# Modeling real convective boundary layers in the terra incognita: evaluation of different approaches

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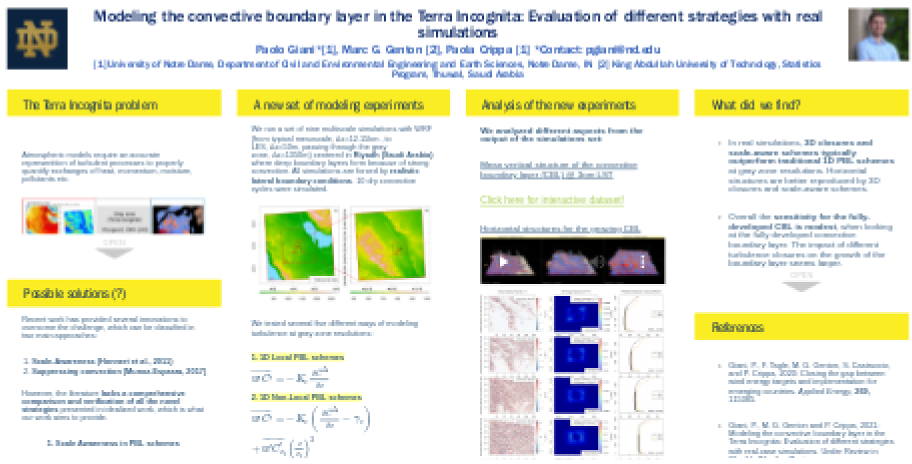
**Abstract**

Turbulent motions regulate vertical transport of momentum, heat, moisture and pollutants in the atmospheric boundary layer. From a numerical perspective, modeling such motions becomes challenging at kilometer and sub-kilometer resolutions, as the horizontal grid spacing of the model approaches the size of the most energetic convective eddies in the boundary layer. In this range of resolutions, typically termed 'terra incognita' or 'gray zone', partially resolved convective structures are grid-dependent and neither traditional 1D mesoscale parametrizations nor 3D closures typical of Large Eddy Simulations are theoretically appropriate. However, accurate numerical modeling at gray zone resolutions is a key aspect in several practical applications, such as proper coupling of mesoscale and microscale simulations. While some progress has been achieved in recent years through idealized simulations and theoretical considerations, the evaluation of different approaches in real convective boundary layers (CBL) is still very limited. Leveraging on a new set of one-way nested, full-physics multiscale numerical experiments, we quantify the magnitude of the errors introduced at gray zone resolutions and provide new perspectives on recently proposed modeling approaches. The new set of experiments is forced by real time-varying boundary conditions, spans a wide range of scales and includes traditional 1D schemes, 3D closures, scale-aware parametrizations and strategies to suppress resolved convection at gray zone resolutions. The study area is Riyadh (Saudi Arabia), where deep CBLs develop owing to strong convective conditions. Detailed analyses of our experiments, including validation with radiosonde data, calculations of spectral characteristics and partitioning of turbulent fluxes between resolved and subgrid scales, show that (i) grid-dependent convective structures entail minor impacts on first order statistics of the flow due to some degree of 'implicit scale-awareness' of 1D parametrizations and (ii) 3D closures outperform traditional and scale-aware 1D schemes especially in the surface layer, among other findings. The new simulation suite provides a benchmark of real simulations that can be extended to assess how new techniques for simulations at gray zone resolutions perform.

# Modeling the convective boundary layer in the Terra Incognita: Evaluation of different strategies with real simulations



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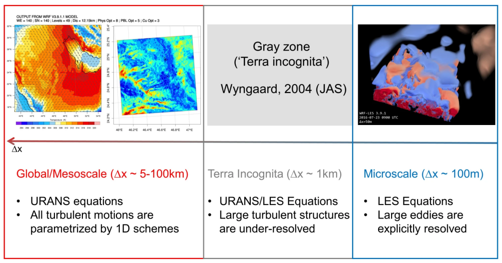
# THE TERRA INCOGNITA PROBLEM

Atmospheric models require an accurate representtion of turbulent processes to properly quantify exchanges of heat, momentum, moisture, pollutants etc.




