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

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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
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, 2010; Liu et al., 2014; Kretschmer et al., 2017]. Furthermore, Kang and Tziperman [2017a,b] 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 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; 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 [2017b, hereafter KT] showed that the effects of the MJO on the SSW frequency monotonically 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 Obrien 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.

2 Methods

A dry dynamic core model is used, with a similar configuration to that of Kang and Tziperman [2017b]. The background climatology is forced to the January climatology in a control Specified-Chemistry Whole Atmosphere Community Climate Model (WACCM-SC) simulation, using the method of Hall [2000]. We enhance the stratospheric vertical resolution to 18 levels (a total of 35 levels), to simulate more realistic SSWs, and run each simulation for 50 years to get robust statistics. MJO-like forcings with various amplitudes are added to four longitudinal windows. Window A corresponds to circumglobal forcing,
and windows B, C, and D are longitudinally restricted, where window B corresponds to
the observed Indo-Pacific sector (60-180E), 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 un-
derstanding 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. Full details of the model setup are given in the
Supporting Information Text S1.

We use two SSW definitions to examine the result, based on the polar night jet
(PNJ) reversal and deceleration, respectively, following Kim et al. [2017]. To investigate
how the total upward propagating EP flux is affected by the MJO forcing, we decompose
the total EP flux into three components: the transmission of the MJO-related waves, the
stationary waves, and non MJO-related transient waves. For details, please refer to the
supporting information Text S2.

3 Results

Our main objective is to study the MJO-jet interaction and its role in the MJO-SSW
teleconnection. We find that window B forcing (corresponding to the location of the ob-
served 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 sta-
tionary 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,
$\mathbf{\nu}^T\mathbf{\nabla}T$, according to the temperature budget [Kang and Tziperman, 2017a, 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) $EP_z$ at the tropopause (100 mb) integrated between 60N and 90N. SSWs are identified based on the wind reversal, 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 green to window D. The number followed by the letter denotes the maximum forcing heating rate in K/day. (c, d) Two examples of climatological temperature responses, showing MJO-forced minus Control experiment for A10 (SSWs are enhanced) in (c) and B10 (SSWs are suppressed) in (d) respectively.

Proceeding to the response of SSW events, Supporting Information Fig. 4a shows that MJO-like forcings applied within different equatorial longitudinal ranges lead to the SSW frequency either being enhanced (windows A,B,D) or suppressed (window C in to which the MJO is projected to expand in a future warmer climate, and window A at strong amplitudes). The dependence on the longitudinal range of the forcing is generally consistent with the results of Kang and Tziperman [2017b] who examined the role of zonal asymmetry of the background state on the teleconnection. It is also consistent with the observational analysis of Garfinkel et al. [2014] and Schwartz and Garfinkel [2017]
who found that the MJO effect on the average polar cap temperature occurs preferentially after certain MJO phases, when the MJO forcing is at specific longitudes. Yet the dependence on the forcing amplitude requires further explanation, which is provided in the next section.

The results are qualitatively similar if using the PNJ deceleration criterion to diagnose SSWs (Supporting Information Fig. 4b). The similarity when using the two criteria 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 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 frequency (Fig. 1a,b). The correlations are based on both methods of estimating the SSW frequencies (wind reversal and wind deceleration, see Supporting Information). The time-mean EP$_z$ shows a better correlation with the frequency of SSWs diagnosed using the reversal criterion ($r = 0.91$, Fig. 1a) than using the deceleration criterion ($r = 0.59$, Fig. 1b).

We next address the mechanism leading to the changes to the upward EP flux at the high-latitude tropopause as the MJO forcing changes in both amplitude and longitudinal range.

### 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. With increasing amplitude, the jet-center speed response (solid line) gradually grows. The important thing to notice in these figures is that window B forcing makes the jet speed more zonally asymmetric, while window C forcing make it more zonally symmetric (e.g., dash orange lines in Fig. 2a,c)
Figure 2. The response of the mid-latitude jet to MJO-like forcing in window B (a,b) and in window C (c,d). Shown in (a,c) are the profiles of the maximum jet speed between 20N and 60N, at 250 mb, as function of longitude, showing the MJO-forced response by the dashed lines (right y axis), and the forced minus unforced response by the solid lines (left y axis). The lines varying from color (blue) to warm color (red) correspond to simulations from weak to strong MJO forcing, at amplitudes of 0, 1, 2, 3, 4, 5, 6, 7, 10 K/day. Shown in (b,d) are the U wind field at 250 mb between 20N and 60N, for B window 10 K/day forcing on the top and for C window 10 K/day forcing on the bottom.

In the range of 0-180°E), 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. 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 dominates other wave components and affects the SSW frequency (next subsection).

The mid-latitude jet decelerates everywhere in response to the window D and window A forcings, and the deceleration is dramatic for the window A (circumglobal) forcing amplitudes stronger than 7 K/day (not shown). 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. PV analysis also ended up being less helpful in providing insight about the mechanism of the response as well. 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, allowing for the different response times in the two cases. 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 $(\cdot)$) 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 $[\cdot]$) over the troposphere (100-1000 mb). The zonal momentum equation becomes,

$$\frac{\partial}{\partial t} [\langle u \rangle] + \langle \bar{u} \rangle \frac{\partial \langle \bar{u} \rangle}{\partial x} + \langle \bar{v} \rangle \frac{\partial \langle \bar{u} \rangle}{\partial y} - f [\langle \bar{v}_a \rangle] = -\frac{\partial}{\partial x} [\langle u' u' \rangle] - \frac{\partial}{\partial y} [\langle u' v' \rangle] + [F_0], \tag{1}$$

