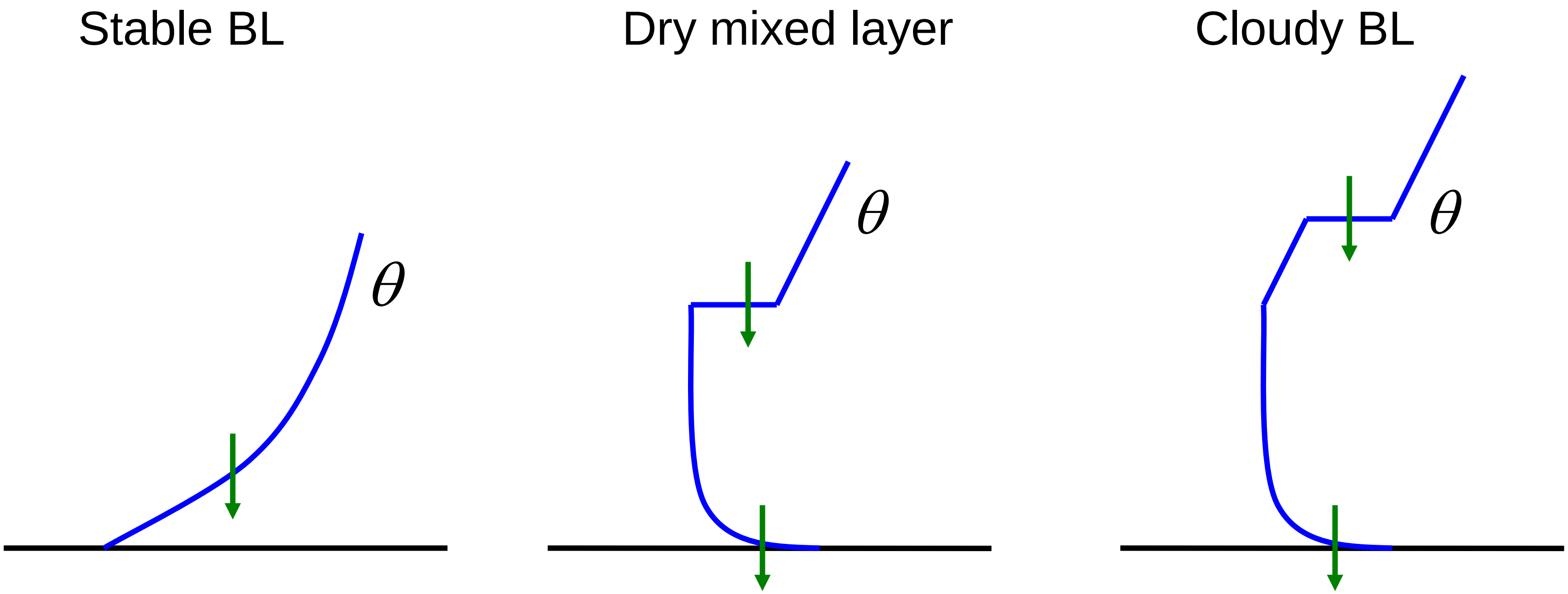
Parameterization of surface fluxes: Outline

- Surface layer formulation according to Monin Obukhov (MO) similarity
- Roughness lengths
- Representation of the different sources of surface stress and impacts of the surface stress on the large-scale circulation

Mixing across steep gradients



Stable BL

Dry mixed layer

Cloudy BL

Surface flux parametrization is sensitive because of large gradients near the surface.

Why is the finite difference formulation in the surface layer different from the other layers?

$$\boxed{F=\rho K(z)\frac{d\varphi}{dz} \qquad (F=\overline{w'\varphi'})}$$

Finite difference formulation:

$$F_{1.5}=\rho K(z_{1.5})\,\frac{\varphi_2-\varphi_1}{z_2-z_1}$$

In surface layer integrate:

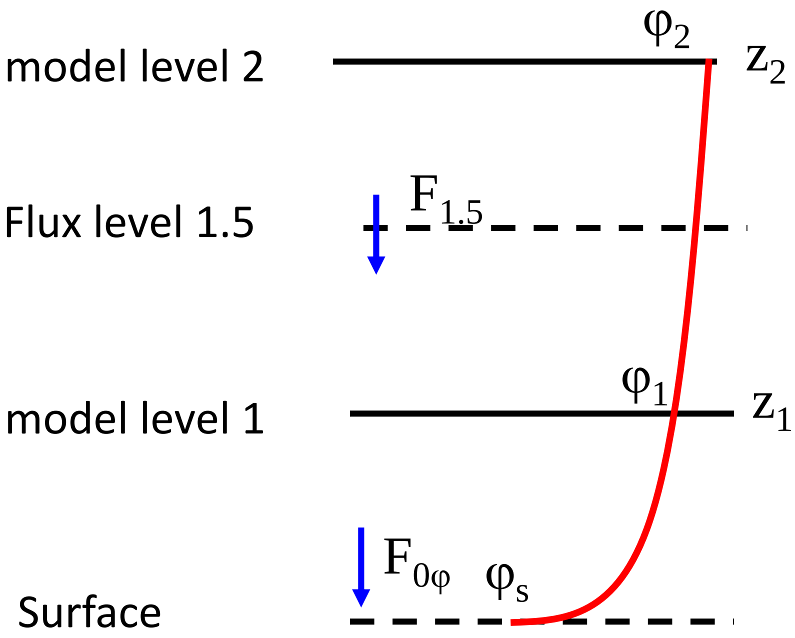
$$\varphi_1-\varphi_s=\int_{z_{o\varphi}}^{z_1}\frac{F_{0\varphi}}{\rho K(z)}\,dz$$

Constant flux layer:

$$\varphi_1-\varphi_s\approx\frac{F_0}{\rho}\int_{z_{0\varphi}}^{z_1}\frac{1}{K(z)}\,dz$$

In neutral flow:

$$K(z)=\kappa z u_*$$



$$\varphi_1-\varphi_s\approx\frac{F_{0\varphi}}{\rho\kappa u_*}\int_{z_{0\varphi}}^{z_1}\frac{dz}{z} \quad\Rightarrow\quad \underset{\underset{u,v,T,q}{\uparrow}}{\varphi_1}-\varphi_s=\frac{F_{0\varphi}}{\rho\kappa u_*}\ln\left(\frac{z_1}{z_{o\varphi}}\right)$$

κ : Von Karman constant (0.4)
u* : Friction velocity
ρ : Density

Log-profiles are directly related to neutral transfer laws

The log-profile for φ

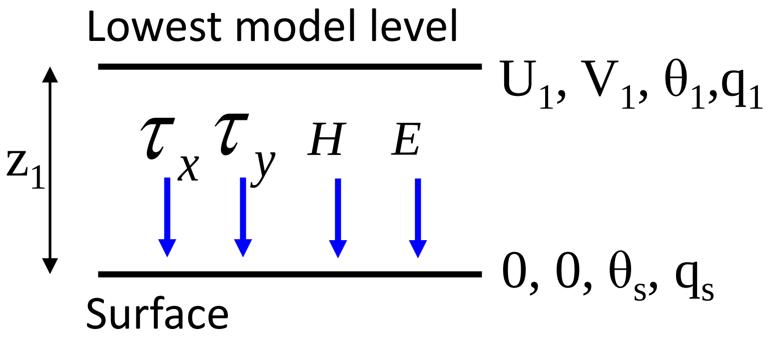
$$F_{0\varphi} = \frac{\rho \kappa u_*}{\ln(z_1 / z_{0\varphi})} (\varphi_1 - \varphi_s)$$

The log-profile for wind relates $|U|$ to u_*

$$u_* = \frac{\kappa |U|}{\ln\,(z_1 / z_{0m})}$$

$$where \quad u_*^2 = \tfrac{1}{\rho} (\tau_x^2 + \tau_y^2)^{1/2}$$

$$and \qquad |U_1| = (U_1^2 + V_1^2)^{1/2}$$



$\tau_{x,y}$: Surface stress components $\overline{u'w'}$ $\overline{v'w'}$

H : Sensible heat flux $\overline{w'\theta'}$

E : Water vapour flux $\overline{w'q'}$

Neutral transfer law for φ :

$$F_{0\varphi} = \rho C_{\varphi n} |U_1| (\varphi_1 - \varphi_s) \quad where \quad C_{\varphi n} = \frac{\kappa^2}{\ln(z_1 / z_{0\varphi}) \ln(z_1 / z_{0m})}$$

$C_{\varphi n}$ is called the neutral transfer coefficient for φ

MO similarity profiles are not limited to neutral transfer laws

neutral conditions: log-profile

$$\varphi_1-\varphi_s=\frac{F_{0\varphi}}{\rho\kappa u_*}\ln(\frac{z_1}{z_{0\varphi}})$$

non-neutral: log-profile + MO stability function

$$\varphi_1-\varphi_s=\frac{F_{0\varphi}}{\rho\kappa u_*}\left[\ln(\frac{z_1}{z_{0\varphi}})-\Psi_\varphi(\frac{z}{L})\right]$$

Obukhov length:

$$L=\frac{u_*^3\;\rho c_p}{\kappa(g/T_v)H}$$

$$F_{0\varphi}=\rho C_\varphi\,|U|\,(\varphi_1-\varphi_s)$$

$$C_\varphi=\frac{\kappa^2}{\ln(\frac{z_1}{z_{0\varphi}})\ln(\frac{z_1}{z_{0m}})}$$

$$C_\varphi=\frac{\kappa^2}{\left[\ln(\frac{z_1}{z_{0\varphi}})-\Psi_\varphi(\frac{z_1}{L})\right]\left[\ln(\frac{z_1}{z_{0m}})-\Psi_m(\frac{z_1}{L})\right]}$$

The non-neutral transfer laws are simply obtained by replacing the log-term by the log+ψ term. The ψ(z/L) functions are observationally based.

