Supporting Information for The Role of Surface Representation in Nested Large-Eddy Simulations over Complex Terrain of Perdigão

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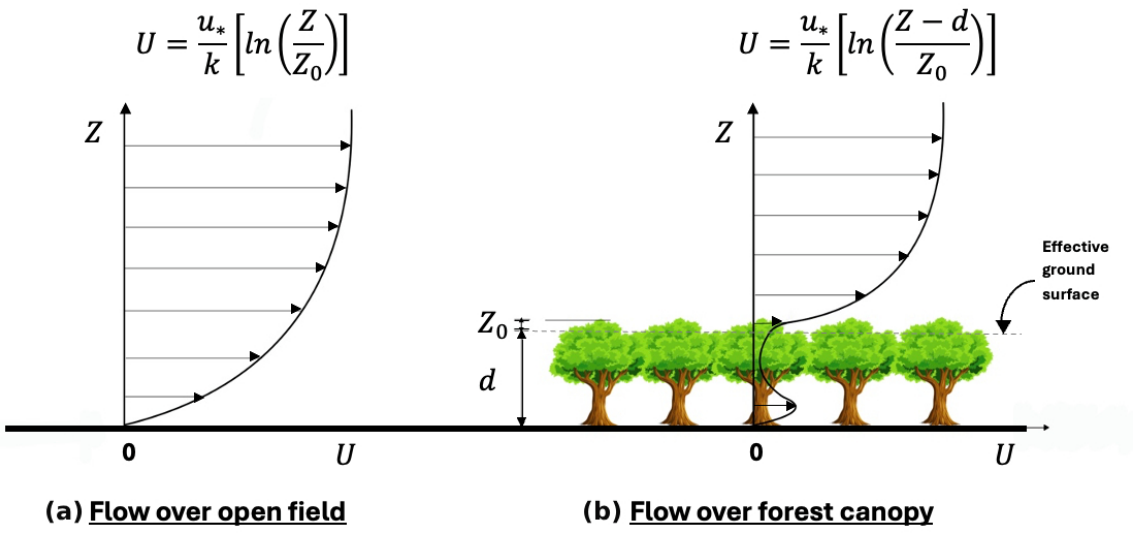


Figure S1. Wind speed (U) versus height (Z). The plots compare wind speed profiles over (a) an open field and (b) a forest canopy. The forest shifts the effective ground level upward to the displacement height (d). Note that wind speed increases more rapidly with height above the canopy compared to the open field (adapted from Rodrigues et al., 2021).

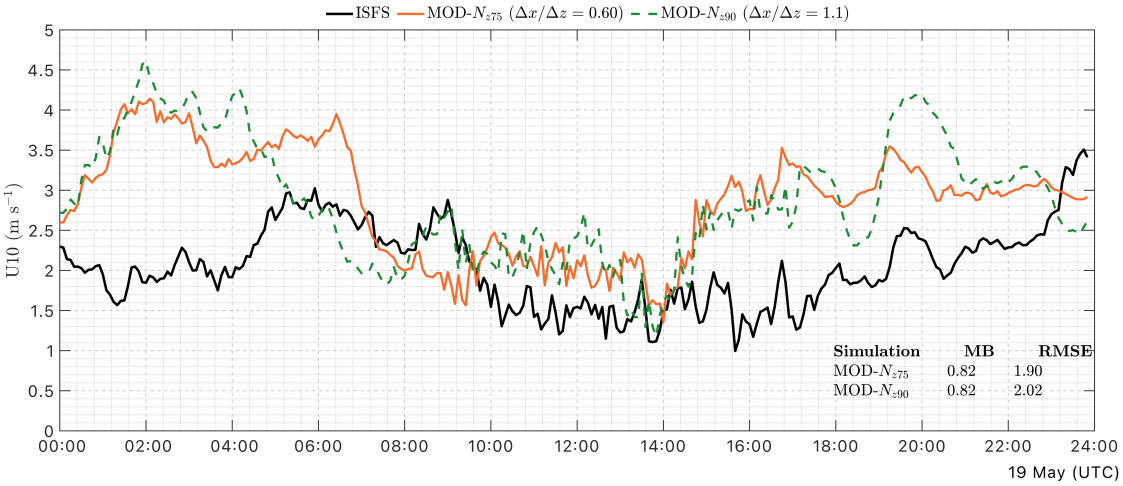


Figure S2. Time series of U10 averaged across all ISFS tower locations on 19 May 2017 for the ISFS observations and the two MOD simulations with different vertical-grid configurations. $MOD\text{-}N_{z75}$ uses 75 vertical levels with a near-surface grid-cell aspect ratio of $\Delta x/\Delta z \approx 0.60$, whereas $MOD\text{-}N_{z90}$ uses 90 vertical levels with $\Delta x/\Delta z \approx 1.1$. MB and RMSE are calculated relative to the ISFS observations across all towers. The comparison illustrates the sensitivity of the simulated near-surface wind speed to the vertical-grid configuration and associated grid-cell aspect ratio.

