Simulating atmosphere flow for wind energy applications with WRF

J. K. Lundquist[1], J. D. Mirocha[1], F. K. Chow[2], K. A. Lundquist[1,2] , B. Kosovic[1], S. Chin[1]

jkl@llnl.gov

[1]Lawrence Livermore National Laboratory

[2]University of California at Berkeley

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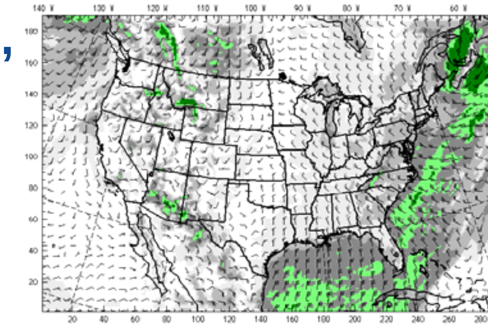
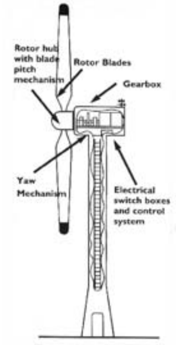


9th WRF User's Workshop

Boulder, Colorado



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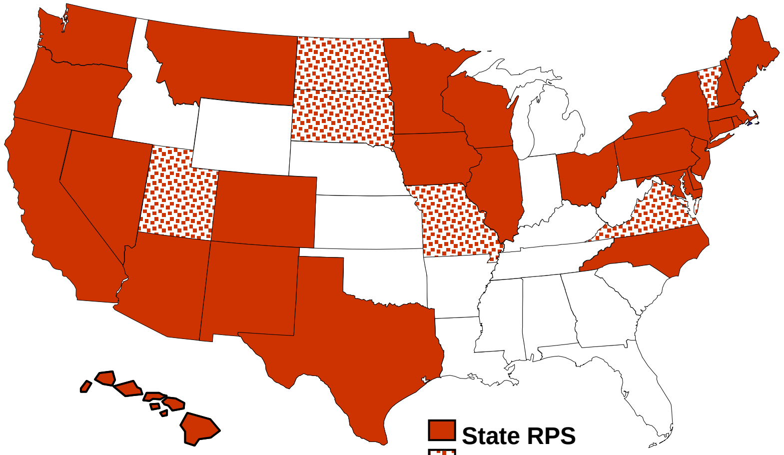
As renewable and carbon-neutral energy sources garner more attention, wind energy industry continues exponential growth

- Wind energy provided over 20% of Danish electrical power in 2007
- Spain, Portugal, Ireland, Germany also have significant wind penetration
- US market wind capacity expanded by approximately 45% or 5200MW in 2007 and is expected to continue expansion due in part to renewable portfolio standards
- Wind is attractive environmentally:
  - Minimal emissions
  - No hazardous waste
  - No depletion of natural resources
  - No environmental damage through resource extraction and transportation
  - No water requirements

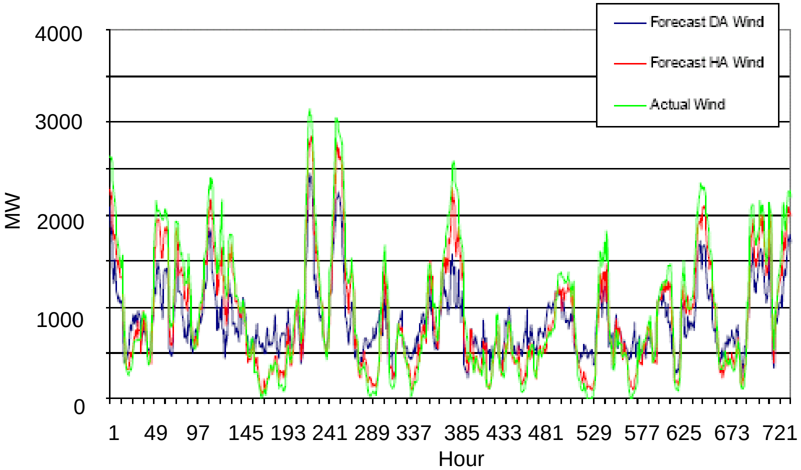


DSIRE: www.dsireusa.org May 2008

Improved atmospheric modeling for wind forecasting benefits wind park siting, wind turbine design, and wind park operations

- Many US wind parks are yielding up to 20% less energy than predicted: more accurate predictions would reduce investment risk
- Many turbines designed for 20- to 25-year lifetime are wearing out in 4–5 years due to unanticipated shear and turbulent stresses
- Accurate and timely forecasts of power availability enable optimal bids on wind park power production. In NY, e.g.,
  - Underproduction penalties are 150% of spot price
  - Overgenerated power is accepted without payment

Premature fatigue of a turbine's main shaft bearing, courtesy S. Schreck, NREL



Thirty days of forecasts for day-ahead (DA) and hour-ahead (HA) wind, compared with actual wind, for January 2001, NY state, from GE Energy Consulting report to NY SERDA

Continued expansion relies on the resolution of technical challenges, many of which are meteorological in nature

http://www.nrel.gov/wrc_workshop/main.cfm

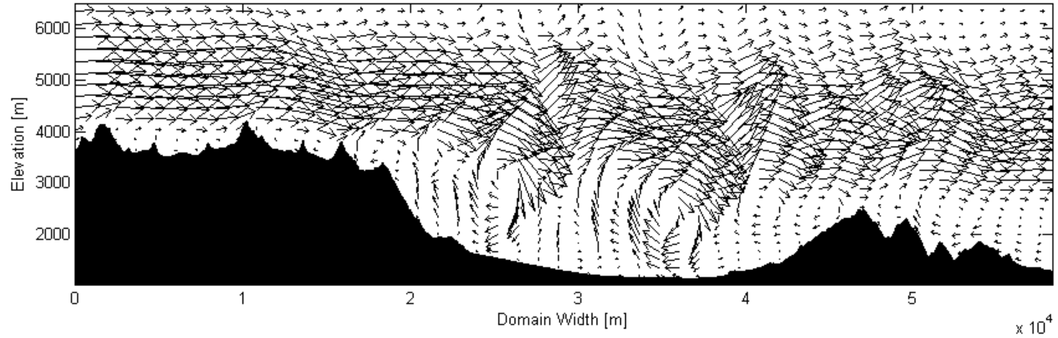
- Improved knowledge of and ability to forecast both the mean and turbulent structure of the lowest 200 m of the atmosphere
- Validation of new theories and models, particularly in complex flows:
  - low-level jets,
  - stable boundary layers,
  - in complex terrain
- Development of wind forecasting technology
  - data assimilation with rapid update cycles,
  - **integration of models of complementary scales**,
  - quantification of forecast uncertainty
- Observations, including development of new platforms and utilization of private data sources, to develop hypotheses and test new parameterizations

Our approach for innovations in atmospheric modeling focuses on turbulence modeling and coordinate systems in WRF

WRF THE WEATHER RESEARCH & FORECASTING MODEL **Community atmospheric modeling system:**

state-of-the-art numerics, multiple physics options, multiple 2-way nests, broad user community

