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JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1029/2018JD028724

Special Section:
Bridging Weather and Climate: Subseasonal-to-Seasonal (S2S) Prediction

Key Points:

- QBO can contribute to enhanced predictability, in a probabilistic sense, of the Northern Hemisphere climate on subseasonal timescales
- Operational subseasonal forecasting models with reasonable stratospheric resolution capture the Holton-Tan effect
- Anomalies may propagate down to surface, though some ambiguities exist

Supporting Information:

- Supporting Information S1

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Citation:
Garfinkel, C. I., Schwartz, C., Domeisen, D. I. V., Son, S.-W., Butler, A. H., & White, I. P. (2018). Extratropical atmospheric predictability from the quasi-biennial oscillation in subseasonal forecast models. *Journal of Geophysical Research: Atmospheres*, *123*, 7855–7866. https://doi.org/10.1029/2018JD028724

Received 27 MAR 2018
Accepted 6 JUL 2018
Accepted article online 12 JUL 2018
Published online 3 AUG 2018

Extratropical Atmospheric Predictability From the Quasi-Biennial Oscillation in Subseasonal Forecast Models

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Abstract The effect of the Quasi-Biennial Oscillation (QBO) on the Northern Hemisphere wintertime stratospheric polar vortex is evaluated in five operational subseasonal forecasting models. Of these five models, the three with the best stratospheric resolution all indicate a weakened vortex during the easterly phase of the QBO relative to its westerly phase, consistent with the Holton-Tan effect. The magnitude of this effect is well captured for initializations in late October and November in the model with the largest ensemble size. While the QBO appears to modulate the extratropical tropospheric circulation in some of the models as well, the importance of a polar stratospheric pathway, through the Holton-Tan effect, for the tropospheric anomalies is unclear. Overall, knowledge of the QBO can contribute to enhanced predictability, at least in a probabilistic sense, of the Northern Hemisphere winter climate on subseasonal timescales.

Plain Language Summary The Quasi-Biennial Oscillation (QBO) is perhaps the most regular atmospheric phenomena that is not directly controlled by solar radiation and can be predicted more than a year in advance. It is characterized by alternating westerly and easterly winds in the tropical stratosphere. Here we show that the QBO can be used to improve month-ahead prediction of the Northern Hemisphere wintertime stratospheric polar vortex, and perhaps even the extratropical tropospheric circulation.

1. Introduction

Tropospheric weather and climate are influenced by variability of the Northern Hemisphere wintertime stratospheric polar vortex (Baldwin & Dunkerton, 1999; Limpasuvan et al., 2004; Polvani & Kushner, 2002). An anomalously weak vortex is often associated with the negative phase of the Northern Annular Mode (NAM; also known as the Arctic Oscillation) in the weeks or months following an event (Baldwin & Dunkerton, 2001; Kidston et al., 2015; Limpasuvan et al., 2004; Polvani & Waugh, 2004), while an anomalously strong vortex has largely opposite impacts (Limpasuvan et al., 2005; Tripathi, Charlton-Perez, et al., 2015). While much polar vortex variability is stochastic (Holton & Mass, 1976) and deterministic predictability of the vortex is generally limited to 2 weeks (Karpechko, 2018; Tripathi et al., 2016; Tripathi, Baldwin, et al., 2015), probabilistic predictability extends for longer: Garfinkel et al. (2010) found that approximately 40% of polar vortex variability on interseasonal timescales is associated with variability occurring outside of the polar stratosphere. One of the main sources of predictable external variability of the polar vortex is the quasi-biennial oscillation (QBO), which is characterized by alternating westerly and easterly winds in the tropical stratosphere (Baldwin et al., 2001; Tripathi, Baldwin, et al., 2015).

Arctic polar cap temperatures are significantly warmer, and polar stratospheric heights significantly higher, when equatorial lower stratospheric zonal winds, for example, near 50 hPa are easterly (easterly QBO) than when they are westerly (westerly QBO). This effect, referred to as the Holton-Tan (hereafter H-T; Holton & Tan, 1980) effect, develops in early winter. Both modeling-based studies (e.g., Calvo et al., 2007; Garfinkel, Shaw, et al., 2012; Hampson & Haynes, 2006; Kinnersley & Tung, 1999; Naito & Yoden, 2006; Naoe & Shibata, 2010; Niwano & Takahashi, 1998; O'Sullivan & Young, 1992; Pascoe et al., 2006) and reanalysis-based studies (e.g., Garfinkel & Hartmann, 2007; Hitchman & Huesmann, 2009; Hu & Tung, 2002; Ruzmaikin et al., 2005) have

Table 1
S2S Model Experiments Chosen

Model (ensemble members)	Years	Reforecasts analyzed	Vertical levels	Model top
CMA (4)	1999–2014	Six per month	40	0.5 hPa
NCEP (4)	1999–2010	Nine per month	64	0.02 hPa
ECMWF (11)	1996–2013	Four per month	91	0.01 hPa
BoM (33)	1981–2013	Six per month	17	10 hPa
UKMO (3)	1998–2009	Four per month	85	85 km

Note. S2S = Subseasonal-to-Seasonal; CMA = China Meteorological Administration; NCEP = National Center for Environmental Prediction; ECMWF = European Centre for Medium-Range Weather Forecasts; BoM = Bureau of Meteorology; UKMO = UK Met Office.

shown a robust effect of the QBO in the polar stratosphere as reviewed by Anstey and Shepherd (2014), though the mechanism(s) for this H-T effect is still under debate (e.g., Garfinkel, Shaw, et al., 2012; Silverman et al., 2017; Watson & Gray, 2014; White et al., 2015). Because the QBO itself is both predictable and persistent, the H-T effect could potentially enhance the skill of seasonal forecasts in the extratropics (Boer & Hamilton, 2008; Butler et al., 2016; Marshall & Scaife, 2009; Scaife et al., 2014). However, the magnitude of the H-T effect is generally weaker in models as compared to reanalysis data (Butler et al., 2016; Scaife et al., 2014).

