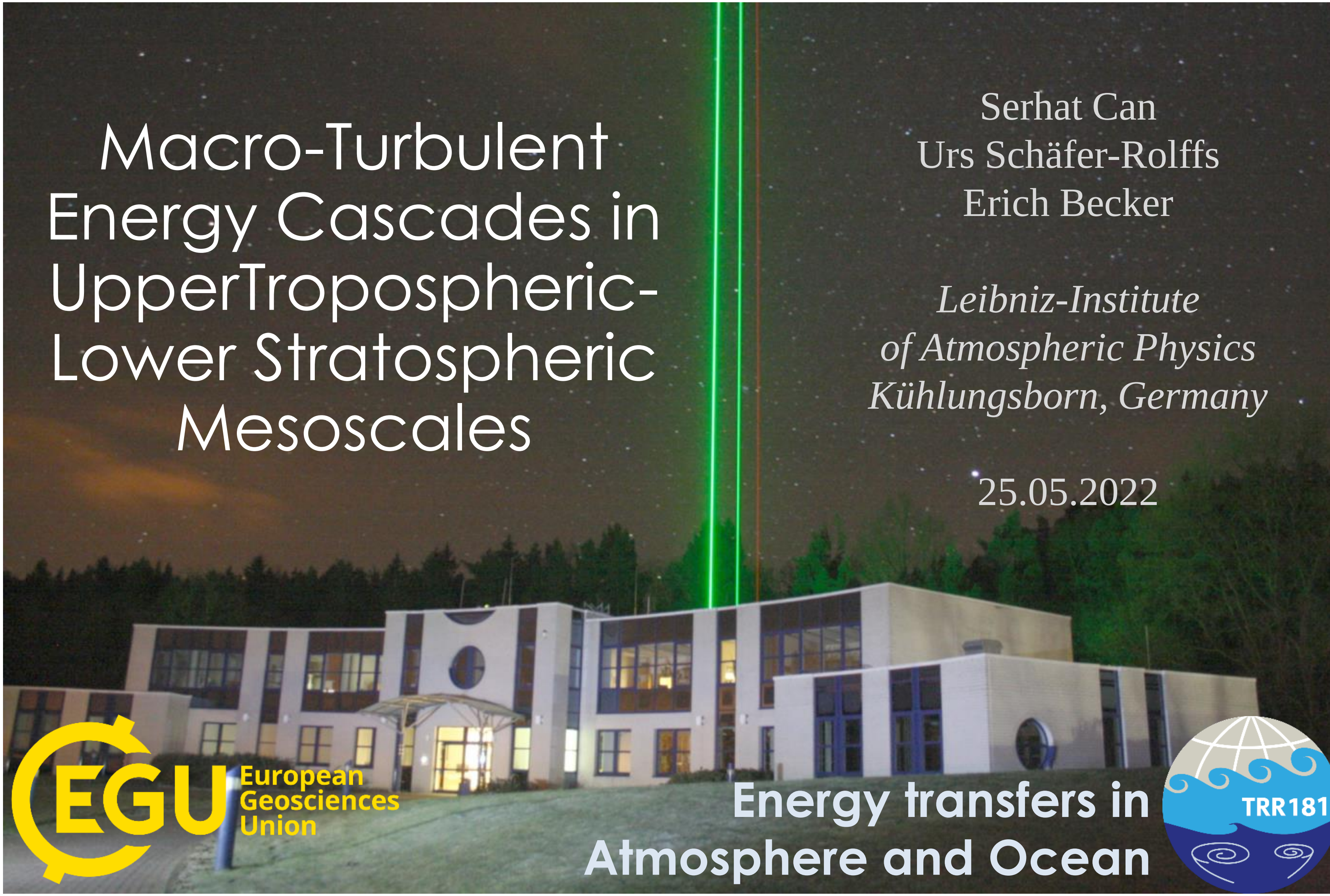

Macro-Turbulent Energy Cascades in UpperTropospheric-Lower Stratospheric Mesoscales

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Energy transfers in Atmosphere and Ocean

