5A.2 Wind and Gust Forecasting in Complex Terrain

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ABSTRACT

The mid-May 2014 Santa Ana event is investigated to evaluate the ability of high-resolution WRF-ARW simulations in predicting winds and gusts in complex terrain. Model reconstructions of sustained wind are calibrated and validated against the exceptionally dense and homogeneous SDGE mesonet in San Diego county. A large model physics ensemble reveals the land surface model to be most crucial in skillful wind predictions, which are particularly sensitive to the surface roughness length. A surprisingly simple gust parameterization is proposed for the San Diego network, based on the discovery that this homogeneous mesonet has a nearly invariant network-averaged gust factor.

1. Introduction

The "Santa Ana" winds of Southern California are a very dry, sometimes hot, offshore wind (Glickman 2000; Fovell 2012; Cao and Fovell 2013) that can produce wind gusts exceeding 100 mph (45 m s^{-1}) in favored areas[1]. Events are associated with the partial damming of a cool or cold Great Basin air mass by the mountains that separate Southern Calfiornia from the inland deserts. In the San Diego area, the Santa Anas possess characteristics of downslope windstorms (Fovell 2012; Cao and Fovell 2013). Santa Ana season is typically thought of as extending from September to April (Raphael 2003), but the last two years (2013 and 2014) have seen events of significant strength during the month of May.

Fire danger is elevated during Santa Ana events, owing to the combination of low-to-very low humidity and strong winds that can spark and spread flames. Owing to this danger, accurate forecasts of winds and gusts are crucial. We have previously shown that simulations of downsloping winds in the San Diego mountains are sensitive to model physics and even the introduction of random noise (Cao and Fovell 2013). Furthermore, weather prediction models such as WRF [the Weather Research and Forecasting model; Skamarock and co authors (2007)] that are designed for use on regional scales cannot capture wind gusts, which produce much of the damage.

In this paper, we examine the skill of the WRF model's Advanced Research WRF (ARW) core in forecasting Santa Ana winds in San Diego county. Model forecasts are validated against sustained wind observations reported by the San Diego Gas and Electric (SDGE) mesonet, a network of more than 140 stations cited primarily in well-exposed, wind-prone areas on the west-facing slopes of the county's mountains. This research has involved large model physics, landuse database, and perturbation ensembles, as described in Cao and Fovell (2013). Although several events of varying strengths have been examined, we will mainly focus on the recent event of mid-May 2014 as an illustrative example. A surprisingly simple gust parameterization is proposed, that is perhaps applicable solely to this homogeneous and exceptionally dense mesonet.

[1] Examples: On 21 October 2007, the weather station on Laguna Peak, overlooking Pt. Mugu, recorded a 111.5 mph (50 m s^{-1}) wind gust. More recently, on 30 April 2014, the Sill Hill station in San Diego reported a 101 mph (45 m s^{-1}) gust, and remained above 90 mph for a total of five nonconsecutive hours.

2. Data and methods

a. *Available observations*

Validating a numerical simulation against available observations is not as straightforward as it might appear. Historically, the surface wind observation network has possessed low station density, especially relative to the expected spatial variation of winds owing to topography in places such as San Diego county. Furthermore, observational networks vary with respect to sensor hardware, mounting height, intervals employed for sampling, averaging and reporting, and station siting philosophies, all of which can dramatically impact the magnitudes of winds and gusts that are reported. The unfortunate fact is that the anemometers at many stations are improperly shielded by buildings and/or trees, or simply were not installed in the areas of greatest wind and/or hazard.

In pointed contrast, the mesonet installed by the San Diego Gas and Electric (SDGE) placed stations in well-exposed areas that are known to be windy (Fig. 1). The network currently consists of over 140 stations and is homogeneous with respect to hardware employed, mounting height, and data collection and reporting. The stations adhere to the RAWS (Remote Automated Weather Station) standard with respect to anemometer height (6.1 m or 20 ft AGL) and averaging interval for the sustained wind (10 min). Every 10 min, SDGE stations report sustained winds as well as maximum gusts based on 3-sec samples; this contrasts with the RAWS networks hourly reporting interval.

b. Model experimental design

All simulations in this report employed recent versions of WRF-ARW, using telescoping nests to 667 m horizontal resolution. The 667 m domain covers about two-thirds of the SDGE mesonet, and its parent 2 km grid encompasses the entire network. The physics ensemble mainly focuses on the role of land surface models (LSMs) and planetary boundary layer (PBL) schemes on forecast skill; see Cao and Fovell (2013) for more information. Simulations of the 13-15 May 2014 Santa Ana wind event used version 3.5 and were initialized with the 12 km North American Mesoscale (NAM) model gridded analysis and forecasts for initial and boundary conditions, respectively. For simplicity, only the MODIS landuse database is considered herein.

c. Validation strategy

The SDGE wind data were employed to validate model output available at hourly intervals. SDGE mesonet data were obtained at full temporal resolution (10 min intervals) from the MADIS (Meteorological Assimilation Data Ingest System) archive. We elected to replace observed winds and gusts on the hour with the largest values of each reported in the previous 50 min. However, this was found to have relatively little impact on the results and conclusions.

