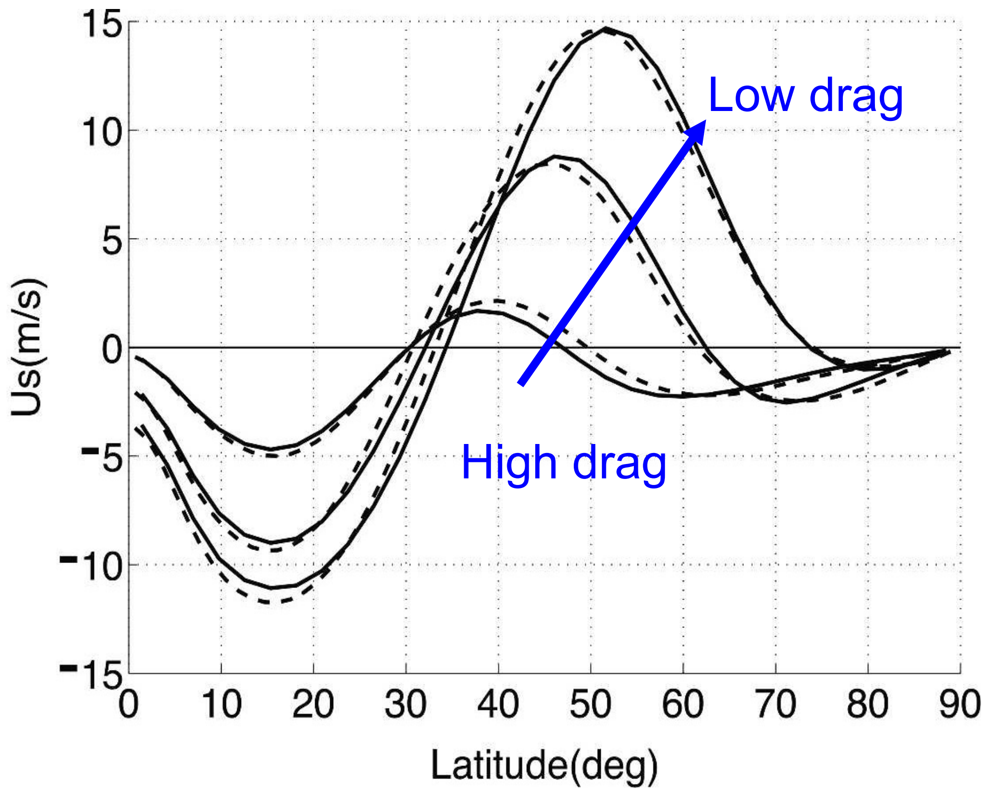
Uncertainties in the representation of drag processes

Irina Sandu

Annelize Van Niekerk, Takafumi Kanehama, Simon Vosper, Ted Shepherd, Anton Beljaars, Andy Elvidge, Ayrton Zadra

Surface drag/stress

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

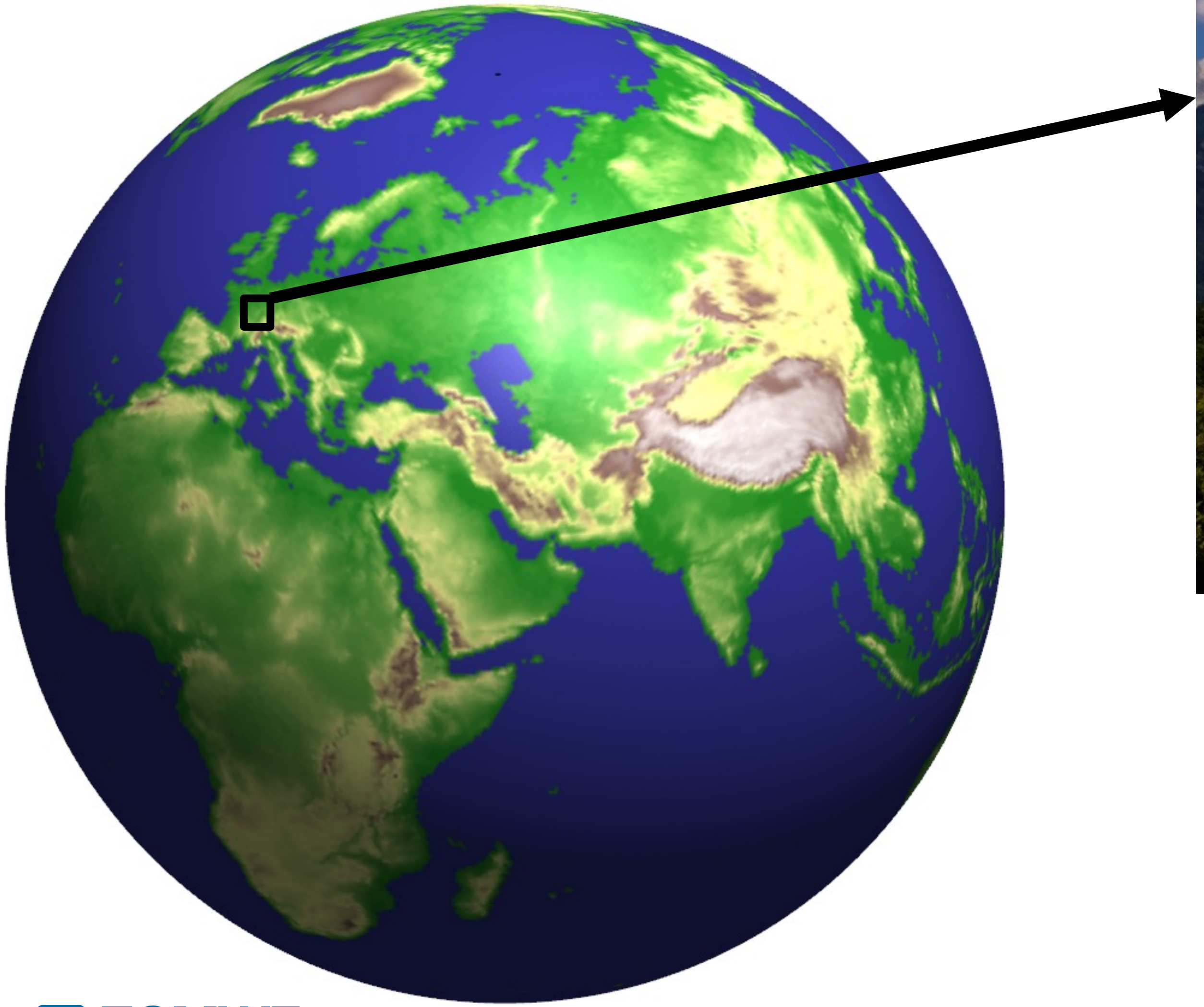


In idealized AGCMs, surface jet strength and latitude are highly sensitive to surface drag, via feedback on baroclinic eddies

ECMWF

Chen, Held & Robinson (2007 JAS)

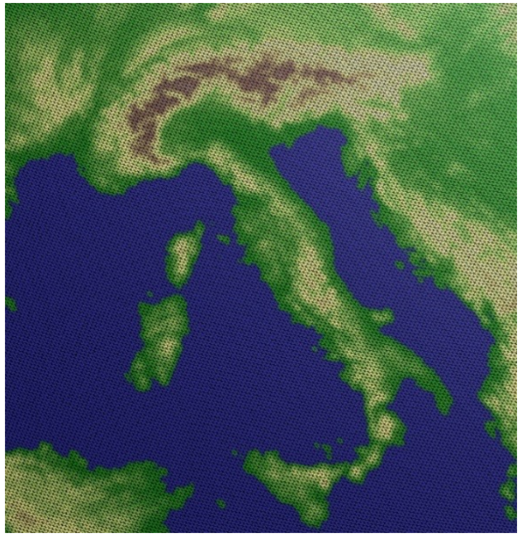
Surface elements contributing to drag



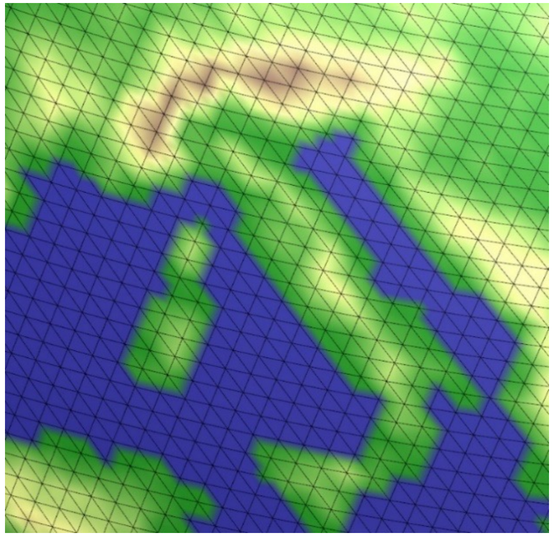
ECMWF

Models cannot represent in detail surface features

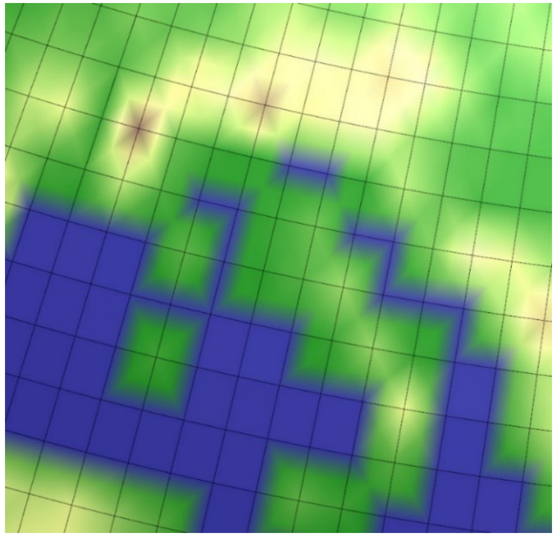
Orography at 9 km resolution



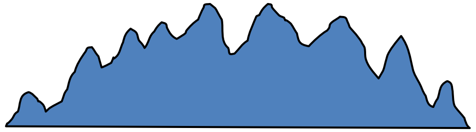
Orography at 50 km resolution



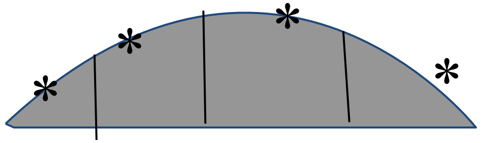
Orography at 125 km resolution



Global NWP models

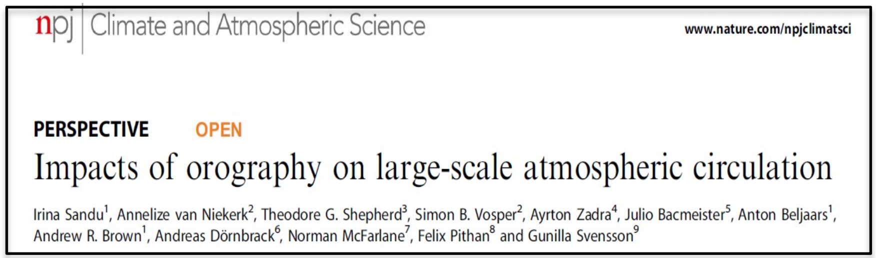


Global climate models



1. Gray zone at all resolutions
2. Poor observational evidence
3. Processes across multiple scales and flow regimes

ECMWF


npj | Climate and Atmospheric Science www.nature.com/npjclimatsci

PERSPECTIVE OPEN

Impacts of orography on large-scale atmospheric circulation

Irina Sandu[1], Annelize van Niekerk[2], Theodore G. Shepherd[3], Simon B. Vosper[2], Ayrton Zadra[4], Julio Bacmeister[5], Anton Beljaars[1], Andrew R. Brown[1], Andreas Dörnbrack[6], Norman McFarlane[7], Felix Pithan[8] and Gunilla Svensson[9]

