Parameterizations for Global Dynamical Models in Climatology, Astrophysics, and Planetology, 16-21 Mar, 2025, Les Houches (France)

Parameterizations for Non-orographic Gravity (Buoyancy) Waves Induced Eddy Diffusion (in Mars PCM)

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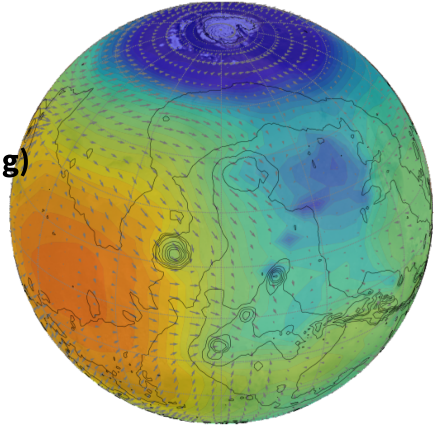
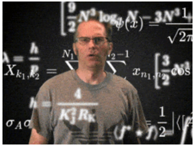
Context

- **Introduction (simulations GWon)**
- **Formalism (GW+mixing)** BOoORING !!!
- **Simulations v.s. Observations (GWon+mixing)**





Warning: The derivation of parameterizations can be extremely boring. One may only look at Introduction (pages 3 to 11), and Comparisons (pages 30 to 33).

Sciences:

1. Waves-tracers interactions.
2. H2O escapes.
3. Impacts to Mars climate and Habitability.

Non-orographic GWs:

> Waves EP-flux

> > Divergences of EP-fluxes (Drags)

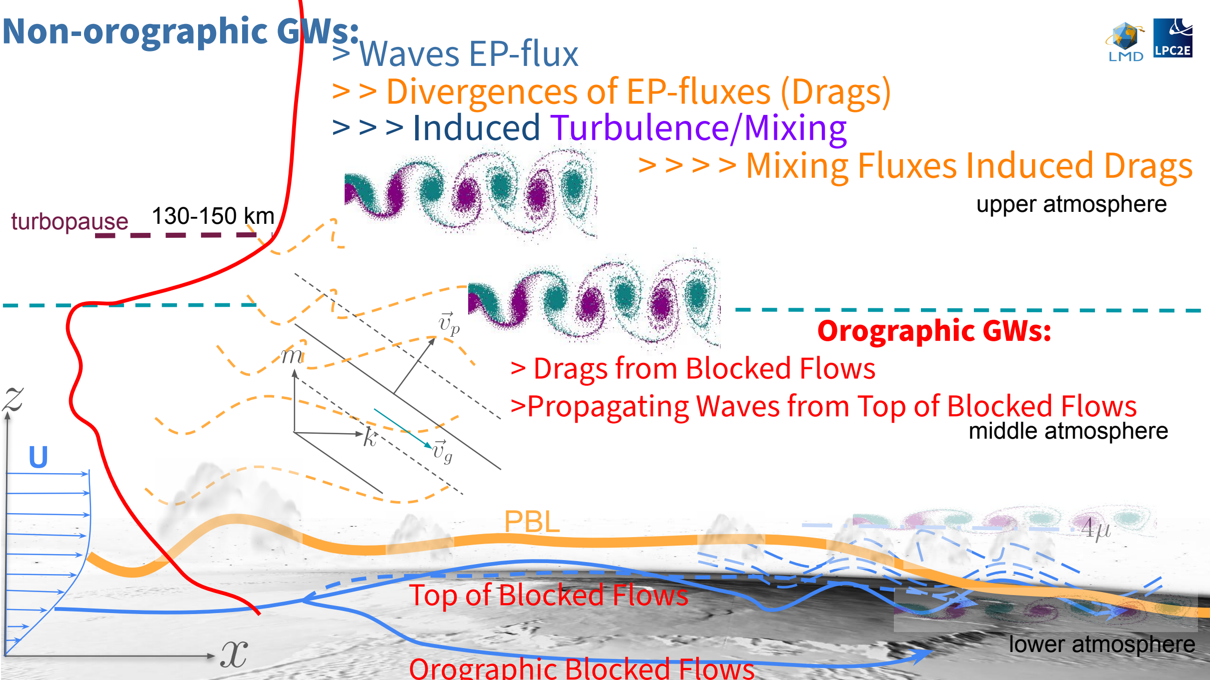
> > > Induced Turbulence/Mixing

> > > > Mixing Fluxes Induced Drags

Orographic GWs:

> Drags from Blocked Flows

>Propagating Waves from Top of Blocked Flows

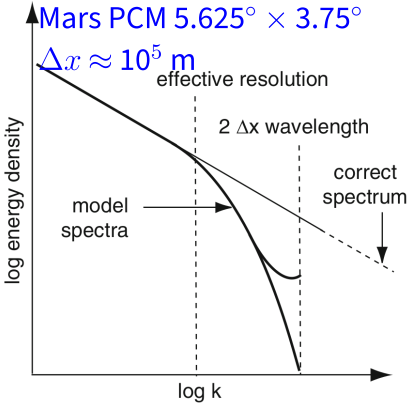


Gravity Waves in Mars PCM

$k_{eff} \in [4\Delta x, 10\Delta x]$ wavelength

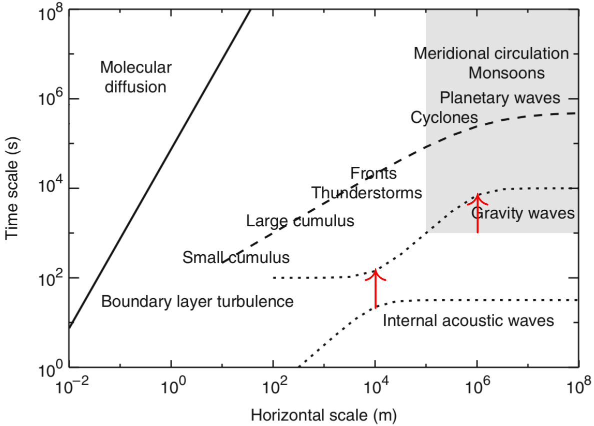
Mars PCM 5.625° × 3.75°

$\Delta x \approx 10^5$ m



Lauritzen et al.(2011)

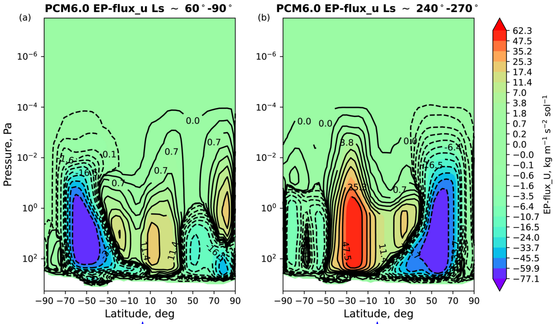
Model physical $\delta t \approx 4.6 \times 10^2$ s



Modeled gravity waves: 10^4-10^6 m
with life cycle of 88775 s

How Do Non-orographic Gravity Waves Propagate ?

