Re-Analysis Data for Fine Temporal Resolution Wind Power Estimation: A Comparison of Boundary Layer Parameterizations

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Research Question

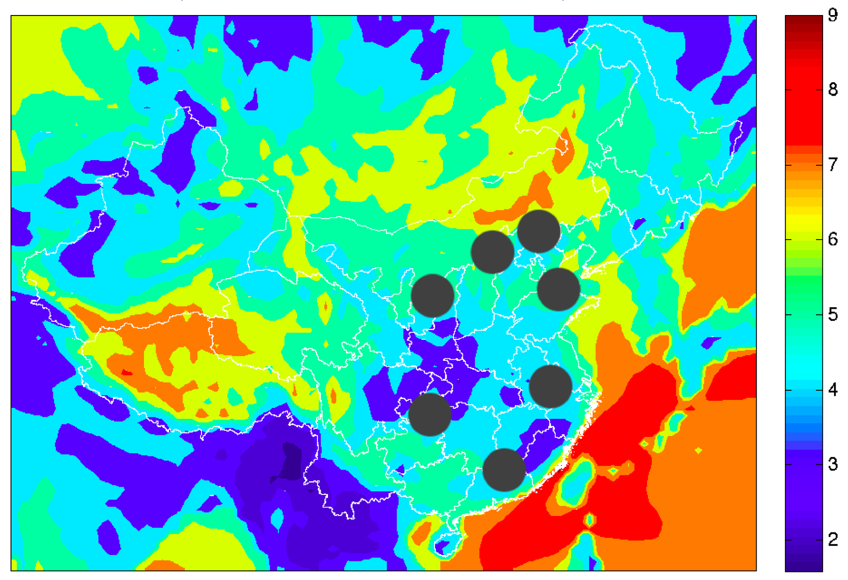
How accurate can re-analysis products simulate near-surface winds at fine temporal and geographic granularity sufficient for electricity systems operations applications?

Motivation

Global wind power resource assessments have benefitted in recent years from re-analysis datasets, which assimilate diverse measurements in a global circulation model to reconstruct complete wind profiles. With high penetration, short-term and localized fluctuations of wind energy are increasingly important relative to annual averages, for reliable and efficient power systems planning and operation. Re-analysis methods have difficulty resolving these fluctuations, which are primarily driven by boundary layer meteorology (*1*), and leading methods to improve their accuracy such as downscaling are computationally expensive (*2*). Tractable methods using available meso-scale data that can appropriately capture the fine temporal variability of wind power distributed across large regions can thus help improve siting, operation and policy for power systems.

MERRA Validation

Wind speeds were constructed from Modern Era Retrospective-analysis for Research and Applications (MERRA) boundary layer flux data produced by NASA at hourly resolution (*3*). Validation studies for limited geographies show high correlations ($R > 0.7$) between MERRA and meteorological (Met) data over daily or annual averages. We obtained wind speed data from 23 locations in China at various mast heights up to 90m over periods of 1-3 years at 10-min resolution. After quality control, eliminating 6 records entirely, and considering only heights in the range 70-90m, we have a sample of $N = 434,320$ (hourly averaged).



Average annual wind speed at 80m and Met locations

Boundary Layer Similarity

Wind speeds at wind power installation heights (20-160 m) are heavily influenced by atmospheric stability in the surface layer. *Monin-Obukhov similarity theory*, in which a dimensionless parameter is formed from relevant variables and fitted empirically, is widely used to calculate fluxes between different heights. For wind speed (*4*):

$$u_* = l_m \frac{du}{dz} = \frac{\kappa z}{\phi_m} \frac{du}{dz} \tag{1}$$

where l_m is the mixing length, u_* is the friction velocity, ϕ_m is the dimensionless wind shear and $\kappa = 0.4$ is the von Kármán constant. Under a neutral stability assumption, $\phi_m = 1$, which leads to the commonly-used "log law":

