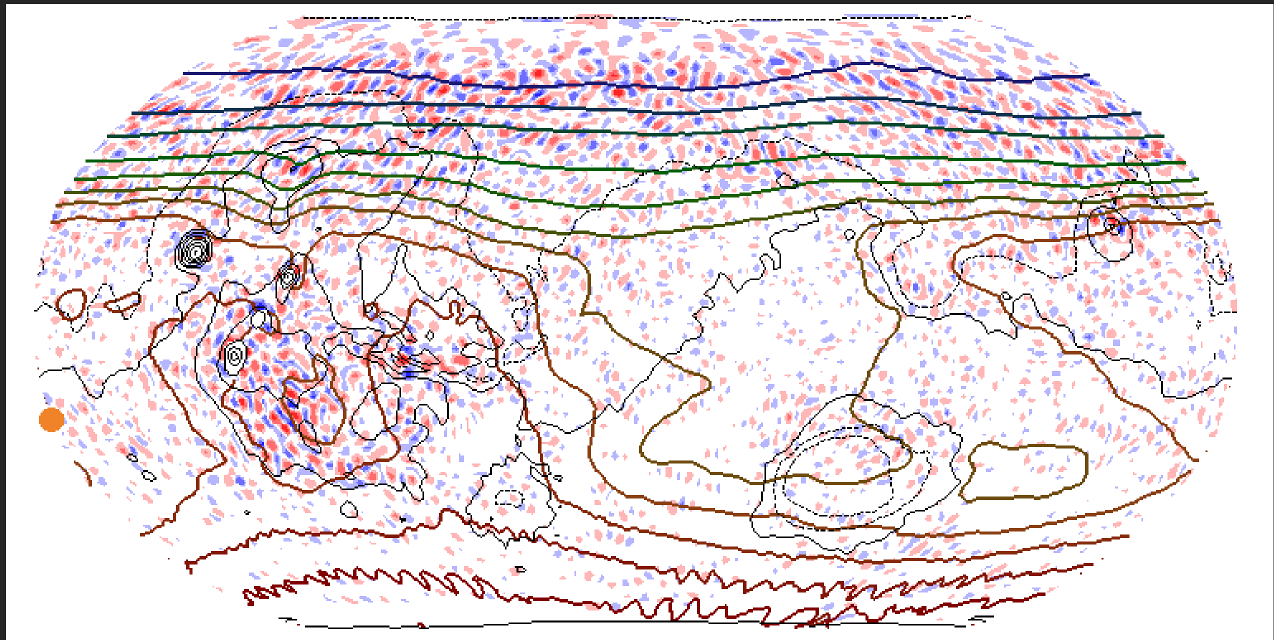
惑星圏研究会, 2016/2/24, 東北大学

Study of the gravity waves on Martian atmosphere using a high-resolution Mars General Circulation Model



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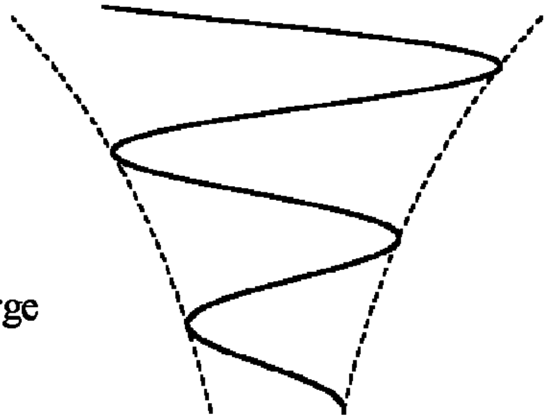
What is the gravity waves (GWs)？

Small scale (wavelength of less than ~2000km), short period (less than ~1 day)

- Restoring force is a buoyancy.
- Possible sources are the topography, convection, dynamical instability of the flow, etc.
- Waves break in upper atmosphere and affect the atmospheric fields.



- Wave amplitudes grow to maintain constant energy $E = \frac{1}{2}\rho_o u'^2$
- Wave amplitude becomes too large and wave breaks.
- Wave momentum deposited.
- Force exerted on atmosphere ("wave drag")
- Drives a meridional (NS) circulation.

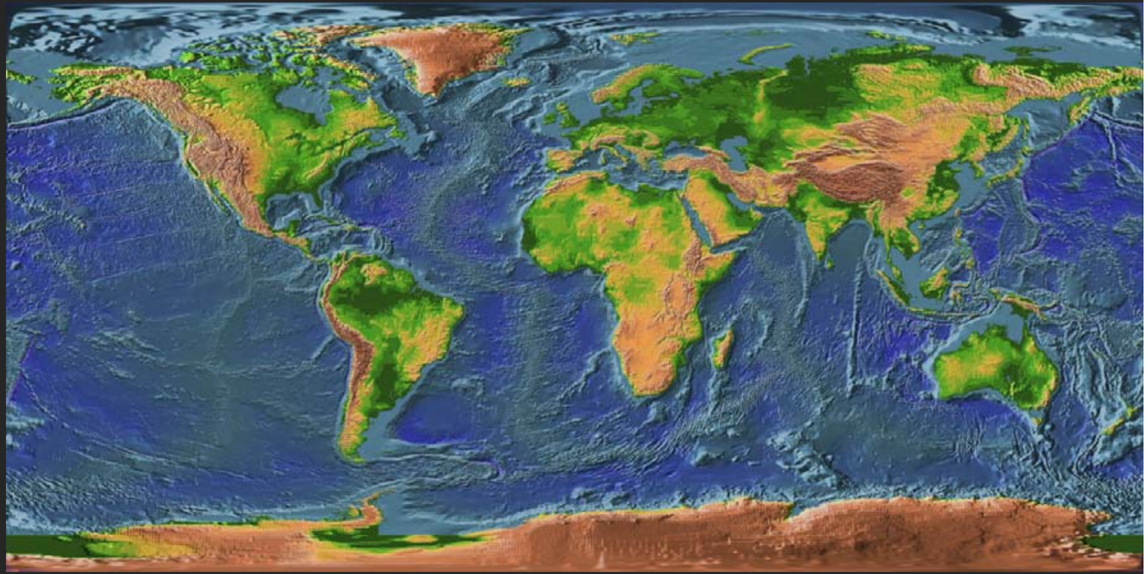
$$\frac{\partial \bar{u}}{\partial t} - f\bar{v} = -\frac{1}{\rho_o}\frac{\partial(\rho_o \overline{u'w'})}{\partial z}$$

$$\bar{v} = \frac{1}{\rho_o f}\frac{\partial(\rho_o \overline{u'w'})}{\partial z}$$