As increasing computational resources are allowing horizontal grid resolutions (Δx) of numerical weather prediction models to move from mesoscale (Δx > 10km) towards the microscale (Δx ~ 100m), new challenges arise on the correct representation of turbulence structures at intermediate resolutions (Δx ~ 1km) termed ***terra incognita*** by Wyngaard (2004).

The problem becomes especially relevant when modeling the convective boundary layer, where the largest turbulent eddies span the entirety of the boundary layer and thus can reach lenght scales of 2-3km.

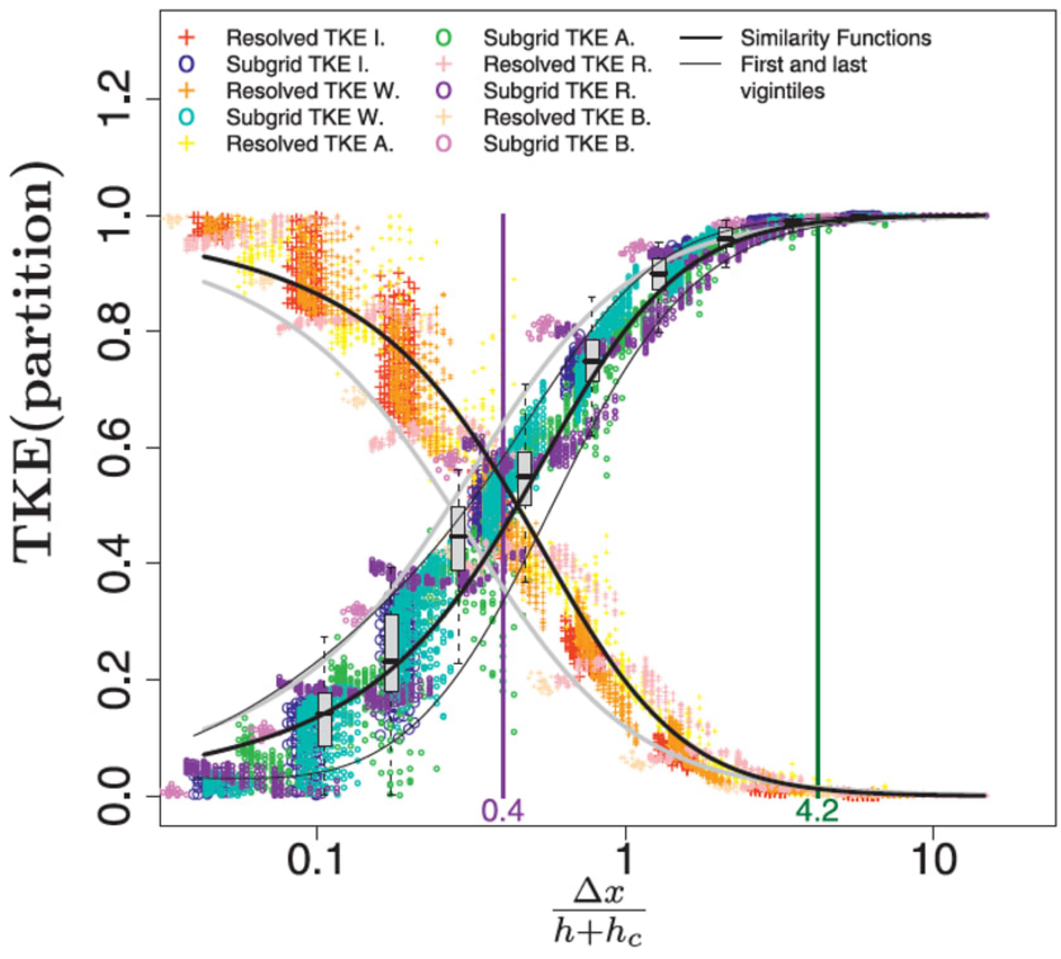
# POSSIBLE SOLUTIONS (?)

