Identifying Gaps in Meteorology Knowledge Required to Further Develop Wind Energy

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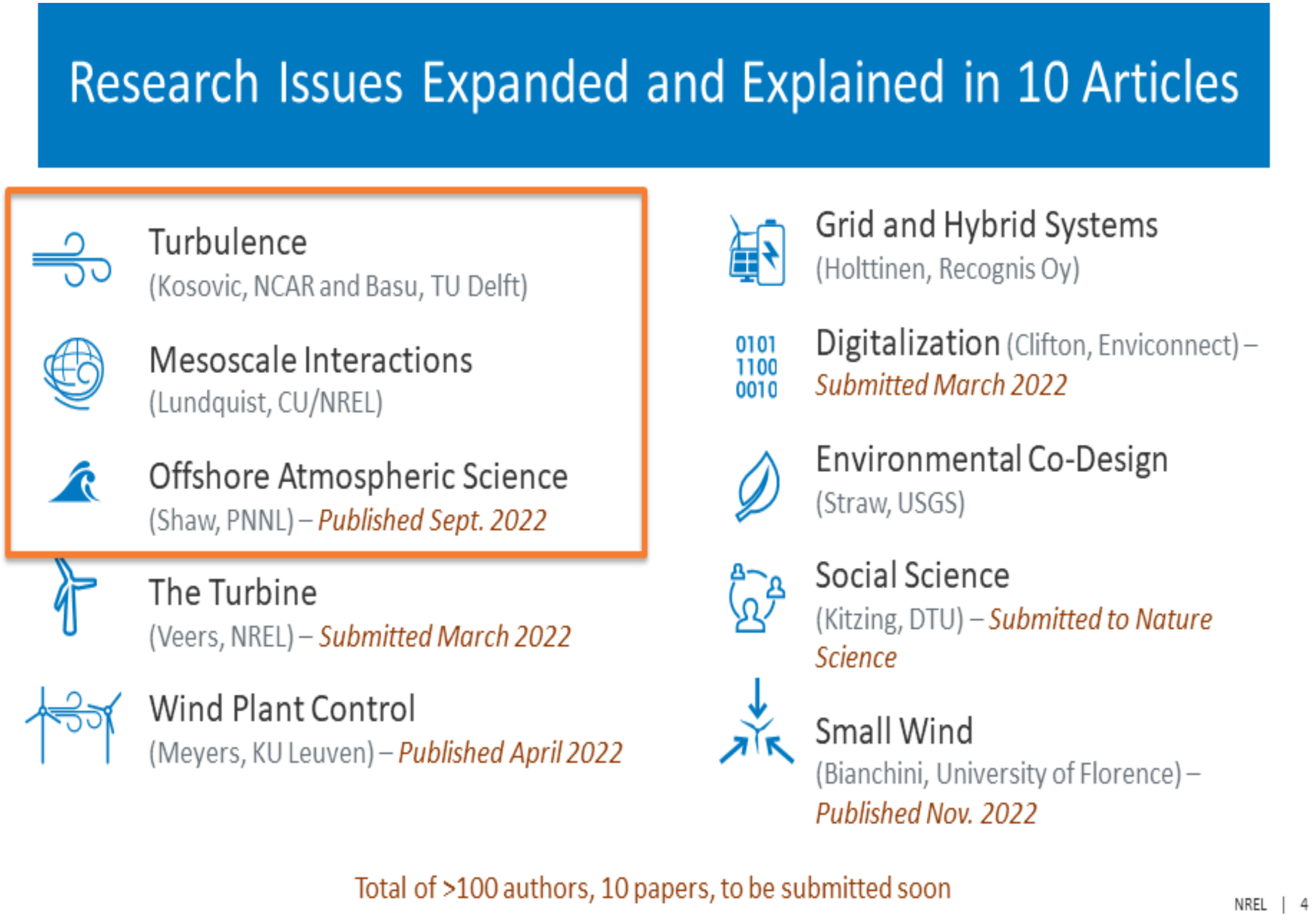
Purpose of Technical Experts Meeting

