CHAPTER

# 11

# Sub-seasonal Predictability and the Stratosphere

*Amy Butler*, Andrew Charlton-Perez†, Daniela I.V. Domeisen‡, Chaim Garfinkel§, Edwin P. Gerber¶, Peter Hitchcock‖, Alexey Yu. Karpechko#, Amanda C. Maycock**, Michael Sigmond††, Isla Simpson‡‡, Seok-Woo Son§§*

*Cooperative Institute for Research in Environmental Sciences (CIRES)/National Oceanic and Atmospheric Administration (NOAA), Boulder, CO, United States †Department of Meteorology, University of Reading, Reading, United Kingdom ‡Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland §Freddy and Nadine Hermann Institute of Earth Science, Hebrew University of Jerusalem, Jerusalem, Israel ¶Courant Institute of Mathematical Sciences, New York University, New York, NY, United States ‖École Polytechniqe, Saclay, Paris, France #Finnish Meteorological Institute, Helsinki, Finland **School of Earth and Environment, University of Leeds, Leeds, United Kingdom ††Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC, Canada ‡‡Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, United States §§School of Earth and Environmental Sciences, Seoul National University, Seoul, Republic of Korea

OUTLINE



*Sub-seasonal to Seasonal Prediction*
https://doi.org/10.1016/B978-0-12-811714-9.00011-5



Crown Copyright © 2019 Published by Elsevier Inc. All rights reserved.

# 1 INTRODUCTION

The stratosphere is the layer of highly stratified air that extends for roughly 40 km above the tropopause and contains approximately 20% of the mass of the atmosphere. The climatology, seasonal evolution, and variability of the stratospheric circulation are strongly governed by the combined influences of solar and infrared radiation, ozone chemistry, and transport and momentum transport by Rossby and gravity waves that propagate upward from the troposphere below. While it contains a smaller fraction of atmospheric mass than the troposphere, the stratosphere is far from being a passive bystander to tropospheric influences. It exhibits a diverse range of variability on a spectrum of timescales with, in many cases, a well-established influence on the tropospheric circulation below. As a result, knowledge of the state of the stratosphere has the potential to enhance the predictability of the troposphere on sub-seasonal to seasonal (S2S) timescales and beyond.

This chapter reviews our knowledge of the coupling between the stratosphere and troposphere in the tropics (Section 2) and the extratropics (Section 3) to provide a clear understanding of where and when coupling is important. In Section 4, we review the progress to date in trying to harness stratosphere-troposphere coupling to enhance predictability on the S2S timescale, a key focus of the World Climate Research Programme/Stratosphere-Troposphere Processes And Their Role in Climate (WCRP/SPARC) Stratospheric Network for the Assessment of Predictability (SNAP) project. Finally, in Section 5, we examine a number of open questions and provide some perspective on where and how improved understanding and simulation of stratosphere-troposphere coupling are most likely to lead to improved skill. Throughout the chapter, it is important to emphasize that one of the significant difficulties in assessing and understanding stratosphere-troposphere coupling (in common with other low-frequency phenomena, such as Deser et al., 2017) is the relatively short observational record that exists for the stratosphere.

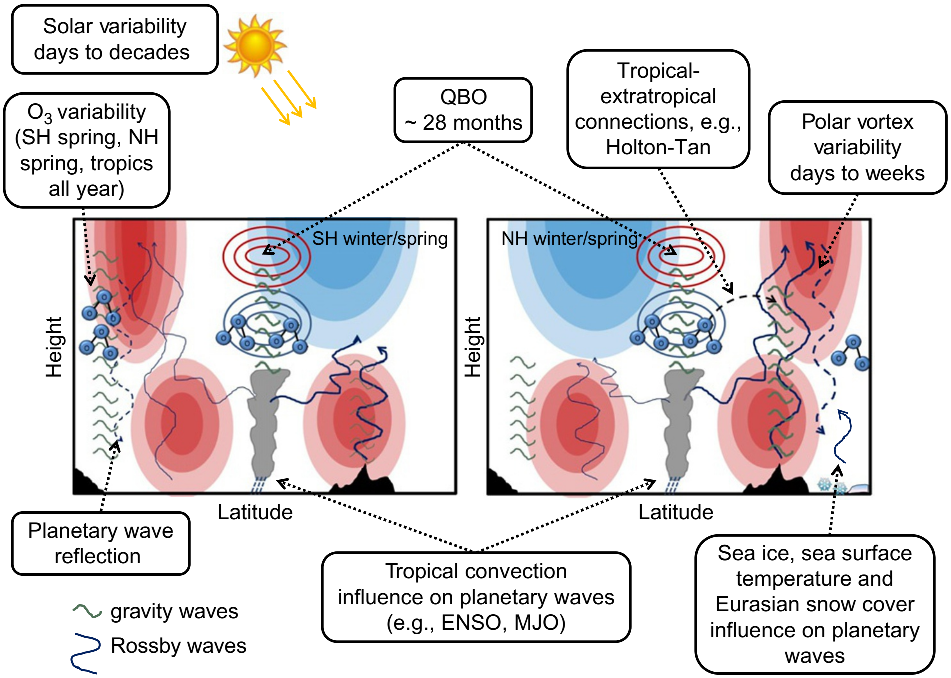


**FIG. 1** Schematic showing phenomena of known relevance to stratosphere-troposphere coupling. Contours show the zonal mean zonal wind schematically (*red*-filled contours indicate mean westerly winds and *blue*-filled indicate easterly winds). Left panel shows Southern Hemisphere (SH) winter and spring and right panel shows Northern Hemisphere (NH) winter and spring. *Red*- and *blue*-unfilled contours indicate zonal mean, zonal wind anomalies associated with the QBO.

Fig. 1 highlights the major phenomena relevant to coupling between the stratosphere and troposphere, including the Quasi-Biennial Oscillation (QBO), solar variability, ozone, and the role of tropospheric planetary-scale waves.

## 2 STRATOSPHERE-TROPOSPHERE COUPLING IN THE TROPICS

In the tropics, the dominant feature of stratospheric variability is a remarkably regular succession of downward-migrating easterly and westerly zonal jets known as the QBO. Over a period of roughly 28 months, the equatorial winds transition between westerly QBO (WQBO) and easterly QBO (EQBO) as a result of the selective absorption of tropical waves propagating upward from the troposphere below (Lindzen and Holton, 1968; Holton and Lindzen, 1972; Baldwin et al., 2001).

In addition to the effects of the QBO on polar vortex variability discussed later in Section 4.3, recent work has emphasized the important role that the QBO may play in determining tropical, tropospheric variability and predictability. This section reviews the understanding of QBO-troposphere coupling in the tropics and the potential to exploit these links for improved predictability.

## 2.1 How Does the QBO Influence the Tropical Troposphere?

The QBO can affect the characteristics of tropical deep convection (e.g., Collimore et al., 2003; Liess and Geller, 2012). Satellite observations and numerical model simulations indicate that tropical deep convection across the western Pacific is stronger during EQBO winters than during WQBO winters (Collimore et al., 2003). Additionally, sub-seasonal Madden Julian Oscillation (MJO)-like convective activity is significantly modulated by the QBO, with stronger and more organized MJO convection during 50-hPa EQBO winters (Liu et al., 2014b; Yoo and Son, 2016; Son et al., 2017; Nishimoto and Yoden, 2017).

