# How uncertainties in surface drag impact the large-scale circulation

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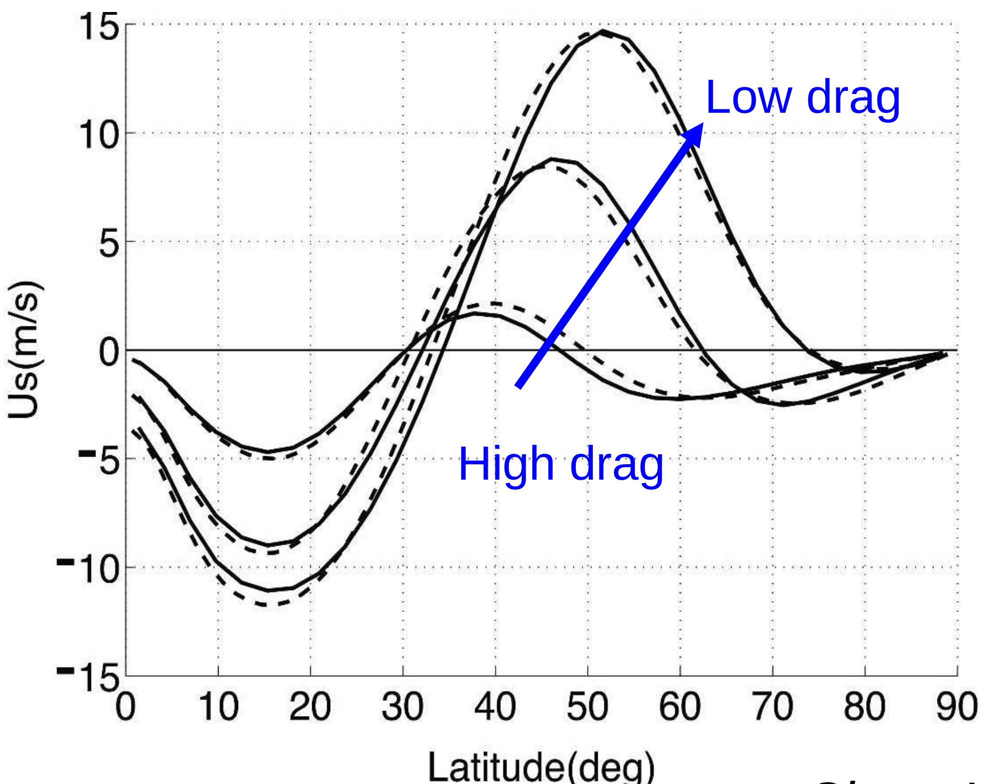
Anton Beljaars, Julio Bacmeister, Andy Elvidge, Felix Pithan, Annelize vanNiekerk, Inna Polichtchouk, Mark Rodwell,Ted Shepherd, Isla Simpson, Simon Vosper, Ayrton Zadra, Nils Wedi

# Surface drag/stress

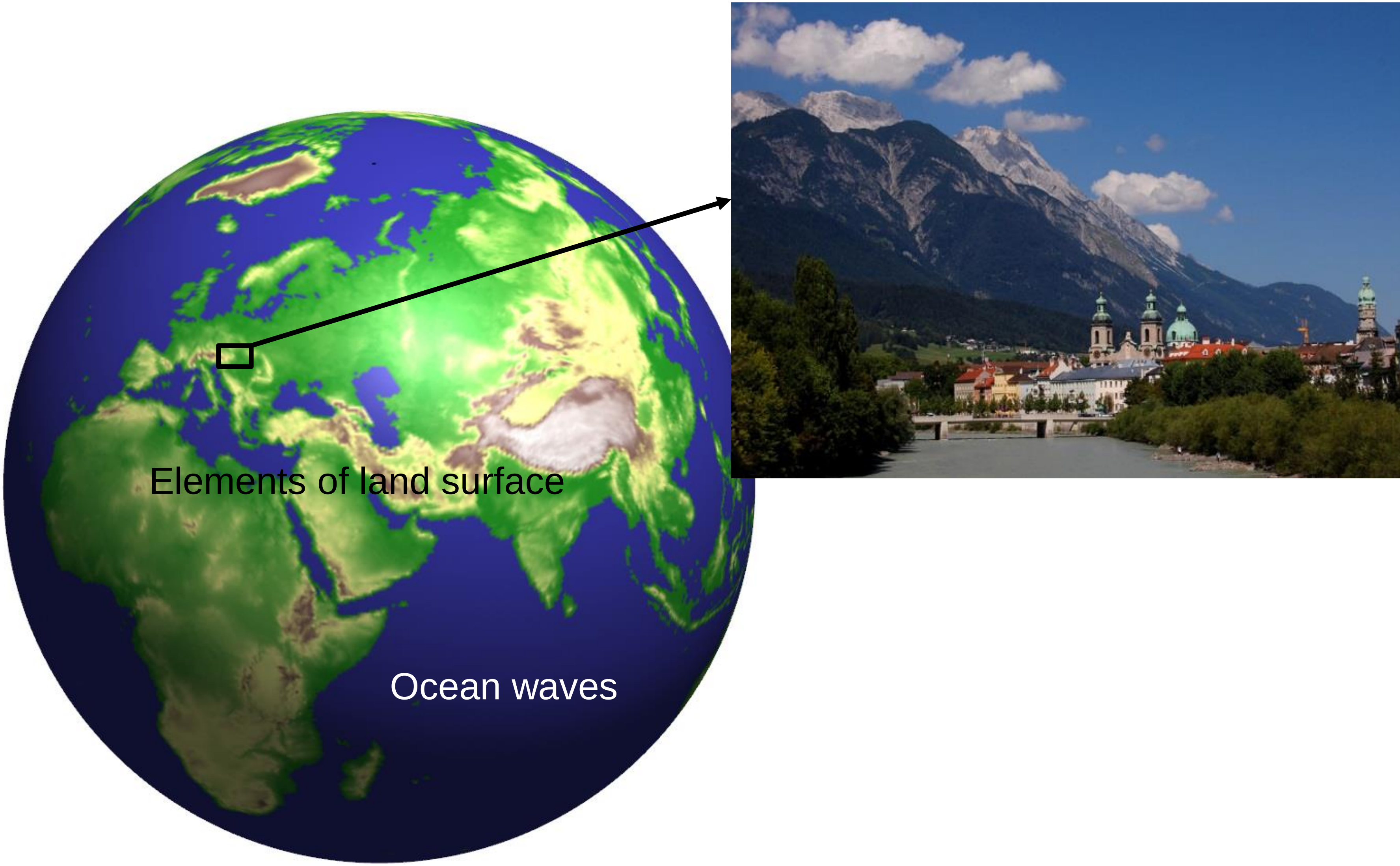
*Surface stress* = force parallel to the surface, per unit area, as applied by the earth's surface on the wind




In idealized AGCMs, surface jet strength and latitude are highly sensitive to surface drag, via feedback on baroclinic eddies

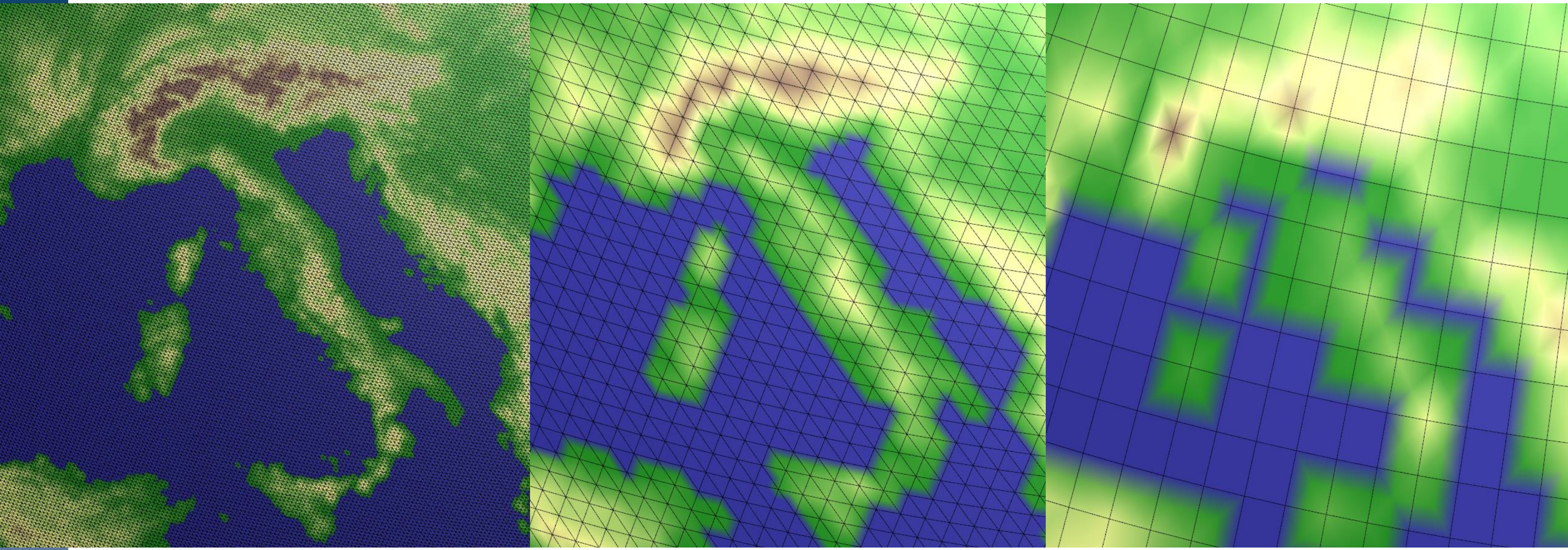
*Chen, Held & Robinson (2007 JAS)*

# Surface elements contributing to drag



# Models cannot resolve in detail surface features

Orography at 9 km resolution | Orography at 50 km resolution | Orography at 125 km resolution