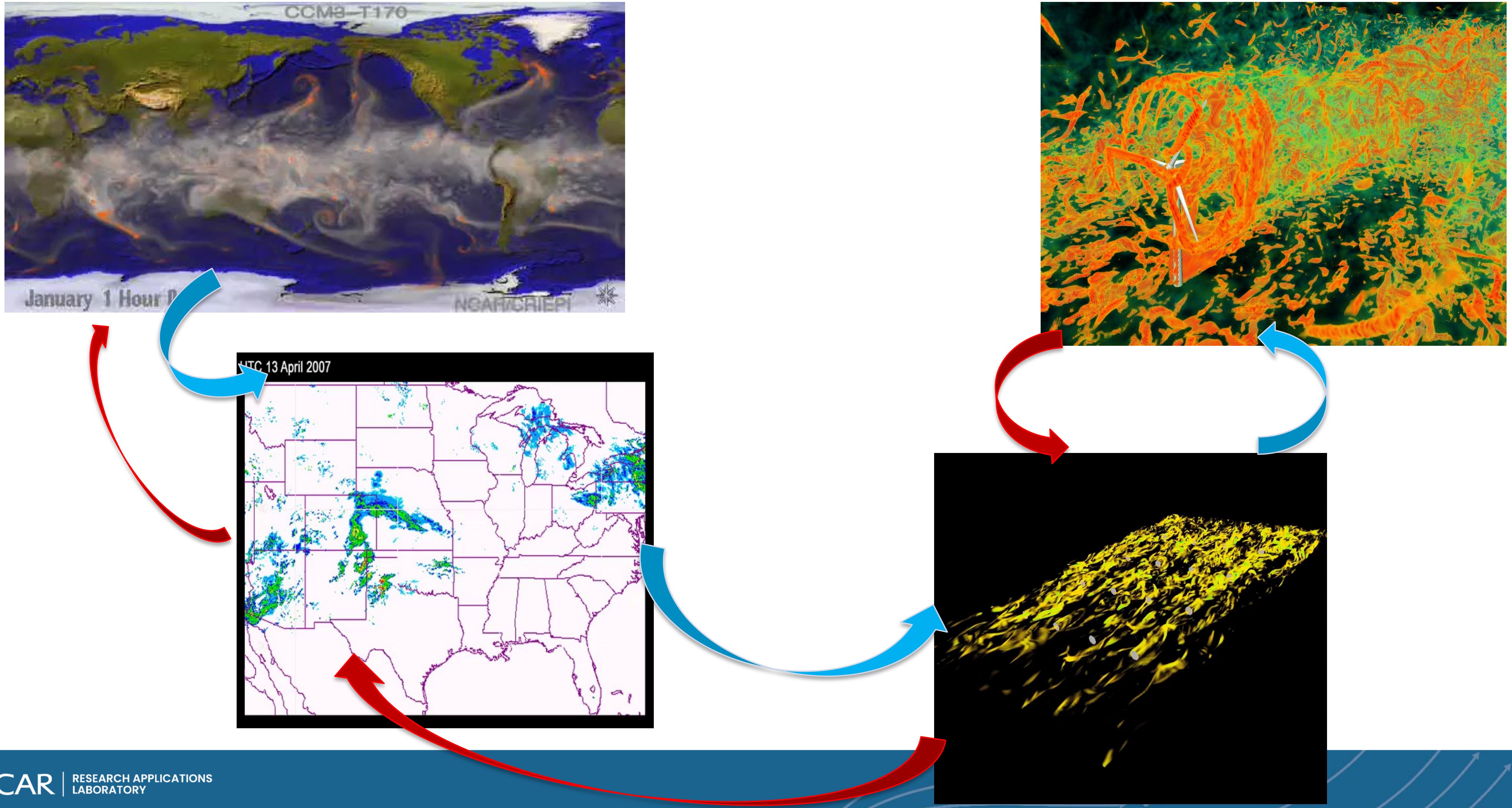
Led by Paul Veers, NREL

The Grand Challenges of Wind Energy Science include:

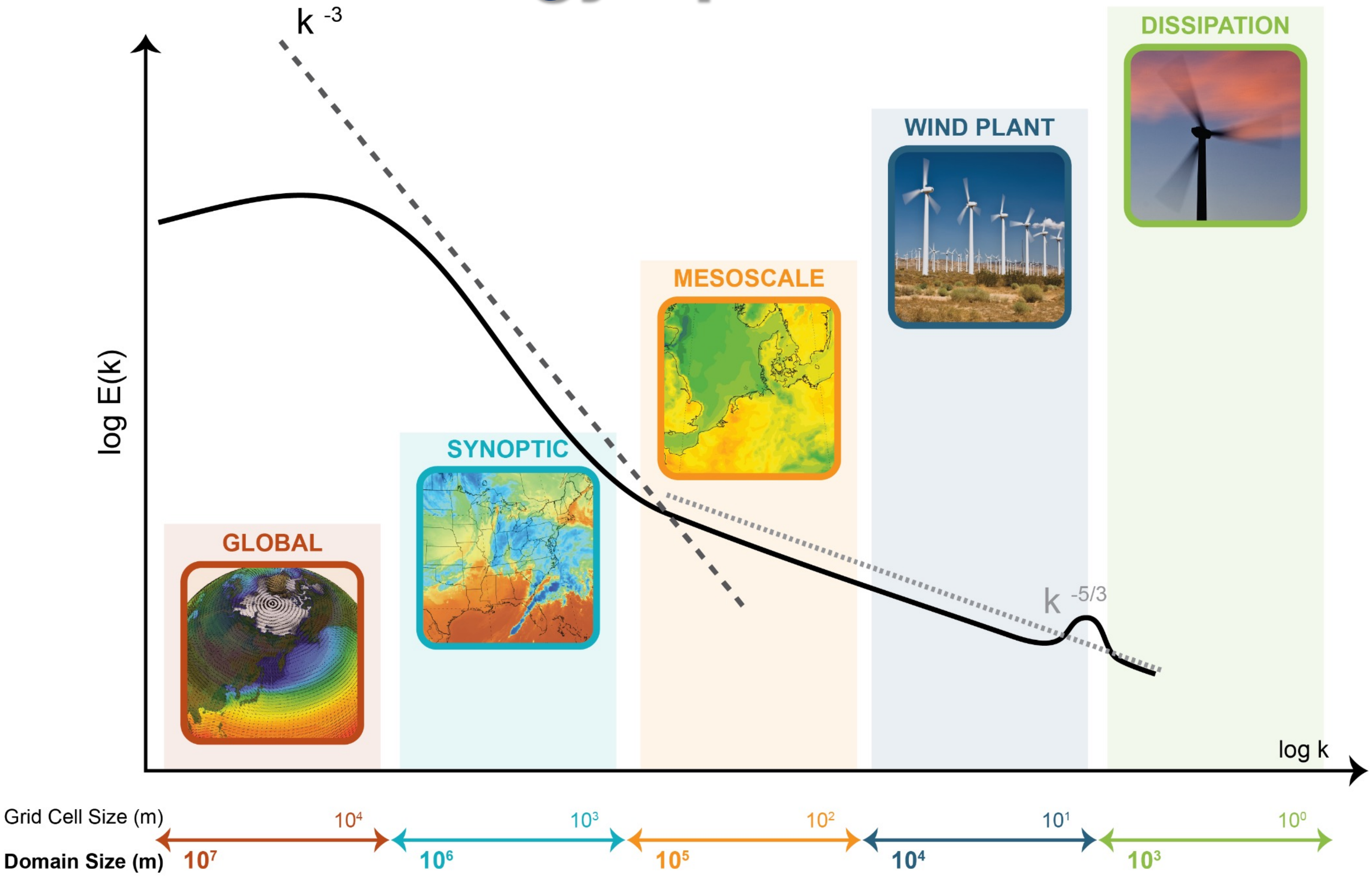
- The **physics of atmospheric flow,** especially in the critical zone of wind power plant operation
- The **system dynamics and materials** of the largest, most flexible machines that have yet to be built
- **Optimization and control of fleets of wind plants** made up of hundreds of individual generators working **to support the electric grid**
- **Social Issues**
- **Environmental issues**



