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Hybrid turbulence models for atmospheric flow

A proper comparison with RANS models

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Abstract.
A compromise between the required accuracy and the need for affordable simulations for the wind industry might be achieved with the use of hybrid turbulence models. Detached-Eddy Simulation (DES) [1] is a hybrid technique that yields accurate results only if it is used according to its original formulation [2]. Due to its particular characteristics (i.e., the type of mesh required), the modeling of the atmospheric flow might always fall outside the original scope of DES. An enhanced version of DES called Simplify Improved Delayed Detached-Eddy Simulation (SIDDES) [3] can overcome this and other disadvantages of DES. In this work the neutrally stratified atmospheric flow over a flat terrain with homogeneous roughness will be analyzed using a Reynolds-Averaged Navier–Stokes (RANS) model called $k - \omega$ SST (shear stress transport) [4], and the hybrids $k - \omega$ SST-DES and $k - \omega$ SST-SIDDES models. An obvious test is to validate these hybrid approaches and asses their advantages and disadvantages over the pure RANS model. However, for several reasons the technique to drive the atmospheric flow is generally different for RANS and LES or hybrid models. The flow in a RANS simulation is usually driven by a constant shear stress imposed at the top boundary [5], therefore modeling only the atmospheric surface layer. On the contrary the LES and hybrid simulations are usually driven by a constant pressure gradient, thus a whole atmospheric boundary layer is simulated. Rigorously, this represents two different simulated cases making the model comparison not trivial. Nevertheless, both atmospheric flow cases are studied with the mentioned models. The results prove that a simple comparison of the time average turbulent quantities obtained by RANS and hybrid simulations is not easily achieved. The RANS simulations yield consistent results for the atmospheric surface layer case, while the hybrid model results are not correct. As for the atmospheric boundary layer case, no meaningful conclusion could be established for RANS, and the DES results are not satisfactory. However the SIDDES model is capable of reproducing accurately the atmospheric boundary layer over flat terrain.

1 Introduction

The wind energy industry relies mostly on Reynolds-Averaged Navier-Stoke Simulations (RANS) turbulence models to simulate atmospheric flow since they have a relatively low computational cost.

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However, in order to have a more detailed description of the turbulence characteristics, better turbulence models are needed. Large-Eddy Simulation (LES) models could potentially be a good alternative to RANS, but their computational cost is considerably higher. A compromise between the required accuracy and the need for affordable simulations for the wind industry is expected to be achieved with the use of hybrid models like the Detached-Eddy Simulation (DES) approach.

DES is a hybrid technique which uses a unsteady-RANS (URANS) model to solve the flow behavior in the boundary layer and a LES model in regions of detached flow [1]. But for wind energy purposes, only the simulation of the atmospheric boundary layer is of interest; thus the aim of a hybrid model is to use URANS only in the near wall regions and LES away from the wall but still inside the boundary layer. In this case, the hybrid model acts as a wall modeled LES which is not in agreement with the original formulation of DES [1]. This may lead to inaccurate velocity and stress values at the URANS and LES interface causing a logarithmic layer mismatch (LLM) [2]. An extended version of DES called Simplify Improved Delayed Detached-Eddy Simulation (SIDDES) [3] can compensate for the LLM and overcome other disadvantages.

Turbulence models based on the RANS approach $k-\omega$ SST (shear stress transport) [4] and the DES and SIDDES techniques are analyzed in this research. This RANS model was chosen for two reasons: first it yields acceptable results in adverse pressure gradient and separations regions, and second the original k and ω equations can be integrated down to the wall and are capable of handling rough surfaces, hence, the use of wall-function can be avoided [6]. Those two characteristics make it a good candidate for complex terrain simulations. As for the hybrid approaches, the SIDDES advantages over DES are studied. Therefore, neutrally stratified atmospheric flow over a flat terrain with homogeneous roughness will be analyzed using $k-\omega$ SST, $k-\omega$ SST-DES, and the $k-\omega$ SST-SIDDES models.

