Idealized Model Simulations of Gravity Wave Propagation – Modifications in the Tropopause Region

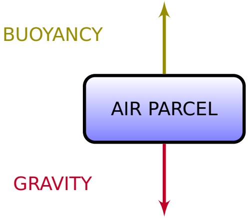
MS-GWaves | GW-TP | High-Resolution Modelling

Vera Bense   Peter Spichtinger

Institute for Atmospheric Physics
Johannes Gutenberg University Mainz

Workshop on numerical and computational methods for simulation of all-scale geophysical flows, 3-6 October 2016

In a fluid medium, equilibrium is restored by:



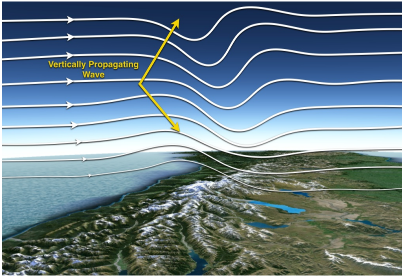


Figure: www2.ucar.edu

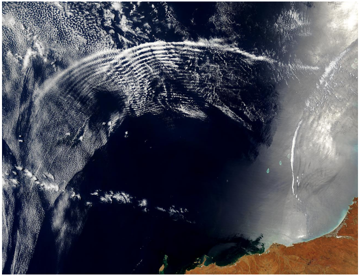


Figure: visibleearth.nasa.gov

- Occurrence on many atmospheric scales ($50 - 500\,\mathrm{km}$)
- Only a portion resolved in global models
- Parameterizations, but inconsistencies remain
- This project: High resolution process studies

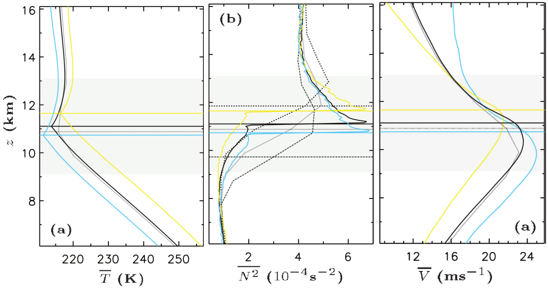


Figure: Radiosoundings, ERA Reanalysis for Munich. Birner et al., 2002

$$N^2 = \frac{g}{\Theta}\frac{d\Theta}{dz}$$

$$\Theta = T\left(\frac{p_0}{p}\right)^{\frac{R}{c_p}}$$

Characteristics

- Changing stratification
- Wind shear
- Dynamically linked to jets and fronts
- Related to regions of enhanced water vapour and ice clouds

Objectives

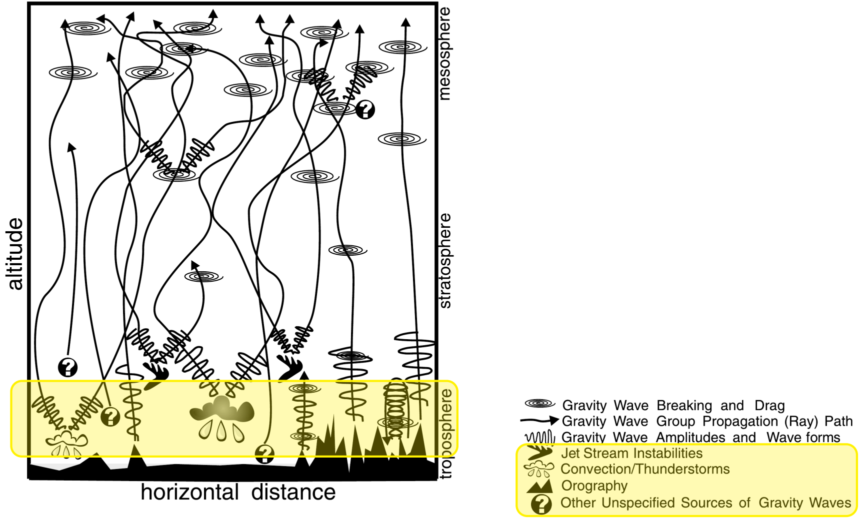


Figure: Kim et al., 2003

Objectives

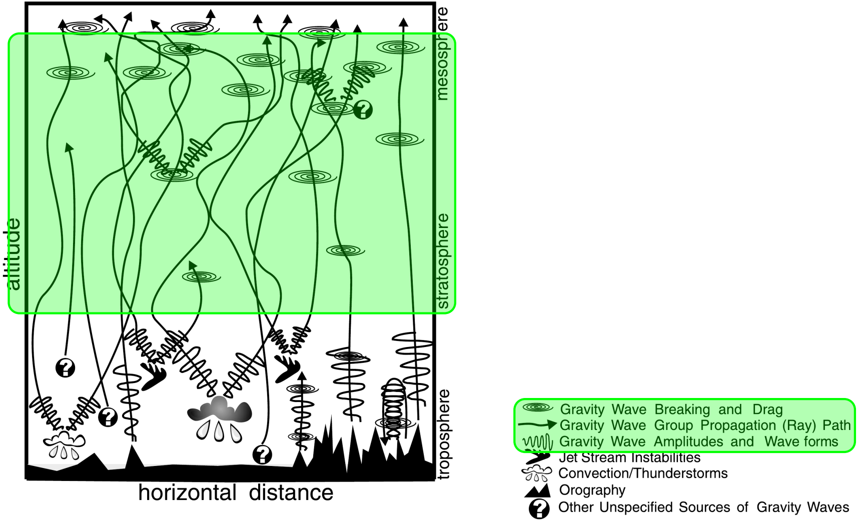


Figure: Kim et al., 2003

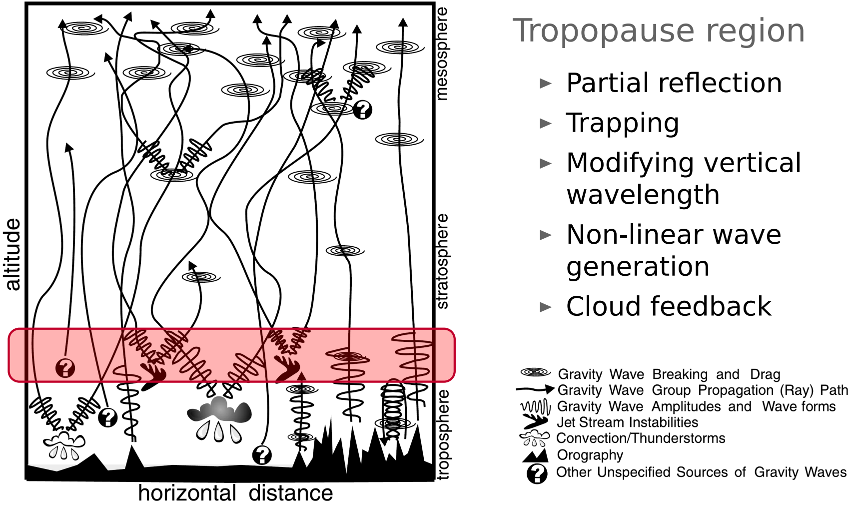


Figure: Kim et al., 2003

Tropopause region

- Partial reflection
- Trapping
- Modifying vertical wavelength
- Non-linear wave generation
- Cloud feedback

