Data Assimilation for Irradiance Forecasting

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RESEARCH, DISCOVERY & INNOVATION
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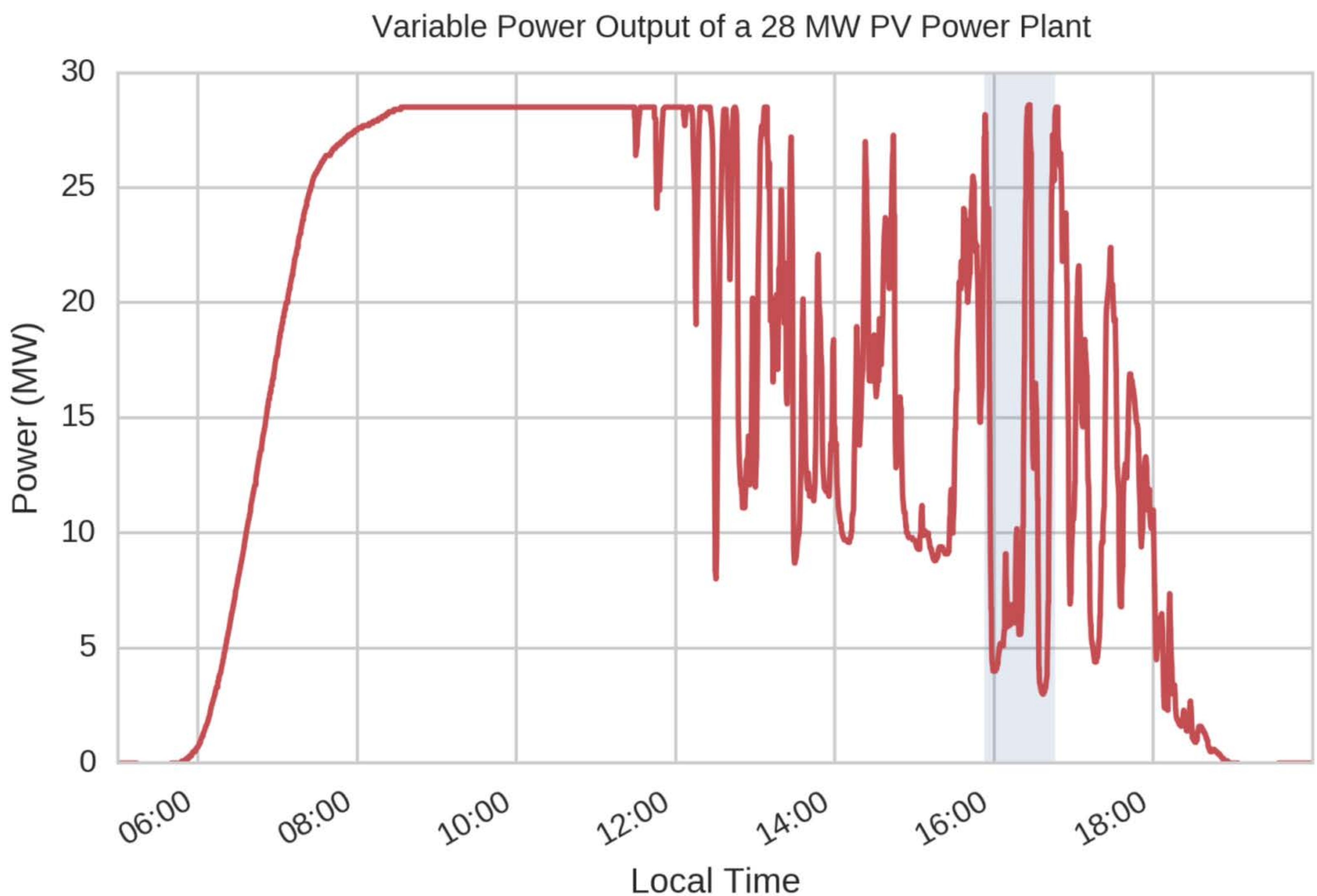
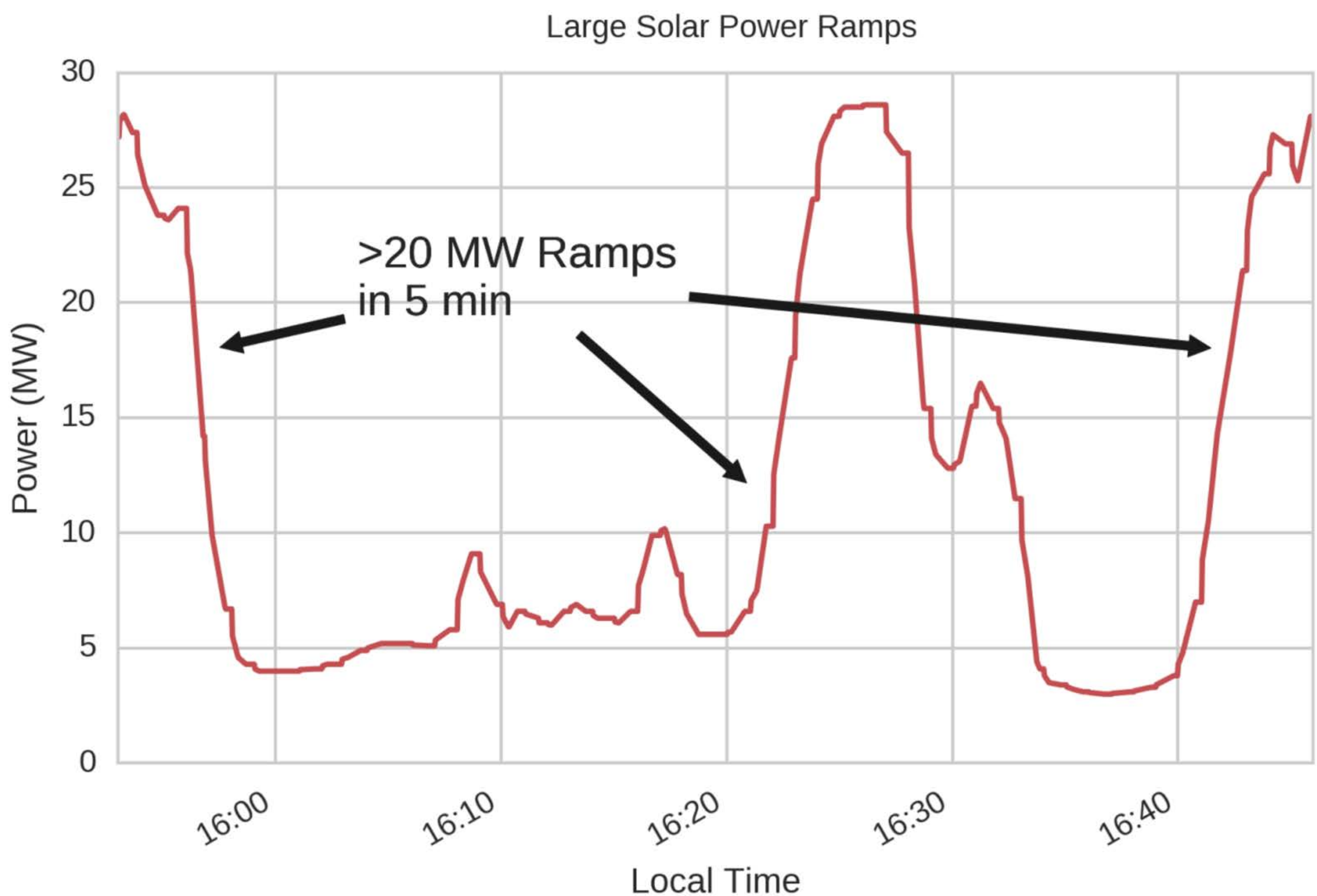
Irradiance forecasting



- Several 20 MW ramps taking about 5 minutes
- A 20 MW is about equivalent to the demand of 10,000 homes

Irradiance forecasting



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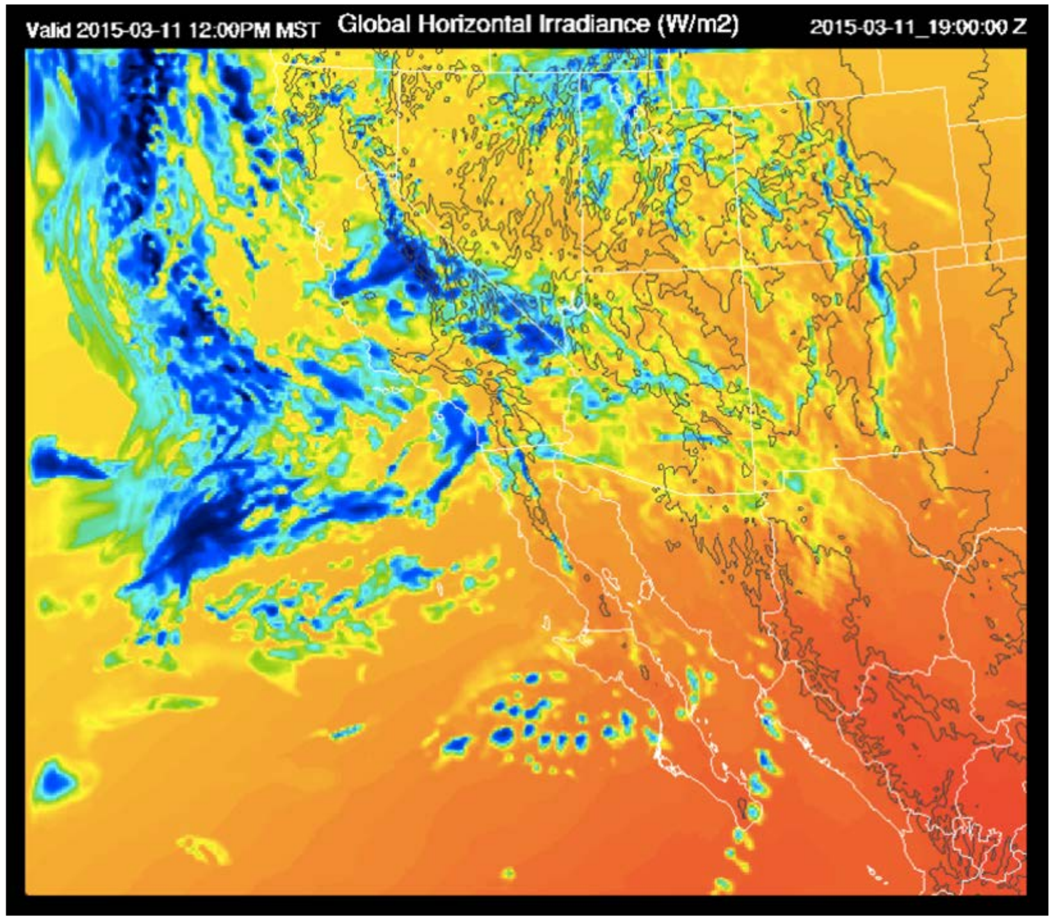
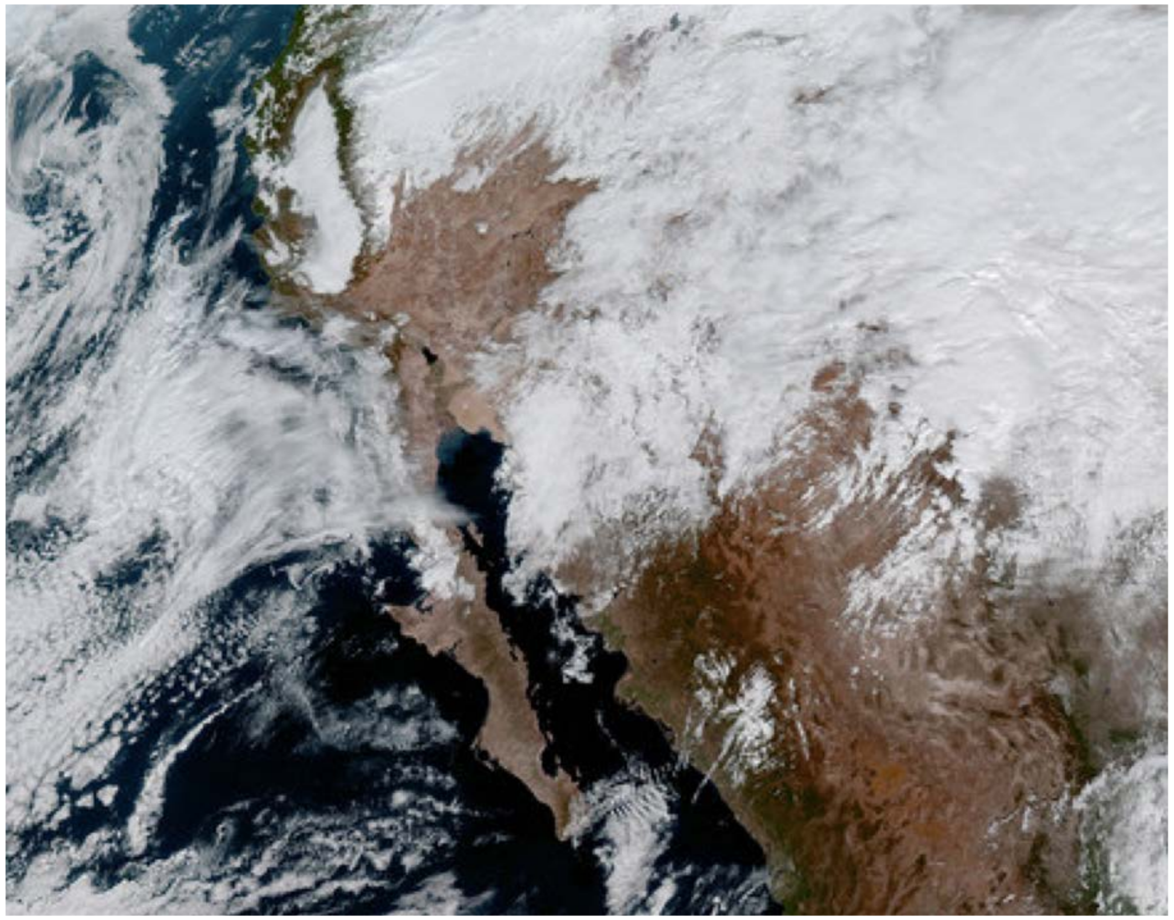
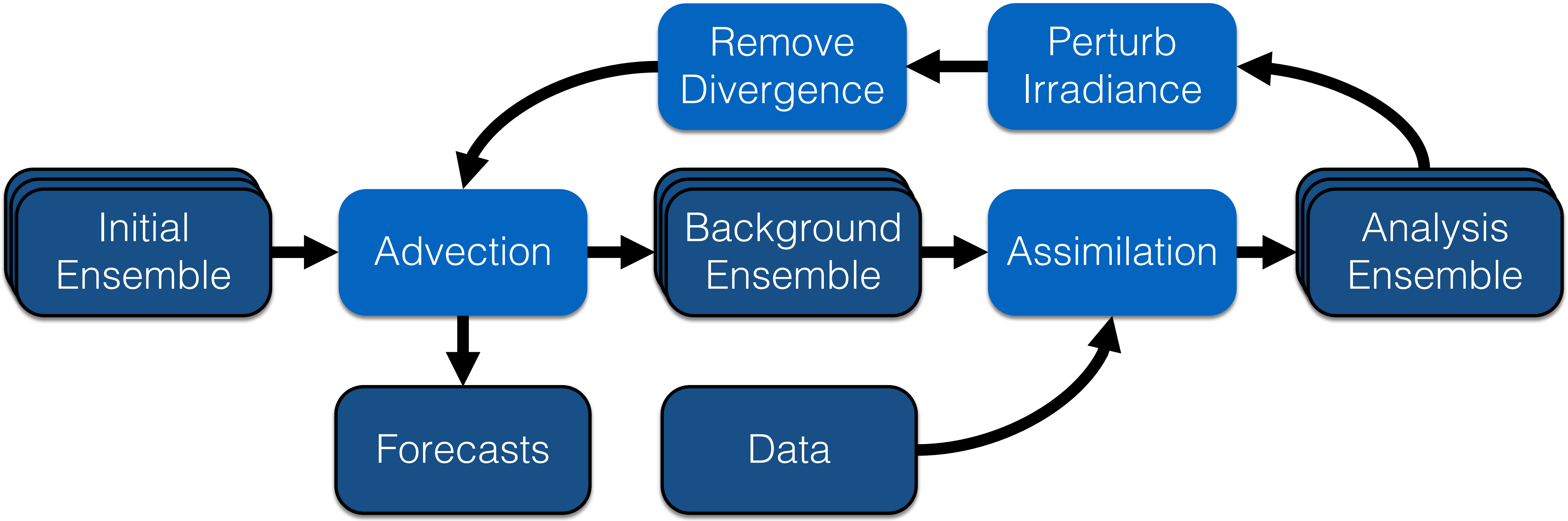
Irradiance forecast techniques





