

# **New Developments in the Application of Weather Information in Electric Grid Analysis for Power System Planning**

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# Overview

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- The purpose of this presentation is to show the benefits of having weather information and other environmental inputs (such as earthquake risks) become a standard part of power flow analysis and, more broadly, electric grid planning
  - The results also apply to related applications such as optimal power flow (OPF), contingency analysis, security-constrained OPF
- This is ongoing research, with several large projects just launching to further develop these capabilities.
- Results presented here have been implemented in PowerWorld Simulator and can now be used in power system planning

# The Power Flow and Weather

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- Human activity depends on the weather, and this has always been reflected in the electric load
- Over the last several decades this dependence has grown substantially with the increase in wind and solar generation
- Major power system input parameters are now heavily weather dependent (e.g., wind and solar generator Max MW)
- Weather information has been used in electric grid planning and operations going back to the initial grids in the 1880's
- The last four years have seen rapid developments in directly using weather in the power flow and other planning applications

# Planning, Weather and Other Resiliency Events

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- As defined by NERC, planning assessment for large-scale grids is, “Documented evaluation of future transmission system performance and corrective action plans to remedy identified deficiencies”
  - Planning is forward looking, leveraging historical information
- Planning can consider timeframes from near real-time to decades
- Weather and other resiliency considerations can include
  - Inputs to set weather dependent power flow values such as wind, solar (irradiation), temperature for transmission line and transfer limits
  - Extreme weather including hurricanes, ice storms, derechos, tornados
  - Other events such as earthquakes, wildfires, geomagnetic disturbances (GMDs), volcanic events, eclipses
  - This are collectively referred to here as Environmental Inputs (ENIs)

# Using Weather and Related Data in the Power Flow

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- To use weather data and other ENIs in the power flow requires
  - The availability of geographic information mapping buses to substations, and then geocoordinates for the substations
    - This is now mostly available for North American grids; some power flow software has long stored it mostly with the substation records (sometimes the buses)
    - Large-scale synthetic grids with geographic information are also available
  - Convenient access to available ENIs (e.g., weather information) over the footprint of interest
    - For planning often the footprint is large, beyond a single utility
  - The availability of models that represent the impact of weather and other ENIs on electric grid components

# Availability of Weather Information

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- We started this effort four years back by using historical weather station measurements (mostly identified by their ICAOs [International Civil Aviation Organization], e.g. KLIT, KCLL)
  - We had lots of data, but much of it had missing values; we also only had surface wind values and no direct solar measurements
  - Such measurements at specific locations can still be very useful (e.g., at electrical substations)
- There are many other sources of free weather information, with good coverage provided by *Weather DataSet Needs for Planning and Analyzing Modern Power Systems*, Energy Systems Integration Group (ESIG), October 2023
  - [www.esig.energy/wp-content/uploads/2023/10/ESIG-Weather-Datasets-summary-report-2023.pdf](http://www.esig.energy/wp-content/uploads/2023/10/ESIG-Weather-Datasets-summary-report-2023.pdf)

# ESIG Report (10/2023)

- “These widespread changes lead to the increasing weather-dependence of supply and demand, making power system planning dramatically more complex and requiring much more comprehensive weather data for robust system planning.”
- “The work required to achieve a long-term solution to weather data needs is not trivial, but it is manageable and is much less costly than blindly building trillions of dollars of infrastructure without the basic tools to cost effectively optimize it and assess its reliability.”
- While weather was beginning to be integrated into planning software about a year before the ESIG report appeared, very rapid progress has been made in the last year