Stationary mountain waves over sinusoidal topography

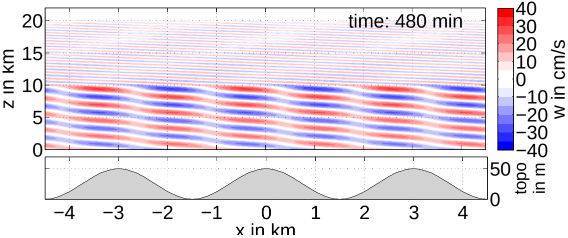


Figure: Vertical wind field w, topography

Varied parameters

- Stability
- Wind shear
- Topography
- Initial wind field

EULAG (Prusa et al., 2008)

- Split in environmental state and deviation: $\psi' = \psi - \psi_e$
- Anelastic equations
- 2-dim on x-z plane: $90\,\mathrm{km} \times (30-55)\,\mathrm{km}$
- Periodic boundaries in x
- Absorbing layer at upper boundary
- Resolution: $\Delta x \approx 90\,\mathrm{m}, \Delta z \approx (50-90)\,\mathrm{m}$
- Topography amplitude: $H_{max} = (50-200)\,\mathrm{m}$

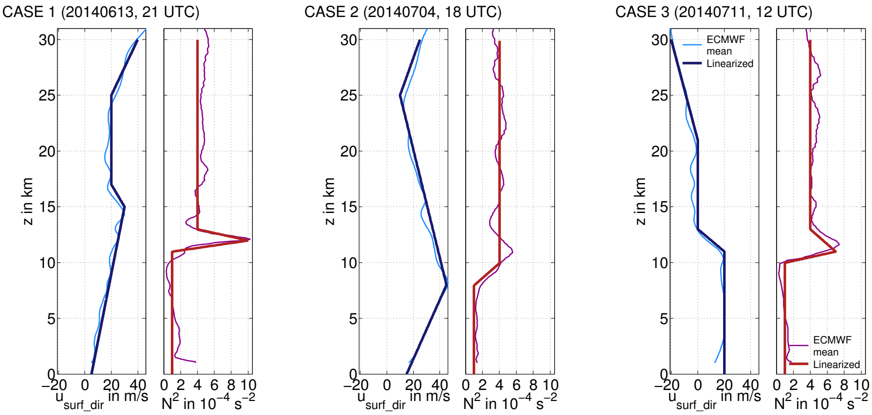
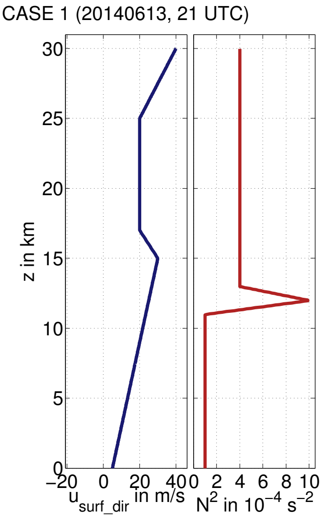


Figure: ECMWF mean profiles over New Zealand (SI) and piece-wise linearization *(S. Gisinger, DLR)*



Characteristics

- Strong tropopause inversion layer (TIL)
- Tropospheric wind speed increases with altitude
- Maximum wind speed above tropopause