TRR181

LEIBNIZ-INSTITUT FÜR ATMOSPHÄREN PHYSIK IAP

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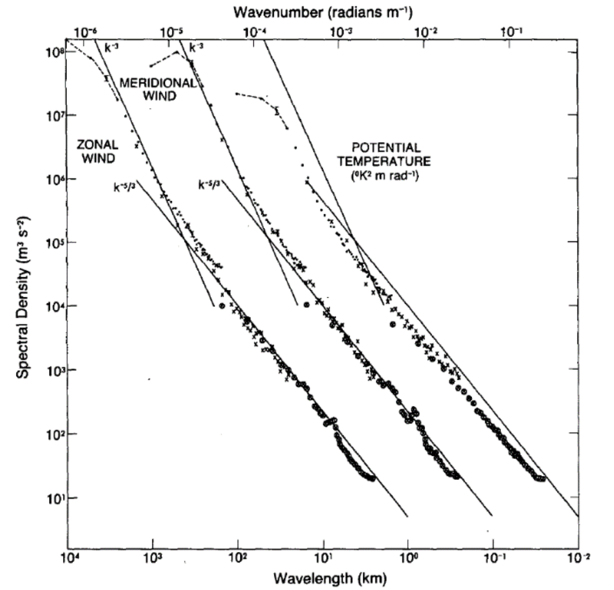
Motivation and Model Specification

Investigate the dynamics behind the simulated Nastrom & Gage Spectra, via **spectral budget analyses of** Kinetic and Available Potential Energies (**KE & APE**), **characteristic** Stratified Turbulence (**ST**) **statistics**, and Gravity Wave (**GW**) **Scale Energetics**



(Nastrom&Gage,1985)

Kühlungsborn Mechanistic Circulation Model (KMCM):

- Spectral Dynamical Core with **T330** Triangular Truncation
- 100 Vertical Levels, extending up to ~0.16hPa (beginning of Mesoshpere)
- Smoothed orography with ∼T160 Resoution
- **Dry** Atmosphere, **no** explicit **moisture** cycle, only **large scale convective** forcing
- 16 Days of **January** Simulations
- Turbulence parameterization with a **Scale Invariant Dynamic Smagorinsky Scheme** for horizontal diffusion of **horizontal momentum** and **sensible heat**

Spectral Budget Analyses for KE & APE

Formulation of Spectral KE Budget:

$$\partial_t \vec{v} = -(\vec{v}_h \cdot \vec{\nabla}_h)\vec{v}_h + \vec{v}_h \times f\vec{e}_z - \dot{\eta}\partial_\eta \vec{v}_h - \frac{RT}{p}\vec{\nabla}_h p - \vec{\nabla}\Phi + \vec{H} + \vec{Z}$$

$$\dot{KE}_n = \frac{a_e^2}{4\pi n(n+1)} \sum_{m=-n}^{n} (\dot{\xi}_{mn}\xi_{mn} + \dot{D}_{mn}D_{mn})$$

$$\dot{KE}_n = \dot{KE}_n^{HA} + \dot{KE}_n^{VA} + \dot{KE}_n^{AC} + \dot{KE}_n^{MD}$$ (Brune & Becker 2013)

Formulation of Spectral APE Budget:

$$\partial_t(c_p T) = -\vec{v}_h \cdot \vec{\nabla}_h(c_p T) - \dot{\eta}\partial_\eta(c_p T) + \frac{RT}{p}\omega + Q \qquad T = \overline{T} + \tilde{T}$$

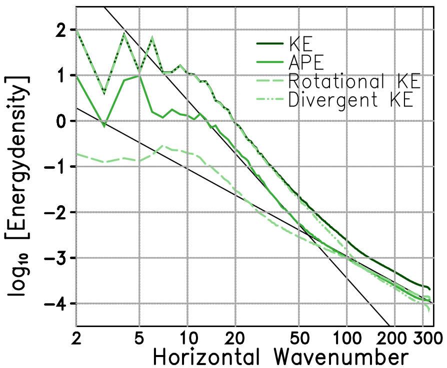
$$\dot{\tilde{T}} = \partial_t \tilde{T} = \left(- \vec{v}_h \cdot \vec{\nabla}_h \widetilde{T} - \omega\partial_p \widetilde{T} - \omega\partial_p \overline{T} + \frac{R}{c_p p}\widetilde{T}\omega + \frac{R}{c_p p}\overline{T}\omega + \frac{1}{c_p}Q\right)$$

