TOUCANS

A compact parametrization of turbulence for atmospheric models

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Turbulence schemes for atmospheric models

- sophisticated but still simple enough to be affordable for NWP/climate purposes
- physically sound: no limitations for particular stability regimes, no singular points; preferable one continuous formulation avoiding switches between regimes introducing a discontinuity
- numerically simple - free of computational errors and numerical mode
- harmonically interacting with the other schemes within the complex model environment

Present Alaro physics turbulence

pTKE = pseudo-prognostic TKE scheme

$$\frac{de}{dt} = -\frac{\partial}{\partial z}\left(\overline{-K_e \frac{\partial e}{\partial z}}\right) + \frac{1}{\tau_\epsilon}\left(\tilde{e} - e\right)$$

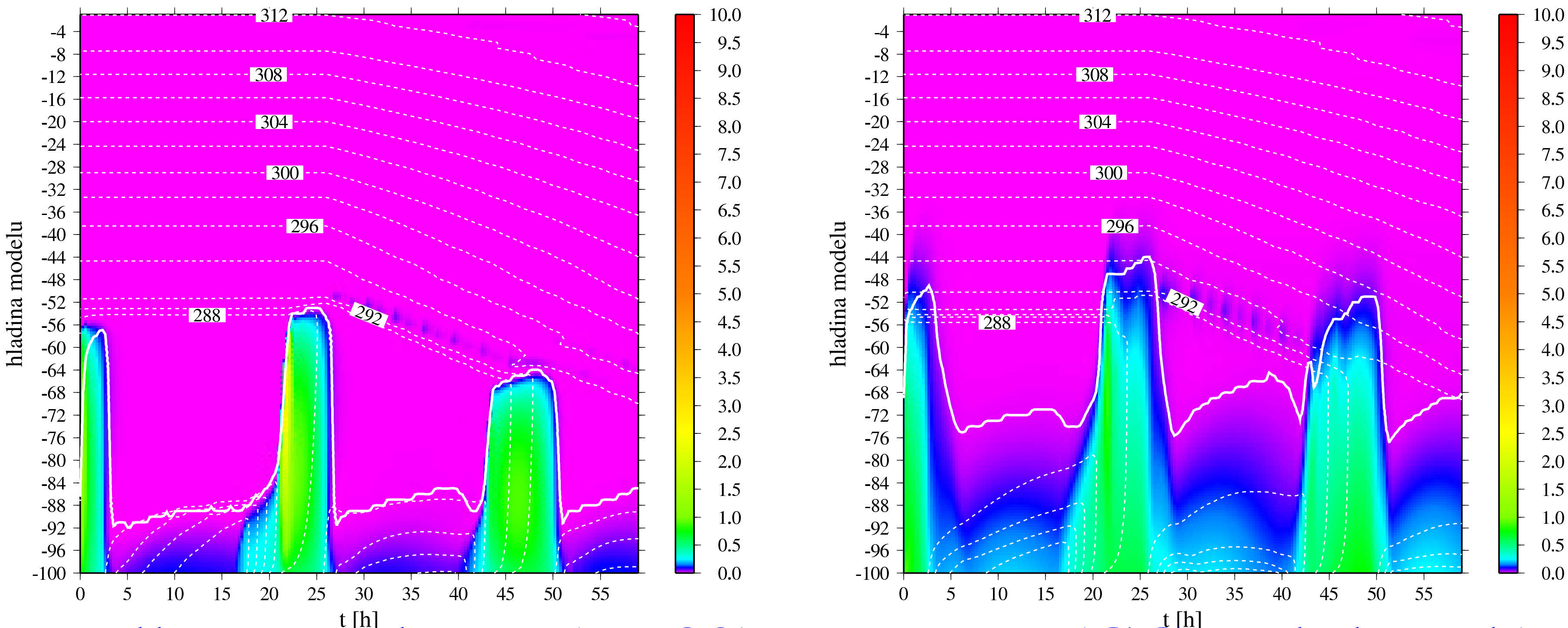
$\tilde{e}$ = TKE of stationary equilibrium as diagnosed from stability functions of Louis

$\Rightarrow$ extension of Louis (1979) scheme by

- allowing auto-diffusion
- pseudo-history
- transport (and diffusion) by advection scheme with SLHD

Present Alaro physics turbulence II.

