Japan-France planetary atmospheric modeling workshop,
2015/05/14, Kobe Univ.

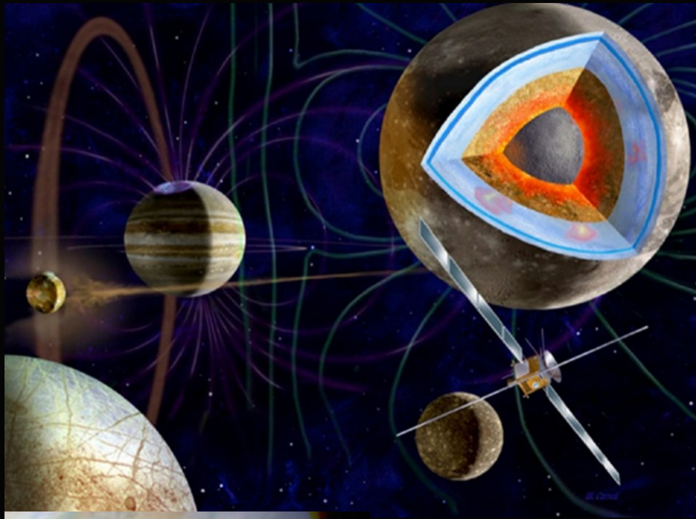
A GCM for the stratosphere of Jupiter being developed in the Max Planck Institute

Takeshi Kuroda
Tohoku University
A.S. Medvedev, J. Sethunadh, P. Hartogh
Max Planck Institute for Solar System Research

Background of the development:

JUICE-SWI (Sub-Millimetre Instrument)

- PI: Paul Hartogh (MPS), with the science and instrumental cooperation of Japan (NICT)
- The main objective of a sub-millimetre wave instrument is to investigate the structure, composition and dynamics of the middle atmosphere of Jupiter and exospheres of its moons, as well as thermophysical properties of the satellites surfaces. (from Yellow Book)
- JUICE-SWI is highly sensitive to CH_4, H_2O, HCN, CO and CS in Jupiter's stratosphere.
- From CH_4 molecular lines, vertical temperature profiles and wind velocities 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).

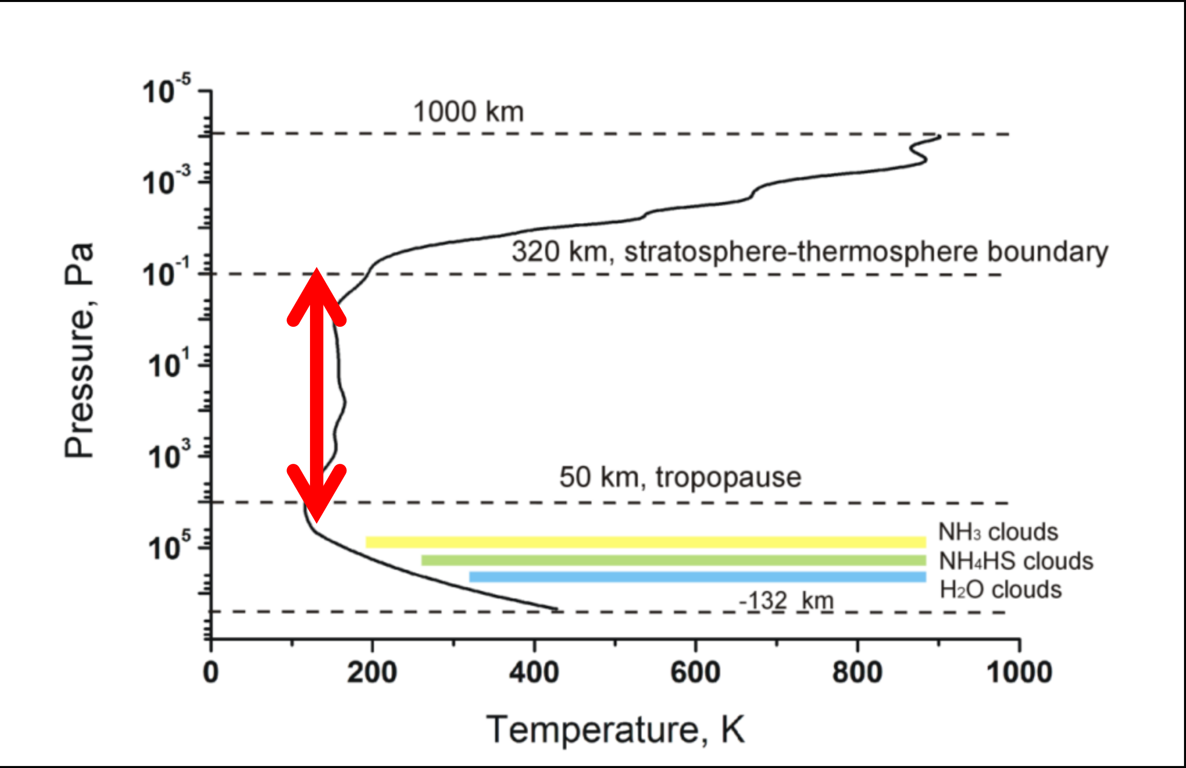


Collision of Shoemaker-Levy 9 [HST, 1994]: Origin of H_2O, CS, CO and HCN?

Atmosphere of Jupiter

Vertical structure: observed by Galileo Probe

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



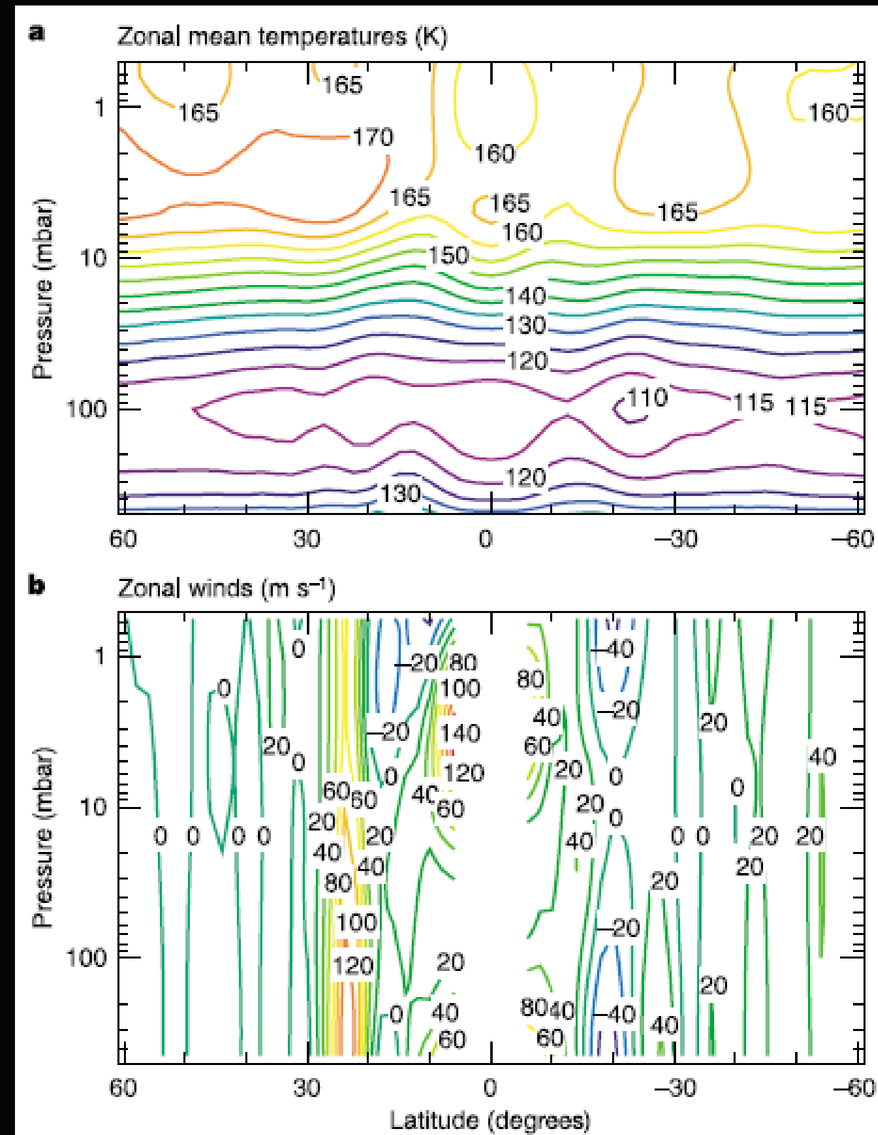
[Seiff et al., 1998]

Here we focus on the <u>stratosphere</u>.

