# Parametrization of turbulent fluxes in the outer layer

Irina Sandu

- ☞ Overview of models
- ☞ Bulk models — 0 order
- ☞ Local K-closure
- ☞ K-profile closure
- ☞ ED/MF closure
- ☞ TKE closure — $1.5^{th}$ order
- ☞ Current closure in the ECMWF model

K-profile closure, ED/MF closure and TKE closure: non-local

Local K-closure, K-profile closure and ED/MF closure: $1^{st}$ order

# Reynolds equations

$$\frac{\partial \overline{u}}{\partial t}+\overline{u}\frac{\partial \overline{u}}{\partial x}+\overline{v}\frac{\partial \overline{u}}{\partial y}+\overline{w}\frac{\partial \overline{u}}{\partial z}-f\overline{v}=-\frac{1}{\overline{\rho}}\frac{\partial \overline{P}}{\partial x}-\frac{\partial \overline{u'w'}}{\partial z}$$

$$\frac{\partial \overline{v}}{\partial t}+\overline{u}\frac{\partial \overline{v}}{\partial x}+\overline{v}\frac{\partial \overline{v}}{\partial y}+\overline{w}\frac{\partial \overline{v}}{\partial z}-f\overline{u}=-\frac{1}{\overline{\rho}}\frac{\partial \overline{P}}{\partial y}-\frac{\partial \overline{v'w'}}{\partial z}$$

$$\frac{\partial \overline{q}}{\partial t}+\overline{u}\frac{\partial \overline{q}}{\partial x}+\overline{v}\frac{\partial \overline{q}}{\partial y}+\overline{w}\frac{\partial \overline{q}}{\partial z}=-\frac{S_{q_t}}{\overline{\rho}}-\frac{\partial \overline{q'w'}}{\partial z}$$

$$\frac{\partial \overline{\theta}}{\partial t}+\overline{u}\frac{\partial \overline{\theta}}{\partial x}+\overline{v}\frac{\partial \overline{\theta}}{\partial y}+\overline{w}\frac{\partial \overline{\theta}}{\partial z}=-\frac{1}{\overline{\rho}c_p}\frac{\partial F}{\partial z}-\frac{L_v}{\overline{\rho}c_p}-\frac{\partial \overline{\theta'w'}}{\partial z}$$

$$u=\overline{u}+u'$$

Reynolds Terms

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- ☞ **Local K closure**
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# Local K closure

K-diffusion in analogy with molecular diffusion, but

$$\overline{u'w'} = -K_M \frac{\partial \overline{u}}{\partial z}, \quad \overline{v'w'} = -K_M \frac{\partial \overline{v}}{\partial z}$$

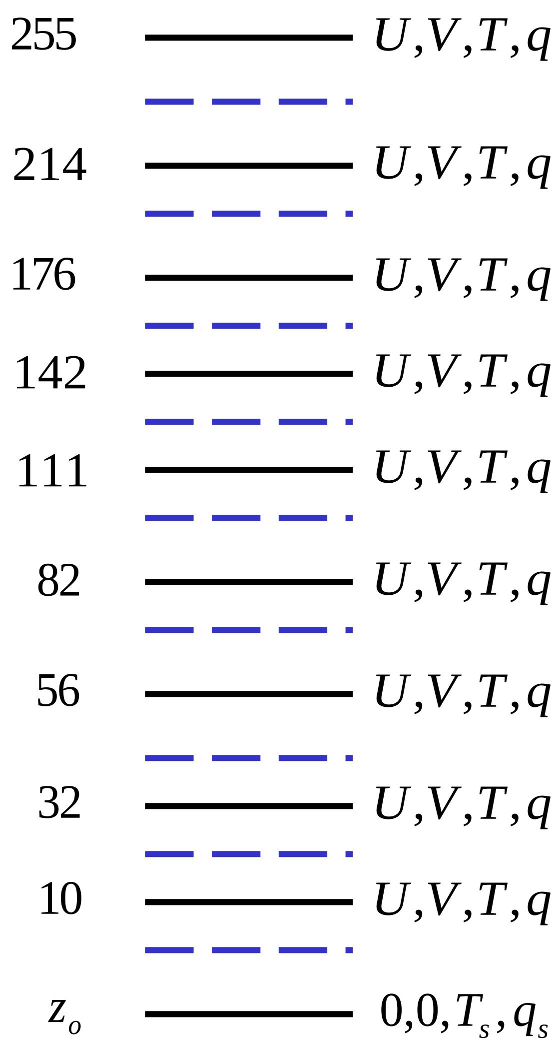
$$\overline{\theta' w'} = -K_H \frac{\partial \overline{\theta}}{\partial z}, \quad \overline{q'w'} = -K_H \frac{\partial \overline{q}}{\partial z}$$

$$\frac{\partial \overline{\phi' w'}}{\partial z} \approx \frac{\partial}{\partial z}\left( -K \frac{\partial \overline{\phi}}{\partial z} \right) \approx -K \frac{\partial^2 \overline{\phi}}{\partial z^2}$$

Diffusion coefficients need to be specified as a function of flow characteristics (e.g. shear, stability,length scales).

## Levels in ECMWF model

137-level model



# Diffusion coefficients according to MO-similarity

$$K_M = \frac{\ell^2}{\phi_m^2}\left|\frac{dU}{dz}\right|, \quad K_H = \frac{\ell^2}{\phi_m \phi_h}\left|\frac{dU}{dz}\right|,$$

Use relation between $Ri$ and $z/L$

$$Ri = \frac{g}{\theta_v}\frac{d\theta_v/dz}{|dU/dz|^2} = \frac{g}{\theta_v}\frac{z\theta_* \phi_h}{u_*^2 \phi_m^2} = \frac{z}{\kappa L}\frac{\phi_h}{\phi_m^2}$$

to solve for $z/L$ .

⬇

$$K_M = \ell^2\left|\frac{dU}{dz}\right| f_M(R_i), \quad K_H = \ell^2\left|\frac{dU}{dz}\right| f_H(R_i)$$

