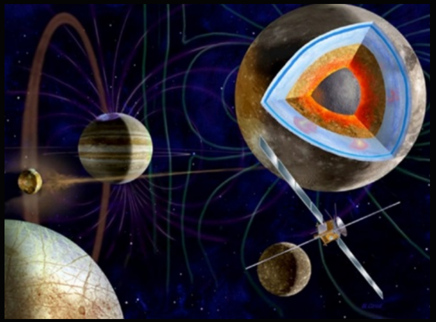
01/06/2015 at Nara Women's University

# Overview of atmospheric dynamics in Jupiter's stratosphere


**Takeshi Kuroda**

*Tohoku University*


# Planned observations of Jupiter's atmosphere by JUICE-SWI (Sub-Millimetre Instrument)



- PI: Paul Hartogh (MPS), with the science and instrumental cooperation of the Japanese team (PI: Yasuko Kasai, NICT)
- SWI is highly sensitive to $CH_4$, $H_2O$, HCN, CO and CS in Jupiter's stratosphere, and the observations by SWI should be able to approach the structure, composition and dynamics of the middle atmosphere of Jupiter.
- From $CH_4$ molecular lines, vertical temperature profiles and wind velocities (from the Doppler shift) can be measured.
- CO and CS, which are chemically stable, can be used as tracers for the investigations of atmospheric flows (general circulation and dynamical processes).

Collision of Shoemaker-Levy 9 [HST, 1994]: Origin of $H_2O$, CS, CO and HCN?

# Why Jupiter?

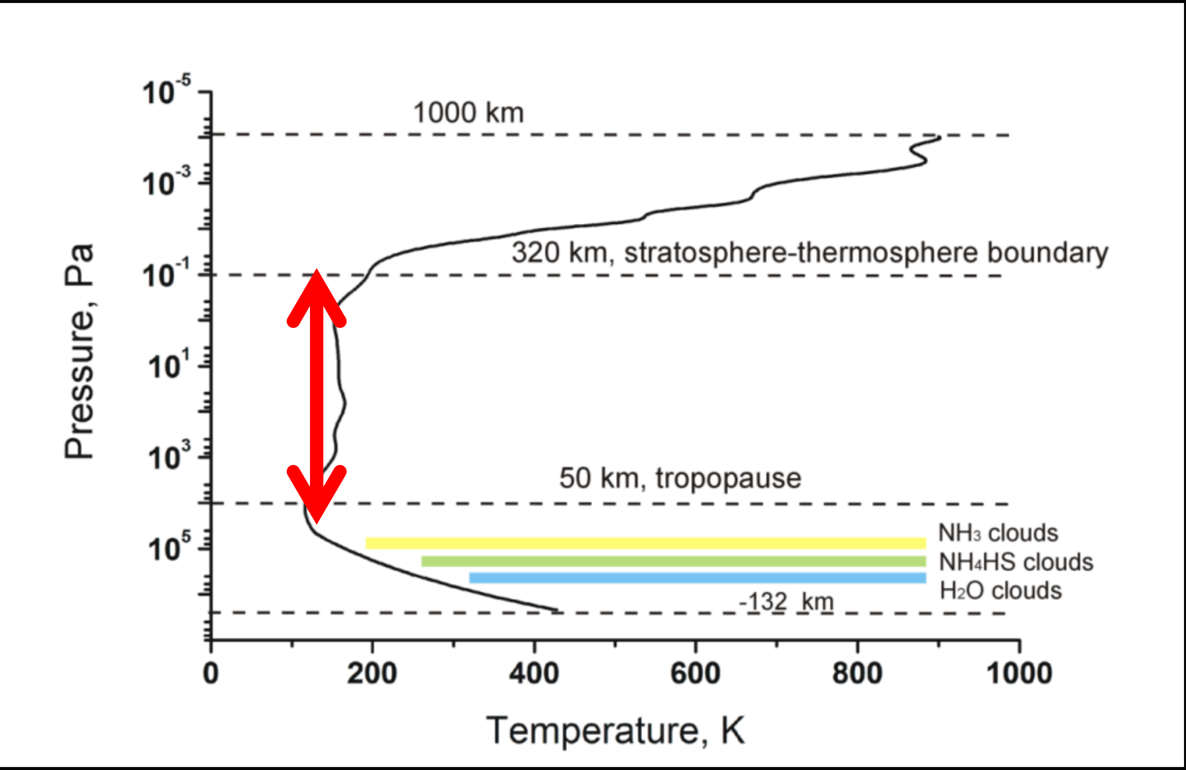
Towards the universal understandings of objects in the space (terrestrial planets, gas giants, brown dwarfs, stars…)

- For universal understandings of formation and evolution of planetary atmospheric circulations, with different viewpoints from the investigations of terrestrial planets.
  (clarifications of physical parameters specific to each planet)
- The field of planetary science is broadening beyond our solar system, and gas giants are especially important in extra-solar stellar systems as far as our current understandings.
  <u>Then we need to understand Jupiter, the closest gas giant to us, thoroughly as the first step.</u>

# Atmosphere of Jupiter

- Thermosphere ($<10^{-3}$hPa)
- Stratosphere ($10^{2}\sim10^{-3}$hPa)
- Troposphere ($10^{4\text{-}5}\sim10^{2}$hPa)
  - With cloud layers
  - Driven by the internal heat source.

Vertical structure: observed by Galileo Probe




[Seiff et al., 1998]

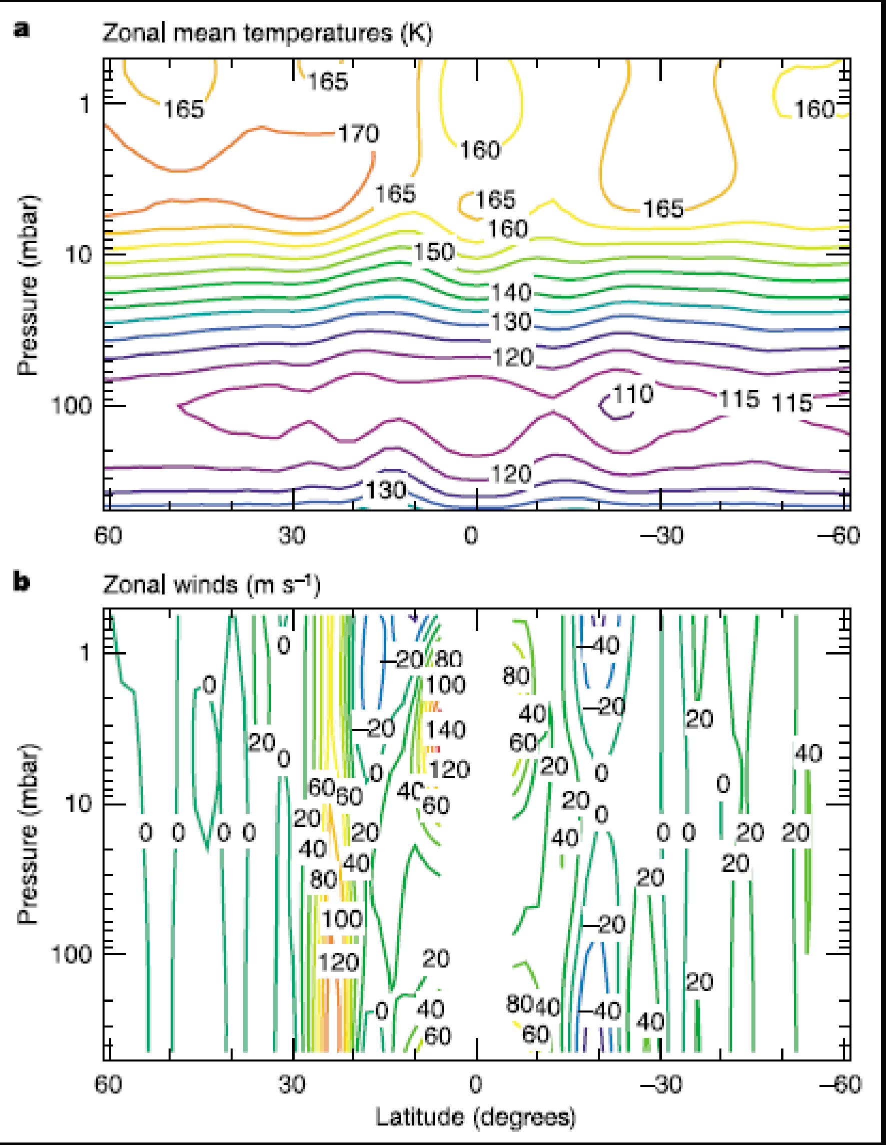
The target of JUICE/SWI is <u>stratosphere</u>.

(complementary with JUNO/MWI, for troposphere)

# Jupiter's stratosphere

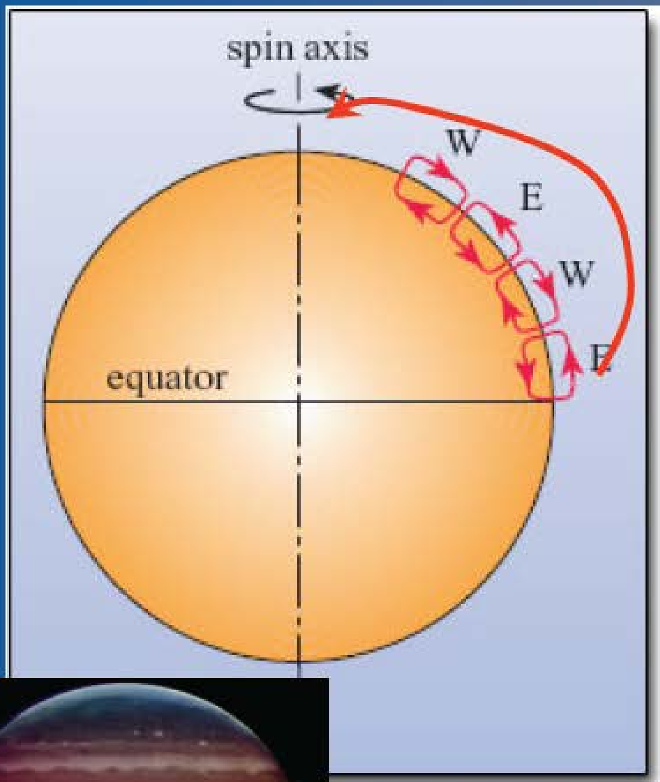
Temperature and zonal wind fields observed by Cassini/CIRS

