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Stratospheric drivers of extreme events at the Earth's surface

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The stratosphere, the layer of the atmosphere at heights between 10-50 km, is an important source of variability for the weather and climate at the Earth's surface on timescales of weeks to decades. Since the stratospheric circulation evolves more slowly than that of the troposphere below, it can contribute to predictability at the surface. Our synthesis of studies on the coupling between the stratosphere and the troposphere reveals that the stratosphere also contributes substantially to a wide range of climate-related extreme events. These extreme events include cold air outbreaks and extreme heat, air pollution, wildfires, wind extremes, and storm clusters, as well as changes in tropical cyclones and sea ice cover, and they can have devastating consequences for human health, infrastructure, and ecosystems. A better understanding of the vertical coupling in the atmosphere, along with improved representation in numerical models, is therefore expected to help predict extreme events on timescales from weeks to decades in terms of the event type, magnitude, frequency, location, and timing. With a better understanding of stratosphere-troposphere coupling, it may be possible to link more tropospheric extremes to stratospheric forcing, which will be crucial for emergency planning and management.

There is increasing demand for skillful prediction of weather impacts, especially for lead times beyond regular weather forecasts of 7–10 days[1]. Although a range of surface components of the coupled ocean-atmosphere system have been identified as sources of predictability on sub-seasonal to decadal timescales, i.e., for weeks to decades[2], another potential source of predictability arises from the stratosphere[3] at 10–50 km above the Earth's surface. The stratosphere exhibits an overall slower evolution and longer predictability as compared to the troposphere[4], and a downward influence from the stratosphere can thus contribute to persistent and predictable changes at the surface on timescales of weeks to years.

The stratospheric circulation consists of three large-scale features as follows: (i) the stratospheric meridional overturning circulation (i.e., the "Brewer–Dobson circulation")[5], which transports mass from the tropical to the extratropical stratosphere on timescales of months to years; (ii) the Quasi-biennial Oscillation (QBO)[6], characterized by periodic (roughly 28 months) descending easterly and westerly equatorial jets driven by tropical Kelvin and Rossby-gravity waves; (iii) The stratospheric polar vortex[7] (hereafter, polar vortex), a circumpolar westerly jet that forms in autumn, peaks in strength in winter, and decays again in spring. The polar vortex is strongly modulated by vertically propagating planetary-scale waves, sometimes leading to rapid changes. A particularly striking example of such a sudden change manifests as a "sudden

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stratospheric warming" (SSW)[8], in which the polar vortex winds rapidly slow and the polar stratosphere warms. The vortex may also intensify and cool in "strong vortex events." In turn, changes in the polar stratospheric circulation influence the propagation of waves, allowing the circulation anomalies to descend to the lower stratosphere and persist for months due to slow radiative recovery times at those levels. The extratropical stratosphere can also reflect upward propagating planetary-scale waves back downward[9], with subsequent surface impacts.

The stratospheric circulation can exert influence on the surface climate in myriad ways. The Brewer–Dobson circulation exerts a direct influence on the temperature of the tropical tropopause and the amount of water vapor entering the stratosphere[10], which in turn impacts surface climate though radiative changes. The QBO has local influences on the tropical tropopause layer and a remote influence on mid-latitude surface climate via modulations of extratropical wave propagation[11]. The downward influence of polar vortex anomalies on the lower stratosphere can modulate the circulation in the troposphere. In the Northern Hemisphere (NH), SSWs occur on average every other year and often lead to persistent blocking over Greenland associated with the negative phase of the North Atlantic Oscillation (NAO)[12,13], altering surface weather for weeks to months[14]. A strengthening of the stratospheric polar vortex, on the other hand, tends to exert a downward influence in an opposite manner, towards the positive phase of the NAO[15]. In the Southern Hemisphere (SH), SSWs tend to be rare due to weaker planetary-scale wave forcing, but a weakening of the spring polar vortex tends to lead to a negative phase of the Southern Annular Mode (SAM) and an equatorward shift of the storm track (Fig. 2). A key point is that while the stratospheric circulation exhibits variability across timescales, it evolves more slowly than surface weather and can exert a persistent downward effect. Thus, the stratosphere can act as a driver of surface weather and a source of predictability for lead times longer than two weeks. This influence allows the stratosphere to also influence surface extreme events. This study provides an overview over the detected stratospheric influences on tropospheric extremes ranging from precipitation and temperature extremes to wildfires and sea ice loss. Further stratospheric influences on surface variability and extremes will likely emerge in future studies.

