Representation of subgrid orography in models

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ECMWF Parametrization Seminar
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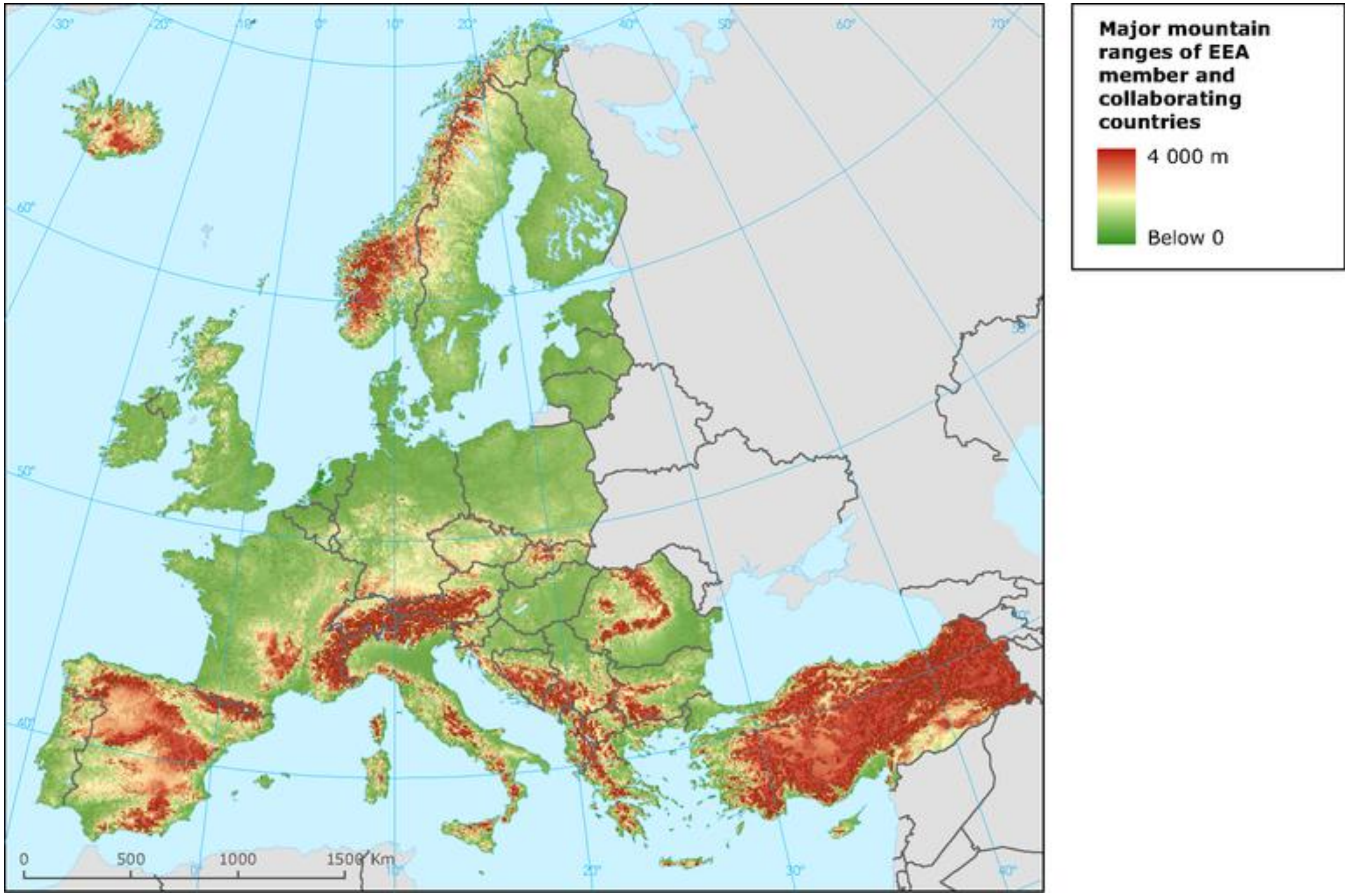
Contents

1. Terms and conditions

(“Representation” of “subgrid” “orography” in “models”)

How do we handle mountainous terrain?

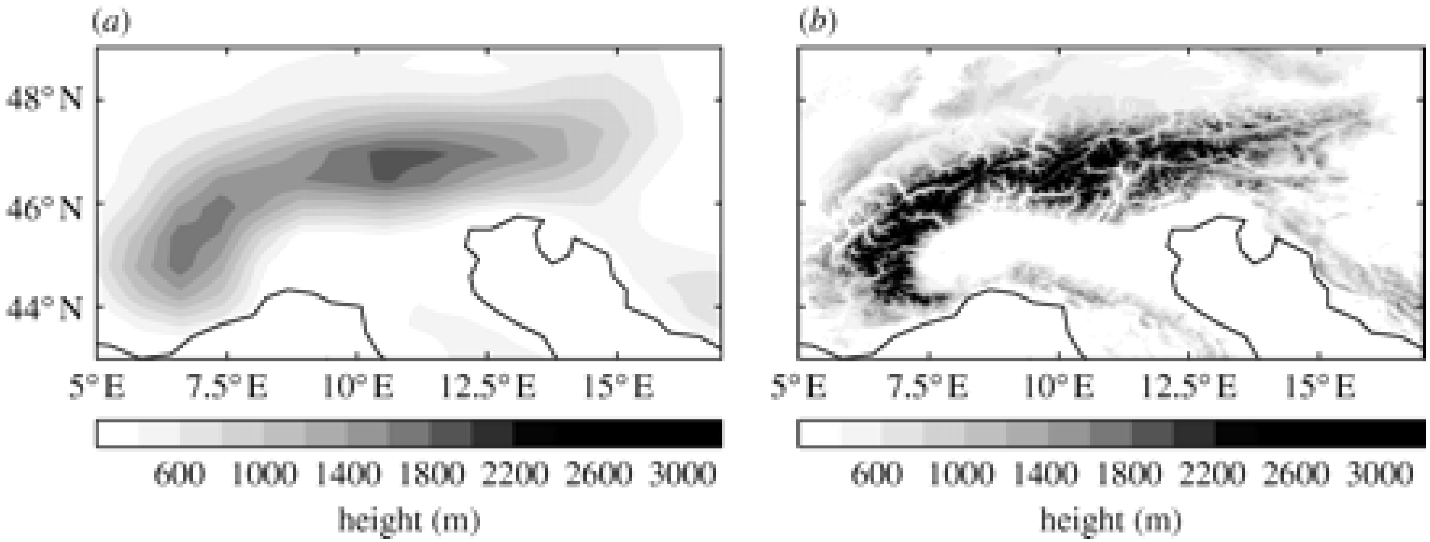


Source: European Environment Agency

“Models” (which?)

- Models at a range of scales: climate, NWP, regional, finescale (greyzone?)..
    - **want “seamless” representation (with continuous dependence on resolution)**
- Here will talk generically about Met Office, ECMWF and other leading models but illustrate mainly from Met Office work.

“Representation” (what? how?)
(i) Resolved orography



Representation of the Alps in models at (a) 60km or (b) 1km resolution. Cullen and Brown (2009), Phil. Trans. R. Soc. A.

"Representation" (what? how?)
(ii) Parametrized orographic effects

- The *parametrized* terms could include
  - Drag
  - Temperature and surface interactions (e.g. cold valleys)
  - Precipitation (typically enhanced)

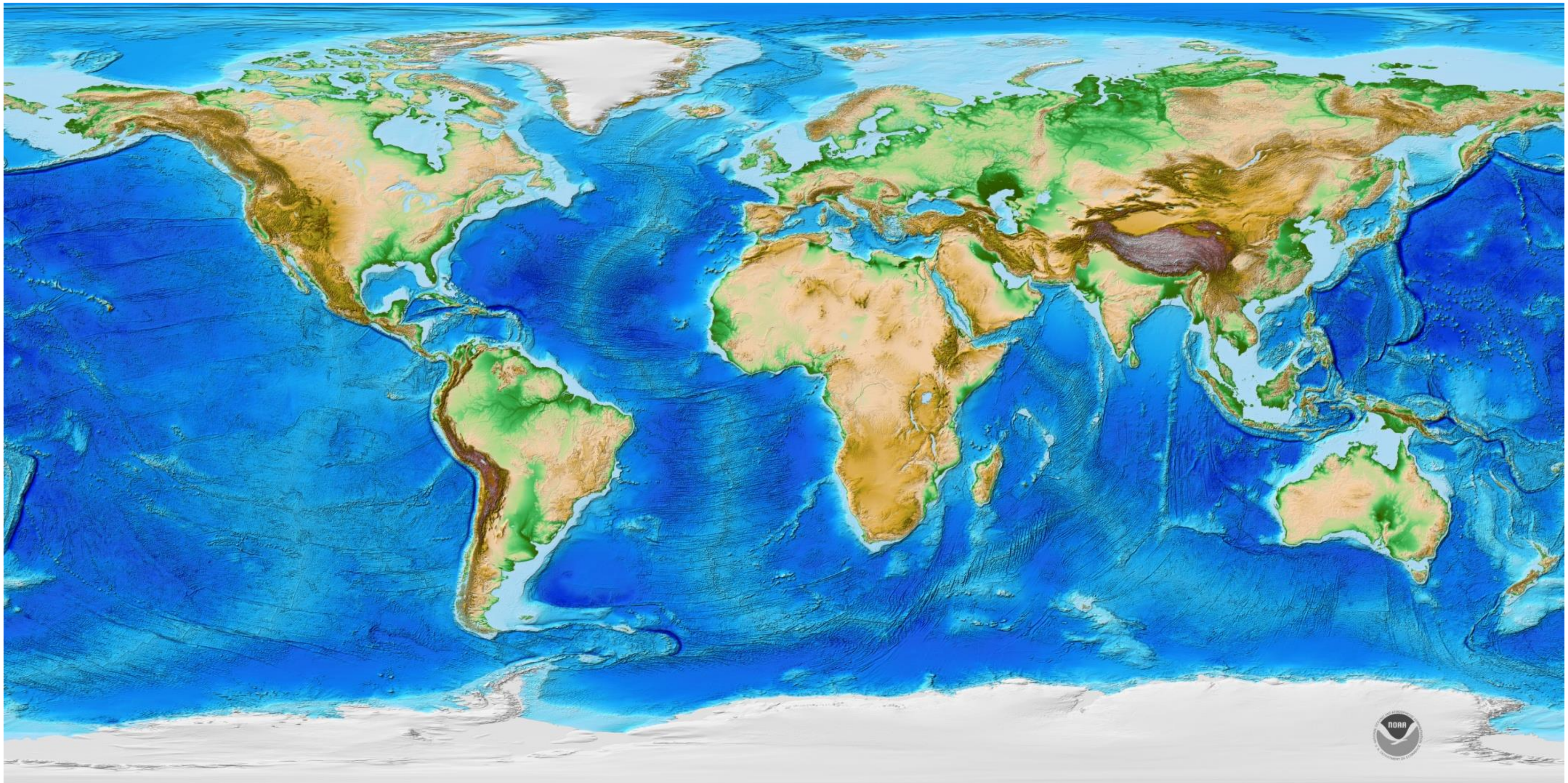
- It's the nonlinear impact of unresolved terms or processes which we need to parametrize (e.g. the unresolved momentum flux $\rho u'w'$)