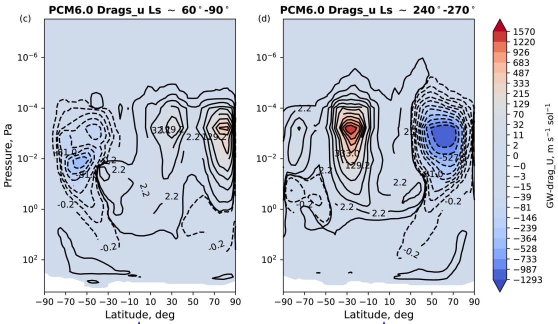
EP-flux [kg m^{-1} s^{-2} sol^{-1}]



clear-sky

dusty

Drags [m s^{-1} sol^{-1}]



clear-sky

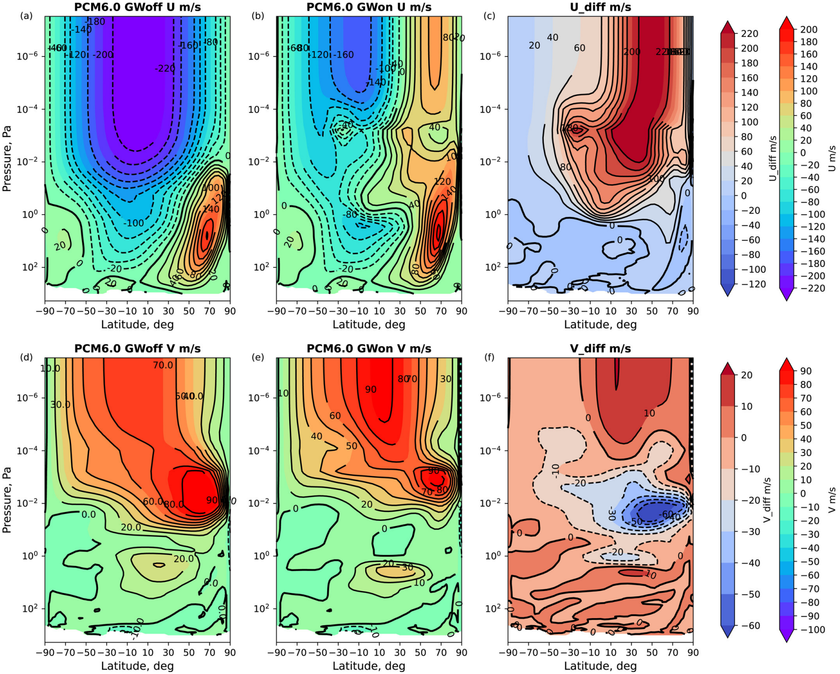
dusty

Liu et al.(2023),JGR-Planets:10.1029/2023JE007769

Effects on Flows

zonal winds

meridional winds



Drag on Circulation

Cold Bottleneck:100-150 km !!!