1D model simulation with GABLS II experiment



Full TKE scheme (BL89) vs. pTKE (GC mxl. length)

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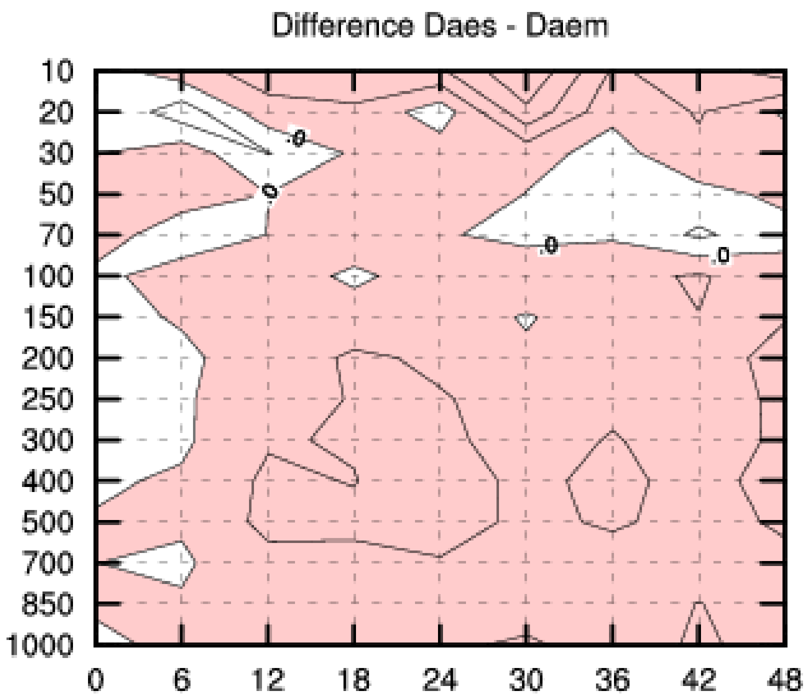
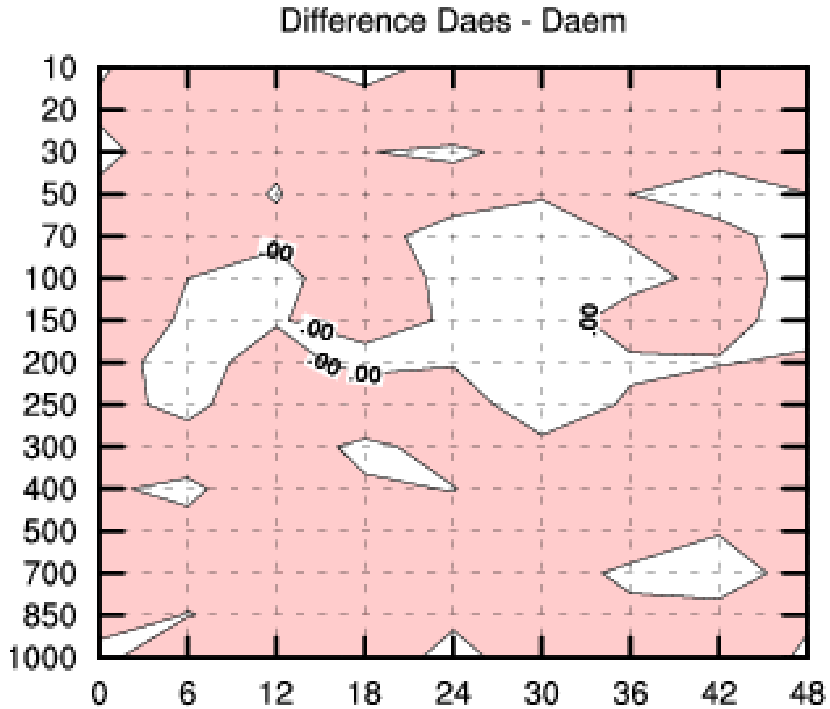
Present Alaro physics turbulence II.

