Parametrization of PBL outer layer

Irina Sandu

- Overview of models
- Bulk models
- Local K-closure
- ED/MF closure
- K-profile closure
- TKE closure
- Current closure in the ECMWF model

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

Parametrization of PBL outer layer (overview)

Parametrization	Application	Order and Type of Closure
Bulk models	Models that treat PBL top as surface	0th order non-local
K-diffusion	Models with fair resolution	1st order local
Mass-flux	Models with fair resolution	1st order non-local
ED/MF (K& M)	Models with fair resolution	1st order non-local
K-profile	Models with fair resolution	1st order non-local
TKE-closure	Models with high resolution	1.5th order non-local
Higher order closure	Models with high resolution	2nd or 3rd order non-local

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Local K closure

K-diffusion in analogy with molecular diffusion, but

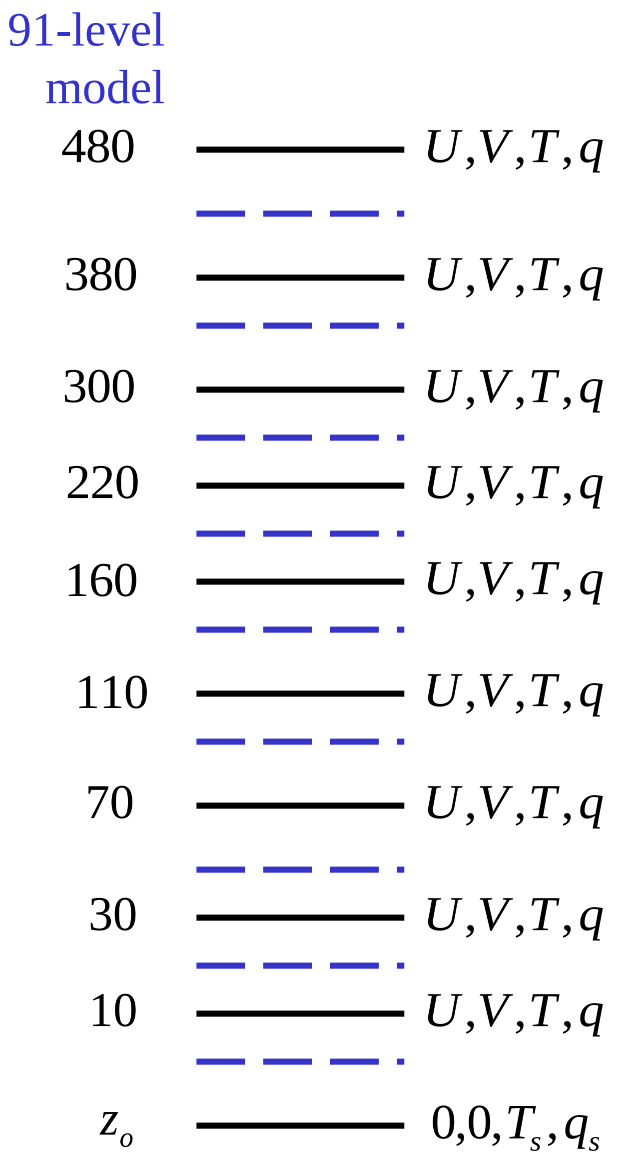
$$\overline{u'w'} = -K_M \frac{\partial \overline{u}}{\partial z}, \quad \overline{v'w'} = -K_M \frac{\partial \overline{v}}{\partial z}$$

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

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

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

Levels in ECMWF model



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/λ , λ=150m

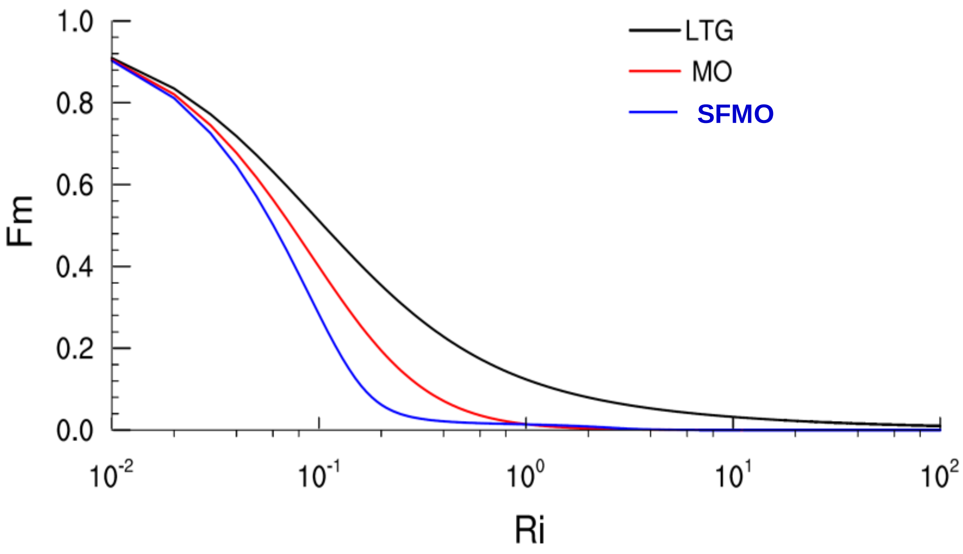
Recent years (36R4 – 38R2)