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.



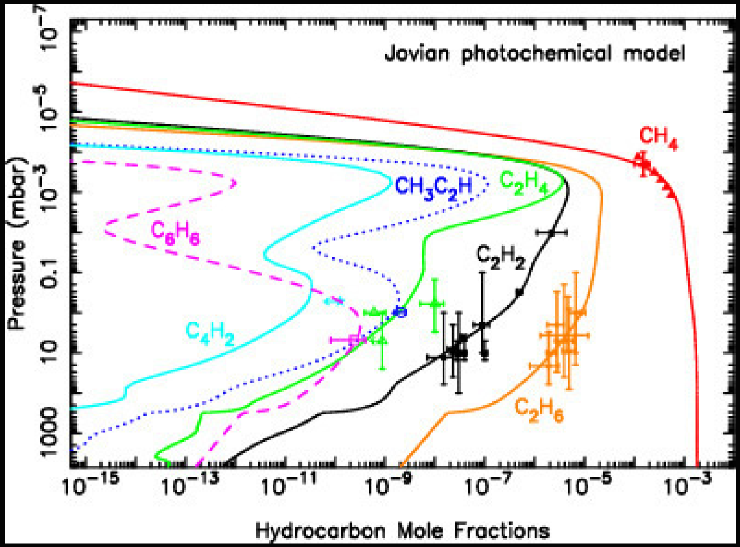
[Flasar et al., 2004]

Radiative processes in Jupiter's stratosphere

- CH_4: Absorber of the solar radiation
- CH_4, C_2H_2, C_2H_6, collision-induced transitions of H_2-H_2 and H_2-He: Effective in the infrared cooling.

We have developed a band radiative transfer model for Jupiter's stratosphere for the fast and effective calculations in the GCM (correlated *k*-distribution approach).

Mixing ratios of hydrocarbons from a photochemical model



[Moses et al., 2005]

Radiative band model

Coordinate

Band	IR(infrared) /SO(solar)	Wavenumber range [cm^{-1}]	Molecules
1	IR	10-200	CH_4, H_2-H_2, H_2-He
2	IR	200-400	CH_4, H_2-H_2, H_2-He
3	IR	400-600	CH_4, H_2-H_2, H_2-He
4	IR	600-700	CH_4, C_2H_2, H_2-H_2, H_2-He
5	IR	700-860	C_2H_2, C_2H_6, H_2-H_2, H_2-He
6	IR	860-960	CH_4, C_2H_6, H_2-H_2, H_2-He
7	IR, SO	960-1200	CH_4, H_2-H_2, H_2-He
8	IR, SO	1200-1400	CH_4, H_2-H_2, H_2-He
9	IR, SO	1400-1700	CH_4, H_2-H_2, H_2-He
10	IR, SO	1700-2100	CH_4, H_2-H_2, H_2-He
11	SO	2100-3450	CH_4, H_2-H_2
12	SO	3450-4800	CH_4, H_2-H_2
13	SO	4800-6300	CH_4, H_2-H_2
14	SO	6300-7800	CH_4, H_2-H_2
15	SO	7800-9200	CH_4, H_2-H_2
16	SO	9300-10800	CH_4, H_2-H_2
17	SO	10800-11800	CH_4, H_2-H_2

- Correlated k-distribution approach
- We made a table of k-distributions in 13 pressure grids (log-equal interval between 10^{-3} and 10^3 hPa), 3 temperature grids (100, 150 and 200 K) for 17 wavenumber bands.

- The atmospheric composition of molecules (1000 ppmv of CH_4, 1 ppmv of C_2H_2, 10 ppmv of C_2H_6, 86.4 % of H_2, 13.6 % of He) is fixed in making the table.

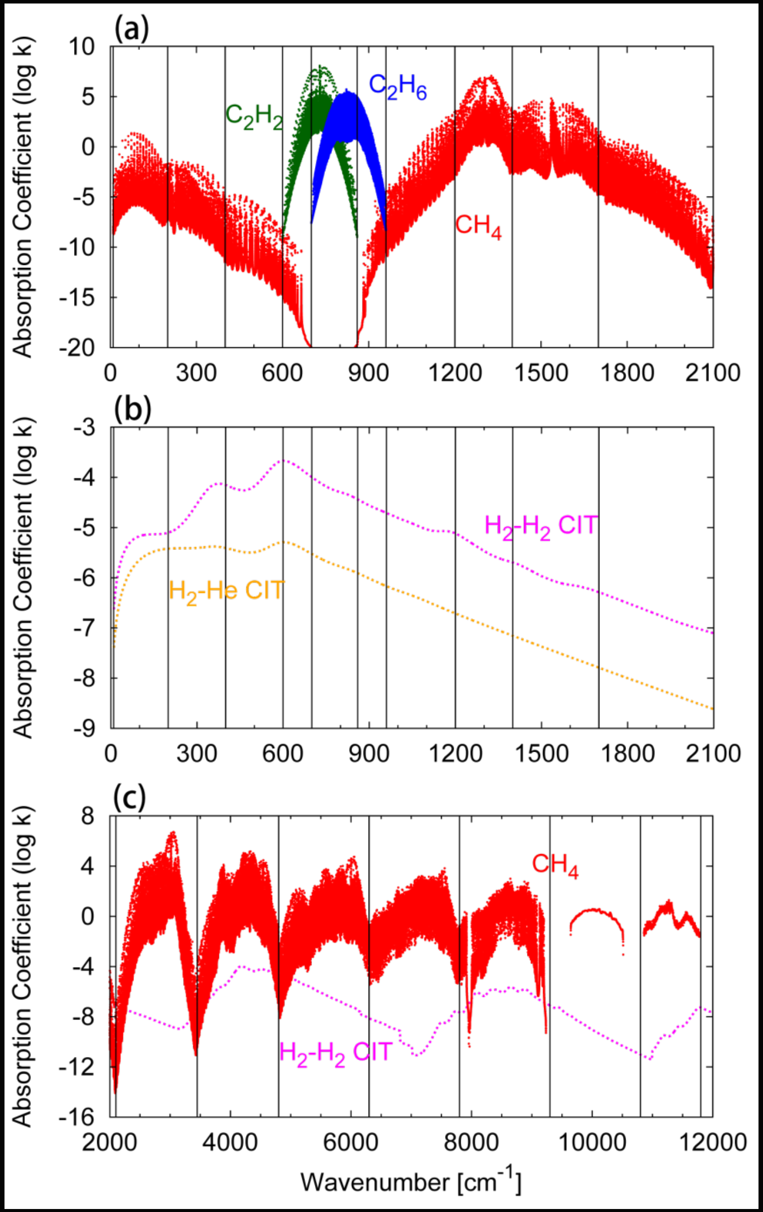
Radiative band model

Line spectra
(1 hPa, 150K)

Molecules
(infrared)

Collision-induced transitions
(infrared)