- The University of Arizona Hydrology and Atmospheric Science WRF model forecasts irradiance.
- Can we do better using more data on intra-hour timescales?
- Require irradiance fields on the scale of a city (Tucson, AZ) every 5 minutes
- We will advect a 2D cloud field using a 2D cloud motion field.
- This work will focus on improving the cloud motion field.

Forecast system

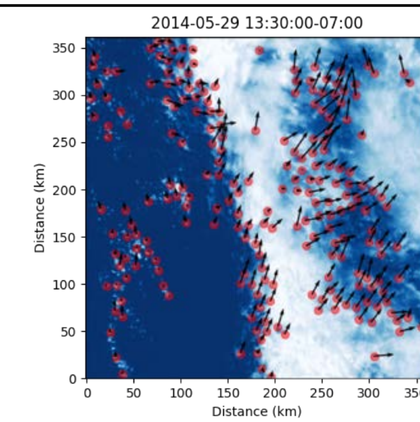


- Each ensemble member has unique cloud field and cloud motion field
- The LETKF and EnKF are used for assimilation
- Irradiance perturbation and divergence removal will be discussed later

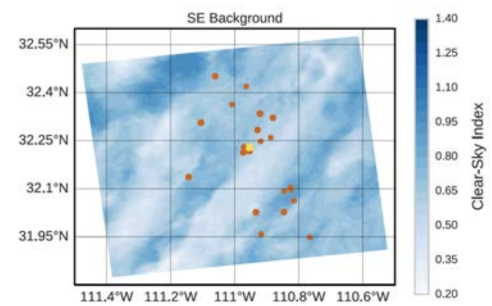
(eg. Hunt et al., 2007)(eg. Burges et al., 1998)

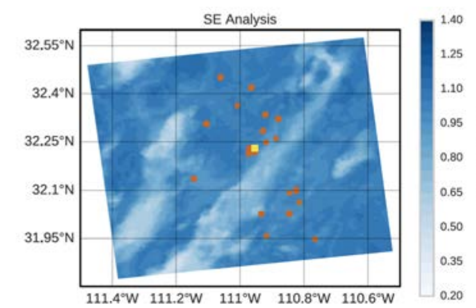
Overview

Data

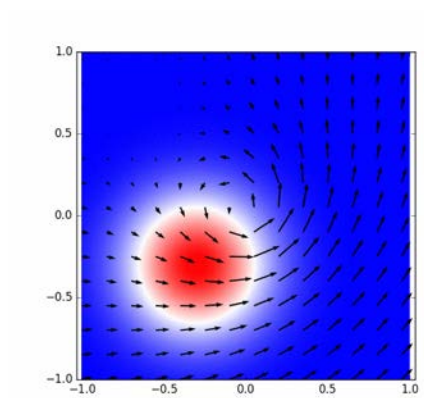


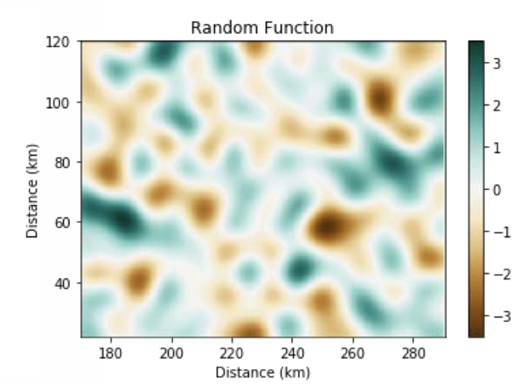
Previous Work



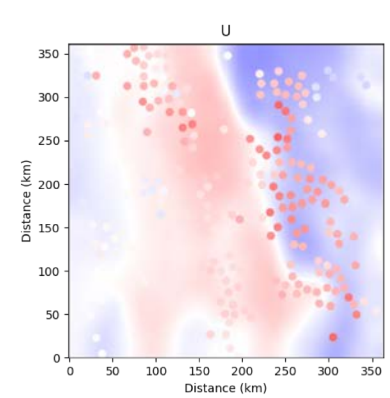


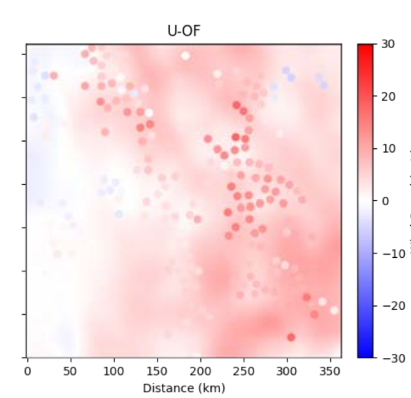
Model & Perturbation



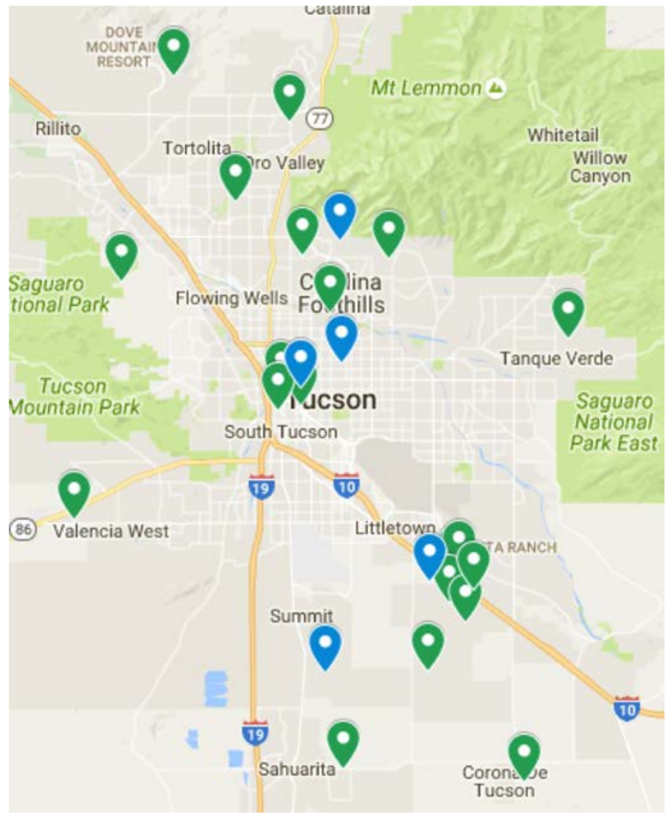


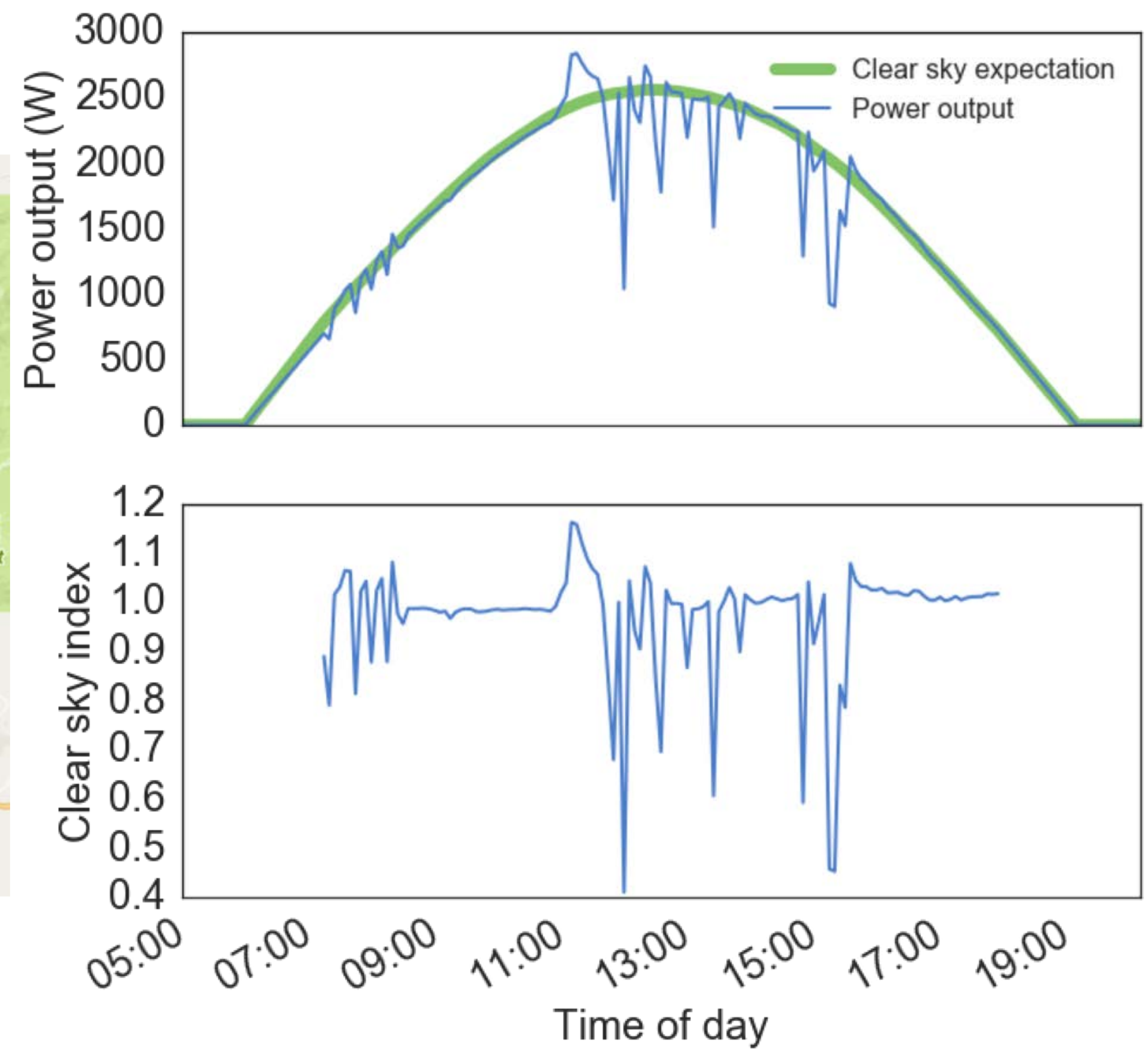
Assimilation





Sensor data

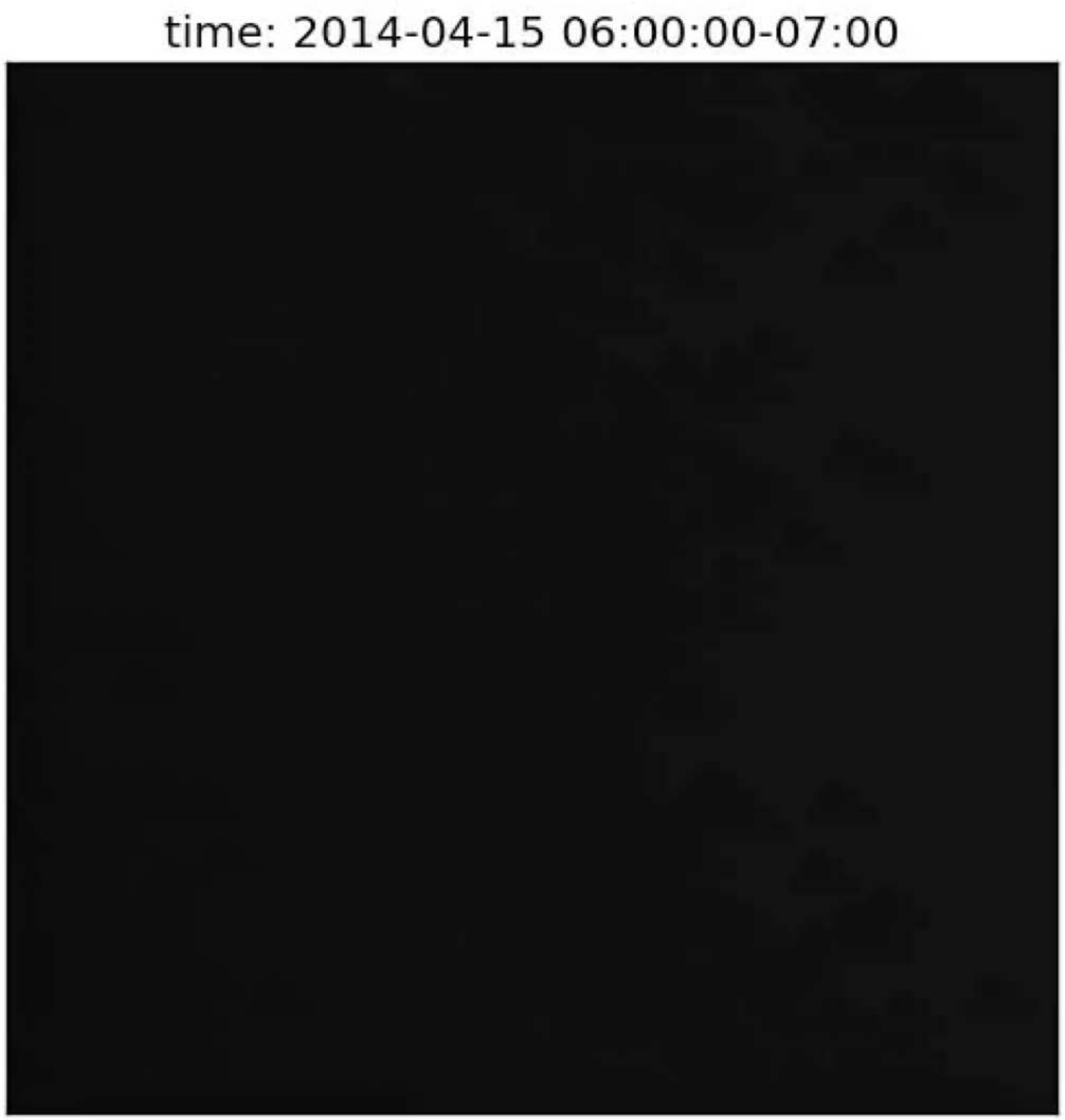




- 15 Solar arrays
- 12 irradiance sensors
- Data is collected approximately every 5 minutes

