Effects of the horizontal propagation and refraction of gravity waves on elevated stratopause after sudden stratospheric warming

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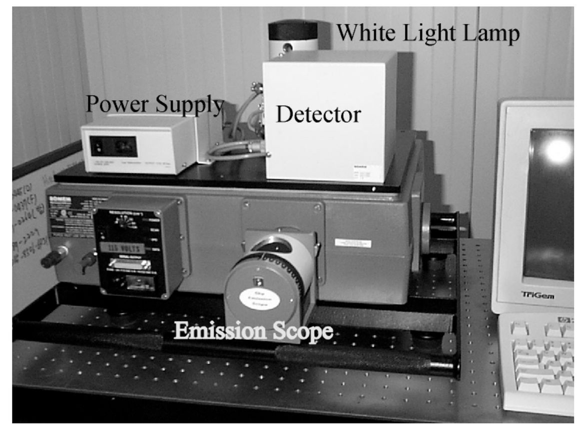
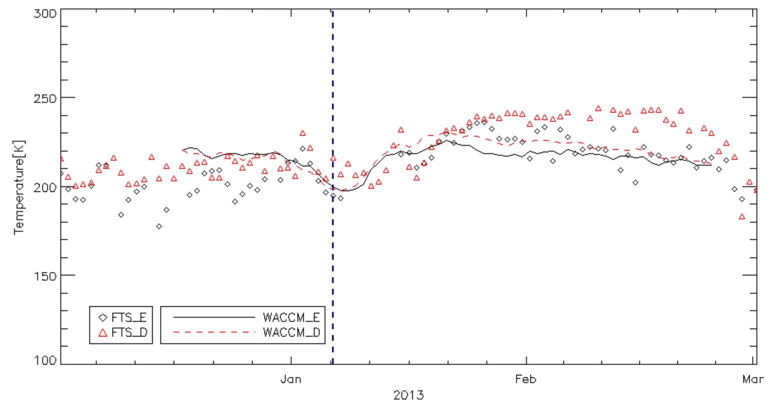
Introduction

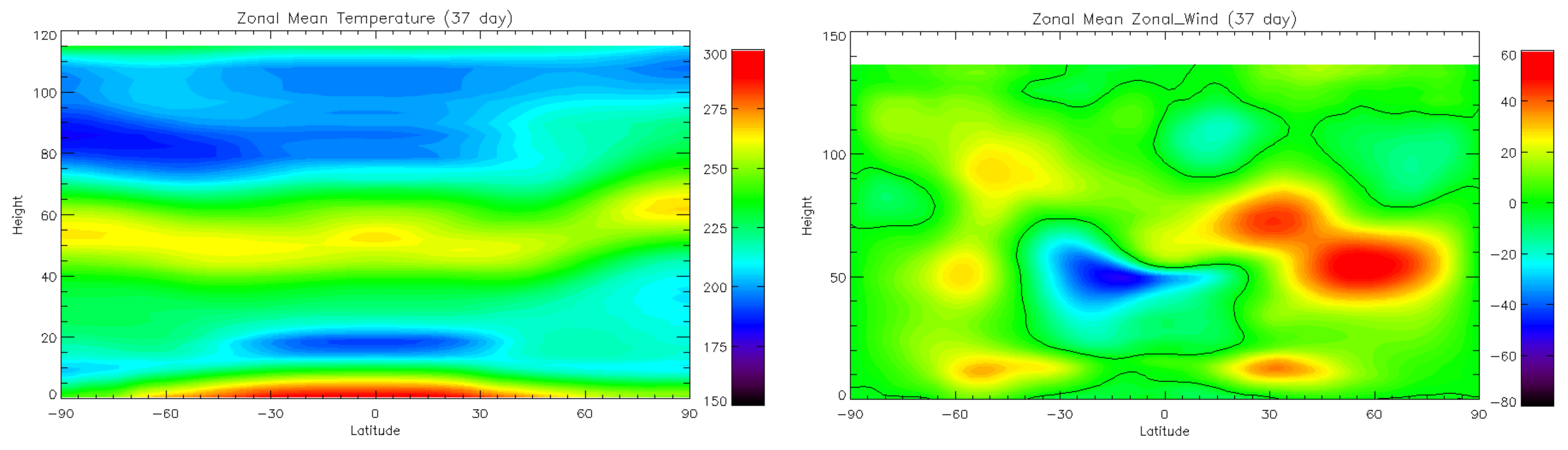


- The Fourier transform spectrometer observations have observed time evolutions of temperature near 87 km altitude in association with **elevated stratopause (ES)** after **major sudden stratospheric warming** (SSW) events.
- **ES-like phenomena simulated using global circulation models such as the WACCM are found to be much weaker compared with the FTS (and satellite) observations** especially in high latitude regions.
- Considering that gravity waves (GWs) may have substantial impacts in the evolution of the ES, **the discrepancy between observation and model may be attributed to unrealism in the propagation of parameterized GWs** (i.e., columnar propagation).
- In this study, we investigate **the effects of the horizontal propagation and refraction of GWs on the warming associated with the ES** after major SSW events using a ray-tracing model with specified GW spectra.

