Developments of turbulence closure schemes in RAMS for high resolution simulations over complex terrain

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The topic: mesoscale models are more and more used to simulate circulation in the atmosphere at relatively high resolutions (1 km or less) for meteorological and pollutant dispersion studies and other applications.

The issue: nesting coarse resolution domains with high resolution grids implies the need of accounting for atmospheric processes at different scales and, in particular here, of dealing with a proper description of the turbulent transport, especially in non-homogeneous conditions and complex terrain.

In this talk: a short (hi)story of the developments of turbulence closure schemes in RAMS during last years is presented and their latest applications are illustrated and discussed.
A short (hi)story, starting from 1999

I. Implementation of two closure models in the model RAMS3b:

*standard E - I*: prognostic equation for the TKE + diagnostic formulation for the mixing length
*standard E - $\varepsilon$*: prognostic equations for the TKE and its dissipation rate $\varepsilon$

Intercomparison and sensitivity analysis of the different turbulence closure schemes in the case of schematic topography in wind tunnel experiments, first tests on the values for the empirical constants and applications to dispersion modelling

References

*Comparison of turbulence closure models over a schematic valley in a neutral boundary layer*

*Turbulence closure in neutral boundary layer over complex terrain*
Trini Castelli S., Ferrero E., Anfossi D. *Boundary Layer Meteorology, n. 100*, 405-419, 2001

*Study of different turbulence closure models simulating a neutral wind tunnel flow experiment*

*Turbulence Fields for Atmospheric Dispersion models in horizontally non-homogeneous conditions*
Ferrero E., Trini Castelli S., Anfossi D. *Atmospheric Environment, 37, n. 17*, pp. 2305-2315, 2003

*Influence of turbulence closures on the simulation of flow and dispersion in complex terrain.*
The E-l and E-ε closures

**TKE equation**

\[
\frac{dE}{dt} = \frac{\partial}{\partial x_j} K_E \frac{\partial E}{\partial x_j} + P - \varepsilon
\]

**TKE dissipation equation**

\[
\frac{d\varepsilon}{dt} = \frac{\partial}{\partial x_j} \left( K_\varepsilon \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{E} \left( c_{1_\varepsilon} P - c_{2_\varepsilon} \varepsilon \right)
\]

**P**

\[
P = -u_i'u_j' \frac{\partial \bar{u}_i}{\partial x_j} + \delta_{ij} E \alpha \theta'
\]

\[
u_i'nu_j' = -K_m \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{2}{3} E \delta_{ij}
\]

\[
u_i'\theta' = -K_\theta \frac{\partial \bar{\theta}}{\partial x_i}
\] (K theory)

**E-l**

\[
K_m = c_\mu E_{1/2} l \quad \varepsilon = \frac{c_\varepsilon E^{3/2}}{l} \quad l = \frac{kz}{1 + \frac{kz}{l_\infty}}
\]

**E-ε**

\[
K_m = c_k \frac{E^2}{\varepsilon} \quad c_{1_\varepsilon} = c_{2_\varepsilon} - k^2 \frac{\alpha_\varepsilon}{2 c_\mu} \quad c_k = c_\mu c_\varepsilon
\]
Valley characteristics:
- maximum valley dept $H=0.117$ m
- valley width $2a$, where $a=0.936$ m
- aspect ratio $a/H = 8$

Experiment characteristics:
- roughness length $z_0=0.16 \times 10^{-3}$ m
- friction velocity $u_* = 0.19$ m/s
- free stream velocity $u_\infty = 4$ m/s.

Measurements at 15 different locations along the x axis:
- vertical profiles of mean wind velocity
- Reynolds stress components $\sigma_u$, $\sigma_v$, $\sigma_w$ and $-uw'$

To perform the numerical simulations the studied phenomenon was reported to the actual boundary layer scale, following the principles of the similitude theory.

