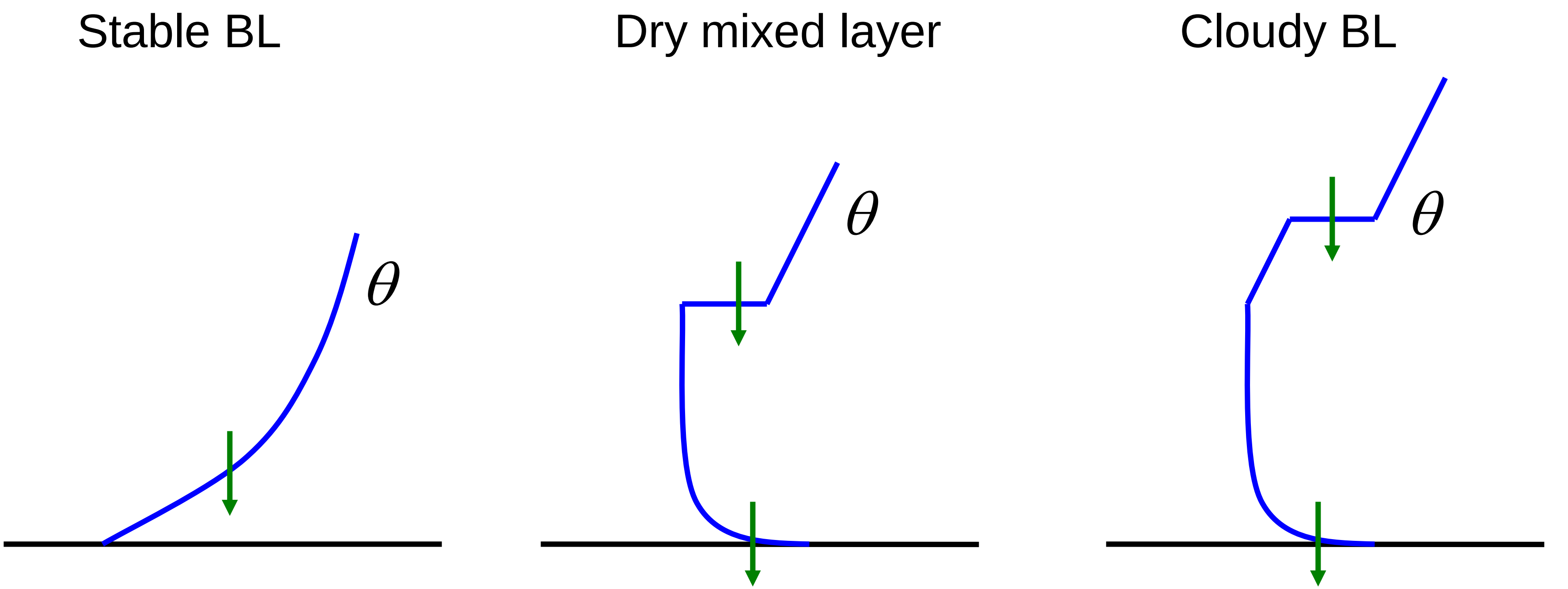
Parameterization of surface fluxes: Outline

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

Mixing across steep gradients



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?

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

Finite difference formulation:

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

In surface layer integrate:

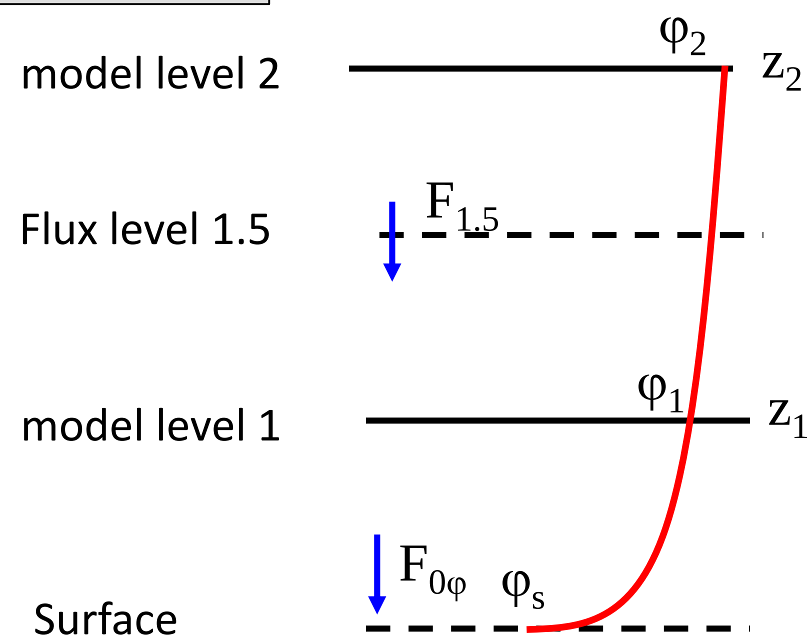
$$\varphi_1 - \varphi_s = \int_{z_{o\varphi}}^{z_1} \frac{F_{0\varphi}}{\rho K(z)}\,dz$$

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:

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



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

u,v,T,q

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

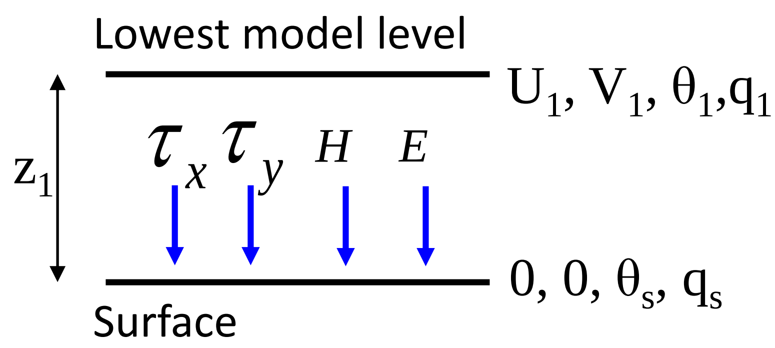
$$F_{0\varphi} = \frac{\rho \kappa u_*}{\ln(z_1 / z_{0\varphi})} (\varphi_1 - \varphi_s)$$

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

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

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

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



$\tau_{x,y}$: Surface stress components
H : Sensible heat flux
E : Water vapour flux

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:

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

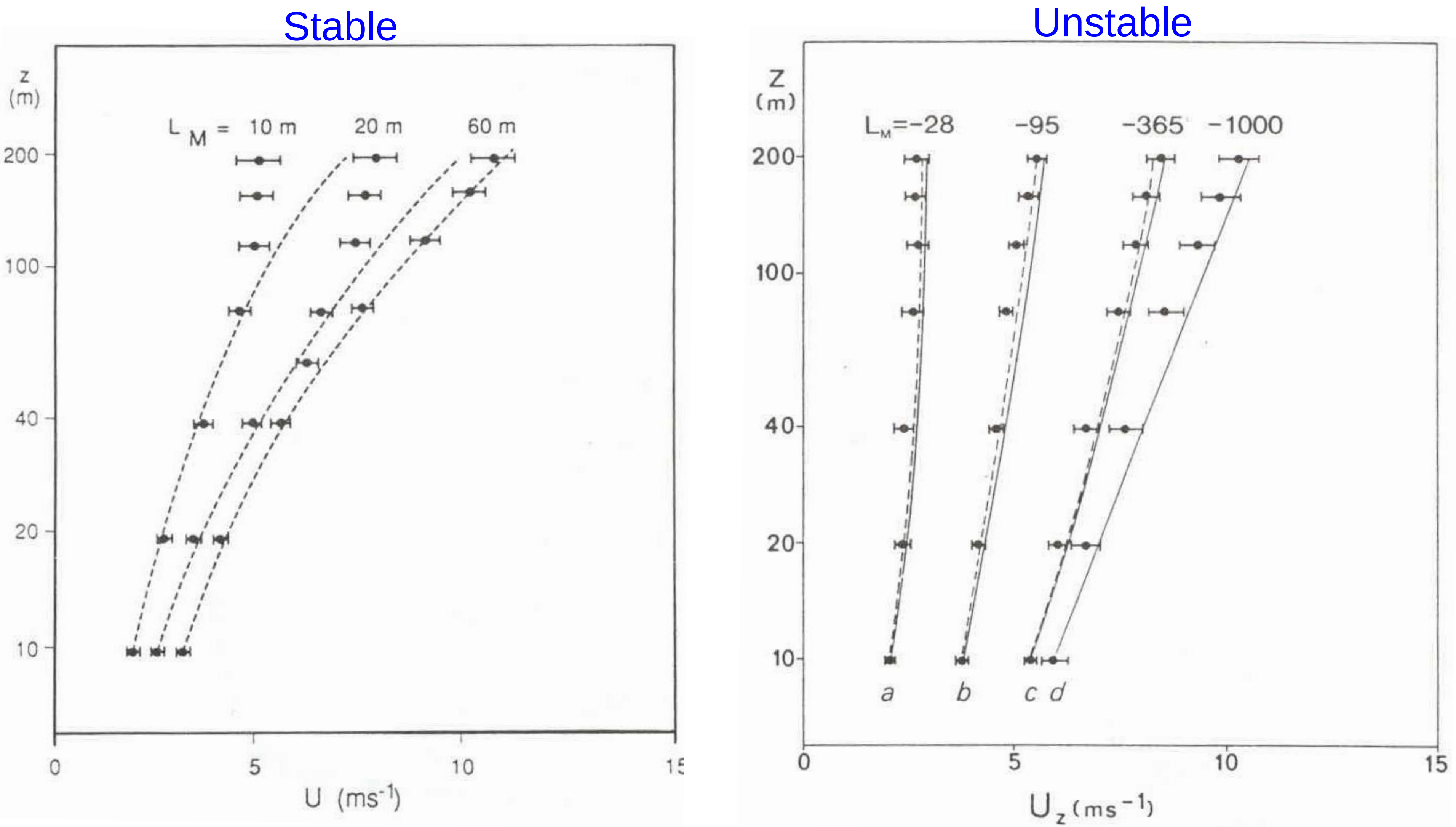
$$F_{0\varphi} = \rho C_\varphi |U| (\varphi_1 - \varphi_s)$$

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

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

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.