- **Enabling large eddy simulations with the Weather Research and Forecasting model via improved subfilter-scale turbulence models** (J. Mirocha, 10.1, Thursday afternoon at 3:30)
- **Imposing land-surface fluxes at an immersed boundary for improved simulations of atmospheric flow over complex terrain** (K. A. Lundquist)



- An ongoing component of this study, commencing this fall, will address the integration of mesoscale modeling capabilities with the improved LES capabilities of WRF
- **Datasets for validation of these modeling capabilities are limited**

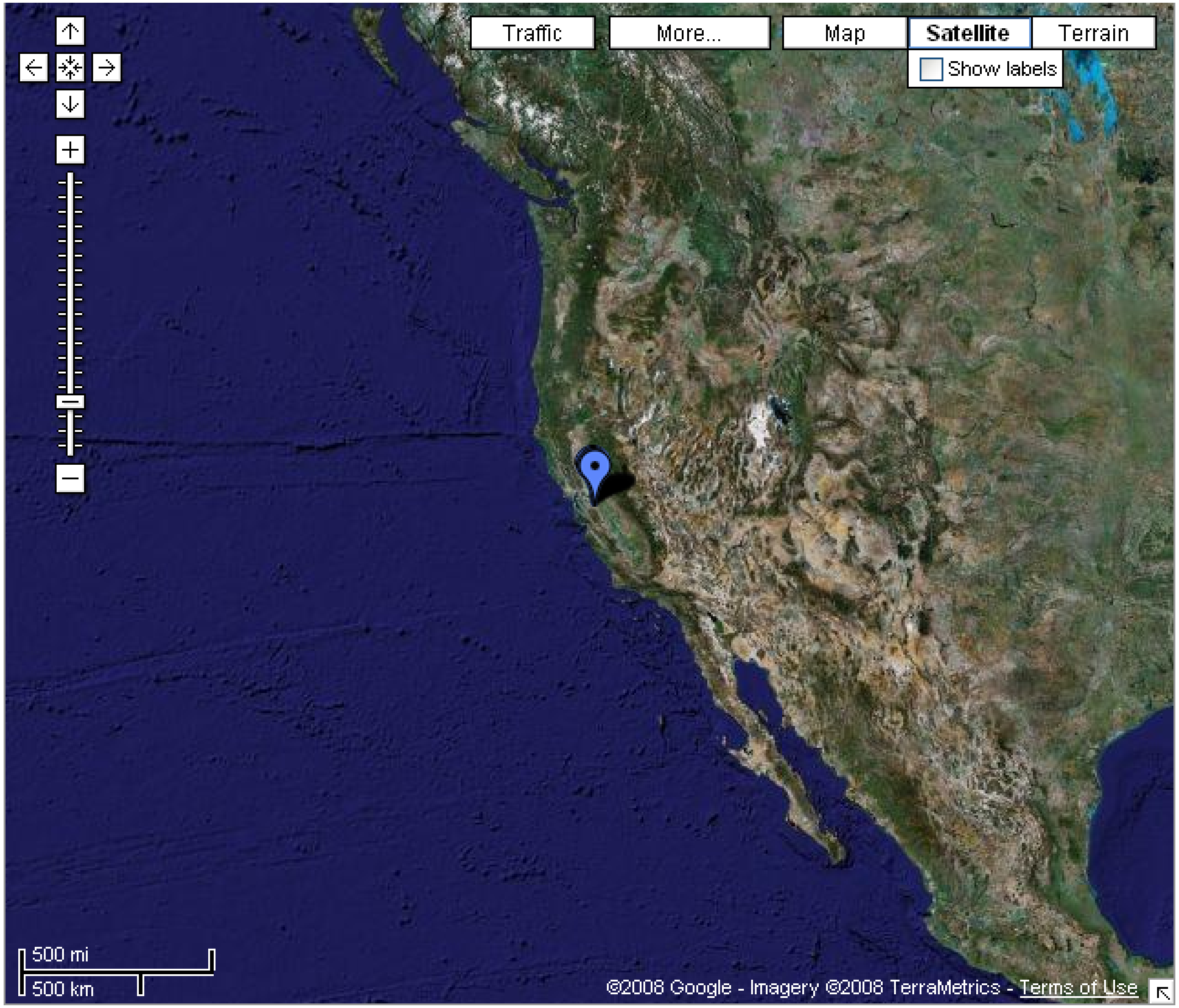
Opportunities for validating wind energy modeling in complex terrain are rare

- Askervein Hill (Scotland, isolated hill, 1982 - 1983)
- Wind tunnel studies
  - CSIRO wind tunnel: Ayotte and Hughes (*BLM,* 2004) evaluate flow over canopies and complex terrain
  - UC Davis Atmospheric Boundary Layer Wind Tunnel Graduate Research Facility (ABLWT): Strataridakis, White, and Greis (AIAA-99-0054) quantify useful turbulence measurements for siting in complex terrain
- Privately-collected datasets, usually involving a wind park operator and/or forecasting company
  - Larson et al., 2004 used an Oregon/Washington state private dataset
  - California Energy Commission / Electric Power Research Institute, Inc. / AWSTrueWind, 2006, used private observations from California's Altamont Pass
- An "honest broker" could collect, for research purposes, the many observations that are currently kept private

Askervein Hill (Taylor and Teunissen, *BLM* 1987)

Photo of Altamont Pass by Steve Deutsch, 2003

We utilize a dataset from the Altamont Pass wind farm in the San Francisco Bay Area of California, approximately 70 km inland from the Pacific Ocean