Wind tunnel ABL (1m) corresponds to a 600 m actual neutral ABL:
- Scaling factor 600 for lengths
- Same aspect ratio has been maintained $a/H = 8$

Actual ABL characteristics:
- roughness length $z_0=0.096$ m
- maximum depth $H_{max} = 70.2$ m
- width $2a$ where $a=561.6$ m.

Logarithmic law for wind profile in neutral conditions:
- Non dimensional form: no scaling of the velocity was needed

Source inside the valley, 17.4 m high
EPA-RUSVAL: some results on mean flow, turbulence and dispersion

Intercomparison between simulations with:
MY2.5 + MY ORIG set (dotted line); MY2.5 + MY EPA set, (dash-dotted line)
E-l (solid line); E-ε (dashed line); Hybrid E-ε-l (dash-dot-dot line); Observations (crosses)

\[ (1) \quad \sigma_u^2 = (1 - 2\gamma)q^2 \quad \sigma_v^2 = \sigma_w^2 = \gamma q^2 \]

\[ (2) \quad \sigma_{u_i}^2 = -2K_{mi} \frac{\partial \overline{u}}{\partial x_i} + \frac{2}{3}E \]

\[ (3) \quad T_Lu_i = \frac{K_{mj}}{\sigma_{u_j}^2} \]

\[ (4) \quad T_Lu_i = \frac{2\sigma_{u_i}^2}{C_{0u_i} \epsilon} \]

MY82 closure + (1) + (3)  E l closure + (2) + (3)  E ε closure + (2) + (4)
A short (hi)story................

II. Implementation of the standard $E-\ell$ and $E-\varepsilon$ closure models in the model RAMS 4.3 and later RAMS5.05:

Investigation of the influence of the closure empirical constants on the simulation of flow and turbulence fields over complex terrain in different stability conditions – idealized cases

References

*Turbulence closure models and their application in RAMS*
Trini Castelli S., Ferrero E., Anfossi D., Ohba R. Environmental Fluid Mechanics, 5, 169-192, 2005

*Turbulence closure coefficients in stratified atmospheric boundary layer flow*
Trini Castelli S. 5th Annual Meeting of the European Meteorological Society; A.W. 1.2: Boundary layer physics in weather and climate predictions. Utrecht, the Netherlands, 12-16 September 2005 (invited talk)

Stable case: dashed line: neutral constants’ set; solid line: stable set
The MHI-3Dhill case

*Wind tunnel:* Suction type, thermally stratified
  width 2.5 m, height 1.0 m,
  length 19.5 m (test section 10 m)
  wind velocity 0.1 – 1.5 m/s

*Simulation:* similarity rule for bulk Richardson number,
  model scale 1/1000 experiment

*The 3D hill:* \( H_{\text{hill}}(x = 0 \text{ mm}) = 100 \text{ mm}; \)
  roughness \( z_0 = 0.01 \text{ mm} \)
  measurement locations: \( x = -500, -200, 0, 190, 380 \text{ mm} \)

Weakly stable conditions, turbulent kinetic energy. \( E \) solid line; \( E \) \( \varepsilon \) dashed line; \( M \) \( \gamma \) 2.5 dash dotted line
The MHI-3DHill case ... in neutral conditions

Mellor Yamada lev. 2.5

Deardorff

Standard E \( \varepsilon \)

Standard E \( l \)
III. Implementation of an ‘anisotropic’ version of E-l (El-anis) in RAMS5.05 and after RAMS6.01

References
Validation studies of turbulence closure schemes for high resolutions in mesoscale meteorological models.

IV. Introduction of standard and modified $E - l$ and $E - \varepsilon$ closure schemes in RAMS4.4 for the new operative RMS (RAMS4.4-MIRS3.0-SPRAY2.0) modelling system

References
Influence of turbulence closures on the simulation of flow and dispersion in complex terrain.
Turbulence closures in atmospheric circulation model and its influence on the dispersion

Simulations in real complex terrain!

