# Bias Correcting NOAA's High-Resolution Rapid Refresh (HRRR) Wind Resource Data for Grid Integration Applications

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2024

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# Abstract

- Many weather years of high-quality wind data are widely accepted in the grid integration community to be important for studying wind energy technical potential, energy system operations, and grid resilience.

- NREL makes high-quality wind and solar resource data publicly available. NREL's Grid-Atmosphere workshop (March 2024) identified NREL National Solar Radiation Database as widely used in grid integration modeling, but there is less agreement on commonly used wind datasets. One important factor identified by ESIG's 2023 report "Weather Dataset Needs for Planning and Analyzing Modern Power Systems" for gold standard wind data is regular updates.

- To address the need for regular updates, NREL's team can now process all currently available and regularly updated High-Resolution Rapid Refresh (HRRR) outputs. The HRRR is an hourly-updated operational forecast product produced by the National Oceanic and Atmospheric Administration (NOAA) (Dowell et al., 2022).

- One barrier to the use of the HRRR in wind power analysis is systematic bias and consistency with NREL's existing wind datasets (e.g., the WIND Toolkit, "WTK") across weather years. To address this barrier, we show that the HRRR can be interpolated and bias-corrected to be consistent with NREL's existing datasets. **We call the new dataset BC-HRRR (bias-corrected HRRR).** As with historical datasets like the WTK, BC-HRRR is intended for use in grid integration modeling (e.g., capacity expansion, production cost, and resource adequacy modeling).

- BC-HRRR's (2015-present) consistency with WTK (2007-2013) allows NREL to extend grid integration tooling with 15+ weather years of wind data with low-overhead extensibility to future years as they are made available by NOAA.

- The rest of this slide deck documents **the BC-HRRR processing methods, validation, and its implications for intended use.**

# The High-Resolution Rapid Refresh (HRRR) Dataset by NOAA

- The HRRR is an hourly-updated operational forecast product produced by the National Oceanic and Atmospheric Administration (NOAA) Global Systems Laboratory (GSL).

- The HRRR is a real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model, initialized by 3km grids with 3km radar assimilation.

- For more information on the HRRR, see the the HRRR website, details of the HRRR v4 model development by Alexander et al., 2020, and the publication by Dowell et al., 2022.

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# HRRR data must be processed for consistency with other wind power datasets

- **Data Format:** HRRR data is available in GRIB files in 1-2 day forecast horizons produced every hour
  - **Solution:** We collate the f02 hour of every forecast run to create an hourly historical wind reanalysis dataset and save to files that match the WTK data format and variable naming conventions.
- **Spatial resolution:** HRRR and WTK have different geospatial projections and spatial resolutions (3km and 2km, respectively).
  - **Solution:** We re-grid the 3km HRRR onto the original 2km WTK meta data using inverse distance-weighted interpolation with four nearest neighbors.
- **Vertical height:** Translation to multiple hub heights for existing and future wind turbine technologies (~40-150+ meters). HRRR is natively available at 10m and 80m above surface and at coarse hybrid vertical levels (typically around 8, 23, 53, 106, and 198m above surface).
  - **Solution:** we linearly interpolate across coarse HRRR vertical levels to desired hub heights. This method is simple, computationally efficient, and preserves conditions with negative wind shear that are important for some wind power analyses.
- **Wind speed Bias**: Interpolated HRRR data has consistent negative bias when compared to ground measurements and similar spatiotemporal windspeed datasets (see subsequent validation results).
  - **Solution:** We apply quantile mapping bias correction to the HRRR data with the WTK as a historical baseline. This method has limitations, but we show that this generally results in a less biased wind dataset that can be used alongside the WTK.

# The Download, Interpolation, and Bias Correction Process

- HRRR files are downloaded from:

  https://noaa-hrrr-bdp-pds.s3.amazonaws.com/index.html#hrrr<YYYYMMDD>/conus/hrrr.t<HH>z.wrfnat<FFF>.grib2

  where <YYYYMMDD> is replaced with the date (e.g. "20140730“ for 30 July 2014), <HH> is replaced with the hour of day (e.g. "01” for the hour 1AM), and <FFF> is replaced with the forecast hour. Whenever possible, we take the third hour (“f02”) of the forecast based on guidance from NOAA and PNNL (e.g. the 06:00 output time step would be taken from HH=4, FFF=f02). Note that WRF timestamped outputs are typically instantaneous.

