Role of Gravity Waves in a Vortex-Split Sudden Stratospheric Warming in January 2009

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Introduction

- Sudden stratospheric warmings (SSWs) are dramatic phenomena associated with rapid temperature increases and polar vortex breakdown in the high-latitude winter stratosphere, which affect large-scale circulations not only in the stratosphere (Holton 1980) but also in the troposphere (Baldwin and Dunkerton 2001).
- SSW is a dynamical phenomenon accompanying enormous changes in atmospheric waves as well as those in the mean wind and temperature. Since Matsuno (1971), it has been generally accepted that the interaction between the mean flow and vertically propagating planetary waves (PWs) generated from the troposphere is the essential dynamical mechanism for SSWs (Andrews et al. 1987).
- However, some recent studies have noted that enhanced PWs alone may not be sufficient to explain the occurrence of SSWs, and the role of GWs has emerged as an additional wave forcing to drive SSW evolution, based on various observations (e.g., Whiteway et al. 1997; Duck et al. 1998, 2001; Wang and Alexander 2009), numerical modeling (e.g., Limpasuvan et al. 2011; Gavrilov et al. 2018; Scheffler et al. 2018), and reanalysis data analyses (e.g., Albers and Birner 2014; Song and Chun 2016).
- Recently, the contribution of GWs to SSW in association with PWs has been investigated. As GW drag (GWD) changes the mean flow in the transformed Eulerian mean (TEM) equation, PWs are modulated by GWs either through changes in the wave propagation condition (Cohen et al. 2014) or by triggering the instability and resonance of PWs (Albers and Birner 2014; Scheffler et al. 2018).

Introduction (cont.)

- Apart from relation to interaction with PWs as in previous studies, GWD itself can generate PWs in the middle atmosphere as a nonconservative source of the potential vorticity (PV) equation.
    - Using a simple general circulation model (GCM), Holton (1984) demonstrated nicely that mesospheric PWs are generated by zonally asymmetric orographic GWD in the mesosphere that propagate through a zonally symmetric stratospheric wind where originally no PWs exist.
    - Smith (2003) showed that stationary PWs in the winter mesosphere can be generated from GWD, and the amplitudes of the in situ generated PWs in the upper mesosphere are larger than those of vertically propagating PWs from the troposphere.
- The 24 January 2009 vortex split-type SSW event (SSW09) is chosen as the best SSW case to examine the interaction between the PWs and GWs, given that SSW09 was characterized by strong GW activities along the polar vortex before the SSW occurrence (Thurairajah et al. 2010; Yamashita et al. 2010; Limpasuvan et al. 2011; Albers and Birner 2014; Song and Chun 2016).

In this study, we examine the role of GWs on a vortex-split type SSW (SSW09), focusing on the nonconservative GWD forcing of the PV equation during the pre-SSW period, using the MERRA-2 reanalysis dataset.

Data and Methodology

❖ MERRA-2 reanalysis data

MERRA-2 reanalysis		
Variables used in this study		u, v, w, T, h, GWD_X, GWD_Y
Period		1980–2015 (36 years) (focusing on SSW09; 1 Dec. 2008–31 Jan. 2009)
Resolution	Temporal	3 hours
	Horizontal	0.625° × 0.5° (lon. x lat.)
	Vertical	42 layers (up to 0.1 hPa)

- A parameterized GWD provided from MERRA-2 is the sum of
  - orographic GWD based on McFarlane (1987)
  - nonorographic GWD based on Garcia and Boville (1994)

Data and Methodology (cont.)

❖ **Nonconservative GWD forcing in the quasi-geostrophic PV (QGPV) equation**

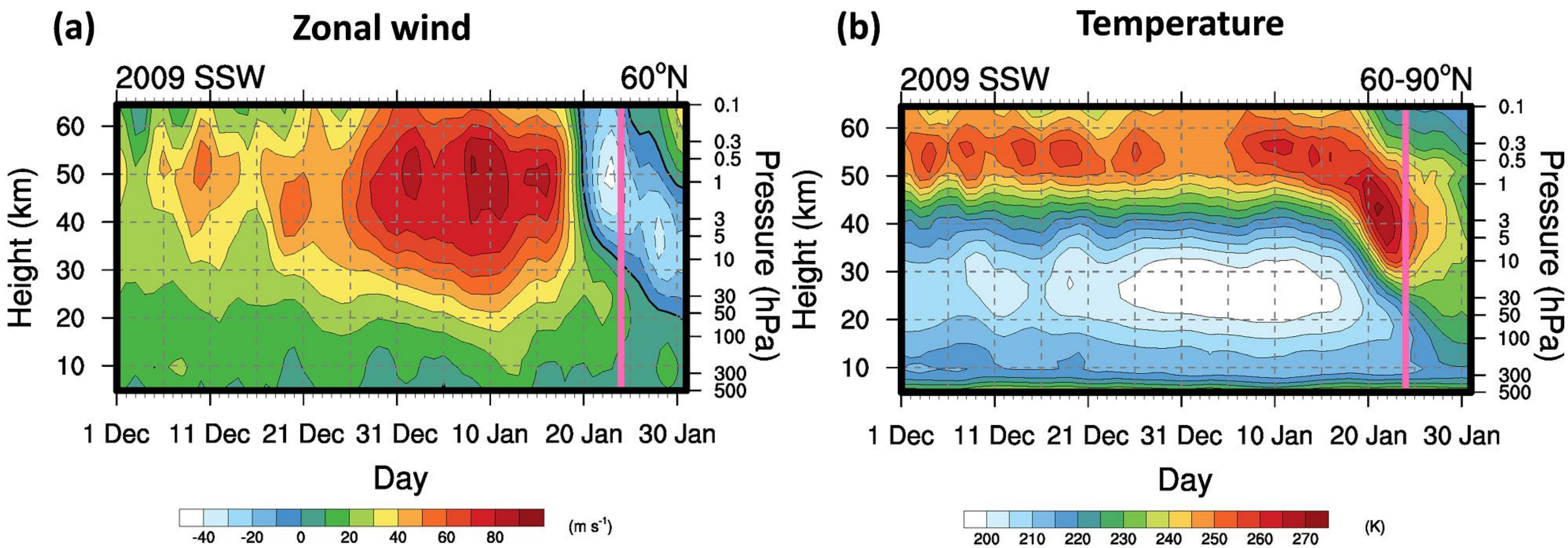
$$\left(\frac{\boldsymbol{\partial}}{\boldsymbol{\partial t}}+\bar{u}\frac{\partial}{a cos\phi\partial\lambda}\right)\boldsymbol{q'}+v'\frac{\partial\bar{q}}{a\partial\phi}=\frac{\mathbf{1}}{\boldsymbol{a cos\phi}}\left[\frac{\boldsymbol{\partial Y'}}{\boldsymbol{\partial\lambda}}-\frac{\boldsymbol{\partial(X' cos\phi)}}{\boldsymbol{\partial\phi}}\right]+\frac{f_0}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0\frac{Q'}{e^{\frac{\kappa}{H}z}\left(\frac{\partial\overline{T_0}}{\partial z}+\frac{\kappa\overline{T_0}}{H}\right)}\right),$$

