Hybrid turbulence models for atmospheric flow  
A proper comparison with RANS models

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Current issues in atmospheric modeling

- Computationally expensive if accuracy is needed
  - **Possible solution**: Hybrid models

- Turbulence theory is mainly based on flat terrain studies
  - i.e. wall-functions are used in complex terrain
  - **Possible solution**: A different approach for wall treatment in ABL

Proposed turbulence model:

\[ k - \omega \text{ SST-SIDDES} \]

(Simplified Improved Delayed Detached-Eddy Simulation)
Objectives

Main research objective:
Thorough validation of the proposed model for use in complex terrain

SOWE 2014 objective:
Validation cases:
- Atmospheric surface-layer*
- Atmospheric boundary-layer*

* Flat rough terrain, neutral stratification and no Coriolis effects
Focusing on comparing with a RANS model
Detached eddy simulation

- **DES**: hybrid model developed for massively separated flows
  - **URANS** to solve the boundary layer
  - **LES** outside the boundary layer

- **but** only the boundary layer is important for atmospheric flows
  - wall-modeled LES → **SIDDES** approach is needed
Proposed turbulence model

\[ k - \omega \text{ SST-SIDDES} \] (Gritskevich et al., 2012)

- Hybrid approach based on:
  - SIDDES
  - RANS \( k - \omega \text{ SST} \) (Menter et al., 2003)
    - Good results for adverse pressure gradient and separation regions, and its roughness treatment

\[
\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_t) \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right]
\]

**URANS-mode**: \( \bar{u}_i \) is the time-average velocity

**LES-mode**: \( \bar{u}_i \) is the filtered velocity
\[ \frac{\partial k}{\partial t} + \ldots = \tilde{P} - \frac{k^{3/2}}{\tilde{l}} \]

\[ \frac{\partial \omega}{\partial t} + \ldots \]

In the URANS-mode and LES-mode:

\[ \nu_t = \frac{a_1 k}{\max(a_1 \omega, SF_2)} \]

The length scale \( \tilde{l} \) will determine the “mode” of the equations locally and varying in time.
Length scale definition

**Detached Eddy Simulation (DES)** (Spalart et al., 1997)

\[ \tilde{l}_{DES} \equiv \min(l_{RANS}, l_{LES}) \]

**Might yield erroneous results for ABL flows**

**Simplified Improved Delayed Detached Eddy Simulation (SIDDES)** (Gritskevich et al., 2012)

\[ \tilde{l}_{SIDDES} \equiv \tilde{f}_d l_{RANS} + (1 - \tilde{f}_d) l_{LES} \]
Roughness treatment

- $k - \omega$ SST can be integrated down to the wall
  - wall-functions can be avoided

- The surface roughness is generally accounted by
  - a modification of the original equations
  - or a wall-function

$k - \omega$ SST accounts for roughness simply through the boundary conditions of $k$ and $\omega$
For fully rough surfaces:

\[ k|_{w,ABL} = \frac{u^*_w}{\sqrt{\beta_*}} \]

\[ \omega|_{w,ABL} = \frac{u_*}{\sqrt{\beta_*} \kappa z_0} \]

\[ u^2_* = (\nu + \nu_t) \frac{\partial u}{\partial n} |_w \]

A proper mesh is needed → \( z_1^+ \approx 0.3 \)

- \( z_1^+ \approx 10^4 \) for practical ABL grids → Can be costly!
- Extremely elongated cells close to the wall
  - The *blockMesh* was the main challenge
Discretization schemes

- **Recommended schemes:**
  - **RANS:** upwind (for stability)
  - **LES:** central difference (to reduce numerical dissipation)

- **Decaying isotropic turbulence test-case (LES-mode):**

![Graph showing normalized one-dimensional spectra](image)
Discretization schemes

- Smooth channel flow using central difference (URANS and LES):

![Graph showing non-dimensional shear stresses](image)

- Shur et al. (2008)
Blended discretization schemes

- Blended schemes based on the instantaneous URANS/LES regions
  - **LES** (light-gray) : 2nd CDS
  - **URANS** (black) : 2nd UDS
Blended discretization schemes

Blended schemes: $U$, $k$ and $\omega$

Central schemes: $U$

Blended schemes: $k$ and $\omega$
How to compare RANS and hybrid simulations?