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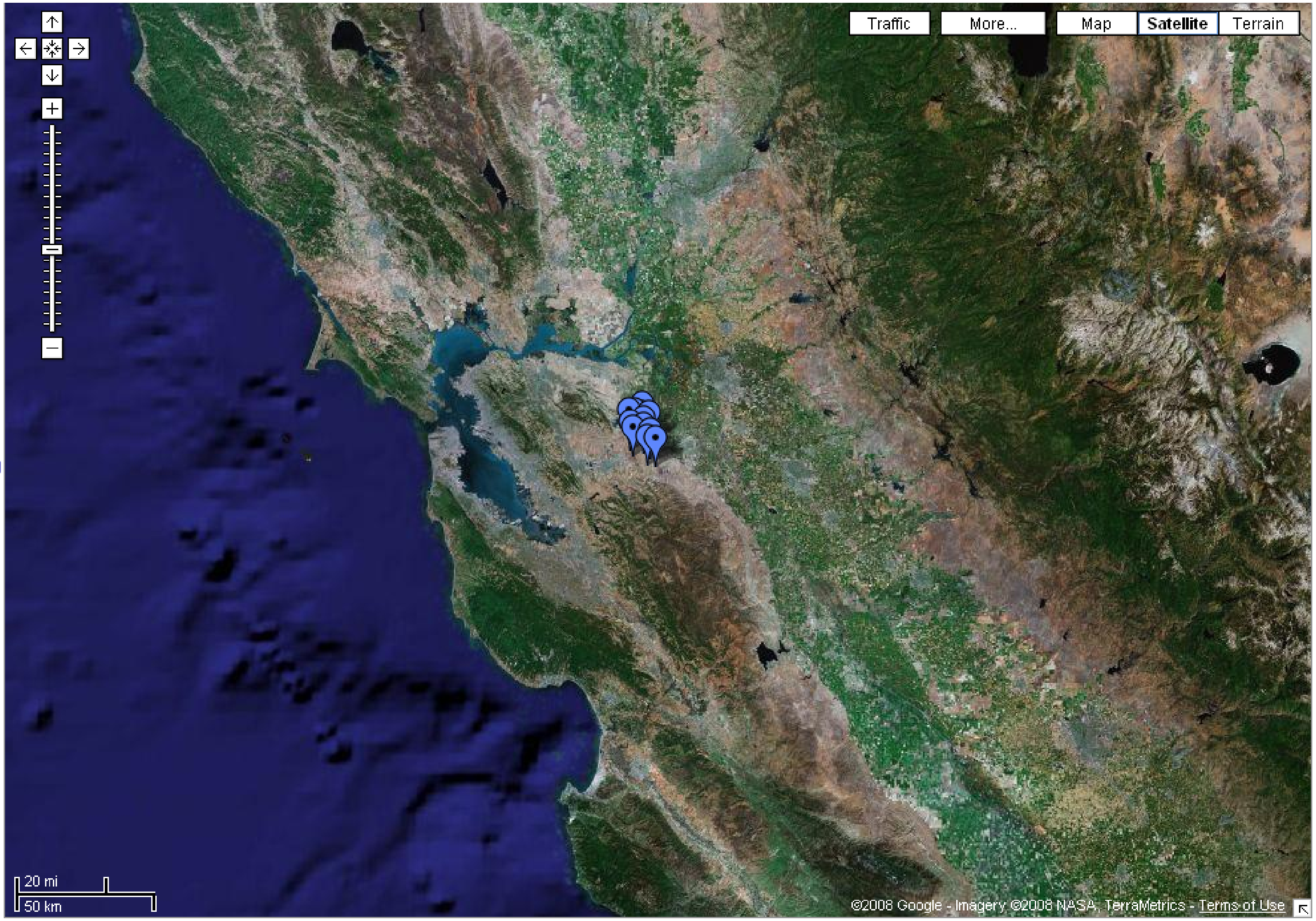

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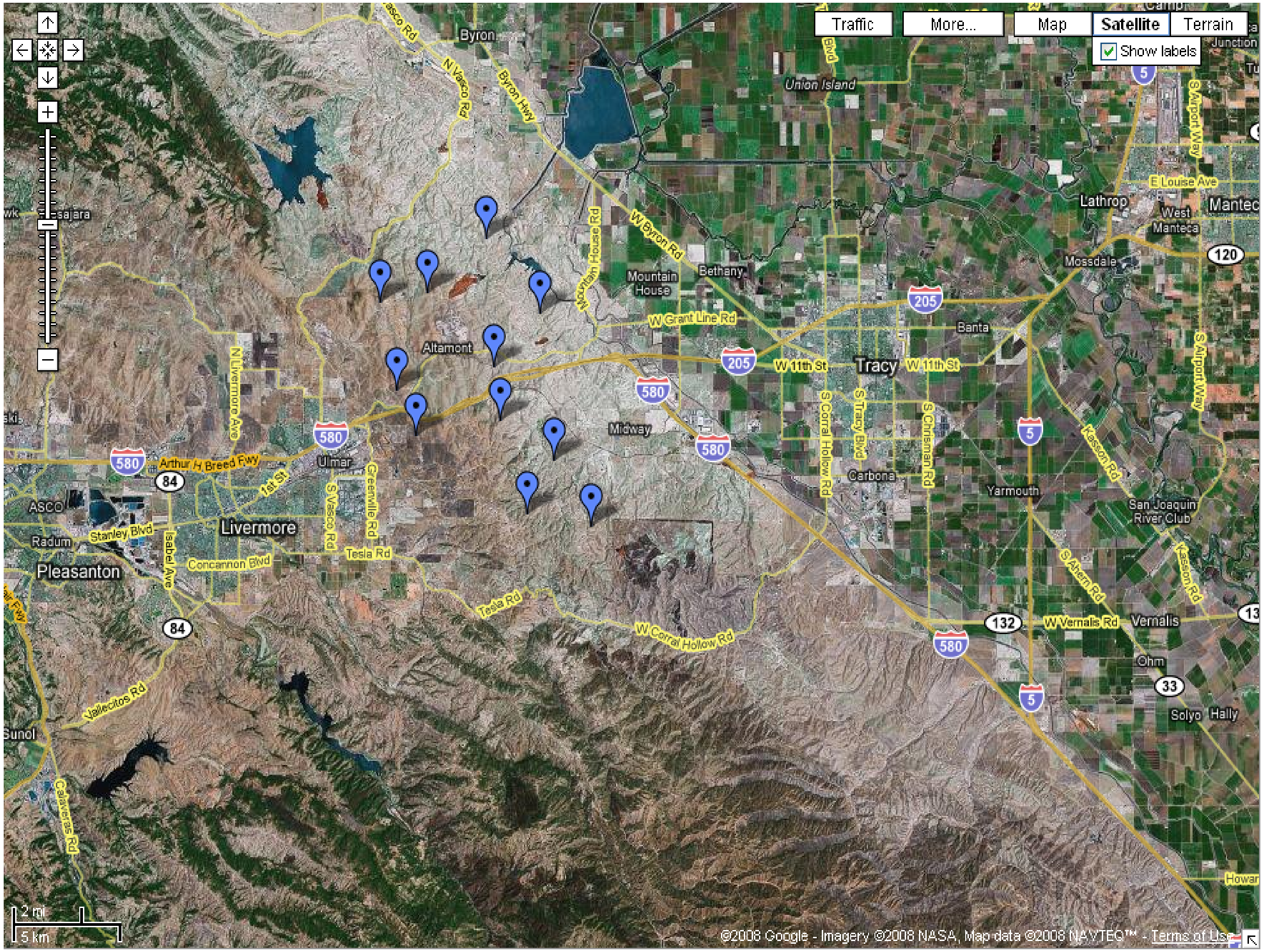
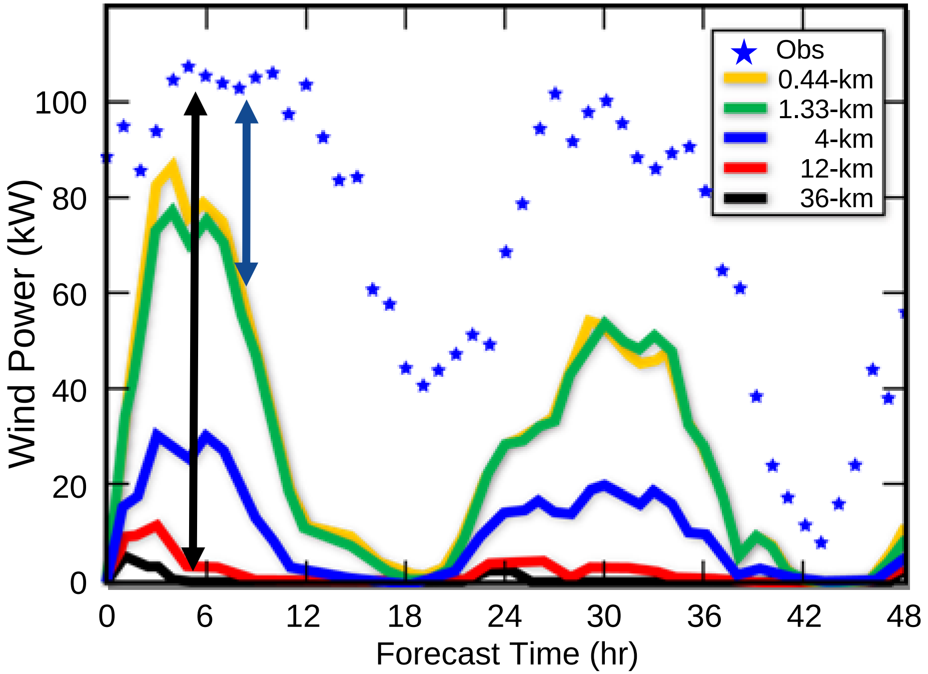