An obvious validation test for these hybrid approaches is to compare its averaged results against the purely RANS model results. However, this comparison is not simple nor straightforward. Most RANS simulations modeled only the atmospheric surface layer (ASL), probably for the simplicity of imposing the necessary boundary conditions or historical reasons (i.e., small early turbines did not reach above the ASL). Hence, the Monin-Obukhov theory is valid throughout. However, imposing those same boundary conditions for an inherently unsteady LES or hybrid model is not trivial. Thus, almost all LES or hybrid models simulate a rather different case, the atmospheric boundary layer (ABL). Since the boundary conditions and the approach to drive the flow is different, the Monin-Obukhov theory is only valid in the bottom $\sim 10\%$ of the domain [7].

The difference in the model cases on a typical RANS simulation and on typical LES or hybrid simulations is a known issue, but to the authors knowledge it has never been thoroughly addressed in the literature. The objective of this work is to illustrate the differences between the two techniques to drive the flow, but most importantly test and validate the proposed hybrid models for atmospheric flow simulations over flat terrain.

2 Turbulence model description

The motion of a wind flow is described by

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

In a Detached-Eddy Simulation approach, $\overline{u}_i$ represents the time averaged velocity in the URANS regions, while in the LES regions this term is the filtered velocity [8]. The pressure term $\overline{p}$ is treated in a similar manner, while ν_t represents the turbulent viscosity or the subgrid viscosity in the URANS and LES regions respectively. Lastly, F_i can represent any external forcing.

The proposed hybrid model uses the RANS $k-\omega$ SST equations [4][1]. However, a modification is required in the turbulent kinetic energy equation. Specifically, the dissipation term ε in such equation is substituted by $k^{3/2}/\tilde{l}$ in order to introduce a universal length scale $\tilde{l} = k^{1/2}/(\beta^*\omega)$. The resulting closure equations for the specific turbulent kinetic energy, k, and the specific dissipation rate, ω, used for any of the DES approaches are [3]

$$\frac{\partial k}{\partial t} + \frac{\partial \overline{u}_j k}{\partial x_j} - \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right] = P_k - \frac{k^{3/2}}{\tilde{l}} \tag{2}$$

$$\frac{\partial \omega}{\partial t} + \frac{\partial \overline{u}_j \omega}{\partial x_j} - \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_t)\frac{\partial \omega}{\partial x_j}\right] = \frac{\gamma}{\nu_t}P_k - \beta\omega^2 + 2(1-F_1)\frac{\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{3}$$

Finally, in both URANS and LES regions the eddy-viscosity is determined as

$$\nu_t = \frac{a_1 k}{\max(\mathrm{a}_1\omega, \mathcal{S}\mathrm{F}_2)}. \tag{4}$$

Here $\mathcal{S} = \sqrt{S_{ij}S_{ij}}$ is the characteristic strain rate, and F_1 and F_2 are blending functions. The other constants are calculated as $\phi = F_1\phi_1 + (1-F_1)\phi_2$ based on the model constants summarized on Table 1.

Table 1: Turbulence model constants.

$k-\omega$ SST constants for atmospheric flows [9]:					
$\beta_1 = 0.0236$	$\beta_2 = 0.0276$	$\gamma_1 = 0.3255$	$\gamma_2 = 0.3011$	$\kappa = 0.40$	$\beta^* = 0.03$
$\sigma_{k1} = 0.85$	$\sigma_{k2} = 1.0$	$\sigma_{\omega 1} = 0.5$	$\sigma_{\omega 2} = 0.67$	$a_1 = 0.31$	$c_1 = 10.0$
SIDDES constants [3] [10]:					
$C_{k-\epsilon} = 0.61$	$C_{k-\omega} = 0.78$	$C_{dt1} = 20.0$	$C_{dt2} = 3.0$	$C_w = 0.15$	

It is the local and instantaneous value of $\tilde{l}$ that regulates if the k and ω equations will be solved in URANS or LES mode. Moreover, is the definition of the universal length scale $\tilde{l}$ that makes the distinction between the different Detached-Eddy Simulation approaches. The universal length scale is a function of the RANS and LES length scales, which are defined as

$$l_{RANS} = \frac{\sqrt{k}}{\beta^*\omega} \qquad\qquad l_{LES} = C_{DES}\Delta \tag{5}$$

([10] and [1] respectively). Where $C_{DES} = (1-F_1)C_{k-\epsilon} + F_1 C_{k-\omega}$, Δ is the filter width, and the rest are model constants from Table 1. The length scale describes the relative size of the modeled turbulence, hence l_{RANS} represents the eddies at a macroscale level, while l_{LES} refers to the grid size turbulence [8]. Finally in the DES approach, the universal length scale is given by

$$\tilde{l}_{DES} \equiv \min(l_{RANS}, l_{LES}) \tag{6}$$

defining the filter width as $\Delta_{DES} = \max(\Delta_x, \Delta_y, \Delta_z)$. While the SIDDES length scale is [3]

$$\tilde{l}_{SIDDES} = \tilde{f}_d\, l_{RANS} + (1-\tilde{f}_d)l_{LES}. \tag{7}$$

[1]According to *http://turbmodels.larc.nasa.gov/sst.html*, this article has a typographical error on the turbulent dissipation equation (Eq. 1) which has been corrected in subsequent references.

