The Thermospheric Gravity Wave Parameterizations in WACCM-X

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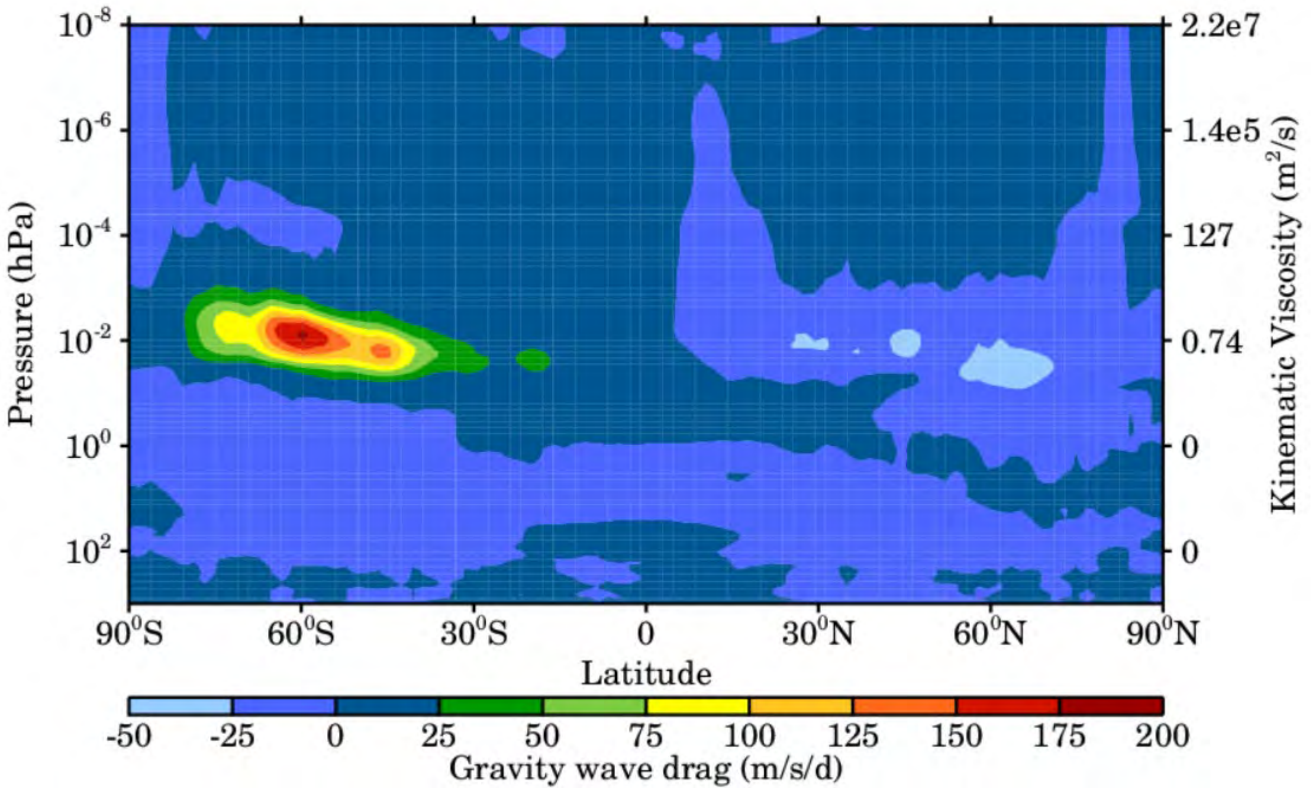
Background

- **Molecular damping (including kinematic viscosity and thermal diffusivity) plays a major role on the dissipation of gravity waves in the thermosphere.**

- **Dissipation mainly occurs near the mesopause due to wave breaking effects in current WACCM-X.**

- **Molecular damping effects are not considered in the thermosphere in current WACCM-X.**

Current WACCM-X results in January



Governing equations

$$\frac{\partial u'}{\partial t} + R\frac{\partial T'}{\partial x} + \frac{{C_s}^2}{\gamma\rho_0}\frac{\partial \rho'}{\partial x} = \mu\left(\frac{\partial^2 u'}{\partial x^2} + \frac{\partial^2 u'}{\partial z^2}\right),\ (1)$$

$$\frac{\partial w'}{\partial t} + R\frac{\partial T'}{\partial z} + \frac{{C_s}^2}{\gamma\rho_0}\frac{\partial \rho'}{\partial z} + \frac{R\rho'}{\rho_0}\frac{\partial T_0}{\partial z} + \frac{{C_s}^2}{\gamma}\left(\frac{\rho'}{H\rho_0} - \frac{T'}{h_\rho T_0}\right) = \mu\left(\frac{\partial^2 w'}{\partial x^2} + \frac{\partial^2 w'}{\partial z^2}\right),\ (2)$$

$$\frac{\partial \rho'}{\partial t} + \rho_0\left(\frac{\partial u'}{\partial x} + \frac{\partial w'}{\partial z}\right) - \frac{\rho_0}{h_\rho}w' = 0,\ (3)$$

$$\frac{\partial T'}{\partial t} + (\gamma - 1)T_0\left(\frac{\partial u'}{\partial x} + \frac{\partial w'}{\partial z}\right) - (\gamma - 1)\frac{\partial T_0}{\partial z}w' = \gamma\eta\left(\frac{\partial^2 T'}{\partial x^2} + \frac{\partial^2 T'}{\partial z^2}\right),\ (4)$$

Where u and w are horizontal and vertical velocities, respectively; T is temperature; ρ is density; R is gas constant for dry air; C_s is acoustic speed; γ is ratio of specific heat; H is pressure scale height; h_ρ is density scale height; μ is kinematic viscosity; η is thermal diffusivity; The prime denotes the first-order gravity wave perturbation variables; and the subscript 0 is for the background variables. The Coriolis force are neglected because we are interested in small-middle scales gravity waves. The iron drag is also neglected in this study.