The representation of surface stress in models

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

$$\vec{\tau} : (\tau_x, \tau_y) = (\overline{u'w'}, \overline{v'w'})$$

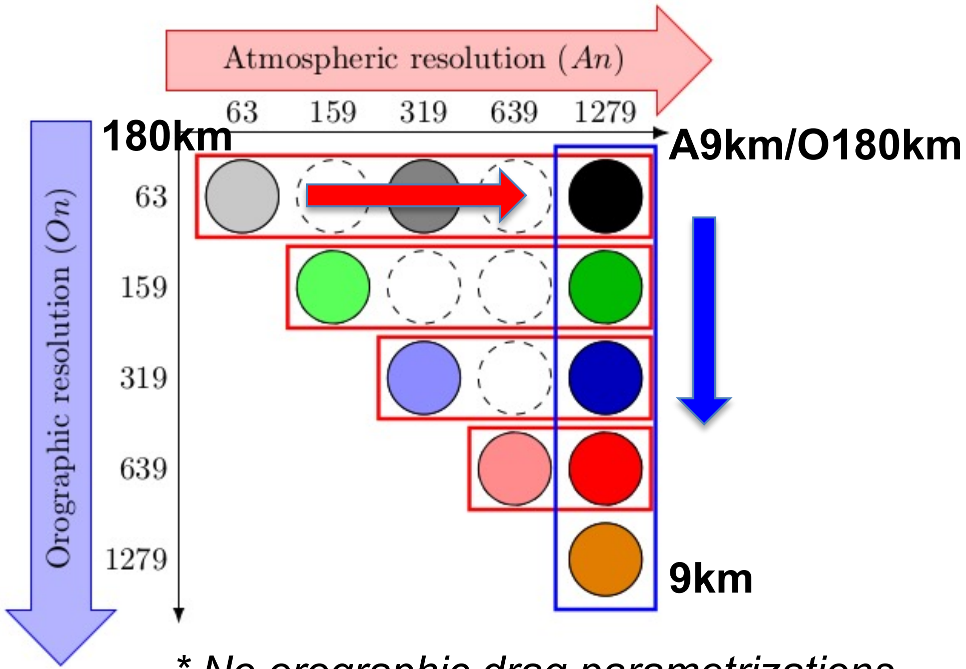
$\vec{\tau}^{res} = p_s \vec{\nabla} \mathrm{h}$ = resolved orographic stress

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

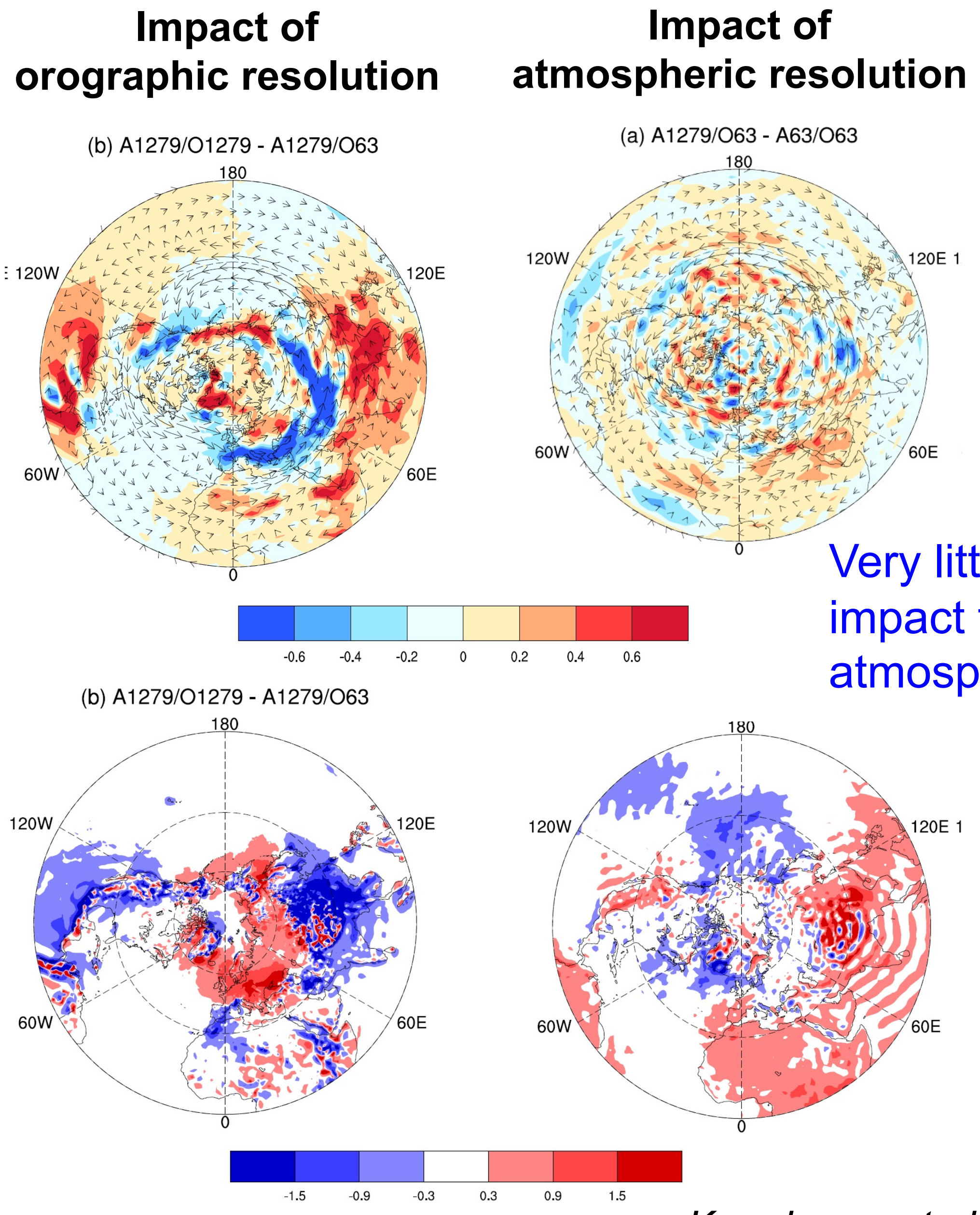
$\vec{\tau}^{pbl}$: Stress from turbulence (or boundary-layer) scheme

