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Buoyancy Effects on the Scaling Characteristics of Atmospheric Boundary Layer Wind Fields in the Mesoscale Range

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We have analyzed long-term wind speed time-series from five field sites up to a height of 300 m from the ground. Structure function-based scaling analysis has revealed that the scaling exponents in the mesoscale regime systematically depend on height. This anomalous behavior is likely caused by the buoyancy effects. In the framework of the extended self-similarity, the relative scaling exponents portray quasi-universal behavior.

I. INTRODUCTION

The atmospheric boundary layer (ABL) spans the lowest few hundred meters [1] of the earth's atmosphere and intensively exchanges mass (e.g., moisture), momentum, and heat with the underlying surface [2, 3]. Wind fields in this turbulent layer play major roles in a wide range of industrial (e.g., stack gas dispersion, wind energy generation), biological (e.g., evapotranspiration, pollen transport, migrations of birds and insects), and natural (e.g., soil erosion, transport, and deposition) activities and processes. Thus, it is not surprising that numerous studies have been conducted over the past decades for the multiscale characterizations of the ABL wind fields. Diverse methodologies with varying degrees of complexities, ranging from the traditional spectral methods [4–8] to the new-generation multifractal approaches [9–14], have been utilized.

To this date, the majority of the studies dealing with the identification of anomalous scaling (sometimes even multifractality [15]) in the ABL wind field focused on the microscale range (time-scale of tenths of a second to tens of minutes). In contrast, only a handful of studies [16–24] delved into characterizing the mesoscale range (approximately, sub-hourly to sub-daily time-scale). They analyzed observational datasets from field sites around the world (e.g., China, France, New Zealand, Italy, the Netherlands, Turkey, and the USA). Even though a few of these studies did not use wind data with adequate temporal resolution or sample size, the evidences of anomalous scaling in the mesoscale range were beyond any doubt. Most remarkably, Muzy et al. [21] and Baile and Muzy [22] found the intermittent nature of mesoscale wind fluctuations to be similar to its microscale counterpart (encompassing the inertial-range of turbulence). Similar conclusions were also recently drawn by Liu and Hu [24].

Owing to the dearth of long-term, high-quality upper ABL data, almost all the aforementioned mesoscale

wind characterization studies focused on the near-surface (around 10–20 m from the ground) region. The only exception being the study by Telesca and Lovallo [23]. They analyzed multi-year sodar-based wind data from various heights (50 m to 213 m) above ground level (AGL). They used the Multifractal Detrended Fluctuation Analysis and the Fisher-Shannon Information Plane approaches to detect any signature of multifractality in wind speed time-series. Interestingly, they found the scaling exponents to be strongly dependent on height. However, no physical explanation was provided. It is, however, plausible to speculate that the buoyancy effects are at the root of this height-dependency trait.

In the literature, it is well-known that the shear production of turbulence overpowers the buoyancy effects near the surface. However, buoyancy forcing becomes increasingly dominant as one moves away from the surface [2, 3]. However, it is not known whether the buoyancy forcing modulates the anomalous scaling behavior of wind speed in the mesoscale range. Therefore, we decided to address this intriguing issue in the present study.

II. DESCRIPTION OF SITES AND DATASETS

We make use of long-term wind datasets from several field sites with diverse geographical and climatological conditions (Table I). These datasets are measured with the aid of different types of research-grade instruments (e.g., cup anemometers, sodars). They all have a common averaging time of 10 min. More importantly, they all span the lower part of the ABL and not just the near-surface region.

FINO 1 is an offshore platform in the North Sea [25–27]. It consists of a 100 m tall meteorological tower equipped with wind speed measurement sensors (cup anemometers) at heights of 33 m, 40 m, 50 m, 60 m, 70 m, 80 m, 90 m, and 100 m. A total of 91 months of wind speed data collected over a period of nine years (2004–2012) are utilized in the present study.

Over the past four decades, observational data from the Cabauw (the Netherlands) meteorological tower have

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been used in various ABL studies [28–31]. We use 170 months of wind speed data (collected during the years 2001–2015) measured by propeller vanes at heights of 10 m, 20 m, 40 m, 80 m, 140 m, and 200 m. We would like to point out that even though the landscape at Cabauw is quite flat and open (grassland), the existence of wind breaks and scattered villages cause significant disturbances in the near-surface region [31]. The impact of this non-equilibrium behavior on scaling characteristics will be noted later in this paper.

Recently, the West Texas Mesonet (WTM) has installed sodars (manufacturer: Scintec, model: MFAS) at San Angelo, Midland, and Reese Technology Center (RTC), Lubbock (the USA). The typical vertical range of these sodars is from 30 m to approximately 300 m AGL. They have a vertical resolution of 10 m. From the past two years (2013–2014), we selected 8 months of wind speed data for scaling analysis.

