AWEA Wind Resource & Project Energy Assessment Seminar

Overview of Extrapolation Uncertainty

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PRESENTATION OUTLINE

- Motivation
- Measurements
- Models
  - Log Law
  - Power Law
  - Displacement
  - Stability
- Ideal Conditions vs. Reality
- Uncertainty
- Concluding Remarks

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MOTIVATION

- Wind shear: variation in wind speed and direction (veer) with height
- Why is it important?
  - Available energy in the wind
  - Energy conversion / losses
  - Climatic suitability of turbines
- We can measure and we can model… usually need both
- Wind shear is dynamic:
  - Variation across the swept area of a turbine
  - Spatial variation across project
  - Temporal variation (various time scales…)

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MEASUREMENTS

- Commonly, multiple on-site met towers
- Sensors at multiple heights (< hub height)
- Measurements used to evaluate the shear profile (2 or 3 levels) and extrapolate to hub height
- Prioritize consistency in anemometry and exposure:
  - Sensor type (avoid vertically varying sensor types)
  - Redundancy (redundant sensors at all levels)
  - Boom lengths and orientation
  - Treatment of data should take into consideration the site-specific configuration…

(North Pole met tower)

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MEASUREMENTS

- Remote sensing provides:
  - More / different data (3D profile over swept area)
  - Avoids many of the challenges associated with met towers: (inconsistency in tower effects and sensors)
- Introduces different challenges
  - Volume averaging (not necessarily a disadvantage…)
  - Data recovery bias
  - Beam angle
  - Noise…

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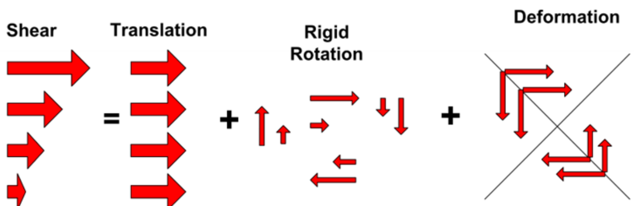
MODELS: LOG LAW

- Conceptually, shear can be defined as the sum of translation, rigid rotation and deformation



(adapted from Blackadar and Baldocchi)

- Momentum is transferred downwards

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MODELS: LOG LAW

$$u_z = \frac{u_*}{\kappa} \cdot \ln\left(\frac{z}{z_0}\right)$$

u_z is the wind speed at height z
u_* is the friction velocity
k is the Von Karman constant (usually taken as 0.4)
z_0 is the roughness length
z is the height above the ground
(Prandtl, 1932)

MODELS: LOG LAW

$$u(z) = u_{ref} \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

u_z is the wind speed at height z
z_0 is the roughness length
z is the height above the ground

MODELS: LOG LAW

$$u_z = \frac{u_*}{\kappa} \cdot \left[\ln\left(\frac{z-d}{z_0} \right) \right]$$

u_z is the wind speed at height z
u_* is the friction velocity
k is the Von Karman constant (usually taken as 0.4)
z_0 is the roughness length
z is the height above the ground
d is the displacement height

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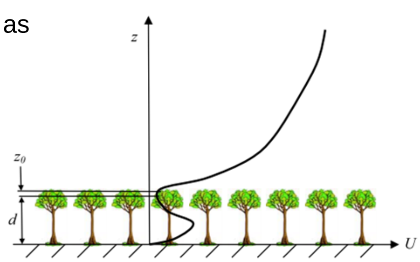
DISPLACEMENT HEIGHT

- Shear profile "displaced" to a virtual ground level by surface features
- Displacement (*d*) can be estimated as a fraction of feature height:
  - Estimates vary: $0.64\,h < d < 1.0\,h$
  - Depends on the density of the forest
- The value of *d* shifts the profile, it doesn't change the shape
- What about near the edge of a forest?
  - Can taper the displacement as a function of the distance from the forest



(from Stangroom, 2004)