$$\boldsymbol{q'}\equiv\frac{1}{a^2 cos\phi}\left[\frac{1}{cos\phi}\frac{\partial^2}{\partial\lambda^2}+\frac{\partial}{\partial\phi}\left(cos\phi\frac{\partial}{\partial\phi}\right)\right]\psi'+\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0\frac{{f_0}^2}{N^2}\frac{\partial\psi'}{\partial z}\right),$$

$$\frac{\partial\bar{q}}{a\partial\phi}\equiv\frac{2\Omega cos\phi}{a}-\frac{1}{a^2}\frac{\partial}{\partial\phi}\left[\frac{1}{cos\phi}\frac{\partial(\bar{u}cos\phi)}{\partial\phi}\right]-\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0\frac{{f_0}^2}{N^2}\frac{\partial\bar{u}}{\partial z}\right).$$

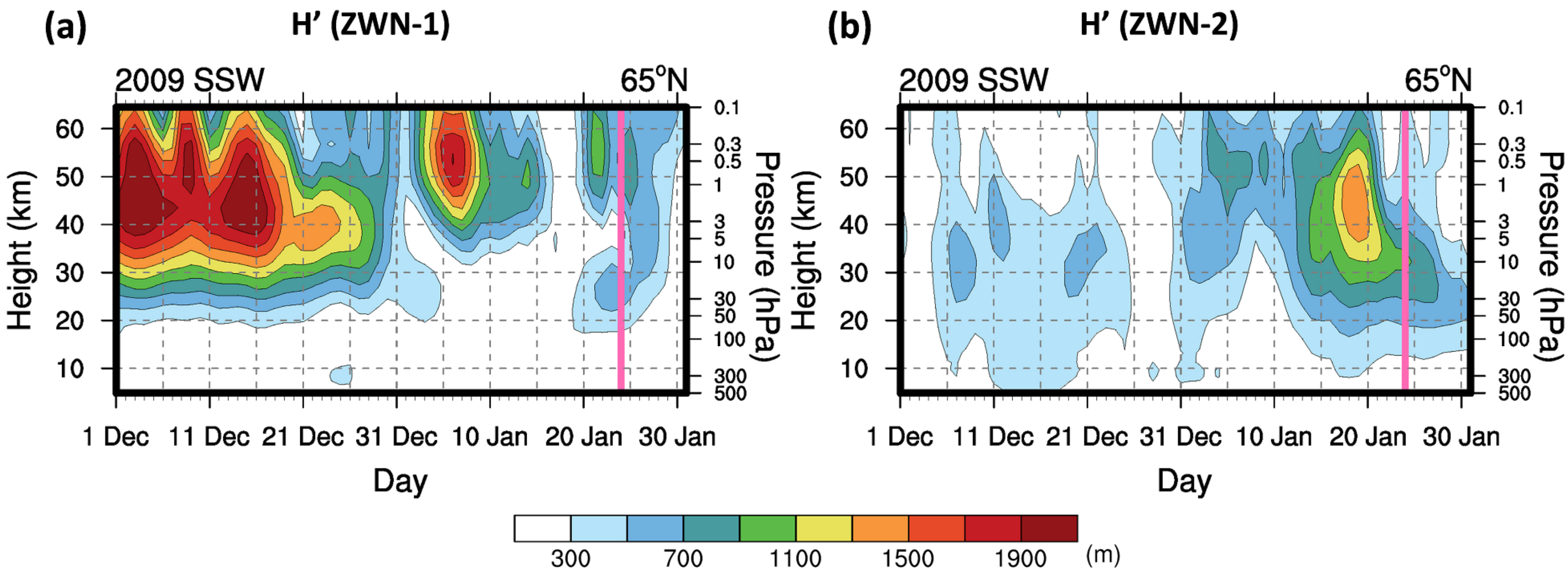
- The perturbation: a departure from the zonal mean
- q': the perturbation QGPV
- X', Y': the perturbation zonal and meridional components of GWD
  - → Z' ($\equiv 1/a cos\phi\,[\partial Y'/\partial\lambda-\partial(X' cos\phi)/\partial\phi]$): nonconservative GWD forcing (NCGWD)
- ψ': the perturbation streamfunction ($\psi'=\Phi'/f_o$, Φ': the perturbation geopotential)
- Q': the perturbation diabatic heating rate (negligible)