All the aforementioned datasets contain variable amount of missing data. This data-loss problem is more severe for the sodars. Since a sodar is an active ground based acoustic remote sensing instrument, it suffers from signal attenuation at higher altitudes [32]. To account for the data-loss problem in an objective manner across the sites, we perform the following data pre-processing procedures. First, instead of analyzing an entire time-series (with sporadic gaps) from any site, we split it into several monthly time-series (each containing about 4300 samples). We discard a specific month’s data from further analysis if any of the vertical levels contain more than 20% of missing samples. By performing this simple data exclusion strategy, we ensure that for a given site, all the tower/sodar levels have more-or-less (within 20%) the same amount of samples. In the case of the WTM sodar data, we have added an additional constraint. We consider only the months during which all the three sodars collected wind data simultaneously.

Prior to scaling analysis, we normalize (zero mean, unit variance) each monthly time-series. Various orders of structure functions (defined below) are computed based on each normalized monthly time-series and then averaged over the different months. The normalization procedure aids in the visual detection of any collapse of computed statistics from various heights (AGL).

III. STRUCTURE FUNCTION ANALYSIS

In the turbulence literature, the scaling exponent spectrum, ζ_p , is defined as [33, 34]:

$$S_p(r) = \langle |\Delta u|^p \rangle \sim r^{\zeta_p} \quad (1)$$

where $S_p(r)$ is the so-called p -th order structure function. The angular bracket denotes spatial averaging and r is a separation distance that varies within a specific scaling range (e.g., inertial-range). For time-series analysis (where Taylor’s hypothesis is inapplicable), the usage of

TABLE I. Description of measurement sites

Site	Elevation (m) ^a	Location	# Months
FINO-1	0	54.01° N, 6.59° E	91
Cabauw	-0.7	51.97° N, 4.93° E	170
San Angelo	597.4	31.54° N, 100.51° W	8
Midland	874.8	31.95° N, 102.21° W	8
RTC	1015.6	33.60° N, 102.04° W	8

^a Mean sea level

time increment, Δt (in lieu of r), and temporal averaging is customary. This approach is followed here.

According to Kolmogorov’s celebrated 1941 hypothesis (K-41; [35]), $\zeta_p = p/3$ in the isotropic inertial-range of turbulence. In the buoyancy-range, for the velocity field, the hypothesis of Bolgiano [36–38] leads to: $\zeta_p = \frac{3}{5}p$. Over the years, several laboratory and numerical studies [39–41] have corroborated the existence of Bolgiano scaling in different types of convection. Its presence has also been indicated in the scaling of near-surface temperature field [42] and vertical wind speed profiles [43, 44]. However, to the best of our knowledge, this scaling has never been reported for the ABL (horizontal) wind field. Forty years ago, Monin and Yaglom (pp. 393 of [38]) wrote: “It is therefore probable that the formulas given above [in the context of Bolgiano scaling] will be valid beginning with heights of the order of 100 m [above the surface]. The verification of this conclusion will require special observations which one hopes will be carried out in the future”[45]. We are fortunate to have access to such ‘special observations’, and thus, will be able to address a few unresolved scaling issues of wind speed in the mesoscale range.

In Figs. 1–3, the second-order structure functions (S_2) and their corresponding local slopes (ζ_2 , [46]) are shown for FINO 1, Cabauw, and WTM sodars. The following assertions can be made based on these figures:

a. FINO 1

- Extended scaling regimes are clearly discernible in all the structure function plots.
- The ζ_2 values increase monotonically with height.
- These slopes are lower for the smaller time-increments (i.e., $\Delta t < 1$ h) in comparison to the larger ones (i.e., $2 \text{ h} < \Delta t < 6 \text{ h}$).
- For lower heights and smaller time-increments, ζ_2 values are close to the K-41 prediction (i.e., $\zeta_2 = 2/3$). Interestingly, the slopes remain significantly smaller than Bolgiano’s prediction of $6/5$ for all heights and for all time-increments.