The WRF model reports a 10 m wind diagnostic that requires adjusting prior to validation against the SDGE network's 6.1 m wind observations, lest an entirely artificial high wind bias would very likely be found. Adjustments were made during post-processing, utilizing the logarithmic wind profile assumption,

$$V_{6.1} = V_{10} \frac{\ln \frac{6.1}{z_0} - \psi_{6.1}}{\ln \frac{10}{z_0} - \psi_{10}}, \qquad (1)$$

where $V_{6.1}$ and V_{10} are the winds at 6.1 and 10 m, respectively, z_0 is the surface roughness length, and $\psi_{6.1}$ and ψ_{10} represent stability correction functions that vanish when the surface layer is neutrally stratified. The latter is often presumed true when wind speeds exceed about 5 m s^{-1} or so (e.g., Wieringa 1976; Verkaik 2000), which does appear valid among our model simulations.

Although somewhat dependent on the LSM and landuse database (e.g., USGS vs. MODIS) employed, we have found network-averaged z_0 to vary between 0.16 and 0.27 m, which result in adjustments to the 10 m wind of about 14%. It is noted that Eq. (1) could have been written with a zero-plane displacement modification of the anemometer heights, which is sometimes used in areas with significant obstacles. We neglect this adjustment because of the siting characteristics of the SDGE mesonet.

We will show that most model physics configurations generate a high wind bias relative to the observed sustained winds, even after anemometer height adjustment. The worst offenders were ostensibly those employing the MYJ PBL scheme. However, we discovered the MYJ code recomputed the LSM's 10 m wind values, specifying smaller roughness length than employed in the model calculations. This purely cosmetic adjustment (shared by the QNSE PBL scheme) exacerbated the high wind bias, and removing the code made physics ensemble members employing the MYJ scheme much more competitive.

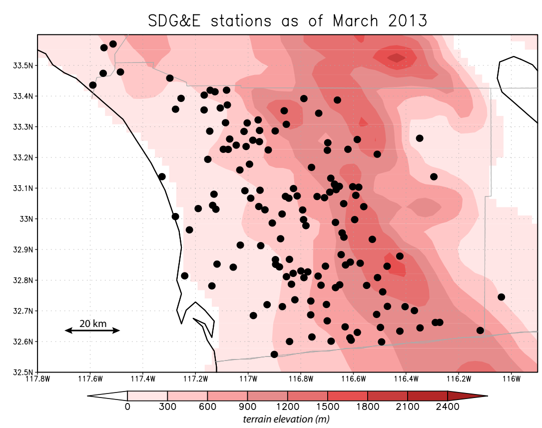

FIG. 1. SDGE surface station locations (black dots), with underlying topography shaded. Stations in place as of March 2013.

3. The 13-15 May 2014 Santa Ana wind event

In mid-May, 2014, a major Santa Ana wind event sparked several fires in the Rancho Bernardo, Oceanside and Camp Pendleton areas. The first fire to ignite was the Bernardo fire, which occurred as strong winds and gusts pushed to the coastline (Fig. 2). We will contrast simulations of this event using the Pleim-Xiu (PX) LSM coupled with the ACM2 PBL scheme (shown in Fig. 2) against runs using the Noah LSM and YSU PBL options. The latter likely represents the most commonly adopted configuration employed with WRF-ARW, while the former has proven to validate well against SDGE wind

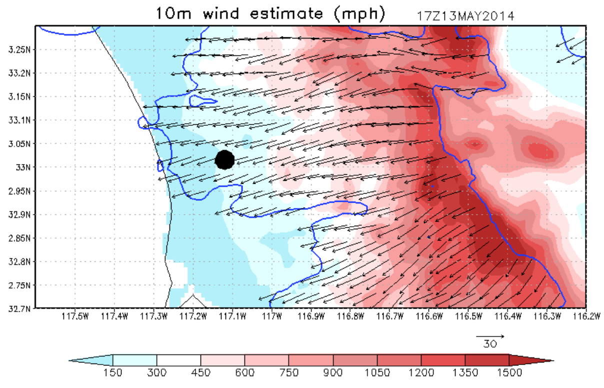

FIG. 2. Model predicted sustained winds at 10 m above ground level, valid at 1700 UTC 13 May 2014, around the initiation time of the Bernardo fire, from a simulation made with the PX LSM and ACM2 PBL schemes. Blue contour represents 20 mph wind speed and red shading is topography. Grid points with speeds < 20 mph are not shown, and vectors have been thinned for clarity. Fire ignition location indicated by large black dot.

observations. As an example, Figure 3 shows results from the physics ensemble of an earlier event, revealing the expected positive correlation between mean absolute error (MAE) and bias for height-adjusted sustained winds. The PX/ACM2 member had one of the smallest event-averaged MAEs for that event, along with an only slightly negative bias, in contrast with YSU/Noah, which was the worst-performing ensemble member overall.

Simulations for the 13-15 May event spanned 55 h, initialized at 0600 UTC on 13 May 2014. Network-averaged wind from the PX/ACM2 and YSU/Noah simulations (Fig. 4) show the former had greater overall agreement with the observations for this event as well. Still, some stations were systematically over- or underpredicted, as illustrated in Fig. 5, although the mean network bias was very small (0.18 m s^{-1}). Clearly, more stations were overpredicted in the YSU/Noah simulation (Fig. 6), which had a mean network bias of 1.63 m s^{-1}.