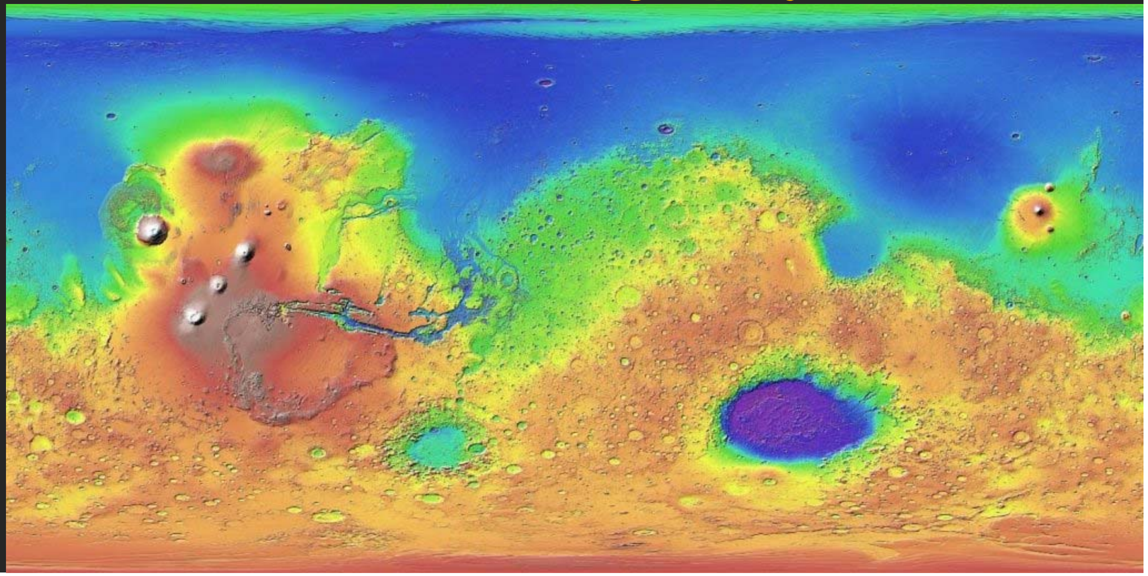
GWs on Mars: expectations

- Atmosphere of Mars is mostly convectively stable (as on Earth) to support gravity wave existence.
- Mars has very rough topography, which is expected to be the significant source of GW generations.
- Convective activities are also possible sources of GWs [Imamura et al., 2016].

Earth topography



Mars topography



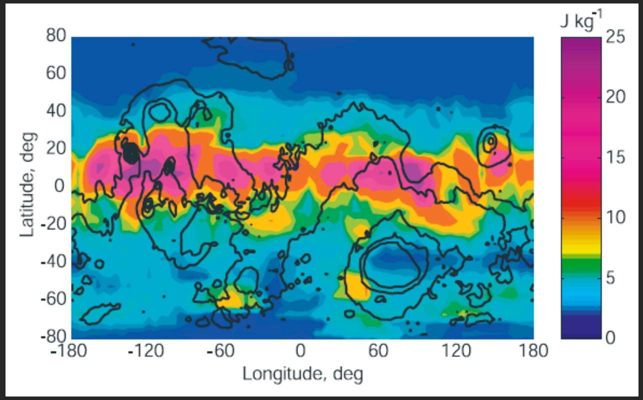
GWs on Mars: from data analyses

Creasey et al. [2006a], GRL 33, L01803

- Using the MGS radio-occultation data (from surface up to ~40 km)
- The observed data did not correlate well with the orographic forcings, suggesting that wave sources other than orography should play an important role on Mars.

GW potential
energy per unit mass

$$E_p = \frac{1}{2}\left(\frac{g}{N}\right)^2 \overline{\left(\frac{T'}{T_0}\right)^2}$$



Creasey et al. [2006b], GRL 33, L22814

- Using the MGS accelerometer data (thermosphere)
- The typical horizontal wavelengths of GWs were 100-300 km.

Fritts et al. [2006], JGR 111, A12304

- Using the density data obtained in the aerobraking of MGS and Mars Odyssey (95-130 km height)
- Estimated the momentary acceleration rates of GWs on the wind fields.

GWs on Mars: from data analyses

Heavens et al. [2010], Icarus 208, 574-589

- Using the MCS temperature data (from surface up to ~80 km)
- Found the existence of convective instability above the winter polar warming.

Ando et al. [2012], JAS 69, 2906-2912

- Using the MGS radio-occultation data (from surface up to ~40km)
- A decline of the spectral density with wavenumber is seen in the similar way as terrestrial stratosphere/mesosphere.
- The saturation tend to occur only in lower latitudes.

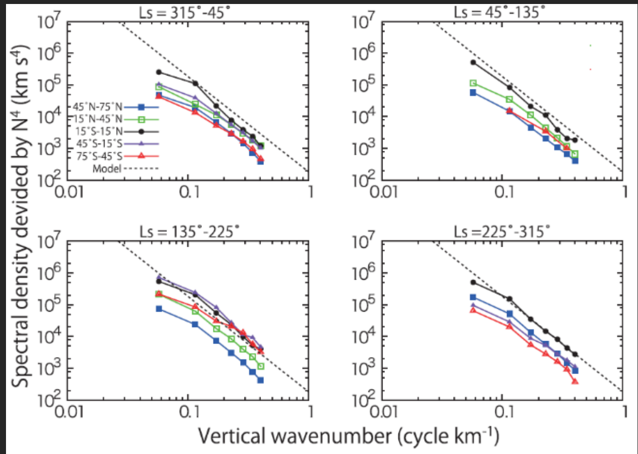
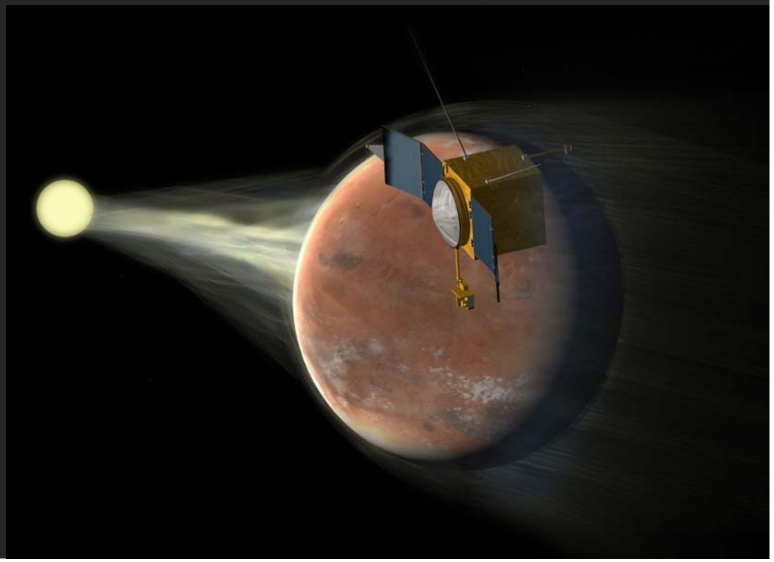


FIG. 4. As in Fig. 3, but in the altitude range 15–32 km.



Now, study of the features in thermosphere with the MAVEN mission (IUVS, NGIMS) is ongoing.