This dataset, compared with COAMPS simulations(2006), has indicated that using higher resolution “improves” mesoscale simulations

- Both weather model resolution and topographical resolution enable reduction of forecasting errors
- Reduced forecast errors enable wind parks to stay in business and promote more renewable energy into the nation’s power grids

Black / red lines	Current (2006) forecast results using 12- to 36-km grid cells
Blue line	Nominal resolution needed
Green / yellow lines	Improved forecasting results using 1.33-km to 0.4-km grid cells



COAMPS simulations by Steve Chin, funded by PIER, California Energy Commission Report **CEC-500-2006-089**

http://www.energy.ca.gov/pier/final_project_reports/CEC-500-2006-089.html

With WRF we have investigated role of terrain and role of vertical resolution, in preparation for nesting LES simulations within mesoscale simulations

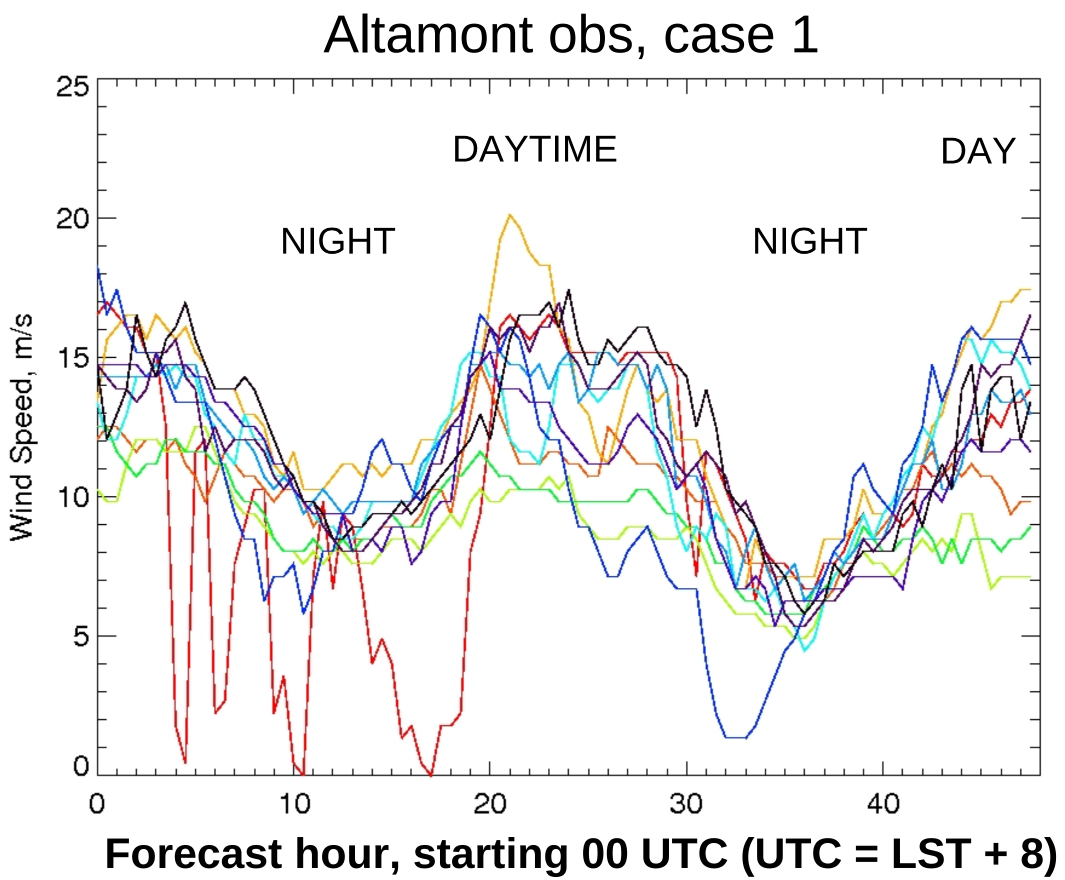
- 48 hrs in July 2004, strong southwesterly flow
- Varied terrain input datasets: →→
- 2-way nested simulations
- MYJ PBL with Monin-Obukhov surface layer
- Noah land-surface model, no urban canopy model
- No microphysics, no cumulus
- RRTM long-wave radiation, Dudhia shortwave.
- 53 vertical levels, with 5 points in the lowest 100m (nominally 20m resolution in the lowest 100m)
- Simulations at ~ 20m, +- 1m, are compared with observations at 18m
- Forced with NCEP/NCAR Reanalysis dataset

WRF Δx, Δy	Terrain dataset
40km	10min
13.3 km	2 min
4.4 km	2 min
1.47 km	30 sec
490 m	30 sec