The Atmospheric Energy Cascades Across Scales

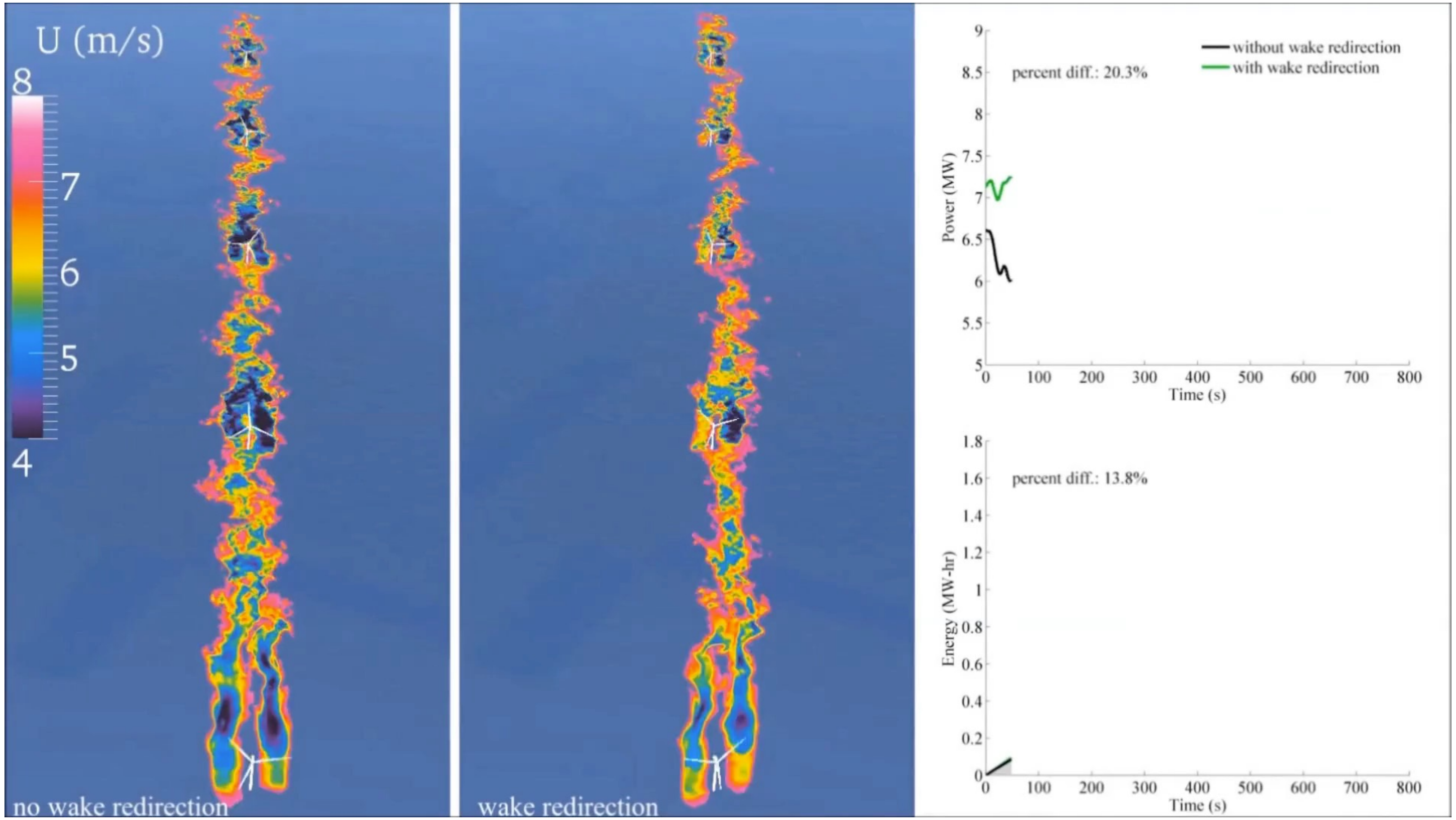


Energy Spectrum

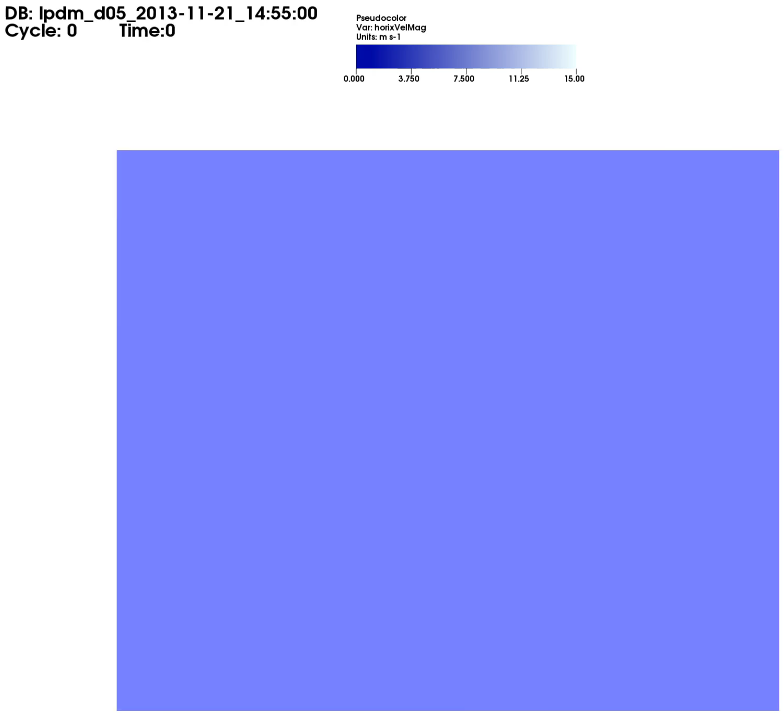


Haupt, S.E., B. Kosovic, J.A. Lee, and P. Jimenez, 2018: Mesoscale Modeling of the Atmosphere, in *Modeling and Simulation in Wind Plant Design and Analysis*, P. Veers, Ed., IET Press.