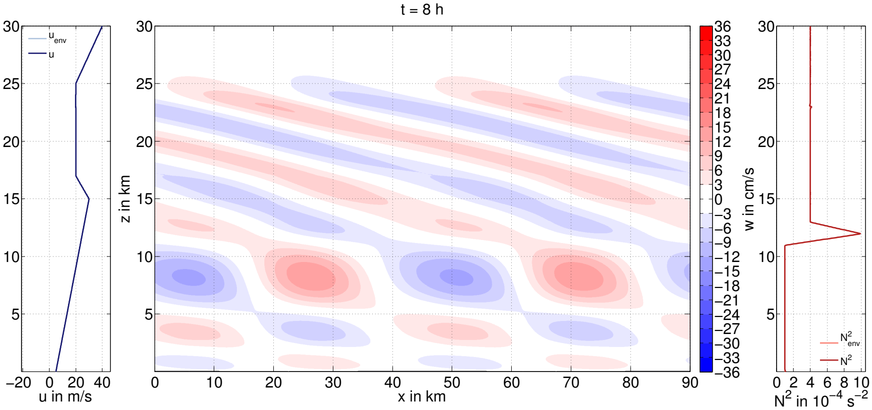


Figure: $\lambda_x = 45\,\text{km}$

CASE 1 - Wind field

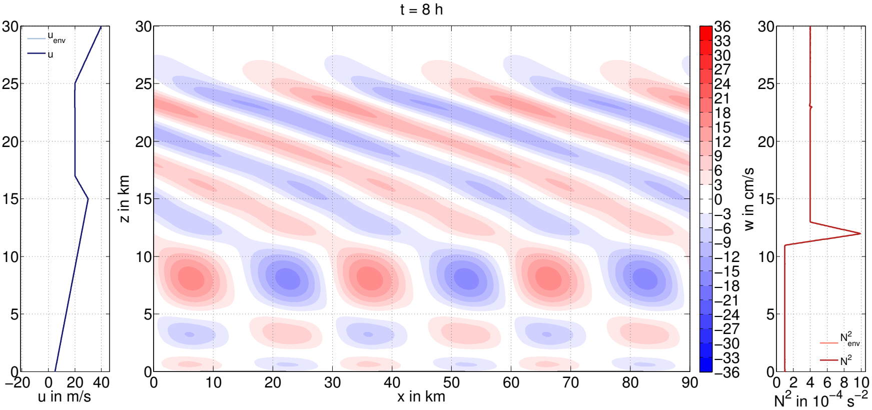


Figure: $\lambda_x = 30\,\text{km}$

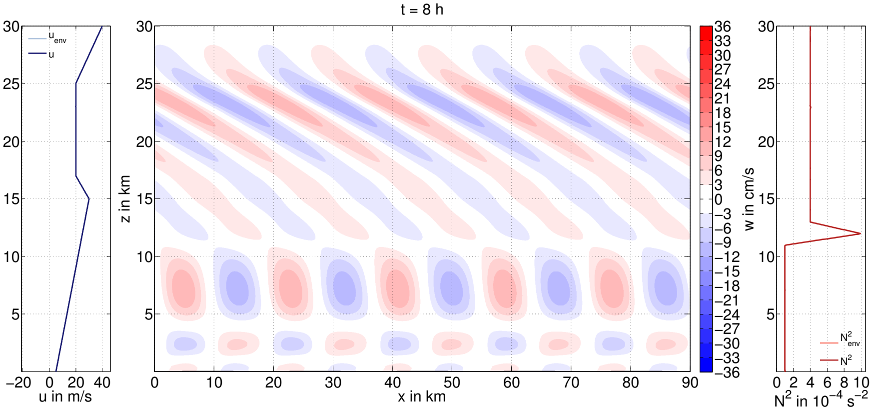
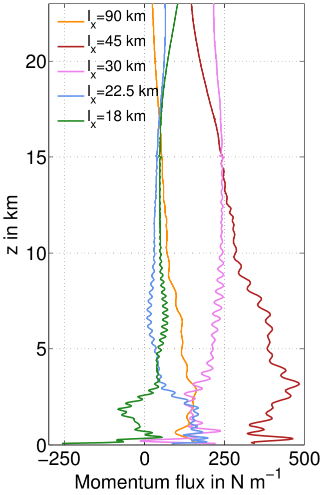
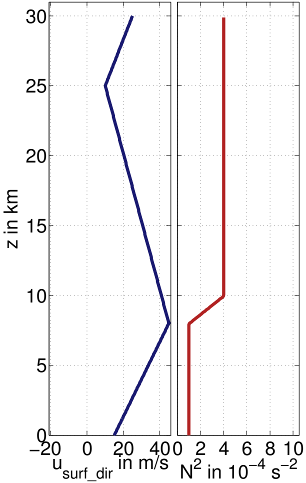


Figure: $\lambda_x = 18\,\text{km}$



- Stratospheric waves almost monochromatic
- Strongest feedback for $\lambda_x = 45\,\mathrm{km}$
- Net downward flux for $\lambda_x = 18\,\mathrm{km}$

CASE 2 (20140704, 18 UTC)



Characteristics

- Tropopause weaker than in CASE 1
- Depth of Tropopause: $2\,\mathrm{km}$
- Wind decreases with altitude in stratosphere