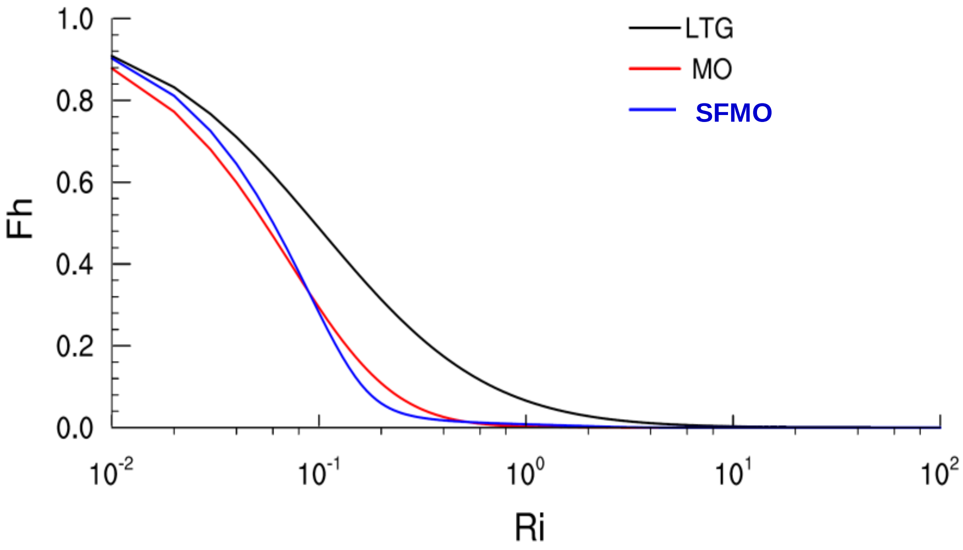
Surface layer – SFMO

Above: f = α* fLTG + (1- α) * fMO

α = exp(-H/150)

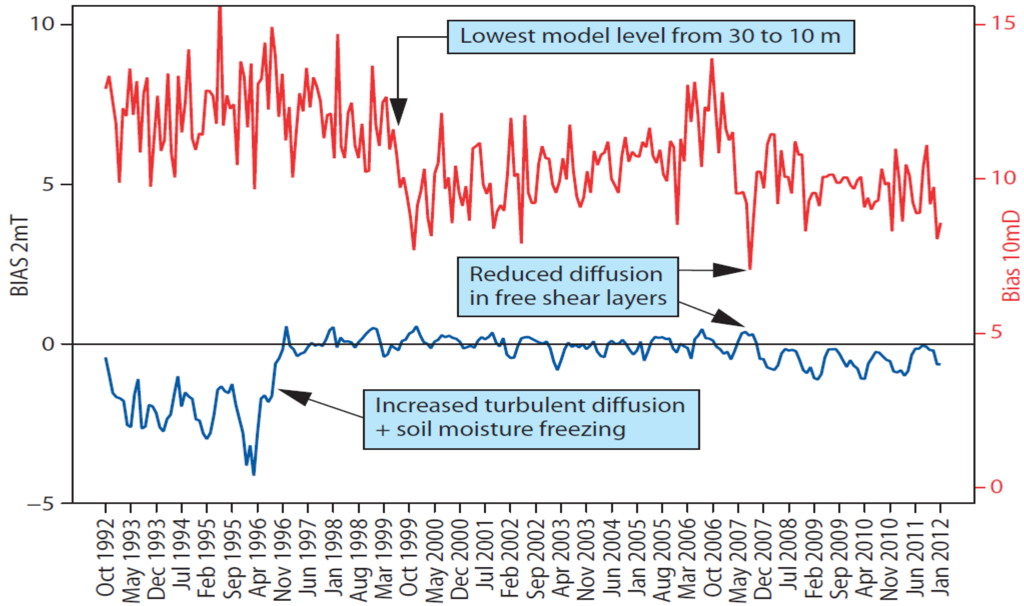
As in other NWP models the diffusion maintained in stable conditions is stronger than what LES or observations indicate