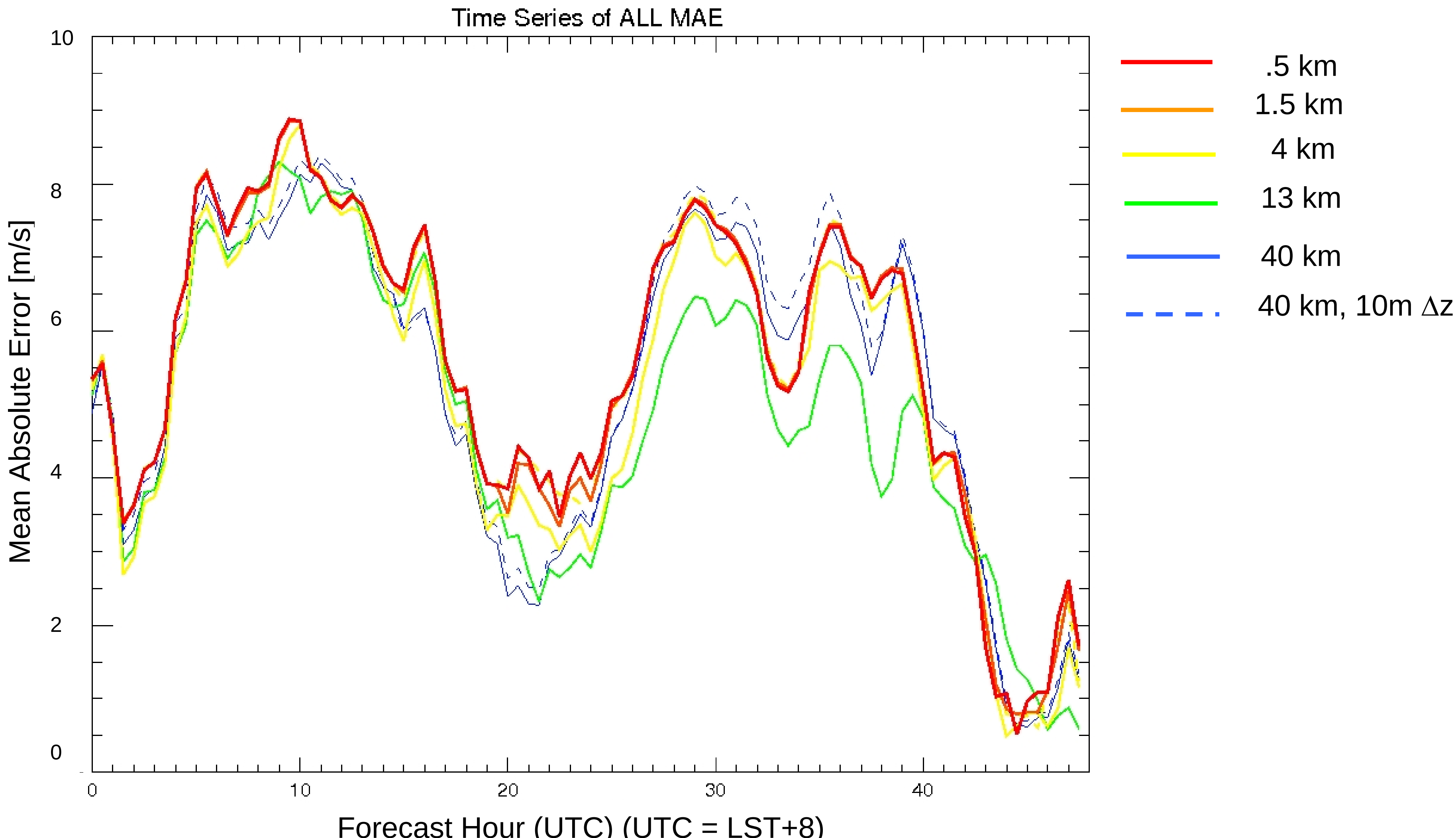
Observations indicated strong diurnal cycle in wind speed, with increases in the late afternoon and wind speed minima in the early morning hours

- Wind direction showed no diurnal cycle, strongly SW for the entire time period
- Indicates a strong temperature gradient between the San Joaquin Valley and the Pacific Ocean, generating a strong sea breeze

Each colored line represents a different observation site



Mean Absolute Error (MAE) indicates that “best” WRF forecast is provided by 13.3km horizontal resolution simulation



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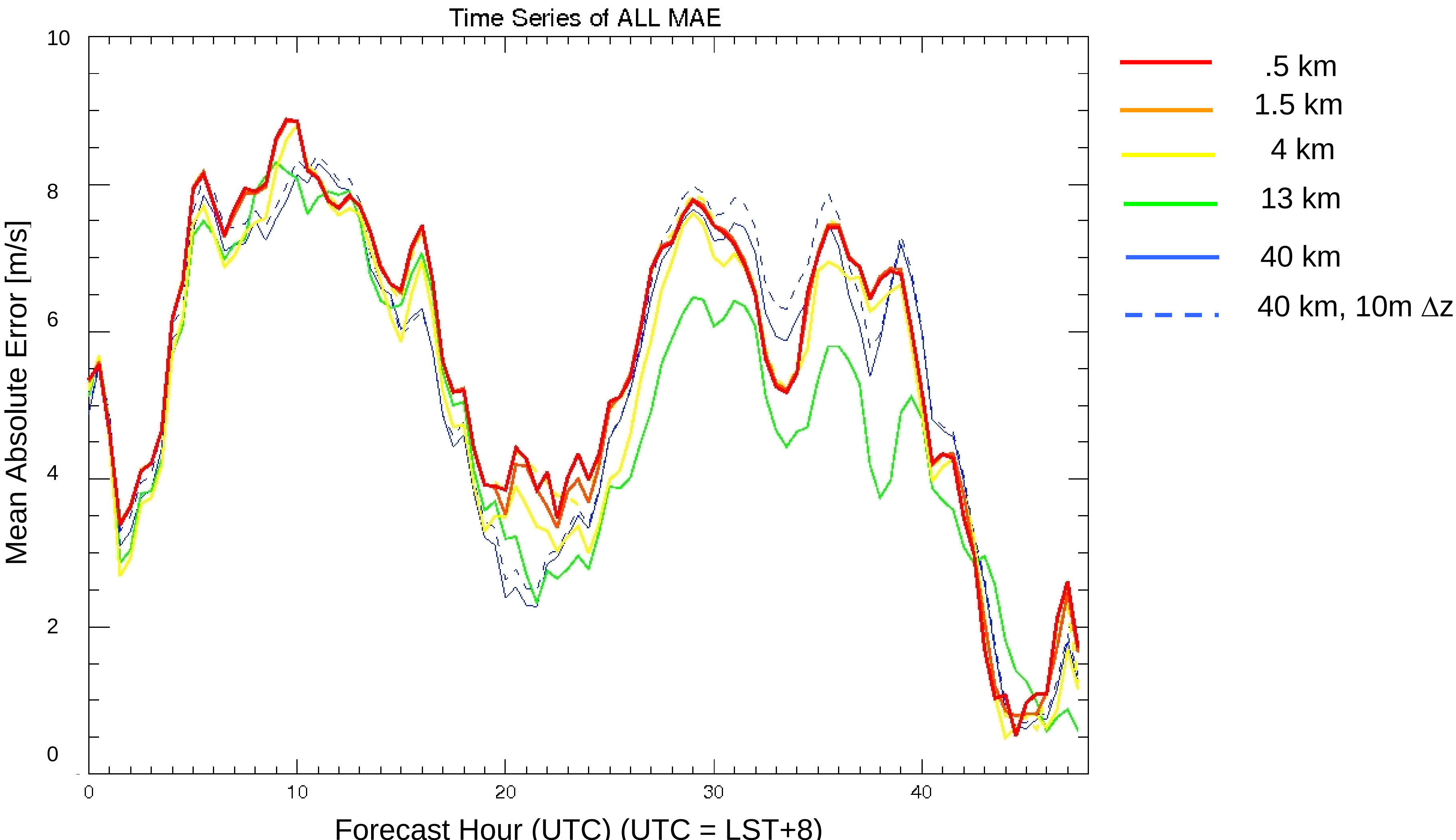
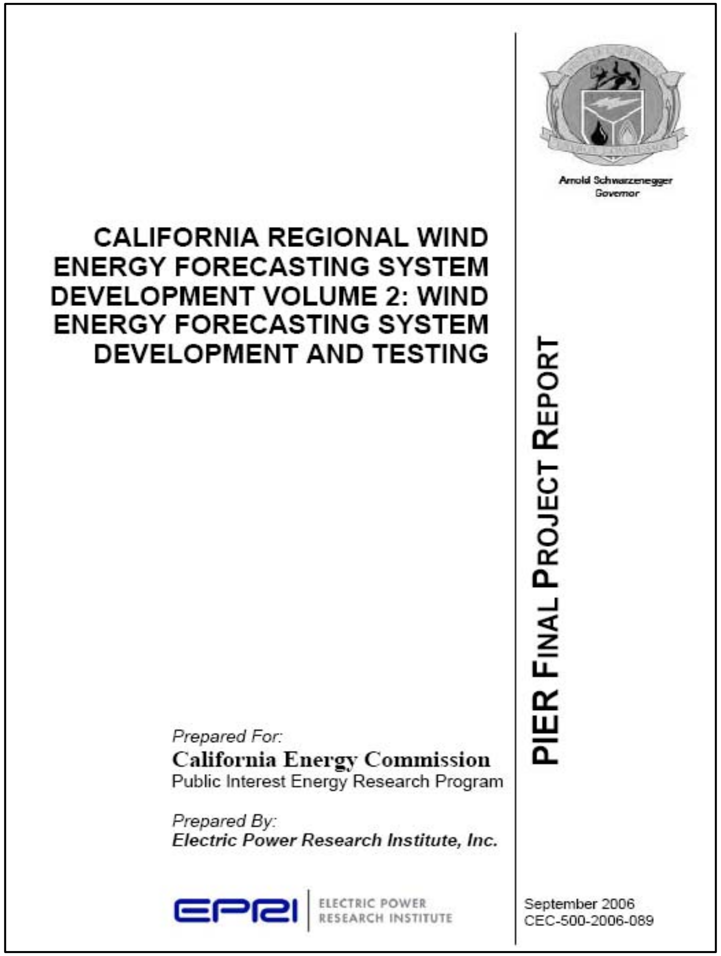


