Overview of models

Bulk models

Local K-closure

ED/MF closure

K-profile closure

TKE closure

Current closure in the ECMWF model
Reynolds equations

\[
\begin{align*}
\frac{\partial \bar{u}}{\partial t} + u \frac{\partial \bar{u}}{\partial x} + v \frac{\partial \bar{u}}{\partial y} + w \frac{\partial \bar{u}}{\partial z} - f \bar{v} &= - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x} - \frac{\partial u'w'}{\partial z} \\
\frac{\partial \bar{v}}{\partial t} + u \frac{\partial \bar{v}}{\partial x} + v \frac{\partial \bar{v}}{\partial y} + w \frac{\partial \bar{v}}{\partial z} - f \bar{u} &= - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial y} - \frac{\partial v'w'}{\partial z} \\
\frac{\partial \bar{q}}{\partial t} + u \frac{\partial \bar{q}}{\partial x} + v \frac{\partial \bar{q}}{\partial y} + w \frac{\partial \bar{q}}{\partial z} &= - \frac{S_{qt}}{\rho} - \frac{\partial q'w'}{\partial z} \\
\frac{\partial \bar{\theta}}{\partial t} + u \frac{\partial \bar{\theta}}{\partial x} + v \frac{\partial \bar{\theta}}{\partial y} + w \frac{\partial \bar{\theta}}{\partial z} &= - \frac{1}{\rho c_p} \frac{\partial F}{\partial z} - \frac{L_v}{\rho c_p} - \frac{\partial \theta'w'}{\partial z}
\end{align*}
\]

\[ u = \bar{u} + u' \]
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Parametrization of PBL outer layer

- Overview of models
- Bulk models
- Local $K$ closure
- ED/MF closure
- K-profile closure
- TKE closure
- Current closure in the ECMWF model
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).
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 \( \ell / L \)

\[ Ri = \frac{g}{\theta_v} \left| \frac{d\theta_v}{dz} \right|^2 = \frac{g}{\theta_v} \frac{\ell \theta_\ast \phi_h}{u_* \phi_m^2} = \frac{\ell}{\kappa L} \frac{\phi_h}{\phi_m^2} \]

to solve for \( \ell / L \).

\[ K_M = \ell^2 \left| \frac{dU}{dz} \right| f_M(R_i), \quad K_H = \ell^2 \left| \frac{dU}{dz} \right| f_H(R_i) \]
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, \lambda = 150m

Recent years (36R4 – 38R2)

Surface layer – SFMO

Above: \[ f = \alpha \ast f_{LTG} + (1-\alpha) \ast f_{MO} \]
\[ \alpha = \exp(-H/150) \]

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

- Obs
- Model

2011 OPERATIONAL

Time (UTC)
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: $\lambda=150m$ → $\lambda=30m$
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
- \( \lambda = 150m \)
- non-resolved shear term, with a maximum at 850hPa

From 40R1
- long tails everywhere
- \( \lambda = 10\% \) PBL height in stable boundary layers
- \( \lambda = 30 \) 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
- Small changes in 2m temperature during nighttime 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 Northern 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
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.
Parametrization of PBL outer layer

- Overview of models
- Bulk models
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K-diffusion versus Mass flux method

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

\[
\phi' w' \approx K \frac{\partial \phi}{\partial z}
\]

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

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

\[
\phi' w' \approx M (\phi^{up} - \bar{\phi})
\]

\[
\frac{\partial}{\partial z} \phi^{up} = -\varepsilon (\phi^{up} - \bar{\phi})
\]

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

analogy to molecular diffusion

mass flux

entraining plume model

detrainment rate
The updraught: small fractional area $a$, containing the strongest upward vertical motions

\[ \phi_u = \phi'_u + \overline{\phi_u} \]
\[ \phi_e = \phi'_e + \overline{\phi_e} \]
\[ \overline{\phi} = a\overline{\phi'_u} + (1 - a)\overline{\phi'_e} \]
\[ a \ll 1 \]

\[ -K \frac{\partial \overline{\phi}}{\partial z} + \frac{w' \phi'}{a w' \phi'_u} + (1 - a) w' \phi'_e + \frac{M}{\rho} (\phi_u - \overline{\phi}) \quad , \quad M = \rho a w_u \]

Siebesma & Cuijpers, 1995
BOMEX LES decomposition

M-flux covers 80% of flux

Siebesma & Cuijpers, 1995
Parametrization of PBL outer layer

- Overview of models
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\[
\theta'w' = -K_H \left( \frac{\partial \theta}{\partial z} - \gamma_\theta \right)
\]

Profile of diffusion coefficients:

\[
K_H = w_s \kappa z (1 - z / h)^2
\]

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

\[
\gamma_\theta = C \frac{\theta'w'}{w_s h}
\]

Find inversion by parcel lifting with T-excess:

\[
\theta_{vs} = \theta_s + \Delta \theta, \quad \Delta \theta = D \frac{w' \theta'_v}{w_s h}
\]

such that:

\[
Ri_c = h \frac{g}{\theta_v} \frac{\theta_{vh} - \theta_{vs}}{U_h^2 + V_h^2 - U_s^2 - V_s^2} = 0.25
\]
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.
Parametrization of PBL outer layer

- Overview of models
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Eddy diffusivity approach:

\[ u'w' = -K_M \frac{\partial u}{\partial z}, \quad v'w' = -K_M \frac{\partial v}{\partial z} \]
\[ \theta'w' = -K_H \frac{\partial \theta}{\partial z}, \quad q'w' = -K_H \frac{\partial q}{\partial z} \]

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:

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

with closure:

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

Main problem is specification of length scales, which are usually a blend of \( k\ell \), 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.
Parametrization of PBL outer layer

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Current closure in the ECMWF model

K-diffusion closure with different $f(Ri)$ for stable and unstable layers

ED/MF (K-profile + M flux)

Figure 3.1 Schematic diagram of the different boundary layer regimes.