MO wind profile functions applied to observations



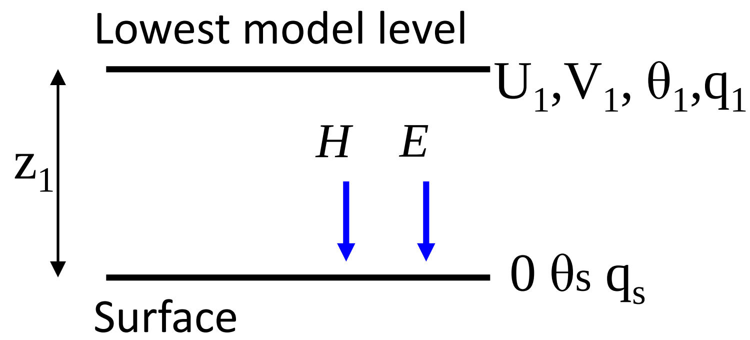
Wind profiles extrapolated from the 10 m level upward using empirical ψ-functions (curves). Data is grouped in different stability classes according to L. The dots with horizontal bars indicate the range of observations at each level and stability class. The vertical axis is logarithmic, so a neutral profile, e.g. |L|→ infinite, will give a straight line (Holtslag 1984, BLM, 29, 225-250)

Low wind speeds and the limit of free convection

At zero wind speed, coupling with the surface disappears e.g. for evaporation and heat flux:

$$E = \rho\, C_M \, |U_1| (q_1 - q_s)$$

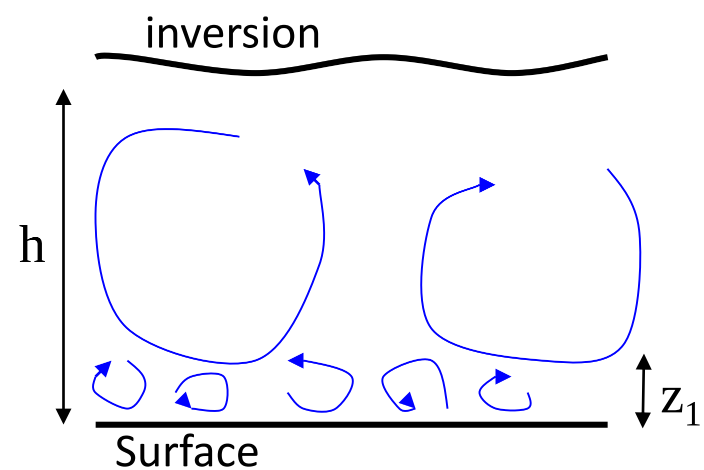
$$H = \rho\, c_p C_H \, |U_1| (\theta_1 - \theta_s)$$



Extension of MO similarity with free convection velocity:

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

$$and \quad w_* = \left(\frac{g}{T_v} \frac{H}{\rho c_p} h\right)^{1/3}, \quad \beta \approx 1$$



c_p : Air specific heat at constant pressure
w_* : Free convection velocity scale (typically 0.5-1 m/s)

Beljaars 1995, QJRMS, 121, 255-270.

Transfer coefficients

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

Surface fluxes can be written explicitly as:

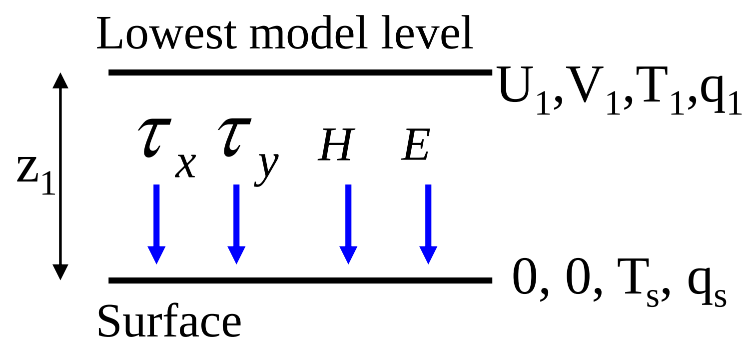
$$\tau_x = \rho \, C_M \, |U_1| \, U_1$$

$$\tau_y = \rho \, C_M \, |U_1| \, V_1$$

$$H = \rho c_p C_H \, |U_1| \, (\theta_1 - \theta_s)$$

$$E = \rho C_E \, |U_1| \, (q_1 - q_s)$$

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



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

$$\varphi = \begin{cases} M \\ H \\ E \end{cases} \qquad \varphi = \begin{cases} m \\ h \\ q \end{cases}$$

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.

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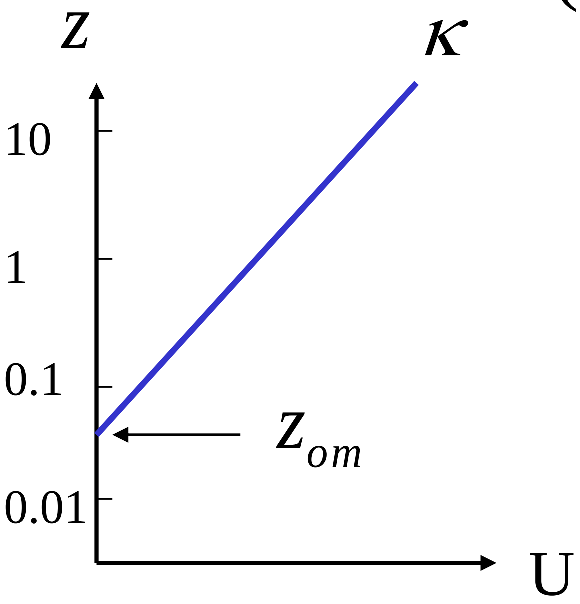
Surface roughness length (definition)

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.