clear-sky

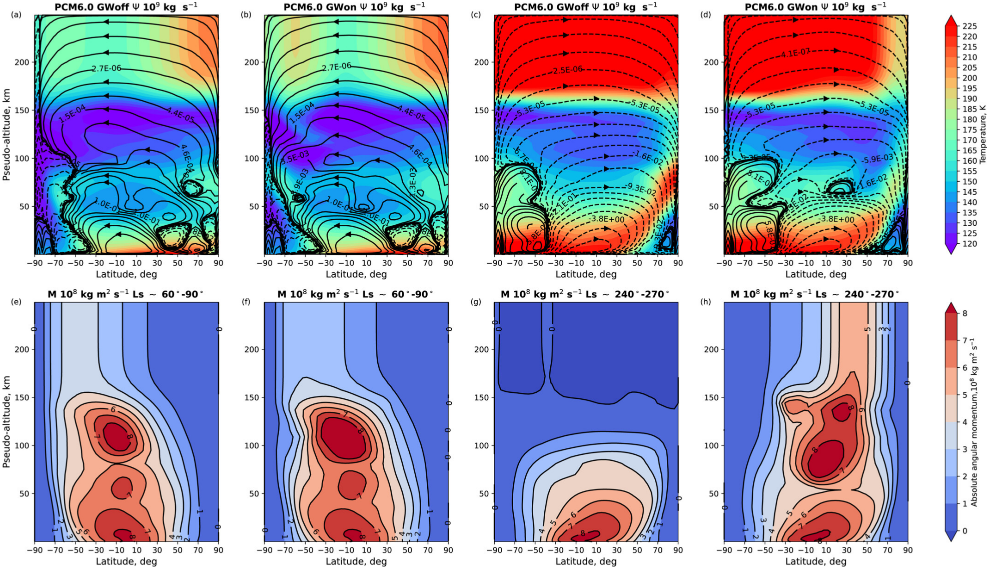
dusty

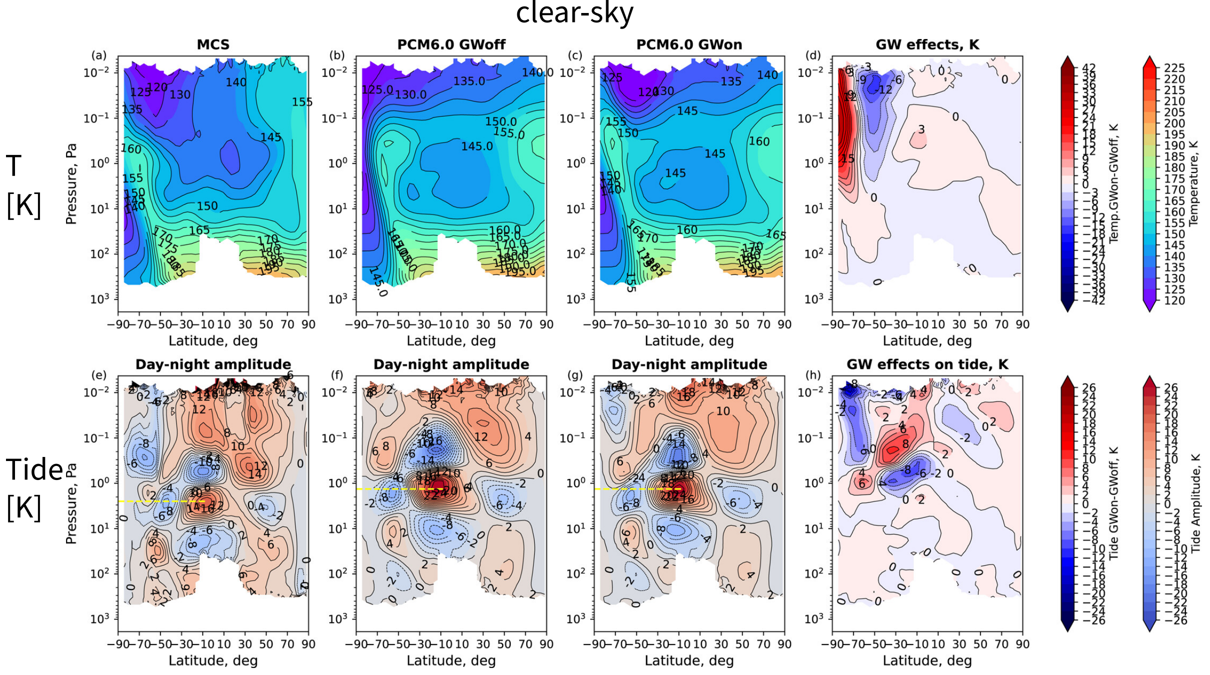
Φ

$[10^9\ \mathrm{kg\ s^{-1}}]$

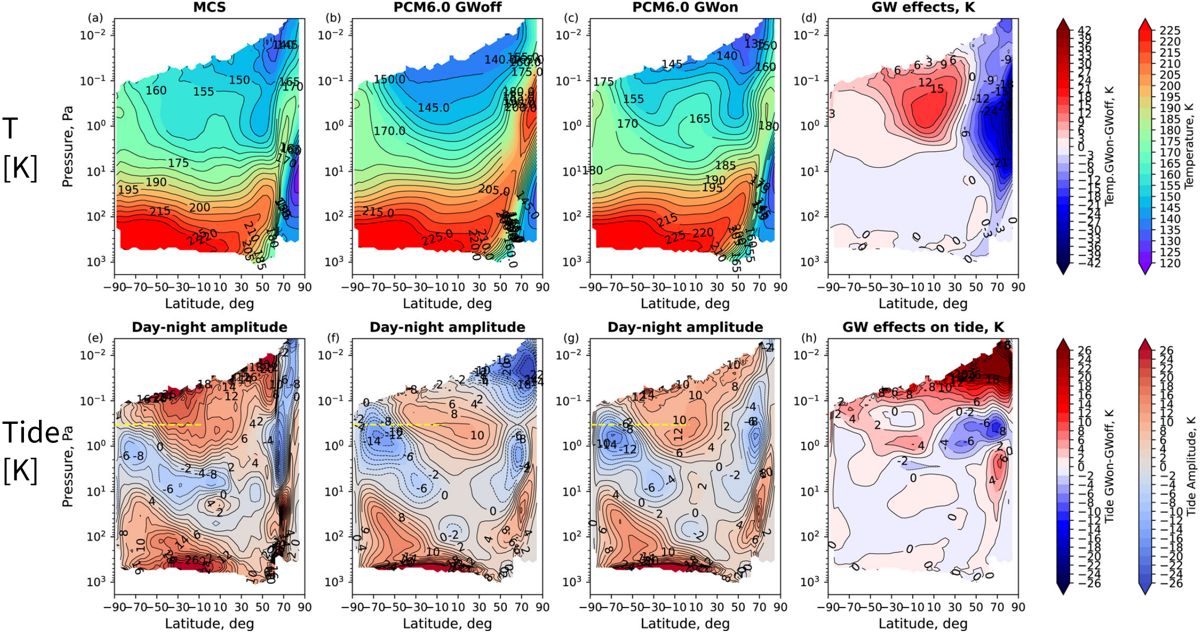
M

$[10^9\ \mathrm{kg\ m^2\ s^{-1}}]$




clear-sky
T
[K]
Tide
[K]
(a) MCS
(b) PCM6.0 GWoff
(c) PCM6.0 GWon
(d) GW effects, K
(e) Day-night amplitude
(f) Day-night amplitude
(g) Day-night amplitude
(h) GW effects on tide, K
Pressure, Pa
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Latitude, deg
−90 −70 −50 −30 −10 10 30 50 70 90
Temp.GWon-GWoff, K
−42 … 42
Temperature, K
120 … 225
Tide GWon-GWoff, K
−26 … 26
Tide Amplitude, K
−26 … 26

dusty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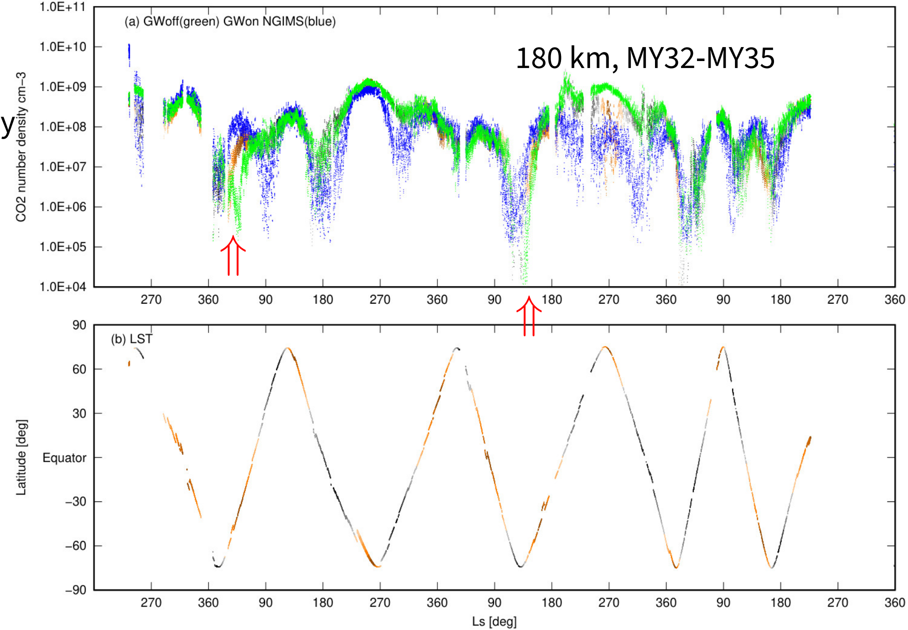
(h) GW effects on tide, K
Pressure, Pa
Latitude, deg
Temp.GWon-GWoff, K
Temperature, K
Tide GWon-GWoff, K
Tide Amplitude, K