# Stable boundary layer in the IFS: closure and caveats

$$K = \left|\frac{\partial U}{\partial z}\right| l^2 f(Ri)$$

$1/l = 1/kz + 1/\lambda$

## Until 2013 (36R4 – 38R2)

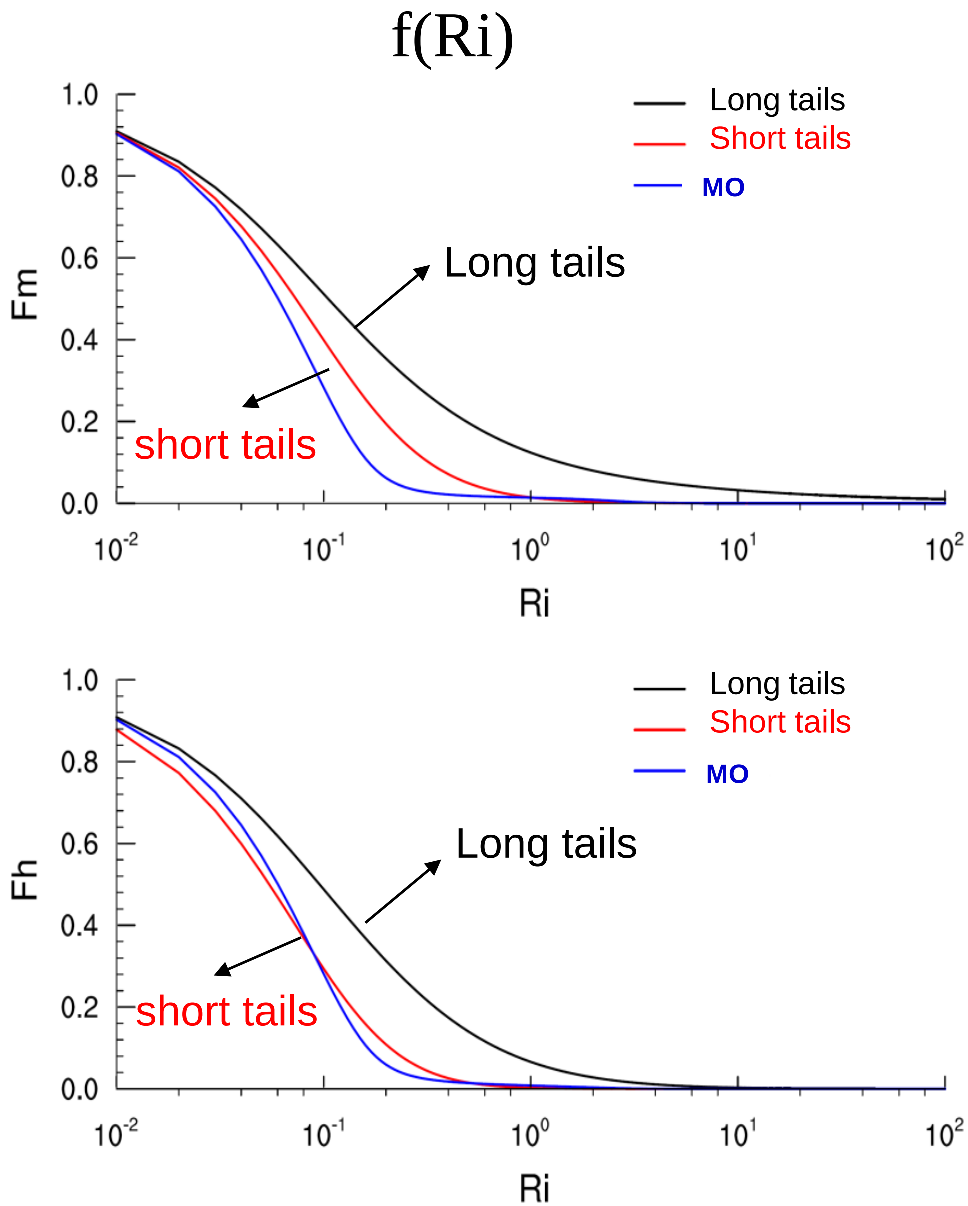
Surface layer – Monin Obukhov

Above: $f = \alpha * f_{LT} + (1-\alpha) * f_{ST}$

$\alpha = \exp(-H/150)$

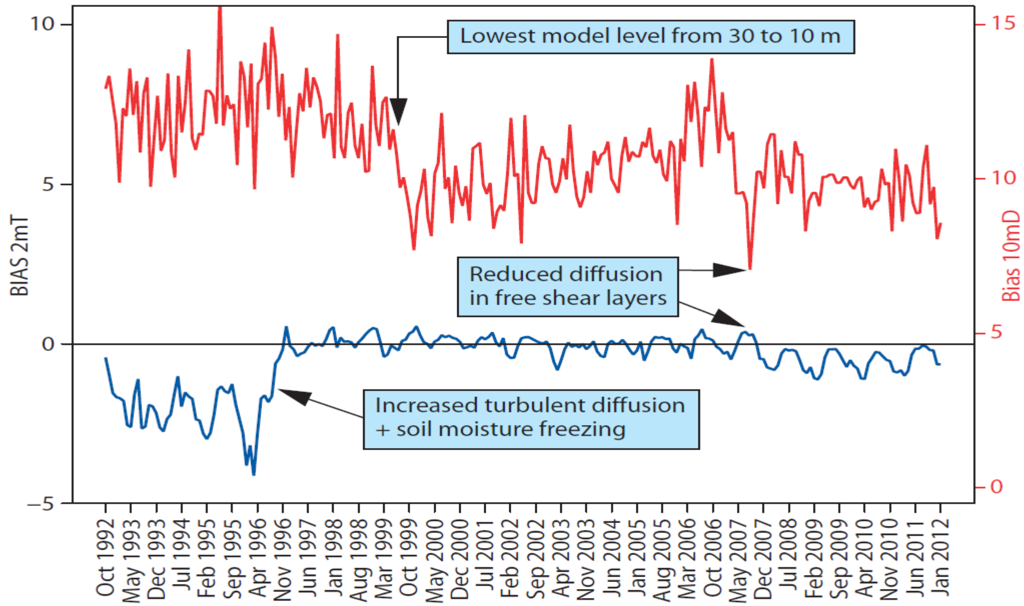
$\lambda$=150m

As in other NWP models the diffusion maintained in stable conditions is stronger than what LES or observations indicate