Tropospheric extremes driven by the stratosphere. Beyond the stratosphere's influence on surface climate, it is less well recognized that the stratosphere can contribute to tropospheric extremes. Although it has long been known that SSW events contribute to extreme weather[16], broader examples of extremes driven by a wide range of stratospheric phenomena have recently emerged in the literature. This section, summarized in Figs. 2 and 3, gives an overview of the surface extremes linked to stratospheric phenomena.

Extremes in the NH mid-latitudes and polar regions. NH stratospheric polar vortex extremes such as mid-winter SSWs or strong vortex events tend to precede a switch towards anomalously persistent weather conditions lasting up to 2 months. SSWs tend to be followed by cold air outbreaks in the mid-latitudes associated with extreme cold daily minimum and maximum temperatures (Figs. 1 and 2), particularly over Northern Europe and Asia[17–20], which are linked to human health impacts[21,22]. Cold air outbreaks also occur over the North Atlantic and Arctic oceans, termed "marine cold air outbreaks" (MCAOs)[23] (Fig. 2). MCAOs are linked to extreme surface wind speeds[24] (Fig. 2), sometimes connected to an increased risk for the development of polar lows (also known as Arctic hurricanes)[25,26], leading to increased exposure of offshore and coastal infrastructure and Arctic shipping. SSW-driven changes in temperatures and surface winds lead to increases in sea ice extent over the Bering Strait and Sea of Ohkotsk in winter and the Laptev, East Siberian, and Chukchi Seas in summer[27,28] (Fig. 2), which can impact Arctic shipping and resource extraction operations, tourism, and local communities[29]. The equatorward shift of the North Atlantic storm track often leads to storms moving into Southern Europe along a persistent path and often in close succession[30], increasing the risk of flooding in the Mediterranean (Fig. 2). Related to this, the 2016/17 drought on the Iberian peninsula abruptly ended after the 2018 SSW event[31] (Fig. 3). Meanwhile, the northwestern parts of Scandinavia and the British Isles tend to experience dry spells (Fig. 2), whereas anomalous warmth is observed over the eastern Canadian Arctic and subtropical Africa and Asia (Figs. 1 and 2).

Strong polar vortex events, on the other hand, are followed by the opposite, i.e., positive phase of the NAO, associated with an increased risk of drought in southern Europe[32], since the storm track is stronger and more zonally oriented towards Northern Europe. A record-strong NH polar vortex in early 2020 was associated with a series of successive storms that hit the UK and Northern Europe, and caused extensive damage[33] (Fig. 3) and unprecedented warmth over Eurasia[34]. Wave reflection events can contribute to cold air outbreaks over central Canada and North America[35,36], such as, e.g., in December 2017[37] (Fig. 3).

Although the above extremes are limited to boreal winter, further impacts are associated with extremes in boreal spring when the polar vortex gives way to summer easterlies in the stratosphere. This transition is associated with an NAO-like shift in surface climate[38] and may influence Arctic sea ice conditions into autumn[39]. The timing of the final vortex breakdown can have significant implications for stratospheric ozone chemistry, as a vortex that stays strong well into spring as sunlight returns to the pole provides ideal conditions for rapid ozone loss, as observed in spring 2020[34]. Stratospheric ozone minima in spring have been suggested to be followed by anomalous cold over subtropical Asia and southern Europe, and anomalous warmth over northern Asia[40,41].

On timescales of years to decades, the NH polar stratosphere may also influence surface variability. For example, decadal variations in the NH polar vortex have been linked to a "hiatus" in Eurasian warming[42]. It remains unclear whether this variability in NH polar vortex strength is anthropogenically forced (e.g., via declining Arctic sea ice and amplified Arctic warming due to increased greenhouse gases[43,44]), or if it represents internal variations of the coupled atmosphere-ocean system[45]. Regardless, the implications are that decadal changes in NH polar stratospheric variability may contribute to decadal variability in the extratropics, against the background of a warming climate. Furthermore, the meridional overturning circulation in the North Atlantic ocean has been suggested to be influenced by stratospheric variability[46].

