Long Range Prediction and the Stratosphere

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Abstract. Over recent years there have been concomitant advances in the development of stratosphere resolving numerical models, our understanding of stratosphere-troposphere interaction and the extension of long-range forecasts to explicitly include the stratosphere. These advances are now allowing new and improved capability in long range prediction. We present an overview of this development and show how the inclusion of the stratosphere in forecast systems aids monthly, seasonal, annual to decadal climate predictions and multidecadal projections. We end with an outlook towards the future and identify areas for improvement that could further benefit these rapidly evolving predictions.

1 Introduction

Daily weather fluctuations are thought to have a deterministic predictability horizon of around two weeks due to the sensitivity of the evolution of the atmospheric state to small errors in initial conditions (Lorenz 1969) - the so-called ‘butterfly effect’. Recent estimates (Leung et al., 2020; Domeisen et al., 2018) as well as tests of the predictability of midlatitude *daily* weather using the latest global prediction models (Zhang et al., 2019; Son et al., 2020) produce similar estimates for this predictability limit. However, this does not preclude skilful forecasts of the *statistics* (most notably the average) of conditions at long range beyond this timescale (e.g. Shukla 1981). This predictability owes its existence to slowly varying predictable components of the climate system in the ocean, and in some cases the atmosphere, as well as externally forced changes such as volcanic or solar variability effects (e.g. Kushnir et al., 2019). Some of the more prominent examples of stratospheric variability such as sudden stratospheric warmings and their subsequent impact on the stratosphere and the troposphere (Baldwin et al., 2021), or the quasi-biennial oscillation and its associated teleconnections (Scaife et al., 2014a), have been shown to be predictable out to timescales well beyond the traditional two-week predictability horizon from initial tropospheric conditions alone. Other examples involve stratospheric pathways for teleconnections originating in the troposphere or ocean (e.g., Schwartz and Garfinkel 2017, Byrne et al. 2019) and are shown in Figure 1. On longer timescales, boundary forcing, for example from composition changes such as ozone depletion and recovery allows the stratosphere to provide relatively slowly varying conditions to guide the turbulent troposphere and hence provide long range predictability (e.g., Thompson et al. 2011). The relative importance of stratospheric initial conditions to boundary conditions decreases with lead time as shown in the schematic in Figure 1.

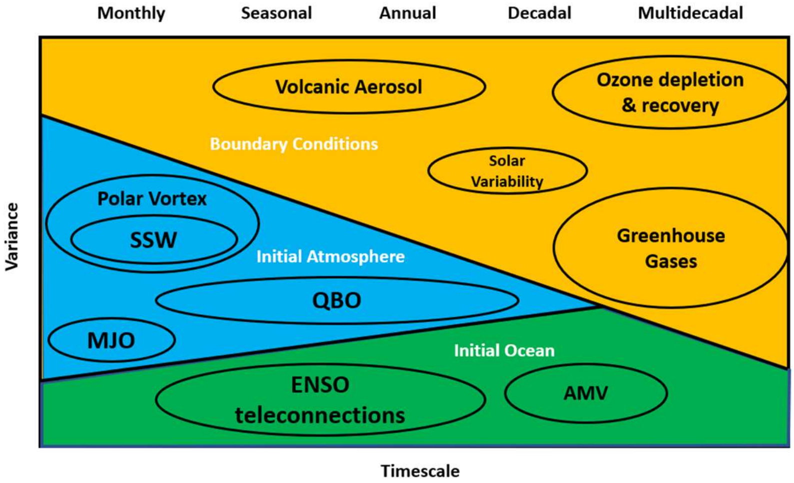

Figure 1: Schematic representation of the role of the stratosphere in long range prediction showing the transition from initial condition predictability in the atmosphere (blue) and the ocean (green), to boundary condition predictability at longer timescales (orange). Individual mechanisms involving the stratosphere are labelled in black. The width of the ellipses in the timescale direction shows the approximate range over which each phenomenon provides predictability. The width of the ellipses in the variance direction show~~sing~~ their ~~approximate~~ relative contributions to forecast variance~~ at different lead times~~.

The extension of long-range prediction systems to explicitly include representation of the stratosphere follows many years of development of stratosphere resolving general circulation models (GCMs). By the late 20th century many leading centres for climate research had started to include the stratosphere in versions of their GCMs (Pawson et al., 2000; Gerber et al., 2012). Much of the early model development was motivated by the discovery of the ozone hole in the 1980s (Farman et al., 1985) and the need for simulations of ozone depletion and potential recovery of the ozone hole following the 1987 Montreal Protocol, which required atmospheric models that represented both the atmospheric dynamics and chemistry of stratospheric ozone depletion (Molina and Rowland 1974; Crutzen 1974). In most cases this was achieved by adding further quasi-horizontal layers to the domain of existing climate models to extend their representation of the atmosphere to the stratopause or beyond (e.g. Rind et al 1988; Beagley et al., 1997; Swinbank et al., 1998; Sassi et al., 2002), while also incorporating key radiative (e.g. Fels et al., 1985), chemical (e.g. Steil et al., 1998) and dynamical (e.g. Scaife et al., 2000) processes.

The early development of so called ‘high top’ climate models, which represent the whole depth of the stratosphere, in general preceded the discovery of the main body of evidence that the variability of the stratosphere is not only affected by, but also interacts with the lower atmosphere and surface climate. Pioneering early studies suggested that the stratosphere might have direct effects on the troposphere and surface climate (e.g. Labitzke 1965; Boville 1984; Kodera et al., 1990, 1995; Haynes et al., 1991; Perlwitz and Graf 1995). In subsequent years, as reliable observational records lengthened and large enough samples of stratospheric variability were amassed it was unequivocally demonstrated that stratospheric variability precedes important tropospheric changes in the extratropics (Baldwin and Dunkerton 1999, 2001). There was debate about causality and whether the stratosphere really does affect the atmosphere below (e.g. Plumb and Semeniuk 2003). However, experiments where the stratosphere is perturbed in numerical models show changes in surface climate and reproduce similar patterns of response at the surface to those found in real world observations (e.g. Polvani and Kushner 2002; Norton et al., 2003; Scaife et al., 2006; Joshi et al., 2006; Scaife and Knight 2008; Hitchcock and Haynes 2016, White et al., 2020). These involve changes to planetary scale waves and also baroclinic eddies in the troposphere that are consistent with changes in baroclinicity near the tropopause (Kushner and Polvani 2004; Song and Robinson 2004; Wittman et al., 2004, 2007; Scaife et al., 2012; Domeisen et al., 2013; Hitchcock and Simpson 2014; White et al., 2020). Importantly, as we discuss below, the same mechanisms also appear to be at work across a broad range of timescales (Kidston et al., 2015).