GWs on Mars: GCM simulations

Works with MPI-MGCM

Horizontal resolution of T21 (grid interval of ~333 km), from surface up to ~150km altitude

Medvedev et al. [2011a], Icarus 211, 909-912 (adopt to MCD)

Medvedev et al. [2011b], JGR 116, E10004 (dynamical effects)

Medvedev and Yiğit [2012], GRL 39, L05201 (thermal effects)

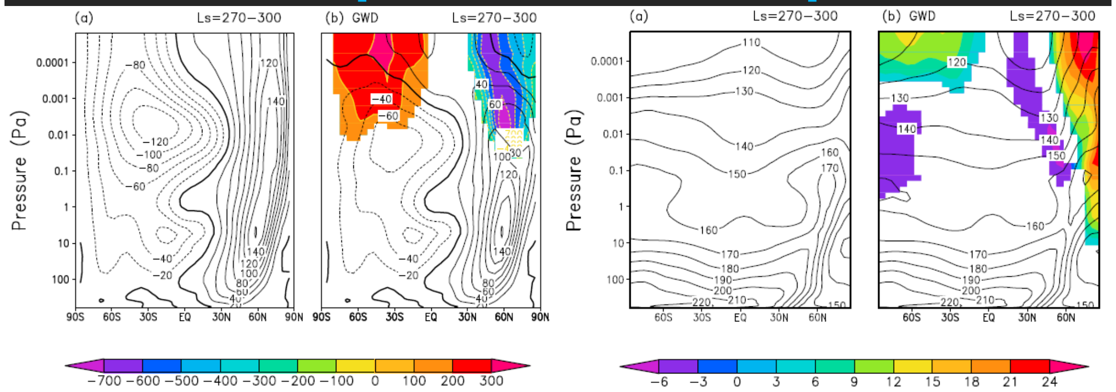
Medvedev et al. [2013], JGR 118, 2234-2246 (effects of dust storms)

Yiğit et al. [2015], GRL 42, 4294-4300 (mesospheric CO_2 ice clouds)

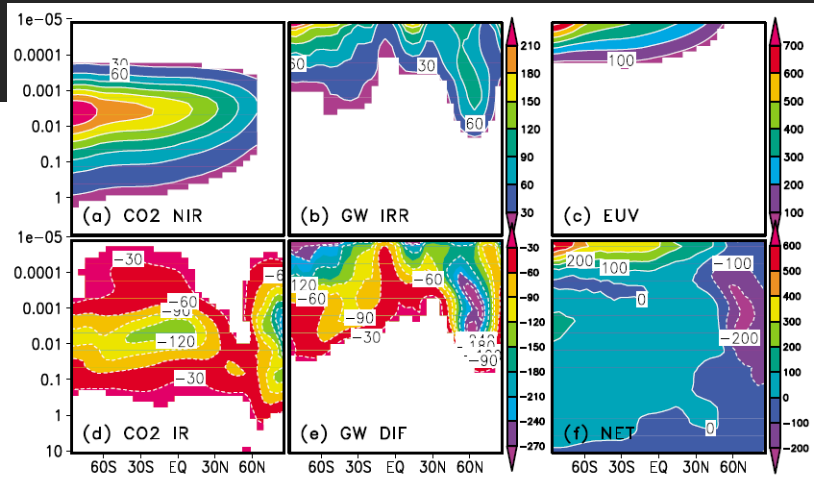
Medvedev et al. [2015], JGR 120, 913-927 (comparison with LMD model)

- GW drag (based on the **terrestrial parameterization**, Yiğit et al., 2008) significantly changes wind velocity and temperature (thermal effects correspond to the CO_2 radiative effects), and essential for the mesospheric CO_2 ice cloud formation (following Spiga et al., 2012) .

[Medvedev et al., 2011b]



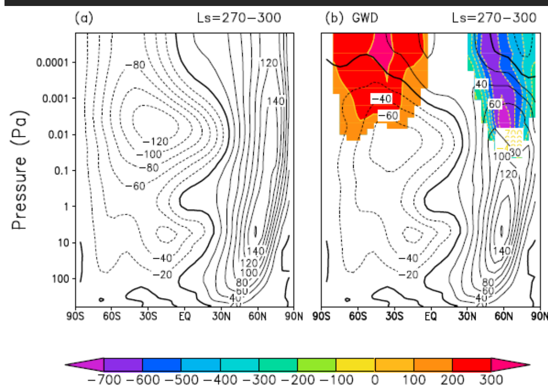
[Medvedev and Yiğit, 2012]

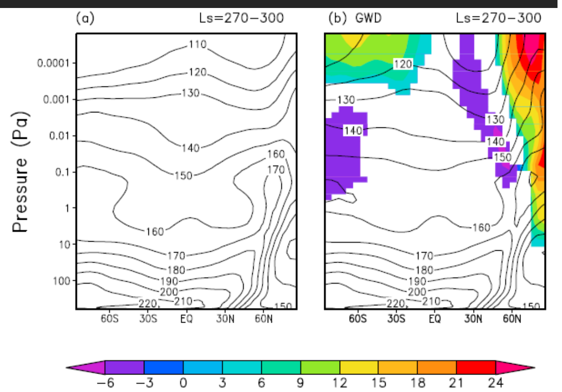


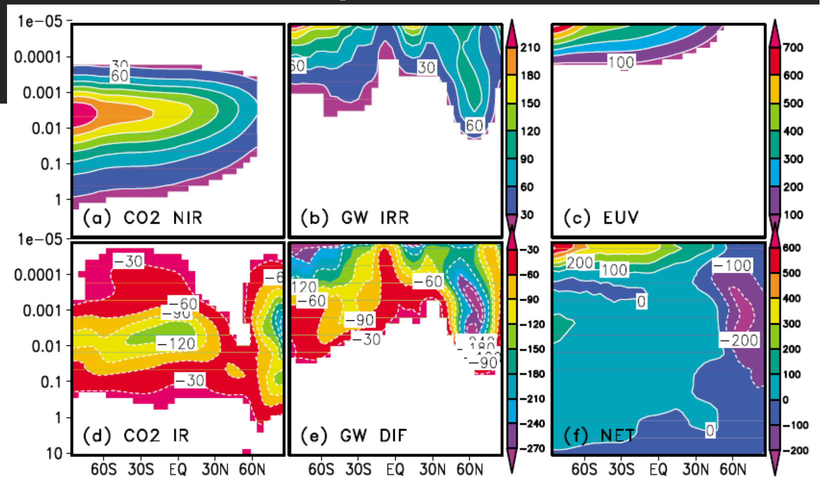
GWs on Mars: significances

Indications from the GCM studies

- The effects of GWs on the Martian atmospheric temperature and wind fields are small below ~60km.
- But, above ~60km, the accurate evaluation of the effects of GWs is important to reproduce the observed atmospheric fields.
- Dynamical forcing of GWs significantly change the wind speed in upper atmosphere (above ~100km), and even reverse the wind direction.
- Thermal forcing of GWs can be the main source of cooling above ~120km, reproducing the consistent temperature with the observations.