AN APPLICATION OF RAMS TO POWER PLANT POLLUTION FORECAST IN COMPLEX TERRAIN
Stefano Alessandrini, Silvia Trini Castelli, Enrico Ferrero, Emiliano Orlandi, Giovanni Manzi
In the next part the turbulence scheme *El-anis* based on the coupling of a standard E-I closure with a deformation-based scheme implemented in RAMS v5.05 and after RAMS6.01 is presented.

Its application in the simulation of the flow and dispersion in two real field campaigns, in the Tsukuba region (Japan) in 1989 and 1990 is discussed.

Its performances are compared to results obtained with the Mellor-Yamada level 2.5 closure scheme, also coupled with the same deformation scheme in RAMS.
**The El-anis scheme**

**Vertical diffusion coefficients from the 3D TKE \( E \) equation:**

\[
\frac{dE}{dt} = \frac{\partial}{\partial x_j} K_E \frac{\partial E}{\partial x_j} + P - \varepsilon
\]

with

\[
K_E = \alpha_E K_m
\]

\[
K_m = c_\mu E^{1/2} I
\]

\[
\varepsilon = \frac{c_\varepsilon E^{3/2}}{l_d}
\]

\[
l_d = l = \frac{kz}{1 + kz/l_\infty}
\]

\[
l_\infty = a_\infty \int z \sqrt{E} dz
\]

\[
\alpha_E \quad \text{empirical coefficients}
\]

**Horizontal diffusion coefficients from a deformation scheme**

\[
K_{m-horz} = \rho_0 \max \left[ K_{min-h}, (C_x \Delta x)^2 \left\{ S_{2.5}^{0.5} \right\} \right]
\]

with

\[
K_{min-h} = 0.075 K_A \left( \Delta x^{4/3} \right)
\]

\[
\rho_0 \quad \text{air density, } C_x \quad \text{dimensionless coefficient, } \Delta x \quad \text{grid spacing}
\]

\[
S_2 \quad \text{horizontal strain rate, } K_A \quad \text{user-specified coefficient of order 1.}
\]
The MY 2.5 scheme (as in RAMS)

Vertical diffusion coefficients from the TKE equation in boundary layer approximation:

\[
\frac{dE}{dt} = \frac{\partial}{\partial z} K_E \frac{\partial E}{\partial z} + P - \varepsilon \quad \text{with} \quad K_E = S_E l(2E)^{1/2}
\]

\[
K_m = S_m l(2E)^{1/2} \quad \varepsilon = \frac{(2E)^{3/2}}{\Lambda_1} \quad l = \frac{kz}{1 + kz} \quad l_\infty = a_\infty \int \frac{z \sqrt{E} dz}{\sqrt{E} dz}
\]

\(S_m, S_E\) are functions depending on the set of empirical constants \((A_1, B_1, A_2, B_2, C) = (0.92, 16.6, 0.74, 10.1, 0.08)\) and on the shear and buoyancy terms (ref. to Mellor and Yamada (1974, 1982)).

Closure length scales: \((l_1, \Lambda_1, l_2, \Lambda_2) = (A_1, B_1, A_2, B_2) l\)

Horizontal diffusion coefficients from the deformation scheme as in El-anis…

\[
K_{m-horiz} = \rho_0 \max \left( K_{min-h}, (C_x \Delta x)^2 \left\{ S_2^{0.5} \right\} \right) \quad \text{with} \quad K_{min-h} = 0.075 K_A (\Delta x^{4/3})
\]
The field campaigns and observations: Tsukuba region

Two campaigns:
I.FC-1989: 13 to 20 November
II.FC-1990: 10 to 18 November

TOP (m): AMeDAS (air temperature: platinum resistance thermometer; wind velocity: a wind vane and propeller anemometer; precipitation: tipping bucket rain gauge; solar radiation sensor)

W3 (m) and W5 (m): windmill anemometers

AA (m): Doppler sodar (**turbulence: 1990 only**)