# Stable boundary layer in the IFS: closure and caveats

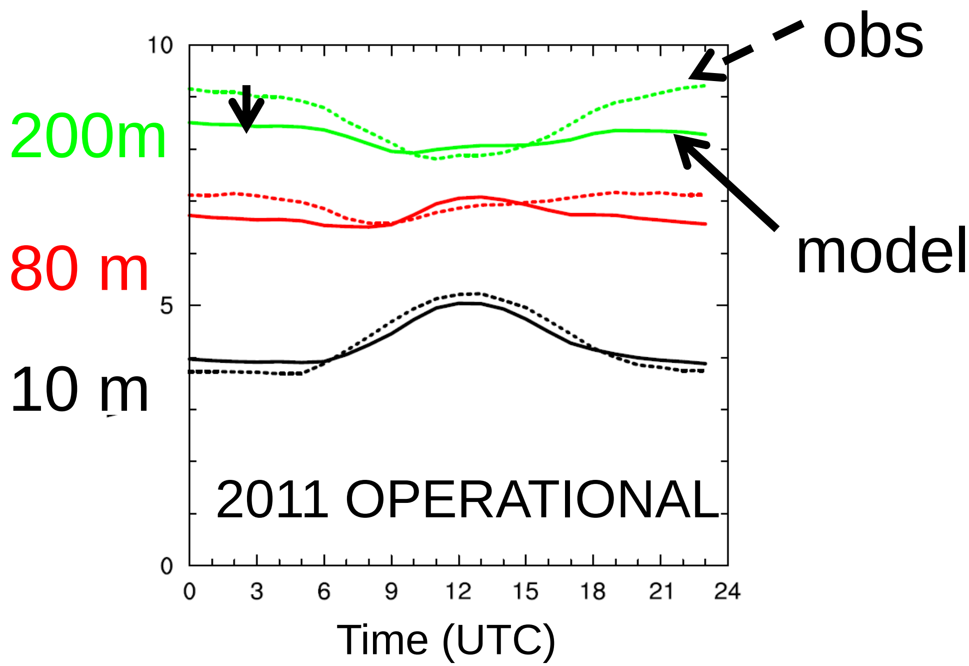
Mean nocturnal bias over Europe




Wind turning is underestimated

2m T is too low despite too strong diffusion

Mean annual wind speed at Cabaw

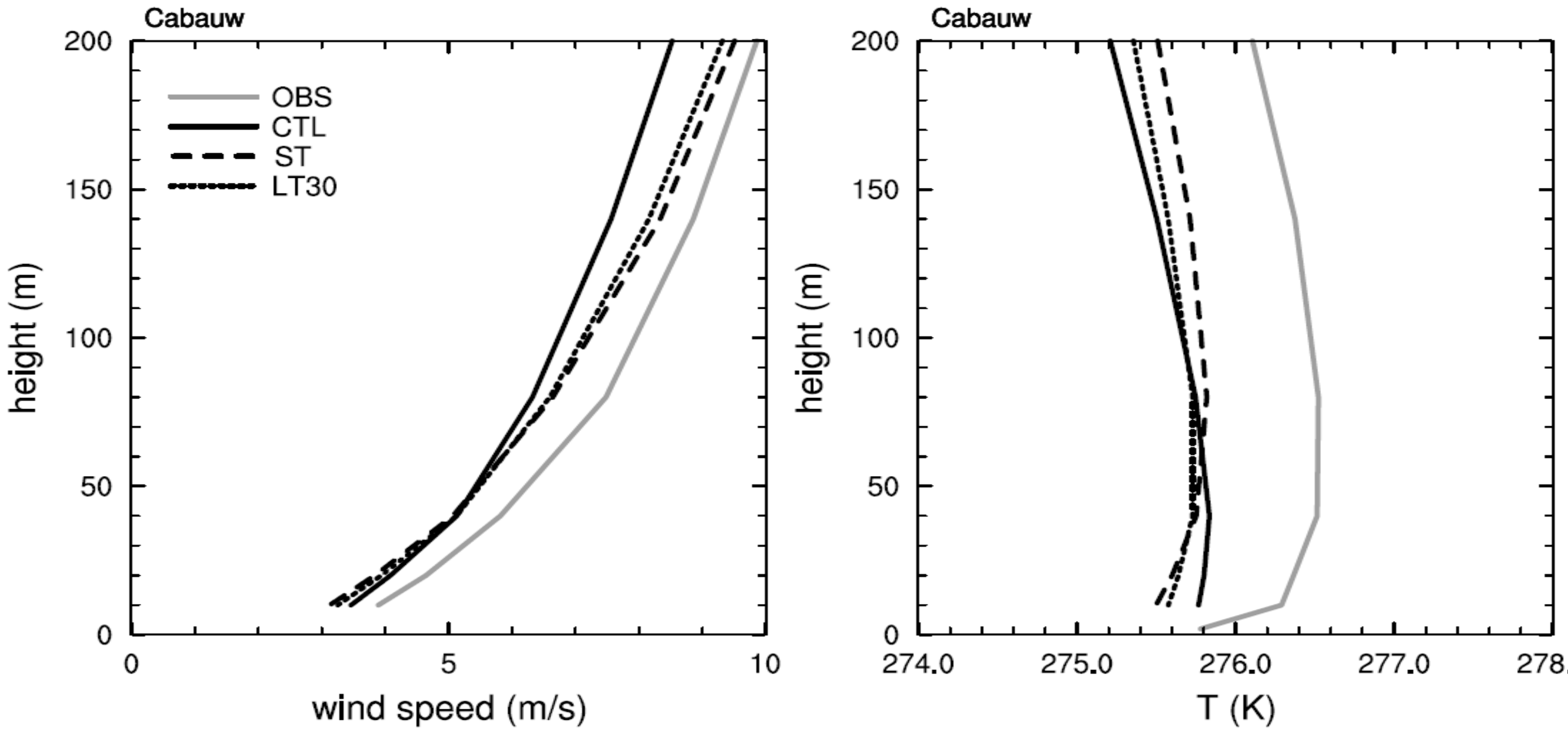


# Impact of reducing the diffusion in stable conditions

**ST: long tails ⟶ short tails**
**LT30: λ=150m ⟶ λ=30m**

$$K = \left|\frac{\partial U}{\partial z}\right| l^2 f(Ri)$$

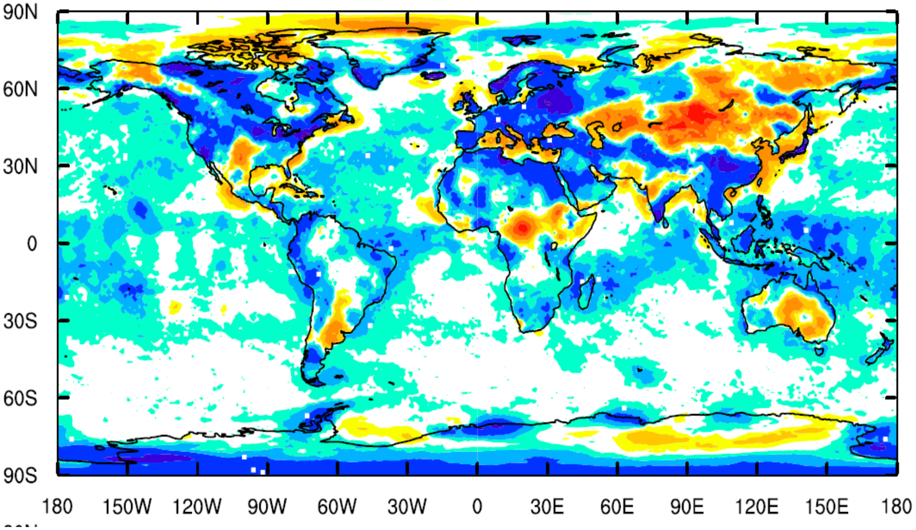
$1/l = 1/kz + 1/\lambda$ , $\lambda$=150m