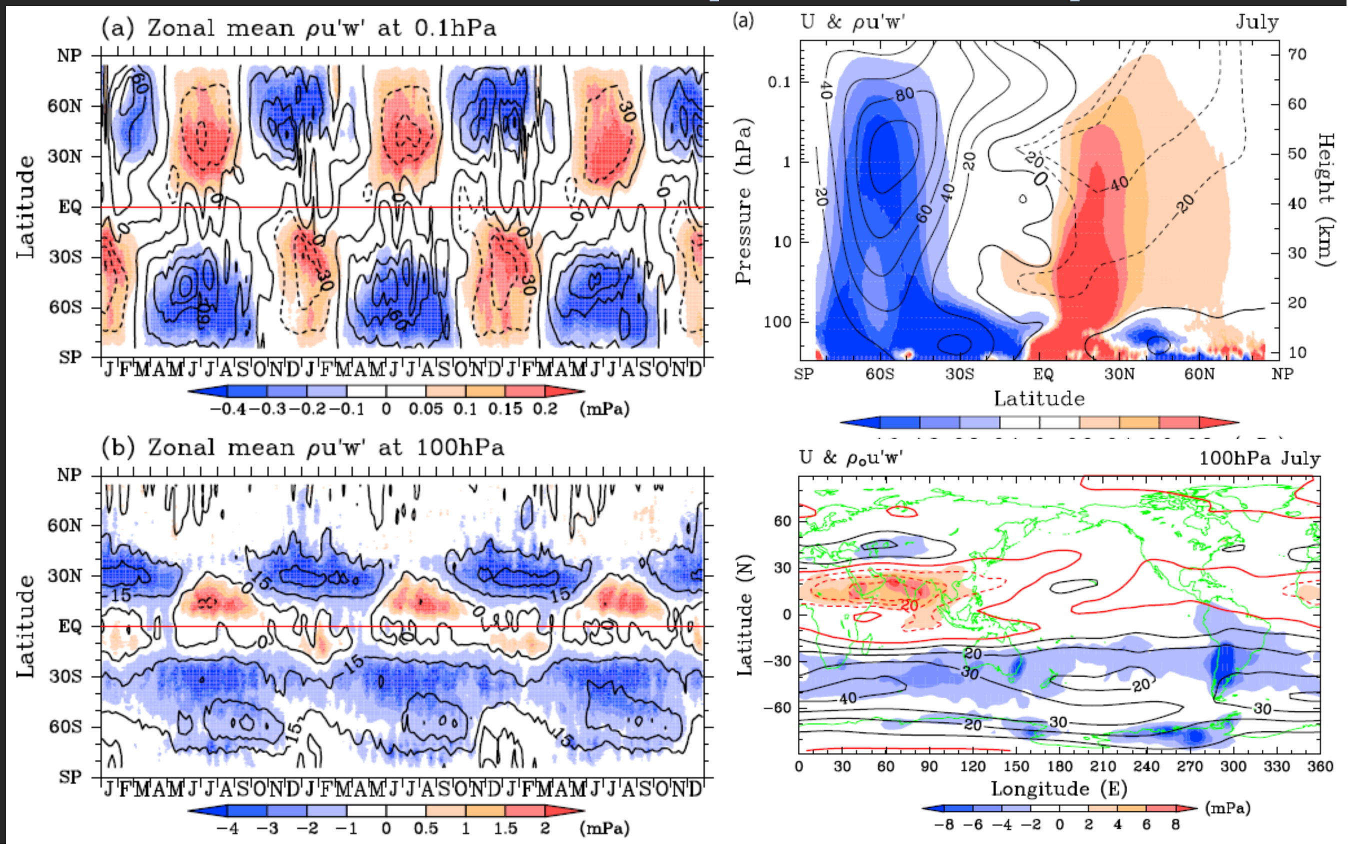


But we don't know that the parameterization would be realistic also on Mars...

→What about a trial with a high-resolution MGCM without parameterization?

Seasonal/vertical/horizontal distributions of momentum flux with a high-resolution (T213L256) terrestrial GCM [Sato et al., 2009]

The application on the Earth already exists…



DRAMATIC MGCM (T106)

DRAMATIC = Dynamics, **RA**diation, **MA**terial **T**ransport and their mutual **I**ntera**C**tions [Kuroda et al., 2005, 2013]

High horizontal resolution coordinate

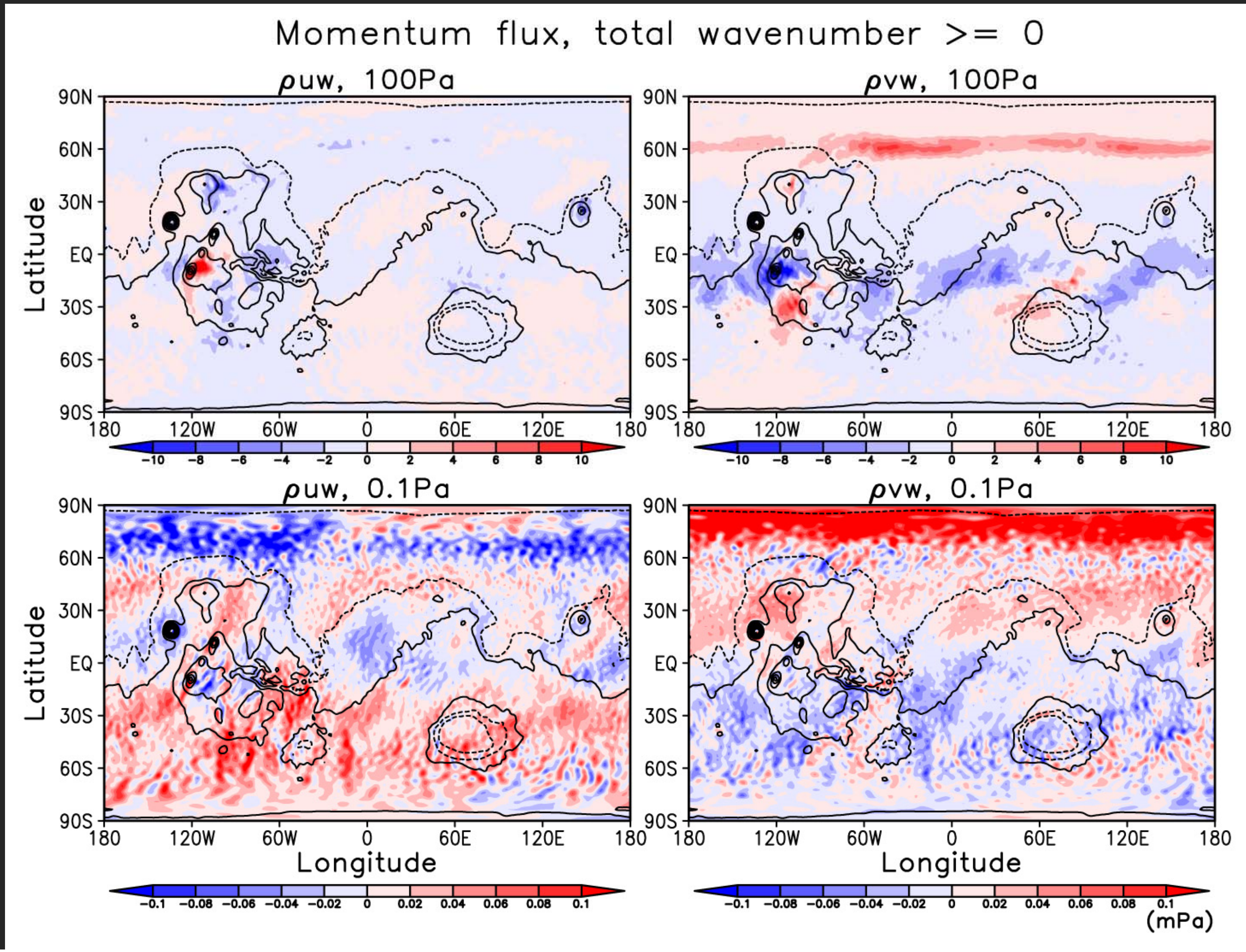
Dynamical core	CCSR/NIES/FRCGC AGCM 5.7b (MIROC 5.0) 3-dimensional primitive equations, spectral solver
Resolutions	**Horizontal resolution of ~1.1° × 1.1° (T106)** **(grid interval of ~60km at the equator)** 49 layers with σ levels, the model top is at ~90km.
Radiation	CO_2: Absorption and emission in the infrared wavelength (15μm, 4.3μm) and near-infrared solar absorption (only LTE effects) Dust: Absorption, emission and scattering in 0.2-200μm
Tracers	H_2O/HDO vapor and ice, CO_2 ice
Surface	Realistic topography, albedo, thermal inertia and roughness, deposition of CO_2 and H_2O/HDO ice

Now the waves with λ>~200km can be resolved!