In recent years, motivated by the evidence of surface effects of stratospheric variability in the mid-latitudes, the high-top model configurations used for stratospheric research were incorporated into leading prediction systems. Improved vertical resolution was already known to improve the atmospheric data assimilation of satellite instrument observations whose sensitivity was often heavily weighted towards stratospheric altitudes. This also provided initial stratospheric conditions for sets of retrospective forecasts, some of which were internationally coordinated (e.g. Butler et al., 2016; Tompkins et al., 2017). A growing number of operational systems are now producing regular ensembles of predictions at lead times of months or years with coupled ocean-atmosphere models that extend to the stratopause or beyond; for example at Environment Canada (Merryfield et al., 2013), the Met Office in the UK (MacLachlan et al., 2014), the German Weather Service DWD (Baehr et al., 2015), the Japan Meteorological Agency (Takaya et al., 2017) and the European Centre for Medium Range Weather Forecasts (Johnson et al., 2019). In the following sections we document the emerging impacts and benefits of this new capability for surface climate predictions at monthly, seasonal, and annual to decadal lead times starting with the shorter-range, initial condition cases and ending with the longer-range boundary-condition cases.

2 The stratosphere and monthly prediction

The best-established phenomenon that gives rise to predictability of surface climate from the stratosphere is the tropospheric circulation changes that follow strong and weak conditions in the stratospheric polar vortex (Baldwin and Dunkerton 1999, 2001). For example, weak vortex conditions such as those found in a sudden stratospheric warming (SSW, Baldwin et al., 2021) are typically followed by a weakening and southward shift of the tropospheric mid-latitude jet stream (see e.g. Kidston et al., 2015 and references therein) and thus the negative polarity of the North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and Northern Annular Mode (NAM). These fluctuations also show a tendency to vacillate between strong westerly and weak (SSW) states on subseasonal timescales (Kuroda and Kodera 2001; Hardiman et al., 2020a). The changes in the troposphere persist roughly as long as those in the lower stratosphere, and last for around two months (Baldwin and Dunkerton 2001; Baldwin et al., 2003; Hitchcock et al., 2013; Son et al., 2020; Domeisen 2019). The impacts on surface climate also include changes in the frequency of extremes of temperature and rainfall (Scaife et al., 2008; King et al., 2019; Cai et al., 2016; Domeisen et al., 2020b).

Although *major* SSW events, involving a complete reversal of the zonal flow in the mid stratosphere, are rare in the southern hemisphere (Wang et al., 2020; Jucker et al., 2021), variations of the Antarctic polar vortex are likewise followed by similar signatures in the underlying tropospheric flow, in this case via the Southern Annular Mode (SAM). Weakening of the vortex is typically followed by a negative shift in the SAM and associated changes in rainfall and near surface temperature (Thompson et al., 2005; E. Lim et al., 2018, 2019, 2021, Rao et al., 2020e). These changes in Southern Hemisphere circulation typically take longer to reach the surface than their Northern Hemisphere counterparts (Graverson and Christiansen 2003), perhaps due to the stronger stratospheric polar vortex and weaker wave driving in the southern hemisphere, but they are nonetheless better predicted by improving stratospheric resolution of forecast models (Roff et al., 2011). The timescale of weeks for the predictability of sudden warmings is limited by the predictability of weather patterns in the troposphere which might trigger SSW events (e.g. Mukougawa et al., 2005; Taguchi 2016; Garfinkel and Schwarz 2017; Jucker and Reichler 2018; Lee et al., 2020a). However, if we add this timescale to the timescale of a month or more for the persistence of lower stratospheric anomalies and their surface effects (e.g. Baldwin et al., 2003; Butler et al., 2019), we arrive at the conclusion that on these occasions at least, initial conditions in the atmosphere can provide predictability well beyond the usual two-week horizon for daily weather in either hemisphere.

Predictability of the atmosphere at monthly lead times is also known to originate in part from the Madden Julian Oscillation (MJO) in the troposphere and its teleconnection to the extratropics (e.g. Vitart 2017). The circulation pattern associated with the MJO resembles a poleward and eastward propagating Rossby wave with centres of action over the Pacific and extending into the Atlantic sector where it also maps strongly onto the North Atlantic Oscillation. The lead time of around 10 days for the impact of a change in the MJO to appear in the extratropical flow (e.g. Cassou 2008; Lin et al., 2009) is also consistent with the timescale for poleward propagation of Rossby waves (e.g. Scaife et al., 2017). It turns out that this tropospheric MJO teleconnection on monthly timescales also interacts with the stratosphere (Garfinkel and Schwartz 2017). The MJO teleconnection to the North Pacific affects the region most strongly associated with tropospheric precursors to SSW events, and consistent with this, SSWs in the observational record have tended to follow certain MJO phases. The subsequent weak vortex anomaly then propagates down to the troposphere (Garfinkel et al 2012), where it may strengthen and prolong any existing negative NAO signal that is directly linked to the MJO via the troposphere (Schwartz and Garfinkel 2017, 2020; Barnes et al., 2019).

In addition to the interaction of the MJO with the extratropical stratosphere, a further, completely different link between the stratosphere and the MJO has recently been uncovered which modulates MJO amplitude and persistence in the troposphere via the phase of the Quasi-Biennial Oscillation (QBO) in the tropical lower stratosphere (Liu et al., 2014; Yoo and Son 2016; Martin et al., 2021). In this case, easterly phases of the QBO appear to energise the MJO compared to westerly QBO phases, likely due to changes in temperature and hence static stability close to the tropopause (Hendon and Abhik 2018; Martin et al., 2019) with a potential contribution of cloud-radiation feedbacks (Son et al., 2017, see Martin et al., 2021 for a review). This modulation of the MJO is in turn important for predictability as it gives rise to higher monthly prediction skill of the MJO and its surface teleconnections during the easterly phase of the QBO (Marshall et al., 2017; Abhik and Hendon 2019; Y. Lim et al., 2019).