- [also (not discussed in detail here) we can have purely diagnostic parametrizations for downscaling/local weather diagnostics]

~~Subgrid~~ *unresolved*

- Traditionally we talk of “subgrid parametrization” (e.g. Lott and Miller 1997)
- But now prefer term “unresolved” in parametrization, because..
  - Numerical representation (e.g. advection) at the grid scale is relatively inaccurate (e.g. Davies and Brown, QJRMS 2001)
  - Orography may be filtered either implicitly through numerics or explicitly through our choice (e.g. Raymond filter in the UM)
  - Hence the resolved field is not necessarily a gridbox average

“Orography” (lit. mountains)



NOAA ETOPO1 Global Relief Model

Key scales

Simpler version

- Brunt-Vaisala frequency $N = (g\, d\ln\theta/dz)^{1/2}$ determines the oscillation timescale to vertical displacements
- Hence U/N is a characteristic lengthscale for interactions of a fixed obstacle with the atmospheric stability (e.g. $N=10^{-2}s^{-1}$, $U=10ms^{-1}$ gives 1km)

Fuller version (Scorer's equation)

- Scorer parameter l defined by

  $l^2=N^2/U^2-(d^2U/dz^2)/U$ (in practice usually $l \sim N/U$)
- The linearized equation for steady sinusoidal perturbations can be written

  $d^2w/dz^2 + (l^2-k^2)w=0$

- where k is the horizontal wavenumber and U is the flow component crossing the ridge

Height, width and slopes

H~8km

H~100m

Nondimensional parameters

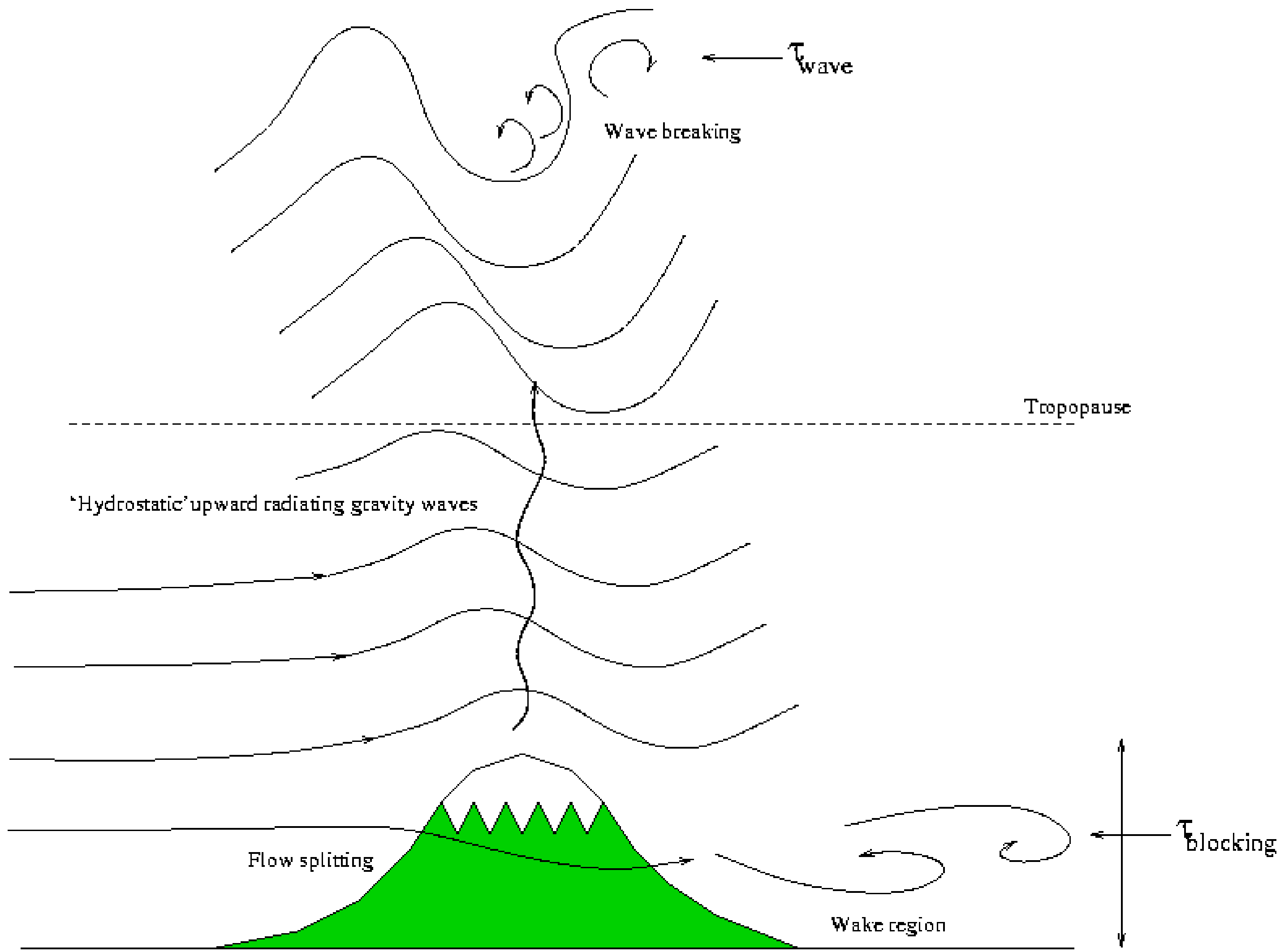
- Key nondimensional parameters
  - Slope ~ H/L where L is a horizontal lengthscale
  - NL/U (mountain width nondimensionalized by the stability lengthscale U/N)
  - NH/U (i.e. height nondimensionalized by the stability lengthscale U/N)

- Narrow mountains (measured by NL/U) don’t generate gravity waves because the wavemaker is too “fast”

- $(NH/U)^2$ is a measure of the potential energy barrier to flowing over a hill or mountain, relative to the kinetic energy available from the flow.
  - Large NH/U: flow can easily go over orography
  - Small NH/U: gravity-dominated, flow may be blocked at low levels

2. History and schematic structure

Orographic drag parametrization
(schematic)



Palmer, Shutts and Swinbank (QJ 1986)

- A true parametrization classic paper!
- Showed overspeeding of general circulation in GCMs could be addressed through a simple representation of gravity-wave drag (GWD)
- Surface drag $\tau_s = \kappa\rho NU\sigma^2$ in our notation
  - κ = tunable orographic wavenumber and U, N taken at level 1
- Vertical propagation through Scorer equation and breaking/saturation condition based on Richardson number estimate
- Still a relevant paper today
  - Important to remember that midlatitude circulation significantly depends on a parametrization
  - Wave drag plays a key role in interaction with the stratosphere (e.g. Quasi-Biennial Oscillation QBO)

McFarlane (1987)

- Independently developed using Canadian Community Model
- In many ways similar to Palmer et al. but...
  - different model of wave breaking, based on convective overturning according to critical local Froude number (we now essentially follow McFarlane in this respect).

Aside:

Both Palmer et al. and McFarlane acknowledged prior work by Doug Lilly (US) and others. Could say that the ideas of GWD were “out there” but Palmer et al. and McFarlane showed how to make it work convincingly with benefit to models.

Lott and Miller (1997)

- Compared/developed against PYREX (Pyrenees) field observations
- Introduced concepts of low-level blocking/flow splitting into the orographic drag framework using NH/U criteria

See also Olafsson and Bougeault (1997)

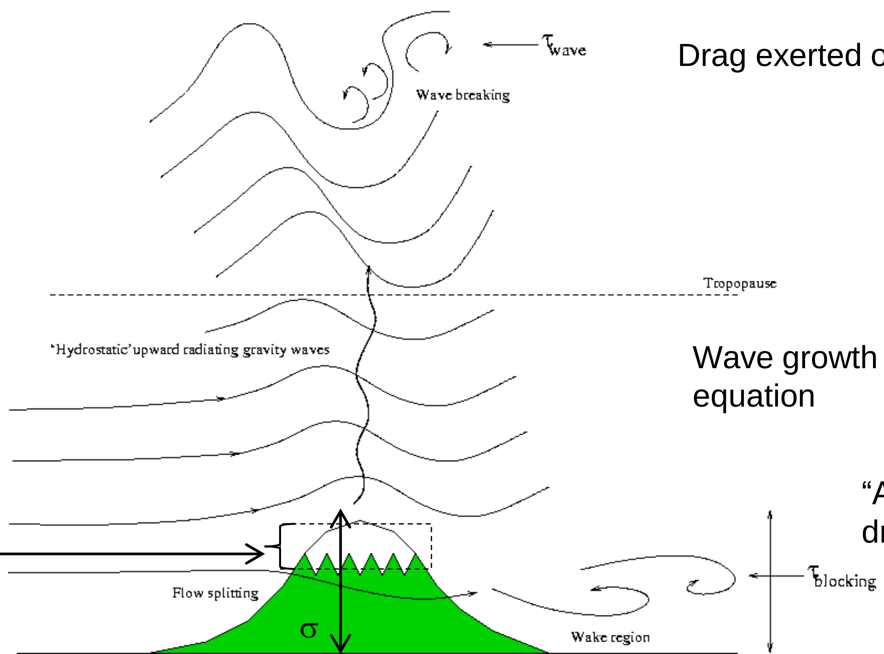
- Also used PYREX data
- Looked at effects of rotation and surface friction

Current Met Office formulation

The Met Office Unified Model includes a gravity-wave/flow-blocking drag scheme to represent the drag due to sub-grid orography.

