and precipitation data, and the RACMO2.3p2 regional climate model, specifically utilized for Antarctica [13].

zones. The brought-in moisture creates clouds and precipitation, and these clouds, together with moisture, lead to greatly enhanced downward thermal radiative energy fluxes that cause substantial warming at the surface [5]. The warm–wet synchrony and the paradigm shift of compound extremes over polar ice sheets are ultimately associated with the distinct physical nature of these extremes, such as passive responses to lower-latitude forcing in forcing, contrasting the self-maintaining hot-dry extremes over ex-polar lands. Interestingly, over Antarctica, strong descending motions or foehn winds can occur along the downstream side of high-elevated mountains, resulting in strong dry-adiabatic warming independent of the warm-moist air intrusion from the lower latitudes. Similarly, the adiabatic descent of the air mass also peaks on the leeward flank of Greenland, especially near coasts, producing warmer and drier conditions that enhance surface melt. This adiabatic warming, driven by topographical features and the ensuing downslope wind, explains why the warm–wet synchrony is noticeably low over the coastal regions of Antarctica and Greenland.

Implications for Cryosphere Change and Sea Level Rise

In conclusion, as climate models project an increase in extreme events worldwide, understanding the dynamic origins and multifaceted implications of these events is becoming increasingly important. The warm-wet synchrony and the resulting paradigm shift of the compound extremes over polar ice sheets show the diverse nature of compound extremes that are evidently climate-zone dependent. Contrasting with the direct socioeconomic impacts of hot-dry extremes in populated regions, the impacts of compound warm-wet extremes in Antarctica and Greenland are more complex but much more far-reaching. Under global warming, intruding air masses are likely to become warmer and moister, leading to more intense compound warm-wet extremes over the polar ice sheets comprising heavy precipitation—in the form of both rain and snow—and surface melt. This increase in intensity could destabilize buttressing coastal ice shelves, leading to dynamic ice sheet mass loss that could accelerate global sea level rise.

Representation of this particular paradigm of compound extremes in climate models is expected to be challenging. This is caused by the complex boundary layer feedbacks associated with extreme moist intrusions over the ice sheets that require high-resolution modeling and the complex dynamics that govern the "passive" nature of moist intrusions, and currently, neither of these aspects are well understood. There are also complex interactions of these extremes with climate variability and climate trends at the lower latitudes. Moreover, the negative effects of extreme warm temperatures include surface melt and rain, and these can destabilize the polar ice sheets; questions remain on whether the positive effects from extreme snowfall accumulation that can offset the dynamic ice sheet mass loss. However, embracing the concept that compound extremes are physically diverse worldwide enables a valuable understanding of the processes that have cause past observed changes in the Antarctic and Greenland ice sheets [11,12]. It also helps us trace the origins of model biases more effectively in the simulation of the polar cryosphere changes and ultimately can better constrain the model projections of future climate change, especially the magnitude and timing of sea level rise.

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Competing interests: The authors declare that they have no competing interests.

Data Availability

ERA5 data are available online at https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5. The RACMO2.3p2 variables for Antarctica are available at https://doi.org/10.5281/zenodo.7334047. Elevation data over both Antarctica and Greenland are from NOAA National Centers for Environmental Information. 2022: ETOPO 2022 15 Arc-Second Global Relief Model, available at https://www.ncei.noaa.gov/products/etopo-global-relief-model.

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