- NREL processes the NOAA HRRR raw data in four steps after download:
  1. HRRR data is linearly interpolated from hybrid vertical levels to fixed height above ground (using the hybrid level geopotential height, surface elevation, and desired hub height).
  2. HRRR data is inverse-distance-weight interpolated from the original HRRR grid to NREL's WTK grid using four spatially nearest HRRR grid neighbors.
  3. Missing HRRR time steps are gap-filled (see next slide for details).
  4. The HRRR wind speed data is then bias corrected via quantile mapping with WTK as a historical baseline (see subsequent slides on bias correction).

# Missing Time Steps

- Publicly available native level NOAA HRRR data is missing a considerable number of time steps for the years 2015-2018.
- Whenever possible, we populate the missing time steps with forecasts from the previous hour(s), up to the seventh-hour forecast "f06". For example, if the 06:00 output time step (HH=4, FFF=f02) is missing, we attempt to populate it with data from HH=3, FFF=f03. If that forecast is missing as well, we attempt to populate it with HH=2, FFF=f04. This process is repeated until valid data is found, or we reach FFF=f06.
- If a time step is still missing after the above procedure, we instead populate it using f02 pressure-level data that was processed and bias corrected using these same methods. Pressure-level data is downloaded from:

  https://noaa-hrrr-bdp-pds.s3.amazonaws.com/index.html#hrrr<YYYYMMDD>/conus/hrrr.t<HH>z.wrfprsf02.grib2

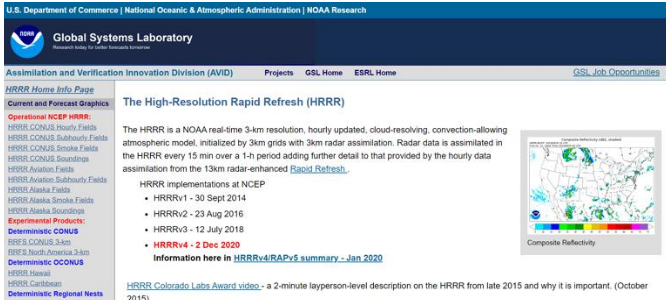
  where the URL components are populated as described before.
- If a time step is still missing after the above procedures, we populate it by linearly interpolating between the closest available time steps. This interpolation extends across consecutive missing time steps, including any missing days.
- The table below summarizes statistics of the missing time steps

| | Original Data | | After forecast gap fill (f02+) | | After pressure level gap fill | |
|---|---|---|---|---|---|---|
| Year | Missing hours | Missing days | Missing hours | Missing days | Missing hours | Missing days |
| 2015 | 354 | 3 | 129 | 2 | 0 | 0 |
| 2016 | 972 | 8 | 256 | 7 | 25 | 1 |
| 2017 | 324 | 2 | 68 | 2 | 0 | 0 |
| 2018 | 139 | 0 | 1 | 0 | 0 | 0 |

*Note: Missing hour tally includes any missing days. Missing hours after pressure population are filled in using linear interpolation. Data for 2019 and beyond have complete hourly records.*

# Diagram: Interpolating HRRR

## NOAA High-Resolution Rapid Refresh


U.S. Department of Commerce | National Oceanic & Atmospheric Administration | NOAA Research

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HRRR Home Info Page

Current and Forecast Graphics

Operational NCEP HRRR:
HRRR CONUS Hourly Fields
HRRR CONUS Subhourly Fields
HRRR CONUS Smoke Fields
HRRR CONUS Soundings
HRRR Aviation Fields
HRRR Aviation Subhourly Fields
HRRR Alaska Fields
HRRR Alaska Smoke Fields
HRRR Alaska Soundings
Experimental Products:
Deterministic CONUS
RRFS CONUS 3-km
RRFS North America 3-km
Deterministic OCONUS
HRRR Hawaii
HRRR Caribbean
Deterministic Regional Nests

The High-Resolution Rapid Refresh (HRRR)

The HRRR is a NOAA real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model, initialized by 3km grids with 3km radar assimilation. Radar data is assimilated in the HRRR every 15 min over a 1-h period adding further detail to that provided by the hourly data assimilation from the 13km radar-enhanced Rapid Refresh.