DRAMATIC MGCM (T106)

Simulated for 20 Sols around Ls=270°, globally constant dust opacity of ~0.5

Momemtum flux ($\overline{\rho u'w'}$ and $\overline{\rho v'w'}$) for all eddies

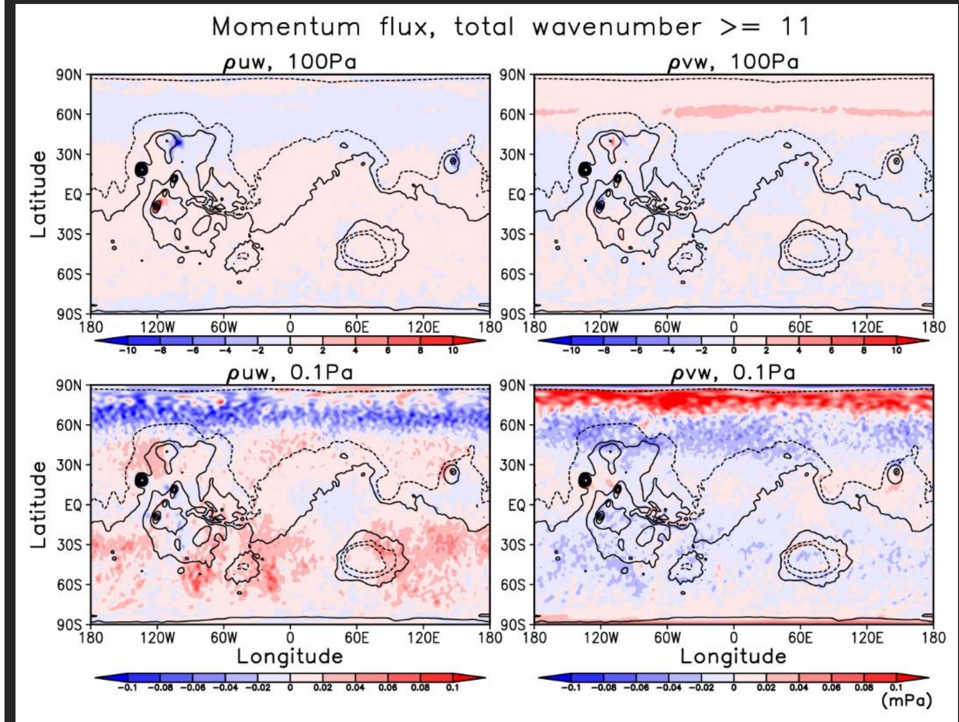


DRAMATIC MGCM (T106)

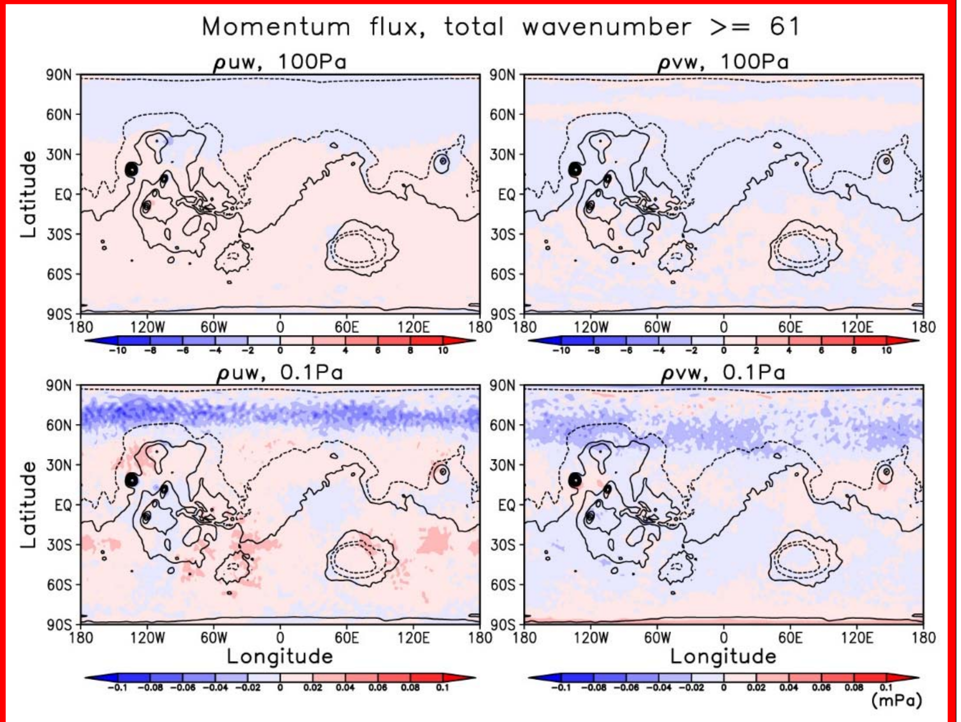
Simulated for 20 Sols around Ls=270°, globally constant dust opacity of ~0.5

$\rho\overline{u'w'}$ and $\rho\overline{v'w'}$ of smaller-scale disturbances

total wavenumber ≥ 11
(λ < ~2000km)



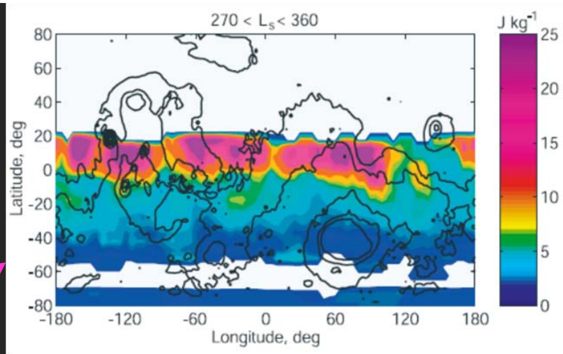
total wavenumber ≥ 61
(λ < ~300km: the most favorable wavelength to propagate to thermosphere)