Transfer coefficients

$$\boxed{F_{0\varphi} = \rho C_{\varphi} \, |U| \, (\varphi_1 - \varphi_s)}$$

Surface fluxes can be written explicitly as:

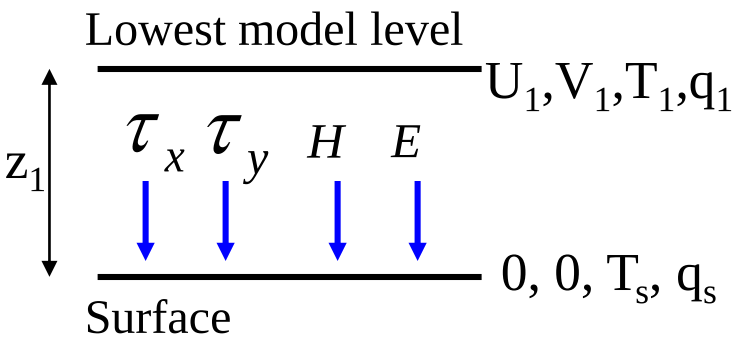
$$\overline{u'w'} \qquad \tau_x = \rho \, C_M \, |U_1| \, U_1$$

$$\overline{v'w'} \qquad \tau_y = \rho \, C_M \, |U_1| \, V_1$$

$$\overline{w'\theta'} \qquad H = \rho c_p C_H \, |U_1| \, (\theta_1 - \theta_s)$$

$$\overline{w'q'} \qquad E = \rho C_E \, |U_1| \, (q_1 - q_s)$$

$$\textit{where} \quad |U_1| = \left(U_1^2 + V_1^2 + \beta w_*^2\right)^{1/2}$$



$$C_{\varphi} = \frac{\kappa^2}{\left[\ln\left(\frac{z_1}{z_{0\varphi}}\right) - \Psi_{\varphi}\left(\frac{z_1}{L}\right)\right]\left[\ln\left(\frac{z_1}{z_{0m}}\right) - \Psi_{m}\left(\frac{z_1}{L}\right)\right]}$$

$$\varphi = \begin{cases} M \\ H \\ E \end{cases}$$

$$\varphi = \begin{cases} m \\ h \\ q \end{cases}$$

Numerical procedure: The Richardson number

The expressions for surface fluxes are implicit i.e they contain the Obukhov length which depends on fluxes. The stability parameter z/L can be computed from the bulk Richardson number by solving the following relation:

$$Ri_b = \frac{gz_1}{\theta}\frac{\theta_1 - \theta_s}{|U_1|^2} = \frac{z_1}{L}\frac{\{\ln(z_1/z_{oh}) - \psi_h(z_1/L)\}}{\{\ln(z_1/z_{om}) - \psi_m(z_1/L)\}^2}$$

This relation can be solved:

- Iteratively;
- Approximated with empirical functions;
- Tabulated.

Surface fluxes: Summary

- MO-similarity provides solid basis for parametrization of surface fluxes
- Numerical procedure:

1. Compute bulk Richardson number: $$Ri_b = \frac{g z_1}{\theta} \frac{\theta_1 - \theta_s}{|U_1|^2}$$
2. Solve iteratively for z/L: $$\frac{z_1}{L} = f\,(Ri_b, z_1 / z_{0m}, z_1 / z_{0\varphi})$$
3. Compute transfer coefficients: $$C_\varphi = \frac{\kappa^2}{\left[\ln(\frac{z_1}{z_{0\varphi}}) - \Psi_\varphi(\frac{z_1}{L})\right]\left[\ln(\frac{z_1}{z_{0m}}) - \Psi_m(\frac{z_1}{L})\right]}$$
4. Use expression for fluxes in solver: $$F_{0\varphi} = \rho C_\varphi \,|U|\,(\varphi_1 - \varphi_s)$$

- Surface roughness lengths are crucial aspect of formulation.
- Transfer coefficients are typically 0.001 over sea and 0.01 over land, mainly due to surface roughness.

Parameterization of surface fluxes: Outline

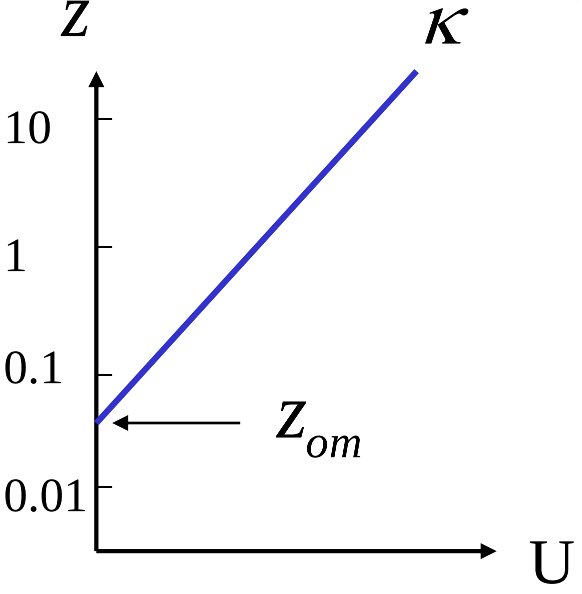
- Surface layer formulation according to Monin Obukhov (MO) similarity
- Roughness lengths
- Representation of the different sources of surface stress and impacts of the surface stress on the large-scale circulation

Surface roughness length (definition)

Example for wind:

$$U = \frac{u_*}{\kappa} \ln(\frac{z}{z_{om}})$$

- Surface roughness length is defined on the basis of logarithmic profile.
- For z/L small, profiles are logarithmic.
- Roughness length is defined by intersection with ordinate.



Often displacement height is used to obtain U=0 for z=0:

$$U = \frac{u_*}{\kappa} \ln(\frac{z + z_{om}}{z_{om}})$$

- Roughness lengths for momentum, heat and moisture are not the same.
- Roughness lengths are surface properties.

Roughness lengths over the ocean

Roughness lengths are determined by molecular diffusion and ocean wave interaction e.g.

$$z_{om} = C_{ch} \frac{u_*^2}{g} + 0.11 \frac{\nu}{u_*}, \; C_{ch} \;\; is \;\; Charnock \;\; parameter$$

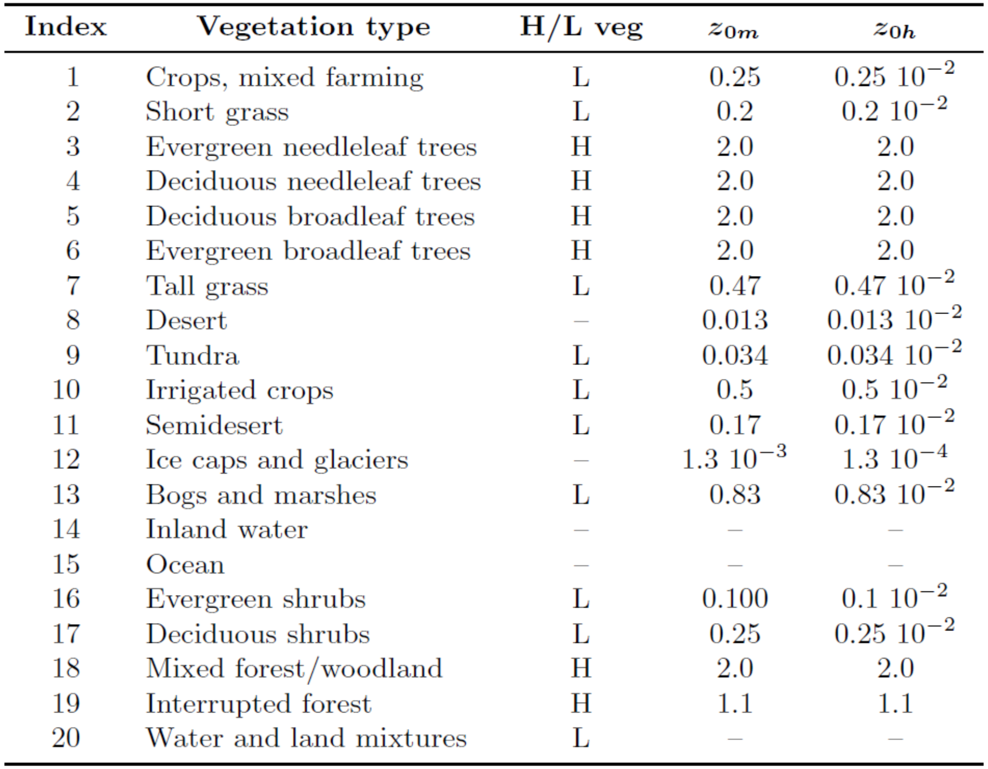
$$z_{oh} = 0.40 \frac{\nu}{u_*}$$

$$z_{oq} = 0.62 \frac{\nu}{u_*}$$

Current version of ECMWF model uses an ocean wave model to provide sea-state dependent Charnock parameter.