Recent work has provided several innovations to overcome the challenge, which can be classified in two main approaches:

1. **Scale-Awareness (Honnert et al., 2011)**
2. **Suppressing convection (Munoz-Esparza, 2017)**

However, the literature **lacks a comprehensive comparison and verification of all the novel strategies** presented in idealized work, which is what our work aims to provide.

**1. Scale Awareness in PBL schemes**

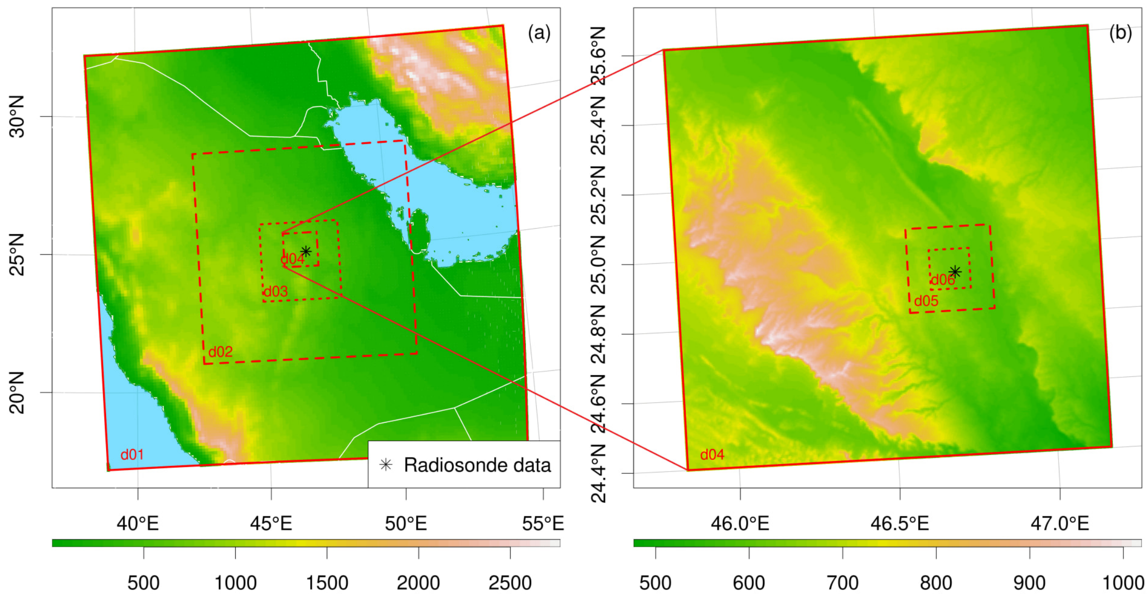



**2. Suppresing convection**

[VIDEO] https://res.cloudinary.com/amuze-interactive/image/upload/f_auto,q_auto/v1638564344/agu-fm2021/ce-8a-53-4a-73-e2-fb-a6-76-2a-c3-b7-7b-6e-c2-3f/image/suppressing_convection_2_ecgz5g.mp4

# A NEW SET OF MODELING EXPERIMENTS

We run a set of nine multiscale simulations with WRF (from typical mesoscale, Δx=12.15km , to LES, Δx=50m, passing through the gray zone, Δx=1350m) centered in **Riyadh (Saudi Arabia)** where deep boundary layers form because of strong convection. All simulations are forced by **realistic lateral boundary conditions**. 10 dry convective cycles were simulated.




