# A Protocol for Investigating the Role of the Stratospheric Polar Vortex in Subseasonal to Seasonal Forecasts

**NB: This is an Interim Document, some details are still subject to final changes**

Peter Hitchcock, Amy Butler, Andrew Charlton-Perez, Tim Stockdale, Chaim Garfinkel, <operational centre contacts>

# 1. Introduction

Dynamical variability in the stratospheric polar vortices that form each winter in both hemispheres is of growing concern for operational centers interested in improving their extended range forecasts on sub-seasonal to seasonal timescales. A number of recent studies have explored the role of major or minor stratospheric warmings in the S2S dataset (Butler et al. 2018, Karpechko et al. 2018, Domeisen et al. 2019a,b, Rao et al. 2019, 2020ab, Lee et al. 2019, Butler et al. 2020) or in individual models (Kautz et al. 2020, Knight et al. 2020). The surface impacts of such stratospheric variability have been robustly demonstrated in many models, but there is a clear need at this point to more carefully evaluate and compare the relevant coupling mechanisms in operational models in order to fully exploit this important source of skill on timescales of weeks to months.

The purpose of this paper is to propose a common protocol for numerical experiments to isolate and evaluate the representation of stratospheric influence on near-surface weather in subseasonal forecast models. The intent is that by outlining and motivating a single protocol that can be adopted by multiple operational centers, such efforts can be directly intercompared, increasing their collective value.

The protocol presented here is based on a zonally-symmetric nudging technique that has been used successfully to identify stratospheric influences on the tropospheric circulation in both hemispheres (Simpson et al. 2011, Hitchcock and Simpson 2014). In essence, by comparing an ensemble hindcast in which the stratosphere is constrained to a ‘perfect’ forecast to a second hindcast in which the stratospheric circulation is constrained to climatology, the tropospheric impacts of the stratospheric anomalies can be isolated. These experiments represent a significant step forward from the previous studies of operational forecasts, because of this experimental design which removes the confounding influence of differences in stratospheric forecast skill.

Although this is related to other nudging approaches (Jia et al. 2017, Kautz et al. 2020, Knight et al. 2020), in this case stratospheric circulation anomalies are imposed through a linear relaxation term that acts only on the **zonally symmetric** component of the stratospheric circulation. The purpose of this is to permit eddies to vary in a dynamically consistent way across the tropopause. This is particularly relevant for the planetary waves that play a central role coupling the stratosphere and troposphere. This approach has been shown theoretically (Hitchcock and Haynes 2014) and practically (Hitchcock and Simpson 2014) to avoid any significant artefacts. Nonetheless, a number of pilot experiments have been carried out to verify that the approach does not introduce complications specific to the operational forecasting context.

While the protocol as outlined is intended to be applicable to any stratospheric event of interest, we suggest that it be initially applied to three specific recent events: the boreal stratospheric sudden warmings that occurred in February 2018 and January 2019, and the austral sudden warming that occurred in September 2019. This experiment will be coordinated by the WCRP-SPARC SNAP project, through collaboration with partners in the WWRP S2S project. This paper seeks to document both the damping approach in general and its specific application for this international collaborative project. Data from the project will be made available to the community, with the aim of providing researchers with a resource to investigate the dynamics of stratosphere-troposphere coupling. While not a central goal of the experiments, the case studies span periods when the quasi-biennial oscillation (QBO) is in several distinct phases, and the occurrence of several large-amplitude MJO events. As such these experiments may prove valuable to several other SPARC and S2S projects, including the S2S MJO group, QBOi, and SATIO-TCS.

This paper is outlined as follows. The next section describes four specific goals that the proposed experiments are intended to achieve. The third section describes in detail the general experimental protocol that can be applied to study any stratospheric event of interest. In the fourth section the three target events of interest are described in further detail. In the fifth section the choice of parameters for the nudging is discussed and further justified, and the results of a sample experiment are presented.

# 2. Overview and goals of proposed experiments

The basic experimental design proposes to focus on the evolution of specific events of interest, using three sets of forecast ensembles:

1. A “**control**” ensemble in which the zonally symmetric stratospheric state is nudged globally to a climatological state derived from the ERA5 reanalysis.

2. A “**nudged**” ensemble in which the zonally symmetric stratospheric state is nudged globally to the time-evolving state from ERA5, but for the stratospheric event of interest.

3. A set of “**free**” or standard forecast ensembles, with no imposed nudging.

The protocol targets forecast integrations of 45 days, and an ensemble size of 50 to 100 members.

The zonally symmetric reference states for the **control** and **nudged** ensembles are computed from ERA5 data at the native model levels. At the stratospheric levels where the nudging is applied these coincide with isobaric surfaces. The climatology is computed from 1979 through 2018 (inclusive).

For each of the three case studies, two specific initialization dates for each type of integration are proposed; these are discussed in the context of the specific target events in Section 3. Thus a total of 18 forecast ensembles are requested: three types of experiments, each initialized at two times during three events of interest.

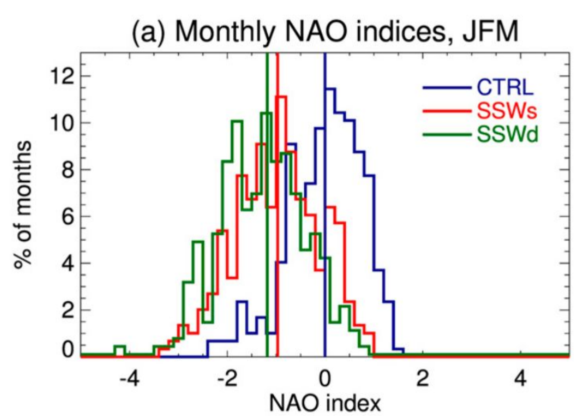
There are four motivations for the proposed forecast experiments:

## I) Quantify stratospheric contributions to surface predictability

Through nudging the stratosphere to observations, the **nudged** ensemble will provide a 'perfect' forecast of the stratosphere's zonal mean state. The forecast skill attained can be compared to that attained by the **control** ensemble (amounting to a 'climatological' stratospheric forecast) and the **free** ensemble to quantify the contribution of a successful forecast of the stratosphere. By including multiple models these experiments will provide for each model both a clear sense of the potential increase in skill associated with an improved representation of the stratospheric state, and an up to date assessment of the present skill that is achieved. By including multiple case studies of interest, this suite of experiments also makes it possible to explore the possibility that not all tropospheric states respond equally to stratospheric anomalies.

## II) Attribute extreme events to stratospheric variability

The proposed protocol may also provide a means of assessing or 'attributing' the contribution of the stratosphere to an extreme event of interest, such as cold air outbreaks that have been associated with sudden warmings in recent years. This is closely related to the growing sub-discipline that focuses on attributing the occurrence of particular extremes to climate change and variability.