The goal of this work is to consider whether the QBO can be used to inform probabilistic forecasts of extratropical atmospheric variability on timescales of up to and beyond 1 month in the operational subseasonal prediction models that are archived in the Subseasonal-to-Seasonal (S2S) Prediction project database (Vitart et al., 2017). This study expands on the analysis of Butler et al. (2016) who focused on seasonal timescales (not subseasonal) and hence considered only monthly mean data and initialization dates on or around 1 November; in contrast, here we consider daily data and initialization dates that span the development of the H-T effect. Overall, this study demonstrates that the QBO can be used beneficially for probabilistic forecasts of the extratropical stratosphere in the three models examined here with the best stratospheric resolution. Of these three, the magnitude of the early-winter H-T effect is also captured in the model with the largest ensemble size for initializations in late October and November. The QBO influence appears to lead to an annular-mode-like response in the extratropical troposphere in two of the models, though there is ambiguity as to the role of the stratosphere for this effect.

2. Data and Methods

The association between QBO and polar stratospheric variability is examined in models that have contributed to the S2S Prediction project (Vitart et al., 2017). As the results of this study are based in large part on analyzing the lagged response well beyond a month, we examine models that archive data beyond 44 days. Five modeling centers provided data that met this criterion at the time we started downloading data—the Australian Bureau of Meteorology (BoM), the European Centre for Medium-Range Weather Forecasts (ECMWF), the China Meteorological Administration (CMA), the UK Met Office (UKMO), and the National Center for Environmental Prediction (NCEP). Table 1 summarizes the reforecasts analyzed in this study. Note that when we downloaded UKMO data, there were only three ensemble members available and fewer calendar years than are currently available. For the ECMWF model we downloaded only one reforecast each week, and for the NCEP model we only downloaded nine reforecasts each month, for consistency with the data availability for the other models. These various models differ in the quality of their representation of the stratosphere: the stratosphere is less well resolved in both CMA and BoM as compared to the other three models (Table 1). After initialization all models are free running, and the quality of the representation of the QBO varies among the models. As shown below, the representation of the QBO in the UKMO model does not degrade even after 2 months (Scaife et al., 2002; Walters et al., 2017), while the BoM model struggles to represent the QBO even in the first week due to its coarse vertical resolution (only 17 levels in the vertical), and as discussed in Garfinkel and Schwartz (2017) the BoM model struggles to simulate sudden stratospheric warmings as well.

We assess whether the models capture the H-T effect as follows. For each reforecast, we define the QBO phase by first averaging the zonal mean zonal wind at 50 hPa from 5°S to 5°N over the first 3 days of the reforecast

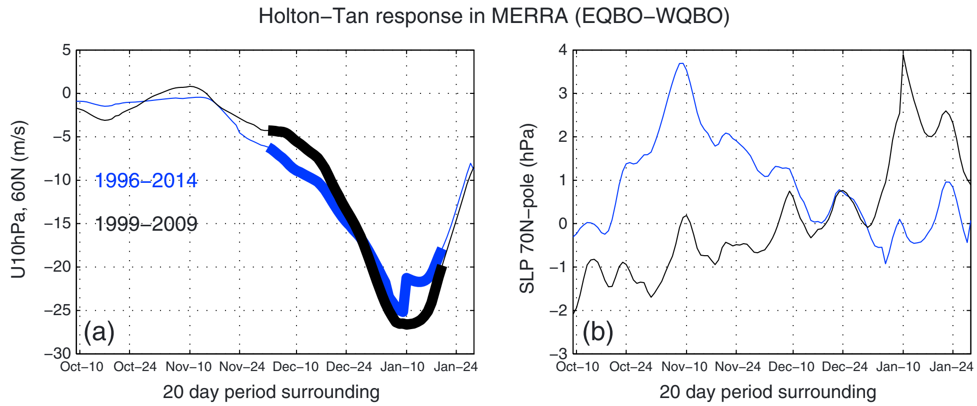

Figure 1. H-T effect in MERRA reanalysis over two periods common to the S2S models. (a) Zonal mean zonal wind at 60°N, 10 hPa; (b) area-weighted average of sea level pressure from 70°N to the pole. For easier comparison to the S2S results we average the MERRA results over a 20-day period. Difference of means between EQBO and WQBO that is statistically significant at the 95% confidence level as given by a Student's *t* test is printed in bold. MERRA = Modern-Era Retrospective Analysis for Research and Applications; S2S = Subseasonal-to-Seasonal.

and then categorize the reforecast as EQBO if the QBO winds are less than −3 m/s, and as WQBO if the QBO winds exceed 3 m/s. Results are similar for a threshold of 2 m/s (cf. Garfinkel & Hartmann, 2007). While the QBO in nature may remain in the same phase for several months, the latest information that the prediction model has available is limited to that of the initialization date, and as shown below some models fail to maintain their QBO. Note that we use the raw equatorial wind values and not the anomalies relative to climatology. We then examine the following metrics of the extratropical circulation for all reforecasts identified as EQBO and WQBO in order to assess the strength of the H-T effects and its downward propagation: zonal wind at 10 hPa and 60°N (U10); 70°N and poleward area-weighted averaged temperature at 50hPa (T50); 70°N and poleward area-weighted averaged geopotential height (Z) at 10, 50, 100, and 500 hPa; heat flux ($\overline{v'T'}$) at 100 hPa and 500 hPa area weighted from 40°N to 80°N for zonal wavenumbers 1 and 2; and sea level pressure (SLP; surface pressure for two models) area-weighted from 70°N to the pole. Zonal wind at 10 hPa and 60°N (U10) is conventionally used to define sudden stratospheric warming events (Charlton & Polvani, 2007) and, together with polar cap geopotential height, is tightly coupled to the NAM (Baldwin & Thompson, 2009). Polar cap temperature and polar cap geopotential height are related via the hypsometric relationship. The heat flux is proportional to the vertical component of the Eliassen-Palm flux, and hence, heat flux at 100 hPa is a proxy for wave activity in the lower stratosphere and subsequent stratospheric variability (e.g., Newman et al., 2001); 100 hPa heat flux peaks between 40°N and 80°N, and hence, we focus on this latitude band (Garfinkel, Butler, et al., 2012). We show the weekly average for each of the aforementioned indices in our figures. Statistical significance of the difference between EQBO and WQBO is determined using a two-tailed difference of means Student's *t* test, and the null hypothesis throughout is that there is no difference between EQBO and WQBO. Note that the S2S database only contains data at three stratospheric levels (10, 50, and 100 hPa), which necessarily limits our ability to diagnose the mechanism behind the H-T effect.