The traditional view of stratosphere-troposphere interaction involves upward propagation of planetary scale Rossby waves (Charney and Drazin 1961), but this linear theory applies equally well to downward propagation. Harnik and Lindzen (2001) and Perlwitz and Harnik (2003) identified a possible source of downward propagating planetary waves in the form of reflecting surfaces in the winter stratosphere. Examples of specific reflection events, showing upwards and then downward propagation have since been observed (e.g. Kodera et al., 2008; Harnik 2009; Kodera and Mukougawa 2017; Mukougawa et al., 2017; Matthias and Kretschmer 2020). These results suggest that the details of the stratospheric circulation such as regions of negative vertical wind shear could be important for the formation of reflecting conditions (Perlwitz and Shaw 2013) and may yet provide a further mechanism by which the stratosphere can affect the troposphere (Domeisen et al., 2019; Butler et al., 2019).

Following studies demonstrating enhanced tropospheric predictability after SSW events in individual climate models (e.g. Kuroda 2008; Mukougawa et al 2009; Marshall and Scaife 2010; Sigmond et al. 2013), subseasonal forecast systems which explicitly represent the stratosphere in the climate system were developed and implemented at operational prediction centres worldwide. It is often difficult to demonstrate significant increases in overall skill (e.g. Richter et al. 2020a) but routinely produced ensembles of subseasonal predictions show that both stratospheric variability and its subsequent tropospheric signature are predictable at monthly lead times (Domeisen et al. 2020a, 2020b). The strongest surface impacts occur if the polar vortex in the lower stratosphere is in a weakened state at the time of the SSW (Karpechko et al., 2017) and there appears to be a roughly linear relationship between the strength of these lower stratospheric anomalies and the tropospheric response (e.g. Runde et al. 2016; White et al. 2020 and see Baldwin et al. 2019 for a review). We should note however that there is no one-to-one correspondence between stratospheric variability and tropospheric events, and some prominent examples of sudden stratospheric warmings are followed by differing tropospheric anomalies (e.g. Charlton-Perez et al., 2018; Knight et al., 2020; Butler et al., 2020; Rao et al., 2020a). Nevertheless, the canonical response is seen in the majority (~70%) of cases and periods of intense wintertime stratospheric variability are important windows of opportunity to provide skilful monthly forecasts (Mariotti et al., 2020; Tripathi et al., 2015a).

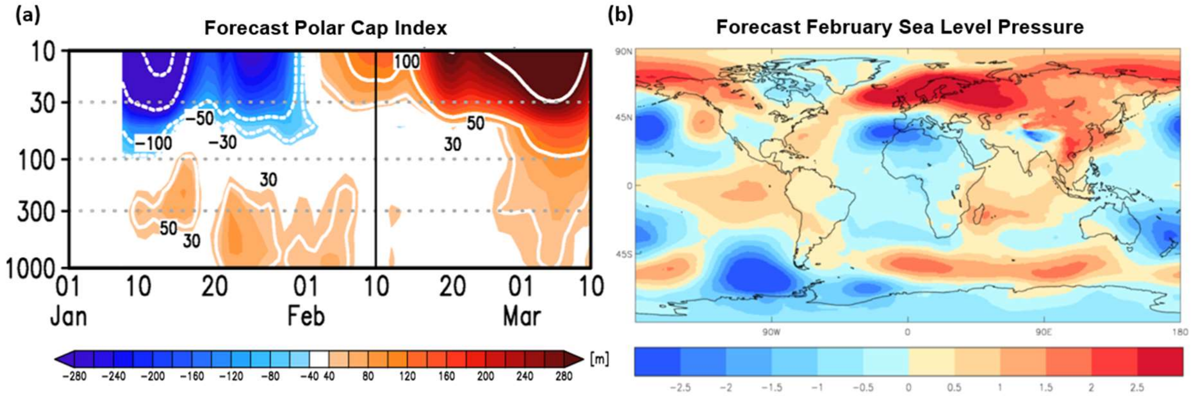

Figure 2: Monthly forecasts prior to the 2018 sudden stratospheric warming and severe cold event over northern Europe. Forecast Polar Cap Index (a) and February sea level pressure anomalies (b). Ensemble mean anomalies are shown for the average of forecasts initialised between 8th and 22nd of January 2018 relative to hindcasts over the 1993-2016 period using the Met Office Hadley Centre GloSea prediction system (MacLachlan et al., 2015). Sea level pressure is measured in hPa and Polar Cap Index is the geopotential height anomaly (m) averaged over 65N to the North Pole.

These forecast systems are now important tools for national meteorological and hydrological services to monitor impending stratospheric variability and associated surface impacts in real time. Recent extreme examples illustrate the importance of this activity. In February 2018 a major SSW occurred and was followed by a strong negative NAO-like pattern at the surface with easterly wind anomalies over Europe and multiple cold air outbreaks over the following weeks, including extreme snowfall across northern Europe (Figure 2, Karpechko et al., 2018; Knight et al., 2020; Rao et al., 2020a) and an abrupt end to Iberian drought in Southern Europe (Ayarzagueña et al., 2018). Studies of monthly ensemble predictions of this event with operational stratosphere resolving systems showed that the stratospheric event was predictable at least 2 weeks in advance (Figure 2) and that the ensemble forecasts indicated increased likelihood of cold surface conditions for several weeks after the event (Karpechko 2018; Butler et al., 2020; Statnaia et al., 2020; Rao et al., 2020a). Again, as in the analysis of previous events, there was also a strong association with the MJO entering Phase 7 with increased convection in the West Pacific (cf. Garfinkel and Schwartz 2017) in the 2018 event. Finally, we should also note that cases of monthly forecasts where the stratosphere plays an important role are not restricted to winters with sudden stratospheric warmings and periods when the stratospheric polar vortex is above normal strength also provide opportunities for skilful monthly forecasts (Tripathi et al., 2015b; Scaife et al., 2016). In this case an opposite but symmetric surface response results, with strong *positive* NAO. A very recent example occurred in February 2020, when, following an extremely strong polar vortex (Hardiman et al., 2020b; Lee et al., 2020b; Lawrence et al., 2020; Rao et al., 2021a), the tropospheric jet in the Atlantic sector strengthened, and the associated increased storminess and rainfall in this case resulted in UK monthly rainfall reaching a new record high (Davies et al., 2021).