Observational and modeling results

- Fourier Transform Spectrometer (FTS) at Esrange (67°53'N, 21°04'E), Kiruna, Sweden and Korea Dasan station (78°55'N, 11°56'E), Ny-Alesund, Svalbard
- Daily mean temperature during winter of 2012/2013 at 87 km altitude from FTS and SC-WACCM composite for 29 split SSW events





Daily-averaged zonal mean temperature (left) and zonal wind (right) from WACCM composite of 29 split SSW cases on 37th day after the central dates of SSW events

Ray-tracing modeling

- Inetia-gravity waves in the anelastic airflow system
- 4D ray-tracing model in spherical geometry for the shallow atmosphere

$$\frac{d\lambda}{dt} = \frac{1}{a\cos\phi}\left[U + \frac{k}{\hat{\omega}\Delta}\left(N^2 - \hat{\omega}^2\right)\right] = \frac{c_{g\lambda}}{a\cos\phi}$$

$$\frac{d\phi}{dt} = \frac{1}{a}\left[V + \frac{l}{\hat{\omega}\Delta}\left(N^2 - \hat{\omega}^2\right)\right] = \frac{c_{g\phi}}{a}$$

$$\frac{dz}{dt} = -\frac{m}{\hat{\omega}\Delta}\left(\hat{\omega}^2 - f^2\right) = c_{gz}$$

$$\frac{dk}{dt} = -\frac{k}{a\cos\phi}\frac{\partial U}{\partial\lambda} - \frac{l}{a\cos\phi}\frac{\partial V}{\partial\lambda} - \frac{1}{2\hat{\omega}\Delta}\left[\frac{k^2+l^2}{a\cos\phi}\frac{\partial N^2}{\partial\lambda} - \frac{\hat{\omega}^2 - f^2}{a\cos\phi}\frac{\partial\alpha^2}{\partial\lambda}\right] + \frac{kc_{g\phi}\tan\phi}{a}$$

$$\frac{dl}{dt} = -\frac{k}{a}\frac{\partial U}{\partial\phi} - \frac{l}{a}\frac{\partial V}{\partial\phi} - \frac{1}{2\hat{\omega}\Delta}\left[\frac{k^2+l^2}{a}\frac{\partial N^2}{\partial\phi} + \frac{m^2+\alpha^2}{a}\frac{\partial f^2}{\partial\phi} - \frac{\hat{\omega}^2 - f^2}{a}\frac{\partial\alpha^2}{\partial\phi}\right] - \frac{kc_{g\lambda}\tan\phi}{a}$$

$$\frac{dm}{dt} = -k\frac{\partial U}{\partial z} - l\frac{\partial V}{\partial z} - \frac{1}{2\hat{\omega}\Delta}\left[\left(k^2+l^2\right)\frac{\partial N^2}{\partial z} - \left(\hat{\omega}^2 - f^2\right)\frac{\partial\alpha^2}{\partial z}\right]$$

$$\frac{d\omega}{dt} = k\frac{\partial U}{\partial t} + l\frac{\partial V}{\partial t} + \frac{1}{2\hat{\omega}\Delta}\left[\left(k^2+l^2\right)\frac{\partial N^2}{\partial t} - \left(\hat{\omega}^2 - f^2\right)\frac{\partial\alpha^2}{\partial t}\right]$$

$$\frac{dF}{dt} = 0 \qquad F = c_{gz}A$$

Constraint for invariance of horizontal wavenumber with respect to curvature effects