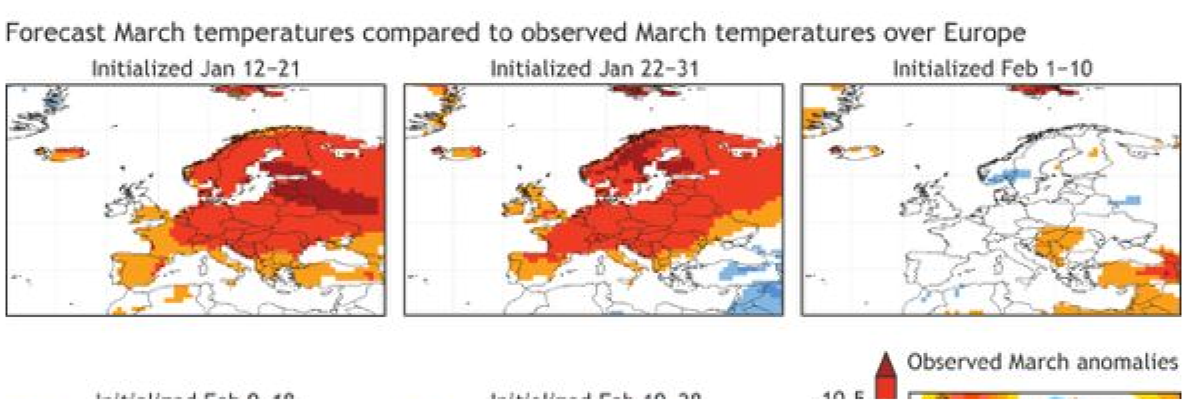

Consider some extreme event A that is thought to have been associated with a specific sudden stratospheric warmings, for instance the cold air outbreak (CAO) that occurred in Europe following the sudden warming in February 2018. Under climatological conditions, the probability of such an event occurring $p_0 = p(A)$ might be estimated from observations or from a sufficiently representative set of forecasts from a given forecast model. Given the **nudged** forecast ensembles one can then estimate the probability of a similar event occurring given the weakened state of the stratospheric polar vortex $p_1 = p(A \mid V-)$. The fraction of attributable risk (see, e.g., NAS 2016 report on attributing extreme events) of this CAO might then be calculated as $FAR = (p_1 - p_0)/p_0$. This can also be compared to the probability of such an event occurring in the counterfactual situation that the sudden warming did not occur, $p_0' = p(A \mid V_0)$, computed from the **control** forecast ensemble, allowing for the calculation of necessary or sufficient causation probabilities (Hannart et al. 2016).

As an example, the figure above shows monthly mean NAO indices (from Hitchcock and Simpson 2014, who used a similar methodology) which could form the basis of such a calculation; for instance, the probability of occurrence of a strongly negative monthly mean NAO state is much more likely in the aftermath of a stratospheric sudden warming than under a ‘counterfactual’ scenario during which the stratosphere was close to its climatological state.

However, the framing becomes more challenging in a forecast context, in which the probability of an extreme event is strongly conditional on the initial conditions for the forecast. As the forecast date grows closer to the event of interest, the forecast ensembles will begin to forecast the event with increasing fidelity; that is, the probability of occurrence conditional on initial conditions n days prior to an event, $p(A|IC(n))$ will grow.

A practical way to frame this question is to ask whether a good forecast of the stratospheric state leads to earlier accurate forecasts of the event in question (a closely related point is made by Baldwin et al. (2002) that the stratospheric NAM index can be a better predictor of the surface NAM than the surface NAM itself).

Below is an example from NCEP CFSv2 monthly forecasts of March 2018 temperatures over Europe for different initialization dates.  A sudden stratospheric warming occurred on February 12 2018.  The forecast model did not predict the SSW with any certainty until the initializations in the February 1-10 period.  There is a significant change in the March surface temperatures over Europe for initializations before and after the stratospheric event was captured in the prediction system, with forecasts initialized with the SSW information more closely capturing the observed March temperatures.  But do these differences arise solely because the forecast model finally captured the SSW, or because the lead-time had decreased?  With the three experiments proposed and applying this to multiple initializations before the event, it would be



clear whether or not having the “perfect” stratosphere (nudged experiment) for runs initialized in mid-January would have given more accurate forecasts at longer leads.

A very similar approach has been adopted by Kautz et al. (2020) who made the distinction between ‘probabilistic’ and ‘deterministic’ forecasts of the extreme event in question. They presented evidence from the ECMWF model that a perfect forecast of the stratospheric anomalies in early 2018 would increase the odds of extreme cold weather over Europe from ~5% to ~45%. These odds then increase further as forecasts are made closer to the event.

A common and comparable set of integrations from a range of operational centers will allow this finding to be extended to other extreme events and further develop this methodology.

## III) Quantify mechanisms of stratospheric coupling in individual models

Imposing stratospheric anomalies through a nudging procedure has been shown to significantly impact the near surface flow (e.g. Douville 2009), even if only the zonally symmetric component is imposed (Simpson et al. 2010, Hitchcock and Simpson 2014, White et al. 2020). By comparing the difference between the **nudged** and **control** ensembles, the processes that drive this downward coupling can be diagnosed in each model for a variety of events of interest. It is of particular interest to better understand why some specific stratospheric events are followed by the ‘canonical’ equatorward shift of the tropospheric annular modes, while others are not. The two boreal and one austral case studies proposed were followed by a diversity of tropospheric responses, including two cases which exhibited the ‘canonical’ equatorward shift of the annular modes and one which did not. This set of experiments will clarify whether these diverse responses were determined by stratospheric causes, or whether they are determined by competing effects such as tropical tropospheric variability or independent mid-latitude dynamical processes (e.g. Knight et al. 2020). In either case, the statistical sampling afforded by a multi-model set of forecast ensembles with detailed diagnostics will allow for new and deeper insights into the mechanisms responsible for the tropospheric response. Moreover, each event also coincided with specific surface extremes that produced significant societal impacts. This set of experiments will provide quantitative insight into the mechanisms responsible for these surface extremes.

## IV) Quantify the role of the stratosphere in upward wave propagation

The onset of a sudden stratospheric warming is marked by the reversal of the climatologically westerly zonal mean zonal winds in the mid stratosphere. Operational forecasts can, on average, successfully forecast this reversal starting about two weeks prior, but this depends strongly on the specifics of the event in question (Domeisen et al. 2019a, Rao et al. 2020a). A key issue is the successful forecasting of the rapid growth in planetary-scale Rossby waves that drives the breakdown of the stratospheric polar vortex. This requires capturing both tropospheric precursors for these waves, as well as their interaction with the stratospheric flow (see, e.g., Hitchcock and Haynes 2016 and de la Camara et al. 2018).

A fourth goal for this protocol is to determine how well forecast systems capture this initial amplification of planetary waves. In particular, the **nudged** and **control** ensembles will be initialized just prior to the periods of enhanced wave driving that led to the breakdown of the stratospheric polar vortex. By comparing the evolution of the wave field in these two ensembles, the role of the stratospheric state in determining the wave amplification can be isolated and compared with the importance of capturing specific precursors. Furthermore, this will reveal how well forecast models can predict the evolution of the planetary waves on a given zonally symmetric background, allowing for quantitative intercomparison.