We tested several five different ways of modeling turbulence at gray zone resolutions:

**1. 1D Local PBL schemes**

$$\overline{w'C'} = -K_c \frac{\partial \bar{C}^{\Delta}}{\partial z}$$

**2. 1D Non-Local PBL schemes**

$$\overline{w'C'} = -K_c \left( \frac{\partial \bar{C}^{\Delta}}{\partial z} - \gamma_c \right) + \overline{w'C'_{z_i}} \left( \frac{z}{z_i} \right)^3$$

**3. 3D Closures**

$$\overline{w'C'} = -K_c \frac{\partial \bar{C}^{\Delta}}{\partial z}$$

Where eddy viscosities/diffusivities are calculated via 3D deformation/TKE is produced on three-dimensional shear.

**4. Scale-aware schemes**

$$\overline{w'C'} = -K_c \left( \frac{\partial \bar{C}^{\Delta}}{\partial z} \right) P_L \left( \Delta x_* \right) + \overline{w'C'_{NL}} P_{NL} \left( \Delta x_* \right)$$

**5. Suppress convection with 1D PBL scheme**

$$K_h = C_s \Delta x \Delta y \sqrt{\frac{1}{4}(D_{11} - D_{22})^2 + D_{12}^2}$$

Where the Smagorisnky Coefficient $C_s$ is artificially increased to remove convection.

# ANALYSIS OF THE NEW EXPERIMENTS

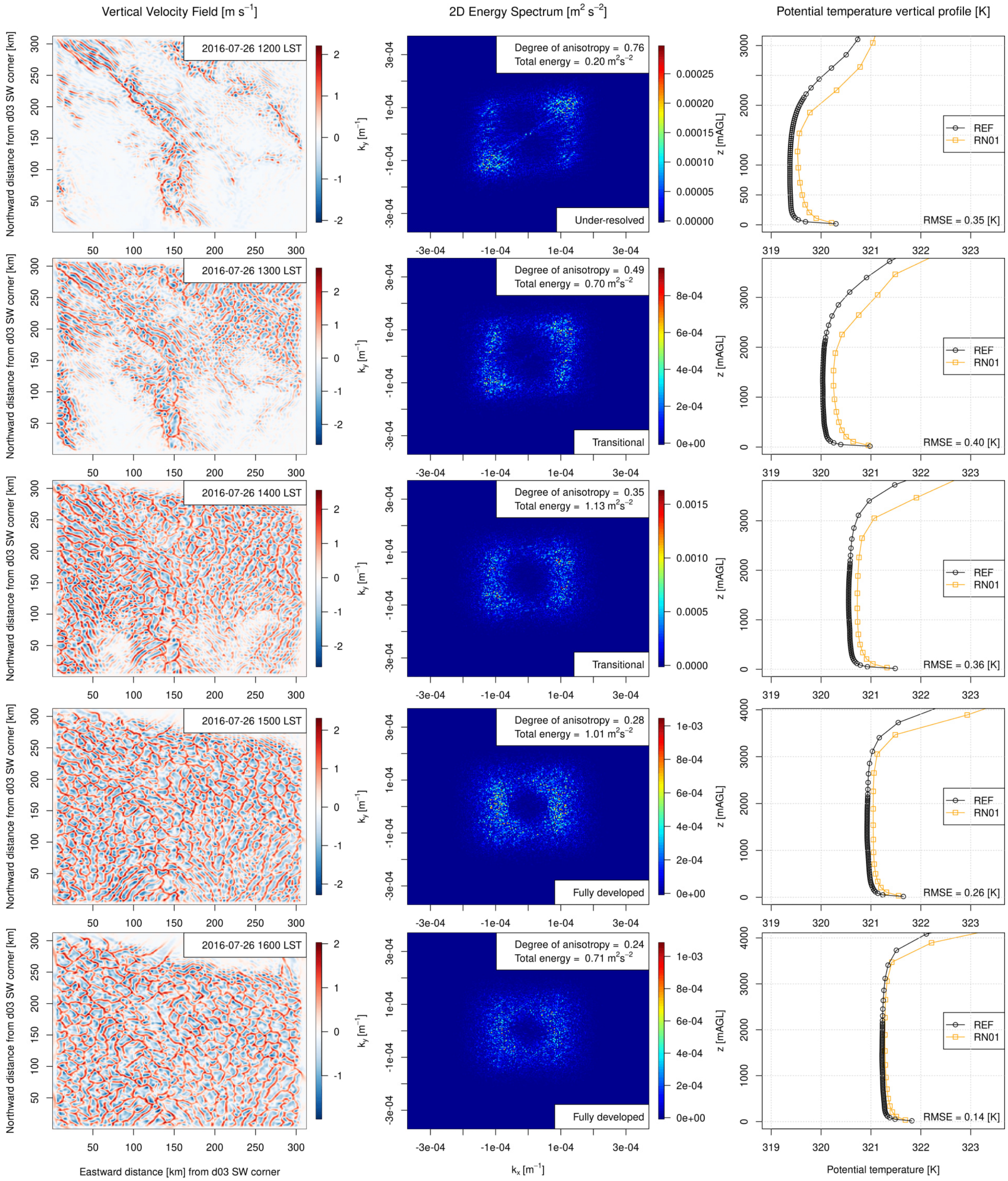
**We analyzed different aspects from the output of the simulations set:**