Other extremes tied to NH polar vortex variability remain to be explored. While the NAO has been linked to a wide range of surface extremes, especially over Europe[17], linking these extremes to polar vortex variability has been explored less, and could provide opportunities for enhanced prediction. For example, the negative phase of the NAO is associated with persistent and extreme warm anomalies over Northern Africa and the Middle East[47] (Fig. 1), and increased Mediterranean rainfall that inhibits Saharan dust transport[48]. Temperature extremes following polar vortex events may contribute to ice loss over Greenland[49] (Figs. 2, and 3), as well as heatwaves and thawing of permafrost in Siberia, such as, e.g., in spring 2020[50] (Fig. 3). In addition, a more detailed analysis of impacts beyond surface temperature and precipitation

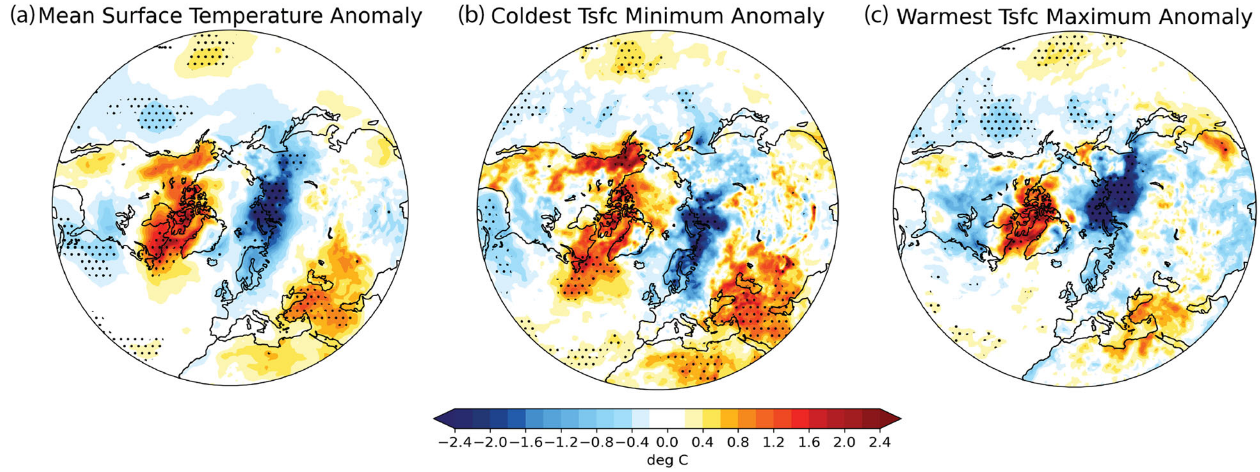

Fig. 1 SSW composites for mean and extreme indices of daily surface temperature. Difference between the composite of the 30 days following 24 observed SSWs and the composite of *n* randomly sampled 30-day periods from Dec-Apr, repeated 3000 times, for **a** daily mean surface temperature anomalies, **b** the coldest (within the 30-day period) daily minimum surface temperature anomaly, and **c** the warmest (within the 30-day period) daily maximum surface temperature anomaly. Surface temperature data and SSW dates are calculated using ERA-interim reanalysis (1979–2016)[131]. Stippling shows where the SSW composite anomalies are significantly different ($p < 0.05$, using a bootstrap with replacement test) from the randomly sampled composite anomalies.