Stable boundary layer in the IFS: closure and caveats

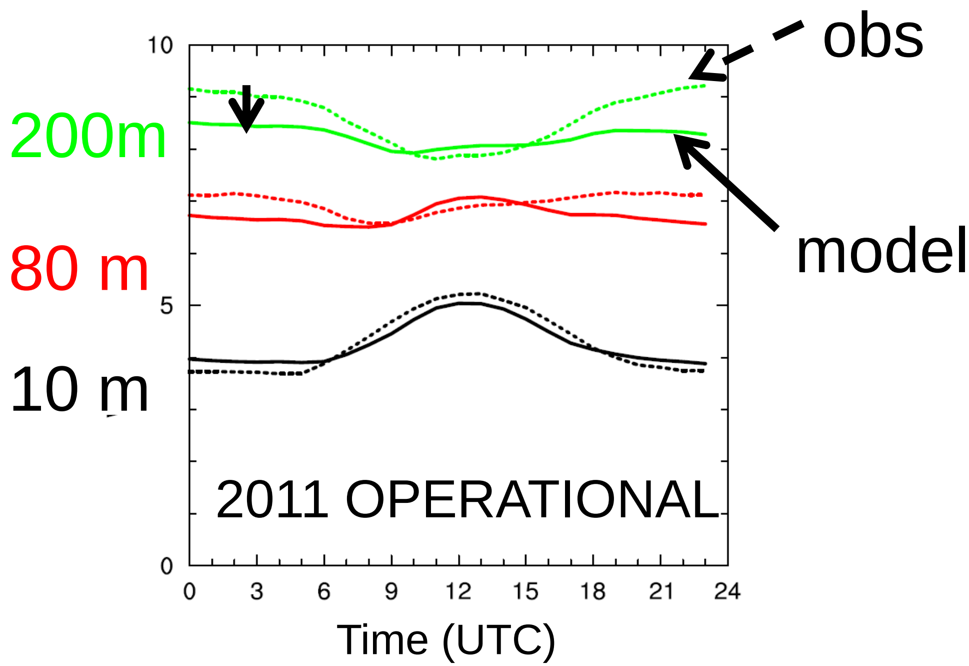
Mean nocturnal bias over Europe



Wind turning is underestimated

2m T is too low despite too strong diffusion

Mean annual wind speed at Cabaw

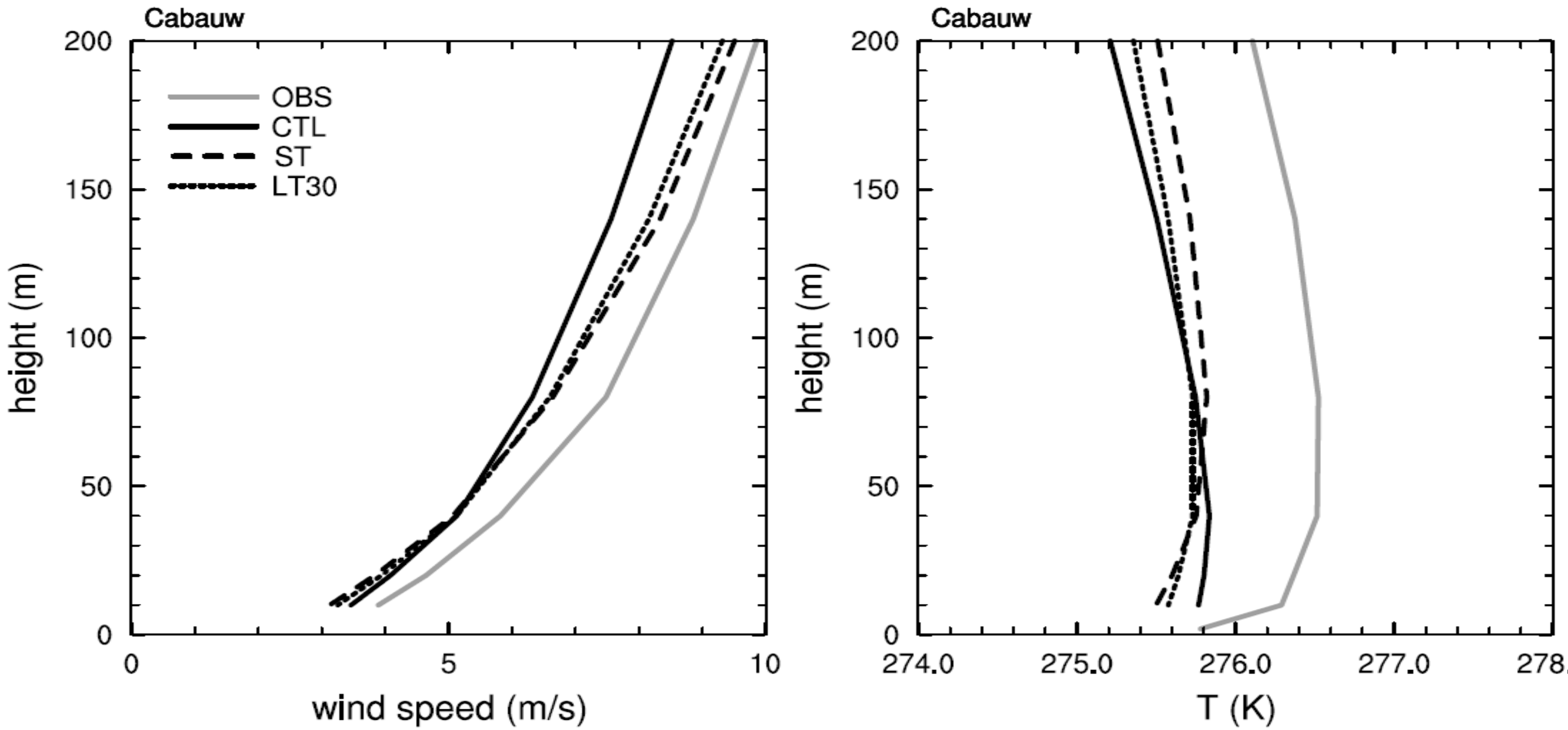


Impact of reducing the diffusion in stable conditions

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