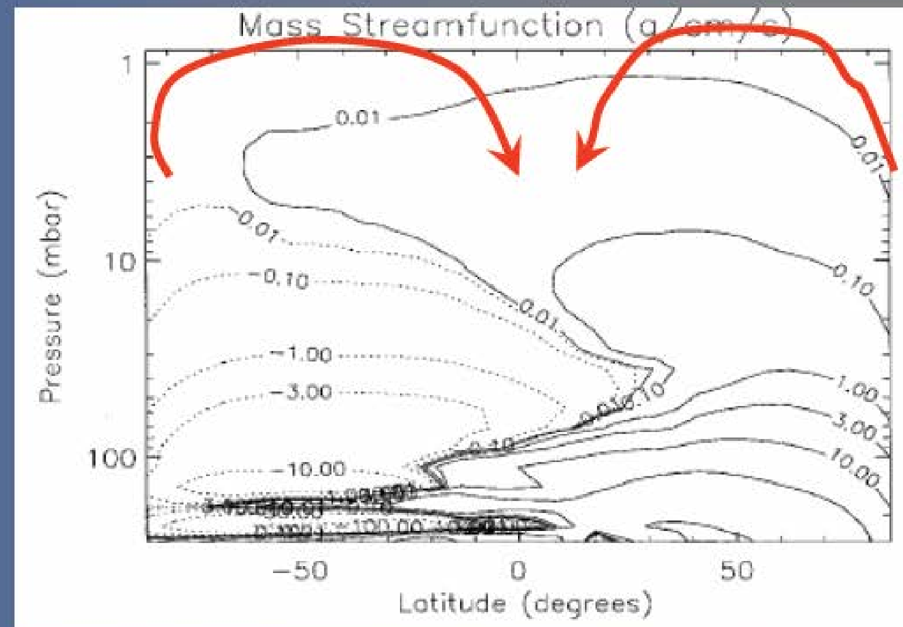
- Affected by radiative processes by molecules in stratosphere, as well as  eddies enhanced from the troposphere.
(cf. troposphere: convection cell structures transport the energy and momentum)
- The estimation from the thermal wind equation and cloud tracking (for lower boundary wind speed) shows the existence of fast zonal wind jets of 60-140 m $s^{-1}$ at  23N and 5N.




[Flasar et al., 2004]

# Meridional circulation




Radiatively forced circulation pattern. Has no correlation with zones and belts above 100 mb

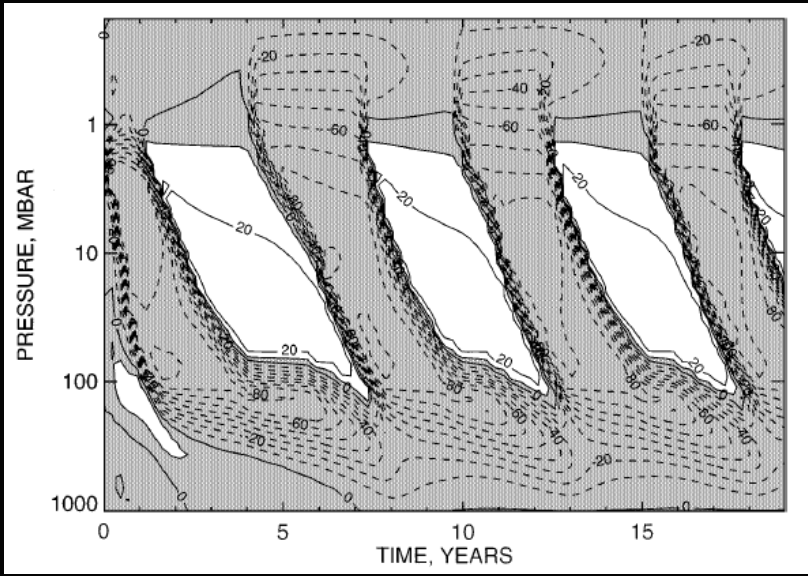
Several models predict equatorward transport above 10 mb, but they are highly dependent on assumed haze and gas optical properties

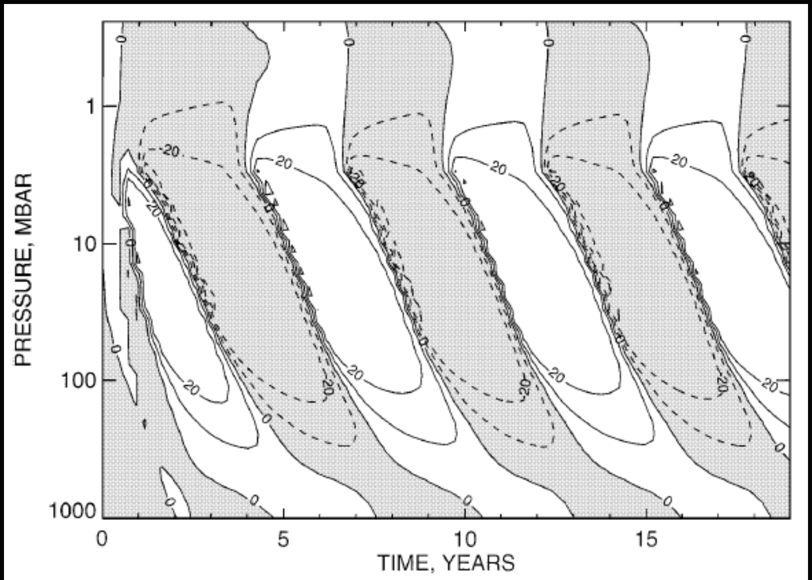
[Moreno and Sedano, 1997]

# QQO
## (quasi-quadrennial oscillation)

- Oscillations with the period of 4-5 years period have been observed from ground-based observations of equatorial temperature, and also simulated. It is thought to be analogous to the terrestrial QBO (quasi-biennial oscillation) which changes the direction of equatorial zonal wind with the period of ~2 years.
- QQO seems to affect not only stratosphere but also upper troposphere, but the driving mechanisms are not known.

Simulation of Jupiter's QQO (upper: accelerations by stationary/ Rossby waves, lower: by gravity waves)

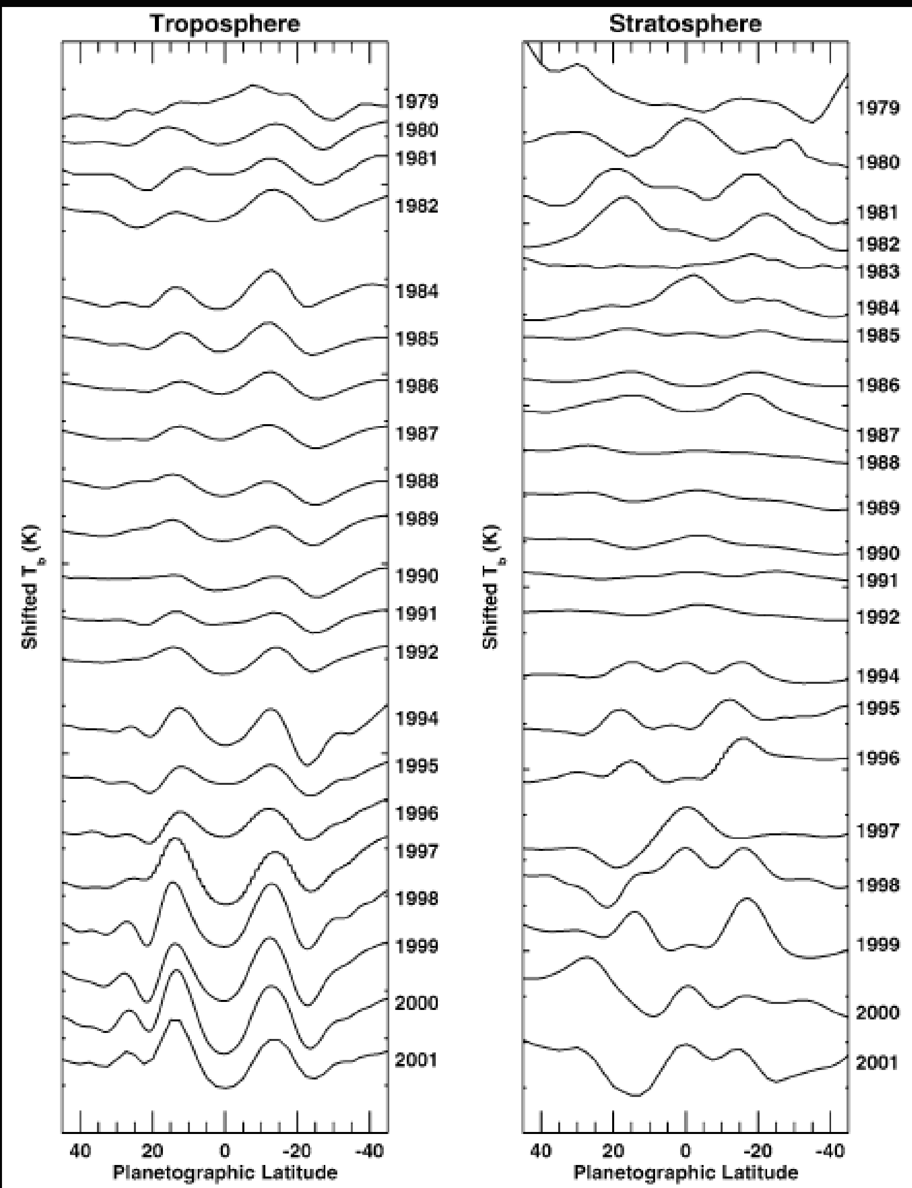



[Friedson, 1999]

# Long-term observation of low-latitudes

250mb 20mb




Observation from IRTF telescope [Simon-Miller et al., 2006]

- Check the difference of temperature between the equator and 15-20 degrees.
- In stratosphere (20Pa), the difference of temperature seems to change in the consistent period with QQO.
- The semi-annual oscillation of Saturn was also discussed in the same way [Orton et al., 2008, Nature].

# Waves in troposphere

- Within 15° of the equator there is zonal structure that may indicate wave activity associated with a QQO.
- However the figure also indicates the variety of thermal features away from the equator. The features appear to be stationary or moving slowly relative to the interior, although they are embedded in large zonal wind currents.
- Quasi-stationary wave-like features in the tropospheres of both Jupiter and Saturn had been identified by previous observations (Voyager and ground-based).
- Their origin remains speculative.