The Need for Understanding of the Atmosphere



Animation courtesy of NREL
Matt Churchfield



Animation courtesy of LLNL

Needs for Wind Energy

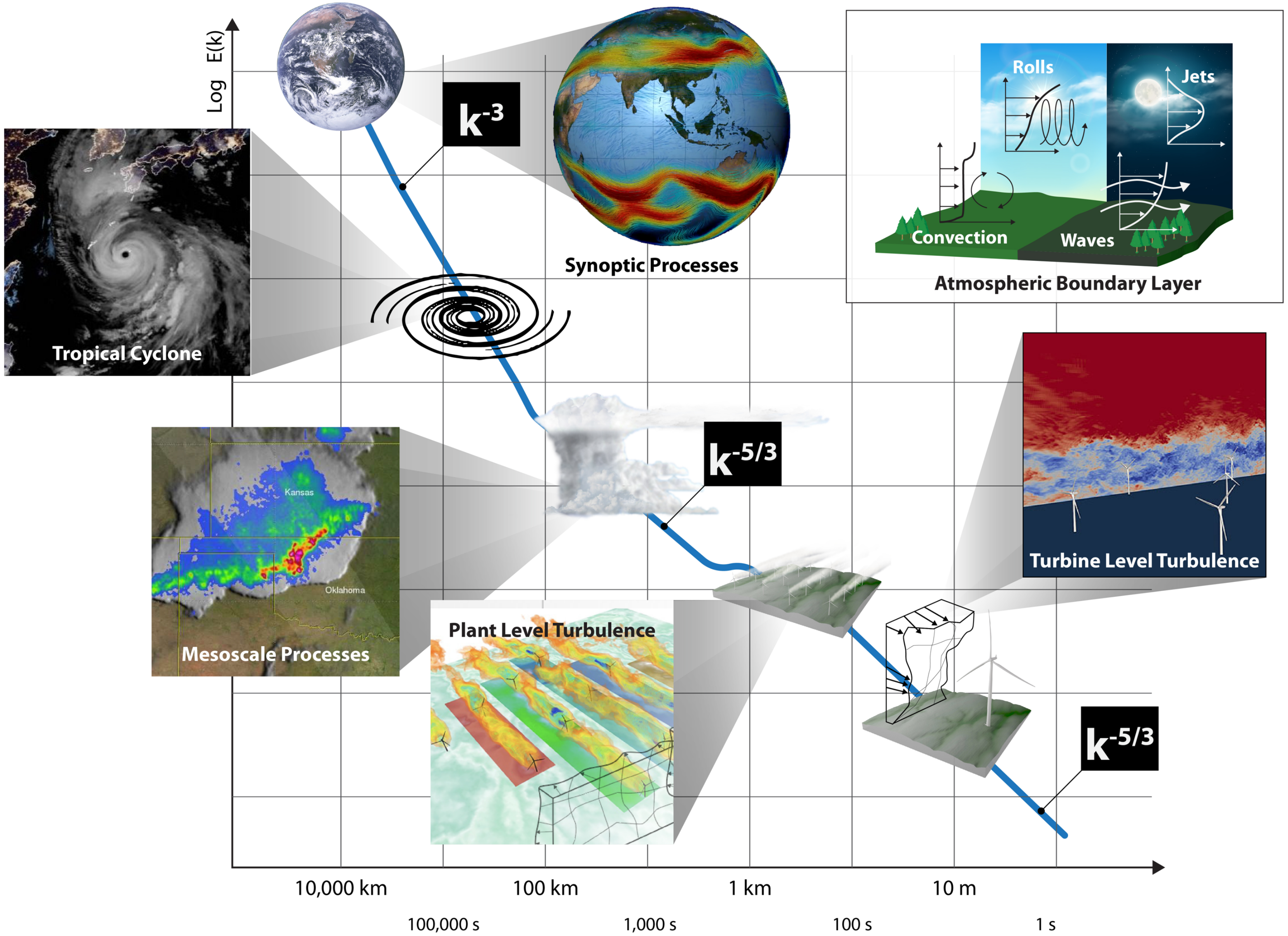
- Resource Assessment
- Siting
- Operation and Maintenance
- Forecasting
- Planning for Extreme Events
- Planning for a Changing Climate

Challenge of Dealing with Complex Environments

- **Complex terrain** must be well represented to capture flow reaction correctly.
- **Coastal flows** must well model atmosphere and coastal boundary, including diurnal effects.
- **Offshore situations** include coupling wave and ocean models to atmospheric models at varying scales.
- **Interactions at multiple scales**, including wind turbine and wind farm wakes.

Atmospheric Turbulence

Kosović, Basu, et al.