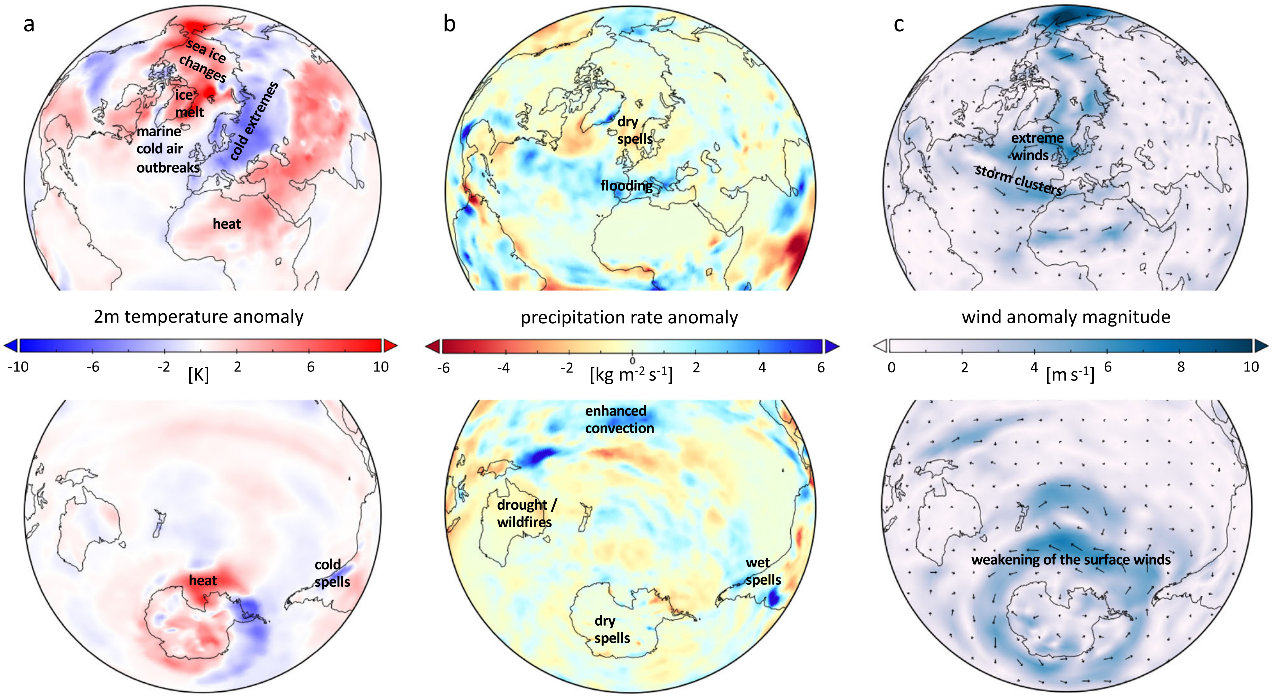

Fig. 2 Overview of the surface extremes expected for weak vortex events. a Two-meter temperature, **b** precipitation rate, and **c** surface wind anomalies (arrows indicate the direction and magnitude of the anomaly, shading indicates the magnitude of the anomaly) after weak vortex events for both hemispheres. The values are averaged over the 45-day period following a case of an extreme weak vortex event in each hemisphere, i.e., the period from 13 February 2018 to 29 March 2018 in the Northern Hemisphere and 26 September 2002 to 9 November 2002 using data from the NCEP/NCAR reanalysis[132].

would be useful information for transportation, energy, and agriculture, such as the type and intensity of precipitation, or other types of severe weather such as hail, lightning, or surface wind gusts, which have a direct impact on infrastructure, property, and life. Links of SSWs to ionospheric irregularities, which can impact global communications and navigation, have also been suggested[51] and could be further investigated. Connections to atmospheric chemistry and air quality would be valuable. For example, modulations of the Brewer–Dobson circulation influence stratospheric ozone[52] and are related to irreversible ozone transport to the troposphere[53], where it can worsen air quality[54]. Meteorological conditions following SSWs could also set up conditions for stagnation of haze and pollution; e.g., the East China Plains saw a record-breaking haze pollution event following the January 2013 SSW[55].

Extremes in the SH mid-latitudes and polar regions. Although wintertime stratospheric variability is smaller in the SH

	stratospheric precursor	tropospheric extreme event	impact	affected region
Northern Hemisphere	sudden stratospheric warming	(marine) cold air outbreak	infrastructure damage, health impacts	Arctic, northern Europe, North Atlantic
		increased storminess	flooding, wind damage	southern Europe
		regional sea ice changes	shipping impacts, resource extraction	Arctic
	strong vortex event	storm series	flooding, wind damage	northern Europe, North Atlantic
		drought	agricultural damage	southern Europe
	wave reflection	cold air outbreak	health impacts	North America
tropics	Quasi-Biennial Oscillation	changes in the Madden-Julian Oscillation	precipitation extremes	tropics, subtropics
		atmospheric rivers	flooding	western North America
		changes in the monsoon	drought / flooding, agricultural impacts	India, Southeast Asia
Southern Hemisphere	early vortex weakening	heat, drought	wildfires, agricultural losses	Australia, Antarctica
		cold spell	health impacts	southeastern Africa, South America
	ozone anomalies	poleward shift of storm track	sea ice changes	Southern Ocean
		increased UV radiation	health impacts	Australia
		hot spells	health impacts	southern Africa, Australia, South America