Viscous dispersion relations

- **The real part of dispersion relation is**

$$\left(8\mu\omega m_i + \frac{2\mu\omega}{H}\right) m_r^3 + \omega^2 m_r^2 + \left(-8\mu\omega {m_i}^3 + 8\mu\omega m_i k^2 - \frac{6\mu\omega {m_i}^2}{H} + \frac{2\mu\omega k^2}{H} + \frac{\mu\omega}{2H^3}\right) m_r$$
$$+ \left(k^2 - m_i^2 + \frac{1}{4H^2}\right)\omega^2 - k^2 N^2 = \ 0, \qquad (5)$$

- **The imaginary part of dispersion relation is**

$$2\mu\omega m_i^4 + \frac{2\mu\omega m_i^3}{H} - \left(12\mu\omega m_r^2 + 4\mu\omega k^2\right) m_i^2 - \left(2\omega^2 m_r + \frac{6\mu\omega {m_r}^2}{H} + \frac{2\mu\omega k^2}{H} + \frac{\mu\omega}{2H^3}\right) m_i$$
$$+ \left(2m_r^4 + 4m_r^2 k^2 + 2k^4 - \frac{1}{8H^4}\right)\mu\omega = 0, \qquad (6)$$

1. Set wave solutions as : $\frac{u\prime}{\hat{u}} = \frac{w\prime}{\hat{w}} = \frac{p\prime}{p_0\hat{p}} = \frac{\rho\prime}{\rho_0\hat{\rho}} = \frac{T\prime}{T_0\hat{T}} = Ae^{i\left(\omega t - kx - (m + \frac{i}{2H})z\right)}$
2. Isothermal atmosphere hypothesis
3. Ignore acoustic speed terms
4. Set Prandtl number as 1
5. Set vertical wavenumber $m = \ m_r + i m_i,\ m_i$ expresses the inverse decay rate

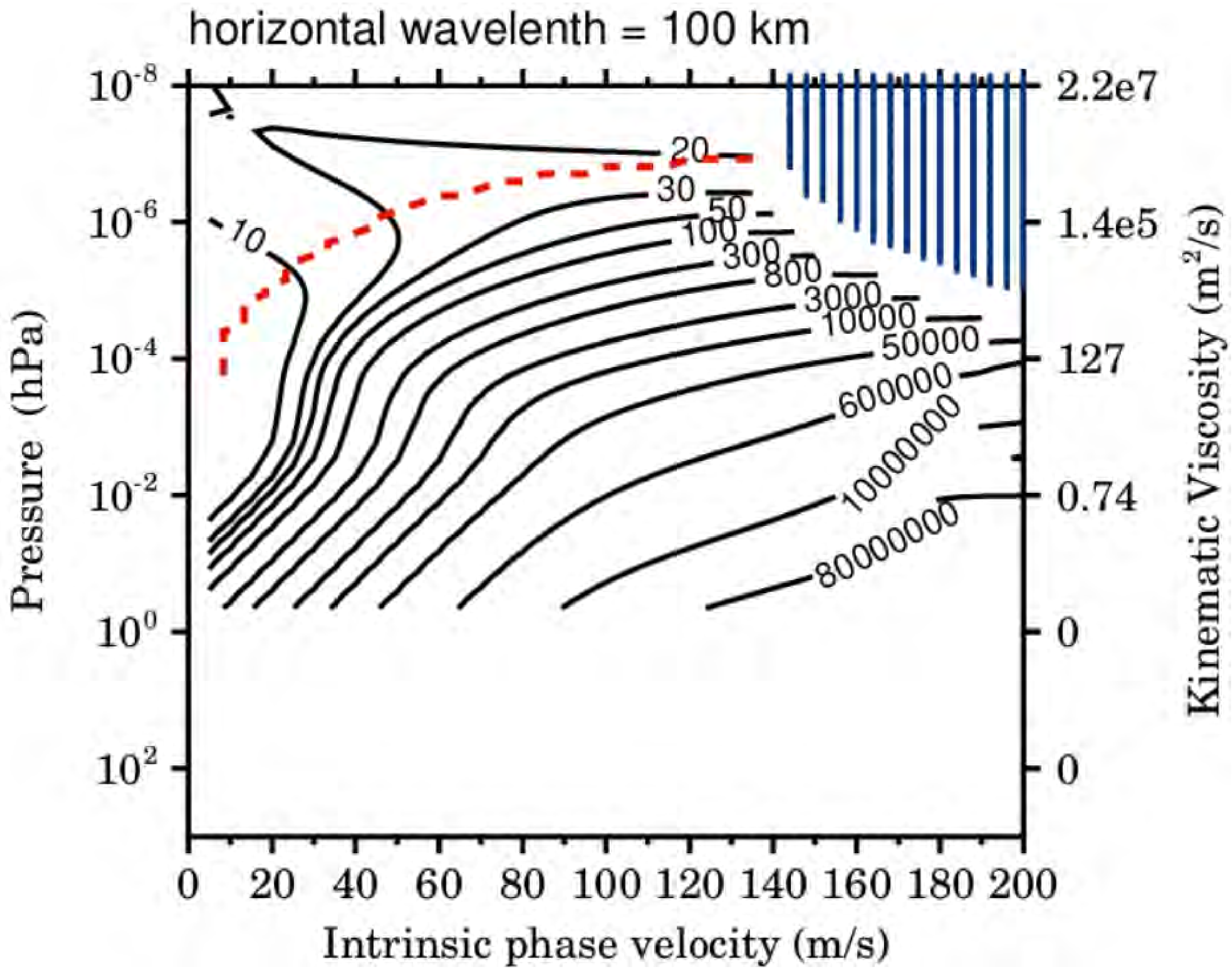
Vadas and Fritts, 2005, (19)