The mechanism for QBO-induced changes in tropical convection is not well understood. The possible impact of the QBO on tropical deep convection often has been explained by local instability and tropopause property changes (Giorgetta et al., 1999; Collimore et al., 2003; Yoo and Son, 2016). Recently, radiative feedback and the associated large-scale vertical motion change have been proposed as possible mechanisms (Nie and Sobel, 2015; Son et al., 2017). Next, these hypotheses are briefly introduced.

The change in vertical wind shear in the upper troposphere associated with the downward propagation of QBO wind anomalies could modify tropical deep convection (Gray et al., 1992). For example, over the Indo-Western Pacific warm pool region, absolute vertical wind shear across the tropopause becomes anomalously strong under WQBO (see Fig. 3 of Gray et al., 1992). This could disrupt convective organization, especially by shearing off deep convection that overshoots into the stratosphere. This may result in less-organized deep convection in WQBO, but more-organized convection in EQBO.

The QBO modifies not only the vertical wind shear, but also the thermal stratification. It is well documented that the secondary circulation induced by the QBO effectively changes the tropical temperature profile (e.g., Baldwin et al., 2001). For instance, 50-hPa easterlies accompany cold anomalies centered at 70 hPa that extend into the upper troposphere. These temperature anomalies can act to destabilize the upper troposphere. If deep convection is influenced by the upper-tropospheric thermal stratification, this destabilization may allow more-organized deep convection during EQBO (Gray et al., 1992; Giorgetta et al., 1999; Collimore et al., 2003; Yoo and Son, 2016).

The two mechanisms described here are essentially based on local instability, which could modify very deep convection. However, in the tropics, cloud tops are typically located a few kilometers below the tropopause (Gettleman and Forster, 2002). Convection that crosses the tropopause is relatively rare. As such, it is questionable whether these mechanisms are really acting in the atmosphere.

Another possible mechanism for QBO influence on tropical convection (Reid and Gage, 1985; Gray et al., 1992) suggests that QBO-induced tropopause changes can modify deep convection. During EQBO, when the lower stratosphere is anomalously cold, tropopause height is slightly increased (Collimore et al., 2003; Son et al., 2017). A higher tropopause may provide a favorable condition for deep convection through enhanced organization. It is also possible that the cold tropopause itself can directly change tropical deep convection (e.g., Emanuel et al., 2013).

A further alternative is that radiative processes could play a role. Son et al. (2017) showed that tropical cirrus clouds are significantly modulated by the QBO. For example, near-tropopause cirrus clouds increase during EQBO winters due to an anomalously cold tropopause. This cirrus cloud change then could cause additional longwave radiative heating in the troposphere (Hartmann et al., 2001; Yang et al., 2010; Hong et al., 2016), as simulated by a cloud-resolving model (Nie and Sobel, 2015). This radiative process might be particularly important in QBO-related MJO convection changes because the MJO is partly organized by cloud-radiative feedback (e.g., Andersen and Kuang, 2012).

Finally, the QBO could influence variability directly in the subtropical troposphere. QBO-related equatorial wind anomalies must be accompanied by a meridional circulation that extends to the subtropical tropopause to maintain thermal wind balance, and this circulation appears to affect tropospheric eddies (Garfinkel and Hartmann, 2011a,b). The effect is particularly strong over East Asia (Inoue et al., 2011; Seo et al., 2013).

## 2.2 Predictability Related to Tropical Stratosphere-Troposphere Coupling

Predictability of the tropical stratosphere is strongly related to the predictability of the QBO and therefore exceeds sub-seasonal timescales. Many modern numerical prediction systems are capable of internally generating the QBO; however, model-generated QBOs often exhibit biases in amplitude and period (Schenzinger et al., 2016). Model forecasts of the QBO have significant skill beyond 12 months (Scaife et al., 2014a), but similar skill can be achieved with a simple statistical model representing a cosine with a period of 28 months. The predictive capabilities of forecast systems were recently tested by an interruption of the regular QBO behavior when an easterly jet unexpectedly appeared within a descending westerly phase in the lower stratosphere in early 2016 (Newman et al., 2016; Osprey et al., 2016). Seasonal forecasts initialized in November 2015 were not able to predict this event, instead predicting a regular descent of the westerly phase. Although unusual in observational records, such interruptions are occasionally seen in long climate model simulations (Osprey et al., 2016). The predictability limits of similar deviations from the regular QBO have not yet been examined.

Predictive skill in the QBO might be translated to tropospheric skill via a direct influence of the QBO on the MJO phase. As described in the previous section, QBO modulates interannual variations of MJO convection and its teleconnection (Son et al., 2017). A series of studies have shown that MJO-like, sub-seasonal convective activities become anomalously strong during EQBO winters (Liu et al., 2014b; Yoo and Son, 2016; Marshall et al., 2016b; Son et al., 2017; Nishimoto and Yoden, 2017). Such enhancement is observed in all phases of MJO from the Indian Ocean to the central Pacific (e.g., Yoo and Son, 2016). In addition, during EQBO winters, MJO convections tend to propagate more slowly and its period becomes longer (Son et al., 2017; Nishimoto and Yoden, 2017). Consistent with these changes, the MJO power spectrum is sharply peaked in the 40–50-day band during EQBO winters (Marshall et al., 2016b).

The fact that the MJO is generally stronger and better organized during EQBO winters could be translated into improved MJO prediction in EQBO winters. Marshall et al. (2016b), looking at 30 years of retrospective forecasts from the Bureau of Meteorology (BoM) seasonal prediction model, showed that the MJO is indeed better predicted when the equatorial lower-stratosphere is in the EQBO phase. In this model, the MJO prediction skill increases by up to 8 days between WQBO and EQBO winters (Fig. 2). Interestingly, this

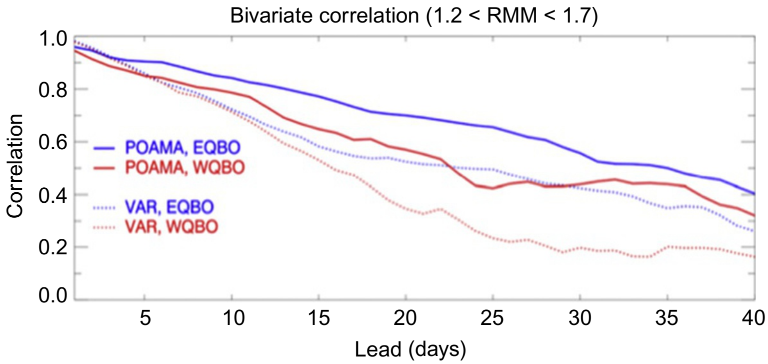


**FIG. 2** Bivariate correlation skill for the ensemble-mean Real-time Multivariate MJO (RMM) index, predicted by the BoM coupled seasonal prediction model, as a function of lead time during EQBO *(blue)* and WQBO *(red)* winters. For reference, the statistical forecast, based on vector autoregression, is also shown by *dotted lines*. Only MJO events that have initial amplitudes of 1.2–1.7 at the initial time are considered over the period of 1981–2010. *Reproduced with permission from Marshall, A.G., Hendon, H.H., Son, S.-W., Lim, Y., 2016. Impact of the quasi-biennial oscillation on predictability of the Madden–Julian oscillation. Clim. Dyn., doi:10.1007/s00382-016-3392-0.*

model simulated an increase in skill from the QBO-MJO connection, even though it does not have a highly resolved stratosphere (Marshall et al., 2016b).