Evolution of RMSE difference between Louis and pTKE



geopotential



temperature

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Basic choices

- Solving for turbulence before computing exchange coefficients and TOM's related quantities for diffusion (p-TKE inheritance); possible aposteriori correction of e^{+}.
- One single turbulent additional prognostic variable, TKE.
- Filtering use of the stationary equation.
- Requiring the no Ri_{cr} property.
- Intentional separation of the stability dependencies for momentum on the one side and for heat/moisture on the other side.

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Basic choices - cont.

- Accounting for anisotropy.
- Merging the RANS and QNSE formalisms $\Rightarrow$ 3 param. & 3 equation system for $Ri \in (-\infty, \infty)$.
- Introducing TOMs effects in a way conceptually as close as possible to a mass-flux parametrization.
- Using the above-connected dry results for moist turbulence just by redefining N, the so-called Brunt-Vaisälä frequency.
- Handling the moist link between turbulence and diffusion consistently with the above, around the Shallow Convective Cloudiness (SCC) concept.

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Third
Order moments
Unified
Condensation
Accounting and
N-dependent
Solver (for turbulence
and diffusion)

Anisotropy

- Anisotropy is an observed property of the flow. Full isotropy of turbulence is only obtained for the free convection limit.
- ECMWF interim reanalysis - isobaric cross section in zonal and meridional directions displays anisotropy: broken assumption already for 2D isotropic turbulence (Lovejoy and Schertzer, 2010)
- Gravity and Coriolis force are natural sources of anisotropy - why then impose the isotropy to systems where those are not neglected?
- Isotropic turbulence allows only two regimes: small scale regime of isotropic 3D turbulence and large scale regime of isotropic 2D turbulence. They both can be scaled realistically but with different characteristics in vertical and horizontal directions. In addition there's no continuous transition between the two.
- Isotropic turbulence doesn't allow scale invariant systems in which a flux is conserved from scale to scale (multiscale functionality). This holds already for the scales from 5000 km down to viscous scales (Stolle et al., 2009)

Simplifying the RANS models to a tractable set of equations

- CCH02 system extended by proposal of CCHE08 to obtain no Ri_{cr} number taken as the basis (yet no hope to have simple system)
- Dropping the simplistic assumption made in CCHE08 and using the filtration condition of static stability the system is becoming very simple:

$$\chi_3(Ri) = \frac{1-\frac{Ri_f}{R}}{1-Ri_f}, \qquad \phi_3(Ri) = \frac{1-\frac{Ri_f}{Ri_{fc}}}{1-Ri_f},$$

$$Ri_f = C_3 Ri \frac{\phi_3(Ri)}{\chi_3(Ri)}$$

with Ri_{fc} being critical flux-Richardson number (Ri_f at ∞)
R parameter characterizing the flow anisotropy
C_3 inverse Prandtl number at neutrality

Simplifying the RANS models to a tractable set of equations - cont.

- Prognostic TKE equation build from the pTKE solver setting the:

$$\tilde{e} = \frac{e}{\epsilon(L_\epsilon)} [\mathbf{I}_{SH}(L_K) + \mathbf{II}_{BU}(L_K)]$$

with mixing lengths relations:

$$L_K C_K = \nu l_m \frac{f(Ri)^{\frac{1}{4}}}{\chi_3(Ri)^{\frac{1}{2}}}, \qquad \frac{L_\epsilon}{C_\epsilon} = \frac{l_m}{\nu^3} \frac{\chi_3(Ri)^{\frac{3}{2}}}{f(Ri)^{\frac{3}{4}}}$$

$$f(Ri) = \chi_3(Ri) - Ri C_3 \phi_3(Ri)$$

Simplifying the RANS models to a tractable set of equations - synthesis

- Spectacular reduction of complexity for Reynolds stress modelling equations
- The stability dependency functions can be inverted $\Rightarrow$ possibility to parametrize shallow convection via a single modification of N^2
- The inclusion of Third Order Moment (TOMs) terms can be performed at relative little computing expense
- The QNSE spectral theory can be well approximated within this new framework $\Rightarrow$ an elegant extension towards the 3D (1D+2D) turbulence