Zonal-mean wind and temperature changes



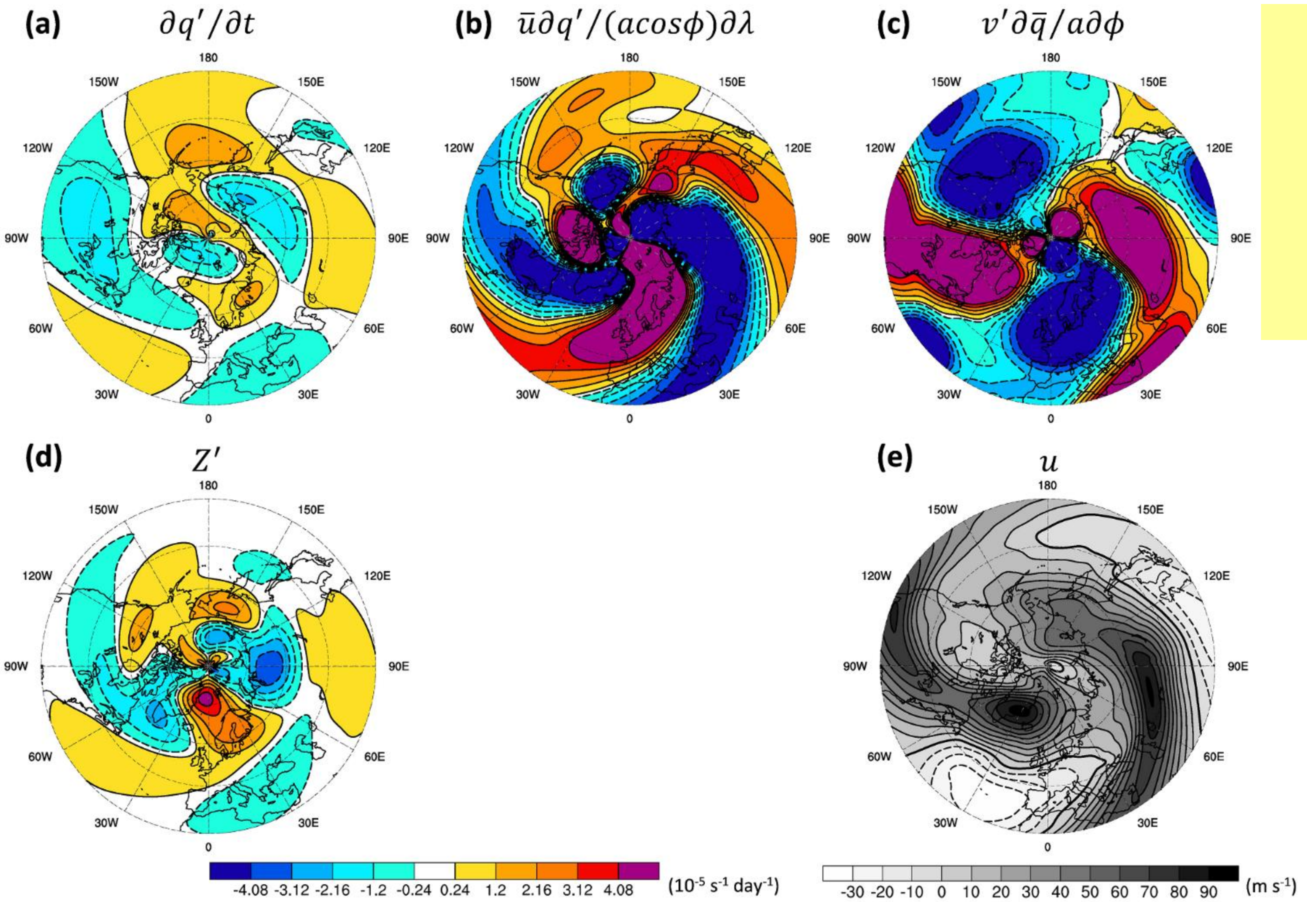
- The westerly jets are enhanced during 26 December–10 January (Lag = –29 to –14), with a maximum value of 90 m s^{-1} on 8 January.
- As Lag = 0 is approached, the westerlies gradually decrease, and their sign is reversed to easterly, starting from the lower mesosphere on 20 January (Lag = –4).
- A rapid temperature increase of more than 30 K occurs in the upper stratosphere starting from Lag = –5, accompanied by the sudden deceleration of the polar night jet.

PW activity changes



- PWs of ZWN-1: enhanced above about z = 30 km during 1–21 December, while it decreases at most altitudes above z = 20 km during January
- PWs of ZWN-2: enhanced below 40 km in early December and significantly enhanced in the altitude range of z = 35–50 km (5–1 hPa) at around Lat = –5
- The amplitude of ZWN-1 is generally predominant in the high-latitude winter stratosphere → a larger amplitude of ZWN-2 than ZWN-1 during the evolution of SSW09 is a distinctive phenomenon that makes this case to be classified as the vortex-split type SSW

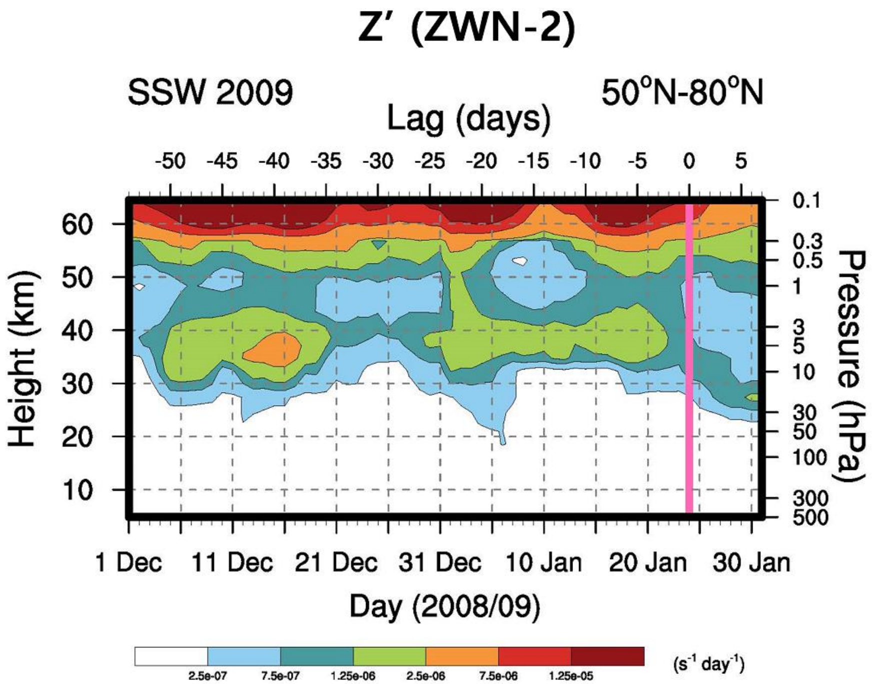
Each term in the linearized QGPV equation at 0.3–0.1 hPa

