The MJO-SSW teleconnection: interaction between MJO-forced waves and the mid-latitude jet

Wanying Kang¹, Eli Tziperman¹,²

¹School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA
²Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA

Key Points:

• SSW frequency is affected by MJO amplitude and longitudinal range which are both predicted to change
• MJO-SSW teleconnection is dominated by response of mid-latitude jet and stationary waves to the MJO
• MJO-forced wave eddy momentum transport drives the response of mid-latitude jet and stationary waves

Corresponding author: Wanying Kang, wanyingkang@g.harvard.edu
Abstract

The Madden Julian Oscillation (MJO) was shown to affect both present-day Sudden Stratospheric Warming (SSW) events in the Arctic, and their future frequency under global warming scenarios, with implications to the Arctic Oscillation and mid-latitude extreme weather. This work uses a dry dynamic core model to understand the dependence of SSW frequency on the amplitude and longitudinal range of the MJO, motivated by the prediction that the MJO will strengthen and broaden its longitudinal range in a warmer climate. We focus on the response of the mid-latitude jets and the corresponding generated stationary waves, that are shown to dominate the response of SSW events to MJO forcing. Momentum budget analysis of a large ensemble of spinup simulations suggests the climatological jet response is driven by the MJO-forced meridional eddy momentum transport. The results suggest that the trends in both MJO amplitude and longitudinal range are important for the prediction of the mid-latitude jet response and for the prediction of SSWs in a future climate.

1 Introduction

Major Sudden Stratospheric Warming events (SSWs) occur in the Arctic stratosphere during winter at a frequency of about six events per decade. An SSW features a distorted or completely reversed stratospheric polar vortex, as well as tens of degrees warming within several days [Craig et al., 1959; Limpasuvan et al., 2004]. In the month following an SSW event, the northern hemisphere is more likely to be in the negative phase of the Arctic Oscillation, and also to experience more extreme weather [Thompson et al., 2002; Kolstad et al., 2010; Mitchell et al., 2013], motivating the need to understand what will affect the SSW frequency in a future climate.

The Madden-Julian Oscillation (MJO) was shown to be linked to SSW events at 3-4 weeks lag [Garfinkel et al., 2012; Liu et al., 2014; Kretschmer et al., 2017]. Still, in the present climate, the MJO seems to have a relatively small effect on SSW, and is dominated by many factors with a stronger effect on SSW events [e.g., Kretschmer et al., 2017]. Kang and Tziperman [2017, 2018] showed that stronger MJO events, projected in global warming scenarios, can lead to a significant increase in the frequency of SSW events, and analyzed the detailed teleconnection mechanism. Given that the MJO is projected to both get stronger [Slingo et al., 1999; Jones and Carvalho, 2006; Lee, 1999; Arnold et al., 2013, 2014], and to expand to a larger longitudinal range [Chang et al., 2015; Arnold et al.,]
2014; Adames et al., 2017] in a warmer climate, a robust prediction of a trend in the SSW frequency should take the MJO change into consideration.

Kang and Tziperman [2018, hereafter KT] showed that the effect of the MJO on the SSW frequency strongly depends on the zonal asymmetry of the mid-latitude jet. In the northern hemisphere, the orography, land-sea contrast, and the zonal non-uniformity of the sea surface temperature, force the mid-latitude jet to tilt northward, and to strengthen over the western ocean basins [Brayshaw et al., 2009, 2011; Tamarin and Kaspi, 2017]. This background zonal asymmetry was found to contribute directly to an upward EP flux [KT, see also O'Brien et al., 1994], and to enhance the transmission of MJO-forced waves [KT]. The jet exit regions, located in the East Pacific and Atlantic, were suggested to help the amplification, accumulation and propagation of Rossby waves initiated from the tropics [Simmons et al., 1983; Webster and Chang, 1988; Naoe et al., 1997; Bao and Hartmann, 2014]. In turn, a transient MJO forcing was also shown to trigger a stationary response in the mid-latitudes, in both a shallow water model [Bao and Hartmann, 2014] and a dry dynamic core model (KT).

We explore here, using a dry dynamic core model with a realistic winter climatology, the response of the SSW frequency to MJO-like forcing with different amplitudes and different longitudinal ranges, motivated by prediction that the MJO will strengthen and broaden in longitude in a warmer climate [Arnold et al., 2013, 2014; Chang et al., 2015; Adames et al., 2017]. We find that SSWs are significantly enhanced when the MJO forcing is restricted to the Indo-Pacific sector as observed, while the response is less significant for other longitudinal ranges. As for the mechanism, the response of the mid-latitude jet and stationary waves to the MJO forcing is found to play a dominant role in determining the Arctic stratospheric response. To understand the jet response, we therefore examine the spin-up of the response when the MJO forcing is turned on, by running a large ensemble of short-term simulations, and identify the physical mechanisms behind the jet response. While this paper focuses on the response of SSW events to a strengthening of the MJO in order to isolate and understand this specific process, future changes to the other factors currently affecting SSW [e.g., Kretschmer et al., 2017] could be significant and perhaps even dominate those due to the MJO.
2 Methods