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

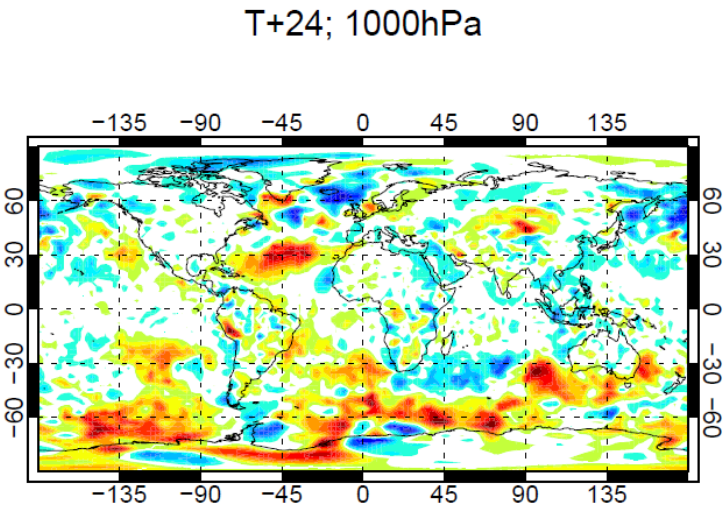
$$z_{oh} = 0.40 \frac{\nu}{u_*}$$

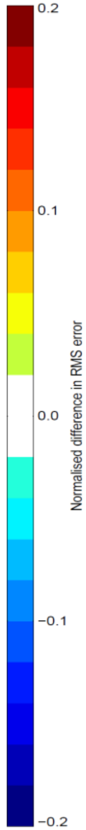
$$z_{oq} = 0.62 \frac{\nu}{u_*}$$

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

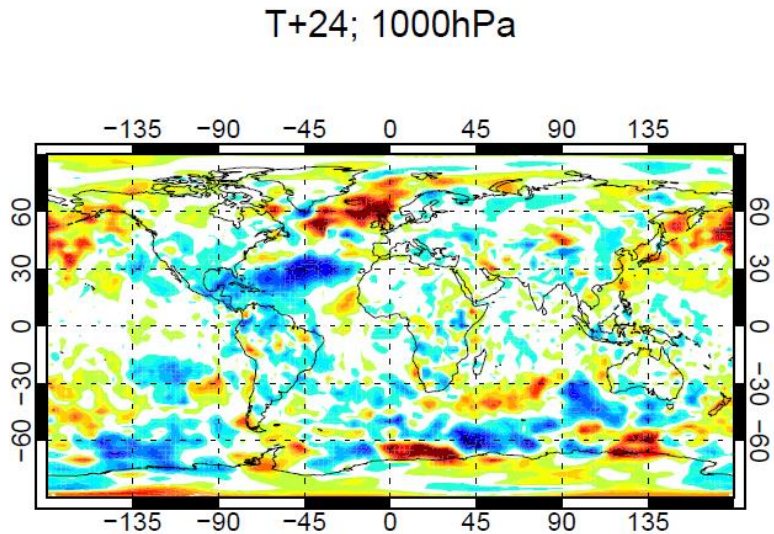
Sensitivity to changes in surface drag over ocean

C_M+10%





C_M-10%



Extremely sensitive to small changes in the transfer coefficients

Roughness length over land

Geographical fields based on land use tables:

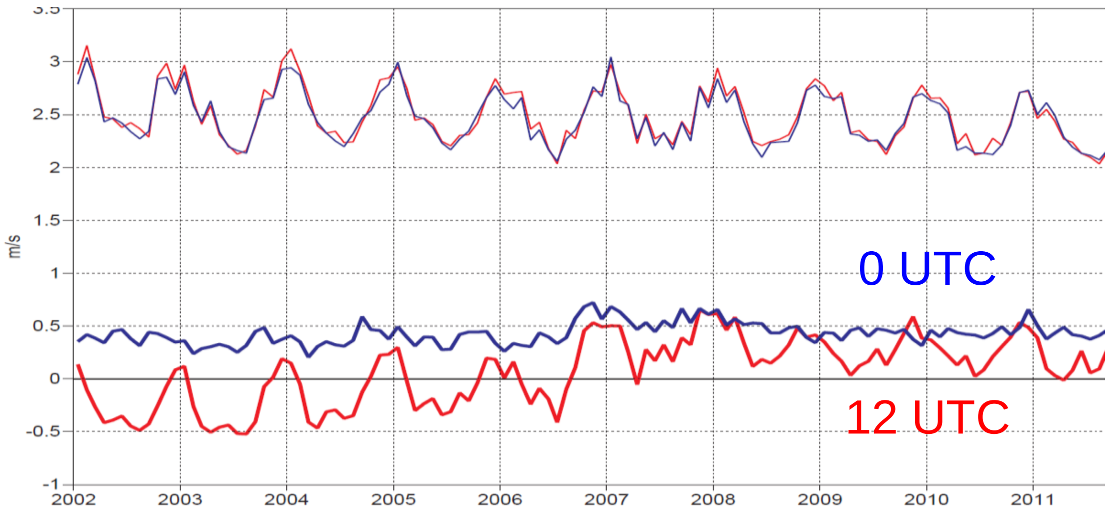
Index	Vegetation type	H/L veg	z_{0m}	z_{0h}
1	Crops, mixed farming	L	0.25	$0.25\ 10^{-2}$
2	Short grass	L	0.2	$0.2\ 10^{-2}$
3	Evergreen needleleaf trees	H	2.0	2.0
4	Deciduous needleleaf trees	H	2.0	2.0
5	Deciduous broadleaf trees	H	2.0	2.0
6	Evergreen broadleaf trees	H	2.0	2.0
7	Tall grass	L	0.47	$0.47\ 10^{-2}$
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