HRRR implementations at NCEP
- HRRRv1 - 30 Sept 2014
- HRRRv2 - 23 Aug 2016
- HRRRv3 - 12 July 2018
- HRRRv4 - 2 Dec 2020

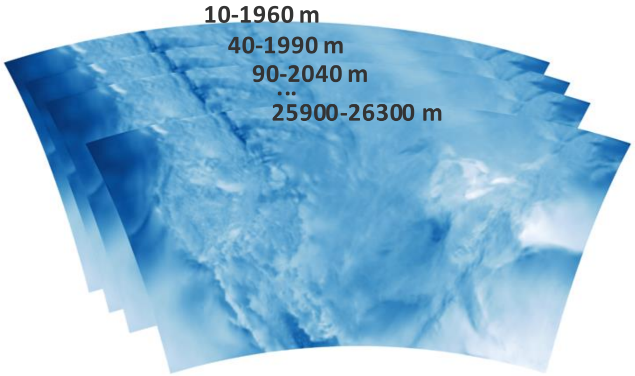
Information here in HRRRv4/RAPv5 summary - Jan 2020

Composite Reflectivity

HRRR Colorado Labs Award video - a 2-minute layperson-level description on the HRRR from late 2015 and why it is important. (October 2015)

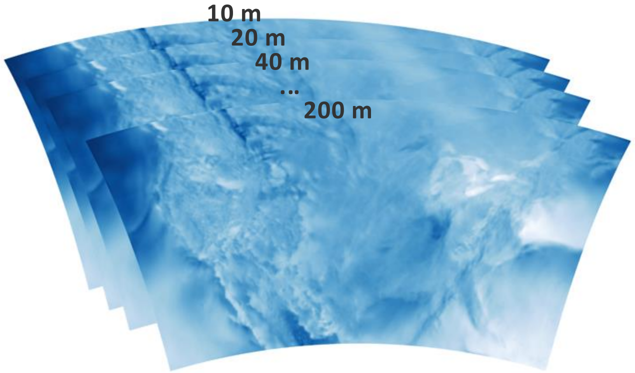
Download GRIB files from https://noaa-hrrr-bdp-pds.s3.amazonaws.com/index.html

## HRRR Grid (3D hybrid levels)



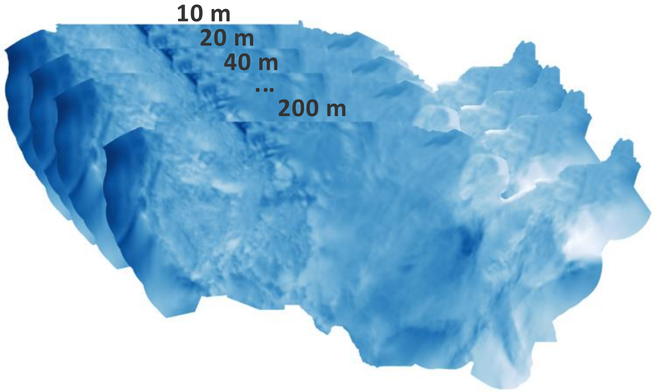

Linearly interpolate from hybrid levels to fixed height above ground

## HRRR Grid (fixed height above ground)



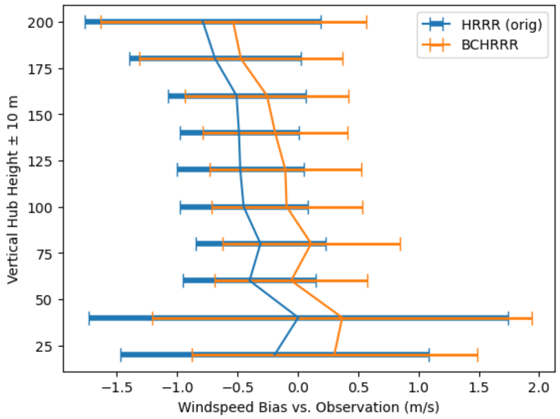

Inverse-distance-weighted interpolation from HRRR grid to WTK grid using 4 spatially nearest neighbors

## WTK Grid (fixed height above ground)

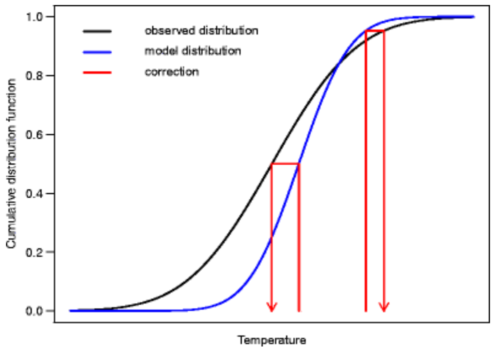


# Bias Correction

- We find HRRR data exhibits negative windspeed bias at modern turbine hub heights (e.g., >= 80m) after interpolation from the hybrid levels (see figure to the right).
- Previous studies (Millstein et al., 2023) have shown acceptably low bias from the HRRR 80m wind output, but many grid integration applications require a wider range of hub heights.
- We use quantile mapping to correct the 2015-2023 HRRR distributions based on the 2007-2013 WTK years
- Quantile mapping is a common non-linear bias correction technique (Maraun 2016) that we implement using cumulative distribution functions (CDFs) per spatial pixel for the HRRR and WTK timeseries.
- Quantile delta mapping (Cannon et al 2015) can be used in future years to represent changes in wind resource.