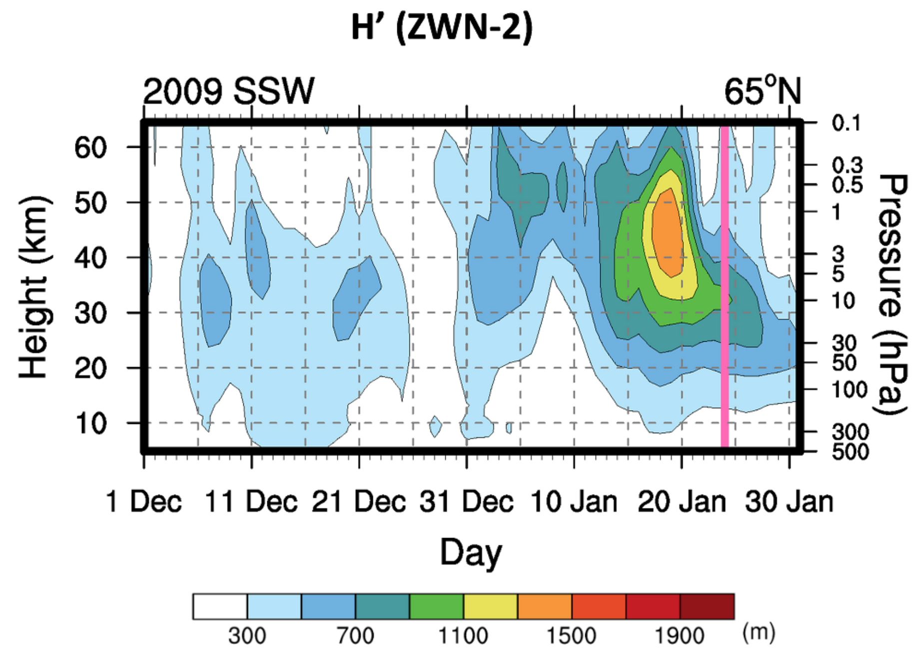


- At Lag = –6 (18 Jan 2009)
- Averaged over 0.3–0.1 hPa (upper stratosphere and lower mesosphere; USLM)
- Zonal wavenumber 1–3

- The major two terms (advection terms in b and c) largely canceled each other.
- Z' is similar to $\partial q'/\partial t$ in its magnitude and phase, with a clear ZWN-2 structure.
  - Statistically significant pattern correlation: 0.47 (50º–80ºN) and 0.64 (40º–60ºN)
- NCGWD forcing in the USLM is nonnegligible and can play an important role in determining the ZWN-2 structure PWs through the tendency of q'

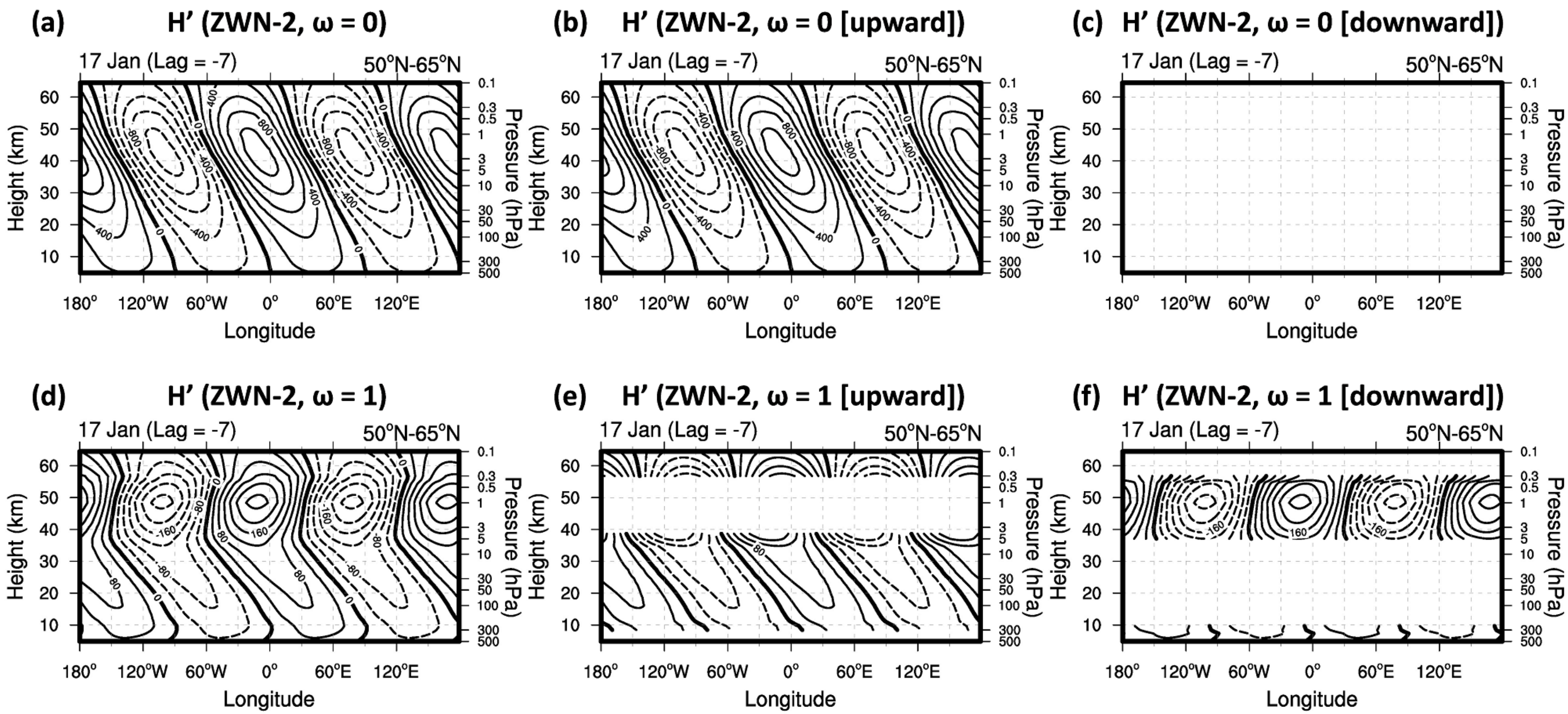
Temporal variations of the Z' during pre-SSW stage