NGIMS/GWoff/GWon

CO2 number density



180 km, MY32-MY35

Local Solar Time:
day/night

Governing Equations

Momentum:

$$\frac{Du}{Dt} = -\frac{uw}{r} - 2\Omega w\cos\phi + \frac{uv\tan\phi}{r} + 2\Omega\sin\phi v - \frac{1}{\rho r\cos\phi}\frac{\partial p}{\partial\lambda}$$

$$\frac{Dv}{Dt} = -\frac{vw}{r} - \frac{u^2\tan\phi}{r} - 2\Omega\sin\phi u - \frac{1}{\rho r}\frac{\partial p}{\partial\phi}$$

$$\frac{Dw}{Dt} = \frac{u^2+v^2}{r} + 2\Omega\cos\phi u - g - \frac{1}{\rho}\frac{\partial p}{\partial r}$$

material derivative

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla$$

Mass Continuity:

$$\frac{\partial\rho}{\partial t} + \nabla\cdot\rho\mathbf{u} = 0$$

Thermodynamics:

$$\frac{D\theta}{Dt} = \frac{\theta}{T}\frac{\dot{Q}}{c_p}$$

Governing Equations: Linearization

Consider the shallow atmosphere of inviscid, adiabatic, non-rotating, steady, hydrostatic, incompressible, governing equations of motion with the Boussinesq approximation in Cartesian coordinates (xi-yj-zk):

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\nabla\mathbf{u} = -\frac{1}{\rho}\nabla p - g\mathbf{k}$$

$$\nabla\mathbf{u} = 0$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho\mathbf{u} = 0$$

$$\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}$$

$$\frac{\partial \theta}{\partial t} + \nabla \cdot \theta\mathbf{u} = 0 \qquad \mathbf{u} = (u, v, w$$

Linearize $\forall \varkappa \in [u, v, w, \rho, \theta, T, p]$:

$$\boxed{\varkappa = \underbrace{\bar{\varkappa}}_{mean} + \underbrace{\varkappa'}_{pertubation}}$$

with $\bar{\varkappa} \backsim \bar{\varkappa}(z), \bar{w} = 0$,and

$$\boxed{\varkappa' = \underbrace{\hat{\varkappa}}_{amplitudes} \quad e^{i(kx+ly+mz-\omega t)}}$$

Governing Equations in $\varkappa'$ and $\hat{\varkappa}$ (Polarized Form)

$$\begin{aligned}
\frac{\partial u'}{\partial t} + \bar{u}\frac{\partial u'}{\partial x} + \bar{v}\frac{\partial u'}{\partial y} + w'\frac{\partial \bar{u}}{\partial z} &= -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial x} \\
\frac{\partial v'}{\partial t} + \bar{u}\frac{\partial v'}{\partial x} + \bar{v}\frac{\partial v'}{\partial y} + w'\frac{\partial \bar{v}}{\partial z} &= -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial y} \\
\nabla \mathbf{u}' &= 0 \\
\frac{\partial \rho'}{\partial t} + \bar{u}\frac{\partial \rho'}{\partial x} + \bar{v}\frac{\partial \rho'}{\partial y} + w'\frac{d\bar{\rho}}{dz} &= 0 \\
\frac{\partial \theta'}{\partial t} + \bar{u}\frac{\partial \theta'}{\partial x} + \bar{v}\frac{\partial \theta'}{\partial y} + w'\frac{d\bar{\theta}}{dz} &= 0
\end{aligned}$$

$$\frac{\partial w'}{\partial t} + \bar{u}\frac{\partial w'}{\partial x} + \bar{v}\frac{\partial w'}{\partial y} = -\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} - \frac{\rho'}{\bar{\rho}}g$$

$$\begin{aligned}
-i\omega\hat{u} + i\bar{u}k\hat{u} + i\bar{v}l\hat{u} + \hat{w}\frac{\partial \bar{u}}{\partial z} &= -\frac{i}{\bar{\rho}}\hat{p}k \\
-i\omega\hat{v} + i\bar{u}k\hat{v} + i\bar{v}l\hat{v} + \hat{w}\frac{\partial \bar{v}}{\partial z} &= -\frac{i}{\bar{\rho}}\hat{p}l \\
ik\hat{u} + il\hat{v} + im\hat{w} &= 0 \\
-i\omega\hat{\rho} + i\bar{u}k\hat{\rho} + i\bar{v}l\hat{\rho} + \hat{w}\frac{d\bar{\rho}}{dz} &= 0 \\
-i\omega\hat{\theta} + i\bar{u}k\hat{\theta} + i\bar{v}l\hat{\theta} + \hat{w}\frac{d\bar{\theta}}{dz} &= 0
\end{aligned}$$

$$-i\omega\hat{w} + i\bar{u}k\hat{w} + i\bar{v}l\hat{w} = -\frac{i}{\bar{\rho}}\frac{d\hat{p}}{dz} - \frac{\hat{\rho}}{\bar{\rho}}g$$

Governing Equations in $\varkappa'$ and $\hat{\varkappa}$ (Polarized Form)

Define Doppler-shifted intrinsic frequency

$$\Omega = \omega - k\bar{u} - l\bar{v} = \omega - \vec{v}_H\vec{\mathbf{k}}$$

Differential IGL and potential temperature θ:

$$\frac{1}{\theta}\frac{d\theta}{dz} = \frac{1}{\rho}\left[\frac{1}{c_s^2}\frac{dp}{dz} - \frac{d\rho}{dz}\right], \frac{1}{c_s^2} = \frac{\rho}{p}(1 - \frac{R}{C_p})$$

The gravity wave has phase speed far less than the sound speed:

$$\frac{1}{\theta}\frac{d\theta}{dz} = -\frac{1}{\rho}\frac{d\rho}{dz}, \frac{\theta'}{\bar{\theta}} = -\frac{\rho'}{\bar{\rho}},$$

$$N^2 = -\frac{g}{\bar{\rho}}\frac{\partial\bar{\rho}}{\partial z}$$

$$i\Omega\hat{u} - \hat{w}\frac{\partial\bar{u}}{\partial z} = \frac{i}{\bar{\rho}}\hat{p}k$$

$$i\Omega\hat{v} - \hat{w}\frac{\partial\bar{v}}{\partial z} = \frac{i}{\bar{\rho}}\hat{p}l$$

$$i\Omega\hat{w} = \frac{i}{\bar{\rho}}\frac{d\hat{p}}{dz} + \frac{\hat{\rho}}{\bar{\rho}}g$$

$$\hat{u} = -\frac{m}{k}\hat{w}; \hat{v} = -\frac{m}{l}\hat{w}$$

$$i\Omega\hat{\rho} + \hat{w}\frac{\bar{\rho}}{g}N^2 = 0$$

$$-i\Omega T' + w'\Gamma = 0$$

Derivation of Taylor-Goldstein Equation

In x-z plane:

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0\Rightarrow u=-\frac{\partial\psi}{\partial z},w=\frac{\partial\psi}{\partial x};$$

$$\hat{u}=-\frac{\partial\hat{\psi}}{\partial z},ik\hat{u}+\frac{d\hat{w}}{dz}=0\Rightarrow\hat{w}=ik\hat{\psi}$$

$$\Omega(-k^2+\frac{d^2}{dz^2})\hat{\psi}+\hat{\psi}k\frac{d^2\bar{u}}{dz^2}=\hat{b}k$$

$$i\Omega\hat{\rho}+\hat{w}\frac{\bar{\rho}}{g}N^2=0\Rightarrow\frac{\Omega^2}{N^2}k\hat{b}=-\Omega k^2\hat{\psi}$$

$$\boxed{\frac{d^2}{dz^2}\hat{\psi}+\frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dz}\frac{d\psi}{dz}+(\frac{k^2N^2}{\Omega^2}+\frac{k\bar{u}_{zz}}{\Omega}+\frac{k}{\Omega}\frac{1}{\bar{\rho}}\frac{d\bar{\rho}}{dz}\frac{d\bar{u}}{dz}-k^2)\hat{\psi}=0}$$

$$\bar{\rho}=\rho_s\exp(-\frac{z}{H})$$

Derivation of Taylor-Goldstein Equation

$\forall j$th monochromatic wave:

$$w_j' = \hat{w}_j(z)\,\underbrace{e^{z/2H}}_{\rho(z)}\,e^{i(k_j x + l_j y + m_j z - \omega_j t)}$$

$$\boxed{\frac{\partial^2 \hat{w}(z)}{\partial z^2} + \Bigg(\underbrace{\frac{|\vec{k}|^2 N^2}{\Omega^2} + \cancel{\frac{|\vec{k}|(\vec{u}_{zz} - \vec{u}_z/H)}{\Omega}} - \frac{1}{4H^2}}_{Q(z)}\Bigg)\hat{w}(z) = 0}$$

vertical wavenumber of gravity wave:

$$m_r^2 = \frac{|\vec{k}|^2 N^2}{\Omega^2}$$

WKB Approximation

Approximation solution to the Taylor-Goldstein equation:

$$\hat{w}_j(z) \approx A(z)|m_r|^{-1/2} exp\left(i \int_0^z m d\zeta\right) \quad \xrightarrow[\Longrightarrow]{\hat{w}_j(z_{ll+1})/\hat{w}_j(z_{ll})}$$

$$\hat{w}_j(z_{ll+1}) = \hat{w}_j(z_{ll}) \sqrt{\frac{m_r(z_{ll})}{m_r(z_{ll+1})}} exp\left(i \int_{z_{ll}}^{z_{ll+1}} m^{ave} d\zeta\right)$$

$$m = m_r + i m_i; \quad i^2 = -1$$ vertical wavenumber of turbulence

Lott et al.2012:

turbulence

$$\hat{w}_j(z_{ll+1}) = \underbrace{\Theta[\Omega(z_{ll+1}) \times \Omega(z_{ll})]}_{critical-layer} Min\left\{ \hat{w}_j(z_{ll}) \sqrt{\frac{m_r(z_{ll})}{m_r(z_{ll+1})}} e^{-\frac{\mu}{\rho}\left(\int_{z_{ll}}^{z_{ll+1}} \overset{\downarrow}{m_i^{ave}} d\zeta\right)}, \underbrace{\hat{w}_{j,s}}_{saturation} \right\}$$

$\uparrow$

kinematic viscosity

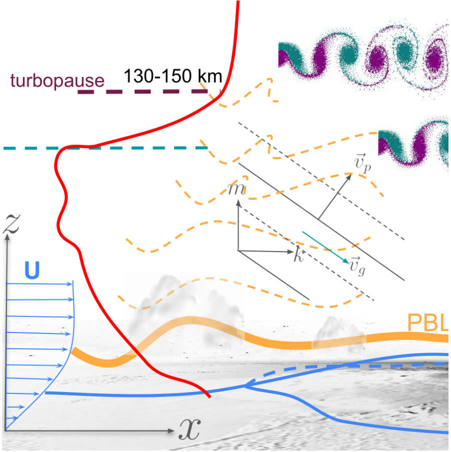
EP-Flux

Pseudo-Momentum:

$$\vec{E}_j^{z_r}(k_j, l_j, \omega_j) = \Re\left\{\rho_r \frac{\hat{u}\hat{w}^*}{2}\right\}$$

$$\hat{u} = -\frac{m}{|\vec{k}|}\hat{w}$$

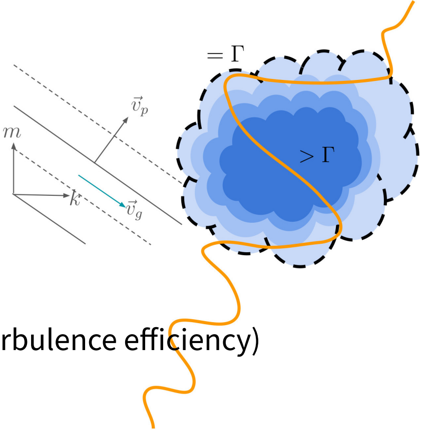
$$\boxed{\vec{E}_j^{z_r}(k_j, l_j, \omega_j) = -\rho_r \frac{\vec{k}}{2|\vec{k}|} m_j(z_r) |\hat{w}_j(z_r)|^2 \frac{\vec{k}\Omega}{|\vec{k}\Omega|}}$$



$$\hat{w}_j(z_{ll+1}) = \underbrace{\Theta[\Omega(z_{ll+1}) \times \Omega(z_{ll})]}_{critical-layer} Min\left\{\hat{w}_j(z_{ll})\sqrt{\frac{m_r(z_{ll})}{m_r(z_{ll+1})}}\, e^{-\underset{\underset{\text{kinematic viscosity}}{\uparrow}}{\frac{\mu}{\rho}}\left(\int_{z_{ll}}^{z_{ll+1}} \overset{\overset{\text{turbulence}}{\downarrow}}{m_i^{ave}}\, d\zeta\right)},\ \underbrace{\hat{w}_{j,s}}_{saturation}\right\}$$

Turbulence from Waves

Assumption 1: Turbulence triggered by the wave momentum releasing, viz.
$Turbulence \propto \nabla(\vec{E})$



Assumption 2: Non-superadiabatic Principle
$|\frac{dT}{dz}|_{gw} \leqslant \Gamma$ (Lindez 1981)