No molecular terms

Hines, 1960, (21)

Solutions of mi

mi scale height

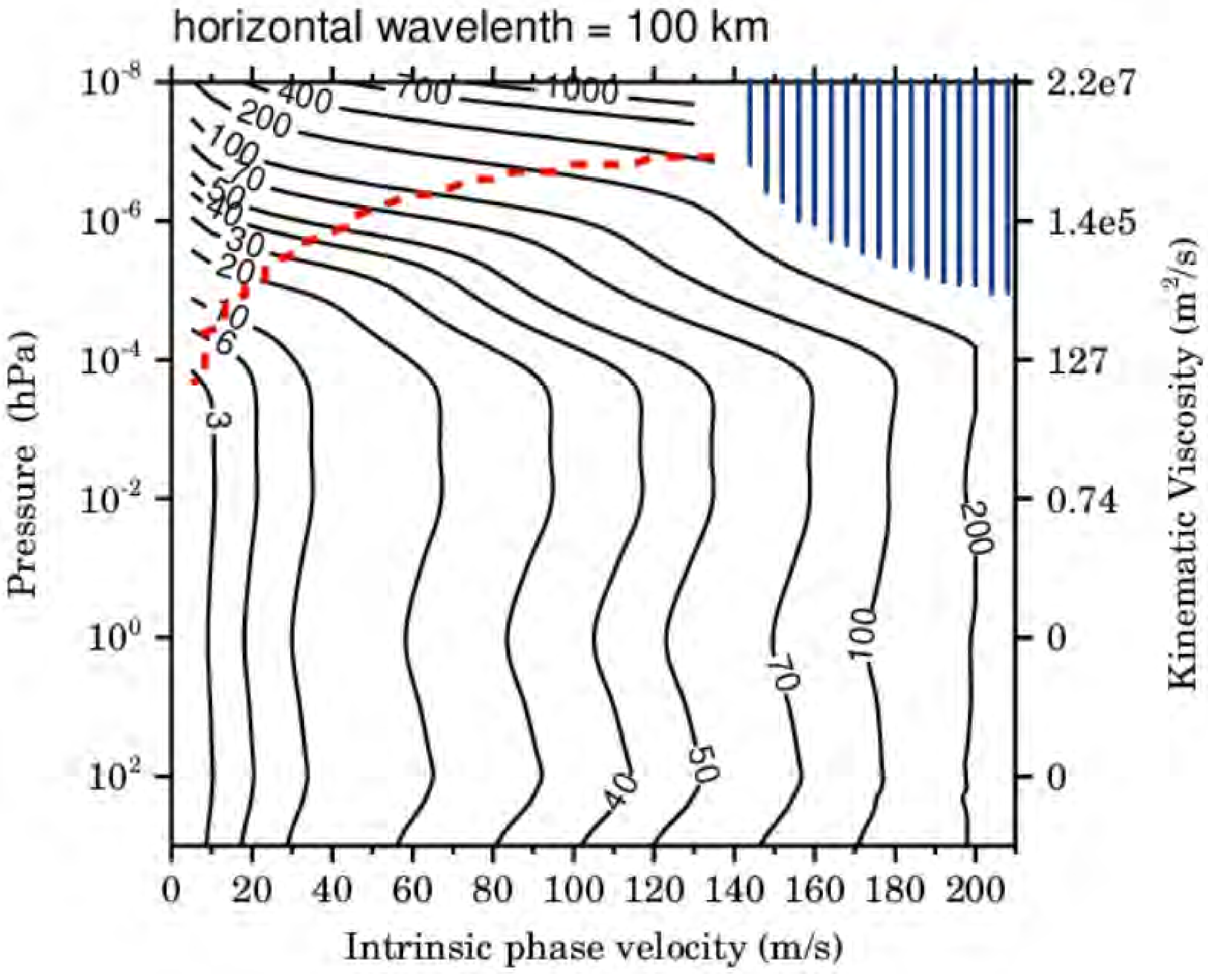


- mi scale height $= -\frac{1}{1000*mi}$
- The red dotted line denotes the dissipation height, where $Period_{molecular\ damping} = Period_{graviy\ wave}$
- The blue stippled field is the reflection region, where the GW frequency is larger than the B-V frequency.

