DYNAMIC LINE RATING USING THE HIGH RESOLUTION RAPID REFRESH (HRRR) MODEL

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Agenda

- Line rating background
- The case for additional capacity
- Sensitivity analysis of line ratings
- Using the HRRR in line ratings

Line Rating Background

- Conductor temperatures are a function of:
  1. Conductor material properties (primarily electrical conductivity and heat capacity for non-steady state)
  2. Conductor diameter
  3. Conductor surface condition (primarily emissivity and absorptivity)
  4. Weather conditions (air temperature, solar heating, wind speed and direction)
  5. Conductor electrical current

Adapted from IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors, IEEE Power and Energy Society, 2013

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Constant

Slow change

Rapid change

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Line Rating Background

- Three cases for conductor temperatures:
  1. Steady State Case – current, weather, and conductor temperature constant
  2. Transient Case – weather is constant, current undergoes a step change that leads to a new conductor temperature over some time
  3. Dynamic Case – weather and current vary over time affecting the conductor temperature

Steady state heat balance equation

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}}$$

Non-steady state heat balance equation

$$\frac{dT_c}{dt} = \frac{1}{m * C_p}\left[R(T_c) * I^2 + q_s - q_c - q_r\right]$$

Adapted from IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors, IEEE Power and Energy Society, 2013

Using the Line Rating Equations

- At the maximum allowable conductor temperature

$$\frac{dT_c}{dt} = 0$$

- This allows for the maximum current to be passed through the line without raising the temperature
- Solving the non-steady state heat balance equation for this condition

$$\frac{dT_c}{dt} = \frac{1}{m * C_p}[R(T_c) * I^2 + q_s - q_c - q_r]$$

$$0 = \frac{1}{m * C_p}[R(T_c) * I^2 + q_s - q_c - q_r]$$

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Steady state equation

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Equations

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$$T_{film} = \frac{T_s + T_a}{2}$$

$$q_{c1} = K_{angle} \cdot \left[1.01 + 1.35 \cdot N_{\mathrm{Re}}^{0.52}\right] \cdot k_f \cdot (T_s - T_a)$$

$$N_{\mathrm{Re}} = \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f}$$

$$k_f = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_{film} - 4.407 \cdot 10^{-9} \cdot T_{film}^2$$

$$q_{c2} = K_{angle} \cdot 0.754 \cdot N_{\mathrm{Re}}^{0.6} \cdot k_f \cdot (T_s - T_a)$$

$$K_{angle} = 1.194 - \cos(\phi) + 0.194 \cdot \cos(2\phi) + 0.368 \cdot \sin(2\phi)$$

$$q_{cn} = 3.645 \cdot \rho_f^{0.5} \cdot D_0^{0.75} \cdot (T_s - T_a)^{1.25}$$

$$\rho_f = \frac{1.293 - 1.525 \cdot 10^{-4} \cdot H_e + 6.379 \cdot 10^{-9} \cdot H_e^2}{1 + 0.00367 \cdot T_{film}}$$

$$\mu_f = \frac{1.458 \cdot 10^{-6} \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4}$$

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$$\delta = 23.46 \cdot \sin\left[\frac{284 + N}{365} \cdot 360\right]$$

$$q_s = \alpha \cdot Q_{se} \cdot \sin(\theta) \cdot A'$$

$$H_c = \arcsin\left[\cos(Lat) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(Lat) \cdot \sin(\delta)\right]$$

$$Z_c = C + \arctan(\chi)$$

$$\chi = \frac{\sin(\omega)}{\sin(Lat) \cdot \cos(\omega) - \cos(Lat) \cdot \tan(\delta)}$$

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Where weather enters the equations

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Now to Solve Those Equations …

- We need:
    1. Properties of the transmission line
    2. Weather conditions
    - Traditionally based on seasonal worst-case conditions
        - High temperature, low wind, full sun

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Values used by Black Hills Corporation

Parameter	Value
Ambient air temperature (Summer) (°C/°F)	40 / 104
Ambient air temperature (Winter) (°C/°F)	10 / 50
Transmission Line Wind Speed (fps/mps)	4.0 / 1.22
Substation Conductor Wind Speed (fps/mps)	2.0 / 0.6
Wind Direction	Perpendicular to conductor axis
Line Orientation	East-West
Time of Day	12:00 pm
Atmosphere	Clear
Absorptivity	0.5
Emissivity	0.5

Adapted from BHC Facility Rating Methodology, 2012

Values used by Kansas City Power & Light Company

Data Items	Input Conditions		
	Summer Peak	Winter Peak Conditions	Spring/Fall Conditions
Date	June 15	January 1	April 1
Time	12:00 Noon	12:00 Noon	12:00 Noon
Latitude	38.5° N	38.5° N	38.5° N
Longitude	94.0° W	94.0° W	94.0° W
Inclination Angle	0°	0°	0°
Ambient Air Temperature	37.7°C 100°F	0°C 32°F	20°C 68°F
Line Axis Azimuth	90°	90°	90°
Elevation	950 feet	950 feet	950 feet
Absorbitivity	1.0	1.0	1.0
Emissivity	0.85	0.85	0.85
Wind Direction	180°	180°	180°
Wind Speed	2 ft/sec	2 ft/sec	2 ft/sec

Adapted from Kansas City Power & Light Company Transmission Facility Rating Methodology, 2016

A Bunch of Numbers

Constants used:

Conductor properties

(e.g. Drake ACSR)
Diameter D = 0.0281 m
Emissivity ε = 0.8
Absorptivity α = 0.8
R_high = 8.688e-5
R_low = 7.283e-5
T_high = 75℃
T_low = 25℃
Tc_max = 90℃

Line properties

Elevation = 1000 m
Line azimuth = 90°
Latitude = 43°N

Weather Conditions:

Seasonal Rating Values

Summer, Winter, Transition
Temperature = 40℃, 18℃, 27℃
Wind Speed = 0.6 m/s
Wind Direction = 90° (parallel to line azimuth)
Solar Flux = 1030 W/m^2, 850 W/m^2, 1000 W/m^2

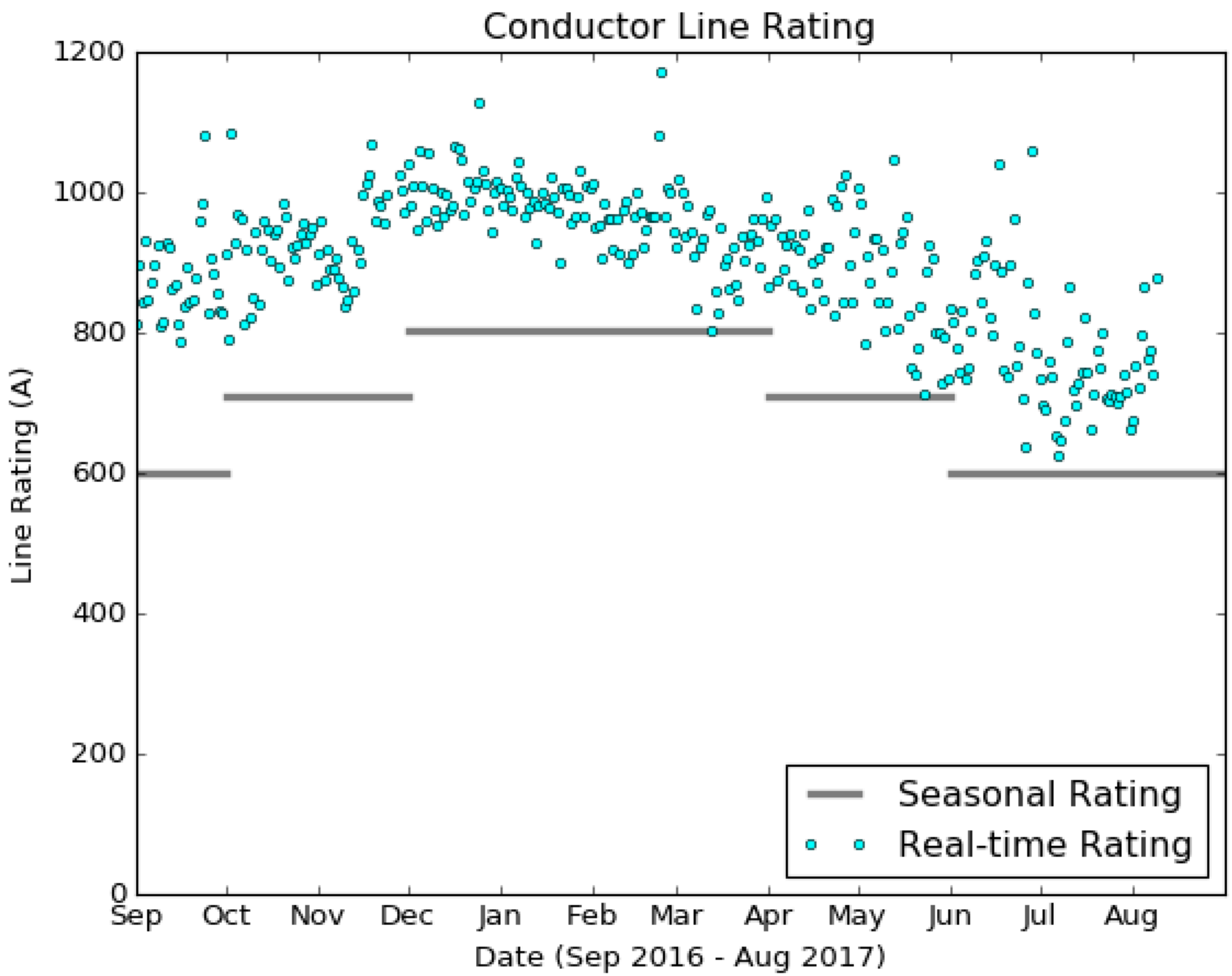
Weather Stations

45 weather stations located in southern Idaho
15-minute time step observations of temperature, wind speed, wind direction, and solar flux
Used the daily minimum ampacity of the 45 weather stations

One Year of Line Ratings

Real-time line ratings based on the minimum daily ampacity value calculated using the observations from 45 weather stations in southern Idaho.

These conservative seasonal values are generally good, the real time ratings do not go lower than the seasonal values.



There is extra capacity between the seasonal rating and the real time rating. Dynamic line ratings could allow this capacity to be used.

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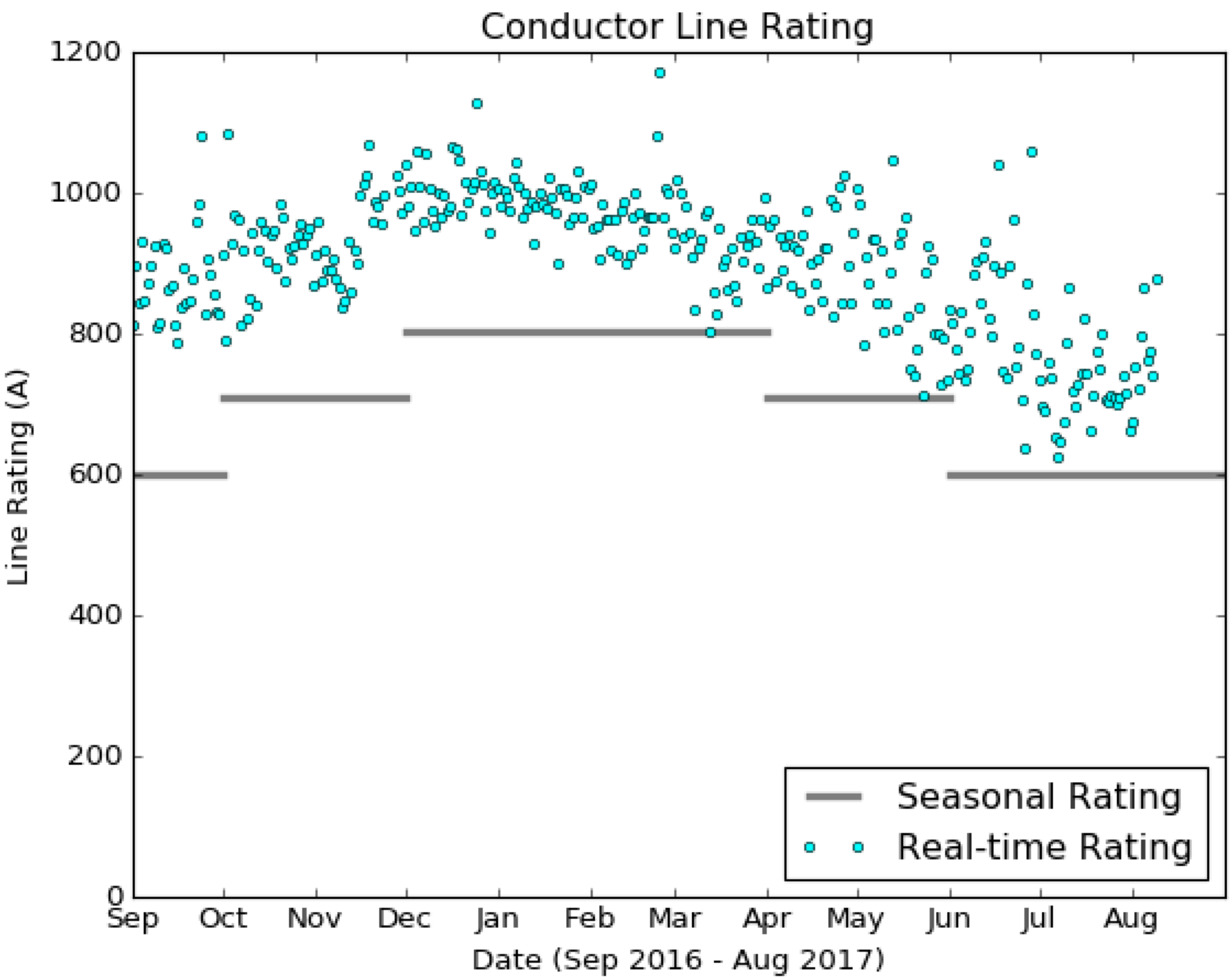

Let’s zoom in on two cases and look at the line ratings at 15-minute time steps over one day:

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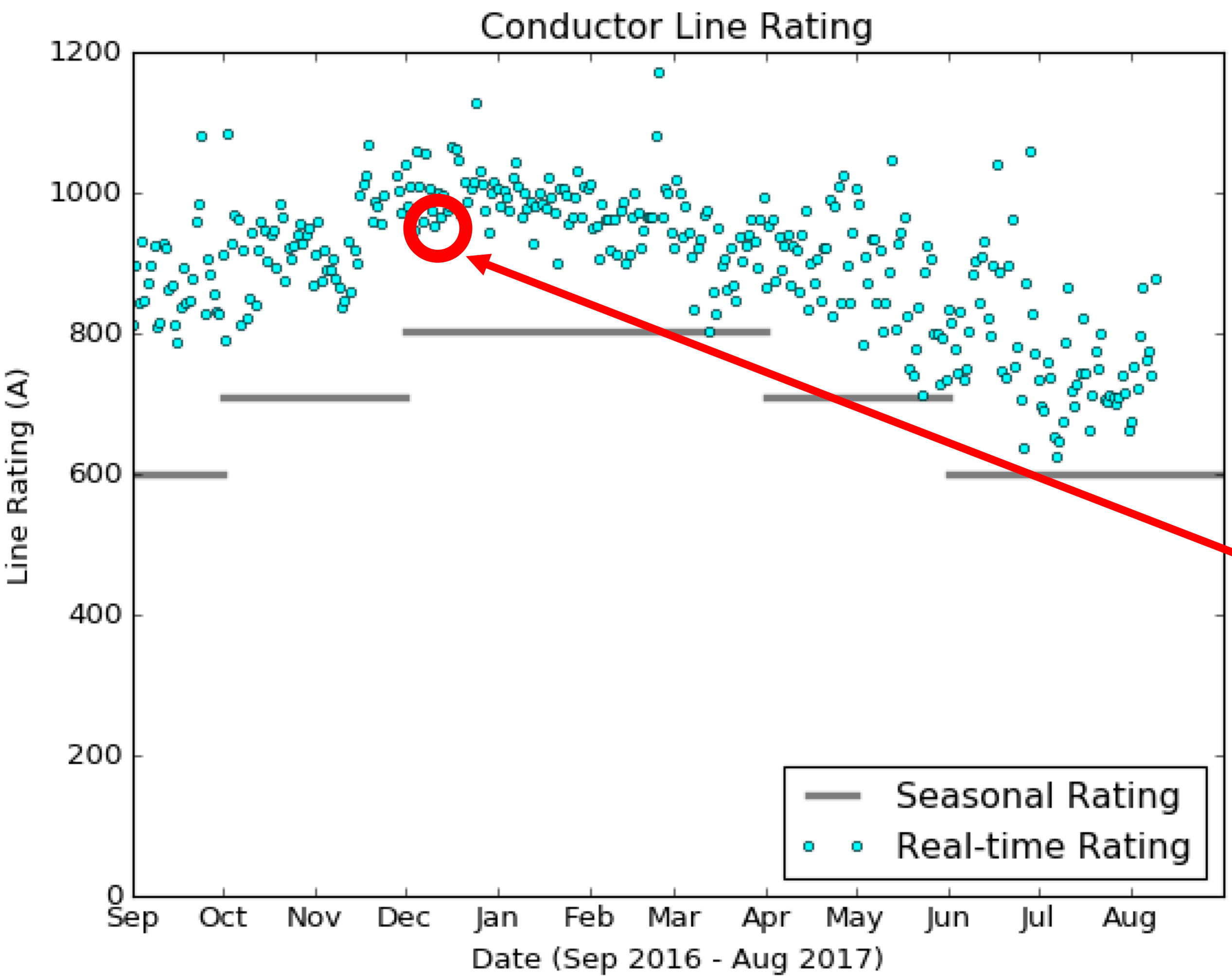