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MODELS: LOG LAW

$$uu_z = \frac{u_*}{\kappa} \cdot \left[\ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right) \right]$$

u_z is the wind speed at height z
u_* is the friction velocity
k is the Von Karman constant
z_0 is the roughness length
z is the height above the ground
Ψ_m is a stability function
L is the Monin-Obukhov stability parameter (length)
(Monin and Obhukov, 1954)

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STABILITY

- There are a few formulations for the stability correction
- Depends on the sign of z/L…
- When *z/L* = 0, neutral

$$\psi_m = \begin{cases} -\beta \dfrac{z}{L} & \text{for } z/L > 0 \text{ (stable)} \\ 2\ln\left(\dfrac{\phi_m^2}{2}\right) - 2\arctan(\phi_m) + \dfrac{\pi}{2} & \text{for } z/L < 0 \text{ (unstable)} \end{cases}$$

$$\phi_m = (1 - \gamma\, z/L)^{1/4}$$ and β = 4.8, γ = 19.3

$$L = \frac{-\theta_v u_*^3}{gk\left(\overline{w'\theta_v'}\right)}$$

$\overline{w'\theta'}$ is sensible heat flux
u_* is friction velocity (related to momentum transfer)

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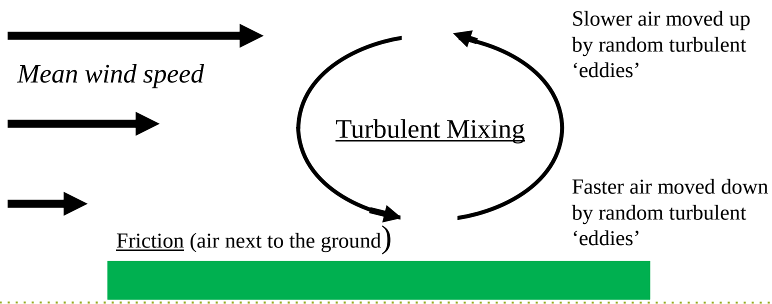
STABILITY

- The sign of *L* (M-O length) depends on the heat flux (dominance of buoyancy over mechanical effects)
- *L* is positive if the surface air cools from below (stable)
- *L* is negative if the surface air cools from above (unstable)



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STABILITY

- Atmospheric stability reflects the thermal effects on wind flow
- Requires fast response measurements (~10 Hz)
- In wind resource assessment models neutral stability commonly assumed
  - Reasonable assumption given that wind resource assessment most concerned with strong wind conditions
  - Strong winds induce mixing, which reduces thermal effects
- This has some limitations:
  - Sites with a low average wind speed
  - Offshore site
  - Fails to characterize true dynamic characteristics
- Truly neutral conditions are infrequent…

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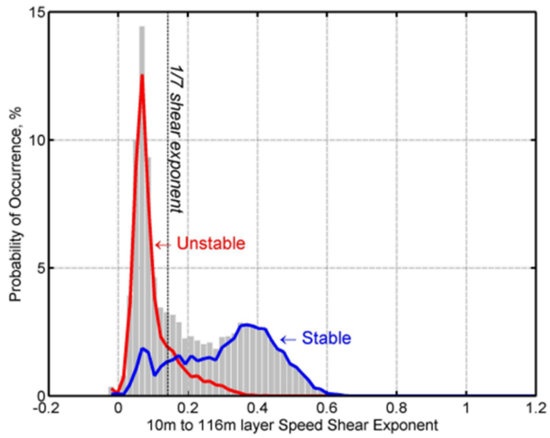
STABILITY



(Walter, 2007)

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MODELS: POWER LAW

$$u_2 = u_1 \cdot \left(\frac{z_2}{z_1} \right)^{\alpha}$$

u_n is the wind speed at height z_n

α is the profile exponent (Hellman)

(Hellman, 1916)