We examine the early-winter development of the H-T effect in order to assess early season predictability of the vortex. Specifically, we take forecasts initialized in October, November, and December and assess the vortex state up to 2 months later. Four different groups of initializations are selected: late October (16–31 October), early November (1–15 November), late November (16–30 November), and early December (1st–15 December). Note that each modeling center has made available reforecasts from different years, and the restart dates differ among the models even for a given year. It is therefore necessary to separately composite the observations according to the actual initializations used for each model in order to more meaningfully compare the modeled H-T effect to the observed H-T effect. Specifically, after determining if a given date is EQBO or WQBO for each model and reforecast, we search for the same date in the MERRA (Modern-Era Retrospective Analysis for Research and Applications; Rienecker et al., 2011) reanalysis to assess the degree to which S2S models capture the observed H-T effect. We thereby subsample MERRA data to match each S2S model.

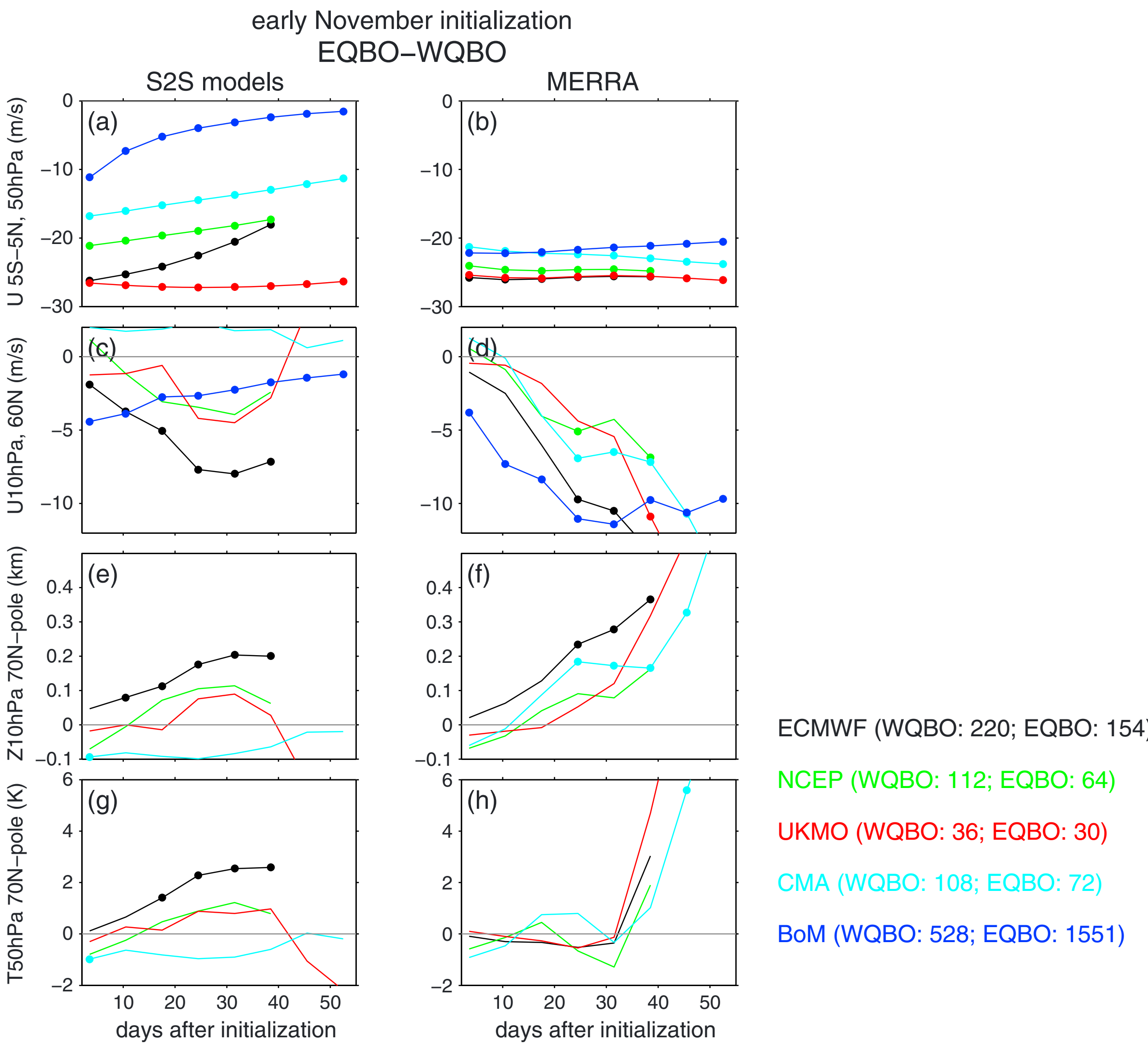

Figure 2. Difference between EQBO and WQBO (EQBO − WQBO) for five different S2S models as a function of forecast day for reforecasts initialized in early November. Difference of means between EQBO and WQBO that is statistically significant at the 95% confidence level as given by a Student's *t* test are denoted with dots. (a, b) Zonal wind at 50 hPa, 5°S to 5°N; (c, d) zonal mean zonal wind at 60°N, 10 hPa; (e, f) area-weighted average of geopotential height at 10 hPa from 70°N to the pole; (g, h) area-weighted average of temperature at 50 hPa from 70°N to the pole. Left column is for the S2S models, and the right column is for MERRA subsampled to match the specific dates included in each composite for each model. The number of reforecast ensemble members for each model and QBO phase is indicated on the figure legend.S2S = Subseasonal-to-Seasonal; MERRA = Modern-Era Retrospective Analysis for Research and Applications; ECMWF = European Centre for Medium-Range Weather Forecasts; NCEP = National Center for Environmental Prediction; UKMO = UK Met Office; CMA = China Meteorological Administration; BoM = Bureau of Meteorology.

