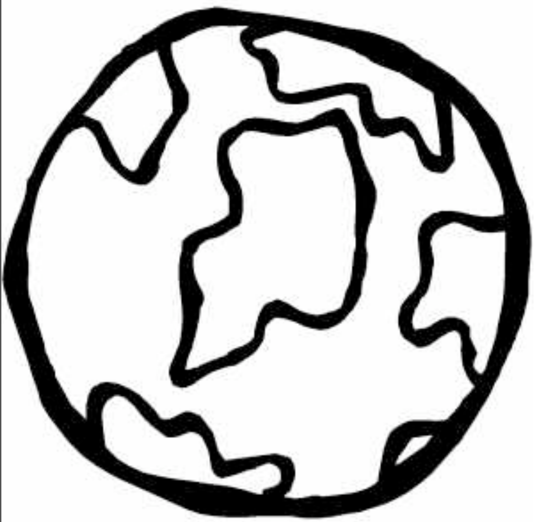
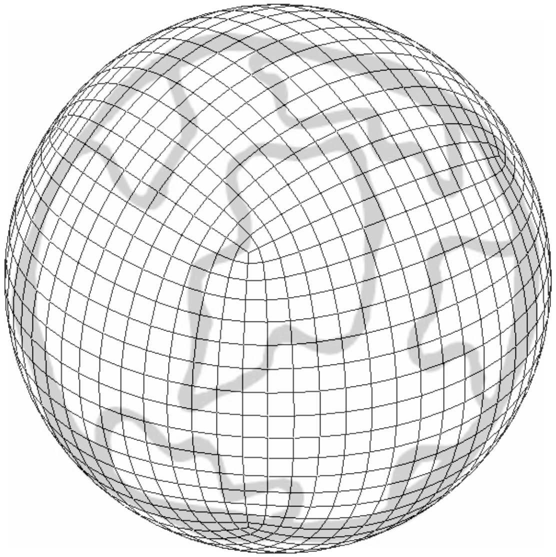
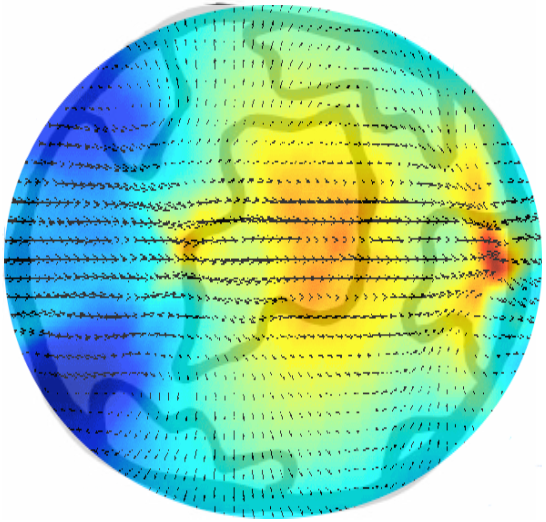
Extra Solar Planets Modeling.







Patricio Cubillos

Dic. 6th, 2010

Atmospheres II.

Introduction:

Hot Jupiters' intense irradiation sets up a strong radiative forcing regime.

Radiative transfer drives temperatures **toward** radiative equilibrium.

Thermal contrasts produce horizontal winds,
drives the atmosphere **away** from radiative equilibrium.

The radiative heating/cooling rate is nonzero,
that feedbacks the dynamics.

Understanding of the redistribution of energy require **radiative transfer** and **atmospheric circulation** models.

Introduction:

Radiative Transference:

Radiative transfer + Hydrostatic equilibrium + Energy Conservation

$\Rightarrow$

Temperature (***T***), Pressure (***p***), and Radiation Field (***F***)
as a function of altitude and wavelength.

A common form of the radiative transfer equation:

$$\cos\theta \frac{\mathrm{d}I(\tau,\lambda,\mu,t)}{\mathrm{d}\tau} + I(\tau,\lambda,\mu,t) = B(\tau,\lambda,t)$$

The physics of radiative transference lays behind the **opacities** and **chemical abundances**.