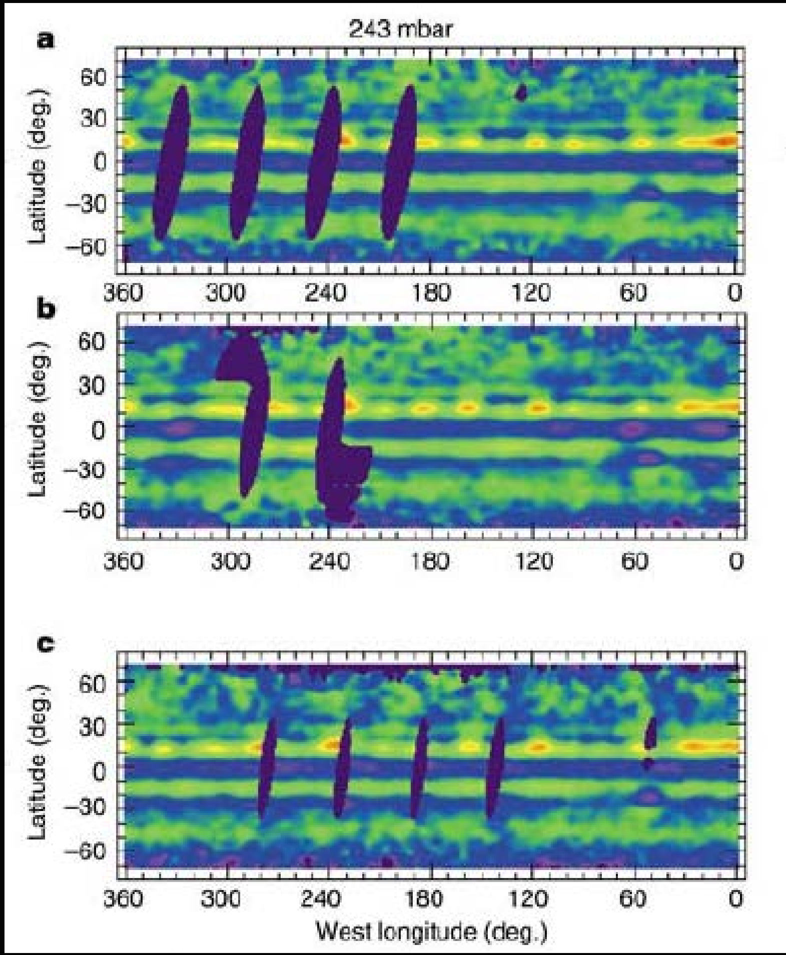
(Forcing by a disturbance deeply seated? The features at the visible cloud level?)

Cassini/CIRS:
Longitude-latitude cross sections of atmospheric temperature at 243mb (upper troposphere)
(Temperature range: 106～140K)

2001
1/1

1/5

1/10

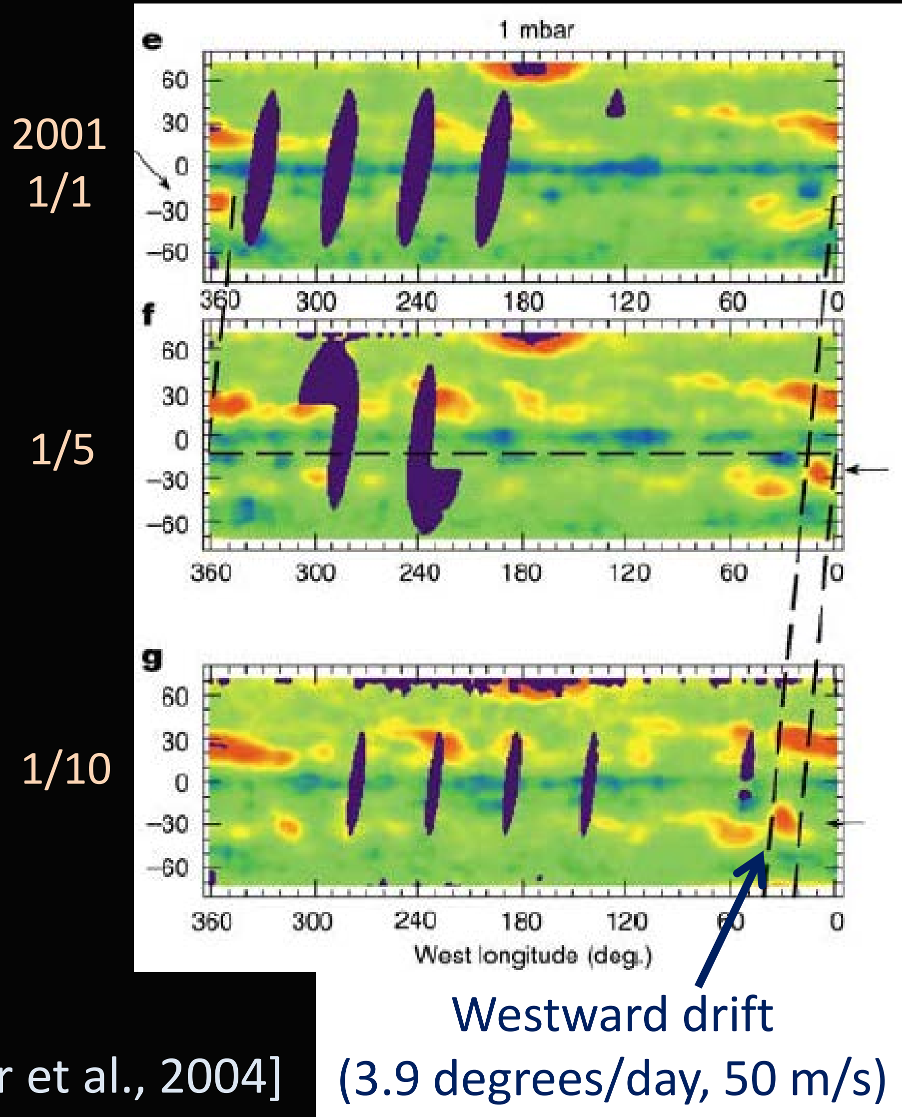



[Flasar et al., 2004]

# Waves in stratosphere

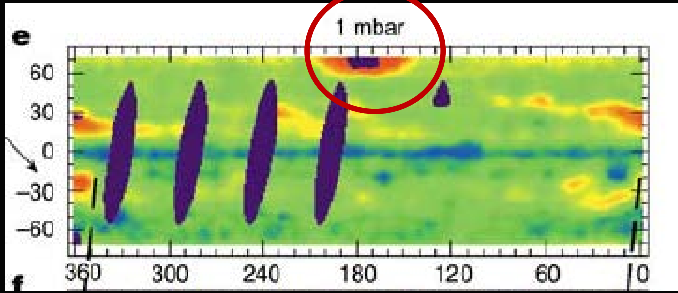
- Zonal features still exist, but less confined in latitude, and some move.
- The data indicated that the temperature features display a systematic westward drift at several latitudes (e.g. 25°S, 35°N).
- The derived zonal wind velocities from the thermal wind equation are quite different from the observed drifts of the thermal features.
- This motion is consistent with planetary, or Rossby waves, but the exact nature of these waves has yet to be determined. (from the troposphere?)

Cassini/CIRS:
Longitude-latitude cross sections of atmospheric temperature at 1mb (middle stratosphere)
(Temperature range: 140～180K)



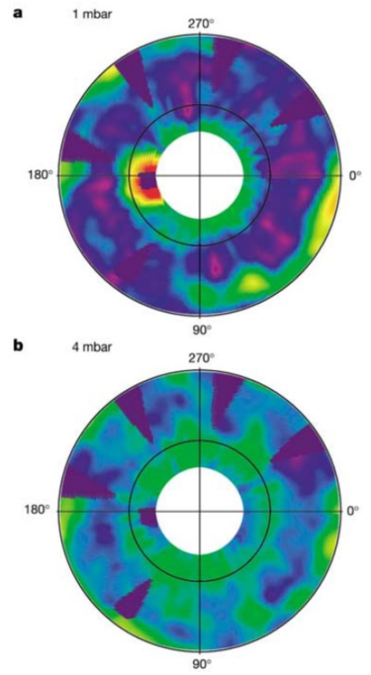

[Flasar et al., 2004]

# Hot spot: interaction with plasma?



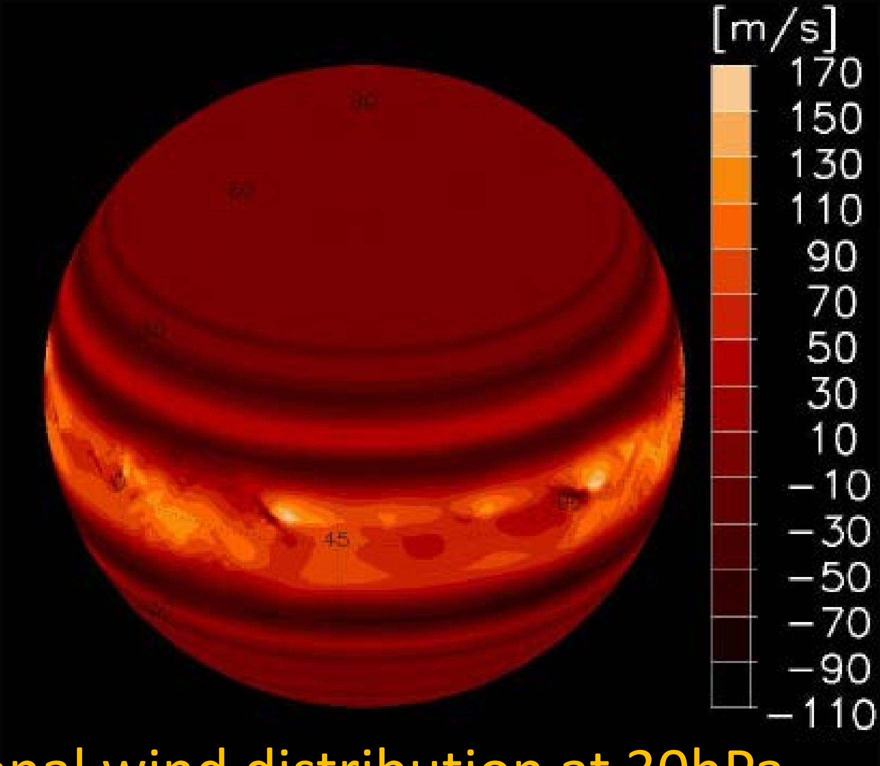

- A 'hot spot' is seen centered near 65°N and 180°W.
- From the ground-based observation, the 'hot spot' appears the same place as the auroral spot, with fixed latitude and longitude.
- It also coincides with a region of excess, pulsating X-ray emission and
- Anomalous far-ultraviolet emission was observed.
- Tracking Jupiter's magnetic field lines from the hot spot indicates an origin in the outer magnetosphere beyond 30 $R_J$ [Gladston et al., 2002]. The impact on the neutral atmosphere must be significant.
- An associated clockwise vortex is expected from the dynamical balance.
- A temperature gradient of at least 15 K per 5° of latitude, and the thermal wind equation implies a vertical shear of at least 30 m/s per scale height (27 km) in the vortex winds.