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

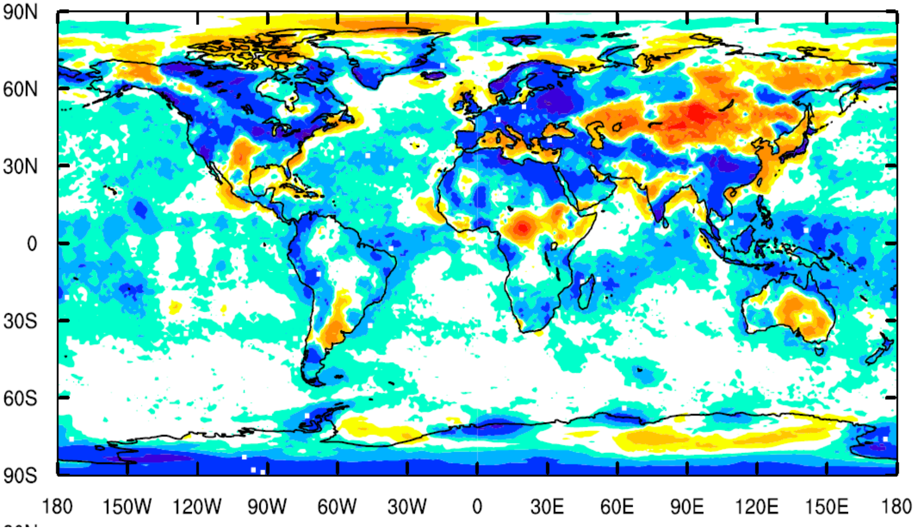
1/l=1/kz+1/λ , λ=150m

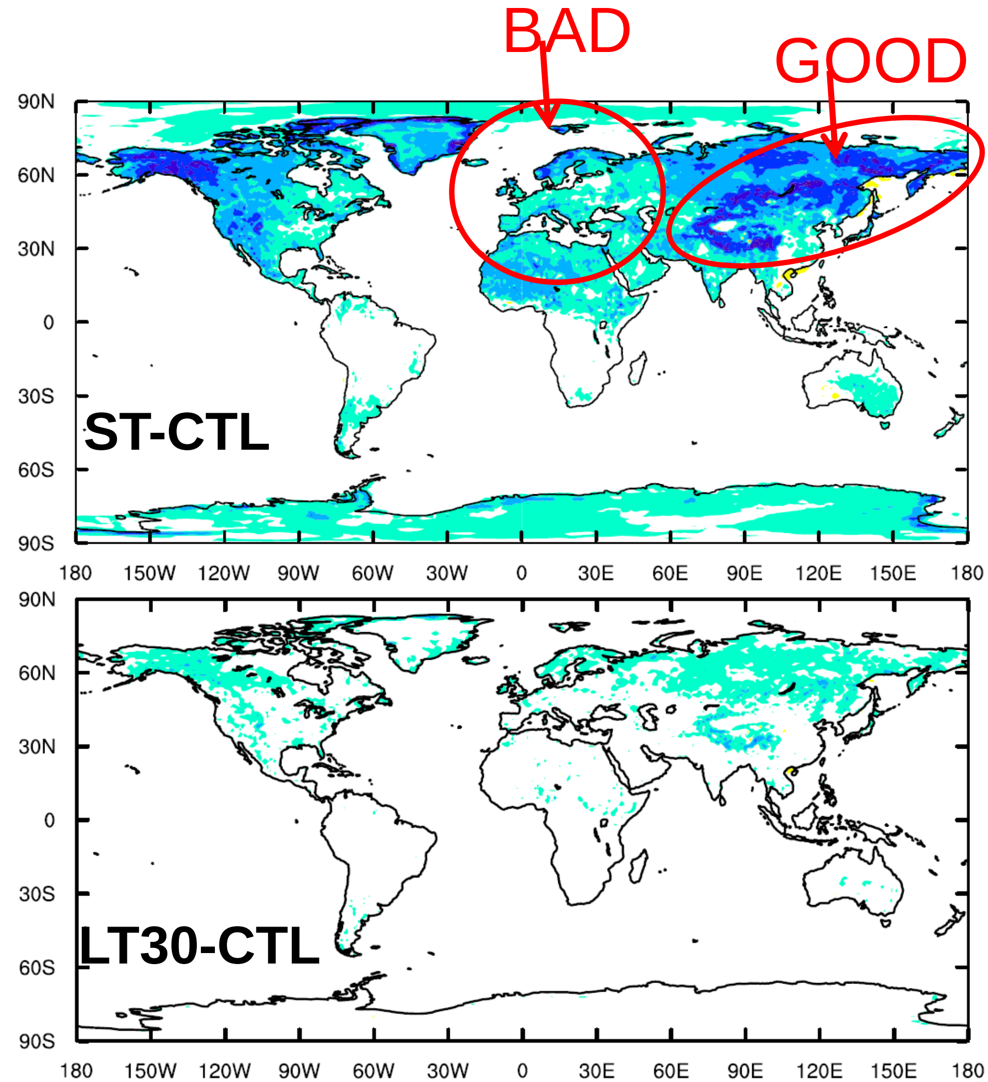


Almost halves the errors in low level jet, also increases the wind turning

Impact of reducing the diffusion in stable conditions

Bias (FC-AN) T2m CTL





ST: long tails ⟶ short tails

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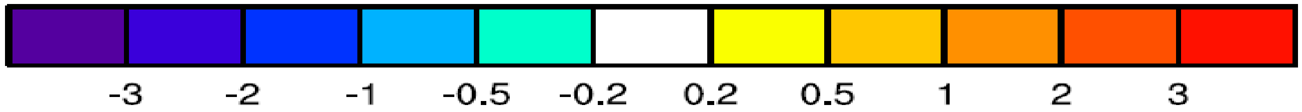