Global NWP models → Global climate models

*Courtesy W. Deconinck*

# Representation of drag (stress) in models

$$\vec{\tau} = \vec{\tau}^{res} + \vec{\tau}^{phy}$$

$$\vec{\tau}^{res} = p_s \vec{\nabla} \mathrm{h}$$ = resolved orographic stress

$$\vec{\tau}^{phy} = \vec{\tau}^{pbl} + \vec{\tau}^{sgo}$$ = unresolved (subgrid) stress

$\vec{\tau}^{pbl}$: Stress from turbulence (or boundary-layer) scheme

$\vec{\tau}^{sgo}$: Stress from subgrid orographic scheme

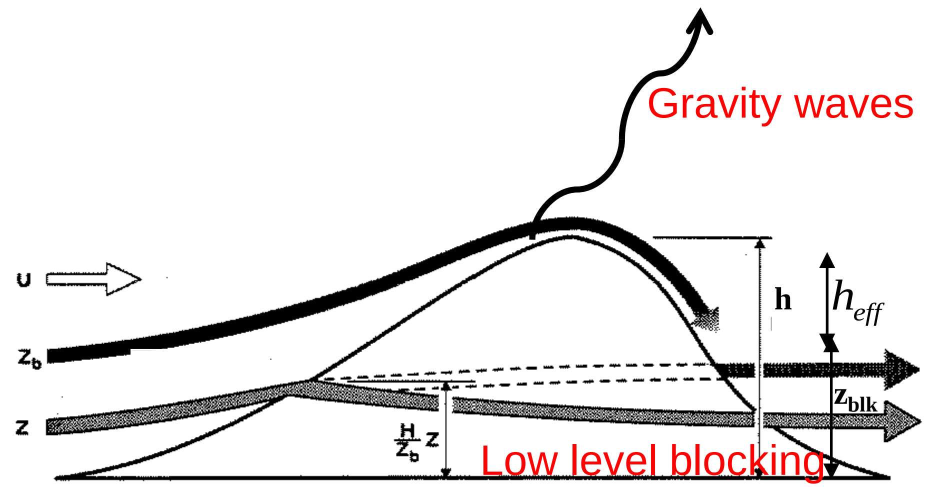
# Subgrid drag (stress) mechanisms ( e.g. in the ECMWF model )

## Scales smaller than 5 km

**a)Turbulent Drag - TURB**: Traditional MO transfer law with roughness for land use and vegetation

**b)Turbulent Orographic Form Drag - TOFD** : drag from small scale orography (Beljaars et al. 2004); Other models use orographic enhancement of roughness.

## Scales larger than 5 km




**a) Gravity Wave Drag - GWD** : gravity waves are excited by the “effective” sub-grid mountain height, i.e. height where the flow has enough momentum to go over the mountain

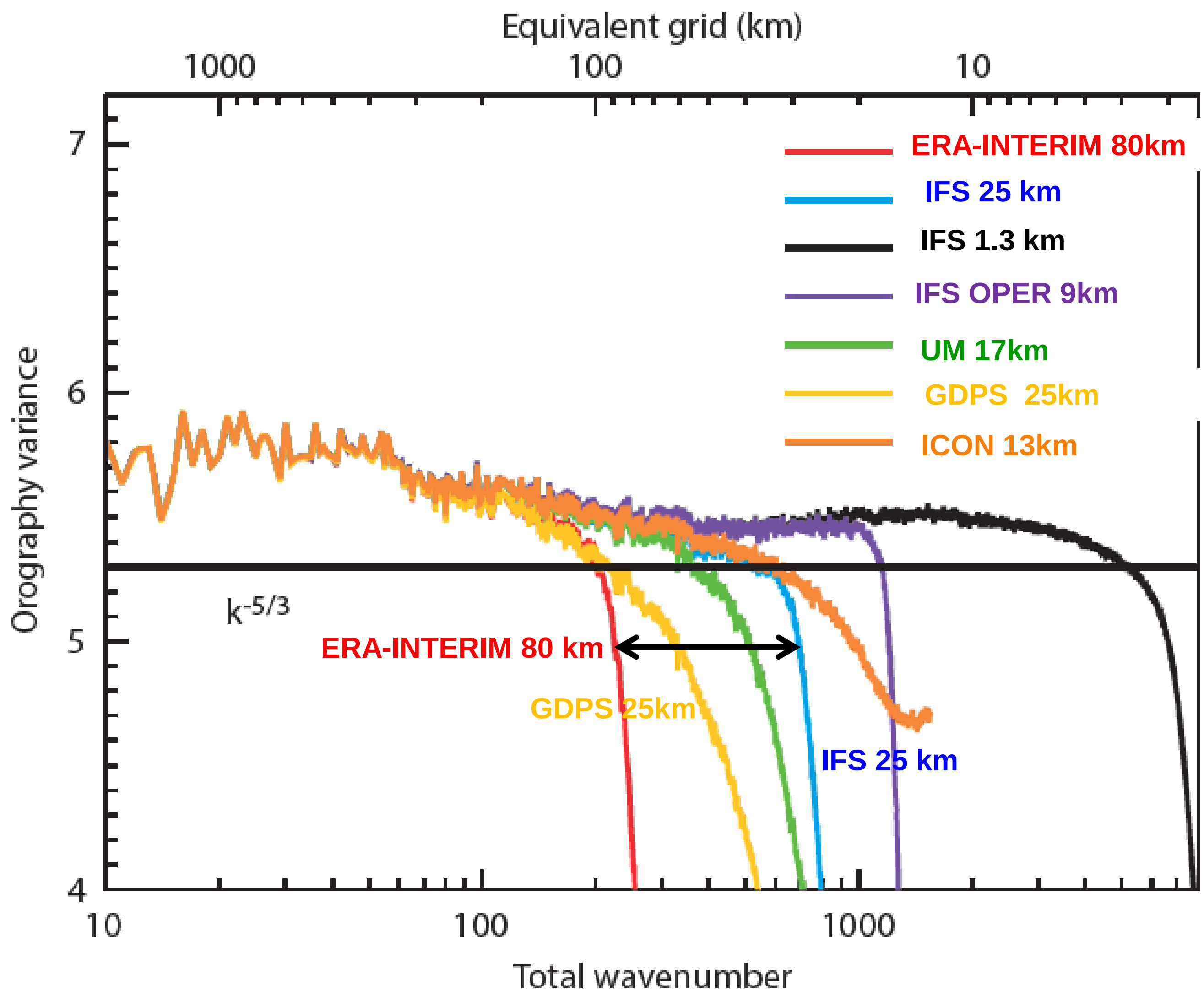
**b) Orographic low level blocking - BLOCK** : strong drag at lower levels where the flow is forced around the mountain

# Outline

1. Impacts of (uncertainties) in resolved orography on circulation*
2. Impact of (uncertainties) in subgrid stress on circulation
   - Surface drag over oceans
   - Orographic drag*
     - Impacts of various subgrid processes
     - Impacts of inter-model differences in stress
3. The way forward : Constraining the representation of drag processes