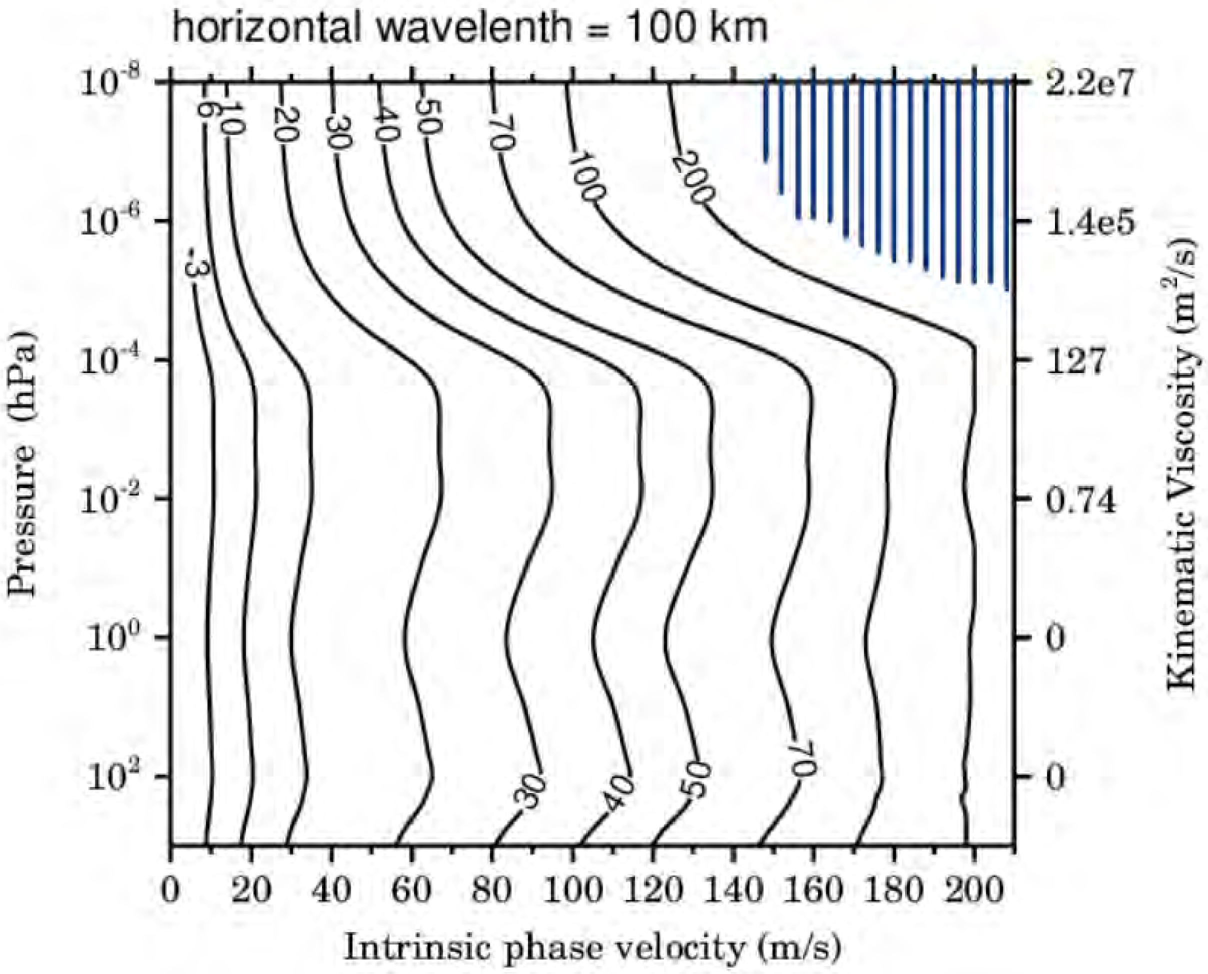
Solutions of mr

- **Vertical wavelength =** $\frac{2\pi}{-\mathrm{mr}}$

Vertical wavelength with molecular damping



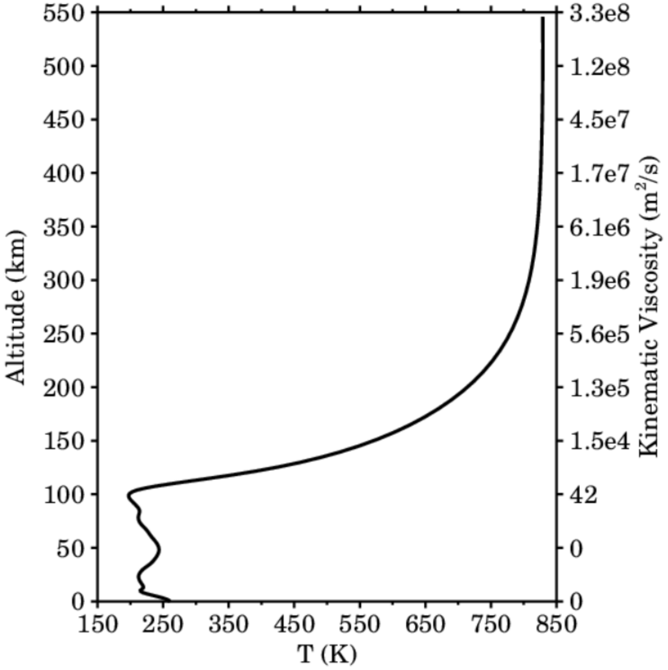
Vertical wavelength without molecular damping