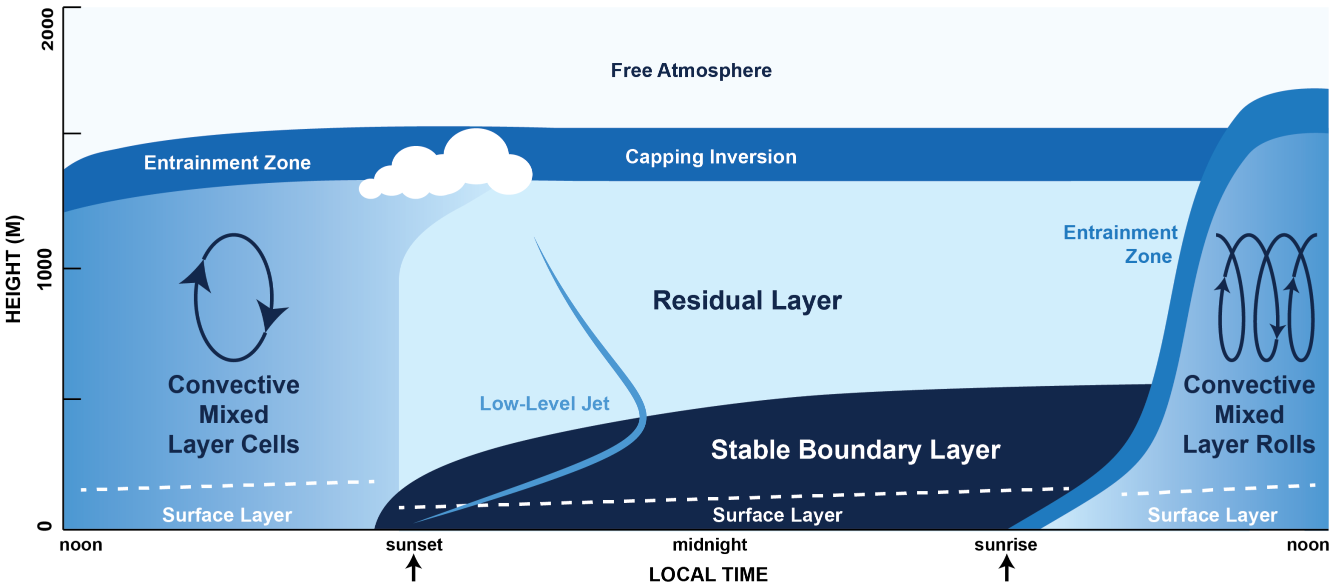


Atmospheric turbulence at all scales, but especially at the more impactful scales of the turbine and plant, has not been characterized in the detail required to achieve optimal wind turbine performance and reliability. There is a need to better characterize turbulence and its effects under the large range of atmospheric conditions under which wind plants are expected to continuously and reliably generate power.

Atmospheric Turbulence

Basu, Kosović, et al.

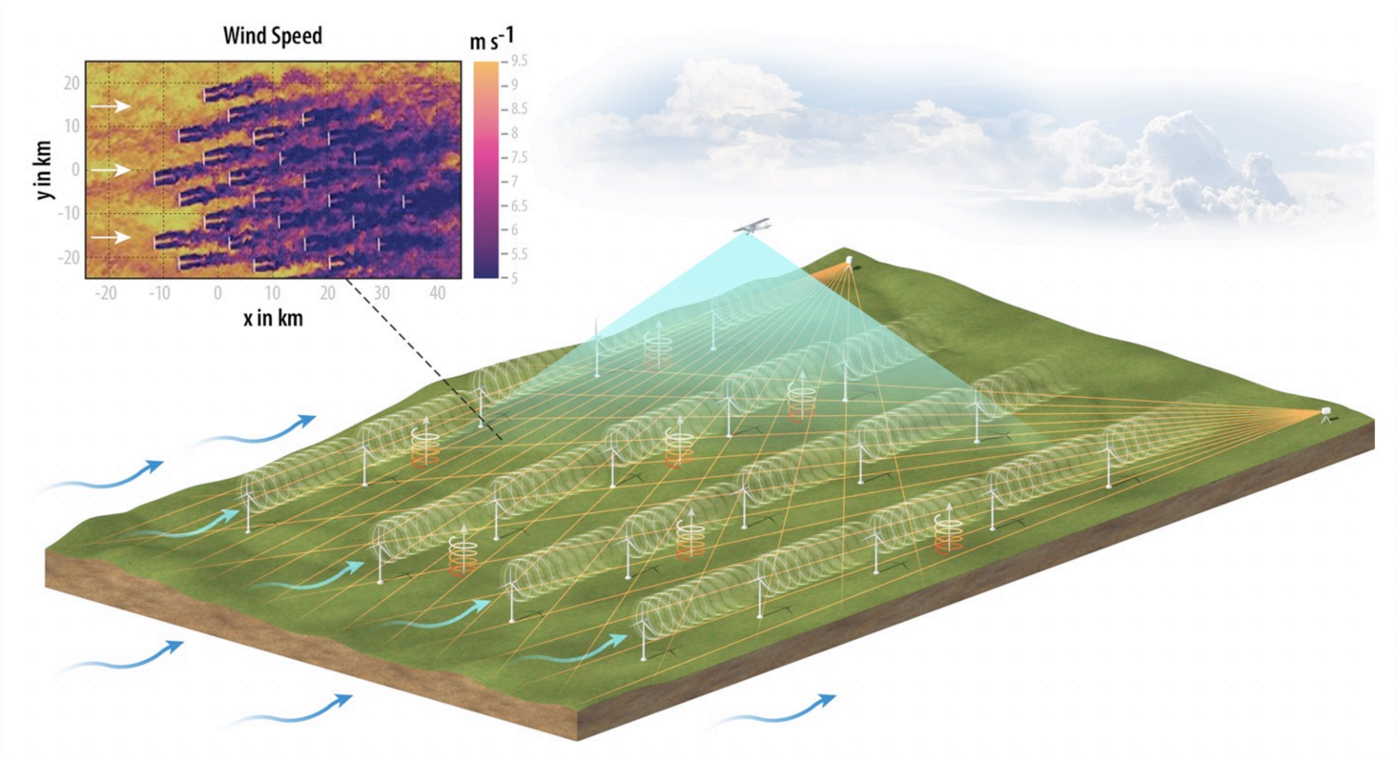
- Atmospheric Energy Cascade
- Atmospheric Boundary Layers
  - Mean vs. Turbulence quantities
  - Dearth of neutral conditions
  - Spectra, coherence, integral length scales, TKE
  - Intermittency & coherent structures
- Atmospheric Phenomena
  - Low-level jets
  - Mesoscale convective circulations
  - Gravity waves
  - Terrain induced circulations
  - Downslope wind storms
- Observations
- Modeling
- Impact on Power Production
  - Extreme loads



The diurnal cycle of the atmospheric boundary layer.