Bias in HRRR data as a function of vertical hub height above surface showing worsening negative bias at greater hub heights and improvement with the bias correction process. Source of observation data is detailed in subsequent slides.




Quantile mapping. A simulated value, a quantile of the simulated distribution, is replaced by the quantile of the observed distribution corresponding to the same probability (Maraun 2016)

# Bias correction makes BC-HRRR usable alongside WTK, but has limitations

- A major limitation of the bias correction method is that it forces the windspeed distribution in the HRRR record (2015-2023) to exactly match the WTK data (2007-2013). This approach will *capture changes in intra-annual variability* in the wind resource across these weather years but will *eliminate average changes* in wind resource (if applicable) between the time periods 2007-2013 and 2015-2023.

- Bias-correcting HRRR to WTK also means high-wind extreme events in the HRRR dataset will not exceed the WTK record, and that pixels without high-wind extreme events in HRRR will have their maximum windspeeds artificially increased to match the WTK. We show how this impacts events like the Marshall Fire and Winter Storm Uri in subsequent slides

- Despite these assumptions, we find that the process results in *less biased* HRRR wind speed estimates for grid integration applications when compared to observations and other benchmark datasets (see subsequent slides).

- Generally, our method is also extensible to corrections against other datasets known to exhibit less bias or have other characteristics preferable to WTK, if available and applicable. However, the recent ESIG report identifies WTK as a high-quality dataset in temporal, spatial, and bias characteristics.

# Validate BC-HRRR against available measurement stations and other datasets

## (1) Measurement Stations

✓ Empirical, many locations across CONUS

✗ Not in all locations

✗ Not always near turbine hub height

## (2) Other Datasets

✓ Cover all locations

✗ Also synthetic

1. NREL WTK
   - Used in many wind power analyses and has existing validation study (King et al. 2014)
2. Vortex 20-Year Wind Data
   - Provided by the International Renewable Energy Agency (IRENA)

# Measurement stations: HRRR is natively biased low, bias correction helps

- Data available for 44 measurement stations (mostly 40m or lower, but some lidars and tall towers with hub-height data)
- The bias correction process reduces mean bias error (MBE) from -0.36 to +0.01

Mean Absolute Error (MAE), Mean Bias Error (MBE), and the Pearson Correlation Coefficient versus Observation

| Dataset | Years | MAE (m/s) | MBE (m/s) | Pearson |
|---|---|---|---|---|
| WTK v1.0.0 | 2007-2013 | 1.81 | 0.39 | 0.72 |
| HRRR | 2015-2023 | 1.85 | -0.36 | 0.78 |
| **BC_HRRR** | **2015-2023** | **1.89** | **0.01** | **0.78** |

Mean Windspeed Bias at Measurement Sites (Bias Corrected HRRR minus Observation)


**Solution:** Bias-correct HRRR to WTK

(Vortex helps motivate but lacks high temporal resolution needed to bias correct against)

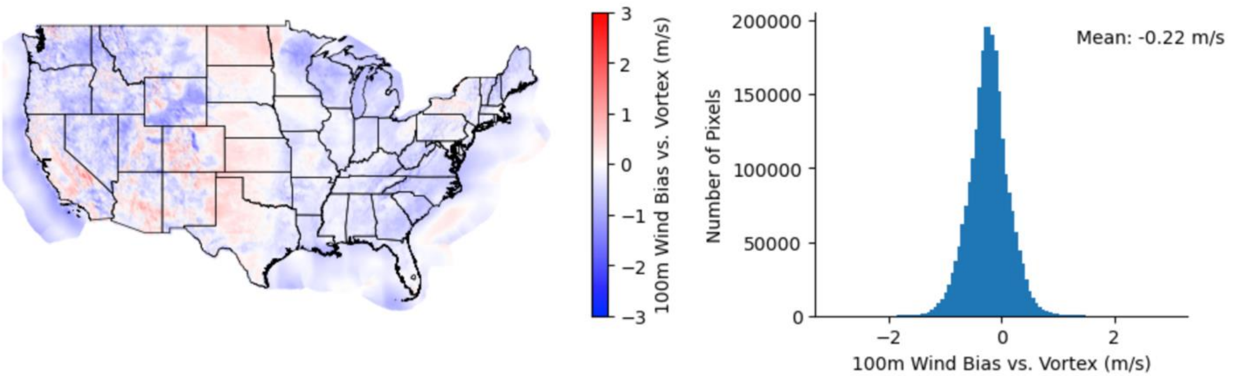
# **Other datasets:** HRRR is negatively biased against WTK and Vortex