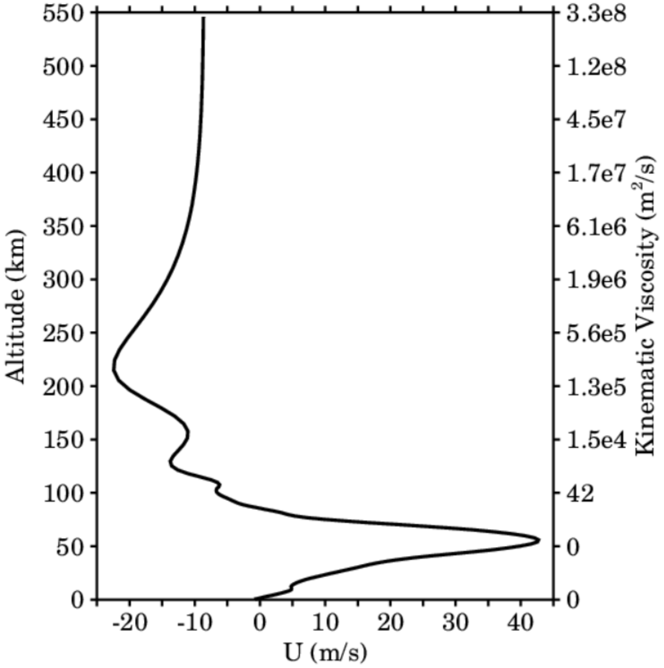


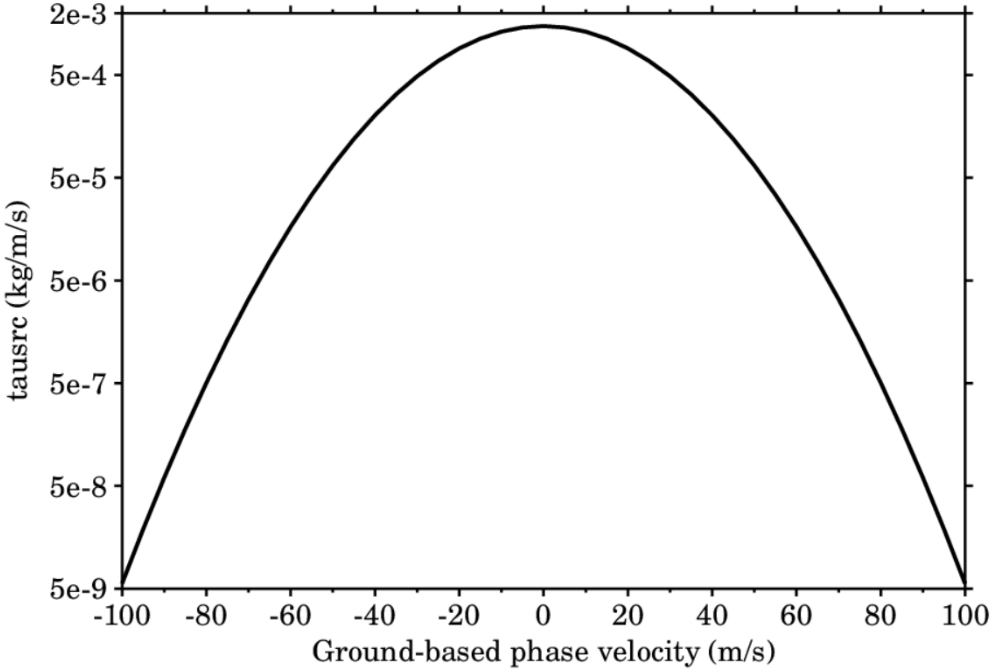
Column WACCM-X model results

Upward propagating GWs at 60°N in January

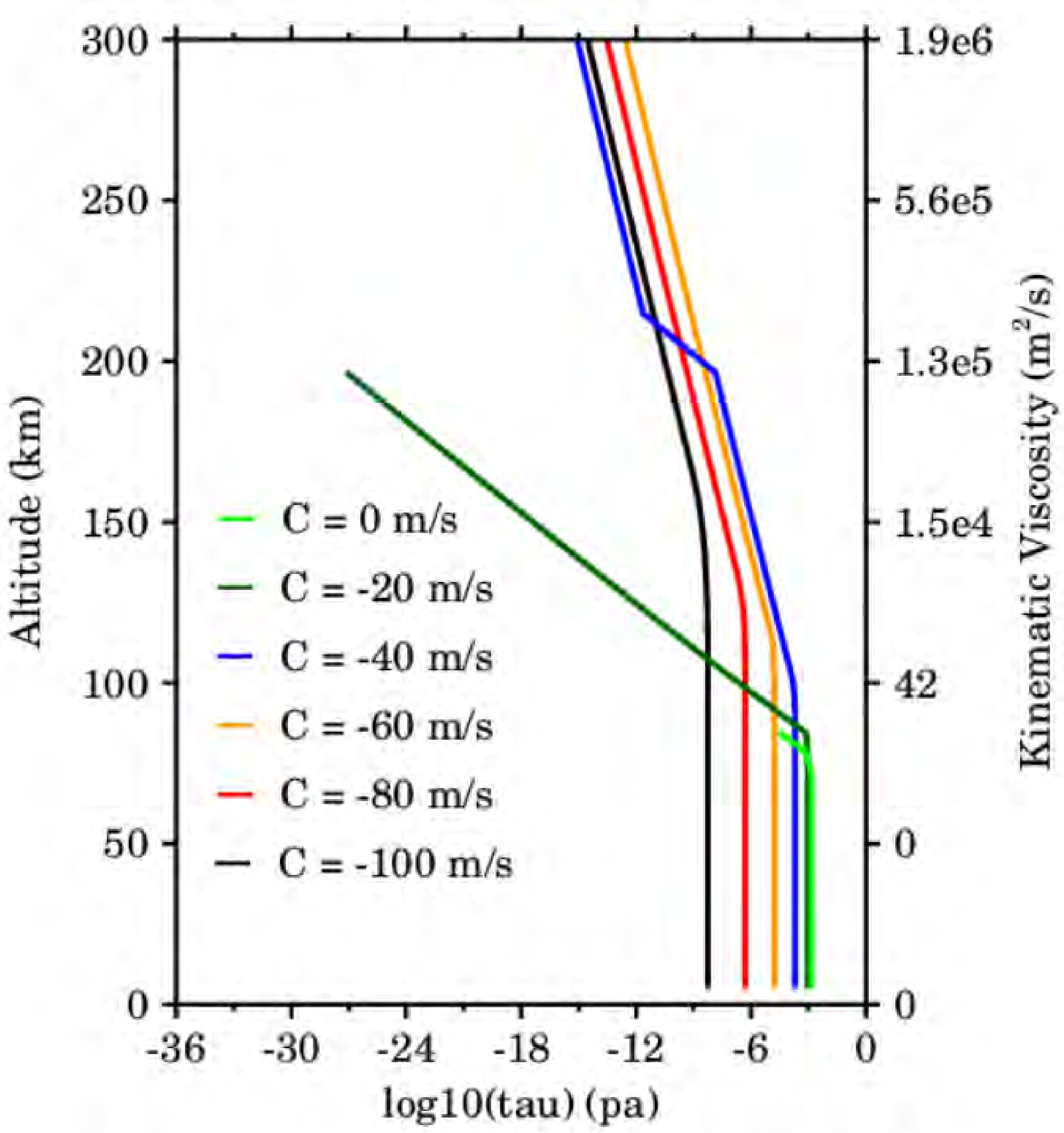
- Zonal mean T and U at 60°N in January are set as background fields
- Gaussian wave sources (tausrc) with C = [-100, 100] m/s are launched at the troposphere
- Momentum flux (Tau) due to molecular damping = $Tau \cdot e^{-2|m_i H \Delta p|}$