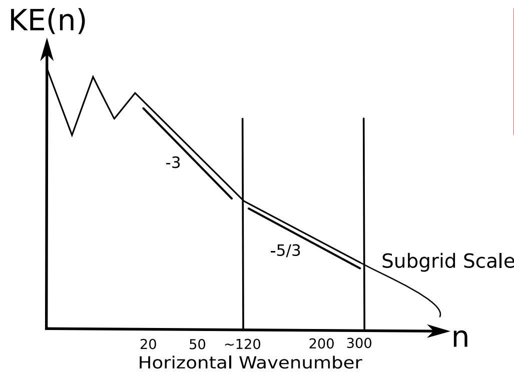
Local APE $\approx \dfrac{g^2}{2\overline{T}^2\overline{N}^2}\tilde{T}.\tilde{T} = \dfrac{1}{2}C\tilde{T}^2$ (Lorenz, 1955)

$$\dot{APE}_n = \frac{1}{4\pi}C \sum_{m=-n}^{n} (\dot{\tilde{T}}_{mn}\tilde{T}_{mn})$$

$$\dot{APE}_n = \dot{APE}_n^{HA} + \dot{APE}_n^{VA} + \dot{APE}_n^{NBP} + \dot{APE}_n^{DH}$$

Integral Scale Velocity and Length Scales





$$U_{h(n)} = \sqrt{2KE_{(n)}} = \sqrt{2\int_n^\infty e_{KE(n')}\,dn'}$$

$$KE_{(n>120)} = KE_{meso} + KE_{sgs}$$

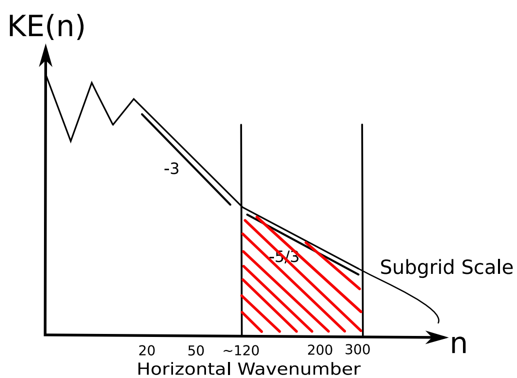
(Becker,2009)
(Avsarkisov, Becker & Renkwitz, 2022)

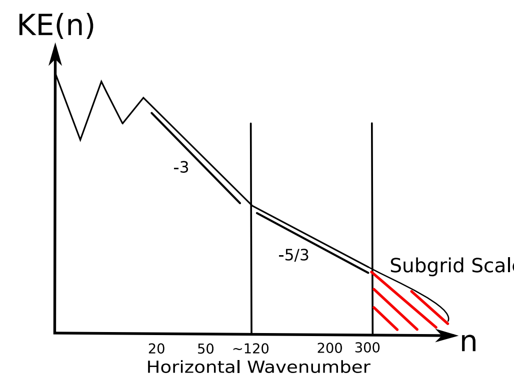
$$KE_{meso} = \frac{\vec{v}^2_{meso}}{2}$$