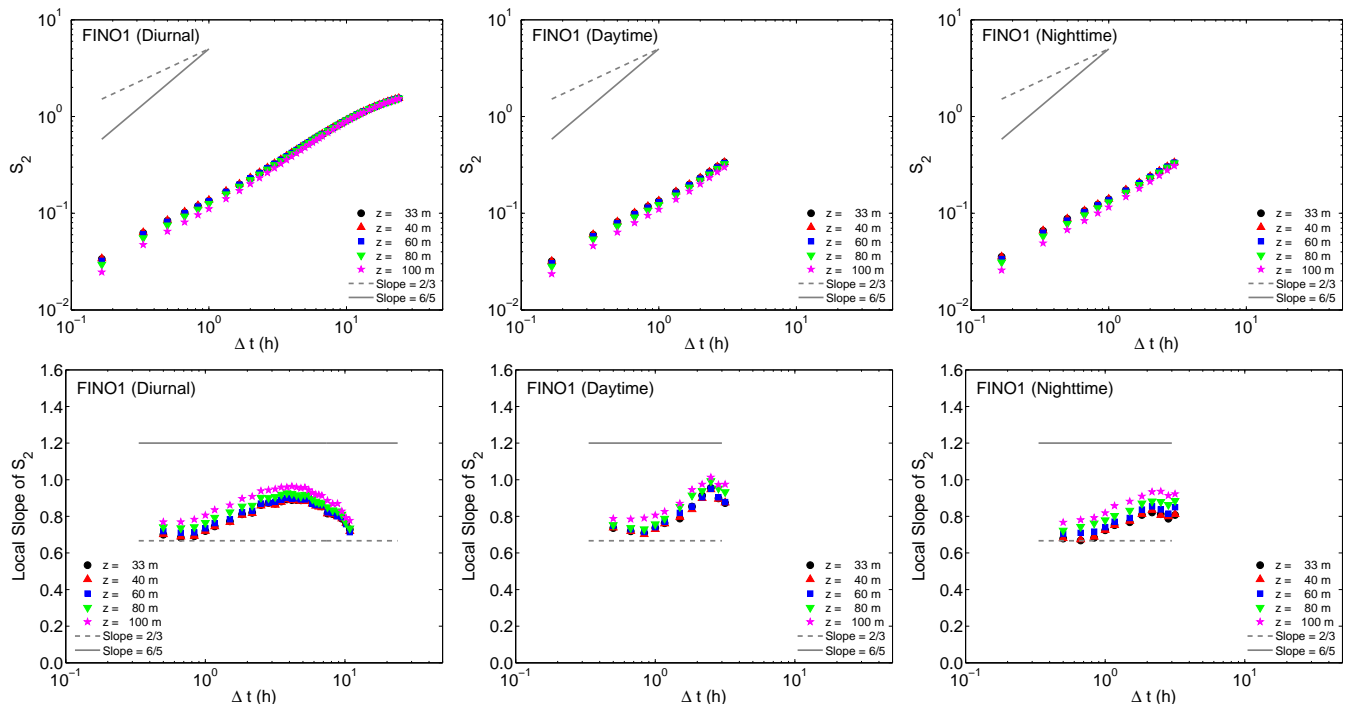


FIG. 1. (Color Online) The second-order structure functions (top panel) and their corresponding local slopes (bottom panel) based on wind speed observations from the FINO1 tower. The left, middle, and right panels represent diurnal, daytime (9–15 UTC), and nighttime (21–3 UTC) data, respectively. The dashed and solid lines represent slopes corresponding to Kolmogorov’s and Bolgiano’s hypotheses, respectively.

- The scaling characteristics is (almost) indistinguishable between the daytime and nighttime cases. This behavior is somewhat expected at an offshore site where sea surface temperature (generally) exhibits a weak diurnal cycle.

b. Cabauw

- Once again, extended scaling regimes are clearly present in all the S_2 plots.
- The ζ_2 values increase with height with the exception of the lowest two tower levels. This discrepancy near the surface is possibly due to the disturbances caused by wind breaks and other sources of heterogeneity.
- In contrast to the FINO 1 results, the scaling characteristics at Cabauw is strongly dependent on the time of the day. During nighttime (typically stably stratified condition over land), ζ_2 values are much larger than their corresponding daytime (typically convective condition over land) values.
- The ζ_2 values (approximately) equal to $2/3$ for specific time-increment ranges and certain heights. However, these ζ_2 values always remain much smaller than $6/5$.

c. WTM Sodars

- Despite the limited sample size, for all the three sodar-based wind speed datasets, extended scaling regimes are visible.
- As before, the height-dependency of ζ_2 is clearly noticeable for all the cases. However, this dependency is more pronounced at RTC followed by Midland. In contrast, the trend is much weaker at San Angelo.
- In the case of San Angelo and Midland, the ζ_2 values are close to the K-41 value of $2/3$ for Δt up to 1 h for all the levels. However, at RTC, only wind speed at the lowest level portrays similar behavior.
- At RTC, for $z \geq 200$ m, the slopes are remarkably stable (long plateau); the ζ_2 values are close to 1.
- At Midland, a dual-scaling behavior is discernible for $z > 100$ m. For $\Delta t \leq 1$ h, ζ_2 is approximately equal to $2/3$; the slopes increase for larger Δt .

In summary, ζ_2 in the mesoscale range systematically depends on height and time-increment range. In the following section, we provide a physical explanation for the height-dependency by further analyzing the WTM sodar datasets.