Roughness length over land

Geographical fields based on land use tables:



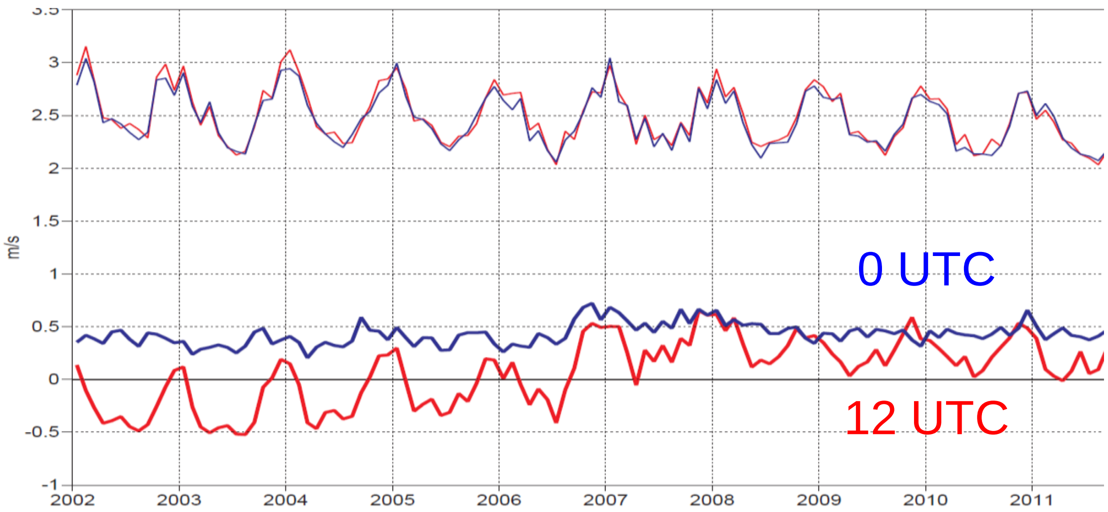
Index	Vegetation type	H/L veg	z_{0m}	z_{0h}
1	Crops, mixed farming	L	0.25	$0.25\ 10^{-2}$
2	Short grass	L	0.2	$0.2\ 10^{-2}$
3	Evergreen needleleaf trees	H	2.0	2.0
4	Deciduous needleleaf trees	H	2.0	2.0
5	Deciduous broadleaf trees	H	2.0	2.0
6	Evergreen broadleaf trees	H	2.0	2.0
7	Tall grass	L	0.47	$0.47\ 10^{-2}$
8	Desert	–	0.013	$0.013\ 10^{-2}$
9	Tundra	L	0.034	$0.034\ 10^{-2}$
10	Irrigated crops	L	0.5	$0.5\ 10^{-2}$
11	Semidesert	L	0.17	$0.17\ 10^{-2}$
12	Ice caps and glaciers	–	$1.3\ 10^{-3}$	$1.3\ 10^{-4}$
13	Bogs and marshes	L	0.83	$0.83\ 10^{-2}$
14	Inland water	–	–	–
15	Ocean	–	–	–
16	Evergreen shrubs	L	0.100	$0.1\ 10^{-2}$
17	Deciduous shrubs	L	0.25	$0.25\ 10^{-2}$
18	Mixed forest/woodland	H	2.0	2.0
19	Interrupted forest	H	1.1	1.1
20	Water and land mixtures	L	–	–

Llanthony valley, S. Wales

Many models use orographic roughness enhancement to represent drag from sub-grid orography. ECMWF also use used this before 2006 with roughness lengths up to a maximum of 100 m.

Longstanding near-surface wind (short-range) forecast errors

10m wind speed bias/st dev - Europe

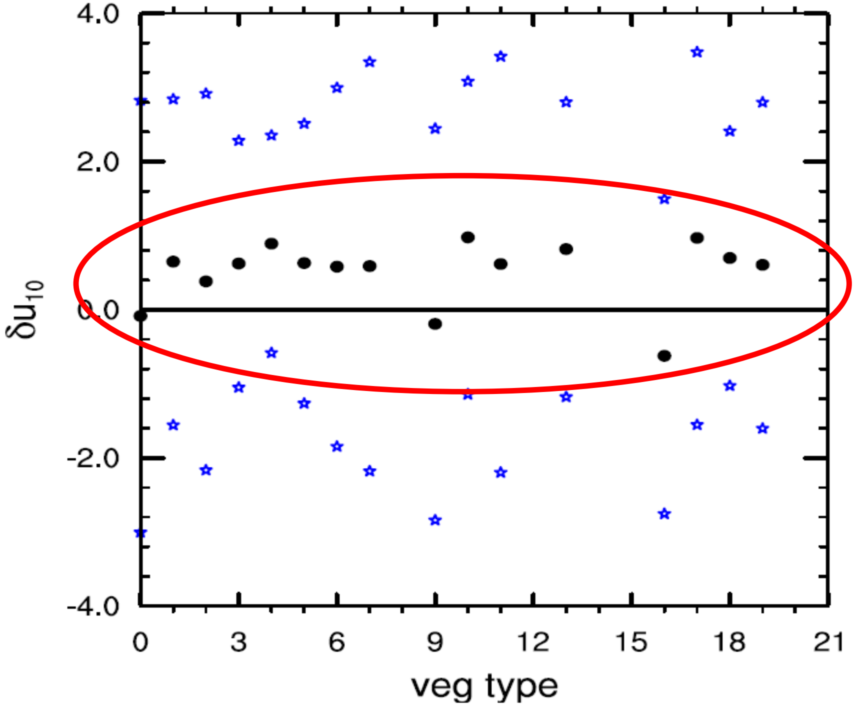


One of the main causes: the values of the roughness length for momentum

Derivation of a new roughness length table

The 10m winds are mainly controlled by the roughness length values and are generally overestimated by the model.

Forecast 10m winds error compared to synop obs.
(daytime – T511 L91 analysis run August 2010)



$$\frac{u_{100}}{u_{10}} = \frac{ln100/z_0^m}{ln10/z_0^m}$$

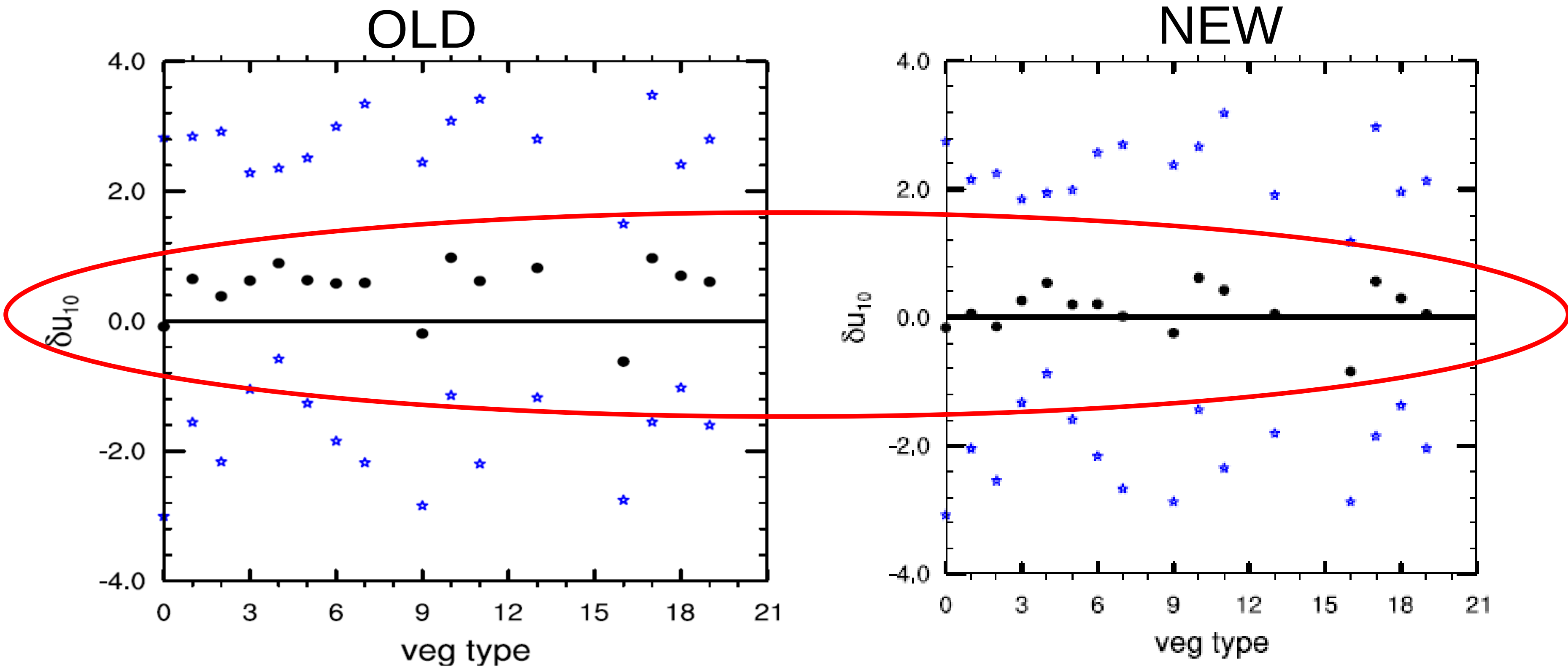
$$\frac{u_{100}}{u_{10}^{obs}} = \frac{ln100/\boxed{z_0^{m*}}}{ln10/z_0^{m*}}$$