3. Importance of the QBO for Month-Ahead Stratospheric Predictability

We begin by reviewing the seasonal evolution of the observed H-T effect in order to establish context for the S2S models. Figure 1 quantifies the development of the H-T effect in MERRA in early winter. We first perform a running 20-day average of zonal wind at 10 hPa 60°N (U10), then form composites of EQBO and WQBO, and then compute the difference between EQBO and WQBO. We only consider the period between 1996 and 2014 to overlap as much as possible with most of the S2S models. The H-T effect at 10 hPa begins to develop in mid-November—winds are weaker during EQBO than during WQBO—and reaches its peak in early January, after which it begins to weaken (consistent with previous work; O'Sullivan & Dunkerton, 1994; White et al., 2016).

We now consider the extent to which the S2S models capture this effect, and we focus on initialization dates in early November as the observed H-T effect is rapidly intensifying 20–40 days later. We begin by assessing

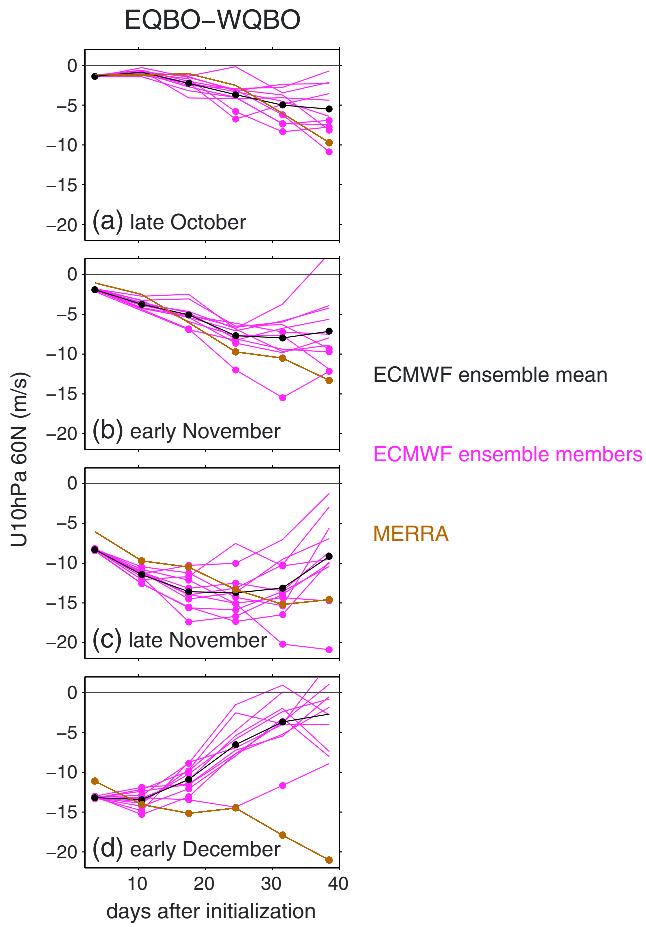

Figure 3. Fidelity of the vortex response to the QBO in ECMWF for start dates in (a) late October, (b) early November, (c) late November, and (d) early December. Difference of means between EQBO and WQBO that is statistically significant at the 95% confidence level as given by a Student's *t* test is denoted with dots. QBO = Quasi-Biennial Oscillation; ECMWF = European Centre for Medium-Range Weather Forecasts; MERRA = Modern-Era Retrospective Analysis for Research and Applications.

whether the models can capture the QBO winds in the tropics. Figure 2a shows the EQBO-WQBO difference in the QBO winds for each model as a function of forecast day, and Figure 2b shows the difference in QBO winds for the corresponding days in the MERRA reanalysis. The QBO in the UKMO model follows that observed for the duration of the experiments (red line; the UKMO model spontaneously generates a QBO, cf. Butler et al., 2016; Scaife et al., 2002). On the other hand, the QBO in the BoM model (blue line) is too weak to begin with, and anomalies quickly relax back to climatology. This bias is especially pronounced for WQBO (not shown). Hence, there is no reason to expect the BoM model to represent the H-T effect, and indeed, it does not (shown on limited figures only for clarity). All other models simulate the QBO on subseasonal timescales (similar to the models analyzed by Scaife et al., 2014, and Butler et al., 2016), though the magnitude is too weak and slowly dies out (Tripathi, Baldwin, et al., 2015).

We now consider whether the other four S2S models represent the H-T effect. Figures 2c–2h compare the modeled difference between EQBO and WQBO to the observed response for three different metrics of the vortex: (c, d) *U* at 10 hPa 60°N, (e, f) *Z* at 10hPa from 70°N to the pole, and (g, h) and *T* at 50 hPa from 70°N to the pole. For these three metrics, three of the four S2S models represent the H-T effect, with only CMA, the model with relatively coarser stratospheric resolution, failing to capture the H-T effect. The H-T effect is strongest (and statistically significant) in the ECMWF reforecasts, the model with the largest ensemble size. Close to the day of initialization the vortex is already slightly weaker for EQBO as compared to WQBO. More importantly, this weakening of the vortex intensifies over the following 30 days, and hence, our results suggest that the QBO can indeed be used for predictability of the early-winter polar vortex. Similar results