Polar projection
[Flasar et al., 2004]

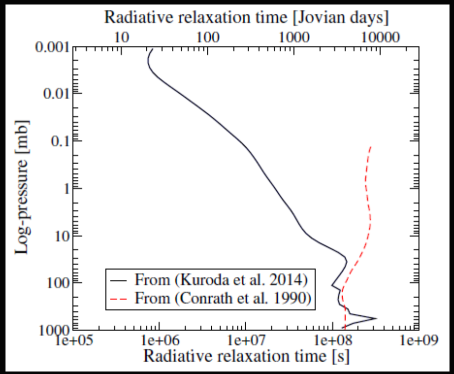


# Jupiter stratospheric GCM

- Log-pressure vertical 41 layers, 0.01-1000 hPa (tropospheric cloud top – upper stratosphere)
- Horizontal resolution: 240(longitude) ×180(latitude) grid points (1.5°×1°)
- Radiation: Newtonian cooling with relaxation time of Kuroda et al. [2014]

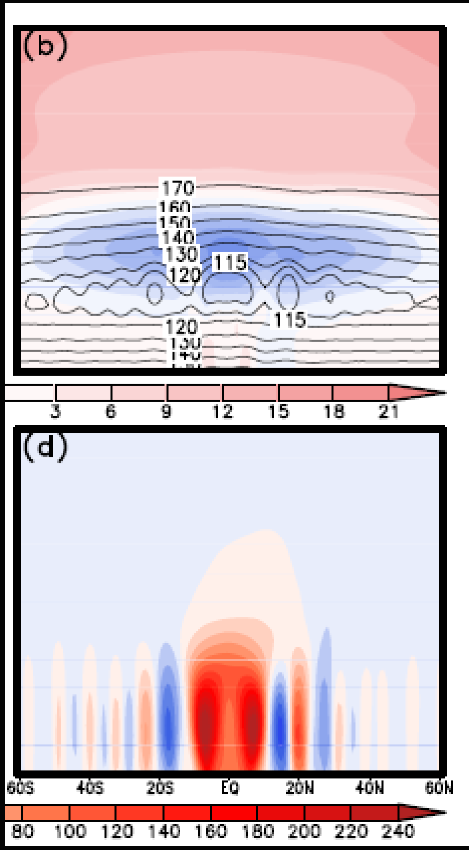



Zonal wind distribution at 30hPa
(Lower boundary wind velocity is defined from Cassini/VIMS cloud tracking)




Temperature

Zonal wind



# Summary

- Driving sources of the stratosphere are radiative effects (solar radiation and infrared molecular emission) and eddies from the troposphere which is governed by the convections driven by the internal heat forcing.
- Troposphere and stratosphere seem to affect each other.
(troposphere -> stratosphere: eddies)
(stratosphere -> troposphere: QQO)
- Quasi-stationary wave-like features in the troposphere, while the westward drift whose velocity is quite different from the zonal wind fields is seen in the stratosphere.
- Stratospheric temperature is also affected by the auroral activities.
- Expectations to the radio observations:
- Investigation of gravity waves generated from the cloud convective activities in the troposphere (hopefully something can be found from the vertically-fine temperature profiles)
- Question: which altitude is sensitive to measure on Jupiter's atmosphere?

01/06/2015 at Nara Women's University

# The importance of gravity waves in Martian atmosphere indicated by the GCM study

**Takeshi Kuroda**

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# History of Mars General Circulation model (MGCM)

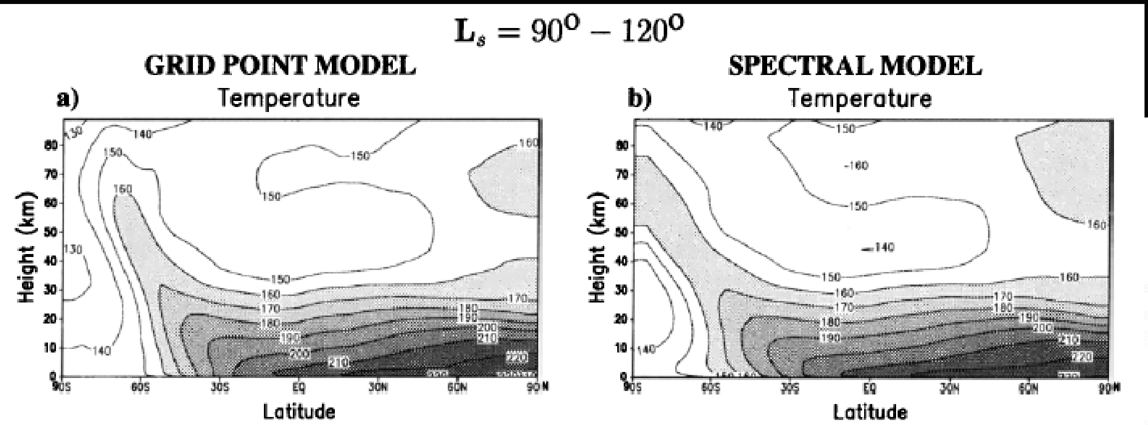
Viking (1976~1981)

MGS-TES (1998~)

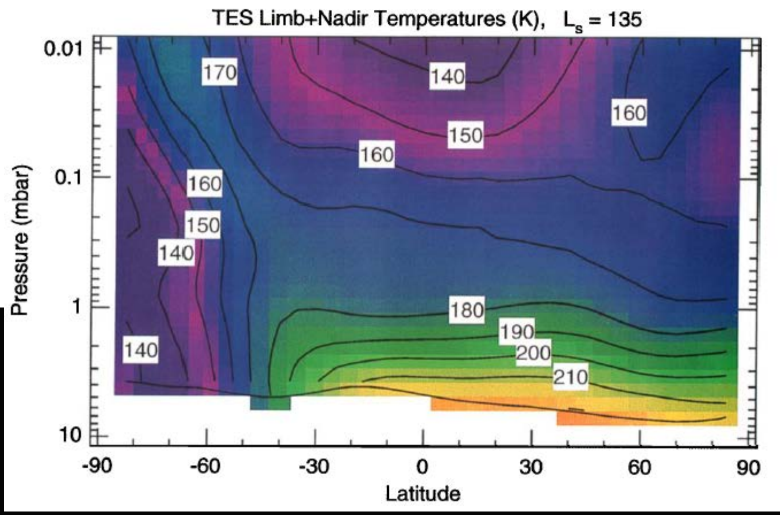
## 20th century: simulations of lower atmosphere

- Started from Leovy and Mintz (1969)
- Introduction of the condensations of $CO_2$ atmosphere (Pollack et al., 1990) and radiative effects of CO2 and dust

Results of LMD MGCM in France [Forget et al., 1999]




MGS-TES observations [Smith et al., 2001]

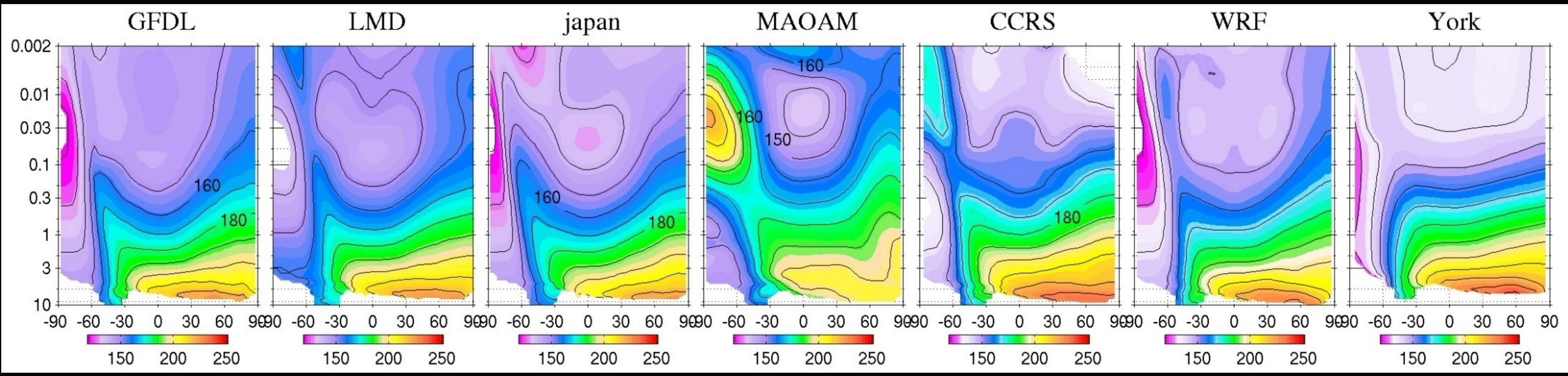



Temperature fields up to 60km height (observational limit at that time) were mostly reproduced

# Intercomparison of MGCMs in 2006 ($L_s$=90°)

At the Second workshop on Mars atmosphere modelling and observations @Granada, Spain [Wilson et al., 2006]

Princeton,USA | France | Y.O. Takahashi (now Kobe Univ.) | MPS, Germany | Kuroda (early DRAMATIC) | Caltech,USA | Canada




- Results of most models were close, but <u>only MAOAM had quite high temperature above the winter pole (~60km height).</u>

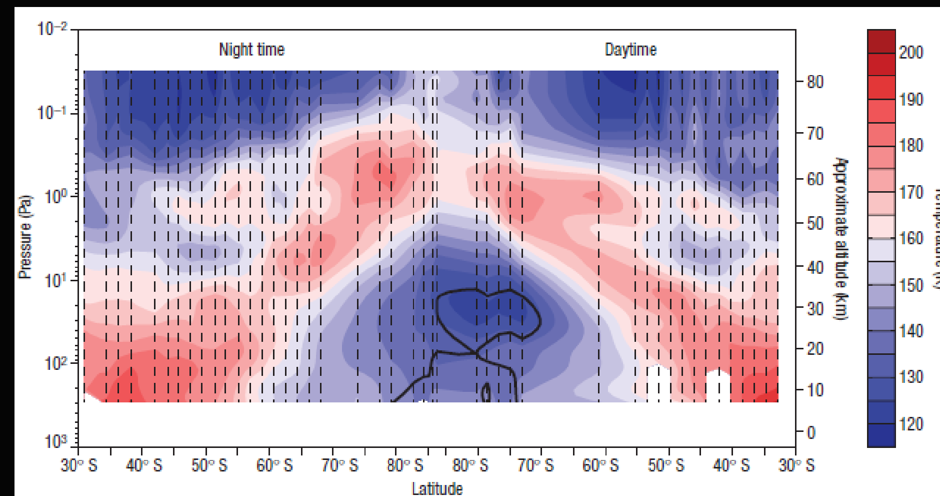
→Was MAOAM wrong? But at that time there were almost no observational data of temperature above ~60km.