* NH winter-time circulation examples

# Differences in resolved orography

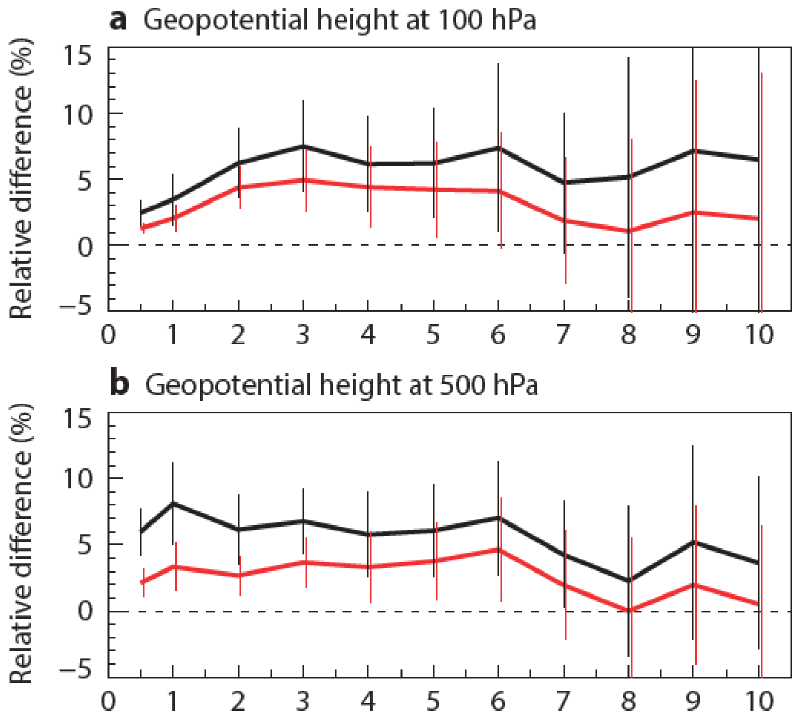


# Impact of resolved orography on forecast skill

CTL – IFS 25km

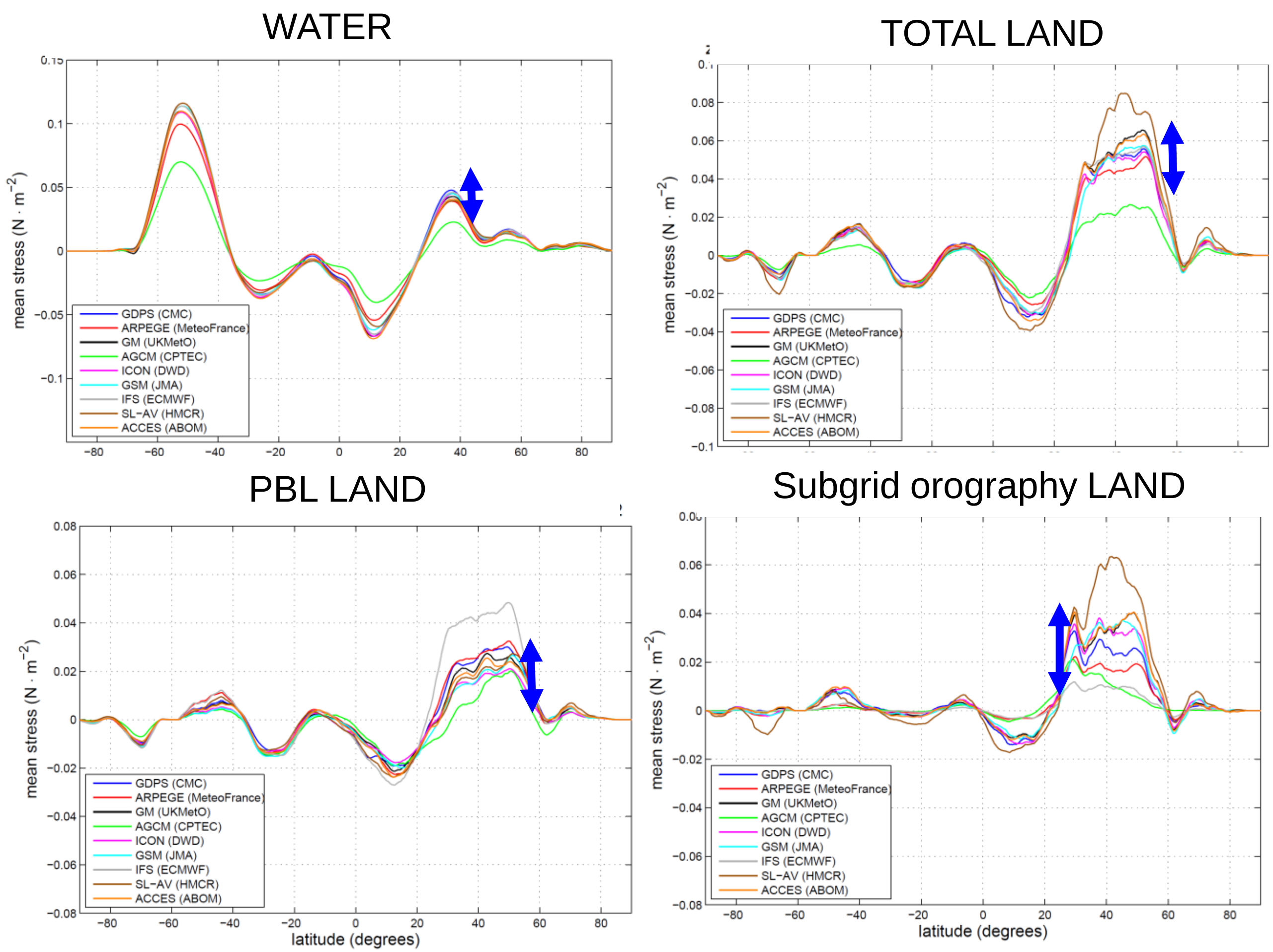
EXP1: 25 km with 80km resolved orography

EXP2: 25 km with 80km resolved and subgrid orography




Using a smoother resolved orography degrades significantly the forecast skill in terms of large-scale circulation, and near surface temperatures (during winter in the NH)

# WGNE Drag project – comparison of subgrid surface stress



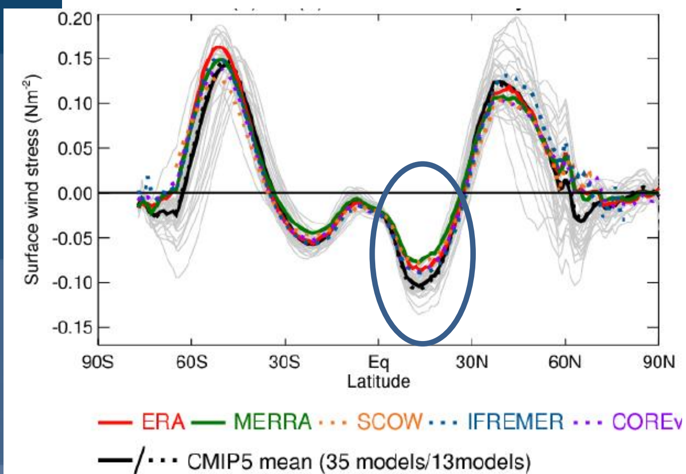

Major NWP models

- Much better agreement over water than over land !
- UKMO BL term < EC BL term, but SGO term >> EC SO term, and relative difference in total stress is 10-20% in NH midlatitudes

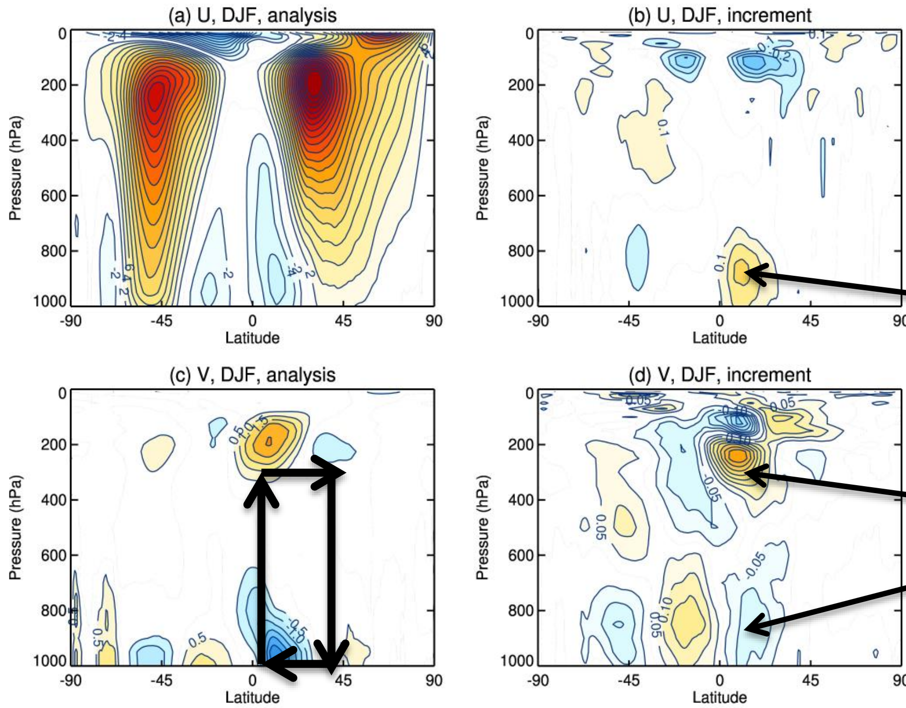
ECMWF

Link to Drag Project website* (A. Zadra and J. Bacmeister):
*http://collaboration.cmc.ec.gc.ca/science/rpn/drag_project/index.html*

# Missing ocean drag in the low level zonal flow




*Simpson et al (2014, JAS)*

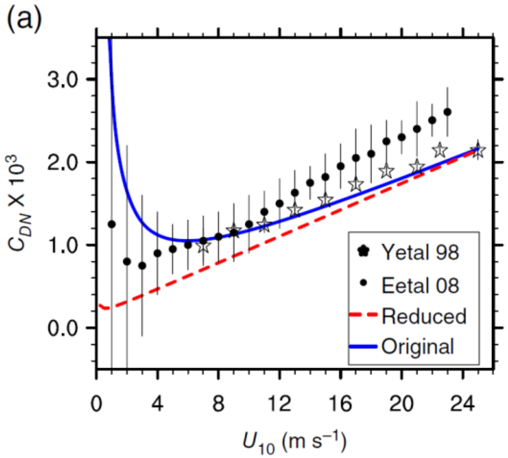



ERA-I analysis increments correcting for:

- too strong tropical easterlies
- too weak Hadley circulation

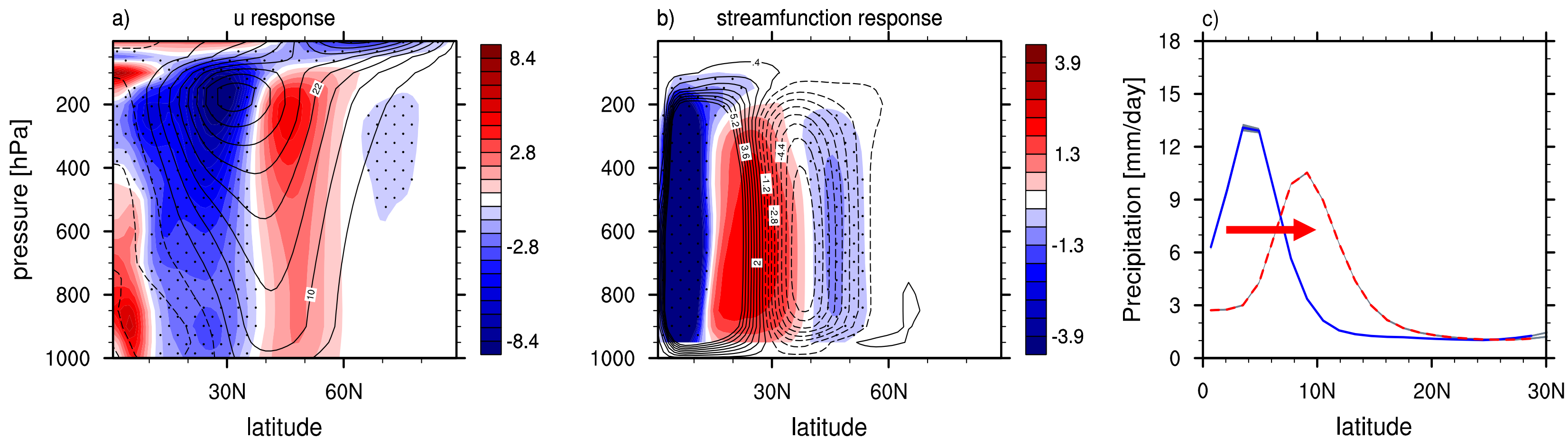
*Simpson et al. (submitted J.Clim.)*

# Response of the zonal-mean circulation to reduced ocean drag in an aquaplanet model




A poleward shift of the tropical surface easterlies, and of mid-latitude westerlies

A weakening of the HC and a poleward shift of the ITCZ.



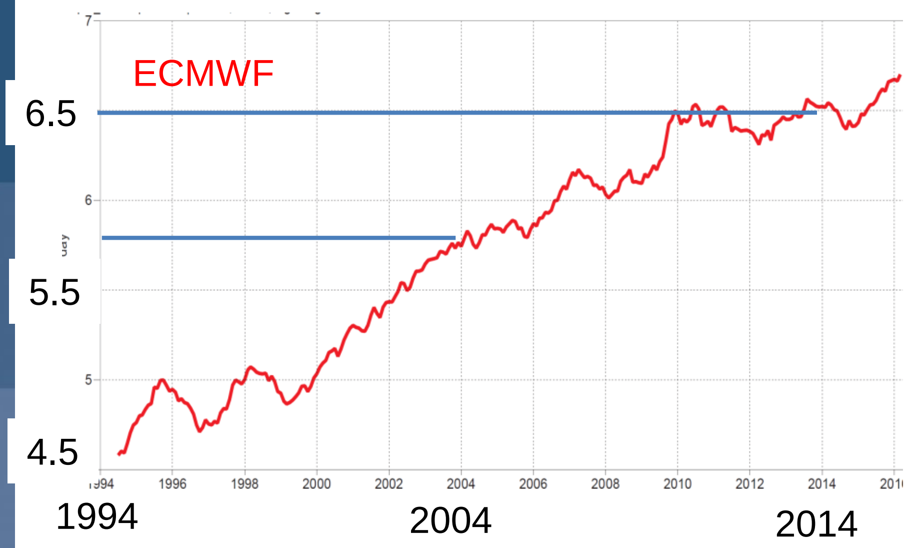

*Polichtchouk & Shepherd (2016,QJRMS)*



See Inna Polichtchouk's poster

# Impact of the turbulent orographic form drag parameterization

Z: NH 20 to 90, 500 hPa
Lead time AC reaches 80%




Forecasts 6 day ahead now are as good as forecasts 4 days ahead 20 years ago

Bauer, P., A. Thorpe, and G. Brunet. "The quiet revolution of numerical weather prediction." Nature (2015)

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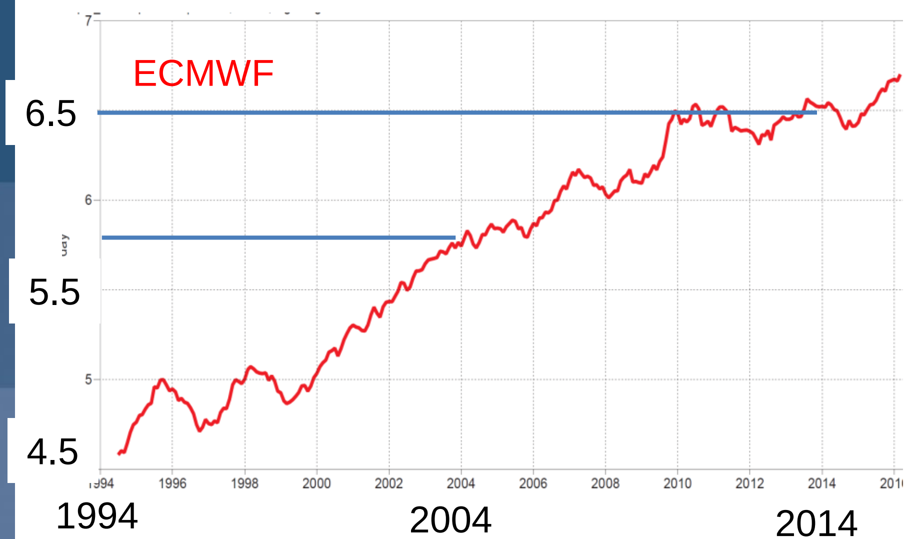
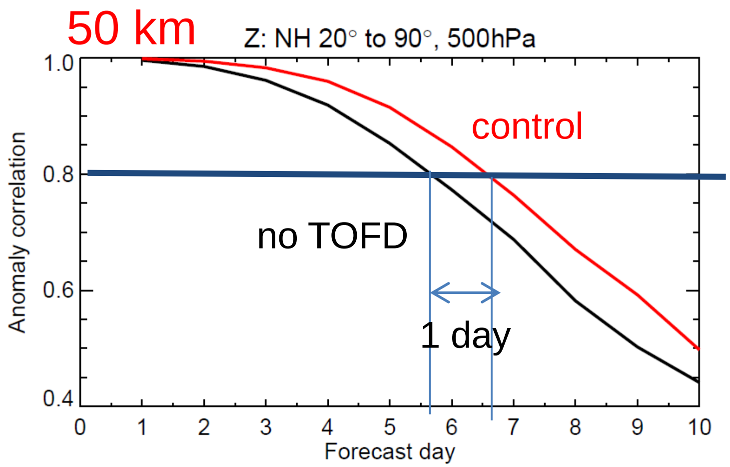
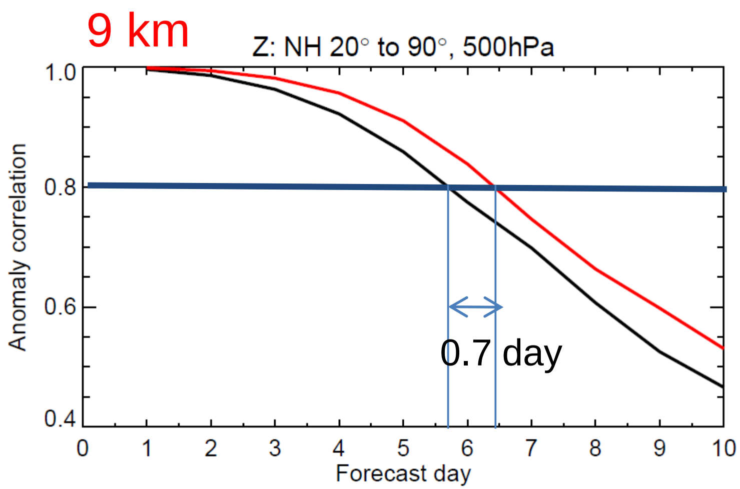
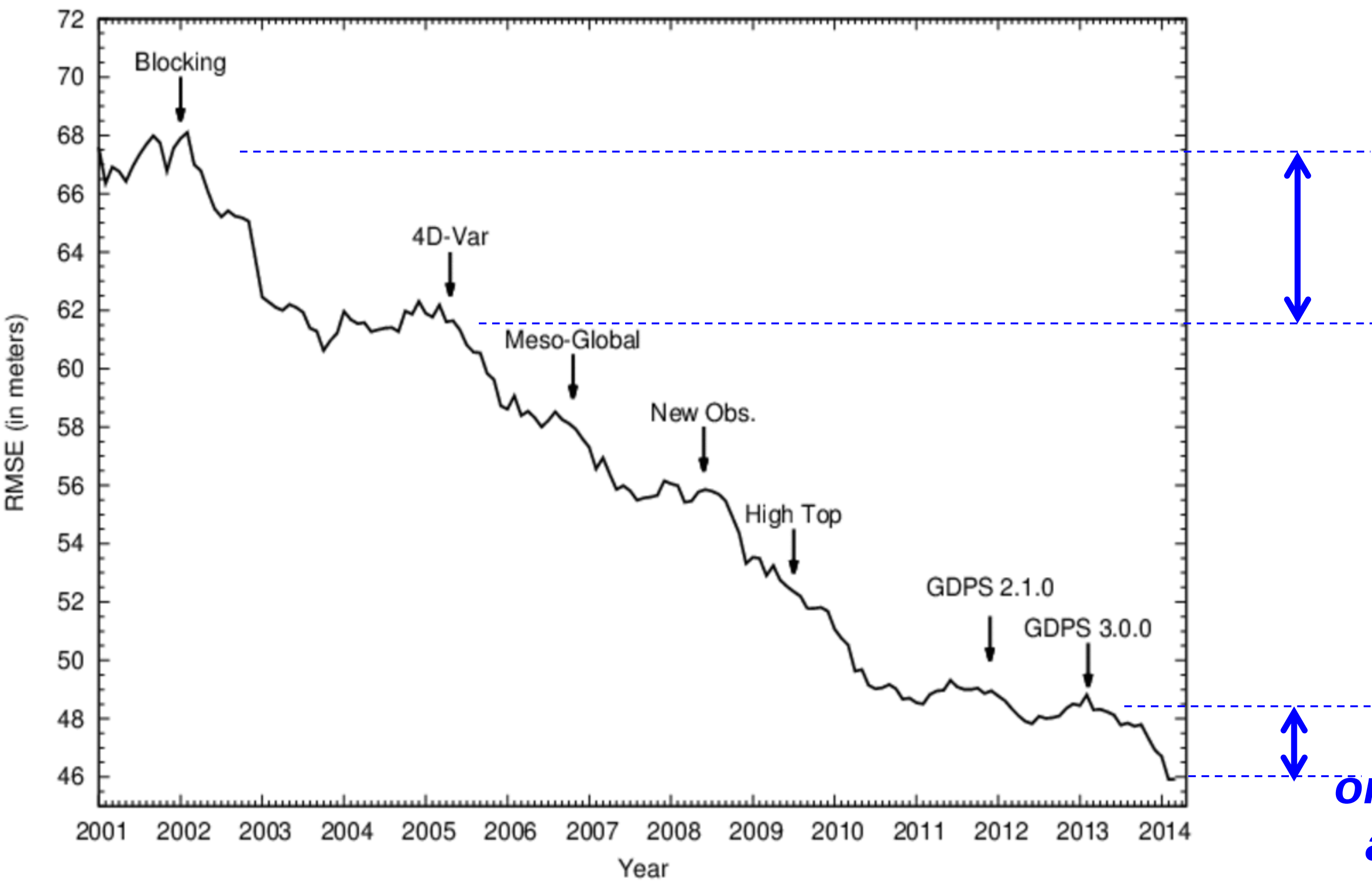