For solar absorption



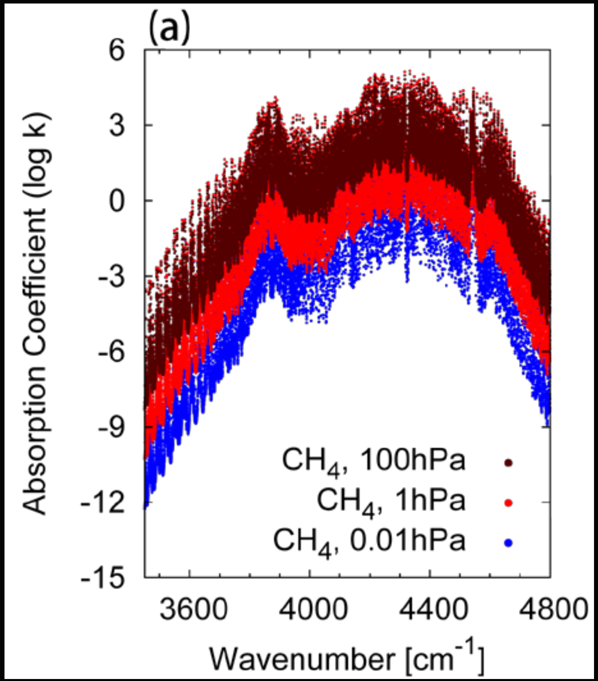
- Molecular lines of CH_4, C_2H_2 (600-860 cm^{-1}) and C_2H_6 (700-960 cm^{-1}): From HITRAN2008 [Rothman et al., 2009].
- Voigt profile is used for the calculation of line spectrum, with wing cutoff of 35 cm^{-1} for all molecules.
- Collision-induced transitions of H_2-H_2 and H_2-He: From Borysow [2002] (H_2-H_2) and Borysow et al. [1988] (H_2-He).

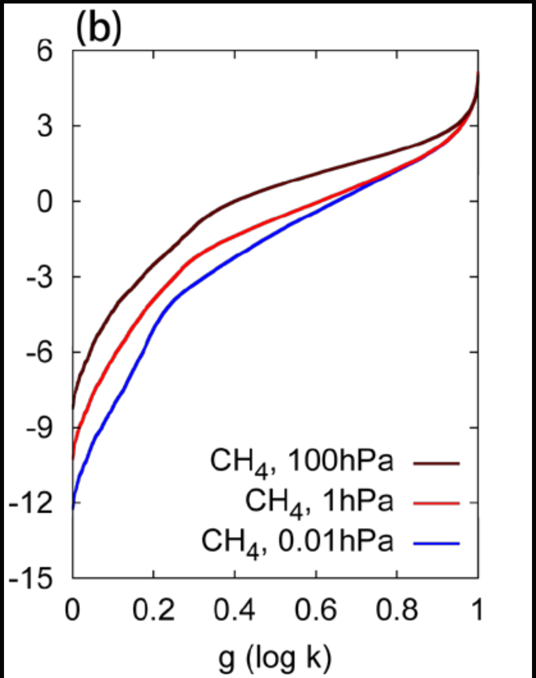
Radiative band model

About k-distribution [e.g. Liou, 2002]

CH_4 line spectra (3450-4800 cm^{-1})

k-distribution of the line spectra





- For fast calculations of fluxes, the line spectrum in each band is ordered to be a monotone increasing function.
- The absorption and emission by molecules in each band are calculated with 12 k-distribution integration points per a molecule (144 points in the bands the lines of 2 molecules are overlapped).
- The effects of collision-induced transitions are added.

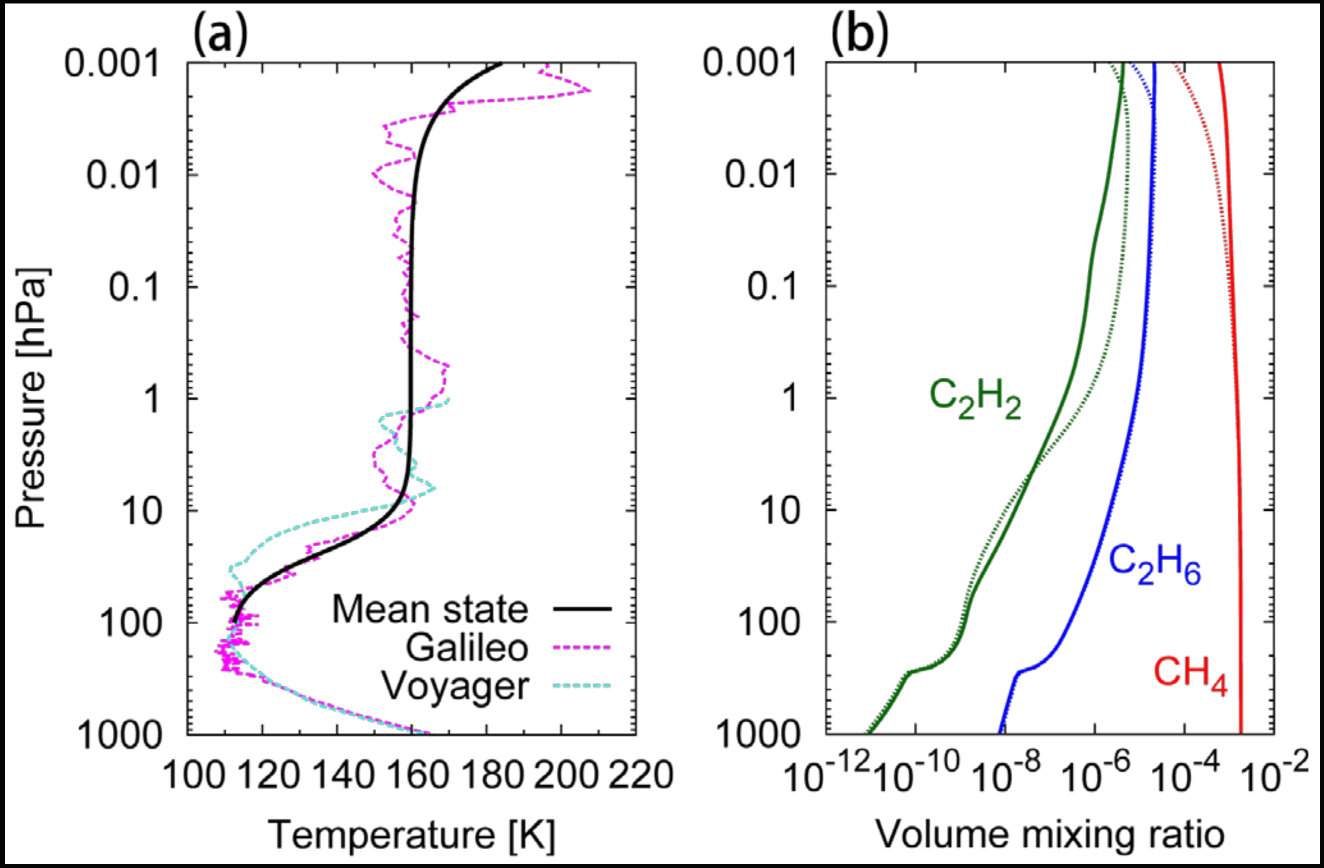
1-D calculation

Setting

1-D calculation with equally-spaced 60 layers between 10^{-3} and 10^{3} hPa has been performed.