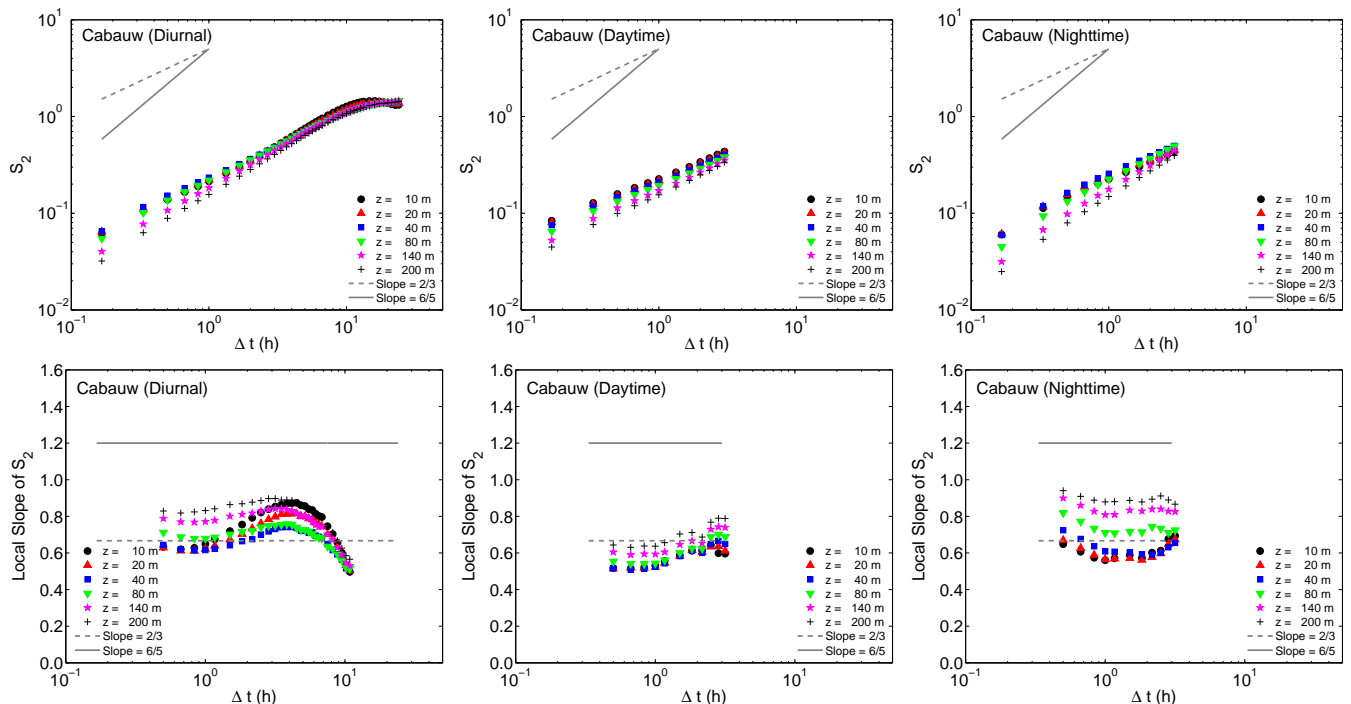


FIG. 2. (Color Online) The second-order structure functions (top panel) and their corresponding local slopes (bottom panel) based on wind speed observations from the Cabauw tower. The left, middle, and right panels represent diurnal, daytime (9–15 UTC), and nighttime (21–3 UTC) data, respectively. The dashed and solid lines represent slopes corresponding to Kolmogorov’s and Bolgiano’s hypotheses, respectively.

IV. LOW-LEVEL JETS

The WTM sodars are located in the West Texas Panhandle region of the US, one of the largest semiarid regions in the world. This region is gently sloping, homogeneous, and sparsely vegetated. Nocturnal low-level jets (LLJs; [47–51]) occur frequently over this region. These LLJs and associated wind speed maxima are one of the most important reasons for the abundance of wind farms, as well as significant nighttime wind power production, over this region [52–54].

In order to explain the height-dependency of ζ_2 , time-height plots of averaged (over an eight month period) wind speed at the measurement sites are shown in Fig. 4. During the daytime, the wind fields are well-mixed as would be physically expected and the differences across the sites are marginal. However, the nighttime scenarios are completely different. Even though the LLJs are frequently present at all of the sites, their locations are significantly different. It appears that the distance between the LLJ and the underlying surface decreases with increasing site elevation (see Table I). Similar observations were reported at a different site over the US Great Plains by Song et al. [50].

One of the primary mechanisms for the formation of the LLJs is the so-called inertial oscillation [47, 55, 56]. According to this mechanism, the buoyancy effects largely contribute to the formation and dynamical evo-

lution of the LLJs. Thus, based on Fig. 4 (please refer to Appendix B for further evidence), one could conjecture that the buoyancy effects will be increasing from San Angelo to RTC (via Midland).

The results in Fig. 3 which show the scaling exponents increasing from San Angelo to RTC (via Midland) are definitely in line with this conjecture. In other words, the height-dependency of the scaling exponents is likely due to buoyancy effects. Similar height-dependency was reported in a wind-tunnel study [57]. In that case, enhanced shear near the surface decreased the scaling exponents from the corresponding inertial-range values. In our case, the trend is reversed due to the buoyancy effects.