Assumption 3: Sysmetric Principle

Assumption 4: Linear Damping (instabilty-to-turbulence efficiency)

Wave Thermodynamics: m_i at z_b

Assumption 2: Non-superadiabatic Principle

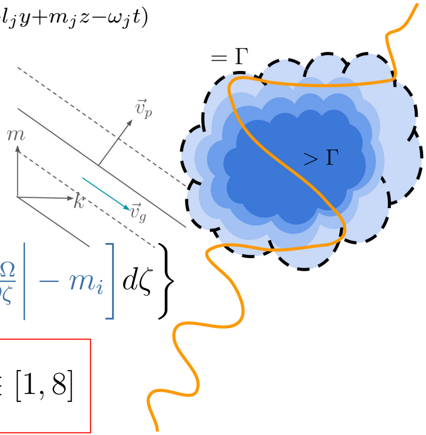
$$-i\Omega T' + w'\Gamma = 0 \qquad w_j' = \hat{w}_j(z)\,\underbrace{e^{z/2H}}_{\rho(z)}\,e^{i(k_j x + l_j y + m_j z - \omega_j t)}$$

$$i\vec{k}_j(c - \bar{u})\delta T = \hat{w}_j e^{z/2H}\Gamma$$

$$\Re\left\{\frac{d\delta T}{dz}\right\} = -\frac{\Gamma A |m_r|^{3/2} e^{\int_0^z \left(\frac{1}{2H} - m_i\right) d\zeta}}{N|\vec{k}|}$$

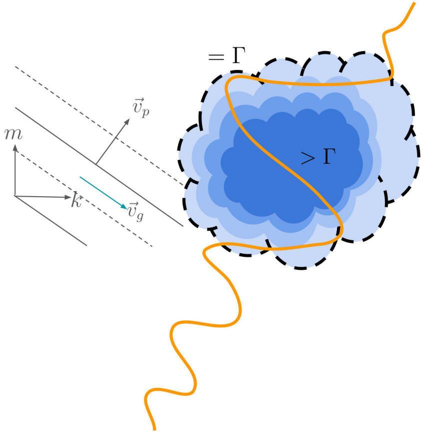
$$\Re\left\{\frac{d\delta T}{dz}\right\} = -\frac{\Gamma A}{N|\vec{k}|}\exp\left\{\int_0^z \left[\frac{1}{2H} + \frac{3}{2}\left|\frac{1}{N}\frac{\partial N}{\partial \zeta} - \frac{1}{\Omega}\frac{\partial \Omega}{\partial \zeta}\right| - m_i\right] d\zeta\right\}$$

$$\boxed{\frac{1}{2H} + \frac{3}{2}\left|\frac{1}{N}\frac{\partial N}{\partial z} - \frac{1}{\Omega}\frac{\partial \Omega}{\partial z}\right| = m_{i,s}, \qquad z = z_b, \forall j \in [1, 8]}$$



Wave Thermodynamics: NSP

Assumption 2: NSP $|\frac{dT}{dz}|^2_{gw} = \Gamma^2$



$$\Re\{\frac{d\delta T}{dz}\} = -\frac{\Gamma A|m_r|^{3/2}e^{\int_0^z(\frac{1}{2H}-m_i)d\zeta}}{N|\vec{k}|}$$

Saturation altitude z_b and A^2

$$\boxed{A^2 m_r^{-1}\exp\left(-2\int_0^{z_b} m_i d\zeta\right) = m_r^{-4}N^2|\vec{k}|^2\exp\left(-\int_0^{z_b}\frac{1}{H}d\zeta\right), \quad z = z_b}$$

Wave Thermodynamics: Saturated EP-flux

Assumption 2: Non-superadiabatic Principle $|\frac{dT}{dz}|^2_{gw} = \Gamma^2$

$$A^2 m_r^{-1}\exp\left(-2\int_0^{z_b} m_i d\zeta\right)$$

$$= m_r^{-4}N^2|\vec{k}|^2\exp\left(-\int_0^{z_b}\frac{1}{H}d\zeta\right) \Longrightarrow |\hat{w}_j(z_b)|^2 \approx A^2 m_r^{-1}\exp\left(-2\int_0^{z_b} m_i d\zeta\right)$$

$$= m_r^{-4}N^2|\vec{k}|^2\exp\left(-\int_0^{z_b}\frac{1}{H}d\zeta\right)$$

$$z \in [z_b, z_b + \delta z_{ll}]$$

$$= \frac{\Omega^4}{N^2|\vec{k}|^2}\exp\left(-\int_0^{z_b}\frac{1}{H}d\zeta\right)$$

$$\vec{E}_j^{z_{ll+1}} = \frac{\vec{k}\Omega}{|\vec{k}||\Omega|}\Theta[\Omega(z_{ll+1})\Omega(z_{ll})]$$

$$\Downarrow$$

$$Min\left\{|\vec{E}_j^{z_{ll}}|e^{-2\frac{\mu m_i}{\rho}\delta z}, \rho_r S_c^2 e^{-\frac{z_{ave}}{H}}\frac{|\Omega|^3 k^{*2}}{2N|\vec{k}|^4}\right\} \Longleftarrow \boxed{\hat{w}_{j,s} = \frac{\Omega^2}{|\vec{k}|N}e^{-z/2H}S_c\frac{k^*}{|\vec{k}|}}$$

Wave Thermodynamics: Linear Damping

Assumption 4: Linear Damping

$$\boxed{D^j_{eddy}\frac{\partial}{\partial z^2}\begin{Bmatrix}\bar{u}\\ \delta T\end{Bmatrix} = -m_r^2 D^j_{thermal}\begin{Bmatrix}\bar{u}\\ \delta T\end{Bmatrix}}$$

$$Prandtl = D^j_{eddy}/D^j_{thermal} = 1$$

$$[i\vec{k}(c-\bar{u}) + m_r^2 D_{eddy}]\delta T = w'\Gamma$$

$m = m_r + im_i$, we rewrite $c = c_r + ic_i$,

$$\vec{k}c_i = m_r^2 D^j_{eddy}$$

Wave Thermodynamics: Linear Damping

Assumption 4: Linear Damping: The turbulence m_i and c_i,

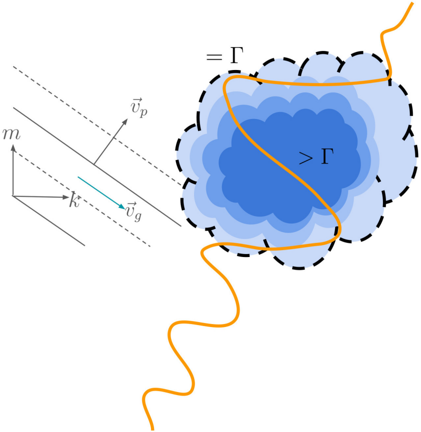
$$c = c_r + i c_i$$

$$m = \frac{N|\vec{k}|}{\vec{k}(\bar{u} - c)} \quad \Longleftarrow \quad \vec{k} c_i = m_r^2 D^j_{eddy}$$