A higher MJO prediction skill is not simply caused by the fact that MJO events initialized in EQBO winters are stronger than those in WQBO winters. In fact, MJO events of similar amplitude at the initial time showed essentially the same result—that is, a higher MJO prediction skill in EQBO winters (Fig. 2). This suggests that a structural change of MJO convection or upper-tropospheric circulation by the QBO may play a role in modulating MJO prediction skill. A more persistent MJO, which is typically found during EQBO winters, may also contribute to the extended MJO prediction. Although further analyses are required, especially using stratosphere-resolving models, this result suggests that the QBO is an untapped source of MJO predictability in boreal winter.

## 3 STRATOSPHERE-TROPOSPHERE COUPLING IN THE EXTRATROPICS

Many of the proposed pathways for a stratospheric influence on near-surface weather and climate have emphasized the role of the polar vortex, particularly the dynamic variability of the vortex in the Northern Hemisphere. This is reinforced by robust evidence from observations and a wide variety of modeling studies. Accordingly, much of the effort toward understanding the mechanisms of stratosphere-troposphere dynamical coupling has focused on this pathway. This section reviews our understanding of these extratropical links between the stratosphere and troposphere.

## 3.1 An Overview of Polar Vortex Variability

Due to the annual variation of solar heating over the poles, the stratosphere undergoes a strong seasonal cycle. In the extratropical winter hemisphere, the stark contrast in stratospheric temperatures between the cold polar night and the warmer low latitudes leads to the development of a strong westerly stratospheric polar vortex (Waugh et al., 2017), as shown in Fig. 3 for the Northern Hemisphere (NH; left panel) and Southern Hemisphere (SH; right panel). In the Northern Hemisphere, the stratospheric vortex exhibits maximum variability in January and February. The seasonal reversal of the climatological stratospheric winds from westerly to easterly as sunlight returns to the pole in the spring (the so-called final warming) occurs on average in mid-April, but it is highly variable due to the presence of significant dynamical variability. The Southern Hemisphere exhibits considerably weaker interannual variability (see shading in Fig. 3), both in midwinter and in the onset of the final warming, due to its weaker wave forcing; see Andrews et al. (1987) for a comprehensive review of stratospheric climate and dynamics.

There is active coupling between the stratosphere and troposphere during periods when significant stratospheric variability occurs (winter and spring in the Northern Hemisphere and spring in the Southern Hemisphere) (Thompson and Wallace, 2000). Variability in the position and strength of the stratospheric polar vortex is largely driven by planetary-scale Rossby waves (whose sources lie within the troposphere), which vertically amplify into the stratosphere and break (see Section 3.2 for more detail). When the polar stratospheric winds become easterly in spring-summer, downward-coupling mechanisms that involve vertically propagating Rossby waves from the troposphere to the stratosphere no longer will be in effect (Charney and Drazin, 1961).

In extreme cases, the wintertime polar vortex is so perturbed by the effects of Rossby wave breaking that the climatological westerly winds become temporarily easterly in events known as major Sudden Stratospheric Warmings (SSWs). Although there is a variety of criteria and terminology used to define these events (Butler et al., 2015), they are typically associated with

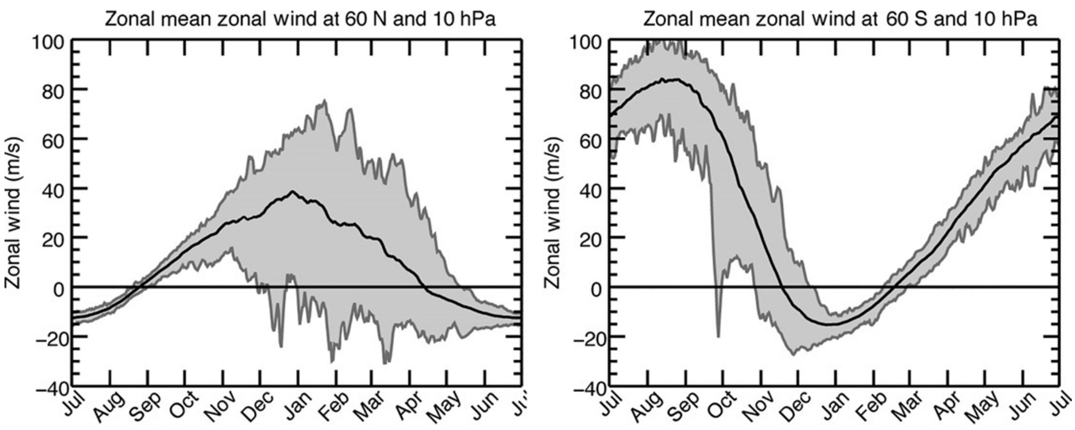


**FIG. 3** Zonal-mean zonal winds at 10 hPa and 60°N (left, for the Northern Hemisphere) and 60°S (right, for the Southern Hemisphere). The *solid black line* is the daily mean value, and the *gray shading* shows the range of values between the daily maximum and minimum values, using JRA-55 reanalysis data from 1958 to 2016.

a rapid adiabatic warming of the polar stratosphere of up to 70K over only a few days (Labitzke, 1977; Limpasuvan et al., 2004). SSWs are often classified by whether the vortex is displaced off the pole or whether it splits into two (Charlton and Polvani, 2007; Mitchell et al., 2011); these permutations correspond roughly to the zonal wave number of the waves responsible for the disruption of the vortex. While some SSW events are followed by a fairly fast recovery of the vortex over a period of a week or two, roughly half of SSWs undergo an extended-timescale recovery that lasts up to 2 months (Hitchcock et al., 2013), producing a stratospheric circulation pattern often termed the *Polar night Jet Oscillation (PJO)* (Kuroda and Kodera, 2001) and resulting in an extended influence on the troposphere below.

In the Northern Hemisphere, midwinter SSWs occur roughly six times per decade (Charlton and Polvani, 2007), most frequently in January and February, though they can occur any time from November through March. SSWs are much less common in the more quiescent Southern Hemisphere; only one event has been observed in September 2002 (Newman and Nash, 2005), although observational records in the Southern Hemisphere are short.