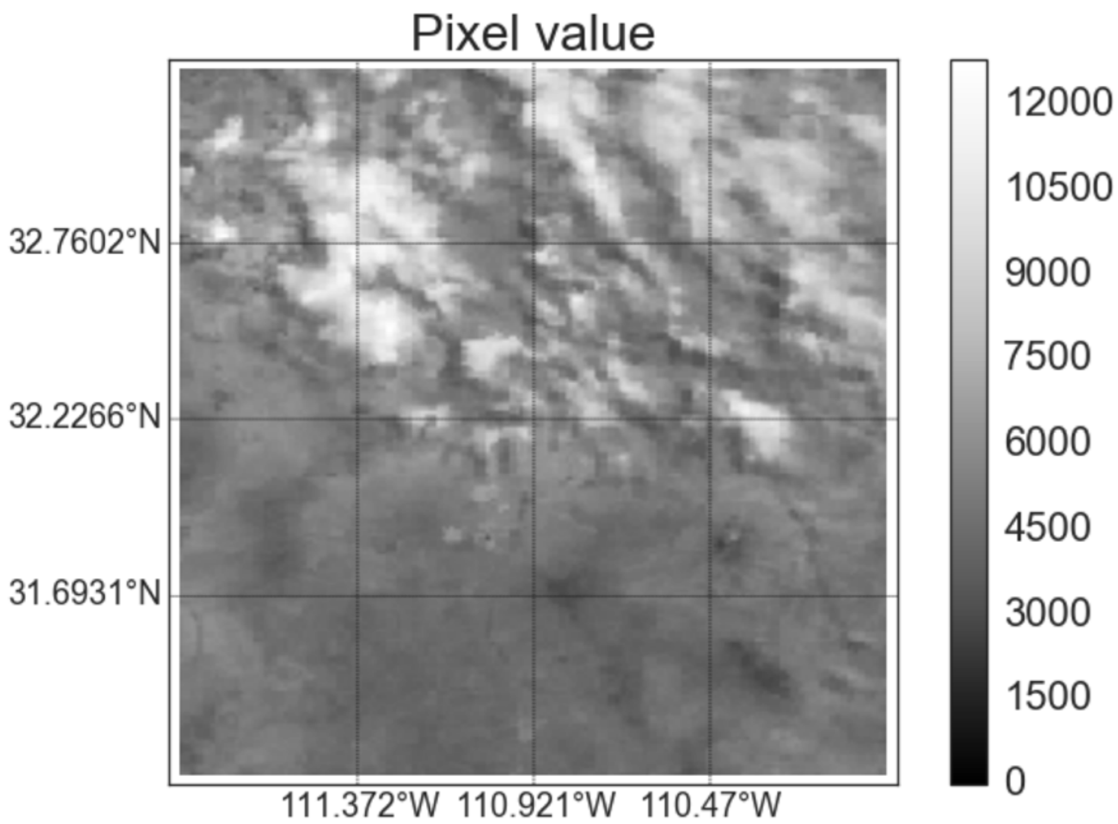
- Normalized by clear sky expectation
- Unitless and detrended

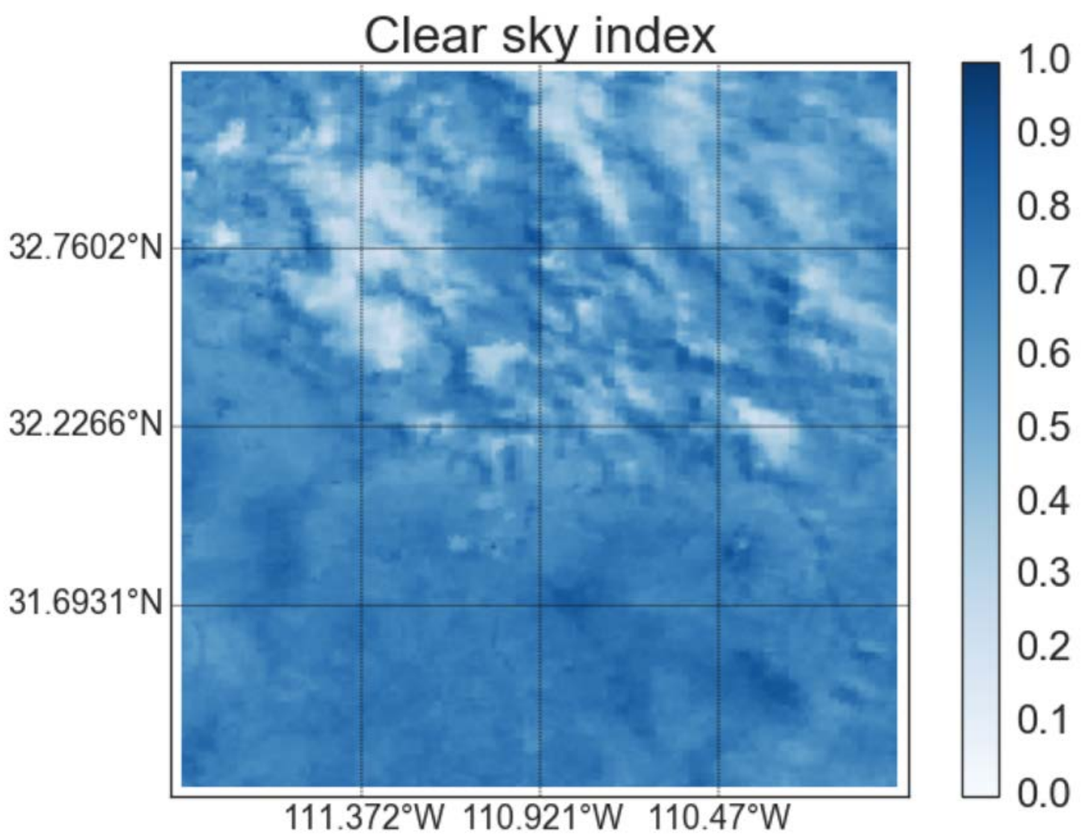
Satellite images

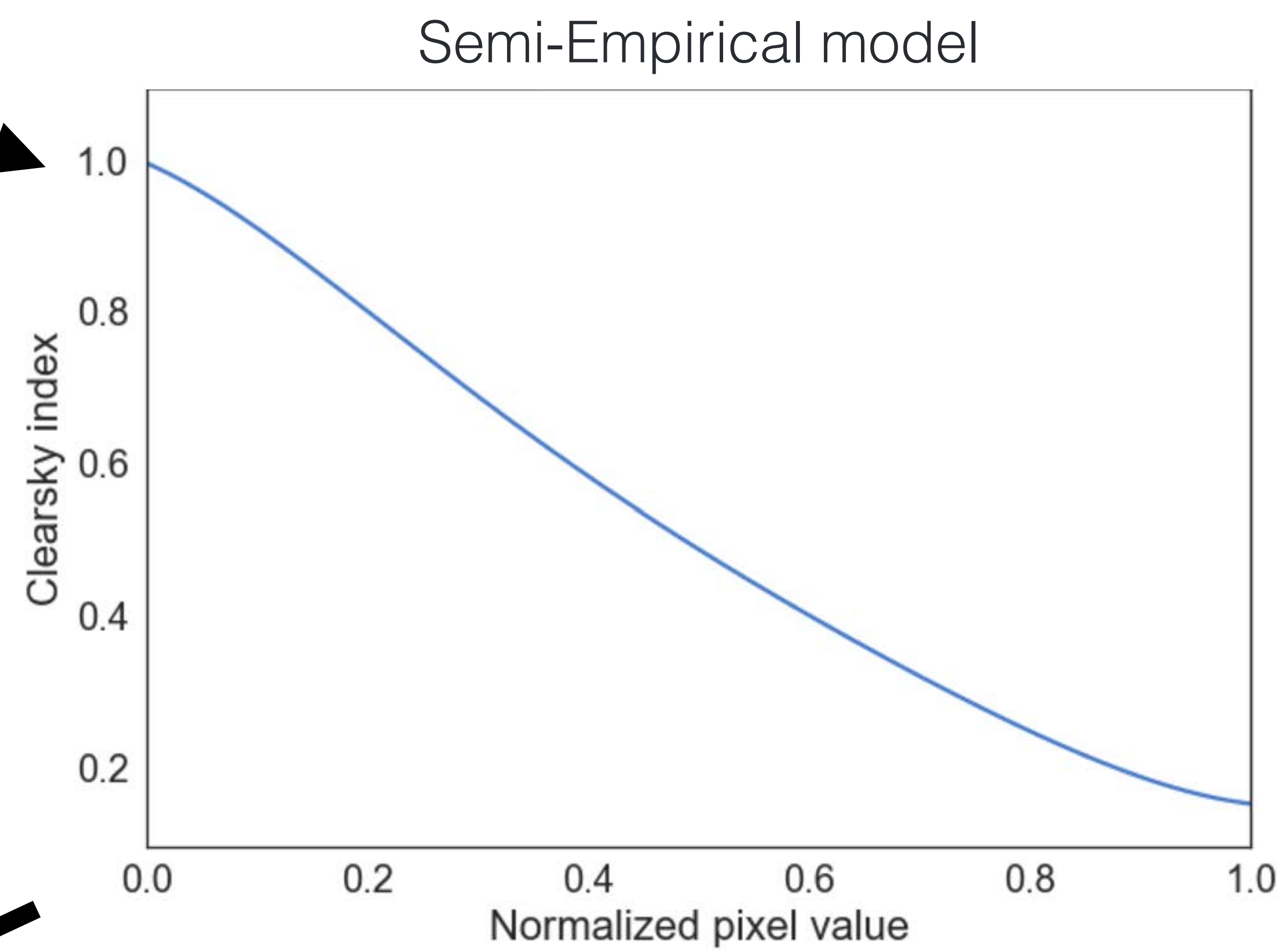


- Geostationary satellite images (GOES-15)
- Available every 15 minutes
- Spatial resolution of 1 km^2
- Converted to clear sky index (normalized irradiance)

Satellite data



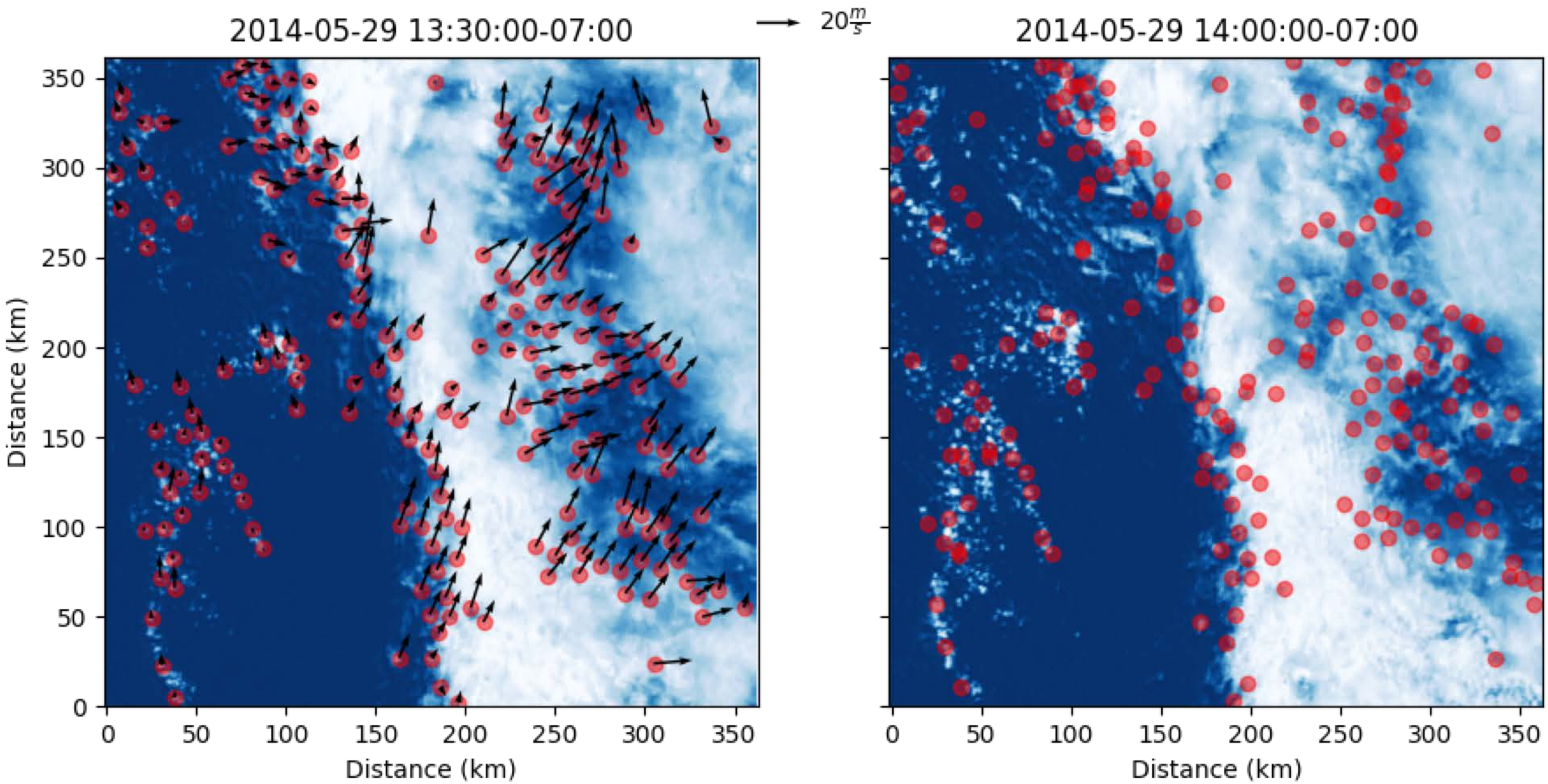




The Semi-Empirical model maps satellite pixel values to a clear sky index value.