The region around Santa Ysabel has a particularly large number of stations, a total of 14 in a roughly 15 km by 10 km area. Even for the PX/ACM2 member, wind bias varied enormously (Fig. 7). There was no mean bias at WSYSD (Fig. 8) over the 55 h event, while at IJPSD (Fig. 9) and YSASD (Fig. 10), residing about 3 km from WSYSD, winds were somewhat underpredicted and very overpredicted, respectively. The YSU/Noah member's general high wind bias exacerbated the overprediction at YSASD and also had a positive bias for WSYSD (Fig. 6). We tested whether WRF-ARW's "topo_wind" option, which presently only works with the YSU PBL, would help to mitigate the YSU/Noah member's high wind bias. However, we found that both versions available in WRF v.3.5 reduced the network-averaged winds by about 50% (Fig. 11), resulting in a systematic low wind bias, not only as a function of time (Fig. 12), but also for most stations (not shown).

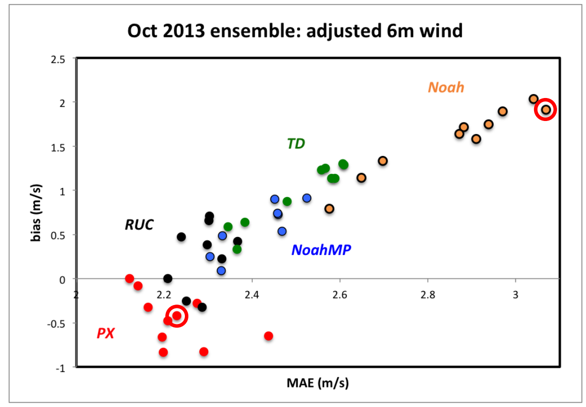

FIG. 3. Mean absolute error (MAE) vs. bias (both m s^{-1}) from an October 2013 event's physics ensemble incorporating 5 LSMs and 10 PBL schemes. Points represent event-averaged values, and are color-coded by LSM, with the PX/ACM2 and YSU/Noah members highlighted.

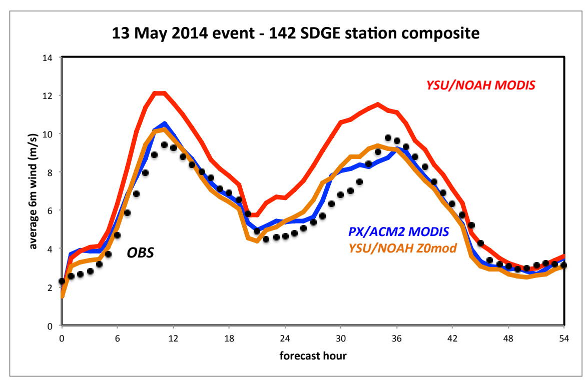

FIG. 4. Time series of SDGE network-averaged sustained wind (m s^{-1}) observations (black dots), for comparison with predictions from the PX/ACM2 and YSU/Noah, along with a YSU/Noah run employing roughness lengths mimicking those employed by PX (YSU/Noah/Z0mod). All three simulations used the MODIS landuse database.

4. Improving wind reconstructions for the 13-15 May 2014 event

The ensembles for various Santa Ana wind events has revealed that the single most important physics option

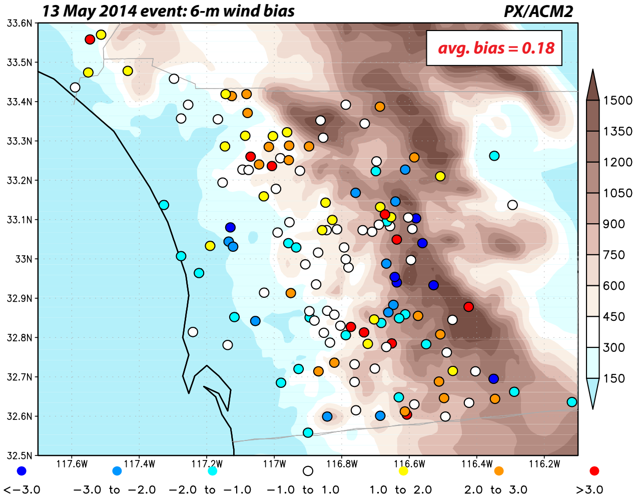

FIG. 5. Spatial distribution of event mean sustained wind bias for SDGE stations for the PX/ACM2 simulation, using the MODIS landuse database. Deep red and blue colors indicate the model overestimates and underestimates the event-averaged 6m wind by 3 m s^{-1}. Brown shading indicates model topography.