Model settings. A dry dynamical core model is used, with a similar configuration to that of Kang and Tziperman [2018]. A realistic topography is used, and the background climatology is forced to the January climatology in a control Specified-Chemistry Whole Atmosphere Community Climate Model [WACCM, Marsh et al., 2013] simulation, using the method of Hall [2000]. We enhance the stratospheric vertical resolution to 18 levels (a total of 35 levels), to more realistically simulate SSWs, and run each simulation for 50 years to get robust statistics. In order to focus on the response of SSWs to future MJO changes, we use the same present-day atmospheric background for all experiments, although changes to the general circulation and overall thermodynamic structure of the atmosphere with climate change may affect the MJO effects on the Arctic stratosphere.

MJO-like forcing. The MJO-like forcing is set to a global $k = 1$ heating/cooling pattern, eastward propagating along the Equator with 40-day period. The specified forcing amplitude ranges from 1 K/day to 10 K/day, and the longitudinal range (window) of the forcing is set to one of four different configurations. Window A corresponds to circum-global forcing, while windows B, C, and D are longitudinally restricted: window B corresponds to the Indo-Pacific sector (60-180E) where the MJO is observed in the present climate, and window C (D) is shifted by 120 degrees eastward (westward) from B. The response to window B forcing is meant to represent the observed MJO-SSW teleconnection, while the other windows are used to enhance our understanding of the role of the longitudinal position and extent of the MJO forcing. Each experiment is named [W][X], where [W] represents the window label and [X] represents the MJO-like forcing amplitude in K/day. Additional details about the experiments’ setup are given in the Supporting Information Text S1.

Although we prescribe a $k = 1$ forcing pattern, the restriction to a specified longitudinal window of 120 degrees longitude spreads the MJO power spectrum over $k = 1 - 5$, similar to the observed MJO. However, the prescribed single 40-day period is clearly unrealistic. We therefore perform additional sensitivity tests by allowing the speed of the $k = 1$ pattern, $c_p$, to fluctuate by ±15% around a mean value of 11.6 m/s, as a red-noise process with a 10 day memory (details in Supporting Information). As a result, the wavenumber and frequency spectra look more realistic for these sensitivity runs (Fig. S1).
Diagnostics. We use two complementary definitions of SSW events, based on reversals and deceleration rates of the polar night jet (PNJ), respectively, following Kim et al. [2017], with details provided in the Supporting information Text S3. To investigate how the total upward EP flux is affected by the MJO forcing, we decompose the total EP flux into three components: 40-day period waves, stationary waves, and transient waves at frequencies other than 40 days. While 40-day period waves exist in the model also without the 40-day MJO forcing, we assume that the majority of the signal at this frequency is due to this forcing so that this frequency mostly represents the direct effect of the forcing. In addition, the forcing changes wave motions at other frequencies, including both stationary waves, and transient waves at frequencies other than 40 days, via nonlinear interactions. For details, please refer to the Supporting Information Text S2. While the structure of the simulated unforced SSW events seems fairly realistic in our model, their frequency is 2-3 events per decade (of perpetual January run) using the reversal criterion and about 6/ decade using the deceleration criterion. The model thus produces too few events, likely due to the many missing factors in our idealized configuration.

3 Results

Our main objective is to study the interaction between the MJO-forced waves and the mid-latitude tropospheric jet, and its role in the MJO-SSW teleconnection. We find that window B forcing (corresponding to the location of the observed present-day MJO) leads to absorption of the MJO-forced waves by the mid-latitude jet, therefore amplifying the zonal asymmetry of the jet and increasing the upward stationary waves emitted from the mid-latitudes. This, in turn, is the dominant mechanism by which the frequency of SSW events is affected. The following subsections explore the different elements of this teleconnection mechanism in detail.

3.1 The Correlation of SSW Frequency with Upward EP Flux

Figs. 1(c,d) present the zonal mean climatological temperature responses (forced minus unforced) for two strongly forced cases, A10 and B10. In A10, SSW events are suppressed, and the Arctic stratospheric climatology is cooled by over 8K; while in B10, which leads to more frequent SSW events, the Arctic stratospheric climatology is warmed by over 6K. These temperature responses are driven by meridional eddy heat transport, $\nabla T$, according to the temperature budget [Kang and Tziperman, 2017, not shown].
Figure 1. (a) A scatter plot of the number of SSW events per decade as a function of large scale \( k = 1, 2 \) vertical EP flux component, \( EP_z \) at the tropopause (100 mb) integrated between 60N and 90N. SSWs are identified based on the wind reversal criterion (Methods section), and \( EP_z \) is time-averaged. (b) Similar to (a), except that SSWs are identified based on a PNJ deceleration criteria (see methods). Colors indicate the MJO-like forcing window: black corresponds to window A, red to B, blue to C, and orange to window D. The number following the letter denotes the prescribed maximum forcing heating rate in \( K/day \). ×-mark denotes the unforced case. (c, d) Two examples of climatological temperature responses, showing MJO-forced minus Control experiment for A10 (SSWs are suppressed) in (c) and B10 (SSWs are enhanced) in (d).
ity indicates that the change of the SSW frequency is not merely due to the climatological
deceleration of the polar night jet, but due to the dynamical wave forcing resulting directly
and indirectly from the MJO forcing.

