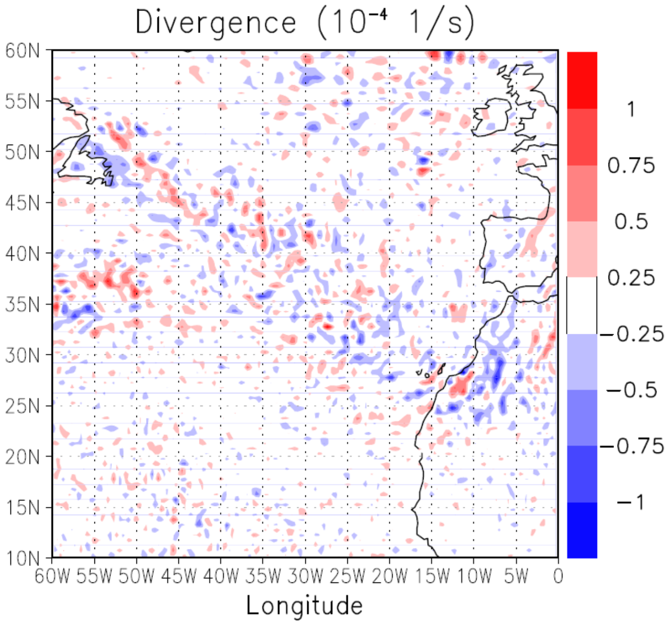
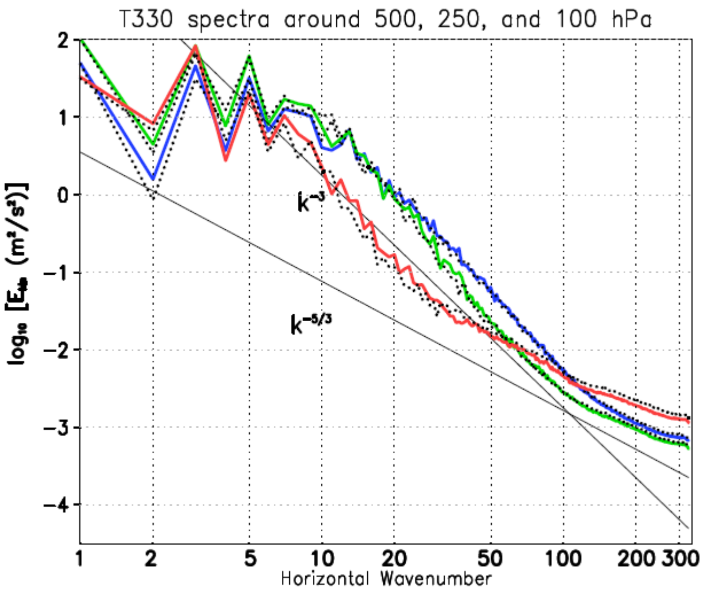
Application of a dynamic turbulence parametrization in a circulation model

Outline:

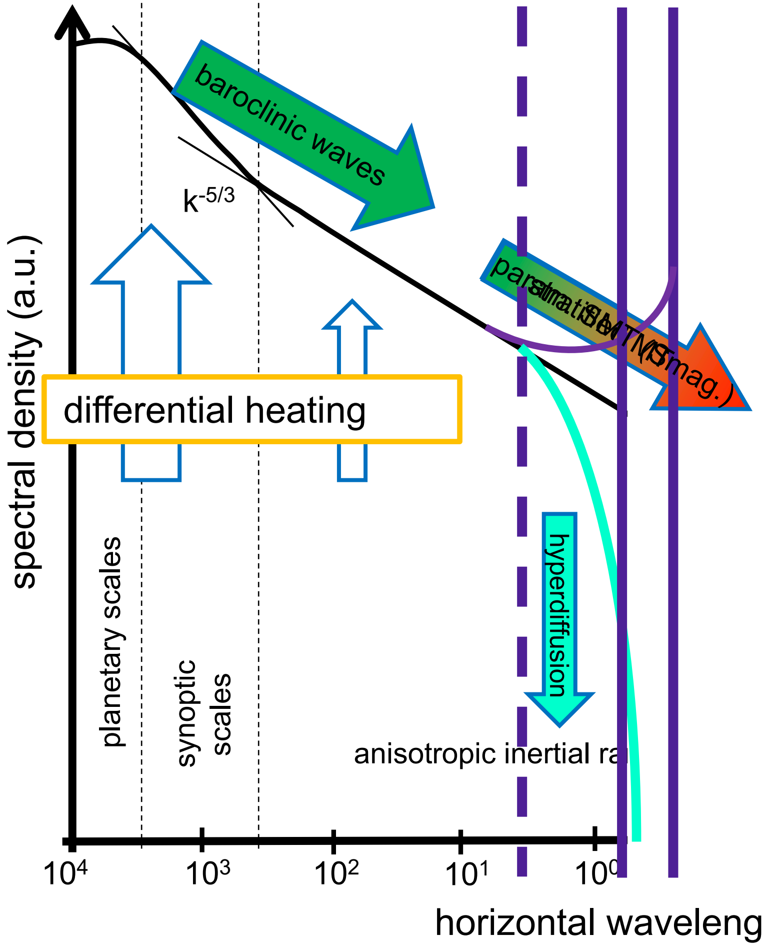
- Retrospective: A consistent turbulence parametrization
- Stratified turbulence – a summary
- Results