3 The stratosphere and seasonal prediction

Prior to the advent of dynamical forecast systems which explicitly represent the stratosphere, seasonal forecasts using empirical relationships and statistical methods were proposed. These relied on the prior state of the polar vortex and other predictable factors such as the QBO that are known to have links to surface climate (Thompson et al., 2002; Charlton et al., 2003; Christiansen et al., 2005; Boer and Hamilton 2008). In some cases they indicated additional predictability that was absent in existing operational forecast systems, providing further evidence of predictability involving the stratosphere and further motivating the extension of dynamical forecast systems to properly represent the stratosphere. Similar empirical forecast studies continue, and although they cannot provide evidence of predictability that is as strong as from GCM experiments based on fundamental physical principles, they do continue to be useful to indicate sources of predictability that need to be properly represented in comprehensive forecast systems (e.g. Folland et al., 2012; Wang et al., 2017; Hall et al., 2017; Byrne and Shepherd 2018).

Following the introduction of dynamical seasonal forecast systems with a good representation of the stratosphere, clear links between successful seasonal prediction of the North Atlantic Oscillation, the closely related Arctic Oscillation and the state of the stratospheric polar vortex have been identified in forecast output (e.g. Scaife et al., 2014b; Stockdale et al., 2015; Jia et al., 2017). Similar signals are also seen in the southern hemisphere in relation to predictability of the Southern Annular Mode (Seviour et al., 2014; Byrne et al., 2019; Lim et al., 2021). Statistically significant increases in overall skill directly attributable to the inclusion of the stratosphere in prediction systems is sometimes difficult to demonstrate (e.g. Butler et al., 2016), especially given that other factors such as horizontal resolution and physical parametrizations are often simultaneously changed. Nevertheless, the body of evidence now weighs heavily in favour of predictability of the NAO and SAM from the stratospheric polar vortex and from analyses showing reduced surface prediction skill in the absence of stratospheric variability (e.g. Hardiman et al 2011; Sigmond et al., 2013; Scaife et al., 2016).

A second clear example of seasonal predictability originating in the stratosphere is the Quasi-Biennial Oscillation (QBO). The QBO has such inherently long timescales that it persists for several months in seasonal forecasts from initial atmospheric conditions alone and its regularity means that it can be predicted from simple composites of earlier cycles. Nevertheless, a growing number of numerical models used in seasonal forecast systems can now simulate and predict the oscillation within climate forecasts (Garfinkel et al., 2018; Richter et al., 2020b; Stockdale et al., 2021) with the aid of forcing from parametrized non-orographic gravity waves, and there is skill in predicting QBO phase changes at lead times of a few months (e.g. Pohlman et al., 2013, Scaife et al., 2014a). The surface impact of the QBO is also well established and has stood the test of time since it was first identified in the 1970s (Ebdon 1975; Thompson et al., 2002; Anstey and Shepherd 2014; Gray et al 2018). Yet again this response projects closely onto the North Atlantic Oscillation (and hence the Arctic Oscillation/Northern Annular Mode) and the Southern Annular Mode. The favoured mechanism involves refraction of vertically propagating Rossby waves in the lower stratosphere (Holton and Tan 1980), although other pathways may also be involved (e.g. Inoue et al., 2011; Yamazaki et al., 2020; Rao et al., 2020b, 2021b). The observed magnitude of the QBO teleconnection is also large enough to provide seasonal predictability of surface climate (Boer and Hamilton 2008) but its modelled amplitude at the surface appears to be under-represented in current operational prediction systems and models (Scaife et al., 2014b; Garfinkel et al. 2018; O'Reilly et al. 2019; Rao et al. 2020b; Anstey et al. 2021).

In addition to the stratosphere acting as a source of predictability, other mechanisms by which the stratosphere plays a role in seasonal predictions involve a pathway for global scale teleconnections. These often originate in the tropics where the longer timescales of coupled ocean-atmosphere variability such as the El Niño Southern Oscillation (ENSO, L'Heureux et al. 2020) provide a predictable source of low frequency variability. Effects on the extratropics can occur by tropical excitation of anomalous Rossby waves which propagate polewards but also upwards into the stratosphere, as in the case of ENSO (Manzini et al., 2006; Domeisen et al., 2019), giving two pathways for extratropical influence (Butler et al., 2014; Kretschmer et al., 2021). These highly predictable tropical sources of climate variability alter the strength and position of the stratospheric polar vortex in the extratropics as well as the frequency of SSWs (Polvani et al., 2017) and these are followed by changes in the seasonal westerly jets in the troposphere and surface climate via the North Atlantic Oscillation (Ineson and Scaife 2009; Cagnazzo and Manzini 2009) or the Southern Annular Mode (Byrne et al., 2019). As might be expected, both the QBO and ENSO teleconnections are best represented in seasonal forecast systems which contain a well resolved stratosphere (Butler et al., 2016). We note that new examples of the stratosphere acting as a conduit for seasonal teleconnections are still being uncovered (Hurwitz et al., 2012, Woo et al., 2015). For example, the Indian Ocean Dipole (IOD) received little attention in this context until the recent record event of late 2019, when it appears to have driven an extreme winter strengthening of the northern hemisphere stratospheric polar vortex. This strengthening took many weeks to decay, giving rise to extreme yet highly predictable conditions in the stratosphere and around the Atlantic sector in late boreal winter (Hardiman et al., 2020b; Lee et al., 2020b). The same event was also implicated in extreme changes in the polar vortex and the near SSW in the southern hemisphere (Rao et al., 2020e); an event that itself likely helped to drive the extreme summer conditions and wildfires over Australia that year (Lim et al., 2021).

Apparent links between Arctic sea ice and seasonal winter climate in the mid latitudes have also been suggested to be mediated by the stratosphere, with increased Rossby wave activity and a weakening of the stratospheric polar vortex in response to reduced sea ice, especially in the Barents-Kara Sea (Jaiser et al., 2013; Kim et al. 2014; King et al., 2016; Kretschmer et al., 2016). Some studies also reproduced surface signals in response to sea ice anomalies in seasonal forecasts of particular years that are in apparent agreement with observational estimates (e.g. Balmaseda et al., 2010; Orsolini et al., 2012). However, recent updates to observational records show a weakening of these apparent effects (Blackport and Screen 2020) and significant non-stationarity (Kolstad and Screen 2019). Subsequent modelling studies with larger samples of simulations have provided mixed results (Zhang et al 2018;

Dai and Song 2020; Smith et al 2021), and some have argued that the atmospheric response to sea ice is weak and that while the sensitivity to Barents-Kara sea ice may be stronger, the stratospheric response in particular is highly variable (McKenna et al. 2017). While there may well be a longer-term effect via the stratosphere from sea ice decline (Sun et al., 2015; Screen and Blackport 2019; Kretschmer et al., 2020), sensitivity of the response to the background state complicates the issue (Labe et al., 2019; Smith et al. 2017), as do possible confounding influences from the tropics (Warner et al. 2020) and to date there is no clear consensus for strong enough year-to-year effects to provide significant seasonal predictability.