The important point to note for the purpose of this paper is that the large-scale ($k = 1, 2$) upward EP flux at the high-latitude tropopause correlates well with the SSW fre-
quency (Fig. 1a,b). The time-mean EP$_z$ shows strong correlation with the SSW frequency
based on the wind reversal criterion ($r = 0.91$, Fig. 1a), and a somewhat weaker yet
still significant correlation with the frequency calculated using the deceleration criterion
($r = 0.59$, Fig. 1b).

![Figure 2](image)

**Figure 2.** The response of the mid-latitude jet to MJO-like forcing in window B (a,b) and in window C
(c,d). (a,c) Profiles of the maximum jet speed averaged between 20N and 60N, at 250 mb, as function of
longitude, showing the MJO-forced jet by the dashed lines (right y axis), and the forced minus unforced jet
response by the solid lines (left y axis). The lines varying from cold colors (blue) to warm colors (red) corre-
spond to simulations using weak to strong MJO forcing, at amplitudes of 0, 1, 2, 3, 4, 5, 6, 7, 10 K/day. (b,d)
The U wind field at 250 mb, averaged between 20N and 60N, for B window 10 K/day forcing at the top and
for C window 10 K/day forcing at the bottom. The forcing ranges of the three longitudinal windows B, C, D
are shown by colored bars between the two panels on the right.

3.2 Understanding the Mid-Latitude Jet and Stationary Wave Response to MJO
Forcing

We show below (section 3.3) that the upward EP flux response at the high-latitude
tropopause shown in Fig. 1 is dominated by the change in stationary waves generated in
the mid-latitudes. We now address our main focus here – the mechanism leading to this change in the mid-latitude jet and the corresponding stationary wave response due to the MJO forcing. Fig. 2a,c shows the zonal profiles of the jet-center speed (dashed lines), and of the corresponding deviation of this speed from the unforced simulation (solid lines), for the window B experiments (representing the present MJO) and the window C experiments (corresponding to the region into some of which a future MJO may expand to). Colors from cold to warm denote increasing MJO amplitudes.

The window B and window C forcings both accelerate the jet near the forcing’s eastern edge (180E for B, and 300E for C), and decelerate the jet near the forcing’s western edge (60E for B, and 180E for C), although the acceleration in the window C experiments is weaker. Since the forcing longitudinal location relative to the background zonal asymmetry is different in the two windows, window B forcing makes the jet speed more zonally asymmetric, while window C forcing makes it more zonally symmetric, as the MJO amplitude is increased (this is particularly obvious in the strongly forced cases, see Fig. 2a,c dash orange line between 0-180E). Supporting Fig. S3 shows that this effect occurs for forcing amplitudes larger than 2–3 K/day.

Figs. 2(b,d) show the spatial structure of the forced jet for the strongly forced B10 and C10 experiments. This again shows that forced by strong MJO-like forcing in window B (C), the mid-latitude jet becomes more zonally asymmetric (symmetric) and is shifted equatorward (poleward). We note that a more zonally asymmetric jet implies to more stationary waves forced in the jet area, which we find to dominate other wave components and to affect the SSW frequency (next subsection).

To verify that our results are not sensitive to the idealized, single frequency MJO forcing, we considered the stochastic MJO forcing described in the methods section applied to the B10 and C10 runs, and compared to the non-stochastic runs. We find the responses in zonal mean climatology and mid-latitude jet to be almost identical (Fig. S4). The SSW frequencies in stochastic B10 (C10) are 22/decade (5.5/decade), similar to the non-stochastic correspondence, 19/decade (6/decade).

The mid-latitude jet decelerates everywhere in response to the window D and window A forcings regardless of the forcing amplitude; and when forced by strong (>7 K/day) MJO forcing in window A, the mid-latitude (30-60N) jet decelerates dramatically, forming one jet over the Equator (Fig. S5). A similar sensitivity of the extratropical response to
the location of the stationary tropical forcing was also noticed by Simmons et al. [1983] and Ting and Sardeshmukh [1993].

To understand the different jet responses in the window B and window C experiments, we cannot use the momentum balance of the equilibrated forced runs, as these would simply show a dominantly geostrophic balance, not explaining how the wave forcing modifies the jet structure. An analysis of the PV budget turned out to be noisy and therefore also insufficient for providing insight about the mechanism of the response. We therefore choose to examine the initial response of the jet to the turning on of the forcing. We draw 800 different initial conditions (IC) from an unforced simulation, at 20-day intervals; then for each IC, we run a 20-day simulation with the strong window B forcing case and a 40-day simulation with the strong window C forcing, and take an ensemble average of the responses. The integration lengths are chosen for the two different windows such that a significant part of the equilibrium jet response features are reproduced by the end of the short simulation. The MJO phase at the beginning of each ensemble member is randomly picked, so that the signal associated with any particular MJO phase will be averaged over, and the ensemble average should therefore represent the climatological response of the jet to the MJO forcing.