Application of a dynamic turbulence parametrization in a circulation model

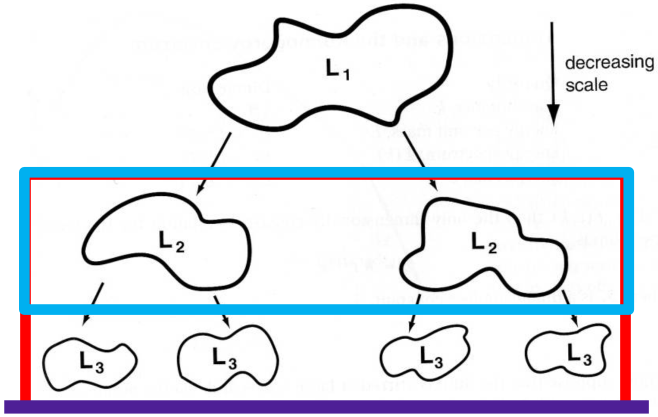
Retrospective: A consistent turbulence parametrization



Application of a dynamic turbulence parametrization in a circulation model

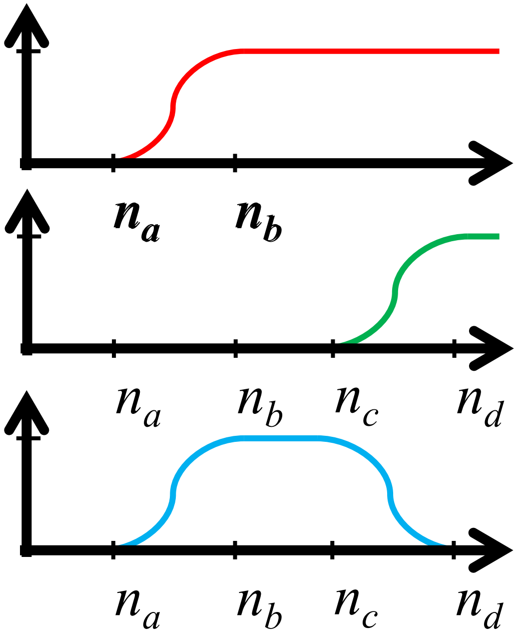
Retrospective: A consistent turbulence parametrization

- Mixing length approach for turbulent harmonic diffusion: $K_T = {l_h}^2|\mathbf{S}_h|$
- Dynamic idea: Estimation of a dynamic mixing length $l_h = c_S \Delta_h$ by applying filter and assumption of self similarity
- Standard DSM: reasonable results, but depends on resolution scale, thus gDSM (Schaefer-Rolffs, Met. Z, 2017)



Scales below L$_3$ are unresolved scales. The test filter fades out scales of L$_2$ and L$_3$ (DSM, red), or only L$_2$ (gDSM, blue).

From: G. Vallis, Atmospheric and Oceanic Fluid Dynamics



Standard DSM: The test filter algorithm is applied once to the prognostic variables (top panel).

gDSM: The test filter algorithm is applied twice to the prognostic variables (top and central panel). The difference of these filtered variables results in a test filter regime (bottom panel) that is denoted hereafter n_a/n_b // n_c/n_d.