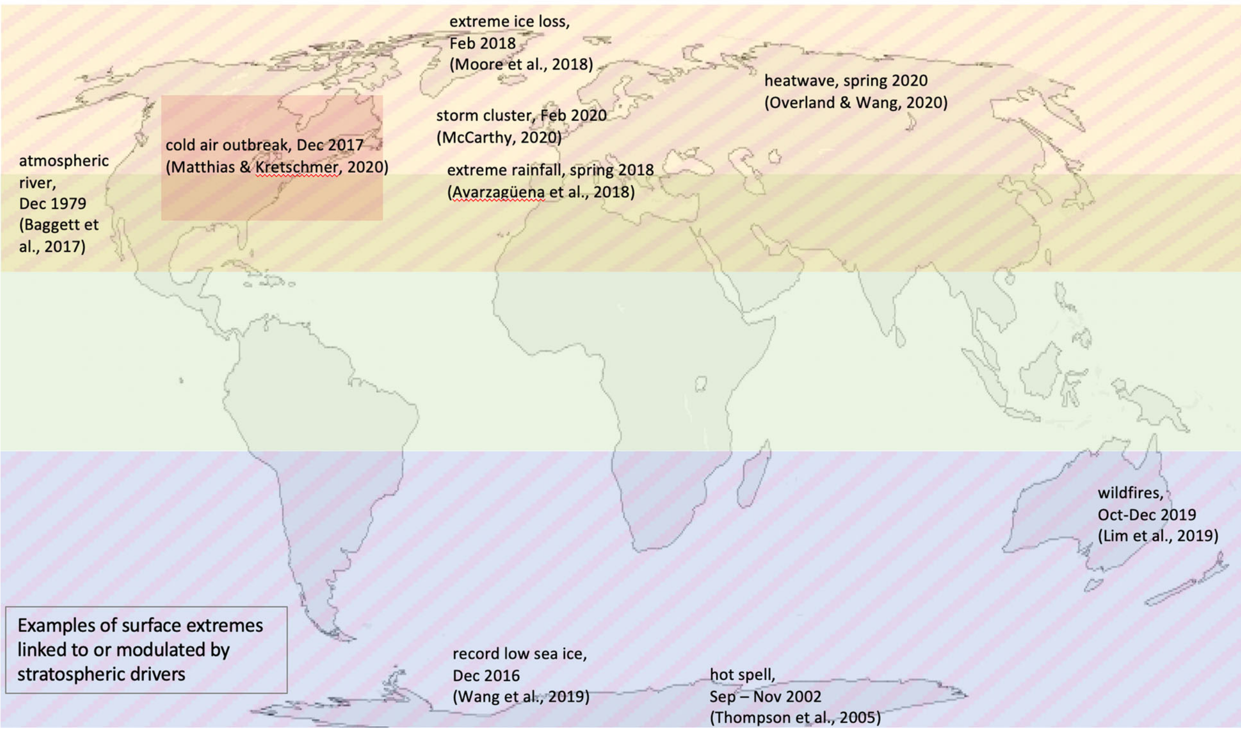

Fig. 3 Surface extremes and impacts associated with stratospheric precursors. The area of influence for each stratospheric precursor is indicated in the map with matching colors. The map gives examples for extreme events that have been linked to stratospheric origins, as detailed in the text.

compared to the NH, the timing of the transition of the polar stratosphere from its winter to summer state has significant implications for surface climate and extremes[56,57]. A weakening of the SH stratospheric polar vortex leads to an equatorward shift of the storm track and a negative phase of the SAM, contributing to extended hot and dry spells over Australia[58], and a weakening of the wind stress at the ocean surface around Antarctica (Fig. 2). Vortex deceleration has also been associated with anomalous cold over southeast Africa and New Zealand, colder and wetter weather over southern South America[59], anomalous warmth over the Ross and Amundsen Seas, and dry and cold spells over Antarctica[56] (Fig. 2). Record low Antarctic sea ice in December 2016 has been linked to an early polar vortex weakening[60] (Fig. 3).

SSWs in the SH—although rare—can similarly have a downward influence that projects onto the negative phase of the SAM, as seen following the only known major SH SSW in 2002, which was associated with anomalous heat over Antarctica[61] (Figs. 2 and 3). It is likely that the devastating 2019 Australian wildfires were related to the minor SSW in austral winter 2019[62] (Fig. 3), which in turn affected the stratosphere[63]. SSWs in the SH lead to substantial increases in polar stratospheric ozone, temporarily mitigating anthropogenic ozone depletion, as observed during the SSW events in 2002 and 2019. On the other hand, a strong stratospheric vortex in spring as sunlight returns can lead to a sudden cascade of chemical ozone loss[64]. Depending on the vortex location this can lead to a significant increase in incoming harmful UV radiation over populated regions, with implications for health, food and water security, and ecosystems[65]. Interannual variations in the ozone hole are also linked to the variability of the SAM and its associated impacts on summertime surface climate and extremes[66].