CASE 2 - Wind field

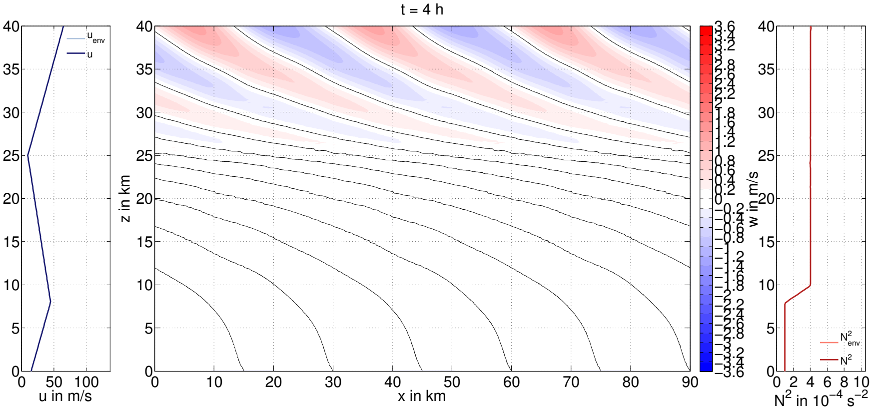


Figure: $\lambda_x = 30\,\mathrm{km}$

CASE 2 - Wind field

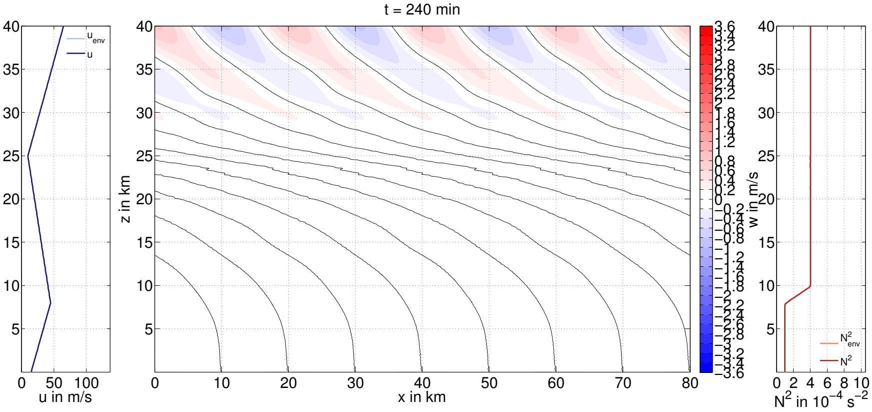


Figure: $\lambda_x = 20\,\mathrm{km}$

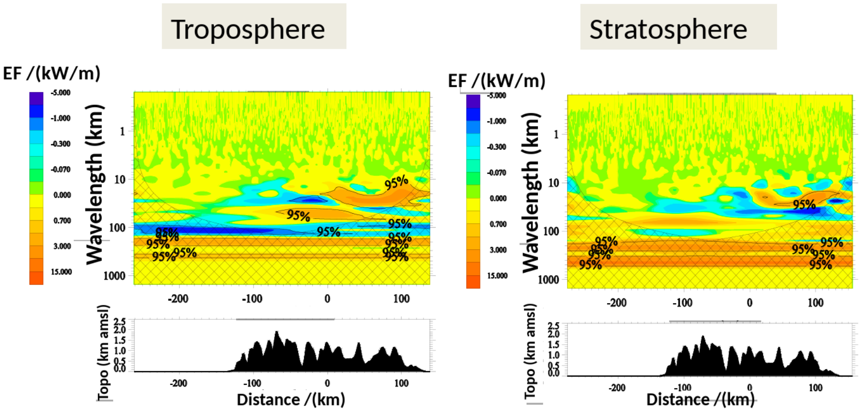


Figure: $p'w'$ Cospectra, *by M. Bramberger, DLR*

CASE 2 - Wavelet Analysis

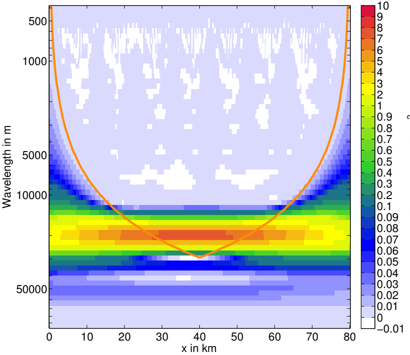


Figure: $\lambda_x = 20\,\text{km}$, $z = 7\,\text{km}$

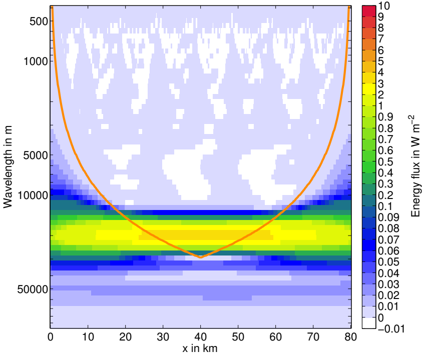


Figure: $\lambda_x = 20\,\text{km}$, $z = 11\,\text{km}$

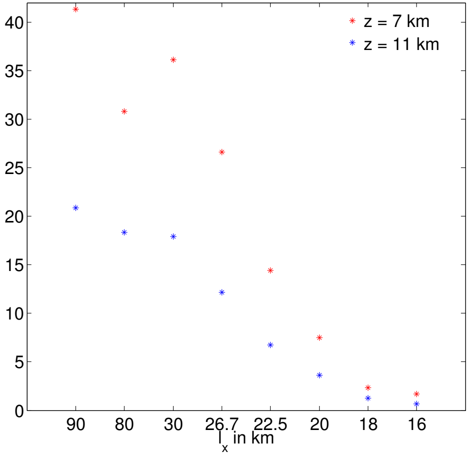
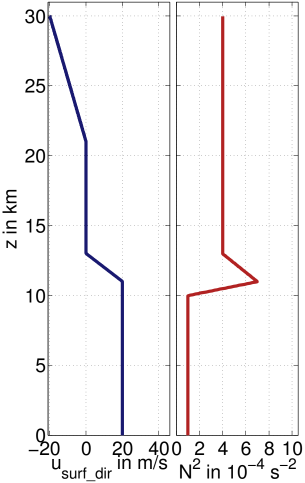


Figure: Maximum wave energy flux

CASE 3 (20140711, 12 UTC)



Characteristics

- Tropopause with moderate TIL
- Critical layer between $17\,\mathrm{km}$ and $22\,\mathrm{km}$

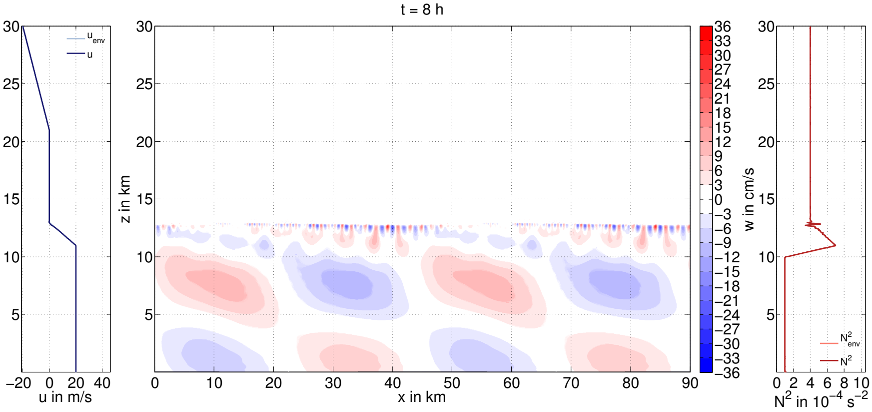


Figure: $\lambda_x = 45\,\text{km}$

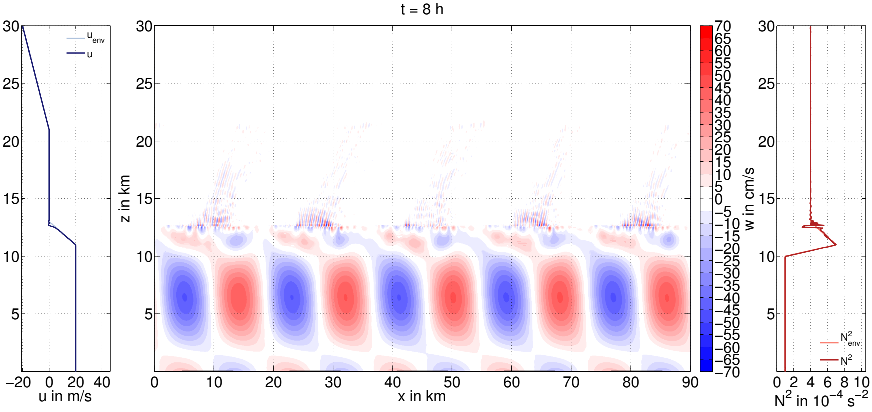


Figure: $\lambda_x = 18\,\mathrm{km}$

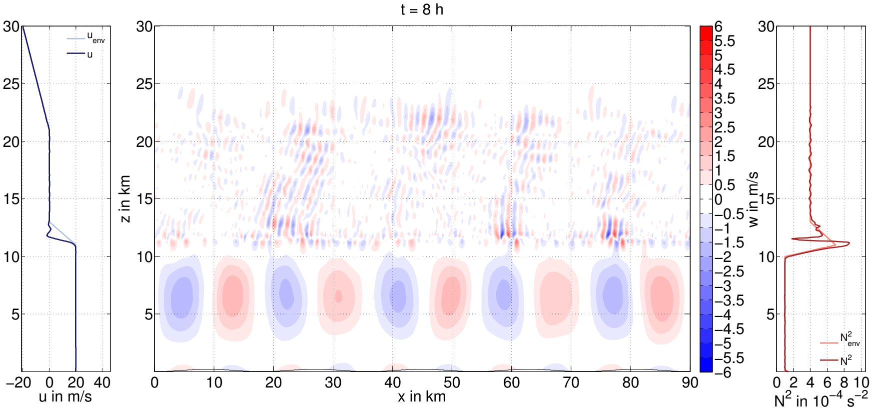


Figure: $\lambda_x = 18\,\mathrm{km}$, $H_{max} = 200\,\mathrm{m}$

CASE 3 - w Wavelet Analysis: Shear Layer

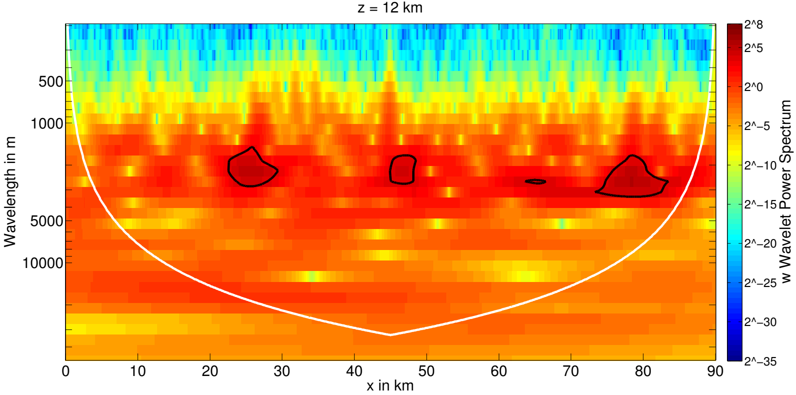


Figure: $\lambda_x = 18\,\mathrm{km}$, $H_{max} = 200\,\mathrm{m}$, $\Delta h = 0.5\,\mathrm{km}$