• Synthesis of various ideas from the literature (Palmer et al. 1986, McFarlane 1987, Lott and Miller 1997..) and our own research (e.g. Vosper, Wells and Brown 2009)

Drag exerted on flow where waves overturn



Wave growth assumes WKB theory in the Scorer equation

"Aerodynamic" low-level **"flow blocking"** drag ~$C_d AU^2$. Applied when $F=U/N\sigma < F_{crit}$

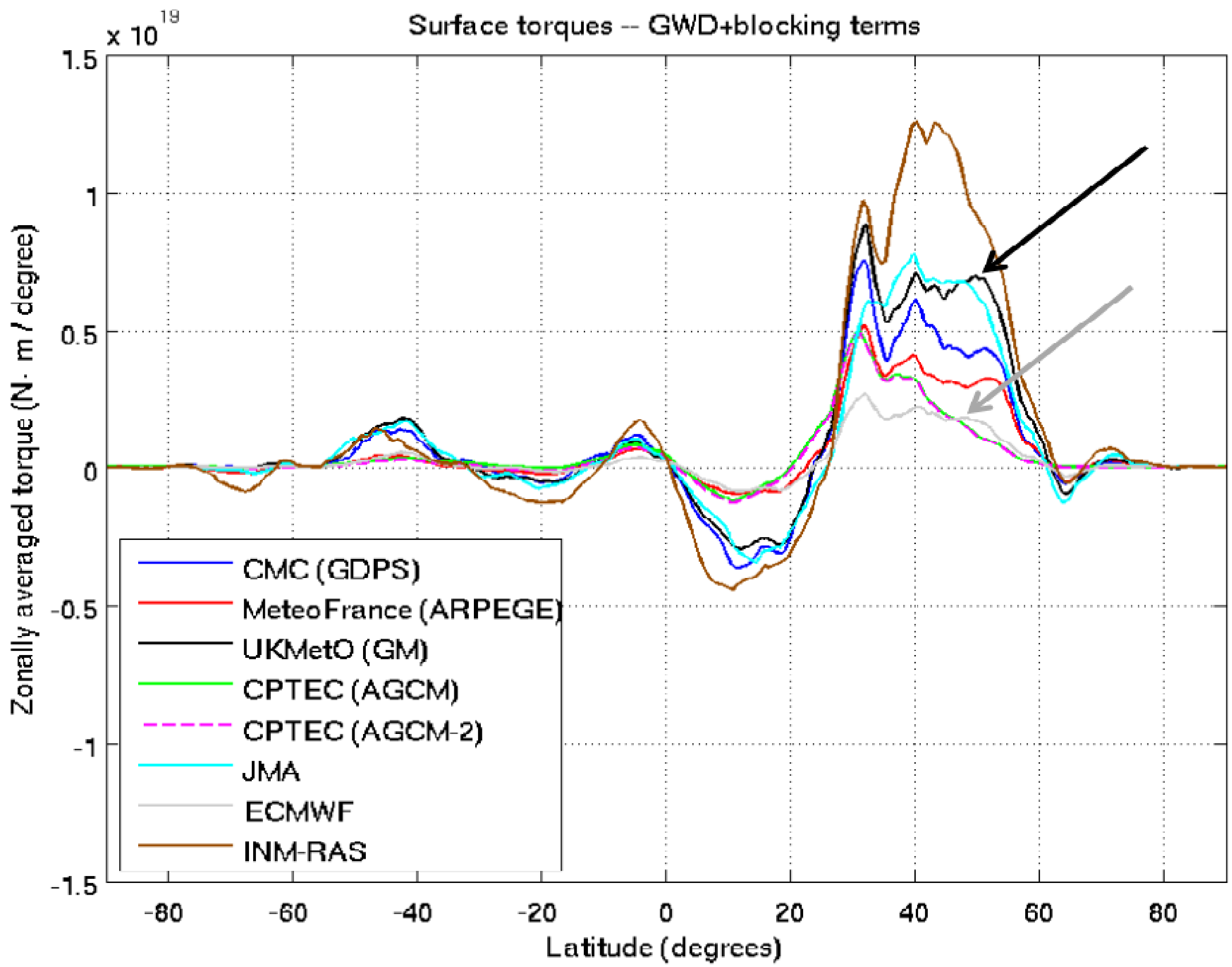
Summit region

3. New research directions

Ayrton Zadra, Environment Canada

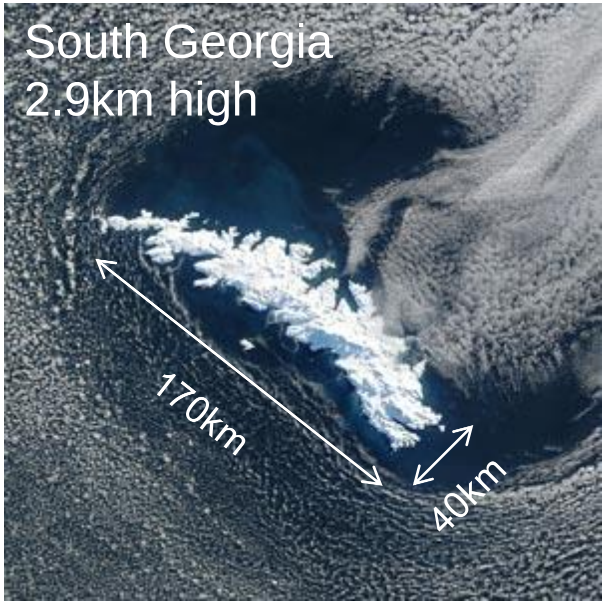
WGNE DRAG-project, torque inter-comparison Step0-24 January 2012

subgrid orography



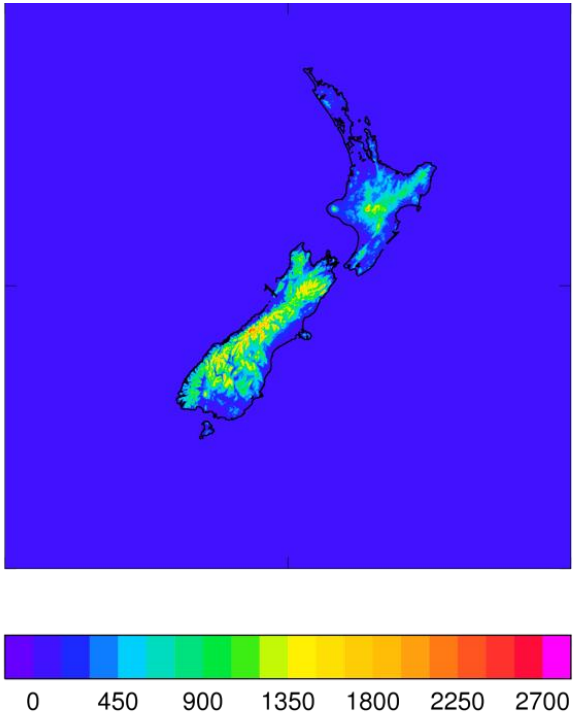
South Georgia - Wave Experiment (SG-WEX)

- Universities of Bath and Leeds, British Antarctic Survey and Met Office
- Aims to understand the nature, variability and influence of GWs generated by South Georgia and their importance relative to other sources.
- Two 1-month radiosonde campaigns (austral summer and winter); analysis of satellite GW measurements; meteor radar on South Georgia



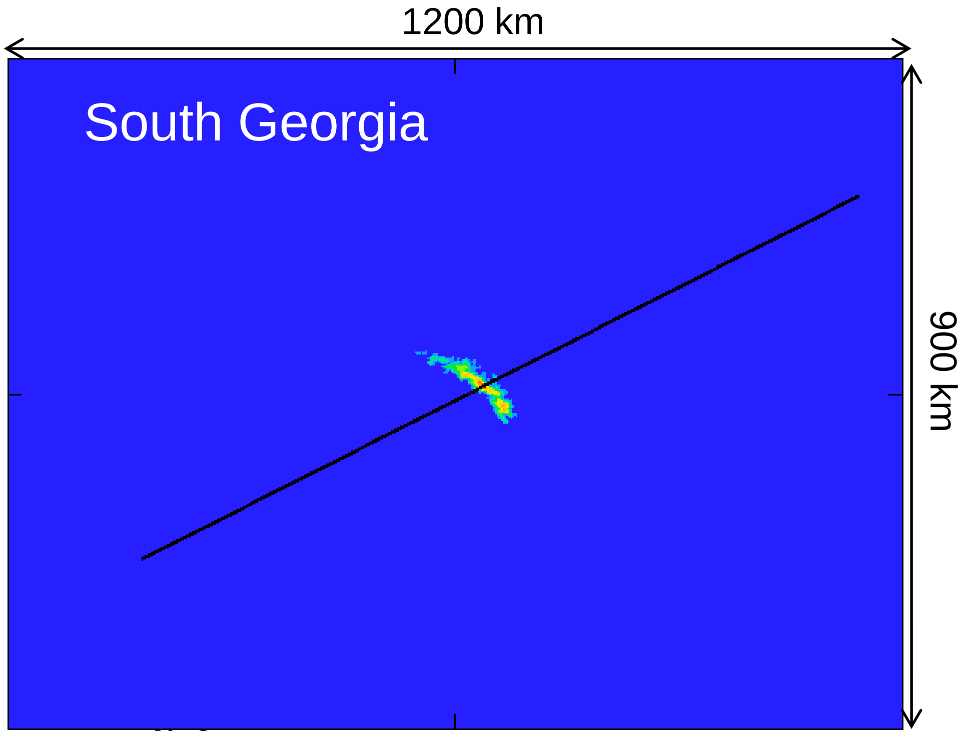
DEEPWAVE

- US-led experiment, along with DLR, NIWA,...
- Aims to investigate deep GW propagation in SH winter, sources and predictability of GWs
- June-July 2014 campaign based in New Zealand. In-situ and remote sensing of GWs from multiple aircraft, radiosondes, ground based remote sensing.



Methodology

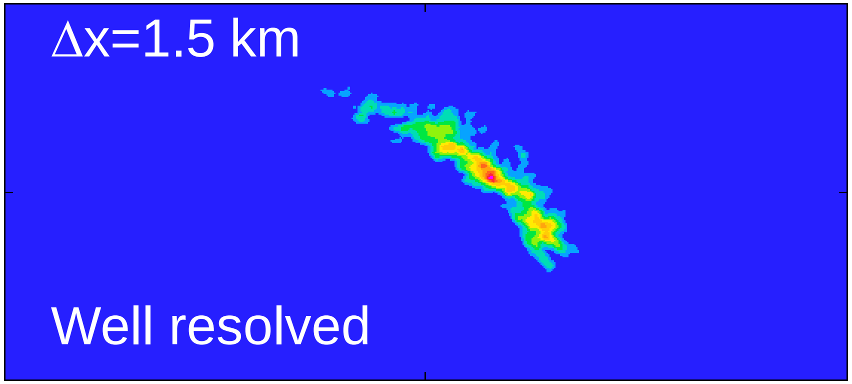
- Met Office Unified Model
- Use latest ENDGame and physics
- Regional simulations nested within series of 24 hour N512 (~25km) global forecasts
- Model top at **80 km**