Other proposed teleconnections acting via the stratosphere have been found in observations but remain to be confirmed with successful reproduction in physically based climate models. A prominent example involves a proposed link between Eurasian snow amounts and the stratosphere, followed by a return influence on the NAO and surface climate. In this case, enhanced snow cover or depth is associated with high pressure over north Eurasia, an increase in the flux of Rossby wave activity into the stratosphere and a subsequent weakening of the stratospheric polar vortex, followed by the expected negative shift in the NAO and AO (Cohen and Entekhabi 1999, Cohen and Jones 2011; Cohen et al., 2014; Furtado et al., 2015). However, the strength of this link in climate models and seasonal predictions is modest (Fletcher et al., 2009; Riddle et al., 2013; Tyrrell et al., 2018, 2019) and does not agree with apparent links to the AO in observations (Kretschmer et al., 2016; Garfinkel et al., 2020) even when model mean state biases are corrected (Tyrrell et al., 2020). It has also been suggested that teleconnections to snow are non-stationary or non-causal and there is continued debate about its long-term robustness (Peings et al., 2013; Henderson et al., 2018).

In summary, a number of mechanisms by which the stratosphere acts to provide seasonal predictability either by acting directly as a source of predictable variability (e.g. the QBO, SSWs), or as a conduit for teleconnections (e.g. ENSO, MJO, IOD) have now been established in observations and have been confirmed using climate model simulations based on first principles. These operate in seasonal forecast systems, albeit with remaining errors such as the weakness of the QBO connection to surface climate. Meanwhile, other mechanisms involving the stratosphere (for example the response to snow cover variations) have been proposed based on apparent observed relationships, but until we have agreement between these observations and theory (model simulations), scientists remain sceptical of whether they represent actual sources of seasonal predictability and these remain topics of current research.

4 The stratosphere and annual to decadal prediction

In recent years, initialised predictions on longer timescales were developed on the premise of multiyear memory in the ocean (e.g. Smith et al 2007), and following the development pathway mapped out by seasonal forecasts in the past, these are now being run operationally to produce real time multi-model forecasts (Smith et al., 2013). Kushnir et al. (2019) mapped out this operational development of annual to decadal predictions and highlighted a number of sources of predictability, some of which involve the stratosphere (Figure 3), but not all of which are fully represented in climate prediction systems.

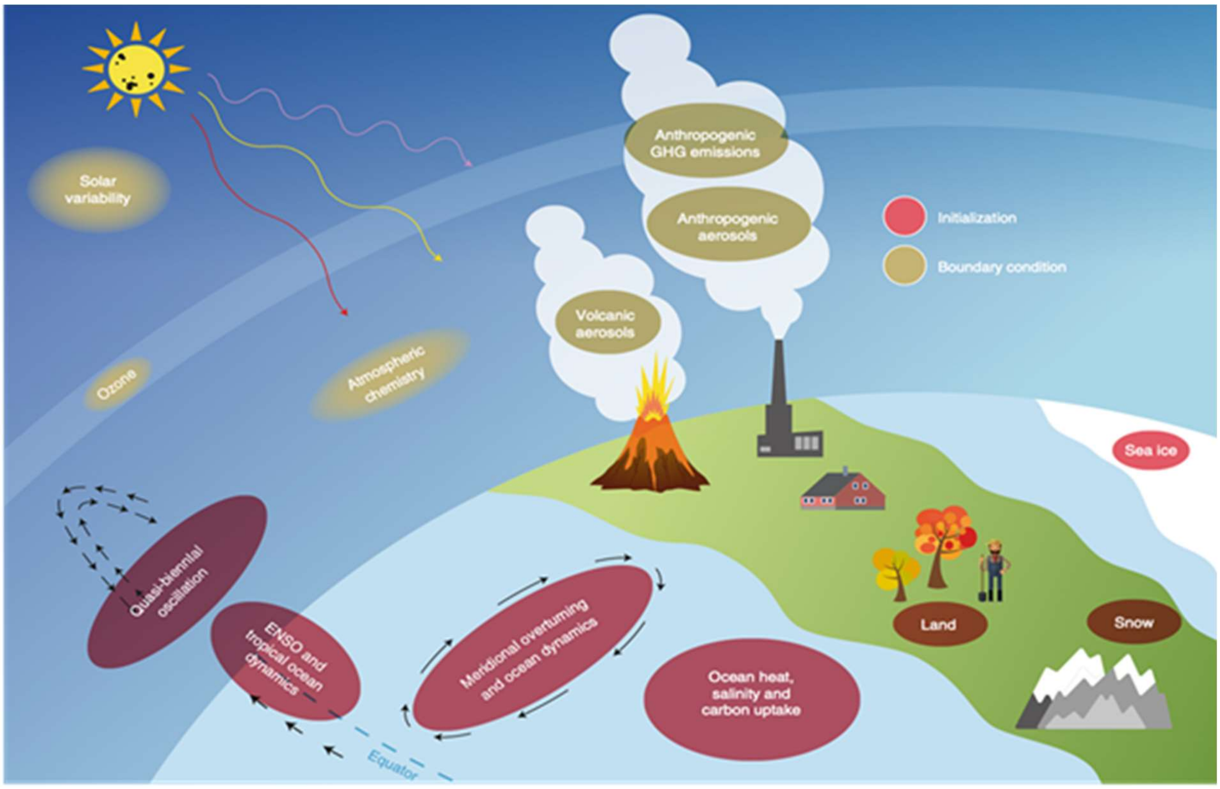

Figure 3. Sources of annual to decadal predictability, some of which involve the stratosphere through the response to external forcing, internal atmospheric dynamics, or ozone chemistry changes. After Kushnir et al., 2019.