Other investigations also indicate site- and time-specific model performance for wind energy forecasting

http://www.energy.ca.gov/pier/final_project_reports/CEC-500-2006-089.html

- Compares multiple models (WRF, COAMPS, MASS-6) for Altamont and other wind-producing regions in CA
- Simulations designed and executed by AWS TrueWind, Inc.
- 40 km WRF performed well in Altamont
- Errors also increased for resolutions higher than 10km


Arnold Schwarzenegger
Governor

CALIFORNIA REGIONAL WIND ENERGY FORECASTING SYSTEM DEVELOPMENT VOLUME 2: WIND ENERGY FORECASTING SYSTEM DEVELOPMENT AND TESTING

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Electric Power Research Institute, Inc.

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

September 2006
CEC-500-2006-089

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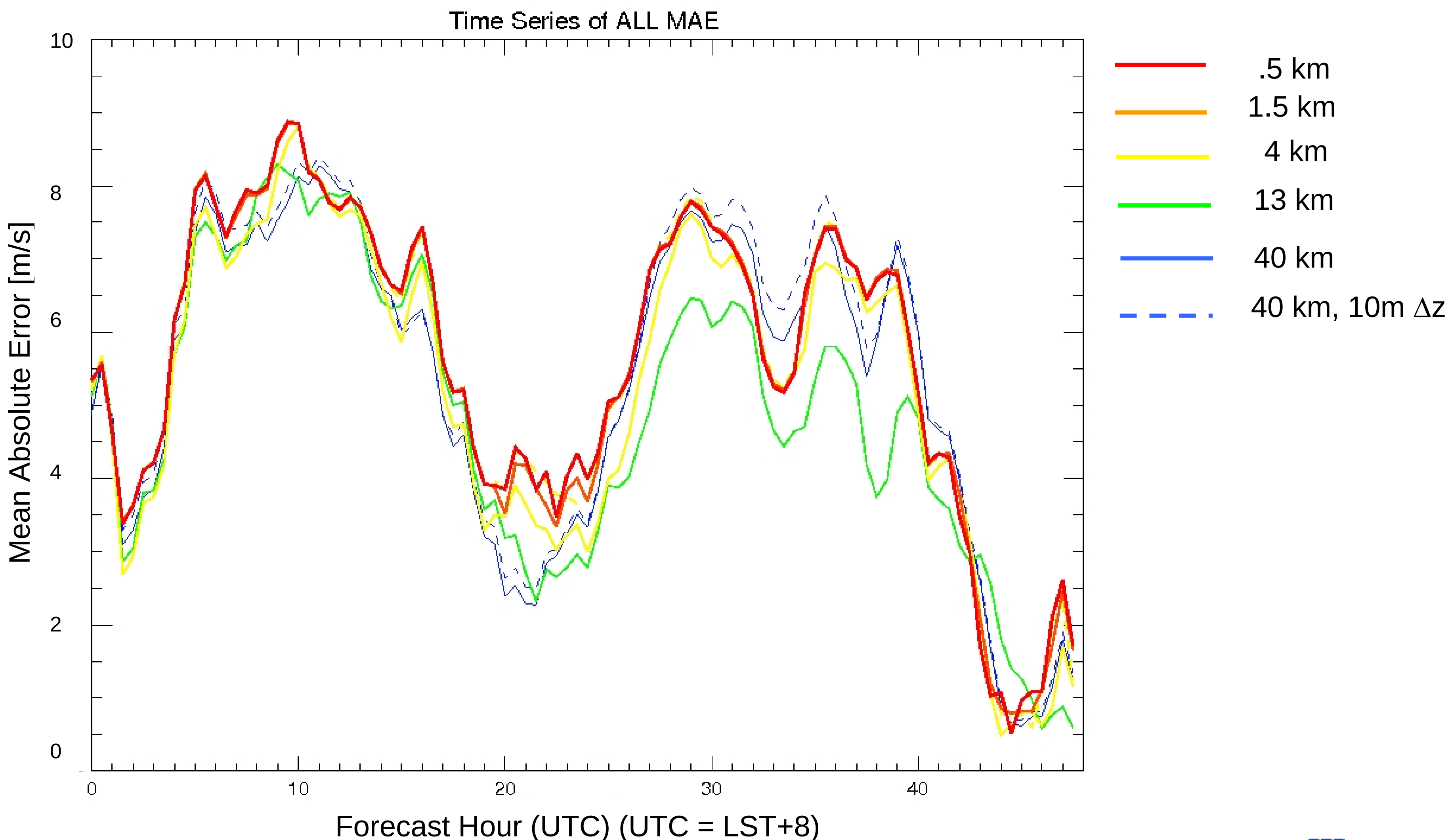

This work is a component of an ongoing project, but some conclusions are already apparent

- The paucity of datasets for validation of new modeling parameterizations is a serious roadblock for progress in wind resource characterization
- Data residing in numerous private datasets could propel the state-of-the-science forward if opened to the research community
- Simply increasing terrain resolution, vertical resolution, and/or computational resolution for mesoscale simulations is not sufficient for improving forecasts
- When nesting LES within mesoscale models, we will consider using a “coarser” mesoscale domain (4km) for providing boundary conditions to the LES

Next Steps

- Evaluate other synoptic situations and other seasons
- Nest LLNL’s WRF-LES within the mesoscale simulations and evaluate forecast skill
- Utilize USGS 30meter terrain database for LES simulations

Acknowledgements

- LLNL Student Employee Graduate Research Fellowship
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- This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 (after Oct. 1, 2007)

- Questions? Contact me at **lundquist1@llnl.gov**

Questions?