- The ZWN-2 structure of Z' is predominant in the USLM (0.3–0.1 hPa), with the secondary maximum in the mid-stratosphere (10–3 hPa)
- The ZWN-2 component of Z' in the ULSM is enhanced during pre-SSW stage
  → matched (but slightly earlier) with enhanced PW of ZWN-2 in the stratosphere
- The abrupt amplification of PWs of ZWN-2 in the stratosphere before the onset of SSW09 is closely related to the enhanced ZWN-2 pattern of Z' at 0.3–0.1 hPa prior to the enhanced PW of ZWN-2 in the mid-stratosphere
  → possibility of downward-propagating PWs of ZWN-2 generated by Z' in the USLM

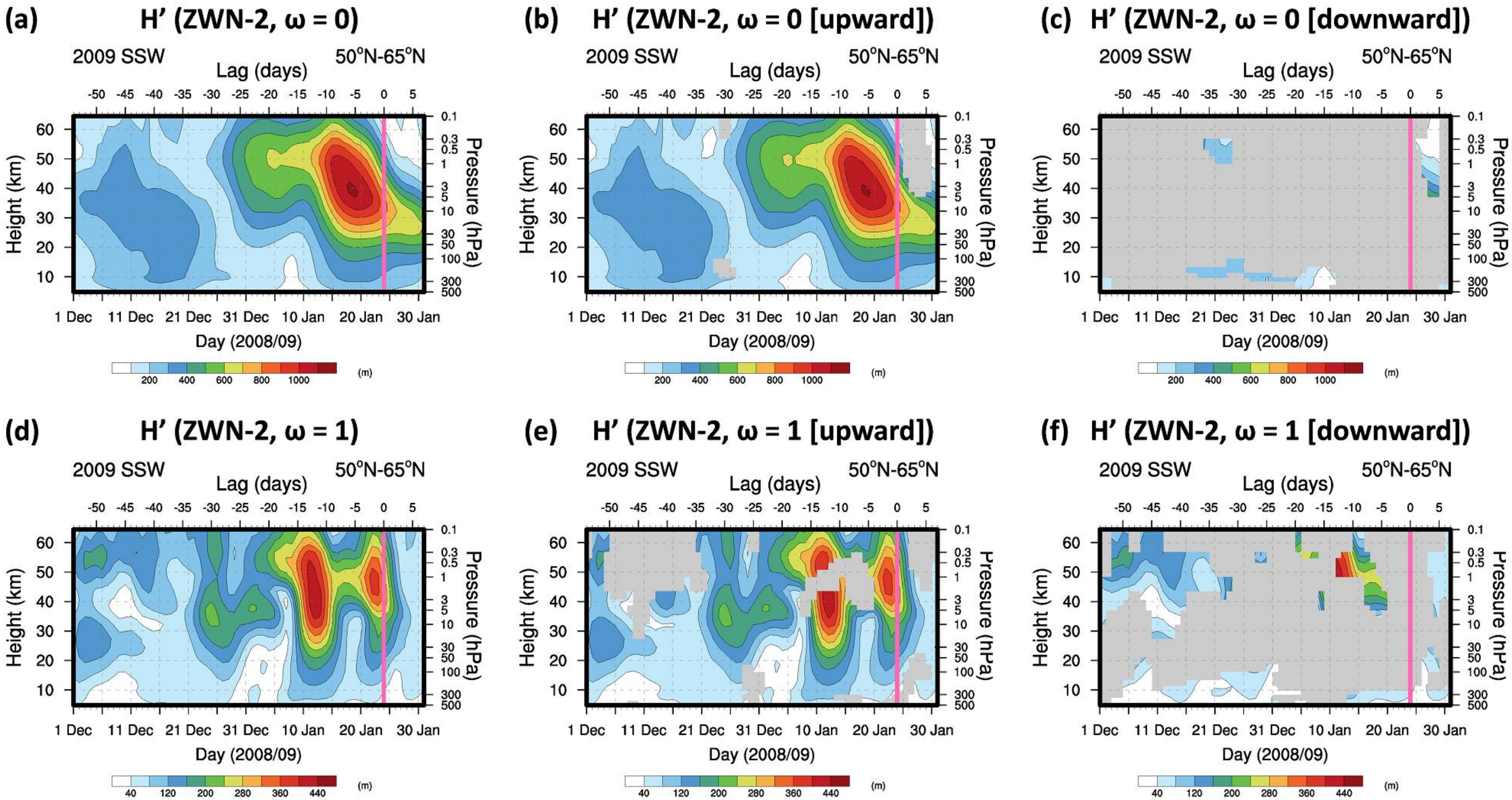
Decomposition of the PW of ZWN-2



- PWs of ZWN-2 are decomposed into upward ($F^{(z)} > 0$) and downward ($F^{(z)} < 0$) propagating components based on a 2D (zonal, time) Fourier analysis ($F^{(z)}$: the vertical component of the Eliassen-Palm flux)
- PWs of ZWN-2
  - stationary ($\omega = 0$) component: strong upward propagation from the troposphere
  - $\omega = 1$ component: substantial downward propagation from the USLM