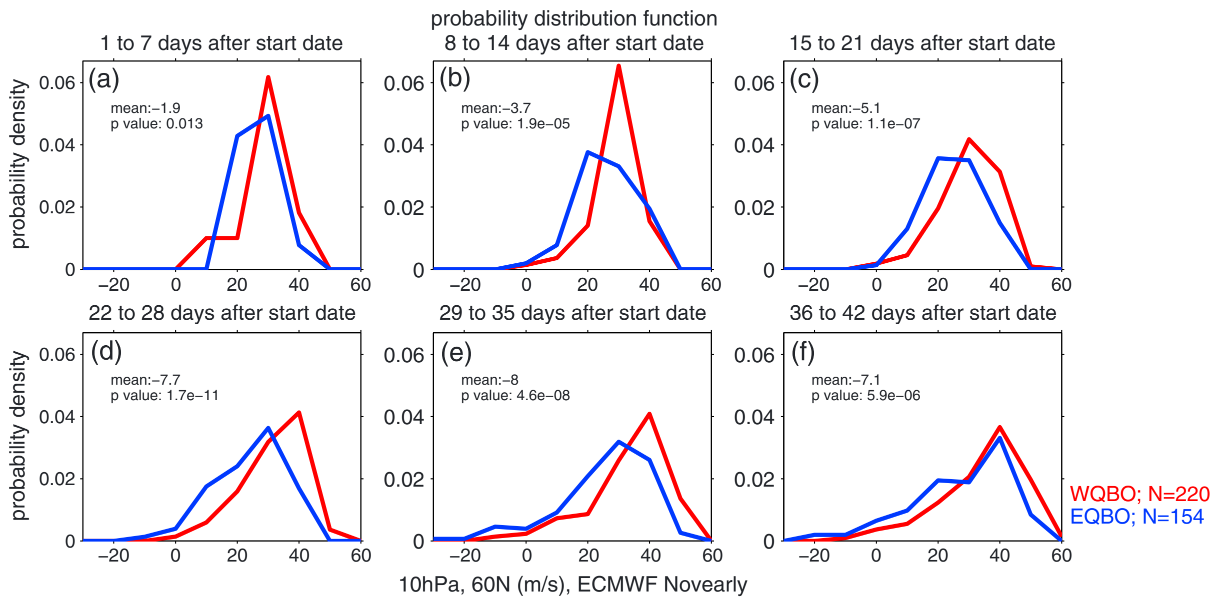

Figure 4. Probability density of zonal wind at 10 hPa, 60°N for reforecasts initialized in early November for ECMWF in the (a) first week, (b) second week, (c) third week, (d) fourth week, (e) fifth week, and (f) sixth week, after initializing. Reforecasts initialized during WQBO conditions are in red, while reforecasts initialized during EQBO conditions are in blue. Each panel indicates the difference in the mean and the likelihood of such a pair of distributions arising from random sampling of a single distribution as given by a Student's *t* test. The probability density is computed by normalizing the histogram of zonal wind during WQBO and EQBO, and no smoothing is applied. ECMWF = European Centre for Medium-Range Weather Forecasts.

are evident for initialization dates in late October or in late November, and for late November initialization dates the H-T effect is statistically significant for the UKMO and NCEP models as well (see supporting information Figures S1 and S2).

Is the magnitude of the simulated H-T effect comparable to that observed? The right column of Figure 2 composites stratospheric vortex anomalies in MERRA from the specific dates chosen for each model for each forecast day. The ensemble mean response (left panels) is weaker than the observed response (right panels) especially at longer forecast lead times for all models. However, a more appropriate comparison is not between the model ensemble mean with the observed response, but rather between each individual ensemble member and the observed response, as the observed response reflects not only the QBO forcing but also internal stratospheric variability. Hence, in Figure 3 we compare the response in 10 hPa 60°N zonal winds in each of the 11 ensemble members from ECMWF (in magenta) to MERRA (in brown). For late October initialization dates, the ensemble mean response in the ECMWF model tracks the observed response closely out to day 30 and some ensemble members track the observed response even beyond (Figure 3a). For early and late November initialization dates (Figures 3b and 3c), the ensemble mean response in the ECMWF model is too weak after 3 weeks, but individual ensemble members envelop the observed response throughout the duration of the reforecast. Hence, the magnitude of the H-T effect in ECMWF is consistent with that observed in early winter. The high-top seasonal forecast models considered by Butler et al. (2016) initialized in early November maintained a H-T effect quantitatively similar to that observed into December as well. However, the ECMWF model fails to capture the observed response for early December initializations (Figure 3d), which extend to the period in which the observed H-T effect peaks.

We emphasize that the QBO can only be used for probabilistic forecasting of the vortex. Figure 4 shows probability distribution functions of zonal wind at 10 hPa and 60°N for all ECMWF reforecasts initialized in early November with EQBO and WQBO reforecasts shown separately (in blue and red), and similar figures for late October and late November are shown in supporting information Figures S3 and S4. The EQBO and WQBO probability density functions are statistically significantly different either using a Kolmogorov-Smirnov test or a Student's *t* test, with anomalously weak zonal winds more common during EQBO and anomalously strong winds more common during WQBO. However, there is substantial overlap between the probability density functions, and hence, the QBO can be used at best for a probabilistic forecast, and not for a deterministic