Stable boundary layer : changes to closure in 40R1 (Nov. 2013)

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

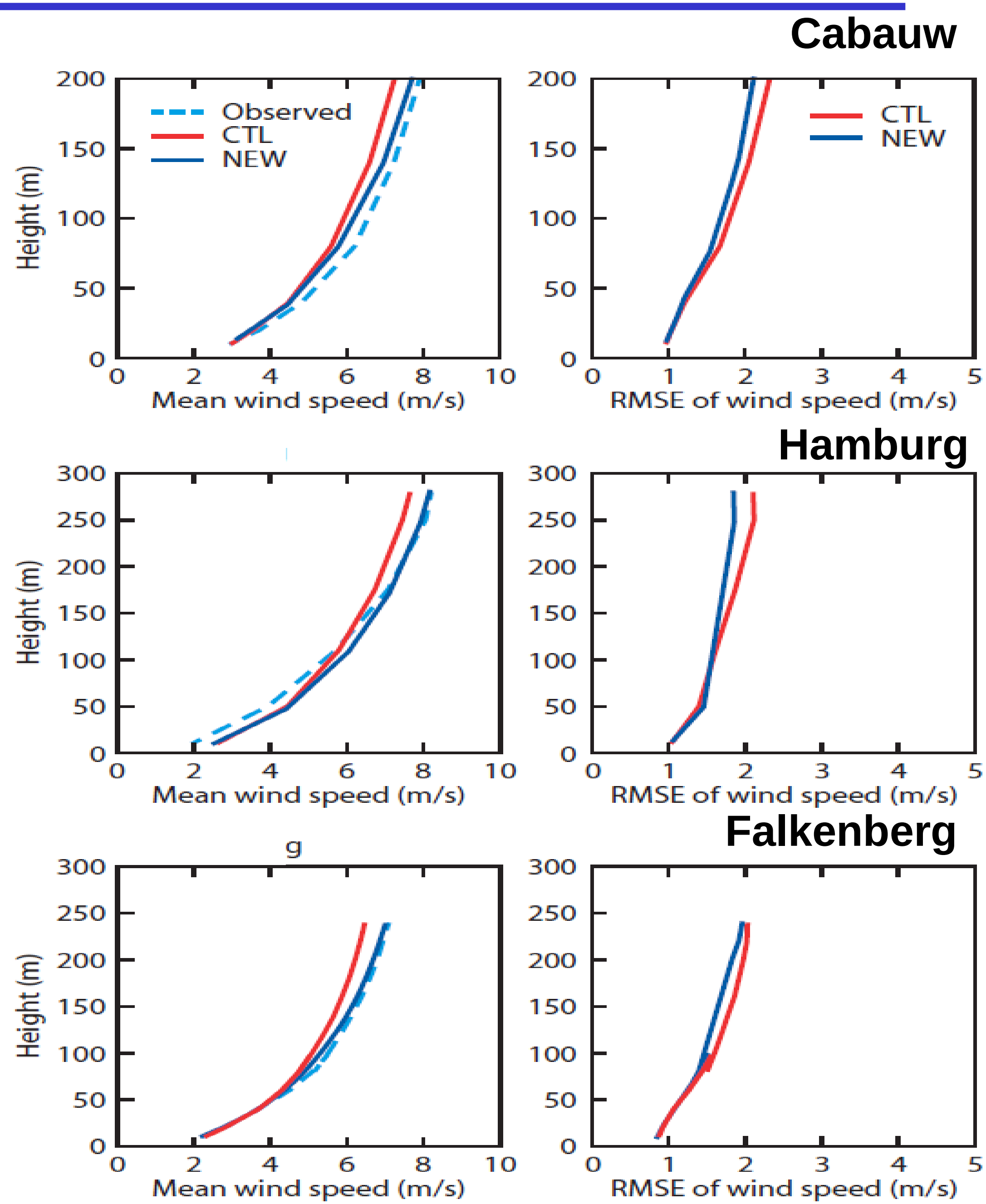
Consequence: net reduction in diffusion in stable boundary layers, not much change in free-shear layers, except at 850 hPa

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 10 °
- 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

K-closure with local stability dependence (summary)

☞ Scheme is simple and easy to implement.

☞ Fully consistent with local scaling for stable boundary layer.