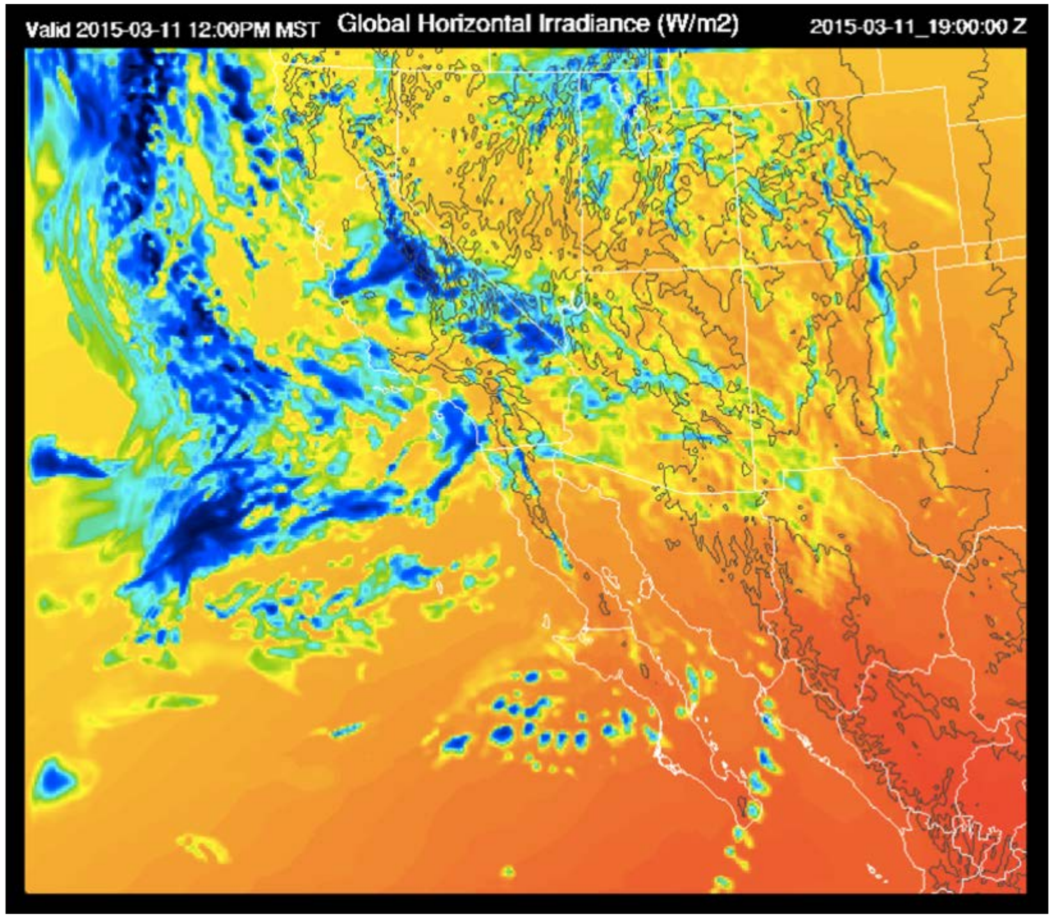
(Perez et al., 2002)

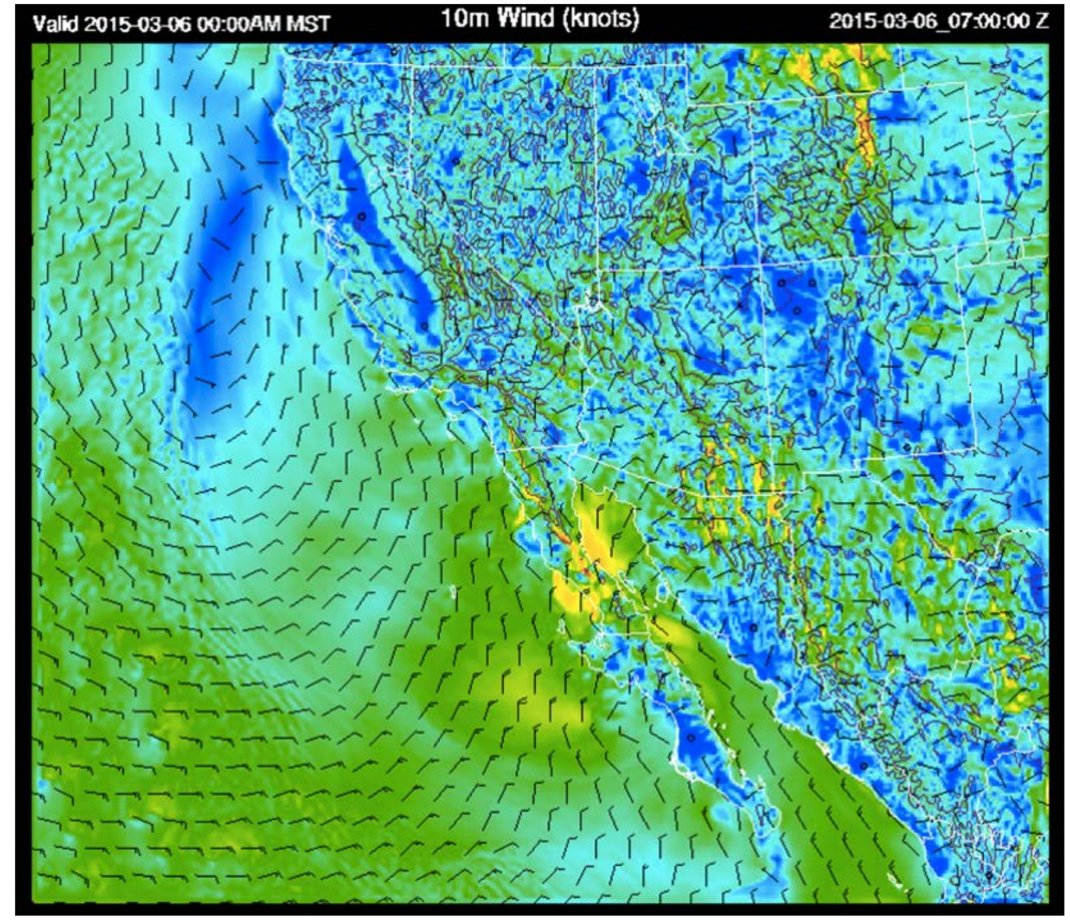
Optical flow



- Choose features on the satellite image based on the gradient of the image and the image’s windowed variance
- Track features to estimate the cloud motion field

Numerical Weather Prediction (NWP)

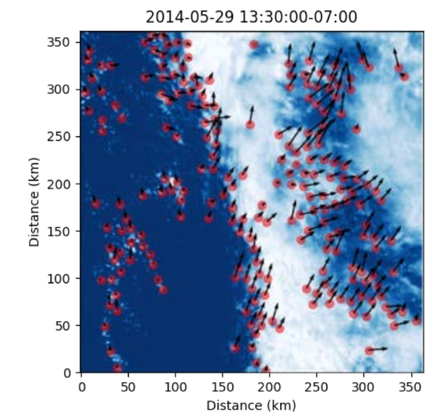




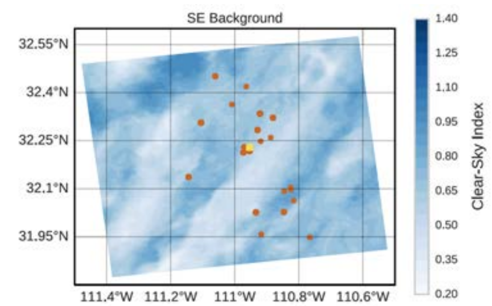
- It has an inner domain with a horizontal resolution of 1.8 km which covers Arizona and New Mexico
- We will use U and V wind components from vertical level with highest relative humidity