QNSE

- very different approach from Reynolds stress modelling
- general spectral-type results about turbulence activity putting waves in the heart of the mathematical derivation
- convertible to the RANS framework (under some additional assumptions)
- derived only for stable regimes
- doesn’t offer tunable

Adapting QNSE to TOUCANS

- extended for unstable regimes by using asymptotic regimes of $\chi_3 \sim R^{-1}$ and $\phi_3 \sim Ri_{fc}^{-1}$ and using continuous derivatives with respect to Ri at neutrality (easy and consistent task with the simplistic system).
- derived analytical relationship between χ_3 and ϕ_3:

$$C_3 Ri \phi_3^2 - \left[\chi_3 + \frac{C_3 Ri}{Ri_{fc}} \right] \phi_3 + \chi_3 = 0$$

Within this framework the ϕ_3 function is recomputed from the fit of χ_3.

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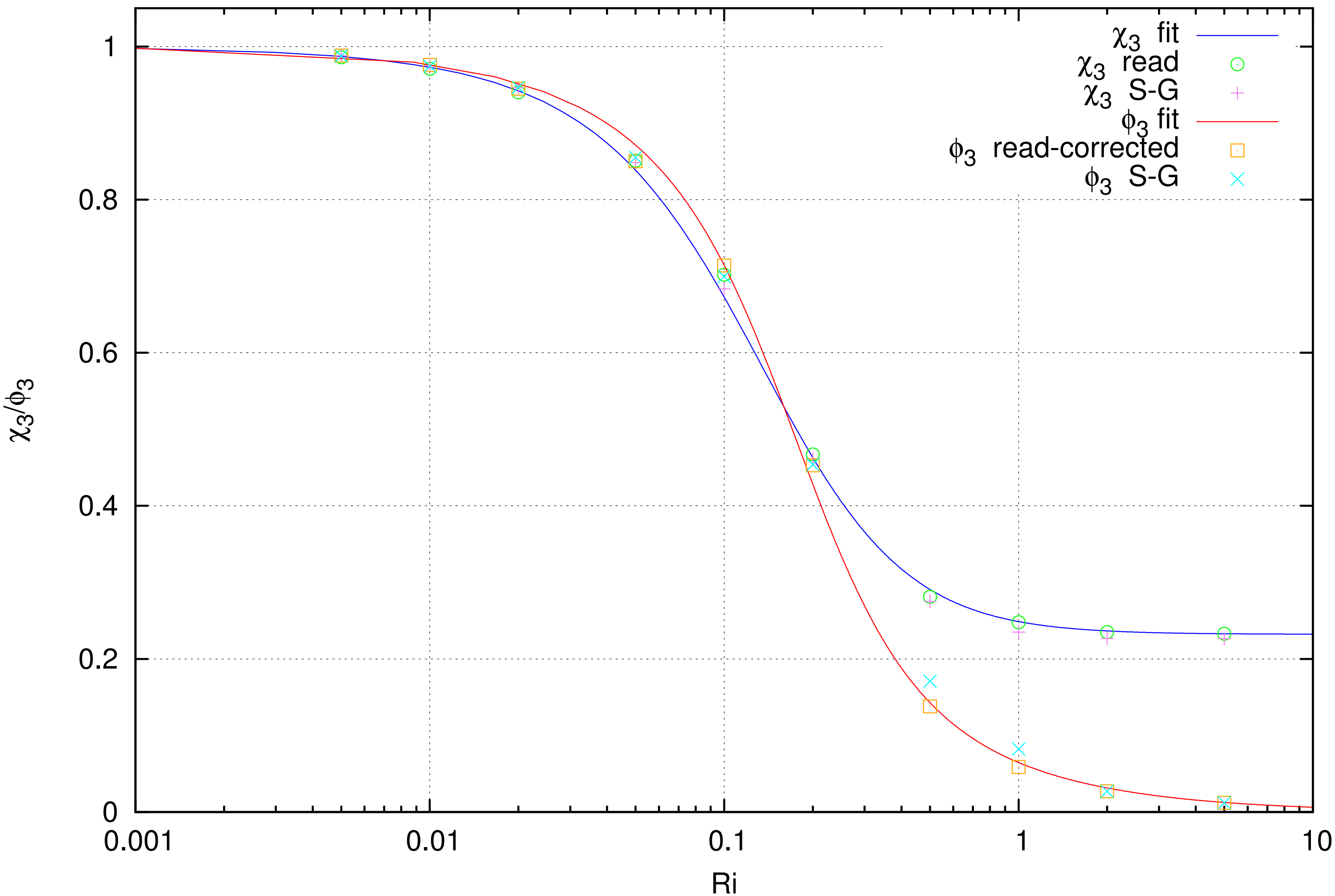
Adapting QNSE to TOUCANS