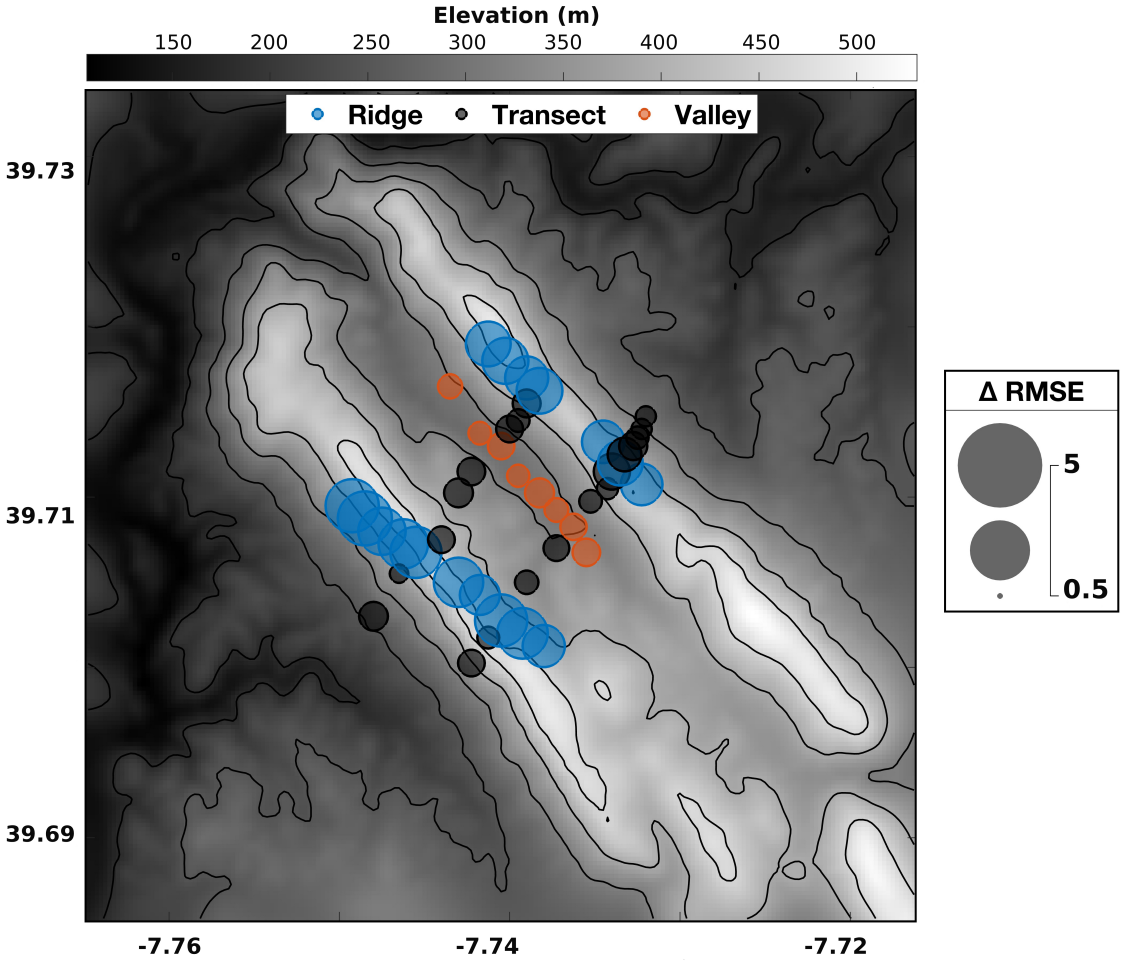


Figure S3. Difference in RMSE of U_{10} (m s^{-1}) between the MOD and $CTRL$ simulations at LES resolution across the ISFS tower locations. Ridge towers are shown in blue, valley towers in red, and transect towers in black. Contour lines represent the terrain elevation.