V. EXTENDED SELF-SIMILARITY

To further characterize scaling in the mesoscale regime, we next invoke the extended self-similarity (ESS) framework by Benzi and his co-workers [58]. Numerous studies (see [59] and the references therein) have demonstrated the strength of ESS in terms of identifying scaling regimes even when the traditional structure function approach completely fails. In Fig. 5, we show S_2 vs. S_3 and S_4 vs. S_3 . All the structure function values corresponding to $\Delta t \leq 6$ h are considered. Remarkably, the height-dependency and dual-scaling behaviors have (al-

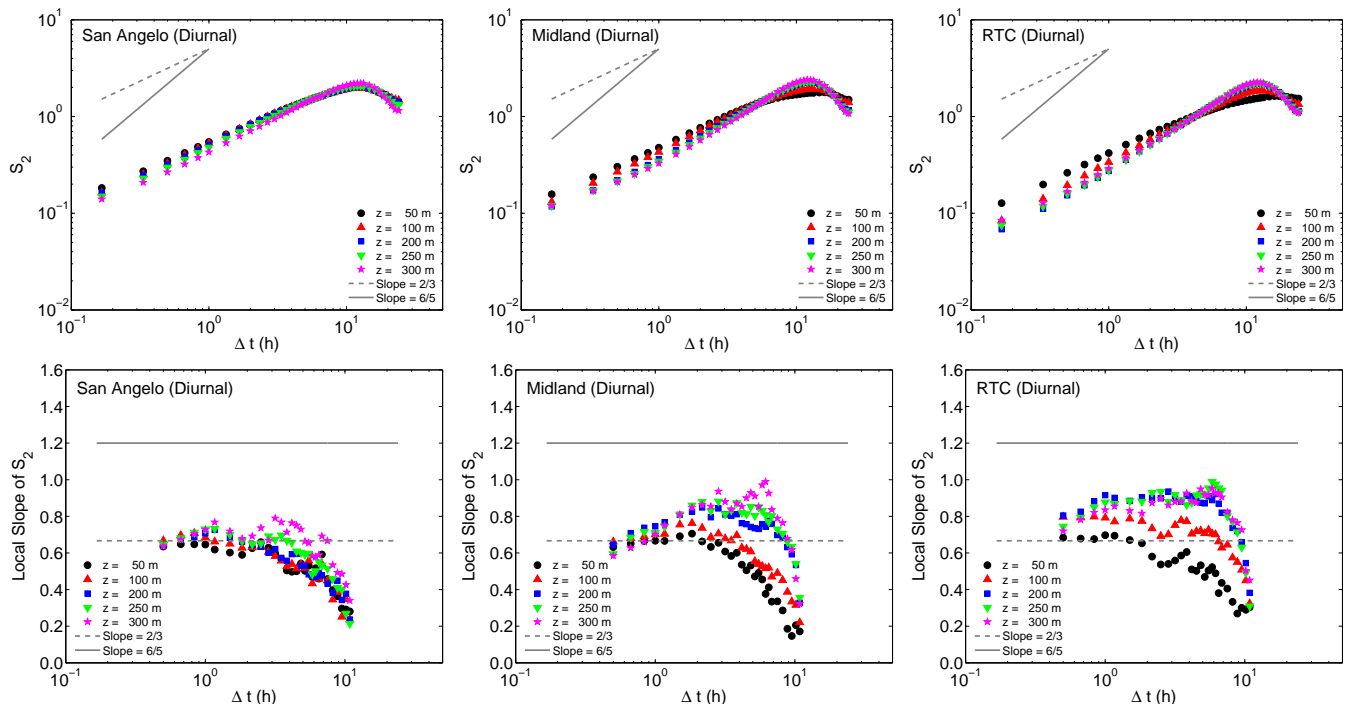


FIG. 3. (Color Online) The second-order structure functions (top panel) and their corresponding local slopes (bottom panel) based on wind speed observations from the San Angelo (left panels), Midland (middle panels), and RTC (right panels) sites. The dashed and solid lines represent slopes corresponding to Kolmogorov's and Bolgiano's hypotheses, respectively.

most) disappeared in these plots. Similar masking effects of ESS were also reported by Ruiz-Chavarría et al. [57] and Aivalis et al. [42] for completely different types of flows.

Based on the ESS plots, one can calculate the relative scaling exponents $\zeta_{p,q}^* = \zeta_p / \zeta_q$. These values are reported in Fig. 5. Given their close agreement across diverse sites, we speculate that $\zeta_{p,q}^*$ values are probably quasi-universal. Please note that these values are marginally different (more intermittent) from the commonly reported inertial-range values in the turbulence literature [33]: $\zeta_{2,3}^* = 0.70$ and $\zeta_{4,3}^* = 1.28$. In other words, the scaling characteristics of the near-surface wind field in the mesoscale regime appears to be similar to the inertial-range, but not exactly the same. This finding is in line with the recent literature [21, 22, 24].