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

(Resolved) orography largely controls NH winter circulation



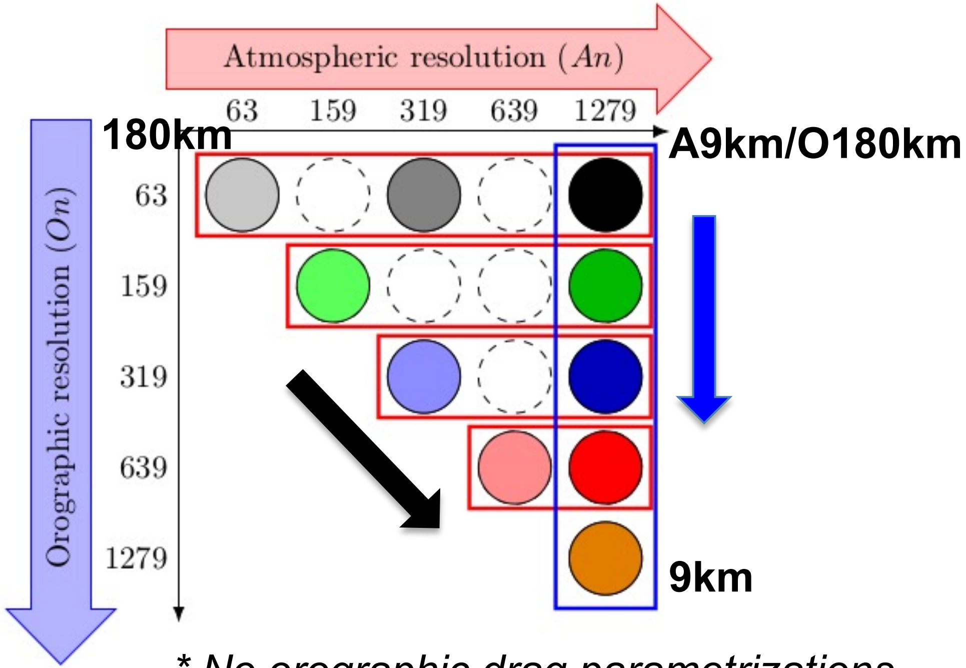
* *No orographic drag parametrizations*



Very little tropospheric impact from increasing atmospheric resolution

Kanehama et al, JAMES, 2019

(Resolved) orography largely controls NH winter circulation



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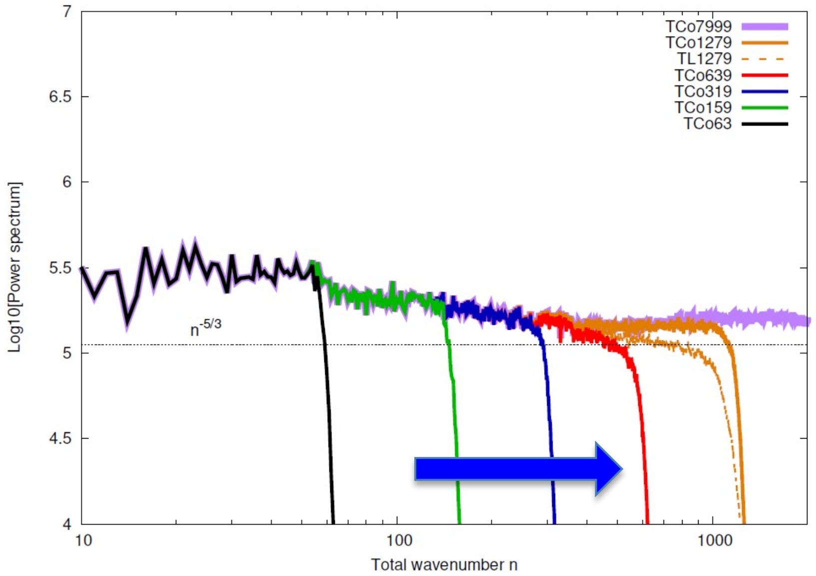
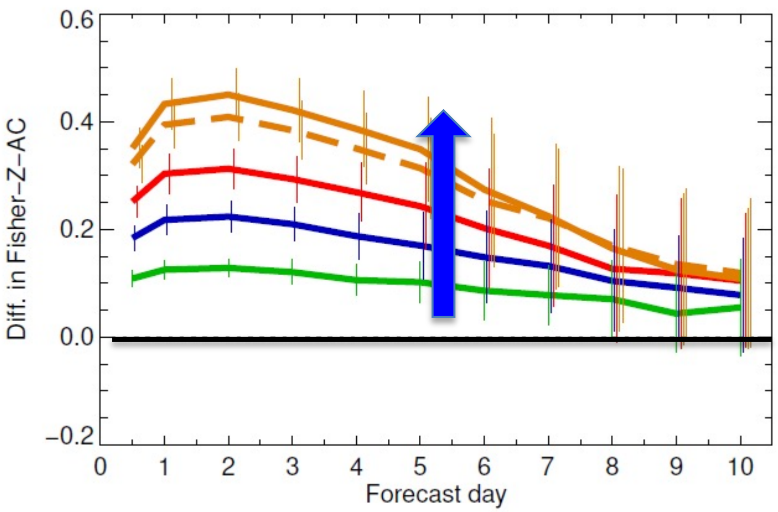


ACC geopotential height 500hPa



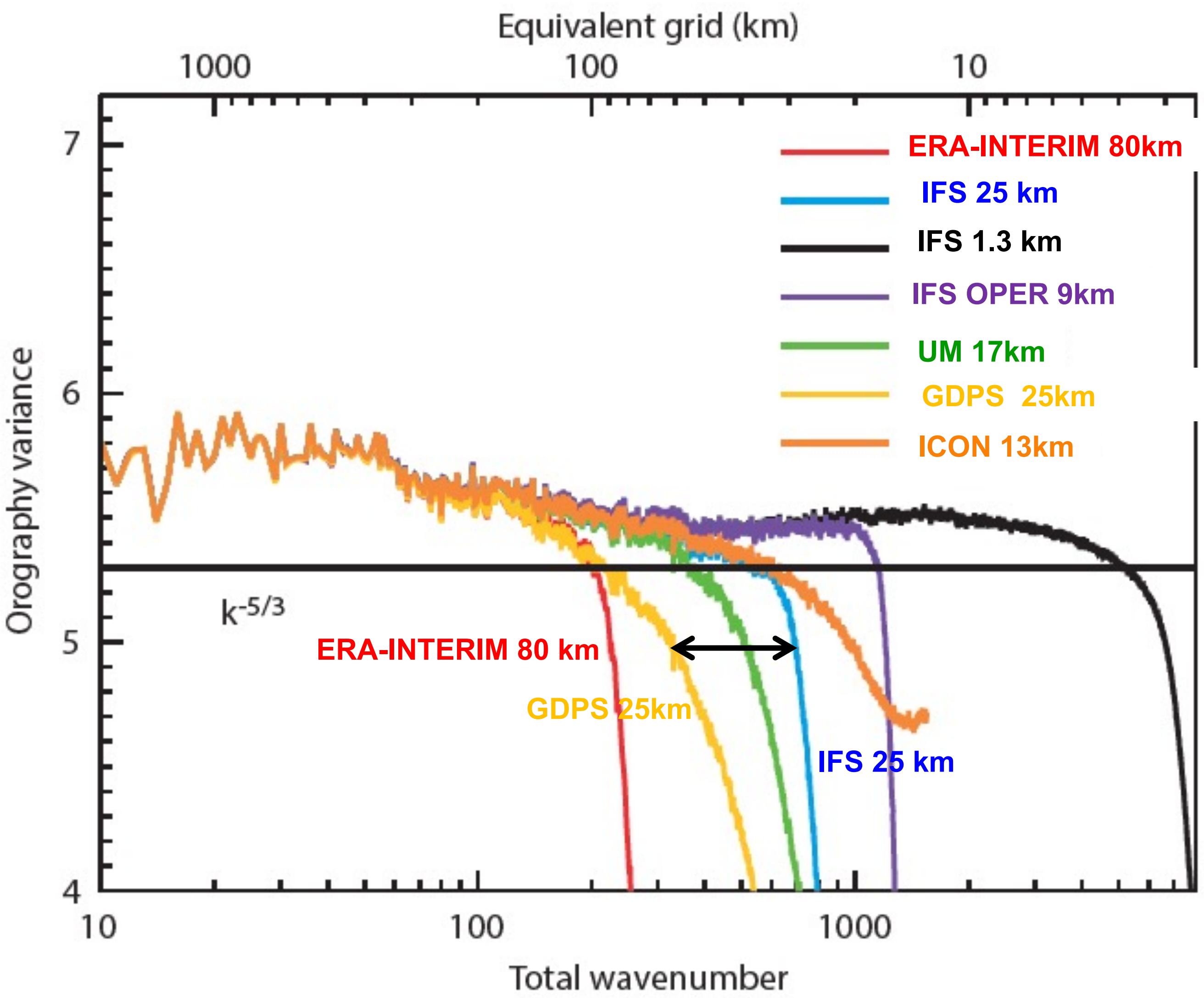
Massive impact from higher resolution orography and linear skill gains with the increase of orographic resolution

Increases in orographic resolution are responsible for almost all the increase in tropospheric skill

* With orographic drag parametrizations
The gap is reduced but does not disappear which means the parametrizations are not perfect

Kanehama et al, JAMES, 2019

Uncertainties in resolved orography



Differences in the filtering of resolved orography significantly impact NH winter forecast skill

Sandu et al, ECMWF Newsletter 150

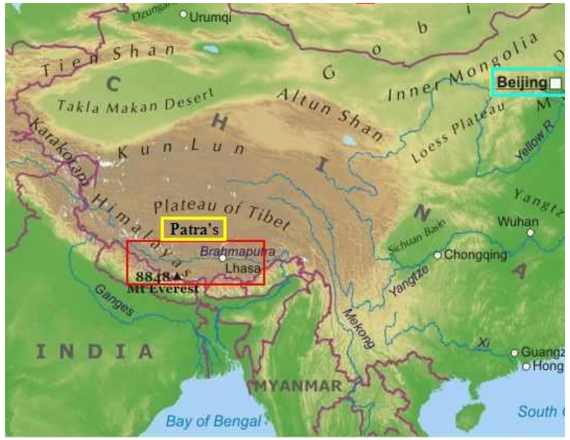
Elvidge et al.,JAMES, 2019

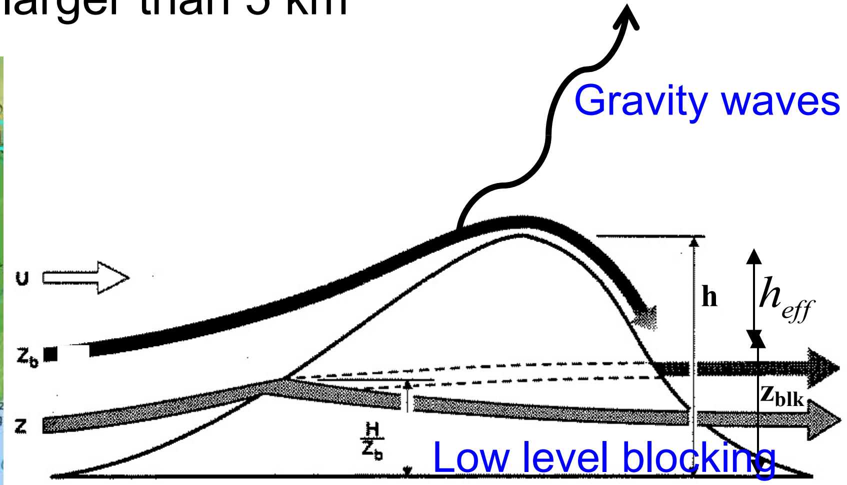
ECMWF

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

Scales smaller than 5 km

Scales larger 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.

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

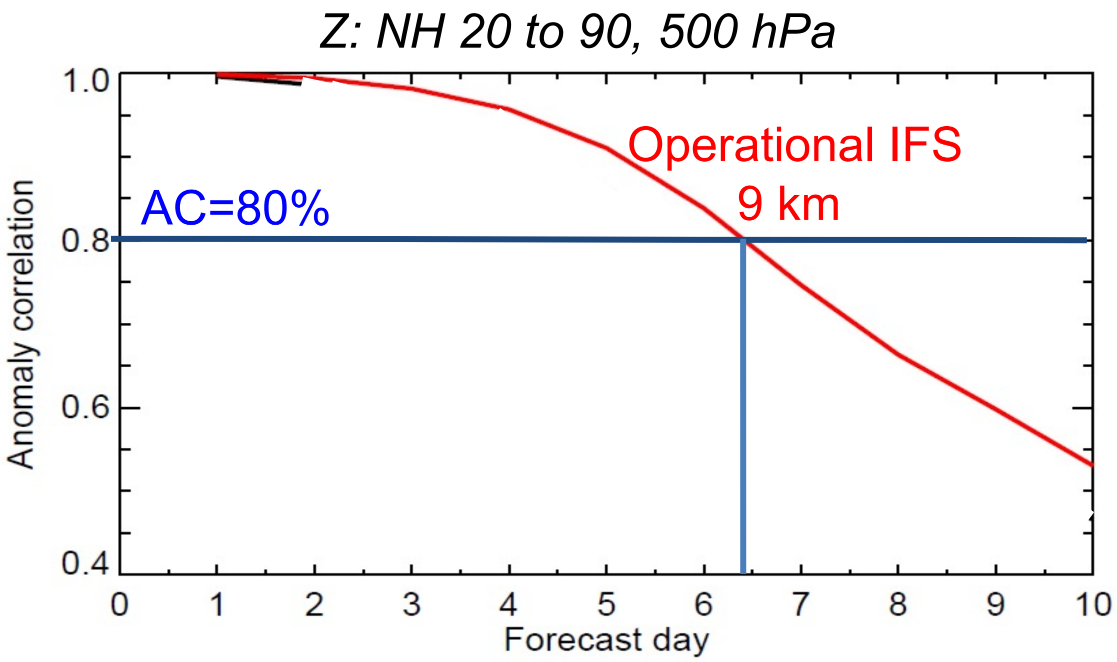
b) Orographic low level blocking - BLOCK : strong drag at lower levels where the flow is forced around the mountain