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1) Minimum daily rating well above the seasonal value

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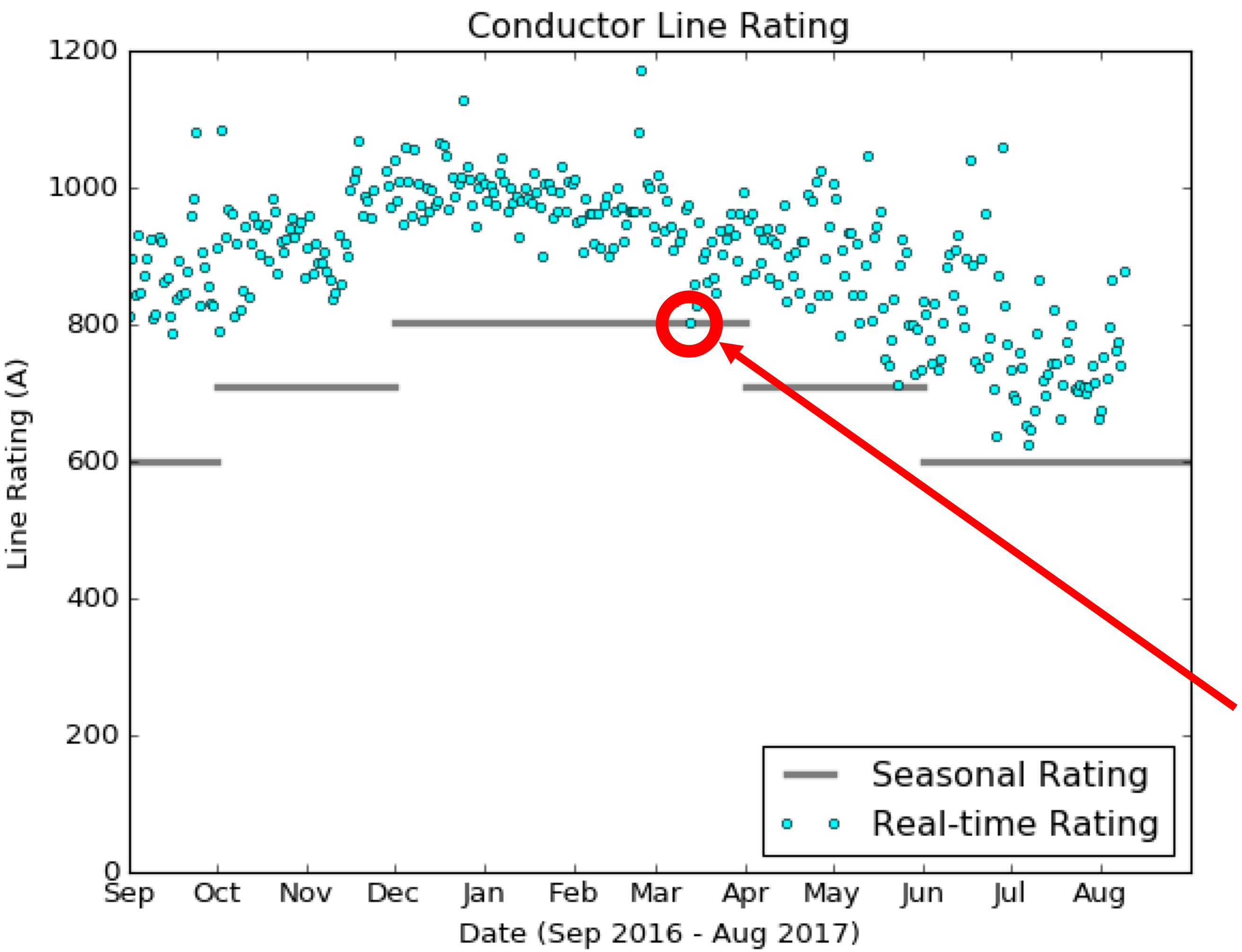
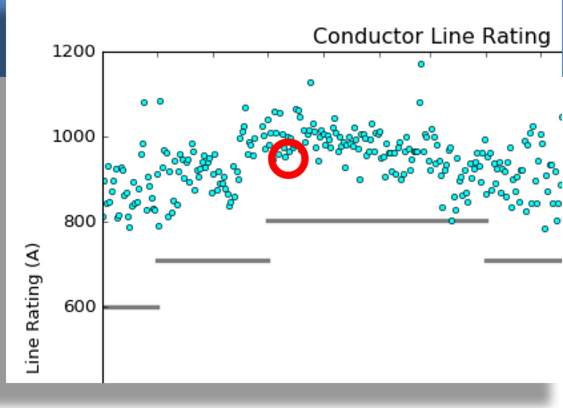
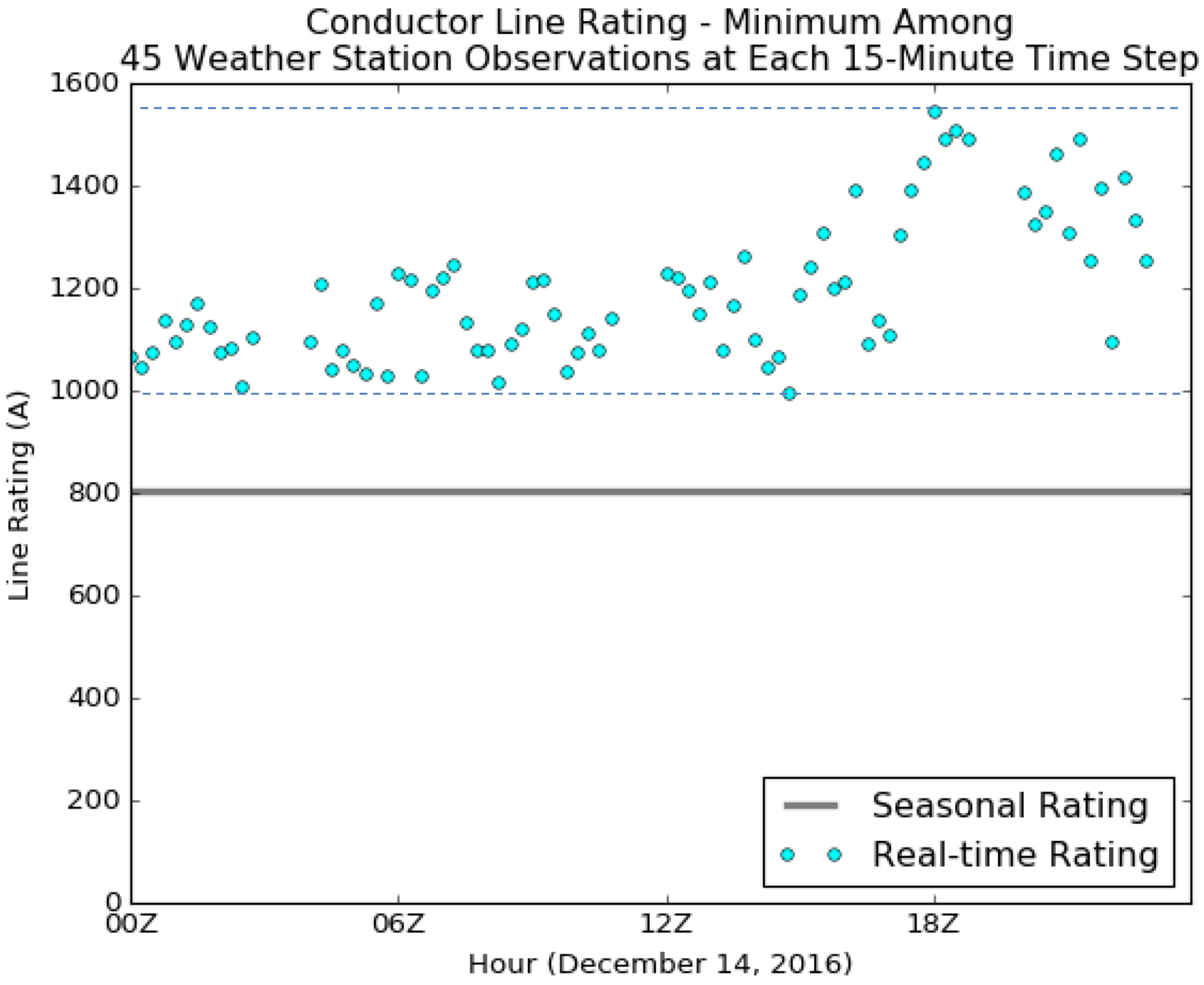


Let's zoom in on two cases and look at the line ratings at 15-minute time steps over one day:

1) Minimum daily rating well above the seasonal value
2) Minimum daily rating at the seasonal value

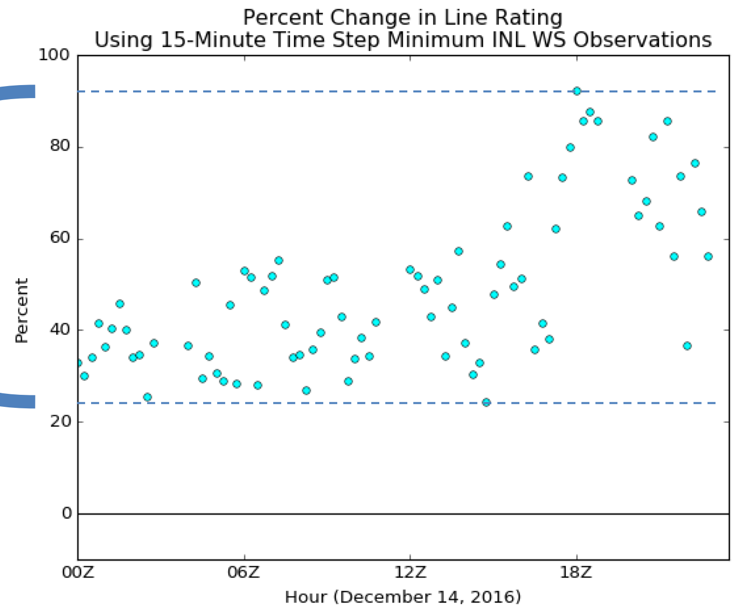
Variability Within a Higher Day



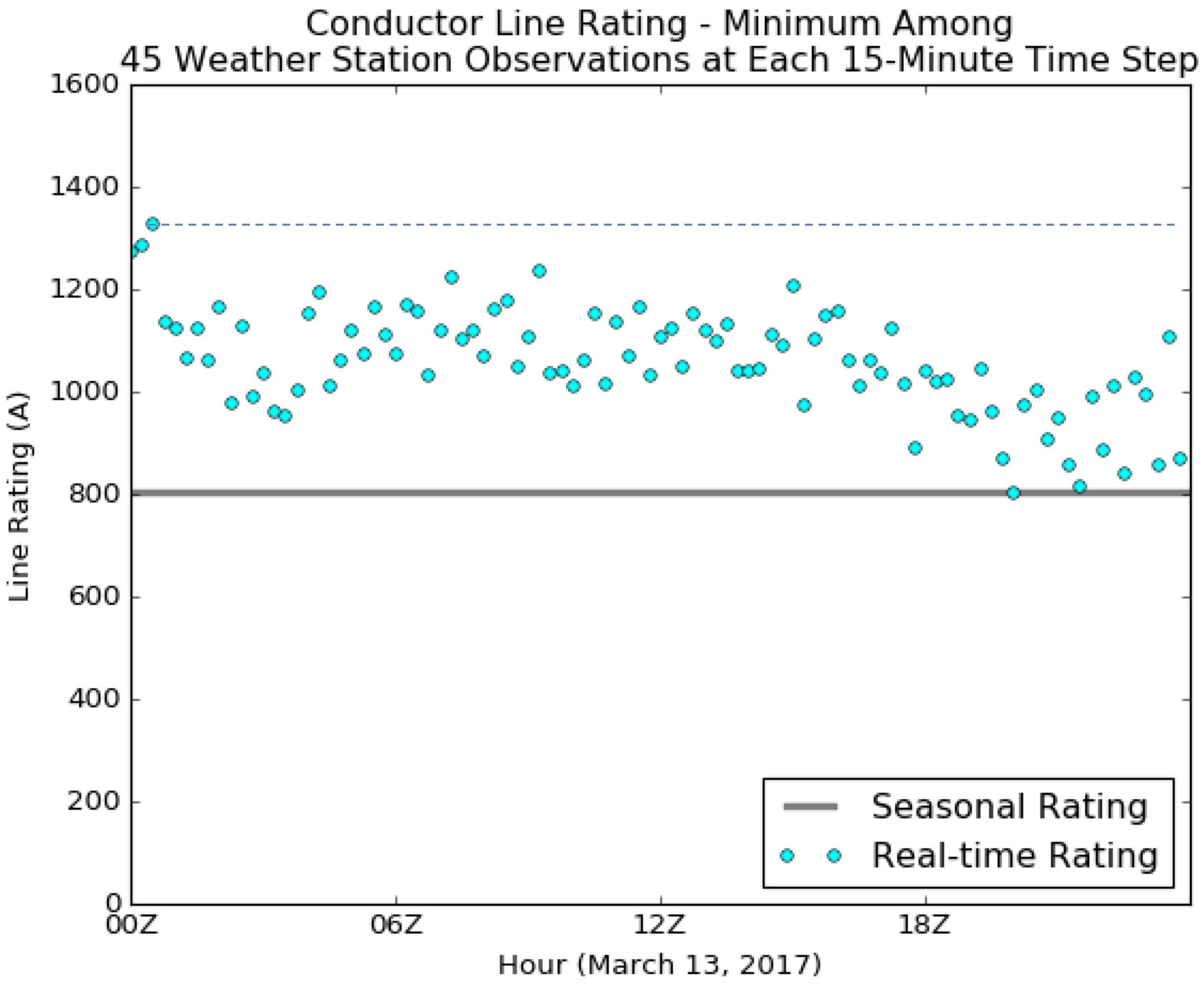


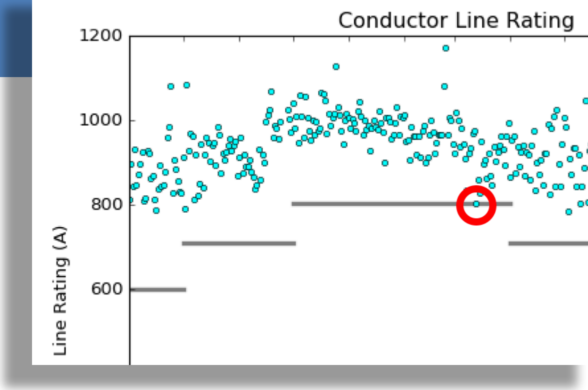
On days where the daily minimum rating remained well above the seasonal rating, there was additional capacity available by adjusting ratings over smaller time scales.

The percent increase available in line rating varied between 22% and 95% throughout the day.



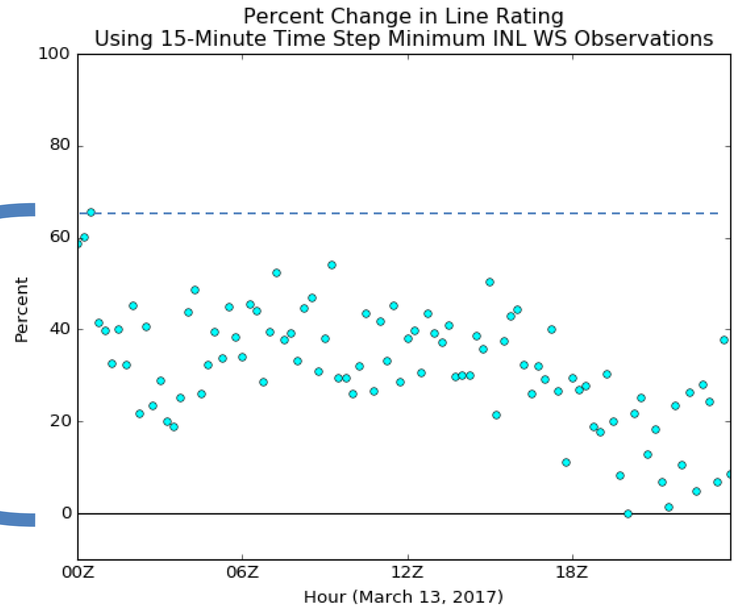
Variability Within a Minimum Day





On days where the daily minimum value lowered to the seasonal value, this only occurred for short periods and there was additional capacity during most of the day.

The percent increase available in line rating varied between 0% and 65% throughout the day.