- Multi-year mean interpolated HRRR windspeed at 100m shows negative bias versus WTK and Vortex over CONUS

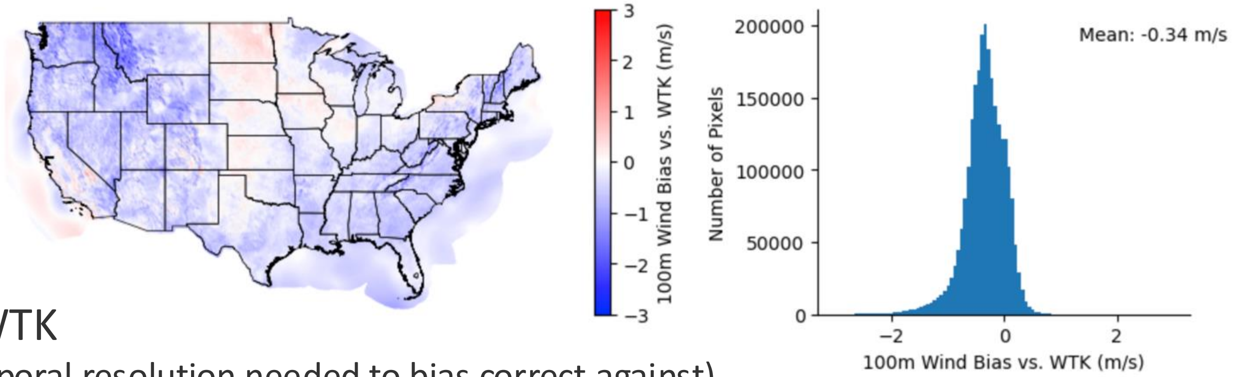
- Conversion from wind speed to power is non-linear and will exacerbate errors

- Consistency across weather years for grid integration studies motivates bias correction

Original Interpolated HRRR (2015-2023) minus Vortex (2001-2020) at 100m




Original Interpolated HRRR (2015-2023) minus WIND Toolkit (2007-2013) at 100m



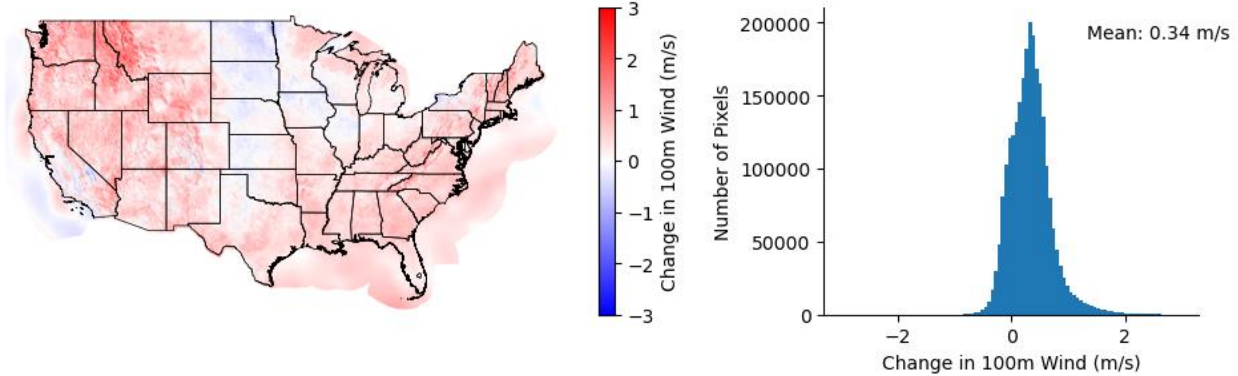

**Solution:** Bias-correct HRRR to WTK

(Vortex helps motivate but lacks high temporal resolution needed to bias correct against)