VI. CONCLUDING REMARKS

In this study, we provide empirical evidence of quasi-universal scaling of ABL wind speed in the mesoscale range. This quasi-universality is only evident when the ESS framework is employed. Without this framework, the scaling exponents portray systematic dependence on height and buoyancy effects. Further observational data analyses are needed in order to gain further confidence on these noteworthy findings. If the ESS-based quasi-universal scaling holds for other geographical and mete-

orological regions (e.g., polar region, complex terrain), then it can be utilized as a benchmark for the development of next-generation planetary boundary layer parameterizations.

Appendix A: Effects of Diurnal Cycles on the Scaling Exponents

In this appendix, we investigate if the diurnal cycles have any impact on the scaling exponents in the mesoscale regime. For this task, we utilize discrete wavelet transform (Symmlet-8 wavelet) with a filter-scale of 21.33 h ($\approx 2^7 \times 10$ min), following Basu et al. [60]. In the top-panel of Fig. 6, an illustration of the filtering approach is provided. In the bottom panel of this figure, various scaling statistics based on the filtered wind speed data from the Cabauw tower are shown. These plots can be compared against their unfiltered counterparts reported in Fig. 2 and Fig. 5. Clearly, the diurnal cycles have insignificant impact on the reported scaling exponents for $\Delta t \leq 6$ h.

Appendix B: Estimation of Stratification in the Surface Layers over the WTM Region

Two 10 m tall mesonet stations are located in close proximity of the sodars at San Angelo and RTC. Air

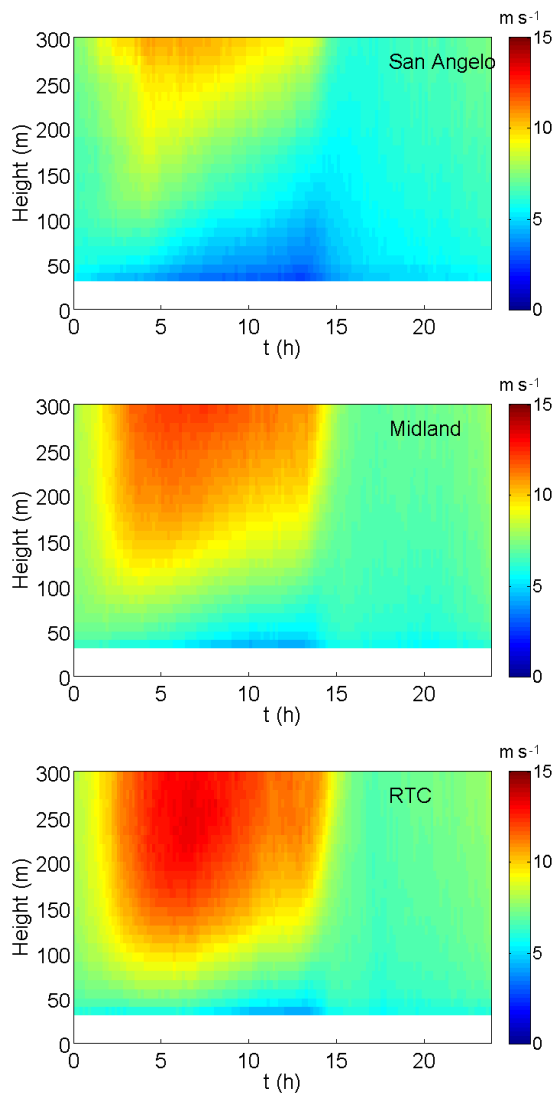


FIG. 4. (Color Online) Time-height plots of averaged wind speed at the San Angelo (top panel), Midland (middle panel), and RTC (bottom panel) measurement sites. Time is in UTC. Height is above ground level.

temperature (5 min average) at heights 2 m and 9 m (AGL) are available from both these stations. We first calculate the temporal evolution of nocturnal cooling as follows:

$$\Delta\Theta_z(t) = \Theta_z(t) - \Theta_z(t = t_0) \quad (\text{B1})$$

where Θ_z is the mean potential temperature at height z . The initial time (t_0) is taken as 9 pm CST (i.e., 3 am UTC). Next, we estimate stratification in the 2 m – 9 m layer via the following relationship:

$$ST(t) = \Delta\Theta_{z=9\text{ m}}(t) - \Delta\Theta_{z=2\text{ m}}(t) \quad (\text{B2})$$

From overall flux-divergence consideration, more negative values of $ST(t)$ signify stronger stratification. In contrast, small positive values denote weakly unstable

condition. Based on 8 months of data (i.e., 243 nocturnal ST time-series), Fig. 7 is created. Clearly, the stratification level is much stronger at RTC than at San Angelo. In other words, Fig. 7 provides further evidence to our earlier conjecture that the buoyancy effects are more dominant at RTC in comparison to San Angelo.