TABLE 2  
Summary of Current Power System Modeling Weather Input Data Sources

	Spatial Resolution	Temporal Resolution	Length	Continuously Extended	Correct Variables/ Levels	Coincident and Coherent	Validated/Uncertainty Quantified for Power System Use	Detailed Documentation	Future-Proofed	Availability/Ease of Access	Curation and Advice	Region Covered
MERRA-2*	-60 km	60 min	1980-present	Yes	Yes/No	Yes	No		Probably		Basic	Global
ERA5*	-30 km	60 min	1940-present	Yes	Yes/No	Yes	Some		Yes		Good	Global
HRRR*	3 km	15 min	2014-present	Yes	Yes/No	Yes/No	No		Unideal		Basic	U.S.
WIND Toolkit*	2 km	5 min	2007-2014	No	Yes/Yes	Yes	Yes		No		Basic	Various
WTK-LED*	2 km/4 km	5 min	3 year/20 year	No	Yes/Yes	Yes	Not yet	Not yet	No	Unknown, dataset not yet available		Various
NSRDB*	4 km/60 km	30 min	1998-present	Yes	Yes/No	Solar only	Yes		Yes		Basic	Most of globe
CERRA*	11 km/5.5 km	60 min	1980-present		No/Yes	No solar	Yes		Possibly		Basic	Europe
CONUS404*	4 km	60 min/15 min (precip)	1980-2020	No	Unknown/Probably	Yes	Not the intended use					Continental U.S.
BARRA <sup>1</sup>	12 km/1.5 km	60 min	1990-2019	No	Yes/Probably	Yes				Fee-based		Australia/New Zealand
Public Observing Networks <sup>1</sup>	Non-uniform, variable density	1 hr or less	Variable	Yes	Yes/No	Mostly	Varies. Not for power systems	Varies	Usually	Usually easy	Varies	Global
Renewable Energy Project Data <sup>1</sup>	Non-uniform, variable density	Usually minutes	Variable but rarely more than 10 years	Varies	Yes/Usually	Yes	Usually	Varies, but usually poor	Varies	Usually poor	Usually none	Very limited
Proprietary Statistically Derived VRE Shapes <sup>1</sup>	Non-uniform, variable density	Usually hourly	Variable, Rarely reliable long records.	Varies	Usually incomplete	No	Partial	See note	No		None	Very limited

■ Fully Met 
 ■ Close to Being Met 
 ■ Partially Met 
 ■ Met in a Very Limited Way 
 ■ Not Met at All 
 ■ Not Enough Info. for Determination

# Power Planning Weather Data Access

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- With respect to weather, the goal is to make it easy to use a wide variety of weather information in all power system planning timeframes, ranging from near real-time to long duration
- We're working on a variety of ways to make weather information available
- The Power Weather (\*.pww) files use a binary format to store weather information and potentially other environmental inputs for a set of time points and a set of locations (e.g., weather stations); the format is relatively general
  - The timepoints can be either uniformly spaced (e.g., hourly) or individually specified (as is the case with forecasts)
  - The weather stations **do not** need to be on a uniform grid

# Simulator Weather Data Access, cont.

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- One suggestion we've received, and are in the process of implementing, is the ability to directly load power system planning related weather information from GRIB or GRIB2 format files
- GRIB (Gridded Binary or General-Regularly-distributed Information in Binary form) is a very common format for the storage and exchange of historical and forecast weather data
  - It is standardized by the World Meteorological Organization (WMO), with GRIB released in 1994 and GRIB2 initially 2003
  - Both GRIB and GRIB2 are widely used, including for ERA5, US NOAA National Centers of Environmental Prediction (NCEP) forecasts, and the HRRR datasets
- This is being implemented now

# ERA5



- One of the datasets we use is ERA5, which is state-of-the art (fifth generation) reanalysis of global climate and weather since 1940
  - It is available hourly on a 0.25 degree grid (GRIB template 0, equidistant cylindrical)
  - It includes 10m and 100m wind, wind gusts, and solar global horizontal irradiance and direct horizontal irradiance
  - ERA5 comes from European Centre for Medium-Range Weather Forecasts (ECMWF), (ERA = ECMWF Re-Analysis) with more details on ERA5 available at [rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803](https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803); available in GRIB and GRIB2
- The ESIG comment on ERA5 is,
  - “However, while ERA5 is unquestionably the best global reanalysis dataset currently available, it is not a panacea. Average validation statistics are very good, but the horizontal grid spacing of 30 km is insufficient to produce detailed meteorological fields present in complex topography, fields that are crucial to resolve for estimating renewable generation in these areas.”