CASE 3 - w Wavelet Analysis: Shear Layer

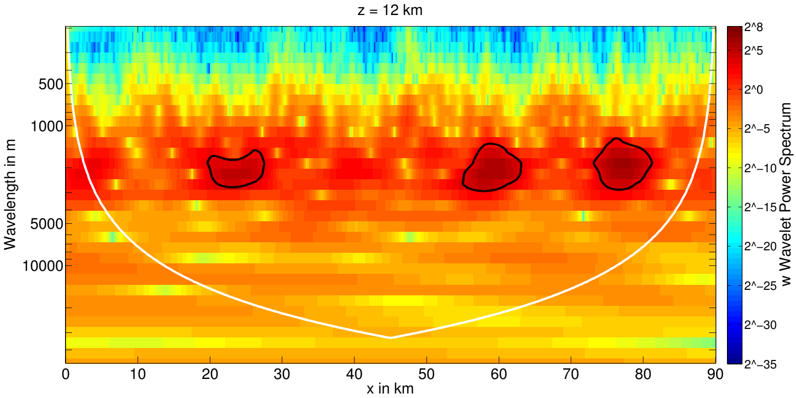


Figure: $\lambda_x = 18\,\text{km}$, $H_{max} = 200\,\text{m}$, $\Delta h = 2\,\text{km}$

CASE 3 - w Wavelet Analysis: Shear Layer

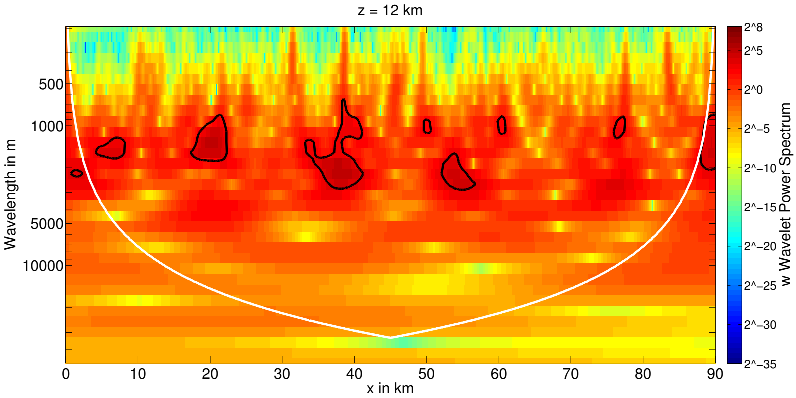


Figure: $\lambda_x = 18\,\mathrm{km}$, $H_{max} = 200\,\mathrm{m}$, $\Delta h = 4\,\mathrm{km}$

CASE 3 - TIL

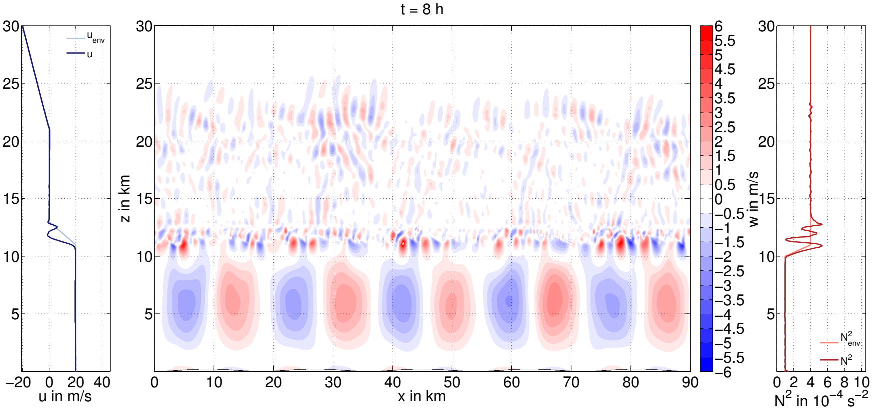
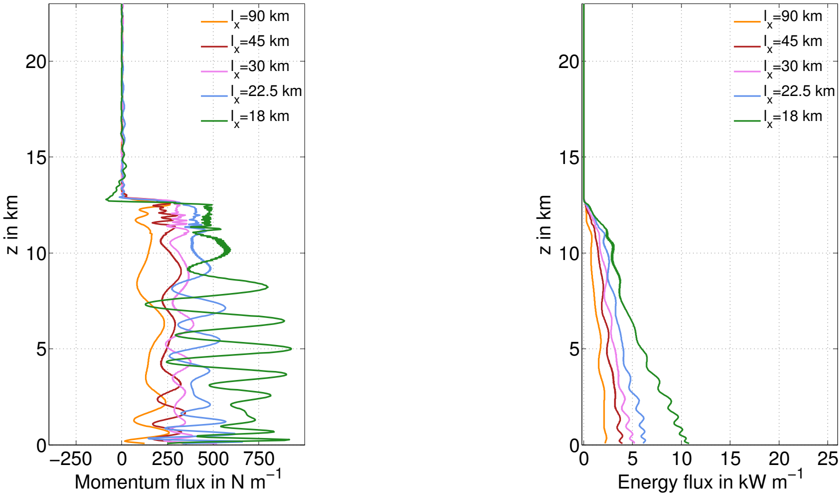


Figure: $\lambda_x = 18\,\text{km}$, $H_{max} = 200\,\text{m}$


l_x=90 km
l_x=45 km
l_x=30 km
l_x=22.5 km
l_x=18 km
z in km
Momentum flux in N m^-1
–250 0 250 500 750
0 5 10 15 20
Energy flux in kW m^-1
0 5 10 15 20 25

- Extension of approach by Sutherland and Yewchuk, 2004
- with Christopher Pütz (FU Berlin)
- Transmission (TC) coefficient calculated as the fraction of incident wave energy that is transported across a region of interest.
- 2D, stationary Boussinesq fluid
- Approximation of N by piecewise-constant function
- Matching of the solutions at the interfaces