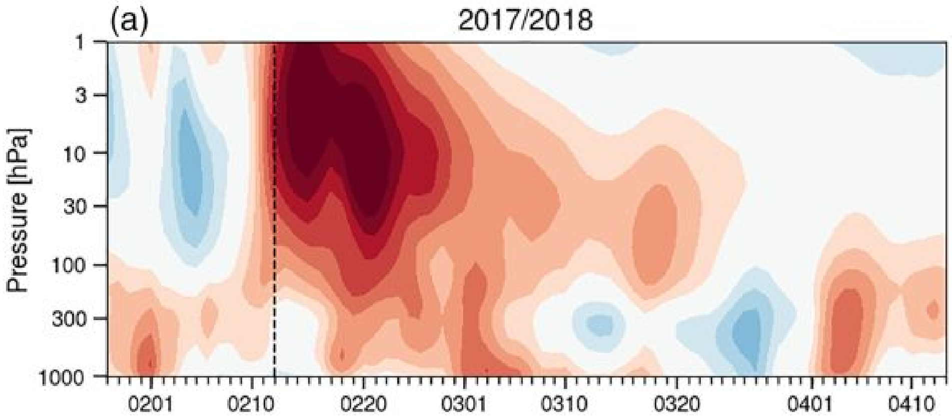
# 3. Case Studies of Interest

We propose applying the protocol just outlined to three recent events: the major warmings of 2018 and 2019 in the Northern Hemisphere, and the near-major warming of 2019 in the Southern Hemisphere. This section reviews the evolution of these three events, highlighting the evolution of the stratospheric polar vortex, the response of the tropospheric annular modes, and notable high-impact events that may be related to the stratospheric anomalies. The state of other modes of climate variability that have important teleconnections relevant to the stratosphere and to the surface impact itself are also discussed, including the Quasi-biennial oscillation (QBO), El Niño-Southern Oscillation (ENSO), and the Madden-Julian Oscillation (MJO).

Two initialization dates are proposed for each event. One date is chosen about three weeks prior to the surface extreme of interest, in order to identify the contribution of the stratosphere to its forecast on subseasonal timescales (motivations I through III). A second date is chosen prior to the onset of the stratospheric warming in order to assess the representation of the onset of the event (motivations I, III, and IV). The former has higher priority than the latter, although they are listed in chronological order below. Thursdays are chosen since nearly all models that contributed to the S2S database contributed forecasts initialized on Thursdays, making it easier to compare them with the present proposed forecast ensembles. These dates are summarized in the following table; they are further justified in the case-by-case discussion below.

| Event | Initialization Date 1 | Initialization Date 2 |
|---|---|---|
| NH: 12 Feb 2018 | 25 Jan 2018 | 8 Feb 2018 |
| NH: 2 Jan 2019 | 13 Dec 2018 | 8 Jan 2019 |
| SH: 18 Sep 2019 | 29 Aug 2019 | 1 Oct 2019 |

## Boreal Major Warming of 12 February 2018

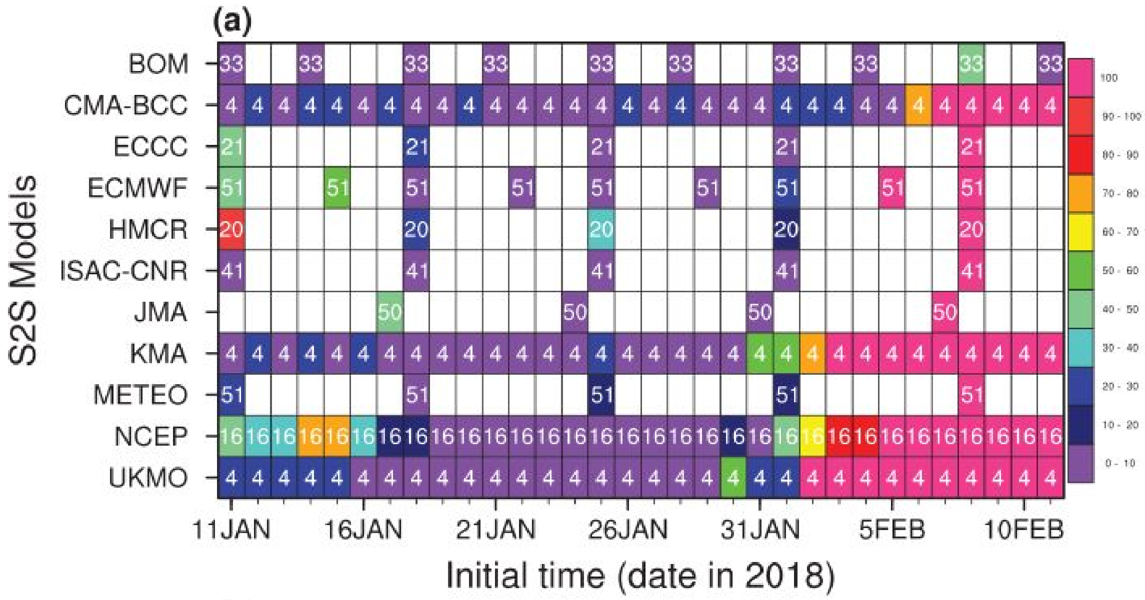



The Arctic polar vortex split in early February of 2018, leading to a reversal of the zonal mean zonal wind at 60 N, 10 hPa on 12 February 2018. Prior to the event (see figure above) the vortex was near to its climatological strength; it weakened rapidly throughout the depth of the stratosphere, coincident with large-amplitude vertical fluxes of wavenumber two wave activity. Lower stratospheric anomalies persisted into late March of 2018.