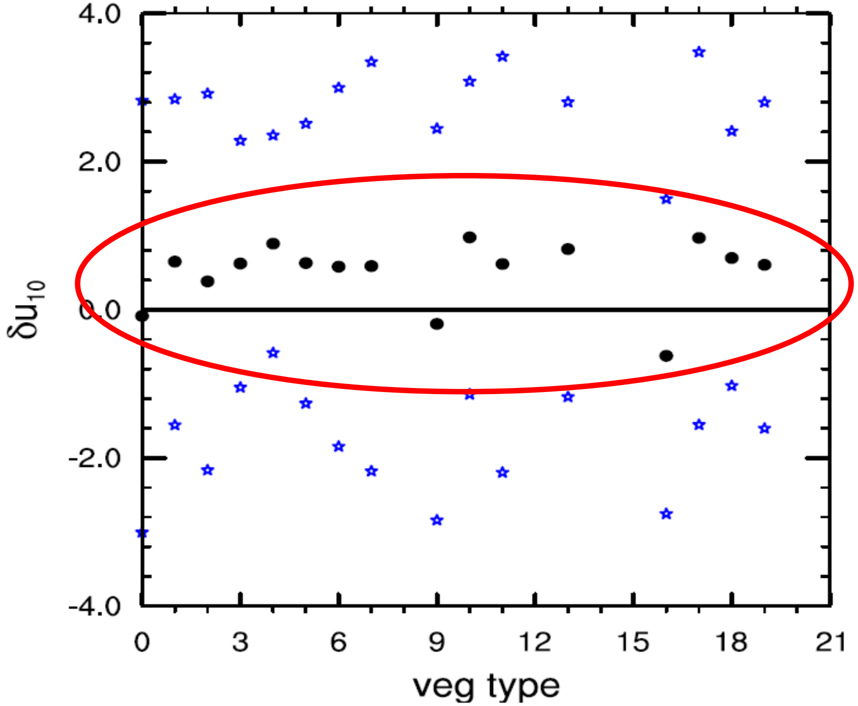


Main cause: the values of the roughness length for momentum

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)



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

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

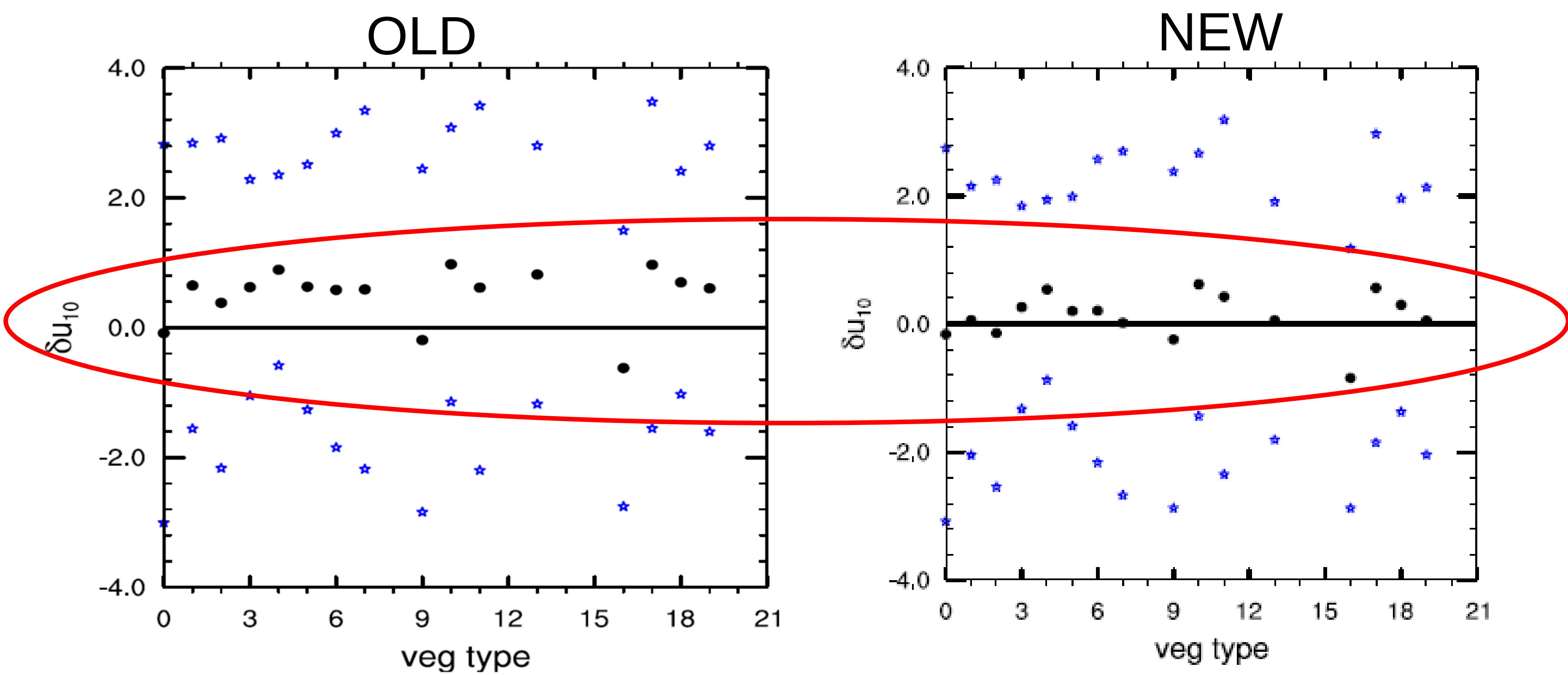
The roughness length for momentum is increased for 10 vegetation types