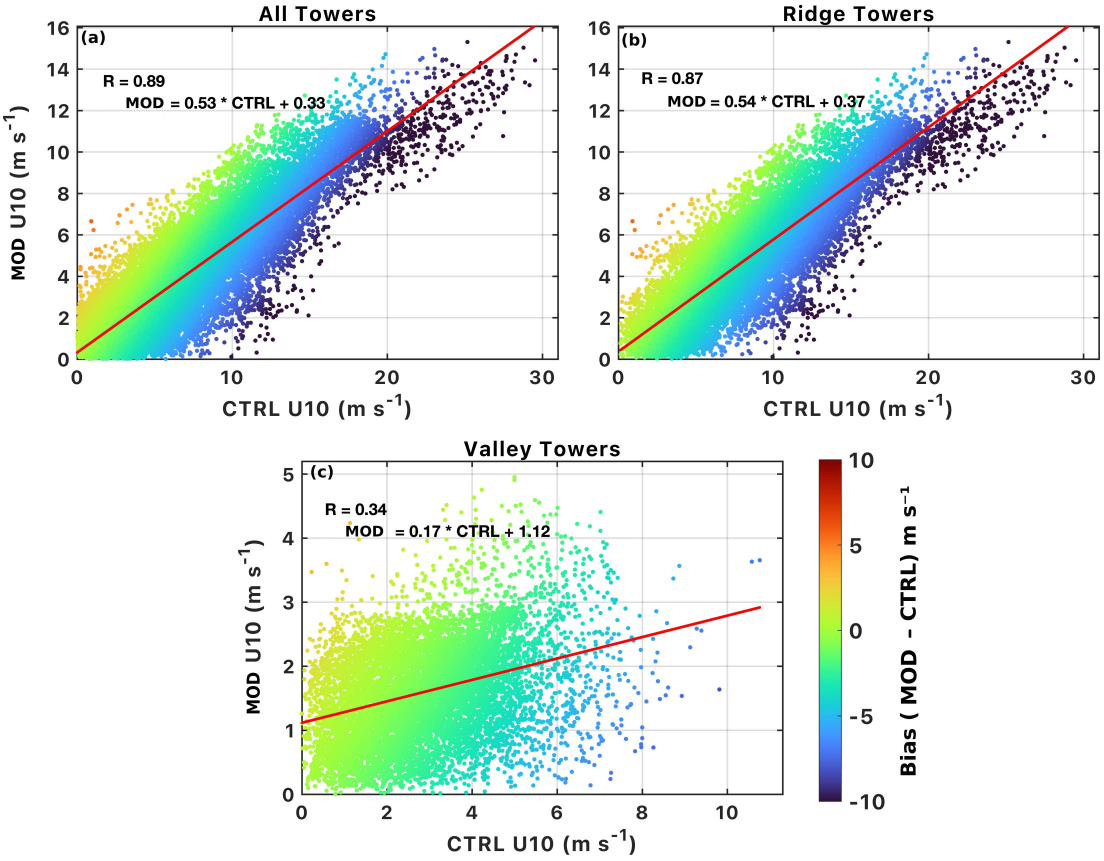


Figure S4. Comparison of U_{10} between CTRL and MOD at (a) all towers, (b) ridge towers, and (c) valley towers. Each panel shows scatterplots of instantaneous U_{10} from MOD versus CTRL saved at 5-min intervals, the red line is the line of best fit, and (R) is the correlation coefficient. Point colors indicate the instantaneous bias (MOD-CTRL) ; warm colors show positive bias and cool colors negative bias.