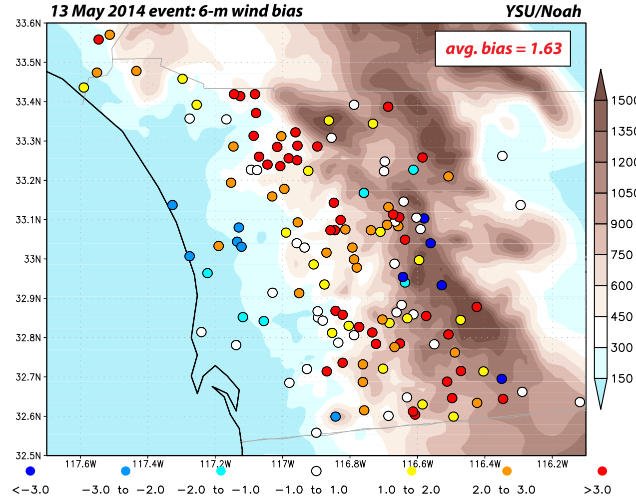

FIG. 6. As in Fig. 5, but for the Noah/YSU simulation, using the MODIS landuse database.

controlling the quality of the mean wind reconstruction is the LSM (Fovell 2012; Cao and Fovell 2013). Analysis has indicated that LSMs differ most with respect to how they handle the roughness of the surface. Table 1 lists the relative fraction of various landuse categories occurring in the 2 km nest that encompasses the SDGE network, along with tabled values of z_0 (from `LANDUSE.TBL` and/or `VEGPARM.TBL`) employed in "summer" simulations (applicable to the present Santa Ana case) and roughness values as assigned in `module_sf_pxlsm_data.F`. Two-thirds of the 2 km nest's land areas are shrublands, which are presumed rougher in the PX LSM than in the MODIS default. Although LSMs like Noah subsequently modify these tabled values, it remains this scheme employed lower roughnesses for many of the categories occurring in the SDGE network.

The importance of z_0 in an LSM is demonstrated by modifying the Noah scheme to mimic PX. This simulation, dubbed "YSU/Noah/Z0mod", yielded a much more faithful reconstruction of the network-averaged wind (Fig. 4) as well as a much lower mean bias of 0.07 m s^{-1} (Fig. 13). The correlation between PX/ACM2 and YSU/Noah Z0mod is very high but not perfect, in part because the PBL scheme does influence the results, and also because the PX and Noah LSMs handle fractional landuse differently. However, using PX-inspired roughness values in Noah clearly resulted in superior wind

TABLE 1. Default roughness lengths employed by surface schemes for MODIS landuse categories occurring in the SDGE network for summer season simulations. Water areas of the 2 km nest excluded.

Landuse index	Fraction (%) of network	PX z_0	Tabled z_0	Type
1	5.9	1	0.5	Evergreen needleleaf
2	0.2	0.9	0.5	Evergreen broadleaf
5	6.0	1	0.5	Mixed forests
6	11.8	0.15	0.05	Closed scrublands
7	54.4	0.15	0.06	Open shrublands
8	0.2	0.25	0.05	Woody savannas
9	0.3	0.15	0.15	Savannas
10	2.3	0.07	0.12	Grasslands
11	0.1	0.2	0.3	Permanent wetlands
12	0.4	0.1	0.15	Croplands
13	11.2	0.8	0.8	Urban
16	7.3	0.05	0.01	Barren/sparse

performance and a very small network-averaged bias.

We are compelled to consider z_0 as a tunable parameter, and feel that the high quality, density and homogeneity of the SDGE network will permit us to improve the land representation in the WRF simulations for this area. However, it is not clear that fine-scale adjustments of the roughness length will be all that useful. The reason is that the remaining wind bias is moderately anti-correlated ($R^2 = 0.40$) with the event mean wind, with positive biases at stations with relatively weaker winds and negative ones at windier locations (Fig. 14), while the correlation of bias with z_0 is nearly zero ($R^2 = 0.14$, not shown). In the next section, we offer an explanation for this trend in the bias, and argue that a fair fraction of the remaining wind bias may be "unfixable" (apart from bias correction).

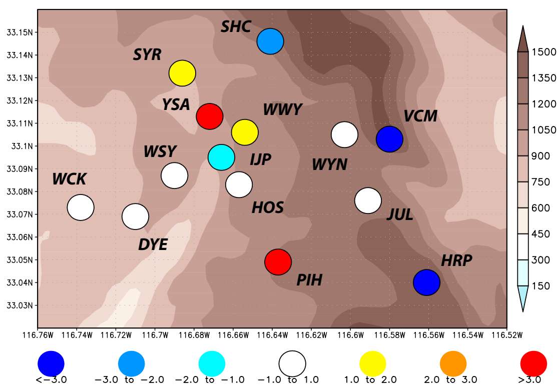

FIG. 7. As in Fig. 5, but zoomed into the region around Santa Ysabel (YSA). Labels indicate names of SDGE stations, with "SD" suffix omitted.

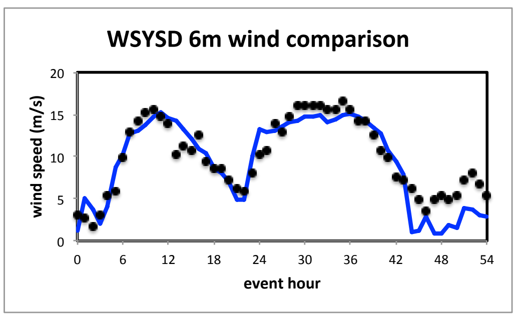

FIG. 8. Time series of observed (black dots) and predicted (blue curve) 6 m sustained winds (m s^{-1}) at WSYSD (see Fig. 7) , from the PX/ACM2 simulation.

5. Further analysis

The *gust factor*, or GF, is the ratio of the gust and the sustained wind. GF should be a function of sampling interval, anemometer hardware and mounting height, anemometer exposure, and perhaps surface roughness as well (Ashcroft 1994). It may also be a function of the sustained wind itself, and vary among stations, and perhaps from event to event.