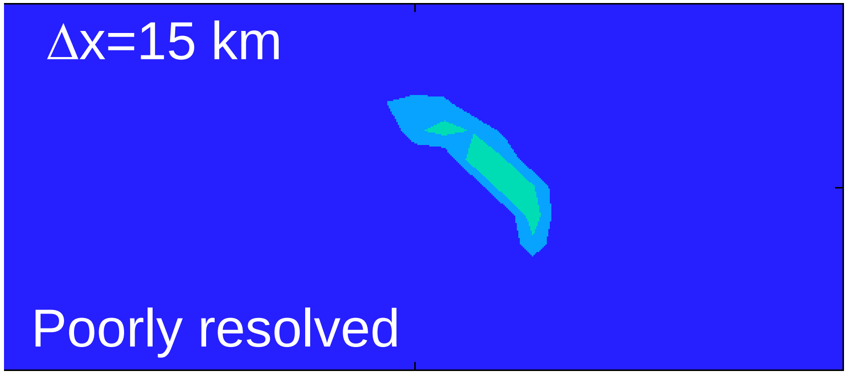


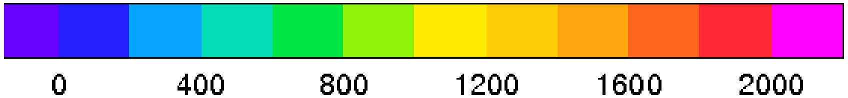
- Two sets of simulations
- Control + flattened orography
- Mountain perturbations:

$$\phi' = \phi_{control} - \phi_{flat}$$

- Range of resolutions from 1.5km to 20km





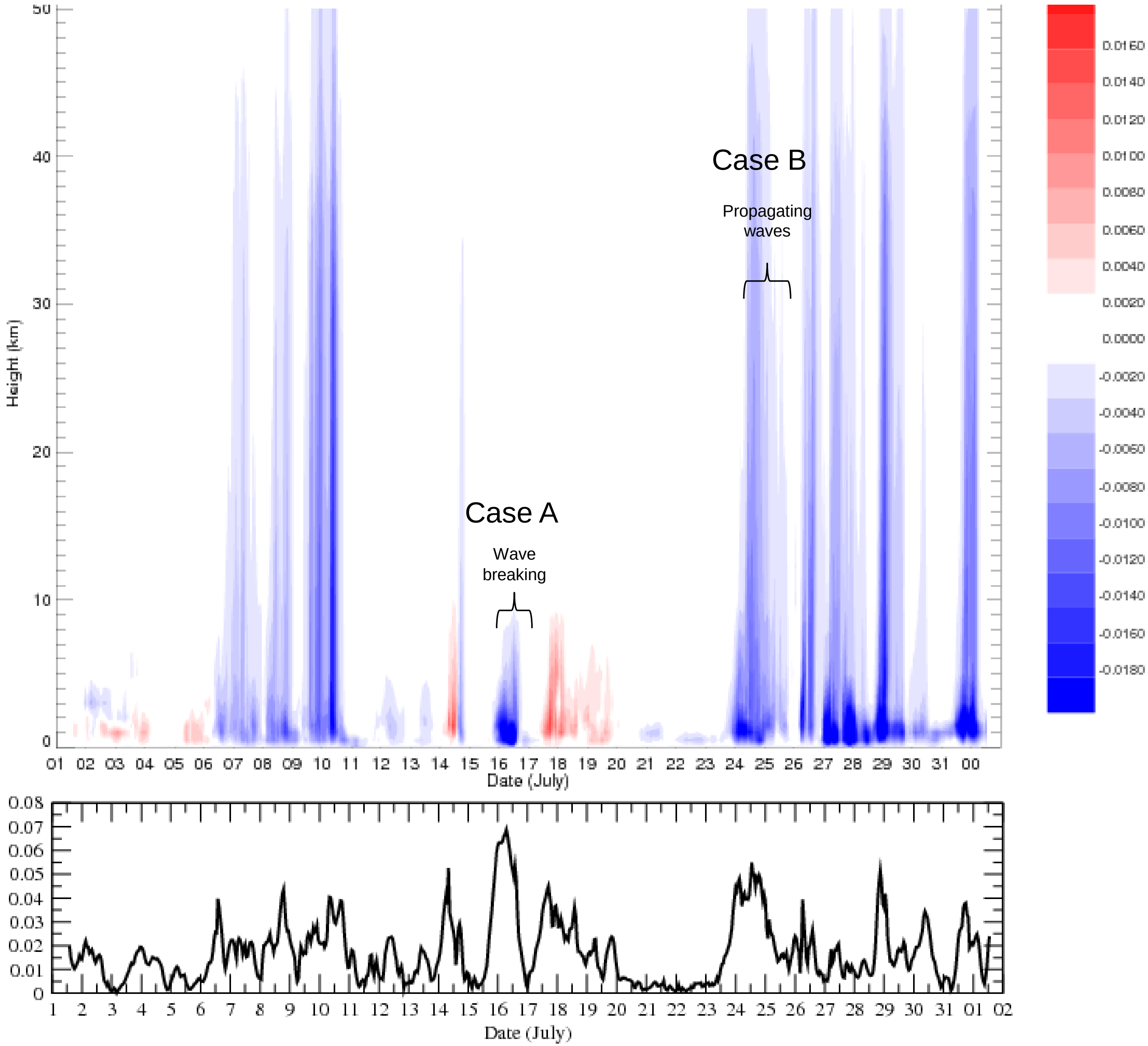


SG-WEX Methodology

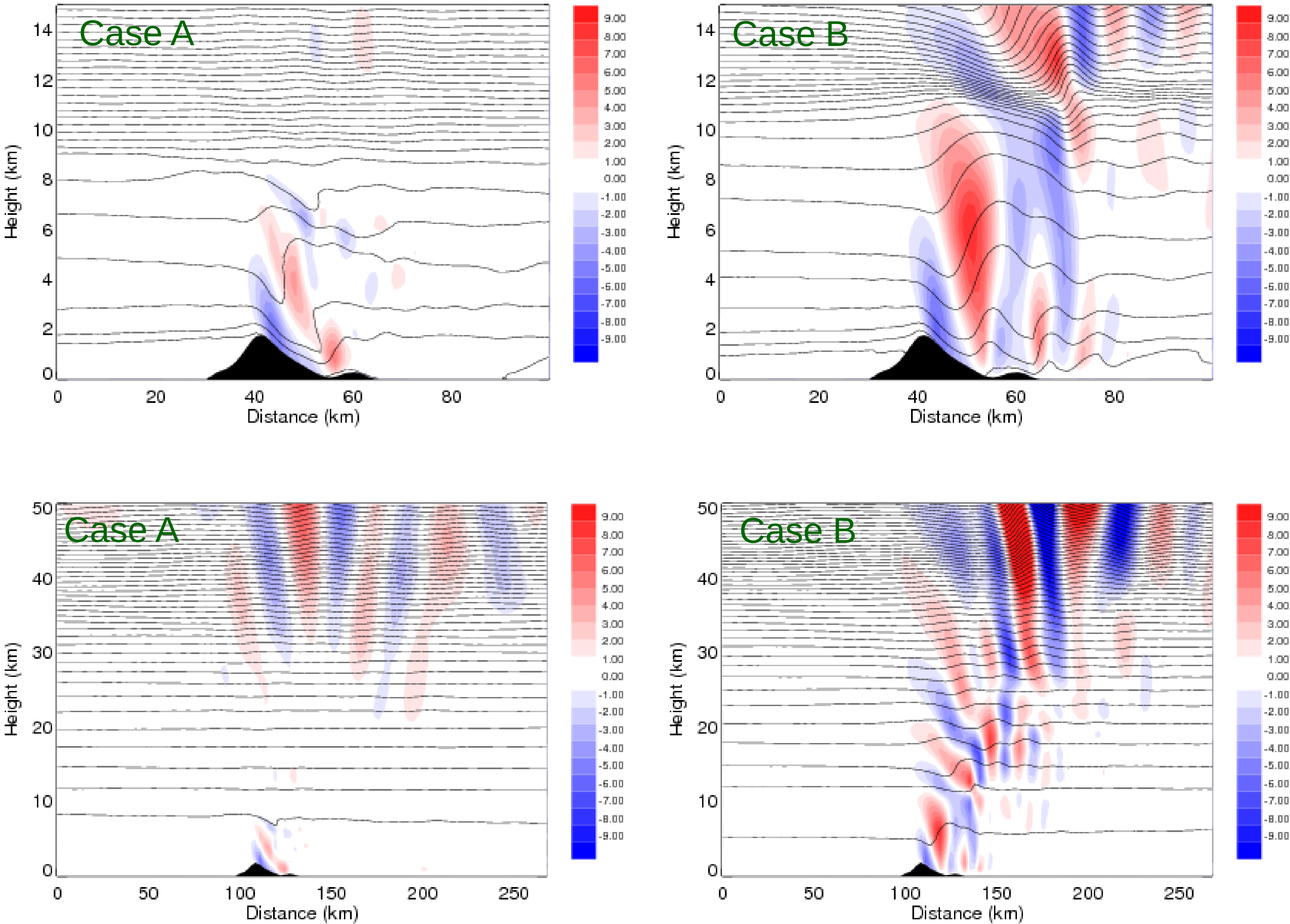
- Run 1-month simulations to generate statistical properties of gravity waves, wakes, pressure drag and momentum fluxes
  - Austral winter (deep GW propagation). July 2013.

- Compare results at high (1.5km) resolution with no drag parametrization, with low (15km) resolution simulations.
  - Can the missing pressure drag and momentum fluxes at low resolution be represented by a parametrization scheme?