## 3.2 What Drives Polar Vortex Variability?

It has long been recognized that SSWs are associated with rapid amplifications of planetary waves from the troposphere (Finger and Teweles, 1964; Julian and Labitzke, 1965; Matsuno, 1971). Just how and why this amplification occurs remains a matter of longstanding debate. Some authors have argued that this is predominantly controlled by changes in the stratospheric basic state on which the waves are propagating; others say that the amplification arises from changes in the tropospheric source of the waves.

On the one hand, SSWs can occur in models that lack any explicit representation of tropospheric variability (Holton and Mass, 1976; Scott and Haynes, 2000; Scott, 2016) or in which the tropospheric variability has been strongly suppressed (Scott and Polvani, 2004). In these models, the internal state of the stratosphere itself determines the wave fluxes at the lower boundary. This control is often understood to occur through a resonance effect: when the phase speed of a free, traveling wave mode of the stratosphere approaches zero, it comes into resonance with the topographic forcing (Tung and Lindzen, 1979). Nonlinear effects can act to tune this resonance, leading to the rapid growth of the wave mode throughout the column (Plumb, 1981; Matthewman and Esler, 2011). Evidence for this behavior has been found in a number of case studies, particularly involving vortex-split events (Smith, 1989; Esler and Scott, 2005; Albers and Birner, 2014). However, just because idealized representations of the stratosphere can produce variability independent of tropospheric sources of variability does not mean that observed SSWs are unaffected by these sources. Many studies have pointed out various tropospheric precursors to SSWs (Nishii et al., 2009; Coy et al., 2009; Colucci and Kelleher, 2015; O'Neill et al., 2017). Constructive interference between climatological stationary waves and the anomalous waves generated by such precursors has been proposed as the relevant mechanism (Garfinkel and Hartmann, 2008; Garfinkel et al., 2010; Cohen and Jones, 2011; Smith and Kushner, 2012; Watt-Meyer and Kushner, 2015; Martineau and Son, 2015).

What implications do these alternate paradigms of the causes of stratospheric variability have for its predictability? Idealized models of vortex variability that show strong stratospheric control over the wave field sometimes exhibit bifurcations in their behavior that are extremely sensitive to initial conditions and external parameters (Yoden, 1987; Matthewman and Esler, 2011). This would imply that SSWs are extremely difficult to predict beyond the predictability horizon of weather systems, at least in a deterministic sense. Evidence for such bifurcations in forecast models has been found (Noguchi et al., 2016). However, sensitivity to the stratospheric basic state suggests that certain processes may provide skill in predicting the likelihood of the occurrence of SSWs, as has been proposed in various contexts, including solar variability and the QBO (Holton and Tan, 1980; Kodera, 1995; Haigh, 1996). On the other hand, if the wave field is primarily controlled by their sources, then tropospheric processes ranging from ENSO to Eurasian snow cover to Arctic sea ice should provide greater skill in predicting SSWs (e.g., Cohen et al., 2007; Ineson and Scaife, 2009; Kim et al., 2014). Tropospheric precursors themselves are also likely subject to both predictable and chaotic influences. The truth likely lies somewhere between the two paradigms; a recent study demonstrated explicitly that both the stratospheric and tropospheric states are essential for reproducing the amplification of the waves in an idealized model (Hitchcock and Haynes, 2016). Much future work remains in order to fully understand the extent to which polar stratospheric variability is predictable.

## 3.3 How Does Stratospheric Polar Vortex Variability Influence Surface Climate?

Much of the interest in stratosphere-troposphere coupling has arisen from studies of annular modes, which are the dominant structures of large-scale extratropical atmospheric variability in each hemisphere (Thompson and Wallace, 2000). To leading order, the annular modes in the stratosphere represent variations in the strength of the stratospheric polar vortex; by convention, positive indices correspond to a stronger, colder vortex. In the troposphere, the annular mode represents a latitudinal shifting of the eddy-driven, midlatitude westerlies; here, positive indices correspond to a poleward excursion.

Although not the first study to propose a downward influence from the stratosphere (e.g., Boville, 1984; Perlwitz and Graf, 1995; Hartley et al., 1998), the Northern Annular Mode (NAM) composites presented by Baldwin and Dunkerton (2001) have become an iconic visualization of stratospheric influence on the troposphere. They demonstrate that the tropospheric eddy-driven jet is, on average, shifted systematically equatorward for days to weeks following weak polar vortex events (essentially SSWs), associated with a negative phase of the NAM, and thus colder surface temperatures over much of the Northern Hemisphere midlatitudes and warmer surface temperatures over the Arctic. Likewise, strong vortex events are usually followed by a poleward shift of the eddy-driven jet (or positive phase of the NAM).

Given that the variability in the Northern Hemisphere polar vortex is primarily driven by planetary-scale Rossby waves whose sources lie within the troposphere, it has been questioned whether the apparent downward descent of annular mode index anomalies represents a true downward propagation of information from the stratosphere to the troposphere (Plumb and Semeniuk, 2003). However, controlled experiments with models of various degrees of complexity, in which stratospheric perturbations are imposed into a tropospheric model state that has no memory of the conditions that contributed to the stratospheric perturbation (Polvani and Kushner, 2002; Jung and Barkmeijer, 2006; Douville, 2009; Gerber and Polvani, 2009; Hitchcock and Simpson, 2014), have shown clearly that the state of the stratosphere does affect the troposphere.

Early attempts to explain the downward influence from the stratosphere to the troposphere focused on the consequences of the large-scale dynamical balance between winds and temperatures. This balance implies that the forcings responsible for inducing the stratospheric anomalies will have a direct (albeit weak) impact on the troposphere as well (Robinson, 1988; Hartley et al., 1998; Ambaum and Hoskins, 2002). Moreover, diabatic processes tend to strengthen this influence in an effect termed "downward control" (Haynes et al., 1991). Efforts to quantify this effect, however, have generally found it to be too weak to explain the full surface response (Charlton et al., 2005; Thompson et al., 2006a; Hitchcock and Simpson, 2016).

Strong feedback between tropospheric eddies and the jet is recognized as an essential component of internal variability of the tropospheric annular modes (Robinson, 1991, 1996; Hartmann and Lo, 1998; Limpasuvan and Hartmann, 2000). The idea that this tropospheric eddy feedback could play a role in the response to anomalous stratospheric conditions was suggested as early as Hartmann et al. (2001) and was confirmed by a series of studies demonstrating that the strength of the stratospheric influence on the troposphere in a given model was closely related to the strength of the tropospheric eddy feedback (Chan and Plumb, 2009; Gerber and Polvani, 2009; Garfinkel et al., 2013). The feedback is often measured by the decorrelation timescale of the annular modes: the stronger the feedback, the more persistent the annular modes (Ring and Plumb, 2008). The relationship between the decorrelation timescale and the response to an external forcing for a given dynamical mode is expected on the basis of a general result known as the *Fluctuation-Dissipation Theorem* (Leith, 1975). However, recent studies have shown that the correspondence between eddy feedback strength and annular mode decorrelation timescales is not always reliable (Simpson and Polvani, 2016), and alternative methods for quantifying this feedback continue to be explored (Lorenz and Hartmann, 2001, 2003; Simpson et al., 2013; Nie et al., 2014).