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

☞ 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-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

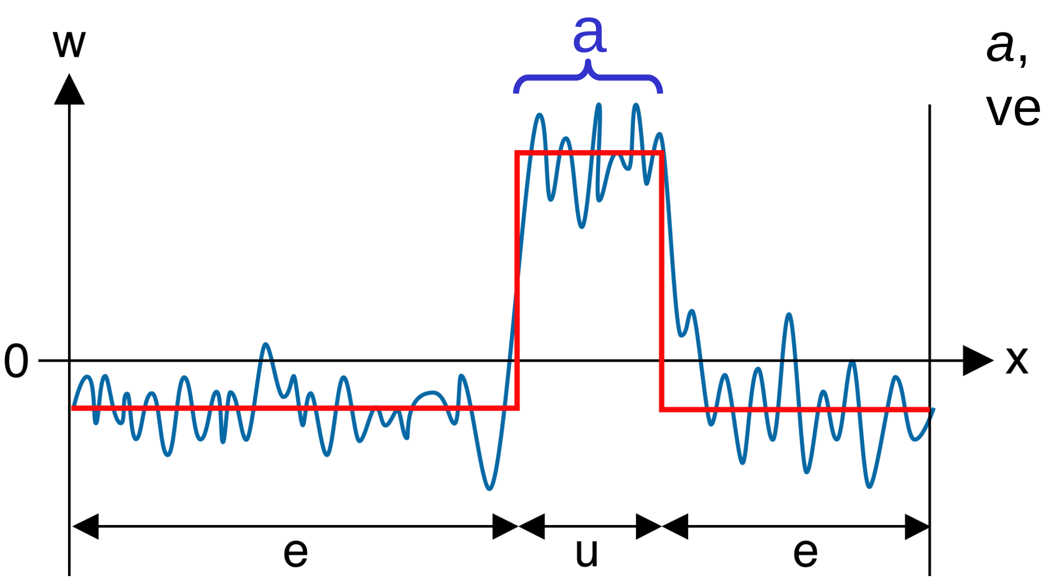
$$\frac{\partial}{\partial z}\phi^{up} = -\varepsilon\left(\phi^{up} - \overline{\phi}\right)$$

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

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

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

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

$$a << 1$$

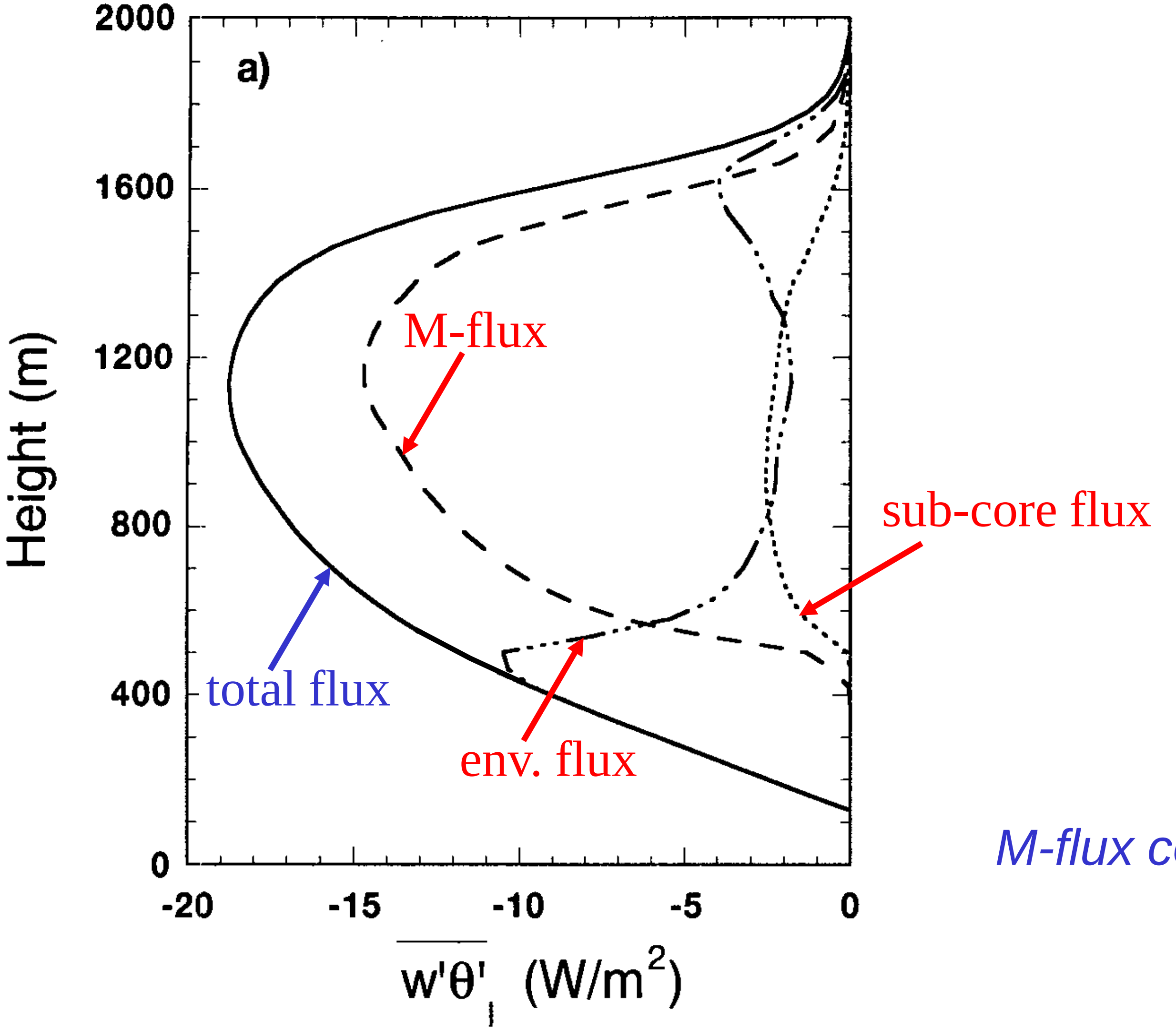
$$\overline{w'\phi'} = a\overline{w'\phi_u'}^u + (1-a)\overline{w'\phi_e'}^e + \frac{M}{\rho}(\phi_u - \overline{\phi}) \quad , \quad M = \rho a w_u$$