The roughness length for momentum is increased for 10 vegetation types

Sandu et al, ECMWF RD Memo 11104, Newsletter 130

Derivation of a new roughness length table

Forecast 10m winds error compared to synop obs.
(daytime – T511 L91 analysis run August 2010)


OLD

NEW

The 10 wind errors are reduced for the types for which the roughness was changed

Impact on 10m wind speed in short range forecasts

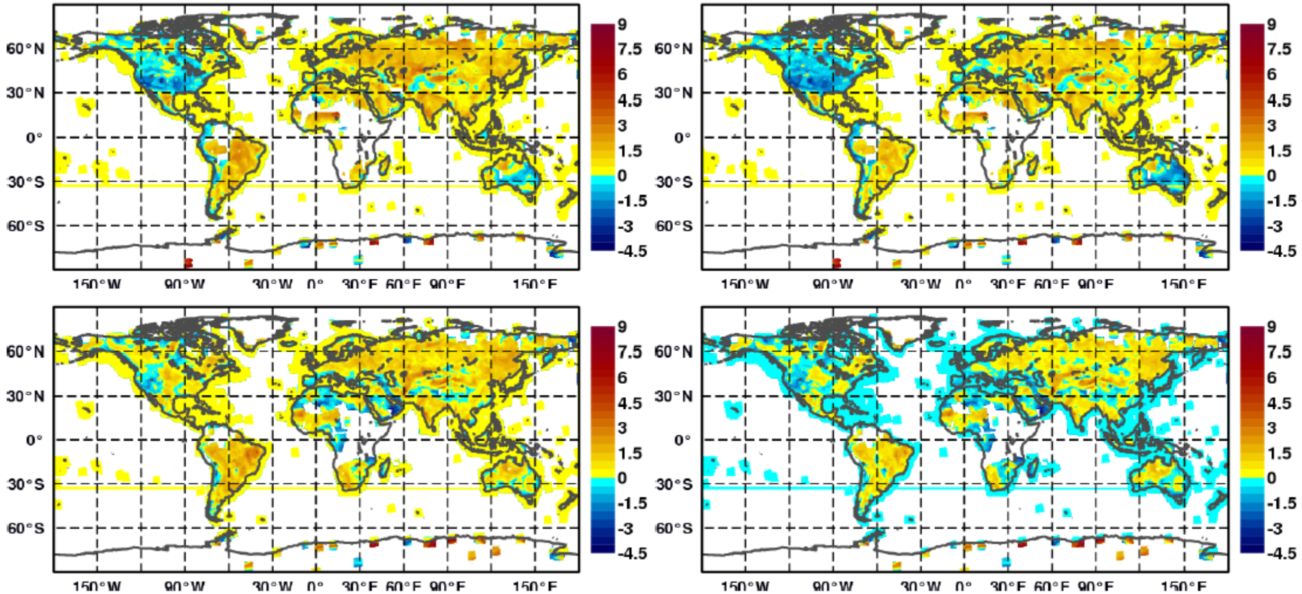
FC - OBS

OLD

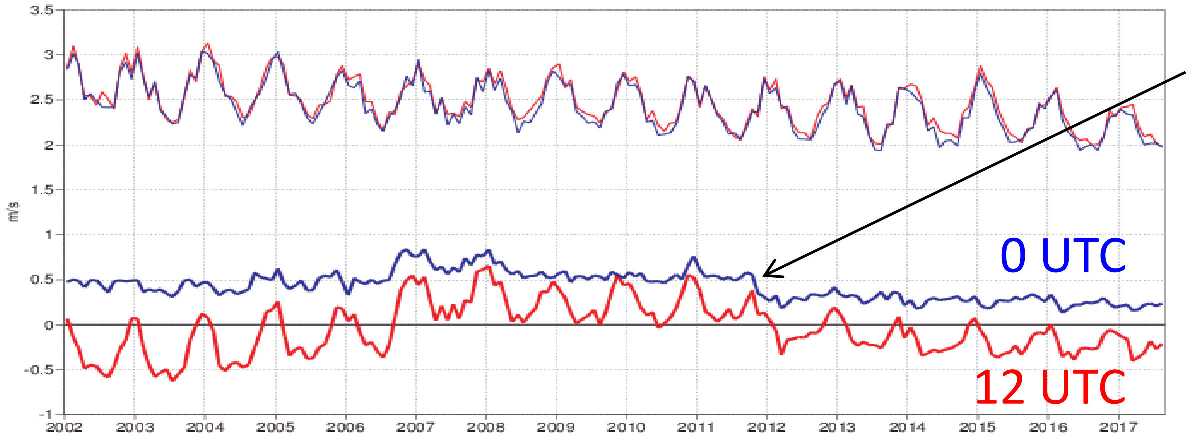
NEW

0UTC

12UTC



10m wind speed bias/st dev - Europe



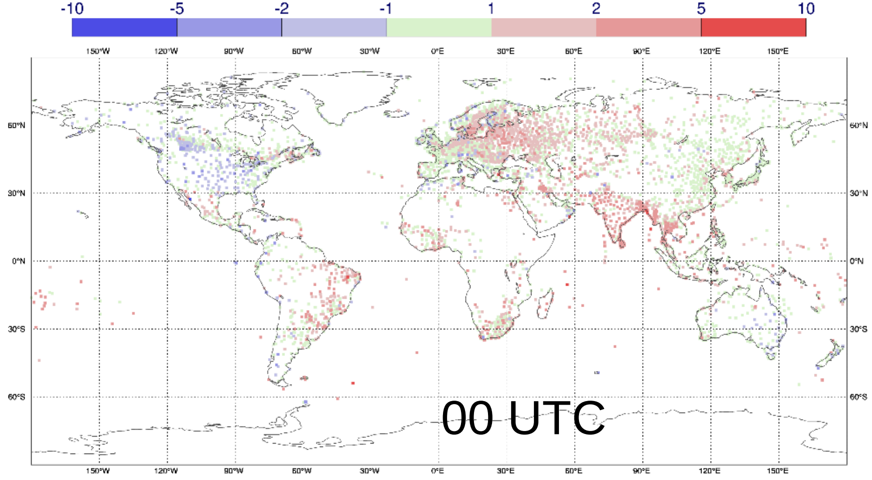
Implementation of the new table, Nov. 2011

0 UTC

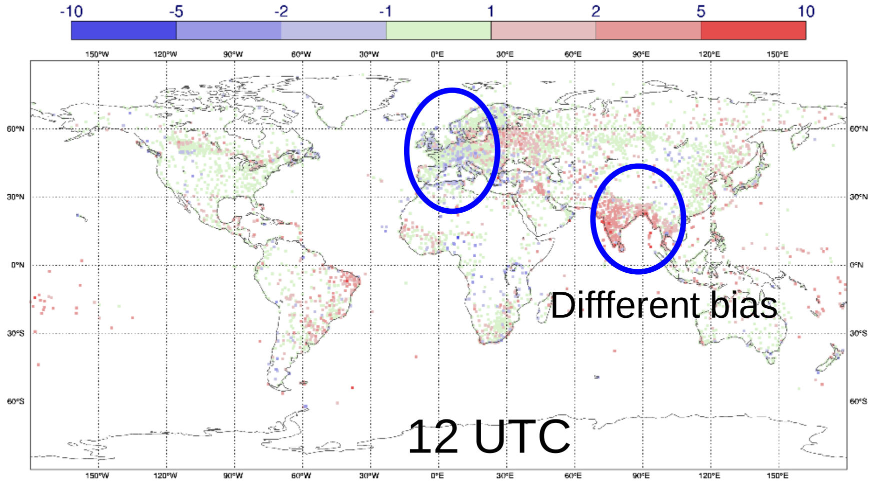
12 UTC

NOTE: This exercise could be redone, but we have to keep in mind that this can only work to a certain extent – the success largely depends on the quality of the underlying vegetation maps