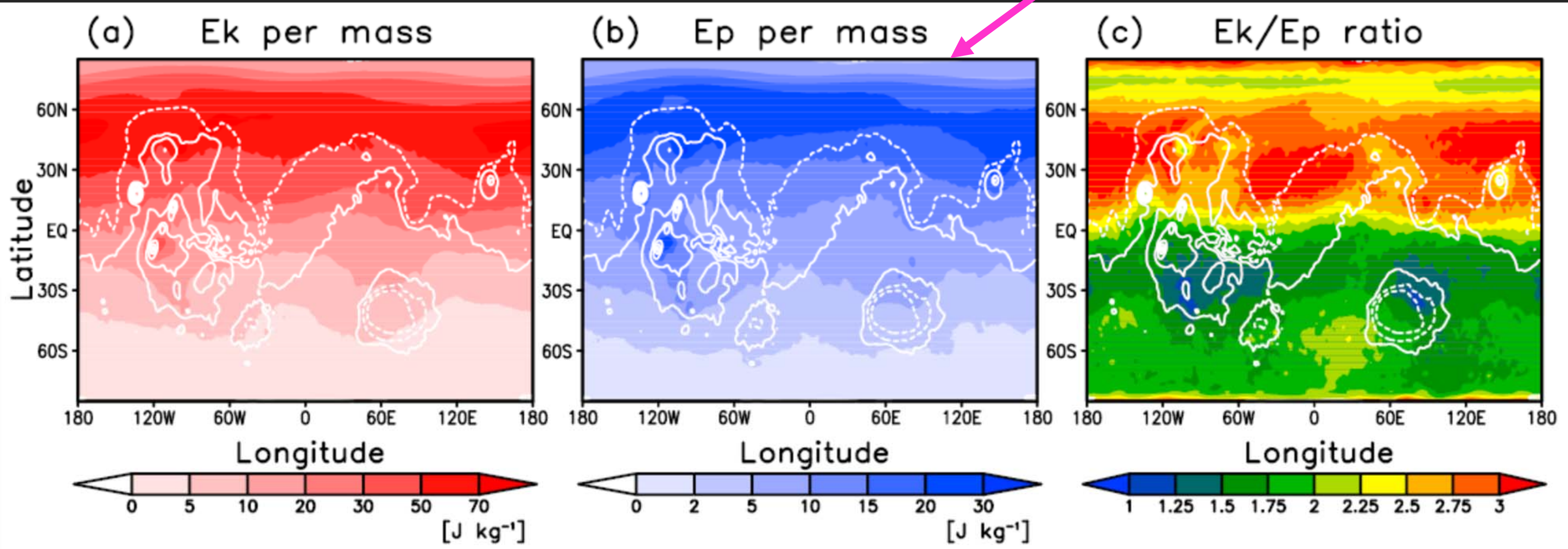


Hereafter analyze the features of GWs with this scale ↑
(for only this season: northern winter solstice)

Kinetic and potential energy (comparison with Creasey et al., 2006a)

- E_p distribution is qualitatively & quantitatively consistent with observation.





Kinetic energy

$$E_k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$$

Potential energy

$$E_p = \frac{1}{2}\left(\frac{g}{N}\right)^2 \overline{\left(\frac{T'}{T_0}\right)^2}$$

(per unit mass)

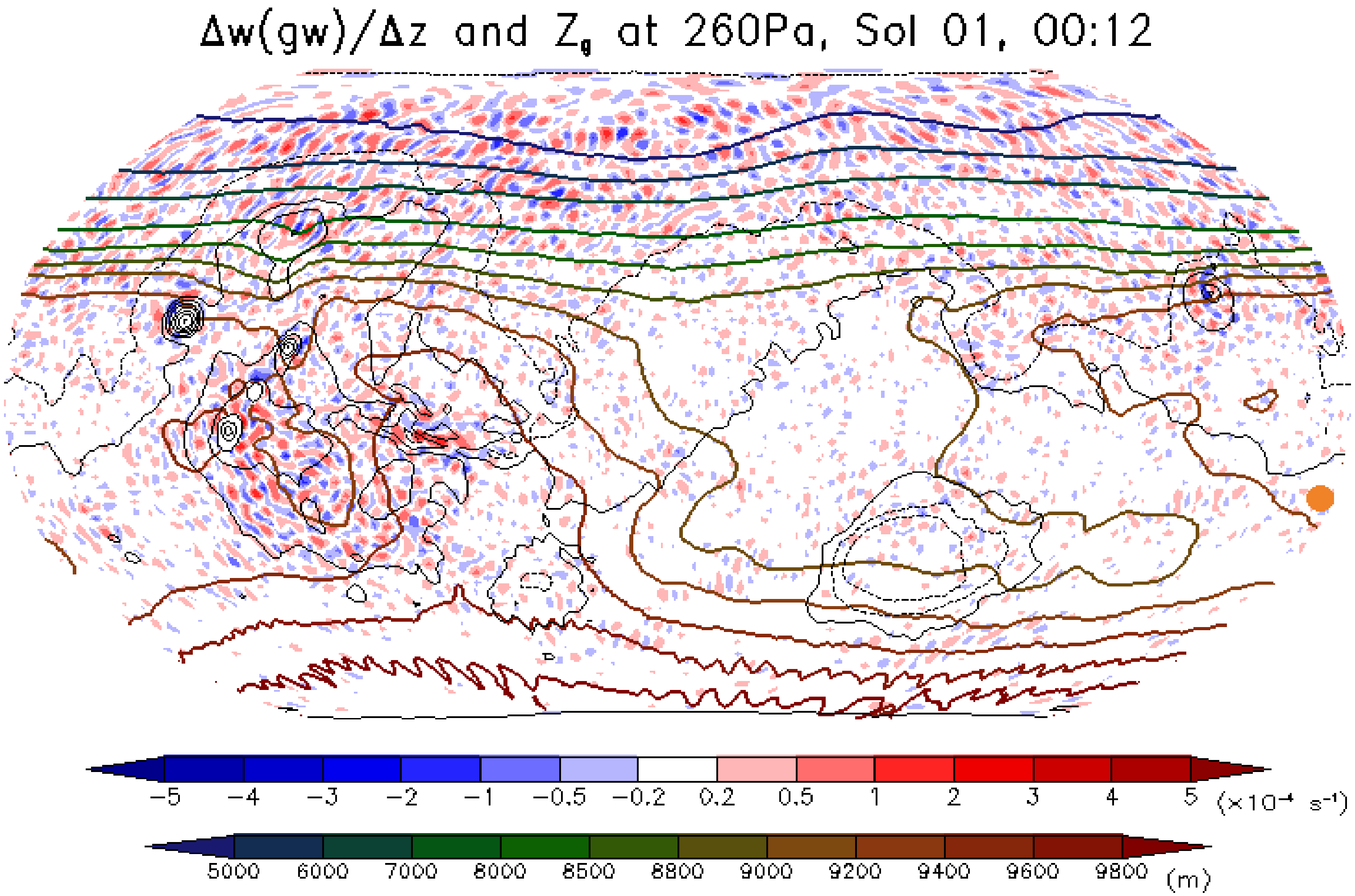
$$\frac{E_k}{E_p} = \frac{1 + \left(\frac{f}{\hat{\omega}}\right)^2}{1 - \left(\frac{f}{\hat{\omega}}\right)^2}$$

$\hat{\omega}$: intrinsic frequency (small → small c - $\bar{u}$)

- Large E_k/E_p in northern hemisphere, showing the GWs are generated in the winter polar jet (small c - $\bar{u}$).
- Small E_k/E_p in southern hemisphere, especially mountain regions, showing the GWs are generated from topography (large c - $\bar{u}$).