Mesoscale Interactions

Lundquist, et al.

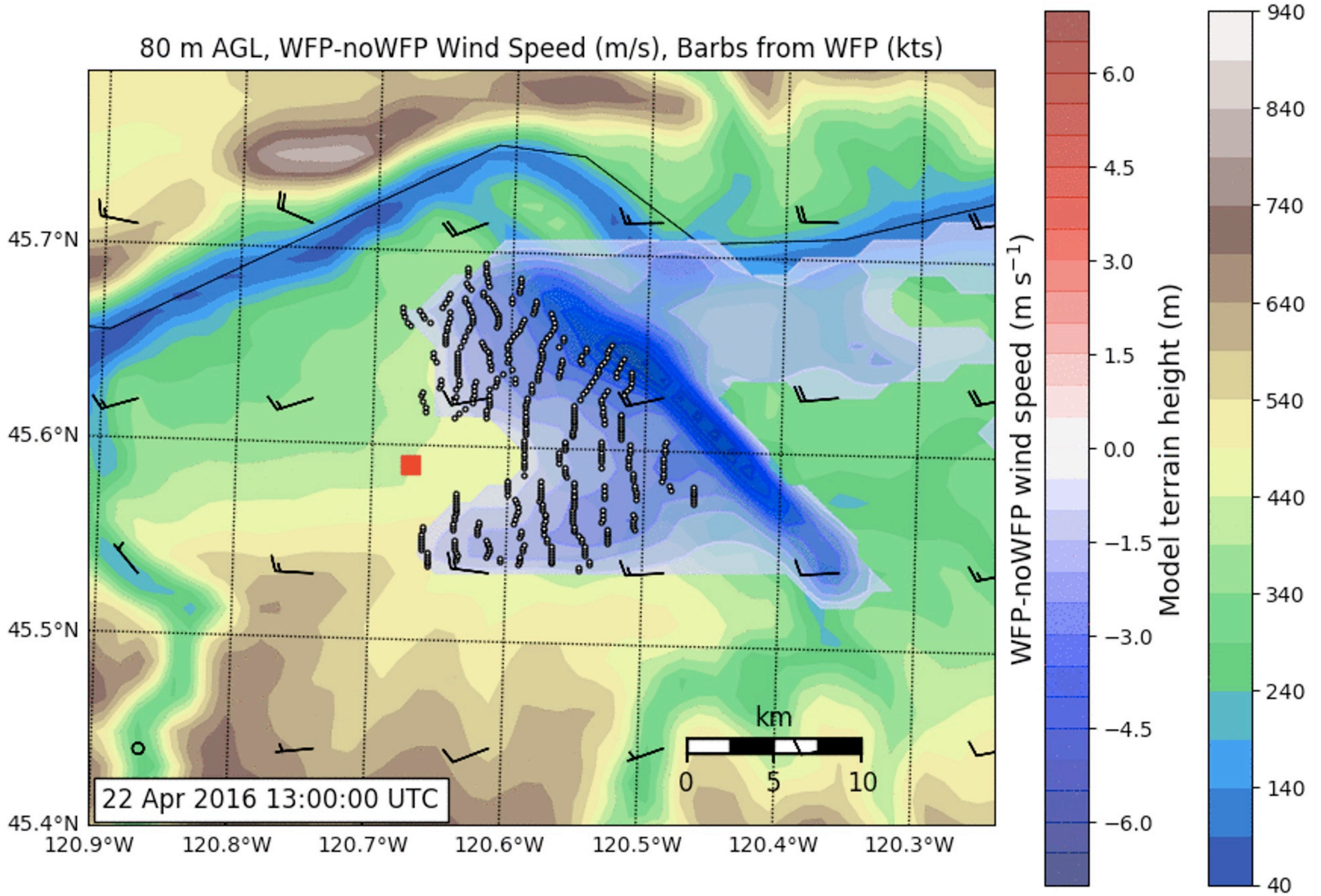


Wakes, or regions of slower and more turbulent air downwind of wind plants, are still not fundamentally well understood, even as interactions between wakes and the atmosphere dictate wind plant cost effectiveness. Further, the large-scale deployment of wind may introduce broad impacts on local microclimates, which must be assessed and evaluated.

Mesoscale Interactions

Lundquist, et al.