10 m wind speed bias



00 UTC



Diffferent bias

12 UTC

Vegetation maps

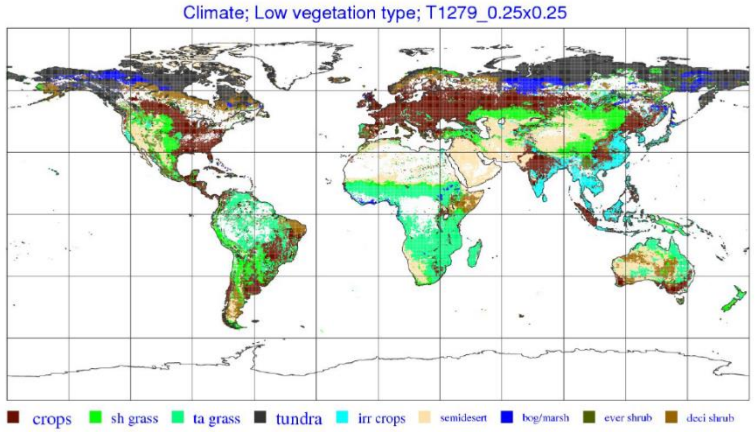
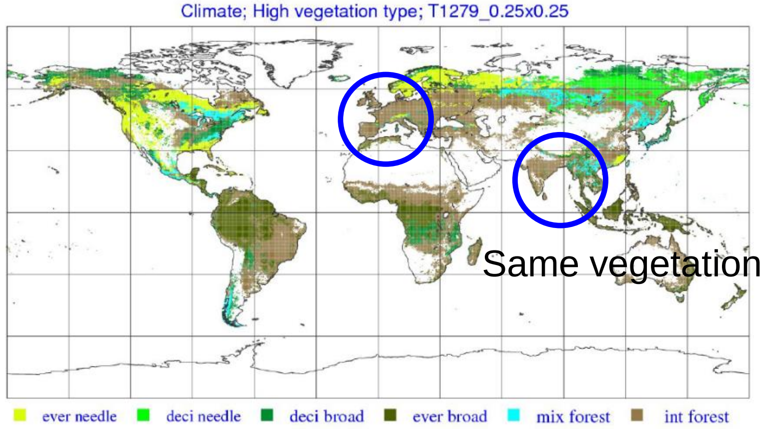


Figure 11.11 *Low vegetation type.*



Same vegetation typ

Figure 11.12 *High vegetation type.*

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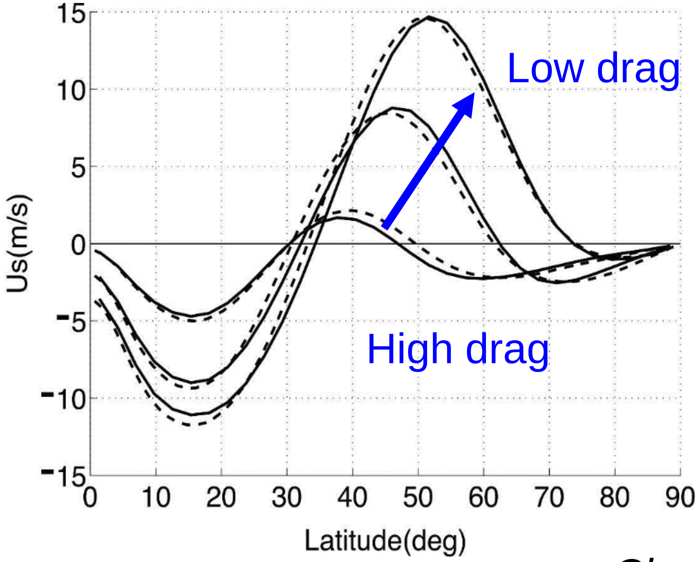
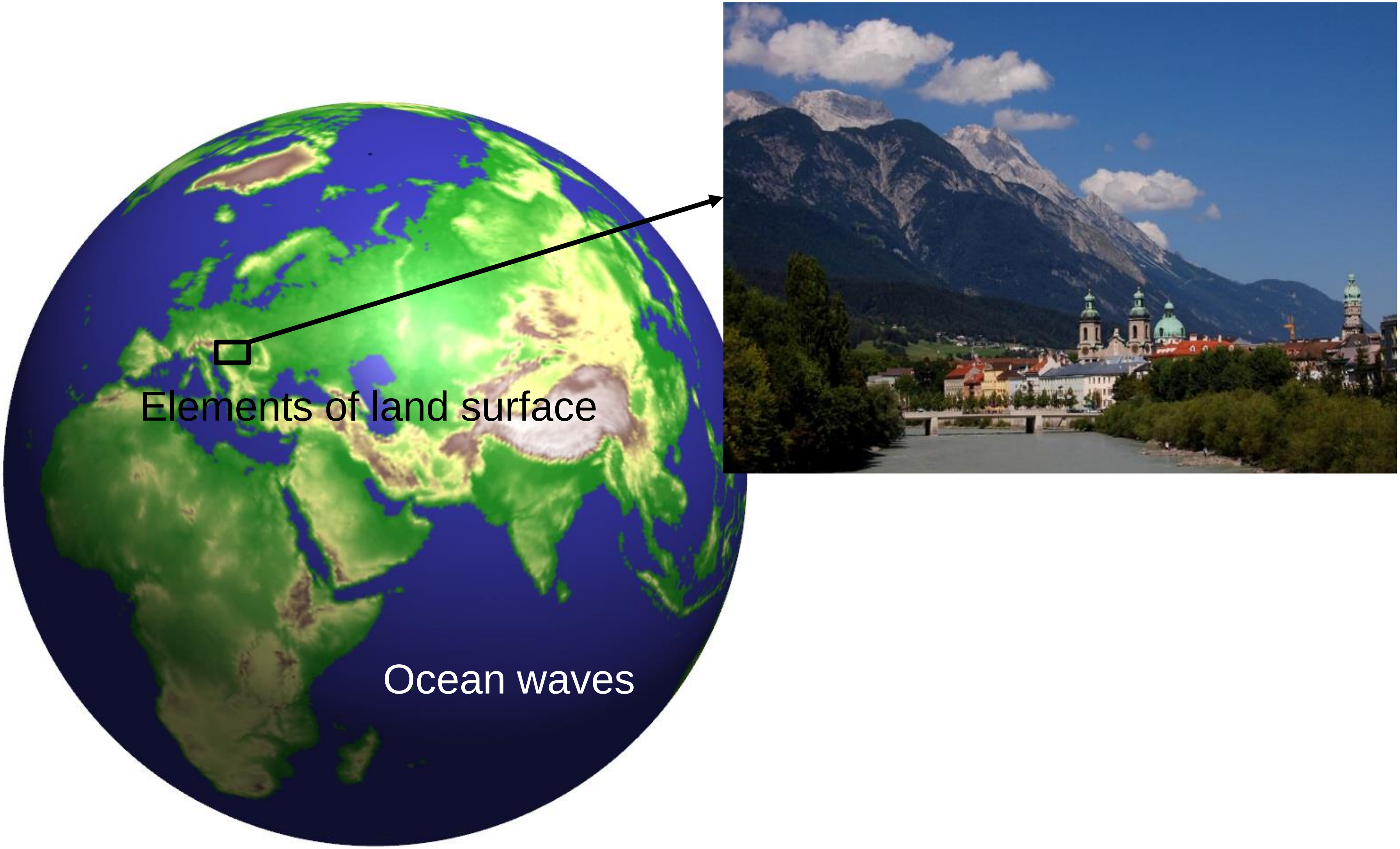


In idealized AGCMs, surface jet strength and latitude are highly sensitive to surface drag, via feedback on baroclinic eddies

Chen, Held & Robinson (2007 JAS)

Subgrid drag (stress) mechanisms in the ECMWF model



Elements of land surface

Ocean waves

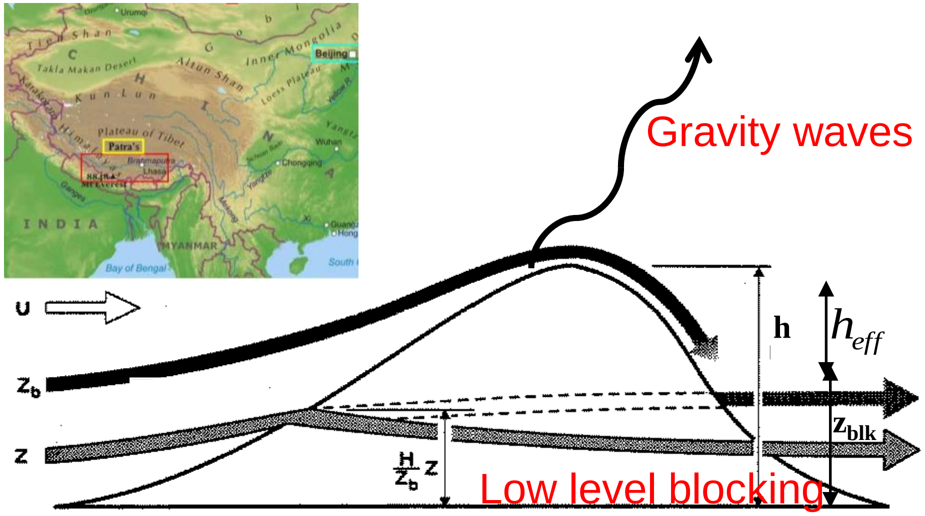
Subgrid drag (stress) mechanisms in the ECMWF model