ECMWF

Orographic drag parametrizations → greater NWP skill

NWP skill increased at a rate of a day per decade

Bauer et al. "The quiet revolution of numerical weather prediction." Nature (2015)



ECMWF

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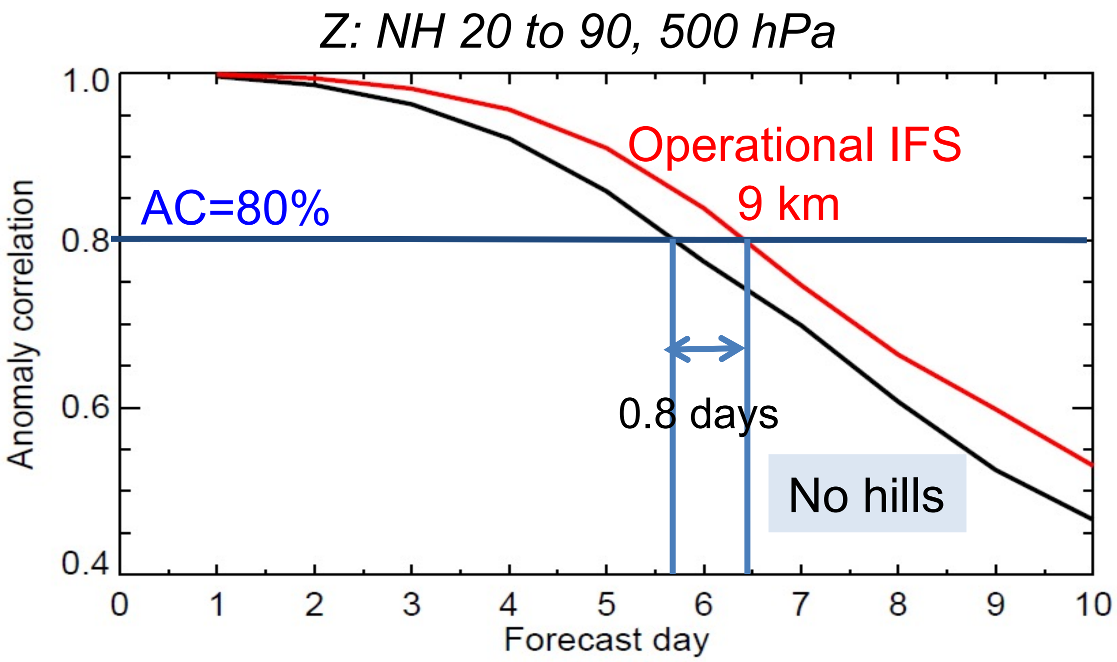
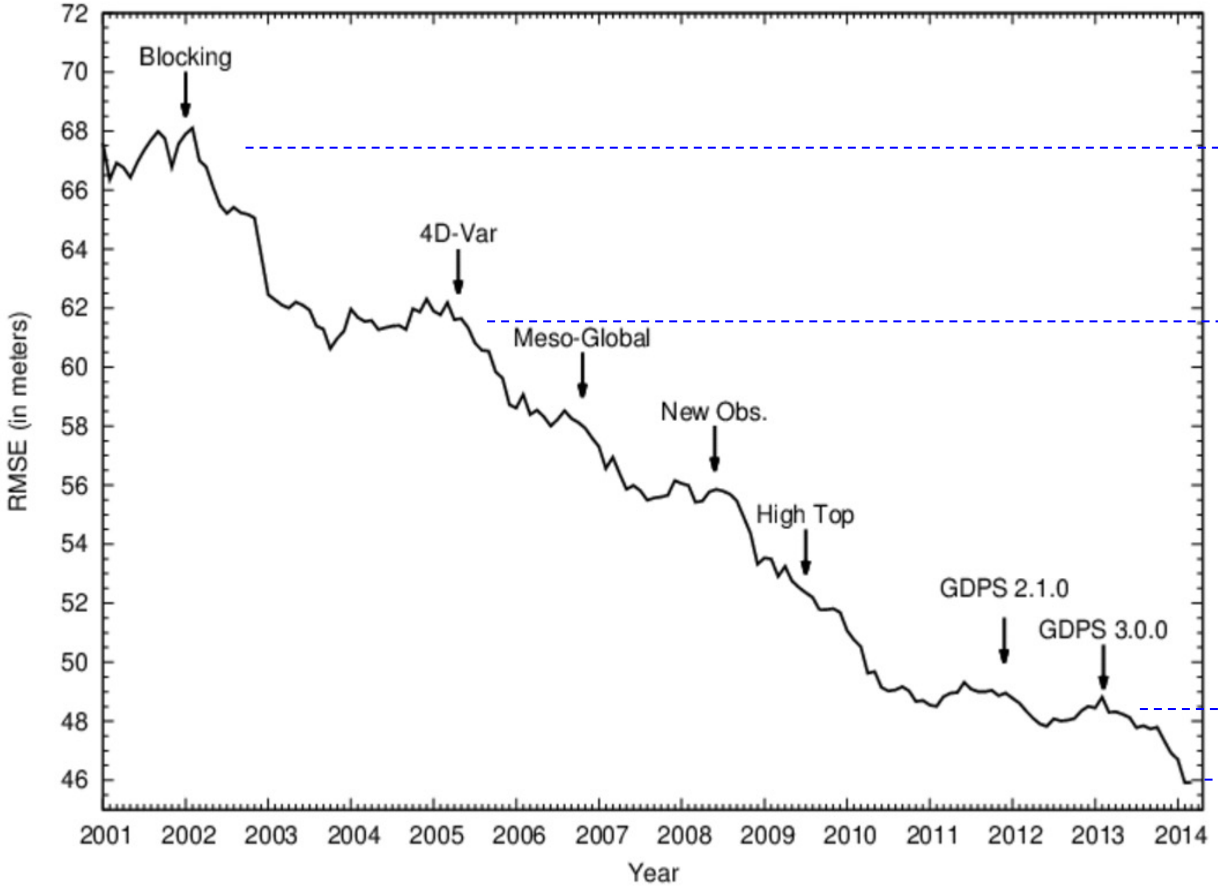


Almost one day in skill is lost by neglecting the impact of subgrid hills on the atmospheric flow

ECMWF

Orographic drag parametrizations → greater NWP skill



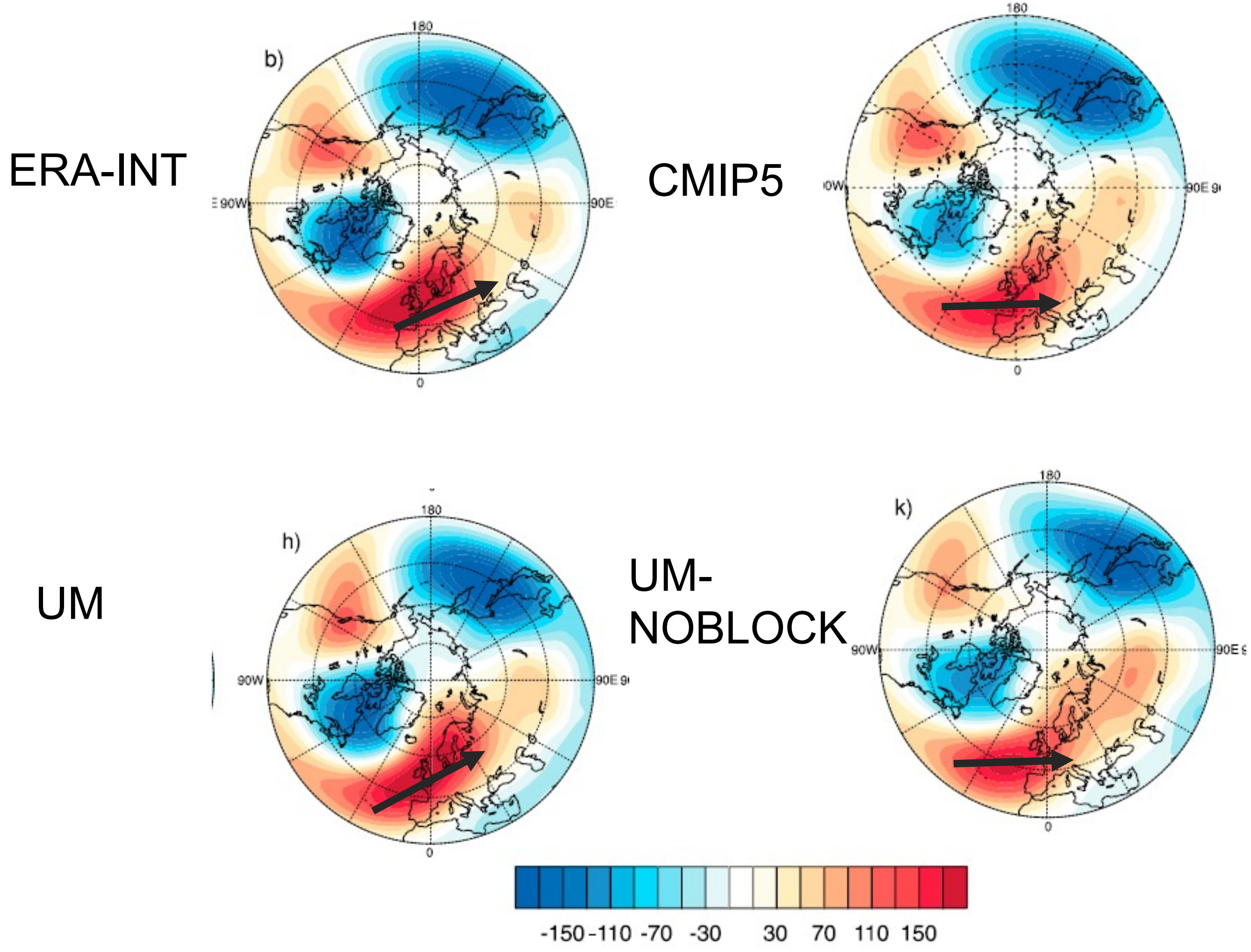
~ 7m
mostly due to introduction of orographic blocking scheme

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

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

Courtesy A. Zadra

Orographic drag parametrizations → more realistic model climate



Climate model biases in the jet stream regions during winter partly result from missing blocking effects of large-scale mountains