Linear change in N at tropopause

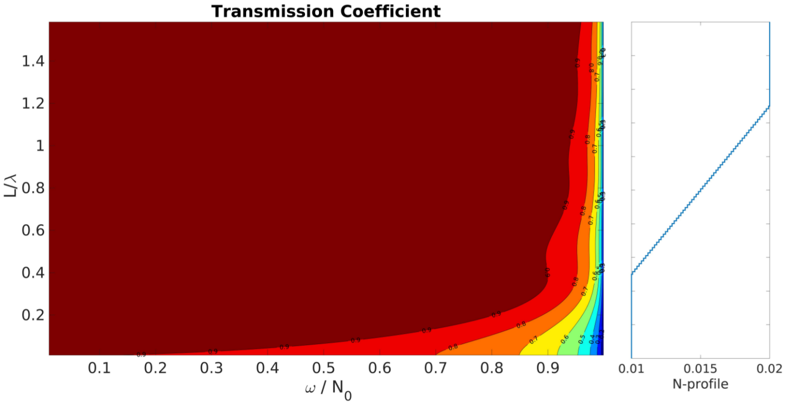


Figure: $u_{env} = 0\,\mathrm{m/s}$ *(C. Pütz)*

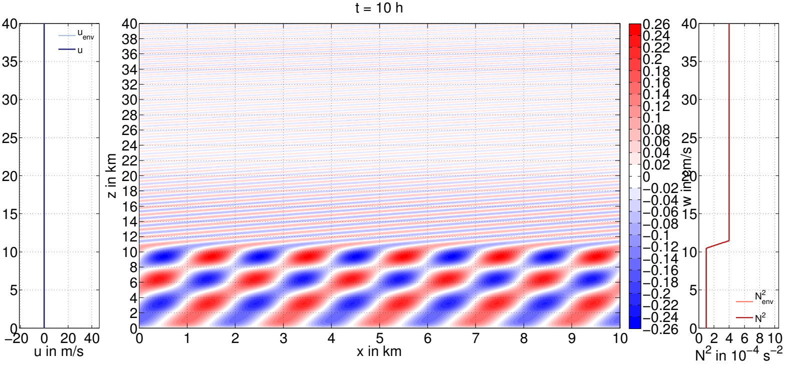
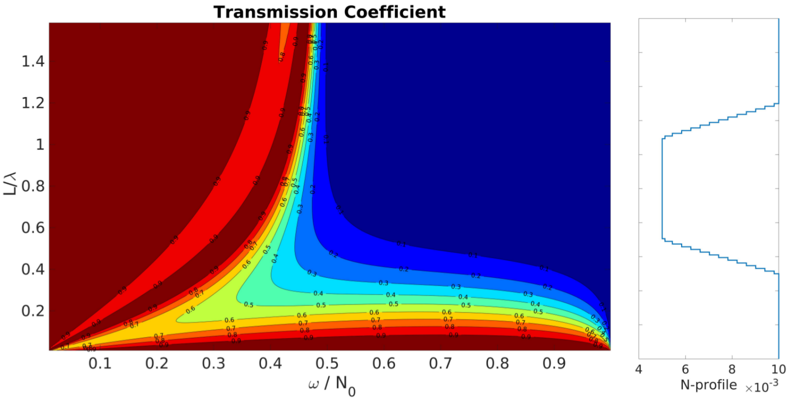


Figure: Tropopause depth $L = 0.5 \cdot \lambda_x$, frequency $\omega = 0.98 \cdot N_0$

$$TC = \frac{m_{ss} \cdot |A_{ss}|}{m_{ts} \cdot |A_{ts}|} = 0.71$$



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Wind tunnelling

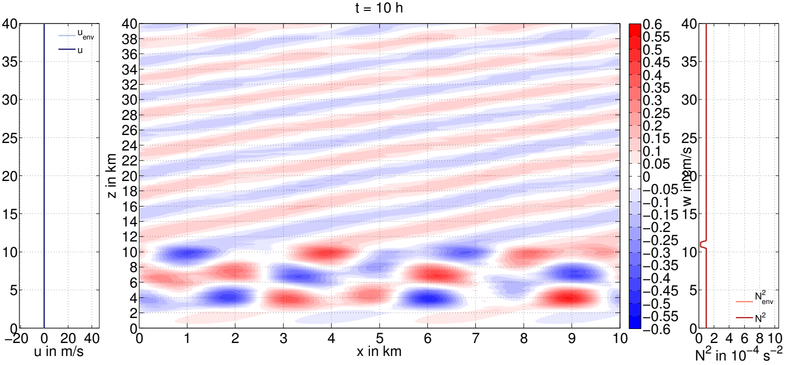


Figure: Tropopause depth $L = 0.5 \cdot \lambda_x$, frequency $\omega = 0.8 \cdot N_0$

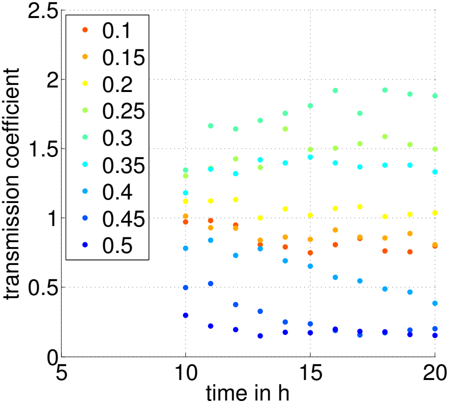
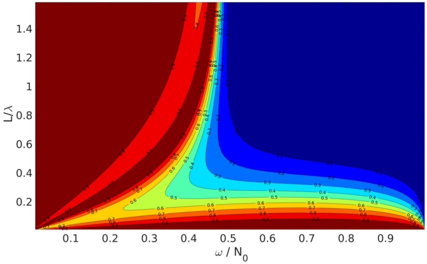
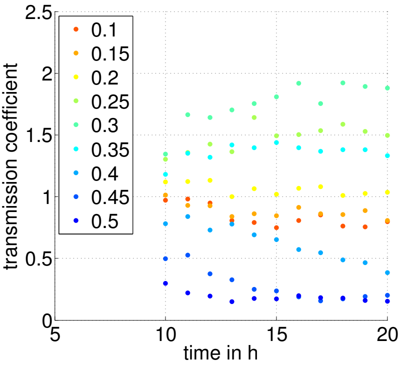


Figure: Various combinations of L/λ_x for $\omega = 0.8 \cdot N_0$

Wind tunnelling





Summary

- Tool allows distinction between regimes
- Secondary wave generation, despite strong TIL
- Wave breaking, feedback on mean flow
- Comparison of transmission coefficient

Outlook

- Extension to larger wavelengths, higher amplitudes
- Confirm CASE 3 with higher resolution
- TC calculations dependent on tropopause height?
- Microphysical model, feedback ice clouds

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Thank you for your attention!