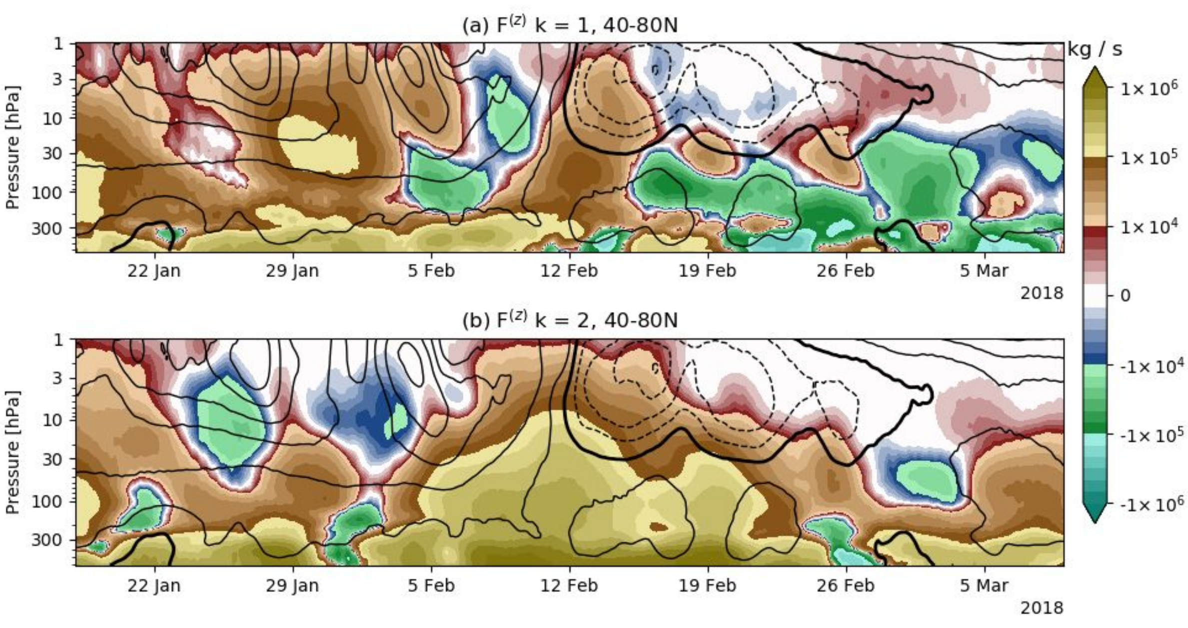
The tropospheric NAM responded strongly to these stratospheric anomalies, exhibiting a strong equatorward shift from mid-February through mid-March, consistent with the composite mean response to stratospheric sudden warmings. The NAO index was strongly negative in late February, coinciding with unusually cold weather over much of Europe and Asia during the last two weeks of Feb. (Lu et al. 2018), bringing, for example, snow to Rome and several notable winter storms to the UK. Precipitation patterns also shifted, bringing persistent rain to the Iberian peninsula, ending an extended period of drought (Ayarzaguena et al. 2018).

Of the three proposed case studies, this first case has been the most actively studied to date. In a study of the S2S database, Rao et al. (2020) showed that those ensemble members that capture the amplitude of the lower stratospheric anomalies during this event (and the 2019 case considered next) were also more successful in forecasting the surface extremes; they also showed that this was more relevant than whether the model forecasted a split or displacement of the vortex. As discussed above, Kautz et al. (2020) explicitly identified the increased risk of extreme cold over Europe arising from the stratospheric anomalies. This was also the case in the nudging experiments of Knight et al. (2020), who examined the impacts of relaxing the stratospheric flow on seasonal forecasts initialized at the beginning of the winter season. The nudged ensemble reproduced a tropospheric response following the SSW in close agreement with observational composites.

The MJO reached near-record strength in phase 6 and 7 prior to the stratospheric wind reversal in February of 2018, i.e, the MJO phase which has been linked to enhanced SSW frequency and predictability for earlier events (Garfinkel et al., 2012; Garfinkel and Schwartz 2017). A week after the event the MJO entered phase 8, which is linked to a negative NAO pattern. While Butler et al. (2020) do not find a correlation between forecast errors in the MJO and those in the NAM, Knight et al. (2020) do find that nudging the tropical evolution produces a negative NAO response in late February, suggesting that tropical circulation anomalies contributed to the anomalous European weather regimes.



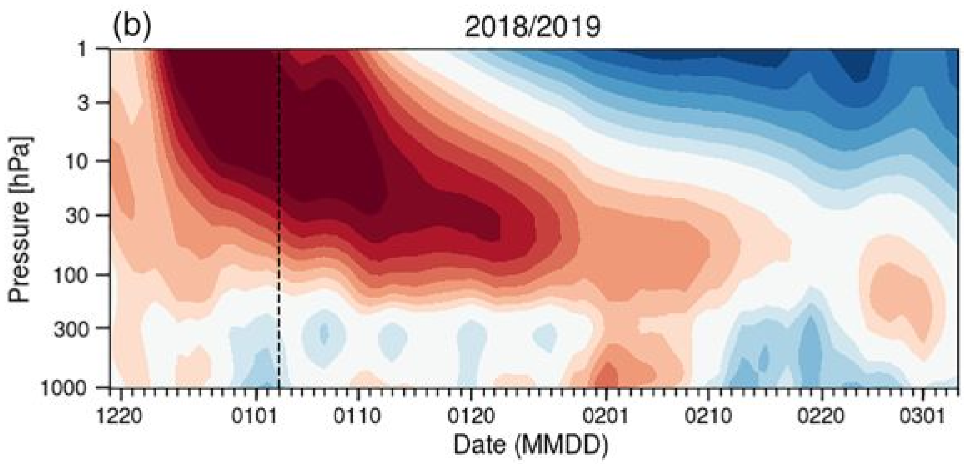

The S2S prediction systems forecast the event about 11 days in advance (Karpechko et al. 2018, Rao et al. 2018; see also figure above), making this event less predictable than some other sudden warmings. Proximately, this is likely due to the nature of the relevant wave driving which amplified rapidly during the week prior to the stratospheric wind reversal (see figure below). Subseasonal forecasts that captured this wave event were more successful in forecasting the vortex breakdown. The difficulty in forecasting the pulse of wave activity has in turn been tied to both anomalous blocking over Siberia (Karpechko et al. 2018) as well as to an episode of anticyclonic Rossby wave breaking in the North Atlantic (Lee et al. 2019).



On longer timescales, Knight et al. (2020) further suggest a role for the large-amplitude MJO event that preceded the stratospheric wind reversal, and Lu et al. (2020) suggest that several large snow falls over Siberia in early and late January contributed to the wave driving responsible for the vortex breakdown. On seasonal timescales, the tropical pacific was in a moderate La Nina state, and the QBO winds were persistently westerly at 50 hPa and easterly at 30 hPa throughout the winter. Thus the state of both ENSO and the QBO may have also contributed.

The first initialization date proposed is January 25th, just prior to the first pulse of wave activity leading to the vortex split. The ensembles will thus produce some diversity in the tropospheric precursors outlined above, allowing for a thorough comparison of their role and that of the stratospheric state in the amplification of the planetary waves. These integrations should still capture some of the development of the European cold air outbreak in late February. The second date, February 8th, is chosen to be closer to the development of the tropospheric extreme event, after the full development of the stratospheric anomalies.