To diagnose the mechanism of the jet response, we first take the ensemble average (denoted $\langle \cdot \rangle$) and the time average (denoted $\langle \cdot \rangle$) of the zonal momentum equation; we then decompose $u$ and $v$ into the reference state (defined to be the ensemble-mean, time-mean state in the short forced simulations), $\langle \bar{u} \rangle$ and $\langle \bar{v} \rangle$, and the deviation from this reference, $u'$ and $v'$ ($\bar{u}' = \bar{v}' = 0$); finally, we take a mass-weighted vertical average (denoted $\langle \cdot \rangle$) over the troposphere (100-1000 mb). The zonal momentum equation becomes,

$$
\frac{\partial}{\partial t} \langle u \rangle + \langle \bar{u} \rangle \frac{\partial \langle \bar{u} \rangle}{\partial x} + \langle \bar{v} \rangle \frac{\partial \langle \bar{u} \rangle}{\partial y} - f \langle \bar{v} \bar{u} \rangle = - \frac{\partial}{\partial x} \langle \bar{w} \bar{w} \rangle - \frac{\partial}{\partial y} \langle \bar{w} \bar{w} \rangle + [F_0],
$$

(1)

where $v_a$ is the ageostrophic component of the $v$ wind, and $F_0$ is the constant forcing term used to set the background state (see methods section). The time derivative term represents the climatology drift through the 20/40-day integration, which we are trying to explain, i.e., $\partial/\partial t \langle u \rangle = ((\langle u(T) \rangle - \langle u(0) \rangle))/T$, where $T$ is the length of the integration.

We write the above equation for both the MJO-forced experiment and the unforced experiment, and take the difference, denoting forced minus unforced variables by $\hat{\cdot}$, and
variables from the unforced experiment by a subscript 0,

\[
\frac{\langle \mu(T) \rangle - \langle \mu(0) \rangle}{T} = -\frac{\partial}{\partial x} \langle u'u' \rangle + \frac{\partial}{\partial y} \langle u'v' \rangle
\]


\[= \left\{ \begin{array}{l}
\langle \tilde{u} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial x} + \langle \tilde{u} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial x} + \langle \tilde{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} + \langle \hat{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} + f \langle \hat{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} \end{array} \right. \] - \left\{ \begin{array}{l}
\langle \tilde{u} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial x} + \langle \tilde{u} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial x} + \langle \tilde{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} + \langle \hat{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} + f \langle \hat{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} \end{array} \right\}.
\]

The left hand side and right hand side of Eq. 2 are shown in the top panels of Supporting Information Fig. S6 by shading and contours, respectively, and the close match between the two indicates a closed momentum budget.

**Figure 3.** The mechanism of the mid-latitude jet response to MJO forcing in different windows. Shown in shadings are the ensemble-averaged forced minus unforced zonal wind field in response to a 10 K/day MJO-like forcing, as shown by the lhs of eqn (2), for (left) window B after 20 days, and (right) window C after 40 days. The units are m/s/day. The 10 and 20 m/s contours of the unforced zonal wind field are superimposed in the top panels for reference. The meridional eddy flux of zonal momentum, Term 4 in Eq. (2), is shown by the contours in the bottom panels, showing a good match with the jet response (shading). The contour interval is 0.25 m/s/day, with positive contour values shown by solid lines and negative by dash lines.

The term representing the response of the zonal wind (Term 1, eqn 2) is shown by the shading in the top panels of Fig. 3, overlaid with contours of the mid-latitude jet zonal velocity in the unforced run. By the end of the short simulations, the averages of both short term experiments reproduce most of the long-term acceleration in the deep tropics,
and the deceleration in subtropics, seen in the long-term climatological responses to the B10 and C10 forcing. In the mid-latitude, the ensemble experiment for window B (C) reproduces the acceleration (deceleration) around 150E, the location of the strongest jet, and the equatorward (poleward) shift of mid-latitude jet, as observed in the long-term responses.

The meridional eddy momentum transport (Term 4) is shown as contours in the bottom panels of Fig. 3, together with the response of the zonal wind (Term 1) shown again by the shading. There is clearly a close correspondence between the two, indicating that the eddy momentum term explains much of the observed jet response. Term 4 accelerates the vicinity of the forced region in the deep tropics, and decelerate the zonal wind on both sides of the equator, especially in the north, indicating wave generation near the equator and wave absorption in the subtropics. In the mid-latitudes, this term accelerates the jet maximum region in window B; and it decelerates the left wing of the jet maximum, and shifts the jet poleward in window C, consistent with the jet response. Therefore, again, it seems that a considerable part of the jet response may be attributed to Term 4, the meridional eddy momentum transport. These transient eddies were also shown to play a dominant role in the extratropical response to stationary tropical forcing [such as due to El Niño, Held et al., 1989], and to affect the Arctic surface temperature by driving a meridional circulation [Yoo et al., 2012].