On decadal and longer timescales, the depletion of the stratospheric ozone layer by man-made chlorofluorocarbons led to a strengthening of the austral spring polar vortex and a poleward shift of the SH storm tracks in austral summer over the period 1960–1999[67]. This trend was associated with a broad range of climate impacts, including increased subtropical precipitation[68], summertime warming of the Antarctic peninsula and cooling over east Antarctica[69], decreases in low-level clouds across the Southern Ocean and increases in mid- to high-level clouds over Antarctica and the subtropics[70], shifts in the fronts associated with in the Antarctic Circumpolar Current[71], reduced carbon uptake[72], and enhanced Southern Ocean acidification[73]. With the recovery of the ozone layer underway due to the Montreal Protocol[74], the associated trends in circulation and climate patterns have started to slow or reverse[75], though they are also affected by climate change.

Tropical and subtropical extremes. Less research has been performed on how tropical and subtropical stratospheric variability influences tropospheric extremes in part because of relatively few QBO cycles during the satellite record, and the inability of most climate models until recently to intrinsically reproduce the QBO, although significant progress has recently been made in QBO representation in models[76,77]. As the QBO is associated with a meridional circulation that induces temperature changes in the tropical tropopause layer, it can influence tropical deep convection via changes to static stability and vertical wind shear, and high-cloud properties near the tropopause[78,79]. In particular, the easterly phase of the QBO is associated with enhanced deep convection over the western tropical Pacific and decreased deep convection over the central and eastern tropical Pacific regions[78], and with reduced intensity of the Indian monsoon in August–September[80,81], with potential impacts on rainfall extremes[82]. The QBO has also been linked to modulations of the tropical Hadley cell, such that easterly QBO winds are associated with decreased precipitation over Australia[83].

Moreover, the QBO is strongly related to modulations in the Madden–Julian Oscillation (MJO)[84,85]: the easterly QBO is linked to a more active and persistent MJO in boreal winter, although the mechanism remains uncertain. The QBO can alter the teleconnections of the MJO[86–88], and thus by extension, its extreme impacts. For example, when the QBO winds are easterly, there is stronger and more organized precipitation over east Asia during certain MJO phases[89] and stronger MJO-related modulations of the amplitude and structure of the North Pacific storm track[90]. Further investigation into if and how the QBO may modify other MJO-related extremes, e.g., ref. [91], would be valuable. The QBO may also impact climate extremes related to polar vortex variability via its own teleconnection to the extratropics[11,92].

Variability in the Brewer–Dobson circulation driven by tropospheric waves can affect tropical upwelling, with implications for tropical convective patterns and precipitation[93]. For example, accelerations of the Brewer–Dobson circulation associated with SSWs lead to enhanced tropical upwelling[94,95], which may reduce the static stability in the tropical tropopause layer and enhance SH tropical convection[96,97] (Fig. 2).

On interannual and longer timescales, lowermost stratospheric temperatures may influence tropical cyclone activity. In recent decades, cooling of the tropical tropopause layer associated with stratospheric ozone depletion and circulation changes may have decreased tropical cyclone outflow temperatures and enhanced tropical cyclone potential intensity in the North Atlantic[98,99].

Pathways towards prediction and projection of extremes driven by the stratosphere. Given the stratosphere's effect on global surface extremes, its downward influence could carry more weight than anticipated for the prediction of surface extremes and their devastating impacts. On sub-seasonal to seasonal timescales, the stratosphere is already known as a predictor of tropospheric anomalies and extremes both in mid-winter[100–103] and spring[104]. In particular, stratospheric events have been used with some success to predict cold air outbreaks e.g.[105–108] and winter storm frequency[109]. Anomalous surface wind speeds, surface temperatures, and precipitation following stratospheric polar vortex anomalies may be used for sub-seasonal to seasonal predictions of energy supply[110,111] and demand[112], as well as transportation[113]. The state of the QBO has been used to improve prediction of atmospheric rivers, which are linked to extreme rainfall events in western North America[114], such as the event in December 1979[115] (Fig. 3). With a better understanding of the vertical coupling, it is likely that more extremes and their impacts will emerge as being driven or modulated by stratospheric forcing, and recognizing the stratosphere as a driver of extremes will benefit prediction on all timescales from weeks to centuries.