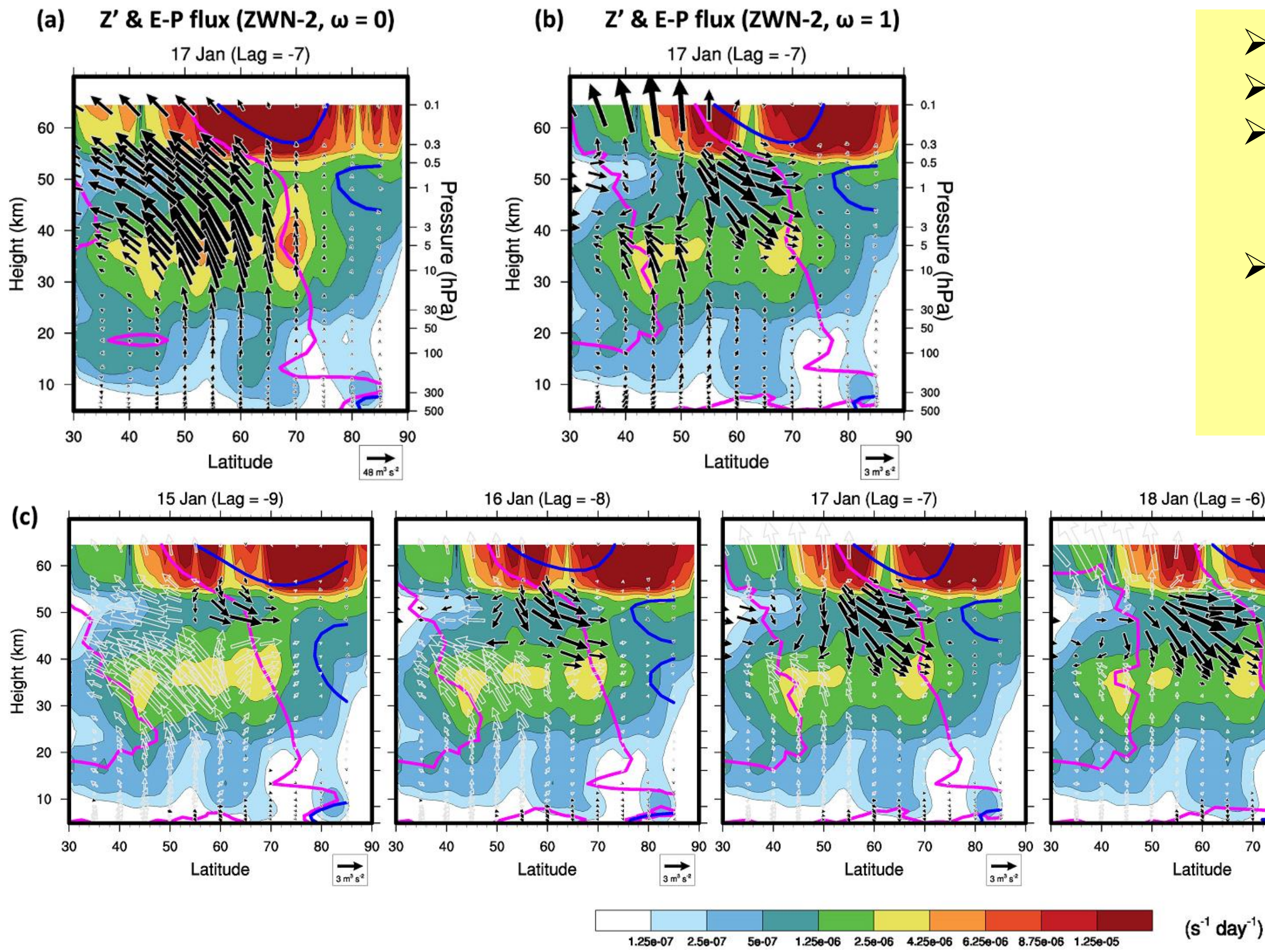
    PWs with a period of 11 days (within the given 11-day time windows)

Upward- and downward-propagating PWs of ZWN-2



- ZWN-2 with stationary components: mainly propagate upward
  - Enhanced amplitudes above 30 km at around Lag = –5, long-lasting enhanced amplitudes below 30 km
- ZWN-2 with $\omega = 1$ components: mixed structures of upward and downward propagation
  - Downward-propagating PW signals gradually descend from 0.1 hPa at Lag = –10 and reach 5–3 hPa at Lag = –5

Z' and EP fluxes by ZWN-2 with $\omega = 0$ and $\omega = 1$



- **shading**: Z'
- **Vector**: EP fluxes
- **Magenta contour**: zero refractive index (PW propagation condition)
- **Blue contour**: zero meridional PV gradient (baroclinic instability condition)

- The generation of the PWs by Z' of ZWN-2 and $\omega = 1$ in the USLM and their downward propagation into the mid-stratosphere (not by baroclinic instability)
- The amplitude of the downward-propagating $\omega = 1$ component of ZWN-2 PWs is approximately 10%–20% of the upward-propagating stationary ZWN-2 PWs → act as an additional (but not negligible) contributor to enhanced PWs of ZWN-2 during SSW09

Summary

- The role of GWs in the SSW event that occurred in January 2009 (SSW09) is investigated using the parameterized GWD provided by MERRA-2 reanalysis dataset.
- To examine the relationship between PWs and GWs, the nonconservative GWD (NCGWD) source term of the linearized QGPV equation (Z') is considered.
- Clear ZWN-2 patterns of Z' are found, especially in the USLM, prior to the onset of SSW09.
- To examine the characteristics of PWs generated by NCGWD forcing, a 2D Fourier wave decomposition is conducted on PWs to separate the upward- and downward-propagating components.
- During Lag = –13 to lag = 0, enhanced upward propagations of the ZWN-2 PWs from the troposphere to the stratosphere are found, which are mainly from the stationary component.
- On the other hand, downward-propagating PWs of ZWN-2 with $\omega = 1$ appear in the USLM around Lag = –10 and then gradually descend to the mid-stratosphere.
- The downward PWs in the ULSM are likely generated by the NCGWD forcing, given that the downward-propagating PWs are accompanied by the enhanced Z' in the USLM.
- The downward-propagating PWs have magnitudes of approximately 10%–20% of the upward-propagating stationary PWs, which contribute to the wave amplification near 5 hPa where the strongest enhancement of the ZWN-2 PWs occurred during the SSW09.