Sandu et al, ECMWF RD Memo 11104, Newsletter 130

ECMWF

Derivation of a new roughness length table

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



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

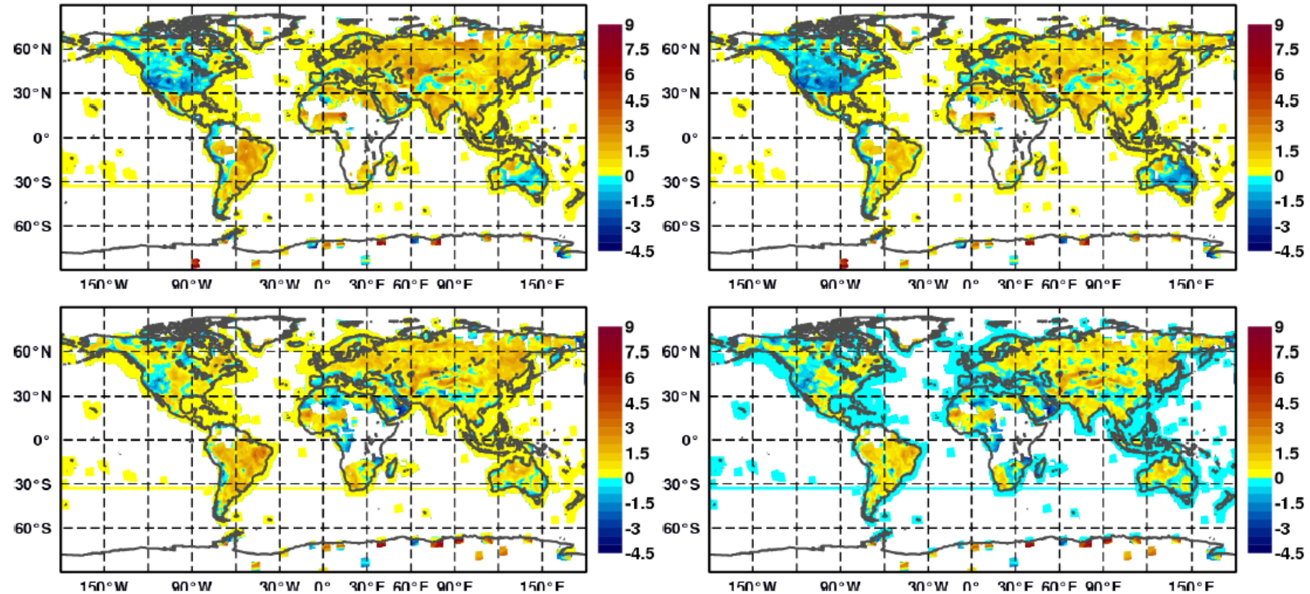
Impact on 10m wind speed in short range forecasts

FC - OBS

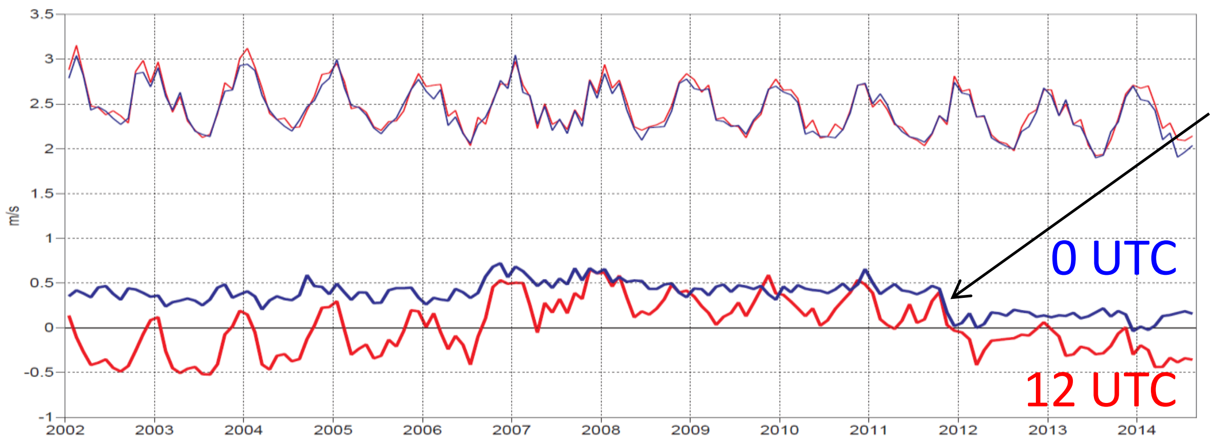
OLD | NEW

0UTC

12UTC



10m wind speed bias/st dev - Europe



Implementation of the new table, Nov. 2011

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Sub-grid surface drag mechanisms in the ECMWF model

1. Turbulence scheme for horizontal scales below 5 km

TURB

a) Turbulent Drag: Traditional MO transfer law with gustiness and roughness for land use and vegetation (correspondence table, max 2m)

TOFD

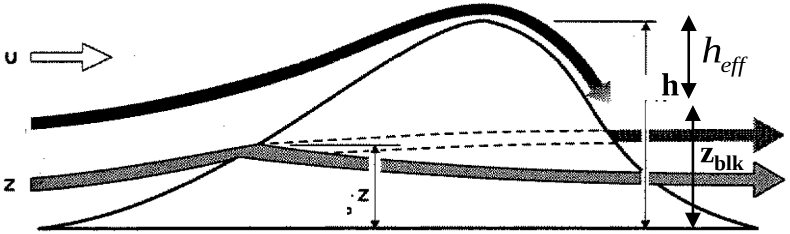
b) Turbulent Orographic Form Drag (TOFD): drag from small scale orography implemented as drag on model levels (Beljaars et al. 2004); Other schemes use orographic enhancement of roughness.