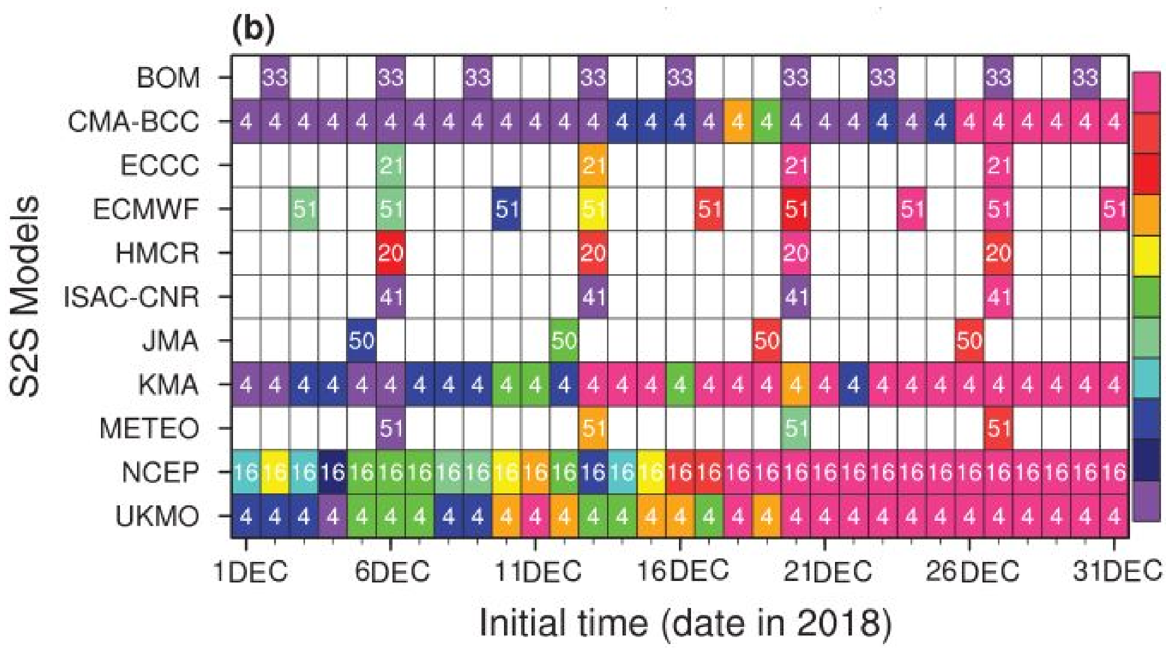
## Boreal Major Warming of January 2 2019




In late December 2018, the Arctic vortex was displaced off of the pole, prior to splitting. The 10 hPa winds reversed on 2 Jan 2019. In contrast to the 2018 event, the stratospheric vortex anomalies developed much more gradually through late December and early January of the 2018-19 winter. The vortex remained split for several weeks. Anomalies in the lower stratosphere persisted nearly to March of 2019. The gradual weakening of the vortex was due to persistent wave-number one forcing that was well predicted even from mid December (Rao et al. 2020).

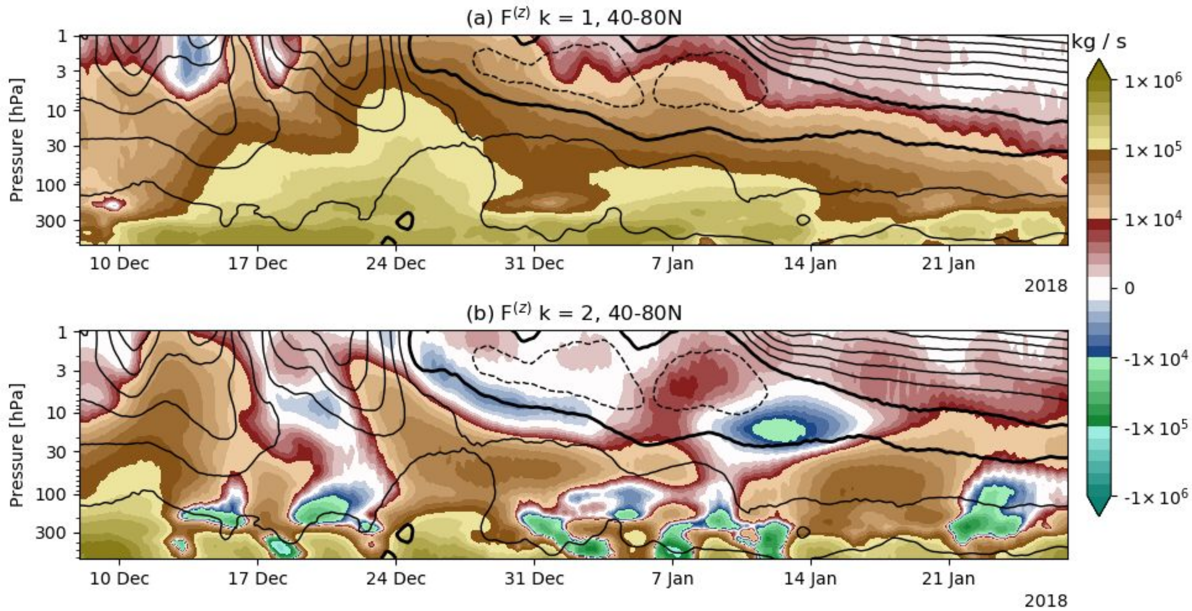
In strong contrast to the 2018 case, the tropospheric NAM did not respond strongly to the stratospheric anomalies, remaining near neutral or even slightly negative through much of the troposphere until early February. However, an extensive cold snap occurred over North America in late January (roughly the 23-29th) in a region vertically aligned with one of the daughter vortices generated by the split.

This event was also considered by Rao et al. (2020), who found that the surface temperatures and precipitation patterns 20 days following the onset date were generally not well forecast by the S2S models. Note, however, that they did not focus specifically on the cold air outbreak over North America. Knight et al. (2020) also performed nudging experiments to explore the impacts of the stratospheric anomalies on the surface. They found that the ensemble mean again reproduced the 'canonical' tropospheric response, with anomalously persistent negative AO pattern coinciding with NAM anomalies in the lower stratosphere, implying that the lack of tropospheric signal in observations was due to some competing effects. One possibility is that these arise from the tropics; their tropical nudging experiments gave rise to North Atlantic mean sea-level pressure anomalies that more closely resembled observations in January. For instance, the MJO also progressed through phase 6 and 7 through early January 2019, but at amplitudes considerably weaker than in 2018.




The S2S prediction systems forecast the stratospheric wind reversal up to 18 days in advance (Rao et al. 2020, figure above), but did not predict the vortex would split more than a few days in advance (Butler et al. 2020). The longer forecast horizon in this case seems to be related to the persistent wave-one forcing from mid-December 2018 that displaced the vortex off the pole, prior to its ultimate splitting (see also figure below). Rao et al., (2020) propose a range of external circulation anomalies, including the state of ENSO, the QBO, the solar cycle, and the MJO as contributing factors for this wave amplification.

In the fall of 2018, the QBO at 50 hPa was strongly easterly, below a westerly shear zone that stretched from 40 hPa to 20 hPa. This shear zone descended through the winter. At the time of the wind reversal, the winds at 50 hPa were easterly and those at 30 hPa were westerly.