Averaged over the entire SDGE network, however, we have found the GF to be nearly constant, with a value of nearly 1.7 and virtually no dispersion (Fig. 15). There were 330 observation times between 0510 UTC on 13 May to 1200 UTC on the 15th, at 10-min intervals. For each time, the sustained wind and gust observations were averaged over the 142 station network, and the results are shown in the figure. The R^2 of the fit is 0.997. Although GFs do vary with station, sustained wind speed, and time, *the network-averaged GF can be represented by a single number*, independent of the magnitude of the network-averaged wind.

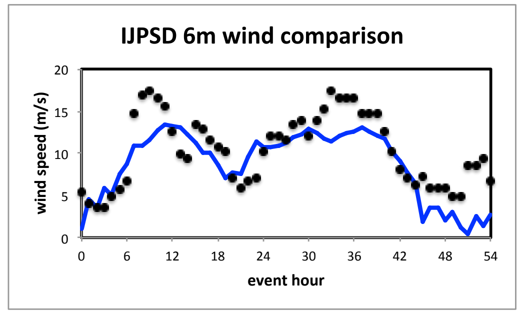

FIG. 9. As in Fig. 8, but for the station at IJPSD.

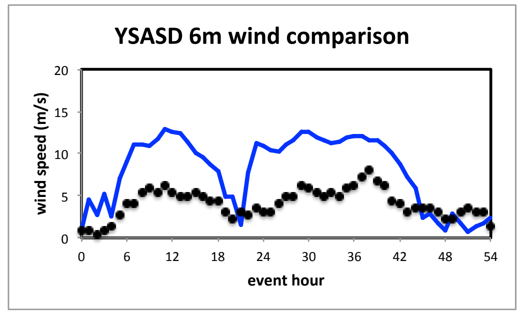

FIG. 10. As in Fig. 8, but for the station at YSASD.

This surprising result is not confined to Santa Ana wind events. Figure 16 presents a composite of 10-min observations over three months, representing summer (June 2013), autumn (October 2013) and winter (February 2014) examples[2]. Santa Ana events did occur during the latter two months, but represent a small fraction of the 12324 observations plotted. This result is not entirely understood, but we will take the SDGE network-averaged GF as 1.7, and refer to it as "G".

The reality is that GFs should and will vary among stations, and it is important to understand why. At any given site, the mean GF tends to decrease (if only very weakly) with increasing sustained wind speed (e.g., Cao and Fovell 2013). Over the SDGE network, GF has a more robust negative association with event-averaged wind (Fig. 17). However, given that the *overall* (network-averaged) gust factor G is nearly insensitive to factors such as offshore vs. onshore winds, day vs. night, cloudy vs. sunny, etc., we hypothesize that stations having individual GFs that vary significantly from the network average may, at least in part, represent the influence of very localized factors. Furthermore, to the degree that these localized factors

[2] For February 2014, observations from two thunderstorm days were removed, as they clearly deviated from the remaining observations. The fact that thunderstorm gusts might have a substantially different character is anticipated from Wieringa (1973).

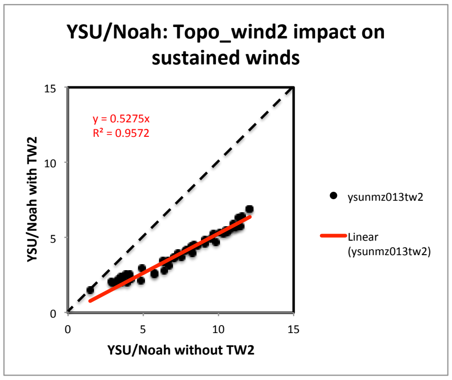

FIG. 11. Scatterplot of hourly network-averaged sustained winds for YSU/Noah simulations before and after application of the topo_wind = 2 option (TW2) .

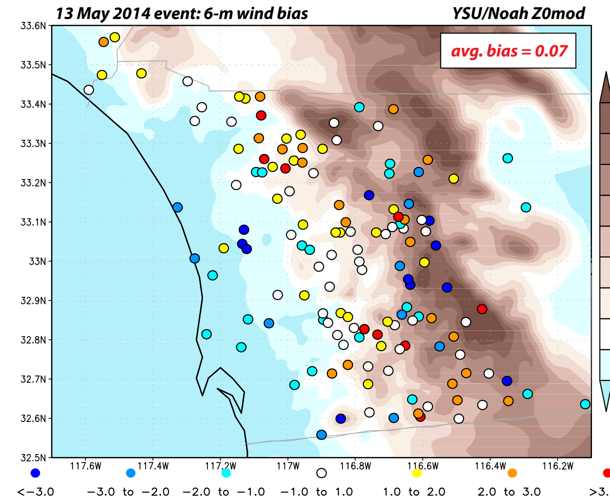

FIG. 13. As in Fig. 5, but for the Noah/YSU Z0mod simulation, using modified roughness values inspired by the PX LSM.