2. Sub-grid Orography scheme for horizontal scales between 5 km and model resolution (Lott and Miller 1997)

SO

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

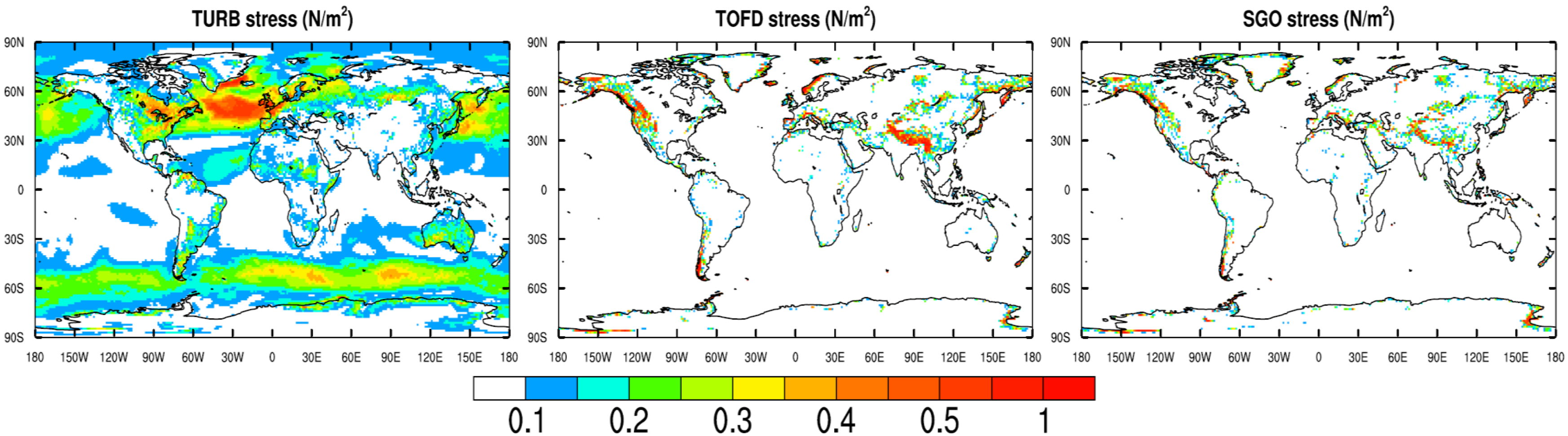
b) Orographic low level blocking: strong drag at lower levels where the flow is forced around the mountain

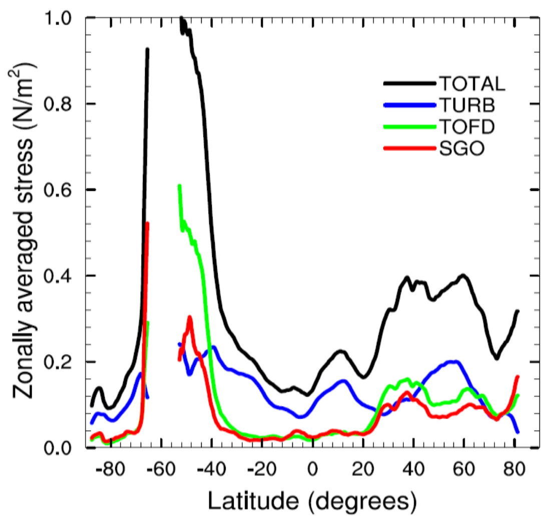


ECMWF

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

ECMWF

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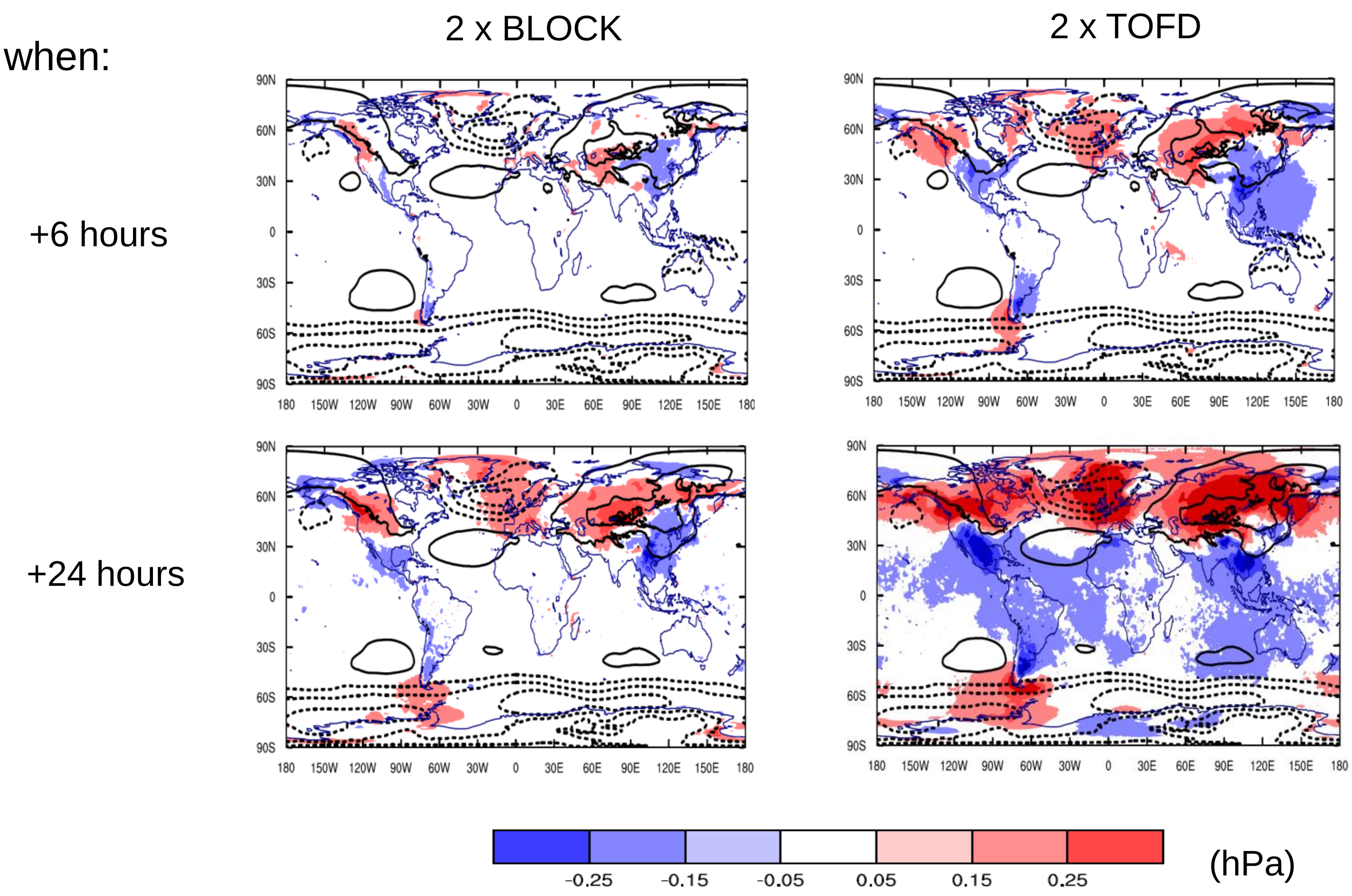
Playing with the TOFD and low level blocking strength…impacts the large-scale circulation from the very short range