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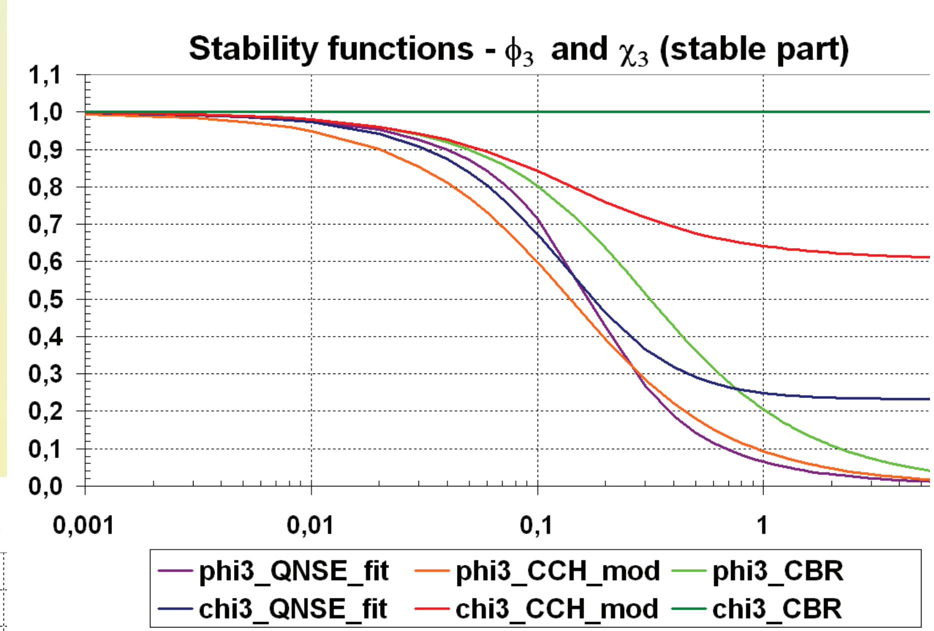
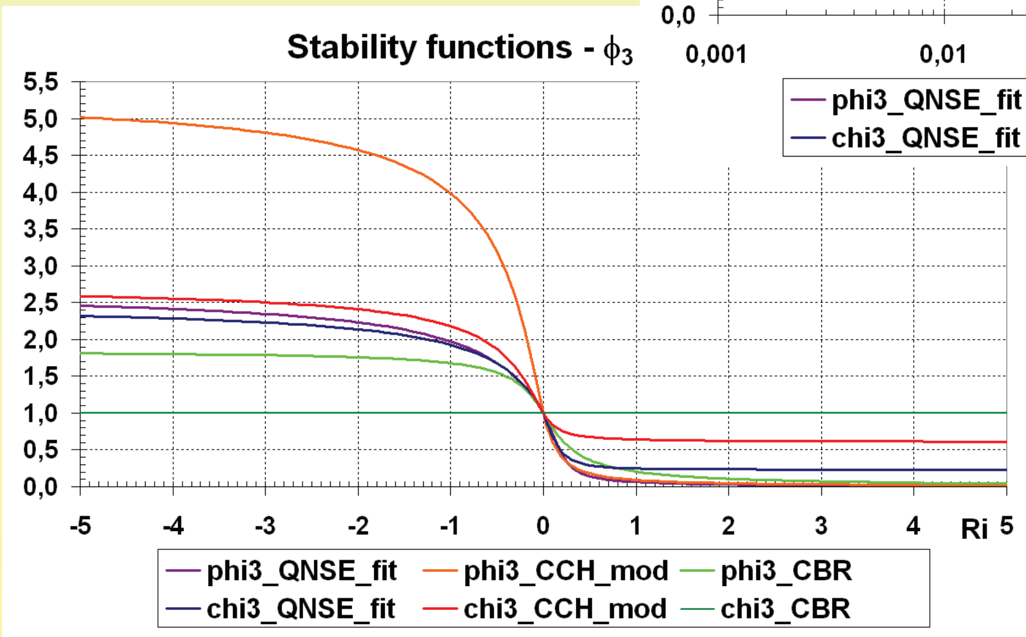
Stability functions χ_3 and ϕ_3