Temperature

Component

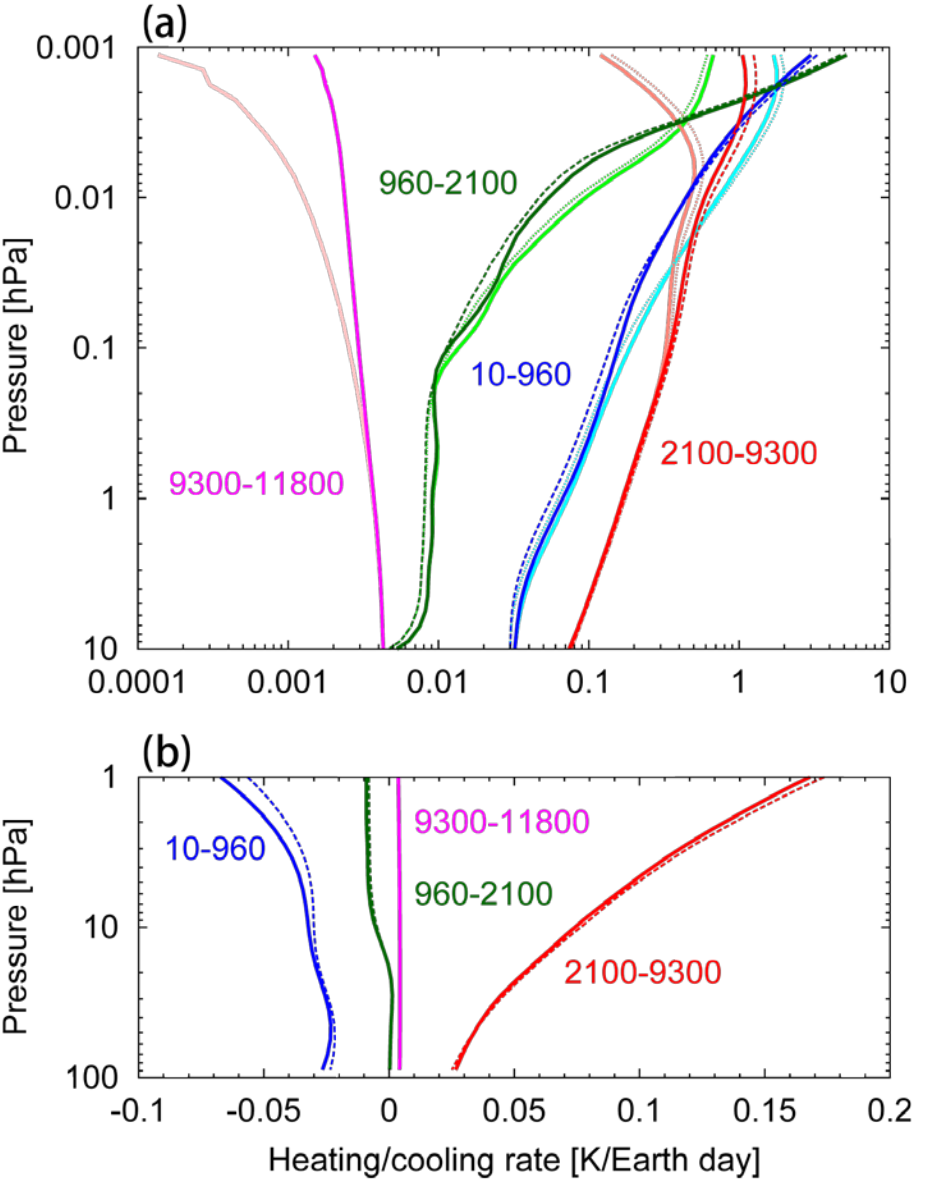


- Temperature: 'Mean state' from Galileo Probe observation [Yelle et al., 2001]
- Component: From 1-D photochemical model [Moses et al., 2005] 2 kinds of results (Models A and C)

1-D calculation

Heating/cooling rates

(Solid: Band, Dashed: Line-by-line)



- Calculation of solar radiation: Assumed zenith angle of 0°
- Differences between band and line-by-line calculations are very small.
- Mid- and far-infrared radiation (10-960 cm^{-1}): Dominant for cooling below ~2.5×10^{-3} hPa.
- CH_4 infrared radiation (960-2000 cm^{-1}): Can be dominant for cooling above ~2.5×10^{-3} hPa, and very small effects below.
- Heating/cooling rates in upper stratosphere strongly depend on the composition.

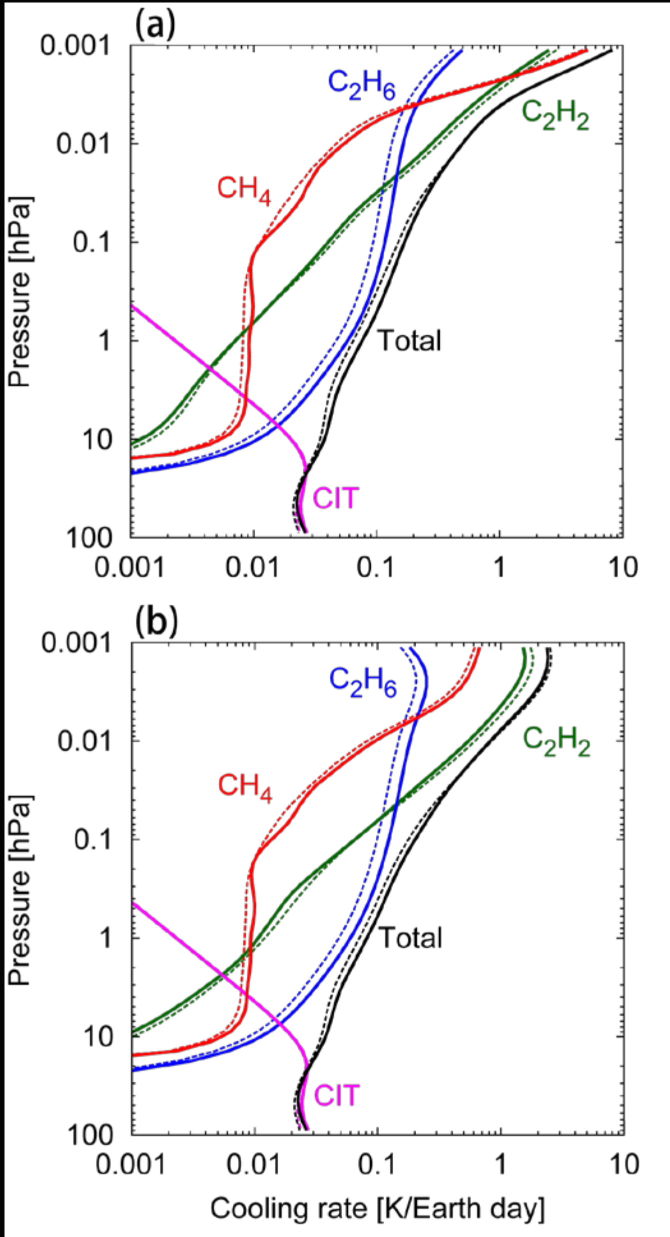
1-D calculation

(Solid: Band, Dashed: Line-by-line)

Sensitivity of molecules (infrared cooling)

'Model A' component

'Model C' component



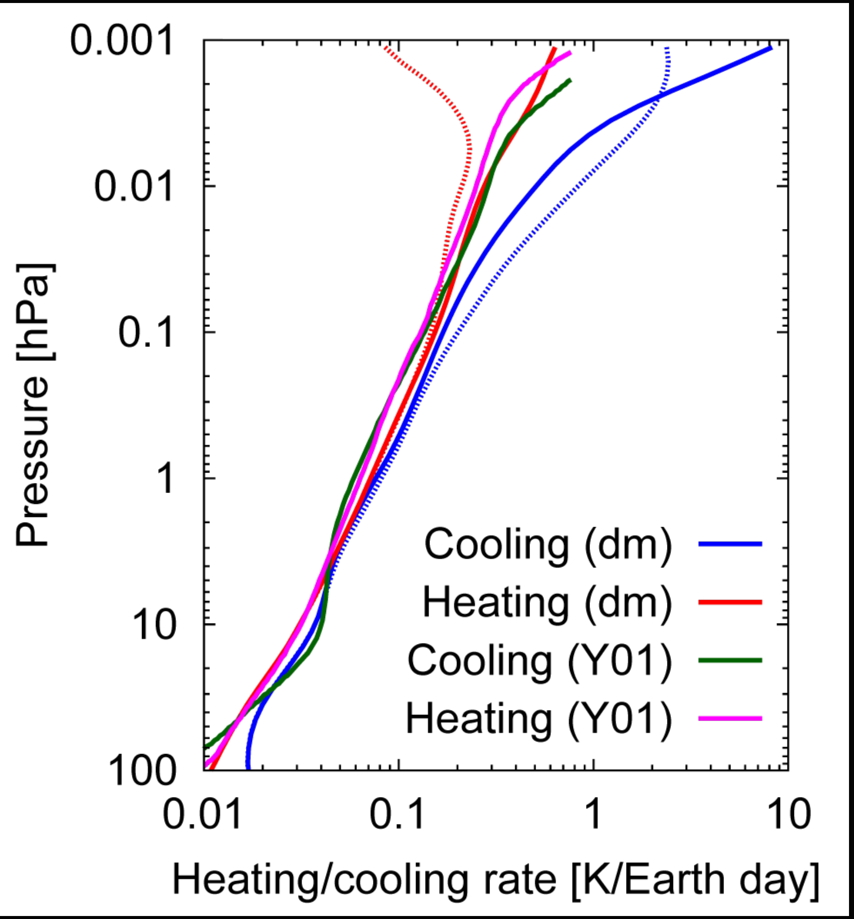
About the effect of cooling in 10-2100 cm^{-1}:

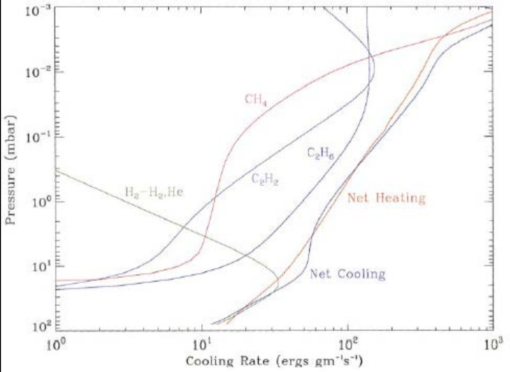
- C_2H_2 is dominant above ~0.03 hPa (up to ~3 K/day).
- C_2H_6 is dominant between 0.03-10 hPa (up to ~0.2 K/day in this height region).
- Collision-induced transitions are dominant below ~10 hPa (up tp ~0.03 K/day).
- CH_4 can be dominant around the boundary to thermosphere, but its effect is small in most of the stratosphere.

1-D calculation

Total heating/cooling rate (in comparison with a preceding study)

Total day-mean heating&cooling rates in comparison with Yelle et al. (2001)





[Yelle et al., 2001]

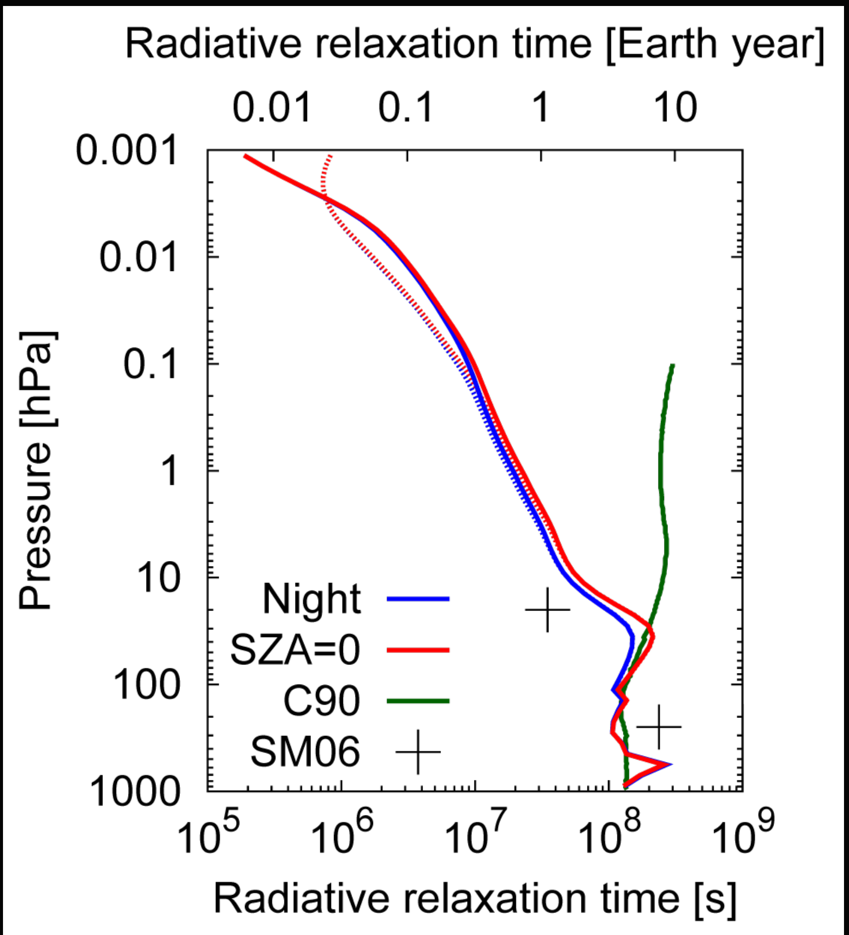
- Our calculations of day-mean net heating and cooling rates are in a good agreement with the results of Yelle et al. (2001), with radiative equilibrium.
- Above 0.1 hPa, our cooling rates exceed the heating rates, mainly due to stronger cooling by C_2H_2 in our model. (due to the lack of non-LTE effects…?)

1-D calculation

$$\tau = -\frac{\Delta T}{\Delta Q}$$

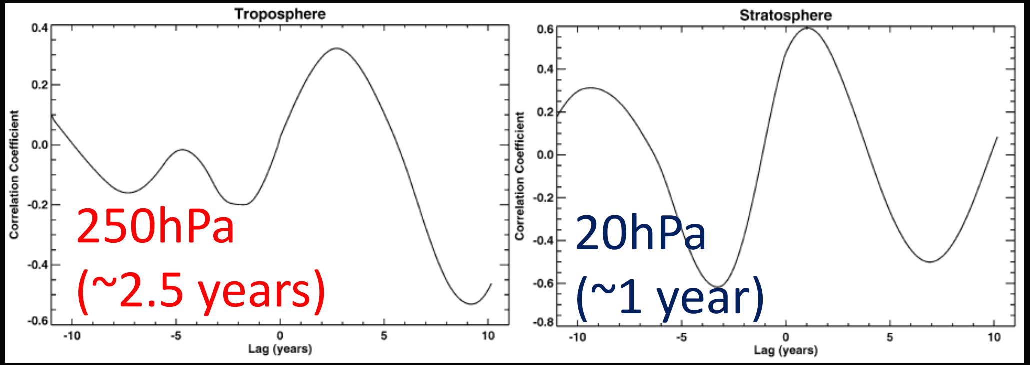
(From the difference of heating/ cooling rates for different temperature)

Daytime & nighttime,
Models A and C components



Radiative relaxation time

Cross correlation of subsolar latitude with the hemispheric temperature contrast (40°N-40°S) from IRTF observation (1979—2001) [Simon-Miller et al., 2006]

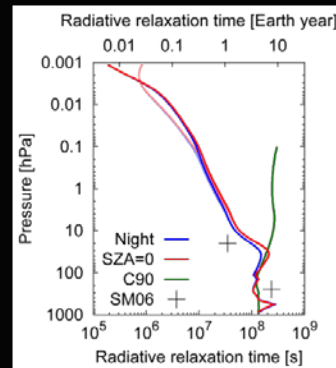


- The hemispheric temperature contrast lags the solar forcing longer in troposphere (~2.5 years) than in stratosphere (~1 year), which means the radiative relaxation time should be longer in troposphere.
- Our model shows qualitatively consistent results with the observation, while a preceding study [Conrath et al., 1990] does not.