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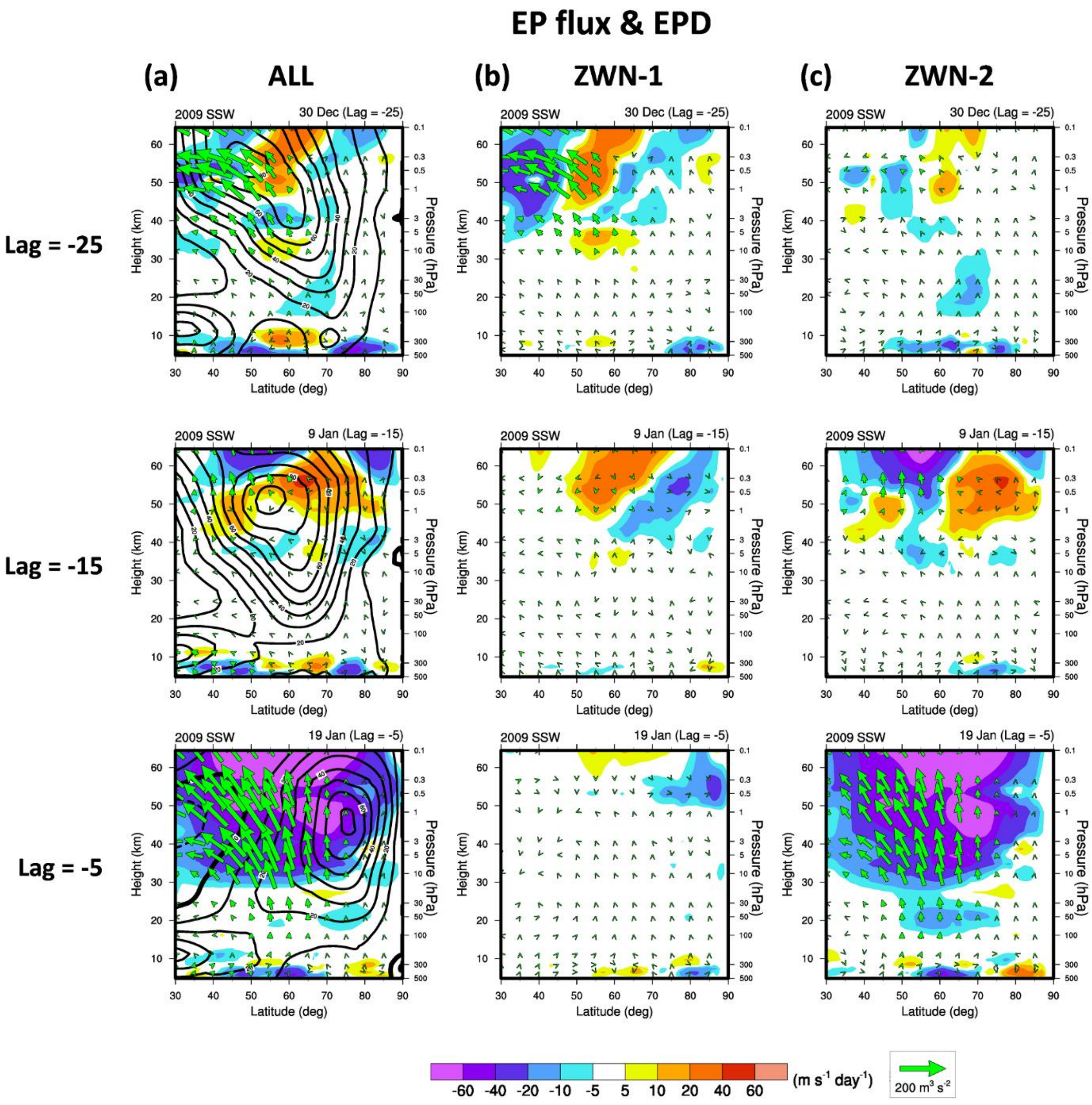
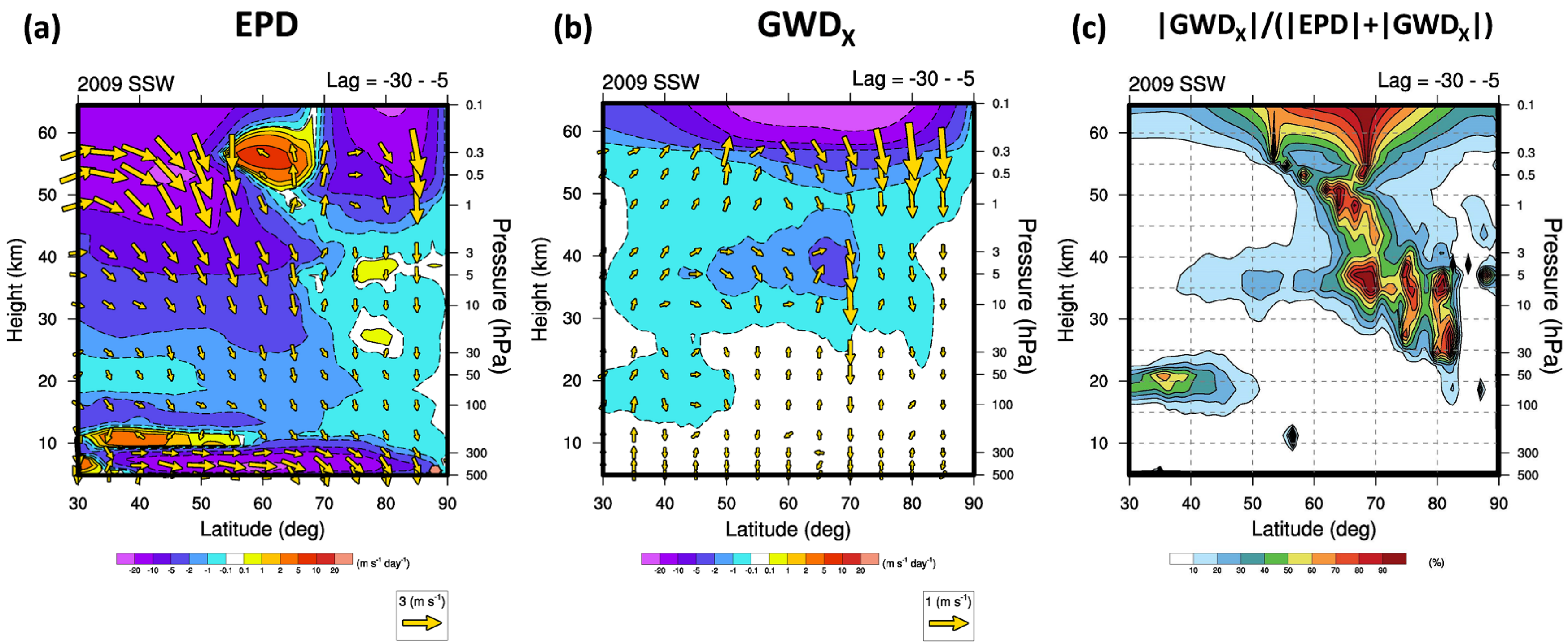
THANK YOU.