Introduction:

Atmospheric circulation:

- The large-scale movement of gas in a planetary atmosphere.
- Distributes the energy.
- Very important in planets with strong external radiative forcing.

Models are based on the fluid dynamic equations:
Conservation of mass, momentum, energy, and equation of state.

Approximations $\Rightarrow$ Primitive equations.

- the vertical momentum $\Rightarrow$ local hydrostatic balance
- drop vertical acceleration, advection, coriolis ...
  such energy is still conserved.

Introduction:

Atmospheric circulation:

- The large-scale movement of gas in a planetary atmosphere.
- Distributes the energy
- Very important in planets with strong external radiative forcing.

Models are based on the fluid dynamic equations:

Approximations $\Rightarrow$ Primitive equations.

$\frac{d\mathbf{v}}{dt} = -\nabla\Phi - f\mathbf{k}\times\mathbf{v} + \mathcal{D}_{\mathbf{v}}$	Horizontal momentum
$\frac{\partial\Phi}{\partial p} = -\frac{1}{\rho}$	Vertical momentum
$\nabla\cdot\mathbf{v} + \frac{\partial\omega}{\partial p} = 0$	Continuity
$\frac{dT}{dt} = \frac{Q}{c_p} + \frac{\omega}{\rho c_p} + \mathcal{D}_T$	Energy

3-D Transmission Spectrum models:

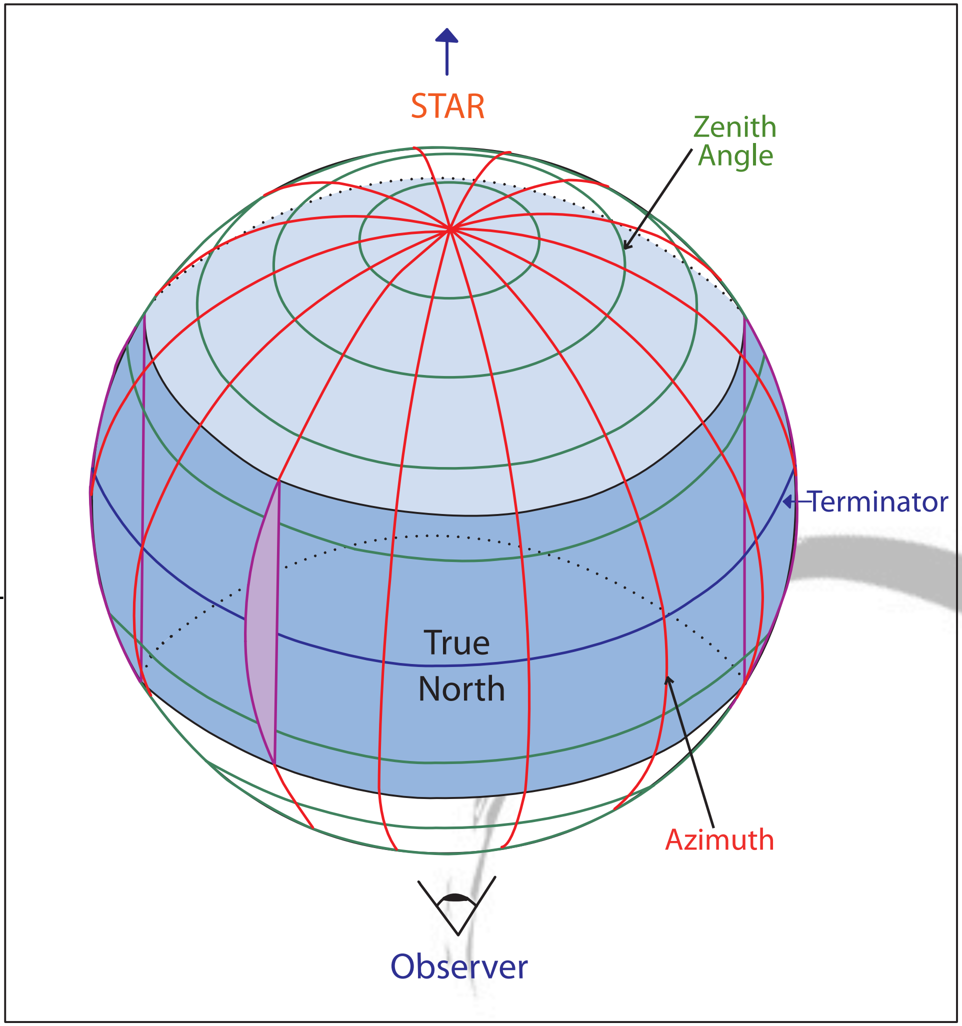
Fortney et al. 2010.