$$= \frac{N|\vec{k}|}{\vec{k}(\bar{u} - c_r) - i m_r^2 D^j_{eddy}}$$

$$= -\frac{N|\vec{k}|\Omega}{\Omega^2 + \cancel{m_r^4 D^2_{eddy}}} + i \frac{N|\vec{k}| m_r^2 D^j_{eddy}}{\Omega^2 + \cancel{m_r^4 D^2_{eddy}}}$$

$$\boxed{m_i = \frac{N|\vec{k}| m_r^2 D_{eddy}}{\Omega^2} = \frac{m_r^3 D^j_{eddy}}{\Omega}, \qquad z \in [surface, top]}$$



Eddy Diffusion Coefficient $z = z_b$

Since

$$m_i = \frac{N|\vec{k}|m_r^2 D_{eddy}^j}{\Omega^2}, z \in [surf, top]$$

Saturated vertical wavenumber of turbulence,

$$\frac{1}{2H} + \frac{3}{2}\left|\frac{1}{N}\frac{\partial N}{\partial z} - \frac{1}{\Omega}\frac{\partial \Omega}{\partial z}\right| = m_{i,s}, \qquad z = z_b$$

$$D_{eddy}^j = \frac{\Omega^4}{N^3|\vec{k}|^3}\left(\frac{3}{2}\left|\frac{1}{N}\frac{dN}{dz} - \frac{1}{\Omega}\frac{d\Omega}{dz}\right| + \frac{1}{2H}\right)$$

$$\boxed{D_{eddy}^j = S_{mix}\frac{\Omega^4}{N^3|\vec{k}|^3}\left(\frac{3}{2}\left|\frac{1}{N}\frac{dN}{dz} - \frac{1}{\Omega}\frac{d\Omega}{dz}\right| + \frac{1}{2H}\right), \quad z = z_b}$$

Eddy Diffusion Coefficient $z > z_b$

Assumption 1: Turbulence triggered by momentum releasing, viz,
$Turbulence \propto \nabla(\vec{E})$

$$
\begin{aligned}
-\frac{1}{\rho}\frac{\partial \vec{E}_j^z}{\partial z} &= \alpha_{eff}\frac{\Omega^3}{N|\vec{k}|^2} m_i \frac{\vec{k}}{|\vec{k}|} \\
&= \alpha_{eff}\frac{\Omega^3}{N|\vec{k}|^2}\left(\frac{3}{2}\left|\frac{1}{N}\frac{dN}{dz} - \frac{1}{\Omega}\frac{d\Omega}{dz}\right| + \frac{1}{2H}\right)\frac{\vec{k}}{|\vec{k}|}, \qquad z > z_b
\end{aligned}
$$

$$
\boxed{D_{eddy}^j = \alpha_{eff}\frac{\Omega}{N^2|\vec{k}|}\left\{-\frac{1}{\rho}\frac{\partial \vec{E}_j^z}{\partial z}\right\}, \qquad z > z_b}
$$

Eddy Diffusion Coefficient $z < z_b$

Assumption 3: Sysmetric Principle: empirical fit

$$D^j_{eddy} = \mathcal{B} \times n_q^{-1/2}$$

Since we know $n \propto \exp -\frac{z}{H}$,

$$\boxed{D^j_{eddy} = D^j_{eddy}(z_b) e^{\beta_{diff}(z-z_b)/H}, \qquad z < z_b}$$

General Equation

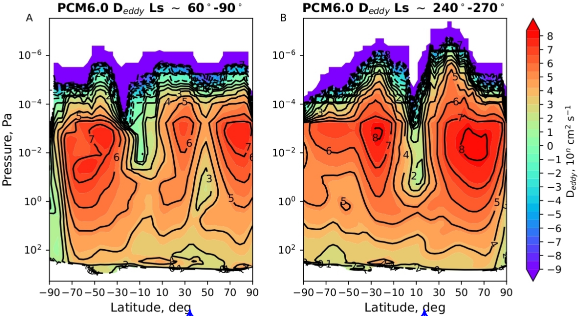
Eddy diffusion coefficient $\forall j$th monochromatic wave:

$$D_{eddy}^{j} = \begin{cases} Min\left[\alpha_{eff}\frac{\Omega}{N^2|\vec{k}|}\left(-\frac{1}{\rho}\frac{\partial\vec{E}}{\partial z}\right), S_{mix}\frac{\Omega^4}{N^3|\vec{k}|^3}\left(\frac{3}{2}\left|\frac{1}{N}\frac{dN}{dz}-\frac{1}{\Omega}\frac{d\Omega}{dz}\right|+\frac{1}{2H}\right)\right] & , z \geq z_b \\ D_{eddy}(z_b)\exp\left[\beta_{diff}\frac{(z-z_b)}{H}\right] & , z < z_b \end{cases}$$

$\alpha_{eff} = S_{mix} = 0.1$ and $\beta_{diff} = \frac{3}{2}$

Eddy Diffusion Coefficient

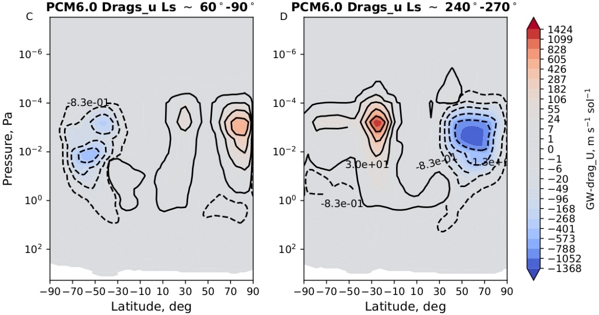
$$D_{eddy} = \sum_{j=1}^{M} D_{Eddy}^{j}, M = 8$$