For this case, the filter width is defined as $\Delta_{SIDDES} = \min[\max(C_w d_w, C_w h_{\max}, h_{wn}),\ h_{\max}]$ where $h_{\max}$ is the maximum edge length of the cell, d_w is the distance to the nearest wall and h_{wn} is the grid step in the normal direction to the surface [11]. Additionally, $\tilde{f}_d$ is an empirical delay function that depends on the grid (i.e., cell aspect ratio and distance to the wall) and on the solution (i.e., local and instantaneous values of ν_t, strain rate and vorticity tensor). It is worth noticing that $\tilde{f}_d$ is a continuous function so the switch between the LES and URANS region has a smooth transition (contrary to the DES switch). Thus SIDDES has URANS or LES regions, as well as blend a of URANS and LES zones.

2.1 Roughness extension and meshing

The terrain roughness has a significant effect on the atmospheric flow. Specifically, the mass transport, and the velocity and the turbulence characteristics in the near-wall region are altered [12]. Most turbulence models, like $k - \varepsilon$, require certain modifications or extra terms inserted into the original equations, or the use of wall-functions to properly deal with surface roughness. On the contrary, the $k - \omega$ SST model is capable of accurately describing the effect of a rough surface without any modifications to the original equations [6].

The roughness effect for the $k - \omega$ SST model is simply taken into account through the wall boundary conditions. Thus the values of k_w and ω_w in this analysis are based on the roughness extension proposed by Knopp *et al.* [13]. Since the atmospheric flow is always considered a fully rough turbulent regime [14], this roughness extension can be simplified to

$$k_{w,ABL} = \frac{u_*^2}{\sqrt{\beta^*}} \qquad \omega_{w,ABL} = \frac{u_*}{\sqrt{\beta^*}\kappa z_0} \tag{8}$$

With these boundaries the use of wall-functions can be avoided for the $k - \omega$ SST model, nevertheless, a fine vertical grid refinement is crucial. This roughness extension requires the first cell center to be located at a non-dimensional distance of $z_1^+ = u_* z_1/\nu \approx 0.3$ regardless of the roughness height [13]. For high Reynolds number flows, such constrain results in extremely fine and high aspect-ratio cells close to the wall. This issue does not increase the computer time drastically because the fine cell regions are being solved by URANS, but it might be a big disadvantage when creating meshes for complex terrains.

The near wall modeling of a rough surface is an important concept that requires special attention. The flow behavior at heights below the equivalent sand-grain roughness $k_{s,ABL} \approx 30\, z_0$ is not physical [12]. Thus, the simulations results for regions were $z^+ < k_s^+$ are not meaningful. This is one of the reasons why it is a common practice in wind energy application to set the height of the first cell center to at least the roughness height z_0 [14] which will correspond to a non-dimensional distance of $z_1^+ \approx 10^4$ for atmospheric flows. Nevertheless for $k - \omega$ SST simulations without wall-function and $z_1^+ \sim z_0^+$, the results are not accurate. A mesh where $z_1^+ \ll k_s^+$ can be consider a waste of computer resources since rather large number of grid cells within the roughness height have to be computed and give no relevant information about the physics of the flow. Nevertheless, this method can be more appropriate for complex flows than the use of wall-functions [12]. Consequently, this RANS turbulence model (or any hybrid model based on it) are good candidates to model the atmospheric flow in complex terrain.