Results: Drag and momentum fluxes



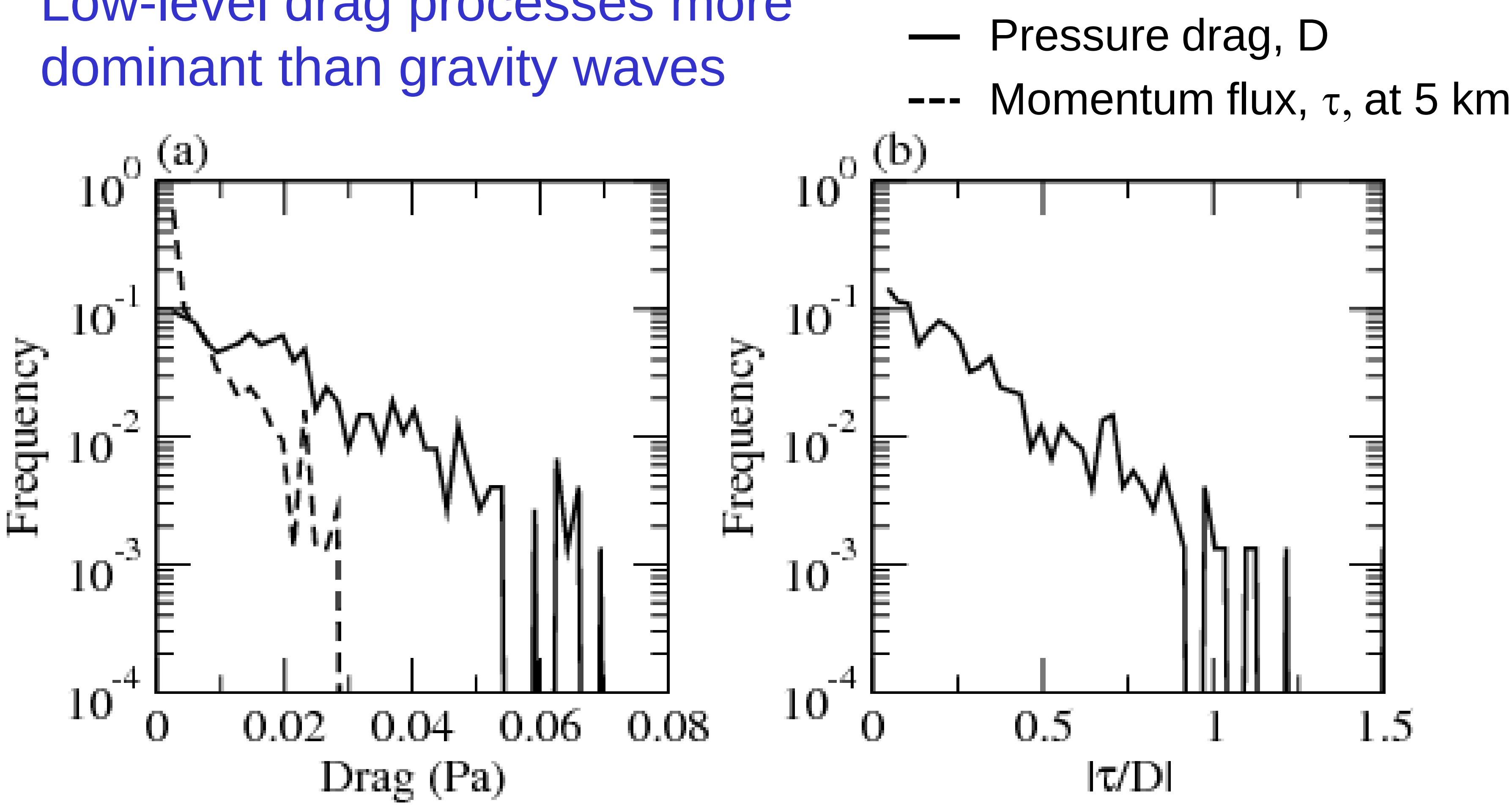
- Intermittent episodes of large surface drag and momentum flux which penetrates into stratosphere and mesosphere
- High drag occurs when flow is perpendicular to ridge
- Smaller fluxes in stratosphere when low-level wave breaking occurs



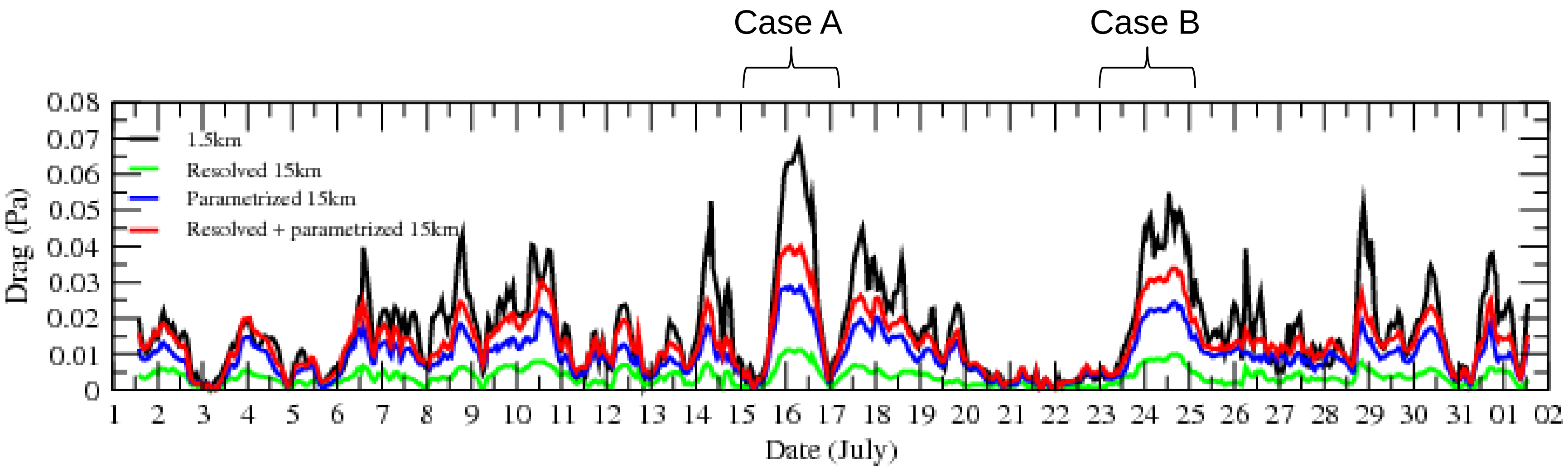
Case A
Case B
Case A
Case B
Height (km)
Distance (km)

Gravity wave vs flow blocking drag

- Low-level drag processes more dominant than gravity waves



Resolved and parametrized drag at coarse resolution



•Drag under-resolved on 15km grid

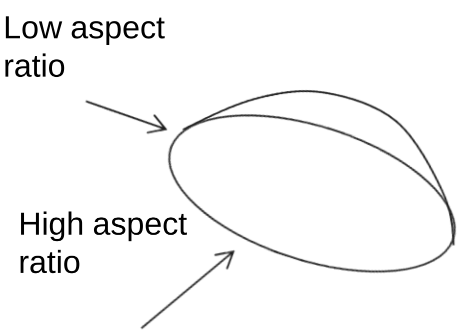
•Parametrized drag correlates well with observed drag in 1.5km simulation

•Sum of resolved and parametrized drag in 15km simulation well correlated with 1.5km drag.

•High drag states are under-represented. *Suggests insufficient drag enhancement when flow is perpendicular to ridge?*

Aspect ratio dependence: A modified scheme

•The sub-grid orography is assumed to take an elliptical form
•The drag is enhanced when the flow is normal to the major axis of the sub-grid orography and "sees" a high aspect ratio, r:

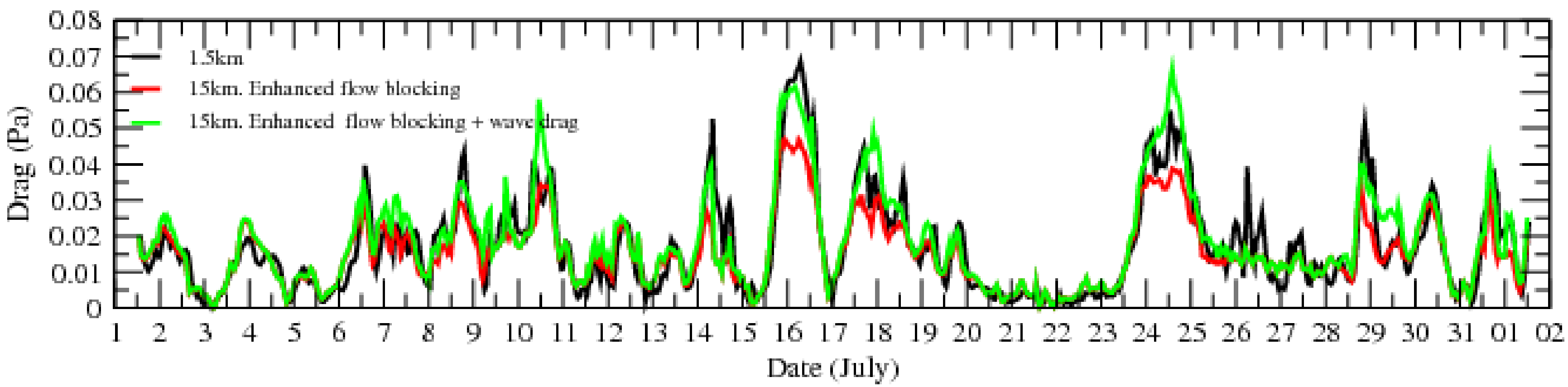


$$\text{drag} \propto \max(2-1/r, 0)$$

•Tests show this enhancement is insufficient. Increase by replacing this with:

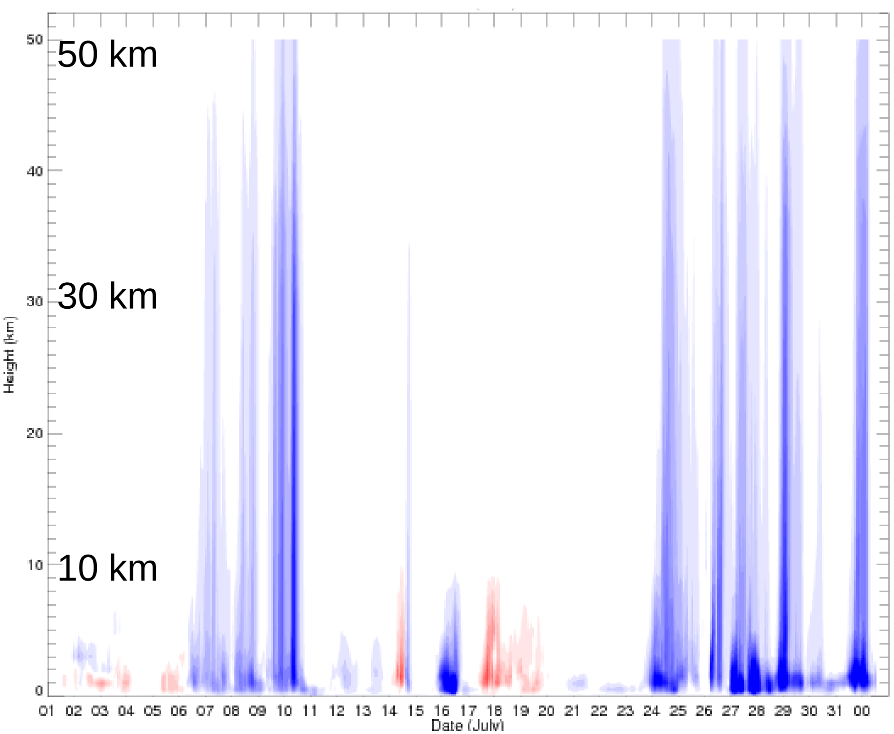
$$\text{drag} \propto \max(5-1/r^3, 0)$$

•Also enhance the gravity wave stress in the same way when $F=U/N\sigma<F_{crit}$