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 method section). The time derivative term represents the climatology drift through the 20/40-day integration which we are trying to explain, i.e., $\frac{\partial}{\partial t} [\langle u \rangle] = ([\langle u(T) \rangle] - [\langle u(0) \rangle])/T$, 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 $0$,

\[
\frac{\langle u(T) \rangle - \langle u(0) \rangle}{T} = \left[ -\frac{\partial}{\partial x} \langle u' v' \rangle \right] + \left[ -\frac{\partial}{\partial y} \langle u' v' \rangle \right] - \left[ \langle \tilde{u}_0 \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial x} + \langle \tilde{u} \rangle \frac{\partial \langle \tilde{u}_0 \rangle}{\partial x} + \langle \tilde{v} \rangle \frac{\partial \langle \tilde{u} \rangle}{\partial y} + \langle \tilde{v} \rangle \frac{\partial \langle \tilde{u}_0 \rangle}{\partial y} - f \langle \tilde{v}_0 \rangle \right].
\]  

(2)

The left hand side and right hand side of Eq. 2 are shown in the top panels of Supporting Information Fig. 4 by shading and contours, respectively, and the close match between the two indicates a closed momentum budget, allowing us to diagnose the dominant mechanism leading to the drift in jet speed on the LHS.

**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 contours shown in solid lines and negative contours shown in dashed 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 response to the B10 and C10 forcing (left panels of Supplementary Fig. 4). 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 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. 4 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, 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].

To summarize, the MJO forcing leads to eddy momentum fluxes that change the jet structure, making it more asymmetric for window B, and less symmetric for window C. This leads to more stationary waves emitted from the jet region in window B and less in C, which then explain 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 $\text{EP}_z$ 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 supplementary information Figure 4) shows that although the SSW frequency is most enhanced in B window experiments, the EP flux contribution by MJO-related waves that are transmitted through the jet region to the Arctic tropopause is quite low compared to that forced by other windows. (Compare red dash lines in Figs. 4ab). At the same time, the stationary waves emitted from mid-latitudes in this experiments are significantly strengthened (green dash lines), leading to a total increase in the upward EP flux seen by the stratosphere, and therefore to the enhancement of the SSW frequency.

The generation and initial propagation of the MJO-related waves is insensitive to the MJO window location: the relative difference of the 100-800 mb integrated $\text{EP}_z$ 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 mainly due to the difference in the transmission of these waves through the mid-latitude background state, which was shown by Kang and Tziperman [2017b] to increase with the background zonal asymmetry, affecting the absorption of waves by the mid-latitude jet. 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.

Fig. 4c shows that the non MJO-related transient $\text{EP}_z$ is negatively correlated with the stationary $\text{EP}_z$ at the Arctic tropopause (60-90N, 100 mb). Fig. 4d shows it to be positively correlated with the upper tropospheric 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 non-MJO related transient waves at mid-latitudes. As a result, the total $\text{EP}_z$ at the Arctic tropopause only changes by 34% of the change in stationary $\text{EP}_z$. While the change in baroclinicity...
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 MJO-related waves. (green) 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 (red) MJO-related waves and (green) stationary waves from the (black) total 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 (mPa/s), 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 (mPa/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, green: window D).
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 indirectly via the change to the stationary waves and 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 fo-
cusing 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 tropo-
spheric jet structure can control the propagation of equatorially forced waves [e.g., Kang
and Tziperman, 2017b] 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 ($\overline{u'v'}$) is the dominant forcing causing the jet response. Specifically, MJO forc-
ing 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 MJO-related waves, non MJO-related transient waves, 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 non MJO-related transient
waves, due to a reduction of the mid-latitude meridional temperature gradient (baroclinic-
ity) 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 ex-
explored the relevant physical mechanisms. We noted that the mechanism of the jet response is complex, and that further studies, perhaps using even more idealized models, are needed to deepen our understanding of this problem. Future studies would also need to consider the effects due to the specific anticipated increase in longitudinal range of the MJO in response to global warming, as well as the effects of changes to the background circulation and stratification due to global warming.

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Supporting Information for ”The MJO-SSW teleconnection: interaction between MJO-forced waves and the mid-latitude jet”

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Contents of this file

1. Figures S1 to S4

Introduction

This document contains the details of model setup and diagnostics, as well as supporting figures and their captions.

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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 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 initial conditions. 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 $2\pi/\omega = 40$ days period,

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

where $\sigma_y = 5$ 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.
Text S2: EP Flux Components

To distinguish the contribution of the direct propagation of MJO-related waves, and the secondary effect due to the change of climatology, we decompose the total EP flux into the MJO-related waves, stationary waves, and non MJO-related transient waves. For the MJO-related 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 non MJO-related transient waves component is the remaining part in the total EP flux 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 the 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 keep decelerating over 5 m/s/day for at least 5 consecutive days. In both criteria, a new 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. 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 lines are for window A, red for window B, blue for window C, and green for window D. The results are using the two criteria for SSW are similar, except that cases showing suppressed SSW frequency based on PNJ reversals show instead a weaker enhancement than in the other cases based on the PNJ deceleration.
Figure S2. 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. (green) 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 (red) MJO-related waves and (green) stationary waves from the (black) total EP flux. See methods section for detail. The four panels correspond to four windows as denoted in the titles.
Figure S3. Budget terms of zonal momentum equation, 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. To show a budget closure, the sum of the right hand side terms in Eq. (2) is superimposed on the jet response term (top panels) in contours. Positive contours are shown in solid lines and negative contours are in dashed lines, with 0.25 m/s/day interval.
Figure S4. The climatological $U_{250}$ response (forced minus unforced) to 10 K/day MJO forcing restricted in Window B (top panels) and Window C (bottom panels). Units are m/s.