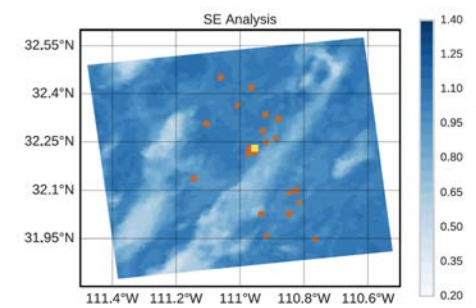
Overview

Data

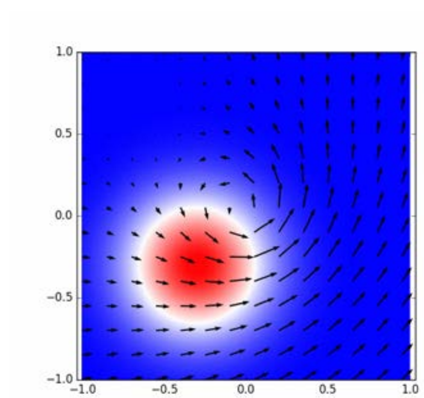


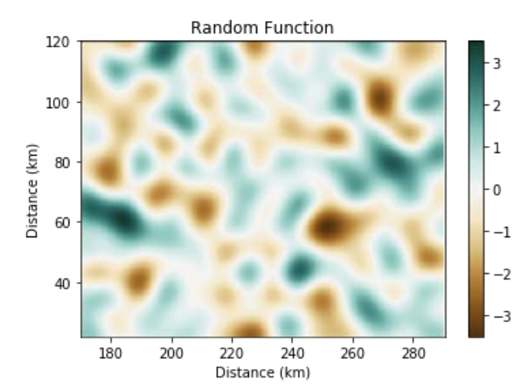
Previous Work



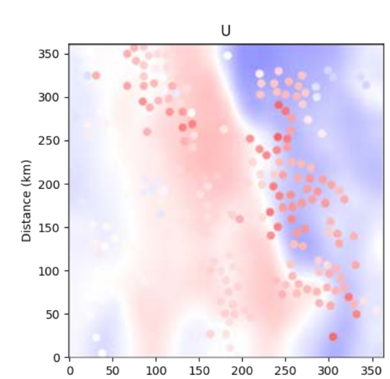


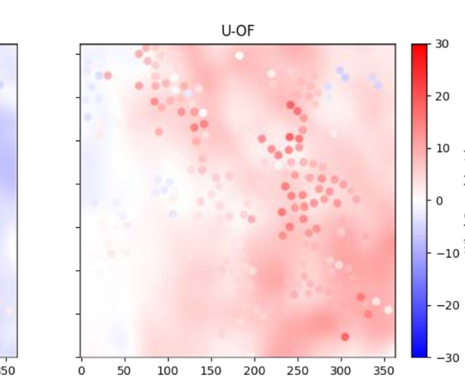
Model & Perturbation



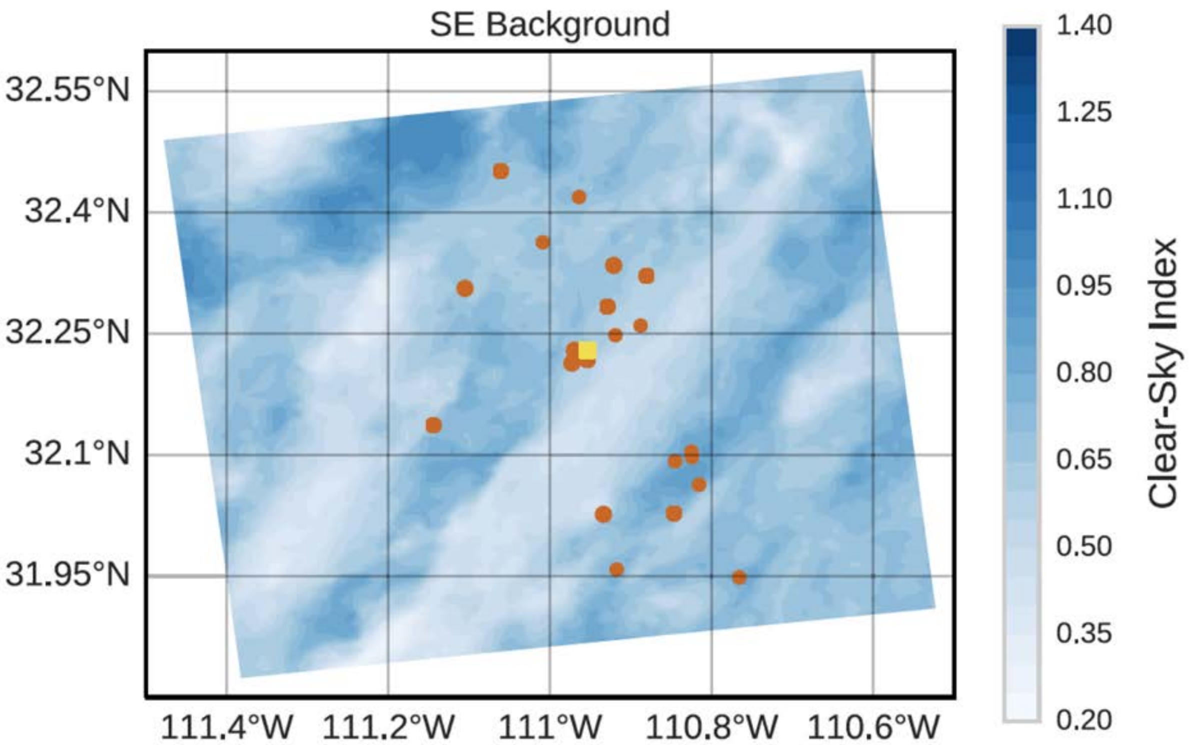


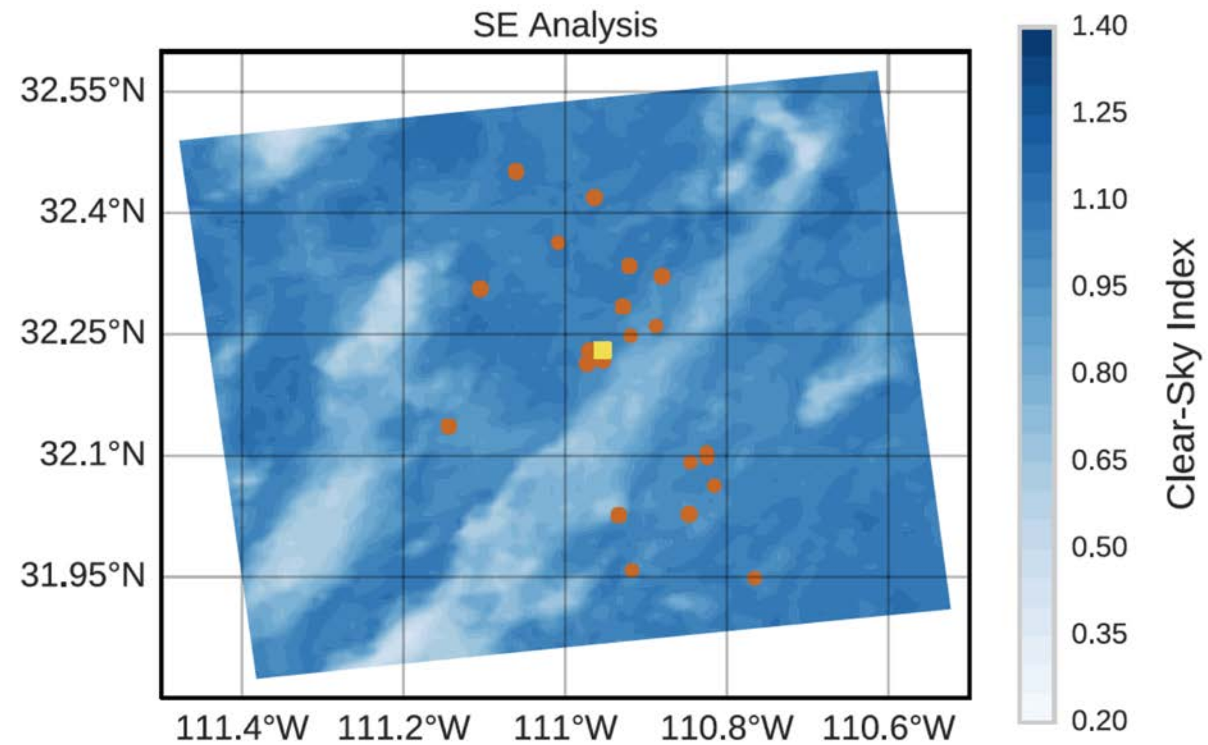
Assimilation





Optimal interpolation of ground sensors





$$\mathbf{P} = \mathbf{D}^{1/2}\mathbf{C}\mathbf{D}^{1/2}$$

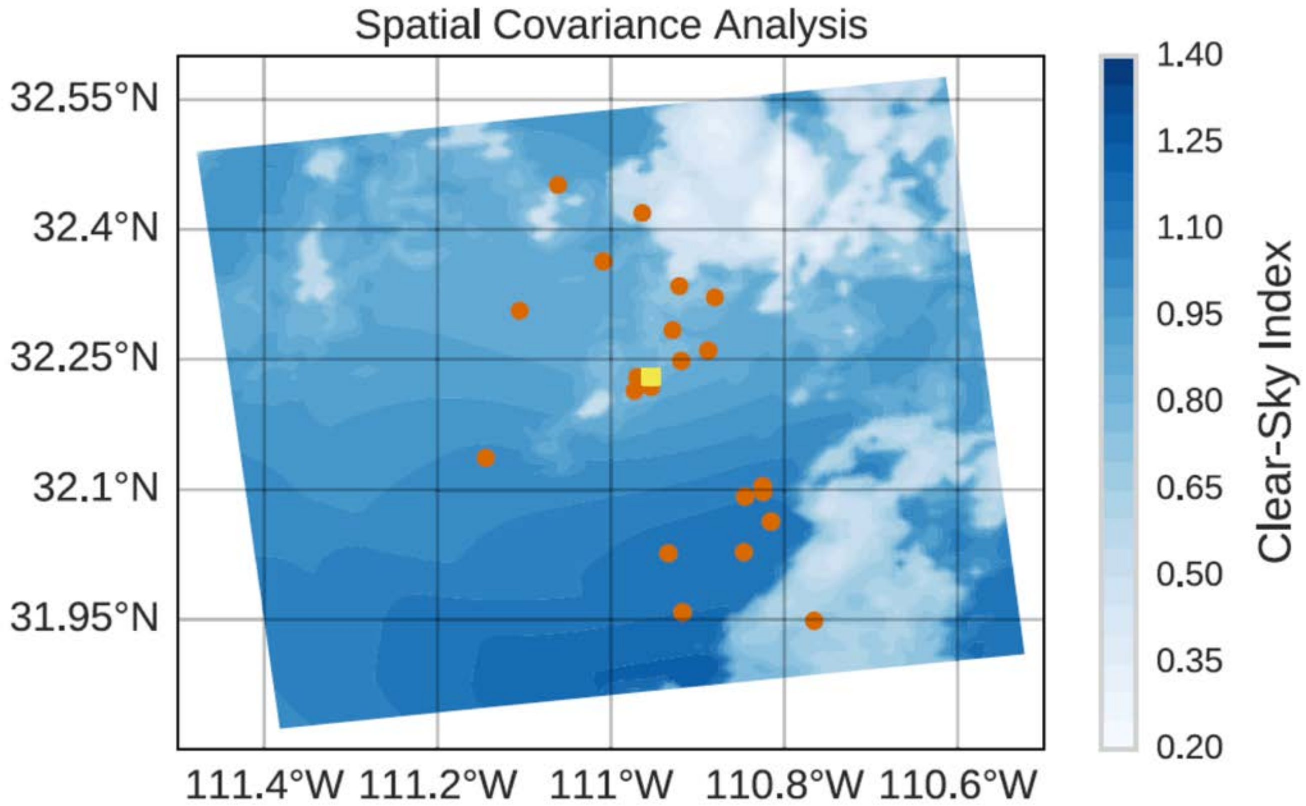
$$\mathbf{W} = \mathbf{P}\mathbf{H}^T(\mathbf{R} + \mathbf{H}\mathbf{P}\mathbf{H}^T)^{-1}$$

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{W}(\mathbf{y} - \mathbf{H}\mathbf{x}^b)$$

- Ground data is sparse but accurate.
- Satellite derived CSI fields are available on a large scale, but less accurate.
- Take semi-empirical (SE) model as background and assimilate ground sensors using optimal interpolation

(Lorenzo et al., 2017)

Different choices of C

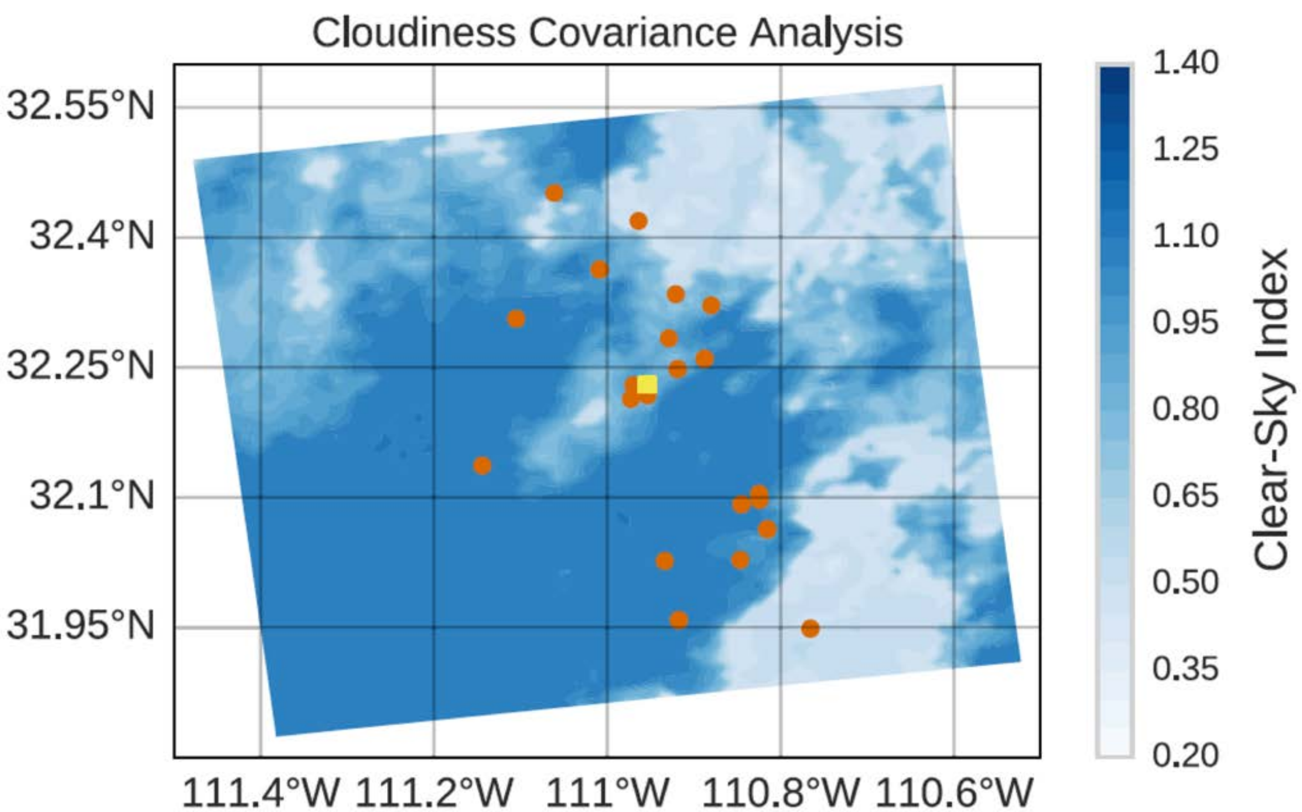


$$r_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

- Correlation based on spatial distance between locations
- Produces gradient which is not seen in original satellite image

Correlation Matrix

$$\mathbf{C}_{i,j} = \exp\left(-\frac{r_{i,j}^2}{2l^2}\right)$$



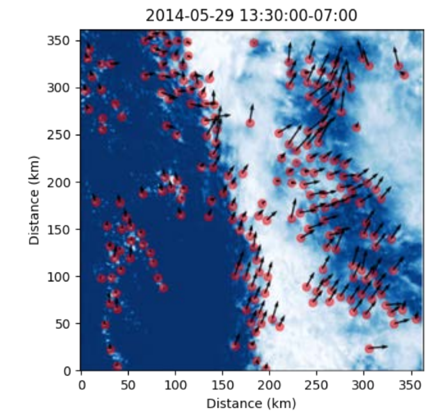
$$r_{i,j} = |z_i - z_j|$$

- Distance based difference in normalized satellite value, z.
- Produces analysis which is more physically meaningful

(Lorenzo et al., 2017)

Overview

Data



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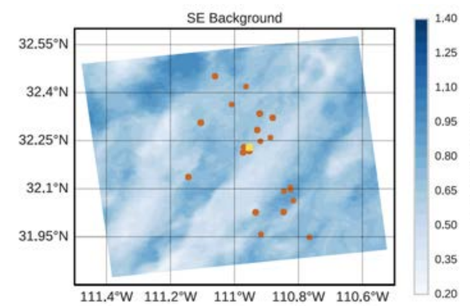
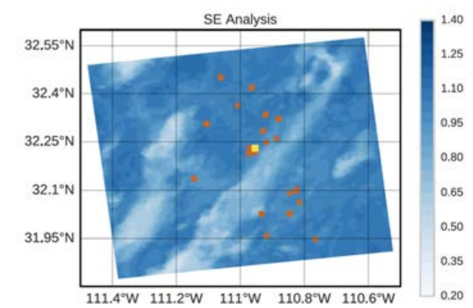
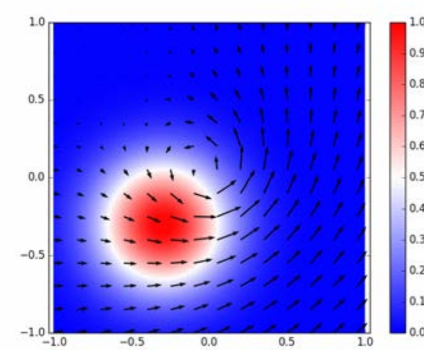
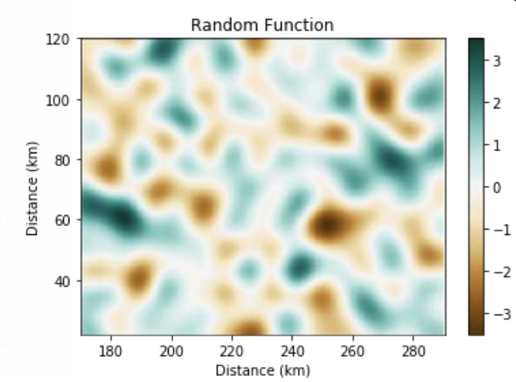


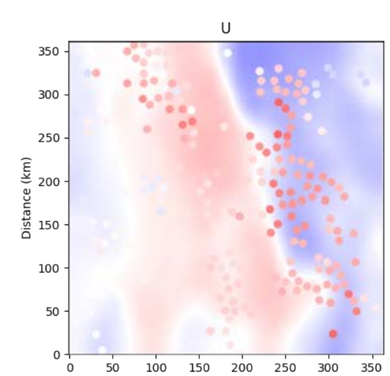


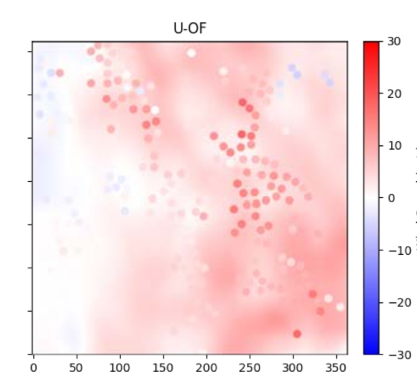
Model & Perturbation





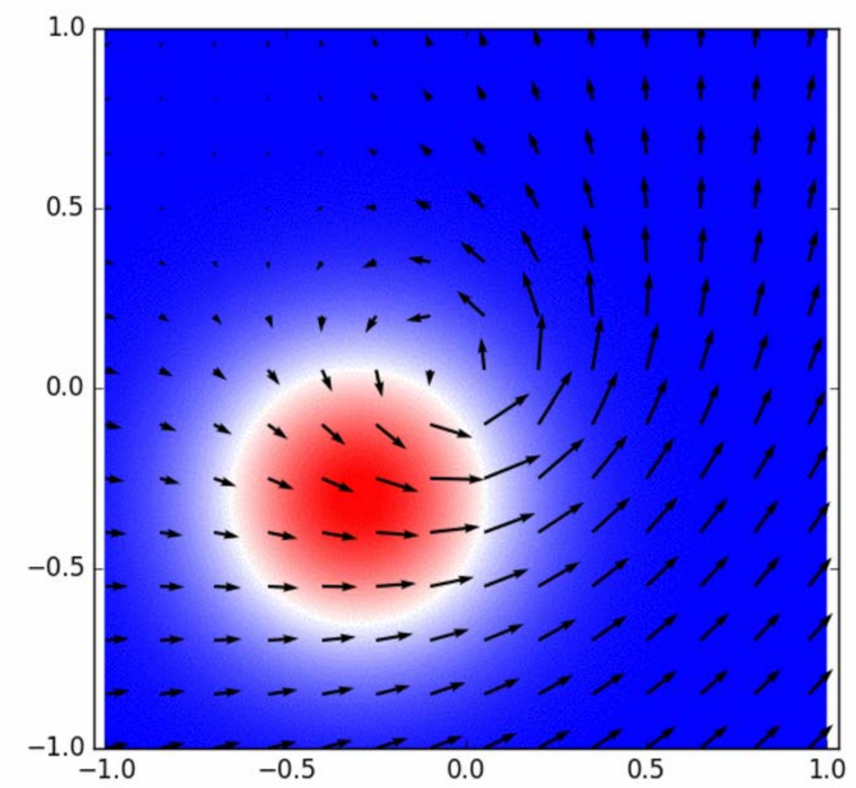
Assimilation





Advection model

A Typical weather model must track many things:



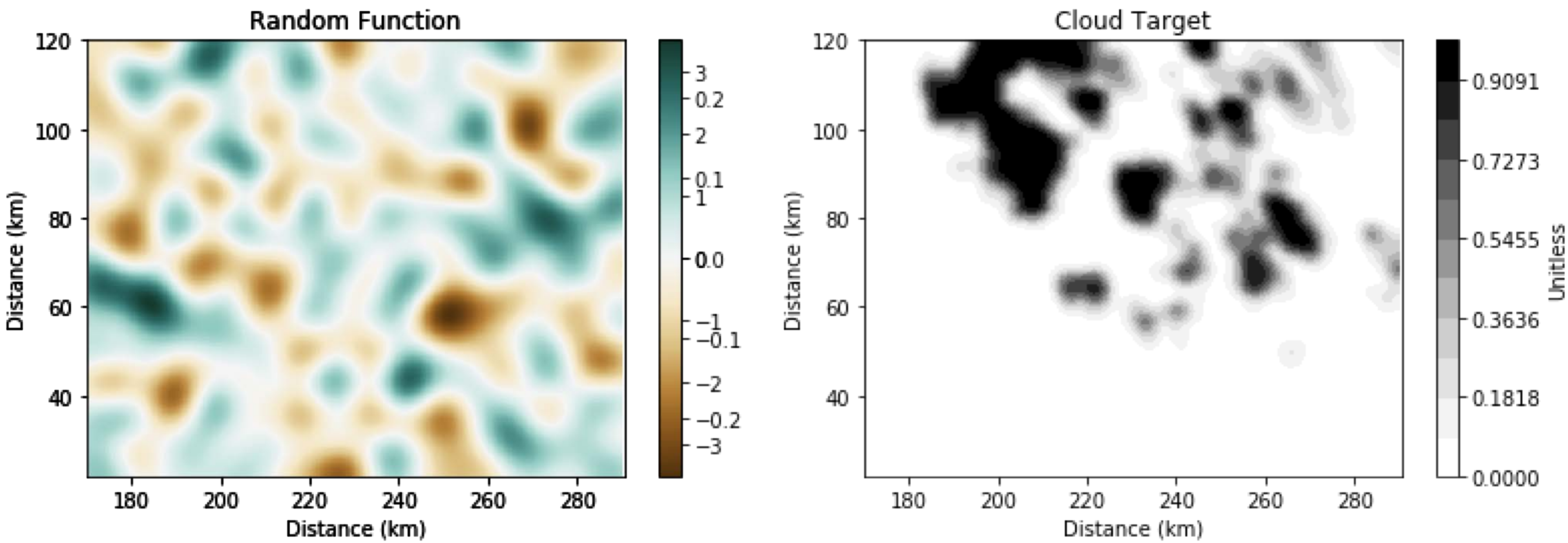
- Wind in three directions
- Density
- Pressure
- Temperature
- Moisture

Simplification is needed to run operational forecasts. Previous studies have shown that satellite advection out performs NWP for short term (3-6 hour) forecasts.

- Track only 2D wind at cloud layer
- Advect clouds represented as normalized pixel value
- Update wind fields hourly based on a numerical weather model
- Use 3rd order R-K method in time and 4th order special derivative based on WRF advection scheme

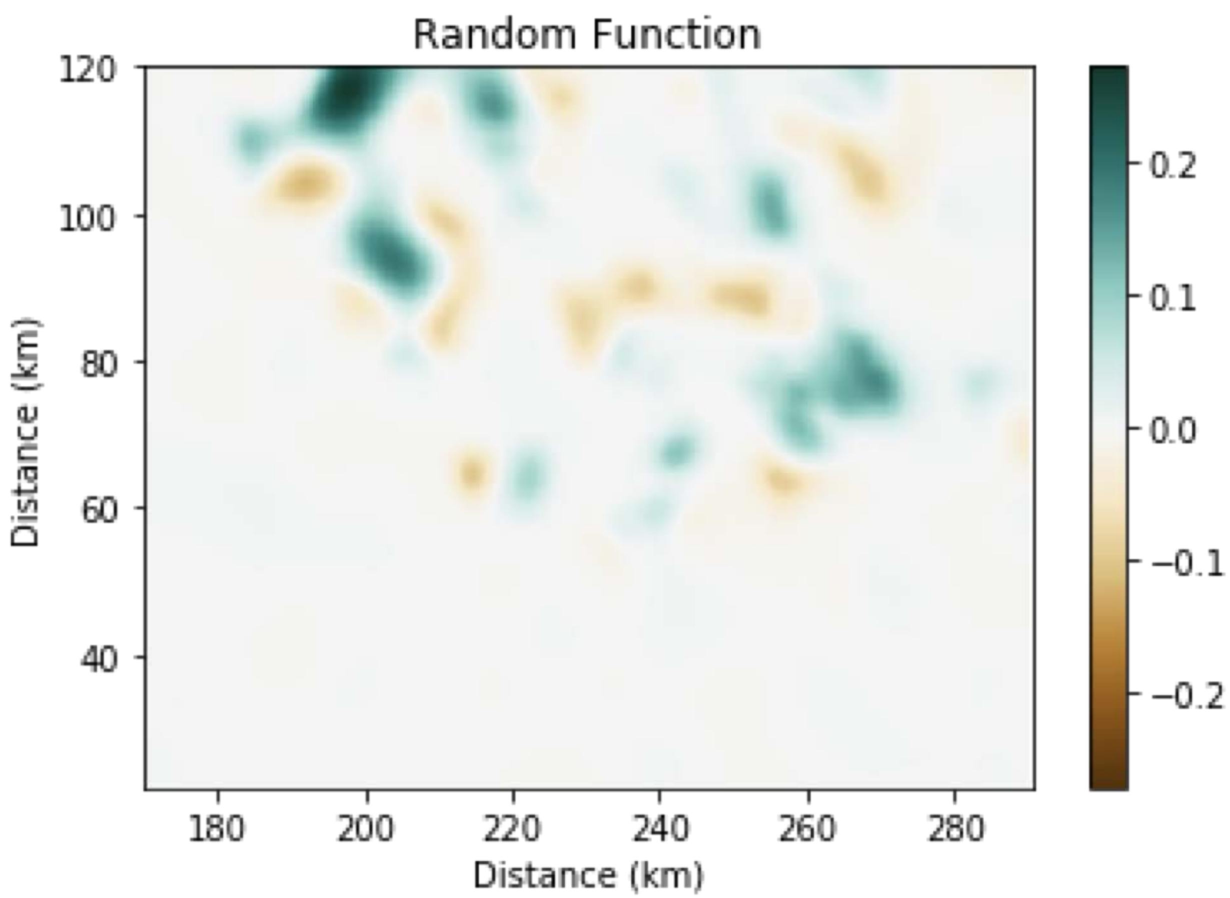
(Kalnay, 2002)(Perez et al., 2010)

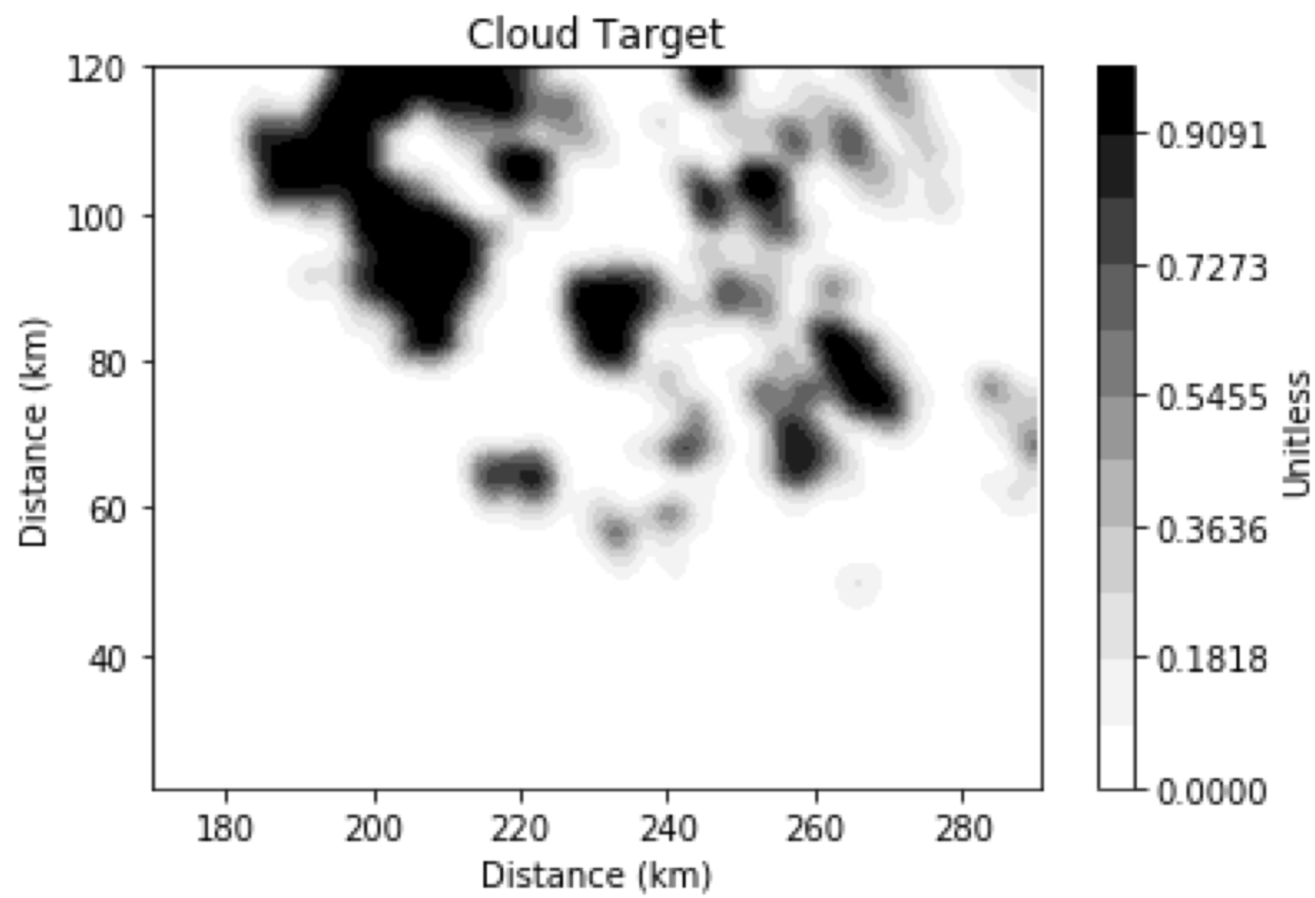
Normalized irradiance perturbation



- Create random function with desired random properties
- Target only those parts of the image which you wish to perturb
- In our case, we target cloudy areas to capture changes taking place inside and on the edges of clouds

Normalized irradiance perturbation





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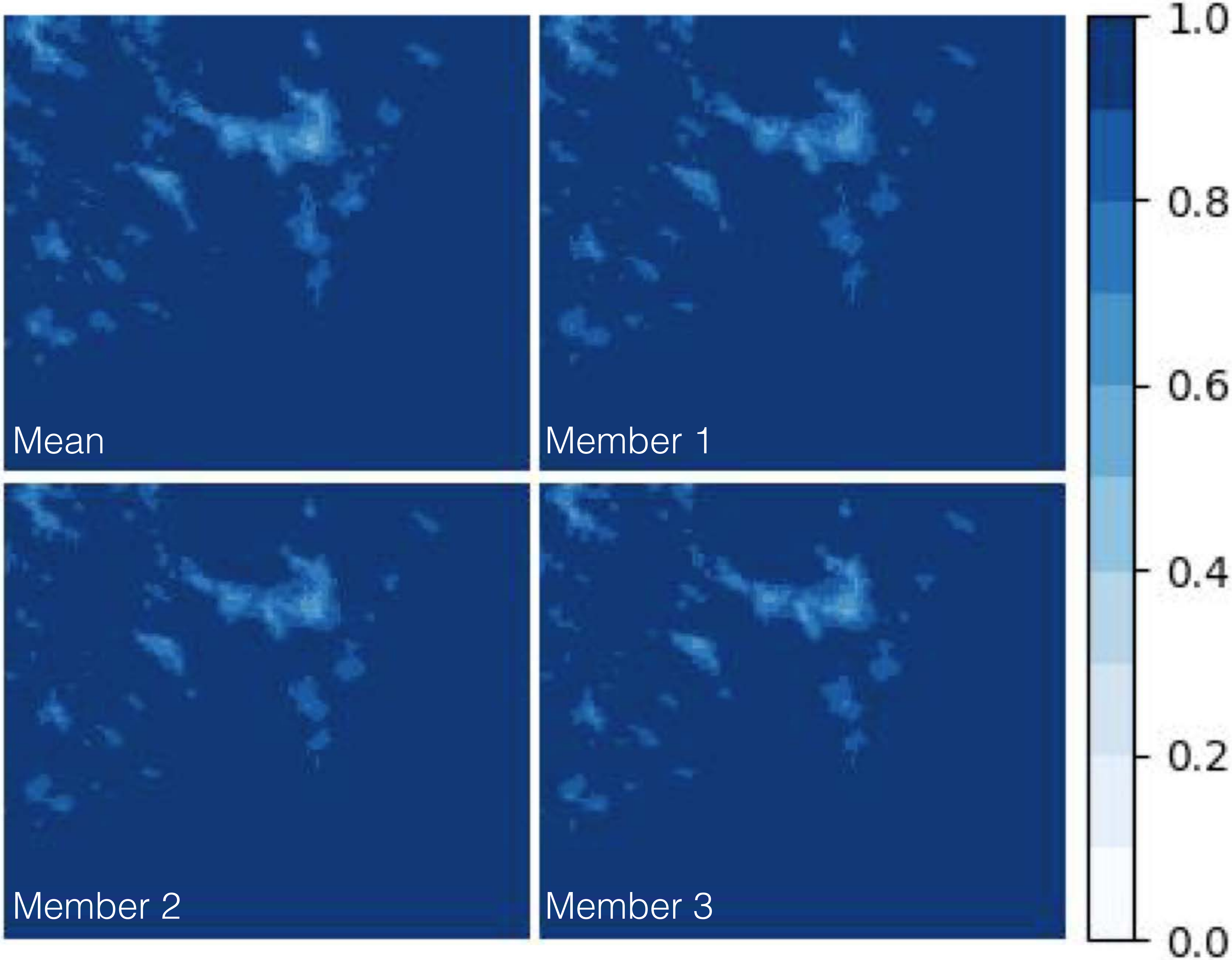
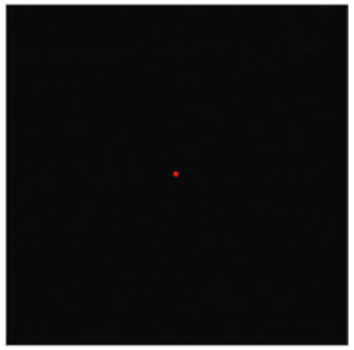
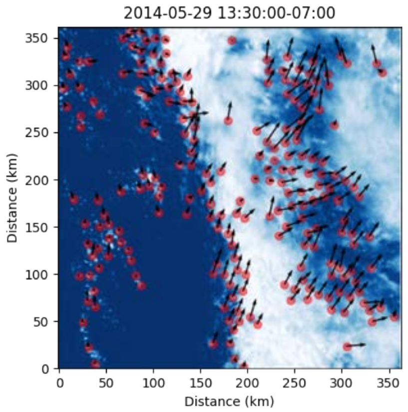
Ensemble of perturbed fields