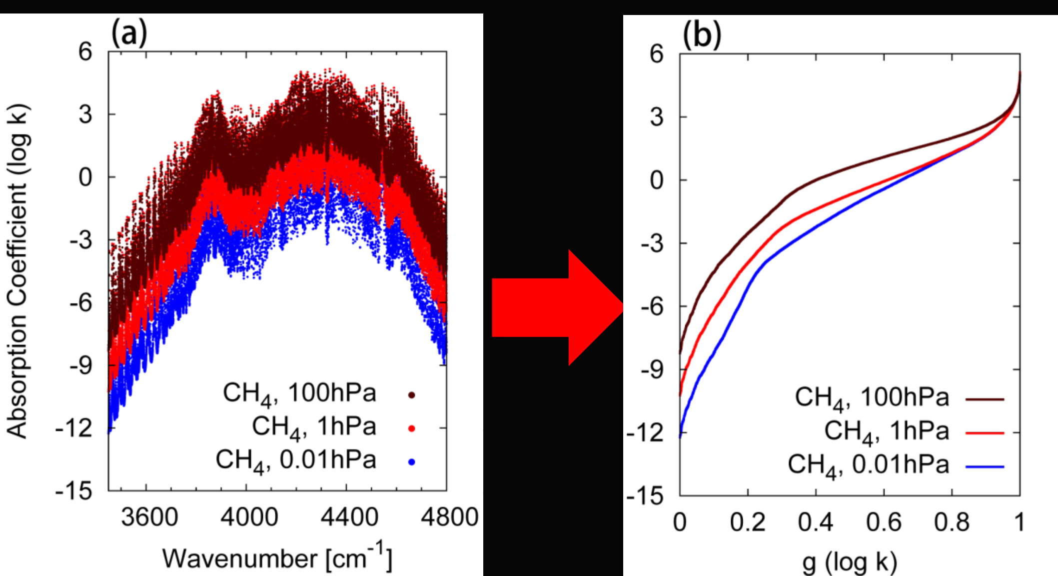
1-D calculation

Equation of solar heating rate in Conrath et al. [1990]

$$Q_S = \rho g \mu_0 \sum_{i=1}^{3} \frac{d \ln(\hat{p}_i N_1)}{dp} F_{\odot i} A_i \times \left[1 + \left(\frac{A_i d_i \mu_0}{2 S_i \gamma_i \hat{p}_i N_i}\right)^{1/2}\right]^{-1} + \rho g \frac{dN_1}{dp} \times (\bar{F}_{\odot a} \Delta\nu_a C_a e^{-C_a N_1/\mu_0} + (\bar{F}_{\odot b} \Delta\nu_b C_b e^{-C_b N_1/\mu_0}).$$



k-distribution



Radiative relaxation time

- The radiative relaxation time by Conrath et al. [1990] was shown to be longer in upper atmosphere, which contradicts the observations.
- It is because their model is simple and the heating/cooling rate is expressed to be proportional to the atmospheric density (pressure), which should underestimate the radiative effects in upper atmosphere.

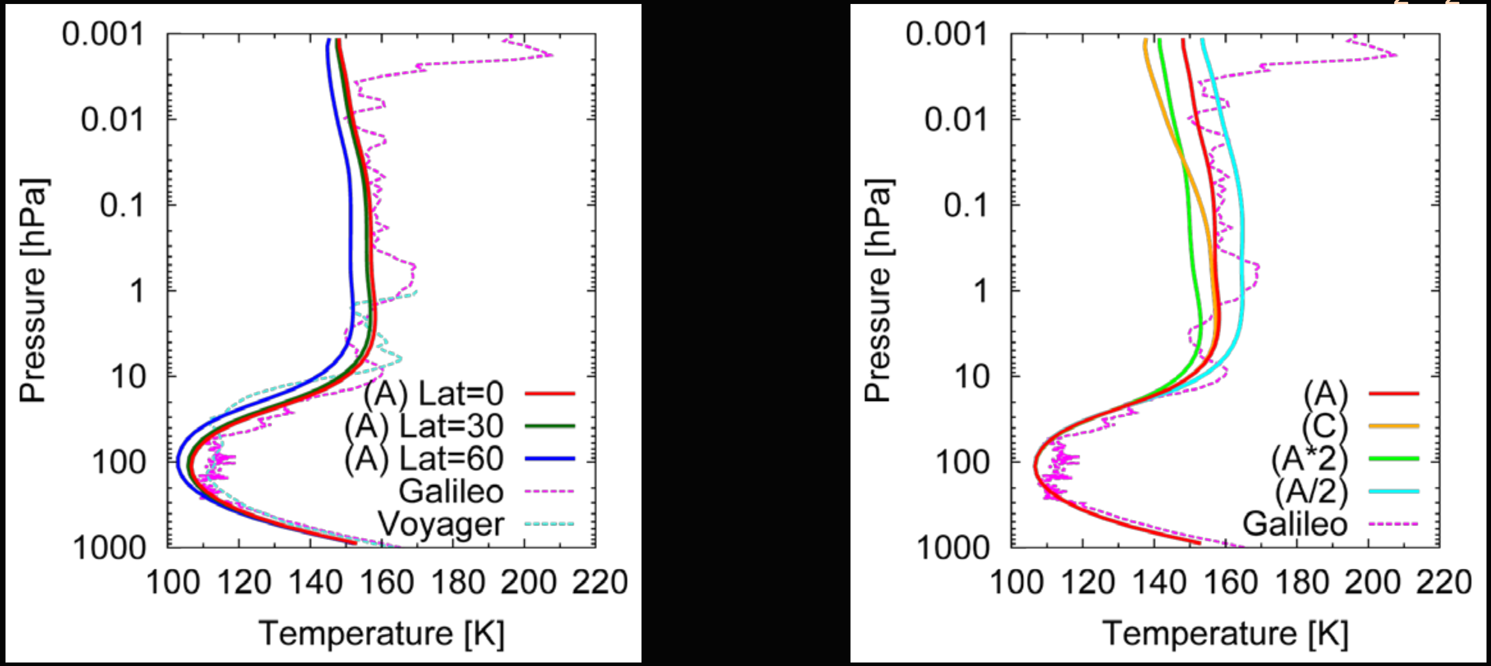
← At the peaks of spectra, the absorption coefficient becomes almost constant against the pressure. (except the peaks, proportional to pressute)

1-D calculation

Radiative-convective equilibrium temperature

Different latitudes (with observations)

Different components (Model A, Model C, Model A with twice more/less C_2H_2 and C_2H_6)



- Radiative-convective equilibrium temperature is close to the observed vertical profiles, except the upper stratosphere (due to the lack of non-LTE effects…?)
- In higher latitude, the equilibrium temperature is several Kelvins colder than the equator in overall. Note that the radiative effects of hazes are not included now, which may affect the temperature in high latitudes to increase.
- In the upper stratosphere, it is sensitive to the components.