Mixing length

- The L_K and L_ϵ obtained from Prandtl-type mixing length l_m
- In addition to the GC mixing length of pTKE $l_m = l_m(H_{PBL})$ there is an alternative to compute l_m from TKE-type of mixing length
  $L(e, N_v^2) = (L_K^3 L_\epsilon)^{1/4}$
- Maintained 5 different approaches to evaluate L based on:
  - Modified Bougeault and Lacarrère (1989) approach
  - $\sqrt{e/N^2}$ type length for stable regimes
  - Prescribed L_{GC} length

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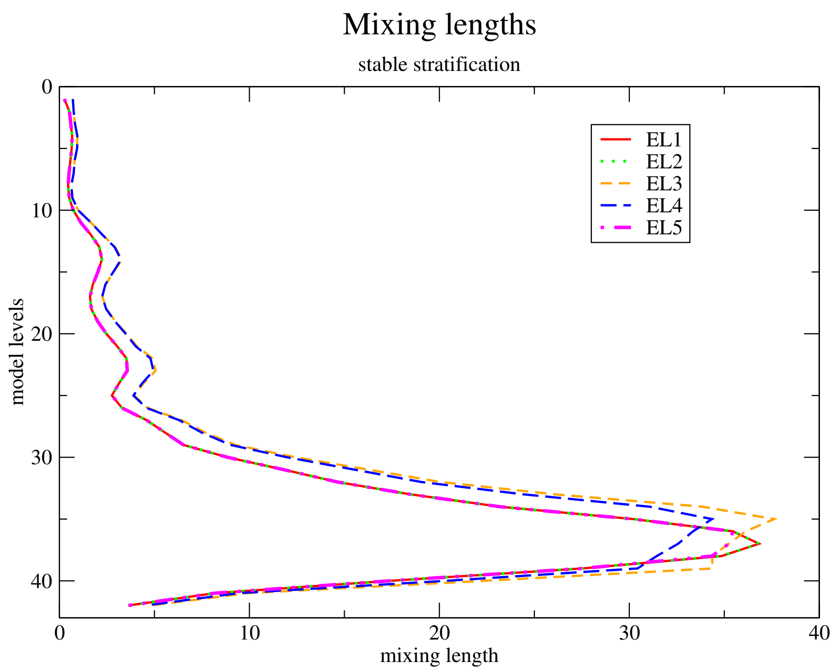
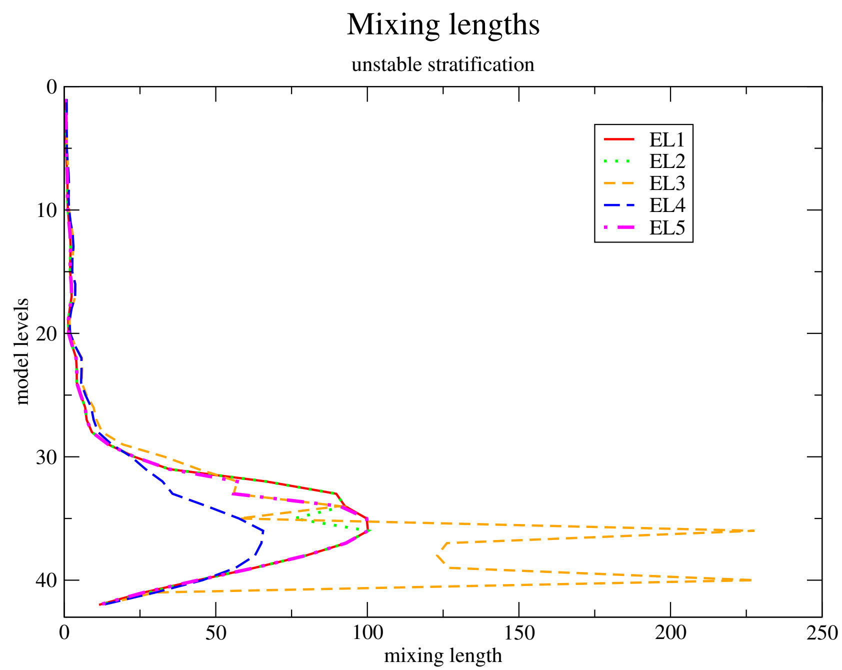
Mixing length