Application of a dynamic turbulence parametrization in a circulation model

Retrospective: A consistent turbulence parametrization

- Introduce scaling transformation of Euler Equations

$$t^* = e^{\frac{2}{3}c_x} t; \quad x_i^* = e^{c_x} x_i; \quad v_i^* = e^{\frac{1}{3}c_x} v_i; \quad a^* = e^{c_a} a; \quad b_l^* = e^{c_{b_l}} b_l$$

- Implications for stratified fluids: Parametrization of vertical diffusion in horizontal momentum equation

$$\rho^{-1}\partial_z(\rho K_z \partial_z \mathbf{u}) \checkmark$$

if the mixing length in $K_z = {l_z}^2 |\partial_z \mathbf{u}|$ obeys scale ratio $c_{l_z} = \frac{3c_z - c_x}{2}$

→ However, without knowing c_z, c_{l_z} is also not determined

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Retrospective: A consistent turbulence parametrization

New dynamic approach for l_z from scale-invariance criterion and stratified turbulence:

- Concept of Stratified Turbulence (Lindborg, J. Fluid Mech., 2006) shows aspect ratio, $Z/X \sim \varepsilon^{1/3} X^{-2/3}/N$
- With $N^2 = const.$, the ratio yields $c_z = \frac{1}{3} c_x$, which could be applied in two ways:

1. Assuming that the ratio is valid for vertical scales, then $c_{l_z} = \frac{3c_z - c_x}{2} = 0$ and $l_z = const.$, in accordance to the classic Smagorinsky model
2. Assuming that the ratio is valid for the mixing lengths, $c_{l_z} = \frac{1}{3} c_{l_h} = \frac{1}{3} c_x$ allowing to formulate a new dynamic vertical mixing length (DVML),

$$l_z \propto {l_h}^{1/3}$$

Application of a dynamic turbulence parametrization in a circulation model

Stratified turbulence – a summary

Two requirements: Strong anisotropy and turbulence

- Anisotropy of the atmosphere: Low horizontal Froude number $F_h = \frac{U}{NL_h} \ll 1$ (and $T = \frac{L_h}{U}$)
- In Boussinesq approximation: Non-dimensionalized equations reveal vertical Froude number $F_z = \frac{U}{NL_z}$ accompanying vertical velocity w (Billant and Chomaz, Phys. Fluids 2001)
- Scale analysis of Billant and Chomaz: Transformation group for z, w, N, and ρ with $c_z = c_w = -c_N = -c_\rho$; hence $L_z \propto \frac{1}{N}$
- Dimensional analysis yields $L_z \sim \frac{U}{N}$ or $\cancel{L_z \sim \frac{W}{N}}$

→ $F_z \sim 1$

Application of a dynamic turbulence parametrization in a circulation model

Stratified turbulence – a summary

Two requirements: Strong anisotropy and turbulence

- Turbulence analysis (Taylor, Proc R. Soc. A 1935): $U \sim (\epsilon\, L)^{1/3}$
- Hence: $F_z = \frac{U}{N L_z} \sim 1$ and $U \sim (\epsilon\, L_h)^{1/3}$ for stratified turbulence (Lindborg, J. Fluid Mech. 2006)
- Aspect ratio: $\frac{L_z}{L_h} \sim \frac{\epsilon^{1/3}}{N\, {L_h}^{2/3}}$ or $L_z \sim \frac{\epsilon^{1/3}}{N} {L_h}^{1/3}$
- Assumption: Horizontal/vertical energy spectra $E_k \sim U^2 L$ depend only on horizontal/vertical length scale, thus

$$E_h \sim U^2 L_h \sim \epsilon^{2/3} {L_h}^{5/3} \sim \epsilon^{2/3} {k_h}^{-5/3}$$
$$E_z \sim U^2 L_z \sim N^2 {L_z}^3 \sim N^2 {k_z}^{-3}$$

- Further: Frequency spectrum exhibits $E_\omega \sim \omega^{-2}$ relation

Application of a dynamic turbulence parametrization in a circulation model

Stratified turbulence – a summary

Two requirements: Strong anisotropy and turbulence

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- In Boussinesq approximation: Non-dimensionalized equations reveal vertical Froude number $F_z = \frac{U}{NL_z}$ (Billant and Chomaz, Phys. Fluids 2001)

- Magnitude of kinetic and potential energy

$$KE \sim (1 + \cancel{F_h{}^2 F_z{}^2})U^2$$
$$PE \sim F_z{}^2 U^2$$

- Hence: Equipartition of kinetic and potential energy, similar as for gravity waves