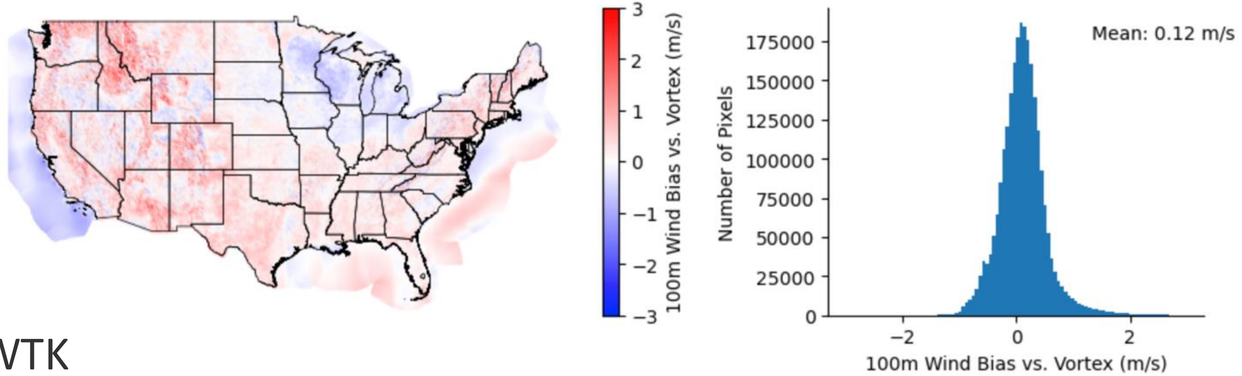
# Benchmarking BC-HRRR vs. Other Wind Data

- Bias correction increases the HRRR windspeeds over CONUS and reduces mean bias versus other widely used wind resource datasets (e.g., Vortex).
- Note that due to the nature of quantile mapping, BC-HRRR data will match the WTK data exactly, so BC-HRRR is not compared to WTK here

Effect of Bias Correction (BC-HRRR minus Original Interpolated HRRR at 100m)




BC-HRRR (2015-2023) minus Vortex (2001-2020) at 100m

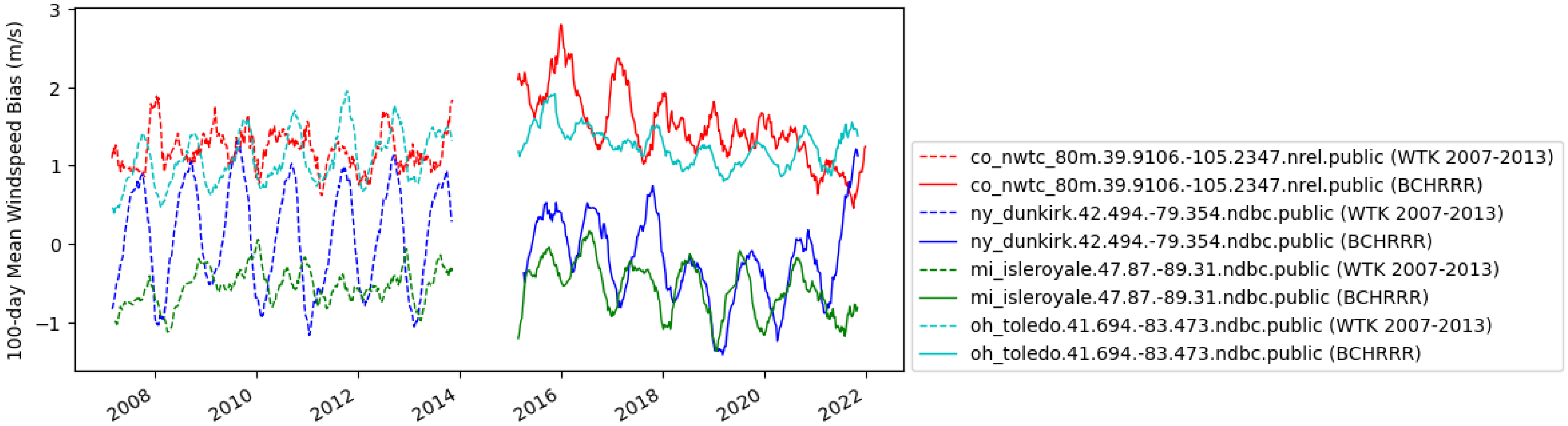



**Solution:** Bias-correct HRRR to WTK

(Vortex helps motivate but lacks high temporal resolution needed to bias correct against)