Nonetheless, the full potential of stratospheric information for improving the prediction of surface extremes has not yet been realized, especially given the limited representation of stratosphere–troposphere coupling and persistent model bias in many prediction systems and climate models[116]. Efforts are ongoing in the stratosphere community to address these problems. Although some stratospheric biases have been greatly mitigated in recent years by raising the model lid and improving vertical resolution[117], others have not been resolved. For example, many climate models either cannot intrinsically simulate a QBO or simulate a degraded version[76], and forecast models initialized with QBO winds lose information about the amplitude and even sign of tropical winds within 1–2 weeks[118]. The full spectrum and amplitude of wave coupling linking the troposphere and the stratosphere is also not well represented or poorly parameterized[119,120]. Other stratospheric processes that are not yet well captured by many numerical models, such as interactive ozone chemistry or radiative effects of aerosols, may influence extremes in ways that remain to be determined. For example, increases in extreme wildfires and pyrocumulus clouds could inject aerosols into the stratosphere, where they can persist for months to even years, affecting radiative balance, convection, and circulation[121,122]. Ongoing efforts to quantify and resolve model biases and to incorporate missing processes are expected to improve the prediction of extremes tied to stratospheric processes.

In light of climate change, it is not resolved to what extent the relationship between the stratosphere and the troposphere will evolve, as both the troposphere and the stratosphere are undergoing significant changes. In particular, greenhouse gas increases are associated with cooling of the stratosphere and warming of the troposphere. The enhanced warming in the tropical upper troposphere is expected to lead to increases in the upper troposphere-lower stratosphere equator-to-pole temperature gradient, which should strengthen the polar vortex and shift the storm tracks poleward in both hemispheres. However, in the NH, the amplified surface warming in the Arctic reduces the surface equator-to-pole temperature gradient at the surface and shifts the storm tracks equatorward, leading to a "tug of war" between the upper and lower tropospheric temperature gradient changes[123–125]. These counteracting influences contribute to highly uncertain trends in the stratospheric polar vortex, with no consensus among climate models on whether the vortex will strengthen or weaken[126]. The uncertain future of the NH polar stratosphere is linked to uncertainties in the projection of the tropospheric jet streams and associated climate extremes[127,128]. In the SH, stratospheric ozone recovery counteracts the predicted poleward shift of the jet stream due to climate change[75,129], with potential effects on regional precipitation extremes and surface wind stress. Finally, in the tropics, it is unclear how the QBO will be affected by climate change, with most models indicating a decreased amplitude, but either enhanced or reduced periodicity[76], whereas extratropical teleconnections of the QBO appear to strengthen[130]. Thus, better understanding of stratosphere–troposphere processes may be imperative for reducing uncertainties in projected likelihoods of future climate extremes.

Outlook towards future research. The downward influence from the stratosphere has been found to trigger or modulate the strength of a range of extreme events. These links can contribute to the understanding and prediction of surface extremes and their impacts on human health, infrastructure, energy, and ecosystems. In particular, extreme events in mid-latitudes and polar regions such as flooding, drought, and cold air outbreaks have been linked to stratospheric forcing. In the tropics, tropical convection and hurricanes can be modulated by the stratosphere. Attribution is however challenging given the often poorly represented stratospheric variability and coupling processes with the troposphere. Further research will benefit from incorporating and modeling additional processes such as aerosols and chemistry, in addition to improved understanding and model representation of the dynamical coupling. Extreme events may then more readily be linked to stratospheric forcing, with benefits for the prediction of extreme events and their impacts at lead times beyond 2 weeks. An improved prediction of the stratosphere itself on sub-seasonal to decadal lead times may also contribute to increased lead times for surface extremes. Large regions in Africa, Asia, and South America, as well as major ocean regions are affected by stratospheric forcing, e.g., through hot or cold and wet or dry spells, but not yet sufficiently studied with respect to extreme events in relation to the stratosphere. Furthermore, the uncertain dynamical response of the stratosphere to a changing climate contributes significantly to uncertainties in projections of future surface extremes.

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D.D. initiated the study. D.D. and A.B. together designed the study, discussed the results, and contributed to the writing. Both authors contributed to making the figures.

Competing interests

The authors declare no competing interests.

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