ECMWF

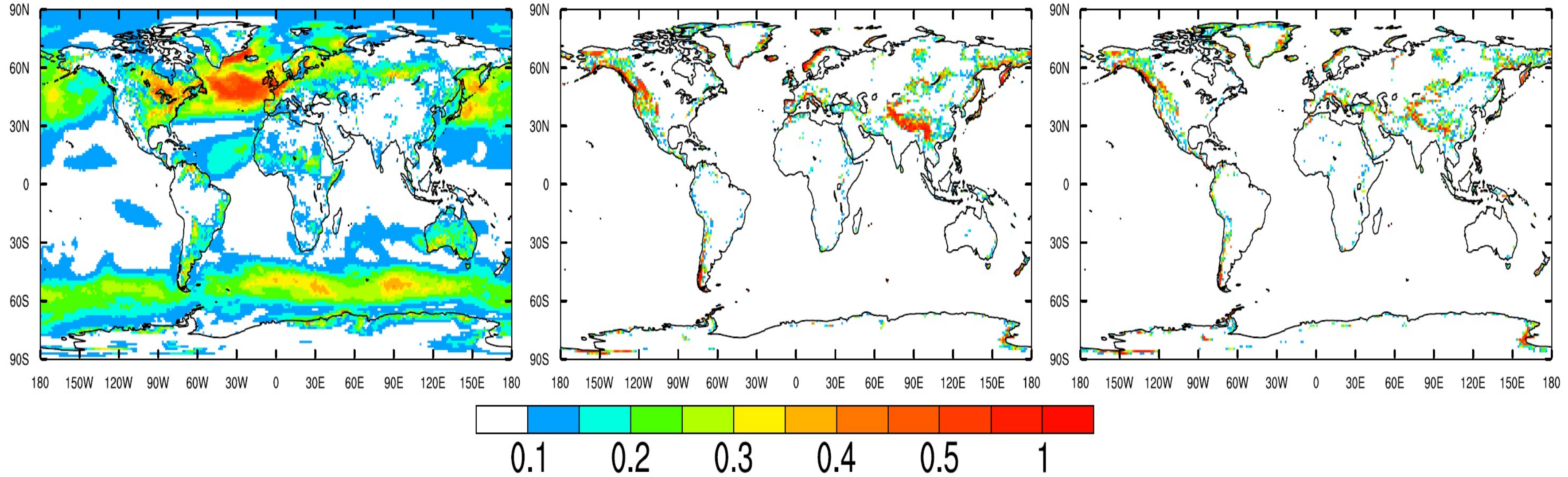
Pithan et al., GRL, 2016

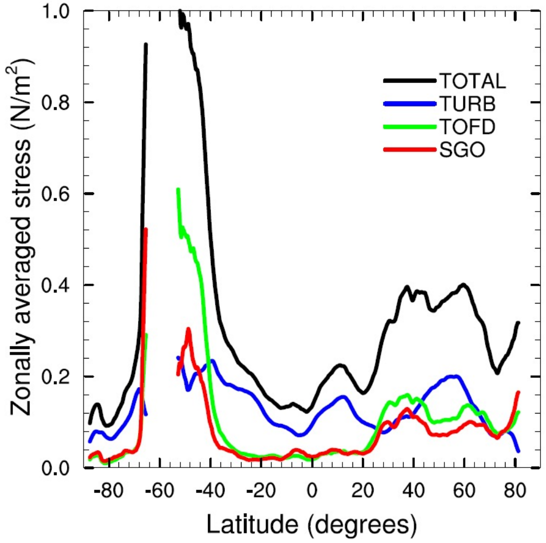
Surface stress components in the ECMWF Integrated Forecasting System

TURB Stress (N/m2)

TOFD Stress (N/m2)

SGO Stress (N/m2)

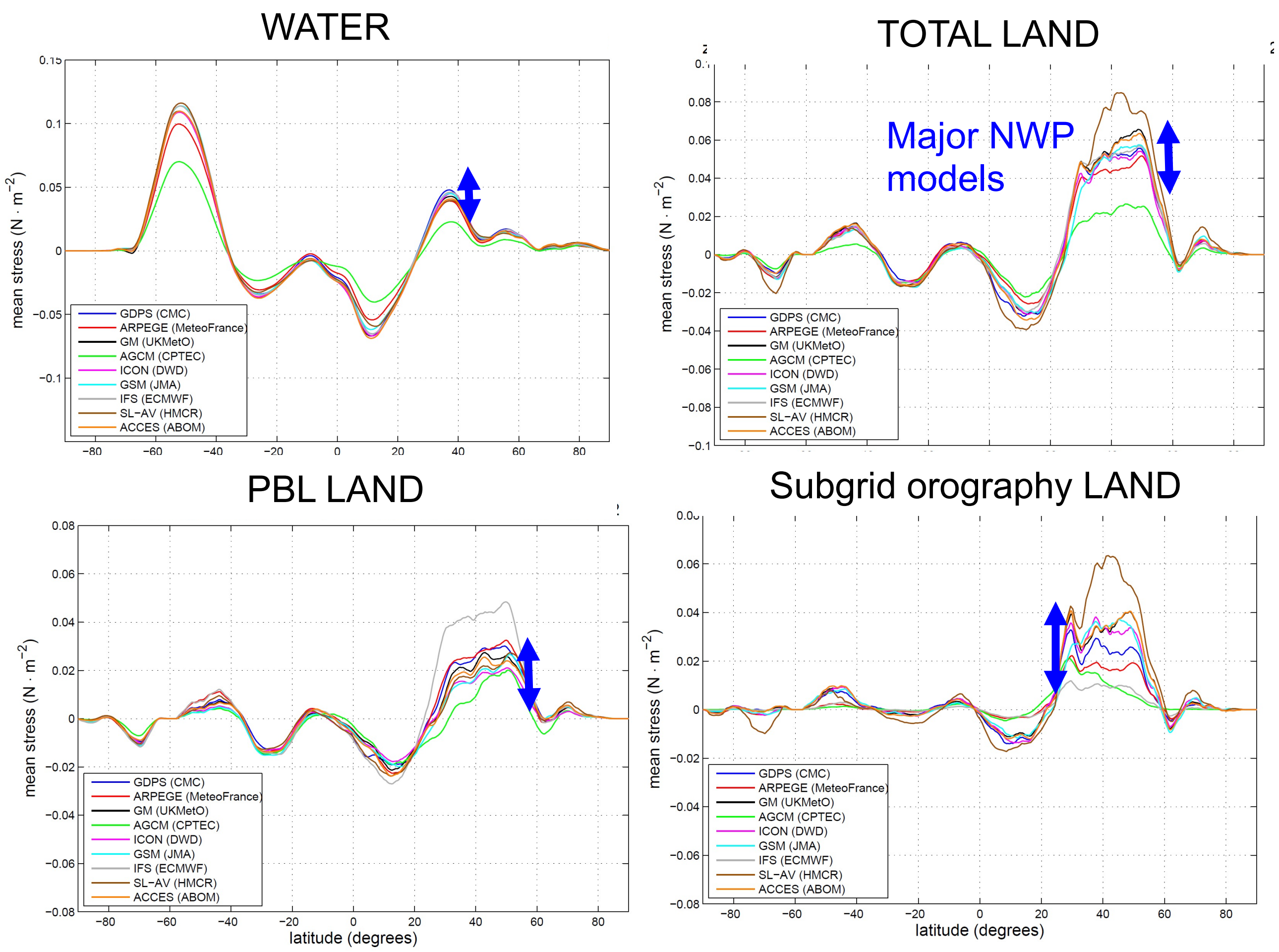




Similar zonal average
but different distribution

ECMWF

WGNE Drag project – comparison of subgrid surface stress



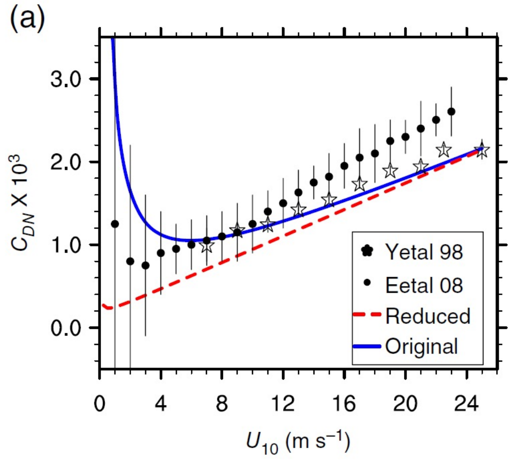
Much better agreement over water than over land !

Models differ widely in the representation of surface stress, especially over orography and in the partition between the different processes

UKMO BL term < EC PBL term, but SSO term >> EC SSO term, and relative difference in total stress is 10-20% in NH midlatitudes

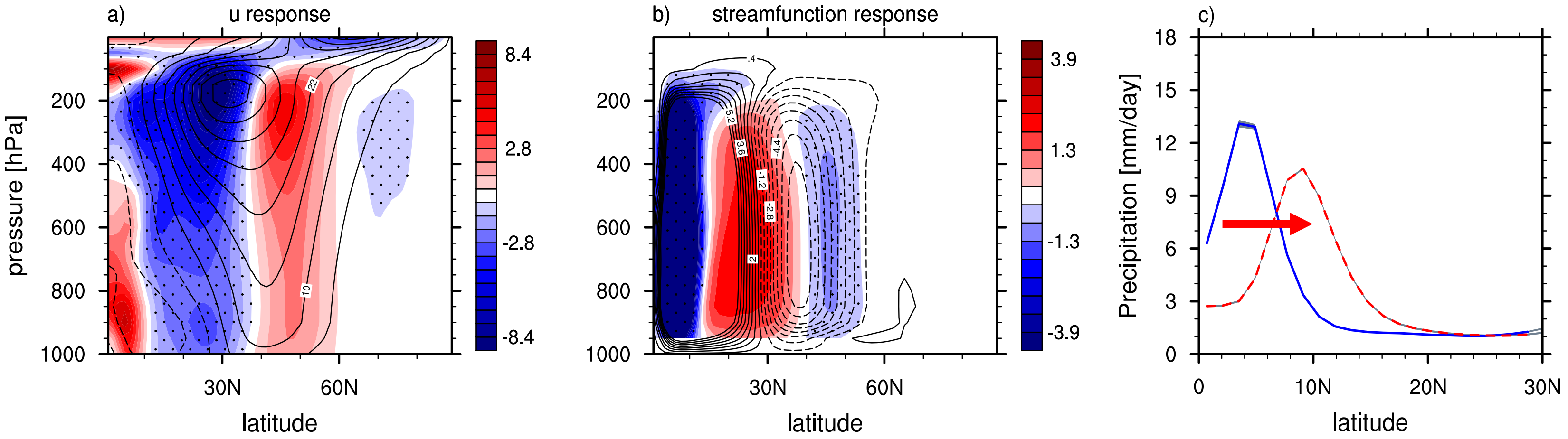
Drag Project website (A. Zadra and J. Bacmeister):
http://collaboration.cmc.ec.gc.ca/science/rpn/drag_project/index.html

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

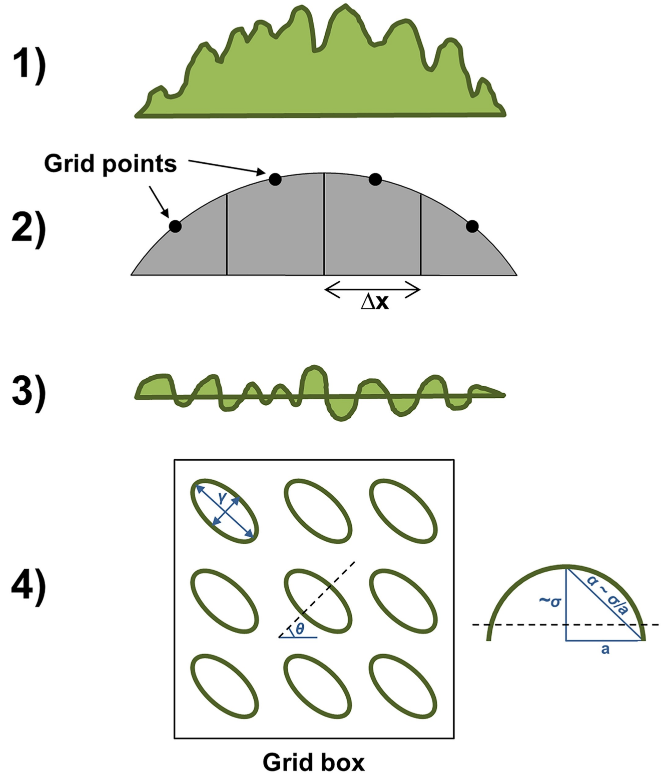
A weakening of the HC and a poleward shift of the ITCZ.