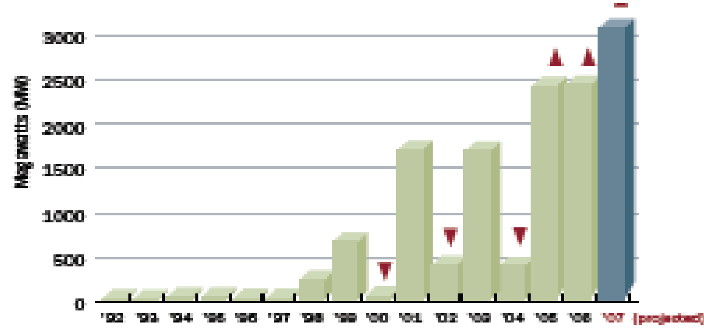
Julie K. Lundquist
jkl@llnl.gov
925-422-1805

Backup slides

Wind energy will become a larger component of energy portfolios

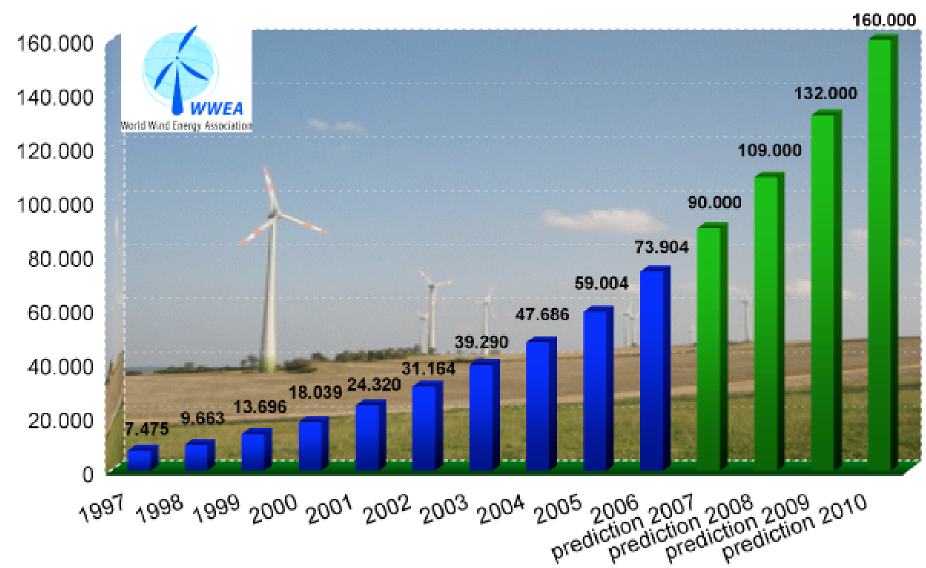
- Renewables are seen as a means for reducing impacts of global climate change
  - 20+ US states have implemented renewable portfolio standards (RPS)
  - No federal RPS yet
  - Most developed nations are attempting to comply with the Kyoto Protocol and reducing CO2 emissions via increased dependence on renewables
  - “Green tags” or renewable energy credits enhance wind’s attractiveness to investors
- Numerous untapped sources of wind exist both in the US and around the world
  - Texas leads the US with ~ 4000 MW installed and 1300 MW under construction; estimated national resources total 136100 MW (AWEA)
  - China Meteorological Administration estimates that wind energy reserves in China total as much as 253000 GW

Annual Installed U.S. Wind Energy Capacity On the Rise (’07 projected)



AWEA data

World Wind Energy - Total Installed Capacity (MW) and Prediction 1997-2010



Enhanced reliability is required for substantial integration of wind energy into power grids

- Wind is the **world's fastest growing** electric energy source
- Yet wind power's **intermittency** currently prevents it from supplying baseload electric power, the amount of steady and reliable electric power constantly being produced, typically by power plants, regardless of demand
- The effects of intermittency can be mitigated in many ways:
  - Linking multiple farms into a large "Supergrid" (such as the European Supergrid designed by Airtricity, Inc.) that spans weather systems
  - Connecting wind with storage capacity (in Sweden, hydropower, also proposed hydrogen/electric cars)
  - Linking wind farms with dispatchable generators
- **Assessing and implementing these strategies requires detailed and accurate forecasts of operating capabilities** as well as analysis of transmission power flows

The 100 GW Foundation project of Airtricity's proposed European Supergrid, which connects large offshore wind banks around Europe with new efficient HVDC transmission lines

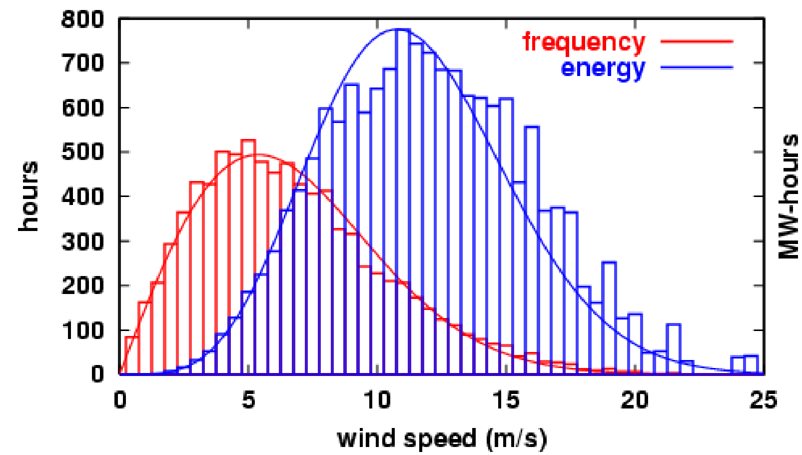
Accurate forecasts of wind power require accurate wind forecasts for windows from a few hours to several days

- More power is generated by higher windspeeds, so much of the energy comes in short bursts that must be exploited

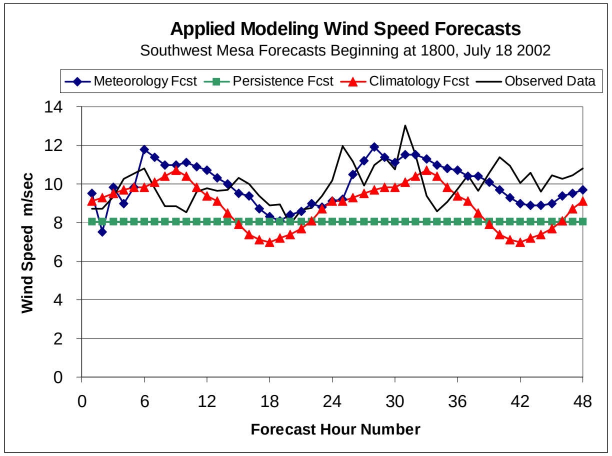
- Short-term, 48-72 hour forecasts enable power system management or energy trading:
  - Optimized power plant scheduling and power balancing
  - Determining reserve power to balance energy
  - Grid operation and congestion management

- Medium-range (up to 5-7 days ahead) forecasts enable planning for maintenance of wind farms, linked conventional power plants, or transmission lines.

  - Optimal maintenance scheduling is particularly important for offshore wind farms with significant maintenance costs



Distribution of wind speed (red) and energy generated (blue) for all of 2002 at the Lee Ranch facility in Colorado.