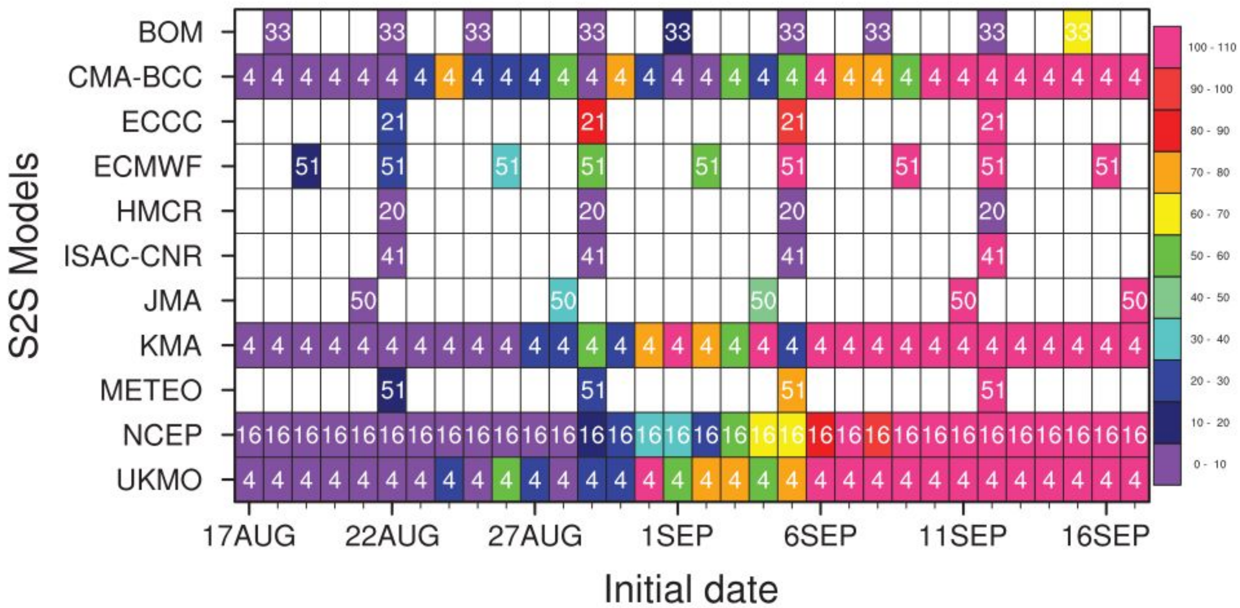

The first suggested initialization date is 13 December 2018, just prior to the onset of the wave one pulse, again motivated by the goal of producing some diversity in the tropospheric wave source in order to distinguish tropospheric and stratospheric contributions to the wave amplification. The second suggested initialization date is 8 January 2018, several weeks prior to the North American cold air outbreak.

## Austral Minor Warming of September 2019

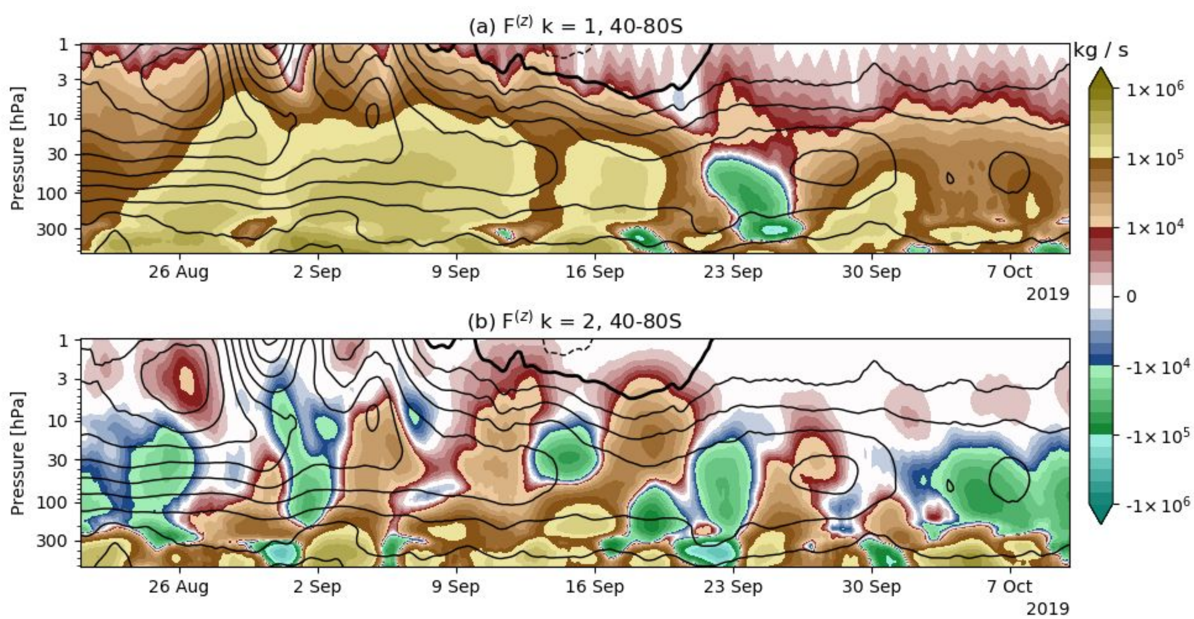
The final event of interest is the minor warming that occurred in the Southern Hemisphere in September of 2019. In contrast to the first two cases, the zonal mean winds at 10 hPa, 60 S did not reverse. However, they did decelerate dramatically, reaching their minimum value on September 18th 2019, which can be considered as the ‘central' date for the event. This was slightly earlier in the spring than the 2002 event, during which the Antarctic westerlies did fully reverse. In late August the mid-stratospheric winds were near their climatological values, before a series of wave-one pulses of upward wave activity weakened the vortex from the stratopause downwards (Lim et al. 2020).

The tropospheric Southern Annular Mode did not initially shift equatorward following the event. However, negative anomalies were observed in late October and November, during which conditions over Australia were hot and dry; severe wildfires were widespread in October through December, potentially due in part to the stratospheric anomalies.

To date, no nudging experiments have been performed on this event.




The event was forecast nearly 18 days prior by models with a reasonably resolved stratosphere (Rao et al. 2020b), including the persistent stratospheric wave-one flux anomalies (see figure below). A number of tropospheric precursors have been linked to this wave activity pulse, including a persistent blocking high over the Antarctic Peninsula and a low over the Southern Indian Ocean.



The first suggested initialization date is 29 August 2019, early in the development of the wave activity pulse responsible for the stratospheric event. The second suggested initialization date is 1 October 2019, after the stratospheric anomalies are established, two to three weeks prior to the onset of the tropospheric SAM response.

# 4. Nudging Methodology

“Nudging” specific components of the atmospheric circulation by means of an artificially imposed relaxation to a given state has been used  by many studies as a means of testing dynamical hypotheses. However, the introduction of an artificial linear relaxation into the equations of motion can produce unintended consequences (e.g. Shepherd et al. 2006, Orbe et al. 2017, Chrysanthou et al. 2019).

This section describes in detail the nature of the nudging relaxation to be used in this protocol. The intent is to prescribe the zonally-symmetric component of the stratospheric flow without indirectly constraining the troposphere or affecting the planetary waves that play a central role in the coupling between the two. The potential for undesired artefacts is also discussed in the context of several pilot experiments that have been carried out with the IFS. Note also that similar approaches have been used in more idealised models without introducing major artifacts.