# Electricgrids.engr.tamu.edu/weather-data/



## Weather Data

This dataset contains historical and forecast weather data for Texas and North America. The historical data starts from 1940 and extends to almost present (5 days from current date). The list of weather values include: temperature, dew point, wind speed, wind direction, wind speed at 100m, cloud cover, global horizontal irradiance, and direct horizontal irradiance for a 0.25 degree latitude and longitude grid across much of North America.

Please contact Thomas Overbye (toverbye@tamu.edu) or Farnaz Saldarian (fsaldarian@tamu.edu) for any questions regarding this data.

### [View Available Weather for Download](#)

### [Weather Data Information and PWW Format Description](#)

## References

If you use these datasets in publications, please cite the following papers, and acknowledge the ERA5 data as described below.

T. J. Overbye, F. Saldarian, W. Linsh, Z. Mao, J. Snodgrass, and J. Yeo, "An Approach for the Direct Inclusion of Weather Information in the Power Flow," *Proc. 56th Hawaii International Conference on System Sciences (HICSS)*, January 2023.

F. Saldarian, M. Stevens, J. Snodgrass, T. J. Overbye, "Detailed Hourly Weather Measurements for Power System Applications," 2024 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, Feb. 2024.

Hersbach, D., Bell, S., Berrisford, P., Biavati, G., Horvath, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Rhin, E., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J.-N. (2023): ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/6.624d182647 (Accessed on 03-01-2024).

Please refer to [How to acknowledge, cite and reference data published on the Climate Data Store](#) for complete details on citing the ERA5 data.

ERA5 Weather Data > PWW

Type People Modified

Name

Texas\_Historical\_1940\_2024

NorthAmerica\_Historical\_1940\_2024

NorthAmerica\_Forecasts

PWW > NorthAmerica\_Historical...