Third order moments

- When $L \ll$ length scale of heterogeneity of the mean flow $\Rightarrow$ local approach fully sufficient (diffusion only which is close to symmetric).
- In the other case, i.e. situations like: deep convection regime caused by loss of surface buoyancy, downward transport of mechanical energy by eddies deepening the mixed layer,... the non-local anti-symmetric part has to be added describing advection (counter-gradient or non-gradient correction expressed in terms of TOMs).
- Historically, the incorporation of non-locality has progressively gone from the fully heuristic to the NWP compatible.

TOMs in TOUCANS

Generalizing the proposal of Canuto et al. (2007) (made only for horizontally homogeneous CBL) the non-local mixing of temperature (and moisture) described by the terms of $\overline{w'^3}$, $\overline{w's'^2}$ and $\overline{w'^2s'}$ can be expressed as:

$$\overline{w's'} = -K_h \frac{\partial \overline{s}}{\partial z} + l^* \frac{\partial \overline{w's'}}{\partial z} + l^{**} \frac{\partial^2 \overline{w's'}}{\partial z^2}$$

Solving then the above equation one expect to come with stable (i.e. implicit in s^+), accurate and immune against singularities (e.g. diagonal dominant) equation

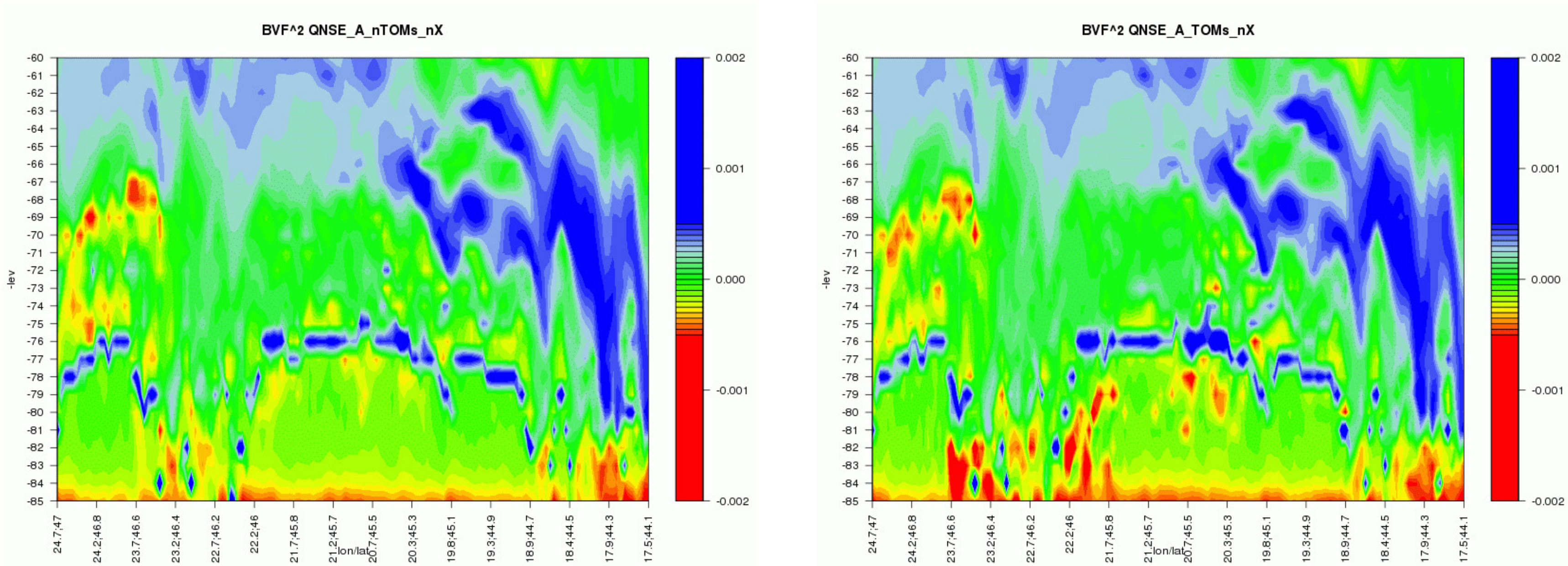
$$\frac{\partial s}{\partial t} = \frac{\partial}{\partial p}\left(-g\rho K_h \frac{\partial \overline{s}}{\partial z} - g\rho l^* \frac{\partial s}{\partial t} + g^2 \rho^2 l^{**} \frac{\partial(\partial s/\partial t)}{\partial p} \right)$$

solved iteratively rewritten for $\delta s^+ = s^+ - s^*$ with SOM term used as a first guess

$\Rightarrow$ Might be regarded as the generalized mass-flux formulations recast in terms of the ensemble-mean quantities.

TOMs in TOUCANS

Cross section of N^2 (12 UTC)



without and with TOMs

Extension to moist turbulence and shallow convection parametrization