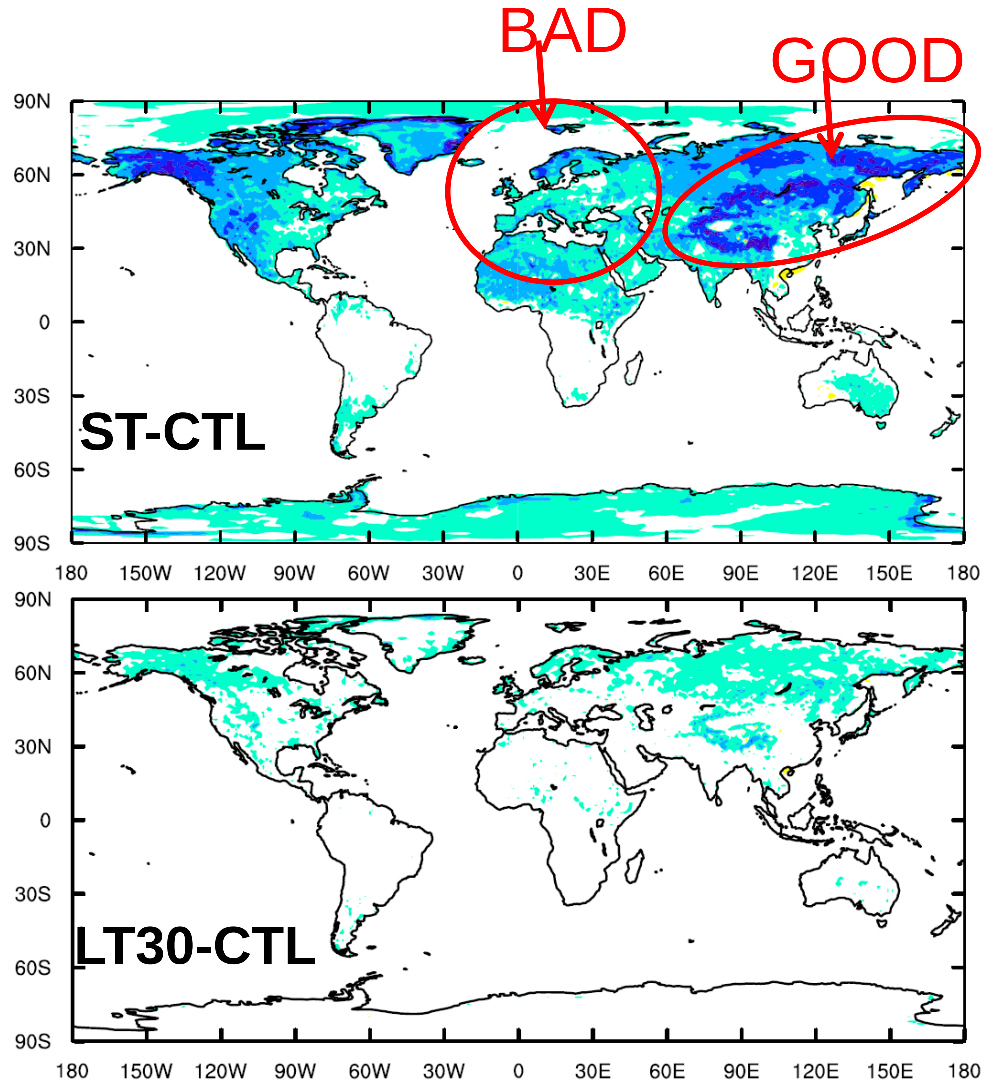



Almost halves the errors in low level jet, also increases the wind turning

# Impact of reducing the diffusion in stable conditions

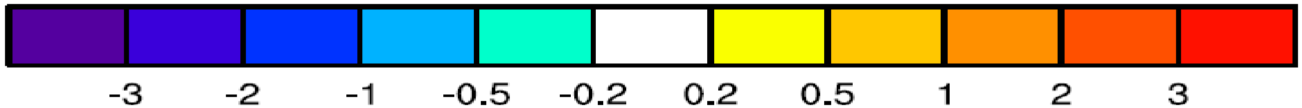
**Bias (FC-AN) T2m CTL**



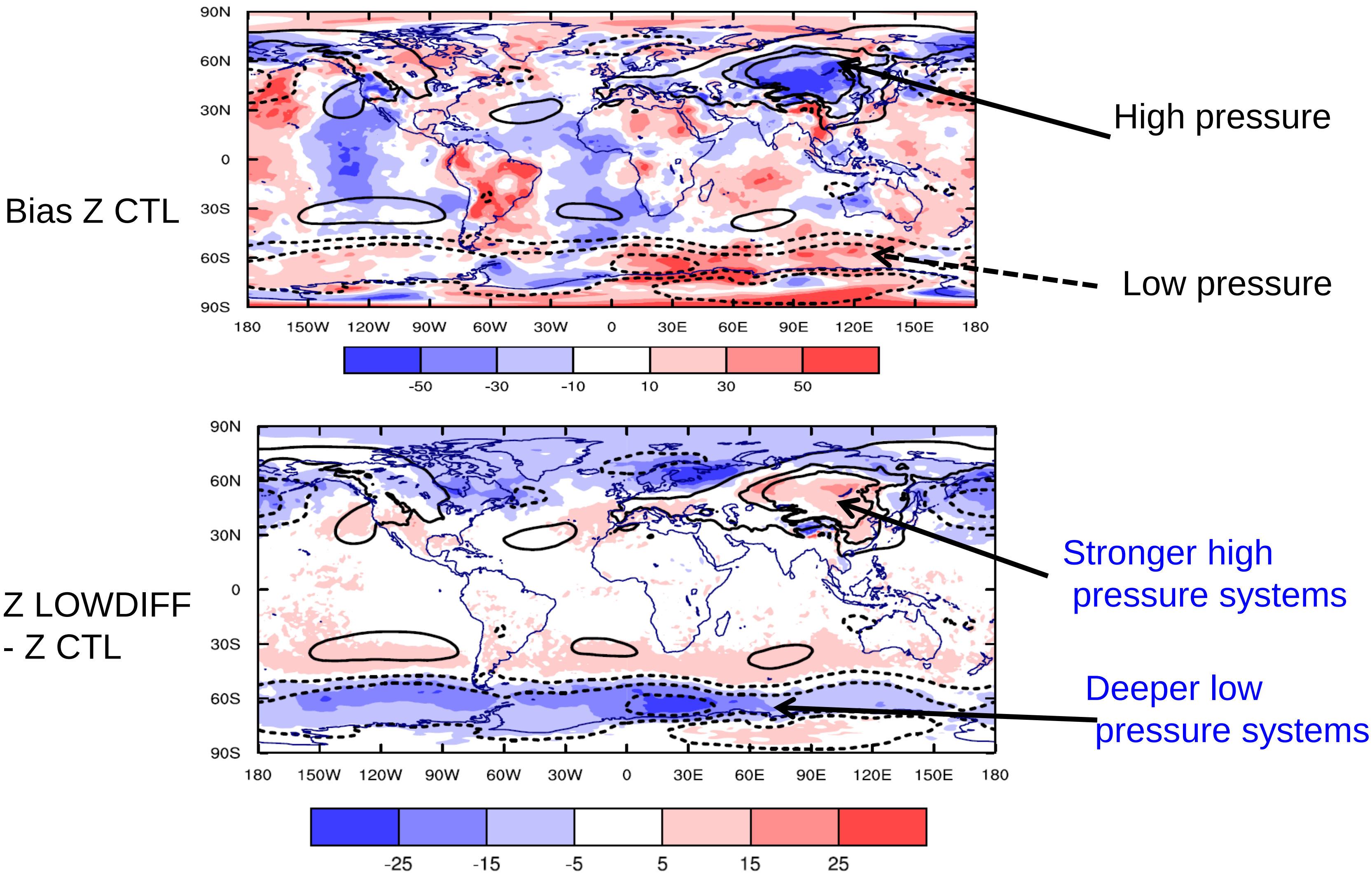




**ST: long tails ⟶ short tails**

**LT30: λ=150m ⟶ λ=30m**

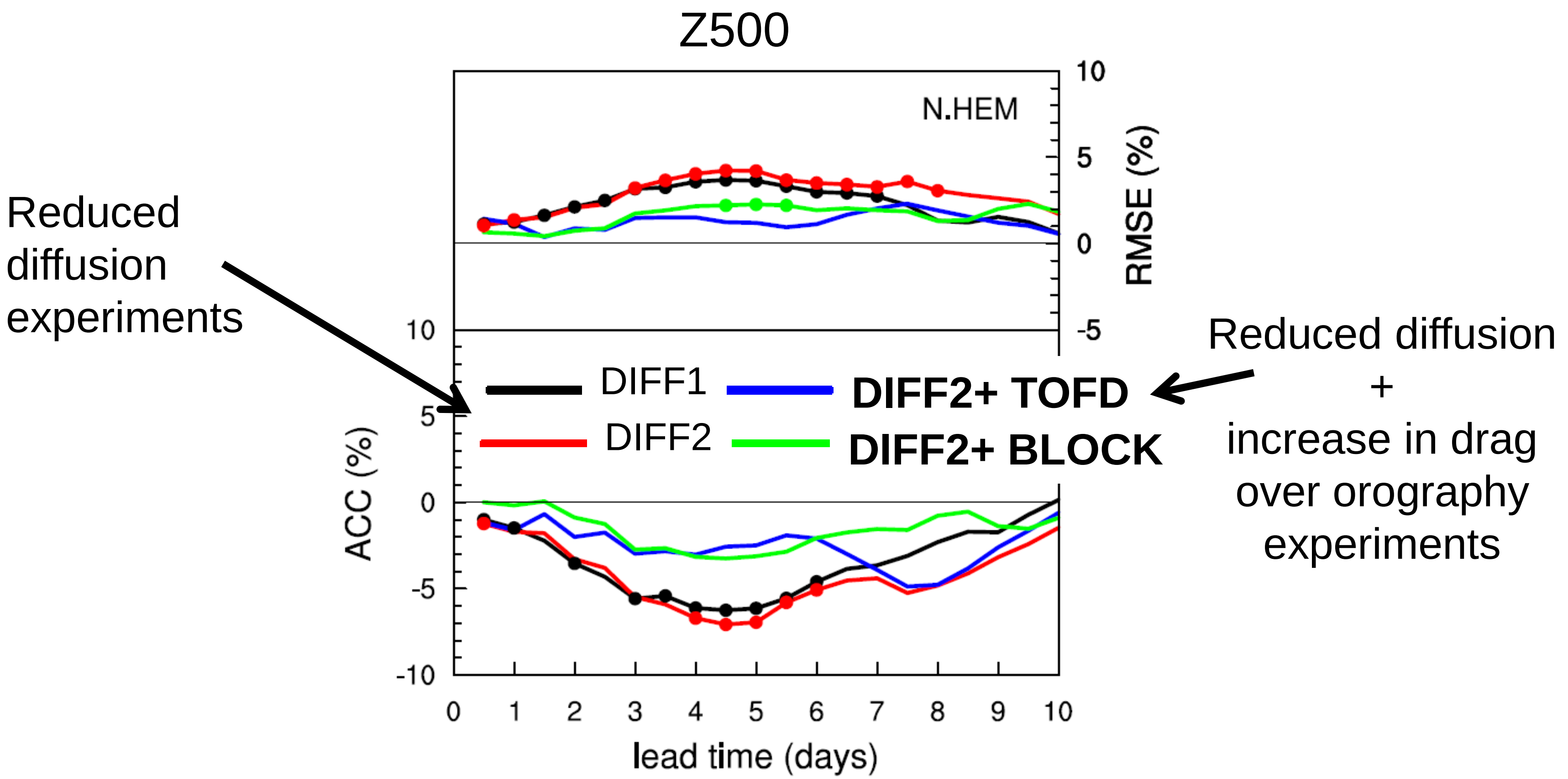


# Reduced diffusion also impacts NH winter circulation




*Sandu et al, 2013, Beare 2007, Svensson et al 2009*

# Compensating errors in NWP




- reduced diffusion in stable layers = deterioration of forecast performance
- the deterioration due to reduced diffusion is outweighed by an increase in orographic drag

*Sandu et al, 2013*

# Stable boundary layer : changes to closure in 40R1 (Nov. 2013)

Turbulence closure for stable conditions: $K_{M,H} = \left|\frac{\partial U}{\partial Z}\right| l^2 f_{M,H}(R_i), \quad \frac{1}{l} = \frac{1}{kz} + \frac{1}{\lambda}$

Up to 38R2

- long tails near surface, short tails above PBL
- λ =150m
- non-resolved shear term, with a maximum at 850hPa

→

From 40R1

- long tails everywhere
- λ = 10% PBL height in stable boundary layers
- λ = 30 m in free shear layers

+

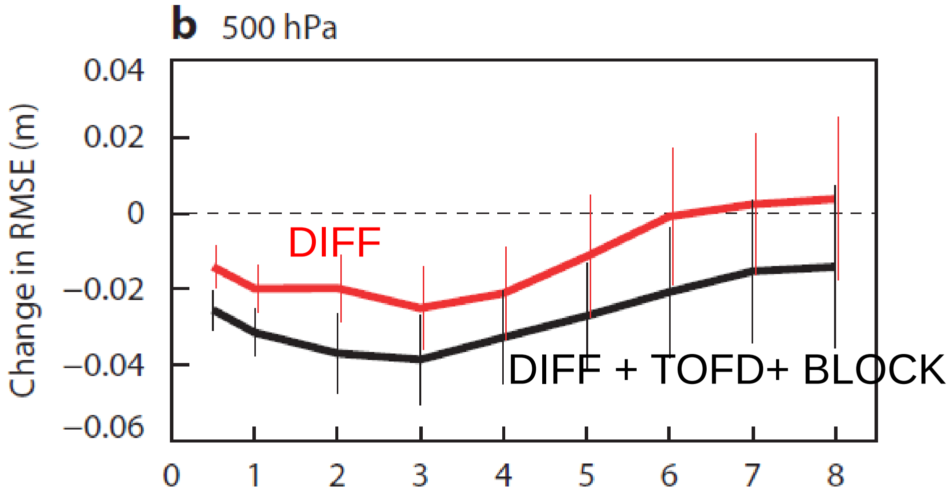
Increase in drag over orography
Increase in atm/surf coupling

Consequence: net reduction in diffusion in stable boundary layers, not much change in free-shear layers, except at 850 hPa