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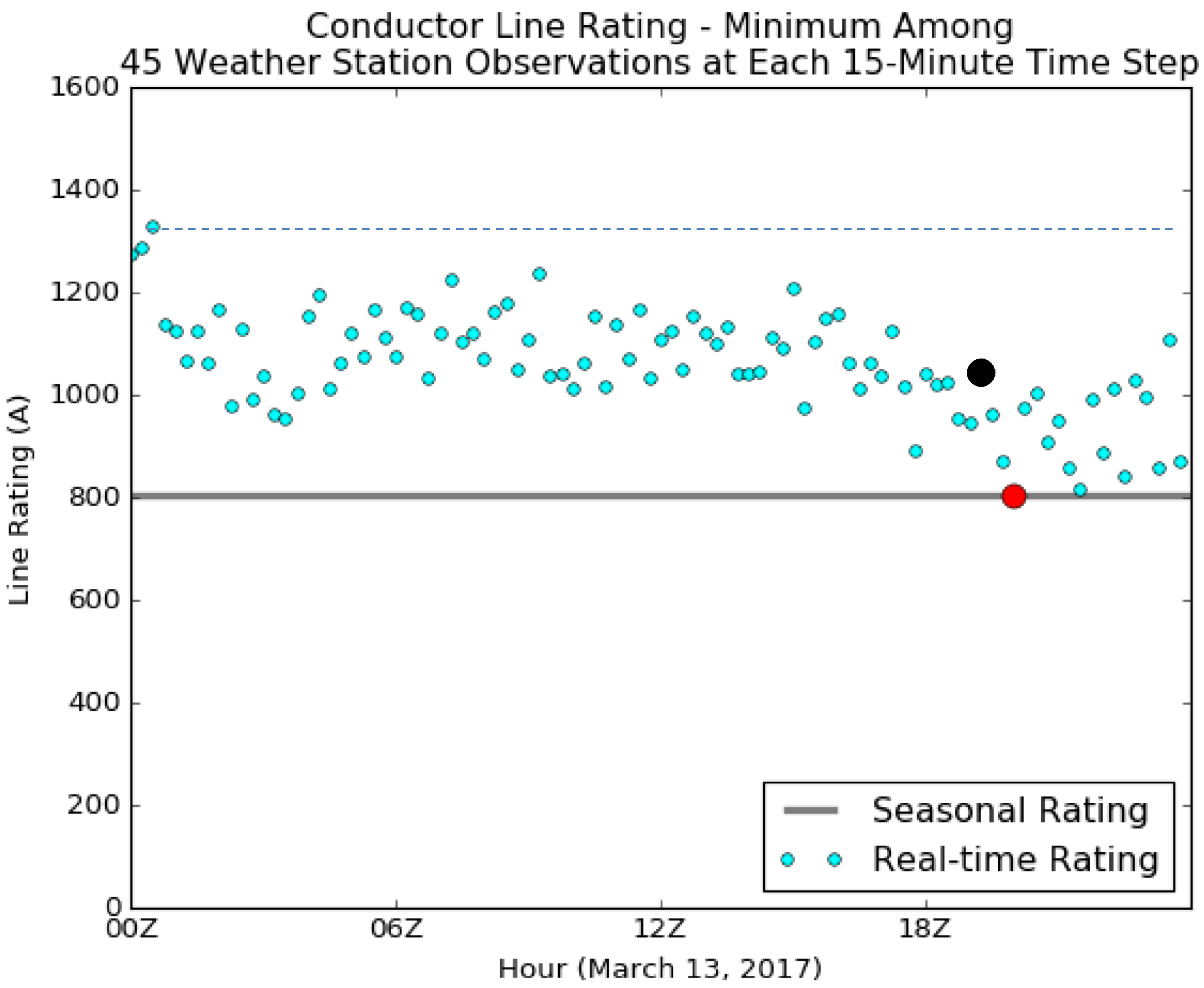

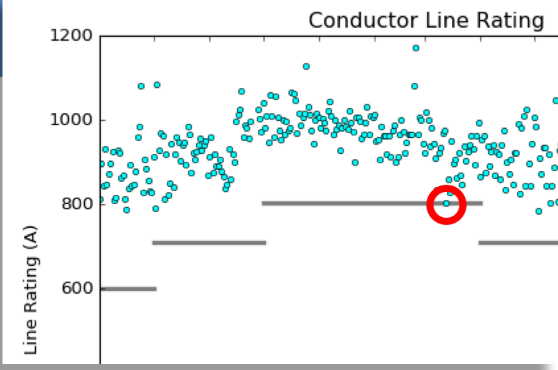

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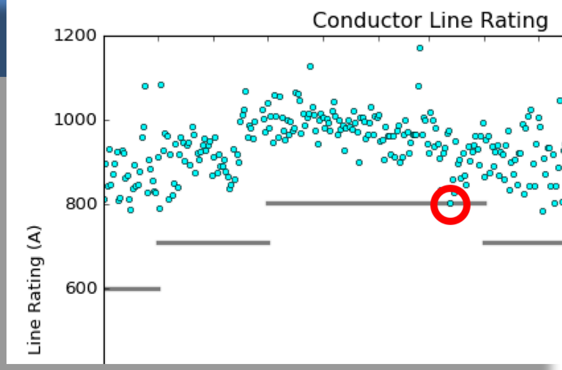
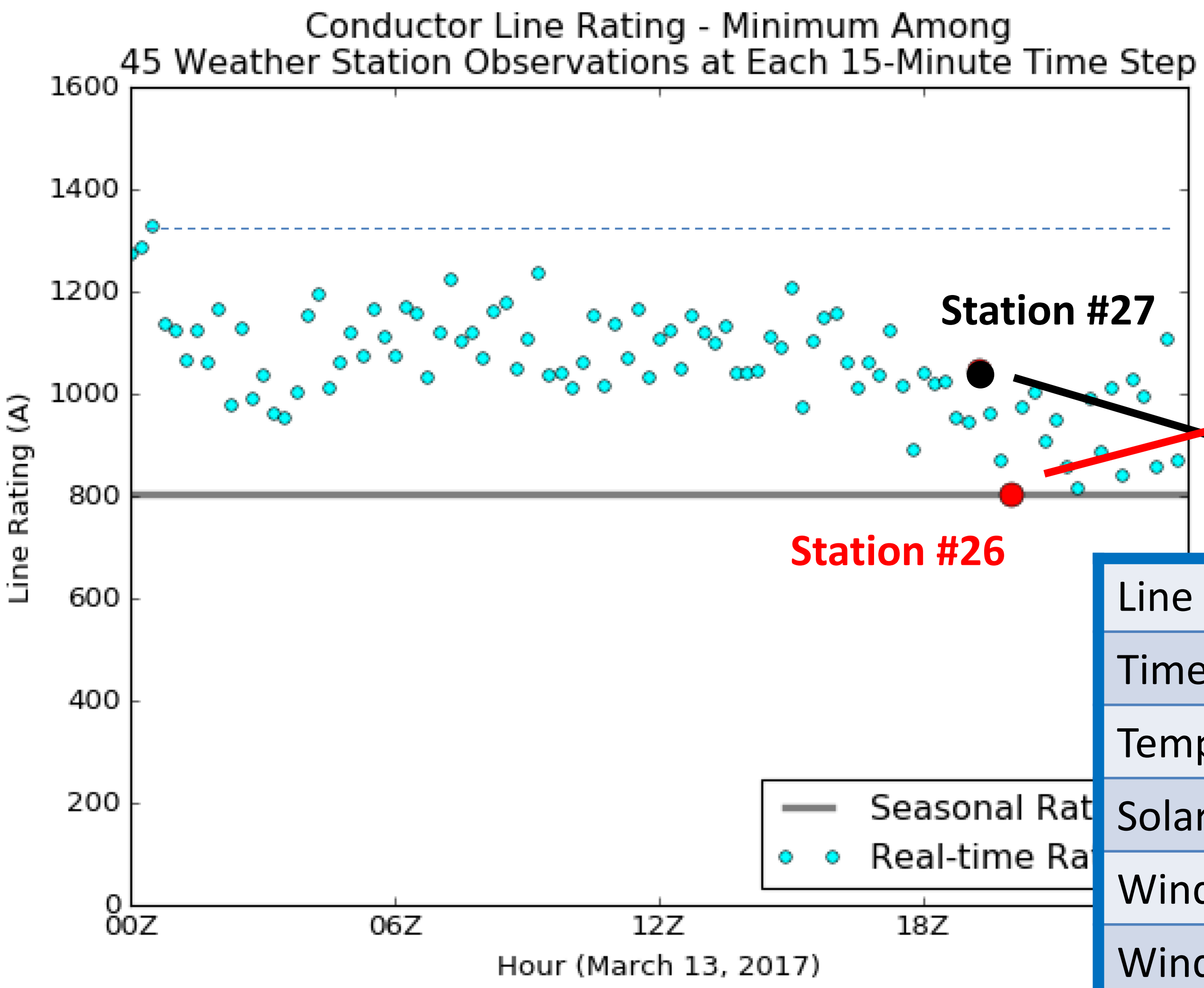
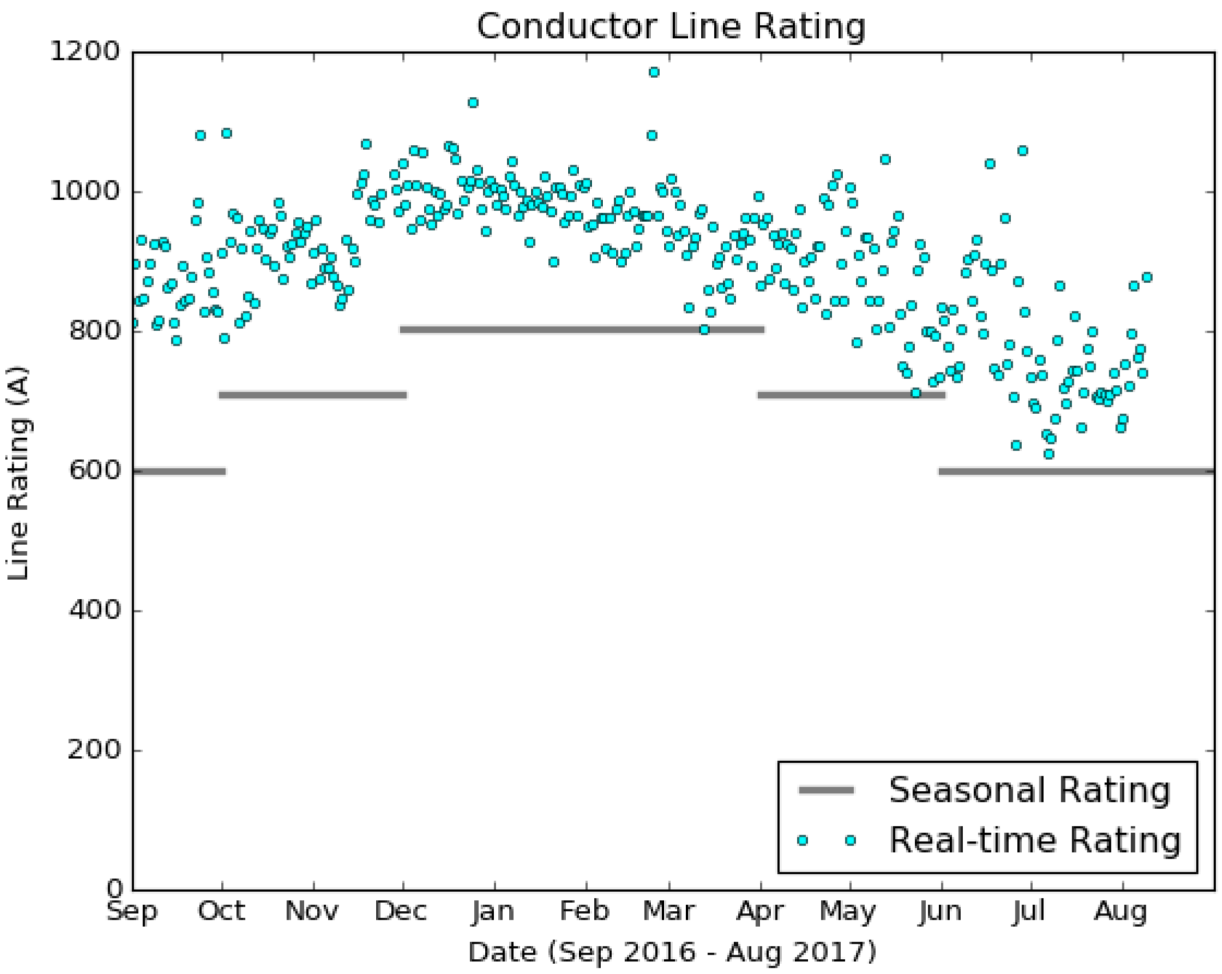




	Station #27	Station #26
Line Rating	1047 A	804 A
Time	1330L	1415L
Temperature	61.15°F	62.91°F
Solar Flux	716 W/m^2	740 W/m^2
Wind Speed	1.12 mph	1.04 mph
Wind Direction	137°	92°
Perpendicular Wind	0.82 mph	0.04 mph

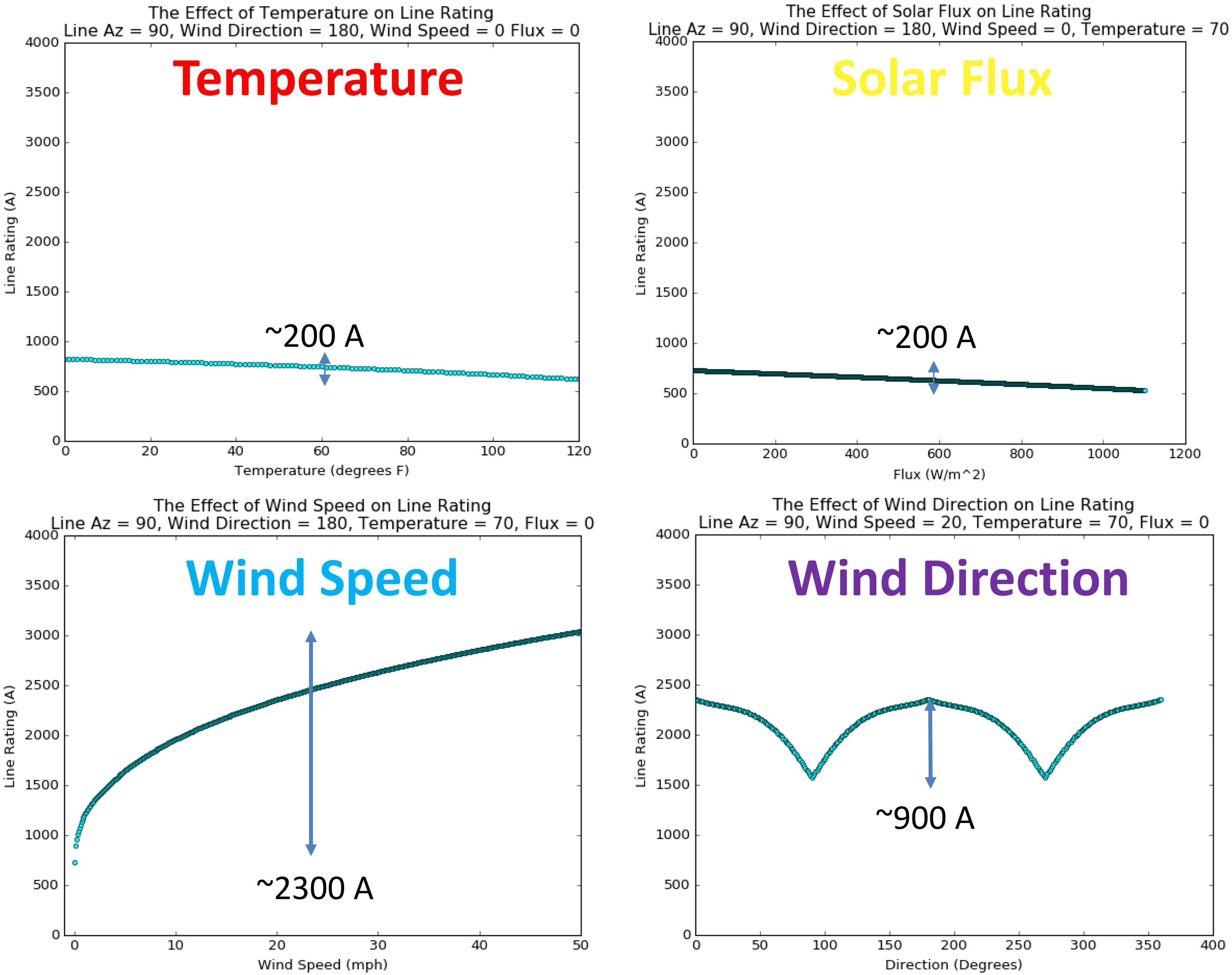
Question: Which environmental factor can we improve upon in the seasonal values?



Is this difference due to:
- Temperature?
- Winds?
- Solar flux?