## Specification

The nudging is specified as a relaxation of the form $x = ...\ \tau^{-1}(\overline{x} - x_r)$, where x is either temperature or the zonal mean wind, the overbar indicates the zonal mean, and $x_r$ is the zonally symmetric reference state to which the flow should be constrained. The nudging tendency is imposed equally on all longitudes (at a given latitude and height), to avoid directly affecting the wave field.  The timescale of the nudging varies with pressure, tapering gradually from infinite (i.e. no nudging) below a lower limit of $p_b$ = 70 hPa, to full strength at $p_t$ = 10 hPa, following a cubic profile $((p_b - p) / (p_b - p_t))^3$. At full strength the nudging timescale is 12 hours. The nudging is to be imposed at all latitudes equally.

While the nudging profile is specified in pressure coordinates, the intent is for the nudging strength to be constant on model levels and can be converted using ‘typical’ pressures appropriate for the details of the vertical coordinate system.

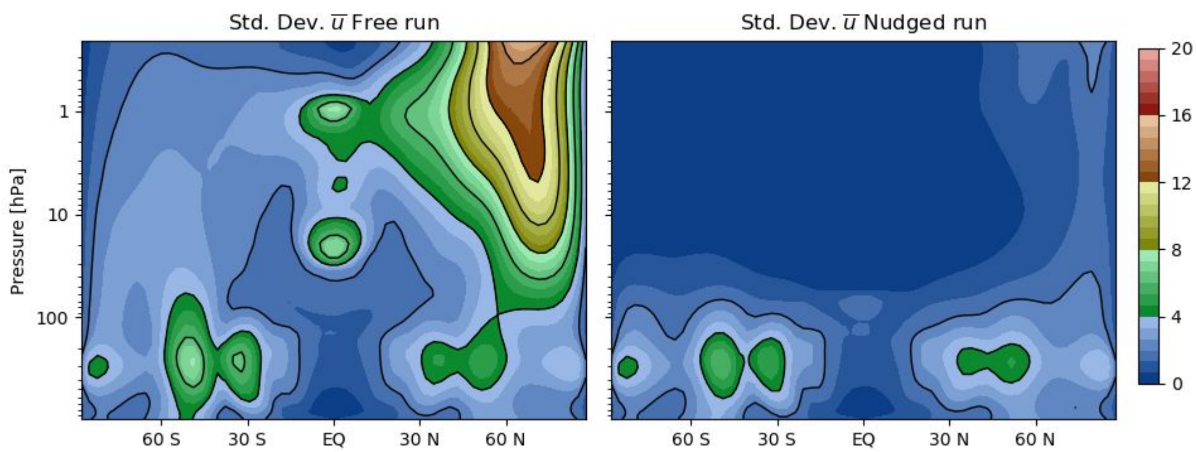
The reference states have been prepared from the ERA5 reanalysis. For the **nudged** ensemble, 6-hourly zonal mean temperature and zonal wind output from ERA5 at the native 137 model levels and N320 Gaussian grid will be made available. For the **control** ensemble, data at the same resolution has been used to compute a 40-year climatology. The fields have been further smoothed in time by a 121-point triangular filter to reduce residual high-frequency features from sampling issues.

## Validation and Sensitivity

This zonally symmetric nudging approach has been successfully applied by a number of studies to study issues of stratosphere-troposphere interactions (Simpson et al. 2011, Hitchcock et al. 2014, Hitchcock and Haynes 2016, Simpson et al. 2018). The approach has also been used to impose a QBO in models that do not internally generate one. However, these studies have been carried out in either climate models or idealized general circulation models, not in the context of operational forecasting, and the technique in general can produce undesirable artifacts in some situations. The intent in this section is to demonstrate that these issues will not pose major difficulties to the goals of this protocol.

The only significant outstanding concern is the potentially rapid transition to a climatological state at the beginning of the **control** ensemble. Several pilot forecasts following the proposed protocol and nudging specification are being carried out using the IFS. This section will be updated with results from these ensembles when they are available; in the interim, several results from a dry-dynamical core are presented.

### 1. Successful constraint of the zonal mean



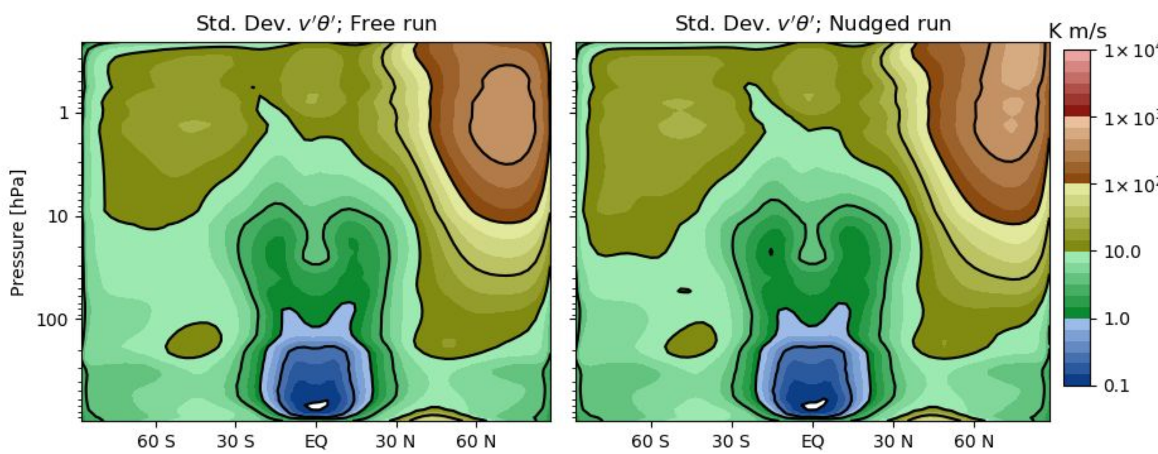

*Standard deviation of the zonal mean winds on pressure levels in a free running dry dynamical core integration (left), and in a second integration in which the zonal mean winds and temperatures are nudged in the stratosphere towards the climatology of the first run (analogous to the control ensemble)*

The nudging specification is intended to constrain the zonal mean state of the stratosphere, while allowing the stratospheric eddies and the troposphere and surface to evolve freely. The choice of nudging should result in a zonal mean state that lies close to the target state, while drastically reducing zonally symmetric variability in the stratosphere. This will be more precisely quantified when IFS results are available.

One important outstanding question involves the initial adjustment to the reference state. For the **control** ensemble, the initial state of the stratosphere will not necessarily be close to the climatology; the initial adjustment will have to be monitored.

## 2. Effects on planetary waves

The nudging specification is intended not to directly impact the zonally asymmetric component of the flow. The statistics of the planetary waves in particular are found to be largely unaffected by the constraint on the zonal mean (see figure below). One exception is that wave amplitudes in the upper stratosphere can grow larger in the presence of nudging; this is in part because the nudging prevents the wave transience from decelerating the mean flow, allowing planetary waves to propagate higher before they encounter critical levels. In some cases this can result in unusually strong winds in the upper stratosphere and lower mesosphere; however this is not expected to influence the evolution of the lower stratosphere or its interactions with the troposphere.