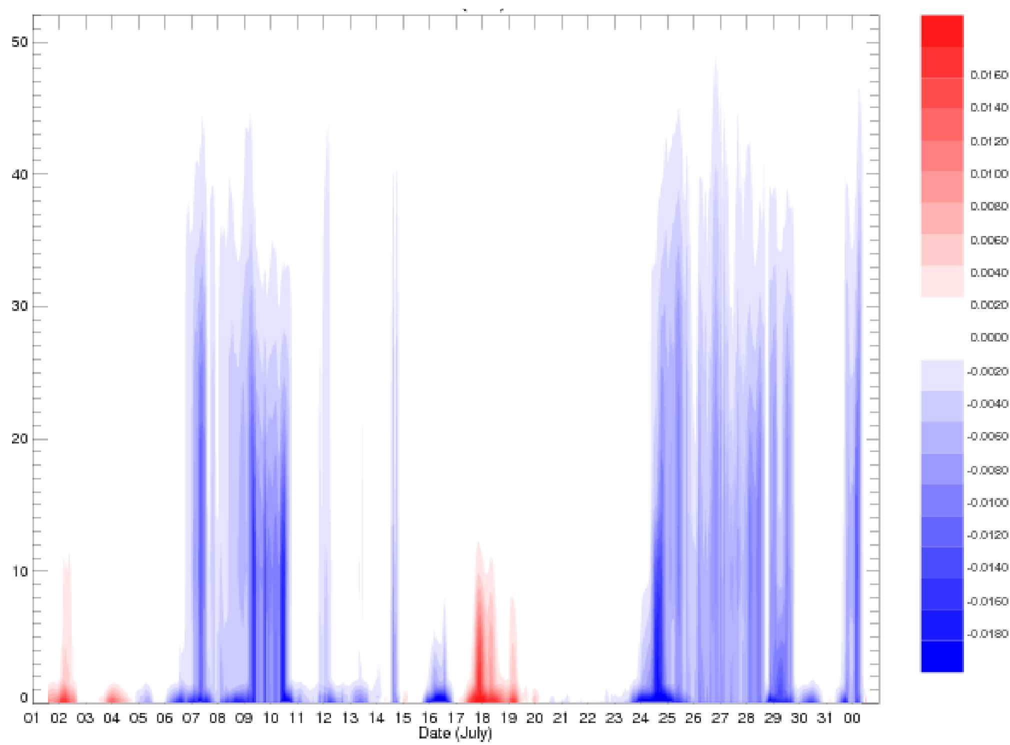


Parametrized vs resolved momentum fluxes

1.5km: resolved fluxes



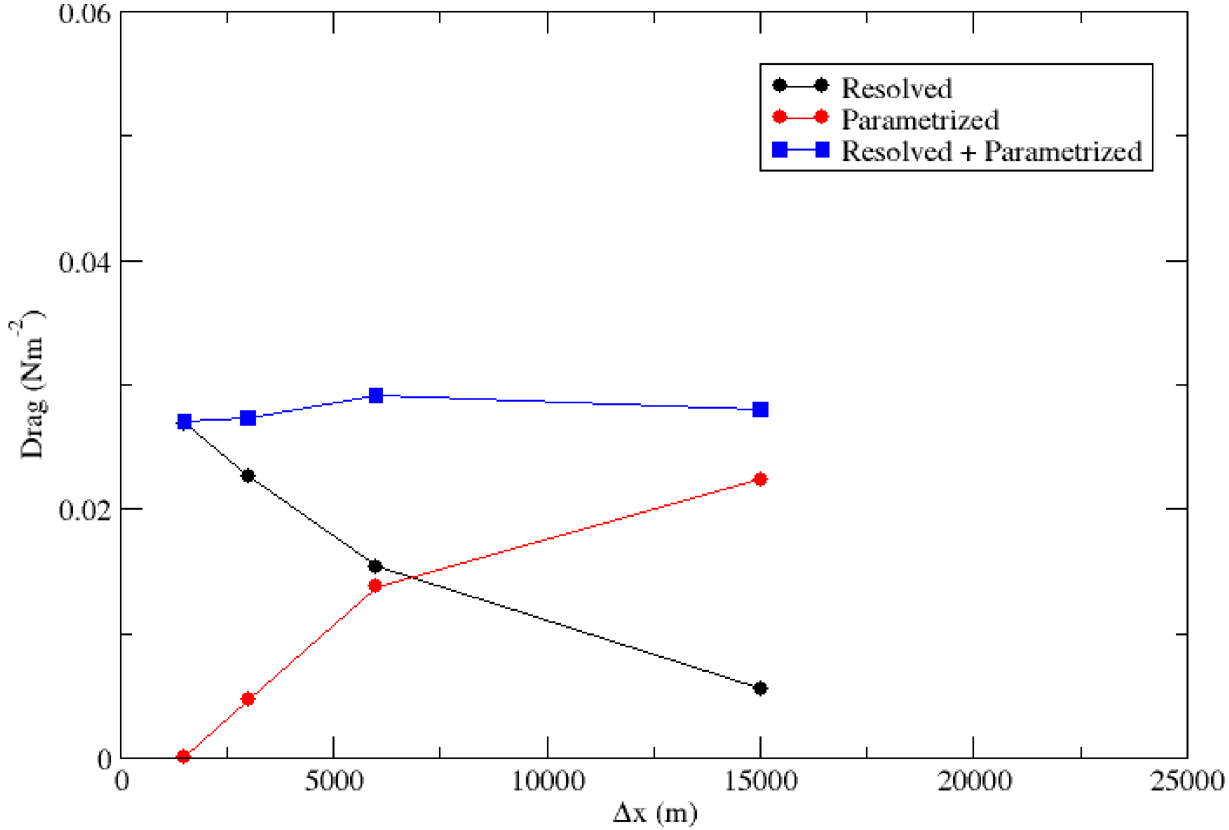
15km: parametrized+resolved fluxes



- Momentum fluxes at coarse resolution compare well with those at high resolution
- Greater intermittency and deeper wave propagation at high resolution

How well is the drag represented across a range of model resolutions?

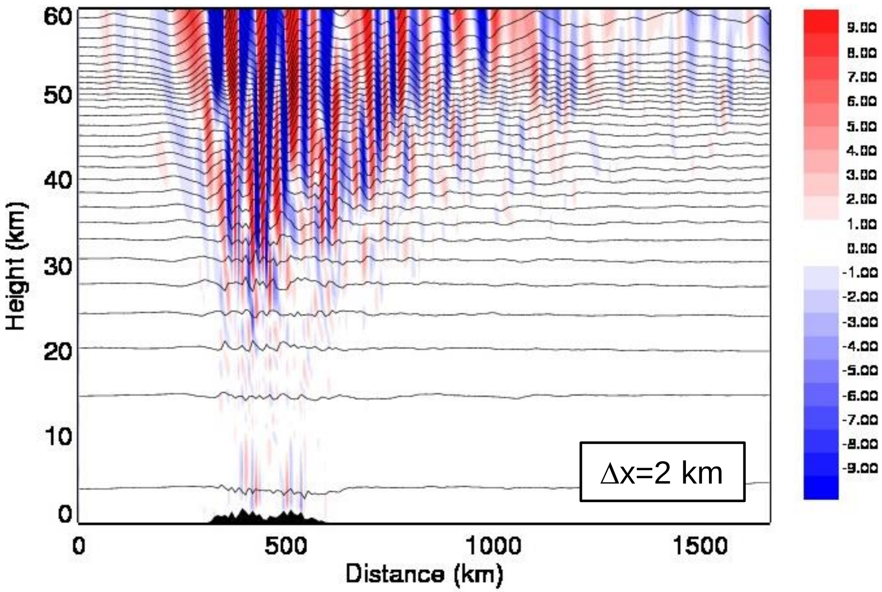
•The “Case A” period 14-18 July 2013, re-run at a range of resolutions
•Drag scheme included in at all resolutions

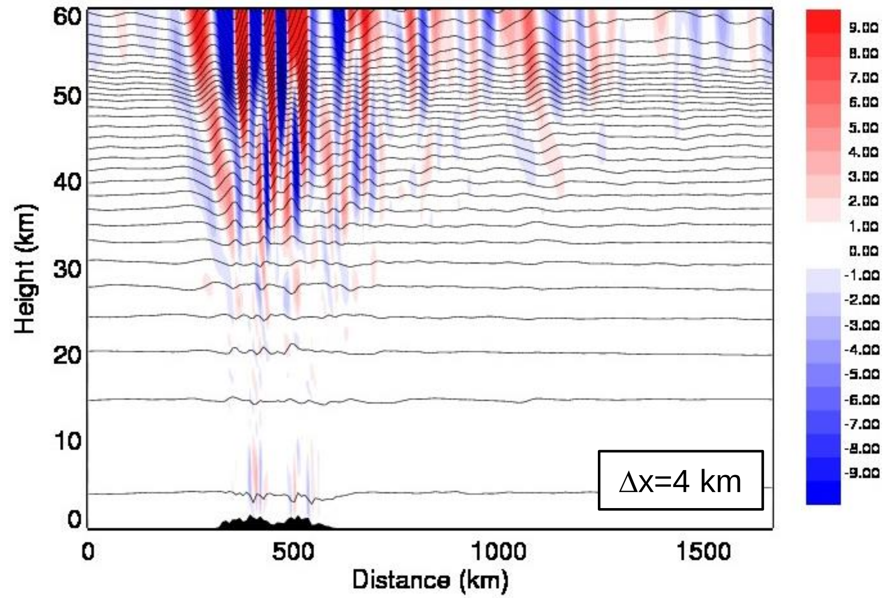


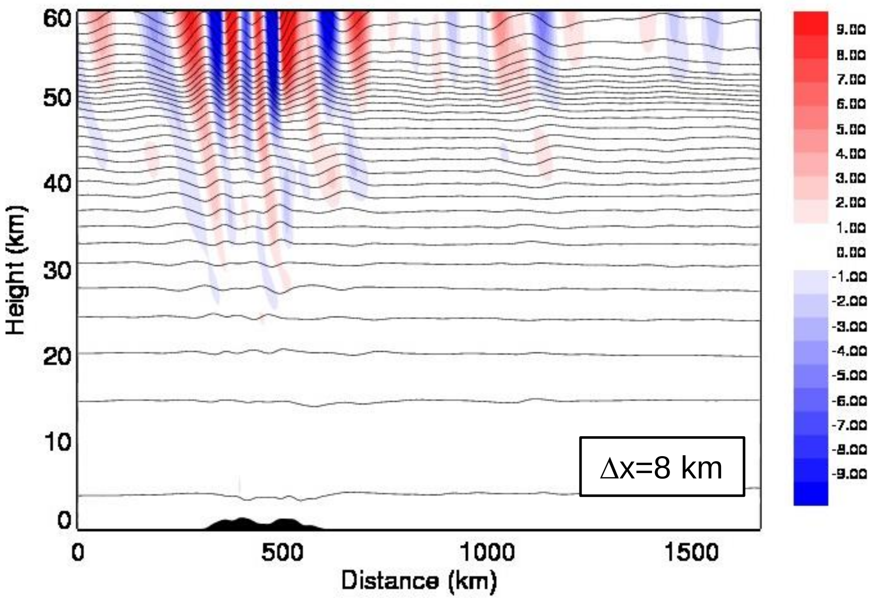
•Total (resolved + parametrized) drag roughly invariant

How well does this work for broader mountain ranges e.g. New Zealand?