Type People Modified

Name

3-Month Data 1940-2023

NorthAmerica2024\_Q3.pww

NorthAmerica2024\_Q2.pww

NorthAmerica2024\_Q1.pww

NorthAmerica\_2020-2023.zip

NorthAmerica\_2010s.zip

NorthAmerica\_2000s.zip

NorthAmerica\_1990s.zip

NorthAmerica\_1980s.zip

NorthAmerica\_1970s.zip

NorthAmerica\_1960s.zip

NorthAmerica\_1950s.zip

NorthAmerica\_1940s.zip

Only get the 3-month data if your download speed is slow

Data for current year, updated daily

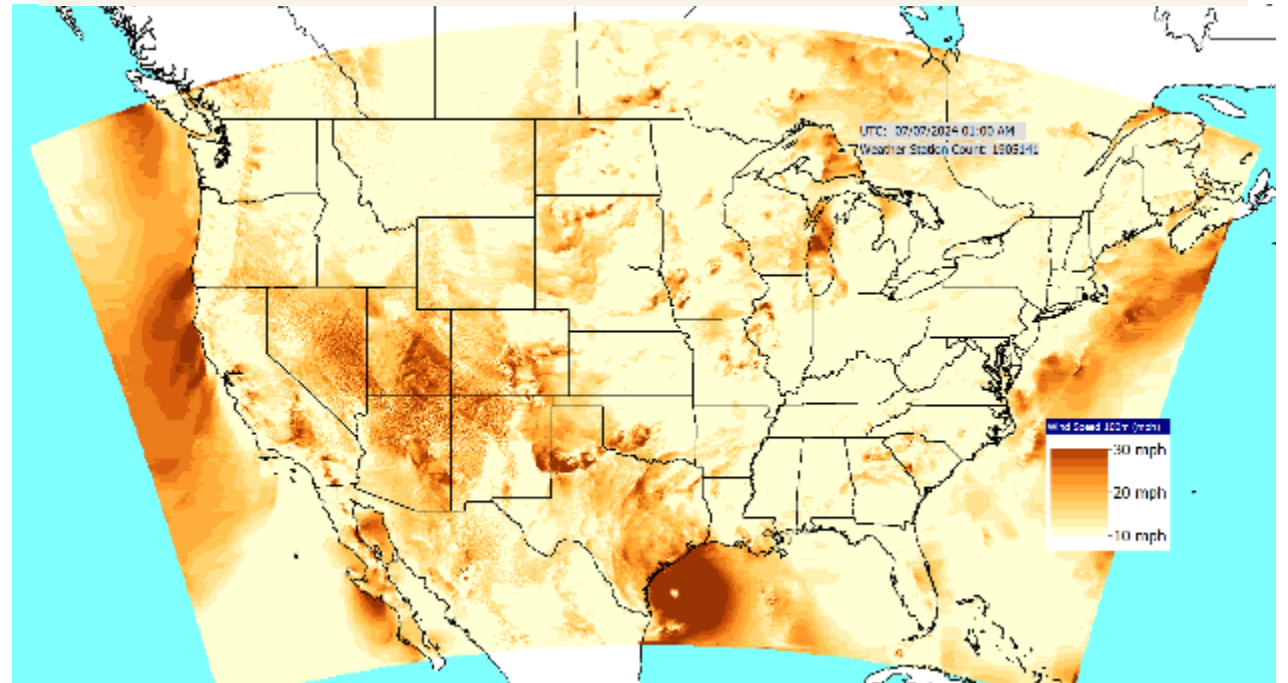
Historical data; that is, a onetime download; getting a decade took me about 4 minutes

# HRRR



- A second dataset is the HRRR (High-Resolution Rapid Refresh), which is provided by the US National Oceanic and Atmospheric Administration (NOAA)
- HRRR is a 3-km resolution, hourly-updated assimilation/modeling system provided by the NOAA National Center for Environmental Prediction (NCEP)
  - Data is provided on a grid with a total of 1.9 million elements

PowerWorld Simulator Contour of HRRR 100m Wind Data (converted from 80m data)



HRRR uses a Lambert Conformal projection (a conic projection)

# Models of Grid Weather Impacts

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- Key focus here isn't weather per se, but modeling the impacts of weather on electric grid components (e.g., generators, lines)
- Certainly a number of models already exist, and undoubtedly more will be created given that weather data is now conveniently available
- The approach used here for handling a growing list of models is to mimic what has been done with power system stability – start small and expand
  - Early (1960) stability codes just had a handful of models, whereas current codes support many hundreds of different model types
- PowerWorld implements this using PFW Models
  - PFW = Power Flow Weather or Power Flow Whatever models

# Example: Customized Wind Power Curve Model



- Customized wind power curve models can also be defined; this only needs to be done once per wind generator

PFW Models Weather Details Apply Time-Varying Weather to PFW Model Weather Interpolation Details