Recognition of the importance of tropospheric eddy feedback in determining the response to a stratospheric perturbation does not clarify how the stratosphere triggers this feedback in the first place. This question was first clearly articulated by Song and Robinson (2004), who proposed that the downward control response, while weak in and of itself, may serve as a trigger for tropospheric feedback between the eddies and the mean flow. However, their numerical experiments also suggested that planetary wave feedback might play a role. The possibility of some direct influence by the stratosphere on the synoptic scale eddies also has been raised (Tanaka and Tokinaga, 2002; Wittman et al., 2007). However, more recently, several modeling studies have clearly identified planetary waves as the key coupling pathway (Martineau and Son, 2015; Smith and Scott, 2016; Hitchcock and Simpson, 2016), at least for the Northern Hemisphere winter.

Although our understanding of stratosphere-troposphere coupling processes has advanced substantially in the last two decades, major open questions remain. Many theoretical and modeling studies to date have focused on the zonally symmetric component of the tropospheric response, despite the clear agreement in observations and models that the Northern Hemisphere response to stratospheric variability is strongest within the storm tracks, particularly in the Atlantic basin (Charlton and Polvani, 2007; Garfinkel et al., 2013; Hitchcock and Simpson, 2014). Additionally, it has been tacitly assumed that the same mechanisms are at play in Northern Hemisphere and Southern Hemisphere stratosphere-troposphere coupling; yet the tropospheric circulation is significantly different, and in particular, planetary wave activity is far weaker in the Southern Hemisphere.

## 3.4 Other Manifestations of Extratropical Stratosphere-Troposphere Coupling

SSWs are certainly the most dramatic form of stratospheric vortex variability, but they are not the only form. A full spectrum of other vortex variability exists, ranging from anomalously strong vortex events, to less dramatic weak vortex events that do not pass the threshold criteria for major SSWs, to individual planetary wave reflection events (Limpasuvan et al., 2005; Dunn-Sigouin and Shaw, 2015; Maury et al., 2016).

Planetary wave reflection events are an example of coupling through wave motions, as opposed to through the zonal mean circulation. The state of the stratosphere can affect the propagation of planetary waves such that they are reflected back down toward the troposphere, with subsequent tropospheric impacts (Perlwitz and Harnik, 2003). Wave coupling events occur on timescales of a few days to weeks and tend to be followed by a positive sign of the NAM or a poleward shift of the North Atlantic storm track (Shaw and Perlwitz, 2013). In the Southern Hemisphere, wave reflection plays a stronger role in stratosphere-troposphere variability, whereas in the Northern Hemisphere, it is found to be of comparable importance to the zonal mean coupling (Shaw et al., 2010). Less is currently known about the predictability of stratospheric wave reflection events (Harnik and Lindzen, 2001; Harnik, 2009; Shaw et al., 2010), although they tend to be sensitive to the QBO and sea surface temperature (SST) variability (Lubis et al., 2016a).

Chemistry-climate feedback is another important factor for stratosphere-troposphere coupling. Over the latter half of the 20th century, anthropogenic emissions of chlorofluorocarbons (CFCs) into the atmosphere have led to the chemical destruction of ozone ($O_3$) within the Southern Hemisphere polar vortex in springtime. Temperatures in the Southern Hemisphere polar stratosphere routinely drop below 195K in winter due to weaker dynamic variability compared to the Northern Hemisphere, which allows significant amounts of polar stratospheric clouds (PSCs) to form, upon which catalytic chemical reactions that destroy ozone can occur. The radiative cooling associated with chemical depletion of ozone at high latitudes results in a stronger polar vortex, and often a delayed seasonal breakup as well, and is thus a key driver of stratosphere-troposphere coupling on interannual (Son et al., 2013) and multidecadal (Thompson and Solomon, 2002; McLandress and Shepherd, 2011; Polvani et al., 2011) timescales in the Southern Hemisphere. While chemical ozone destruction within the Northern Hemisphere polar vortex is much lower than in the Southern Hemisphere, as temperatures are not typically cold enough to form large amounts of PSCs, substantial springtime Arctic ozone loss also can occur (Manney et al., 2011) and may be linked to interannual Northern Hemisphere tropospheric variability in the spring (Karpechko et al., 2014; Smith and Polvani, 2014; Calvo et al., 2015; Xie et al., 2016; Ivy et al., 2017). Ozone layer recovery, due to the Montreal Protocol and its amendments, may reverse these effects in the future, particularly if greenhouse gases continue to increase (Eyring et al., 2013).

# 4 PREDICTABILITY RELATED TO EXTRATROPICAL STRATOSPHERE-TROPOSPHERE COUPLING

The fact that variability in the stratospheric polar vortices has a substantial impact on the tropospheric circulation in both hemispheres is now well established. Because the stratospheric anomalies associated with SSWs can persist for several weeks, this fact alone is of considerable value for S2S forecasts in the extratropics (Sigmond et al., 2013). However, if the onset of stratospheric polar vortex anomalies can themselves be forecast, the value for forecasting is even greater, potentially leading to higher skill of extratropical surface climate at longer lead times. In order to exploit stratosphere-troposphere coupling, sub-seasonal prediction models need to be able to:

1. Skillfully forecast stratospheric variability
2. Accurately simulate the dynamical coupling between the stratosphere and troposphere

These issues are discussed in turn in the following subsections.

## 4.1 How Accurately Can the Polar Stratosphere be Predicted?

The smaller role of baroclinic instabilities and the strongly reduced Rossby wave spectrum in the stratosphere suggest that, in general, predictability timescales in the stratosphere should be longer than in the troposphere. One way to demonstrate the intrinsic, enhanced predictability of the stratosphere is to look at the decorrelation timescales of the annular modes (Baldwin et al., 2003; Gerber et al., 2010). In the Northern Hemisphere extratropical stratosphere (Fig. 4C), the characteristic timescale of NAM anomalies is about 1 month during winter. Even longer timescales exceeding 2 months can be seen in the Southern Hemisphere extratropical stratosphere during late winter and early spring (Fig. 4D). This contrasts sharply with decorrelation timescales in the troposphere, which are typically less than 10 days and peak at about 2 weeks during December–January in the Northern Hemisphere and November–December in the Southern Hemisphere. Note that extended persistence in the troposphere tends to coincide with enhanced variance in the stratosphere (Fig. 4A and B).

Numerical Weather Prediction (NWP) models have long been able to reproduce extended predictability in the stratosphere compared to the troposphere. For example, Waugh et al. (1998, in the Southern Hemisphere), Jung and Leutbecher (2007, in the Northern Hemisphere) and Zhang et al. (2013b, in both hemispheres) showed that forecast skill in the stratosphere is roughly twice that of the troposphere for the same forecast lead time. This skill is mostly linked to the ability to capture and maintain anomalies in the zonal mean circulation, even if models are unable to skillfully forecast planetary waves.