Sample forecast and validation from AMI Environmental

Predictions of wind characteristics and wind resources at high spatial resolution would also benefit wind park siting and wind turbine design

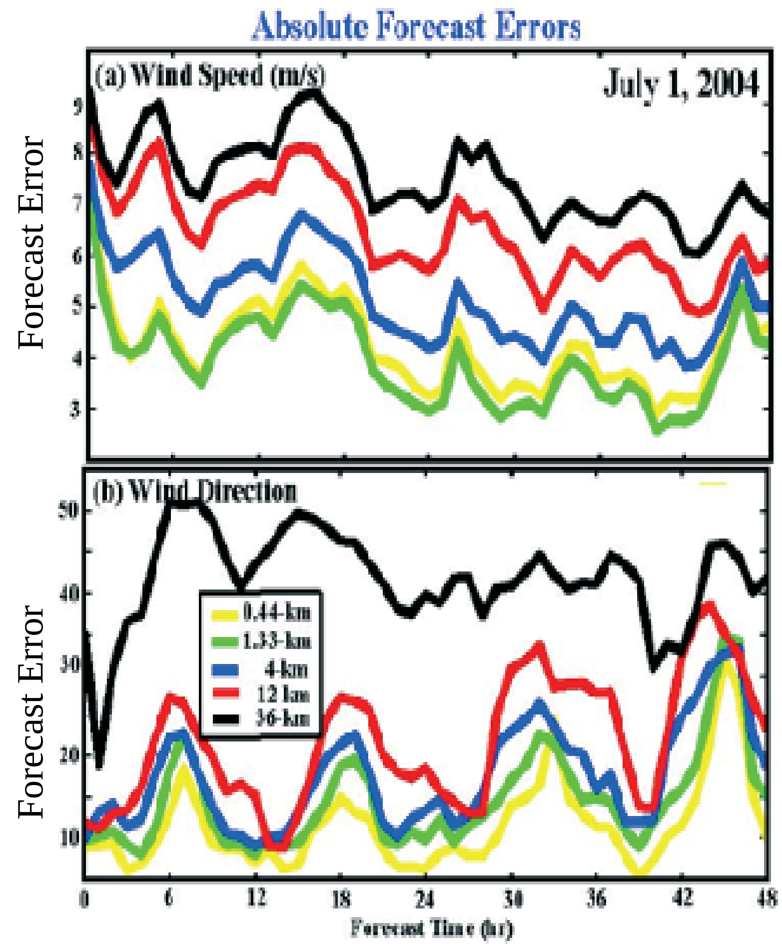
- Many wind parks are yielding up to 20% less energy than predictions for initial financing indicated
- Predictions which consider high-resolution terrain effects and varying atmospheric stability would reduce investment risk
- Many turbines designed for 20-25 year lifetime are wearing out in 4-5 years due to larger wind shears and turbulent stresses than anticipated in the turbine design
- Accurate estimates of shear and turbulent stresses, particularly for next-generation 150m hub turbines, may reduce gearbox burnout

LLNL research on simulating wind energy for Altamont Pass show forecast error is reduced with higher resolution simulations

Errors in forecasts, compared to observations, decrease as finer and finer grid cells are used:

- 36 km
- 12 km
- 4 km
- 1.33 km
- 0.44 km

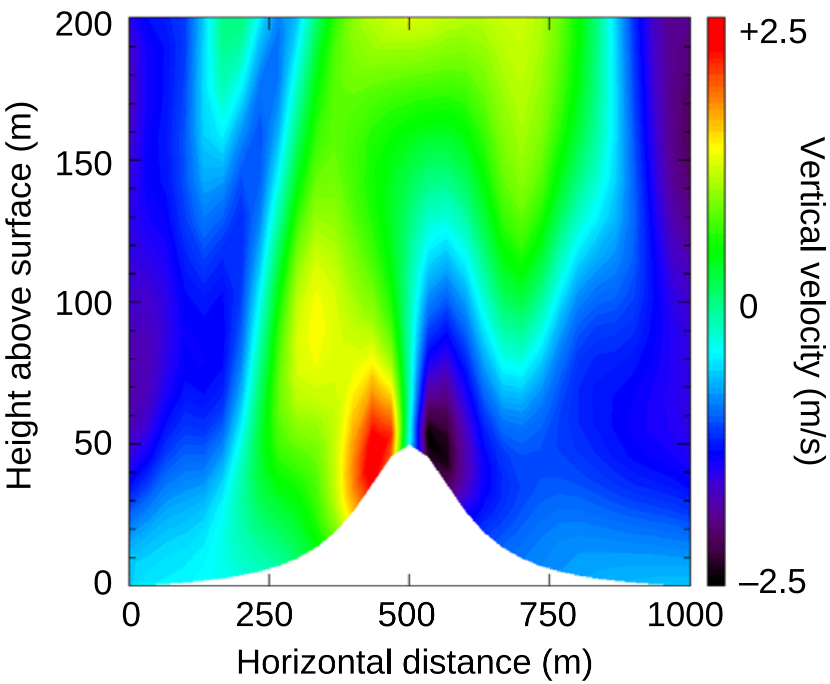
(Topographic data used was 1 km resolution)



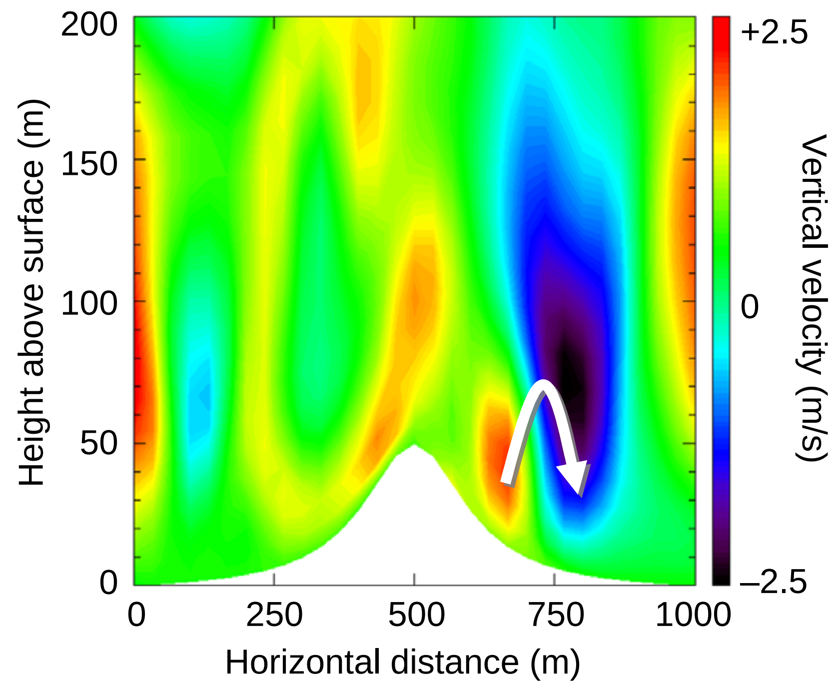
Research funded by PIER, results courtesy S. Chin, LLNL

Photo of Altamont Pass by Steve Deutsch, 2003

LLNL's new approach captures the relevant physics for siting wind turbines behind hills, with reduced computational expense



"Out of the box" WRF TKE closure fails to predict recirculations



LLNL's Nonlinear Backscatter with Anisotropy WRF closure correctly predicts recirculations at ¼ the computational expense