U1 (m) and U2 (m): sonic anemometers (**1990 only**)

A and B: air temperature from radiosoundig
# The simulations

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The effect of the closure scheme on the mean flow: I_FC-1989

TOP station
The effect of the closure scheme on the mean flow: I_FC-1989

AA station
The effect of the closure scheme on the mean flow: I_FC-1989

W5 station
The effect of the closure scheme on the mean flow: II_FC-1990

TOP station
The effect of the closure scheme on mean flow and turbulence: II_FC-1990
The effect of the closure scheme on turbulence: II.FC-1990

U1 and U2 stations
The effect of the closure scheme on turbulence

Relative frequency histogram of turbulent kinetic energy values at AA, U1 and U2 stations.
The effects of the closure scheme on the dispersion

Gas dispersion at ground level
Run 90-5, stable conditions

Observed plume dispersion

MY 2.5 closure model

E/-anis closure model
The effects of the closure scheme on the dispersion

**Particle dispersion**

- **MY 2.5 closure model**
- **E/-anis closure model**

*Run90-5, stable condition*
The effects of the closure scheme on the concentration

Dispersion Run 90-5:
calm wind conditions, stable atmospheric stratification: the tracer gas was stagnant near the source position.

Warning: sampling points were not regularly distributed, so observed data do not always indicate the axial ground level concentration

Relative axial ground level concentration
Summary…..

*El-anis* is a modification of the E-I turbulence closure scheme to account for the non-isotropic characteristics of the atmosphere in mesoscale numerical model RAMS.

*El-anis* performance was tested and compared against the Mellor and Yamada (1982) level 2.5 scheme, already available in RAMS, considering that:

- the TKE equation is: 1D in the vertical with boundary layer approximation in MY2.5; 3D in *El-anis* scheme
- vertical diffusion coefficient: estimated on the basis of the different closure parameterisation
- horizontal diffusivities: derived from a deformation-based parameterisation inspired to Smagorinsky (1963)

Simulations in real complex terrain and comparisons with different kind of rough observed data were performed for two field campaigns (1989 and 1990) in the Tsukuba region, a hilly and mountainous region in proximity to the East coast of Japan
Main outcome:

E/-anis version maintained a similar quality as the Mellor-Yamada scheme for the reproduction of the mean wind and temperature fields, while it significantly improved the simulation results when considering the turbulence field and its effects on tracer dispersion.

Future work:

- analogous simulations and data comparisons using E/-anis in all the grids
- further improvement of the E/- closure introducing non-linear relationships between the Reynolds stresses and the strain rate, in an attempt to obtain a better description of the real anisotropy of the atmosphere in the boundary layer.
Last but not least!!!!!

V. Implementation of an RNG E-ε closure in RAMS6.0 for high-resolution simulations of the flow around buildings: towards the urban scale!

NUMERICAL SIMULATIONS OF HIGH RESOLUTION URBAN FLOW USING THE RAMS MODEL

Tamir Reisin, Orit Altaratz Stollar and Silvia Trini Castelli
VI. Reformulation of the turbulence RAMS modules to include 

NEW arrays 

for $K_{\text{Mhoriz}}, K_{\text{Mvert}}, K_{\text{Hhoriz}}, K_{\text{Hvert}}, K_{E}$

and harmonization of the routines solving the diffusion

Modified modules:

turb$_{\text{ke}},$ turb$_{\text{k}},$ turb$_{\text{k}_\text{adapt}},$ turb$_{\text{diff}},$ turb$_{\text{diff}_\text{adapt}},$ mem$_{\text{turb}}$
Future is coming 

Turbulence closure in meteo meso model and ...

- **mesoscale to local scale**
  - $\Delta x \sim 1$ km

- **grey zone**
  - $\sim 100$ m

- **building to urban scale**
  - $\Delta x \sim 1 - 10$ m

... its effect on dispersion modelling