ECMWF

Polichtchouk & Shepherd (2016,QJRMS)
Also see Simpson et al. (2018, J. Clim)

WGNE comparison of subgrid orography fields

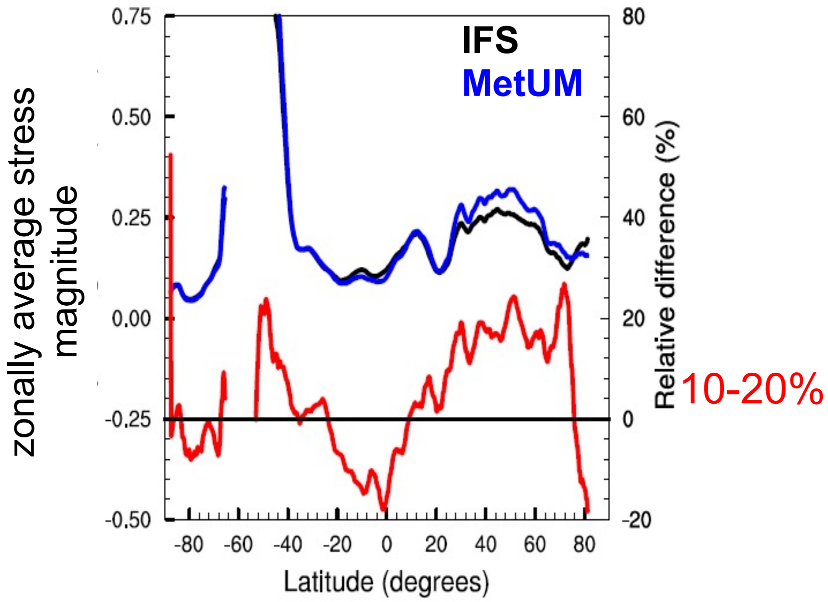


Elvidge et al, JAMES, 2019

WGNE comparison of subgrid orography fields

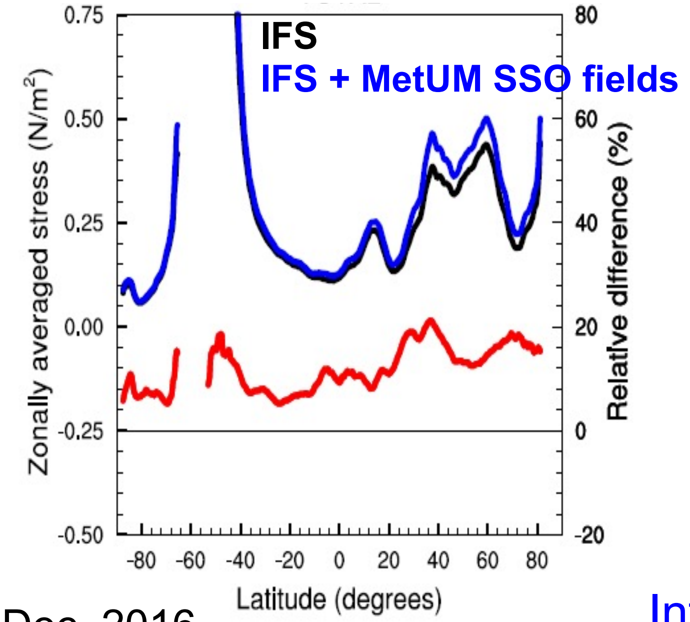
WGNE Drag project

TOTAL stress land

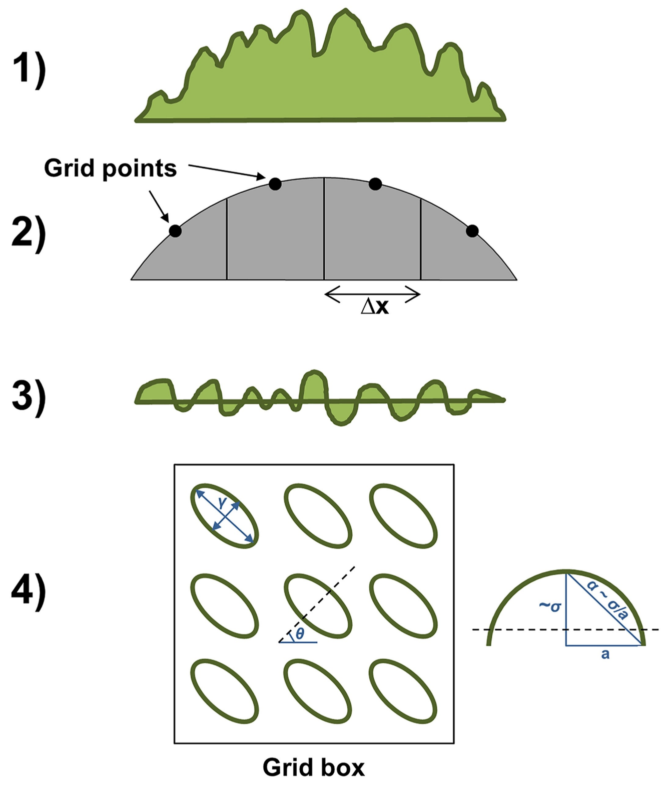


Jan, 2012

TOTAL stress land



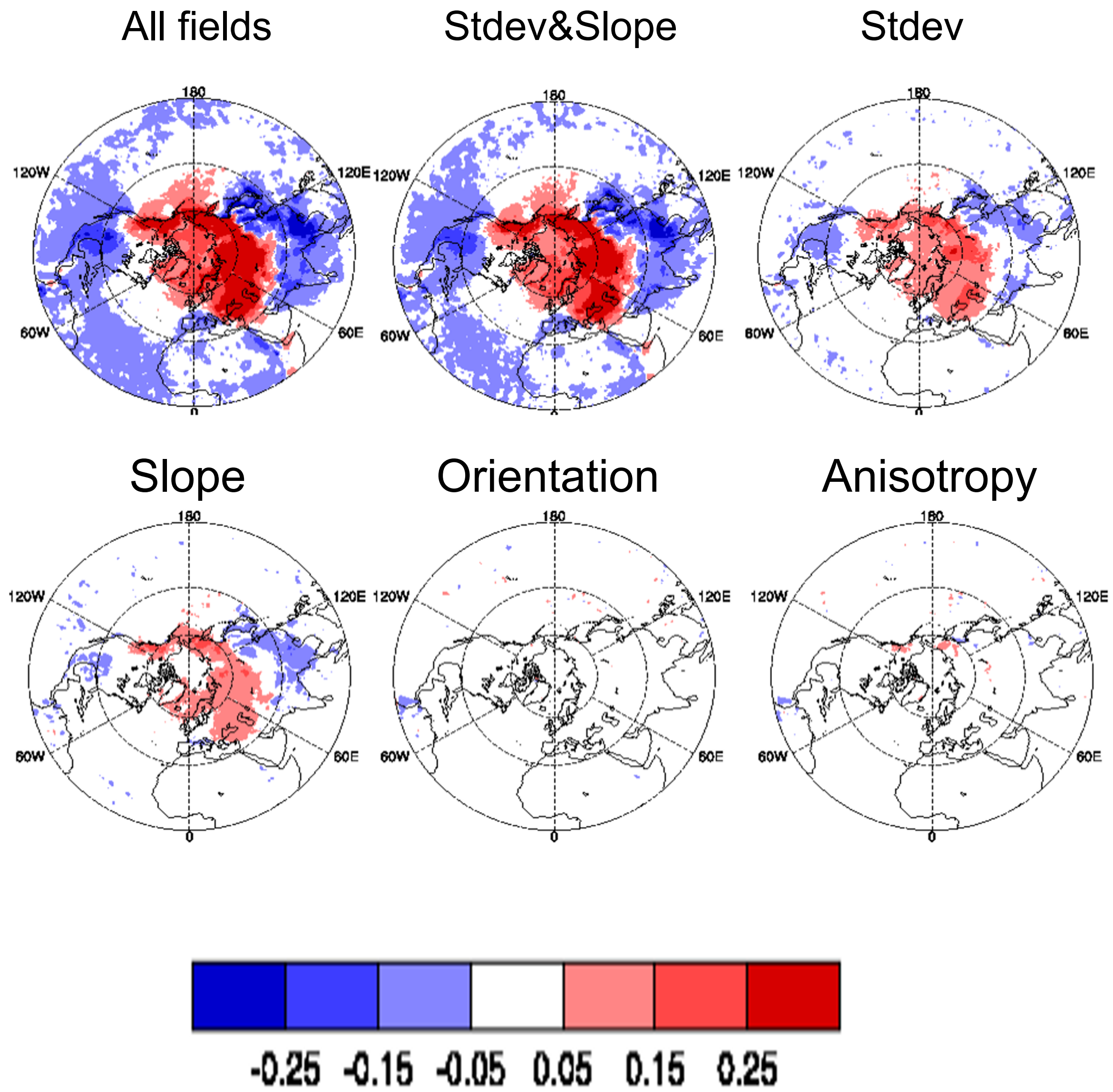
Dec, 2016

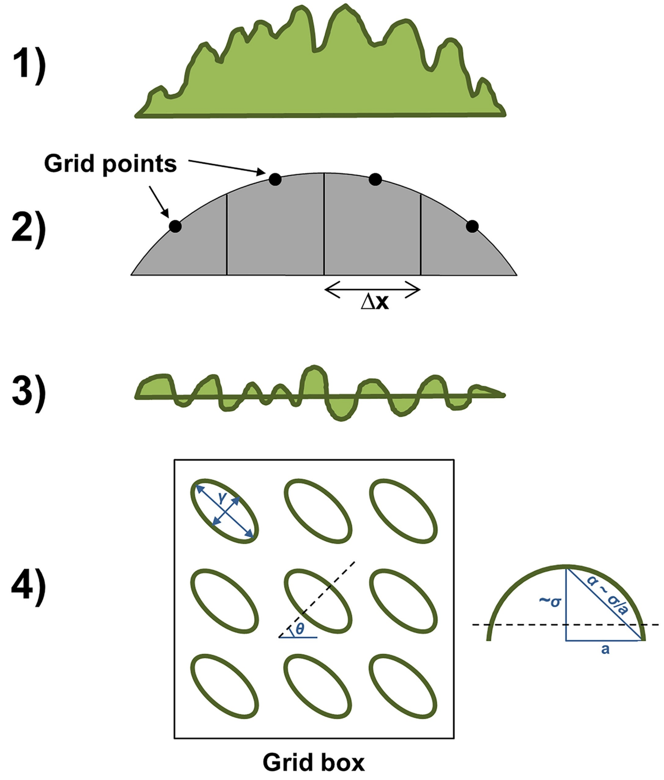


Inter-model variability in SSO fields can be of first-order importance to the variability in surface stress seen across models