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

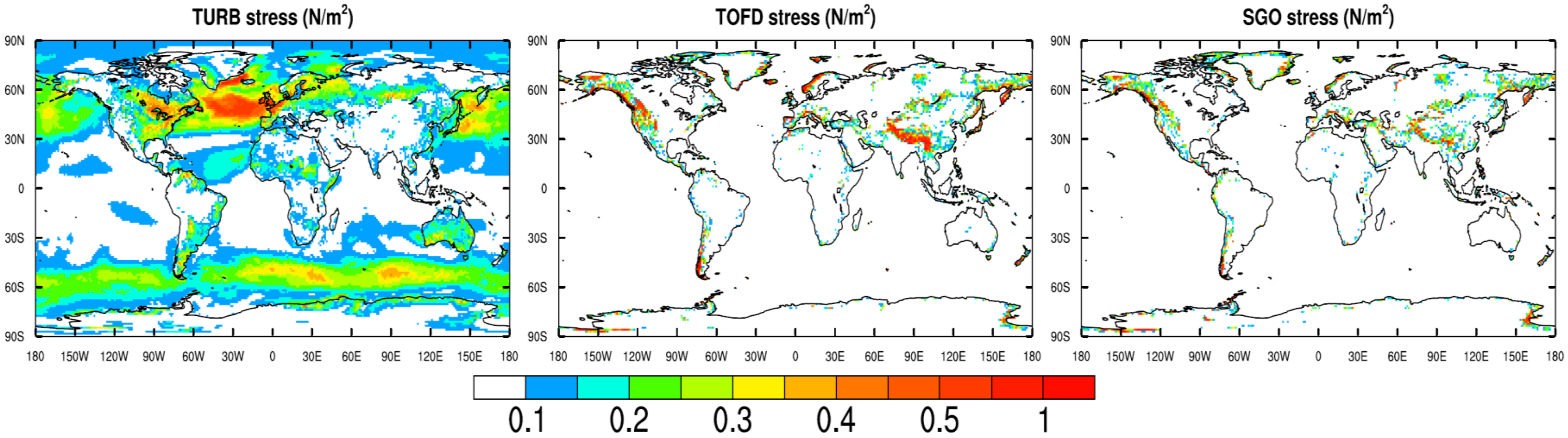


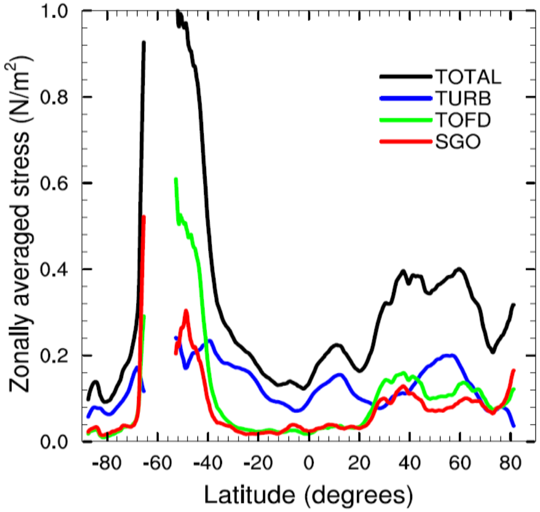
a) Gravity Wave Drag - GWD : gravity waves are excited by the "effective" sub-grid mountain height, i.e. height where the flow has enough momentum to go over the mountain

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

An illustration of the surface stress from the different schemes (u-component)

u-component TURB stress (N/m2) u-component TOFD stress (N/m2) u-component SO stress (N/m2)