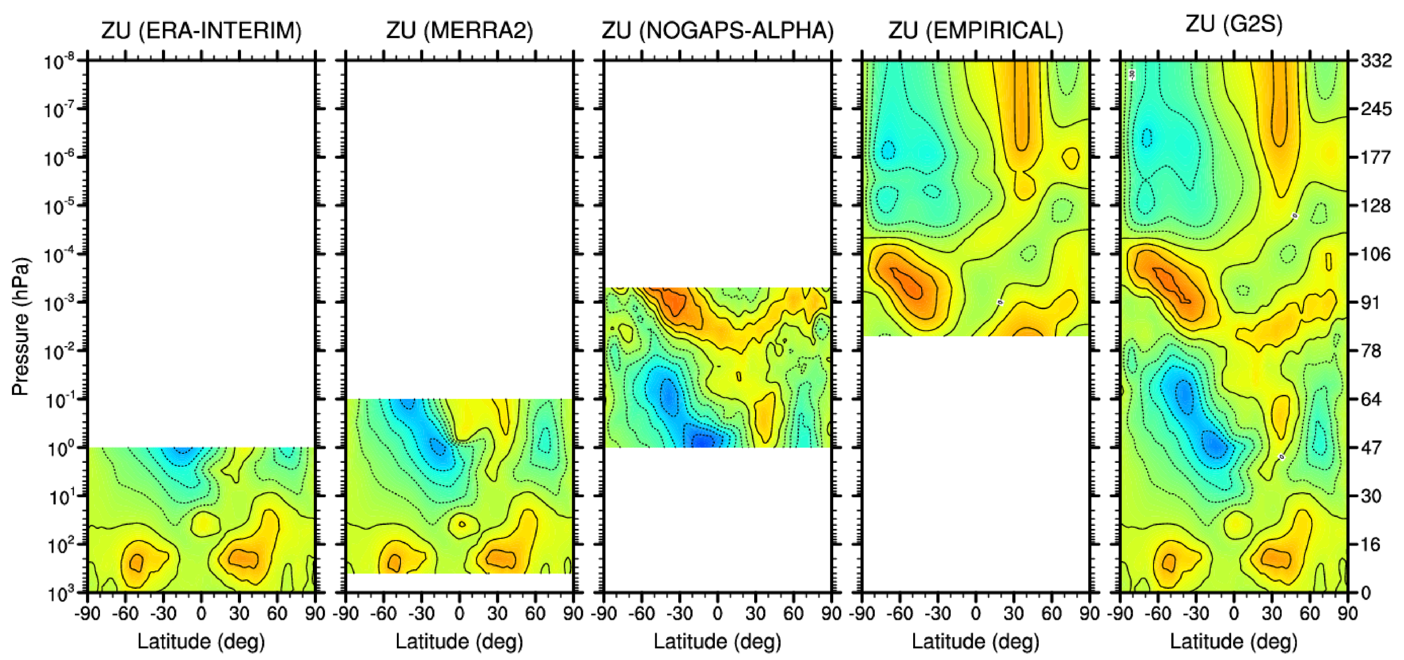
$$lc_{g\lambda}\tan\phi = kc_{g\phi}\tan\phi$$

Wave saturation based on vertical displacement

$$\zeta \le \zeta_{sat} = \frac{F_c N}{|m|\hat{\omega}}\sqrt{\frac{\hat{\omega}^2 - f^2}{\rho_0\left(N^2 - \hat{\omega}^2\right)}}$$

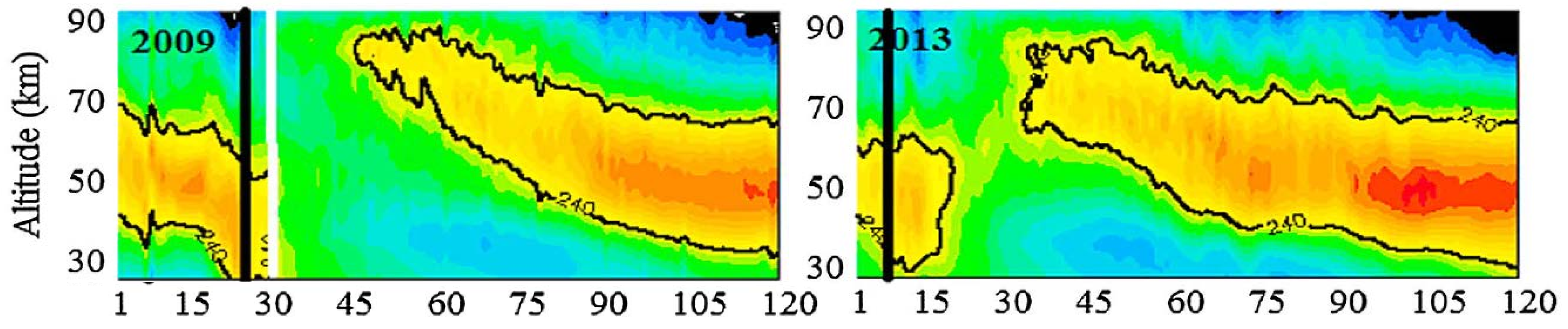
Specification of the whole atmosphere

- Vertical 3rd-order spline fit to reanalysis and empirical model results
- Hourly whole atmospheric data (interpolated from 6-hourly data)
- 2009 and 2013 SSW events
  - ERA-Interim (ground – 1 hPa), MERRA2 (400 – 0.1 hPa), HWM14 and NRLMSISE (0.005 hPa – space)
- NOGAPS-alpha (1 – 0.0005 hPa) for 2009 and UKMO (1 – 0.01 hPa) for 2013