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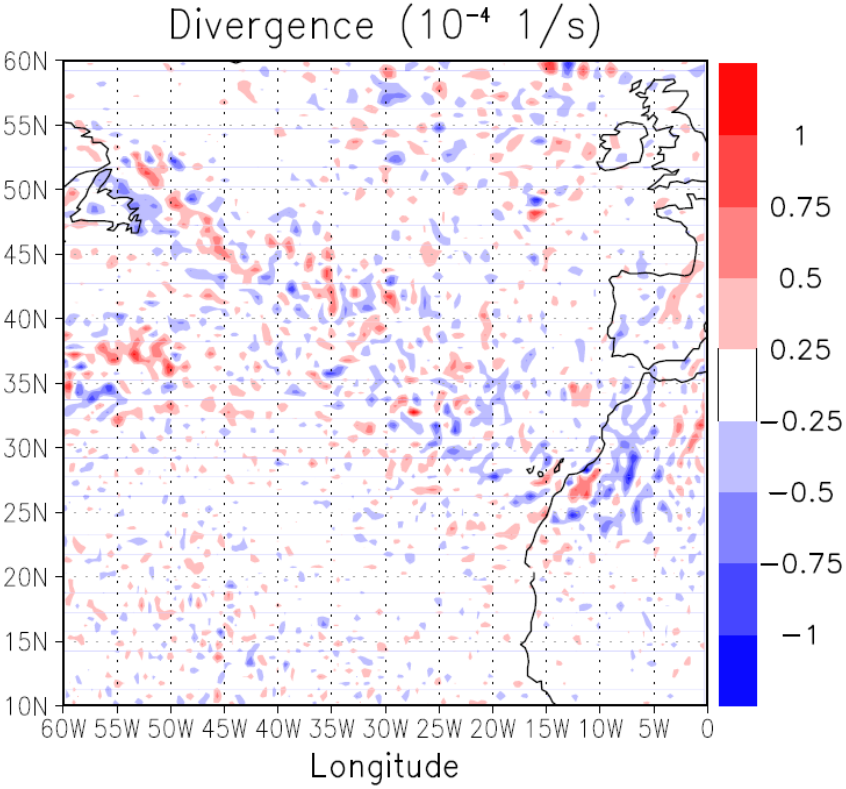
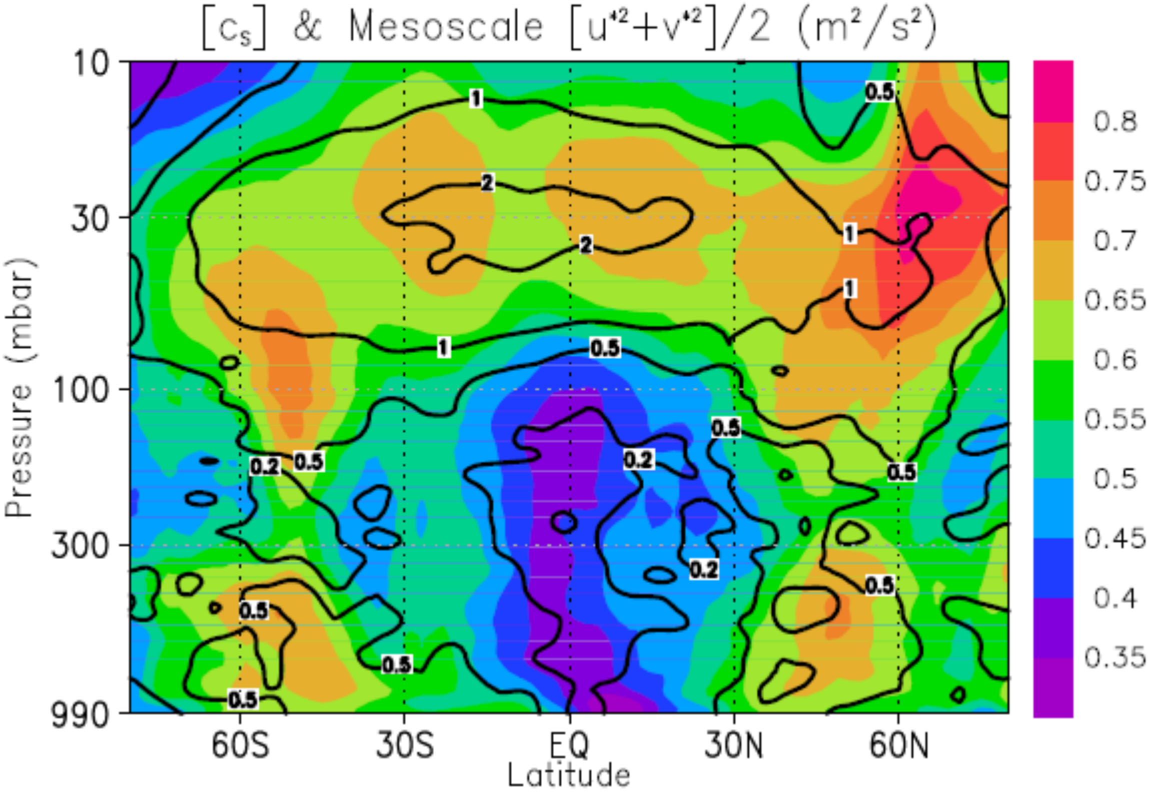
Results: Snapshot of horizontal divergence at 100 hPa



