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

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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 CH₄, H₂O, HCN, CO and CS in Jupiter’s stratosphere.
- From CH₄ 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).
Atmosphere of Jupiter

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

Here we focus on the **stratosphere**.

[Seiff et al., 1998]
Jupiter’s stratosphere

- 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$_2$H$_2$, C$_2$H$_6$, 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).
# Radiative band model

<table>
<thead>
<tr>
<th>Band</th>
<th>IR(infrared) /SO(solar)</th>
<th>Wavenumber range [cm(^{-1})]</th>
<th>Molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IR</td>
<td>10-200</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>2</td>
<td>IR</td>
<td>200-400</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>3</td>
<td>IR</td>
<td>400-600</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>4</td>
<td>IR</td>
<td>600-700</td>
<td>CH(_4), C(_2)H(_2), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>5</td>
<td>IR</td>
<td>700-860</td>
<td>C(_2)H(_2), C(_2)H(_6), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>6</td>
<td>IR</td>
<td>860-960</td>
<td>CH(_4), C(_2)H(_6), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>7</td>
<td>IR, SO</td>
<td>960-1200</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>8</td>
<td>IR, SO</td>
<td>1200-1400</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>9</td>
<td>IR, SO</td>
<td>1400-1700</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>10</td>
<td>IR, SO</td>
<td>1700-2100</td>
<td>CH(_4), H(_2)-H(_2), H(_2)-He</td>
</tr>
<tr>
<td>11</td>
<td>SO</td>
<td>2100-3450</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
<tr>
<td>12</td>
<td>SO</td>
<td>3450-4800</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
<tr>
<td>13</td>
<td>SO</td>
<td>4800-6300</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
<tr>
<td>14</td>
<td>SO</td>
<td>6300-7800</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
<tr>
<td>15</td>
<td>SO</td>
<td>7800-9200</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
<tr>
<td>16</td>
<td>SO</td>
<td>9300-10800</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
<tr>
<td>17</td>
<td>SO</td>
<td>10800-11800</td>
<td>CH(_4), H(_2)-H(_2)</td>
</tr>
</tbody>
</table>

- 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\(_2\)H\(_2\), 10 ppmv of C\(_2\)H\(_6\), 86.4 % of H\(_2\), 13.6 % of He) is fixed in making the table.
Molecular lines of CH$_4$, C$_2$H$_2$ (600-860 cm$^{-1}$) and C$_2$H$_6$ (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

CH$_4$ line spectra (3450-4800 cm$^{-1}$)

- 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 molecule (144 points in the bands the lines of 2 molecules are overlapped).
- The effects of collision-induced transitions are added.

About k-distribution
[e.g. Liou, 2002] k-distribution of the line spectra
1-D calculation

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

- 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)
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 \(\sim 2.5 \times 10^{-3}\) hPa.

CH\(_4\) infrared radiation (960-2000 cm\(^{-1}\)): Can be dominant for cooling above \(\sim 2.5 \times 10^{-3}\) hPa, and very small effects below.

Heating/cooling rates in upper stratosphere strongly depend on the composition.
About the effect of cooling in 10-2100 cm\(^{-1}\):

- \(\text{C}_2\text{H}_2\) is dominant above \(\sim 0.03\) hPa (up to \(\sim 3\) K/day).
- \(\text{C}_2\text{H}_6\) is dominant between 0.03-10 hPa (up to \(\sim 0.2\) K/day in this height region).
- Collision-induced transitions are dominant below \(\sim 10\) hPa (up to \(\sim 0.03\) K/day).
- \(\text{CH}_4\) can be dominant around the boundary to thermosphere, but its effect is small in most of the stratosphere.
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$_2$H$_2$ in our model. (due to the lack of non-LTE effects...?)
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]

\[ Q_s = \rho g \mu_0 \sum_{i=1}^{3} \frac{d \ln(\hat{p}_i N_i)}{dp} F_{\odot i} A_i \times \left[ 1 + \left( \frac{A_i d_i \mu_0}{2 S_{i} \gamma_i \hat{p}_i N_i} \right)^{1/2} \right]^{-1} + \rho g \frac{dN_i}{dp} \]

\[ \times \left( F_{\odot a} \Delta \nu_a C_a e^{-C_a N_i/\mu_0} + \left( F_{\odot b} \Delta \nu_b C_b e^{-C_b N_i/\mu_0} \right). \]

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.

\[ \leftarrow \text{At the peaks of spectra, the absorption coefficient becomes almost constant against the pressure. (except the peaks, proportional to pressure)} \]
• 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

- 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 $240 \times 180$ grid points ($1.5^\circ \times 1^\circ$) 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 $\tau_{rad}$: from Conrath et al. (1990) to this study

Newtonian cooling

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

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

- 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

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

\[ \tau_{\text{rad}} \text{ profile of this study} \]

- It is seen that temperature adjusts closely to the prescribed \( T_{\text{eq}} \) 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

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

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

(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

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.

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”.