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A new gust parameterization for weather prediction models

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ABSTRACT

We analyze Uruguayan measurements, focusing on gusts at turbine hub height. Large gusts, exceeding 15 m/s, are observed to occur when the surface layer (as assessed by the bulk Richardson number *Ri*) is neutral, and are uncommon when the layer is stable or even unstable. Gust factors (the ratio of the gusts to the mean winds) are inversely related to the mean winds but increase as the atmosphere becomes more unstable. Numerical simulations using different planetary boundary layer (PBL) schemes and mesoscale grid resolutions are employed in the development of a gust parameterization (GP) utilizing forecasts of surface layer *Ri* and winds above hub height. The GP, which provides gust factors to be applied to predicted turbine-level winds, provides higher skill at relatively coarser resolution than a simpler algorithm based solely on surface layer information, although its success is strongly dependent on the PBL and surface layer schemes selected.

1. Introduction

Wind gusts represent the maximum wind speed observed over a fixed period (WMO, 2018), and reliable gust forecasts can potentially mitigate the destruction and human losses they can cause (Friederichs et al., 2009). Gusts are particularly relevant to engineering applications such as wind energy production, especially in systems such as Uruguay's, which has a wind power participation of 35% (UTE, 2017). Gusts can cause equipment failures and pose danger to human life during maintenance activities. Additionally, commercial wind turbines typically have model-dependent cut-out velocities between 15 and 25 m/s, and when this threshold is reached, the machine abruptly stops (Barros, 2011). Thus, cut-out events pose a risk because they cause transitory changes in power transmission in electric lines (Hansen et al., 2010). Furthermore, as wind gusts can occur over synoptic or mesoscale time and length scales, the entire electric grid of a small nation like Uruguay can be at risk when extreme wind gusts occur, which would in turn affect electricity supply. As a consequence, the development of a skillful wind and gust forecasting model can help in electrical system management.

Wind energy is harvested at the lowest region of the planetary boundary layer (PBL), the region of the atmosphere that is directly affected by exchanges of momentum, heat, and mass with the surface and where diurnal variations are significant. Turbine blades in onshore wind farms sweep through areas between 60 and 120 m above ground level (AGL), which includes the portion of the PBL known as the surface layer (SL) (Monin and Obukhov, 1954). Stability in this region of the atmosphere is particularly relevant to gust analysis (Wieringa, 1973); explored the relationship among gusts, friction velocities, the variation of measurements, and vertical stability. During the day, a convective mixed layer driven by buoyant plumes is typically found above the SL, perhaps reaching a depth of 1–2 km by mid-afternoon. Around sunset, a rapid decrease in turbulent motion in the boundary layer occurs as the SL stabilizes and the buoyant plumes that maintain the motion lose their energy source near the surface (Acevedo and Fitzjarrald, 2001). As a consequence, the diurnal cycle of solar radiation determines the stability of the PBL.

While wind gusts can be produced by convective systems such as thunderstorms and downbursts (cf., Choi and Hidayat, 2002; Shu et al., 2015), and other synoptic and mesoscale phenomena (e.g., Letson et al., 2018), the energy-containing turbulent eddies themselves are usually far too small to resolve in mesoscale numerical models (Wyngaard, 2004). As a consequence, when mesoscale models are used, gusts must be parameterized in some fashion, just as the PBL and surface layer must be. This is tricky because for practical reasons, operational models may need to employ horizontal resolutions that reside within the so-called gray zone (Wyngaard, 2004), in which turbulence is only partially resolved. Also, it may be necessary to handle convective and non-convective gusts separately, as the former may have different characteristics and yet still

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be a threat to wind power systems (e.g., Kwon et al., 2012).

Many wind speed and gust forecasting methods have been proposed and evaluated for a wide variety of locations, phenomena, and conditions (Sheridan, 2011). has summarized some parameterizations in use for non-convective and convective gusts. Some are directly based on physical processes, such as (Brasseur, 2001), which characterizes gusts as boundary layer parcels drawn downward to the surface (Goyette et al., 2003); evaluated that approach in a regional climate model. Others utilize friction velocity (the surface turbulent momentum flux; Panofsky et al., 1977) or even constant gust factors (the ratio of the gusts and mean winds; Stucki et al., 2016; Fovell and Cao, 2017; Cao and Fovell, 2018). Still others, such as (Patlakas et al., 2017) and (Friederichs et al., 2009), combine model forecasts or analyses with statistical methods. Regarding convective gusts (Gray, 2003), used an algorithm to predict the maximum gust utilizing cloud top height, cloud depth, and virtual potential temperature, while the (Nakamura et al., 1996) approach incorporated downdraft depth and precipitation mixing ratio.

In this paper, we explore using the Weather Research and Forecasting (WRF) model (Skamarock and co-authors, 2008) as a tool to identify wind gust occurrence and large gust magnitude, irrespective of origin, motivated by and verified against observations collected at towers maintained by the Uruguyan electric utility. The emphasis is on crafting skillful “gust alarms”, based on a relevant speed threshold and appropriate forecast time windows. This will necessarily depend on the mean wind simulations being of reasonable quality. Wind forecasts are potentially sensitive to a wide variety of model factors, including initialization, resolution, and parameterizations such as the PBL and land surface models (LSM) (e.g., Stucki et al., 2016; Siuta et al., 2017; Cao and Fovell, 2016, 2018). In particular (Stucki et al., 2016), reported that WRF tended to overpredict the mean wind, while (Cao and Fovell, 2016, 2018), which utilized a dense mesonet to verify winds and gust forecasts during “Santa Ana” windstorms, demonstrated that this can be LSM-dependent, owing to its specification of surface roughnesses.