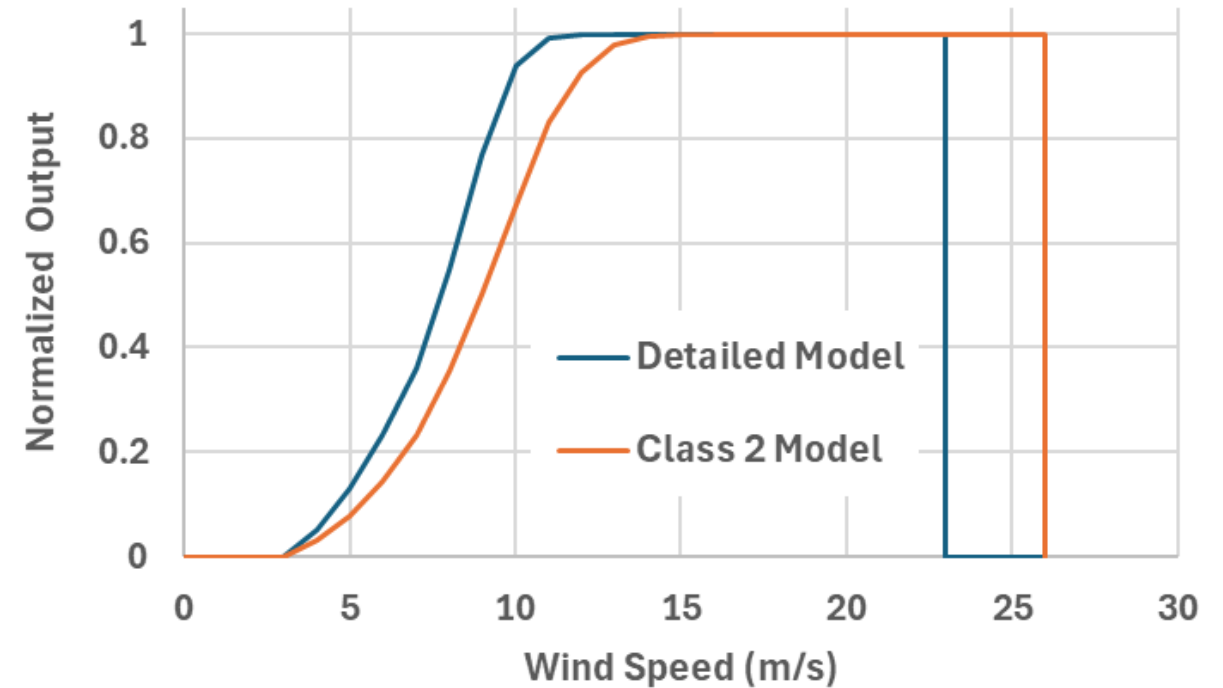
PFW Gen Object

Insert Delete

Type Active - WindGeneral  Active (only one may be active) Set to Defaults

Parameters

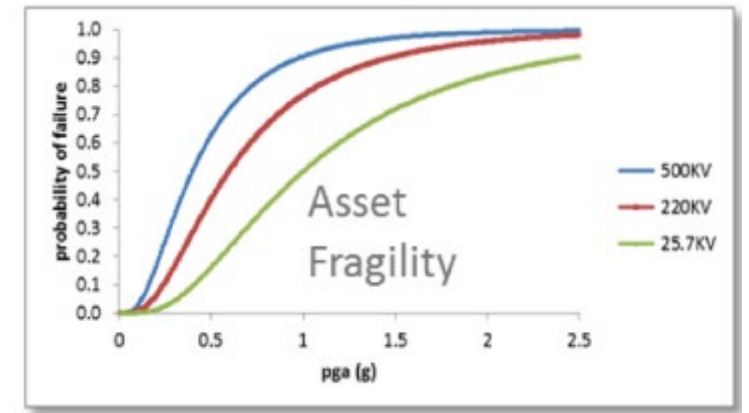
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AllowTurnOff	1	PowerScalar1	0.00062	Speed6	5.0000
AllowTurnOn	1	Speed2	1.0000	PowerScalar6	0.1599
MWMax	217.0000	PowerScalar2	0.00062	Speed7	6.0000
HubHeightScalar	1.5000	Speed3	2.0000	PowerScalar7	0.3111
WindSpeedScalar	1.0500	PowerScalar3	0.00062	Speed8	7.0000
HubHeightM	80.1624	Speed4	3.0000	PowerScalar8	0.4988
CutOut1MS	26.0000	PowerScalar4	0.00062	Speed9	8.0000
CutOut2MS	26.0000	Speed5	4.0000	PowerScalar9	0.7154
				Speed14	1



# Additional PFWs, Including Stochastic Models



- Many different PFW models are possible, and they could certainly be stochastic
- Examples include ambient-adjusted line ratings, dynamic line ratings, thermal generator output variation with temperature, line outage due to wind gusts, asset failure during earthquakes (see figure with pga=Peak Ground Acceleration), incremental impacts of temperature on load, etc.
- Many such models exist in the literature, with others needing to be developed;