- Thanks to all other characteristics of TOUCANS, it is possible to obtain the wished change of Ri only through the early definition of SCC.
- At the moment the SCC equivalent (moist anti-fibrillation included) is based on a slightly improved version of the shallow convection parametrization after Geleyn (1987).
- It is expected that by using the Marquet's moist entropy potential temperature it will possible to further progress with respect to this.
- All this only takes its full meaning when TOMs are activated, since thermals are the most likely turbulent features to foster condensation.

Summary

- By sequential evolution of the Louis scheme we have arrived to a brand new system still in a way still compatible with its predecessors.
- By terms of closure assumptions the new systems is constructed with: pressure correlation terms describing the contribution of the slow part (turbulence self-interactions) but also the rapid part (mean shear-turbulence interactions and buoyancy-turbulence interactions), it maintains third order momentum terms for scalar variables and TKE and N_v^2 driven mixing length.
- The new system is based on one prognostic prognostic quantity ($e - l$ system). The conversion between TKE and TPE is however under control... It is somewhere between level-2 and level-2.5 schemes $\Rightarrow$ level-2.25.
- The system is sufficiently stable and computationally affordable.
- The system is valid for whole range of regimes (no Ri_{cr}).

Summary - II.

- There are several alternatives allowed: RANS vs. QNSE, ways to become no Ri_{cr}, options for mixing length,... making it possibly attractive for multi-physics.
- It offers unique framework for studying different approaches to turbulence (QNSE vs. RANS).
- It is also hoped to become a tool for a unified description of turbulence and shallow convection.
- The scheme is at low cost easily extensible by horizontal components.