Elvidge et al, JAMES, 2019

WGNE comparison of subgrid orography fields



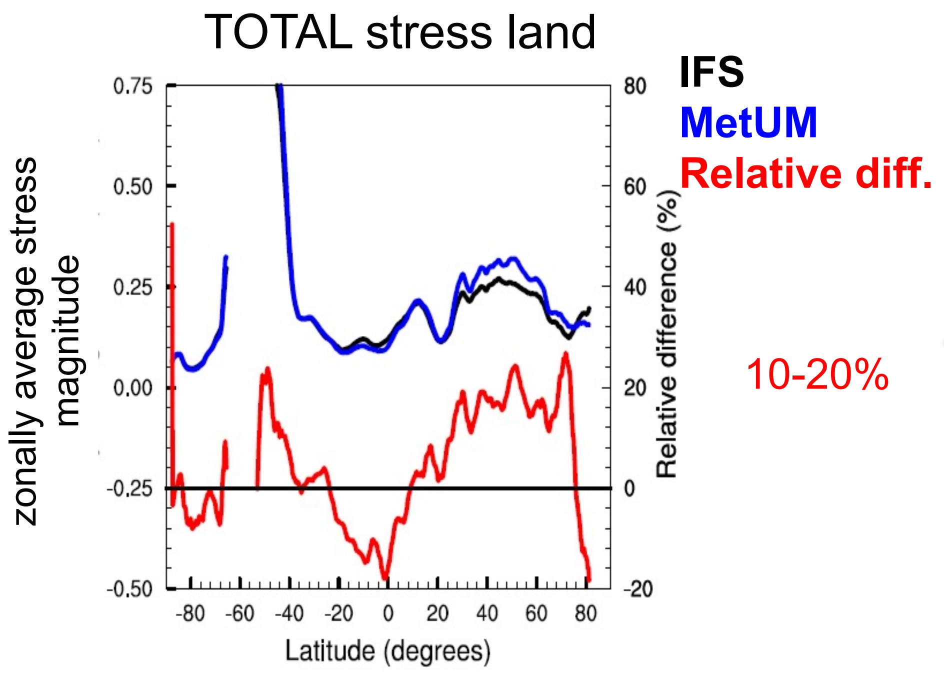


Combined effect of stdev & *slope* required to explain response in surface pressure when running IFS with the MetUM SSO fields (t+24h)

Elvidge et al, JAMES, 2019

Inter-model differences in orographic drag (and its partition) impact circulation

Changing the magnitude of the stress in IFS by an amount comparable to inter-model differences

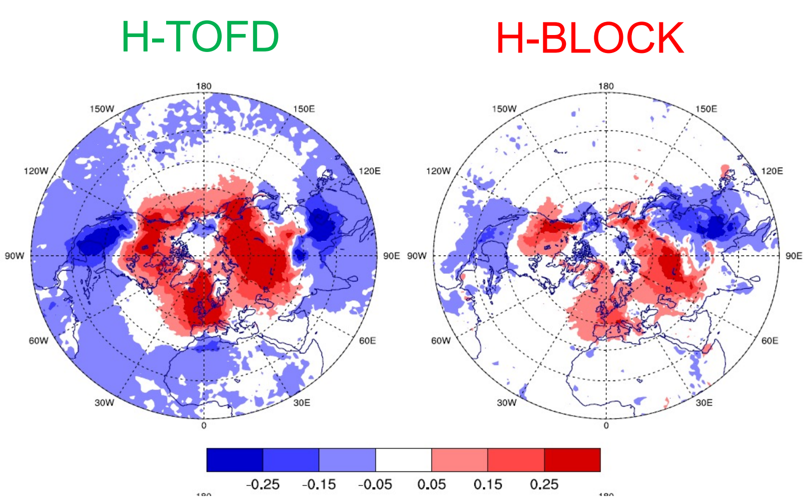


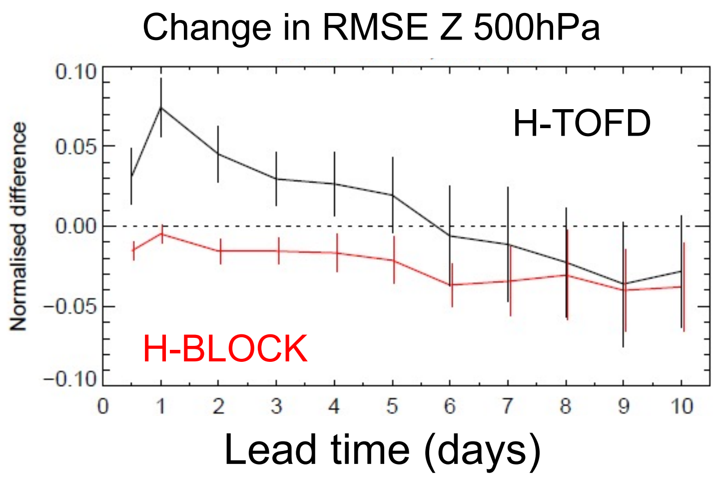
10-20%

More TOFD

More BLOCK

Mean change in surface pressure +24h





Partition of orographic drag matters from daily to seasonal timescales

Sandu et al, JAMES,2016

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

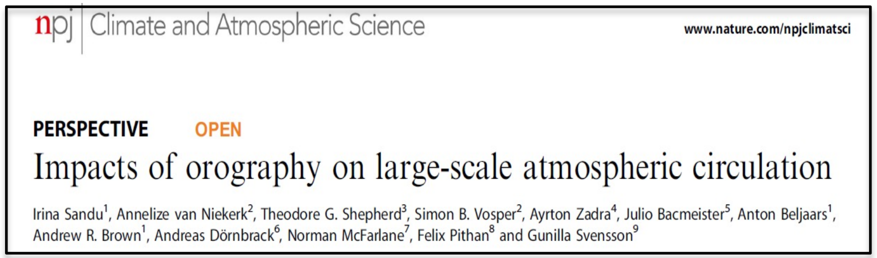
Models don’t agree:

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

Community efforts to constrain drag processes – based on high resolution modelling, theory and observational constrains *(see Sandu et al, 2019, NPJ Climate and Atmospheric Sciences for a perspective, and the GASS white paper on 'Constraining surface drag and momentum processes')*

Long list of open questions, some of which we start answering…:

- What causes inter-model differences? parameterizations, underlying subgrid orography ? filtering of resolved orography? *(Elvidge et al., 2019)*
- Is the transition between resolved and parametrized handled well? *(Van Niekerk et al. 2016, Vosper 2016, Kanehama et al., 2019)*
- Can we learn from high resolution simulations whether the schemes well suited for complex mountain ranges? (*Vosper et al., 2015, 2016*, *Van Niekerk et al, 2018, 2020 Vosper et al, 2019*)
- How should the partition between different schemes done?
- How does small scale orography affects the large (planetary scales)?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PERSPECTIVE OPEN

Impacts of orography on large-scale atmospheric circulation

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COnstraining Orographic DRag Effects (COORDE) – a GASS/WGNE intercomparison

Aims:

- Use high resolution simulations to quantify drag from low-level blocking and gravity wave effects, typically unresolved in models used for climate/seasonal projections
- Explore differences in resolved and parametrized orographic drag effects across models
- Understand implications of differences in orographic drag parametrizations for modelled circulation
- Explore differences in orographic drag parametrization formulation between models

ECMWF

Protocol following Van Niekerk et al. 2018
https://osf.io/37bsy/?view_only=ce80990f1a0745d294938e548203156f

COnstraining Orographic DRag Effects (COORDE) – a GASS/WGNE intercomparison

Method: building on *Van Niekerk, Sandu and Vosper, JAMES, 2018*

1) High resolution experiments (1.8km to 10km) with high resolution and low resolution orography are used to determine impact of resolved orography on circulation (zonal winds)

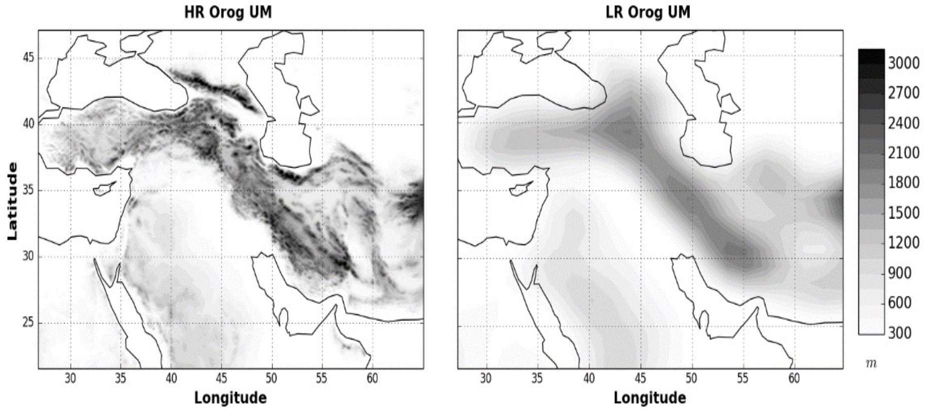
2) Low resolution experiments (80km to 150km) with and without parametrized orographic drag used to determines impact of parametrized orographic drag on circulation

Simulations are run for 24 hours over 1-14th Jan 2015 and analysed at the end of 24 hours