2.2 Numerical framework

The $k - \omega$ SST-DES and the $k - \omega$ SST-SIDDES models have been implemented in OpenFOAM® version 2.2.2. The pressure-implicit split-operator (PISO) algorithm is used for the momentum-pressure coupling with three outer correction loops (`nCorrectors`) for pressure. The geometric-algebraic multi-grid method (`GAMG`) with a diagonal incomplete-Cholesky with Gauss-Seidel (`DICGaussSeidel`) smoother was used to solve the pressure linear equation; while the velocity, k and ω linear equations are solved by the `smoothSolver` method and the `GaussSeidel` smoother. If instead of the latter, the preconditioned biconjugate gradient solver method (`PBiCG`) was used, the simulations became unstable when run in parallel and the number of pressure iterations needed to reach the defined tolerance increased considerably. To assure stability, a time step that assured a Courant–Friedrichs–Lewy (CFL) number of 0.7 is used throughout. Finally the simulations ran for the equivalent of at least 20 longitudinal flow-through-times ($L_x/\langle u\rangle$), then, the time averaged statistics were gathered for the following 20 flow-through-times for all cases.

The choice of discretization schemes is essential to reproduce the turbulence characteristics. Yet this choice is not simple for hybrid models since RANS and LES have much different requirements. RANS simulations are more stable if an upwind discretization scheme is used, but for LES the numerical dissipation introduced by the upwind schemes is excessive. For LES simulations, less numerically dissipative central schemes should be used. In order to verify these facts, a decaying isotropic turbulence (DIT) case is studied. More importantly, DIT is used as a benchmark to validate if the hybrid model is able to reproduce the transfer of energy between the different turbulent scales within this particular numerical framework (i.e., OpenFOAM® code, linear solvers and especially discretization schemes).

The computed DIT case consists of a turbulent flow in a cubic domain with only periodic boundary conditions. With this simple configuration, the turbulence decays over time since there is no turbulence production. Figure 1 shows the $k-\omega$ SST-SIDDES simulation results compared against a Direct Numerical Simulation (DNS) [15]. The slope of the one dimensional spectrum is reproduced correctly when second order central schemes (`linear`) are used to discretized the convective terms of the momentum equation regardless of the schemes used for the divergence terms in the k and ω equations. The cusp at higher wavenumber is a well known phenomena present in eddy viscosity models [16]. Additionally, the spectrum shape is not greatly affected if the OpenFOAM® `filteredLinear` scheme (which contains some upwind components) is used. However, the quadratic upwind interpolation (`QUICK`) and a second order upwind (`linearUpwind`) prove to be too dissipative.

Due to the absence of solid surfaces in the DIT case, only the LES mode of the hybrid model is active. Therefore using central schemes does not affect the stability of the simulation. But for cases that have a URANS region, the hybrid simulations are very likely to diverge if only central schemes are used. For this reason `localBlending` discretization schemes are chosen. The `blendingFactor` is defined based on the local and instantaneous URANS and LES regions in the domain. For cells located on pure URANS regions, the `blendingFactor` is defined as 0 and the `linearUpwind` scheme is chosen; while for cell in pure LES zones, the `blendingFactor` equals to 1 and the `linear` central scheme is used. For the temporal discretization the second order backward scheme is always employed.

To validate the blended schemes a smooth half channel flow case is studied. This test case was carried with the same flow and mesh parameters as Shur *et al.* [11], using an almost identical hybrid model, but different discretization schemes. Since OpenFOAM® has intrinsically a second order spatial discretization, the schemes used in our model implementation are all second order; while the original reference case used fourth order central schemes. As expected in Figure 2a our second order central implementation could not reproduced the fourth order reference case. But using locally blended discretization schemes for the divergence terms in the k and ω equations and even a higher CFL number, the shear stresses are in agreement as it can be seen in Figure 2b. Additionally, the simulations prove to be stable with this type of blended schemes.