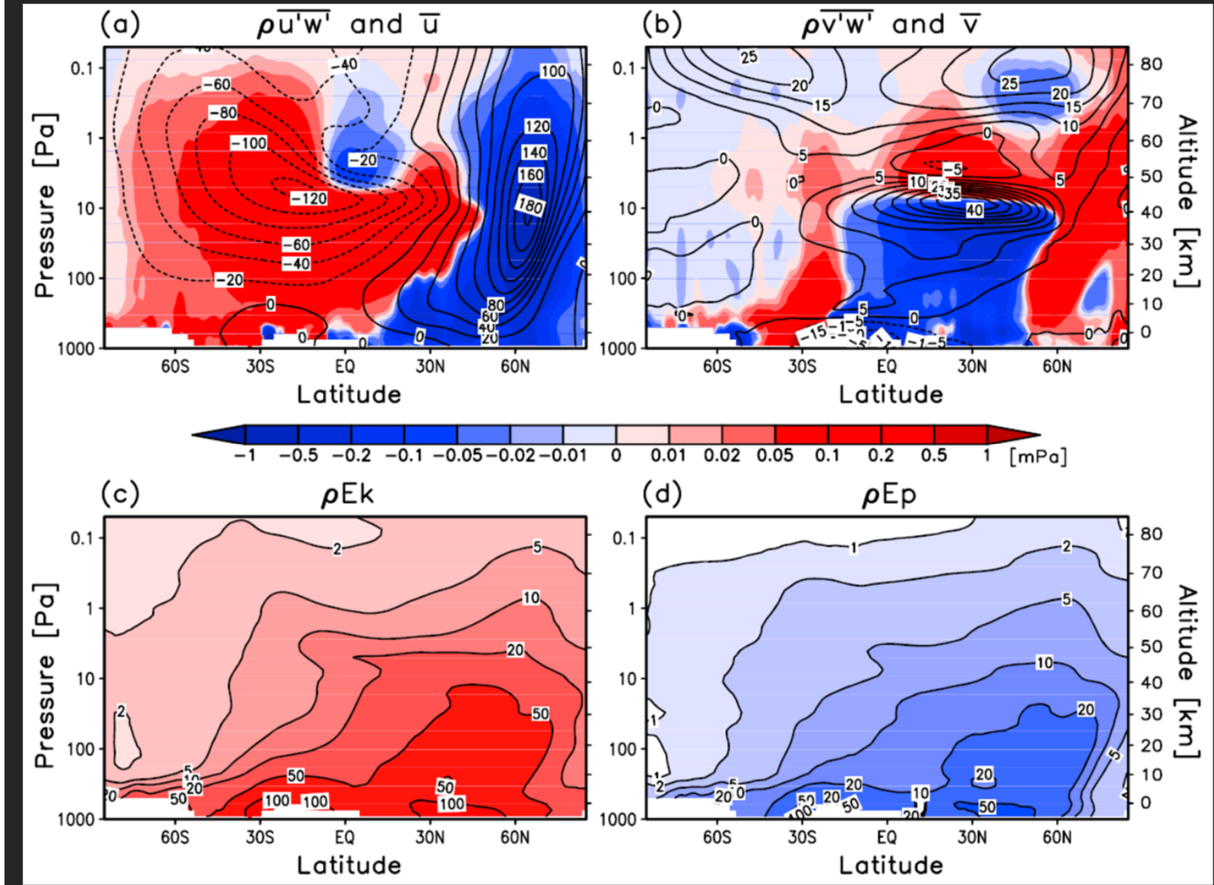
Generation of GWs

Wind divergence (shade) and geopotential height (contour)

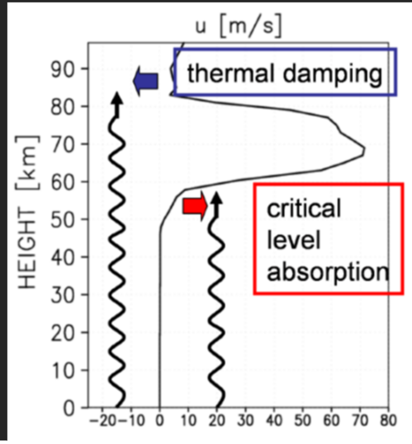


Vertical propagation

Momentum flux and energy



- Zonal/meridional momentum fluxes propagate in principle to lag the flow, but the direction can change with dissipation/filtering of specific harmonics.
- GWs penetrate higher in the winter hemisphere, because of asymmetry of sources in lower and some other possibilities (propagation in horizontal direction is not clear…)

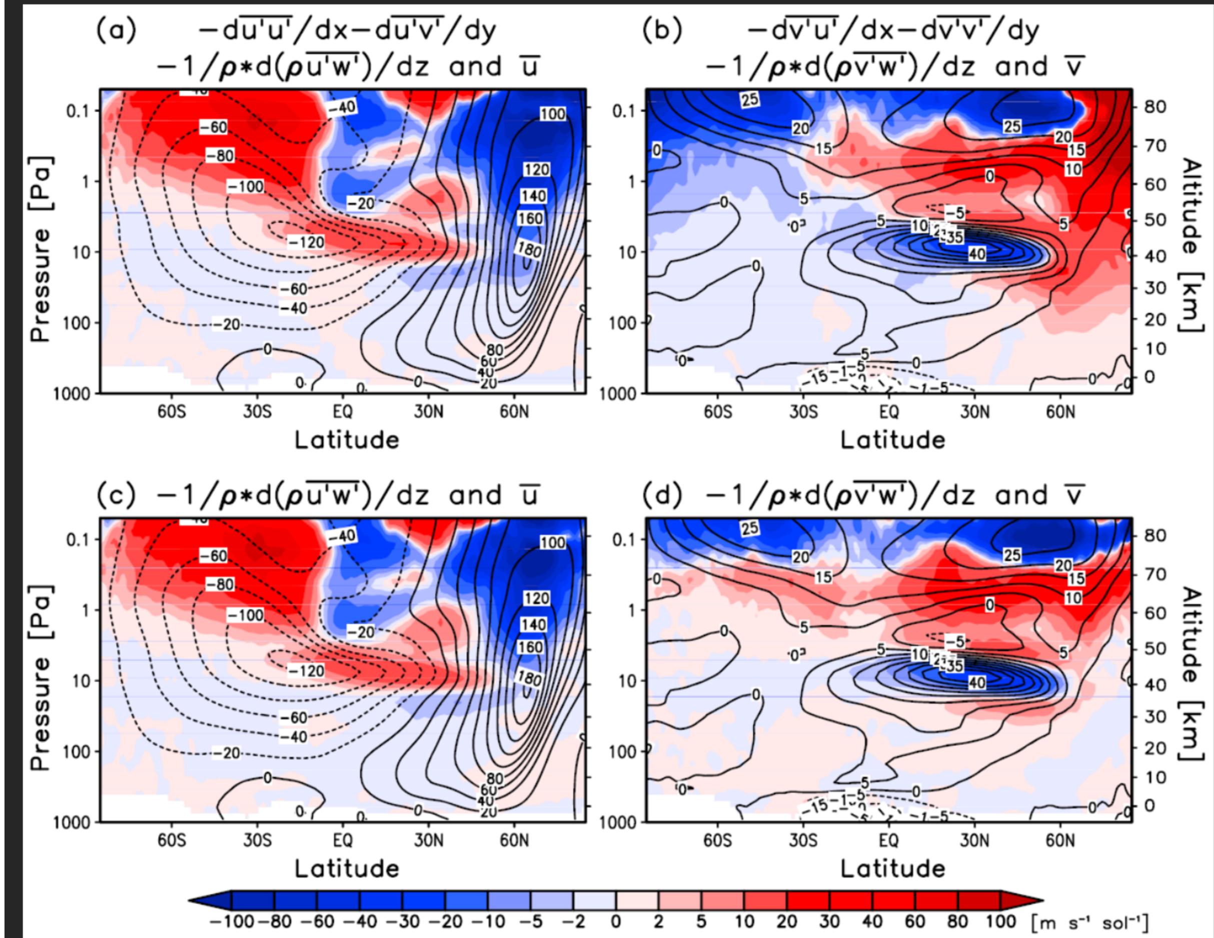


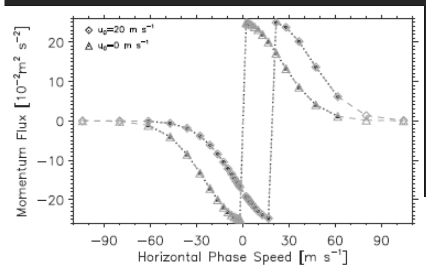
Vertical propagation

$$a_x = -\frac{\partial}{\partial x}\overline{u'u'} - \frac{\partial}{\partial y}\overline{u'v'} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{u'w'})$$

$$a_y = -\frac{\partial}{\partial x}\overline{v'u'} - \frac{\partial}{\partial y}\overline{v'v'} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{v'w'})$$