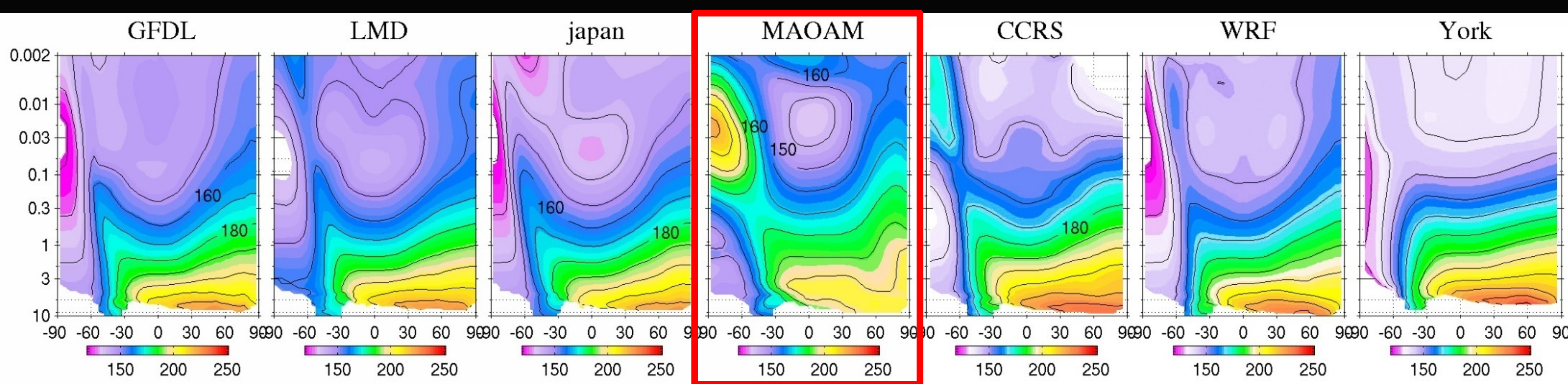
Just wait for the observations!

# First observational data of temperature above ~60km (2008)

- The Mars Climate Sounder onboard Mars Reconnais-sance Orbiter (MRO-MCS) first observed the temperature in 60-80km height.
- It showed much higher temperature above the winter pole than expected, which was close to the results in MAOAM model.

MRO-MCS observations of temperature (Ls=136°) [McCleese et al., 2008]

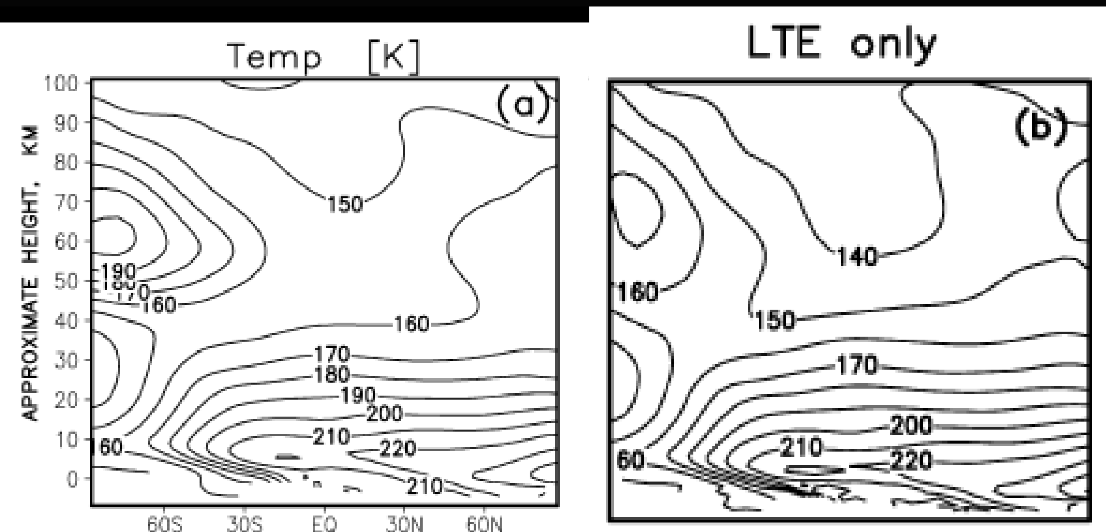


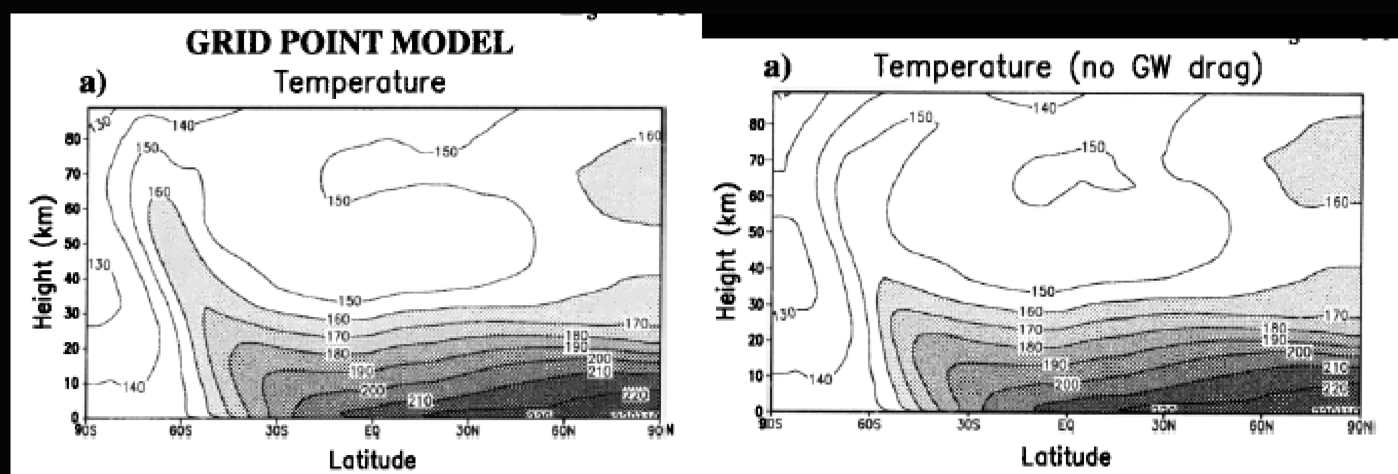
# Why did MGCMs except MAOAM underestimate the temperature above the winter pole?

1. Non-LTE effects of $CO_2$ radiation
2. Gravity waves (small-scale eddies)

Start of active discussions about the effects of gravity waves (GWs) on the atmospheric fields above ~60km




Effects of non-LTE radiation [Medvedev and Hartogh., 2007]

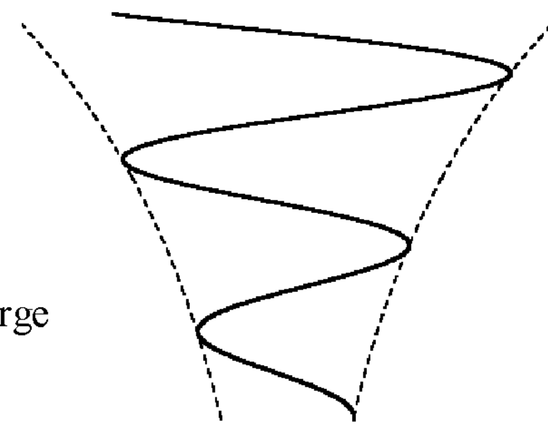



Effects of gravity wave drag scheme [Forget et al., 1999]

# What is the gravity wave？

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


- Restoring force is a buoyancy.
- Atmosphere of Mars is mostly convectively stable (as on Earth) to support gravity wave existence.
- 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.

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

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

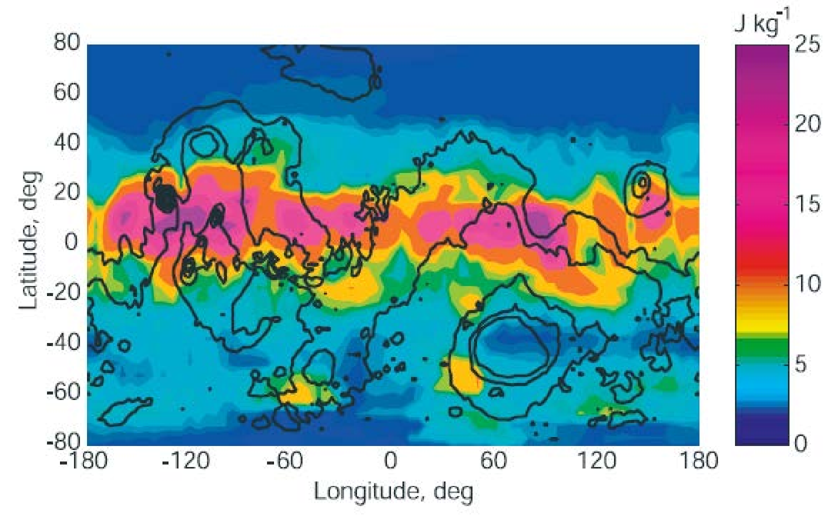
# Gravity waves on Mars: from data analyses

## Creasey et al. [2006a], Geophys. Res. Lett., 33, L01803

- Using the MGS radio-occultation data (from surface up to ~40km)
- 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.

Gravity wave 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], Geophys. Res. Lett., 33, L22814

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

# Gravity waves on Mars: from data analyses

## Fritts et al. [2006], J. Geophys. Res., 111, A12304

- Using the density data obtained in the aerobraking of MGS and Mars Odyssey (95-130km height)
- Amplitudes of GWs varied significantly with in space and time, and seemed to be related to the planetary-scale motions.
- Effects of the GWs on the atmospheric circulations were estimated as ~1000 m $s^{-1}$ $sol^{-1}$ at 70-80km height, and became one-fifth and five times of that at ~50km and ~100km heights, respectively.