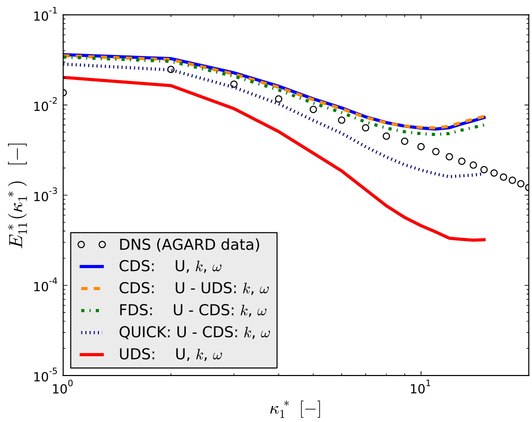
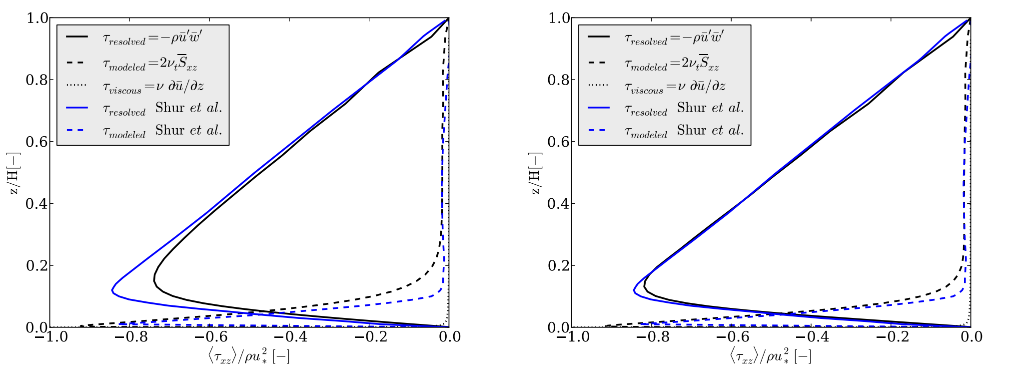


Figure 1: Normalized 1D energy spectra of decaying isotropic turbulence. SIDDES results are compared against a DNS simulation from the AGARD database [15]. The divergence terms in the U, k and ω equations are discretized using central (CDS), `filteredLinear` (FDS), QUICK or upwind (UDS) discretization schemes.



(a) Central discretization schemes. CFL=0.2

(b) Locally blended schemes for k and ω. CFL=0.7

Figure 2: Non-dimensional resolved, modeled and viscous shear stresses for a smooth half channel flow. These SIDDES results are compared against the digitalized data obtained from Shur *et al.* [11]. A better agreement is obtained with local blended schemes at a higher CFL as in (b) than using second order central discretization schemes as seen in (a).

2.3 Atmospheric flow modeling

Following the previous analysis of the $k-\omega$ SST-SIDDES model within the OpenFOAM® framework, the hybrid model is validated for atmospheric flows. The two rather simple cases studied are the ASL and ABL in rough flat terrain. In all simulations a value of $z_0 = 0.1$ m and $u_* = 0.3880$ m/s is used. As to the meshes, a $z_1^+ \sim 1.0$ with an expansion ratio of $\Delta z_{i+1}/\Delta z_i \sim 1.17$ is set up to $z = 100$ m; from there, uniform cells with $\Delta = 15$ m are specified.

2.3.1 Atmospheric surface layer

The majority of the RANS simulations only focus on the ASL and impose a velocity or a shear at the top of the domain [5]. In this case, the Monin-Obukhov similarity theory is valid in the whole domain height (i.e., the velocity profile is logarithmic and the turbulence kinetic energy profile is constant) [17]. Nevertheless, imposing a velocity or shear in a LES or hybrid simulation is not obvious.

To have a constant shear stress throughout the domain as in the ASL, the value of the wall shear stress $\tau_0 = \rho u_*^2$ could be imposed as the top boundary condition, thus $\tau_{top} = \rho u_*^2$ [18]. It is worth mentioning that contrary to models that use a wall-function, with this $k-\omega$ SST surface treatment the value of τ_0 is not imposed. Nevertheless the initial estimation of the wall shear stress is always in agreement with the calculated final values, so τ_{top} is just set from the beginning of the simulation. τ_{top} has to represent the total stresses, hence $\tau_{total} = \tau_{viscous} + \tau_{modeled} + \tau_{resolved}$ where the viscous part can be neglected in atmospheric flows. Additionally for RANS simulations the resolved part is absent, thus

$$\text{RANS}: \qquad \tau_{top} \approx \rho \nu_t \frac{\partial \overline{u}}{\partial z} \tag{9}$$

From here the value of the velocity at the top boundary can be calculated. On the other hand, for hybrid or LES models the resolved part is the most relevant contribution, hence

$$\text{LES/hybrids}: \qquad \tau_{total} \approx \rho \nu_t \frac{\partial \overline{u}}{\partial z} - \rho \langle \overline{u}' \overline{w}' \rangle \tag{10}$$