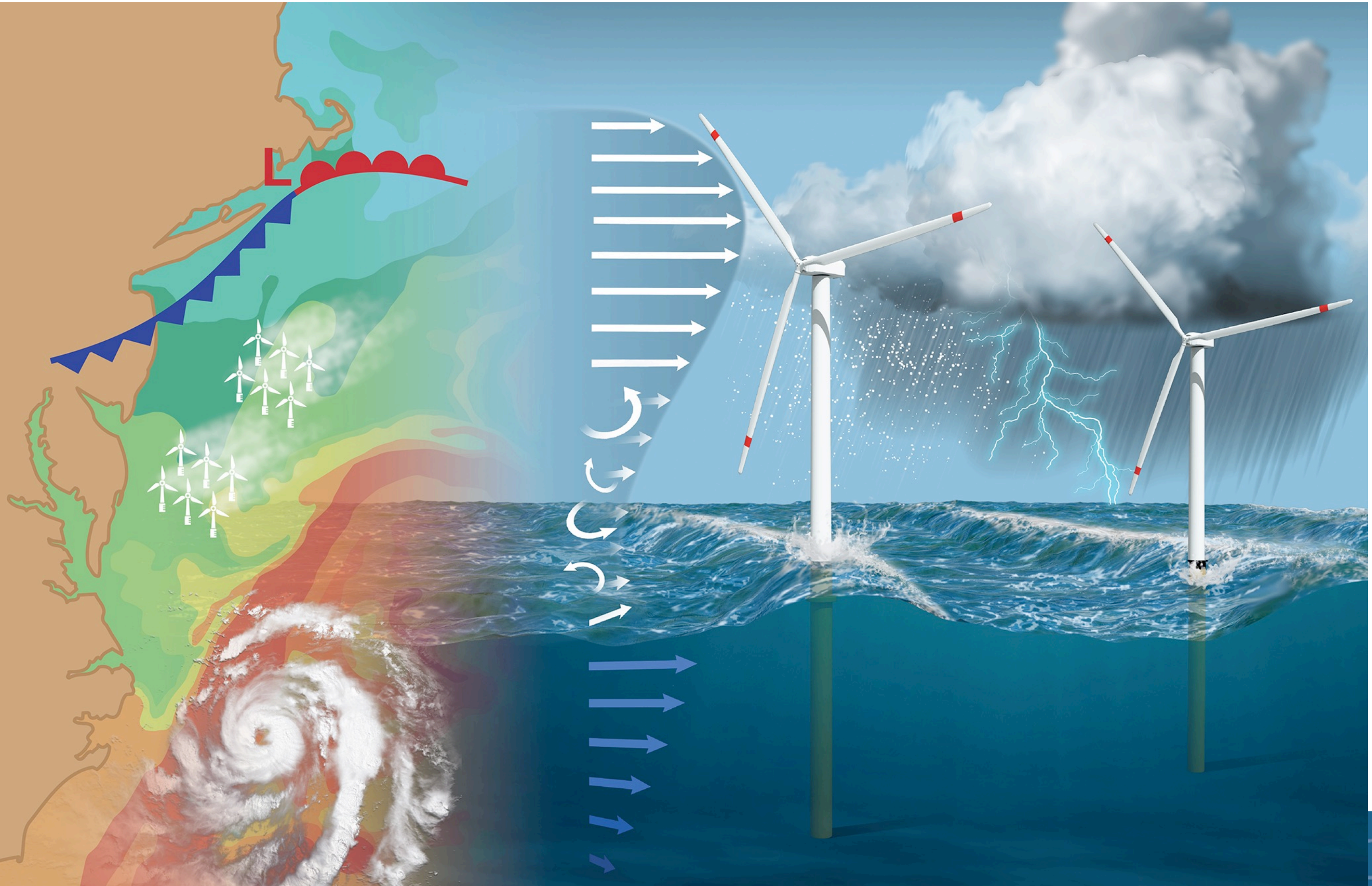
- Observations of Wind Plant Wakes
- Mesoscale Modeling approaches
  - Enhanced drag
  - Elevated roughness
  - Added TKE
  - Role of wind farm layout
  - Rotor-equivalent wind speed
  - Comparing with LES
  - Comparing with observations
  - Resolution issues
  - Impacts on weather phenomena
  - Impacts on power balancing
  - Problems with simplified models
- Open Questions
  - Effects of large wind farm clusters
  - Impact of climate change
  - Mesoscale modeling issues
  - Role of stability in propagating wakes



WRF simulations of the wind farm wake in the Columbia River Gorge region. The wake wind speed deficit follows the subtle terrain of the John Day River south of the Columbia River Gorge rather than propagating directly downwind. From Rochelle Worsnop's unpublished simulations.

Offshore Atmospheric Science

Shaw, et al.