Bauer, P., A. Thorpe, and G. Brunet. "The quiet revolution of numerical weather prediction." Nature (2015)

# Impact of changes to drag-related schemes at the Canadian center



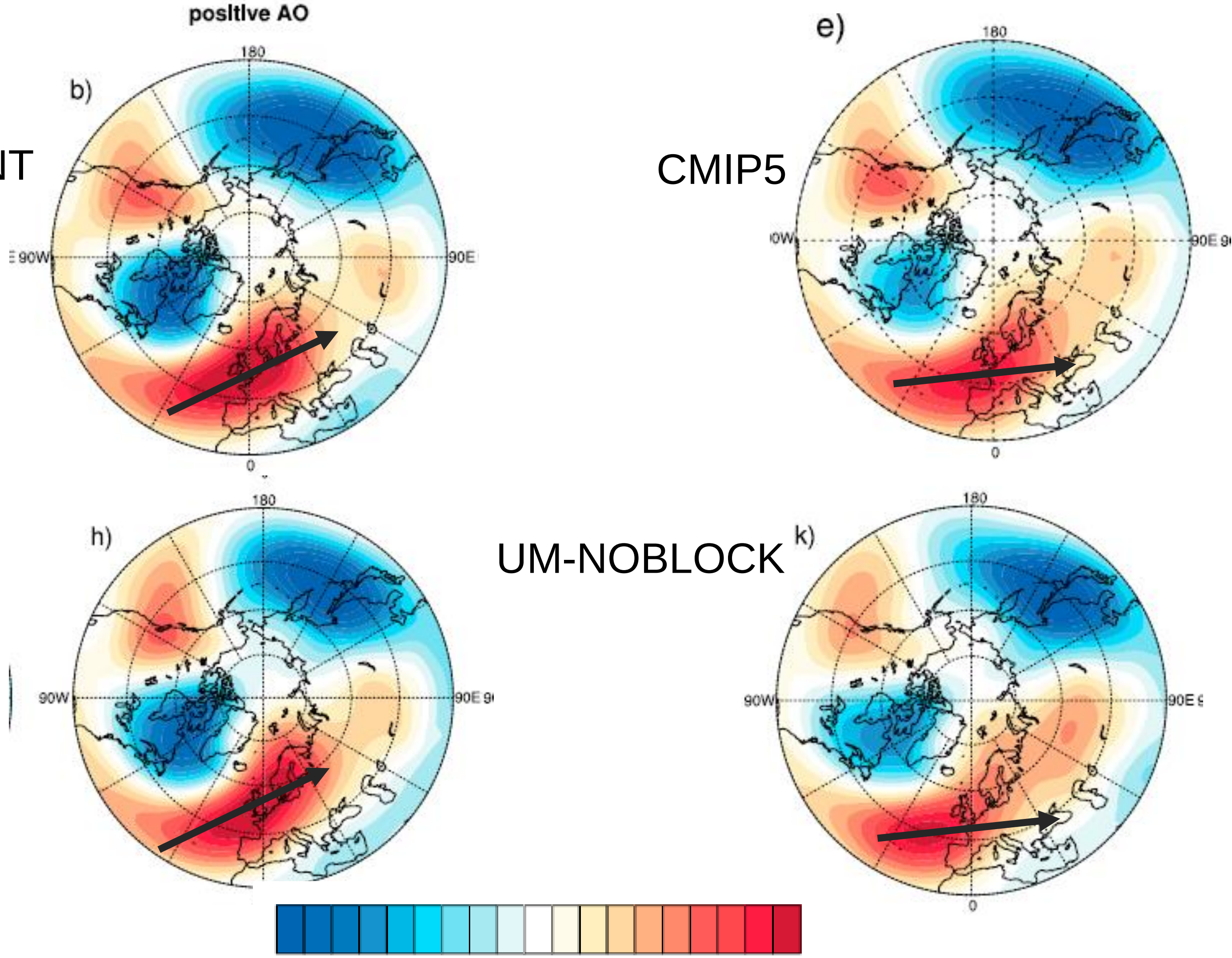

***~ 7m***
***mostly due to introduction of orographic blocking scheme***

***~ 2m***
***mostly due to adjustments in orographic blocking and PBL schemes***

***Fig.: Evolution of 500-hPa RMS errors over the N. Hemisphere: 12-month running mean, from 2001 to 2014.***

*Courtesy A. Zadra*

# Climate model biases in jet streams resulting from missing orographic blocking




*Pithan et al., GRL, 2016*

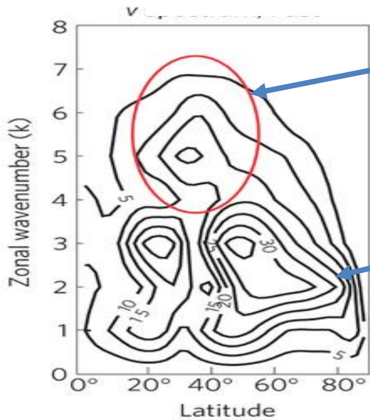
See Felix Pithan's poster

# Parametrized orographic blocking modulates the stationary wave response to climate change

**Spectrum of V* at 300hPa**

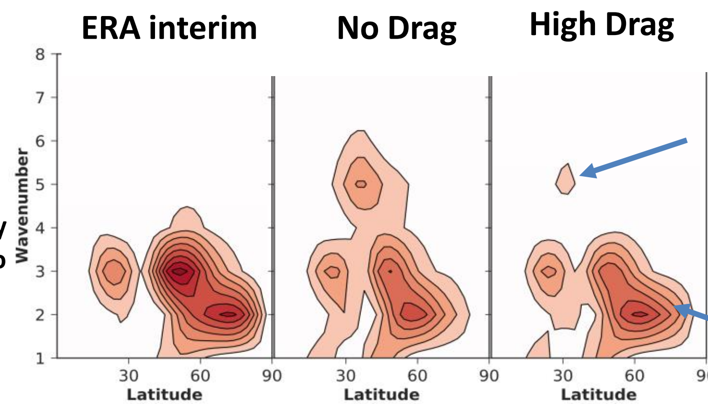
**CMIP5**

*Simpson et al. 2016 (Nature CC)*




**Stationary waves too strong**

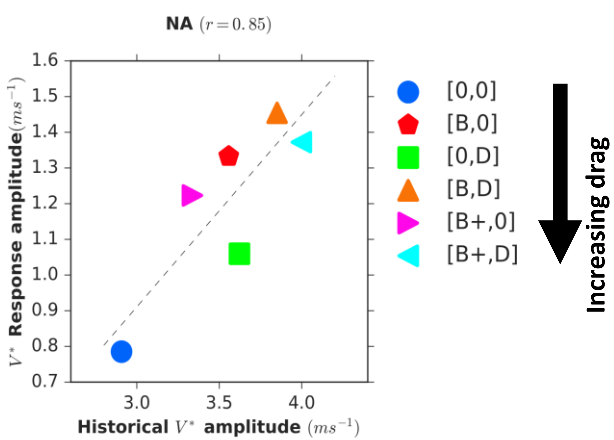
**Stationary waves too weak**




Parametrized orographic drag damps stationary waves over the Pacific

Parametrized orographic drag amplifies stationary waves over the North Atlantic

**North Atlantic**



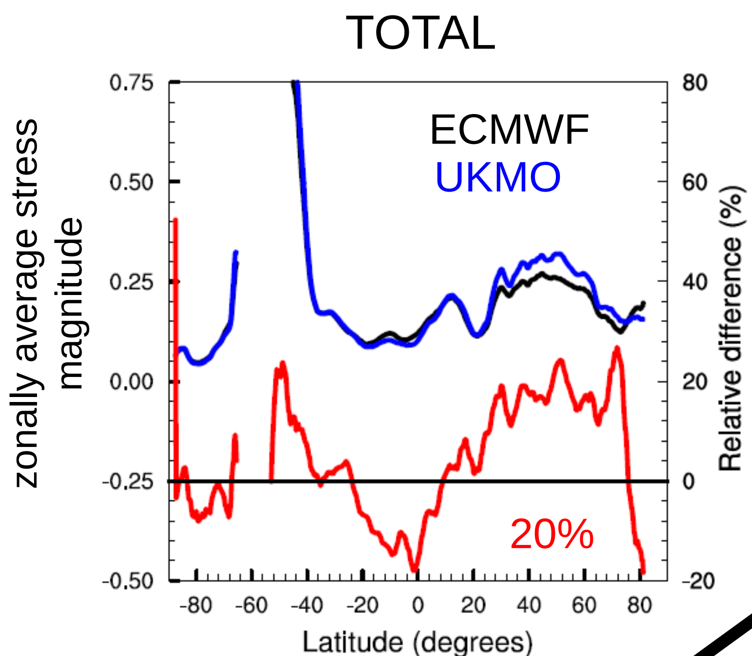