# Mapping Weather to the Electric Grid Components

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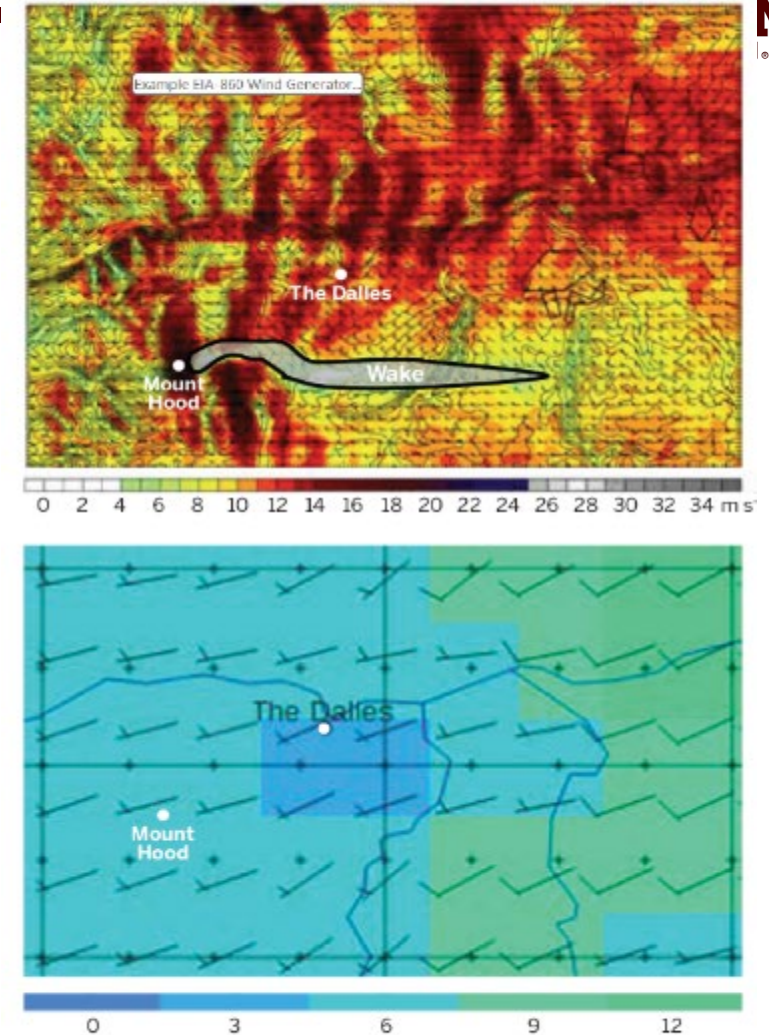
- While the newer weather datasets have lots of points, there is still usually at least some distance between power grid components and the nearest weather measurement, requiring interpolation
- There is no single best algorithm for doing the needed 2D scattered data interpolation, but there are a number of good and fast algorithms (grid-based, closest neighbor, Delaunay Triangulation, Shepherd's)
  - Since the weather values have an associated elevation, if the power grid component's elevation (or profile for a line) is known this could be considered
- If high resolution is needed, then HRRR data can be quite useful

# Dealing with Local Terrain

- In some situations, particularly wind, the local terrain variation can be significant, meaning that by themselves datasets like ERA5 may not be sufficient
  - High resolution datasets like HRRR can certainly help in these situations
- It is important to keep in mind the ultimate goal of using weather in planning; often quite acceptable results can be obtained including compensation terms in the PFW models that only need to be set once