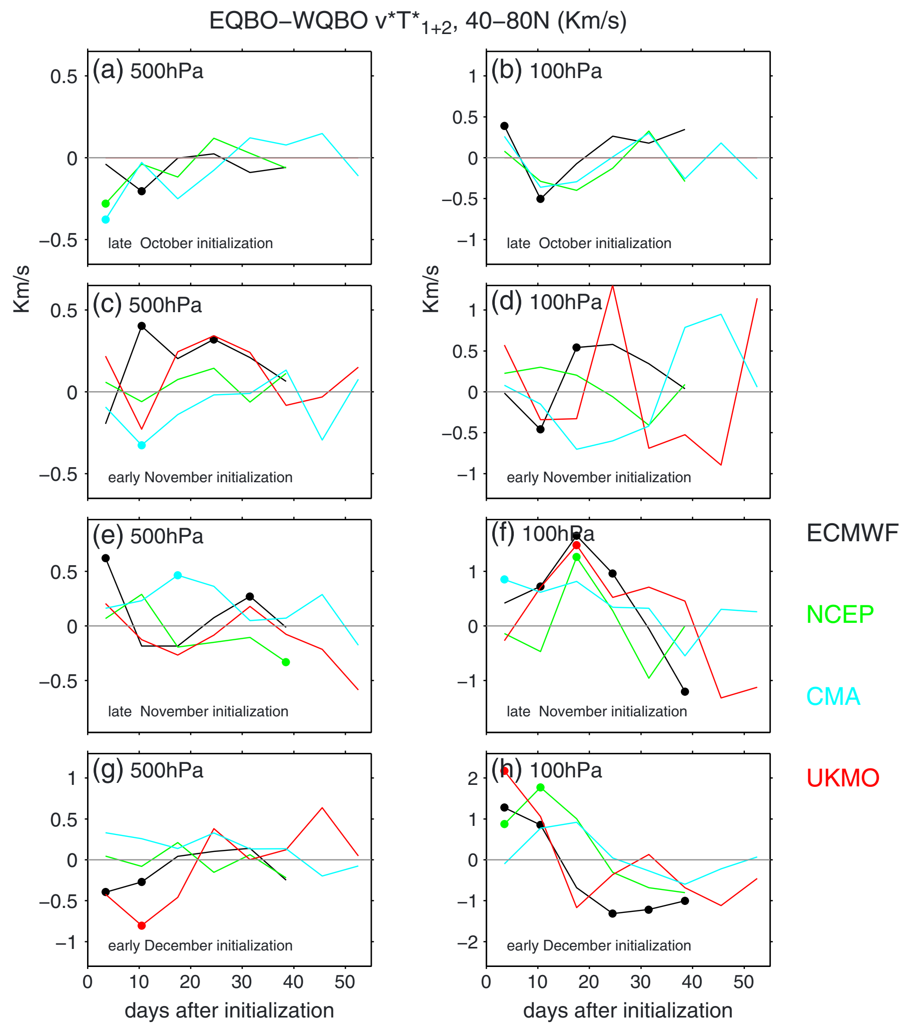

Figure 5. Area-weighted average of wavenumbers 1 and 2 heat flux ($\overline{v'T'}$) at (left) 500 and (right) 100 hPa from 40°N to 80°N for initialization dates in (a, b) late October, (c, d) early November, (e, f) late November, and (g, h) early December. Difference of means between EQBO and WQBO that is statistically significant at the 95% confidence level as given by a Student's *t* test is denoted with dots. CMA = China Meteorological Administration; NCEP = National Center for Environmental Prediction; ECMWF = European Centre for Medium-Range Weather Forecasts; UKMO = UK Met Office.

forecast of the polar vortex (cf. Dunkerton & Baldwin, 1991). Results are similar but for polar cap temperature and geopotential height (not shown).

Several tropospheric phenomena have been linked to vortex variability on subseasonal timescales by modulating wave flux propagating upward from the troposphere (e.g., the Madden-Julian Oscillation or October snow cover; Cohen et al., 2007; Garfinkel et al., 2014), and here we check that the source of the vortex anomalies we have associated here with the QBO is not due to aliasing with such tropospheric phenomena. Specifically, we would expect to see enhanced heat flux during EQBO as compared to WQBO at both 500 and 100 hPa if a tropospheric phenomenon is driving the vortex response to the QBO, and we therefore show the heat flux at 500 and 100 hPa for zonal wavenumbers 1 and 2 in subpolar latitudes in the S2S models in Figure 5. Subpolar heat flux in the troposphere and lowermost stratosphere is not modulated by the QBO over the first 2 weeks after initialization for late October or early November initialization dates (Figures 5a and 5b, consistent with Garfinkel, Shaw, et al., 2012), and if anything EQBO leads to less upward wave flux in the ECMWF and UKMO models. Rather, the vortex is initially modulated due to processes internal to the stratosphere. For initialization dates in late November and early December (i.e., after the vortex is already weakened) 100 hPa heat flux is apparently enhanced during EQBO. However, this enhanced heat flux could be consistent with the tendency of an already weakened vortex to allow enhanced wave transmission into the stratosphere