$$\vec{v}_{meso} = \vec{v}_{full} - \vec{v}_{(n<120)} = \vec{v}_{((n>120))}$$

$$KE_{sgs} = \sqrt{\frac{\epsilon_{ke} K^{tot}}{C}}$$

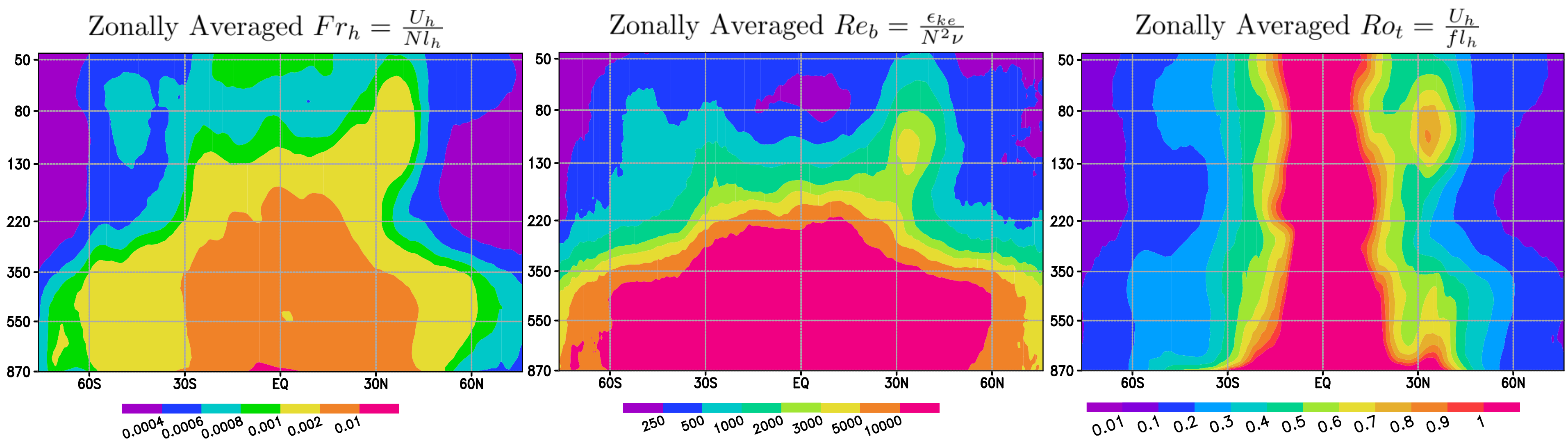
(Launder et al., 1973)





$$l_h = \frac{U_h^3}{\epsilon_{ke}}$$ (Taylor,1935)

Characteristic ST Statistics



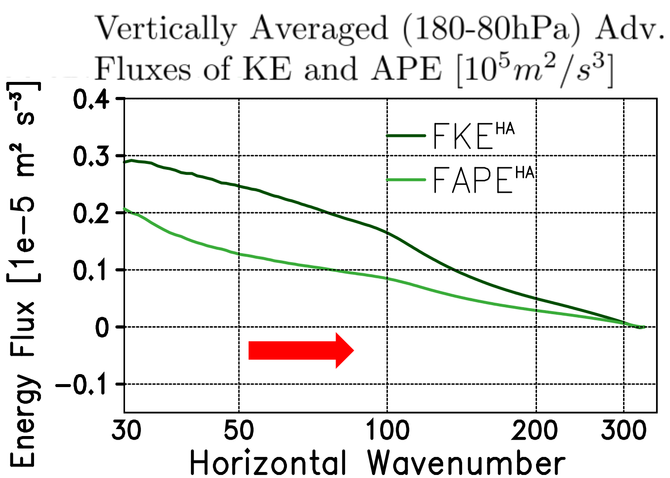
(Li&Lindborg, 2018)

- Threshold for $Fr_h < 0.02$ (Lindborg,2006)

- Re_b in comparison to is Fr_h reasonable
  - ➢ $Re_b \sim 10^4$ at Japan on $\sim 4.5km(\sim 550\ hPa)$ altitude & $\sim 35N$ latitude is reported from UAV measurements (Luce et al., 2019)