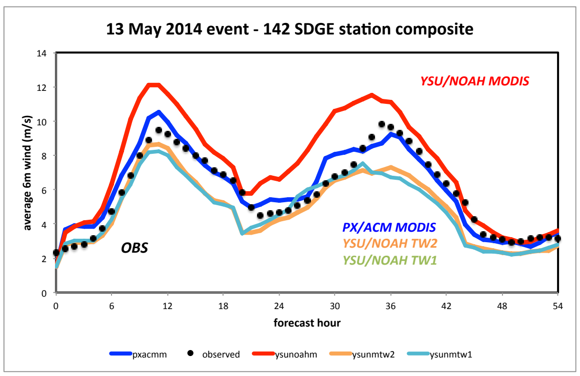

FIG. 12. As in Fig. 4, but adding YSU/Noah simulations made with topo_wind = 1 and 2 (TW1 and TW2), with the MODIS landuse database.

are unresolvable, even on a very high resolution grid, we may find that even a model that is properly configured overall will be more likely to have systematic biases at these stations.

Thus, other factors being equal, *we anticipate overpredicting the sustained wind at stations with $GF > G$, while underpredicting winds at stations with $GF < G$*, for the reasons demonstrated in Fig. 18. Figure 18a illustrates the standard case. The wind profile is described by the log wind profile (1), being calm at height z = z_0. A parcel possessing faster horizontal velocity is transported downward, and manifested at anemometer level as a gust (U_{max}) exceeding the sustained wind ($\bar{U}$). If gust factor for this station is comparable to the network average, we anticipate that a properly configured model will be able to represent the winds at this location without significant bias.

Despite best efforts regarding siting, however, some stations will experience at least very localized obstructions. For example, anemometers might have to be installed relatively close to landforms that might partially shield them, or be placed in an area with denser and/or taller vegetation than is representative of the grid cell in which it is found. In those cases, we anticipate that the sustained wind is slowed more than would be expected given the z_0 value employed for the grid cell. However, a parcel from farther aloft has less time to be influenced by the obstructions, and thus would appear stronger relative to $\bar{U}$, resulting in a larger station GF, as illustrated in Fig. 18b. If these obstructions cannot be resolved on the model grid, or represented by the grid's z_0, we anticipate overpredicting the wind at these stations.

Alternatively, some stations may be located with areas with landforms that serve to further accelerate the wind, including flow through favorably-oriented canyons, near steep ravines, or over small hills. These may serve to enhance the sustained wind at anemometer level, such that a descending parcel has a relatively smaller speed advantage over the mean flow there, resulting in GF < G (Fig. 18c). If those features are unresolvable, we hypothesize that we will underpredict the wind there.

The hypothesis is tested in Fig. 19, which presents station gust factor for the 13-15 May 2014 event plotted against event-averaged bias from the YSU/Noah simulation with PX-inspired roughness lengths. For each station, the GF from an intercept-suppressed least squares fit was determined. The largest value (3.15) was for station MLGSD near Mt. Laguna, which is known to be directly impacted by trees (S. Vanderburg and B. D'Agostino,

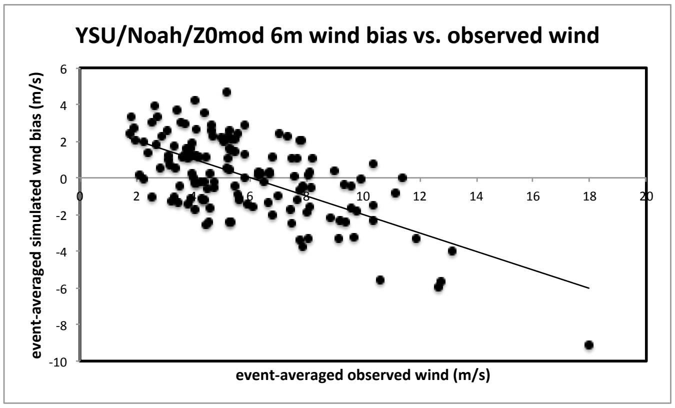

FIG. 14. Scatterplot of event-mean observed wind vs. mean bias in the YSU/Noah/Z0mod simulation for SDGE stations. A least-squares fit is shown for reference.

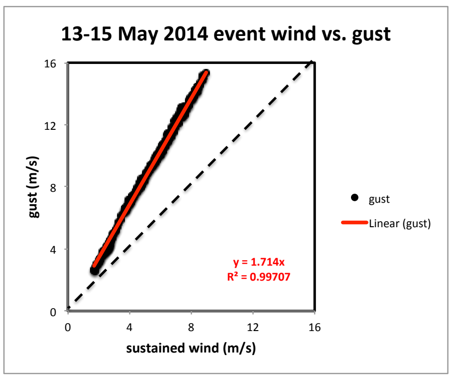

FIG. 15. Scatterplot of network-averaged sustained wind vs. gust for the 13-15 May 2014 Santa Ana wind event. 330 observation times are plotted, each representing a 142-station average. The intercept-suppressed least squares fit is also shown, with slope 1.714 and $R^2 = 0.997$.

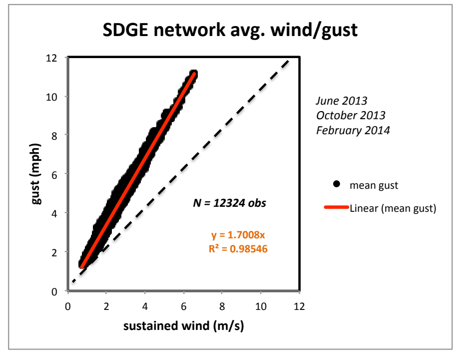

FIG. 16. As in Fig. 14, but for three non-consecutive months, June and October of 2013, and February of 2014, representing 12324 total observation times. Two thunderstorm days in late February were excluded.