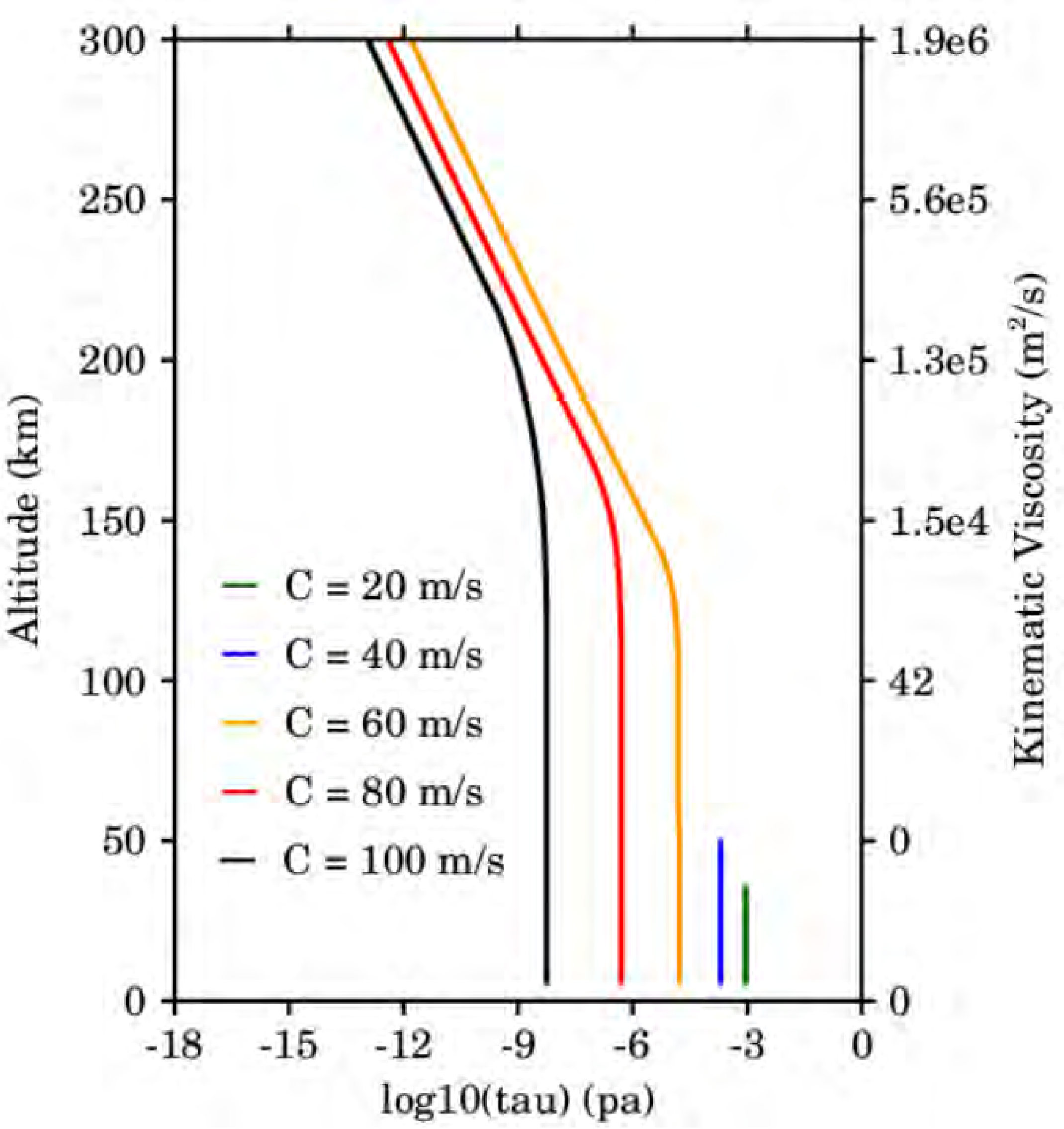




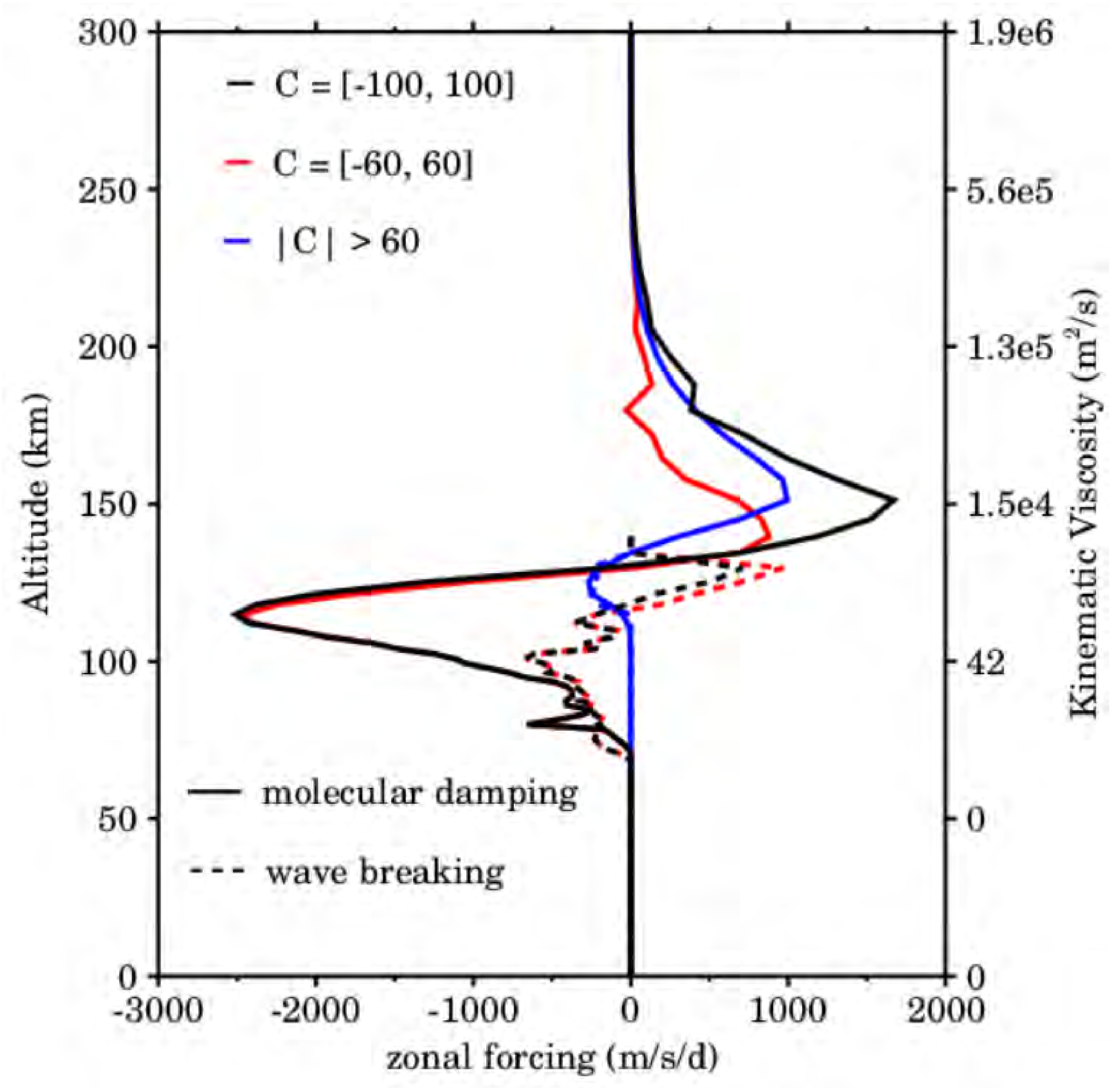


Dissipation only due to molecular damping





Zonal forcing due to MD and WB, respectively



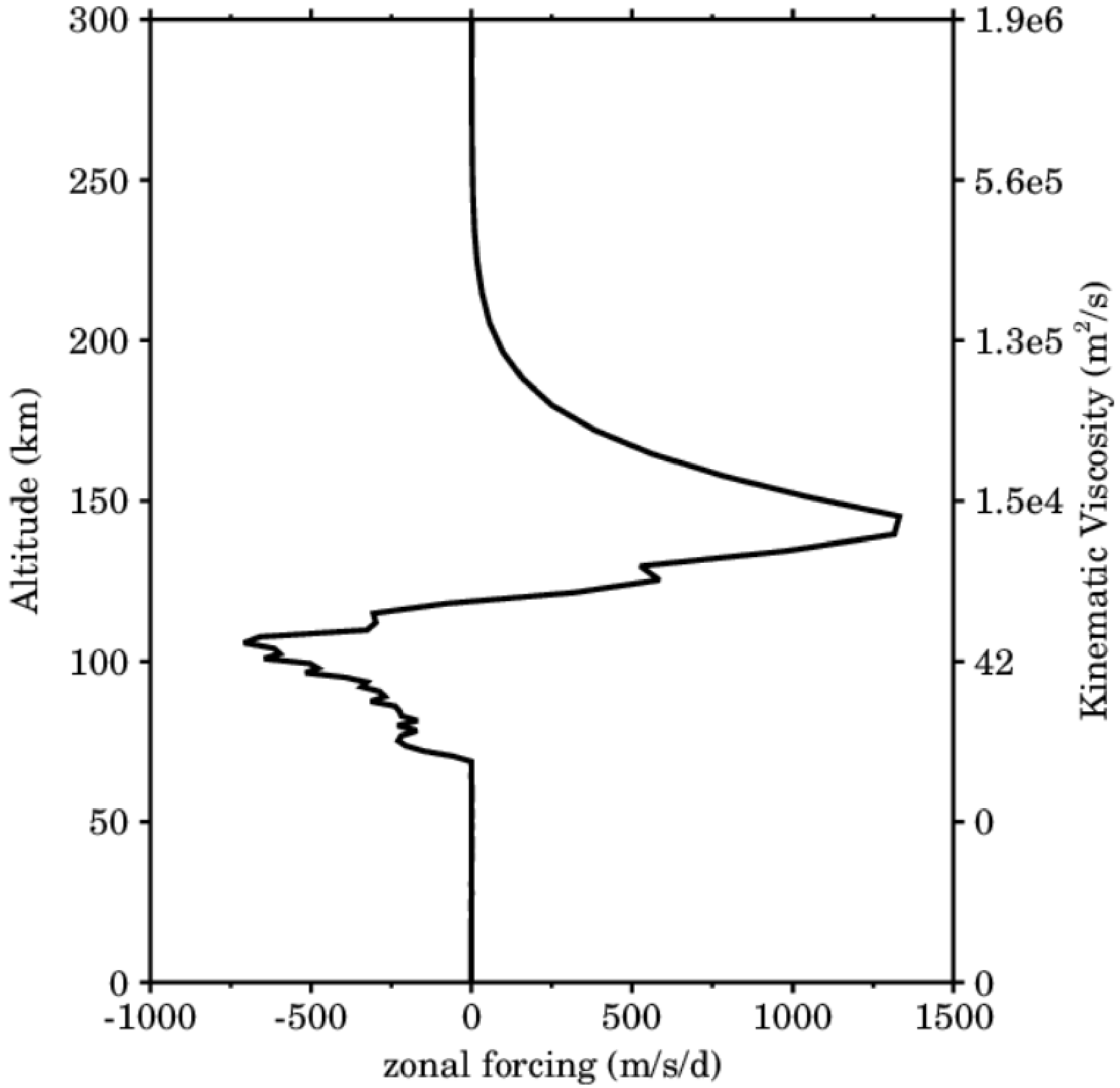
- Westward forcing near the mesopause is mainly from lower speed GWs.

- Molecular damping may contribute to the zonal wind reversal .

- Eastward forcing in the thermosphere is generated due to molecular damping.

- The faster phase speed has a higher peak altitude in the thermosphere.

Zonal forcing due to both MD and WB



- Set a wave source at the troposphere.
- Take the min value of tau by molecular damping and wave breaking in the lower-middle atmosphere to remain the forcing unchanged there.
- Only consider molecular damping in the thermosphere.
- We are working on setting wave source with a wider phase spectrum in the middle-upper atmosphere to get a higher peak altitude and closer to the secondary wave theory.

Summary

- **The properties of gravity waves in the thermosphere, including vertical wavenumber, inverse decay rate, and dissipation height is derived from a viscous gravity wave dispersion relation.**

- **Large wave forcing in the thermosphere occurs in WACCM-X implemented by a thermospheric gravity wave parameterization. And forcing in the lower-middle atmosphere remain unchanged.**

- **We are working on a new scheme, which is closer to the secondary wave theory to more comparable with SE WACCM-X.**

- **Full WACCM-X model results including thermospheric gravity wave forcing and effective vertical diffusion will be performed in the further to reduce the model bias (e.g., ΣO/N2).**

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Thanks!