Region of interest for current validation:
the Middle Eastern mountain range

High resolution orography

Low resolution orography

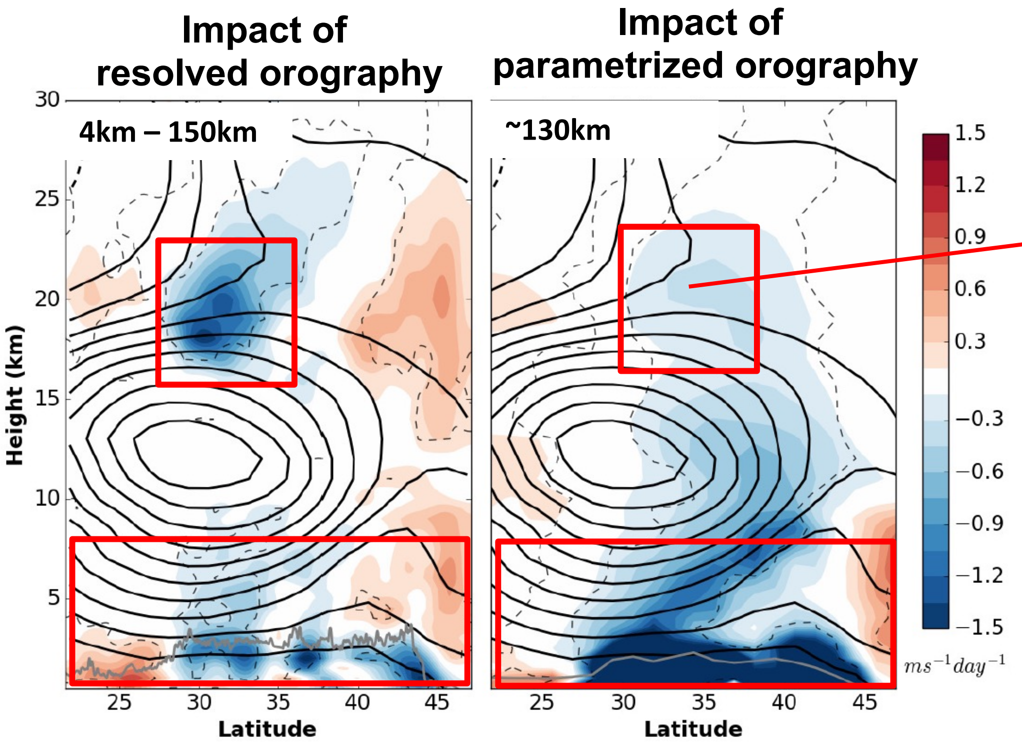


ECMWF

Protocol following Van Niekerk et al. 2018
https://osf.io/37bsy/?view_only=ce80990f1a0745d294938e548203156f

Middle East

MetUM



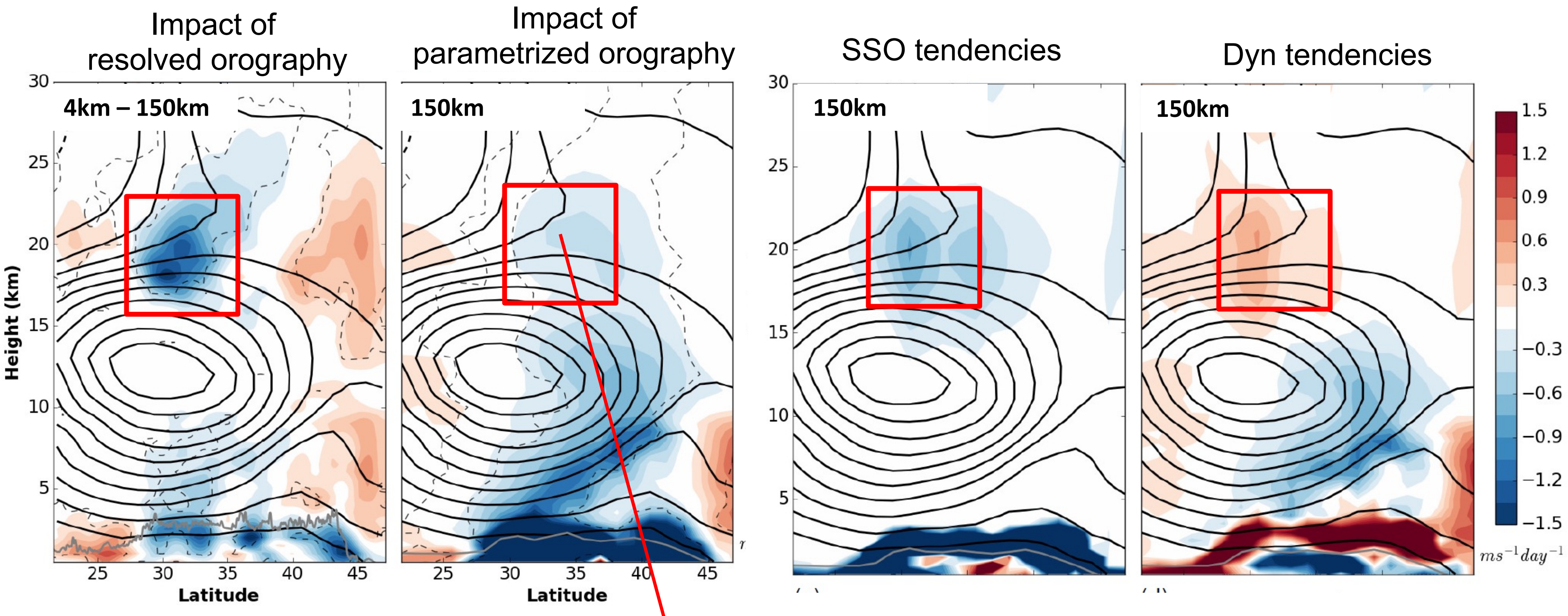
Not enough GWD in both models

Low-level parametrized drag much larger in MetUM

Van Niekerk et al, JAMES,2018

Middle East

MetUM



Not enough GWD in both models: in part due to the manner in which the resolved dynamics interacts with parametrized orographic gravity wave drag

Van Niekerk et al, JAMES,2018

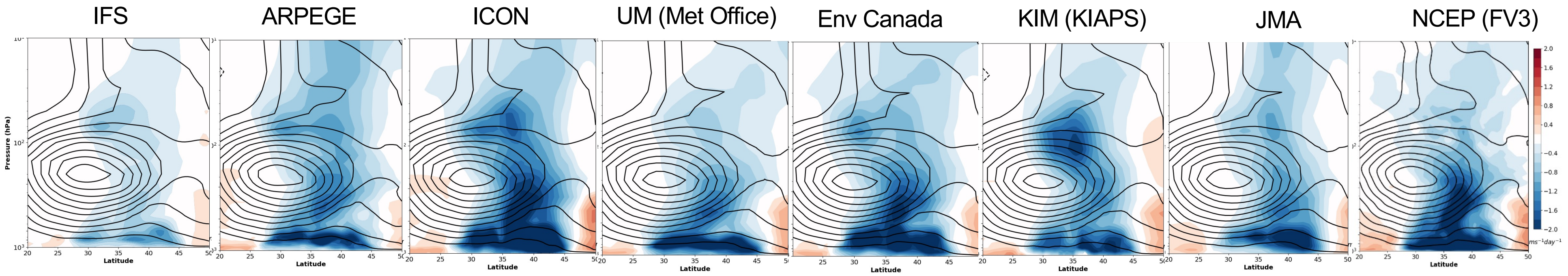
COORDE: Participating models

Centre	Model	Low resolution simulation	High resolution simulation
ECMWF	IFS	125km	9km
Met Office	UM	130km	1.8km
KIAPS	KIM	100km	6km
JMA	GSM1705 GSM19XX	120km 120km	-------- 10km
DWD	ICON	80km	2.5km
Meteo-France	ARPEGE AROME	80km --------	-------- 2.5km
NOAA/NCEP	FV3GFS WRF	100km --------	-------- 3km
Environment-Canada	GDPS RDPS	100km --------	-------- 3km

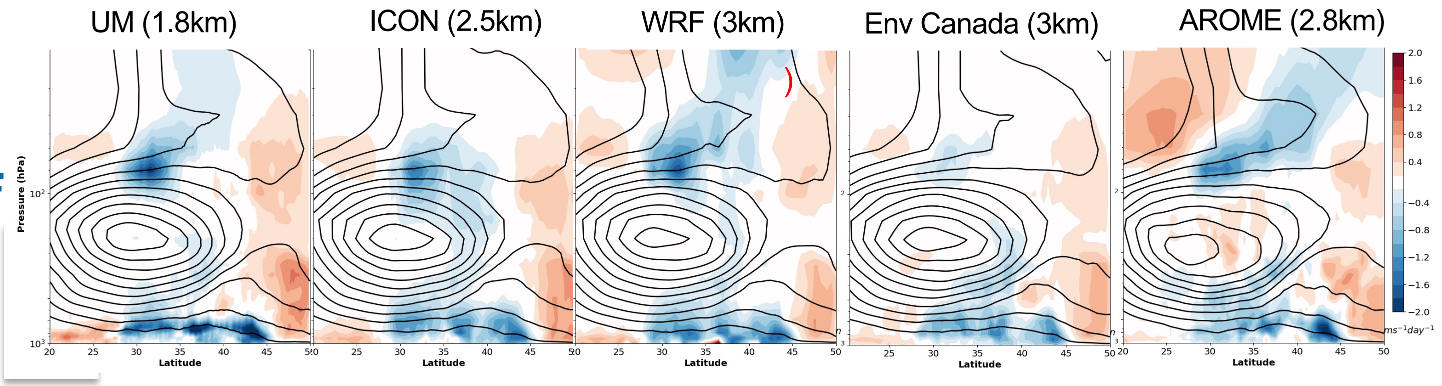
COORDE contributors: Hyun-Joo Choi (KIAPS), Eric Bazile (METEOFRANCE), Martin Kohler (DWD), Michael Toy (NOAA), Valery Yudin (NOAA), Yukihiro Kuroki (JMA), Ayrton Zadra (ENV CAN)

COORDE results

Change in winds after 24 hours due to parametrized drag (from 80-100km scale simulations)



Change in winds after 24 hours due to resolved drag (from km-scale simulations)



- Km-scale models agree quite well in terms of the impact of resolved orography, which suggest they can be used to constrain parametrisations
- The low and intermediate resolution models differ widely in the impact of parametrized orographic drag from low-level blocking and gravity wave

van Niekerk et al., 2020

COORDE – lessons learned

- High resolution simulations are more similar in their response to resolved orography – reinforces that they can be used to constrain parametrizations
- Models have diverse range of responses to parametrized orographic drag – reflected in differences in partitioning and magnitude of drag
- Model drag partitioning may matter for the forecast accuracy since the diurnal cycle and spatial distribution is very different between orographic and boundary layer drag – need a better understanding of the regime dependence and its importance of for forecast accuracy
- Model errors can be directly related to drag parametrizations (either excessive or insufficient/misplaced) – e.g. stratospheric gravity wave drag

Rapid progress for orographic drag processes is within reach by making combined use of theoretical approaches, emerging observational constraints and inverse modelling and high-resolution simulations