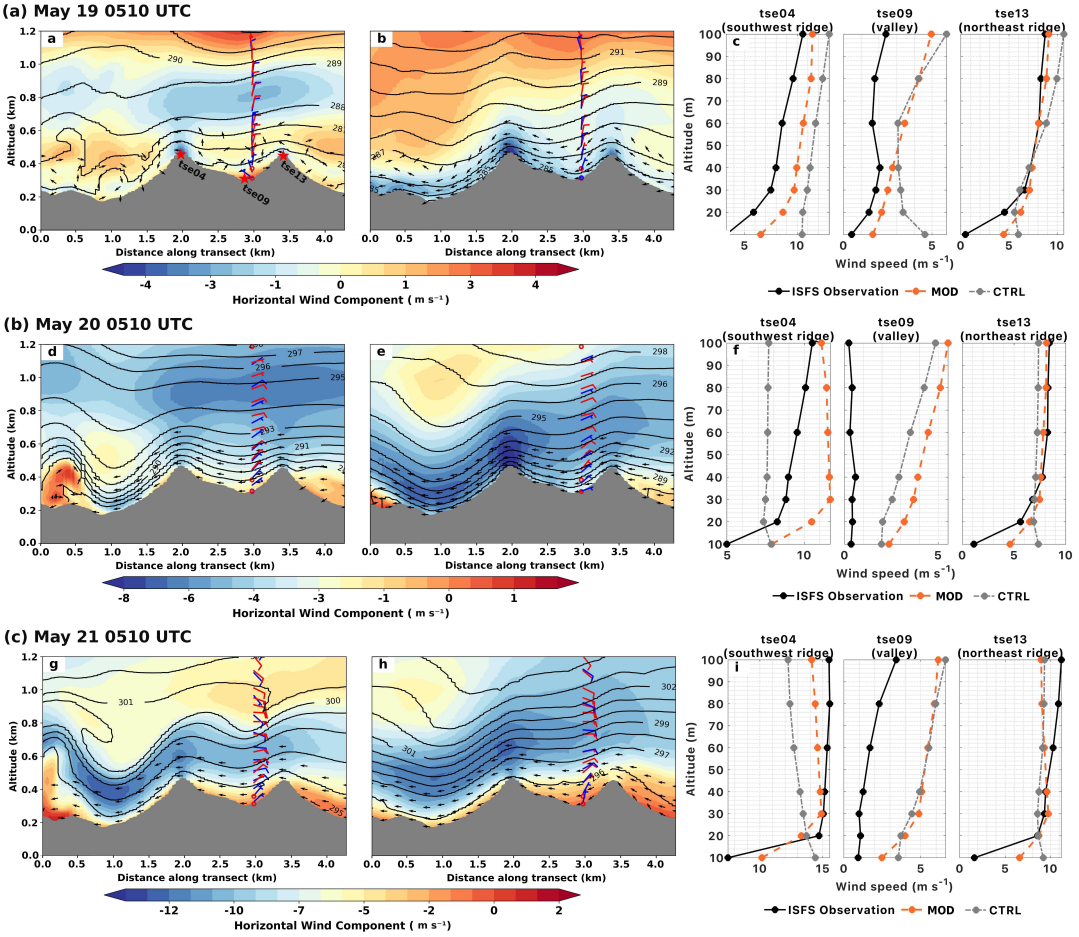


Figure S5. Cross-sections of horizontal wind speed (shaded, m s^{-1}) and potential temperature (contours, K) at 0510 UTC on 19, 20, and 21 May. Panels (a–c), (d–f), and (g–i) correspond to the three days, respectively. Within each row, the left panels show CTRL and the middle panels show MOD. Red wind barbs denote radiosonde wind speed and direction at 0510 UTC, while blue wind barbs denote simulated wind at the radiosonde launch location and time. The right panels (c, f, i) compare vertical profiles of horizontal wind speed at three ISFS tower locations: tse04 (southwest ridge), tse09 (valley), and tse13 (northeast ridge). Black lines indicate observations, orange markers show MOD, and gray markers show CTRL.