## Ando et al. [2012], J. Atmos. Sci., 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.

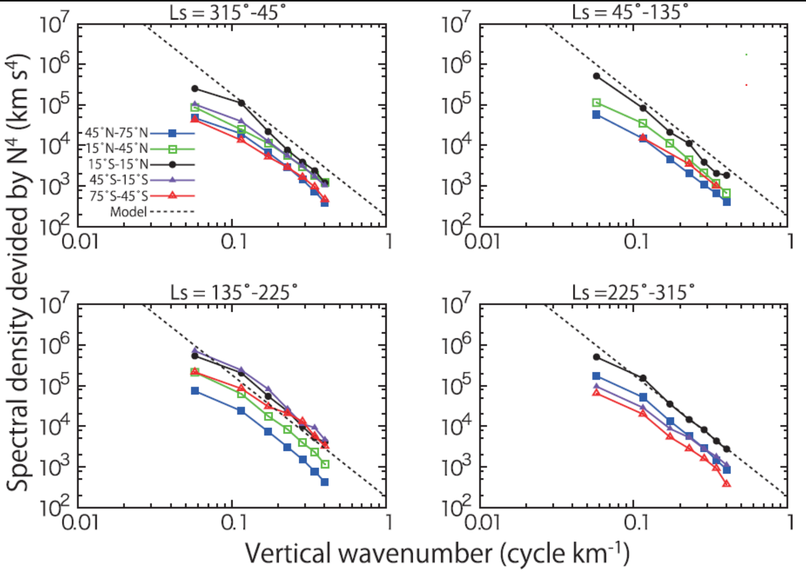
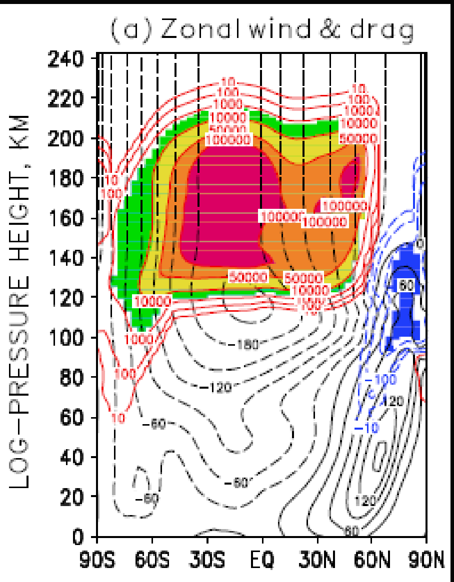



FIG. 4. As in Fig. 3, but in the altitude range 15–32 km.

# Gravity waves on Mars: theoretical investigation

Medvedev et al. [2011a], Icarus, 211, 909-912




Zonal wind accelerations by the GW drag [m $s^{-1}$ $sol^{-1}$]

Red contours: westerly wind acceleration

Blue contours: easterly wind acceleration

- Estimated the acceleration of winds in thermosphere by the GW drag from the wind fields of Mars Climate Database (LMD MGCM)
- The strength of GW drag is consistent with the estimations by Fritts et al. [2006].

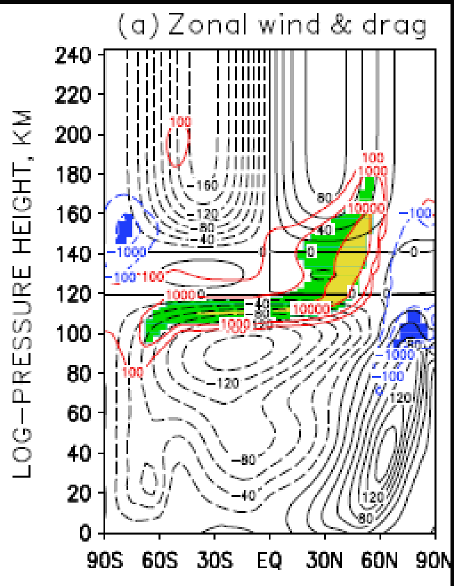
(From the scheme of terrestrial thermosphere, with source height of ~250 Pa, $-60 \le (c-\bar{u}_0) \le 60$ m $s^{-1}$, horizontal wavelength of 200km)

$$F_i(z) = F_i(z_0)\exp\left[-\int_{z_0}^{z}\left(\beta^i_{non} + \beta^i_{mol}\right)dz'\right]$$

$$\beta_{non} = \sqrt{2\pi}\frac{1}{\sigma_i}\exp\left(-\alpha_i^2\right), \quad \beta_{mol} = \frac{2\nu_{mol}N^3}{k_h(c_i - \bar{u})^4}$$

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

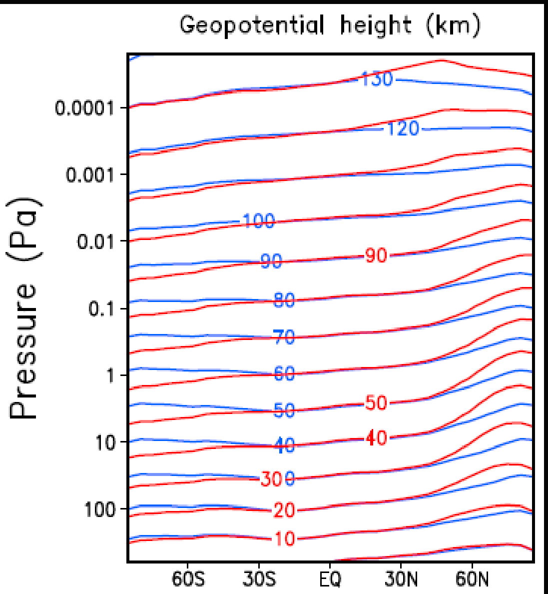
- GWs change the wind fields above ~100km height significantly, decreasing and even reversing the mean zonal wind.




Zonal wind accelerations by the GW drag [m $s^{-1}$ $sol^{-1}$] for the changed wind field

# Gravity waves on Mars: MGCM simulation

Medvedev et al. [2011b], J. Geophys. Res., 116, E10004




Geopotential heights of the model

Red: $L_s$=270°

Blue: $L_s$=180°

## MAOAM-GCM

Spectral model

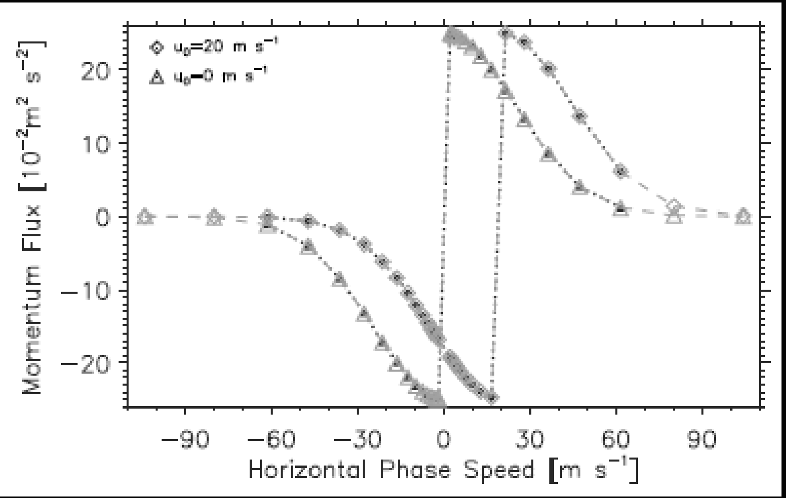
Horizontal resolution: T21

(64 × 32 grids)

Vertical 63 layers (hybrid)

Top of the model: $1.6 \times 10^{-5}$ Pa

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



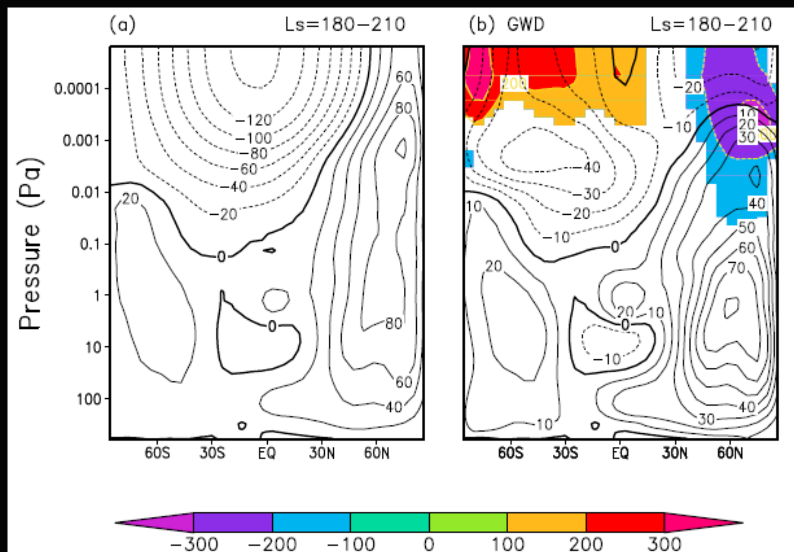

Dynamical forcing of GWs:
Implemented momemtum flux of GWs at the source,
setting the source height of ~260 Pa and horizontal wavelength of 300km

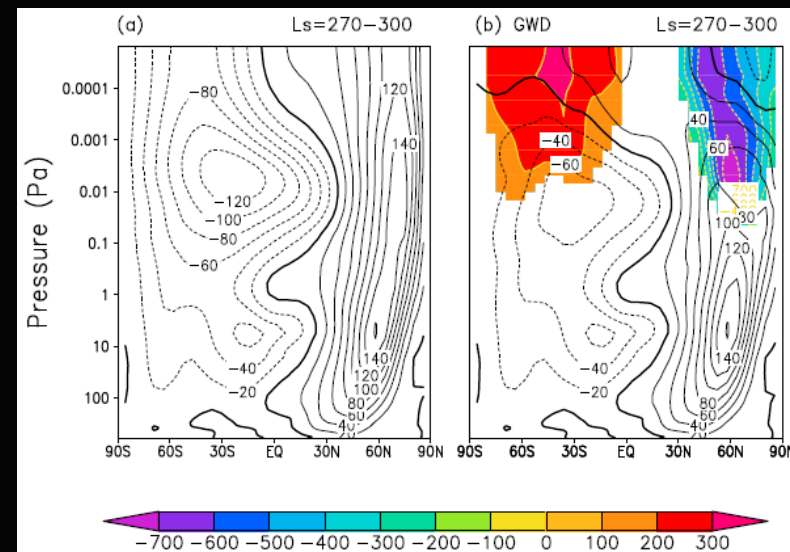
# Gravity waves on Mars: MGCM simulation