clear-sky

dusty

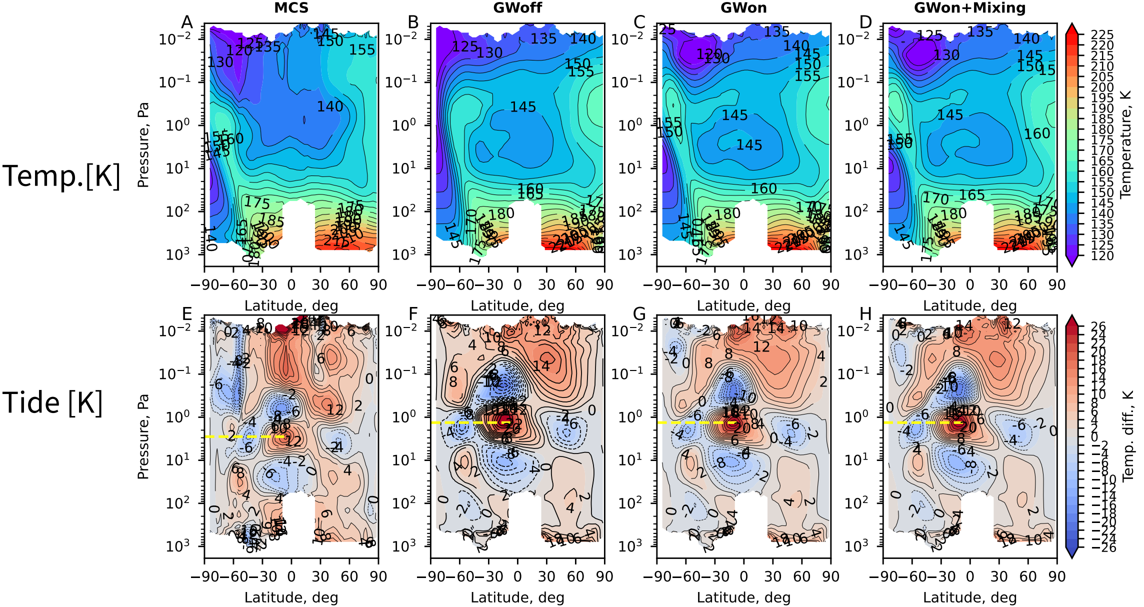
Drags (GW drags not mixing drags)

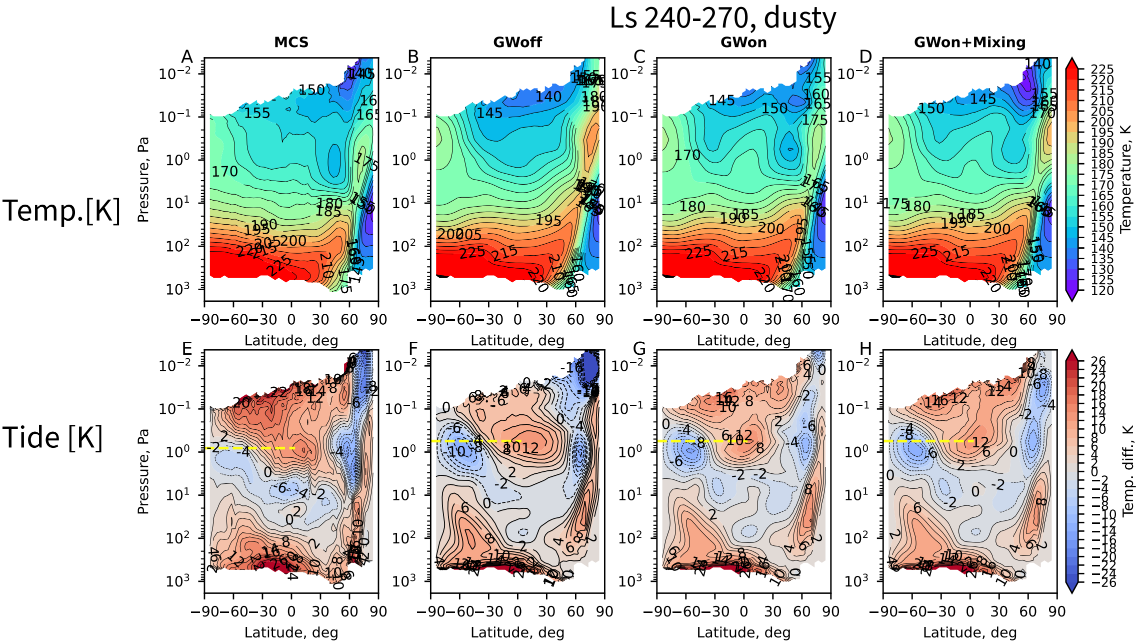


clear-sky

dusty

Ls 60-90, clear-sky



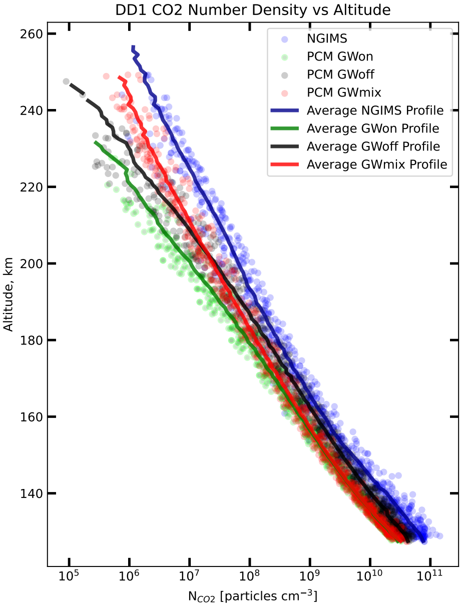

Ls 240-270, dusty
MCS
GWoff
GWon
GWon+Mixing
Temp.[K]
Tide [K]
A
B
C
D
E
F
G
H
Pressure, Pa
Latitude, deg
−90 −60 −30 0 30 60 90
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Temperature, K
120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205 210 215 220 225
Temp. diff., K
−26 −24 −22 −20 −18 −16 −14 −12 −10 −8 −6 −4 −2 0 2 4 6 8 10 12 14 16 18 20 22 24 26

MAVEN/NGIMS

GWoff

GWon

GWon+mixing



Thank you for your time and interest in this topic. Please feel free to ask any questions.

Je vous remercie pour votre temps et votre intérêt. N’hésitez pas à poser vos questions.

承蒙聆听，不胜荣幸，有疑但问.

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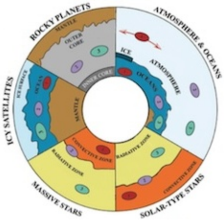
jiandong.liu@cnrs-orleans.fr


ROCKY PLANETS
MANTLE
OUTER CORE
INNER CORE
ATMOSPHERE & OCEANS
ICE
ATMOSPHERE
OCEANS
ICY SATELLITES
ICE SURFACE
OCEAN
MANTLE
CONVECTIVE ZONE
RADIATIVE ZONE
MASSIVE STARS
RADIATIVE ZONE
CONVECTIVE ZONE
SOLAR-TYPE STARS