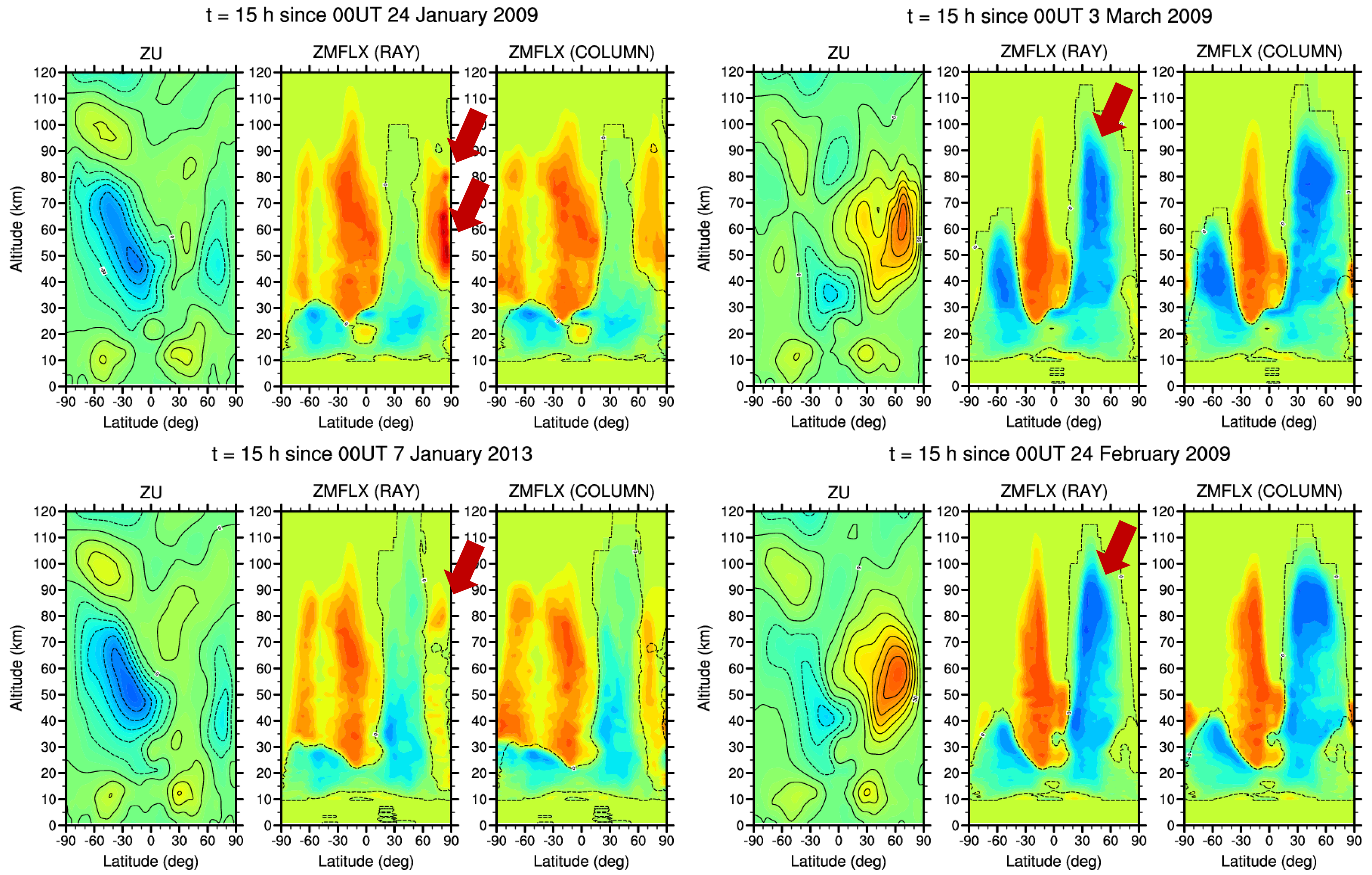
Results

- 2009 major SSW events (Central date : 24 January), ES event (3 March)
- 2013 major SSW events (Central date : 7 January), ES event (14 February)
- GW ray ensemble (Senf and Achatz 2011) are launched at 10 km altitude every 1 hour



SOFIE zonal-mean temperature observations (Thurairajah et al. 2014)

- Zonally-averaged zonal GW (pseudo)momentum fluxes



- SSW events (left) : GWs with eastward momentum fluxes refracted or propagated from other regions toward NH polar mesosphere and stratosphere for RAY cases
- ES events (right) : GWs with smaller westward momentum fluxes for RAY cases

Acknowledgement: This work was supported by the Korea Polar Research Institute (PE17020 and PE17130).