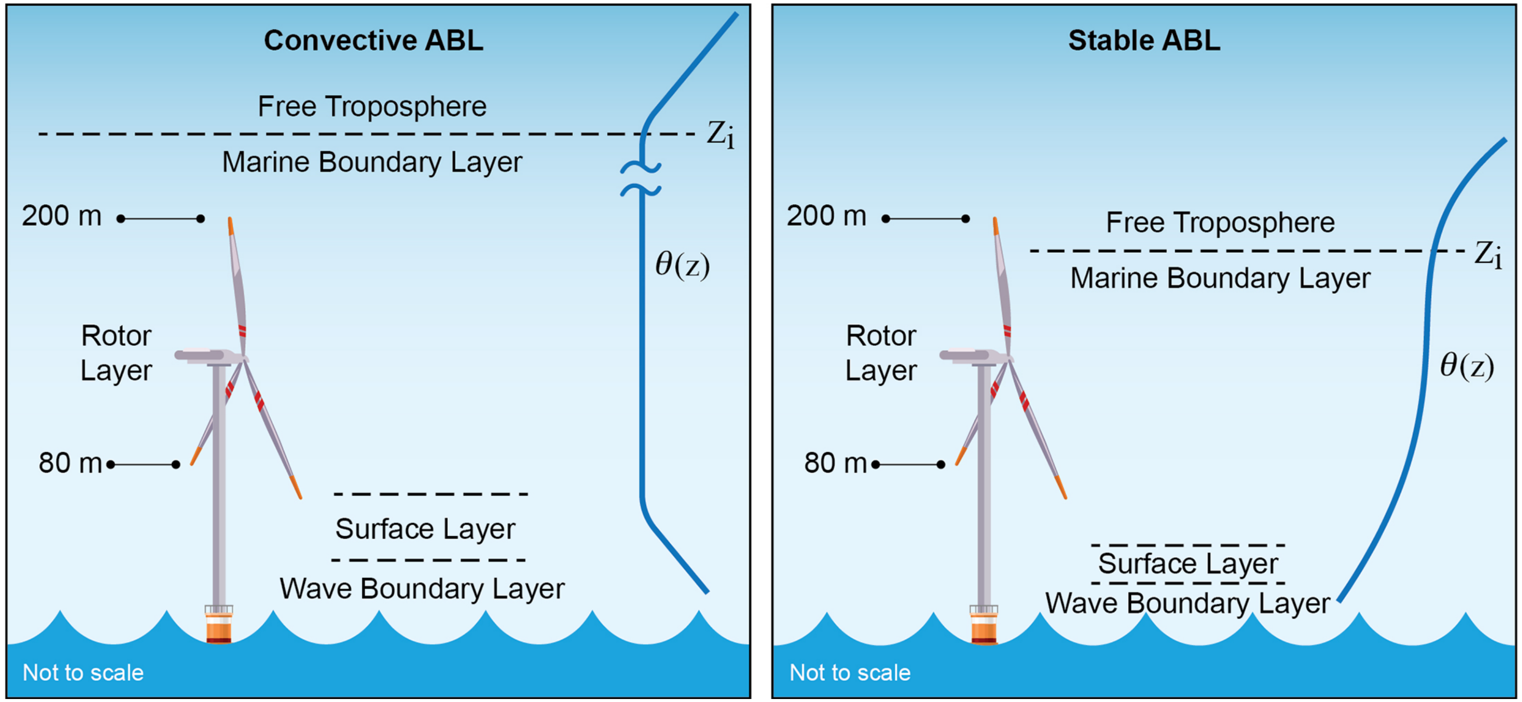


The offshore metocean environment differs significantly
from that on land, while one coastal area differs from another. The offshore environment needs greater definition and physical understanding to optimize offshore wind plants to
suit their local environments.

Offshore Atmospheric Science

Shaw, et al.

- Physical Characteristics of the MBL
  - Wave boundary layer
  - Surface layer
  - Mixed layer
- Role of stratification and surface temperature heterogeneity
- Wind shear and turbulence in the rotor layer
- Modeling the marine BL
  - Microscale
  - Mesoscale
- Impacts of precipitation
- Applications of Machine Learning



Depiction of the different components of the marine ABL and how those components and overall structure vary with changes of atmospheric stability. in the figure is potential temperature and z_i is the inversion at the top of the boundary layer. The break in the profile indicates that the depth of the convective boundary layer can be much greater than the height of the surface layer. The figure is exaggerated in the vertical for illustration.

Pre-TEM Virtual Workshop

Jakob Mann, Co-Lead

Paula Doubrawa, Scribe

What are the largest kno[...] gaps in [...] at have the potential to advance the developme[...] energ[...]

- Articulation of wind resource at national and global scale to public and policy makers, including extreme events and how it will change over time.
- Lightning physics and statistics
- Atmospheric conditions that affect operations & maintenance (freezing sea spray, lightning, long-term extreme winds)
- [...]recipitation
- lack of measurements (at relevant scales) and the understanding of the accuracy of these
- upwind blockage, its spatial extent, and variability with stability
- low cost and/or publicly availab[...] near and short-term forecasting, especially with very limited local data
- [...]nsform physics [...] numerical [...]culations for [...]mplicated flows (e.g. tropical cyclones, coastal flows, complex terrain)
- the overall output not for the individual farm but the energy system as a whole
- [...]inistic [...]listic microscale modelling.
- Is it possible to measure 3D inflow fields with sufficient spatial (10 m) and temporal (10+ Hz) resolution at diverse locations?
- How are we going to characterize the ABL layer beyond 100 m (say 100-500 m)? Very few towers exist; commercial sodars/lidars have data dropoouts.
- new engineering models for turbulence based on
- Improved, low cost remote sensing and the ability to take limited local measurements to complete long term performance assessment
- how realistic, specific inflow phenomena might affect wind turbine design and how it relates to standards
- When is a wind farm cluster area enough to not only affect the regional/mesoscale but also the larger-scale flow and how does this impact look like?
- inter vs intrafarm wakes
- what is the fundamental physics of above-surface layer atmospheric flow
- understanding of turbulence
- Impact of (less)accurate surface modelling to the wind estimates at >200m above ground
- Challenging wind-related weather phenomena that include flows of multiple scales: measurements & modeling abilities
- Better global modeled wind resource data - higher fidelity over more of the planet
- identify key aspects of conversion of wind speed into wind power at different time averaging (subdaily, day, monthly)
- Characterizing impacts of extreme wind events.
- How to effectively communicate to the public the risks and non-risks of wakes
- Wake variability
- Impact of inflow on wakes
- How to democratize new tools
- Low cost, high fidelity modeling
- ease of access to high performance computing
- Understanding regional variability of wind flow, important for wide spread wind deployment for both wind farm and distributed assets
- How does the wind resource change in a changing climate?
- the role of machine learning in all this modelling
- Better characterization of turbulence structure given computing advances newer measurement technology
- Idealized conditions are rare. How to translate realistic set of conditions to design.
- Computationally efficient full physics based models.
- new engineering models for turbulence, derived from our understand of
- Understanding the impact of nonstationary and non-equilibrium processes.
- What is the frequency of extreme events, and how will that change in the future?
- (Extreme events to include strong winds as well as wind lulls, and coupled extremes like solar outages due to wildfire smoke
- [...]teraction of wind and wave climate (on relevant scales)
- Power performance and turbine reliability related to complex flow - especially for smaller turbines or areas outside of more "standard" siting specifications
- Better modeling and characterization of wind resource close to the earth surface (less than 50m)
- Better understanding and appreciation of how mesoscale affects microscale
- Flow in complex terrain
- Improved obstacle modeling, leading to improved long term performance production as local conditions change

Consensus Re. Atmospheric Actions

Jakob Mann, Co-Lead

Paula Doubrawa, Scribe

Needs for Continued Wind Energy Development

1. Atmospheric Observations
   - Development of measurement systems
   - Long-term observational systems
   - Field campaigns to define specifics of cross-scale interactions
2. Predictive Capability Across Scales
   - Predict at all spatial/temporal scales
   - Predict in all conditions (complex and offshore)
3. Integration and Adoption
   - Communication
   - Workforce Development