Despite common misconceptions, not all annual to decadal predictability stems from the ocean. Indeed, it has been clearly demonstrated that multiyear predictability of the QBO exists in current decadal predictions systems out to lead times of several years (Pohlman et al., 2013; Scaife et al., 2014a). This offers the prospect of a stratospheric contribution to multiyear predictability of the extratropics through the teleconnection with the Arctic Oscillation (Anstey and Shepherd 2014, Gray et al., 2018) and to tropical predictability through links to the MJO (e.g. Martin et al., 2021) and wider tropical climate variability (Haynes et al., 2021).

Although it is more important on multidecadal timescales (see below), external forcing of the stratosphere can also act as a source of decadal predictability. Forced climate signals from changes in greenhouse gases or stratospheric effects such as ozone depletion occur on a much longer timescale than the lead time of decadal forecasts but their contribution to the skill of predictions is not trivial. For example, it is not immediately obvious whether the slow changes from multidecadal forced signals would simply be swamped by unpredictable internal variability on decadal timescales, rendering long term external forcing changes useless for decadal predictions. However, this is not the case and long-term forcing is now known to be an important source of decadal prediction skill (Smith et al., 2019, 2020).

External forcing involving the stratosphere on shorter timescales is also important for annual to decadal predictions. The stratosphere has long been known to be influenced by volcanic eruptions, particularly in the case of tropical volcanic eruptions which are powerful enough to inject significant quantities of sulphur dioxide into the atmosphere. Here it reacts with water to form sulphuric acid and persists in aerosol form, leading to predictable multiyear global surface cooling, tropical stratospheric warming and an intensification of the westerly stratospheric polar vortex in the extratropics (Robock and Mao 1992). Although the sample of observed events is limited, modelling studies have reproduced an observed post-eruption intensification of the westerly winds in the stratosphere and some impacts on the surface Arctic Oscillation. However, generations of models have struggled to reproduce the two-year persistence of volcanic effects seen in observations and the observed magnitude of the effect on the winter AO (e.g. Stenchikov et al., 2006; Marshall et al., 2009; Charlton-Perez et al., 2013, Bittner et al., 2016). In addition to these changes in the atmosphere, the intensification of stratospheric westerlies and hence Arctic Oscillation also combines with surface cooling of the ocean to generate predictable changes in the Atlantic meridional overturning circulation (Reichler et al., 2012) which can extend the volcanic influence to decadal timescales (Swingedouw et al., 2015). Finally, although the mechanism is debated, there is also evidence of a multiyear effect of tropical volcanic eruptions on ENSO, presumably requiring the persistent radiative forcing that arises through the long residence time of volcanic products, particularly sulphate aerosols, in the stratosphere. This reportedly increases the frequency of El Nino events by a factor of two in the years following volcanic eruptions (Adams et al., 2003), again suggesting an important source of multiannual predictability via the stratosphere.

A second source of multiannual predictability from external forcing originates from solar variability and in particular the 11-year solar activity cycle. Although a number of alternative mechanisms have been proposed (see Gray et al., 2010 for a review), the established mechanism for surface effects via the stratosphere is the change in the polar vortex that results from changes in upper stratospheric heating over the course of each cycle between solar minimum and solar maximum. Atmospheric wave-mean flow interactions amplify the initial radiatively driven change and drive its descent to the troposphere (Kodera and Kuroda 2002; Marsh et al 2007; Ineson et al., 2011; Givon et al., 2021), where changes in the extratropical jets result in a negative (positive) Arctic Oscillation pattern following solar minimum (maximum). There is also evidence that it contributes to interannual prediction skill (Dunstone et al., 2016) and an interesting aspect that has emerged in recent years is the integrating effect of the ocean on solar induced changes in the NAO via interannual persistence of ocean heat content anomalies which leads to a lag of around 3 years ($\pi/2$ cycles) in the peak response, as would be expected if the ocean is integrating the effects of a periodic solar forcing (Scaife et al., 2013; Gray et al., 2013; Andrews et al., 2015; Thiéblemont et al., 2015). However, debate continues as to whether the solar signal is indeed large enough to be detectable in observations in the presence of large internal tropospheric variability (Chiodo et al., 2019).

Perhaps the longest known timescale for predictability from initial conditions, which also involves the stratosphere, is the interaction of Atlantic Multidecadal Variability (AMV) with the stratospheric circulation. The Atlantic has followed pronounced multidecadal variations over the last century (Mann et al., 1995) and these variations are predictable out to years ahead (Hermanson et al., 2014). Some studies link these variations to the stratosphere and the NAO/AO (Reichler et al., 2012; Omrani et al., 2014). Indeed, the pronounced multidecadal increase in the surface NAO between the 1960s and 1990s is strongly coupled to changes in the strength of the stratospheric polar night jet (Scaife et al., 2005). Although current models simulate weak coupling between the AMV and the free atmosphere, this coupling appears to increase with model resolution (Lai et al., 2021) suggesting that the links between AMV, the stratosphere and the NAO offer potential for improved decadal scale prediction involving the stratosphere.

The currently recognised role of the stratosphere in decadal forecasts of surface climate again appears mainly via the impact on annular modes and, in the northern hemisphere, the North Atlantic Oscillation. Indeed, while current decadal prediction systems are now able to produce skilful predictions of variations in the NAO on multiyear lead times (Smith et al., 2019, 2020; Athanassiadis et al., 2020), much work is still needed to attribute these variations to external forcing or internal variability and to understand the interaction between boundary and initial conditions which blurs the simple distinction between the two. These new results are important because they indicate new-found decadal predictability of events like the high NAO of the 1990s which yielded a run of mild but wet and stormy winters in northern Europe and the eastern USA. These winters are well known to have caused significant impact for example on the insurance sector (Leckebusch et al., 2007) and coincided with the longest observed absence of SSW events (Pawson and Naujokat 1999; Domeisen 2019). Given the indications of coupled stratosphere-troposphere variations on decadal timescales (Scaife et al., 2005; Omrani et al., 2014; Garfinkel et al., 2017; Woo et al., 2015), understanding the role of the stratosphere in extratropical decadal predictions needs further investigation.

5 The stratosphere and multidecadal projection

The importance of the stratosphere for climate projections on multidecadal timescales was generally recognised before its role in predictions on shorter timescales. This is in part a legacy of the early development of stratosphere-troposphere models for ozone depletion studies described in the introduction. On these longer timescales, coupling between stratospheric composition, thermal structure and atmospheric circulation gives rise to ~~surface climate predictability~~improved climate projections.