env. flux: $-K\frac{\partial\overline{\phi}}{\partial z}$

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

Siebesma & Cuijpers, 1995

BOMEX LES decomposition



M-flux covers 80% of flux

Siebesma & Cuijpers, 1995

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K-profile closure Troen and Mahrt (1986)

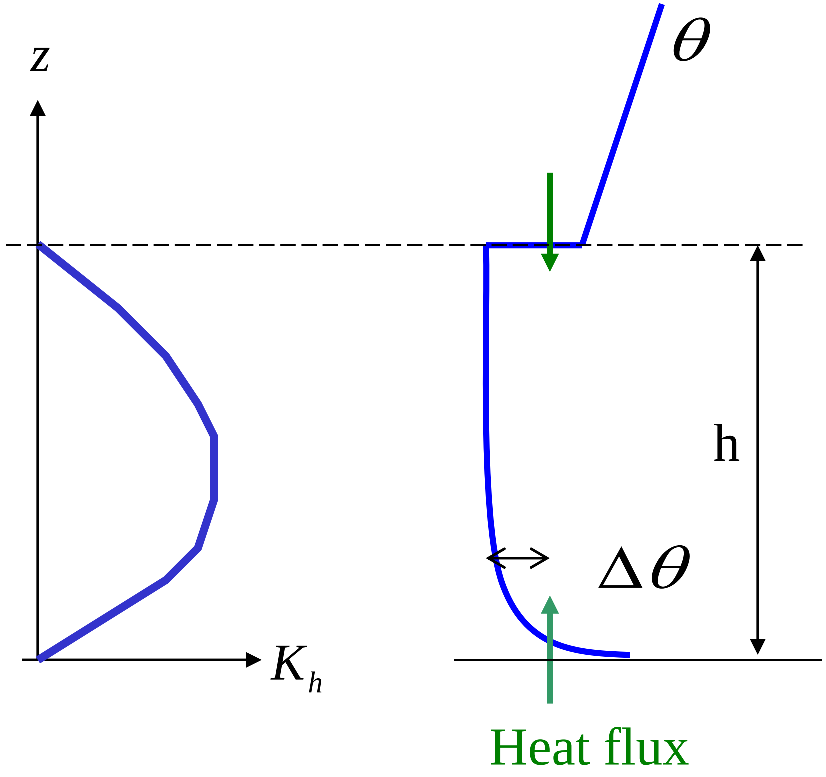
$$\overline{\theta' w'} = -K_H \left(\frac{\partial \theta}{\partial z} - \gamma_\theta \right)$$

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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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:

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

Closure of TKE equation

TKE from prognostic equation:

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

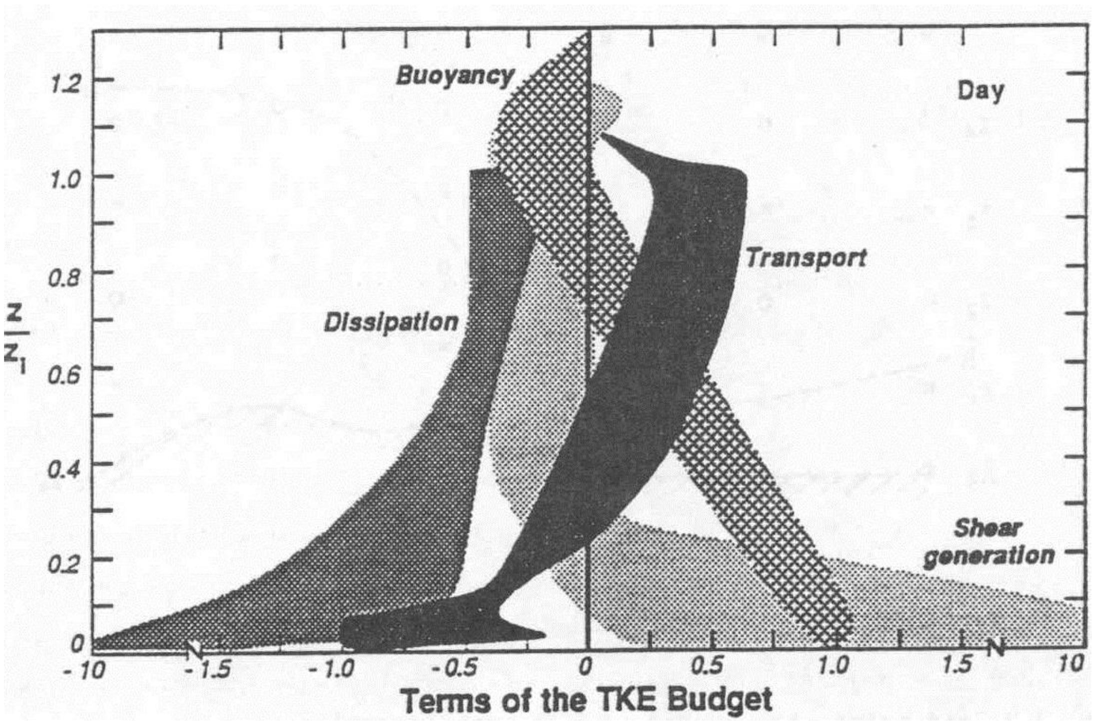
Storage | Shear production | Buoyancy | Turbulent transport | Pressure correlation | Dissipation