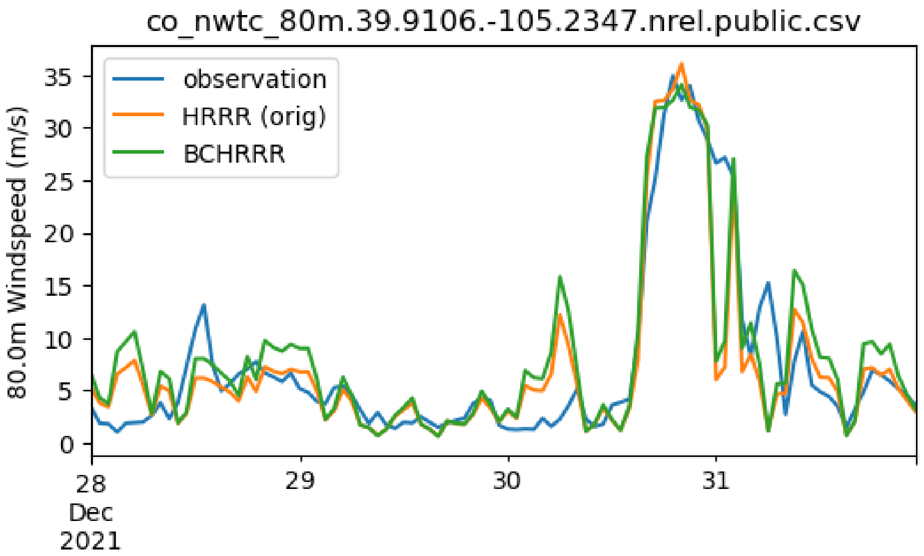
# BC-HRRR bias is consistent with WTK over time at four measurement stations

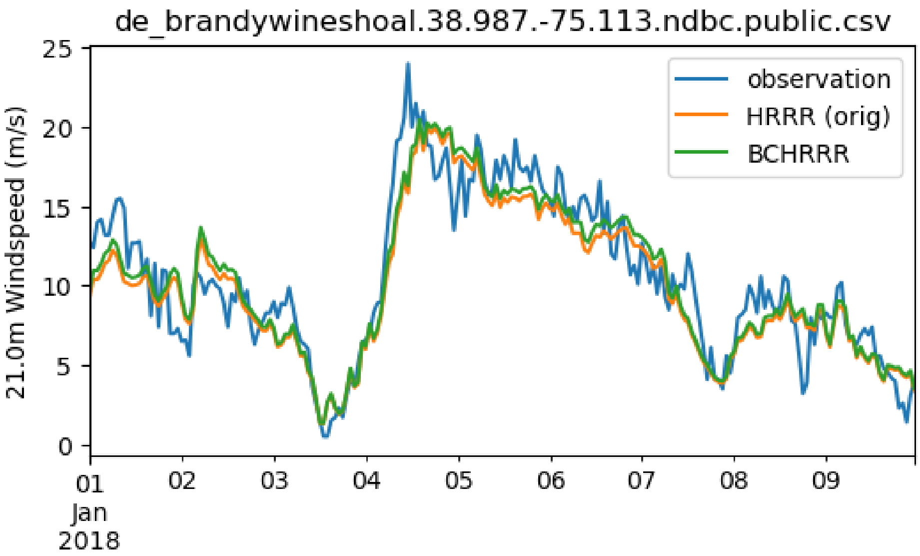
- NOAA has periodically updated HRRR, with four versions released since September 2014.
- We do not see an obvious or significant change in bias over time based on four ground stations with the most complete timeseries of observations for BC-HRRR.
- BC-HRRR has bias that is generally consistent with WTK data, though seasonal variance is different in some weather years at some measurement stations



# Checking Extreme Events

- Bias correction with quantile mapping has the potential to corrupt high-winds during extreme events.
- Despite this, BC-HRRR appears accurate for the Marshall Fire (left) and winter storm Grayson (right).
- This does not guarantee accuracy for all extreme events of interest for grid integration



# Summary

- Many weather years of high-quality wind data are widely accepted in the grid integration community to be important for studying uncommon-but-impactful meteorological events as wind generation shares increase. NREL's in-house WTK is high-quality but covers limited weather years. Using HRRR can extend coverage to recent weather years (complete 2023) and enhance future extensibility.
- HRRR is high-quality but inconsistent with NREL's other wind data due to limitations on spatial resolution, vertical height, and output format. HRRR is also negatively biased against existing datasets.
- NREL's team undertakes re-gridding, interpolation, and bias-correction to the native HRRR data to overcome limitations on spatial resolution, vertical height output format, and negative bias, respectively. **This results in the now-publicly-available BC-HRRR dataset for weather years 2015 to 2023.**
- Bias correction is necessary for dataset consistency across weather years to be used simultaneously in planning-focused grid integration studies. We show that quantile mapping with the WIND Toolkit as a historical baseline is an effective method for bias correcting the interpolated HRRR data. The bias corrected and interpolated HRRR data (BC-HRRR) has reduced mean bias versus comparable wind datasets (+0.12 m/s versus Vortex) and has very low mean bias versus ground measurement stations (+0.01 m/s).
- We release BC-HRRR (2015-2023) on this basis as fit for use in renewable energy grid integration analysis (e.g., capacity expansion, resource adequacy, and production cost modeling) both independently and alongside the WTK (2007-2013).