Perhaps the best-known case for the stratosphere affecting multidecadal projections of surface climate is the influence of ozone depletion on the southern annular mode (SAM; Thompson and Solomon 2002, 2005; McLandress et al., 2011; Polvani et al., 2011; Son et al., 2018) where decreasing ozone in the late 20th century led to a strengthened pole-to-equator temperature gradient, a stronger stratospheric polar vortex and a shift to strong positive SAM phases at the surface. In this case, studies again show the importance of stratospheric resolution to generate the full response, consistent with a genuine downward influence (Karpechko et al., 2008). The associated poleward shift in the tropospheric jet is connected to a delay in the spring breakdown of the stratospheric polar vortex (Byrne et al., 2017) and delivered significant and prolonged changes in rainfall across many regions of the southern hemisphere (Kang et al., 2011; Purich and Son 2012). Implementation of the Montreal Protocol in 1987 and subsequent reductions in the rate of ozone depletion mean that recovery of the ozone layer is now expected over the coming decades and the reversible effects of this on the surface climate form an important element of current multidecadal projections (Thompson et al., 2011; Previdi and Polvani 2014; Solomon et al., 2016; Banarjee et al., 2020, Zambri et al., 2021) where they are expected to play an important role alongside other changes in the southern stratosphere due to continuing increases in greenhouse gases (Son et al., 2009; Barnes et al., 2012), some of which occur via the stratospheric polar vortex in a similar way to those from ozone depletion and recovery (Ceppi and Shepherd, 2019).

The more limited effects of ozone depletion in the northern hemisphere meant that the role of the stratosphere in multidecadal projections took longer to become established. Some early studies found potential amplification of positive Arctic Oscillation trends under climate change when the stratosphere was included (Shindell et al., 2001). However, this was not borne out in later studies as simulations with other fully coupled ocean-troposphere-stratosphere models suggested weakening of the stratospheric polar vortex (e.g. Huebener et al., 2007). Subsequent studies with multiple models also indicated a southward shift in the polar night jet with weakening high latitude winds and strengthening subtropical winds (Scaife et al., 2012; Manzini et al., 2014). These changes result from increased atmospheric wave driving of the winds which can overwhelm the cooling effect of greenhouse gases (Karpechko and Manzini 2012) and can lead to important differences in future surface climate, for example in regional rainfall in areas typically affected by the stratosphere via the Arctic Oscillation and NAO (Scaife et al., 2012). There is still significant uncertainty due to the diversity of modelled stratospheric responses to greenhouse gas increases (Manzini et al., 2014, Simpson et al., 2018, Zappa and Shepherd 2017), and it has proved difficult to identify any clear change in the frequency of sudden stratospheric warmings (Ayarzagüena et al., 2018, 2020; Rao et al., 2020c). This is perhaps due to the competition between strengthening latitudinal temperature gradients near the tropopause and enhanced meridional overturning in the mid stratosphere. There is also strong inherent unpredictable variability from decade to decade in the frequency of SSW occurrence (Butchart et al., 2000; McLandress and Shepherd 2009).

Other aspects of future climate change where the stratosphere plays a role have also been identified, for example, in the debate over the response to future levels of Arctic sea ice. In this case it seems that the response of the mid-latitude circulation involves a negative shift in the Arctic Oscillation (Screen et al., 2018; Zappa et al., 2018; McKenna et al., 2018). This could again be amplified by interaction with the stratosphere as some studies suggest that the stratospheric response is necessary for a large surface response (Kim et al., 2014), while others highlight that the stratospheric interaction is sensitive to the regional pattern of sea ice decline (McKenna et al., 2018), and still others show evidence of non-linear stratospheric, and stratosphere-mediated surface response (Manzini et al., 2018), coincident with the time when the Barents and Kara seas become ice-free (Kretschmer et al., 2020). Furthermore, studies also indicate that the surface climate response to sea ice decline depends systematically on the phase of the stratospheric QBO (Labe et al., 2019).

Although it is much less certain than anthropogenic climate change, there have also been suggestions of a multidecadal decline of external solar irradiance which can impact multidecadal climate projections via the stratosphere. Previous multidecadal solar minima, so called ‘grand minima’, have occurred in sunspot records and have been connected to the Little Ice Age period around the end of the 17th century using proxy and other data (Owens et al., 2017). Given recent weak amplitude 11 year solar cycles, there are now suggestions of a future solar ‘grand minimum’ where the 11 year cycle described above could become muted or even absent for a prolonged period (Lockwood et al., 2010). In this case, the upper stratospheric cooling in the tropics and summer hemisphere can change the meridional temperature gradient in a similar fashion to the 11 year cycle (Maycock et al., 2015) and leads to a negative shift in the AO and the NAO, and hence affects regional climate (Ineson et al., 2015). However, in this case it appears that while regional changes could be significant, they are generally much smaller than the surface warming due to anticipated levels of anthropogenic greenhouse gases (Anet et al., 2013; Ineson et al., 2015; Maycock et al., 2015).

Finally, we note that although low frequency variability in teleconnections is observed (e.g. Garfinkel et al., 2019), it is often unclear whether this is a systematic variation or simply due to sampling variability of an underlying stationary process (Jain et al., 2018). Nevertheless, there is growing evidence for systematic climate change in some of the teleconnections by which the stratosphere enables surface predictability. Under future climate change it appears that some of the teleconnections discussed above may *strengthen* in amplitude. For example, the strength of ENSO induced anomalies in the extratropical Atlantic/European sector increases in future climate projections (Müller and Roeckner 2006; Fereday et al., 2020). Similarly, recent analyses suggest that the MJO teleconnection to the extratropics increases in amplitude under climate change (Samarasinghe et al., 2020). The same is also true of the extratropical effects of the stratospheric QBO, where in this case, the amplitude of the teleconnection in composite anomalies doubles under future climate change (Rao et al., 2020d) despite the QBO itself becoming weaker (Richter et al., 2020c).