*Standard deviation of the meridional potential-temperature flux, again showing that the presence of nudging does not strongly impact the spatial structure of the eddies, at least at this coarse level of diagnostic.*

## 3. Effects on the meridional circulation

Because the wave field is not directly controlled by the nudging, the zonal mean forcing produced by the internally-generated wave field can differ substantially from that consistent with the evolution of the reference state, particularly for the **control** ensemble. Since the meridional circulation is largely determined by this forcing (e.g. Plumb 1982, Haynes et al. 1991), this can give rise to spurious meridional circulations and the potential for unintended remote effects.

However, it has been shown that the spurious circulations are largely confined to within the region of nudging, while the non-local circulation associated with ‘downward control’ is to a close approximation consistent with the forcings that produced the reference state (Hitchcock and Haynes 2014). This implies that any downward influence associated with these circulations can be expected to be present in the **nudged** ensemble, and absent in the **control** ensemble. Spurious circulations within the nudging region may give rise to anomalous transport of constituents within the stratosphere, but this is not expected to be of concern on the subseasonal timescales relevant to the present protocol.

The presence of a nudging layer can also give rise to a ‘sponge-layer feedback’ like response (Shepherd et al. 2006), which is characterized by spurious zonal mean temperature and wind anomalies generated just below the layer of nudging in response to tropospheric torques that differ from the reference state. These effects have also been shown to be negligible on these timescales (Hitchock and Haynes 2014).

## Data Request

In order to be able to adequately diagnose the coupling mechanisms involved in the events of interest, the protocol requests data output following the DynVarMIP specification (Gerber and Manzini 2016).

# Conclusions

The application of the proposed experimental protocol to the three case studies will allow for a controlled, multi-model assessment of the contribution of stratospheric extreme events to surface predictability on subseasonal timescales. The protocol will provide a testing ground for methods of attributing specific surface extremes to this stratospheric variability. It will allow for detailed comparisons of the mechanisms responsible for the surface impacts across the forecast models, controlling for the magnitude and nature of the zonally symmetric stratospheric anomalies that are thought to be most directly responsible for the surface impacts. Finally, it will also allow for an improved understanding of the upward coupling from the troposphere to the stratosphere.

While not the central focus of this protocol, the experiments may prove valuable to other SPARC and S2S projects, including the S2S MJO group, the QBOi, and SATIO-TCS. The protocol may serve to isolate other aspects of stratospheric influence on subseasonal timescales, including its effects on the tropics. Notably, both the 2018 and 2019 boreal sudden warming case studies span periods with significant MJO activity and differing phases of the QBO.

In summary, these experiments will prove invaluable as a foundation for identifying, quantifying, and improving the fidelity of processes relevant to stratosphere-troposphere coupling in operational models.

## References


Ayarzagüena, B., D. Barriopedro, J. M. Garrido-Perez, M. Abalos, A. de la Cámara, R. García-Herrera, N. Calvo, and C. Ordóñez, 2018: Stratospheric connection to the abrupt end of the 2016/2017 Iberian drought. *Geophys. Res. Lett.*, 45, 12 639–12 646, doi:10.1029/2018GL079802.

Butler, A., and Coauthors, 2019: Chapter 11: Sub-seasonal predictability and the stratosphere. *Sub-Seasonal to Seasonal Prediction*, A. W. Robertson, and F. Vitart, Eds., Elsevier, 223 – 241, doi:https://doi.org/10.1016/B978-0-12-811714-9.00011-5.

Charlton, A. J., and L. M. Polvani, 2007: A new look at stratospheric sudden warmings. Part I: Climatology and modelling benchmarks. *J. Clim.*, 20, 449–469.

Domeisen, D. I. V., and Coauthors, 2019a: The role of the stratosphere in subseasonal to seasonal prediction Part I: Predictability of the stratosphere. J. Geophys. Res., doi: 10.1029/2019JD030920.

Domeisen, D. I. V., and Coauthors, 2019b: The role of the stratosphere in subseasonal to seasonal prediction Part II: Predictability arising from stratosphere-troposphere coupling. *J. Geophys. Res.*, doi:10.1029/2019JD030923.

Douville, H., 2009: Stratospheric polar vortex influence on Northern Hemisphere winter climate variability. *Geophys. Res. Lett.*, 36, L18 703, doi:10.1029/2009GL039334.

Gerber, E. P. and Manzini, E., 2016: The Dynamics and Variability Model Intercomparison Project (DynVarMIP) for CMIP6: assessing the stratosphere–troposphere system, *Geosci. Model Dev.*, 9, 3413–3425, doi:10.5194/gmd-9-3413-2016.

Hitchcock, P., and P. H. Haynes, 2014: Zonally symmetric adjustment in the presence of artificial relaxation. *J. Atmos. Sci.*, 71, 4349–4368, doi:10.1175/JAS-D-14-0013.1.

Hitchcock, P., and I. R. Simpson, 2014: The downward influence of stratospheric sudden warmings. *J. Atmos. Sci.*, 71, 3856–3876, doi:10.1175/JAS-D-14-0012.1.

Jia, L., and Coauthors, 2017: Seasonal prediction skill of northern extratropical surface temperature driven by the stratosphere. J. Clim., 30, 4463–4475, doi:10.1175/JCLI-D-16-0475.1.

Karpechko, A. Y., A. Charlton-Perez, M. Balmaseda, N. Tyrrell, and F. Vitart, 2018: Predicting sudden stratospheric warming 2018 and its climate impacts with a multimodel ensemble. *Geophys. Res. Lett.*, 45, 13 538–13 546.

Kautz, L.-A., I. Polichtchouk, T. Birner, H. Garny, and J. G. Pinto, 2020: Enhanced extended-range predictability of the 2018 late-winter Eurasian cold spell due to the stratosphere. *Q. J. R. Meteorol. Soc.*, 146, 1040–1055, doi:10.1002/qj.3724.

Knight, J., and Coauthors, 2020: Predictability of european winters 2017/2018 and 2018/2019: Contrasting influences from the tropics and stratosphere. *Atmos. Sci. Let.*, e1009, doi:10.1002/asl.1009.

Lee, S. H., A. J. Charlton-Perez, J. C. Furtado, and S. J. Woolnough, 2019: Abrupt stratospheric vortex weakening associated with North Atlantic anticyclonic wave breaking. *J. Geophys. Res.*, 124, 8563–8575, doi:10.1029/2019JD030940.

Rao, J., C. I. Garfinkel, and I. P. White, 2020: Predicting the downward and surface influence of the February 2018 and January 2019 sudden stratospheric warming events in subseasonal to seasonal (S2S) models. *J. Geophys. Res.*, 125, e2019JD031 919, doi:10.1029/2019JD031919.

Rao, J., C. I. Garfinkel, I. P. White, and C. Schwartz, 2020: The Southern Hemisphere minor sudden stratospheric warming in September 2019 and its predictions in S2S models. *J. Geophys. Res.*, 125, e2020JD032 723, doi: 10.1029/2020JD032723.