- The mesoscale activity is induced by the breakdown of baroclinic Rossby waves, reflecting the instantaneous gravity-wave activity

Application of a dynamic turbulence parametrization in a circulation model

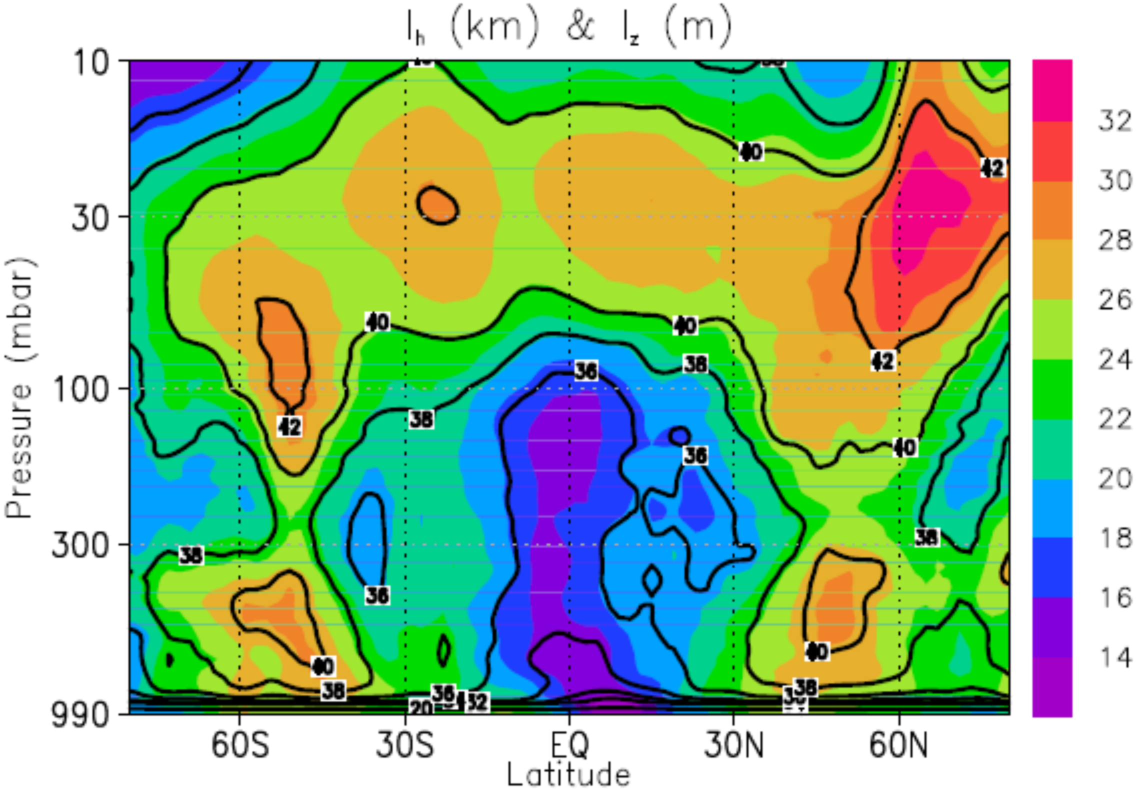
Results: Smagorinsky parameter (colors) and eddy kinetic energy (contours)