6 Outlook

Long range prediction has evolved quickly in recent years (Merryfield et al., 2017; 2020, Butler et al., 2019; Meehl et al., 2021) and this rapid development is due in part to the improved representation of stratospheric processes and stratospheric initial conditions in ensemble prediction systems. The long-range forecast community originally focused on predictability from initial ocean conditions and this remains the primary source of long-range predictability, for example from ENSO, but some of these long-range prediction systems contained poor representations of the stratosphere. In the meantime, those working in parallel on climate modelling of the stratosphere were rarely involved in initialised long-range prediction, instead being driven primarily by the ozone depletion problem. Knowledge exchange across fields is important in science and precursors to a new paradigm often occur when a topic is investigated by researchers from outside the field (Kuhn 1970). The crossover and collaboration between long range prediction and stratospheric research communities is no exception and the interaction between these communities has yielded rapid progress and new insights. Examples where initial atmospheric conditions can provide predictability beyond the usually assumed limit have been demonstrated, particularly for the extratropics but also for the tropics, and we now know that in some situations, for example when sudden stratospheric warmings occur, the initial conditions in the stratosphere can have more impact than initial conditions in the ocean (Thompson et al 2002; Scaife and Knight 2008; Polvani et al 2017). This suggests that initial atmospheric conditions in the stratosphere are likely to be more important for long range forecasts than previously assumed (Mukougawa et al., 2005, 2009; Stockdale et al., 2015; Noguchi et al., 2016, 2020a; Choi and Son 2019; O'Reilly et al., 2019; Nie et al., 2019), not least because the overturning and breaking of Rossby waves in the stratosphere is followed by long lived atmospheric anomalies due to synoptic scale eddy feedbacks that prolong the effects in the troposphere (Kunz and Greatbatch 2013Kang et al., 2011; White et al., 2020). More research on the initial conditions in the stratosphere might therefore help to reveal potential for further improvements in prediction skill.

A notable simplification to understanding the role of the stratosphere, at least in extratropical long-range predictions, is its apparently seamless mechanism across different timescales and different phenomena. Following the early ground-breaking studies showing surface impacts of stratospheric variability (e.g. Labitzke 1965, Boville 1984) and a multitude of studies on individual teleconnections between the stratosphere and surface climate, the projection of stratospheric variability onto the Arctic Oscillation/North Atlantic Oscillation/Annular Mode circulation patterns across timescales and hemispheres is now well established (see the review by Kidston et al., 2015). This suggests that similar coupling processes occur between the stratosphere and troposphere from months to decades and these processes lead to some of the most intense extratropical climate extremes, in winter in the northern hemisphere and in late spring/early summer in the southern hemisphere (Karpechko et al., 2018; Fereday et al., 2012, Kautz et al., 2019; Domeisen and Butler 2020). While studies point to changes in upper tropospheric baroclinicity and tropospheric eddy feedbacks as crucial in these teleconnections, a full mechanistic understanding of how this occurs is still lacking.

Some, but not all, leading forecast systems now include a well resolved stratosphere with reasonable representation of relevant processes such as the body force from sub-grid orographic and non-orographic gravity waves. However, many outstanding problems remain. Although their number is increasing, only a subset of current GCMs have the ability to simulate a realistic QBO beyond its decay from initial conditions and it seems that all GCMs have problems with the fidelity of modelled QBO teleconnections, which are either too weak or absent altogether (Scaife et al., 2014a; Kim et al., 2020; Anstey et al., 2021). Even the relatively well studied ENSO teleconnection via the stratosphere to the extratropics still has outstanding questions, such as whether the northern hemisphere stratosphere exhibits more SSW events during the La Niña phase (Butler and Polvani 2011; Song and Son 2012). This is not generally reproduced in modelling systems (Garfinkel et al., 2012) but occurred in the recent La Niña winter of 2020/2021. Similarly, while the increased monthly predictability from the MJO during the easterly phase of the QBO has been detected in monthly forecast experiments, the QBO-MJO connection does not persist in longer predictions and simulations with current models (Kim et al., 2020). Research and model development on stratosphere-troposphere interaction, including tropical effects (Noguchi et al., 2020b), will no doubt lead to further progress in resolving this issue (Haynes et al., 2021).

Errors in the modelled climatological mean climate are inevitably present to varying degrees in even the latest climate models. The common protocol of running a set of retrospective predictions to allow these mean biases to be estimated and hence subtracted from real time predictions may well correct for much of this error. However, the degree to which biases have a nonlinear, state dependent impact on the predictions is not fully understood. In some contexts, the nonlinear impacts of biases may be minimal (Karpechko et al., 2021) while others show sensitivity (Sigmond et al., 2008, 2010) and increases of prediction skill occur under certain background conditions, for example during Easterly QBO phases (Taguchi 2018). Other processes generally omitted from long range predictions include interactive variations of ozone and other trace gases. Although reports of impacts and benefits have varied, it is thought that surface signals on interannual timescales come mainly from dynamical rather than chemical changes (Seviour et al., 2014; Harari et al., 2019). Nevertheless, some studies suggest detectable effects from interannual variability of ozone and it may be that ozone fluctuations could help to amplify surface signals (Karpechko et al., 2014; Son et al., 2013; Smith and Polvani 2014; Oehrlein et al., 2020; Hendon et al., 2020), providing a further area for future development. Given that the cost of full atmospheric chemistry schemes remains computationally expensive, it seems likely that simple parametrizations of ozone chemistry (e.g. Monge-Sanz et al., 2021) would be valuable in this context.

We end with a pointer to an issue that has now been found to affect long-range predictions from monthly to seasonal to decadal and multidecadal timescales, particularly in the extratropics. So called ‘perfect model studies’, which test the ability of models to predict their own ensemble members, are now known to *underestimate* the true predictability of climate in some regions, particularly around the Atlantic basin, and so models are better at predicting real world variations than they are at predicting themselves. This so-called ‘Signal to Noise Paradox’ (Scaife and Smith 2018) is at first surprising, because perfect model prediction scores are often assumed to represent an upper (rather than lower) limit for prediction skill of the real world. The problem can be understood in terms of unrealistically weak ensemble mean predictions (e.g. Eade et al., 2014) but whether the stratosphere is involved directly in the cause of this problem remains to be seen (Saito et al., 2017; Stockdale et al., 2015), as it initially appears in the troposphere rather than the stratosphere in long range forecasts (Domeisen et al., 2020a). Nevertheless, the unrealistically weak amplitude of ensemble mean predictions may well have the same root cause as the weaker than observed amplitude of modelled teleconnections to the stratosphere discussed in this review, including, for example, the under-representation of the surface impact of the QBO. Resolving this problem will therefore likely amplify these signals, provide greater levels of prediction skill, and further strengthen the role of the stratosphere in long range predictions of surface climate.

Author Contributions

AAS wrote the draft manuscript. All other co-authors contributed relevant references and input to revisions and editing of the manuscript. SWS helped produce Figure 1.

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