Sensitivity Analysis

Wind speed has the greatest effect on line rating



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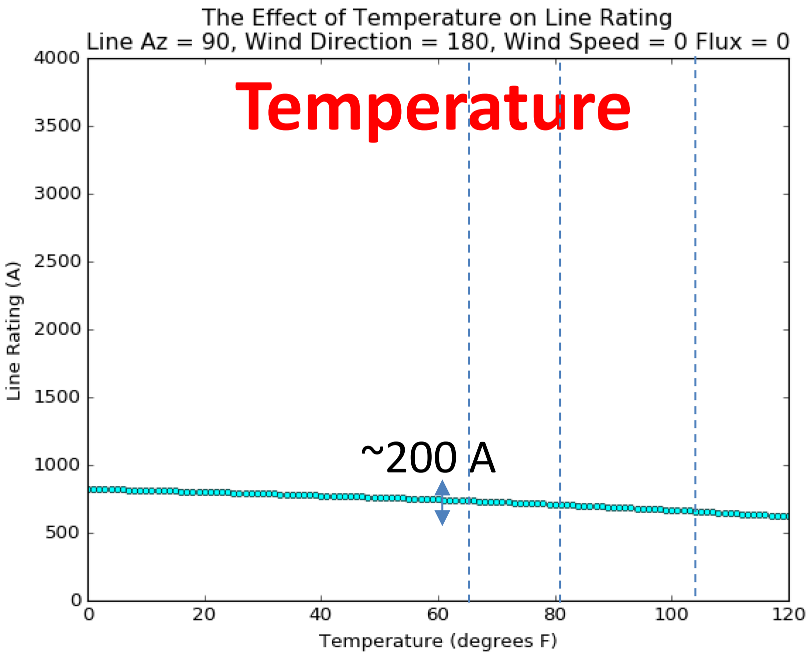
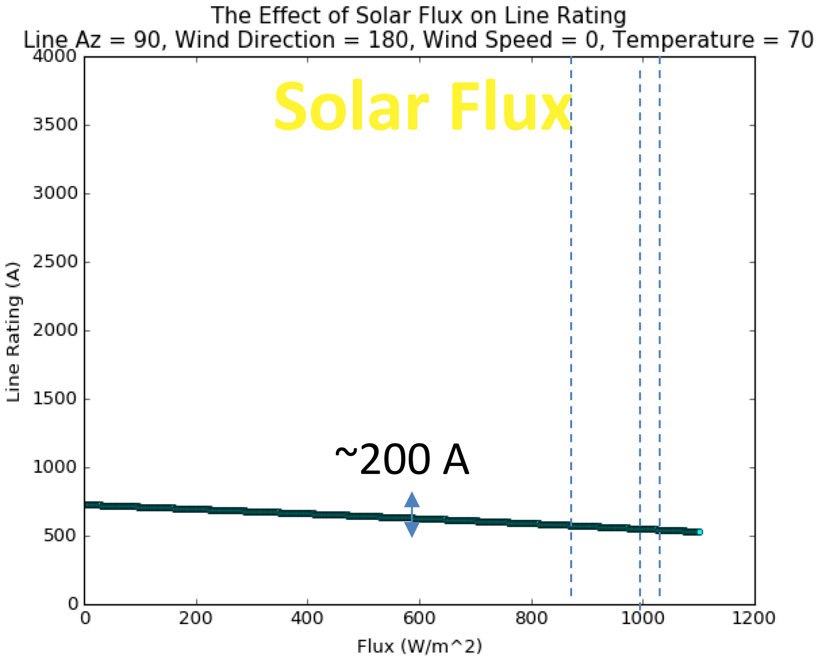
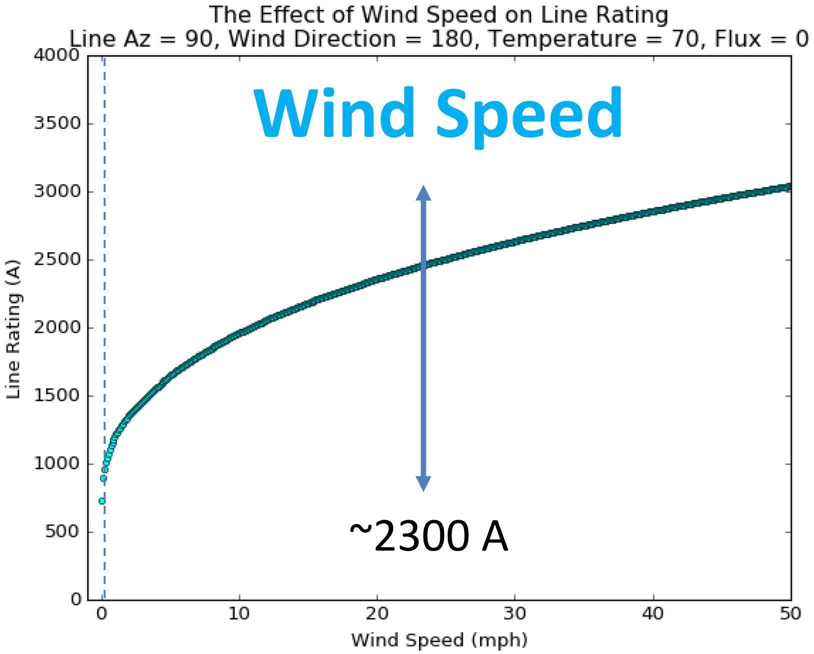
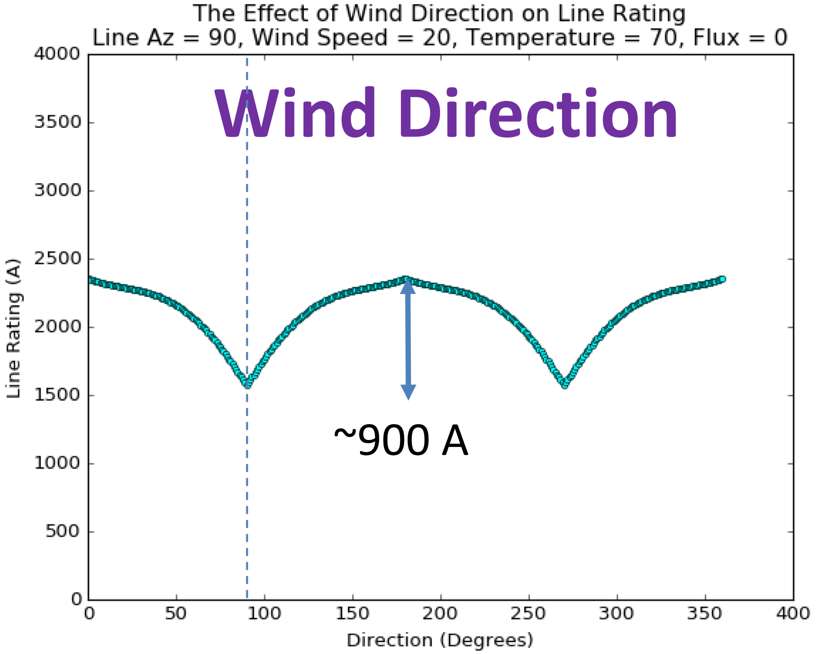




Seasonal values are conservative

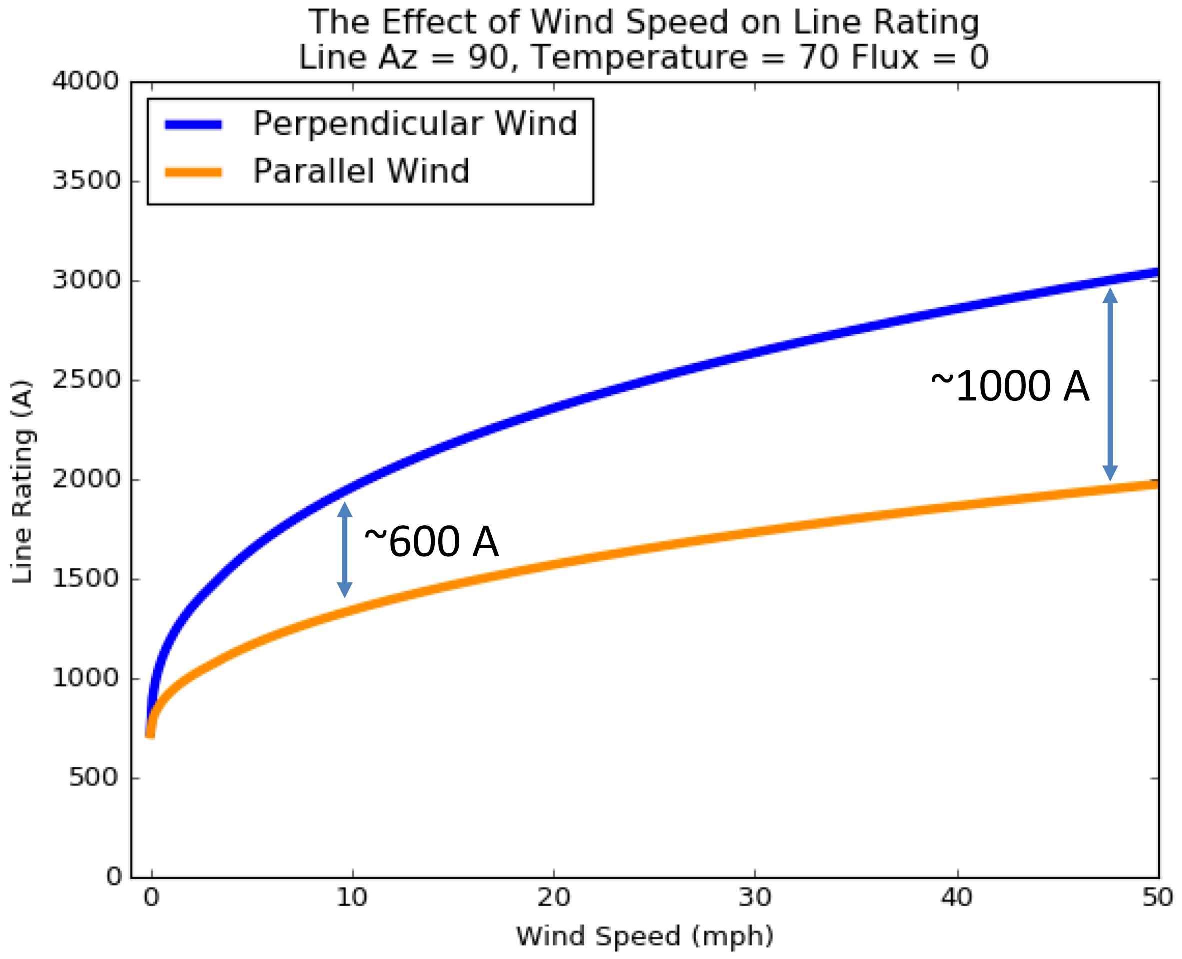




<u>Seasonal Rating Values</u>
(Summer, Winter, Transition)
Temperature = 40℃, 18℃, 27℃
Wind Speed = 0.6 m/s
Wind Direction = 90° (parallel to line azimuth)
Solar Flux = 1030 W/m^2, 850 W/m^2, 1000 W/m^2

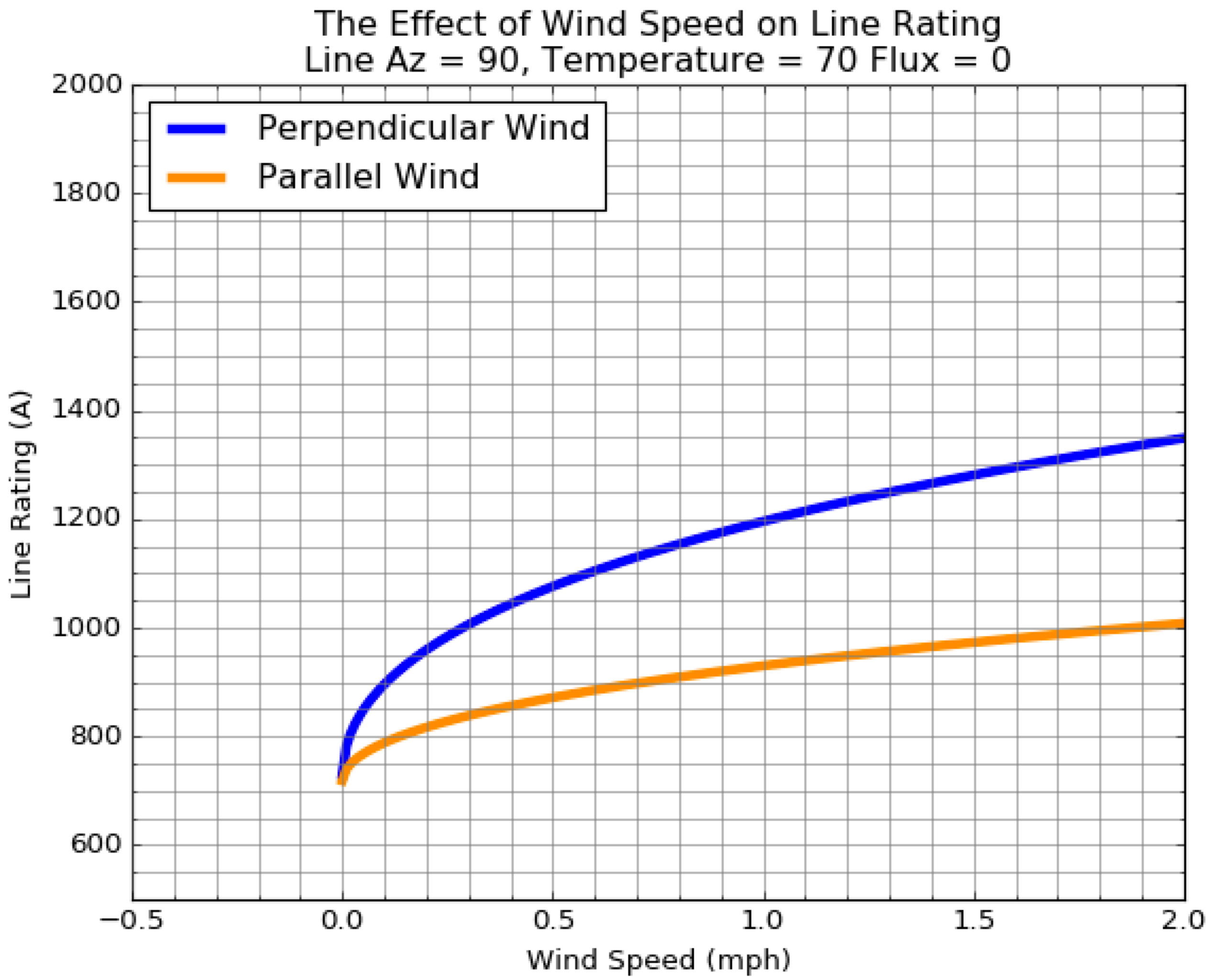
Parallel vs Perpendicular Wind

A parallel wind generates 60% less convective heat loss than a perpendicular wind



Sensitivity Analysis

The line rating changes more rapidly at lower wind speeds

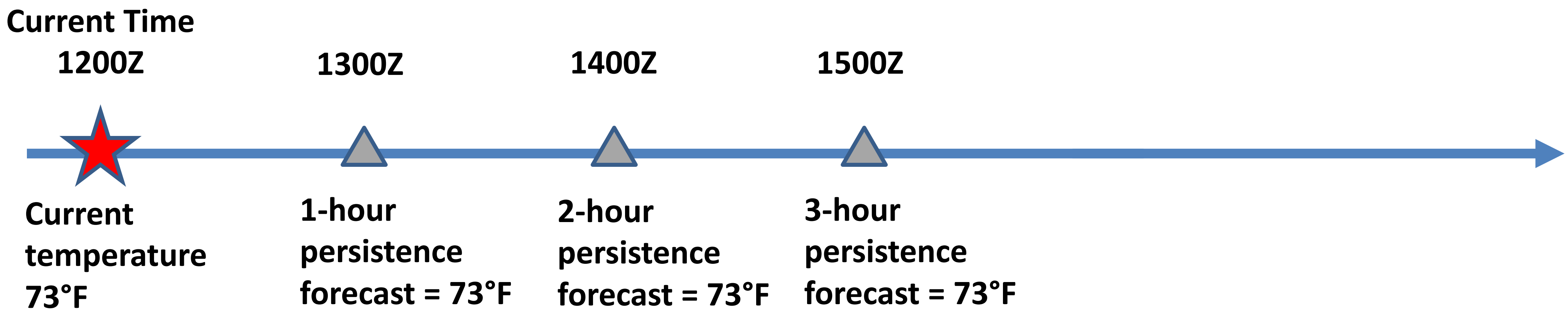


How can we better account for future weather?