All terms on the rhs of Eq. 2 are shown in the Supporting Information Fig. S6 to be large compared with the lhs term showing the response of the jet, and there are significant cancellations between them, highlighting the complexity of the jet response. While the meridional eddy momentum flux does seem the strongest candidate for explaining the jet response based on its spatial structure, the results are still noisy, and a more complete understanding of this response may require using a yet simpler model, perhaps along the lines of the shallow water model study of Bao and Hartmann [2014].

Ensemble members are quite different, because each member starts from a different initial condition, and is forced by a different MJO initial phase. However, the ensemble mean, which is the important quantity as far as the long-term interaction of the jet and the MJO is concerned, is very robust: recalculating the ensemble average using 320 additional initial conditions for window B, taken from an extension of the control run, leads to nearly identical results (Fig. S7).
To summarize, the MJO forcing leads to eddy momentum fluxes that change the jet structure, making it more asymmetric for window B, and less asymmetric for window C. This leads to more stationary waves emitted from the jet region in window B and less in C, which then explains the larger increase in the SSW frequency in the window B experiments.

### 3.3 The Dominance of Stationary Wave Response and Partial Cancellation due to Transient Wave Response

We now show that the response to MJO forcing of the total large-scale EP$_z$ at the Arctic tropopause, which we showed to be correlated with the SSW frequency response (Fig. 1a), is dominated by the response of stationary waves produced in the mid-latitude jet region. This is explained by the changes to the zonal asymmetry of the mid-latitude jet discussed in the previous subsection. First, Fig. 4a,b (complemented by supporting information Fig. S8) shows that although the SSW frequency is most enhanced in B window experiments, the EP flux at the Arctic tropopause contributed by directly MJO-forced 40-day period waves is quite low compared to that forced by other windows. (Compare red dash lines in Figs. 4a,b). At the same time, the stationary waves emitted from mid-latitudes in experiment B are significantly strengthened (orange dash lines), leading to a total increase in the upward EP flux seen by the stratosphere, and therefore to the enhanced SSW frequency.

The generation and initial propagation of the directly MJO-forced 40-day period waves is insensitive to the MJO window location: the relative difference of the 100-800 mb integrated EP$_y$ at 25N is at most 30% among the B, C, D window experiments (not shown). Therefore, the difference in the transmission rate between different windows is due to two factors. First, different longitudinal windows of the wave source would lead to an interaction with the jet at different longitudes, and therefore to different transmission rates. Second, the transmission is also affected by the nonlinear interaction between these waves and the background zonal asymmetry (e.g., the jet exit). Bao and Hartmann [2014] analyzed a shallow water model and noticed a quasi-stationary response to an idealized MJO forcing, corresponding to the change to the jet observed in our window B experiments.
Figure 4. The response of stationary vs transient waves to MJO-like forcing. (a) Response to B-window forcing: number of SSW events per decade (thick solid black line, left axis) and the vertical component of the large scale EP flux at the tropopause, integrated over 60-90N, for forced minus unforced experiments (dashed lines, right axis): (red) EP flux associated with directly MJO-forced 40-day period waves; (orange) EP flux associated with large-scale stationary wave; (black) total large scale EP flux, where anomalies are filtered by wavenumber 1 and 2; (blue) EP flux due to “other waves”, calculated by subtracting the directly MJO-forced 40-day period waves (red) and the stationary waves (orange) from the total (black) EP flux. See methods section for detail. (b) same as (a), for window C. (c) A scatter plot of the contribution of transient waves to the Arctic tropopause EP$_z$ flux (m Pa/s$^2$), against the contribution of large-scale stationary wave to the Arctic tropopause EP$_z$. (d) A scatter plot of the contribution of transient waves to the Arctic tropopause EP$_z$ flux (m Pa/s) against the zonal mean zonal wind at 300 mb. Both EP$_z$ and the zonal mean zonal wind are averaged over 60-90N. Each dot represents one experiment, with the experiment name labeled. Different colors are used to distinguish the experiments with different MJO windows (black: window A, red: window B, blue: window C, orange: window D).
Finally, consider the wave components responsible for the forced changes to the EP flux at the tropopause, which causes the SSW frequency changes analyzed above. Fig. 4c shows that the EP$_z$ due to transient waves that were not directly forced by the MJO (methods section) is negatively correlated with the stationary EP$_z$ at the Arctic tropopause (60-90N, 100 mb). Fig. 4d shows it to be positively correlated with the upper tropospheric (300 mb) zonal wind speed at similar latitudes, which is proportional to the meridional temperature gradient, i.e., the baroclinicity. Both correlation coefficients are greater than 0.90, and insensitive to the choice of latitude bands used for the averaging. This suggests that the stationary waves affect the mid-latitude jet and baroclinicity (previous subsection), and this, in turn, reduces the production of transient waves at mid-latitudes. This cancellation of transient vs stationary waves causes the total EP$_z$ at the Arctic tropopause to changes by only 34% of the change in stationary EP$_z$ there. While the change in baroclinicity is consistent with the effect on the non MJO related transient waves, we did not rule out the possibility that these transient waves react somehow directly to the MJO forcing, rather than being reduced indirectly via the change to the baroclinicity.