Recent studies have demonstrated stratospheric predictability in operational forecast models at sub-seasonal timescales in the Northern Hemisphere (Zhang et al., 2013b; Taguchi, 2014; Vitart, 2014). Correlation skill scores for stratospheric parameters can be higher than 0.6 for forecasts with a lead time of more than 20 days. During SSWs or periods of anomalously strong polar vortex, correlation skill scores can be as high as 0.8 for forecasts at 4 weeks lead time (Tripathi et al., 2015). There is also some evidence for modest skill in predicting the probability of an SSW or strong vortex event in seasonal forecasts initialized on November 1, based

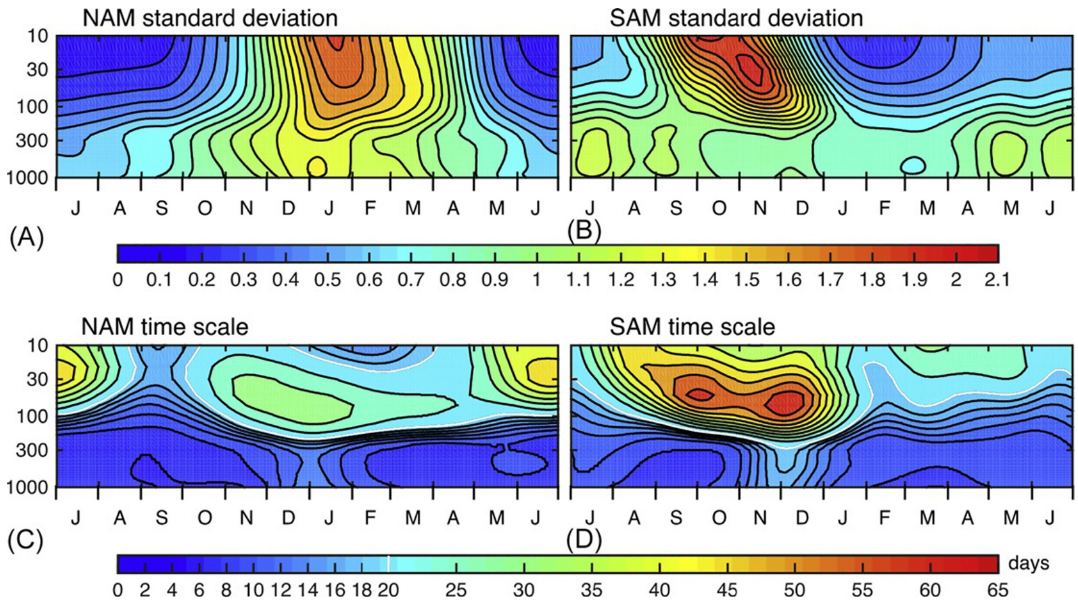


**FIG. 4** Standard deviation of the (A) Northern Hemisphere and (B) Southern Hemisphere annular modes (normalized such that indices at each pressure level have unit variance in the annual mean), and the estimated decorrelation timescale of the (C) Northern Hemisphere and (D) Southern Hemisphere annular modes, as a function of pressure and month, using JRA-55 reanalysis data (after Gerber et al., 2010). The NAM is based on data from 1960 to 2009, and the Southern Annular Mode (SAM) from 1980 to 2009.

on ensemble spread (Scaife et al., 2016). To date, fewer studies have assessed stratospheric predictability in the Southern Hemisphere, but similar or higher levels of skill have been found on sub-seasonal timescales (Roff et al., 2011), with some indications of even higher skill on seasonal timescales (Seviour et al., 2014).

As might be expected intuitively, stratospheric predictability is lowest just prior to SSW events when pulses of planetary wave activity reach the stratosphere, leading to nonlinear interactions between waves and the mean flow and weakening of the polar vortex (Taguchi, 2014; Noguchi et al., 2016). The predictability of SSW events is typically between 5 and 15 days (Tripathi et al., 2015), comparable to that of tropospheric weather systems. Tripathi et al. (2016) found high predictability for the onset of the January 2013 SSW in initialized numerical prediction systems for lead times of up to 10 days, but diminished predictability for longer lead times. This was partly attributed to decreased predictability of the amplified wave number-2 activity in the troposphere that induced the SSW. In general, vortex-weakening cases are thought to be less predictable than vortex-strengthening cases, even when the wave activity anomalies leading to these events—either wave amplification or attenuation—were of comparable magnitude (Taguchi, 2015). The largest stratospheric forecast errors are associated with cases where models fail to correctly predict wave activity fluxes over western Siberia and northern Europe, which is likely linked to an underestimation of tropospheric blocking (Lehtonen and Karpechko, 2016). In some cases, accounting for a mismatch of a few days between forecast and observed dynamical events (which is comparable to considering time-averaged forecasts) may lead to improved predictability (Cai et al., 2016).

## 4.2 S2S Extratropical Forecast Skill Associated With Strong and Weak Polar Vortex Events

In general, initializing forecast models with information about the state of the stratosphere does improve tropospheric prediction skill on S2S timescales. For example, Baldwin et al. (2003), Charlton et al. (2003), and Christiansen (2005) used simple statistical models and found modestly improved Northern Hemisphere extratropical surface skill at 10–45 days when using a stratospheric predictor as opposed to tropospheric predictors. More recent studies have combined information about the state of the stratospheric polar vortex with other tropospheric predictors to show significant skill in forecasting the winter North Atlantic Oscillation (NAO), the Atlantic-sector manifestation of the NAM. For example, Dunstone et al. (2016) used a linear regression model based on four November predictors (tropical Pacific SSTs, the Atlantic SST tripole pattern, Barents-Kara sea ice, and the strength of the stratospheric polar vortex) and found significant skill in the wintertime NAO ($r = 0.60$). Even higher skill ($r \sim 0.7$) using statistical forecasts with stratospheric predictors is found in other recent studies (Wang et al., 2017).

Following early experiments that examined the tropospheric response to a significant diminution in the stratospheric representation in models (Norton, 2003; Kuroda, 2008), two main modeling approaches have been used to demonstrate and quantify the impact of stratospheric perturbations on tropospheric predictability:

- Imposing perturbations to the stratospheric state through artificial nudging or damping to bring the stratospheric state closer to observations can produce model forecasts with substantially increased skill in the extratropical troposphere (Charlton et al., 2004; Scaife and Knight, 2008; Douville, 2009; Hansen et al., 2017; Jia et al., 2017), although not for all cases and models (e.g., Jung et al., 2011).
- Splitting a large set of hindcasts into groups initialized during strong, weak, and neutral stratospheric vortex conditions. S2S forecast skill of atmospheric circulation (including the NAO), surface temperature (particularly in eastern Canada and northern Russia), and North Atlantic precipitation is enhanced for both weak-vortex (Mukougawa et al., 2009; Sigmond et al., 2013) and strong-vortex (Tripathi et al., 2015) cases.

These studies show that S2S predictability associated with weak and strong stratospheric vortex conditions can be realized in dynamical forecast systems, with generally higher skill of surface climate predictions when forecasts are initialized during periods when the stratospheric state is significantly disturbed from its climatology.