References

- Birner, Thomas et al. (2002). "How sharp is the tropopause at midlatitudes?" In: *Geophysical research letters* 29.14, p. 1700.
- Kim, Y.-J. et al. (2003). "An Overview of the Past, Present and Future of Gravity-Wave Drag Parametrization for Numerical Climate and Weather Prediction Models". In: *Atmosphere-Ocean* 41.1, pp. 65–98.
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- Sutherland, Bruce R. and Kerianne Yewchuk (2004). "Internal wave tunnelling". In: *Journal of Fluid Mechanics* 511, pp. 125–134.
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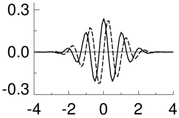
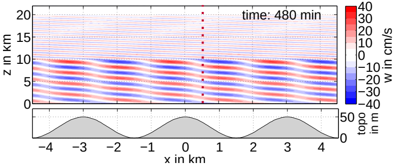
Appendix

Wavelet Analysis

- Decomposing vertical wind profile $w(z)$: determine dominant modes of variability and how these modes vary in z
- Choice of wavelet base function adaptable to type of series



Morlet wavelet, from Torrence and Compo, 1998



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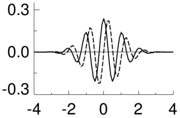

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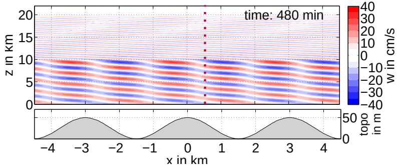


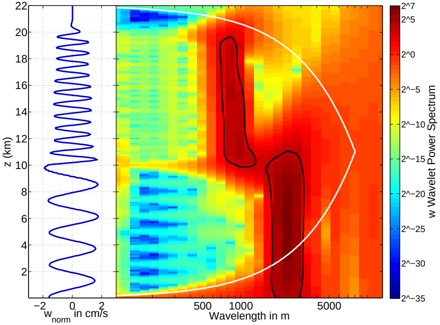


Figure: Vertical wind w (normalized by stdev), local wavelet power spectrum

Deep Tropopause Layer

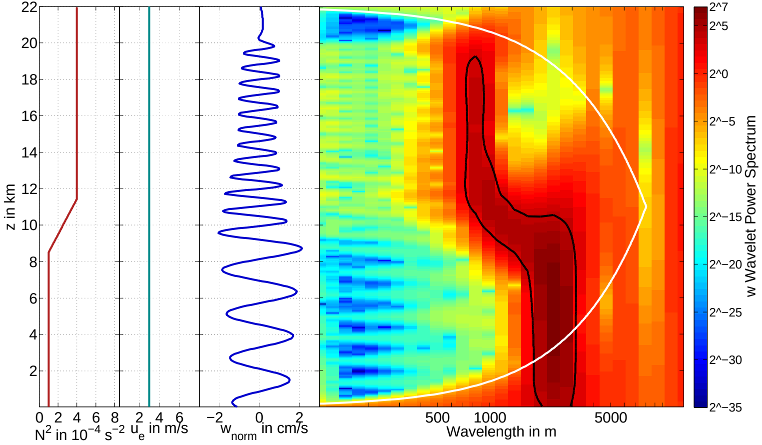


Figure: Tropopause depth Δz_{TP} 3000 m

Stepwise Change in Stratification

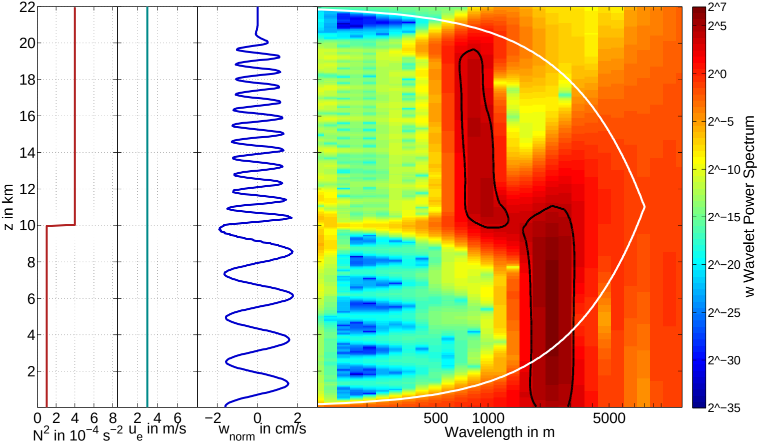


Figure: Tropopause depth $\Delta z_{TP} = 0\,\text{m}$, $N^2_{\text{strato}} = 8 \cdot N^2_{\text{tropo}}$

Strong Tropopause Inversion Layer (TIL)

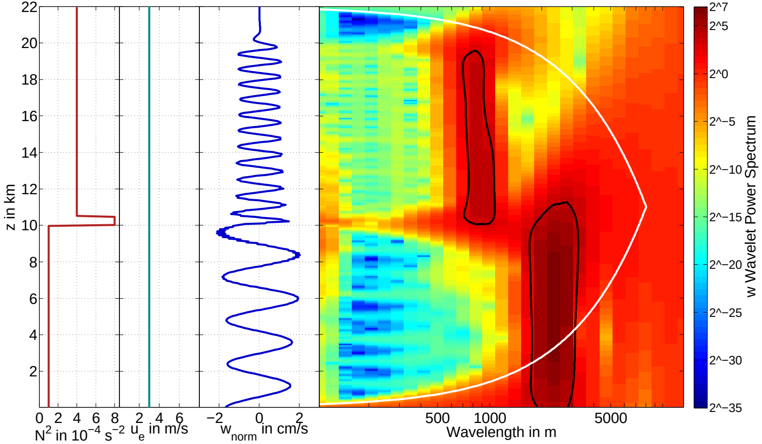


Figure: $N^2_{\mathrm{TIL}} = 8 \cdot N^2_{\mathrm{tropo}}$, $N^2_{\mathrm{strato}} = 4 \cdot N^2_{\mathrm{tropo}}$

Wind Maximum below Tropopause

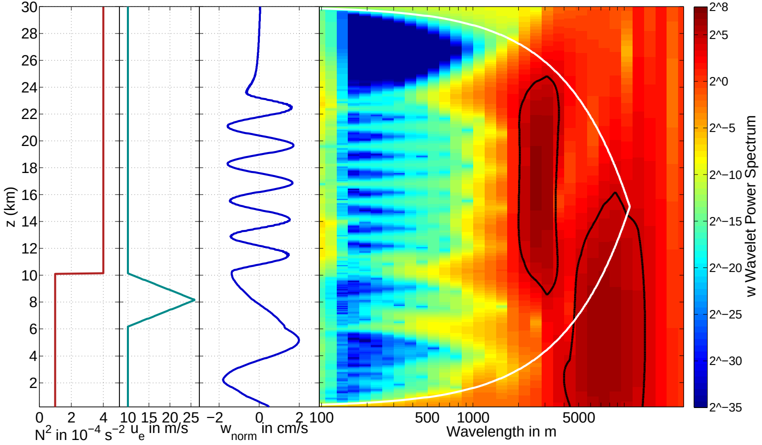


Figure: $N^2_{\text{strato}} = 8 \cdot N^2_{\text{tropo}}$, $u_{max} = 25\,\text{ms}^{-1}$ at $z = 8\,\text{km}$