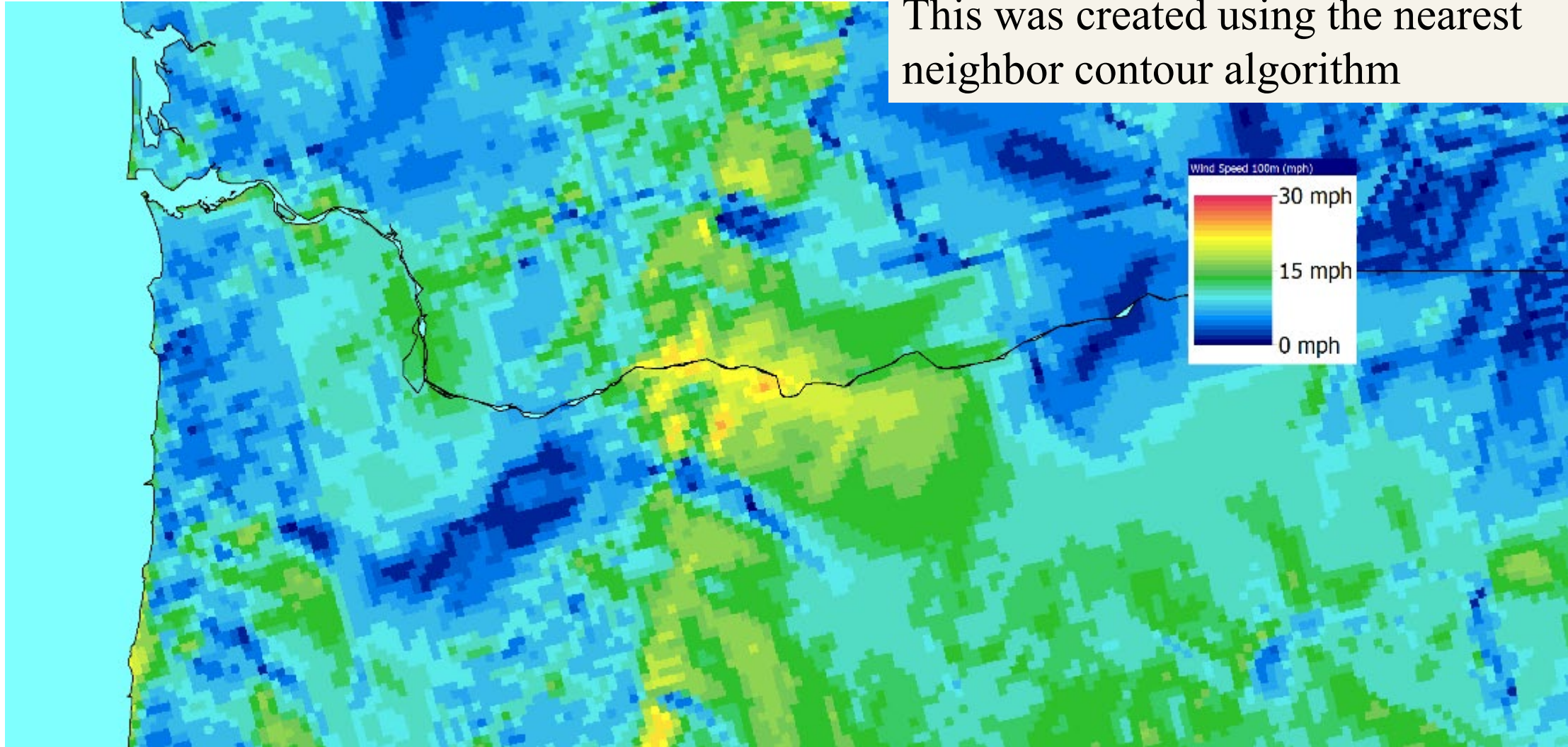
FIGURE 5

Wakes and Waves Observable in a 1 km, But Not 30 km, Simulation of the Columbia Gorge in the U.S. Pacific Northwest



The output from a 1 km Weather Research and Forecasting (WRF) simulation (top) clearly shows mountain wake and wave activity to the east of Mount Hood, whereas the output from the 30 km ERA5 dataset (bottom) for the same hour in April 2010 does not show this activity.