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# Validation Station References

| State | Latitude | Longitude | Heights (m) | Reference |
|---|---|---|---|---|
| AL | 30.228 | -88.024 | 36 | NBDC |
| Atlantic | 39.55 | -73.43 | 18-198 | NYSERDA |
| Atlantic | 39.97 | -72.72 | 18-198 | NYSERDA |
| CA | 35.169 | -120.754 | 14 | NBDC |
| CA | 38.987 | -120.966 | 23 | LBNL |
| CO | 39.305 | -105.5464 | 26 | LBNL |
| CO | 39.9106 | -105.2347 | 10-80 | NREL |
| CO | 40.05 | -105.00 | 40-200 | BAMS |
| CT | 41.306 | -72.077 | 20 | NBDC |
| DE | 38.987 | -75.113 | 21 | NBDC |
| FL | 25.591 | -80.097 | 44 | NBDC |
| FL | 29.408 | -84.858 | 35 | NBDC |
| IL | 41.70121 | -87.99495 | 10 | ANL |
| LA | 29.441 | -92.061 | 20 | NBDC |
| MA | 42.22327 | -72.96826 | 40 | UMass |
| ME | 43.969 | -68.128 | 23 | NBDC |
| MI | 47.87 | -89.31 | 47 | NBDC |
| MO | 40.033 | -92.2 | 30 | LBNL |
| NJ | 40.657 | -74.065 | 21 | NBDC |
| NY | 40.870731 | -72.88884 | 10 | BNL |
| NY | 42.494 | -79.354 | 20 | NBDC |
| NY | 43.464 | -76.511 | 15 | NBDC |

| State | Latitude | Longitude | Heights (m) | Reference |
|---|---|---|---|---|
| OH | 41.629 | -82.841 | 21 | NBDC |
| OH | 41.694 | -83.473 | 26 | NBDC |
| OH | 41.764 | -81.281 | 21 | NBDC |
| OK | 36.6 | -97.48 | 13-195 | ARM |
| OR | 45.500263 | -120.7669 | 30 | BPA |
| OR | 45.555 | -123.919 | 18 | NBDC |
| OR | 45.558324 | -122.4017 | 30 | BPA |
| OR | 45.59 | -120.69 | 40-200 | Energy.gov |
| OR | 45.633598 | -121.2668 | 15 | BPA |
| OR | 45.95008 | -118.6834 | 31 | NBDC |
| OR | 45.96 | -118.69 | 40-200 | Energy.gov |
| Pacific | 35.71 | -121.86 | 40-200 | Energy.gov |
| Pacific | 40.97 | -124.59 | 40-200 | Energy.gov |
| RI | 41.807 | -71.401 | 18 | NBDC |
| SC | 33.41 | -81.83 | 34 | SRNL |
| VA | 37.538 | -76.014 | 17 | NBDC |
| VT | 44.52647 | -72.866062 | 16 | FEMC |
| WA | 46.421801 | -123.7969 | 30 | BPA |
| WA | 46.429654 | -119.35917 | 10 | BAMS |
| WA | 47.675 | -124.485 | 31 | NBDC |
| WI | 42.589 | -87.809 | 20 | NBDC |
| WI | 47.079 | -90.728 | 25 | NBDC |

For additional information on the HRRR, see the NOAA website: https://rapidrefresh.noaa.gov/hrrr/

To access the BC-HRRR dataset, see the NREL Wind Resource Database: https://wrdb.nrel.gov/

**www.nrel.gov**

NREL/PR-6A20-91749

The authors would like to thank Dave Turner from NOAA for providing guidance on proper use of the HRRR data. This work would not be possible without the significant efforts by NOAA to produce and maintain the HRRR.

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the DOE Wind Energy Technologies Office (WETO). The research was performed using computational resources sponsored by the DOE Office of Energy Efficiency and Renewable Energy and located at the National Renewable Energy Laboratory. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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