Three dimensional code to compute the transmission spectrum.

- Star-planet-Earth oriented ~Latitude/Longitude coordinates.

- "Two streams" approximation radiative-transfer code.

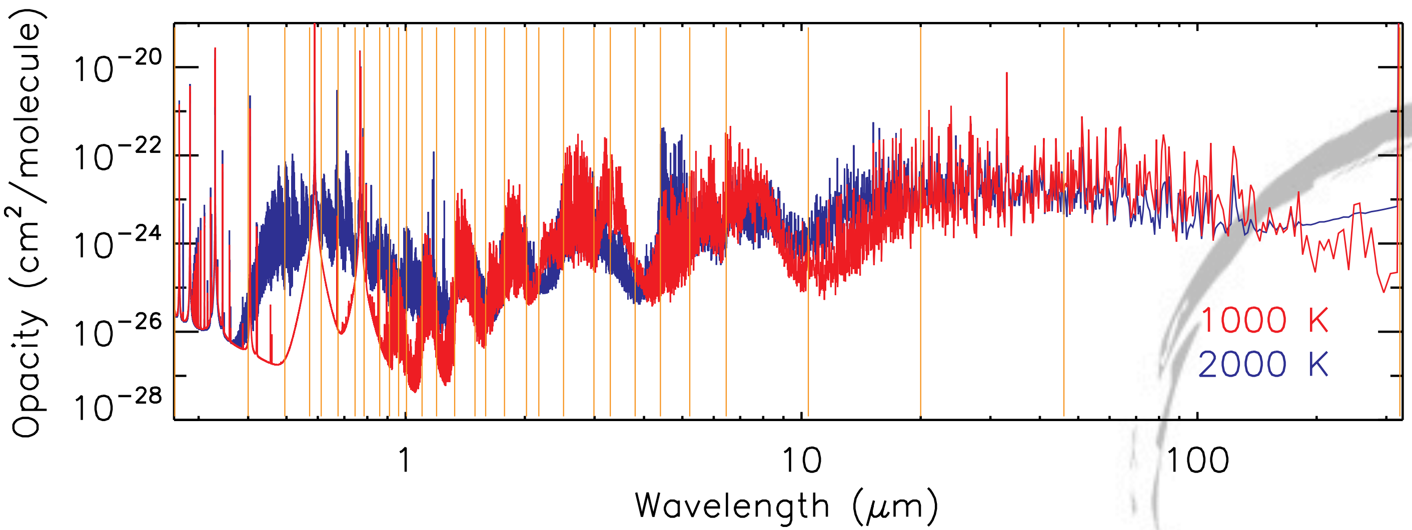
- Fed by MITgcm circulation model to obtain *T*(*p*) and calculate vertical flux.



3-D Transmission Spectrum models:

Fortney et al. 2010.

- Opacities first calculated Line-by-line.
- Voigh profile broadened.
- Wavelength binned spectrum.
- Gas depletion via condensation.
- Cloud/hazes opacities neglected.
- Rayleigh scattering accounted.



Opacities:

Freedman et al. 2008.

- Accounts for cloud depletion.
- Neglects clouds opacity.
- Chemistry determines the source of opacity.

- Main molecules: H_2O, CH_4, NH_3, CO, H_2S, PH_3, TiO, VO, FeH, CrH.
- Voight profile.
- Alkali Atoms: Cs, Rb, Li, and particularly Na and K.

- Collision Induced Absorption due to H_2–H_2, H_2–He, and H_2–H.
- Bound-free absorption by H and H^-
- Free-free absorption by H, H_2, H_2^- and H^-.

- Rayleigh scattering from H2 and Thompson scattering are also included.