*ECMWF Newsletter, no 138*

# Stable boundary layer : changes to closure in 40R1 (Nov. 2013)

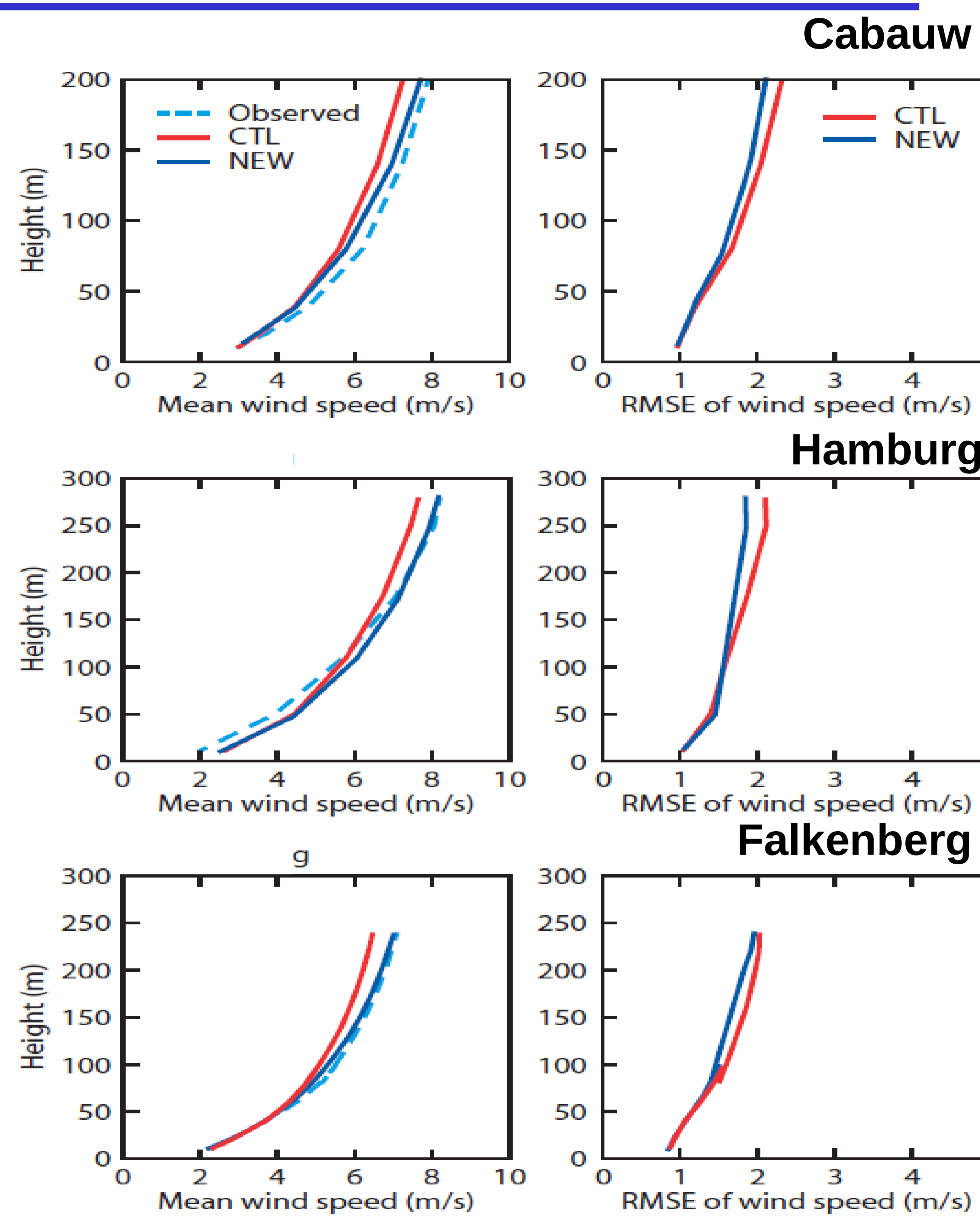
- small changes in 2m temperature during nigh time in winter (~0.1 K over Europe)
- Reduction of wind direction bias over Europe by 3° in winter, 1 ° in summer (out of 7 °)
- Improvement in low level jets (next slide)
- Improvement of the large-scale performance of the model in winter N.Hemisphere
- Deterioration of tropical wind scores (against own analysis, not against observations)



# Improvement of low level winds

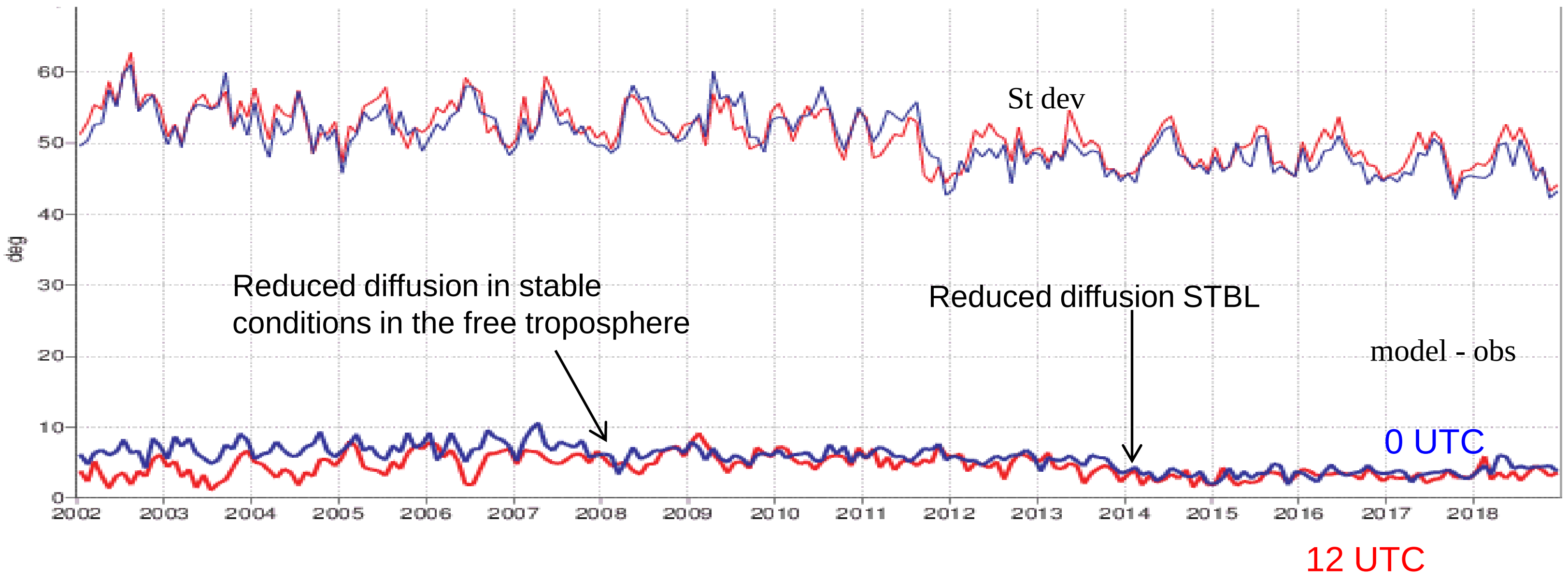
Comparison with tower data
T511L137 analysis runs
JJA 2012, 0 UTC, step 24h

Improvement in both mean and RMSE in the upper part of stable boundary layers



# Historical evolution of 10m wind direction biases in IFS

**Europe**



# K-closure with local stability dependence (summary)

$$K = \left|\frac{\partial U}{\partial z}\right| \cdot l^2 \cdot f\left(Ri\right)$$

☞ Scheme is simple and easy to implement.

☞ Fully consistent with local scaling for stable boundary layer.

☞ A sufficient number of levels is needed to resolve the BL i.e. to locate inversion.

☞ Entrainment at the top of the boundary layer is not represented

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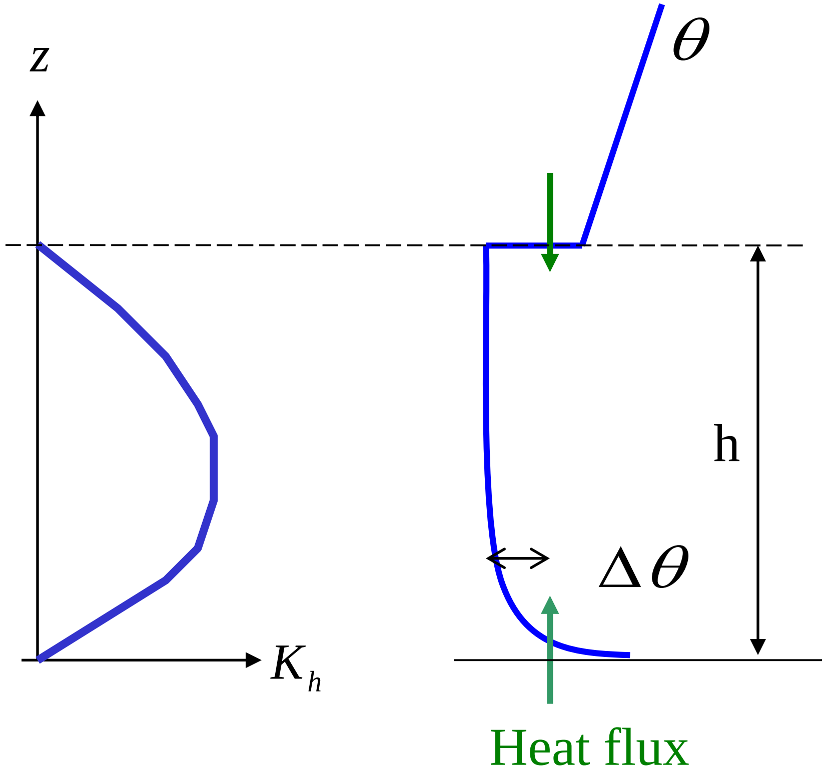
# K-profile closure Troen and Mahrt  (1986)

$$\overline{\theta' w'} = -K_H \left( \frac{\partial \theta}{\partial z} - \gamma_\theta \right)$$




Profile of diffusion coefficients:

$$K_H = w_s \, \kappa \, z (1 - z/h)^2$$

$$w_s = \left( u_*^3 + C_1 w_*^3 \right)^{1/3}$$

$$\gamma_\theta = C \overline{\theta' w'}^s / w_s h$$

Find inversion by parcel lifting
with   T-excess:

$$\theta_{vs} = \theta_s + \Delta\theta, \quad \Delta\theta = D \overline{w' \theta_v{}'}^s / w_s$$

such that:

$$Ri_c = h \frac{g}{\theta_v} \frac{\theta_{vh} - \theta_{vs}}{U_h^2 + V_h^2 - U_s^2 - V_s^2} = 0.25$$

# K-profile closure (summary)

- ☞ Scheme is simple and easy to implement.
- ☞ Numerically robust.
- ☞ Scheme simulates realistic mixed layers.
- ☞ Counter-gradient effects can be included (might create numerical problems).
- ☞ Entrainment can be controlled rather easily.
- ☞ A sufficient number of levels is needed to resolve BL e.g. to locate inversion.