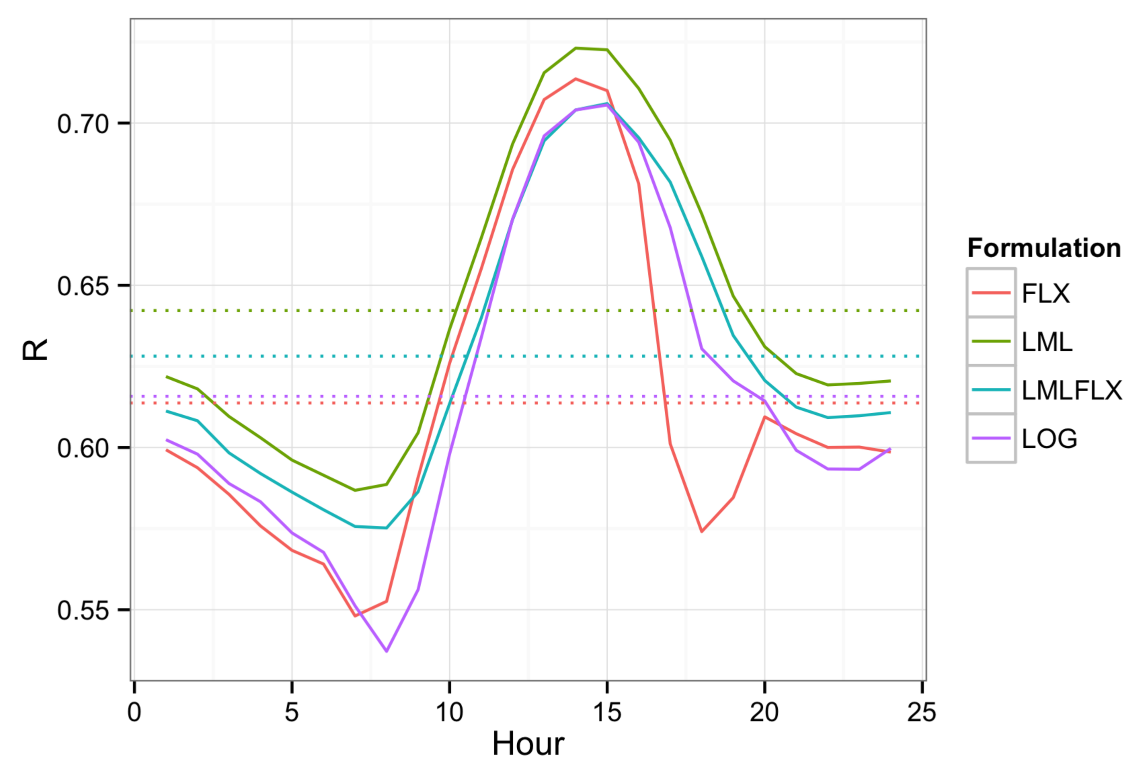
$$u(z) = \frac{u_*}{\kappa} \log(\frac{z-d}{z_0}) \tag{2}$$

where d is a (typically small) displacement height related to surface obstructions and z_0 is the surface roughness, defined as the constant for which $u(z_0) = 0$ in (1). However, the logarithmic law is less reliable in stable conditions, because of weak fluxes caused by stratification and the possible presence of low-lying jets due to low boundary layer heights (*5*). Correction terms are derived from different forms of ϕ_m, frequently defined in terms of the Obukhov length, which under stable conditions is the height above which buoyant turbulence dominates shear turbulence:

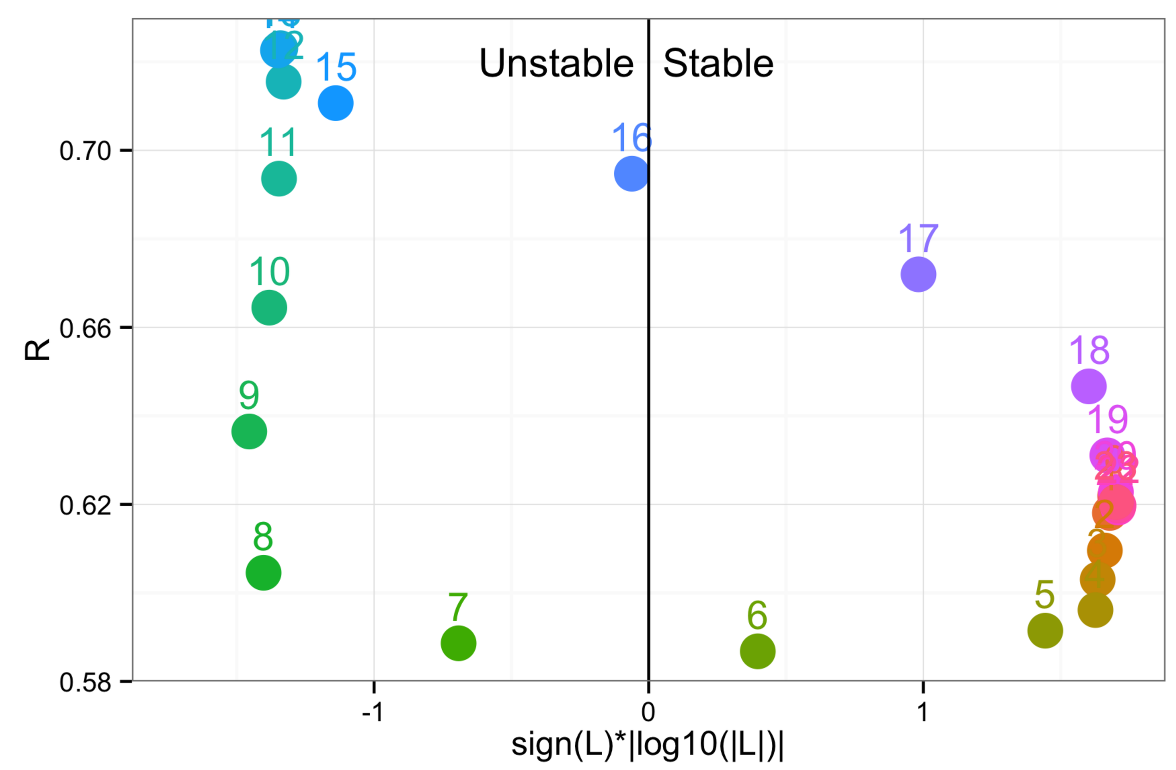
$$L = -\frac{u_*^3 \overline{\theta_v} \rho_a c_{p,d}}{(\kappa g H_f)} \tag{3}$$