Atmospheric surface layer (ASL)

- Monin-Obukhov theory is valid throughout the domain
  - Logarithmic velocity profile, constant tke, ...

- The height of the ASL is fixed

- Relevant case (?):
  - historical reasons
  - more control over the incident flow on wake studies (Jimenez et al. 2010)

Case 1: modeling the ASL

- **RANS**: Fixed shear stress at the top boundary

- **LES/hybrids**: Imposing a fixed shear stress is not as evident and some undesired phenomena may occur
Case 1: Atmospheric surface layer

- Periodic: streamwise and spanwise
- RANS: steady $k-\omega$ SST
- Hybrid: unsteady and taller domain (to account for the buffer layer)
- $z^+ \sim 1$ with a stretching up to 100 m, then uniform $\Delta = 15$ m
How to impose a constant shear stress?

The value of the wall shear stress, 

\[ \tau_0 = \rho u_*^2 \]

is imposed at the top boundary:

\[ \tau_{\text{top}} = \rho u_*^2 \]

\[ \tau_{\text{total}} = \tau_{\text{viscous}} + \tau_{\text{modeled}} + \tau_{\text{resolved}} \]

**RANS:**

\[ \tau_{\text{total}} \approx \rho \nu_t \frac{\partial \bar{u}}{\partial z} \]

**LES:**

\[ \tau_{\text{total}} \approx \rho \nu_t \frac{\partial \bar{u}}{\partial z} - \rho \langle \bar{u}' \bar{w}' \rangle \]
Case 1: ASL results

![Graph showing non-dimensional velocity vs. z/H](image)

- **Monin-Obukhov**
- **Jimenez et al. (2010)**
- **RANS**
- **DES**
- **SIDDES**
Case 1: ASL results

Non-dimensional total turbulent kinetic energy

\[ \frac{z}{H} \]

Monin-Obukhov
RANS
DES
SIDDES

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Case 1: ASL results - SIDDES

Non dimensional resolved shear stresses

\[ \tau_{xx}, \tau_{yy}, \tau_{zz}, \tau_{xy}, \tau_{xz}, \tau_{yz} \]

\[ z/H[\text{--}] \]

Non dimensional resolved shear stresses

Mary C. Bautista (ETS)
How to compare RANS and hybrid simulations?

Atmospheric boundary layer (ABL)

- Monin-Obukhov is only valid in \( \sim 10\text{-}20\% \) of the domain
- It might be more representative of what happens in reality.

Case 2: modeling the ABL

- **RANS**: Introducing a length-scale delimiter (i.e. eddy-viscosity models)
- **LES/hybrids**: Flow is driven by a pressure gradient source term
Case 2: Atmospheric boundary-layer

- Periodic: streamwise and spanwise
- RANS: steady and no length-scale delimiter
- $z^+ \sim 1$ with a stretching up to 100 m, then uniform $\Delta = 15$ m
Case 2: ABL results

Non-dimensional velocity vs. $z/H$ for different models:
- Monin-Obukhov
- RANS
- DES
- SIDDES
- Porte-Agel et al. (2000)

The graph shows the comparison of non-dimensional velocity against $z/H$ for various atmospheric boundary layer (ABL) models.
Case 2: ABL results

The graph illustrates the non-dimensional total turbulent kinetic energy as a function of $z/H$ for different models: Monin-Obukhov, RANS, DES, and SIDDES. The data points and lines represent the models' predictions across various $z/H$ values, indicating their performance in simulating the ABL conditions.
Conclusion

The $k \sim \omega$ SST-SIDDES:

- could provide a good compromise between accuracy and computational cost
- avoids the use of wall functions

The flat terrain analysis:

- is crucial to understand the model and its limitation
- is not based on “flat terrain assumptions”
A simple comparison between RANS and the mean values obtained in hybrid simulations prove to be not really straightforward.

Atmospheric surface-layer validation case
- Imposing a shear stress did not yield acceptable results for the hybrid models:
  - velocity profiles are not correct
  - but the shear stresses are constant

Atmospheric boundary-layer validation case
- SIDDES gives more accurate results than DES
- Further analysis is needed to compare the hybrid simulations to RANS. (i.e. include length-scale delimiter)
- A more complete grid analysis might be needed, including Brasseur and Wei (2010) criteria to avoid a possible “overshoot”.
Thank you!

Questions?
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