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# K-diffusion versus Mass flux method

K-diffusion method - used to describe the small-scale turbulent motions:

$$\overline{\phi' w'} \approx -K \frac{\partial \overline{\phi}}{\partial z}$$

$$\frac{\partial \overline{\phi' w'}}{\partial z} \approx \frac{\partial}{\partial z}\left( -K \frac{\partial \overline{\phi}}{\partial z} \right) \approx -K \frac{\partial^2 \overline{\phi}}{\partial z^2}$$

analogy to molecular diffusion

Mass-flux method – used to describe the strong large-scale updraughts:

$$\overline{\phi' w'} \approx M(\phi^{up} - \overline{\phi})$$

mass flux

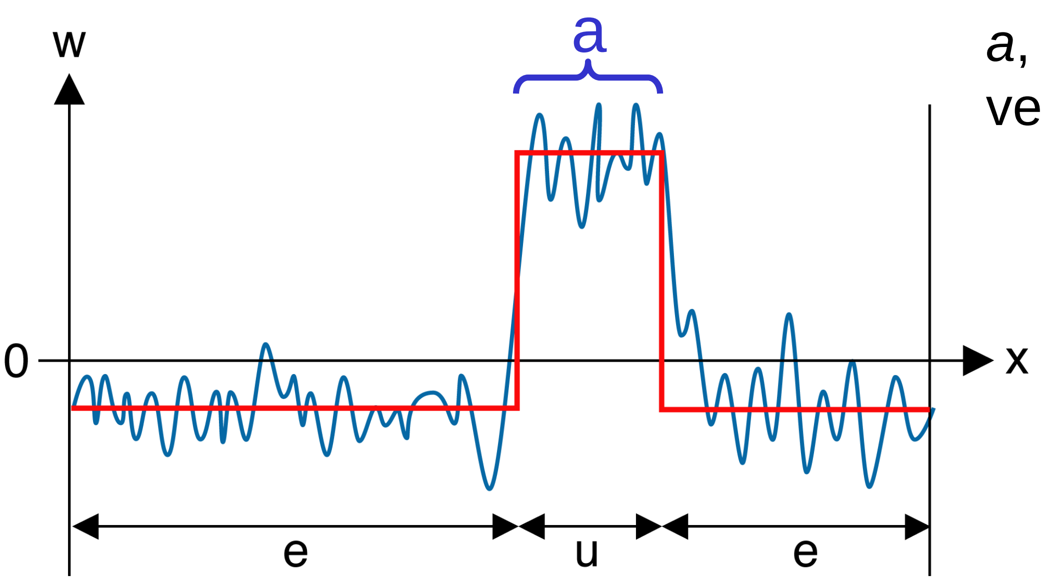
$$\frac{\partial}{\partial z}\phi^{up} = -\varepsilon\left(\phi^{up} - \overline{\phi}\right)$$

entraining plume model

$$\frac{\partial M}{\partial z} = (\varepsilon - \delta)M$$

detrainment rate

# ED/MF framework




The updraught: small fractional area *a*, containing the strongest upward vertical motions

$$\phi_u = \phi'_u + \overline{\phi_u}^u$$

$$\phi_e = \phi'_e + \overline{\phi_e}^e$$

$$\overline{\phi} = a\overline{\phi_u}^u + (1-a)\overline{\phi_e}^e$$

$$a << 1$$

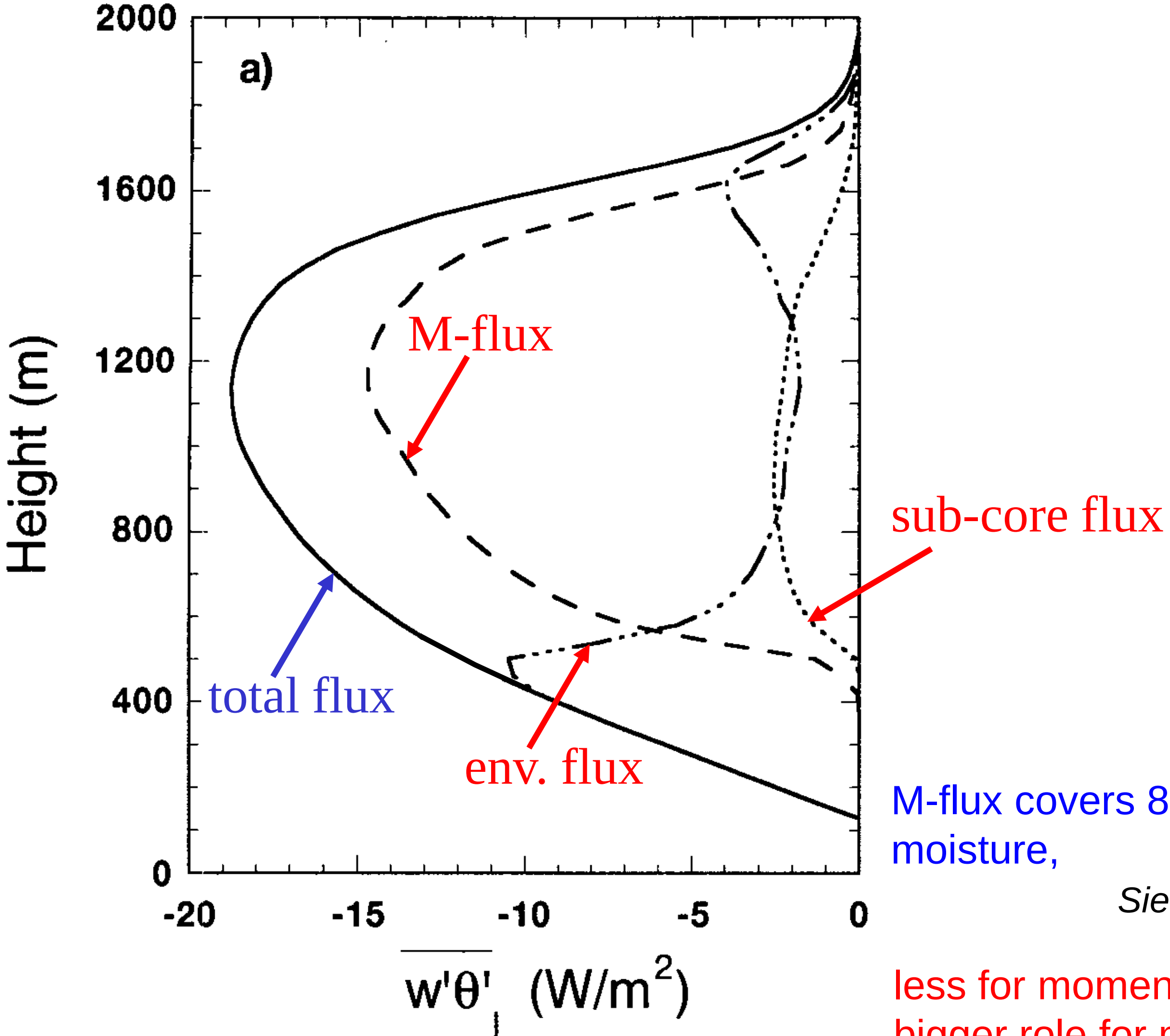
$$-K\frac{\partial\overline{\phi}}{\partial z}$$

$$\overline{w'\phi'} = a\overline{w'\phi'_u}^u + (1-a)\overline{w'\phi'_e}^e + \frac{M}{\rho}(\phi_u - \overline{\phi}) \quad , \qquad M = \rho a w_u$$

sub-core flux (neglected) — env. flux — M-flux

Siebesma & Cuijpers, 1995

# BOMEX LES decomposition




M-flux covers 80% of the flux for heat and moisture,

*Siebesma & Cuijpers, 1995*

less for momentum – environment plays a bigger role for momentum transport

*Zhu 2015, Schlemmer et al, 2016*

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# TKE closure (1.5 order)

Eddy diffusivity approach:

$$\overline{u'w'} = -K_M \frac{\partial \overline{u}}{\partial z}, \quad \overline{v'w'} = -K_M \frac{\partial \overline{v}}{\partial z}$$

$$\overline{\theta'w'} = -K_H \frac{\partial \overline{\theta}}{\partial z}, \quad \overline{q'w'} = -K_H \frac{\partial \overline{q}}{\partial z}$$

With diffusion coefficients related to kinetic energy:

$$K_M = C_K \ell_K E^{1/2}, \quad K_H = \alpha_H K_M$$

# Closure of TKE equation

TKE from prognostic equation:

$$\frac{\partial E}{\partial t} = -\overline{u'w'}\frac{\partial U}{\partial z} - \overline{v'w'}\frac{\partial V}{\partial z} - \frac{g}{\rho_o}\overline{\rho' w'} + \frac{\partial}{\partial z}\left(\overline{E'w'} + \frac{\overline{p'w'}}{\rho}\right) - \varepsilon$$

