Overview of models

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

Model orders:
- $0$ order
- $1$st order
- $1.5$th order
Reynolds equations

$$\frac{\partial \bar{u}}{\partial t} + u \frac{\partial \bar{u}}{\partial x} + v \frac{\partial \bar{u}}{\partial y} + w \frac{\partial \bar{u}}{\partial z} - f \bar{v} = -\frac{1}{\rho} \frac{\partial P}{\partial x}$$

$$\frac{\partial \bar{v}}{\partial t} + u \frac{\partial \bar{v}}{\partial x} + v \frac{\partial \bar{v}}{\partial y} + w \frac{\partial \bar{v}}{\partial z} - f \bar{u} = -\frac{1}{\rho} \frac{\partial P}{\partial y}$$

$$\frac{\partial \bar{q}}{\partial t} + u \frac{\partial \bar{q}}{\partial x} + v \frac{\partial \bar{q}}{\partial y} + w \frac{\partial \bar{q}}{\partial z} = -\frac{S_{q,t}}{\rho}$$

$$\frac{\partial \bar{\theta}}{\partial t} + u \frac{\partial \bar{\theta}}{\partial x} + v \frac{\partial \bar{\theta}}{\partial y} + w \frac{\partial \bar{\theta}}{\partial z} = -\frac{1}{\rho c_p} \frac{\partial F}{\partial z} - \frac{L_v}{\rho c_p}$$

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

Reynolds Terms
Overview of models

Bulk models

**Local K closure**

K-profile closure

ED/MF closure

TKE closure

Current closure in the ECMWF model
K-diffusion in analogy with molecular diffusion, but

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

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

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

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<td>(z_o)</td>
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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 \( z/L \)

\[ Ri = \frac{g}{\theta_v} \left| \frac{d\theta_v}{dz} \right|^2 = \frac{g}{\theta_v} \frac{z \theta* \phi_h}{u* \phi_m} = \frac{z}{\kappa L} \frac{\phi_h}{\phi_m^2} \]

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

\[ K = \left| \frac{\partial U}{\partial z} \right| i^2 f(R_i) \]

\[ 1/l = 1/kz + 1/\lambda \]

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

200m
80 m
10 m

2011 OPERATIONAL

Time (UTC)
Impact of reducing the diffusion in stable conditions

ST: long tails $\rightarrow$ short tails
LT30: $\lambda=150m$ $\rightarrow\lambda=30m$

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

$\frac{1}{l} = \frac{1}{kz} + \frac{1}{\lambda}$, $\lambda=150m$

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: $\lambda=150m$ → $\lambda=30m$
Reduced diffusion also impacts NH winter circulation.

Bias Z CTL

Z LOWDIFF - Z CTL

High pressure

Low pressure

Stronger high pressure systems

Deeper low pressure systems

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
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
- \( \lambda = 150\) m
- 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 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
Reduced diffusion in stable conditions in the free troposphere

Historical evolution of 10m wind direction biases in IFS

Europe

Reduced diffusion STBL

St dev

model - obs

0 UTC

12 UTC
K-closure with local stability dependence (summary)

- 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.

\[ K = \left| \frac{\partial U}{\partial z} \right| \cdot l^2 \cdot f(Ri) \]
Parametrization of turbulent fluxes in the outer layer

- Overview of models
- Bulk models
- Local K-closure
- K-profile closure
- ED/MF closure
- TKE closure
- Current closure in the ECMWF model
\[ \theta' w' = -K_H \left( \frac{\partial \theta}{\partial z} - \gamma_\theta \right) \]

Profile of diffusion coefficients:

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

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

\[ \gamma_\theta = C \theta' w'^s / w_s h \]

Find inversion by parcel lifting with \( T \)-excess:

\[ \theta'_{vs} = \theta_s + \Delta \theta, \quad \Delta \theta = D \theta'_v w'^s / w_s \]

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.
Parametrization of turbulent fluxes in the outer layer

- Overview of models
- Bulk models
- Local K closure
- K-profile closure
- ED/MF closure
- TKE closure
- Current closure in the ECMWF model
K-diffusion versus Mass flux method

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

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

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

analogy to molecular diffusion

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

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

mass flux

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

entraining plume model

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

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

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

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

$$\overline{\phi} = a\overline{\phi}_u + (1-a)\overline{\phi}_e$$

$a \ll 1$

$$-K \frac{\partial \overline{\phi}}{\partial z} = aw' \overline{\phi}'_u + (1-a)w' \overline{\phi}'_e + \frac{M}{\rho} (\phi_u - \overline{\phi})$$

$$M = \rho a w_u$$

Siebesma & Cuijpers, 1995
BOMEX LES decomposition

M-flux covers 80% of the flux for heat and moisture,
less for momentum – environment plays a bigger role for momentum transport

Siebesma & Cuijpers, 1995
Zhu 2015, Schlemmer et al, 2016
Parametrization of turbulent fluxes in the outer layer

- Overview of models
- Bulk models
- Local K closure
- K-profile closure
- ED/MF closure
- TKE closure
- Current closure in the ECMWF model
TKE closure (1.5 order)

Eddy diffusivity approach:
\[
\bar{u}'w' = -K_{M} \frac{\partial \bar{u}}{\partial z}, \quad \bar{v}'w' = -K_{M} \frac{\partial \bar{v}}{\partial z}, \\
\bar{\theta}'w' = -K_{H} \frac{\partial \bar{\theta}}{\partial z}, \quad \bar{q}'w' = -K_{H} \frac{\partial \bar{q}}{\partial z}
\]

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:

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

Main problem is specification of length scales, which are usually a blend of \( k_z \), 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.
Overview of models
Bulk models
Local K closure
ED/MF closure
K-profile closure
TKE closure
Current closure in the ECMWF model
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

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

ED/MF

Parcel method:
If no cloud base
IF cloud base

Mixed layer

\begin{align*}
\text{dry BL} & \quad \text{Stratocumulus} \\
PBL\_TYPE=1 & \quad PBL\_TYPE=2 \\
\end{align*}

Shallow cumulus
Deep cumulus

\begin{align*}
Z_i = W < 0 & \quad K_{\text{entr}} \\
Z_i = Z_{\text{cb}} & \quad K_{\text{prof}} \\
EIS > 7 & \quad EIS < 7
\end{align*}
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
A cleaner interaction between the physical parameterizations representing moist processes

- Software entropy – increasing disorder with time
- Becomes difficult to understand how different parts of the code are interacting
- Numerical algorithm can be far from optimal (important for solution and code efficiency)
- Need an integrated system that is as simple as possible, **but no simpler**

→ **Concerted effort to understand and simplify moist processes interactions in the IFS**
Revision of the convective cloudy boundary-layer

One test parcel
DRY transport – EDMF
Moist transport – shallow + deep convection
Cloud – cloud scheme
Revised moist physics interactions in IFS

Good progress being made for the revised moist physics interactions:

• Correction of long-standing saturation adjustment bug
• Simplified calling sequence for moist physics
• Consistent treatment of mixed-phase saturation
• Correct SL physics averaging supersaturation check
• Improved convection – cloud scheme interaction
• Improved turbulent mixing – cloud scheme interaction

Consistency and interaction between parametrizations as important as the parametrizations themselves
Physics Expts for 39r1 (fulj-ftjl) ownan
Winter 20120101-20120321 (81 days)

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