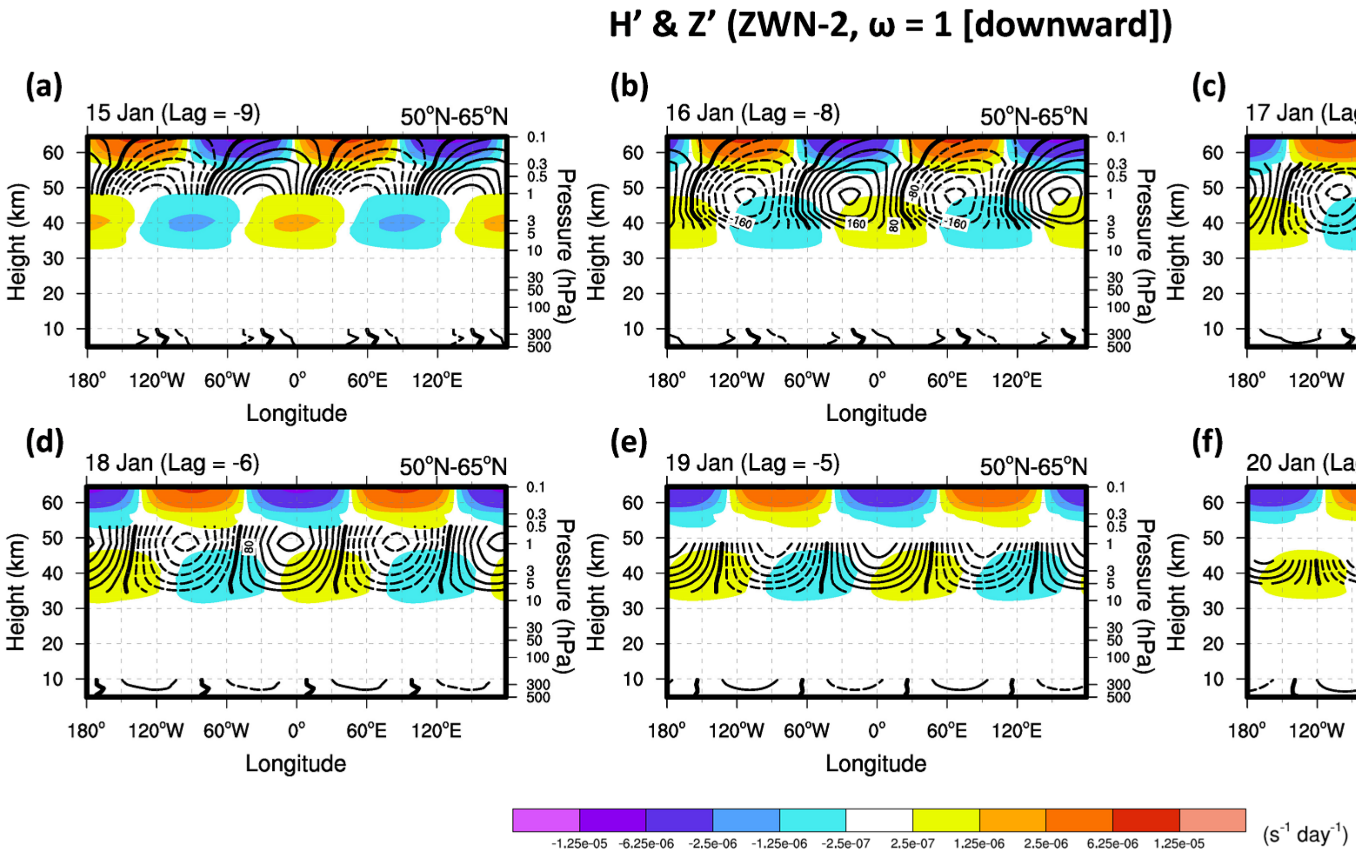
Lat.-height cross sections of the EP fluxes and EPD



Lat.-height cross sections of EPD and GWD



Lon.-height cross sections of H' and Z' of ZWN-2 and $\omega = 1$



PW generations: baroclinic instability vs NCGWD