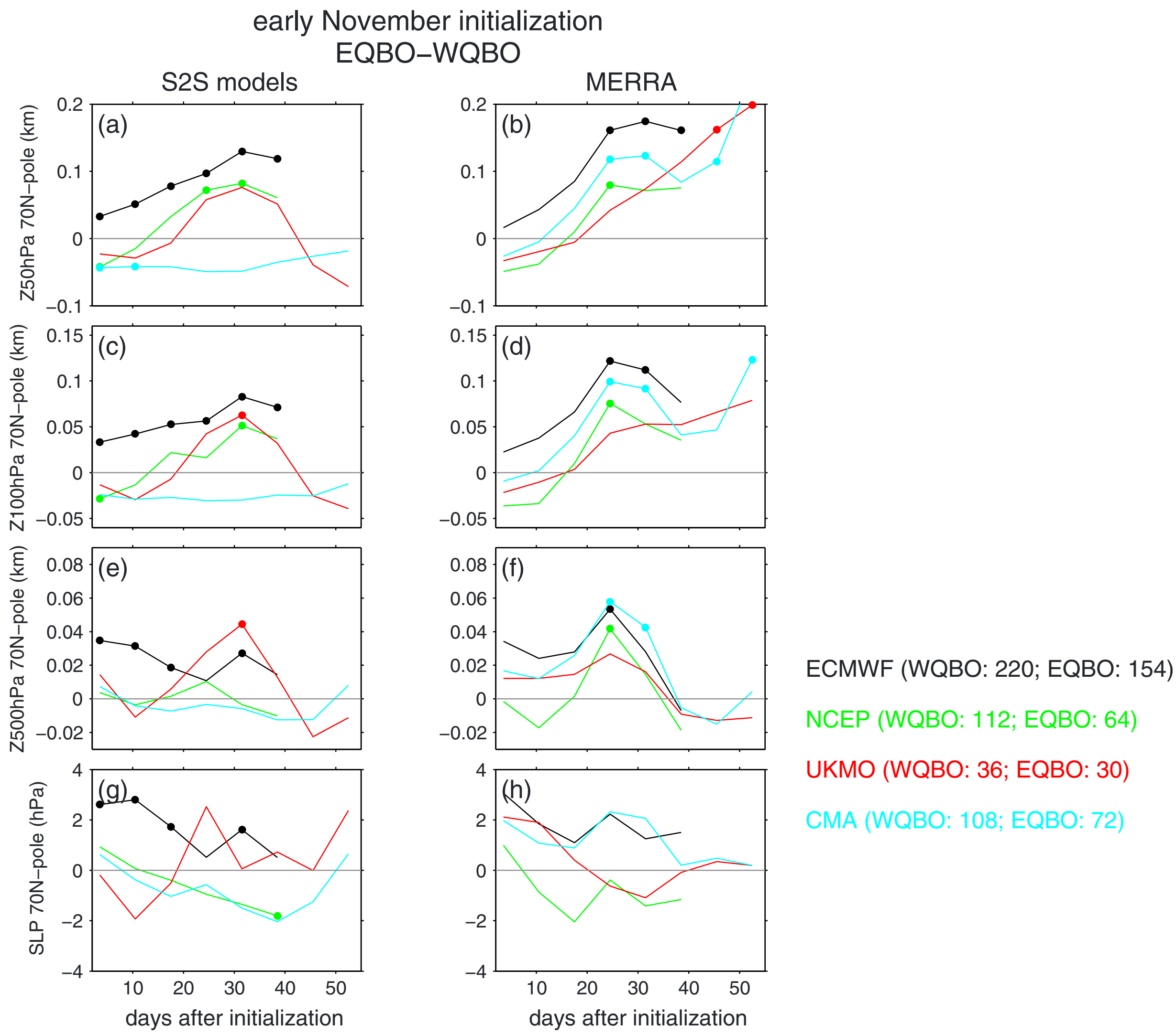

Figure 6. As in Figure 2 but for metrics of the downward impact: (a–f) area-weighted average of geopotential height from 70°N to the pole at 50, 100, and 500 hPa in the S2S models and in MERRA; (g, h) area-weighted average of sea level pressure from 70°N to the pole in the S2S models and in MERRA. S2S = Subseasonal-to-Seasonal; CMA = China Meteorological Administration; NCEP = National Center for Environmental Prediction; ECMWF = European Centre for Medium-Range Weather Forecasts; MERRA = Modern-Era Retrospective Analysis for Research and Applications; UKMO = UK Met Office.

(Charney & Drazin, 1961; Dunkerton & Baldwin, 1991; Holton & Mass, 1976; Sjoberg & Birner, 2014; the limited resolution available in the S2S database precludes a detailed analysis) as tropospheric heat flux is only slightly changed and is even reduced under EQBO for early December initializations. Overall, the weaker vortex simulated under EQBO during the early stages of the response appears to be more related to processes internal to the stratosphere, as one would expect given the H-T effect, rather than tropospheric processes.

4. Does the Impact of the QBO on the Arctic Stratosphere Extend to the Surface?

As discussed in section 1, Arctic stratospheric variability has been shown to impact surface climate in models and in observational studies with a large enough sample size (Baldwin & Dunkerton, 1999, 2001; Garfinkel et al., 2013; Kidston et al., 2015; Limpasuvan et al., 2005, 2004; Polvani & Kushner, 2002; Polvani & Waugh, 2004), and we now explore whether the QBO can influence surface climate through its effect on the extratropical stratosphere. As in section 3, we first review the observed changes in SLP area weighted from 70°N to the pole during alternate phases of the QBO (in Figure 1) to establish context for the S2S models. Polar cap SLP is higher during EQBO throughout the fall and early winter if the longer period of 1996 to 2014 is examined, while if the limited period 1999 to 2009 is examined (to more closely match the period simulated by the UKMO and NCEP

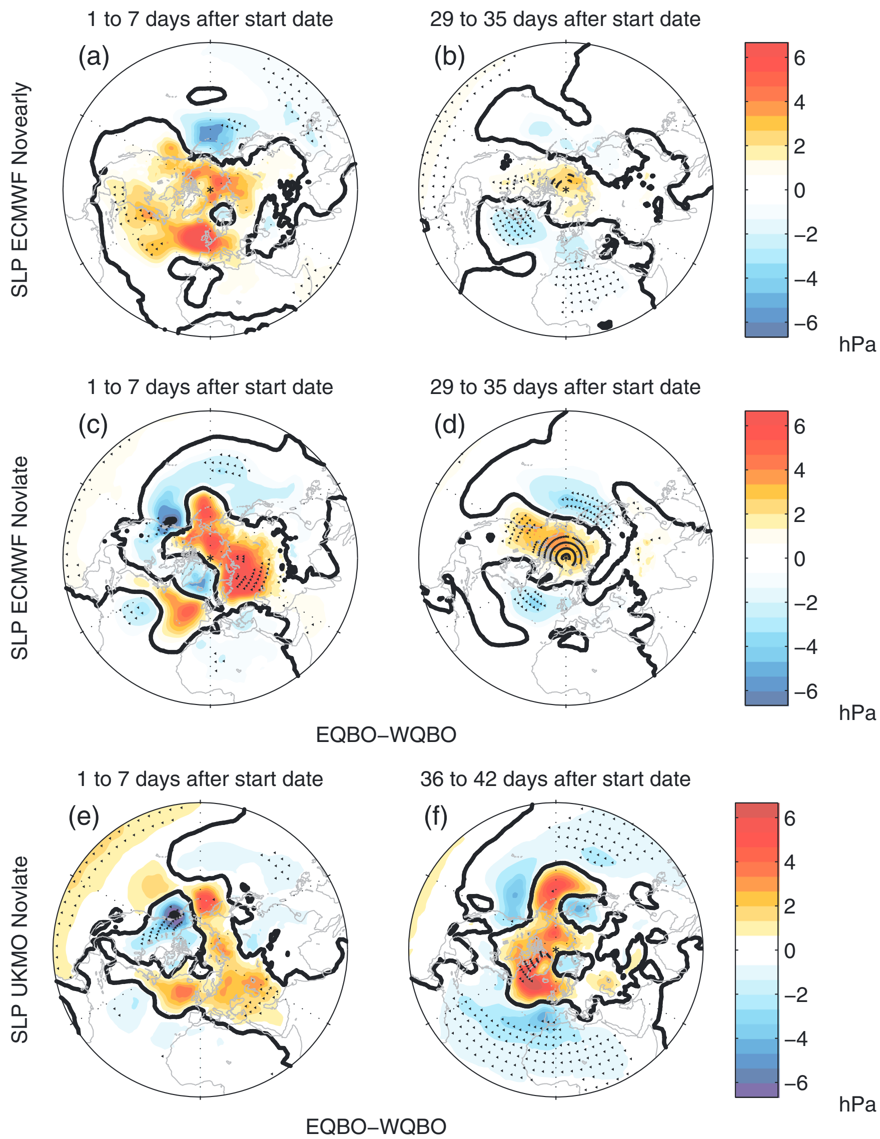

Figure 7. Surface anomalies (EQBO-WQBO) in SLP for initializations in (a, b) early and (c, d) late November in the ECMWF model; (e, f) late November in the UK Met Office model. Difference of means between EQBO and WQBO that is statistically significant at the 95% confidence level as given by a Student's *t* test is denoted with dots. The zero line is indicated in thick black. SLP = sea level pressure; ECMWF = European Centre for Medium-Range Weather Forecasts.

models), the peak in early winter is no longer present. The peak in the SLP response in January follows the weakening of the vortex, but the peak in October does not (compare Figures 1a and 1b). However, none of the anomalies in polar cap SLP are statistically significant at the 95% level over either period of interest. Hence, the role of the stratosphere for the observed early-winter tropospheric circulation response to the QBO over the period simulated by the S2S models cannot be clearly distinguished from internal atmospheric variability.