4 Conclusions

The Madden-Julian Oscillation (MJO) is projected to be stronger and expand to a larger longitudinal range in a warmer climate [Slingo et al., 1999; Jones and Carvalho, 2006; Lee, 1999; Arnold et al., 2013, 2014; Chang et al., 2015]. We used a dry dynamical core model to investigate how MJO-like forcing, with different longitudinal ranges and amplitudes, affect the frequency of Sudden Stratospheric Warmings (SSW), especially focusing on the interaction between the mid-latitude jet and the MJO-like forcing.

We first showed a strong correlation between the SSW frequency and the large-scale EP$_z$ at the Arctic tropopause, in response to MJO forcing with varying amplitudes and longitudinal ranges. Thus, in order to explain the SSW response, we need to explain the changes to this high latitude vertical EP flux. It is known that the mid-latitude tropospheric jet structure can control both the propagation of equatorially forced waves [e.g., Kang and Tziperman, 2018], and the generation of stationary waves there, and we therefore focused here on the analysis of the mechanism of this mid-latitude jet response. We showed that MJO-forced eddy meridional flux of zonal momentum ($\bar{u}'\bar{v}'$) is the dominant forcing causing the jet response. Specifically, MJO forcing at the longitudinal range corresponding to present-day forcing causes an increase to the zonal asymmetry of the jet,
therefore strengthening the stationary waves generated in the jet region and increasing
the SSW frequency. We also showed that MJO-like forcing applied at other longitudes
can have an opposite effect, highlighting the importance of future changes in not only the
MJO amplitude, but also its longitudinal range. We then decomposed the total large-scale
EP$_z$ flux in the Arctic tropopause into contributions due to the directly MJO-forced 40-day
period waves, transient waves at other frequencies that are forced nonlinearly by the MJO,
and stationary waves generated in the mid-latitudes. The increase in stationary waves was
found to dominate the effect on SSW events, yet to be partially canceled by a decrease in
transient waves not directly forced by the MJO. We show indications that these transient
waves are weakened due to a reduction of the mid-latitude meridional temperature gradi-
ent (baroclinicity) by the MJO forcing.

This work demonstrated the complex interplay between MJO forcing, the mid-latitude
jet, mid-latitude generated stationary and transient eddies, and the SSW frequency, and
explored the relevant physical mechanisms. We noted that the mechanism of the jet re-
sponse is complex, and that further studies, perhaps using even more idealized models, are
needed to deepen our understanding of this problem. This work focused on the anticipated
strengthening of the MJO in a warmer climate, but did not take the expected change of
the static stability, storm track and other general circulation features into account. Such
changes may affect the Arctic stratosphere directly, and may also change the way the MJO
impacts SSWs. Future work will need to consider not only changes to the MJO, but also
many other intervening factors that may change in response to a global warming [e.g.,
blocking events, stationary wave patterns, storm track structure, ENSO, QBO Cohen and
Jones, 2011; Garfinkel et al., 2010; Kretschmer et al., 2017; Martius et al., 2009; Polvani
and Waugh, 2004].

Acknowledgments

This work was supported by the NSF P2C2 program, grant OCE-1602864, and by the
Harvard Global Institute and Harvard Climate Solutions funds. ET thanks the Weizmann
Institute for its hospitality during parts of this work. We would like to acknowledge high-
performance computing support from Yellowstone provided by NCAR’s Computational
and Information Systems Laboratory, sponsored by the National Science Foundation. Model
parameter files and analysis scripts used to generate model output and analyze it are avail-
able on the authors’ web-page, under
References


Martius, O., L. M. Polvani, and H. C. Davies (2009), Blocking precursors to stratospheric
114806.

The influence of stratospheric vortex displacements and splits on surface climate, J. Cli-
nate, 26(8), 2668–2682, doi:10.1175/JCLI-D-12-00030.1.

Naoe, H., Y. Matsuda, and H. Nakamura (1997), Rossby Wave Propagation in Idealized
and Realistic Zonally Varying Flows, Journal of the Meteorological Society of Japan,
75(3), 687–700.

Obrien, E., D. A. Stewart, and L. E. Branscome (1994), Tropical extratropical interactions
on intraseasonal time scales in a global spectral model, Journal of the Atmospheric Sci-

Polvani, L. M., and D. W. Waugh (2004), Upward wave activity flux as a precursor to ex-
treme stratospheric events and subsequent anomalous surface weather regimes, J. Cli-

Simmons, A. J., J. M. Wallace, and G. W. Branstator (1983), Barotropic wave propagation
and instability, and atmospheric teleconnection patterns, J. Atmos. Sci., 40(6), 1363–

Slingo, J., D. Rowell, K. Sperber, and E. Nortley (1999), On the predictability of the inter-
annual behaviour of the Madden-Julian oscillation and its relationship with El Niño, Q.