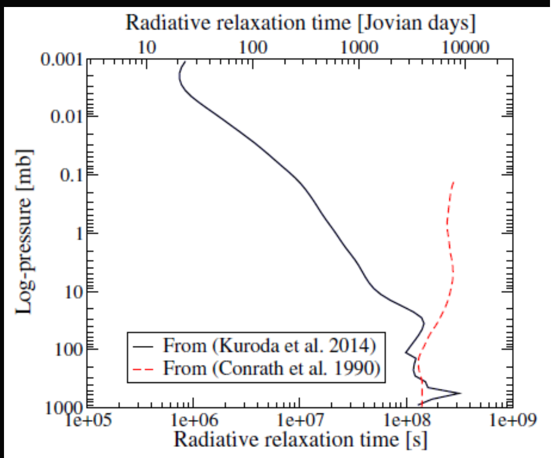
Development of the Jupiter stratospheric GCM

Current descriptions

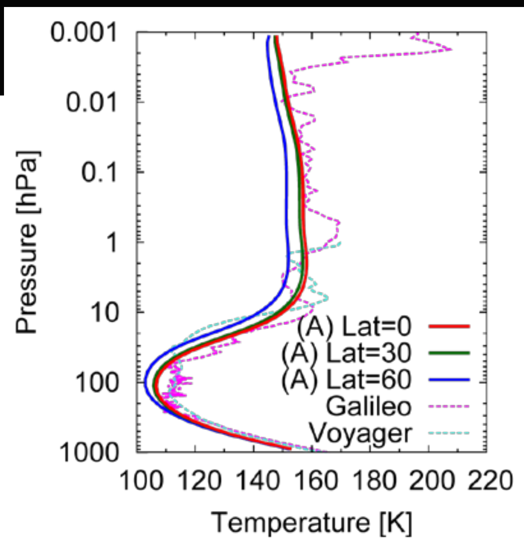
- Log-pressure coordinate in vertical
- 41 equally-spaced log-pressure levels in 0.01-1000 hPa (from cloud-top level to upper troposphere)
- Horizontal resolution of 240×180 grid points (1.5°×1°) in longitude and latitude, correspondingly
- Radiative parameterization with Newtonian cooling, which relaxes the simulated temperature toward the prescribed equilibrium T_{eq}
- With different radiative relaxation time τ_{rad}: from Conrath et al. (1990) to this study

Newtonian cooling

$$F_T = (T_{eq} - T)/\tau_{rad}.$$



T_{eq} is defined from this result



Development of the Jupiter stratospheric GCM

Why the high-resolution is required?

Rossby radius of deformation $L_D = NH/f \propto T/gf,$

Comparison with different planets [Showman et al., 2010; Sethunadh, 2014]

Planet	a (10^3 km)	Ω(rad s^{-1})	gravity(ms^{-2})	T_{eff}(K)	H(km)	U_c(ms^{-1})	L_D/a	L_β/a
Venus	6.05	3×10^{-7}	8.9	232	5	20	70	7
Earth	6.37	7.27×10^{-5}	9.82	255	7	20	0.3	0.5
Mars	3.396	7.1×10^{-5}	3.7	210	11	20	0.6	0.6
Titan	2.575	4.5×10^{-6}	1.4	85	18	20	10	3
Jupiter	**71.492**	**1.7×10^{-4}**	**24.79**	**124**	**27**	**40**	**0.03**	**0.1**
Saturn	**60.268**	**1.65×10^{-4}**	**10.44**	**95**	**60**	**150**	**0.03**	**0.3**
Uranus	25.56	9.7×10^{-5}	8.7	59	25	100	0.1	0.4
Neptune	24.76	1.09×10^{-4}	11.1	59	20	200	0.1	0.6

- The buoyancy force dominates the inertia for motions with the horizontal extent shorter than the Rossby radius of deformation.
- To simulate wave-mean flow interactions properly, GCMs must resolve motions shorter than the Rossby radius of deformation.
- Rossby radius of deformation is small for cold (small T), fast-rotating (large f), and massive (large g) planets like gas giants.

Development of the Jupiter stratospheric GCM

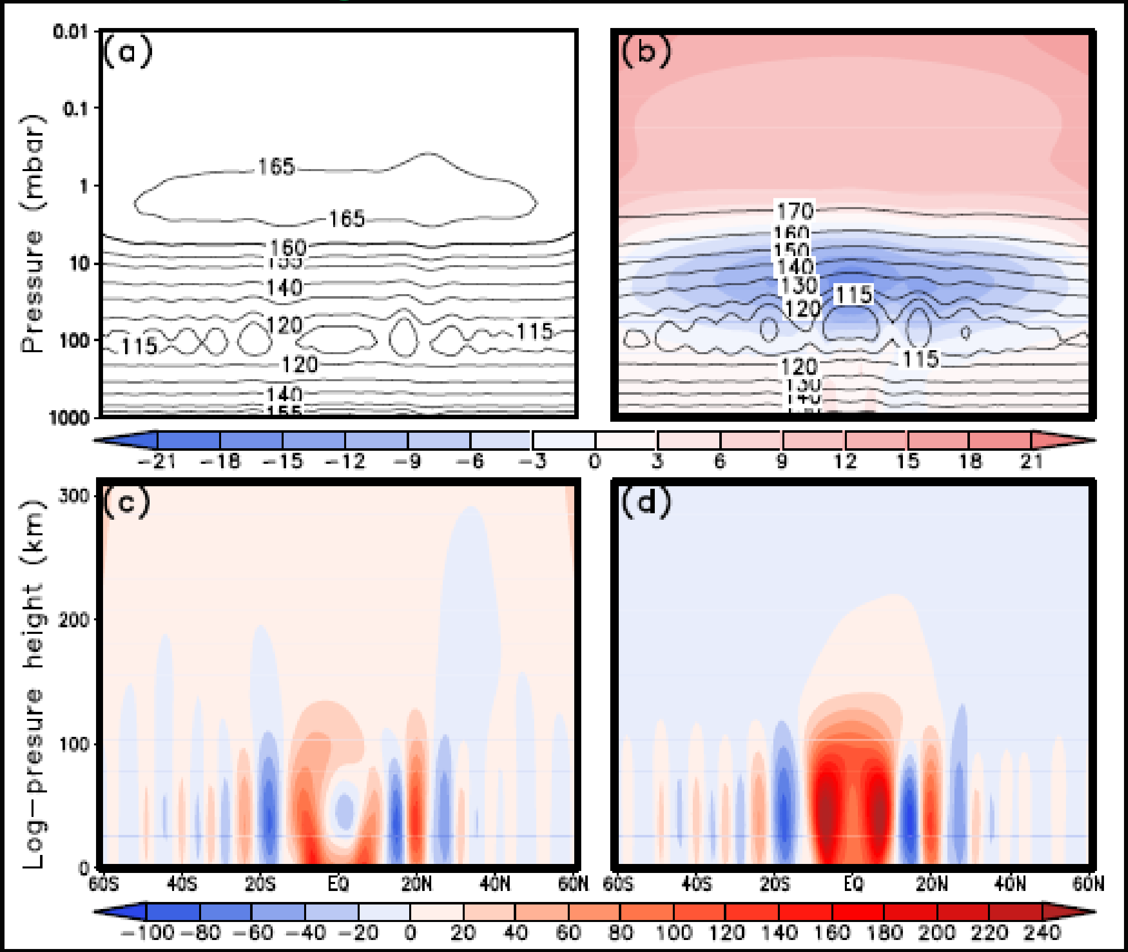
Current results

$\tau_{rad}=10^5$ s for all height (too strong in lower)

τ_{rad} profile of this study

Tempe-rature

Zonal wind



- It is seen that temperature adjusts closely to the prescribed T_{eq} under the strong radiative forcing.
- The zonal wind jets extend into the lower stratosphere and steeply decay with height.