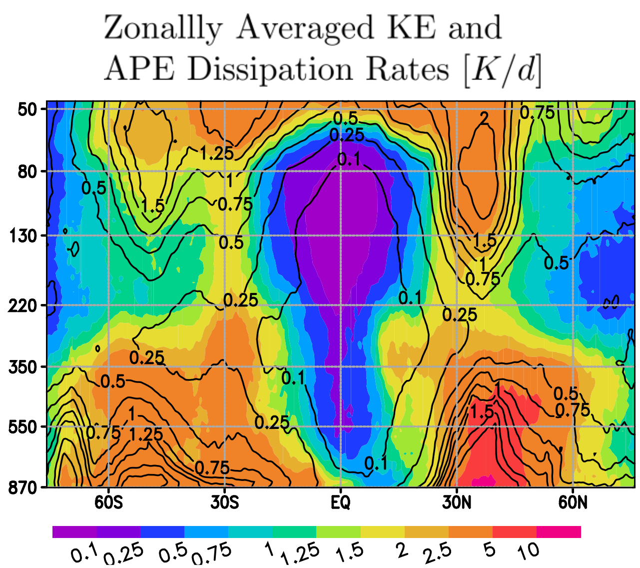
- Identified regime:
  - ➢ Altitude: **180<p<80hPa** - Upper Troposphere – Lower Stratosphere (UTLS)
  - ➢ Latitude: **Sub-tropical Midlatitudes**

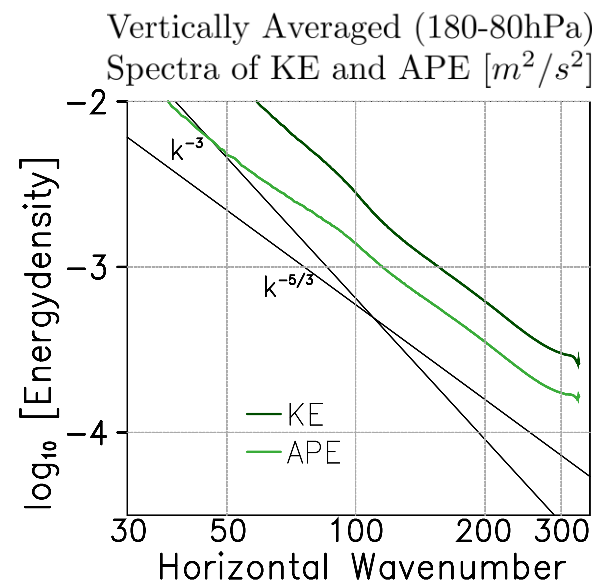
ST Fluxes and Scaling Laws



- Forward flux → dissipation at smallest scales
- Scaling laws of ST for KE and APE (Riley&Lindborg, 2013):

$$e_{KE(n)} = C_1 \epsilon_{ke}^{2/3} n^{-5/3} \quad e_{APE(n)} = C_2 \frac{\epsilon_{ape}}{\epsilon_{ke}^{1/3}} n^{-5/3}$$





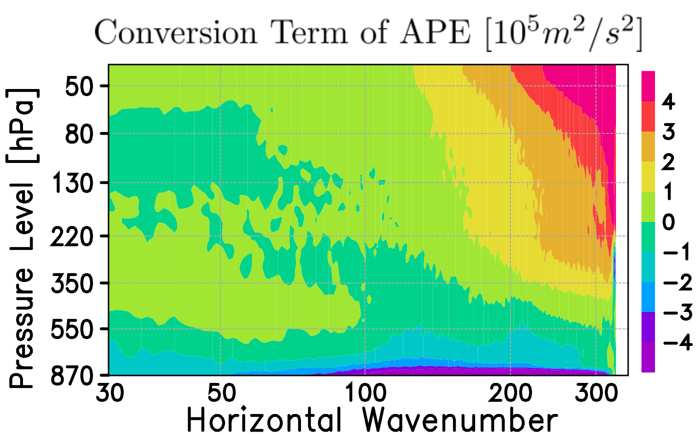
Conversion of Energy

- Adiabatic conversion couples KE and APE. **<u>In global mean</u>**, the conversion is represented by the **<u>same term</u>** in both energy reservoirs.