Chemical Equilibrium:

Lodders and Fegley 2002.

CONDOR code computes chemical equilibrium:

- Depends on abundances, temperatures and pressures.
- Metallicity: solar abundance uniformly enhanced or depleted.
- Condensates "rain out", and deplete atmosphere above.
- Few components found to be important opacity sources.

Parametric P-T atmospheric profile:

Madhusudhan and Seager 2009.

1D parametric pressure-temperature profile.

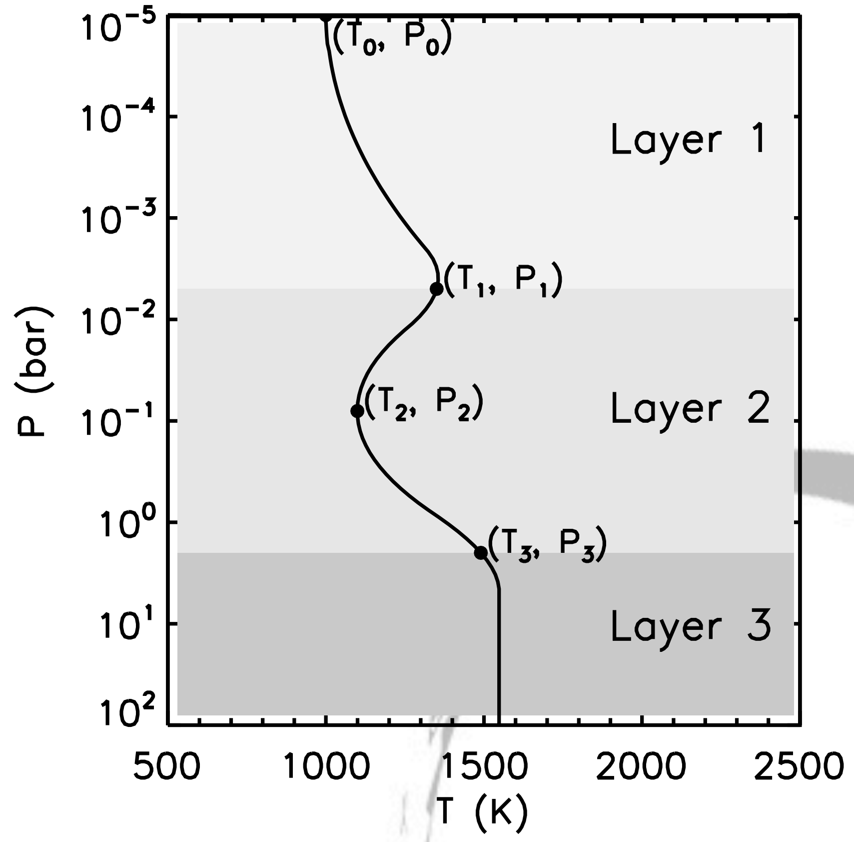
- Line-by-line radiative transfer.
- Assumes LTE.

- Does not include scattering.

- Does not include photochemistry.

- Does not include clouds.

- Finds parametric prescriptions for molecule abundances, chemistry, cloud opacity.



MIT global circulation model:

Showman et al. 2009.

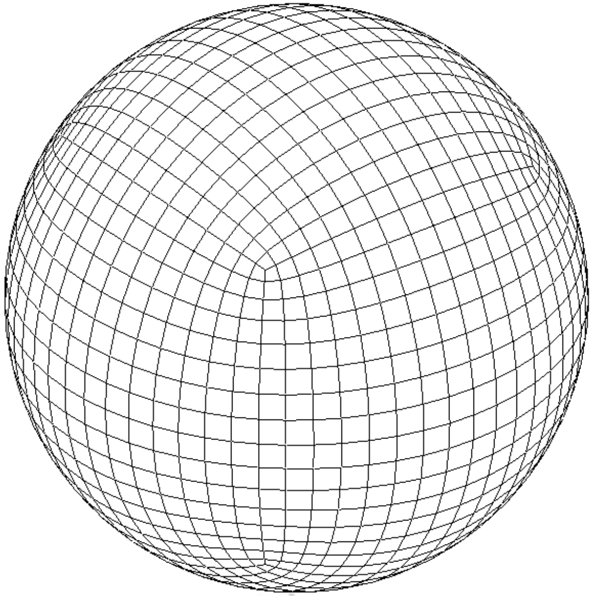
State-of-the-art atmospheric and oceanic circulation model to solve the global primitive equations.