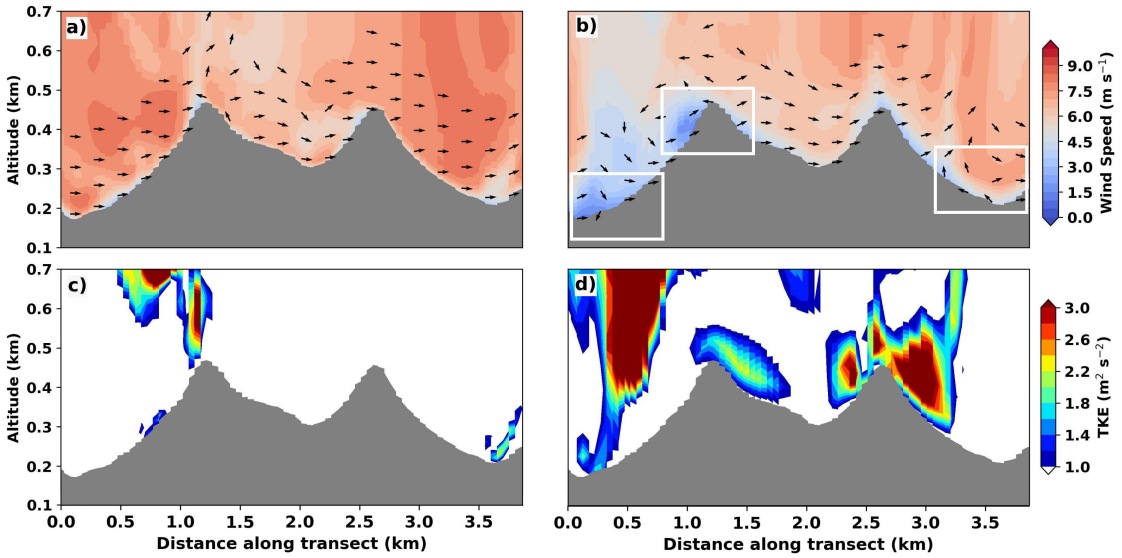


Figure S6. Cross-sections of wind speed (shaded, m s^{-1}) and TKE averaged over 15 minutes between 18:20 and 18:35 UTC on 21 May. Panels (a–c) refer to $CTRL$, while panels (b–d) refer to MOD. Black arrows indicate wind direction, and the white box highlights regions of flow reversal and enhanced turbulence intensity.

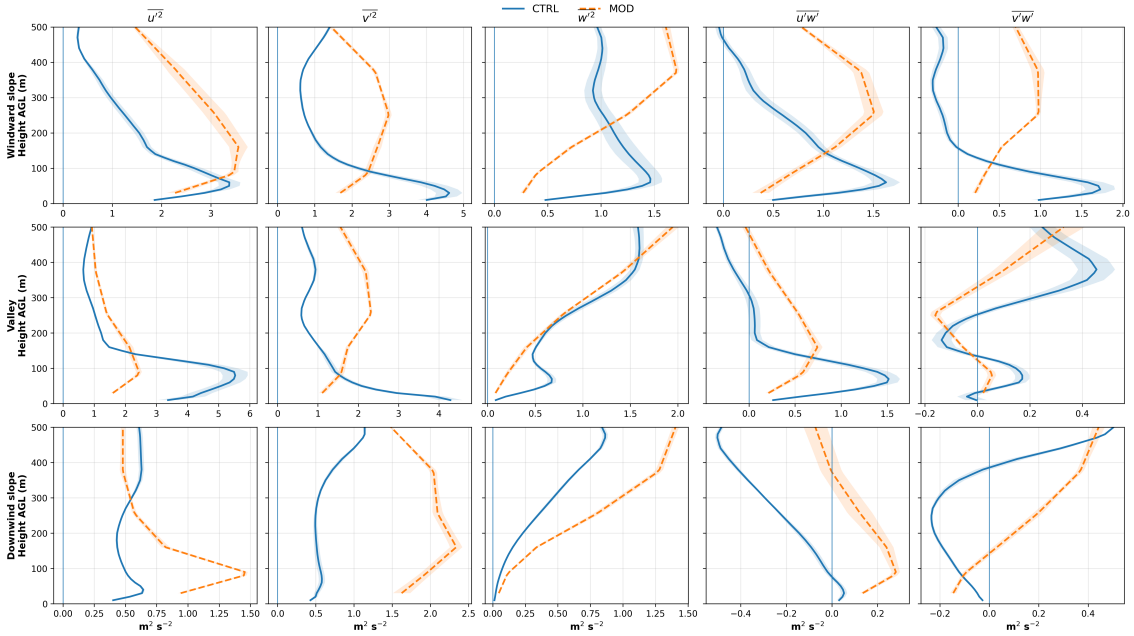


Figure S7. Vertical profiles of the resolved velocity variances ($\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$) and resolved Reynolds stresses ($\overline{u'w'}$ and $\overline{v'w'}$) for the $CTRL$ and MOD simulations over the windward slope (top row), valley (middle row), and downwind slope (bottom row) for the northeasterly case (Figure 8). The profiles are averaged over the one-hour period from 15:30 to 16:30 UTC on 19 May. The solid and dashed lines represent the horizontal mean profiles over the corresponding representative regions along the cross-section, and the shading represents the spatial standard error of the mean across each region. Height is given above ground level (AGL).