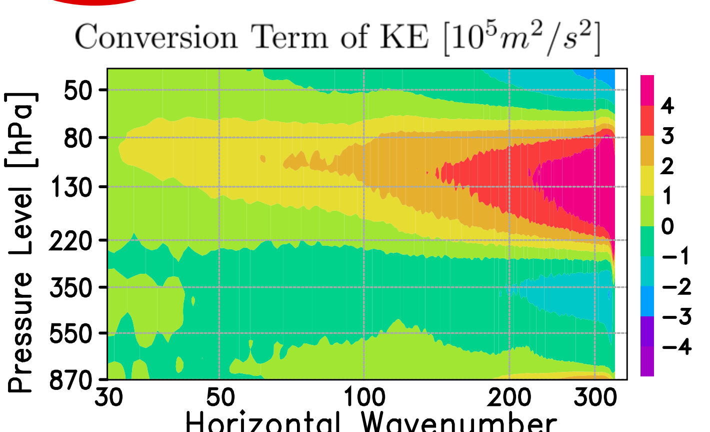
$$< \dot{KE} >= C - D^{KE}$$
$$< \dot{APE} >= G - C + D^{APE}$$

- **<u>In horizontal mean</u>**, where vertical coordinate is retained, **conversion from KE includes vertical geopotential fluxes as well**! (Brune&Becker,2013 & Augier&Lindborg2013)

$$[\dot{KE}]_{(p)} = C^{KE}_{(p)} - D^{KE}_{(p)}$$
$$[\dot{APE}]_{(p)} = G_{(p)} - C^{APE}_{(p)} + D^{APE}_{(p)}$$



$$C^{APE}_{(p)} = -\left[\frac{\omega}{\rho}\right]$$



$$C^{KE}_{(p)} = \left[\frac{\omega}{\rho}\right] - \partial_p\left[gz\omega\right]$$

GW Scale Energetics

Define KE and APE budget for GW scale perturbations:
(Becker,2017)

- Anelastic
- For mid-frequency GWs
- No GW Scale (mesoscale) forcing
- Single-Column Approximation

$$\dot{KE}^{GW} = -(\overline{\vec{v}'w'}) \cdot \partial_z \vec{v} + \frac{g}{T_r}\overline{T'w'} - \frac{1}{\rho_r}\partial_z \overline{p'w'} - (K_z)\overline{(\partial_z \vec{v}')^2} - K_h\overline{|\mathbf{S}_h'|^2}$$

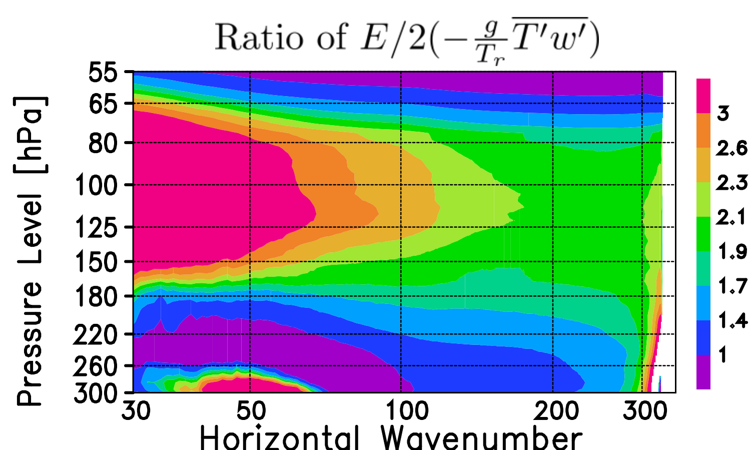
$$\dot{APE}^{GW} = -\frac{g}{T_r}\overline{T'w'} - \frac{g^2}{N_r^2 T_r^2}\left[\frac{K_z}{P_r}\overline{(\partial_z T')^2} + \frac{K_h}{P_r}\overline{((\vec{\nabla} T')^2}\right]$$

Define accordingly the Energy Deposition of nonconservative GWs:
(Hines&Reddy,1967 & Lindzen,1973)

$$E = -\frac{1}{\rho_r}\partial_z \overline{p'w'} - (\overline{\vec{v}'w'}) \cdot \partial_z \vec{v} = -\frac{g}{T_r}\overline{T'w'} + (K_z)\overline{(\partial_z \vec{v}')^2} + K_h\overline{|\mathbf{S}_h'|^2}$$