Energy equation solved as function of the potential temperature:

$$\frac{d\theta}{dt} = \frac{\theta}{T}\frac{q}{c_p} + \mathcal{D}_\theta$$

Adopt "cubed sphere" grid:

- Allows near uniform coverage.
- Longer time-steps.
- No polar singularities.

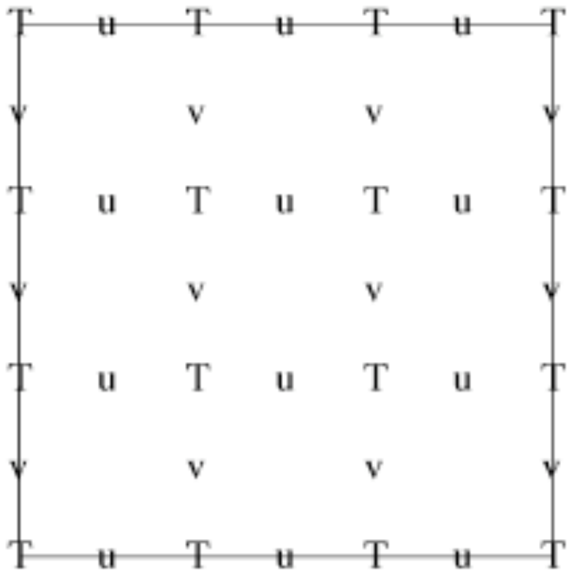


MIT global circulation model:

Showman et al. 2009.

Price:
- Non orthogonal grid.
- Eight "corners".

Variables spatially staggered using the Arakawa C-grid.



Coupled to Radiative Transference model

$\Longrightarrow$

No newtonian relaxation scheme.

Intermediate Global Circulation Model:

Menou and Rauscher 2009.

Pseudospectral solver of meteorological equations.

- Earth-like and hot Jupiter planets
- Does not address radiative or chemical structure.
- Latitude/ Longitude scheme.
- The horizontal momentum equations are solved for vorticity and divergence:

$$\frac{d\mathbf{v}}{dt} = -\nabla\Phi - f\mathbf{k}\times\mathbf{v} + \mathcal{D}_{\mathbf{v}} \quad \Rightarrow$$

$$\frac{\partial\zeta}{\partial t} = \frac{1}{1-\mu^2}\frac{\partial\mathcal{F}_V}{\partial\lambda} - \frac{\partial\mathcal{F}_U}{\partial\mu} + Q_{\mathrm{vor}} + Q_{\mathrm{vor}}^{\mathrm{hyp}}$$

$$\frac{\partial D}{\partial t} = \frac{1}{1-\mu^2}\frac{\partial\mathcal{F}_U}{\partial\lambda} + \frac{\partial\mathcal{F}_V}{\partial\mu} - \nabla^2\left[\frac{U^2+V^2}{2(1-\mu^2)} + \Phi + T_{\mathrm{ref}}\ln p_{\mathrm{surf}}\right] + Q_{\mathrm{div}} + Q_{\mathrm{div}}^{\mathrm{hyp}}$$

Intermediate Global Circulation Model:

Menou and Rauscher 2009.

Pseudospectral solver of meteorological equations.