While it is difficult to discern downward propagation from the stratosphere to the surface over this limited period in reanalysis data, the larger sample sizes afforded by the S2S model may enable a clearer identification of downward propagation. We now consider whether the stratospheric H-T effect can be used for surface predictability in the S2S models. Figures 6a–6d show the response of polar cap geopotential height at 50 and 100 hPa, respectively, to the QBO. The impact of the QBO extends to the lowermost stratosphere in all models except CMA, though the ensemble-averaged anomalies are weaker than those observed and there is no indication of a time delay of the lower stratospheric anomalies as compared to the midstratospheric anomalies. While the response of 500 hPa polar cap geopotential (Figures 6e and 6f) indicates a slight bump

20 to 40 days after forecast initialization that could be traced back to the stratosphere in the UKMO, NCEP, and ECMWF models, this feature is rather weak and hard to distinguish from the preexisting negative NAM anomalies (except in the UKMO model, where it is more distinct). Similar results are found for initialization dates in late October or in late November (supporting information Figures S5 and S6)

This ambiguity in the tropospheric response extends to the surface: there is no clear signal in SLP from 70°N to the pole (Figures 6g and 6h) 20 to 40 days after initialization that can be distinguished from the anomalies in polar SLP in the first 20 days after initialization. However, this lack of a clear signal does not reflect a failure of these models to capture reality. The response in the ECMWF model follows that in reanalysis data (Figures 6g and 6h); we remind the reader that in Figure 1, SLP over the pole is anomalously high during EQBO even before the stratospheric H-T effect developed for the period 1996 to 2014. The UKMO model shows an apparent signal in polar cap SLP in the fourth week after initialization; however, the sample size is limited, this effect occurs before the peak stratospheric response, and no similar effect is seen in MERRA reanalysis data. The NCEP model appears to have a weak downward extension from the stratosphere to the troposphere, but for the initialization dates relevant to NCEP the QBO appears to have no influence on the troposphere even in observations.

While zonal mean metrics are ambiguous as to whether there is robust downward propagation to the troposphere, the pattern of SLP anomalies in the extratropics does change over the course of the reforecasts. Figures 7a–7d show the EQBO-WQBO difference in SLP in the (left column) first week and (right column) 29 to 35 days after initialization in the ECMWF model. In the first week after initialization SLP anomalies are generally noisy and disorganized, reflecting the large amount of internal atmospheric variability, even as polar cap SLP is higher during EQBO than during WQBO. After a month the SLP anomalies more closely resemble the negative phase of the NAM, indicating that the stratosphere has helped to organize the tropospheric circulation. While the UKMO model shows a similar change to that in the ECMWF model (Figures 7e and 7f), the NCEP model does not (not shown). Overall, the stratospheric anomalies appear to modify the tropospheric circulation in at least two of the S2S models.

5. Summary

Polar stratospheric variability has important implications for surface climate (Baldwin & Dunkerton, 1999; Limpasuvan et al., 2004; Polvani & Kushner, 2002), and hence, it is crucial to understand the timescale over which polar stratospheric variability can be predicted. For three different operational models, reforecasts that are initialized during EQBO conditions in late October and in November simulate a weaker vortex for more than a month later (Figure 2). The H-T effect reaches the lower stratosphere in the S2S models (Figure 3). Given the long time scales on which the QBO itself is predictable (Scaife et al., 2014), the vortex state can be predicted based on the QBO state at the beginning of the forecast.

It is ambiguous whether the QBO can lead to enhanced surface predictability. While subpolar SLP appears to have a negative annular mode-like pattern a month after reforecasts are initialized during EQBO relative to those initialized during WQBO (Figure 7), zonal mean metrics cannot highlight clear downward propagation from the stratosphere. Perhaps more fundamentally, over certain periods subpolar SLP is negative for EQBO even before stratospheric anomalies develop in reanalysis data (Figures 6 and 7), likely because the periods considered in this paper (which are chosen to match the S2S database, and hence are less than 20 years in duration) are too short to quantify the tropospheric response to the QBO and remove internal variability. Hence, it is difficult to ascertain whether the models capture surface predictability when the observations do not indicate a strong downward propagating signal over the period common to all models.

Of the five models examined in this study, three successfully simulated the H-T effect (those from UKMO, ECMWF, and NCEP), and two did not (from CMA and BoM). The CMA and BoM models have coarser resolution in the stratosphere; hence, it is not altogether surprising that the H-T effect is more pronounced in the other three models (consistent with the seasonal forecast models considered by Butler et al., 2016).

The mechanism whereby the QBO modulates the vortex is still unclear: at least three distinct mechanisms have been proposed, and it is not yet clear which dominates (Garfinkel, Shaw, et al., 2012; Holton & Tan, 1980; Silverman et al., 2017; Watson & Gray, 2014; White et al., 2015, 2016). Unfortunately, the S2S database offers only limited stratospheric resolution, and hence, we cannot use these models to provide insight on the mechanism, other than a general suggestion that processes internal to the stratosphere are most important during the initial stages of the stratospheric response.

Acknowledgments
C. I. G., C. S., and I. P. W. are supported by the Israel Science Foundation (grant 1558/14) and by a European Research Council starting grant under the European Unions Horizon 2020 research and innovation program (grant agreement 677756). D. D. is supported by the Swiss National Science Foundation through grant $PP00P2_170523$. S.-W. Son's work is partly supported by the Basic Science Research Program through the National Research Foundation (NRF) funded by the Ministry of Science and ICT (2017R1E1A1A01074889). We thank the three anonymous reviewers for their comments. This work is based on S2S data. S2S is a joint initiative of the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP). The original S2S database is hosted at ECMWF as an extension of the TIGGE database and can be downloaded from the ECMWF server http://apps.ecmwf.int/datasets/data/s2s/levtype=sfc/type=cf/. Correspondence and requests for data should be addressed to C. I. G. (email:chaim.garfinkel@mail.huji.ac.il.

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