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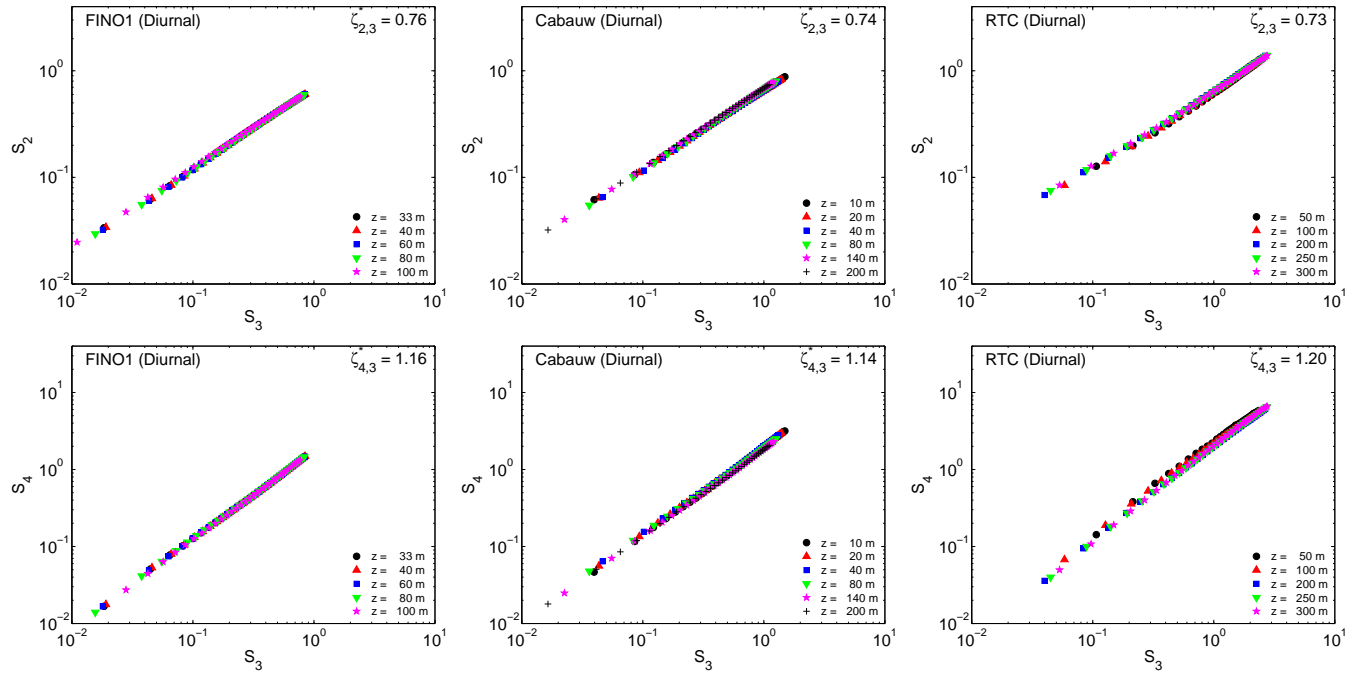


FIG. 5. (Color Online) Top-panel: the variation of the second-order structure function with respect to the third-order structure function. Bottom-panel: the variation of the fourth-order structure function with respect to the third-order structure function. The left, middle, and right panels represent FINO 1, Cabauw, and RTC cases, respectively. The overall relative exponents $\zeta_{p,q}^*$ are reported on the top right corner of each plot.