- Forecast!
  - Persistence

2 types of persistence

1. General persistence - forecast the last known observed value to continue into the future



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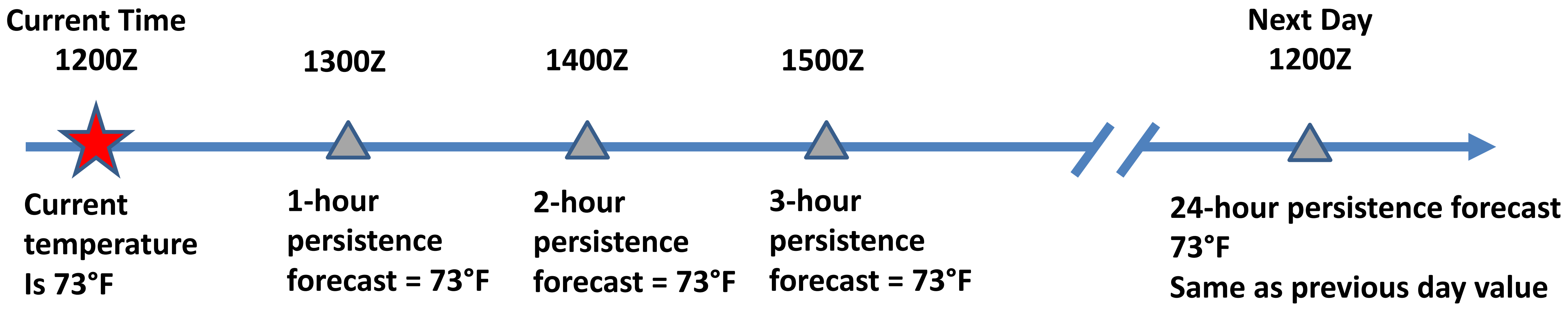
  - Persistence →

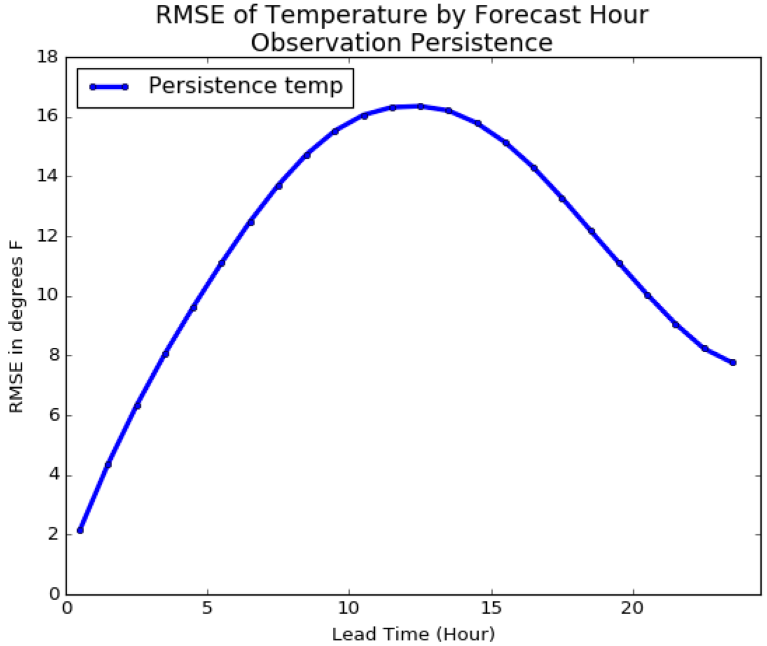
2 types of persistence

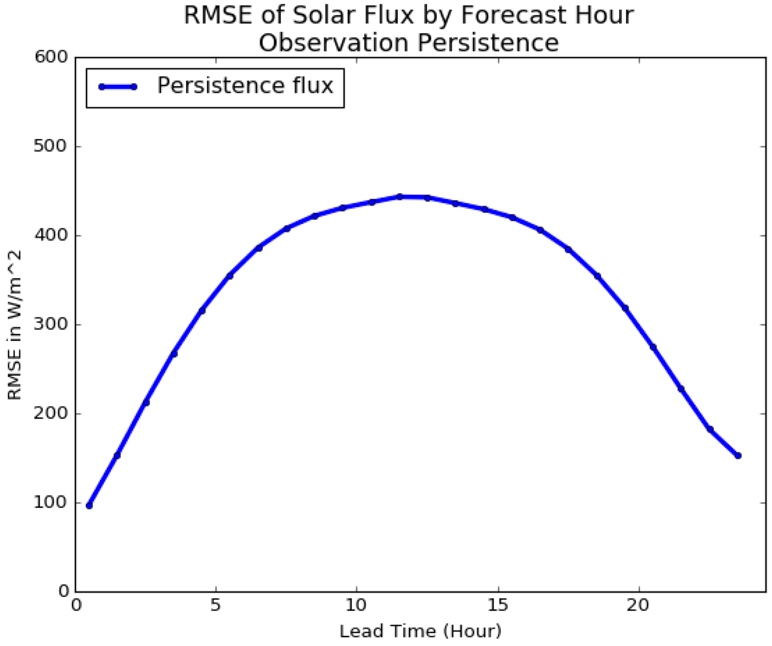
1. General persistence - forecast the last known observed value to continue into the future
2. 24-hour persistence - use the observed value from the previous day at the same time

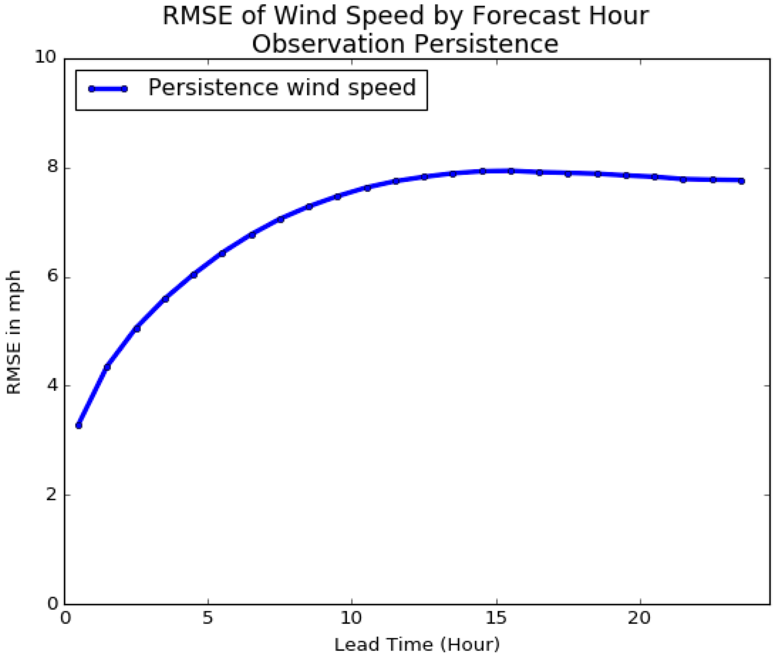


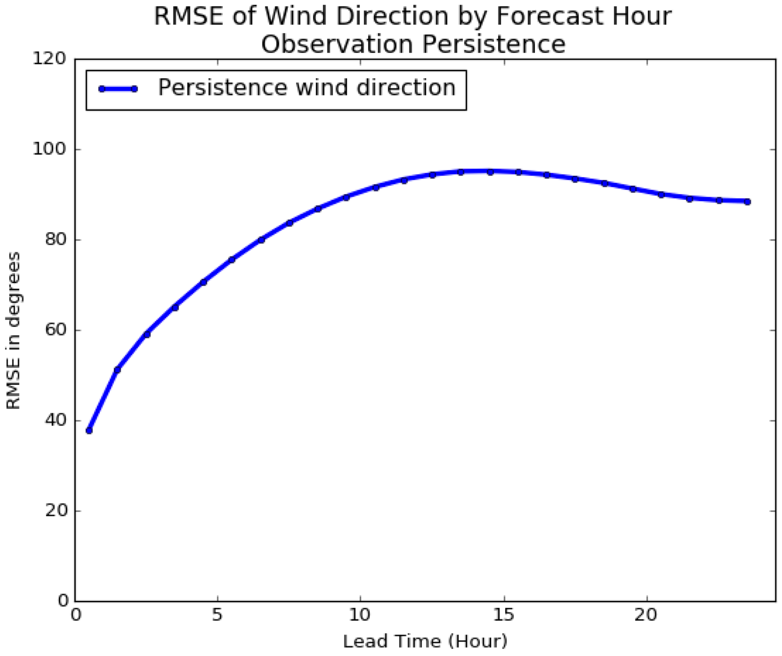
Accuracy of Persistence Forecasts

Persistence forecasts are accurate in the short-term, but the errors quickly grow with time.





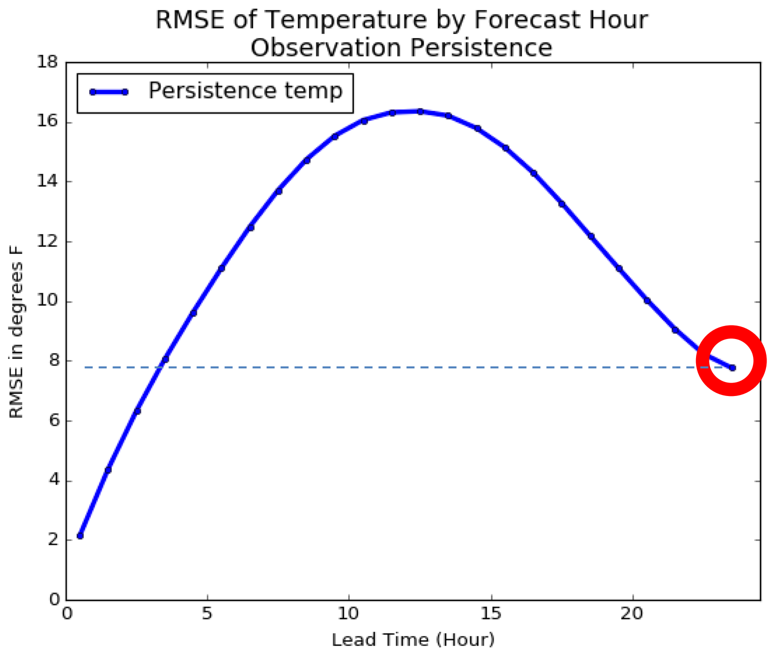


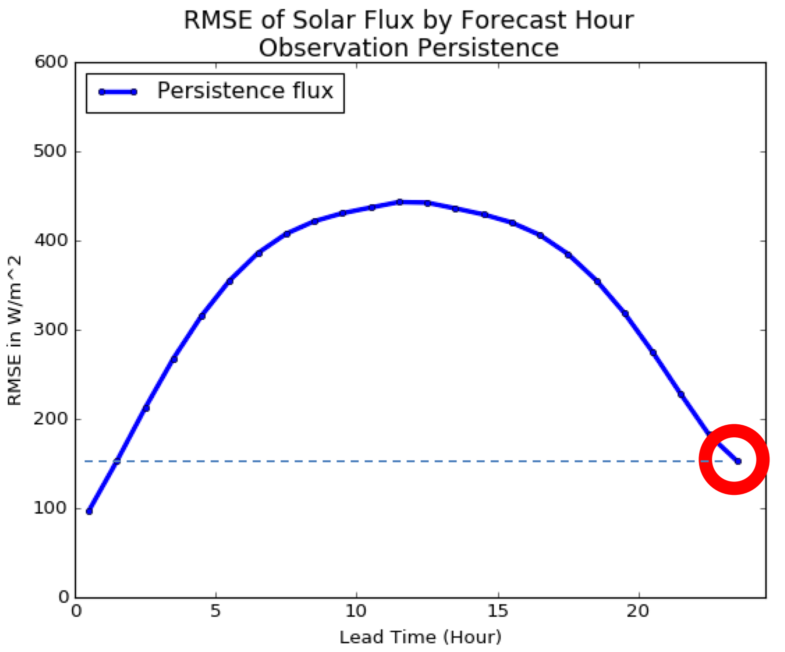


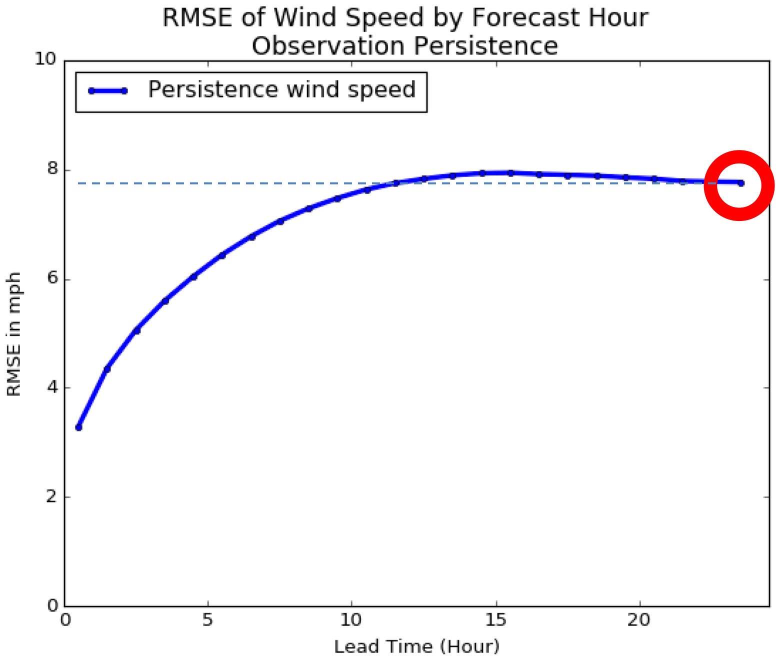
Accuracy of Persistence Forecasts

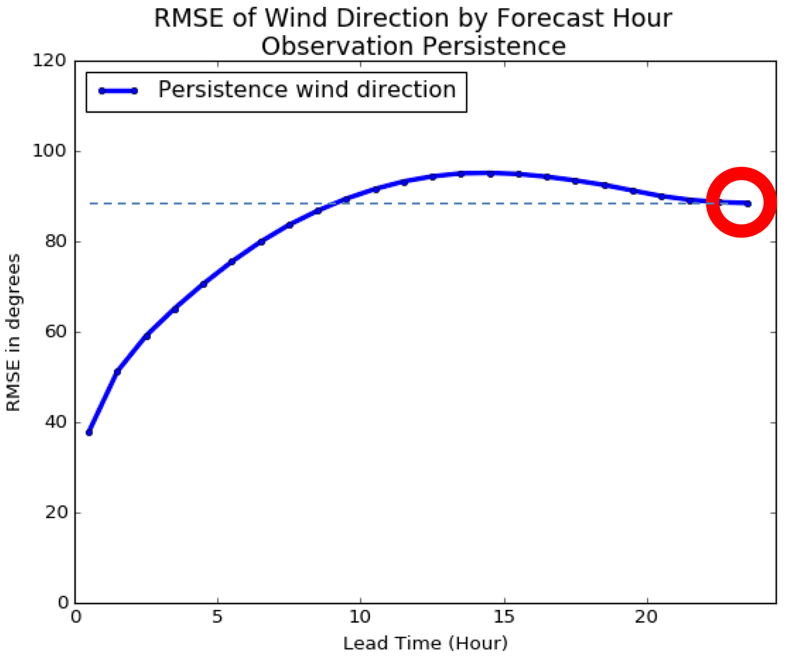
Persistence forecasts are accurate in the short-term, but the errors quickly grow with time.

Short-term persistence is better than 24-hour persistence (using value from previous day).









Can We Do Better Than Persistence?

- Forecast!
  - Persistence
  - Weather models

Forecast the last known observed value to persist into the future

Physics-based algorithms that use partial differential equations to predict the future state of the atmosphere.

<u>High Resolution Rapid Refresh (HRRR)</u>

What is the HRRR?

Inputs

Weather observations (temperature, wind, humidity, pressure)

Radar

Satellite

HRRR

Processing:

Partial differential equations

Parameterizations

Numerical approximations

Outputs – Forecasts of:

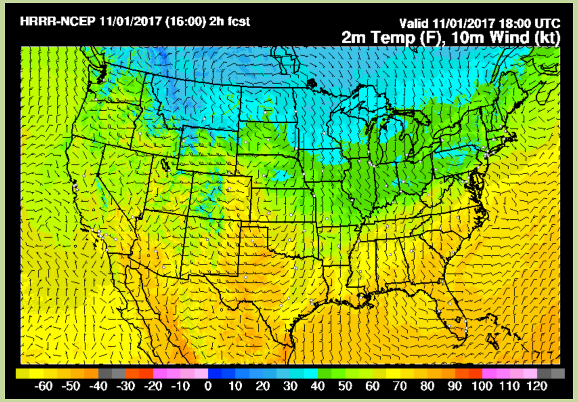
Temperature

Wind

Humidity

Rain

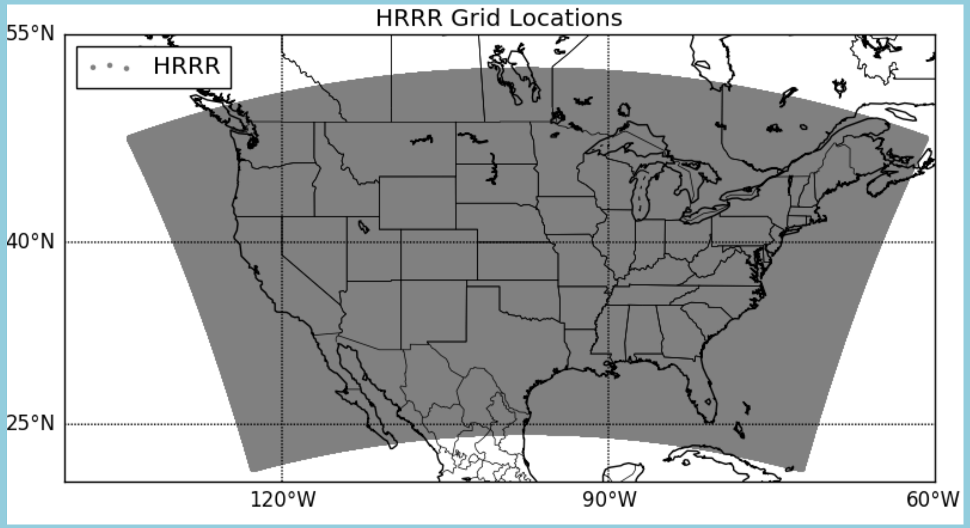
Clouds



Output of the HRRR

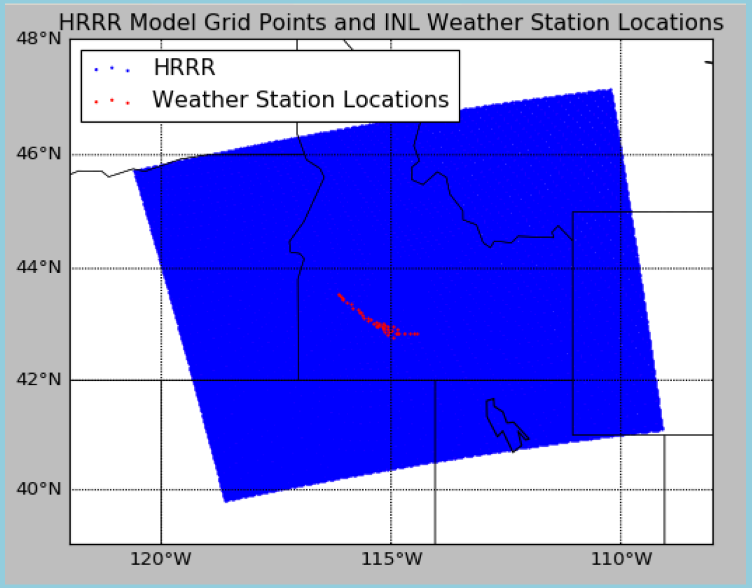
General Information

- Created by NOAA, publicly available for free at: http://www.nco.ncep.noaa.gov/pmb/products/hrrr/
- Covers CONUS at 3 km horizontal grid spacing
- Forecasts produced ever hour with output from 0-18 hours into the future at 15-minute intervals