Stronger climatological stationary waves are associated with a stronger response to climate change

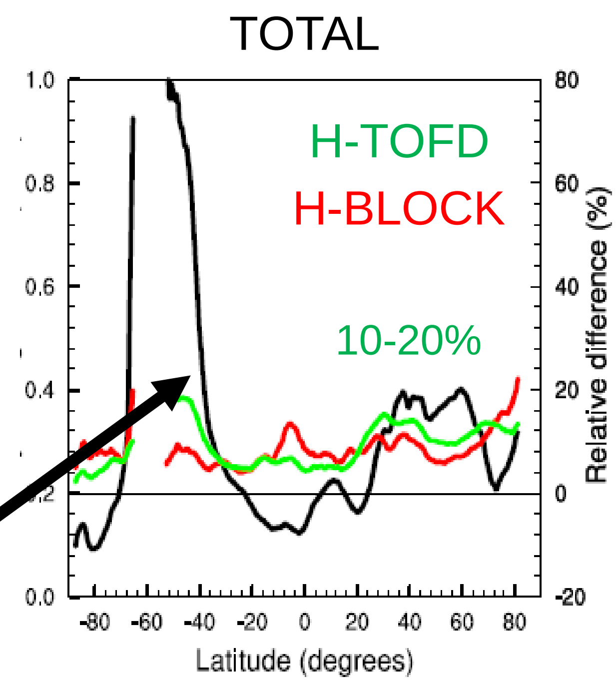
*van Niekerk et al. 2017 (JAS)*



See Annelize vanNiekerk's poster

# Do inter-model differences in orographic drag (and its partition) impact circulation?



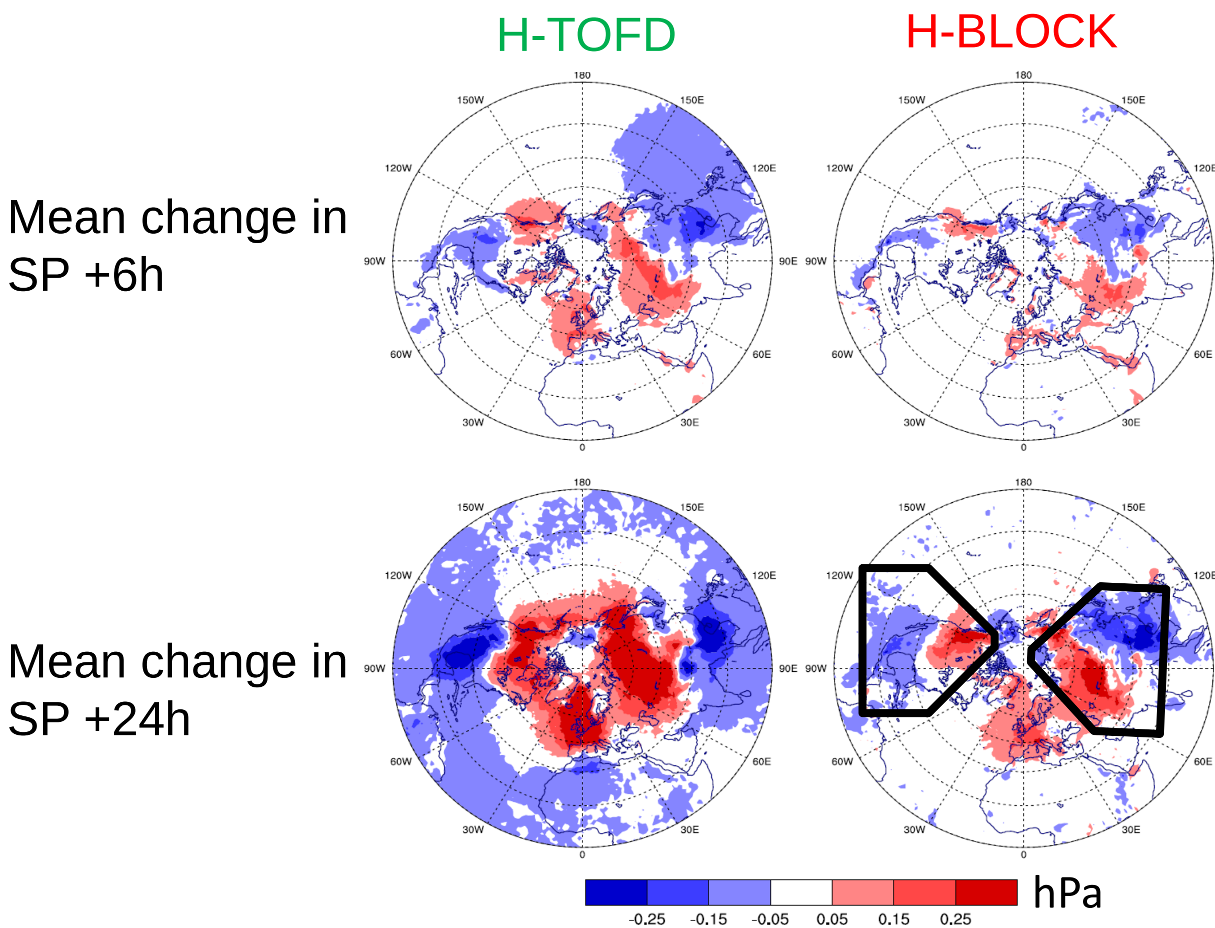

*(Daily 10 days forecast only runs, for February 2014, at T639 ~ 32 km at the Eq.)*

Easy to change the magnitude of the stress by an amount comparable to inter-model differences

*Sandu et al, JAMES,2016*

# Do inter-model differences in orographic drag (and its partition) impact the circulation?

Short-range forecasts

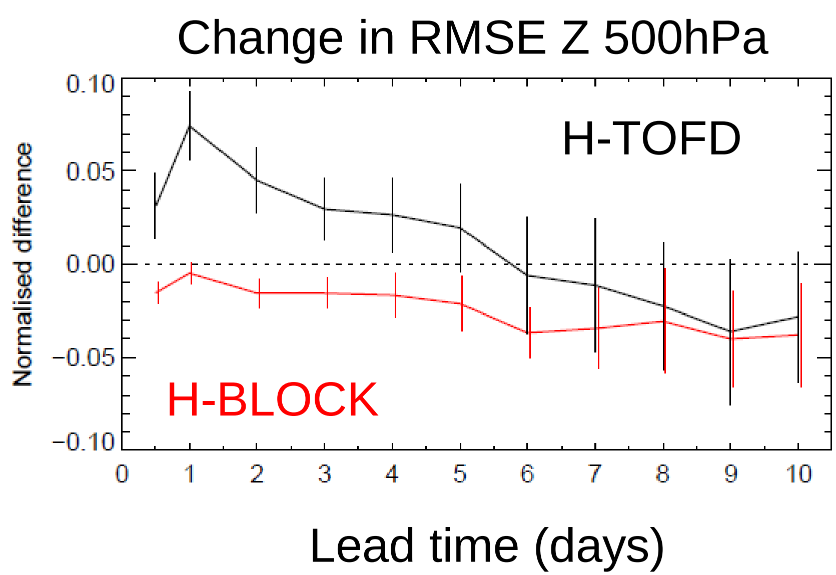



Local response in SP, through geostrophic balance. The meridional pressure gradient is induced by a deceleration of the mid-latitude westerlies

*corroborates Zadra et al 2003*

# Do inter-model differences in orographic (and its partition) impact the circulation?

Medium-range forecasts




Fine balance between improving and degrading the forecast!

It matters how the drag is partitioned between the two schemes

At least for TOFD the trouble won't go away with high resolution anytime soon!