# Simulator HRRR 100m Wind Contour Columbia River



# Some Potential Additional Models

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- With external information a part of the power flow a wide variety of additional power flow model enhancements become possible. Some examples are given below, recognizing that many are already done using external analysis
  - Transmission line limits that depend on temperature, wind and insolation along the right-of-way; working with industry we already have some quite sophisticated models
  - Transformer limits
  - Load models (recognizing that the load depends on many factors, initial models could be linearizations about a specified value)
  - Line resistance (though this would be more complex since it is operating point dependent)
  - Just implemented models to model device susceptibility to harmonics (THDv)

# Future Directions

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- There are many future directions to pursue
  - A number of models that relate weather to electric grid values already exist, but many more certainly need to be developed
  - Integration of weather into tools such as contingency analysis; better tools for dealing with stochastic models
  - Support for more weather types, greater integration of reading primary sources such as GRIB and GRIB2 files
  - Determining the required level of weather details; higher resolution datasets are available; also other potentially severe resiliency events
  - More validation!!
  - Increased automation of the updating process; maybe more footprints
  - Machine learning applications given lots of potential operating points

# Thank You

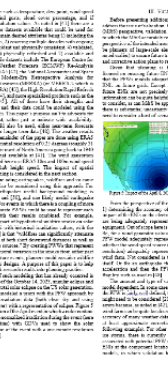
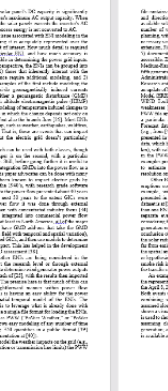
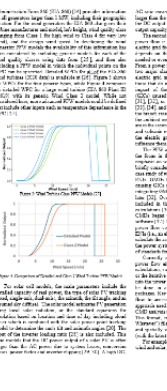
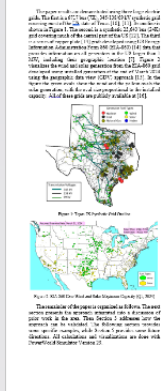


- I have a paper in the 58<sup>th</sup> Hawaii International Conference on System Sciences (HICSS) titled, "Power Flow Modeling of the Impacts of Weather and Other Resiliency Hazards With a Focus on Transmission Planning"; available at [overbye.engr.tamu.edu/publications](http://overbye.engr.tamu.edu/publications)

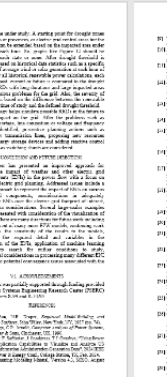
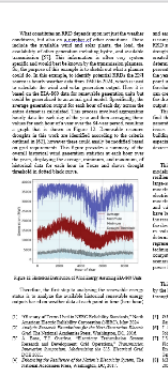
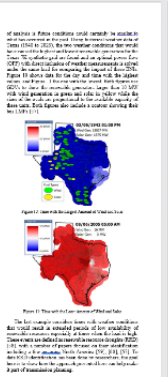
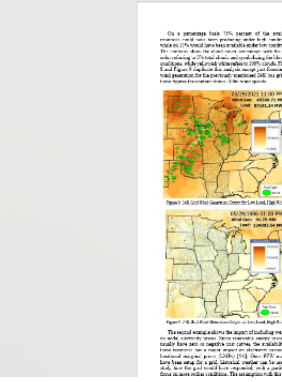
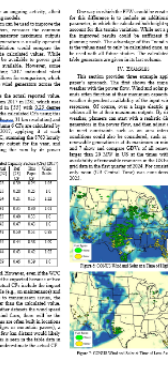
**Power Flow Modeling of the Impacts of Weather and Other Resiliency Hazards With a Focus on Transmission Planning**

Abstract: This paper presents a power flow modeling framework for assessing the impacts of weather and other resiliency hazards on the transmission system. The framework is based on a detailed power flow model that includes the effects of weather and other resiliency hazards on the transmission system. The framework is used to assess the impacts of weather and other resiliency hazards on the transmission system. The framework is used to assess the impacts of weather and other resiliency hazards on the transmission system.

Index Terms: Power flow modeling, weather, resiliency hazards, transmission planning.



Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Power Flow (MW)	100	110	120	130	140	150	160	170	180	190	200



Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Power Flow (MW)	100	110	120	130	140	150	160	170	180	190	200