RF08: 20-22 June 2014

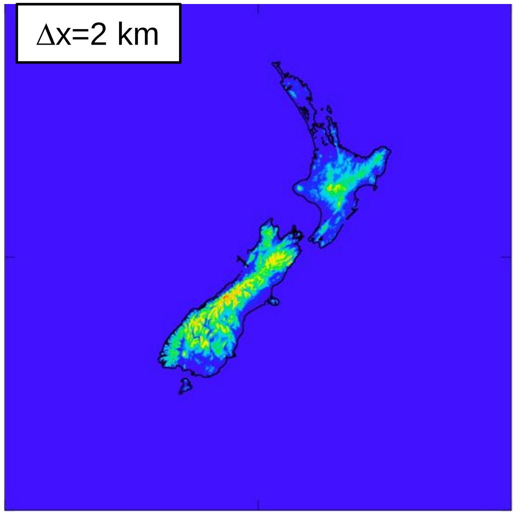


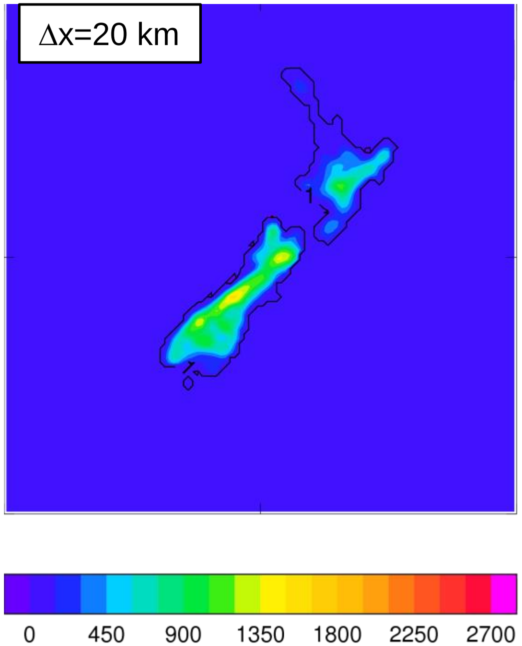


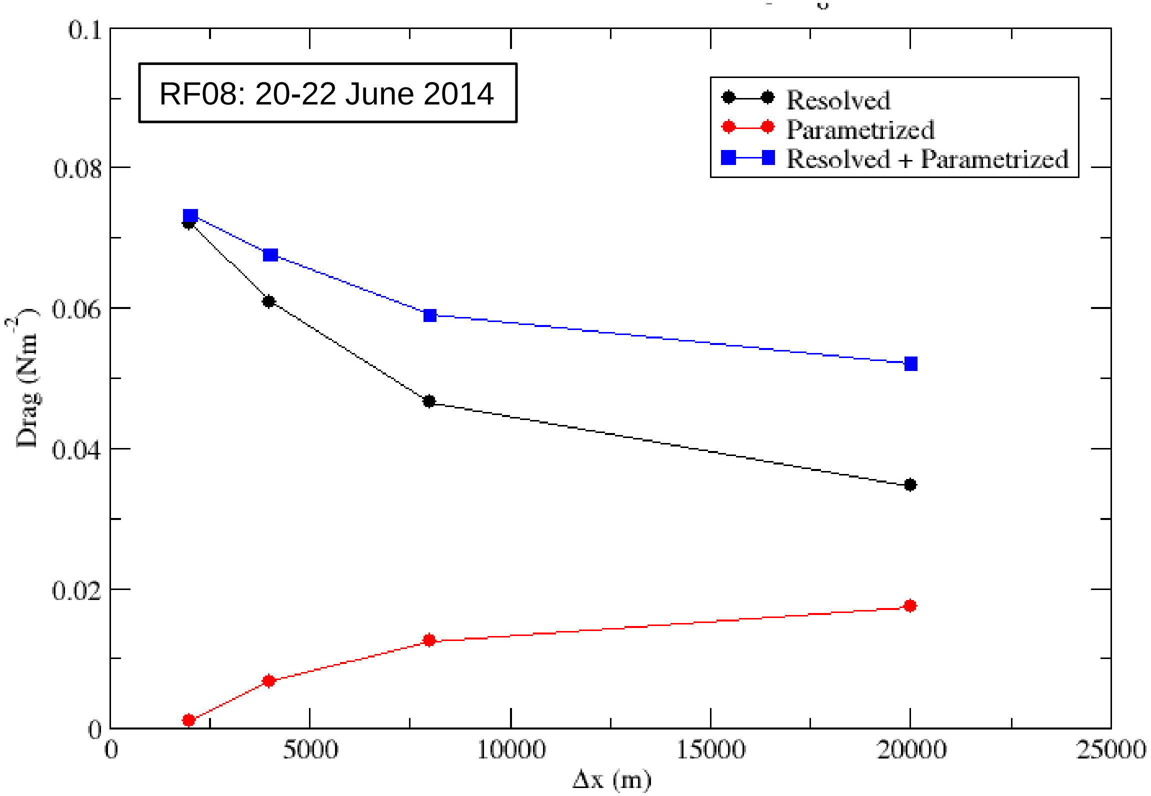


- Simulations for two DEEPWAVE cases
- Clear resolution sensitivity to resolved mountain waves

How well does this work for broader mountain ranges e.g. New Zealand?







- Total (resolved + parametrized) drag roughly invariant across range of NWP resolutions

- Case dependent ?

4. Conclusions and challenges

Conclusions (i) overall

- Orographic drag schemes play an important role in current NWP models
- There has been some convergence towards a broadly standard type of representation drawing on e.g. Palmer et al. (1986), McFarlane (1987) and Lott and Miller (1997).
- There has been a shift towards increased emphasis on low-level flow blocking as well as GWD
- However there are still differences in detailed formulation and systematic differences in orographic drag magnitude between models. The WGNE DRAG project is highlighting further research needs.

Conclusions (ii) new research

- Hi-res simulations suggest mountain-wave momentum fluxes penetrate high into the stratosphere and mesosphere.
- The high drag / momentum flux episodes are intermittent.
- A simple parametrization scheme, *when suitably tuned*, can represent the variation in low-level drag and momentum flux well.
- The drag and momentum fluxes are deterministic, at least for *relatively simple orography.*
- Total drag and momentum fluxes roughly invariant across resolution, *at least for NWP resolutions (~1km to ~20km).*

But…

- Not clear whether the tuning of the GWD scheme is universal
  - Results presented for South Georgia and New Zealand use a different scaling of the sub-grid orographic heights

- Further work needed to understand how small islands will be represented at much coarser (climate) resolution
  - For a grid box containing isolated mountains, the total drag force should be independent of grid size

- Will the results hold for more complex mountain ranges?
  - E.g. continental ranges, coastal mountains

Selected Refs..

- Lott, F. and Miller, M. J., 1997. A new subgrid-scale orographic drag parametrization: Its formulation and testing. Q. J. R. Meteorol. Soc., 123, 101-127.

- McFarlane, N.A., 1987. The Effect of Orographically Excited Gravity Wave Drag on the General Circulation of the Lower Stratosphere and Troposphere. J. Atmos. Sci., 44, 1775-1800.

-Palmer, T.N., Shutts, G.J. and Swinbank, R., 1986. Alleviation of a systematic westerly bias in general circulation and numerical weather-prediction models through an orographic gravity wave drag parametrization. Q. J. R. Meteorol. Soc., 112, 1001-1039.

- Vosper, S. B., Wells, H. and Brown, A. R., 2009. Accounting for non-uniform static stability in orographic drag parametrization. Q. J. R. Meteorol. Soc., 135, 815-822.

- Webster, S., Brown, A.R., Cameron, D.R. and Jones, C.P., 2003. Improvements to the representation of orography in the Met Office Unified Model. Q. J. R. Meteorol. Soc., 129, 1989-2010.

Thanks for listening!

Any questions?

Vertical grid

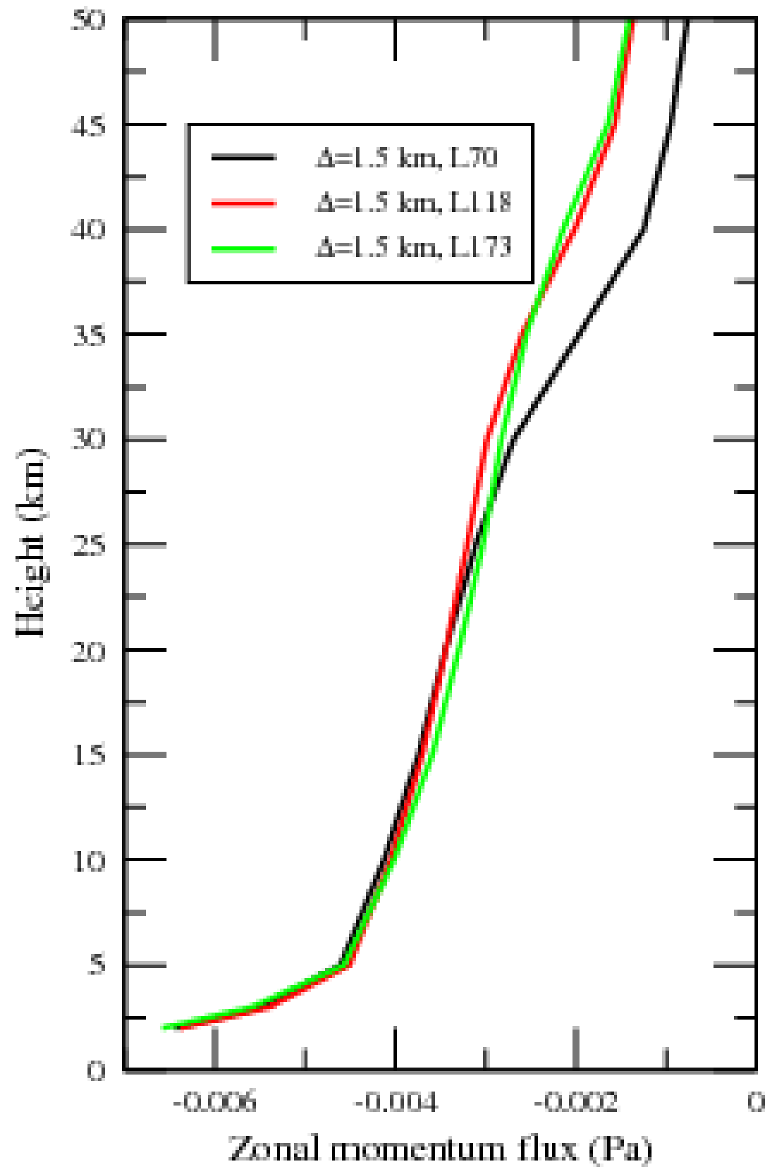
Vertical grid determined from tests with a 5-day simulation 06-10 July 2013