→ Convenient but empirical, no theoretical basis

→ Profile exponent ~= 1/7 in neutral conditions

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MODELS: POWER LAW

→ The profile exponent can be related to the roughness length (...roughly):

$$\alpha \cong \left(\frac{1}{\log_e (z_{ref} / z_0)} \right)$$

z_{ref} is the reference height
z_0 is the roughness length

Terrain	Surface Roughness Length z_0 (m)	Wind Shear Exponent α
Calm sea	0.0002	0.09
Cut grass	0.007	0.14
Short-grass prarie	0.02	0.16
Crops	0.05	0.19
Scattered trees and hedges	0.15	0.24
Trees, hedges, a few buildings	0.3	0.29
Forest	0.5	0.33
Suburbs	1.5	0.53

(based on a reference height of 10 m)

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IDEAL VS. REALITY

Other factors that affect the shear profile:

→ Terrain
- Steep slopes
- Mountain waves

→ Low-level jets
- decoupling of flow during stable conditions (i.e. not affected by the surface)

→ Local circulation
- Heating imbalances such as sea breezes and mountain valley breezes

→ Weather fronts

→ Roughness changes

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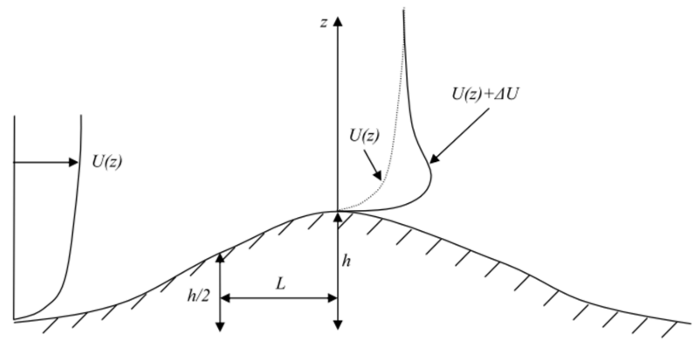
IDEAL VS. REALITY



Development of a shear profile over a hill

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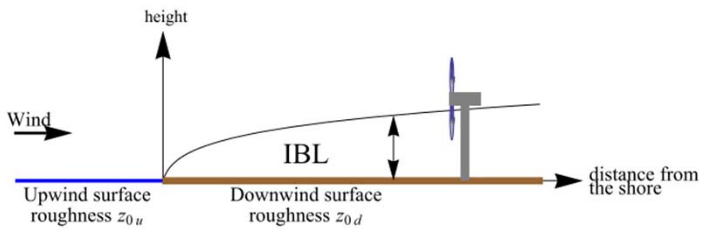
IDEAL VS. REALITY



Influence of the depth of the internal boundary layer, roughness changes, stability and fetch on the shear profile

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SELECTING A MODEL

- Validations haven't shown a clear winner…
- Significant variation in how models are applied
- Other models exist… (Deaves and Harris, 1978; Wilson and Flesch, 2004)
- Consider use of data when performing extrapolation (energy estimates, climatic suitability, losses…)

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OTHER MODELS

- Re-examine last year's shear trial data...
- Which variables are most influential?
- Evaluated a variety of different inputs:
  - Lower level shear (50/30)
  - Wind direction
  - Month
  - Wind speed
  - dT/dz
  - dT/dt
  - Turbulence
  - Time of day

(dT/dz, dT/dt, Turbulence, Time of day: Surrogates for stability)

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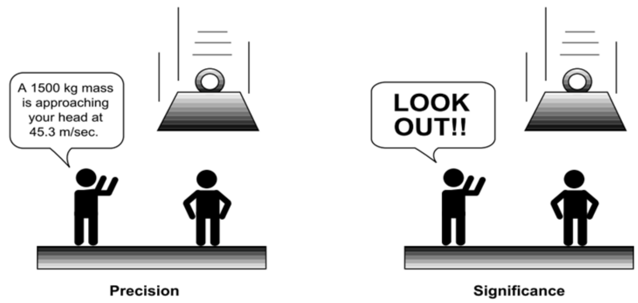
OTHER MODELS

Fuzzy Logic

→ Can be an efficient way of handling complex problems since it allows for uncertainty / “fuzziness” in relationships
(although the name isn’t particularly confidence-inspiring…)



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OTHER MODELS

→ Sub-divide 80 m wind speeds into “training” and “checking” data sets

→ Iteratively select input variables in order to determine order of “importance”:

1. Time of day
2. Wind speed, Shear
3. dT/dt, Turbulence
4. Wind direction
5. dT/dz
6. Month

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OTHER MODELS

- → Variables related to stability were influential
- → Results did not show the bias that was prevalent in last year's trial ... but we cheated! (training with 80 m data)
- → At this point, technique isn't intended as an extrapolation methodology but rather as a tool for evaluating the inputs
- → Can be used to help assess binning of data
- → Objectives can be tailored, for example matching of diurnal shear patterns

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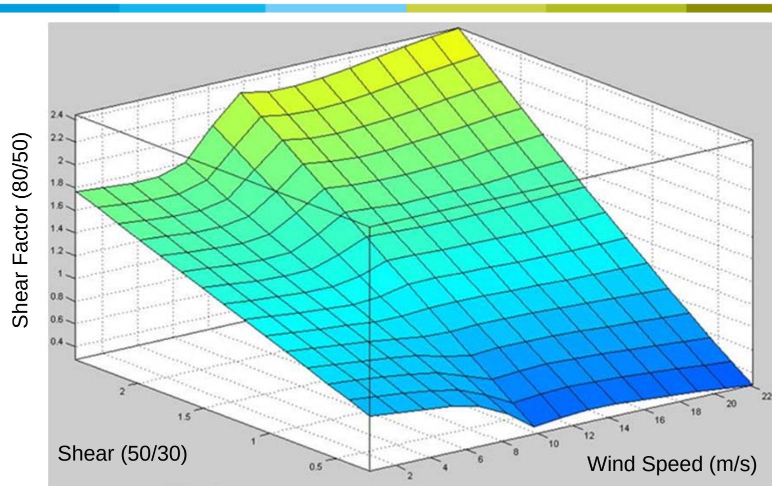
OTHER MODELS



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UNCERTAINTY

- In our experience, uncertainty in the shear profile is commonly one of the most significant uncertainty components in a wind resource assessment
- Estimating the uncertainty related to shear is both qualitative and quantitative
- Consider:
  - Uncertainty in measurements (sensors, configuration, data acquisition...)
  - Representativeness of measurements (seasonality, data recovery bias)
  - Consistency of measurements (at a given location and across site)
  - Site complexity (terrain, roughness, meteorological conditions)
  - Distance of extrapolation

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UNCERTAINTY

- GENIVAR typically performs a sensitivity analysis for the shear profile
- The results of the sensitivity are then used to define an uncertainty distribution
- Generally, the uncertainty estimate increases with stronger shear
- The estimated standard uncertainty (from the sensitivity) commonly corresponds to approximately 1/3 of the magnitude of the profile exponent

Profile Exponent	Top Height (m)	Hub Height (m)	Wind Speed Uncertainty
0.20	40	80	4.5%
0.20	50	80	3.1%
0.20	60	80	1.9%
0.14	60	80	1.3%
0.28	60	80	2.6%

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CONCLUDING REMARKS

- → There are a variety of models used to extrapolate wind speeds to hub height (more on this...)
- → Wind flow models include implementations that incorporate effects of terrain, roughness and stability
- → Models should be calibrated/validated using measured data
- → Increasingly challenging as turbines reach further up (and beyond) the surface boundary layer
- → Important to evaluate the site-specific uncertainty, this can be a guide for planning the measurement campaign (more on this...)
- → As always, data quality is of fundamental importance
- → A staged approach to shear assessment could allow us to isolate particular conditions
    - e.g. Neutral stability and solve for the roughness length

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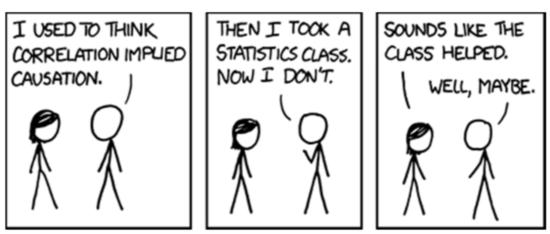
Thank You



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