## 4.3 S2S Extratropical Forecast Skill Associated With Stratosphere-Troposphere Pathways

As shown previously in Fig. 1, the stratospheric circulation is sensitive to a number of different processes in the Earth system. Certain relationships, or pathways, between the troposphere and the stratosphere persist for weeks, or even over the course of a season or longer, and can be exploited to improve probabilistic forecasts of surface variables. In the context of sub-seasonal predictability, these relationships can contribute to the overall likelihood of significant variability in the polar vortex. These relationships, and related studies examining associated forecast skill, are briefly reviewed here, arranged in order from shorter to longer timescales:

- *Blocking*: Tropospheric blocking exerts an influence on wave propagation into the stratosphere and can act as a precursor to SSW events (Quiroz, 1986) in terms of their spatial structure (Martius et al., 2009; Castanheira and Barriopedro, 2010), and also in terms of their characteristic anomalies in heat fluxes (Ayarzagüena et al., 2015; Colucci and Kelleher, 2015).
- *The Madden-Julian Oscillation (MJO)*: Both Garfinkel et al. (2012b) and Kang and Tziperman (2017) have demonstrated that the likelihood of SSW events increases during MJO events. Further, Garfinkel and Schwartz (2017) showed that there is a tight relationship between tropical convection in the West Pacific and polar stratospheric variability.
- *Snow cover and sea ice*: Extratropical surface conditions, such as snow cover and sea ice extent, can modulate the tropospheric wave field, and therefore, through promotion of a large-scale wave pattern that linearly interferes with the climatological Rossby wave field, can affect wave amplification and propagation into the stratosphere (Cohen and Entekhabi, 1999; Smith et al., 2010). Arctic sea ice variability also has been found to influence Northern Hemisphere polar vortex variability (Peings et al., 2013; Kim et al., 2014; Kretschmer et al., 2016), although the linkages seem to depend on the region of sea ice change (Sun et al., 2015; Screen, 2017a), with loss of sea ice in the Barents and Kara seas tied to a weakening of the polar vortex in late winter and spring (Kim et al., 2014; King et al., 2016; Yang et al., 2016). In some studies, these relationships have been tied to improved seasonal forecast skill (Cohen and Jones, 2011; Riddle et al., 2013; Orsolini et al., 2013, 2016; Kretschmer et al., 2016).
- *El Niño–Southern Oscillation (ENSO)*: On seasonal timescales, the ENSO tends to affect the midlatitudes through Rossby wave trains that propagate poleward on timescales of days to weeks (Hoskins and Karoly, 1981). El Niño events tend to strengthen the Aleutian low in the North Pacific (e.g., Barnston and Livezey, 1987), which in turn increases the wave flux into the Northern Hemisphere stratosphere through linear interference with the climatological stationary wave pattern (Garfinkel and Hartmann, 2008; Fletcher and Kushner, 2011; Smith and Kushner, 2012). The increased wave flux from the troposphere tends to weaken the Northern Hemisphere polar vortex and increase the probability of a negative NAO. This stratospheric pathway has been found to constitute a significant influence of ENSO on Eurasian climate (Ineson and Scaife, 2009; Bell et al., 2009; Cagnazzo and Manzini, 2009; Manzini, 2009; Li and Lau, 2013; Butler et al., 2015; Polvani et al., 2017). A few studies have indicated improved seasonal prediction skill for Eurasian climate during El Niño winters, when the stratospheric pathway is active (Domeisen et al., 2015; Butler et al., 2016).
- *The QBO*: The QBO exerts an influence on the polar vortex via the Holton-Tan effect (Baldwin et al., 2001), whereby the EQBO is typically associated with a weaker and more variable polar vortex in Northern Hemisphere winter, through its influence on planetary wave propagation (Holton and Tan, 1980; Naito et al., 2003). The communication between the tropical stratosphere and the polar vortex occurs through the altered characteristics of Rossby wave propagation in the subtropical stratosphere between the WQBO and EQBO (Garfinkel et al., 2012c; Anstey and Shepherd, 2014). Prediction skill

based on the phase of the QBO can be translated into an enhanced or reduced likelihood of polar stratospheric variability and coupling to the extratropical tropospheric jet. The QBO has been shown to enhance skill over the North Atlantic (Boer and Hamilton, 2008; Marshall and Scaife, 2009; Scaife et al., 2014a), although models appear to underestimate the magnitude of the effect apparent in observational or reanalysis data (Scaife et al., 2014b; Butler et al., 2016).

- *Decadal variability*: On decadal timescales, the 11-year solar cycle can affect the stratospheric temperature structure in the tropics (Crooks and Gray, 2005), and it has been proposed that this has subsequent effects on the stratospheric polar vortex (Bates, 1981; Kodera, 1995; Camp and Tung, 2007). In addition, tropical lower stratospheric temperature anomalies associated with the solar cycle may influence the tropospheric eddies and jet streams directly (Haigh et al., 2005).
- *The Pacific Decadal Oscillation (PDO)*: The PDO also may influence polar stratospheric variability (Woo et al., 2015; Kren et al., 2016) and any future large volcanic eruption likely would influence the stratospheric polar vortex for at least 1–2 years (Timmreck et al., 2016). Decadal changes in the polar vortex strength (Garfinkel et al., 2017) or position (Zhang et al., 2016) have been found to influence the extratropical tropospheric circulation; whether these changes are internally generated or forced via a tropospheric or surface driver is unclear (e.g., Kim et al., 2014; McCusker et al., 2016).

Nonlinear interactions among the various factors that can influence the polar vortex strength described here also may be important. For example, the QBO can affect the magnitude of the ENSO-stratosphere teleconnection (Richter et al., 2011, 2015), yielding a strengthening of the teleconnection during the QBO westerly phase (Calvo et al., 2009; Garfinkel and Hartmann, 2011a). The Indian Ocean Dipole (IOD) has been found to alter the teleconnection of ENSO into the stratosphere (Fletcher and Cassou, 2015). The QBO relationship to the extratropical polar stratosphere may be altered by the 11-year solar cycle (Labitzke and van Loon, 1992), although the relationship is less clear in some long climate simulations (Kren et al., 2014). The QBO also may modulate the NAO's response to snow forcing (Peings et al., 2013), and ENSO's influence on the stratosphere may be modulated by the solar cycle (Calvo and Marsh, 2011). Understanding these complex interactions may improve our ability to simulate these processes and ultimately improve extratropical predictive skill. Taken together, multiple forcings may provide windows of opportunity for forecasts in which sub-seasonal forecasts are and could be expected to be more skillful, but a great deal more work is required to clearly establish the dynamical basis for such periods.

## 5 SUMMARY AND OUTLOOK

The previous sections of this chapter have provided an overview of the wide-ranging scientific literature demonstrating stratosphere-troposphere dynamical coupling and its effects on S2S predictions. However, a number of outstanding research questions remain regarding the mechanisms underpinning stratosphere-troposphere coupling and its representation in numerical models, which we discuss next. In the sub-seasonal context, the ultimate aim of any research targeted at stratosphere-troposphere coupling should be to improve its representation in models so that it can be exploited to improve tropospheric predictability. The recent widespread availability of sub-seasonal prediction hindcast data sets presents a unique and unprecedented opportunity to study the predictability of the stratosphere-troposphere system.