Mean vertical structure of the convective boundary layer (CBL) @ 3pm LST

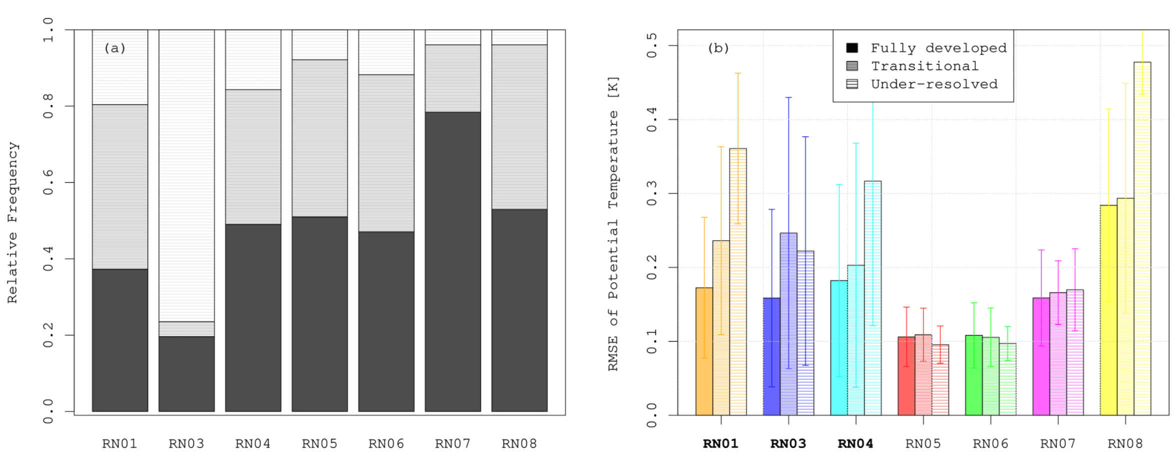
Click here for interactive dataset! (https://kranke-acamg.shinyapps.io/shiny-app1/)

Horizontal structures for the growing CBL

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639011918/agu-fm2021/CE-8A-53-4A-73-E2-FB-A6-76-2A-C3-B7-7B-6E-C2-3F/Video/movie-YSU-SH-TKE3D_yuvqpk.mp4