(Lower boundary wind velocity is defined from Cassini/VIMS cloud tracking)

Development of the Jupiter stratospheric GCM

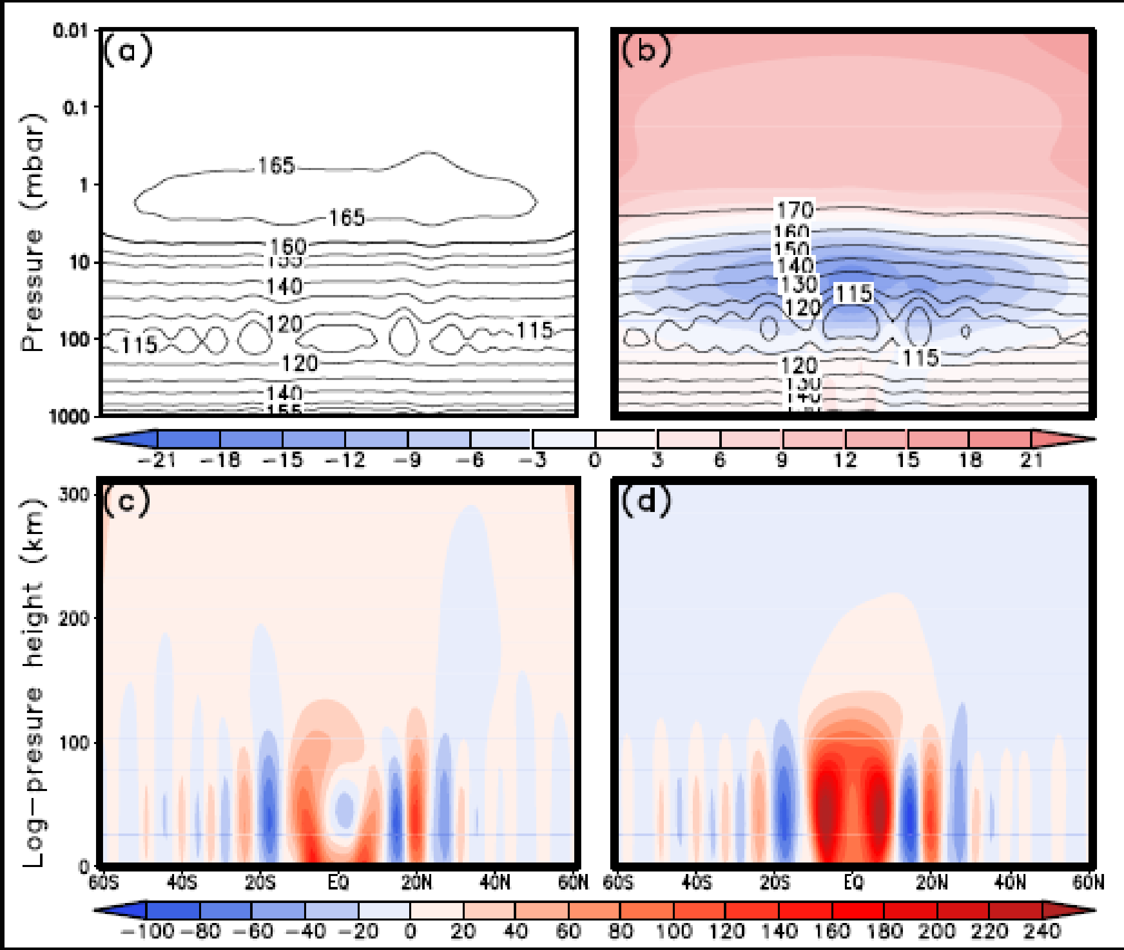
Current results

τ_{rad}=10^5 s for all height (too strong in lower)

τ_{rad} profile of this study

Tempe-rature

Zonal wind

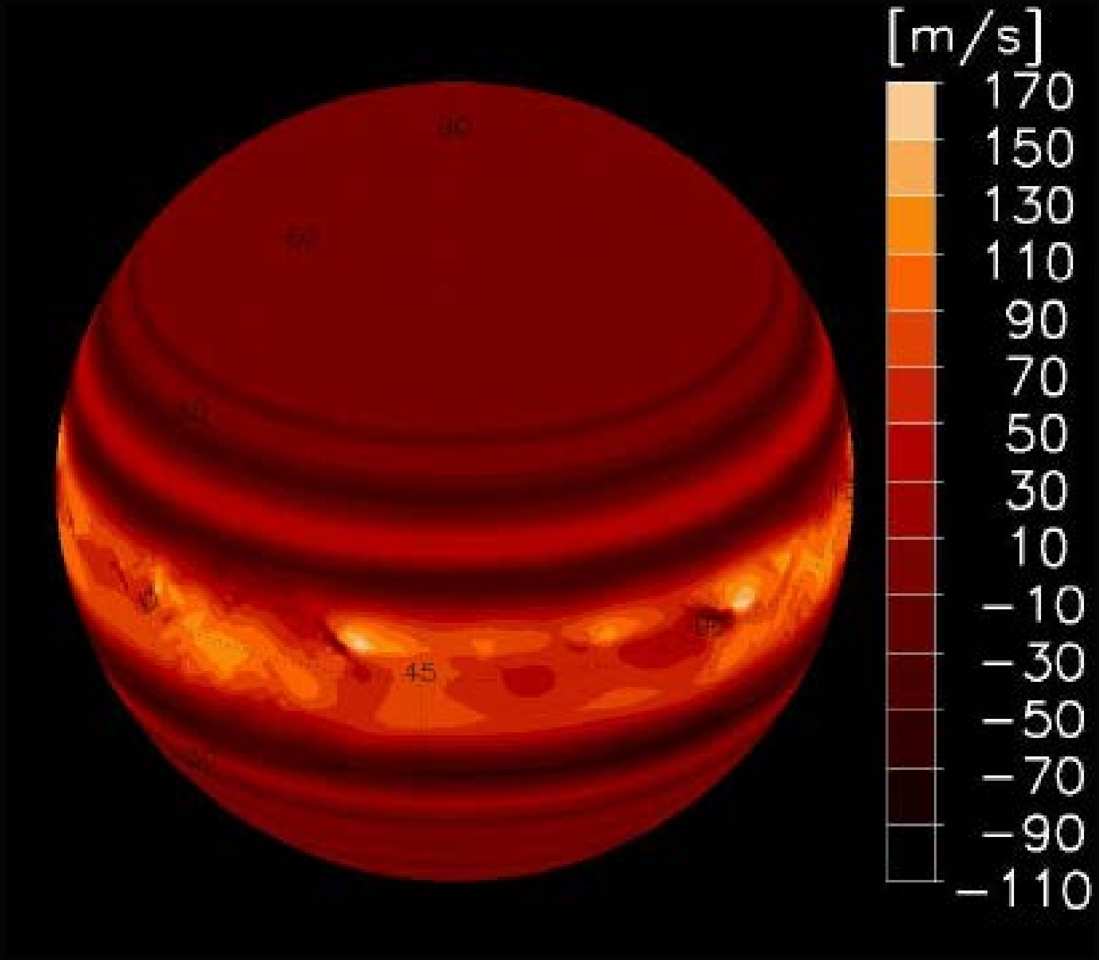


- With larger τ_{rad} (corresponding to Conrath's) the calculation fails very rapidly with temperature dropping continuously.
- With τ_{rad}= 10^6 s, simulations were very sensitive to the initial temperature disturbances.

(Lower boundary wind velocity is defined from Cassini/VIMS cloud tracking)

Development of the Jupiter stratospheric GCM

Current results



Zonal wind distribution at 30hPa using the vertical profile of radiative relaxation time in this study

Now the implementation of the k-distribution radiation code of this study into the GCM is ongoing!

(Lower boundary wind velocity is defined from Cassini/VIMS cloud tracking)

Summary

Publication about the k-distribution radiation code and 1-D calculations: Kuroda et al., Icarus 242, 149-157, 2014 "Parameterization of radiative heating and cooling rates in the stratosphere of Jupiter".

- A fast and effective band model for Jupiter's stratosphere was developed, calculating the heating/cooling rates in a good accuracy in comparison with the line-by-line calculations.
- The band model showed radiative equilibrium in the middle of Jupiter's stratosphere. In the upper stratosphere, the heat balance is very sensitive to the mixing ratios of hydrocarbons.
- It also showed that the radiative relaxation time becomes shorter in upper atmosphere, which is consistent with observations [Simon-Miller et al., 2006] and corrects the theoretical error in a preceding study [Conrath et al., 1990].
- Radiative-convective equilibrium temperature was calculated for different latitudes and composition. In low-latitude region, it is close to the observed temperature profiles.
- Radiative effects of stratospheric hazes are not included in the current version, which should be considered to implement in the future, as well as the non-LTE effects for upper stratosphere.
- Now we are starting the study with a Jupiter's stratospheric GCM which requires a high resolution. Implementation of this radiation code to the GCM is now ongoing.