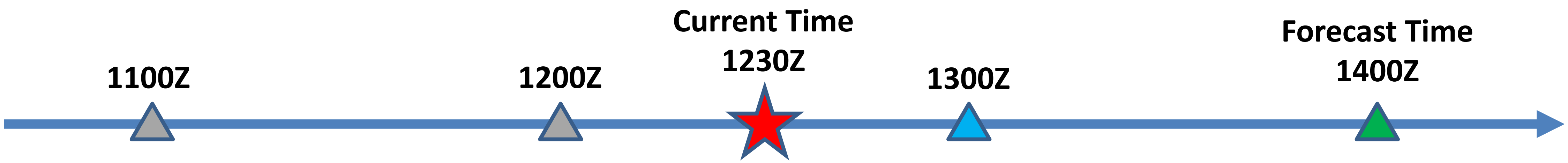


Used in this study

- Cut-out over Idaho with 3-km horizontal grid spacing
- Forecasts at 15-minute intervals from 2-18 hours
- Output variables of temperature, wind speed, wind direction, and solar flux



Applying HRRR Forecast Times to Operations



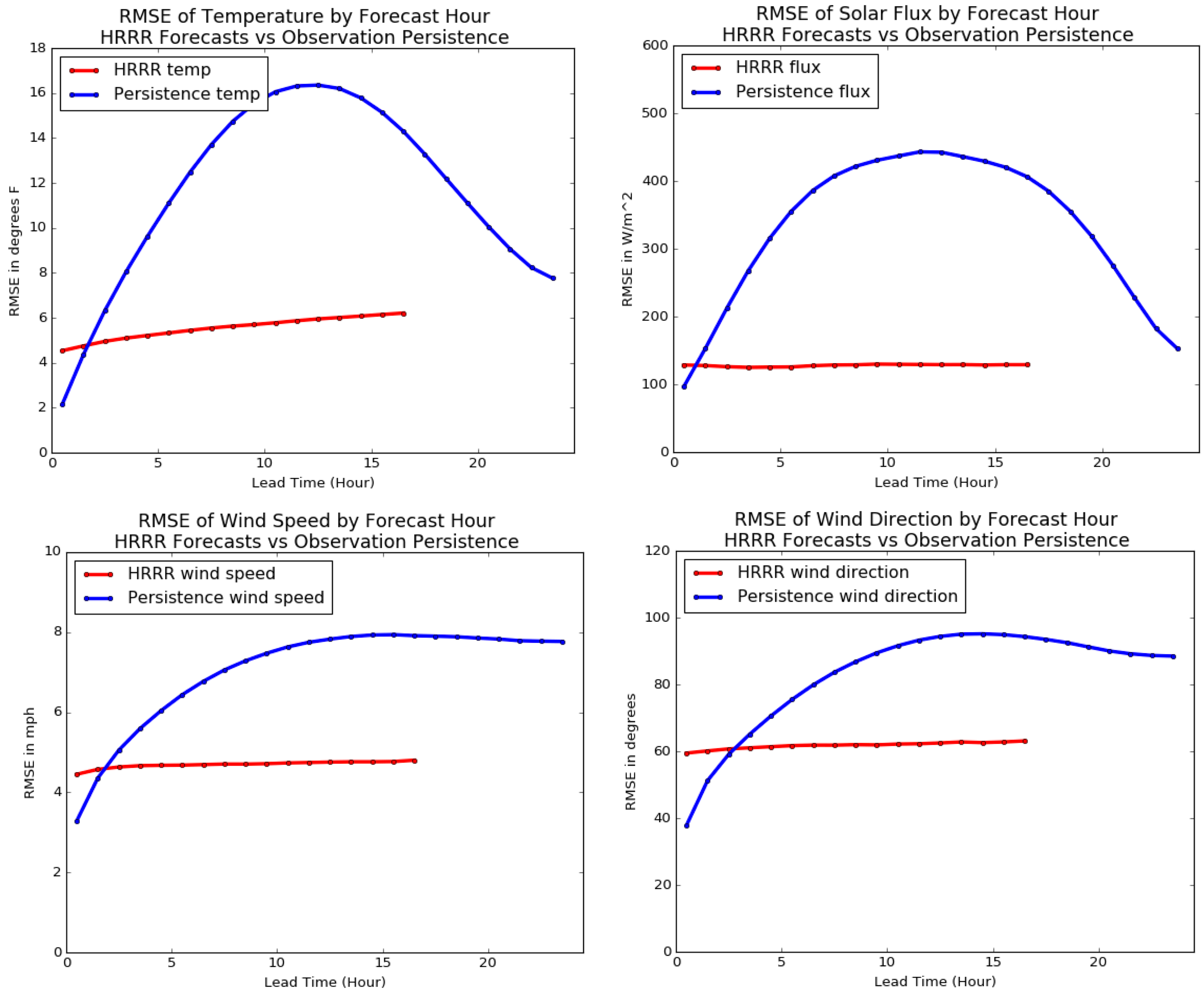
At 1230Z, you want to make a forecast for 1400Z

What is available?
1) 1100Z run of the HRRR, 3-Hour Forecast valid at 1400Z
2) Persistence from the most recent observation at 1230Z

→ Compare 3-Hour HRRR Forecast to 90-minute persistence forecast

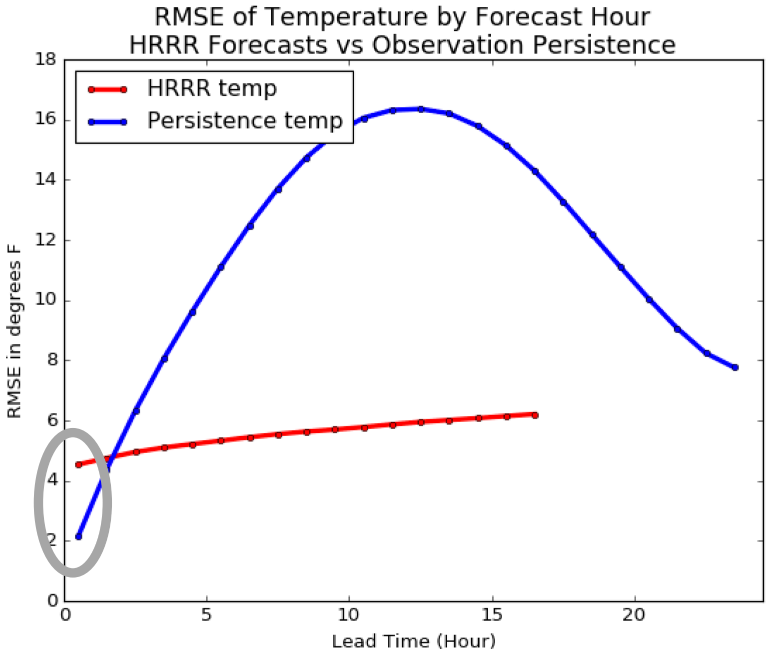
Assumptions:
1) HRRR is available 80 minutes after its 0-Hour time
2) Observations from weather stations are available in real-time

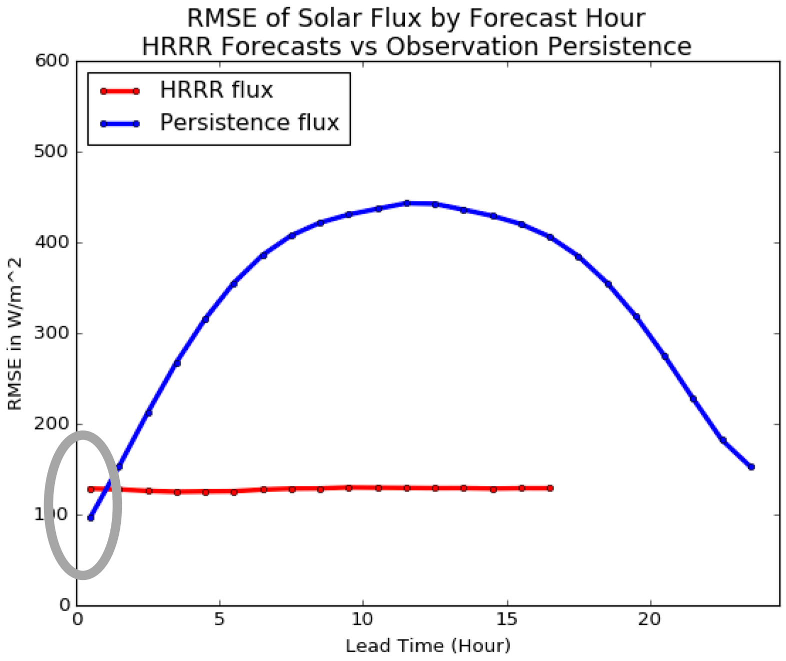
Accuracy of HRRR Forecasts

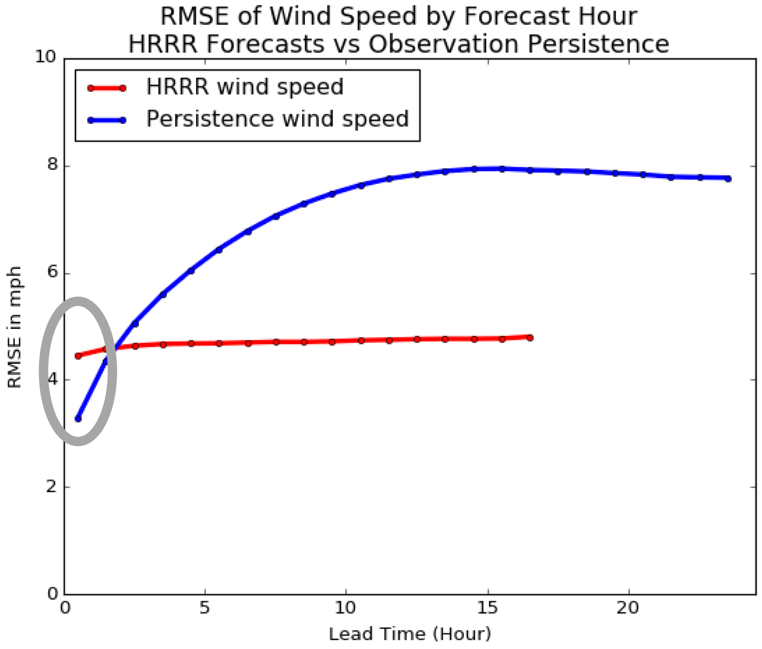


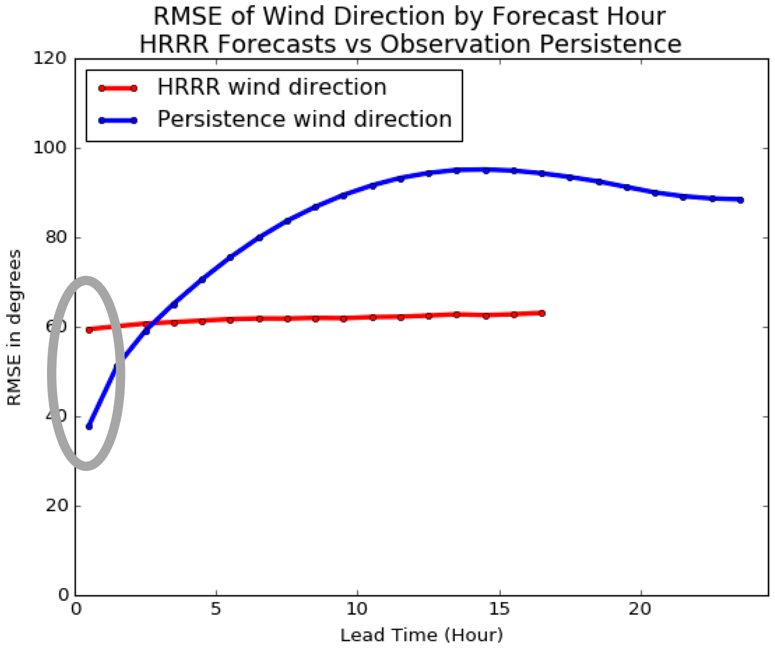
Accuracy of HRRR Forecasts

Persistence is better than the HRRR at the 30-minute lead time





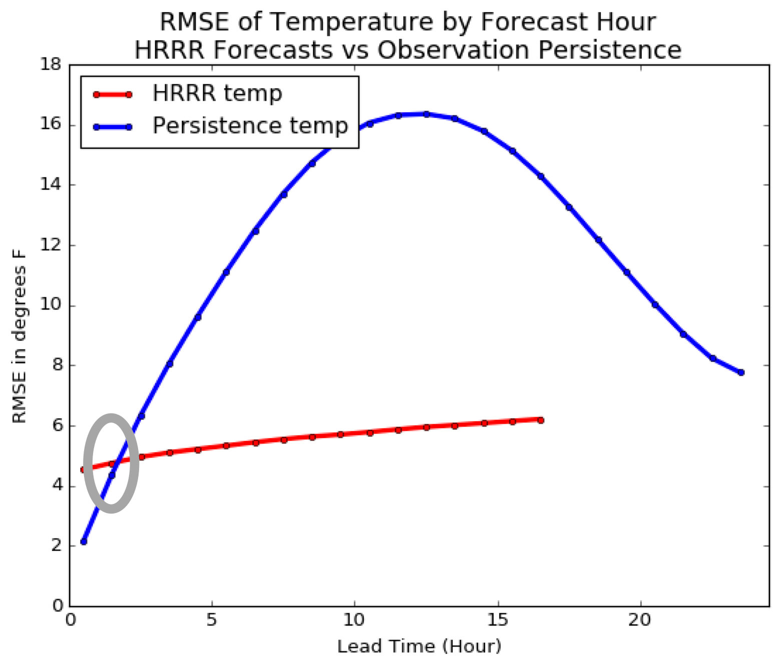


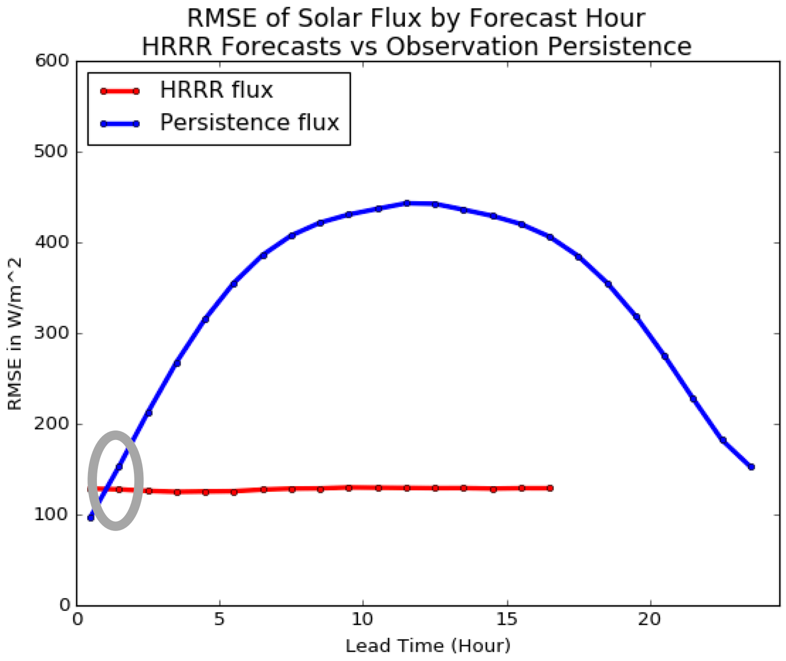


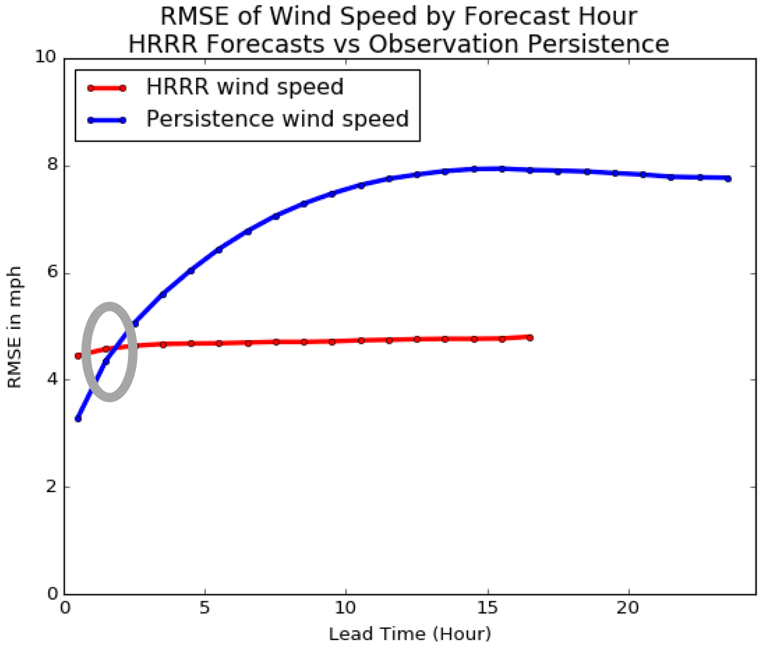
Accuracy of HRRR Forecasts

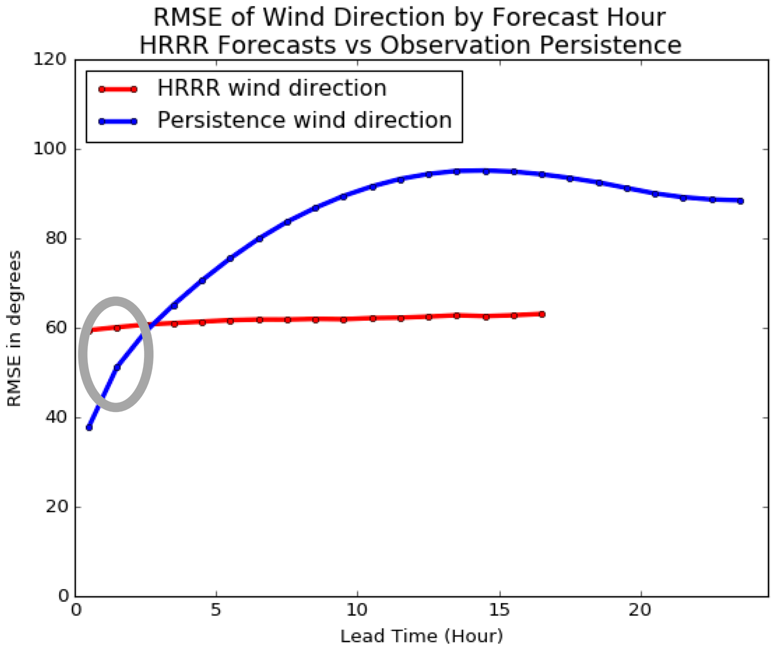
Persistence is better than the HRRR at the 30-minute lead time