Vertical Velocity Field [m s$^{-1}$]
2D Energy Spectrum [m$^2$ s$^{-2}$]
Potential temperature vertical profile [K]
2016-07-26 1200 LST
Degree of anisotropy = 0.76
Total energy = 0.20 m$^2$s$^{-2}$
Under-resolved
RMSE = 0.35 [K]
2016-07-26 1300 LST
Degree of anisotropy = 0.49
Total energy = 0.70 m$^2$s$^{-2}$
Transitional
RMSE = 0.40 [K]
2016-07-26 1400 LST
Degree of anisotropy = 0.35
Total energy = 1.13 m$^2$s$^{-2}$
Transitional
RMSE = 0.36 [K]
2016-07-26 1500 LST
Degree of anisotropy = 0.28
Total energy = 1.01 m$^2$s$^{-2}$
Fully developed
RMSE = 0.26 [K]
2016-07-26 1600 LST
Degree of anisotropy = 0.24
Total energy = 0.71 m$^2$s$^{-2}$
Fully developed
RMSE = 0.14 [K]
REF
RN01
Northward distance from d03 SW corner [km]
Eastward distance [km] from d03 SW corner
$k_y$ [m$^{-1}$]
$k_x$ [m$^{-1}$]
z [mAGL]
Potential temperature [K]

(a)
Relative Frequency
RN01
RN03
RN04
RN05
RN06
RN07
RN08
(b)
Fully developed
Transitional
Under-resolved
RMSE of Potential Temperature [K]
RN01
RN03
RN04
RN05
RN06
RN07
RN08

# WHAT DID WE FIND?

- In real simulations, **3D closures and scale-aware schemes typically outperform traditional 1D PBL schemes** at gray zone resolutions. Horizontal structures are better reproduced by 3D closures and scale-aware schemes.

- Overall the **sensitivity for the fully-developed CBL is modest**, when looking at the fully developed convective boundary layer. The impact of different turbulence closures on the growth of the boundary layer seems larger.

- Convective structures are grid-dependent **but there is a significant amount of implicit scale-awareness** that guarantees satisfactory results in calculating turbulent fluxes even with 1D PBL schemes.

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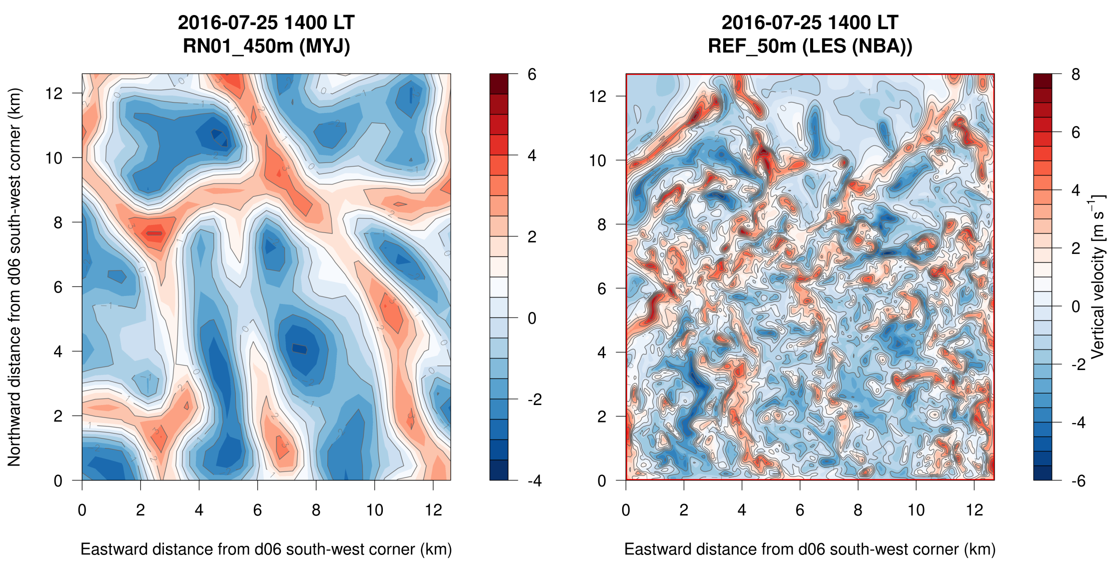


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