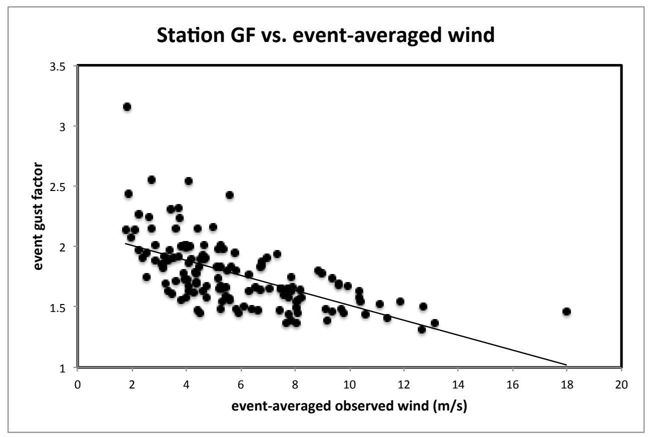

FIG. 17. Scatterplot of GF vs. event-averaged wind from the 13-15 May 2014 Santa Ana case, for the 142 SDGE stations. The least squares line is shown for reference only. The linear association is $R^2 = 0.37$.

personal communication) and routinely overpredicted in our simulations. The smallest value (1.31) was for VCMSD, a station in the Santa Ysabel area (Fig. 7) that is substantially underpredicted in nearly all WRF model reconstructions. The station-averaged GF for this event was 1.77, which is fairly close to G. Curiously, we have found that station GF and assigned z_0 to be very nearly uncorrelated.

If our hypothesis is correct, the network stations should preferentially cluster into the lower left and upper right quadrants. For the YSU/Noah/Z0mod simulation, 76% of the stations do fall into those quadrants (52 underpredicted with GF < G and 56 overpredicted having GF > G), and many of the remainder do not stray far into the other two quadrants. Very similar results hold for the PX/ACM2 reconstruction (not shown). That said, stations falling well into the other two quadrants are likely candidates for closer examination, either of the surface landuse category or roughness length assigned to them, or for station siting and/or quality factors. Still, the figure indicates there are probably too few of those to matter in a network of this size. For the correctly assigned stations, we feel that the simulation bias largely represents *uncorrectable error* that must be handled subsequently via bias correction (or possibly further resolution enhancement).

6. A very simple gust parameterization for the SDGE network

Owing to the preceding, we suggest a very simple gust parameterization for use by properly configured model

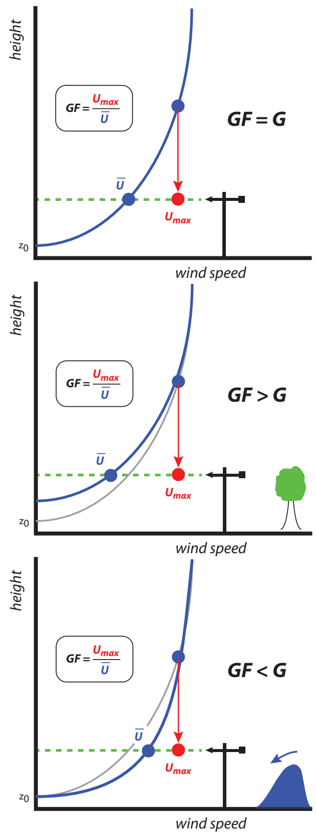

FIG. 18. Illustration of wind bias concept, based on station GF relative to network average G: (a) standard case; (b) obstructed case; (c) enhanced case.

simulations of winds in the SDGE mesonet. It seems most reasonable to apply a GF of about 1.7 to all stations, i.e., equal to G, at all times (except possibly during thunderstorms, which are rare in Southern California). When sustained winds are lighter, larger GFs are probably appropriate, but the threat from weak gusts is not very substantial. Figure 20 shows how well this simple gust scheme reproduces the event-averaged wind gusts observed at the 142 SDGE stations.

It is clear that the employment of a constant GF works to remove the dependence of wind forecast bias on sustained wind speed (see Fig. 14). To a large degree, stations with GF > G tend to be overpredicted already, so using a smaller GF value than justified from the observational record works to mitigate the positive sustained wind forecast bias at those locations. Similarly, underpredicted stations we generally have GF < G, so using a larger than observed GF helps correct the negative sustained wind forecast bias. Certainly, a more sophisticated treatment could be designed, and the results

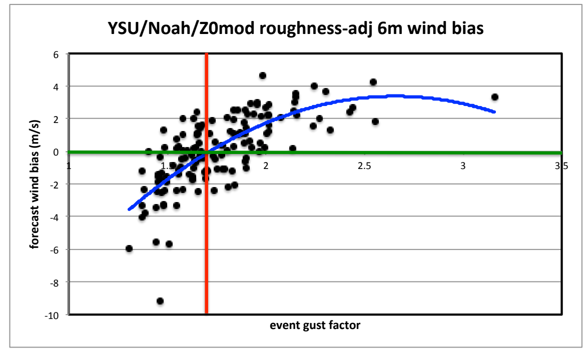

FIG. 19. Scatterplot of event-mean sustained wind bias from the YSU/Noah/Z0mod simulation vs. 13-15 May 2014 event GF. The red vertical line represents the SDGE network gust factor average, G ≈ 1.7. The blue curve represents a curvilinear least squares fit, predicting model bias from station GF.

presented herein need to be tested against more Santa Ana wind events, but we are encouraged that an attractively simple gust parameterization could be utilized with skillful sustained wind forecasts in this region.