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 κz, an asymptotic length scale λ 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 closure in the ECMWF model

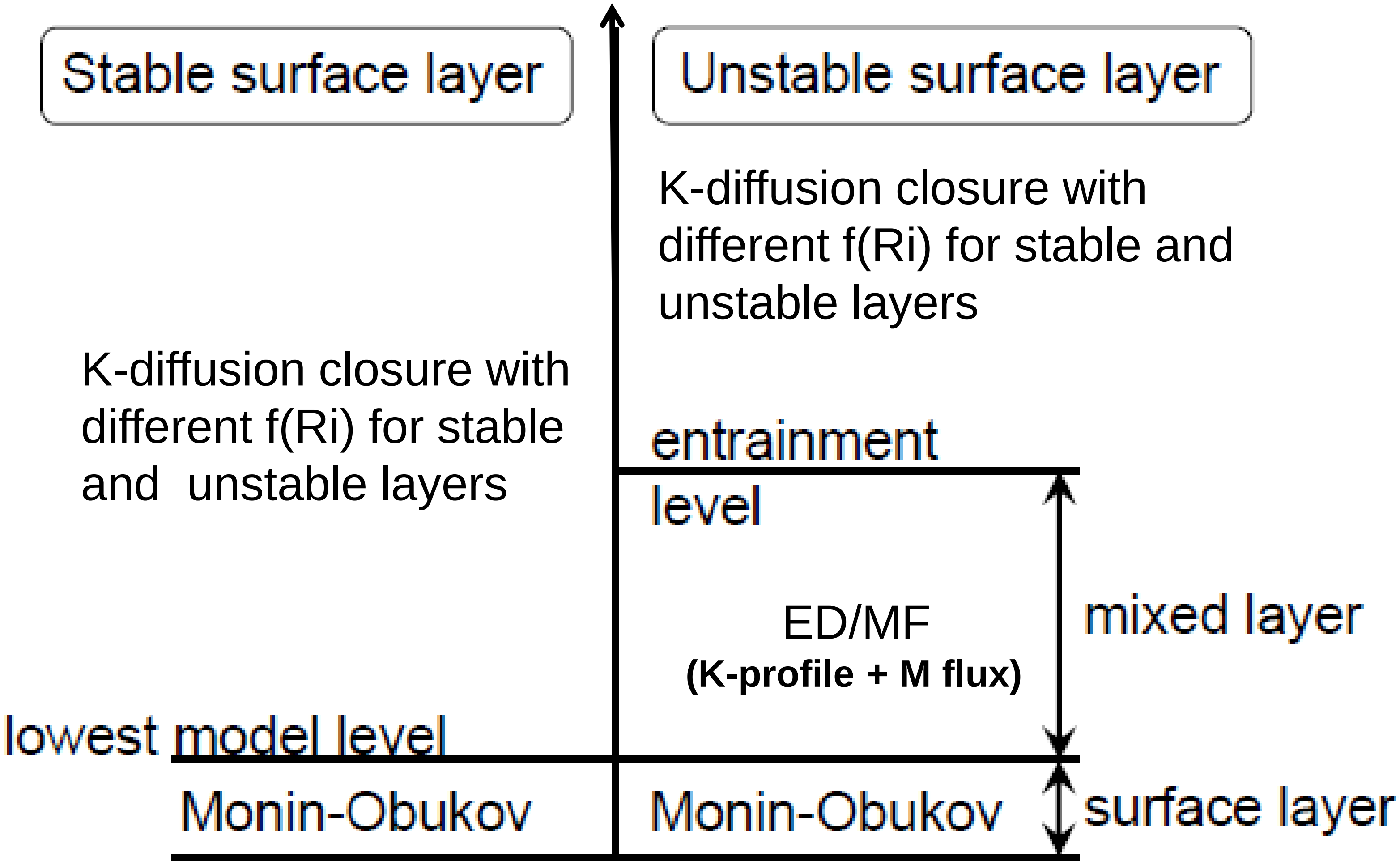

Figure 3.1 *Schematic diagram of the different boundary layer regimes.*