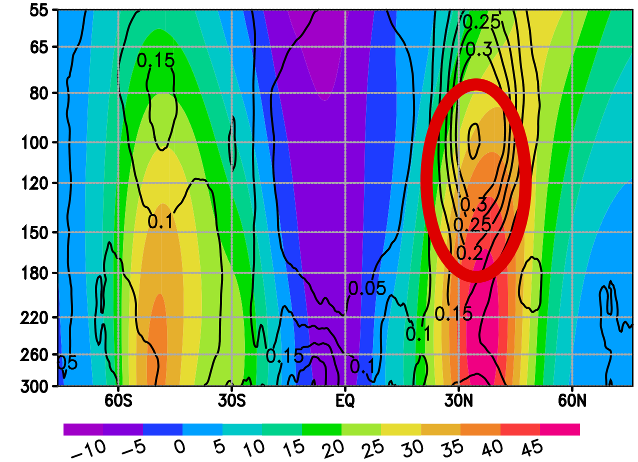
Impose ST argument for similar amounts of KE and APE dissipation rates:

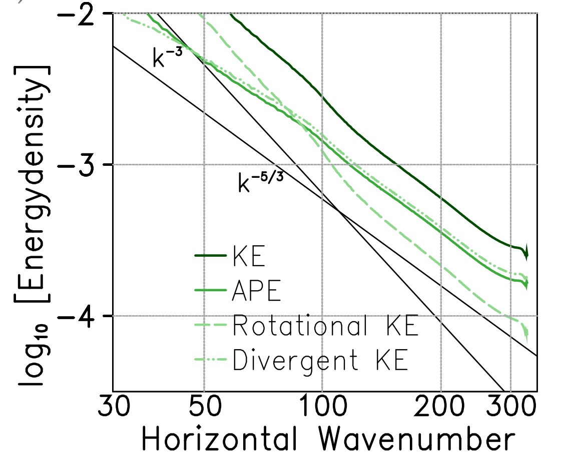
$$E = 2(-\frac{g}{T_r}\overline{T'w'})$$



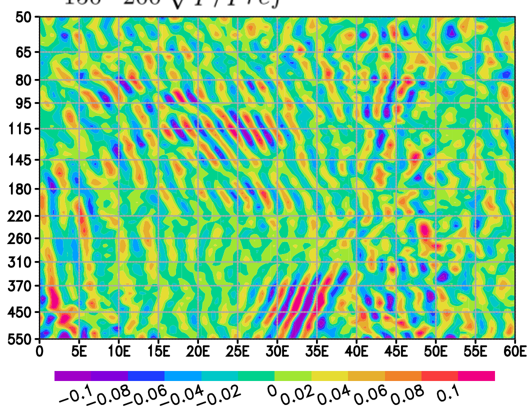
Resolved Saturated Westward GWs

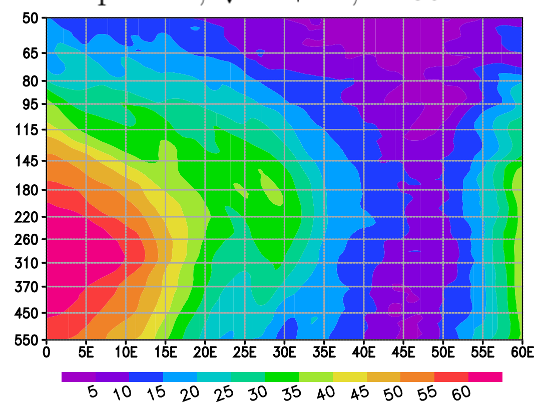
Further predictions from the theory of Superposition of **Saturated GWs** hold as well (Lindzen,1981 & Becker, 2004):





Instantaneous snapshots of Temperature perturbations and wind amplitude further supports the **existence of Westward GWs**(Viudez,2007 & Plougonven&Zhang,2014 & Yasuda et al.,2015) :





Conclusions & References

1. Mesoscale shallowing at UTLS altitudes are **primarily governed by resolved westward mid-frequency GWs**, for which each GW is at the **saturation level due to the direction** of their propagation.
2. This saturation is the cause of energy deposited at UTLS altitudes, **which can be explicitly formulated** via the anelastic, single column approximated GW scale energetics.
3. **Resolved saturated WGWs induce the forward cascades** of both APE and KE, which are **governed by strongly nonlinear ST dynamics**.

Thank you for your attention! Any questions?

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