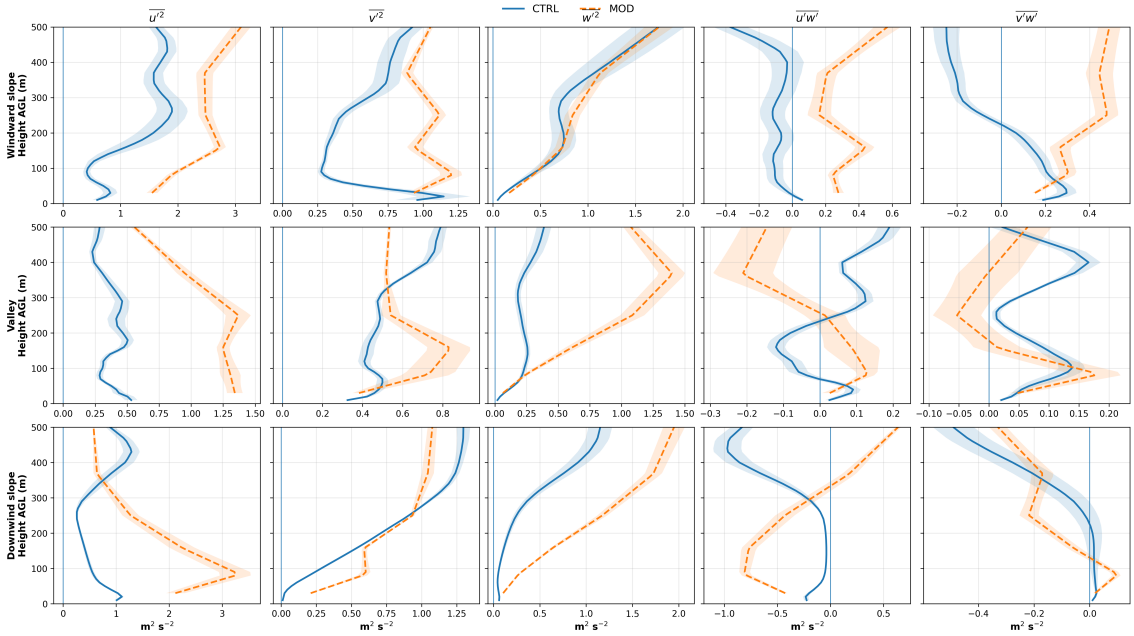


Figure S8. Vertical profiles of the resolved velocity variances ($\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$) and resolved Reynolds stresses ($\overline{u'w'}$ and $\overline{v'w'}$) for the $CTRL$ and MOD simulations over the windward slope (top row), valley (middle row), and downwind slope (bottom row) for the southwesterly case (Figure S5). The profiles are averaged over the one-hour period from 18:00 to 19:00 UTC on 21 May. The solid and dashed lines represent the horizontal mean profiles over the corresponding representative regions along the cross-section, and the shading represents the spatial standard error of the mean across each region. Height is given above ground level (AGL).