## 5.1 What Determines How Well a Model Represents Stratosphere-Troposphere Coupling?

Broadly, a minimum requirement in order for numerical prediction systems to exploit the potential predictability associated with stratosphere-troposphere coupling is that they are capable of simulating the range of atmospheric and climate phenomena that induce the coupling described in Sections 2–4. In reality, there is likely to be a complex array of factors that determine how stratosphere-troposphere coupling and its impacts on tropospheric predictability are manifest in individual modeling systems.

### *5.1.1 Role of Model Lid Height and Vertical Resolution*

On sub-seasonal timescales, adequately simulating the Northern Hemisphere polar vortex and its variability during winter and spring (including the planetary Rossby waves that drive this variability) is essential for reproducing the observed connections between the polar vortex and surface climate. Numerical models with an upper boundary below the stratopause consistently underestimate the frequency of SSWs compared to "high-top" stratosphere-resolving models (Marshall and Scaife, 2010; Maycock et al., 2011; Charlton-Perez et al., 2013), showing that model lid height may be an important limitation in some models. Biases in Northern Hemisphere vortex variability are also related to the ability of models to capture the relative occurrence of wave number-1 and wave number-2 type disturbances (Seviour et al., 2016). Low model lid height also has been connected to biases in the occurrence of extreme eddy heat flux events in models, which may have a causal influence on biases in the midlatitude tropospheric circulation (Shaw et al., 2014).

Coarse vertical resolution in the stratosphere also may affect a model's ability to simulate stratosphere-troposphere coupling, including the evolution of stratospheric wind anomalies during an SSW event and the spring breakup of the polar vortex in the Southern Hemisphere (Kuroda, 2008; Wilcox and Charlton-Perez, 2013). Realistic simulation of the QBO is also highly dependent on model lid height (Osprey et al., 2013) and model vertical resolution (Geller et al., 2016; Anstey et al., 2016). However, as yet, there is no theoretical basis for determining what is adequate vertical resolution, and this is likely to depend on several other factors, such as the representation of parameterized processes (Sigmond et al., 2008), and thus will vary from model to model.

### *5.1.2 Influence of the Tropospheric State and Biases*

Simulating the low-frequency climate phenomena that are known to influence stratospheric variability (including ENSO, QBO, sea ice, and snow cover) is likely to be important for producing skillful probabilistic forecasts of polar vortex variability. However, simply simulating all relevant phenomena alone is unlikely to be sufficient because in many cases, the impact of stratosphere-troposphere coupling on predictability occurs via complex pathways, along which a model may fail to resolve key processes at multiple stages. Thus, the tropospheric state and biases in its representation in models could influence stratosphere-troposphere coupling through the following:

1. Modulation of drivers and precursors to the tropospheric processes forcing stratospheric variability
2. Modulation of the tropospheric response to stratospheric variability

For example, in relation to point 1, simulation of ENSO effects on the Northern Hemisphere polar vortex requires a realistic representation of the Rossby wave train response to anomalous tropical convection and the impact of tropospheric Rossby waves on stratospheric dynamics (Garfinkel et al., 2013). In this regard, some models simulate more linear ENSO teleconnections—particularly over the North Pacific, an important precursor region for stratospheric variability—than those observed (Garfinkel et al., 2012a).

In relation to point 2, a model's ability to simulate the tropospheric response to stratosphere-troposphere coupling also can be affected by systematic biases in the representation of the tropospheric circulation and its response to external forcing (e.g., Kidston and Gerber, 2010; Son et al., 2010). This may include the representation of tropospheric jet streams and storm tracks; tropospheric stationary and transient waves; feedback between eddies and the mean flow; the effects of parameterized processes (e.g., surface drag) on the tropospheric flow; and tropical circulation and convection. However, the representations of these factors may not be independent of the stratosphere itself (e.g., Shaw et al., 2014), posing the potential for complex, interdependent relationships to exist.

### *5.1.3 Influence of Different Drivers on Stratosphere-Troposphere Coupling Efficacy*

As outlined in Sections 2–4, stratosphere-troposphere coupling is associated with a wide range of climate phenomena. At present, the equivalence of these different drivers for inducing stratosphere-troposphere coupling events is not well understood. Many of the drivers discussed in this chapter occur in tandem, and their combined effects may not be linearly additive. Thus, there is a need to study the combined effects of various phenomena on the coupled stratosphere-troposphere system.

Furthermore, there is a lack of quantitative understanding of the comparability of stratosphere-troposphere coupling induced by different phenomena. For example, is the coupling efficacy associated with a midwinter SSW comparable to that associated with Arctic springtime ozone depletion? Are the dynamical mechanisms underlying stratosphere-troposphere coupling in these two cases similar? How sensitive is the efficacy of stratosphere-troposphere coupling to the initial state of the troposphere and stratosphere; the type of stratospheric event, such as whether the vortex is displaced or split in two; and the amplitude of stratospheric anomalies (e.g., Son et al., 2010; Maycock and Hitchcock, 2015; Karpechko et al., 2017)?

Addressing these questions requires a set of quantitative dynamical metrics that can be applied consistently to study stratosphere-troposphere coupling related to different phenomena and its representation in models (Son et al., 2010; Shaw et al., 2014; Maycock and Hitchcock, 2015; Lubis et al., 2016b,a).

## 5.2 How Can We Use Sub-seasonal Prediction Data in New Ways to Study Stratospheric Dynamics and Stratosphere-Troposphere Coupling?

Following its renaissance in the early 2000s, the study of stratosphere-troposphere dynamical coupling has advanced rapidly, as described in Sections 2–4. Evidence for the importance of this coupling for extratropical climate in winter and spring is now clear, and a number of mechanisms for how this coupling works have been developed and refined. Much of the recent improvement in prediction on the S2S timescale is thought to have been related to the improvements that modeling centers have made in their representation of the stratosphere and its coupling to the troposphere.

However, challenges remain in arriving at a set of general unifying principles that can provide a quantitative description of the role of stratosphere-troposphere coupling on an event-by-event basis (Gerber and Polvani, 2009; Butler et al., 2017). It is, therefore, desirable to shed new light on the characteristics that determine the efficacy of stratosphere-troposphere coupling and its influence on weather and climate prediction. The large S2S hindcast data set (Vitart et al., 2017) offers a tremendous resource for pursuing such inquiries. At present, we see four main opportunities by which the study of stratosphere-troposphere coupling can benefit from the increased availability of high-quality sub-seasonal hindcast data sets:

1. Examination of the growth of model errors in the troposphere and stratosphere and their impact on coupling
2. Separating competing drivers of stratospheric variability and coupling and examining how these interact either linearly or nonlinearly
3. Determining what sets the efficacy of stratosphere-troposphere coupling on an event-by-event basis
4. Developing a probabilistic understanding of the likelihood of significant stratospheric variability

Improving our understanding in these areas may allow us to further exploit the enhancements in predictability that the stratosphere has to offer.