Overview

Data





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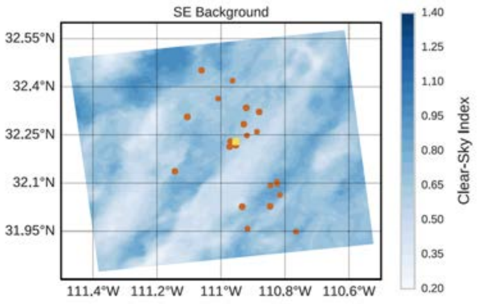
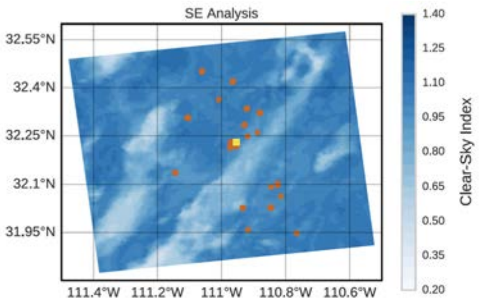
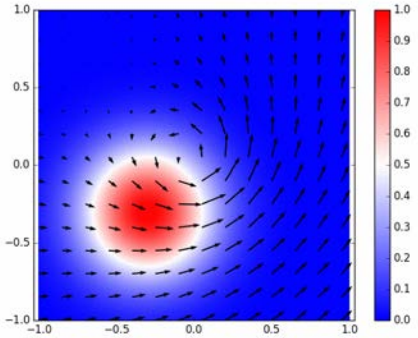
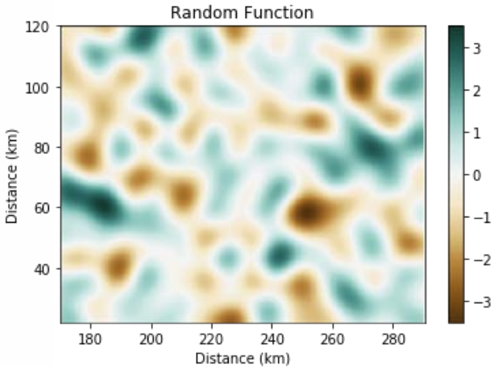


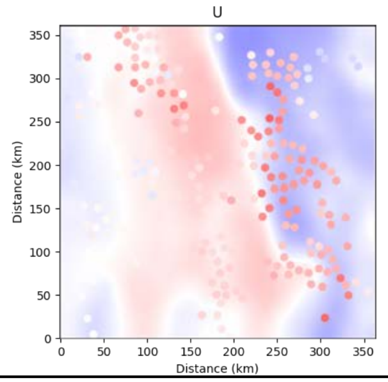


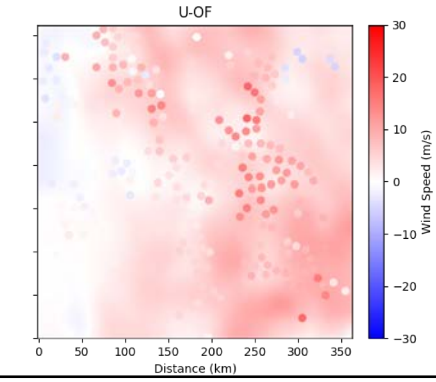
Model & Perturbation



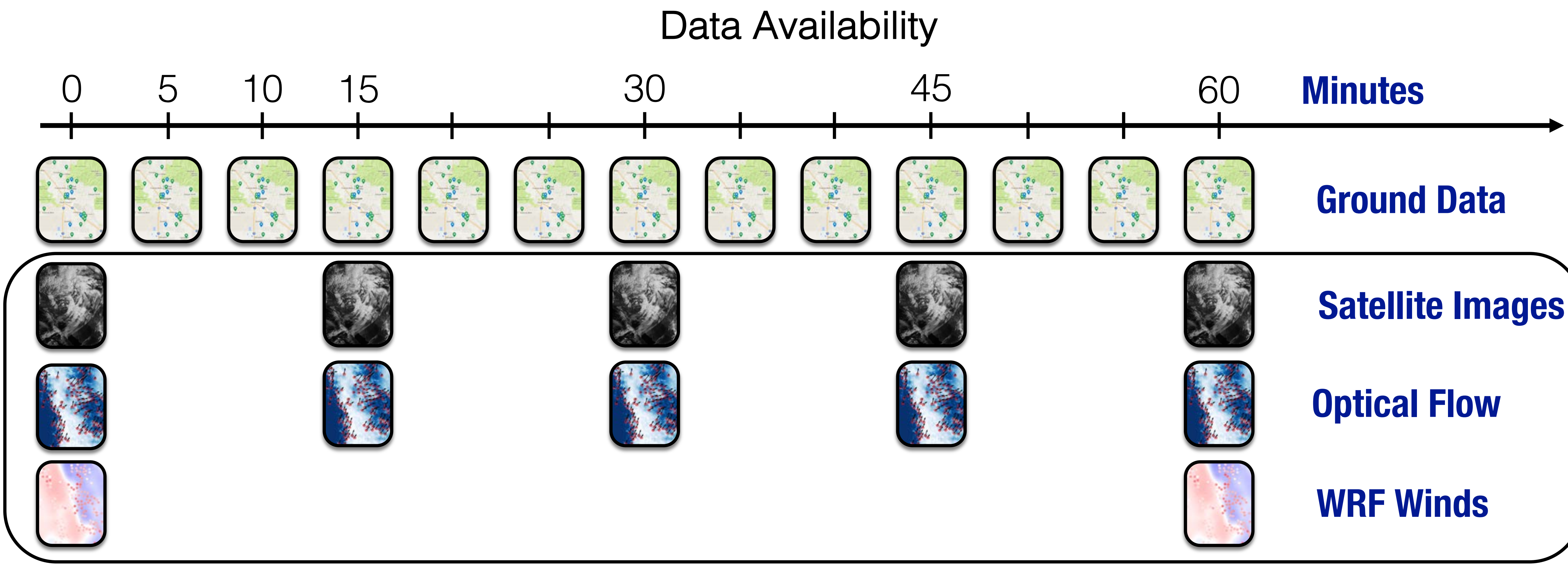


Assimilation



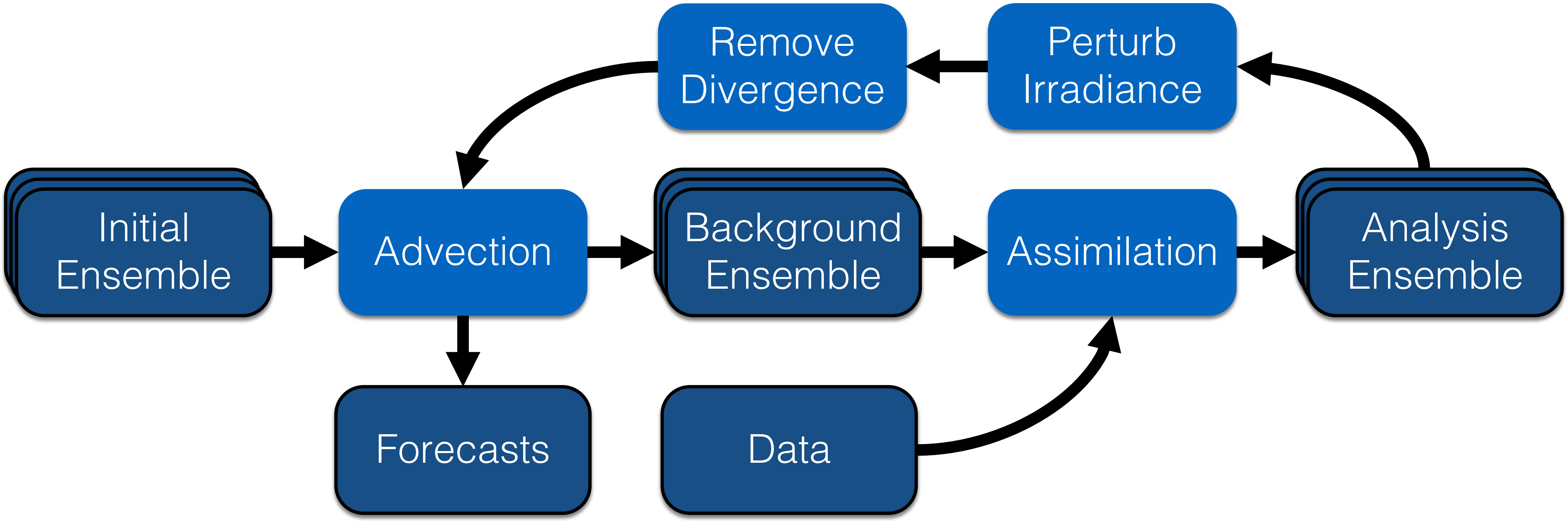


Data summary



- Ground data is available every 5 minutes
- Satellite data are available every 15 minutes (5 minutes with GOES-17)
- Optical flow vectors are available with every new satellite image
- Wind fields coming from numerical weather prediction are available every hour