- The mesoscale eddy kinetic energy includes only wavenumbers $n > 90$

Application of a dynamic turbulence parametrization in a circulation model

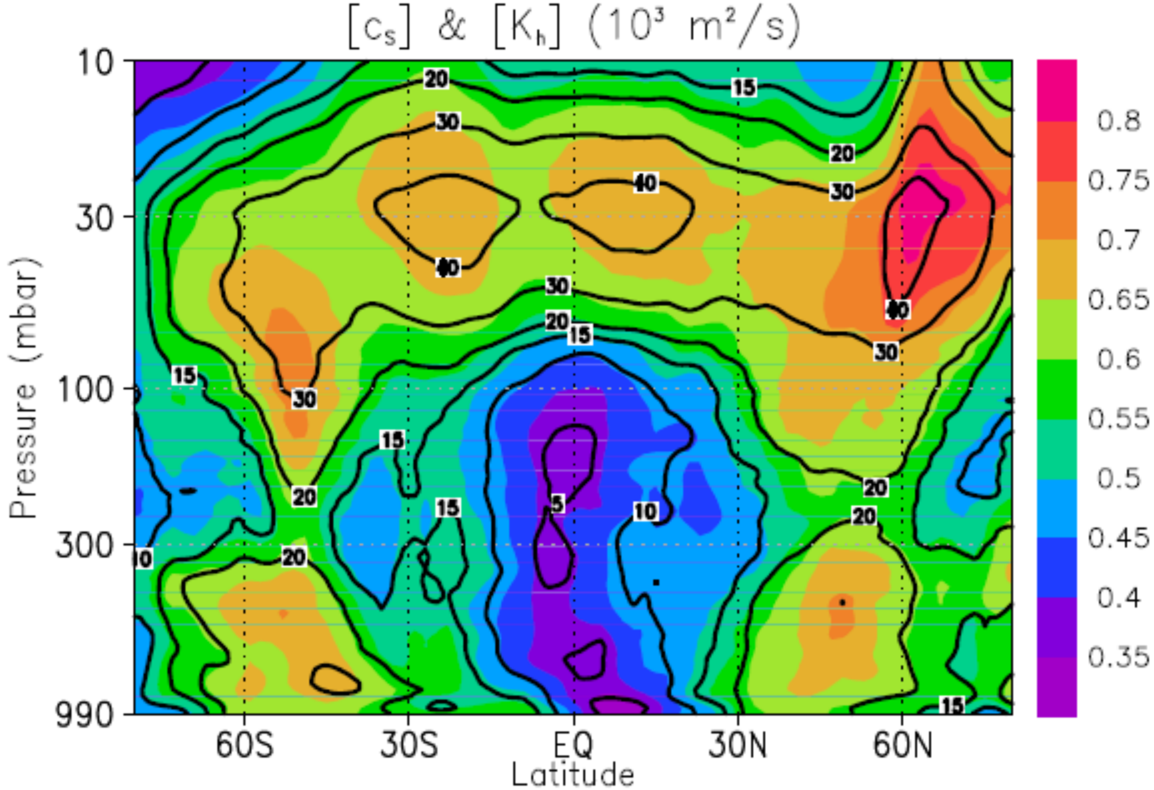
Results: Horizontal (colors) and vertical mixing lengths (contours)



- Due to $l_z \propto {l_h}^{1/3}$, the variations of l_z are much smaller than the variations of l_h