Wind acceleration rate





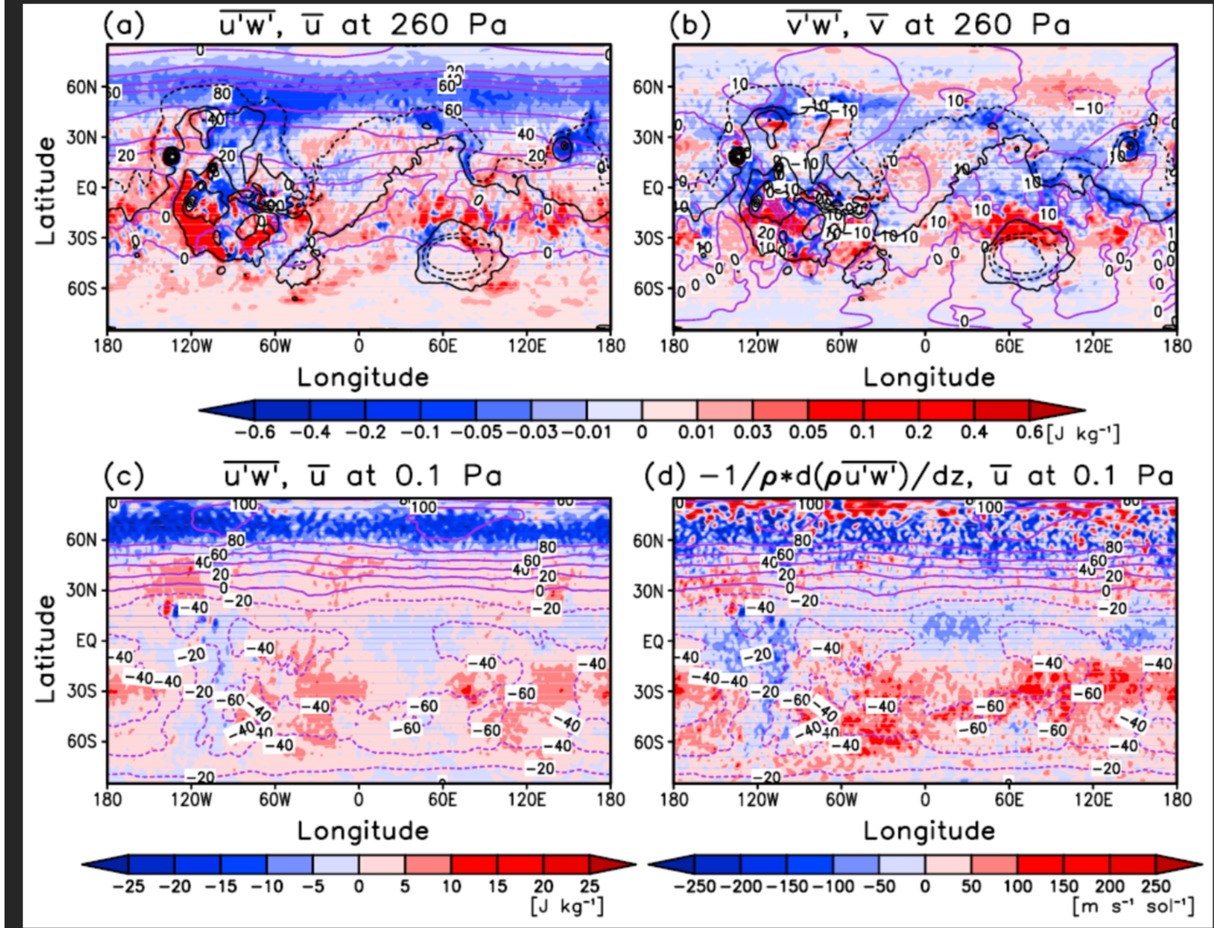
GW drag parameterization [Medvedev et al., 2011b]

$$\overline{u'w'} = \mathrm{sgn}(c_i - \bar{u}_0)\overline{u'w'}_{max}\exp\left[-(c_i - \bar{u}_0)^2/c_w^2\right]$$

- The acceleration rates simulated in this model are comparable to those obtained from a GW drag parameterization [Yiğit et al., 2008; Medvedev et al., 2011a, 2011b].
- Clear relation is seen between wave dissipation and wind acceleration (~10Pa around equator).
- Effects of horizontal propagation on the acceleration are much smaller than those of vertical propagation.

Horizontal distribution of wave fluxes

Momentum fluxes and acceleration rate at 260 and 0.1 Pa



Note that these plots represent 20-sols averaged values!

- In low latitudes, sources are extremely localized both in space and time. (especially clear shapes along with the mountains are seen, even at much-smoother 0.1Pa)
- In northern mid-and high-latitudes, the distribution of the zonal flux is significantly smoother. (associated with the winter westerly jet, Kelvin waves)
- A high degree of horizontal inhomogeneity is seen in the acceleration rates of upper atmosphere.

Summary

- The GW sources and conditions of propagation to the upper atmosphere are demonstrated with a high-resolution (T106) Mars GCM, for Ls=270.
- Simulated potential energy of GWs is in a good agreement with the observed feature [Creasey et al., 2006a].
- Sources of GWs are the topography (in low latitudes) and winter westerly jet (in northern mid- and high-latitudes): especially the effects of mountains are clearly seen!
- Most of GWs are produced in the lower atmosphere, and their fluxes and energy decay with height.
- GWs surely affect the wind fields of thermosphere significantly: first demonstrations without the parameterization!

Future work

- Investigation of seasonal dependences of GW generation/ propagation features

Paper published (GRL 42, 9213-9222)

A global view of gravity waves in the Martian atmosphere inferred from a high-resolution general circulation model

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Abstract Global characteristics of the small-scale gravity wave (GW) field in the Martian atmosphere obtained from a high-resolution general circulation model (GCM) are presented for the first time. The simulated GW-induced temperature variances are in a good agreement with available radio occultation data in the lower atmosphere between 10 and 30 km. The model reveals a latitudinal asymmetry with stronger wave generation in the winter hemisphere and two distinctive sources of GWs: mountainous regions and the meandering winter polar jet. Orographic GWs are filtered, while propagating upward, and the mesosphere is primarily dominated by harmonics with faster horizontal phase velocities. Wave fluxes are directed mainly against the local wind. GW dissipation in the upper mesosphere generates body forces of tens of m s^{-1} per Martian solar day (sol^{-1}), which tend to close the simulated jets. The results represent a realistic surrogate for missing observations, which can be used for constraining GW parameterizations and validating GCM simulations.