where $\overline{\theta_v}$ is the virtual temperature and H_f is sensible heat flux (negative if directed upwards). We use a piecewise ϕ_m quadratic for unstable conditions, linear for $z < L$ and constant for $z \geq L$ (FLX)(*6*). Similarity theory can be extended by integrating (1) from any height z_1 for which horizontal wind speed is known. In particular, we test $z_1 = LML$, center of the MERRA lowest model layer ($LML \sim 50m$), for which speed is given at hourly resolution.

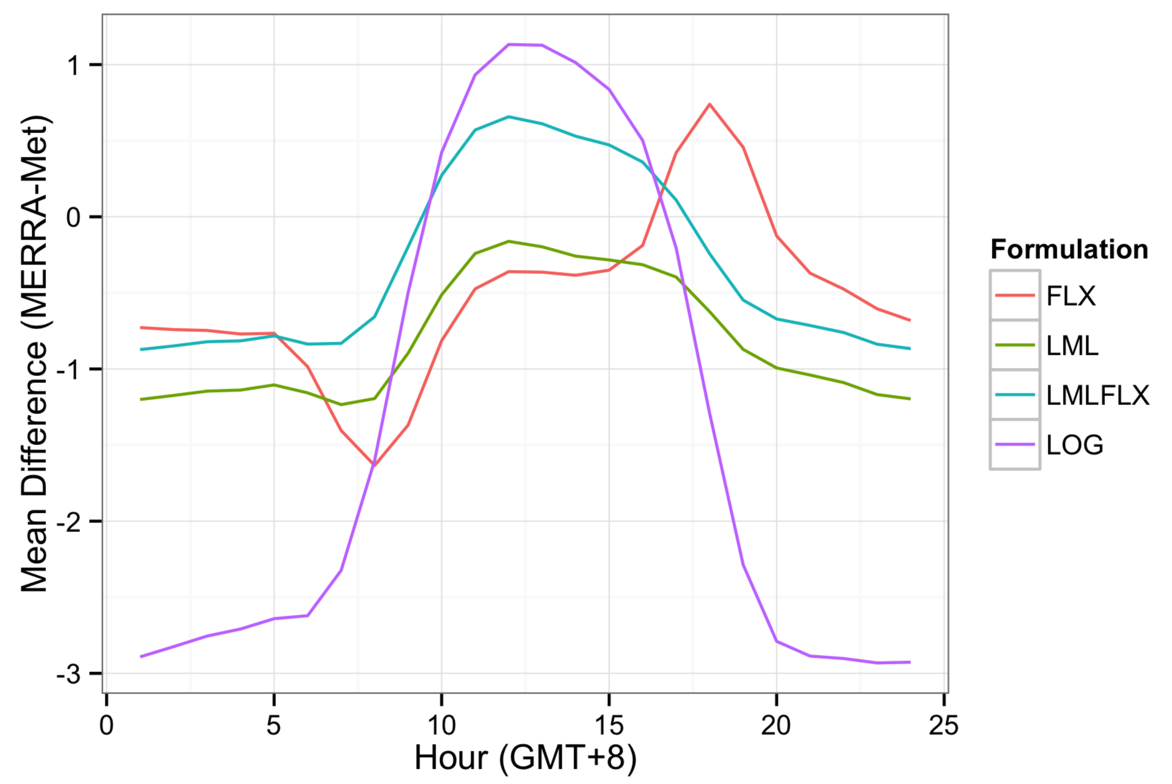
Diurnal Correlation Results



Correlation coefficients (dashed=average)



Obukhov lengths and correlations (LML) by hour



Mean prediction bias

All formulations show strong diurnal effect on accuracy measured by the correlation coefficient R, with the worst estimation during nighttime under typically stable conditions. Stability correction terms to the "log law" lead to deterioration around 1800 local time, which has a positive mean error ($MERRA > Met$) in contrast to negative mean errors for other hours (not shown). LML (where $\phi_m = 1$) is consistently better than $LML + Correction$ and z_0-based formulations. Examining average Obukhov lengths, correlations are worst during transitions from stable to unstable – and interestingly, not vice versa. The low mean Obukhov lengths ($10 \sim 100m$) implicate some errors in the MERRA-derived u_* and H_f.

Conclusions

Stability correction worsens estimates

Attempting to modify wind speeds using MERRA-derived stability parameters did not improve accuracy compared to neutral stability assumptions, which we hypothesize is due to sensitivity to key model outputs such as sensible heat flux.

Towards improving MERRA wind estimates

Integrating from mid-LML is better than lower surface roughness-derived estimates but does not resolve consistent nighttime bias. In particular, the morning transition from stable to unstable requires further research, including w.r.t. estimated ramping requirements for power system operations.

References

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