Application of a dynamic turbulence parametrization in a circulation model

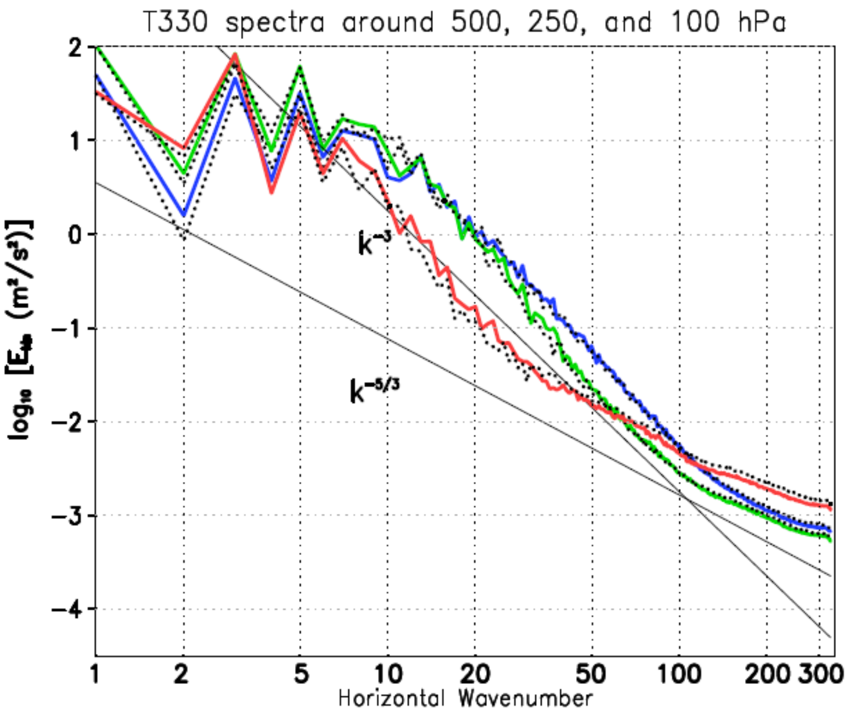
Results: Smagorinsky parameter (colors) and diffusion coefficient (contours)

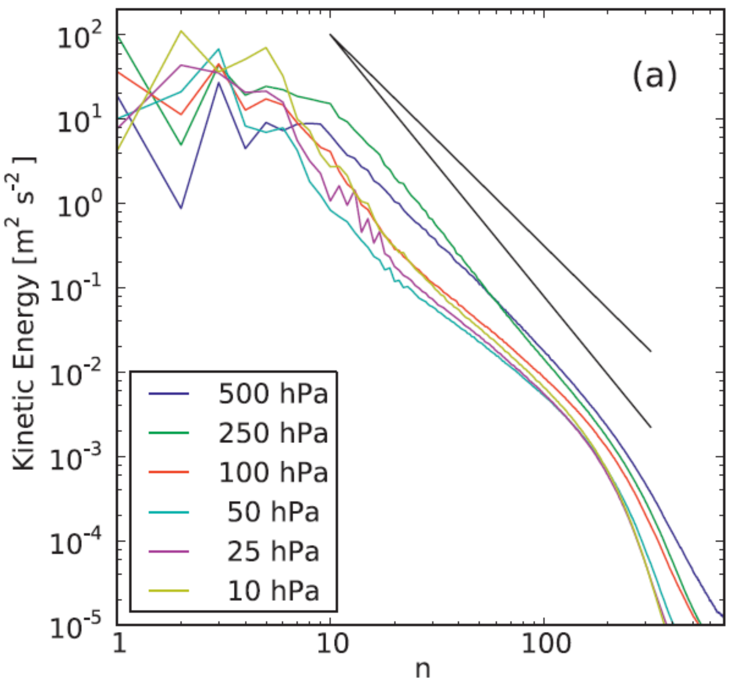


- The variability of $K_h = {l_h}^2 |\mathbf{S}_h|$ is controlled by the variability of c_S, unlike to the CSM

Application of a dynamic turbulence parametrization in a circulation model

Results: Kinetic energy spectra at 500 (blue), 250 (green), and 100 (red) hPa



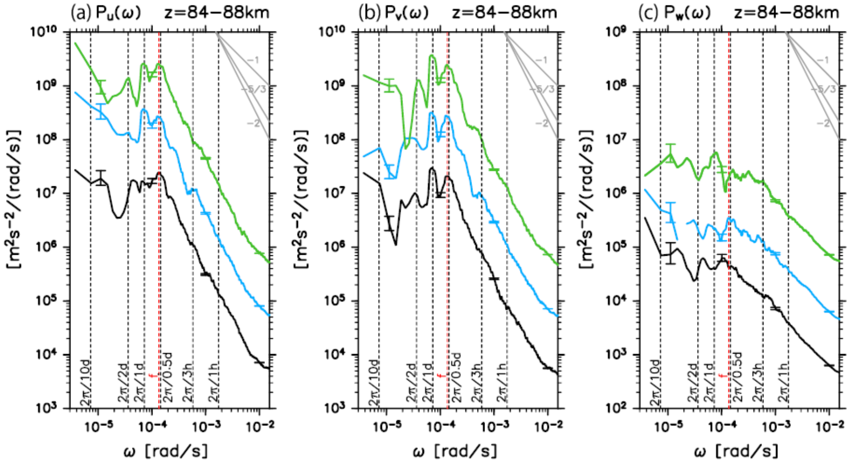


- The black dotted curves are the energy spectra that are obtained when using a constant asymptotic vertical mixing length of 30 m
- Similar transition as seen in ECMWF analyses (Burgess et al, J. Atmos. Sci., 2013)