CASE 1 - Single Mountain

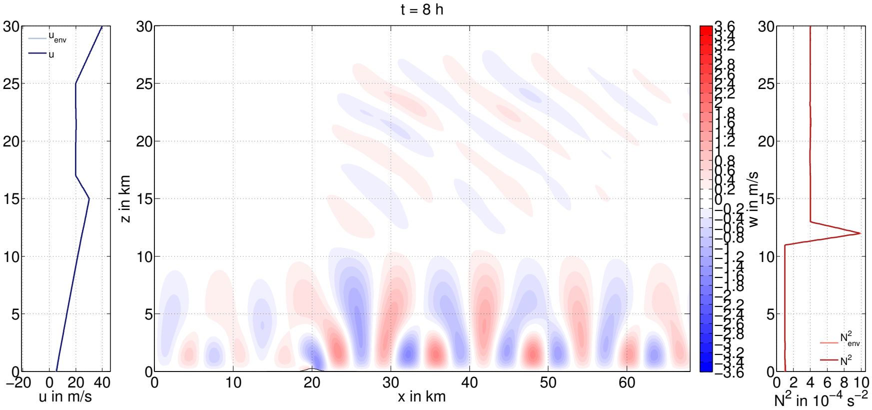


Figure: Gaussian mountain with $H_{max} = 250\,\mathrm{m}$

CASE 3 - Single Mountain

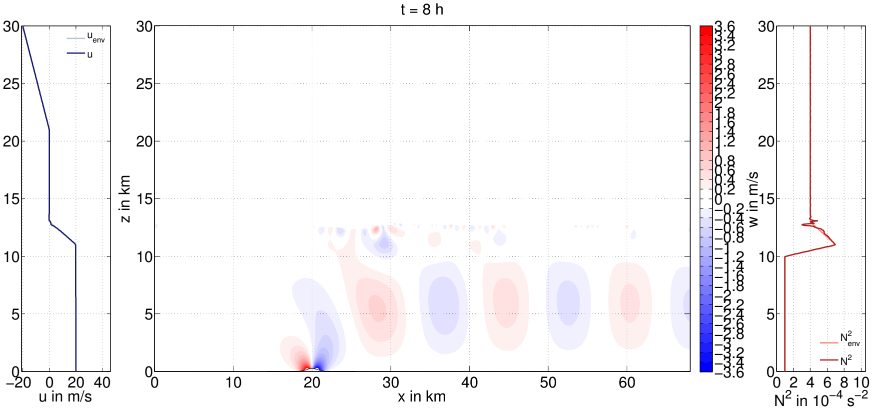


Figure: Gaussian mountain with $H_{max} = 250\,\mathrm{m}$

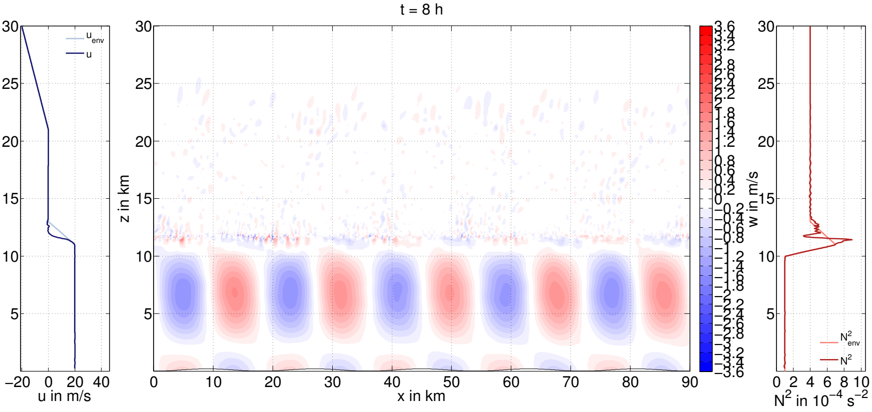


Figure: $\lambda_x = 18\,\mathrm{km}$, $H_{max} = 200\,\mathrm{m}$

CASE 3 - 3D: p'w' Wavelet

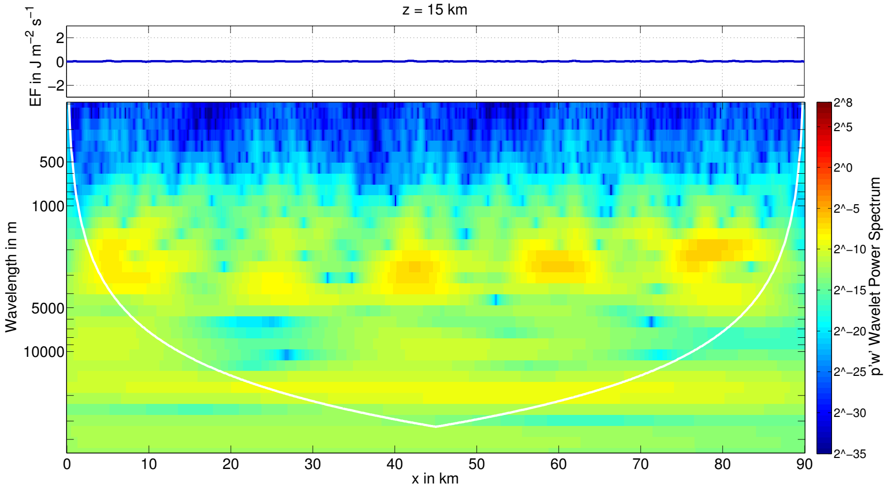
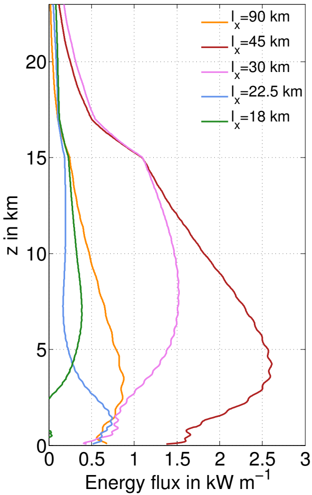


Figure: Gaussian mountain with $H_{max} = 250\,\mathrm{m}$

CASE 2 - EF



l_x=90 km
l_x=45 km
l_x=30 km
l_x=22.5 km
l_x=18 km
z in km
0
5
10
15
20
0
0.5
1
1.5
2
2.5
3
Energy flux in kW m^{-1}

CASE 2 - Fluxes