The model assumes Newtonian relaxation to T_{eq}, and linear drag on vorticity and divergence:

$$Q_T = \frac{T_{eq} - T}{\tau_{rad}} \qquad Q_{vor} = -\frac{\zeta - 2\mu}{\tau_{fric}}, \qquad Q_{div} = -\frac{D}{\tau_{fric}}$$

Equilibrium temperature used has a troposphere, where temperature decreases with height at a fixed rate, and a isothermal stratosphere.

$$T_{eq}^{vert}(z) = T_{surf} - \Gamma_{trop}\left(z_{stra} + \frac{z - z_{stra}}{2}\right) + \sqrt{\left(\frac{1}{2}\Gamma_{trop}[z - z_{stra}]\right)^2 + \delta T_{stra}^2}$$

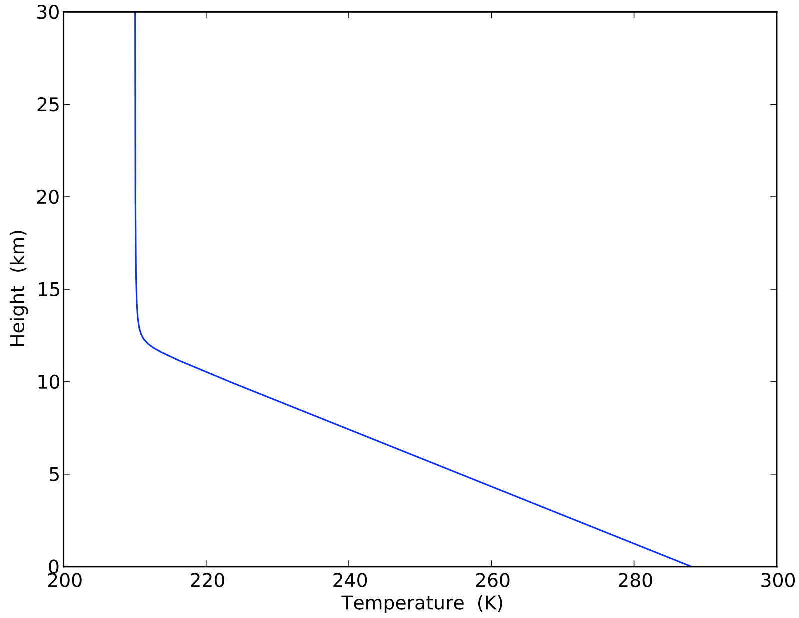
Intermediate Global Circulation Model:

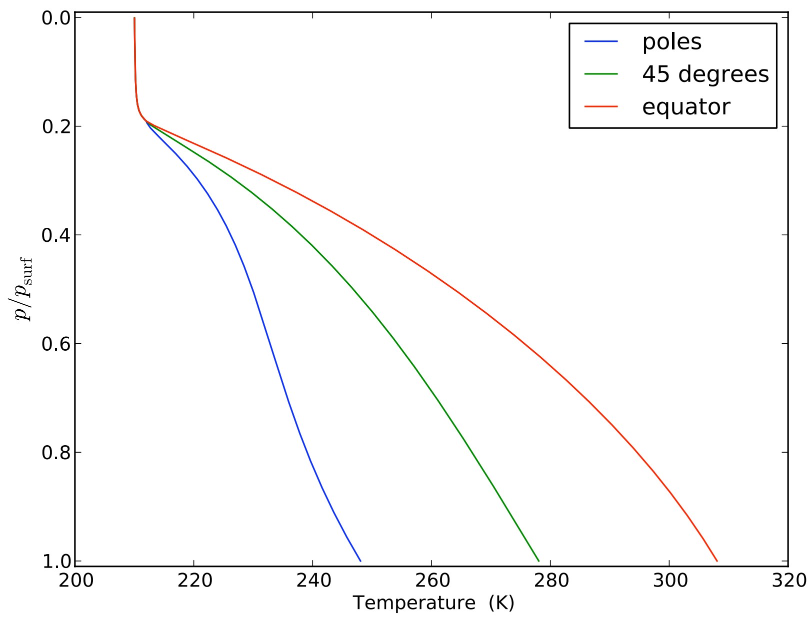
Menou and Rauscher 2009.

Earth like equilibrium *p-T* profile:

Differential profile is forced in the troposphere:

$$T_{\rm eq}(\sigma,\lambda,\phi) = T_{\rm eq}^{\rm vert}(\sigma) + \beta_{\rm trop}(\sigma)\Delta T_{\theta}(\lambda,\phi)$$





Intermediate Global Circulation Model:

Menou and Rauscher 2009.