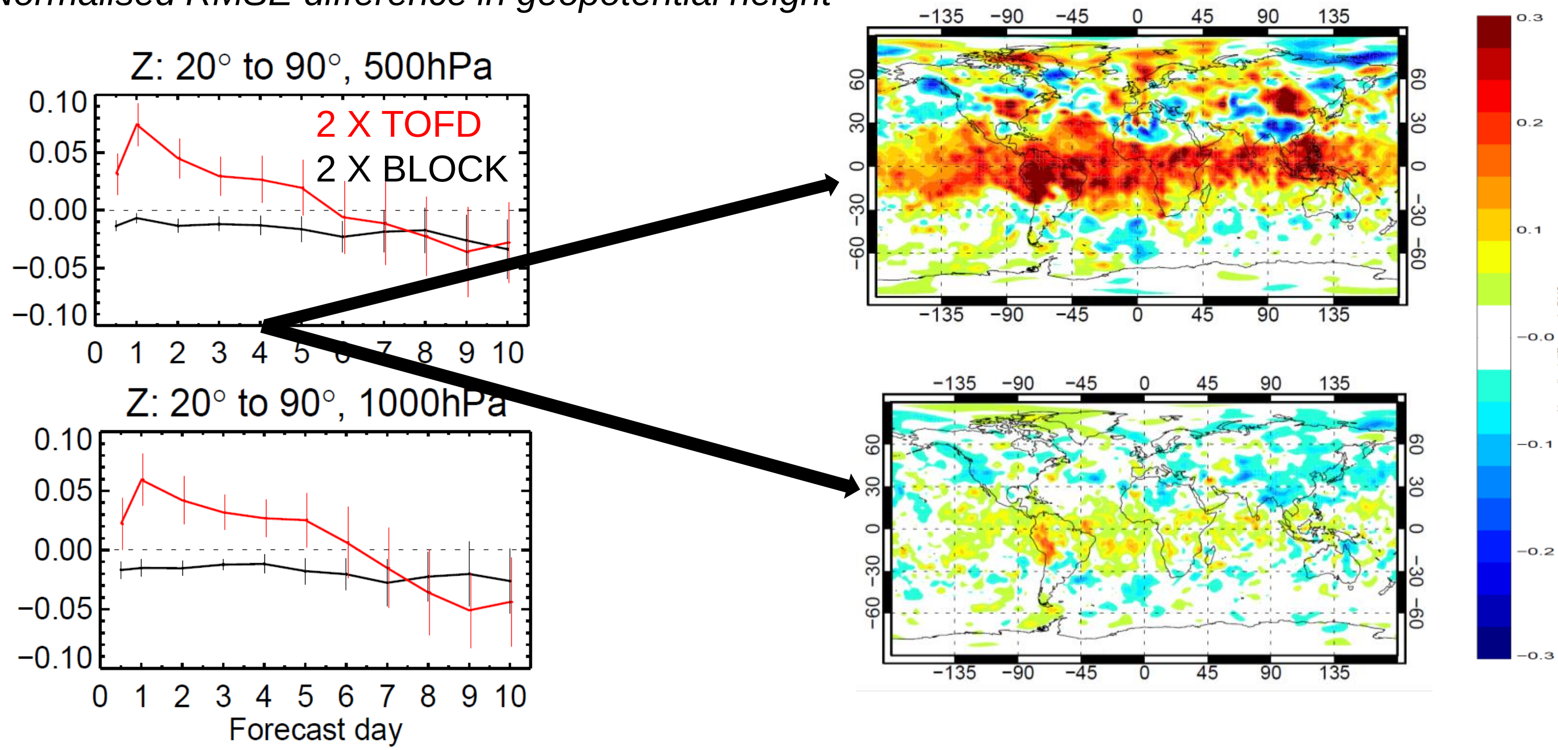
Change in SP when:



Sandu et al. 2016, JAMES

Playing with the TOFD and low level blocking strength…impacts the forecast performance

Normalised RMSE difference in geopotential height



Fine balance between improving and degrading the forecast performance !

Thank you