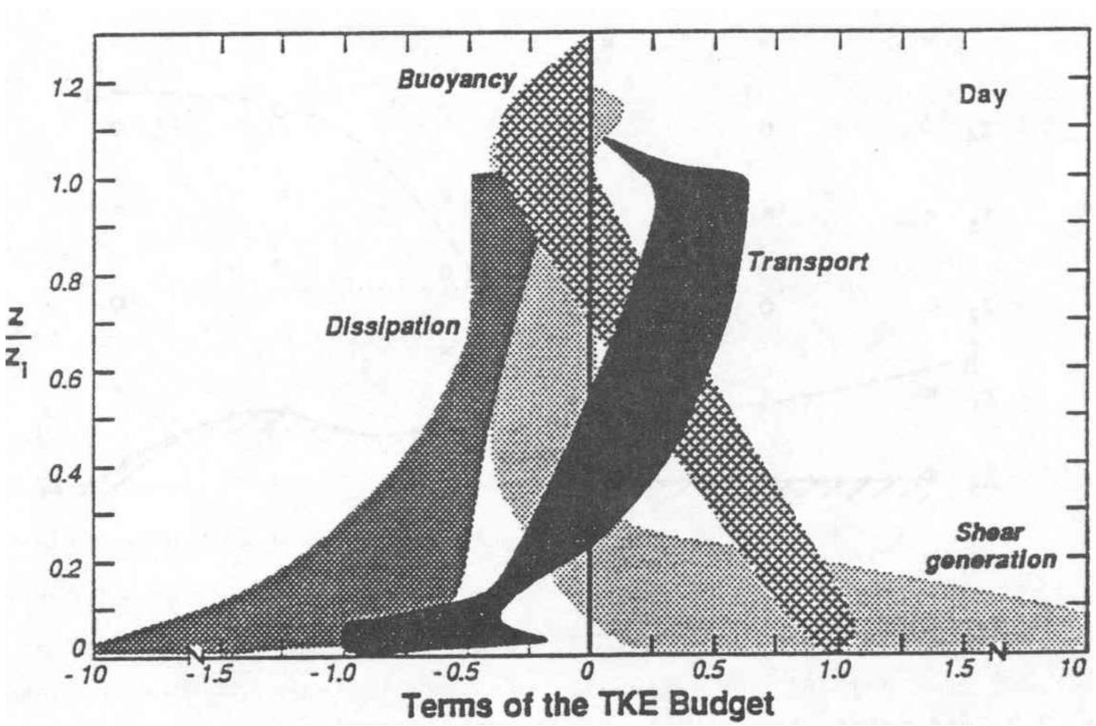
Storage — Shear production — Buoyancy — Turbulent transport — Pressure correlation — Dissipation

with closure:

$$\varepsilon = C_\varepsilon \frac{E^{3/2}}{\ell_\varepsilon}, \qquad \left(\overline{E'w'} + \frac{\overline{p'w'}}{\rho}\right) = -K_E \frac{\partial E}{\partial z}$$

Main problem is specification of length scales, which are usually a blend of $\kappa z$, an asymptotic length scale $\lambda$ and a stability related length scale in stable situations.

# TKE (summary)




- TKE has natural way of representing entrainment.
- TKE needs more resolution than first order schemes.
- TKE does not necessarily reproduce MO-similarity.
- Stable boundary layer may be a problem.

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# Current turbulence closure in the ECMWF model

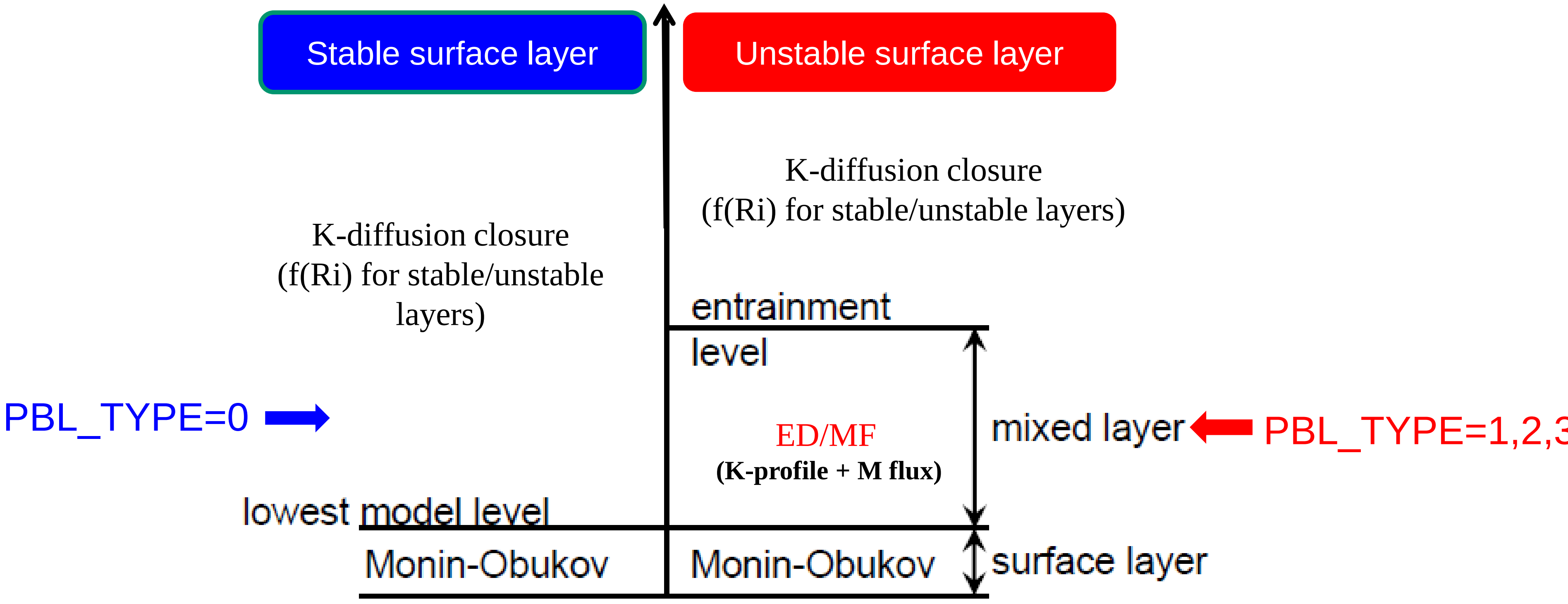
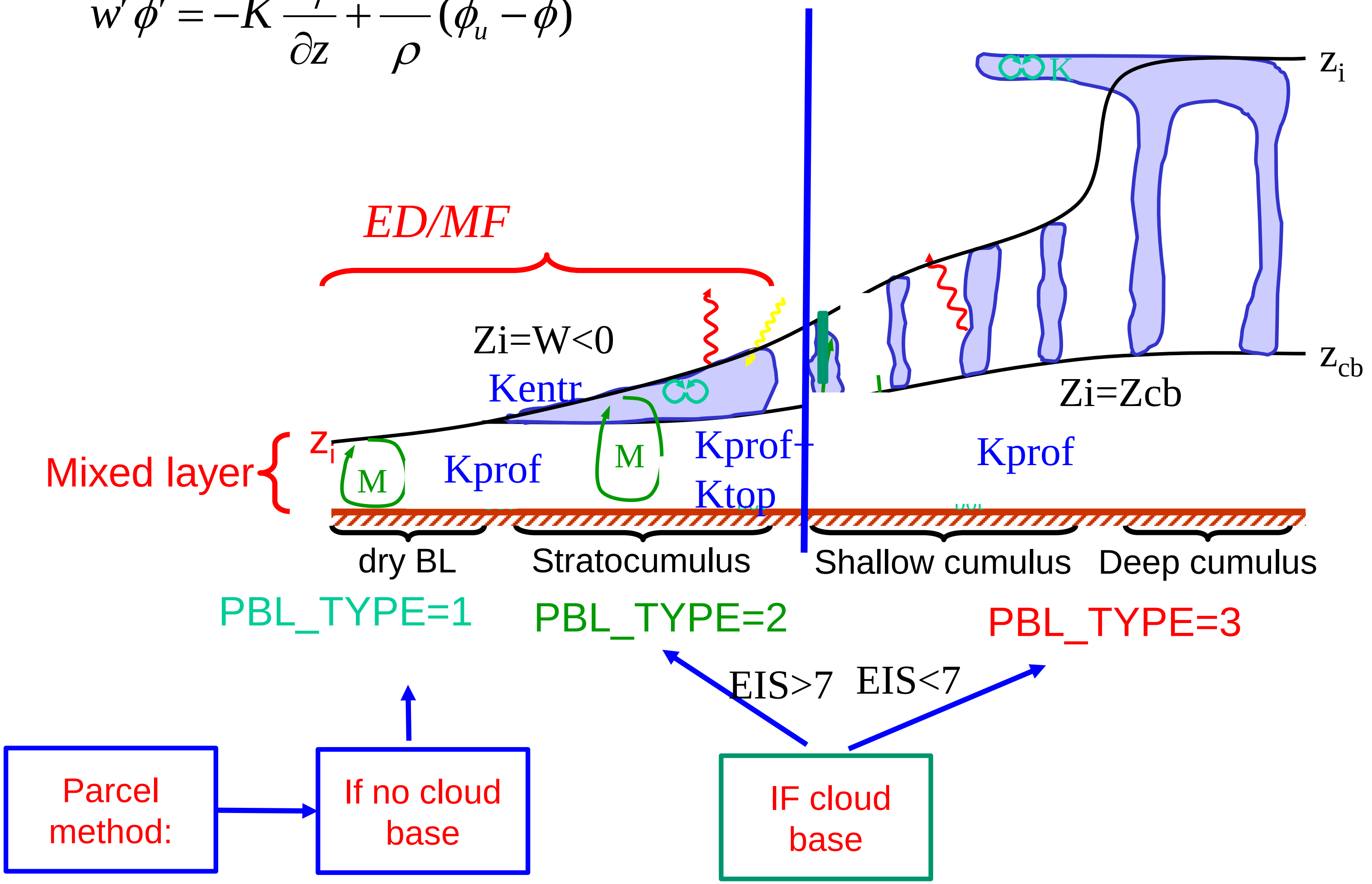