Tamarin, T., and Y. Kaspi (2017), Mechanisms controlling the downstream poleward de-
flection of midlatitude storm tracks, Journal of the Atmospheric Sciences, 74(2), 553–
572.

to northern hemisphere wintertime weather: implications for prediction, J. Climate,

Ting, M. F., and P. D. Sardeshmukh (1993), Factors determining the extratropical response
to equatorial diabatic heating anomalies, Journal of the Atmospheric Sciences, 50(6),

Webster, P. J., and H.-R. Chang (1988), Equatorial energy accumulation and emanation
regions: Impacts of a zonally varying basic state, Journal of the Atmospheric Sciences,
Supporting Information for ”The MJO-SSW teleconnection: interaction between MJO-forced waves and the mid-latitude jet”

Wanying Kang\textsuperscript{1}, Eli Tziperman\textsuperscript{1,2}

Contents of this file

1. Text S1 to S3,
2. Figures S1 to S6.

Introduction

Corresponding author: Wanying Kang, School of Engineering and Applied Science, Harvard University, 20 Oxford St., Cambridge, MA 02138 (wanyingkang@g.harvard.edu)

\textsuperscript{1}School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA

\textsuperscript{2}Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA
This document contains the details of model setup and diagnostics, as well as supporting figures and their captions.

**Text S1: Model Setup**

The idealized model experiments used here are configured following Held and Suarez [1994], based on the idealized physics component set in the Community Earth System Model version 1.2.2 [CESM, Neale et al., 2010], replacing radiation, convection and other physics processes by a restoring term to an equilibrium temperature, $T_{eq}$, with a time scale set to 40 days in the upper atmosphere above 850 mb. Surface friction is represented by strongly restoring $U$, $V$ and $T$ in the bottom 3 layers toward the equilibrium state with 4-day time scale. The finite volume core is used, and the horizontal resolution is 1.875° in latitude and 2.5° in longitude. We use the bottom 35 pressure-sigma hybrid layers from the standard WACCM model, with the model top located at 3 mb. Of these, 18 layers are in the stratosphere, which guarantees the vertical resolution is finer than 2 km everywhere and that SSW events are reasonably simulated [Richter et al., 2014], although we note that previous low-top models struggled to simulate a realistic SSW frequency [Charlton-Perez et al., 2013]. To avoid numerical instability due to wave reflection at the model top, the temperature restoring timescale is gradually reduced from 40 days to 30 days over the top four layers, at pressure levels of 6 mb and above. We thus expect the model response above 6 mb to the MJO forcing to be slightly damped. The “realistic” background state for the prognostic variables that integrated forward in time, $U$, $V$ and $T$, is set to the winter January climatology of a $1 \times$CO$_2$ Specified Chemistry WACCM run, using the method of Hall [2000]. Hundreds of one-step simulations are started from
instantaneous meteorological states taken from equilibrated January states of a WACCM run. The averaged negative of the time tendency (the $U$, $V$, $T$ at time step 0 minus those at time step 1) is then used as an extra static forcing of the prognostic variables. This forcing thus nudges the model state toward the averaged WACCM equilibrium state. The use of an average over multiple initial conditions leads to a nudging toward the climatology of WACCM, representing missing physics in the idealized model, including eddy fluxes, and making sure that the idealized model climatology is as consistent with the WACCM climatology as possible.

An MJO-like forcing is added to the idealized model as an external heating/cooling source, with a $k = 1$ zonal wavenumber structure, and $2\pi/k_{c_p0} = 40$ days period,

$$H = A \exp\left(-\frac{\sin^2 \phi}{2\sigma_y^2}\right) \sin(k(\lambda - c_{p0}t)) \cos\left(\frac{\log(p_0/p)}{\log(p_{surf}/p_0)} \frac{\pi}{2}\right) \times W(\lambda), \quad (1)$$

where $\phi$ denotes latitude in radians, $p_0 = 100$ mb, $p_{surf} = 1000$ mb, $\sigma_y = 5$ degree, $A$ is the heating amplitude, ranging from 0 K/day to 10 K/day, and $W(\lambda)$ is a tanh window function used to restrict the forcing to a specified longitudinal range as discussed in the main text.

In order to create an MJO forcing that has a broader, more realistic, frequency signature, while still propagating coherently, we write the propagating signal as $\cos(k(x - c_pt))$, calculating the pattern propagation speed as $c_p = c_{p0} + \Delta c_p$, such that $\Delta c_p$ corresponds to up to $\pm 15\%$ of the specified mean value $c_{p0}$, varying as a red noise process with a memory of $T_{mem} = 10$ days,

$$\Delta c_p(t^{n+1}) = R\Delta c_p(t^n) + \sqrt{1 - R^2} \zeta^{n+1} \quad (2)$$
\[
R = \exp(-\delta t/T_{mem})
\]
\[
\xi^i \sim \sqrt{3} \sigma \text{Unif}[{-0.5, 0.5}],
\]

where \(\delta t\) is the model time step, \(\text{Unif}[{-0.5, 0.5}]\) denotes independent and identically distributed random numbers between \(-0.5\) and 0.5. The variance of \(\Delta c_p\) is set to \(\sigma = 0.15 c_{p0} = 1.74 \text{ m/s}\). The factor \(\sqrt{3}\) is used to re-scale the uniform distribution to have a variance of 1.
Text S2: EP Flux Components