# In summary:

## Models don't agree:

- in the resolved orography
- in total subgrid drag, nor in its partition between different processes and the diurnal cycle, particularly over orography

## Subgrid drag processes:

- have a large impact on the large-scale circulation, at all timescales
- are responsible for known systematic circulation biases
- the orographic drag parametrizations are fairly simplistic and especially poorly constrained, and don't necessarily behave well with resolution (van Niekerk, 2016, Vosper, 2016)

ECMWF

# Long list of open questions

- What causes inter-model differences? parameterizations, underlying subgrid orography ? filtering of resolved orography? see andy's talk
- How should the partition between different schemes done?
- Is the transition between resolved and parametrized handled well? (greyzone) see andy's talk
- Are the schemes well suited for complex mountain ranges?

# The way forward: constraining drag processes

Use observations, inverse modelling and high resolution simulations to better understand these processes, identify caveats of existing parameterizations, and improve upon them, and thereby reduce the associated systematic errors

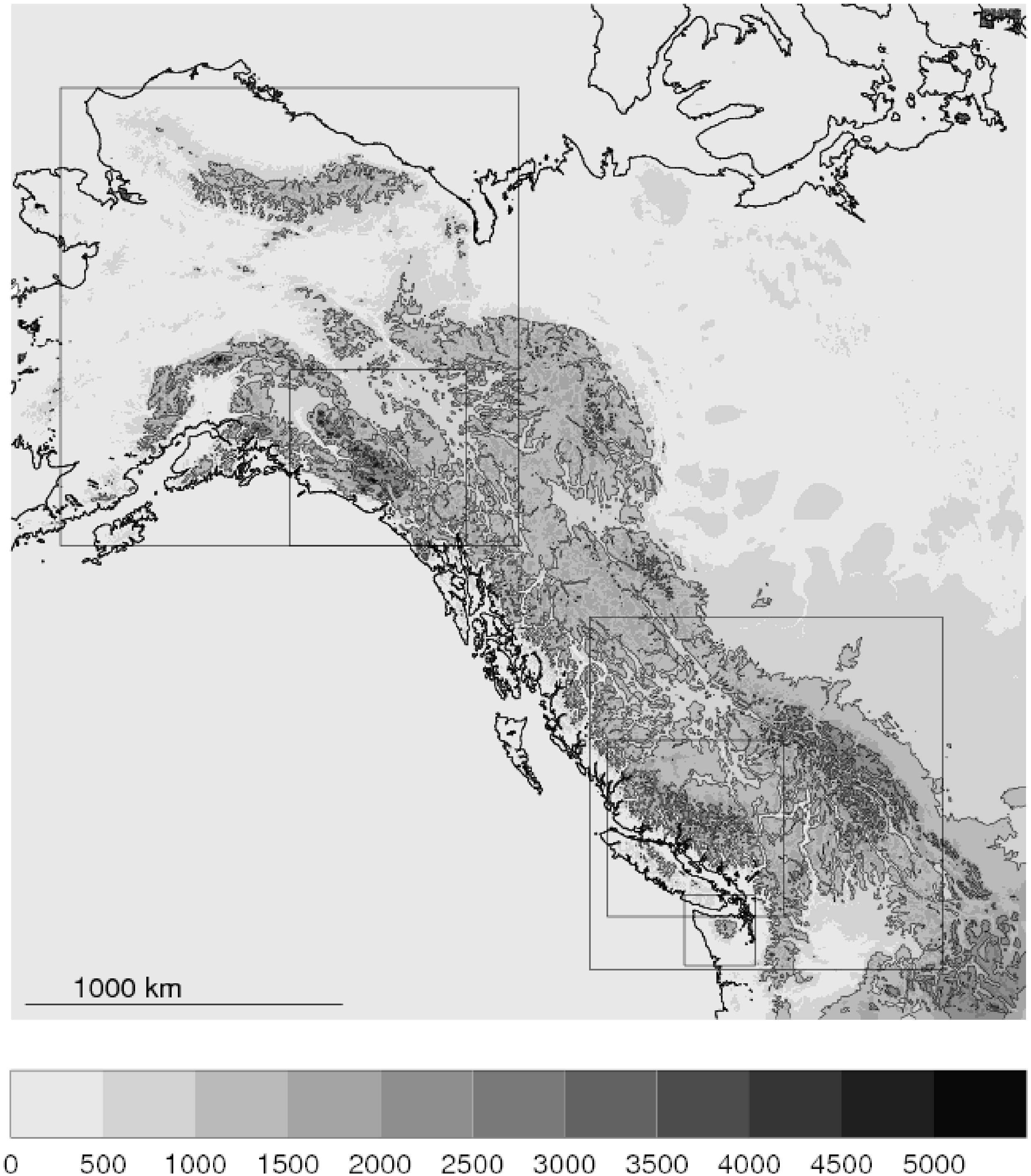
*For more info, see Outcomes of a workshop on 'Drag processes and their links to the large scale circulation, ECMWF Newsletter, Autumn 2016*

# High-resolution simulations of the Rockies

(building on Vosper et al. 2015,2016)

- 2, 4, 8, 16, 32 km
- 1 month simulation: 01-31 Dec 2015
- Each directly nested within N512 GA6.1
- GA7 GWD