## Change of numerical results due to the GW drag

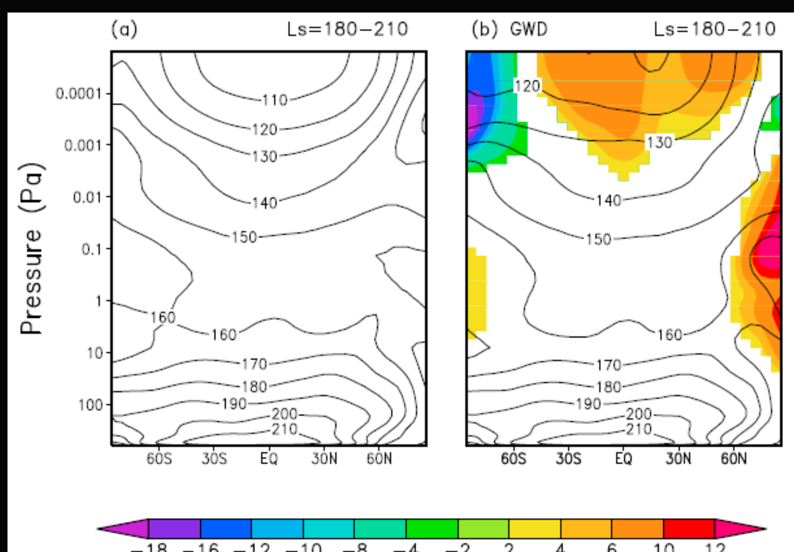
$L_s$=180° | $L_s$=270°

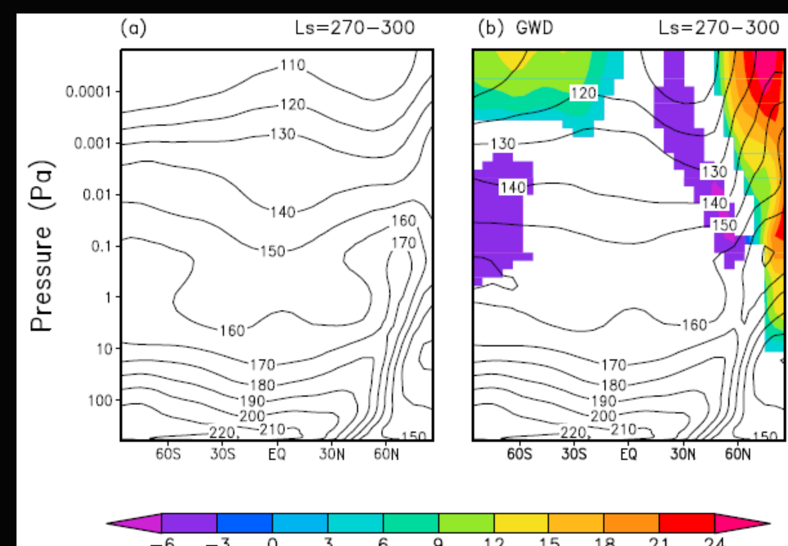
Zonal wind




Tempera-
ture



# Gravity waves on Mars: MGCM simulation

## With different GW drag conditions

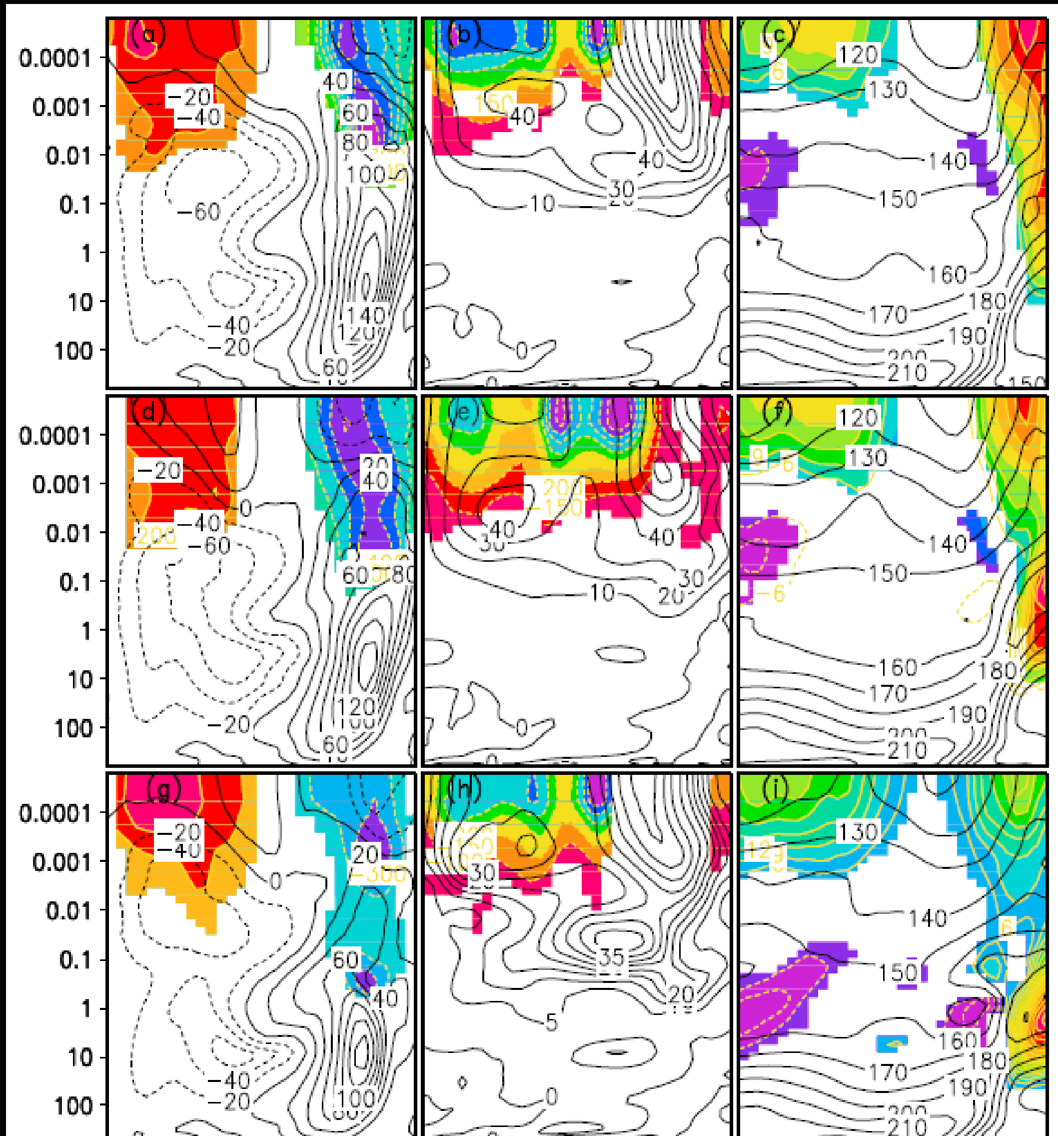
$L_s$=270°

Zonal wind | Meridional wind | Temperature

Benchmark

Lower source (few hundred meters above the surface)

10 times stronger forcing



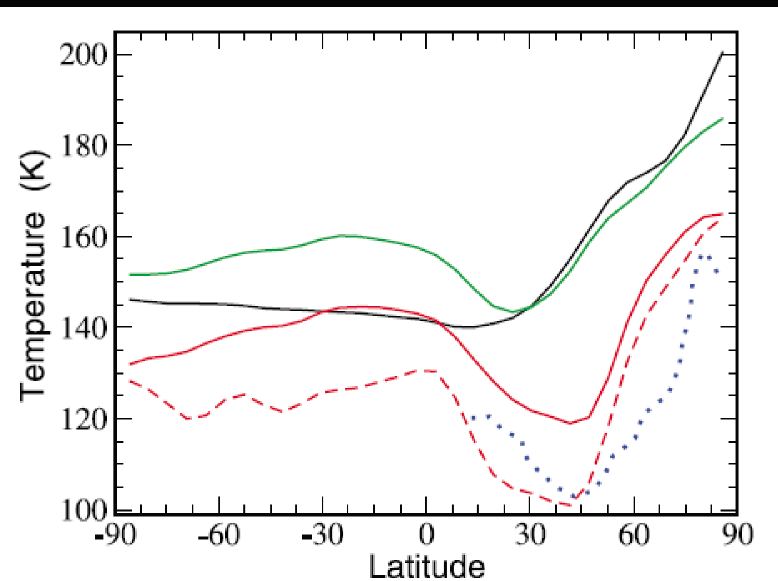

- GWs significantly decrease the wind speed in upper atmosphere, and even reverse the wind direction.
- GWs increase the temperature above the winter pole.
- Different results were obtained in different forcing conditions, but GWs definitely affect the atmospheric fields in upper atmosphere anyway.

# Gravity waves on Mars: MGCM simulation

## Thermal forcing of GWs

Medvedev and Yigit [2012], Geophys. Res. Lett., 39, L05201

Temperature at ~120km height




Black: No GW drag

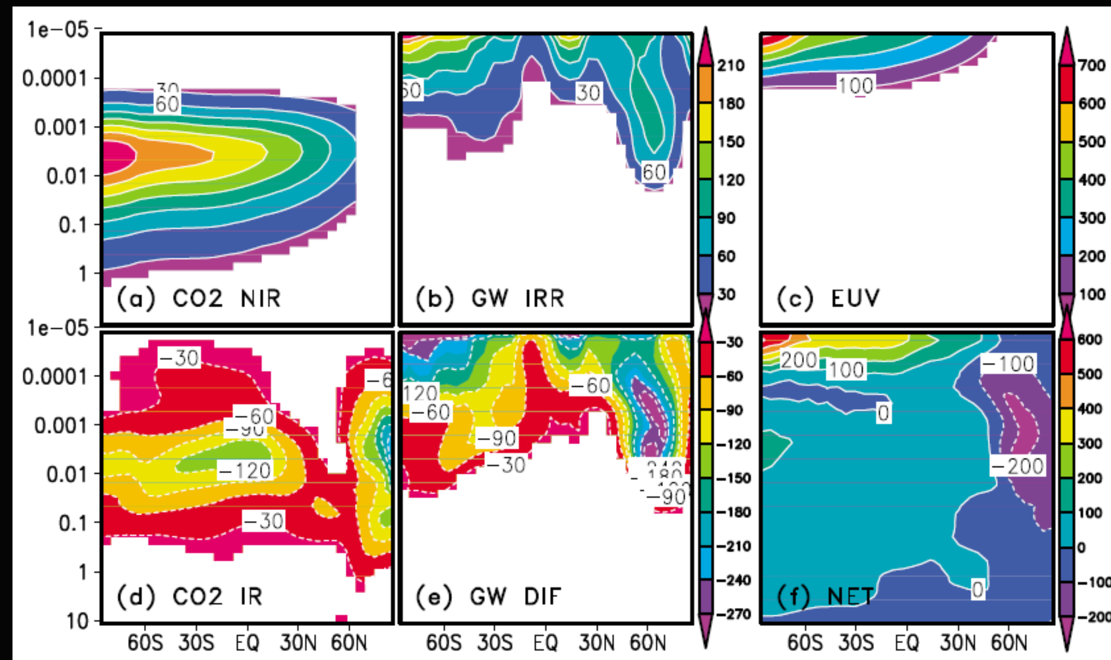
Green: Only dynamical forcing

Red: With dynamical+thermal forcing (daily averaged)

Red dashed: With dynamical+thermal forcing (night)

Blue dots: Mars Odyssey aerobraking observation (night)

Heat/cool balances in thermosphere




From exchange of energy (eddy to heat)

$$Q^i_{irr} = c_p^{-1} a_i (c_i - \bar{u}),$$

From vertical gradient of sensible heat flux

$$Q^i_{dif} = \frac{H}{2\rho R} \frac{\partial}{\partial z} [\rho a_i (c_i - \bar{u})]$$