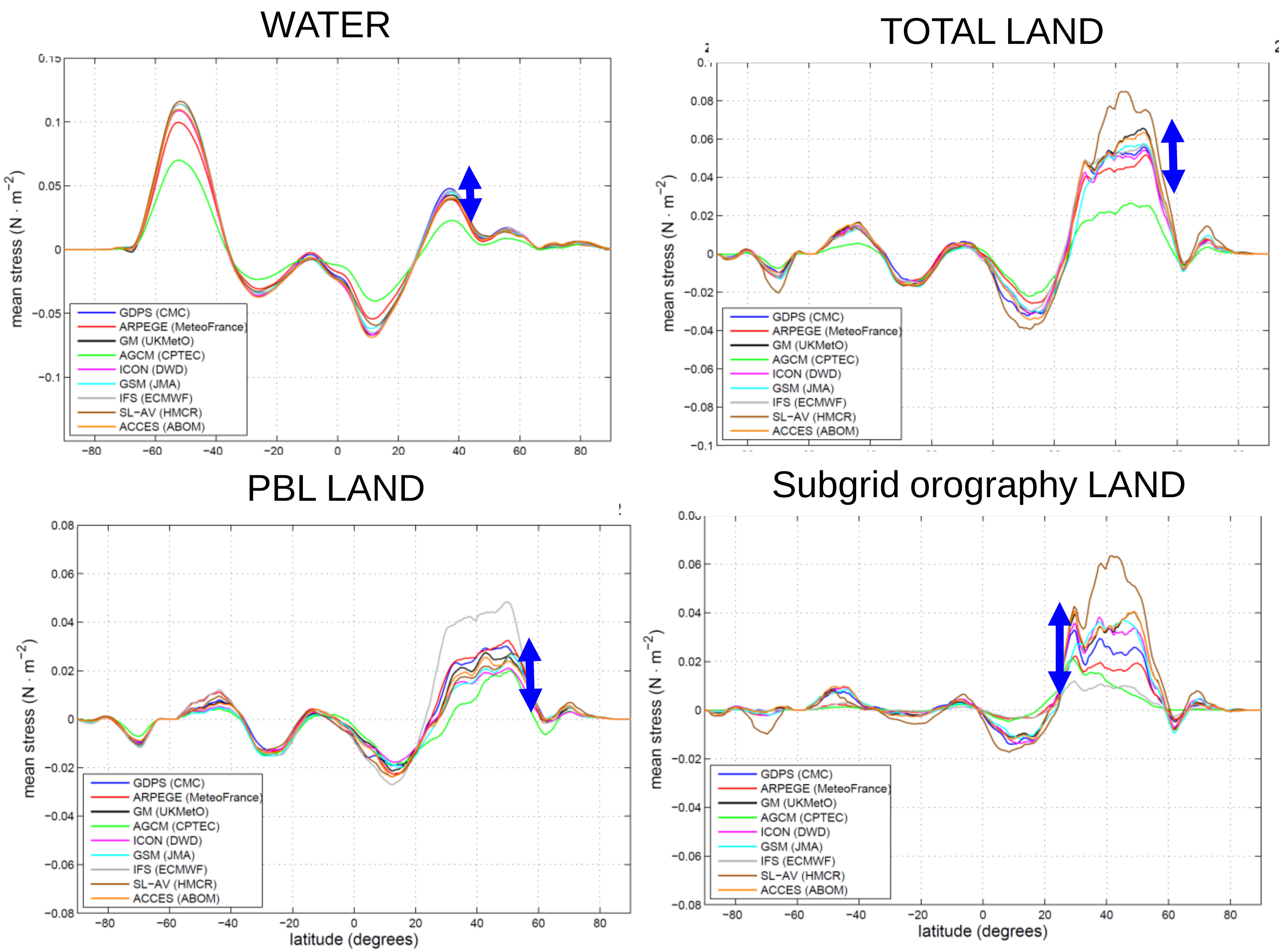




Total
TURB
TOFD
SO

Similar zonal average but different zonal distribution

WGNE Drag project – comparison of subgrid surface stress



WATER

TOTAL LAND

PBL LAND

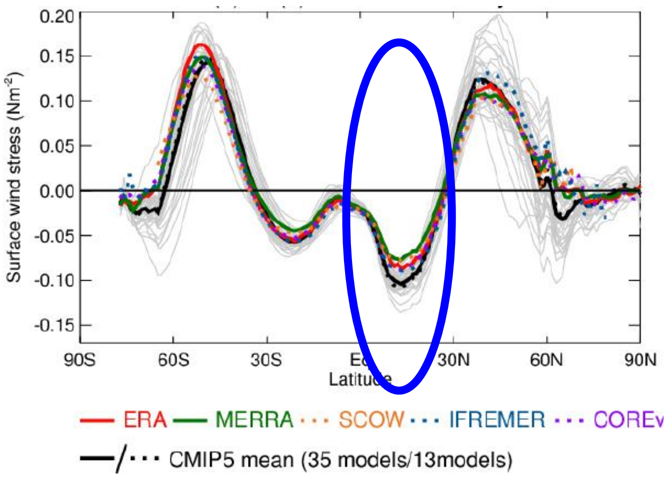
Subgrid orography LAND

Major NWP models

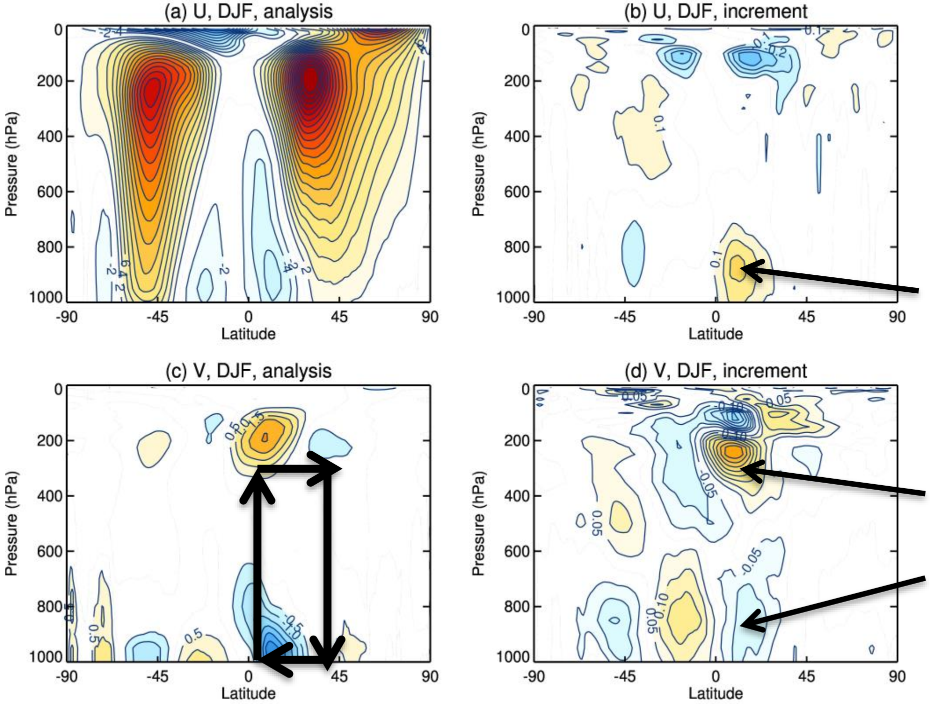
- Much better agreement over water than over land !
- UKMO BL term < EC BL term, but SGO term >> EC SO term, and relative difference in total stress is 10-20% in NH midlatitudes

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 can explain systematic biases in CFMIP5 models



Simpson et al (2014, JAS)

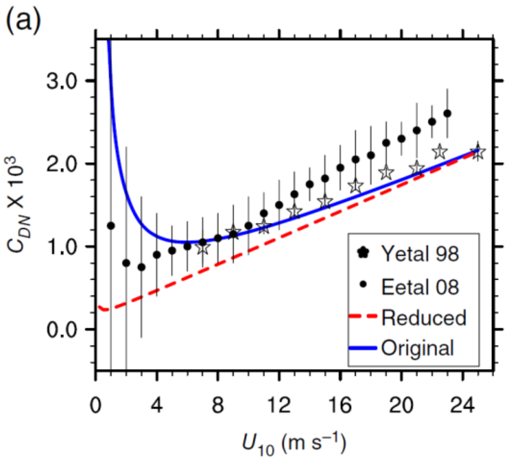


ERA-I analysis increments correcting for:

- too strong tropical easterlies
- too weak Hadley circulation

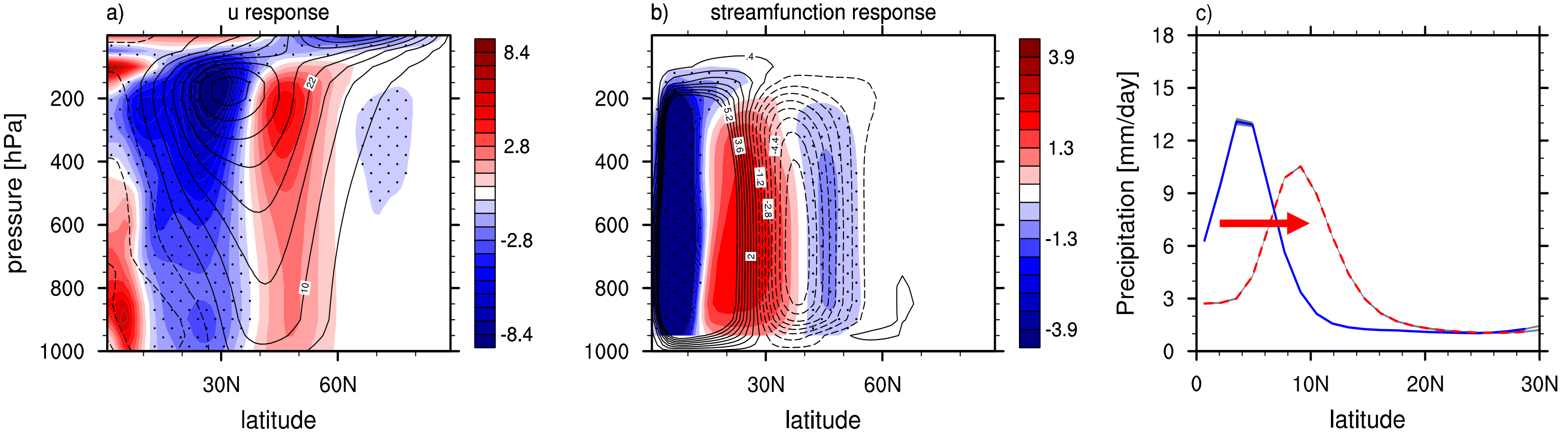
Simpson et al. (J.Clim, 2018), also see Politchouck and Shepherd, QRMS (2016)

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

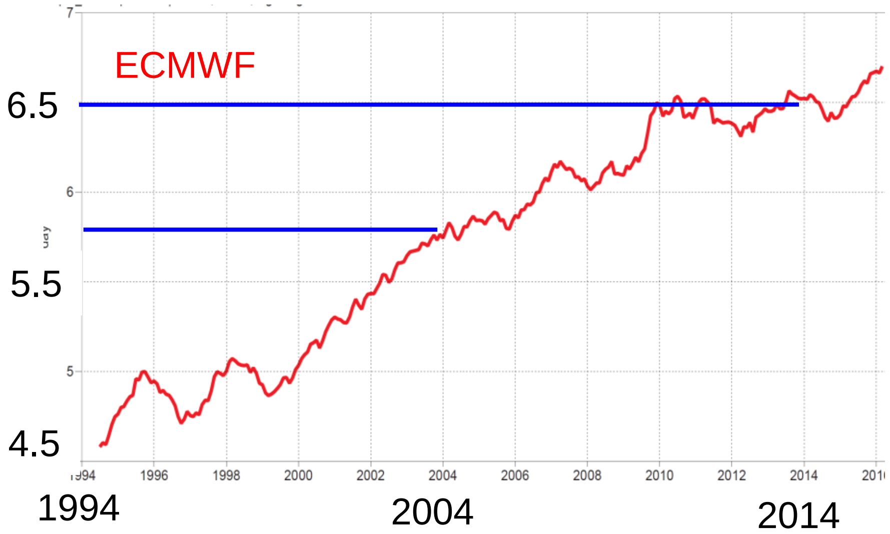
A weakening of the HC and a poleward shift of the ITCZ.



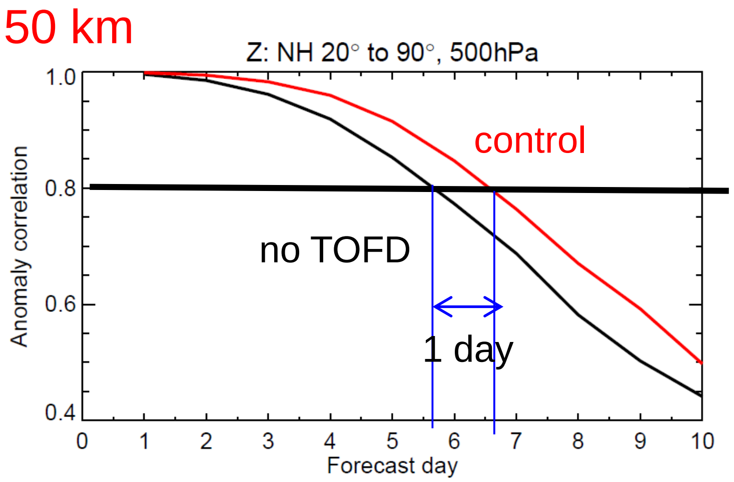
Polichtchouk & Shepherd (2016,QJRMS)