To distinguish the contribution of waves directly forced by the MJO and therefore having a 40-day period, from waves at different frequency (transient or stationary) that are nonlinearly forced by the MJO, we decompose the total EP flux into 40-day waves which we assume are dominated by direct MJO-forcing, stationary waves, and transient waves at different frequencies. To calculate the third category of waves, we first filter the meteorological fields $U$, $V$, and $T$ at a 40-day period and at zonal wavenumbers $k = 1, 2$, denoting the result $U'_{MJO}$, $V'_{MJO}$, $T'_{MJO}$, and then evaluate the EP flux component based on these filtered fields. The stationary waves component is evaluated based on the deviation of the climatological fields, $\bar{U}$, $\bar{V}$, $\bar{T}$, from their zonal mean, and these deviations are hereafter denoted as $\bar{U}^*$, $\bar{V}^*$, $\bar{T}^*$. The transient waves indirectly forced by the MJO are the remaining part in the total EP flux, after excluding the former two components. Since only the waves with $k = 1, 2$ can propagate to the Arctic stratosphere, the meteorological fields are filtered by $k = 1, 2$ before evaluating any of the above EP flux components.
Text S3: Diagnosing SSW Events

Following Kim et al. [2017], we diagnose SSWs using two methods based on the daily zonal mean zonal wind at 60N, 10mb. One criterion requires a wind reversal, i.e., \( U < 0 \) m/s; the second criterion requires this \( U \) wind to decelerate by over 5 m/s/day for at least 5 consecutive days, which is the typical deceleration rate of observed SSWs [Fig. 4 of Limpasuvan et al., 2004]. In both criteria, an SSW event has to be at least 50 days apart from the previous one.

References


Neale, R. B., C. C. Chen, and A. Gettelman (2010), Description of the NCAR community atmosphere model (CAM 4.0), *NCAR Tech Note*.

**Figure S1.** The stochastic MJO-forcing structure and spectrum. (Left) Hovmoller of the stochastic MJO forcing as a function of longitude and time. Middle two panels show the wavenumber (frequency) spectrum across the peak frequency 40 day (peak wavenumber $k=1$). Right panel shows the 2D wavenumber-frequency power spectrum (using a log scale).

**Figure S2.** Number of SSW events per decade as a function of MJO amplitude for the four window experiments, using (left) the wind reversal criterion, and (right) the wind deceleration criterion: (black) window A, (red) window B, (blue) window C, and (orange) window D. The results using the two criteria for diagnosing SSW events are similar, except that cases showing suppressed SSW frequency based on PNJ reversals show instead a weaker enhancement than those when based on PNJ deceleration.
**Figure S3.** The zonal asymmetry of the mid-latitude jet, calculated as the standard deviation of the jet center speed (maximum 250 mb westerly speed between 20N and 60N in climatology) along the zonal circle, as a function of the MJO amplitude, for all MJO forcing windows.
Figure S4. Comparison of the climatological jet response to periodic MJO forcing, and to stochastic MJO forcing. From top to bottom: experiments B10, B10-stochastic, C10, C10-stochastic. From left to right: zonal mean temperature response, zonal mean zonal wind response, and zonal wind response at 250 mb.
Figure S5. The climatological $U_{250}$ response (forced minus unforced) to 10 K/day MJO forcing restricted to Windows A–D. Units are m/s.
Figure S6. Terms in the zonal momentum equation, ensemble averaged based on 800 short ensemble simulation. From top to bottom, shown in shading are Terms 1-4 in Eq. (2) in the main text for (left) window B ensembles and (right) window C ensembles, in units of m/s/day. The (top panel) Term 1 is multiplied by a factor of 2 to be shown in the same colormap. (Top panels) In order to demonstrate that the momentum budget is appropriately closed, the sum of the RHS terms in Eq. (2) is superimposed on the jet response term on the LHS, in contours. Positive contours are shown in solid lines and negative contours are in dashed lines, with 0.25 m/s/day interval.
Figure S7. Demonstrating the robustness of the ensemble averages. The left panels are copied from Fig. S3 left column showing Terms 1-4 in Eq. 1 in the manuscript, and right panels are corresponding ones using an additional 320-ensemble experiment for B10 case.
Figure S8. Number of SSW events per decade (thick solid black line, left axis) and the vertical component of the large scale EP flux at the tropopause, integrated over 60-90N, forced minus unforced (dashed lines, right axis): (red) EP flux associated with MJO-related waves; (orange) EP flux associated with large-scale stationary wave; (black) total large scale EP flux, where anomalies are filtered by wavenumber 1 and 2. (blue) “other waves” which is calculated by excluding the MJO-related waves (red) and stationary waves (orange) from the total EP flux (black). See methods section for details. The four panels correspond to the four forcing windows as denoted in the titles.