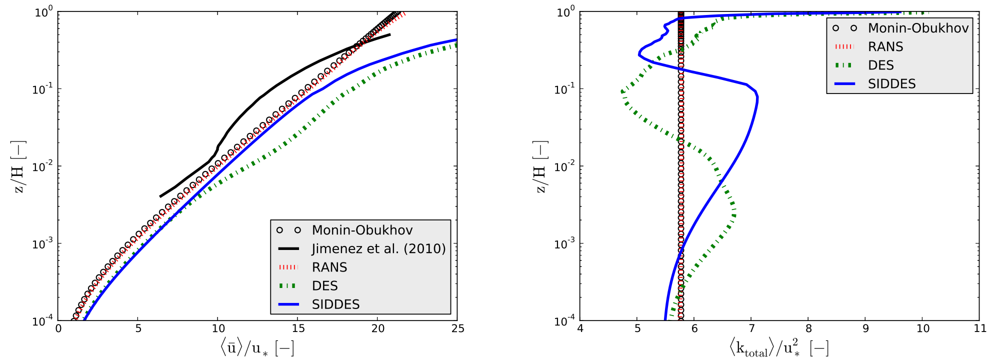
where $\overline{u}'$ and $\overline{w}'$ represent the resolved velocity fluctuation. However, the top boundary is not a true free boundary and the fluctuations close to it are damped. For this reason the resolved stresses are incorrectly estimated. In similar manner, if instead the velocity is specified at the top boundary the results will not be satisfactory. The ASL case boundary conditions and domain size are summarized in Table 2. The hybrid domains are taller to try to diminish the damping effect but without success.

Table 2: Boundary conditions and domain size for the atmospheric flow cases.

	ASL	**ABL**
bottom:	no-slip + roughness ext. (Eq. 8)	no-slip + roughness ext. (Eq. 8)
top:	fixed shear stress	stress free (`slip`)
stream + spanwise:	periodic	periodic
F (in Eq. 1):	0	$F = \partial P / \partial x = u_*^2 / H$
U_{init}:	logarithmic + random fluctuations	logarithmic + random fluctuations
domain size:	RANS: (3000, 500, 500) m hybrid: (3000, 500, 1000) m	RANS: (3000, 500, 500) m hybrid: (3000, 500, 500) m

Figure 3 shows the model comparison of the velocity profiles and the turbulent kinetic energy taken at the center of the domain. It is evident that the RANS $k-\omega$ SST model agrees with the Monin-Obukhov theory. However, the hybrid models do not represent the profiles correctly but they are consistent with other published results [18]. As expected the LLM is clearly observed on the DES velocity profile. But more important, since the resolved shear stresses erroneously tend to zero at the top due to damping, the velocity gradient (on Eq. 10) increases drastically to try to compensate. Nevertheless Figure 4 shows that the resolved shear stresses are constant throughout the domain.

These stresses are slightly underestimated from the atmospheric measurements [19] as it is expected for any eddy viscosity model [20]. Jimenez *et al.* [18] have taken advantage of the constant shear stresses to analyze turbine wakes in spite of the velocity profiles.



(a) Non-dimensional velocity

(b) Non-dimensional total turbulent kinetic energy

Figure 3: Atmospheric surface layer case. The Monin-Obukhov theoretical profiles for velocity (a) and turbulent kinetic energy (b) are well reproduced by RANS, but not by the hybrid models.