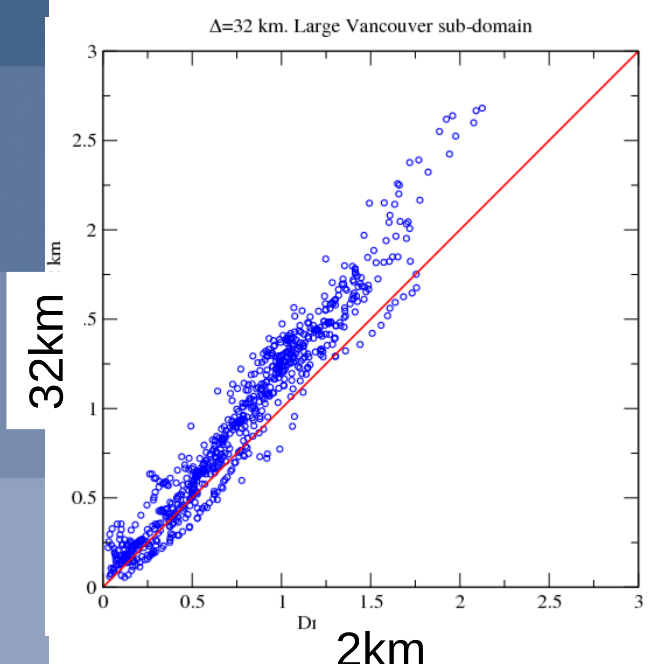
*Courtesy Simon Vosper*

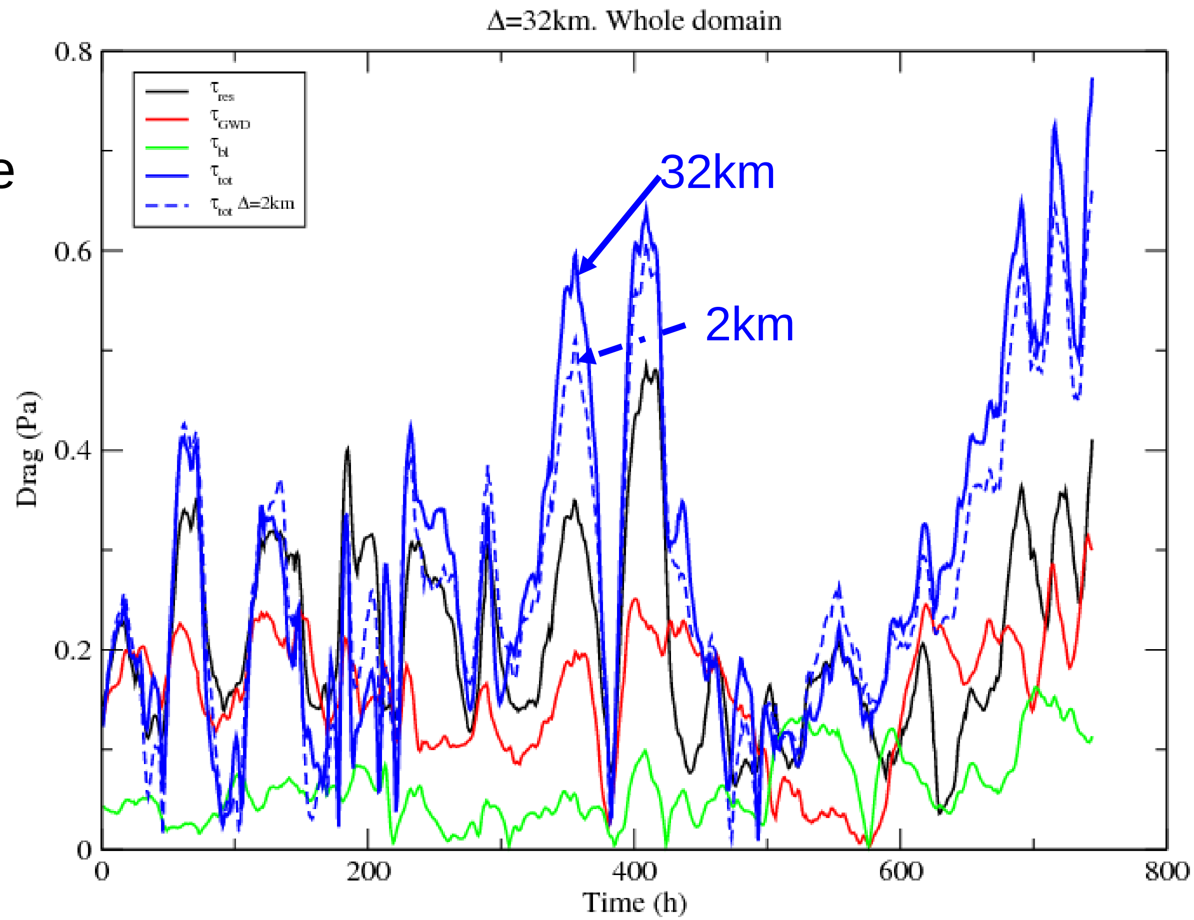


# High-resolution simulations of the Rockies

## Time series of magnitude of surface drag.

Resolved pressure drag computed using Smith et al (2006) method



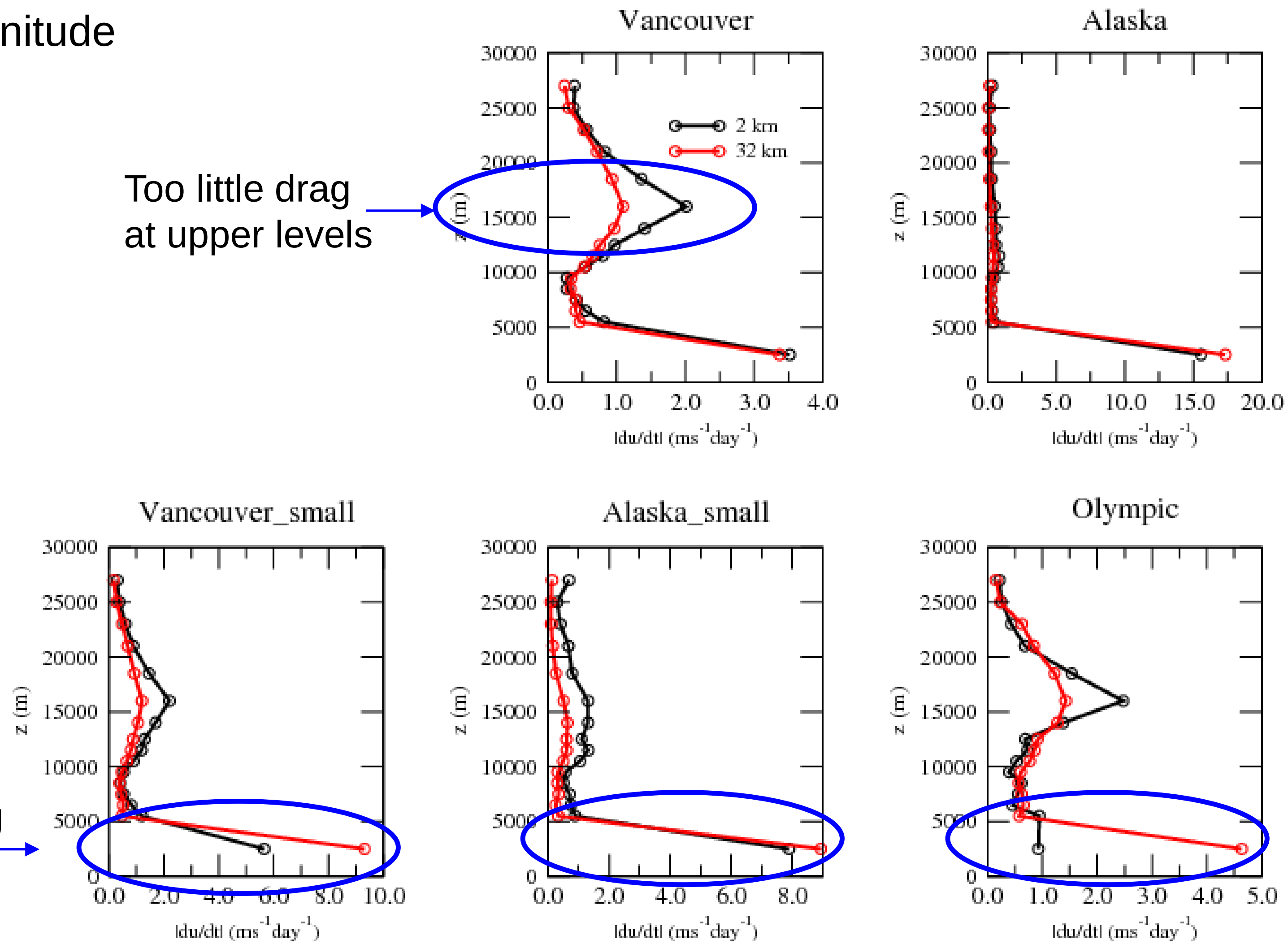




*Courtesy Simon Vosper*

# High-resolution simulations of the Rockies

Profiles of magnitude of acceleration

Too little drag at upper levels




Too much blocking at low levels

*Courtesy Simon Vosper*

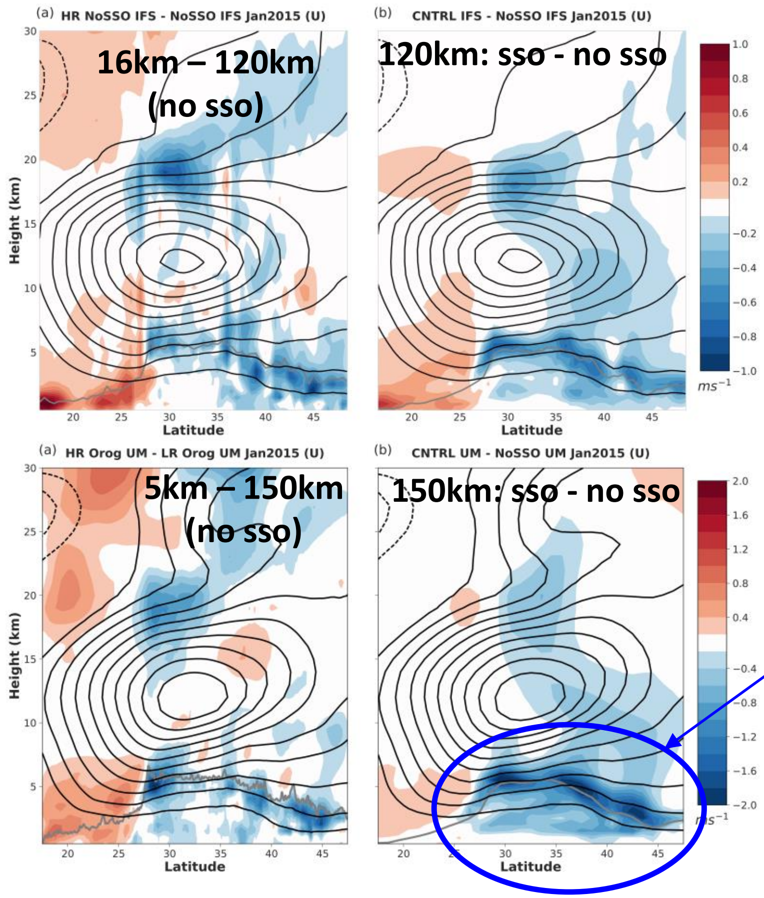
ECMWF

# Resolved versus parametrized orographic drag
## (gravity wave plus blocking)

Impact of resolved orographic drag | Impact of parameterized orographic drag

ECMWF IFS

Met Office UM



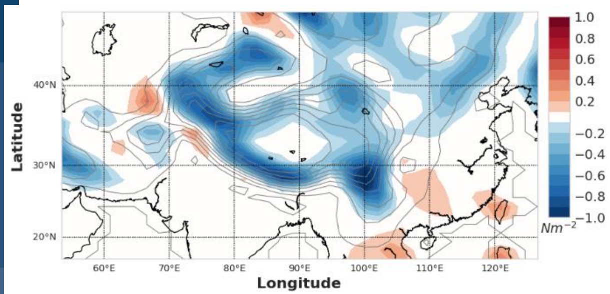

Parameterized orographic drag does a good job terms of location in both models and magnitude (in the IFS).

However, the drag at low levels is much larger than the resolved drag at in the Met Office UM.

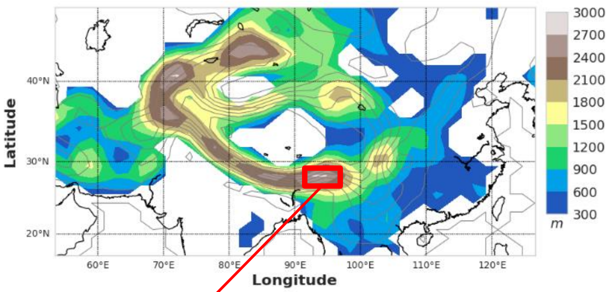
*Van Nierkerk et al, in preparation*

# Caveats of the blocking parametrization

Blocking stress (N96)

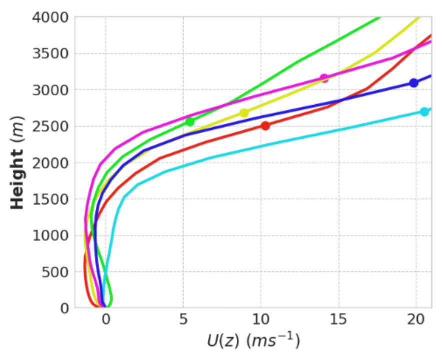



Blocking depth (N96)




Blocking depth $= h_{SSO} - \frac{U}{N}$

Vertical wind profile




Assumption of constant vertical wind over subgrid orography is strongly violated over the Himalayas

Leads to large blocking depths and parameterization scheme intersecting with upper level jet.

Circles = height of blocked layer

*Van Nierkerk et al, in preparation*