# Gravity waves on Mars: MGCM simulation

## Effects of the global dust storm on the thermosphere

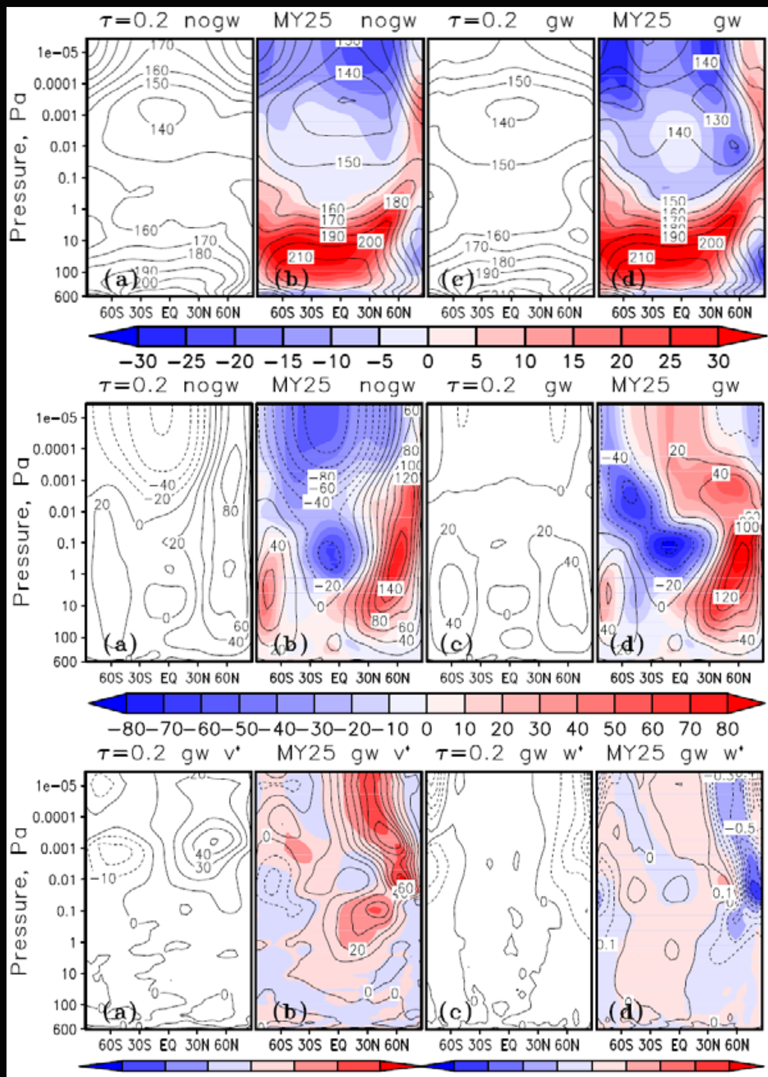
Medvedev et al. [2013], J. Geophys. Res., 118, 2234–2246

Temperature (noGW, GW)

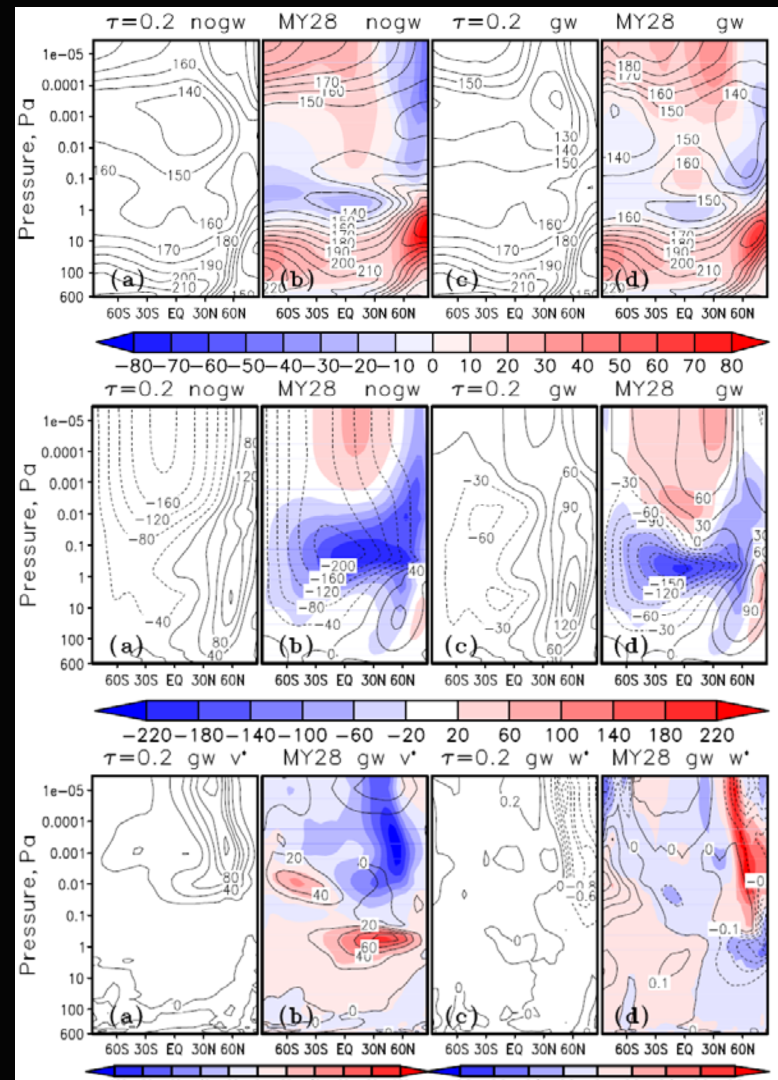
Zonal wind (noGW, GW)

v*, w* (GW)

MY25



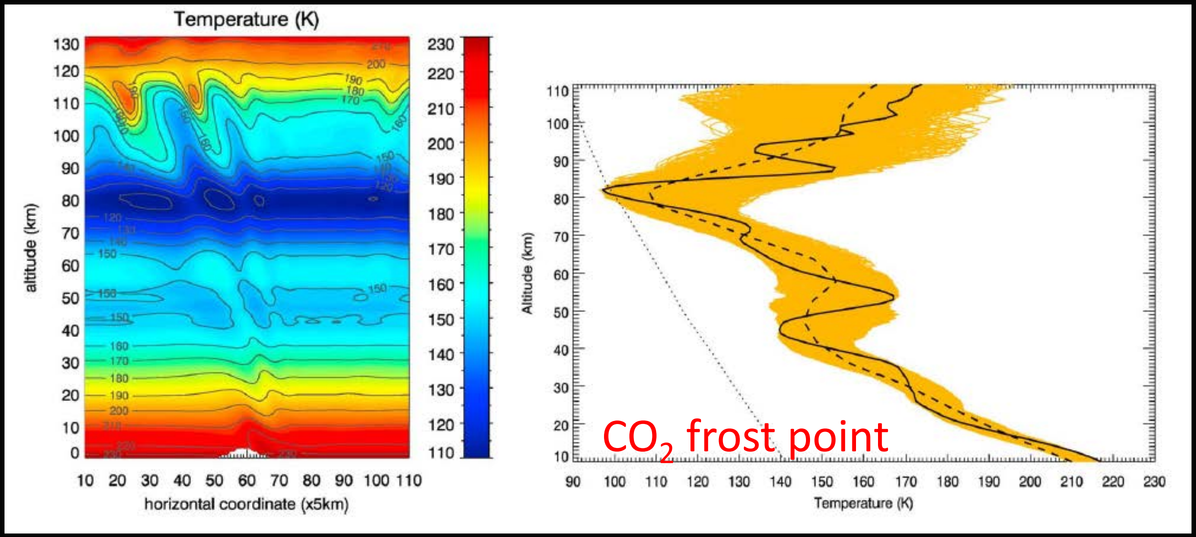

MY28



# Gravity waves and mesospheric $CO_2$ ice cloud formation

Spiga et al. [2012], Geophys. Res. Lett., 39, L02201

Temperature disturbance by a mountain (4km height): from a regional model



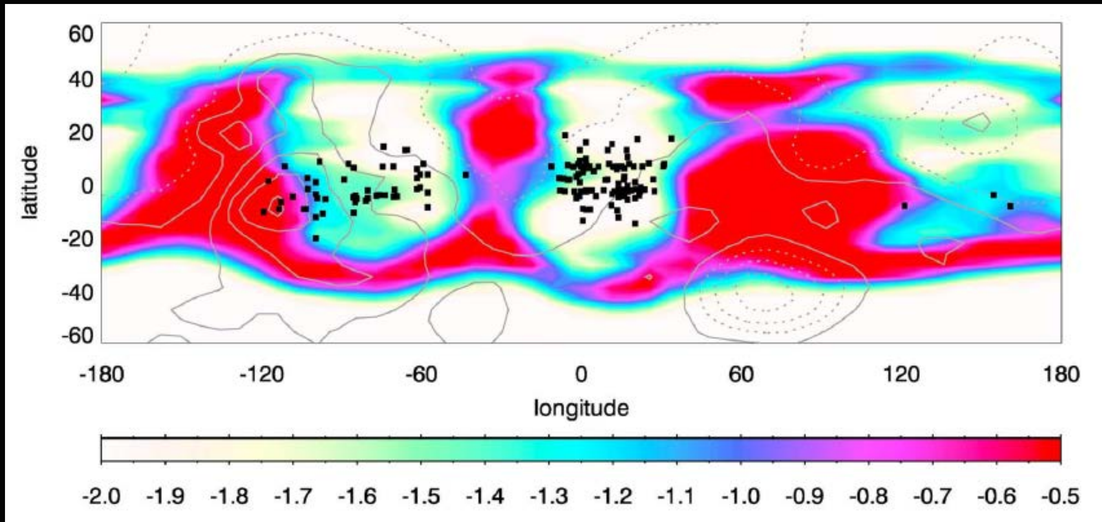

- Temperature profile changes in the orange regions in 2 hours.

Black dots : $CO_2$ ice clouds
Color shade : $\log_{10}(S)$
(Red represents the regions with small mesospheric GW activities)

Saturation index (S)

$$S = \frac{T'}{T'_m} = \sqrt{\frac{\alpha N}{\langle\rho\rangle |\langle u\rangle - c|^3}} \quad \text{with} \quad \alpha = \frac{F_0 \lambda_H}{2\pi}$$

- Mesospheric $CO_2$ ice cloud formation strongly coincides with the GW activities.



# Summary

- The effects of GWs on the Martian atmospheric temperature and wind fields are ignorable 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.
- The effect of GWs is critical also for the formation of mesospheric $CO_2$ ice clouds in low-latitudes.
- However, the implemented GW drag scheme is based on the terrestrial parameter, so the accuracy on Mars is not known.
- Expectations to the radio observations:
  - Mapping of the generations of GWs from the surface
  - Investigation of the generation sources of GWs (topography? convections? dust storms?)