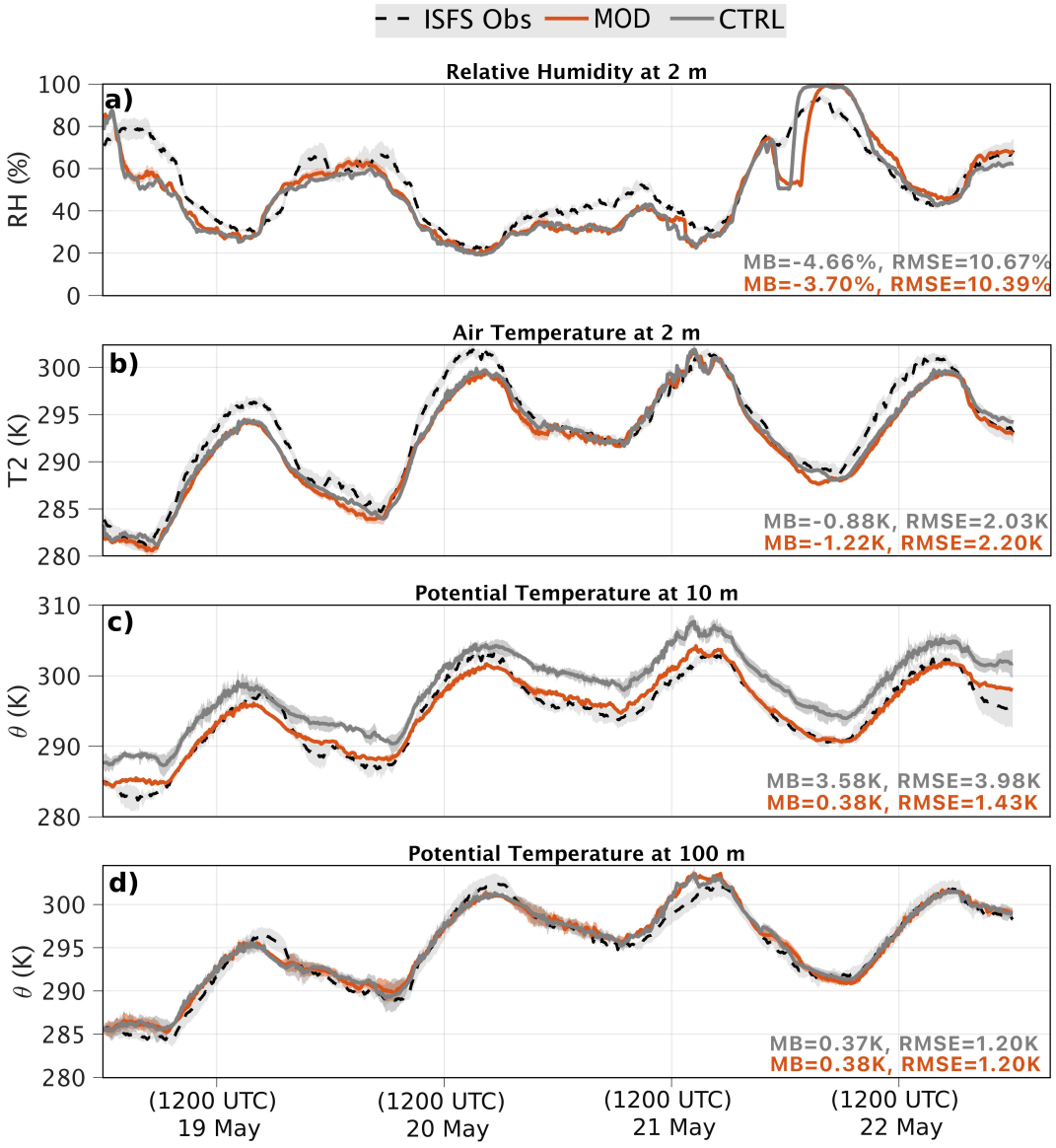


Figure S9. Time series of relative humidity at 2 m, air temperature at 2 m, potential temperature at 10 m, and potential temperature at 100 m from 19 to 22 May. Black dashed lines show ISFS observations, gray lines show the CTRL simulation, and orange lines show the MOD simulation. Shaded areas represent variability across stations. Mean bias (MB) and root mean square error (RMSE) values are given for CTRL (gray) and MOD (orange) relative to ISFS observations.

Table S1. Summary of the WRF model configurations used in this study. Shared configurations are listed in the upper panel, while the lower panel highlights the differences among the simulations. Vegetation structural properties, including albedo (α), leaf area index (LAI), and emissivity (ϵ), are prescribed according to the land-use category through the WRF vegetation parameter look-up table (`VEGPARM.TBL`) associated with the CORINE land-use dataset. The default surface roughness length ($Z_0 \approx 0.1$ m) corresponds to the value assigned by the look-up table for the Mixed Shrubland/Grassland category, whereas the higher value ($Z_0 = 1.9$ m) is prescribed based on observational estimates representative of the forest canopy in the Perdigão area.

Shared model configurations				
Domains	5 one-way nested domains (d01–d05)			
Grid dimensions	$196 \times 196 \times N_z$			
Grid spacing	Δx = 11250, 3750, 750, 150, 30 m			
Topography (d05)	SRTM (30 m)			
Land use dataset (d05)	CORINE (100 m)			
Initial & boundary conditions	ERA5 ($\Delta x = 0.25^\circ$, hourly)			
Surface layer scheme	Revised MM5			
Land surface scheme	Noah LSM			
Radiation (LW/SW)	RRTMG / Dudhia			
Turbulence scheme	Shin–Hong (d03–d04)			
LES closure	Deardorff TKE (d05)			
Cumulus scheme	Kain–Fritsch (only d01)			
Distinct configurations between simulations				
Feature	**CTRL**	**CTRL-N_z**	**CTRL-Z_0-N_z**	**MOD**
[l]Vertical levels (N_z)	[l]d01–d03: 77			
d04: 91				
d05: 109	All domains: 75			
First model half level (z_1)	$\sim$ 6 m	$\sim$ 25 m	$\sim$ 25 m	$\sim$ 25 m
[l]Land use category				
(d05)	Mixed Shrubland / Grassland			[l]Evergreen Needleleaf
Forest				
Surface roughness (Z_0)	$\sim$0.1 m	$\sim$0.1 m	1.9 m	1.9 m
Albedo (α)	0.22	0.22	0.22	0.12
Leaf Area Index (LAI)	0.60–2.60	0.60–2.60	0.60–2.60	5.00–6.40
Emissivity (ϵ)	0.93-0.95	0.93-0.95	0.93-0.95	0.95-0.95

Table S2. RMSE and MB for MOD and CTRL at different towers on May 19 until May 22 at 05:00 UTC.