**Figure 3.1** *Schematic diagram of the different boundary layer regimes.*

# Unstable surface layer : ED/MF approach in the PBL

$$\overline{w'\phi'} = -K\frac{\partial\overline{\phi}}{\partial z} + \frac{M}{\rho}(\phi_u - \overline{\phi})$$



# Caveats and challenges

- If stratocumulus (PBL_TYPE=2)
  - no shallow convection
  - Extra Kdiff due to cloud top radiative cooling
  - mixing in thetal, qt, then qc computed with simple pdf scheme, and given to cloud scheme
  - only scheme which gives explicitly dqc to cloud scheme

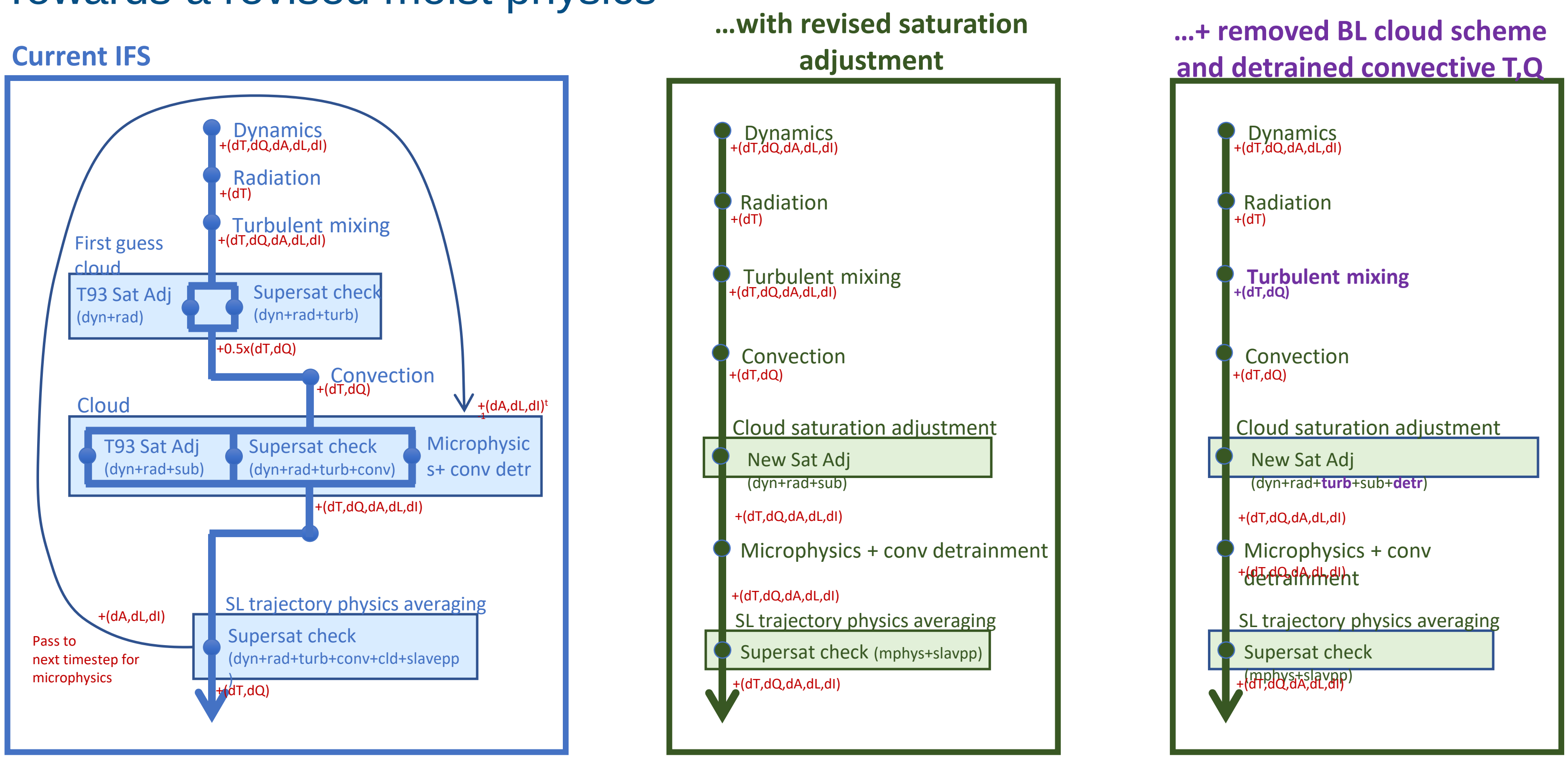
- If decoupled (PBL_TYPE=3)
  - No top entrainment
  - No mass flux from PBL

- PBL parcel different from shallow convection parcel

- Handling of stratocumulus to cumulus transitions

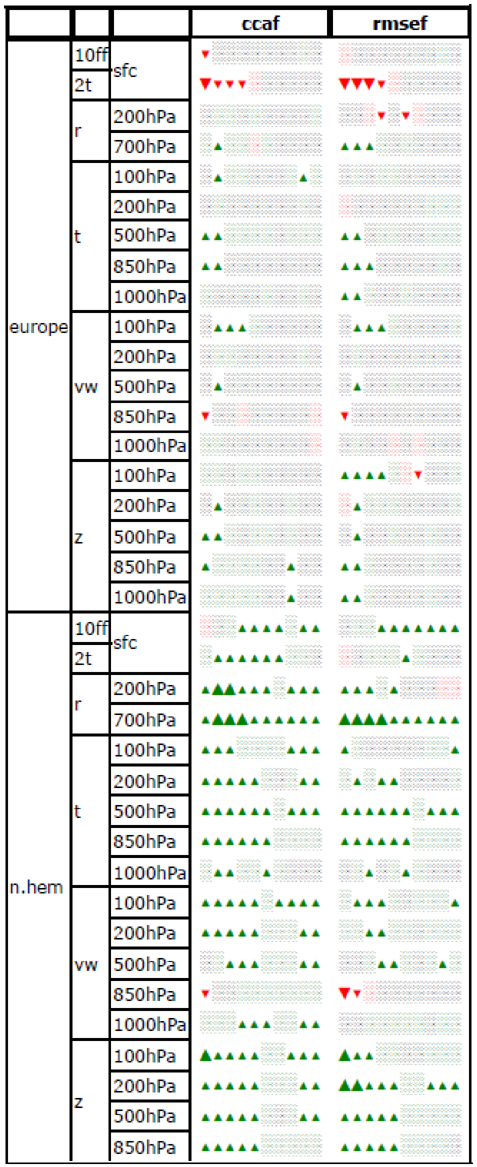
Ongoing work towards a more better interaction between diffusion, shallow convection and cloud schemes

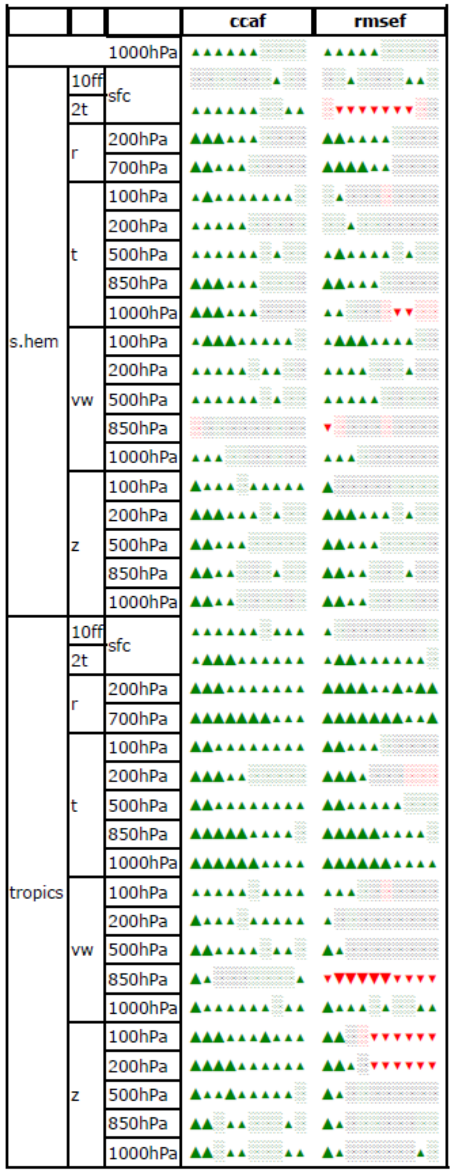
# Towards a revised moist physics




Consistency and interaction between parametrizations as important as the parametrizations themselves

# Physics Expts for 39r1 (fulj-ftjl) ownan
Winter 20120101-20120321 (81 days)




# Physics Expts for 39r1 (ful4-ftjq) ownan
Summer 20120601-20120821 (82 days)