A variety of horizontal resolutions, ranging from 12 to 0.444 km, are examined herein. The WRF model contains a large number of PBL and SL schemes, some based on estimating turbulent kinetic energy (TKE) and others utilizing non-local closures (such as (Hong et al., 2006)) or representing hybrid approaches (e.g., Pleim, 2007a; Pleim, 2007b). At least one non-local scheme (Shin and Hong, 2013, 2015) specifically addresses the gray zone issue by directly considering the horizontal grid scale. Information from the PBL and SL parameterizations will be used in the construction of a gust parameterization that will predict the appropriate gust factor to be applied to simulated mean winds at hub height ($\sim$ 100 m AGL). Our approach, which extends the work of (Gutiérrez and Fovell, 2015), will be compared to a simpler model for non-convective gusts based on (Panofsky et al., 1977) that has been used at ECMWF (ECMWF, 2015), but applied to sustained winds predicted at hub height rather than at 10 m AGL.

The structure of this paper is as follows we present: in Section 2, the observational data available in Uruguay are described, followed in Section 3 by an analysis of the observed diurnal cycle in gusts, gust factors, and stability parameters. Section 4 describes the WRF experiments, and sensitivity to horizontal grid spacing and PBL/SL treatment is discussed in Section 5, along with our proposed parameterization. The performance of that gust model and the ECMWF algorithm is assessed in Section 6. Conclusions are offered in Section 7.

2. Wind gusts: observational data

With a focus on developing a gust parameterization, we analyzed observational data recorded by the UTE (Administración Nacional de Usinas y Transmisiones Eléctricas) to assess wind energy resources. UTE installed a set of towers with anemometers, wind vanes, pyranometers, and thermometers throughout Uruguay, which is dominated by rolling plains and low mountain ranges with all elevations being < 500 m above mean sea level. The four towers are located in three distinct geographical regions (Fig. 1). The first region is close to the La Plata River, including an estuary composed of seawater and freshwater from the Parana River and the Uruguay River, and is the site of the Rosendo Mendoza (RM) and Colonia Eulacio (CE) towers. The second region is close to the Atlantic Ocean, its tower being called Jose Ignacio (JI). The third region is further inland, at least 300 km from the La Plata River and the Atlantic Ocean, represented by the Aparicio Saravia (AS) tower.

The towers are equipped with two anemometers mounted orthogonally to filter the effect of the tower wake. The installation adhered to IEC standard 61400-12 (IEC, 1998). The wind measurements were performed with cup anemometers (NRG Systems 40, with a distance constant of 3 m) and wind vanes (NRG Systems 200P) mounted at various heights, including turbine level (approx. 100 m). Table 1 describes the measurements considered in this work. The time periods were selected based on the quality and completeness of the wind data. Gusts were determined from 2-s samples (0.5 Hz being the sampling frequency) and the mean winds averaged these samples over 10-min intervals.

3. Analysis of observational data

3.1. Diurnal variation

The analysis of the observational data in this section begins with a description of the mean diurnal cycle and seasonal variations of near-surface stability and wind gusts. The data analyzed consisted of periods of twelve consecutive months, representing 2012 or 2014–15 (see Table 1). To determine the diurnal cycles, hourly values were sampled from the 10-min data and then averaged within four conventionally-defined seasons (e.g., winter is June 21-September 20, etc.). Then, a more detailed analysis is given for significant gust events, the goal being to identify the dimensional and nondimensional parameters that could be helpful in the development of a wind gust parameterization.

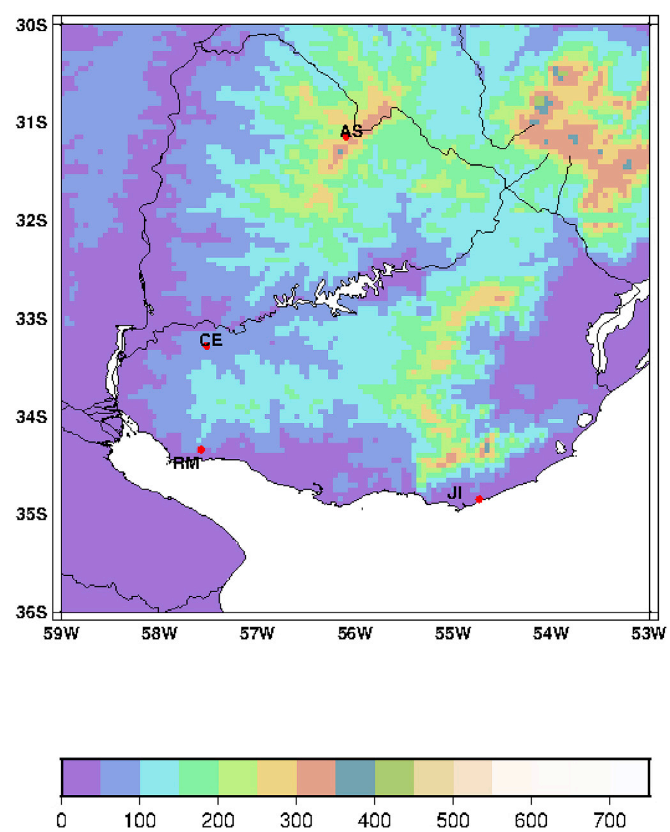

Fig. 1. Locations and topography (m) of towers from where observational data was measured.