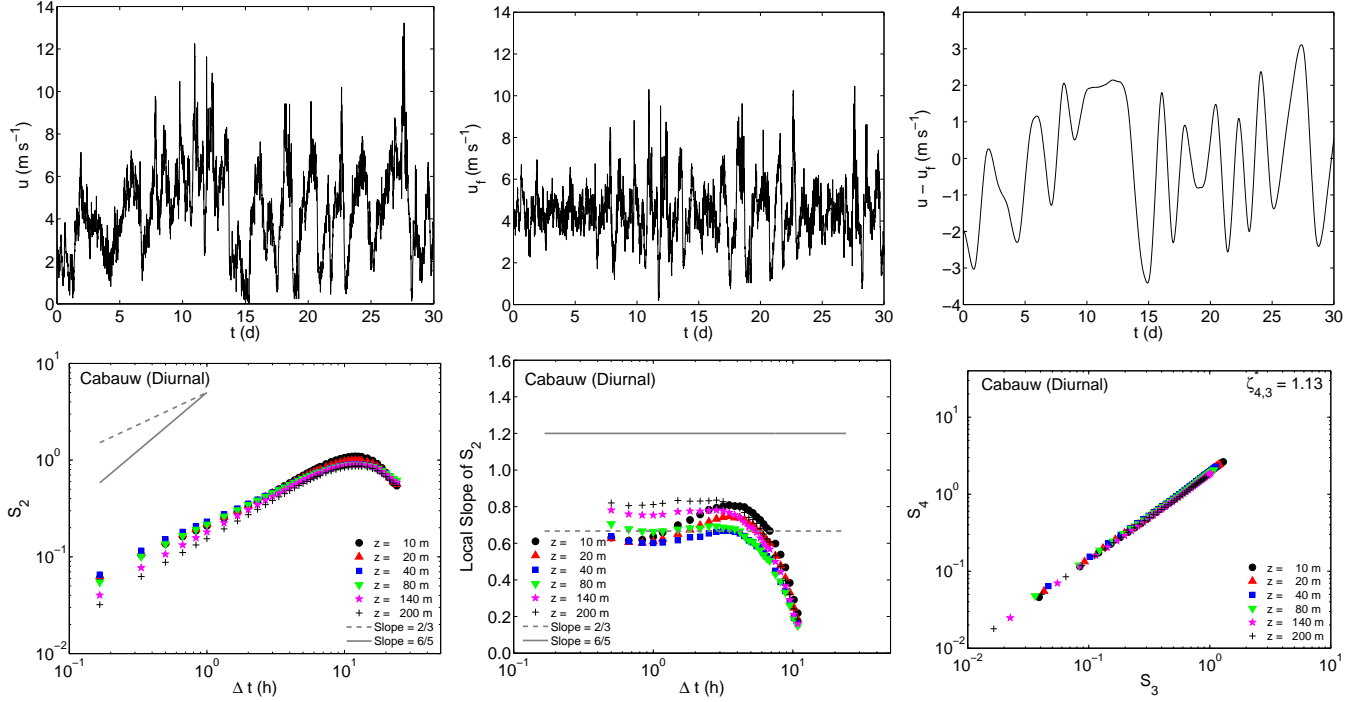


FIG. 6. (Color Online) Top panel plots provide an illustration of the filtering of diurnal cycles from an observed wind time-series. One month-long wind data (u) from the Cabauw tower is shown in the top-left panel. The top-middle panel shows the wavelet-based (high-pass) filtered series (u_f). The difference between the original and filtered series ($u - u_f$) is shown in the top-right panel. The plots in the bottom panel utilize 170 months of wind speed observations from the Cabauw tower. Prior to the structure function analyses, wavelet-based filtering has been employed as illustrated in the top panel. The second-order structure functions and their corresponding local slopes are shown in the bottom-left and bottom-middle panels, respectively. The dashed and solid lines represent slopes corresponding to Kolmogorov's and Bolgiano's hypotheses, respectively. The variation of the fourth-order structure function with respect to the third-order structure function is shown in bottom-right panel. The relative exponent $\zeta_{p,q}^*$ is reported on the top right corner of this plot.

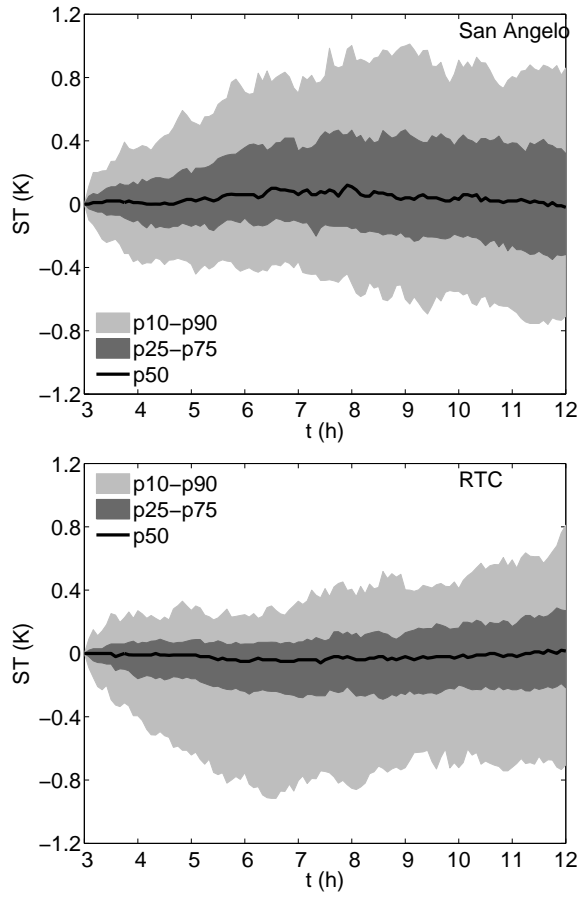


FIG. 7. Time-series plots of stratification (ST) during nighttime periods. Eight months of observational data from the San Angelo (top panel) and RTC (bottom panel) mesonets are utilized. Time is in UTC. The solid black lines, dark grey shaded areas, and the light grey areas correspond to the medians, 25th–75th percentile ranges, and 10th–90th percentile ranges, respectively.

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