Tower	Metric (m s^{-1})	MOD	CTRL
May 19 0510 UTC			
tse04	RMSE (MB)	2.24 (2.13)	4.14 (3.86)
tse09	RMSE (MB)	1.65 (1.45)	2.50 (2.26)
tse13	RMSE (MB)	1.66 (1.03)	3.92 (1.47)
May 20 0510 UTC			
tse04	RMSE (MB)	1.81 (1.65)	2.42 (-1.77)
tse09	RMSE (MB)	3.64 (3.59)	2.53 (2.50)
tse13	RMSE (MB)	1.29 (0.41)	2.41 (0.23)
May 21 0510 UTC			
tse04	RMSE (MB)	1.37 (-0.36)	2.45 (-0.95)
tse09	RMSE (MB)	3.27 (3.17)	3.33 (3.30)
tse13	RMSE (MB)	2.21 (0.09)	3.07 (0.22)
May 22 0510 UTC			
tse04	RMSE (MB)	1.51 (1.39)	2.72 (2.71)
tse09	RMSE (MB)	1.86 (1.72)	2.41 (2.19)
tse13	RMSE (MB)	3.34 (3.28)	3.92 (3.89)

Table S3. Surface variables from the $CTRL$ and MOD simulations, averaged over the daytime period (06:00–20:00 UTC) and across the LES domain (d05). All fluxes are in W m^{-2}, and TSK is in K. Differences (column four) are calculated as $MOD - CTRL$, such that positive values indicate an increase in MOD relative to $CTRL$, while negative values indicate a decrease.

Surface Variable	**CTRL**	**MOD**	**Difference**
TSK	301.2	299.2	-2.0
$\boldsymbol{\alpha}$	0.22	0.12	-0.10
$\boldsymbol{SW}_{\text{net}}$	390.44	443.53	+53.09
$\boldsymbol{LW}_{\text{net}}$	-131.44	-118.5	12.94
$\boldsymbol{R}_{\text{net}}$	259	325	+66.00
LE	97.17	150.68	+53.51
H	112.05	132.4	+20.35
G	51.90	43.28	-8.62

Table S4. Root-mean-square error (RMSE; $m^2\ s^{-2}$) of hourly $\overline{u_{\parallel}'^2}$, $\overline{w'^2}$, and TKE for CTRL and MOD relative to ISFS observations at three Perdigão towers and five heights above ground level over 19–22 May 2017. Bold values indicate the lower RMSE.

Tower	Height (m)	$\overline{u_{\parallel}'^2}$		$\overline{w'^2}$		TKE	
		CTRL	MOD	CTRL	MOD	CTRL	MOD
tse04	30	2.249	**1.800**	0.213	**0.087**	1.999	**1.115**
	40	2.126	**1.792**	0.327	**0.096**	1.898	**1.104**
	60	2.010	**1.763**	0.572	**0.125**	1.781	**1.136**
	80	1.890	**1.769**	0.734	**0.186**	1.670	**1.234**
	100	1.757	**1.594**	0.814	**0.231**	1.586	**1.156**
tse09	30	1.561	**0.755**	0.128	**0.055**	1.268	**0.561**
	40	1.455	**0.874**	0.184	**0.079**	1.253	**0.571**
	60	1.727	**0.975**	0.282	**0.108**	1.442	**0.613**
	80	1.977	**1.283**	0.336	**0.133**	1.616	**0.832**
	100	1.875	**1.261**	0.357	**0.155**	1.637	**0.826**
tse13	30	1.752	**1.257**	0.111	**0.042**	1.705	**0.941**
	40	1.617	**1.222**	0.163	**0.066**	1.593	**0.927**
	60	1.403	**1.190**	0.278	**0.111**	1.463	**0.967**
	80	1.356	**1.237**	0.386	**0.177**	1.413	**1.093**
	100	1.376	**1.149**	0.477	**0.222**	1.387	**1.034**