7. Summary

We seek to skillfully predict winds and gusts during Santa Ana wind events in rural San Diego county, with model configurations validated and calibrated against the dense, homogeneous SDGE network. Large physics ensembles for past events have revealed that skill depends most crucially on the LSM, far more than on other factors such as the PBL scheme, radiation, and the landuse database. However, at least for wind, the role of the LSM depends mainly on how the surface roughness is handled. Most WRF simulations result in a high wind bias because the surface is treated as too smooth.

To our surprise, we have discovered that the SDGE network-averaged gust factor, which we termed G, is nearly constant with season, time, and event (apart from thunderstorm activity), with a value of about 1.7. While this finding is not well-understood, we anticipated, and demonstrated, that stations with gust factors (GF) smaller than G were likely to be underpredicted in the model, while the winds at stations with GF > G were likely overpredicted. This was used to separate the forecast error into that which might still be rectified, by modifying surface characteristics and perhaps model physics, and that which was probably "unfixable" other than via *ex post facto* bias correction. Thus, we propose a simple gust parameterization, with a GF of 1.7, for all stations in the network, because the constant GF works to mitigate wind biases found at the more problematic stations.

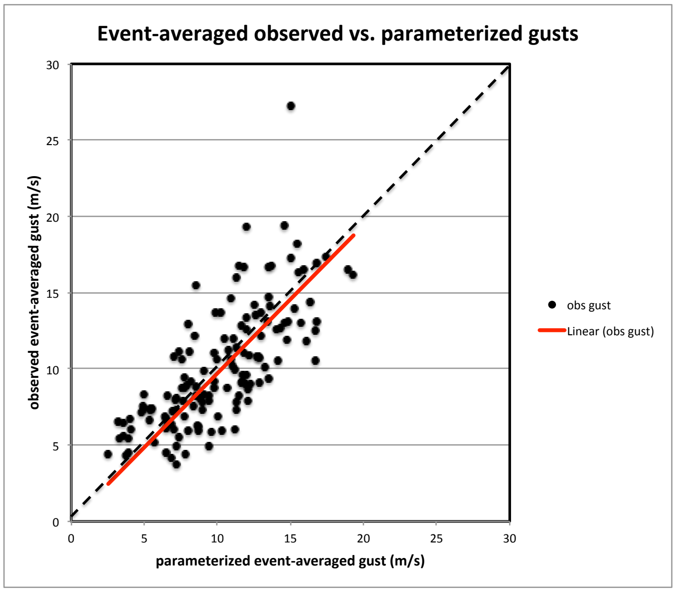

FIG. 20. Scatterplot of observed event-averaged gust (vertical axis) vs. parameterized gust, based on event-averaged wind multiplied by a station-independent GF of 1.7. The least-squares fit is shown for reference. R^2 is 0.50.

It is cautioned that the constant network GF may reflect, and very likely depend on, the homogeneity of the SDGE network, with respect to hardware, mounting height, sampling interval and siting philosophy, and therefore may not be applicable outside of the San Diego mesonet.

Acknowledgments.

This research was sponsored by San Diego Gas and Electric company. The authors thank Brian D'Agostino, Steve Vanderburg, Tom Rolinski, and Scott Capps for helpful discussions.

REFERENCES

Ashcroft, J., 1994: The relationship between the gust ratio, terrain roughness, gust duration and the hourly mean wind speed. *J. Wind. Eng.*, **53**, 331–355.

Cao, Y. and R. G. Fovell, 2013: Predictability and Sensitivity of Downslope Windstorms in San Diego County. *15th Conf. on Mesoscale Processes*, American Meteorological Society.

Fovell, R. G., 2012: Downslope windstorms of San Diego county: Sensitivity to resolution and model physics. *13th WRF Users Workshop*, Boulder, CO, Nat. Center for Atmos. Res.

Glickman, T., 2000: *Glossary of Meteorology*. Amer. Meteor. Soc., 855 pp.

Raphael, M. N., 2003: The Santa Ana Winds of California. *Earth Interact.*, **7**, 1–13.

Skamarock, W. C. and co authors, 2007: A description of the Advanced Research WRF Version 2. NCAR Tech. Note NCAR/TN-468+STR, 88 pp.

Verkaik, J. W., 2000: Evaluation of Two Gustiness Models for Exposure Correction Calculations. *J. Appl. Meteor.*, **39**, 1613–1626.

Wieringa, J., 1973: Gust factors over open water and built-up country. *Boundary Layer Meteor.*, **3**, 424–441.

Wieringa, J., 1976: An Objective Exposure Correction Method for Average Wind Speeds Measured at a Sheltered Location. *Quart. J. Roy. Meteor. Soc.*, **102**, 241–253.