Application of a dynamic turbulence parametrization in a circulation model

Region of interest for IAP: mesosphere/lower thermosphere (MLT, 60…110km)

- Developments and changes in MLT much stronger than in troposphere
- (Secondary) gravity waves have higher wavelengths in MLT than in troposphere
- Assumption: Stochastic generation and superposition of (secondary) gravity waves in MLT is visible as stratified turbulence
- Experimental radio data (Sato et al, J. Geophys. Res. Atmos. 2017): $E_\omega \sim \omega^{-2}$ spectrum at 84…88 km



Application of a dynamic turbulence parametrization in a circulation model

Outlook:

- Investigation of GW spectra in the MLT with respect to scaling ratio of stratified macro-turbulence
- ➢ Framework is set (Schaefer-Rolffs and Becker, Mon. Wea. Rev. 2018), extension to MLT will follow

- Comparison with GW measurements in MLT: new lidar/radar techniques detect GW in lower thermosphere with high temporal and horizontal resolutions
- ➢ Experimental set-up of MMARIA (Multistatic/Multifrequency Agile Radar for Investigations of the Atmosphere) started in 2014, will be extended
- ➢ Approval for VAHCOLI (Vertical And Horizontal COverage by LIdar) in January 2018

- Application of gDSM to calculate turbulent diffusion of
  - temperature
  - tracers

    → self-consistent Prandtl/Schmidt numbers
- ➢ Two Postdocs within the TRR 181 „Energy transfers in Atmosphere and Ocean“

TRR181

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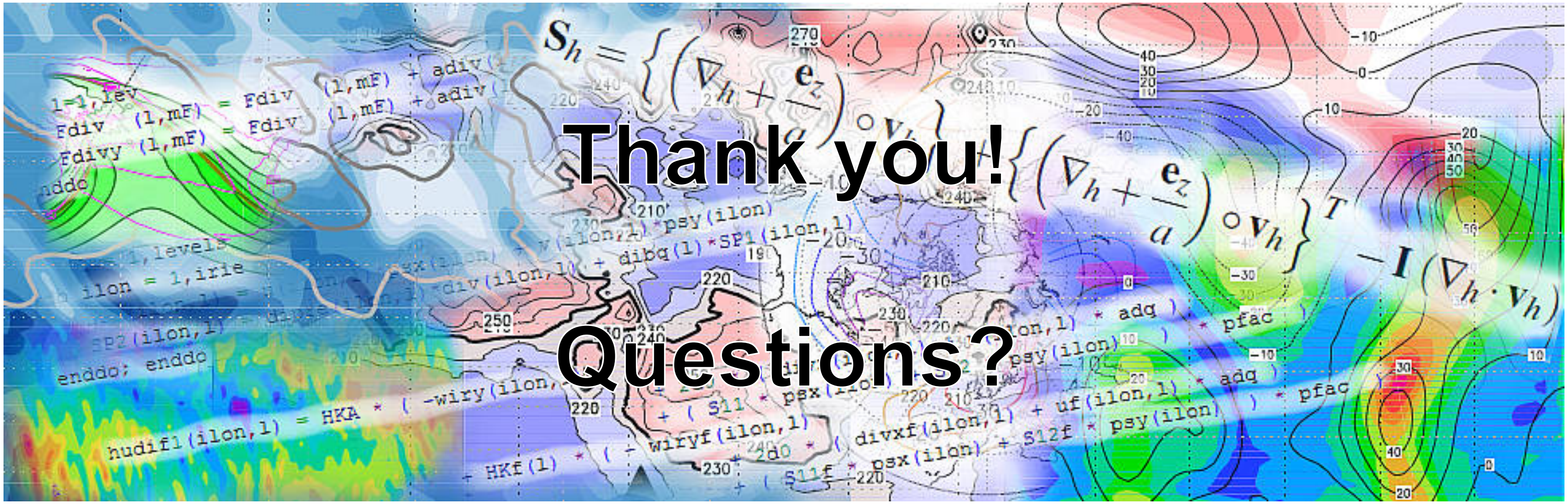

Thank you!

Questions?