Similar errors at 1.5 hour lead time (except wind direction)







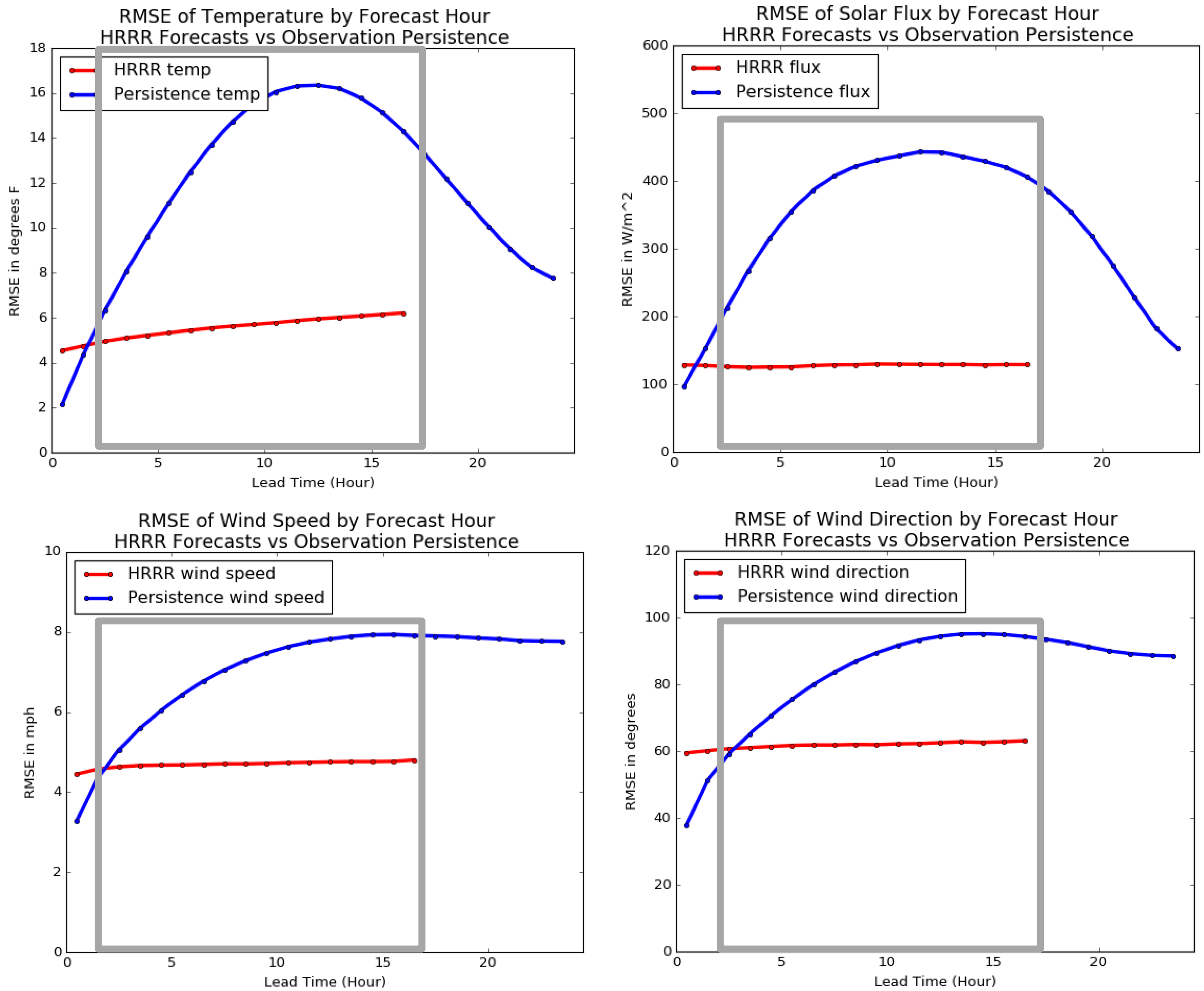


Accuracy of HRRR Forecasts

Persistence is better than the HRRR at the 30-minute lead time

Similar errors at 1.5 hour lead time (except wind direction)

HRRR forecasts are more accurate than persistence for lead times 2.5 – 16.5 hours



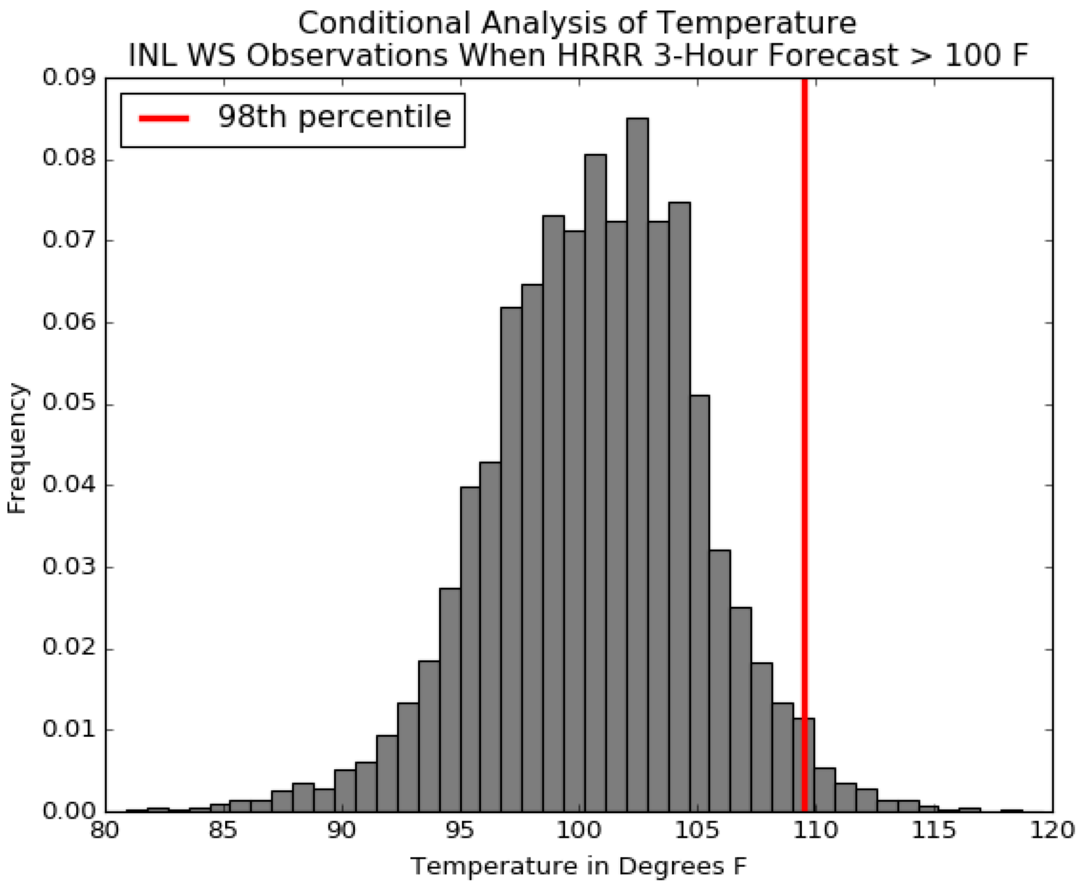
How to Use HRRR Forecasts?

We know that there is some error in the HRRR forecast and we want to account for it to make our line ratings conservative.

How do we do this?

Threshold analysis of errors

- Given a HRRR forecast in a certain range, 98% of the weather station observations were found to be below (above) the threshold for temperature and flux (wind speed)



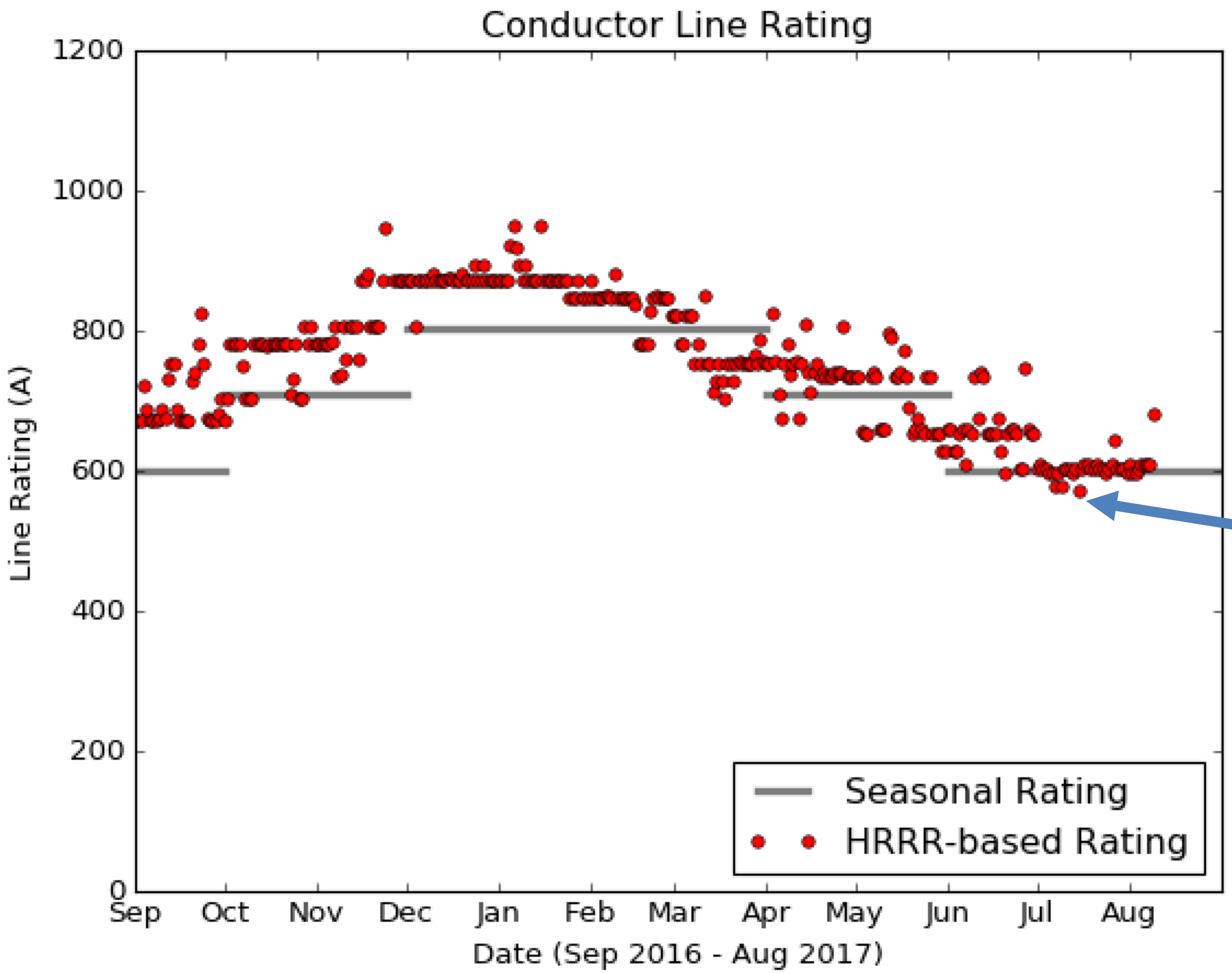
Error of HRRR Forecasts

- Conditional analysis at various thresholds for temperature, wind speed, and solar flux
- Used these values to modify the HRRR forecast and account for the potential error
  - For example, if the HRRR forecasted 103°F, then a value of 109.54°F was input into the line rating equation

	Given HRRR forecast of:	98% threshold of observations:
Temperature	<20F	25.08F
	20-49.9F	52.35F
	50-69.9F	72.59F
	70-89.9F	92.82F
	90-99.9F	103.38F
	>100F	109.54F
Wind Speed	15-19.9 mph	2.56 mph
	>20 mph	2.83 mph
Solar Flux	5-19.9 W/m^2	35 W/m^2
	20-99 W/m^2	280 W/m^2
	100-299 W/m^2	438 W/m^2
	300-499 W/m^2	580 W/m^2
	500-699 W/m^2	752 W/m^2
	700-899 W/m^2	923 W/m^2
	>900 W/m^2	988 W/m^2

Line Rating with HRRR Forecasts

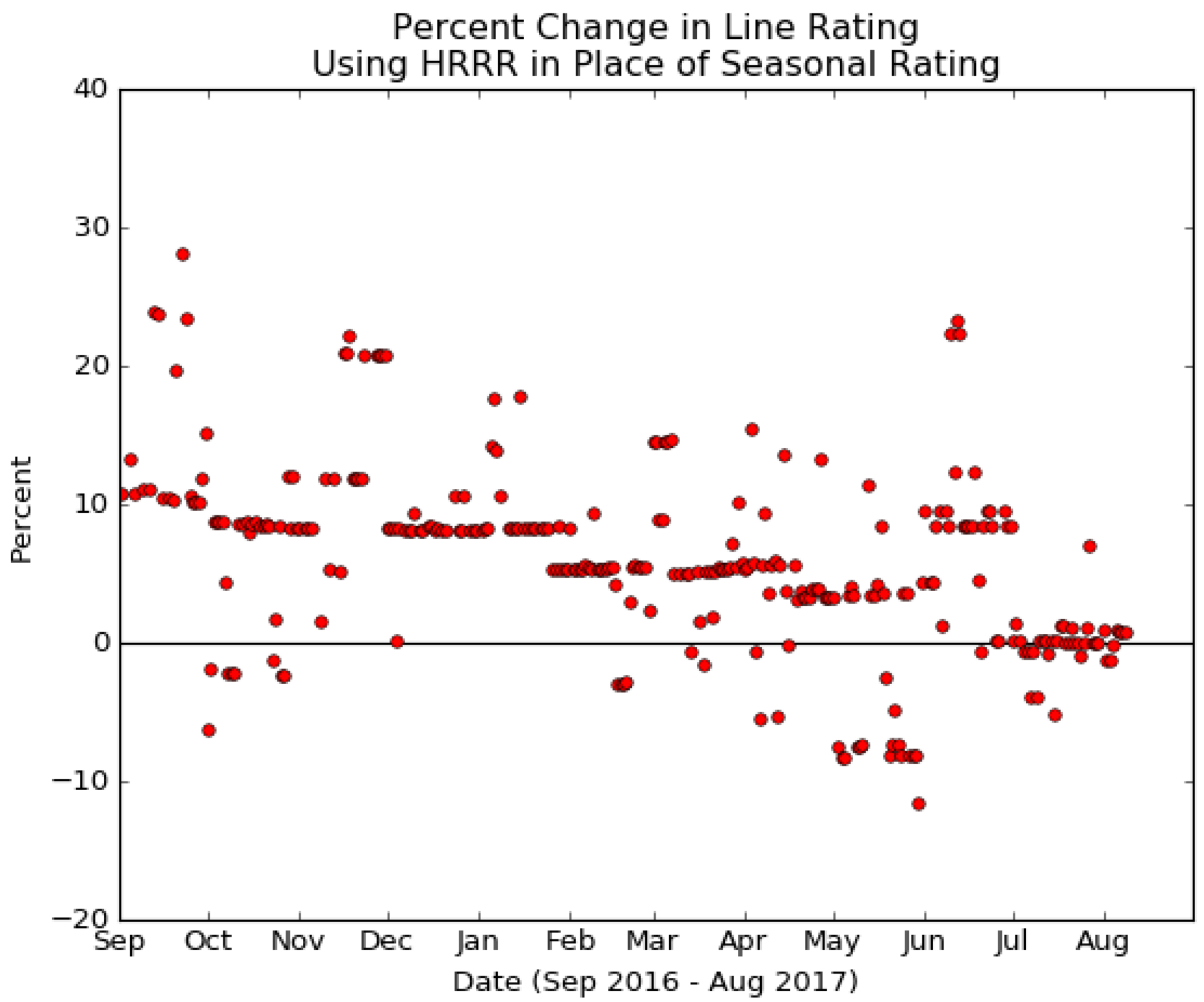
This is the additional capacity in the lines that could have been gained over the last year by using HRRR 90-minute forecasts.