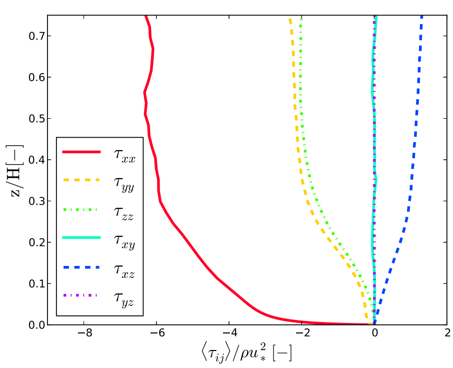


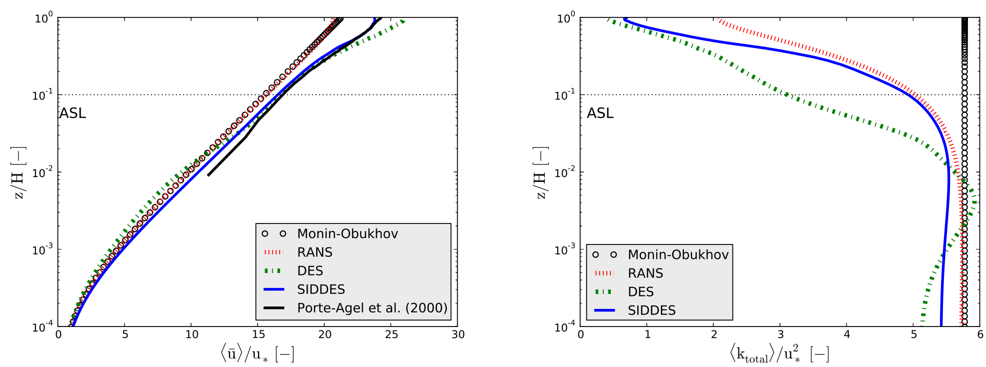
Figure 4: Resolved shear stresses $\tau_{ij} = -\rho \overline{u}_i' \overline{u}_j'$ from the ASL case using SIDDES. This model has a significant URANS region close to the wall, thus the resolved stresses in that zone are small. Above the near wall region, the shear stresses are constant.

2.3.2 Atmospheric boundary layer

The majority of LES and hybrid simulations model the whole ABL so the flow is driven by a constant pressure gradient term added to the Navier-Stokes equations and a stress free boundary condition is imposed at the top of the domain. A pressure driven flow simulation yields a logarithmic velocity profile and a constant turbulence kinetic energy profiles only in the bottom ∼10% of the domain [7]. However, eddy viscosity RANS models require a length scale delimiter to account for the unphysical and unlimited increase of the calculated length scale [21]. To the authors knowledge, only the length scale delimiter for $k - \varepsilon$ models has been analyzed in the literature, and the extrapolation to the

$k-\omega$ SST might not be as straightforward nor the objective of this work. Therefore, the RANS ABL simulation presented here does not contain a length scale delimiter.

The ABL results are shown in Figure 5 and compare with a LES standard dynamic model [7]. With the RANS and SIDDES models, the Monin-Obukhov theory is valid up to $\sim 10\%$ of the domain as expected, while the LLM is seen in DES results. It is evident that the SIDDES model yields considerably better results than DES, but the URANS regions are greater in the former. The mean values of velocity and total turbulent kinetic energy (i.e., resolved and modeled) of the SIDDES model differ from the RANS model. However, due to the lack of length scale delimiter in the RANS model no significant conclusions can be drawn. Additionally, a thorough grid analysis might be needed for the hybrid cases including possibly the "high accuracy zone" criteria [22].



(a) Non-dimensional velocity

(b) Non-dimensional total turbulent kinetic energy

Figure 5: Atmospheric boundary layer case. The Monin-Obukhov theoretical profiles for velocity (a) and turbulent kinetic energy (b) are well reproduced by RANS and SIDDES within the ASL as expected. On the contrary, the LLM is evident in the DES results.

3 Conclusion

The $k-\omega$ SST-SIDDES hybrid model is being thoroughly validated for atmospheric flows. This model is expected to be a good candidate for complex terrain simulations for two main reasons: it might provide a good compromise between accuracy and computer cost due to the hybrid approach, and its particular wall treatment is not based on flat terrain assumptions (i.e., no wall-function required). Its implementation within the OpenFOAM® framework has been validated for simpler flows (i.e., decaying turbulence and smooth channel flow) and it is being tested for atmospheric flows.

In this article, neutral ASL and ABL cases over rough and flat terrain are analyzed using the RANS $k-\omega$ SST model and the $k-\omega$ SST-DES and $k-\omega$ SST-SIDDES hybrid models. The main objective is to compare the time average values of some turbulent quantities obtained by these models. This is not so simple due to the different techniques required to drive the flow in RANS and hybrid models. The results for the ASL case show that the RANS model agrees with the theory, while the velocity and turbulent kinetic energy profiles computed with the hybrid models are incorrect. However the shear stresses are constant throughout the domain for these hybrid models. As for the ABL case, a meaningful conclusion regarding the RANS and hybrid model comparison could not be established because the RANS simulation lacks a length scale delimiter. Nevertheless it can be observed that the SIDDES model compensates for the LLM thus it provides more acceptable results than DES.

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