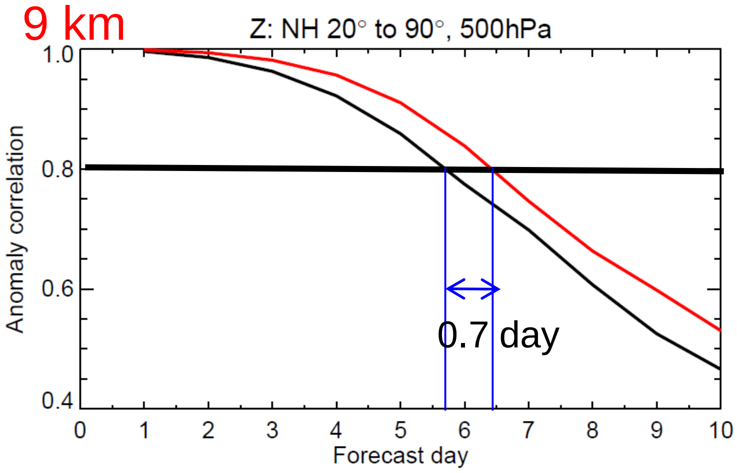
Each of the drag parametrizations is key for the large-scale skill : Impact of the turbulent orographic form drag parameterization in NWP

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

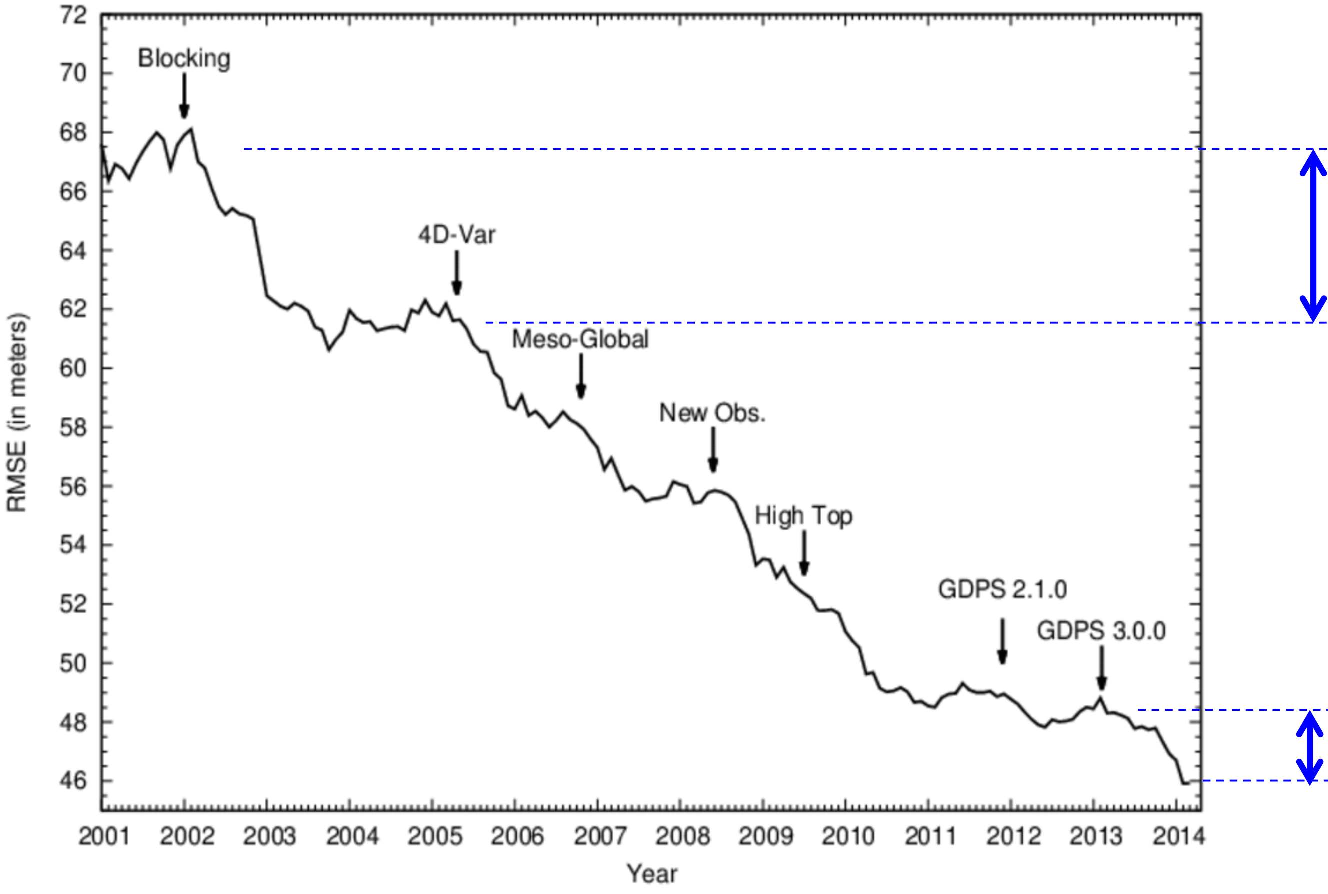


Bauer, P., A. Thorpe, and G. Brunet. "The quiet revolution of numerical weather prediction." Nature (2015)





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



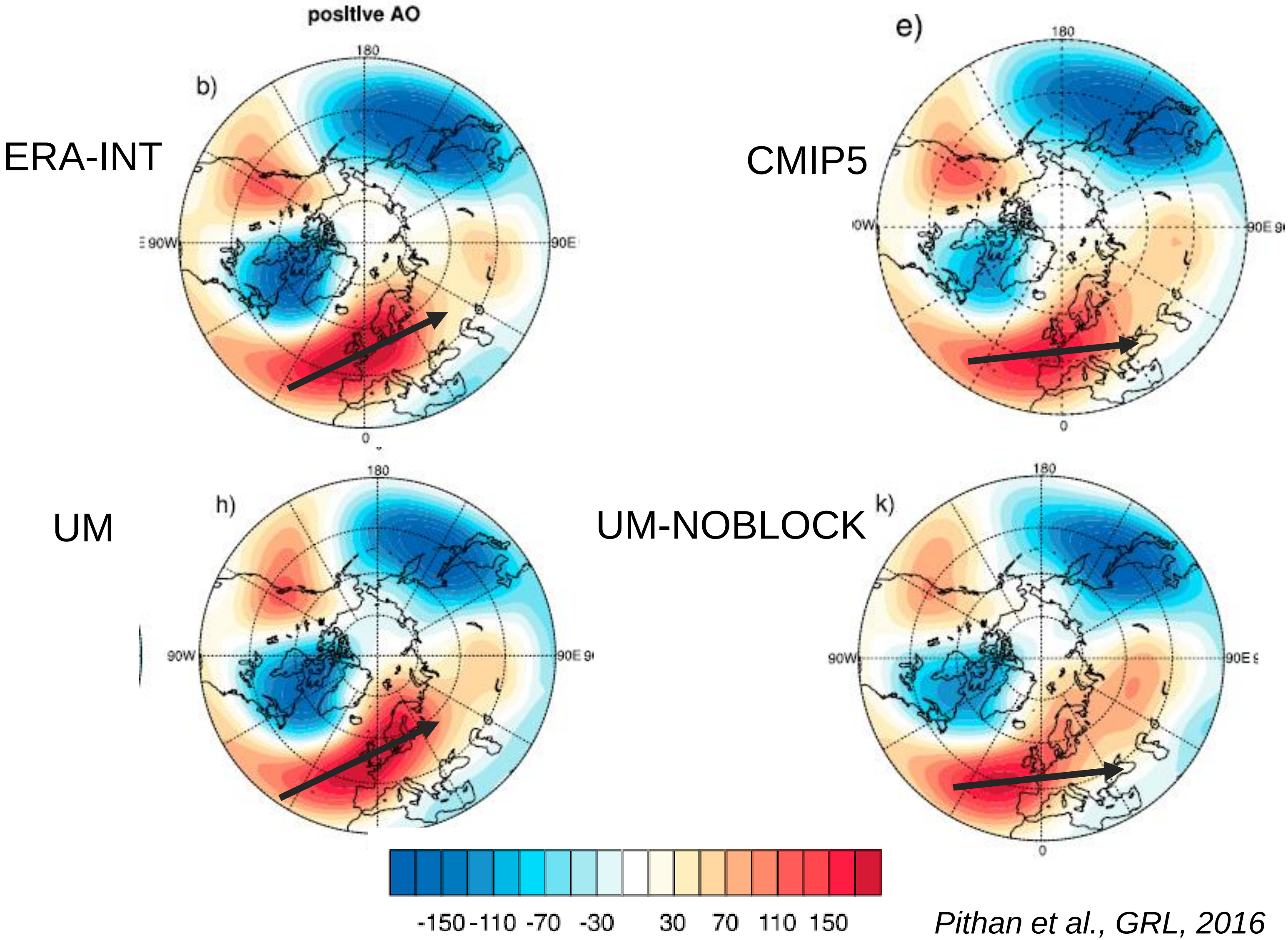
~ 7m
mostly due to
introduction of
orographic
blocking scheme

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

Evolution of 500-hPa RMS errors ver 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

In summary:

Models don’t agree:

- in total subgrid drag, nor in its partition between different processes and the diurnal cycle, particularly over orography
- The differences in subgrid drag and in its partition are partly the result of repeated tuning exercises designed to improve model skill (NWP or climate) – length scales are an example, coefficients in various schemes are another example

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) - more in the Friday lecture

Thank you