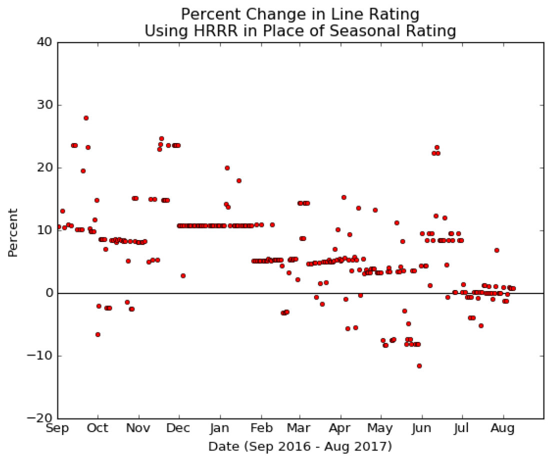
There are some times, particularly during the spring and summer, where using the HRRR forecast would have led to a lower line rating, which includes the safety factor.

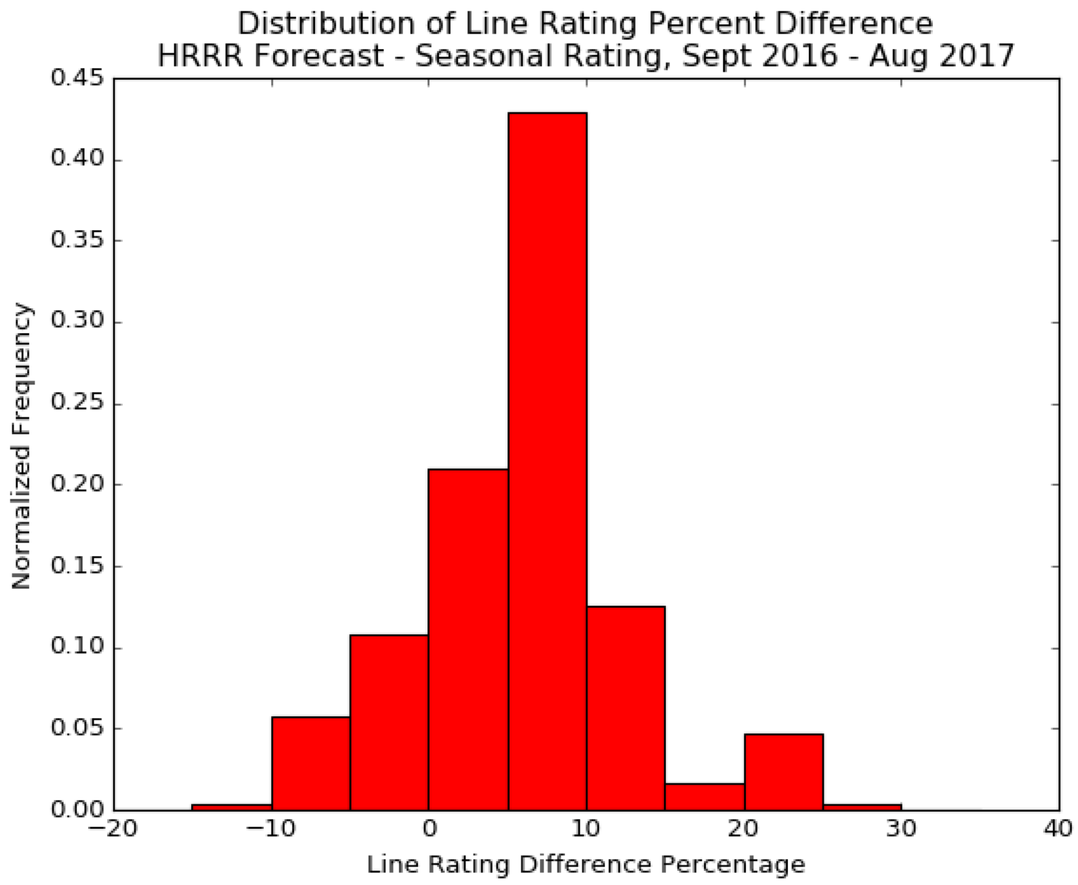
Percent Difference in Line Ratings with HRRR

Generally, 8% additional capacity September through February, then 5% additional capacity March through June. High temperatures during July and August prevented additional capacity during the summer.



Distribution of Percent Differences with HRRR



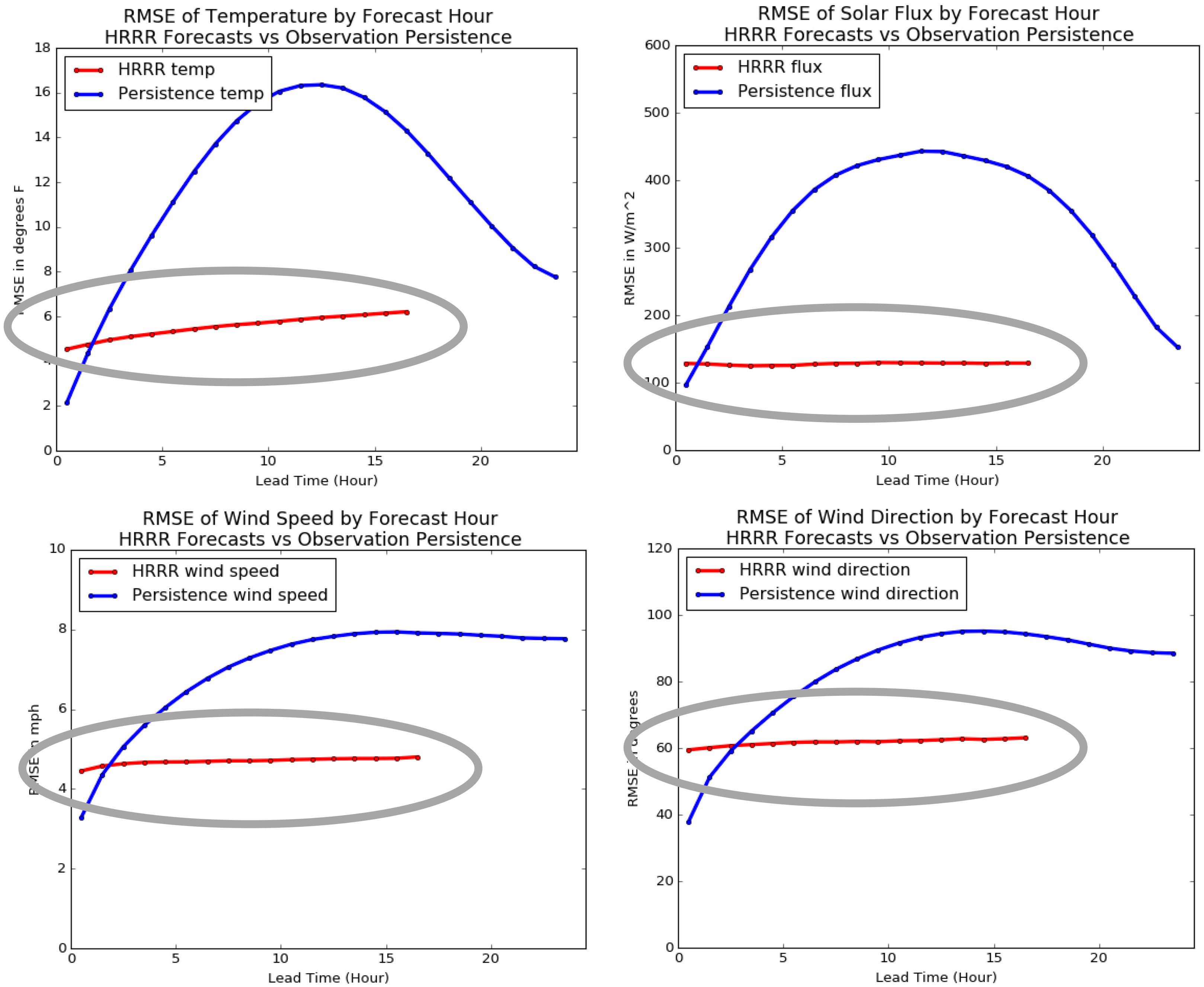


The most frequent differences between HRRR forecast ratings and seasonal ratings were line rating increases of 0-15%.

~20% of days the minimum rating using the HRRR was below the seasonal rating (usually due to calm winds and seasonally high temperatures)

Can We Achieve Similar Results at Longer Lead Times?

Yes. The error of HRRR forecasts is similar across all leads times. This means that longer range forecasts can be used for line rating with similar results.



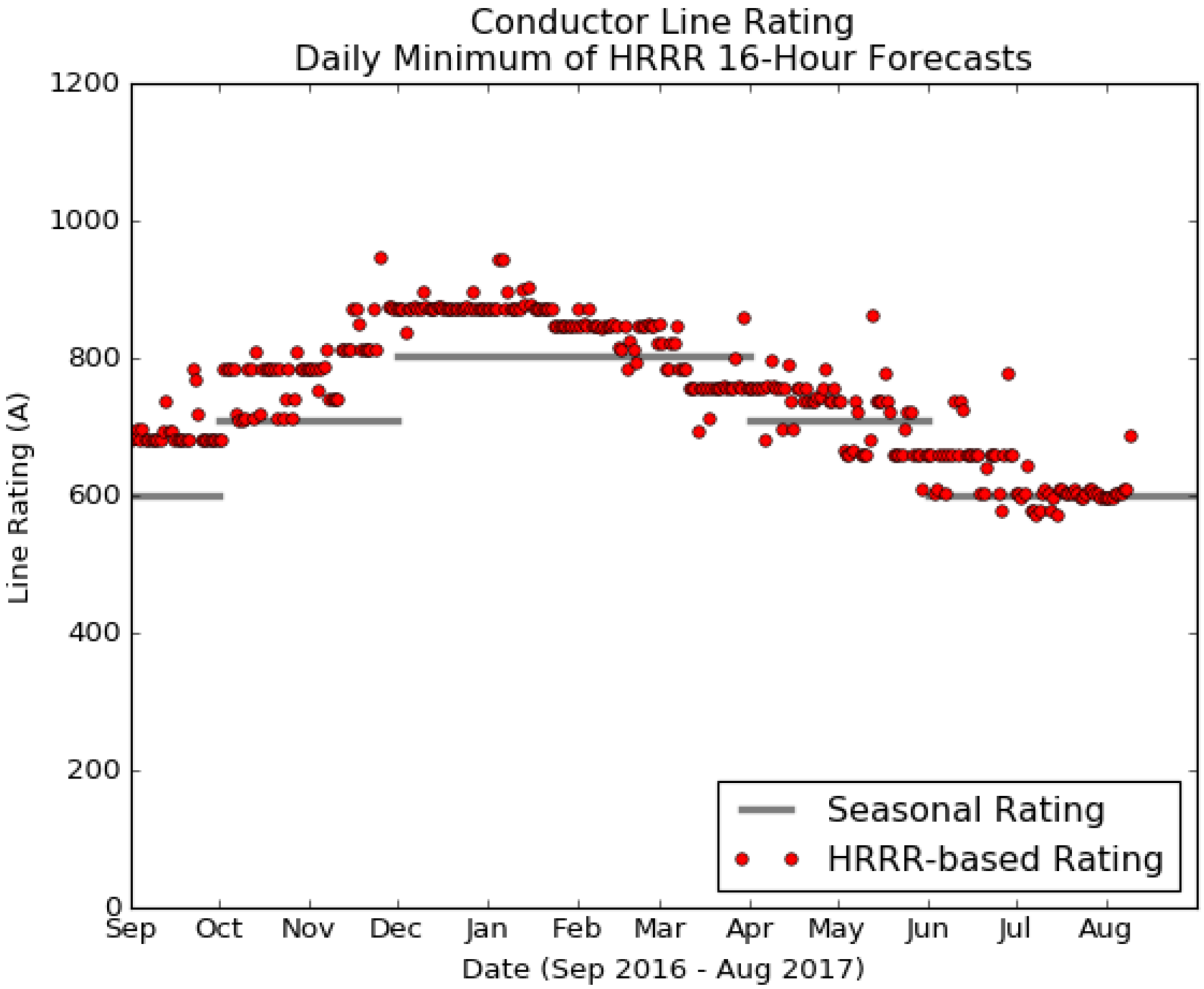
Thresholds at Various Lead Times

	Given HRRR forecast of:	HRRR Forecast: 98% threshold of observations 30-minute	90-minute	6-hour	12-hour	16-hour
Temperature	<20F	25.08	25.08	25.96	26.84	26.84
	20-49.9F	52.35	52.35	52.35	52.35	52.35
	50-69.9F	72.59	72.59	72.59	71.71	71.71
	70-89.9F	92.82	92.82	91.94	91.94	91.06
	90-99.9F	103.38	103.38	103.38	103.38	103.38
	>100F	109.54	109.54	109.54	109.54	109.54
Wind Speed	15-19.9 mph	2.95	2.56	2.1	2.01	1.82
	>20 mph	4.93	2.83	4.65	3.88	3.14
Solar Flux	5-19.9 W/m^2	35	35	34	35	35
	20-99 W/m^2	289	280	255	242	243
	100-299 W/m^2	433	438	432	422	408
	300-499 W/m^2	580	580	578	574	574
	500-699 W/m^2	758	752	757	751	751
	700-899 W/m^2	933	923	922	924	922
	>900 W/m^2	988	988	984	989	992

The 98% thresholds change very little as forecast lead time increases.

Line Rating with HRRR 16-Hour Forecasts

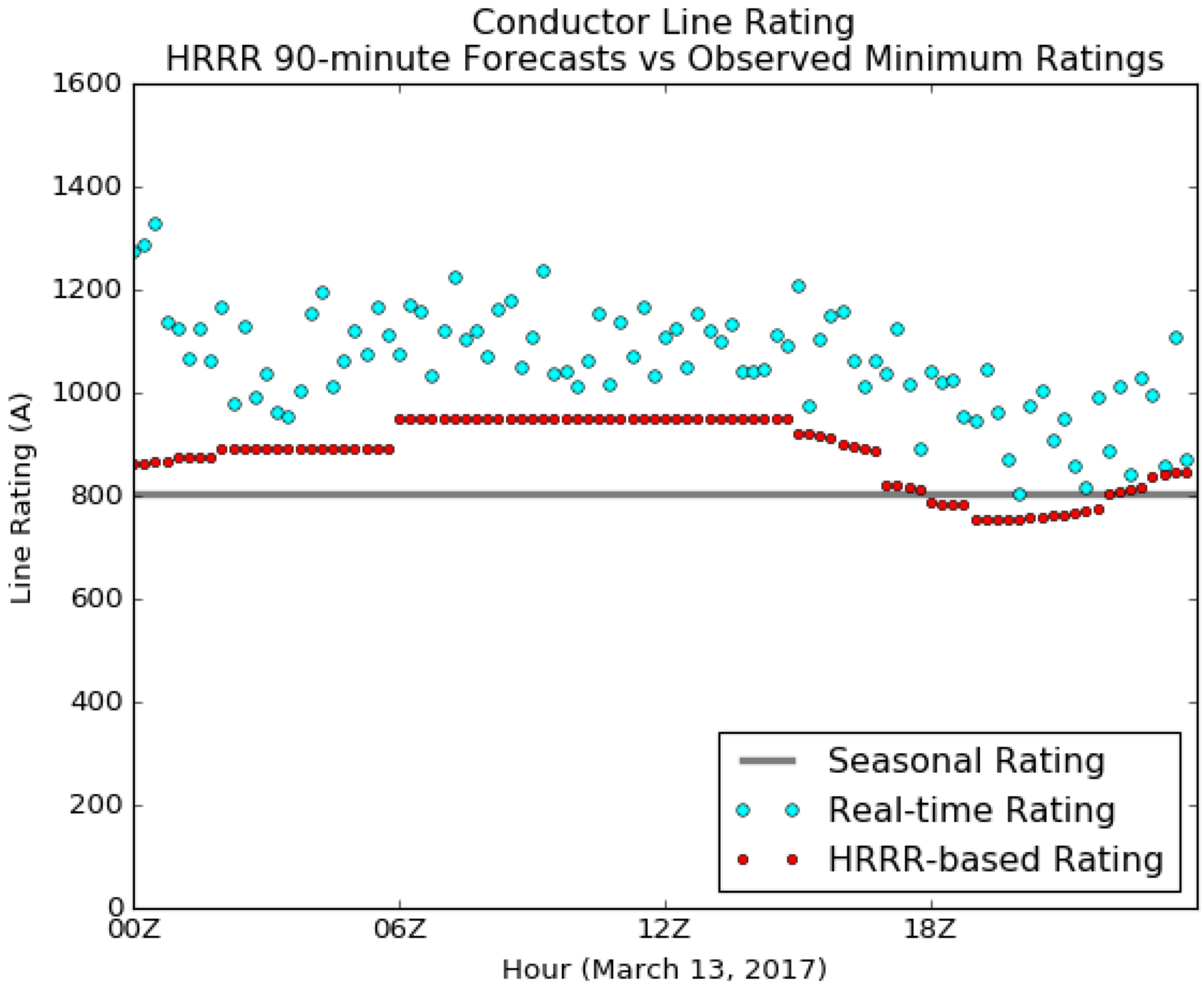
Similar ratings to other HRRR forecast times.



In April 2018, the next version of the HRRR will produce operational forecasts out to 36 hours.

What's possible …

HRRR 90-minute forecasts would have increased the line rating from the seasonal value during the early part of the day (00-18Z) while decreasing the rating during a period (18-21Z) when the real-time rating approached the seasonal value



HRRR 90-minute forecasts remain below the real-time rating from observations

Result = increased line rating and better safety margins

Conclusions

- Seasonal line ratings are conservative and line ratings could be raised by using forecasts from the HRRR
  - Weather forecasts add flexibility in operating and planning; additional time to decide how to operate efficiently
- Wind speed is the primary meteorological variable driving line ratings
- Additional work can be done to improve the thresholds and better account for specific line orientations and use cases

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