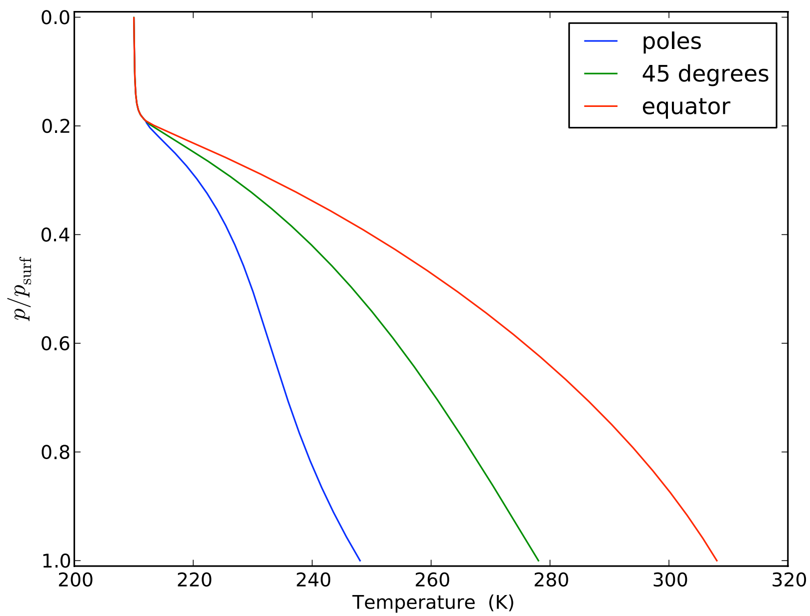
Differential irradiation forcing:

$$T_{\text{eq}}(\sigma,\lambda,\phi) = T_{\text{eq}}^{\text{vert}}(\sigma) + \beta_{\text{trop}}(\sigma)\Delta T_\theta(\lambda,\phi)$$

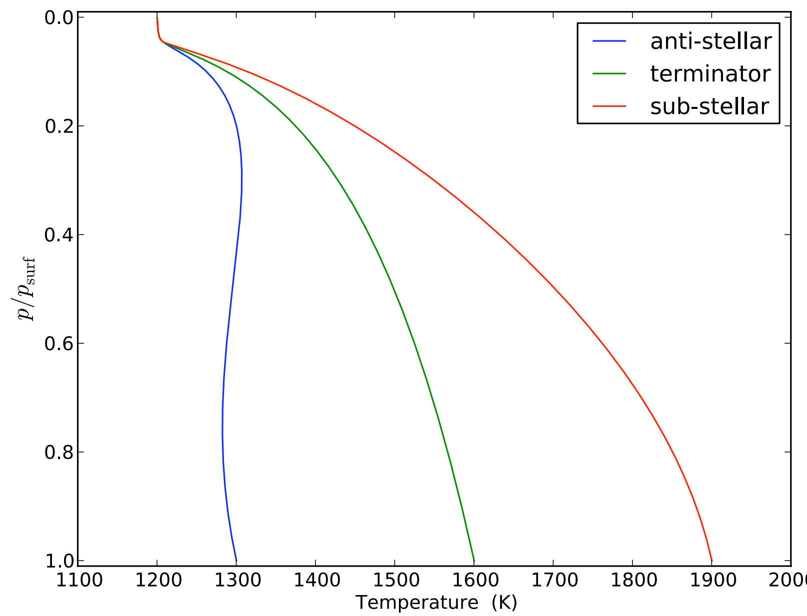
$$\Delta T_\theta(\lambda,\phi) = \Delta T_\theta(\phi) = \left(\tfrac{1}{3} - \sin^2\phi\right) \times \Delta T_{\text{EP}}$$

$$\Delta T_\theta(\lambda,\phi) = \cos\lambda\cos\phi \times \Delta T_{\text{EP}}$$

Earth-like:



Hot Jupiter:



Global Circulation Models:

To wrap up:

Showman et al. 2009 uses a coupled radiative transference and global circulation model.

Most other authors include a radiative forcing that drives the temperature to an assume $T_{eq}(\lambda, \phi)$, e.g.:

Cho et al. 2008.
Langton and Laighlin 2008.
Menou and Rauscher 2009.