L70:
Δz=1.0 Km at 20km
Δz=3.1 Km at 40km

L118:
Δz=0.6km at 20km
Δz=1.3km at 40km

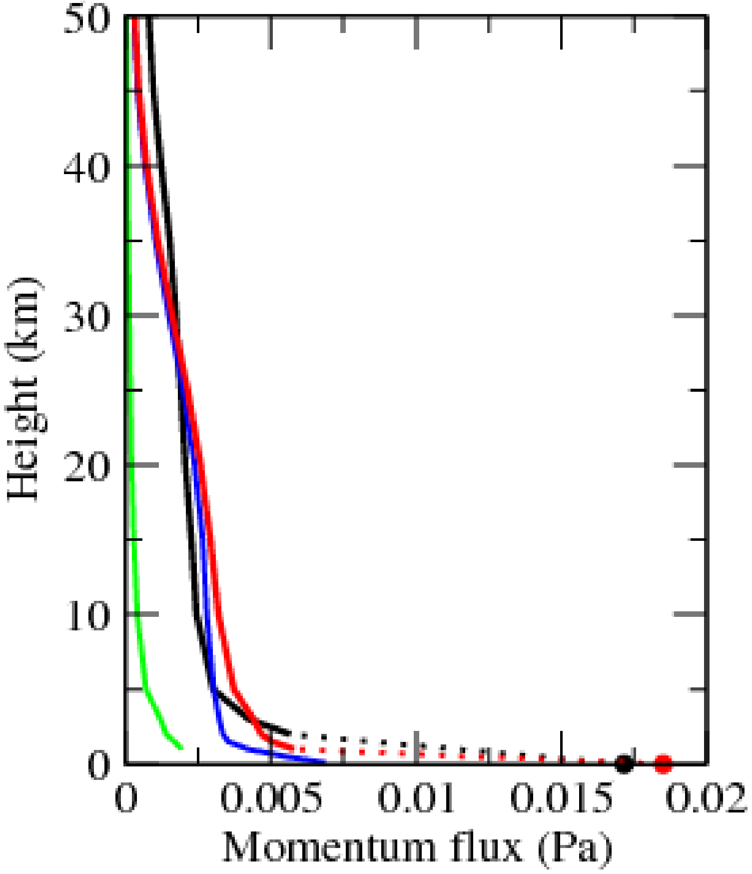
L173:
Δz=0.5km for z> 20km

- Momentum flux profile converged for L118
- Use L118 for further simulations



Parametrized vs resolved momentum fluxes

•Monthly mean 15km resolved + parametrized drag and momentum fluxes closely approximated those resolved in 1.5km simulations

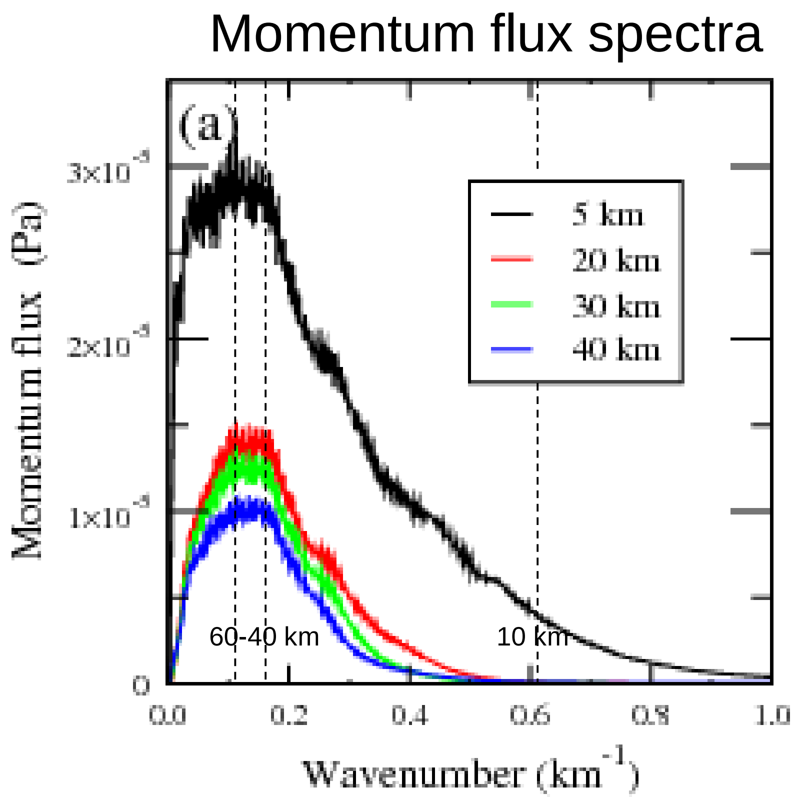


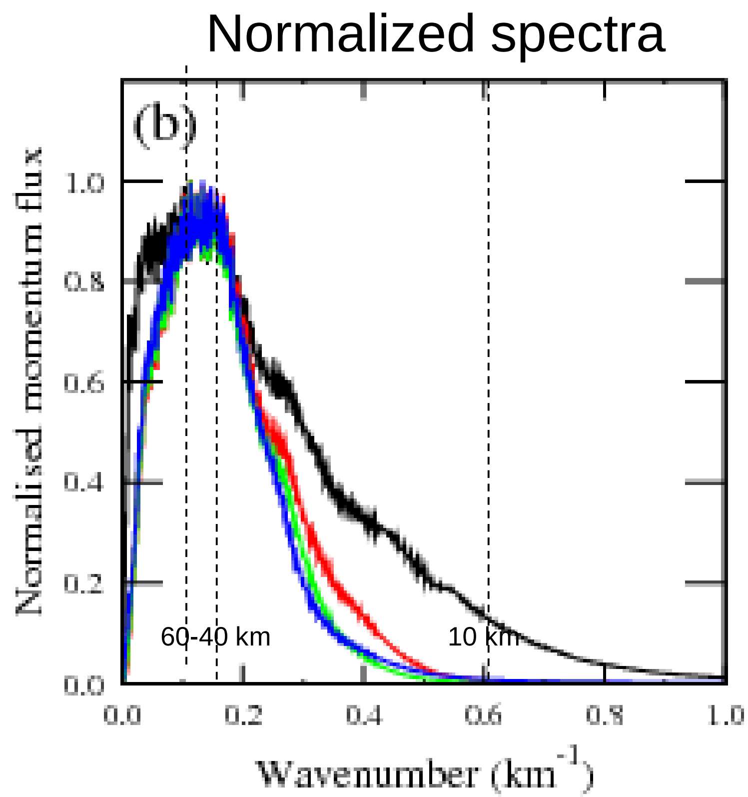
Momentum flux spectra

- Compute fluxes in Fourier space:

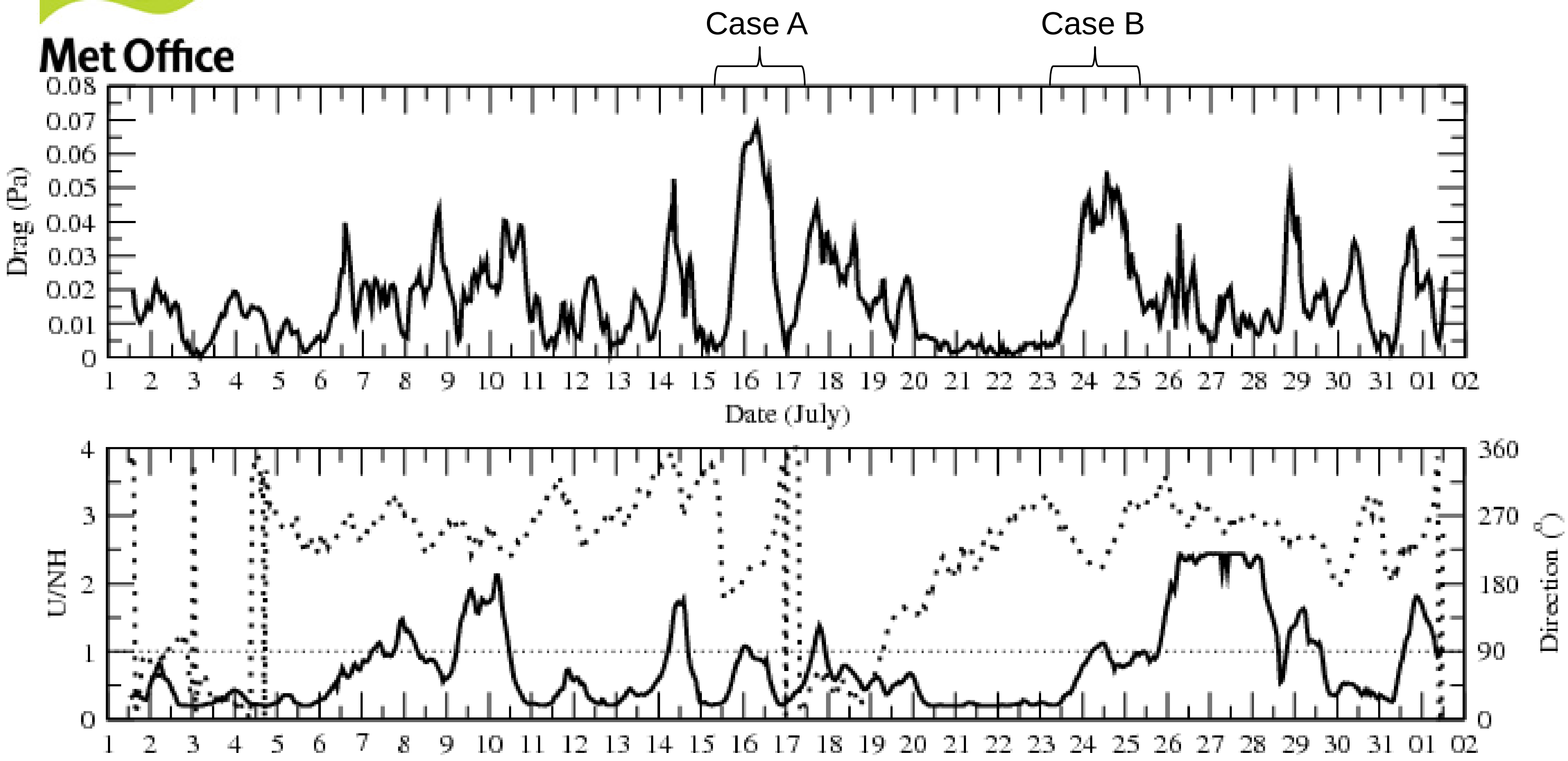
$$\int \rho u'w' \, dxdy = \int \rho \hat{u} \, \hat{w}^* \, dkdl$$

- Largest contributions from λ~40-60 km
- Long tail to much shorter wavelengths in troposphere
- Contribution from shorter wavelengths reduces at higher altitudes





Surface pressure drag



- High drag occurs when flow is roughly SSW'ly or NNE'ly, corresponding to flow perpendicular to ridge
- Low drag for NW'ly or SE'ly flow
- Higher drag also for U/NH~1

Variation of mean drag with low-level wind direction

- Drag binned by domain average low-level wind direction
- Resolved + parametrized drag does not capture variation