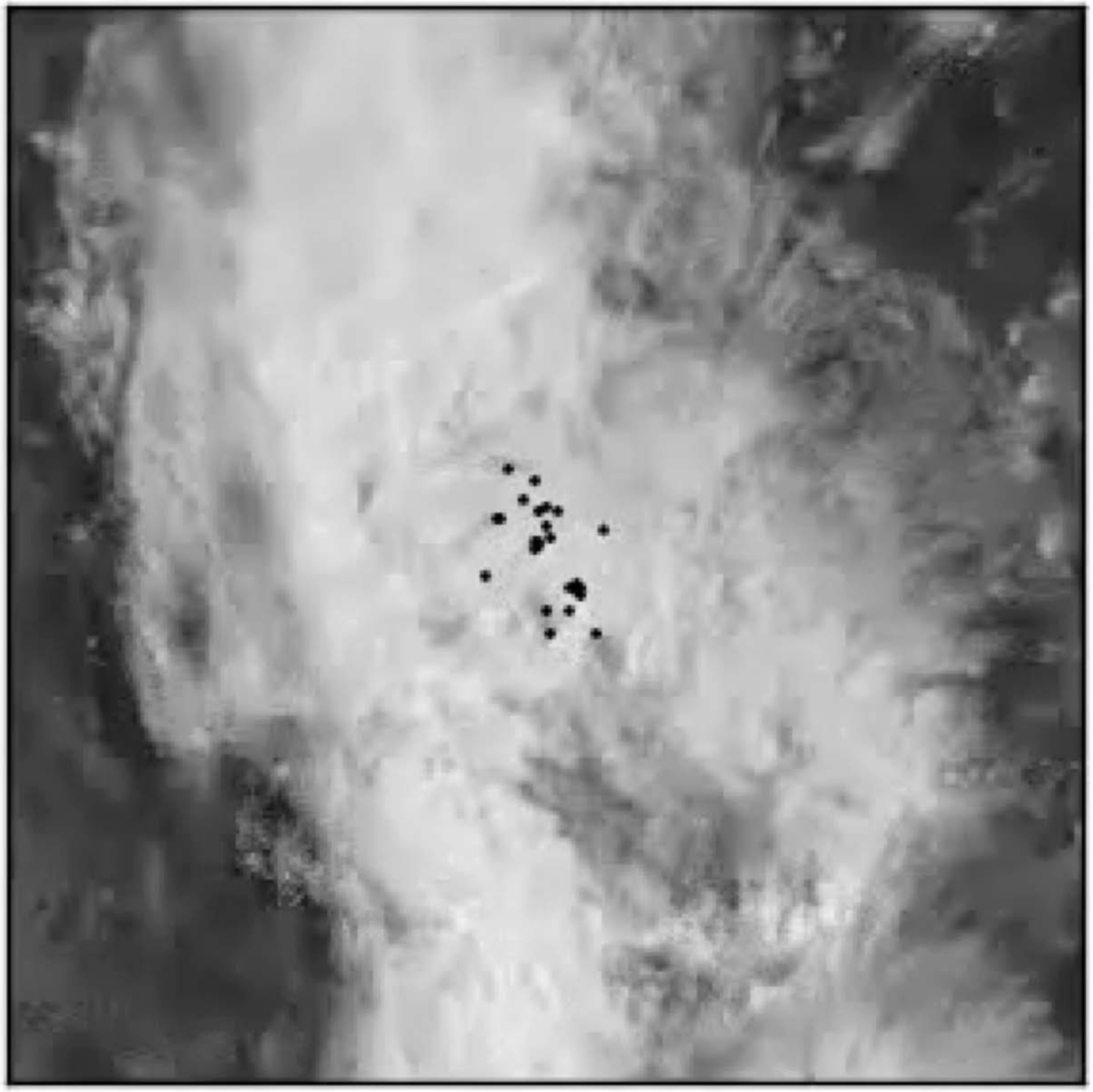
Forecast system



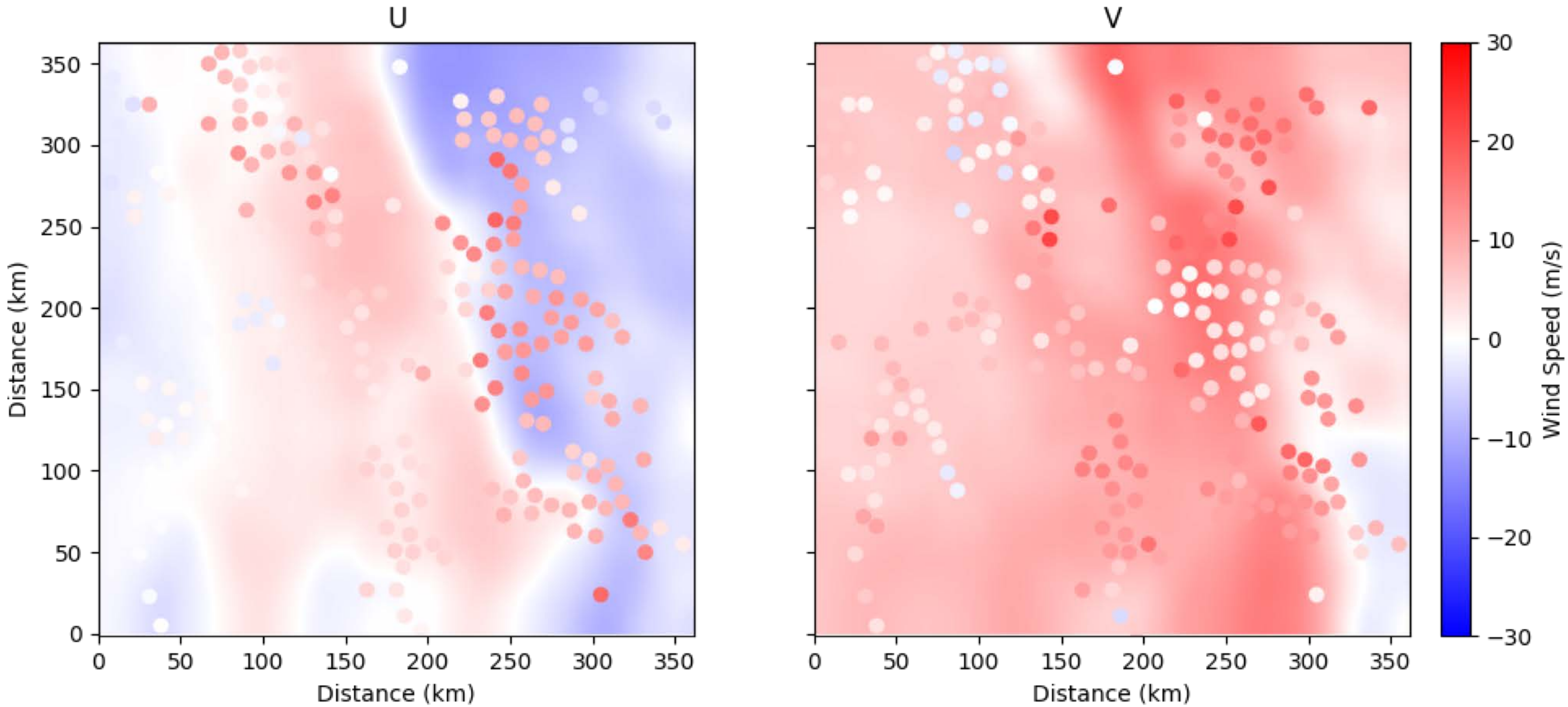
- Each ensemble member has unique cloud field and cloud motion field
- The LETKF is used to assimilate large amounts of observations such as when assimilating WRF wind fields
- The EnKF is used to assimilate small amounts of observations such as sparse optical flow

(eg. Hunt et al., 2007)(eg. Burges et al., 1998)

An example day: May 29th 2014

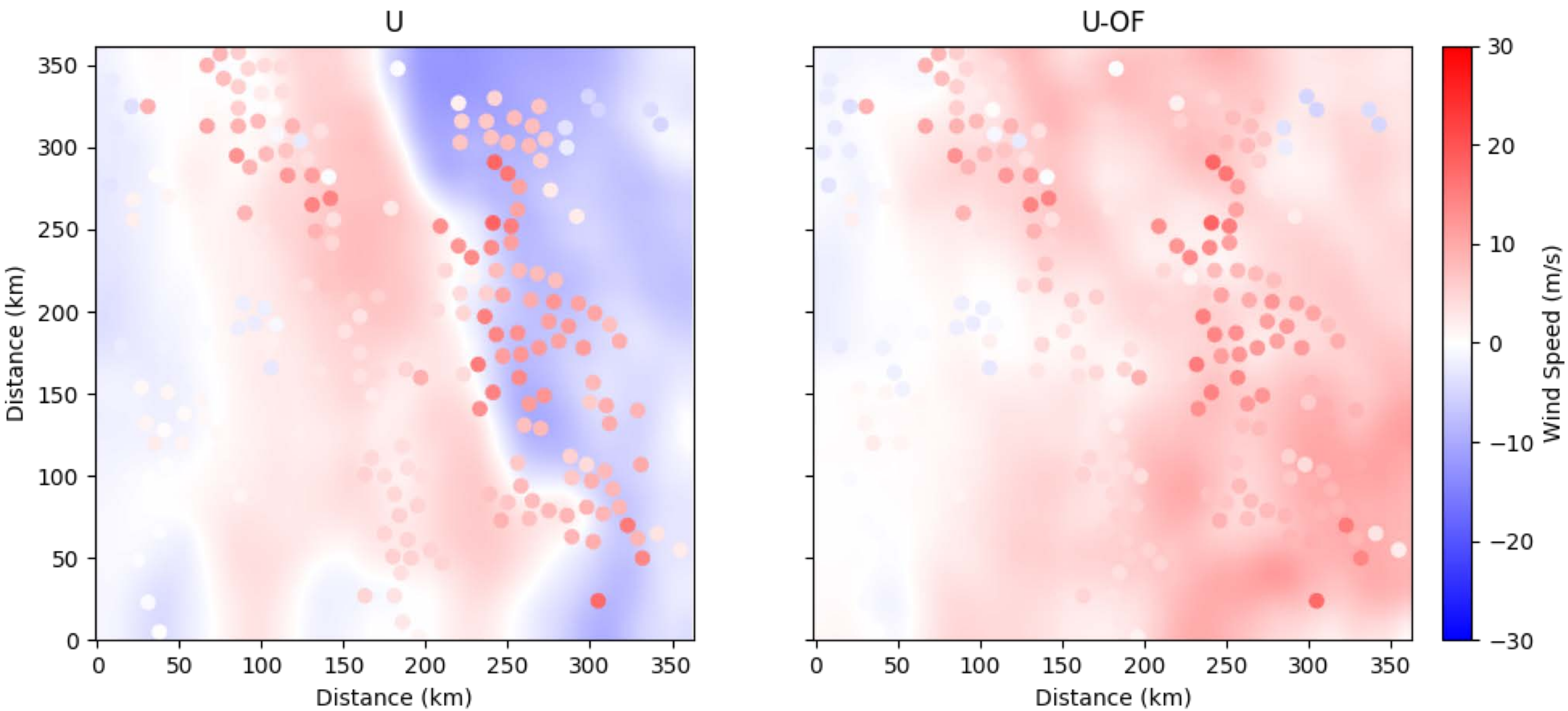


Wind observation



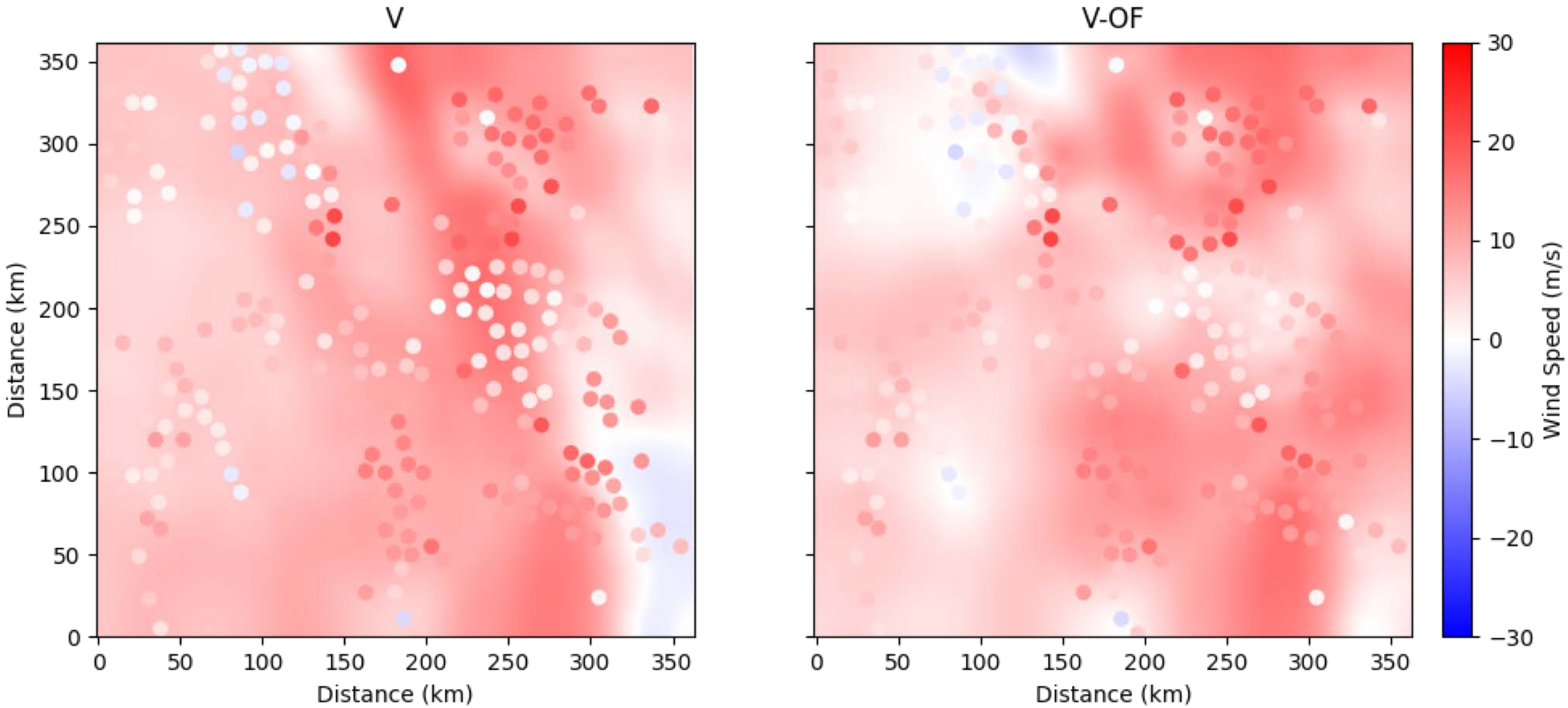
- The resulting vectors (scatter plot) can be thought of as observations of the cloud motion field
- These can then be assimilated into the cloud motion field derived from a numerical weather model (background)

Assimilate optical flow data



- Assimilate optical flow to improve cloud motion field
- The analysis cloud motion field has greater agreement with our optical flow vectors

Assimilate optical flow data



- Assimilate optical flow to improve cloud motion field
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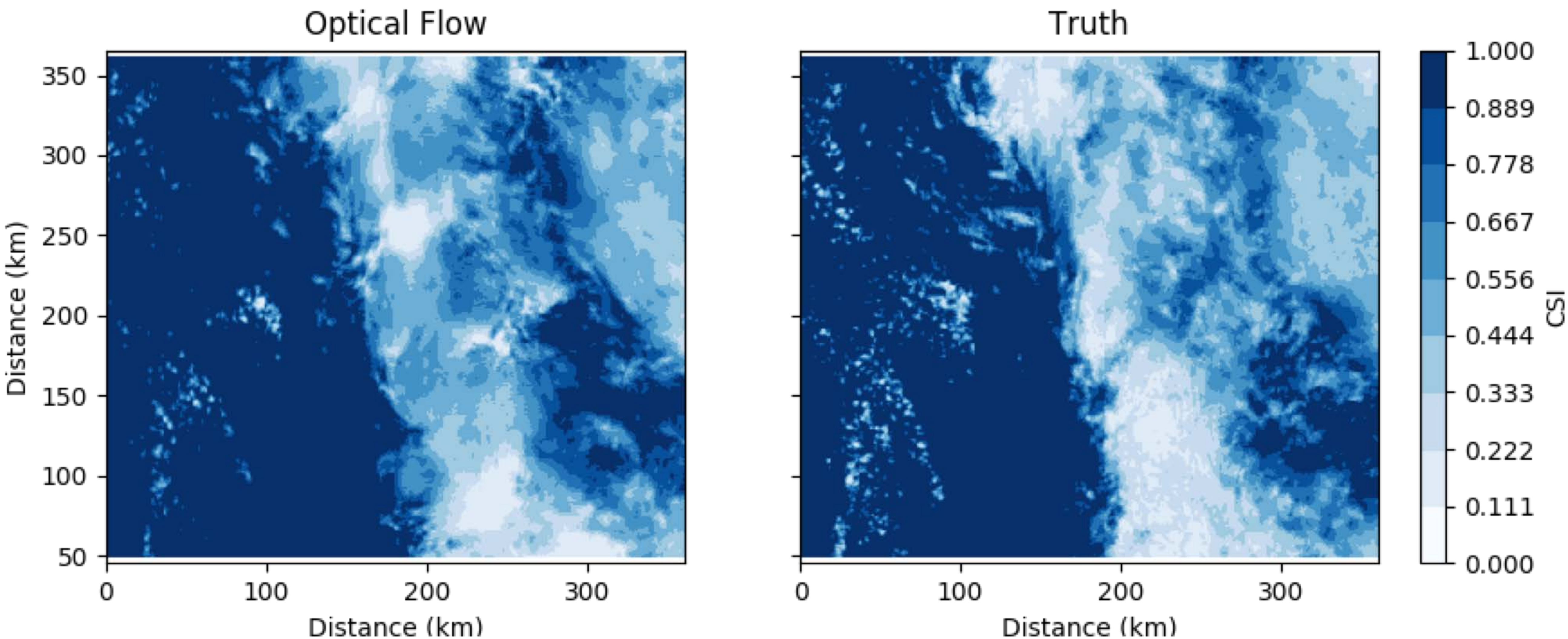
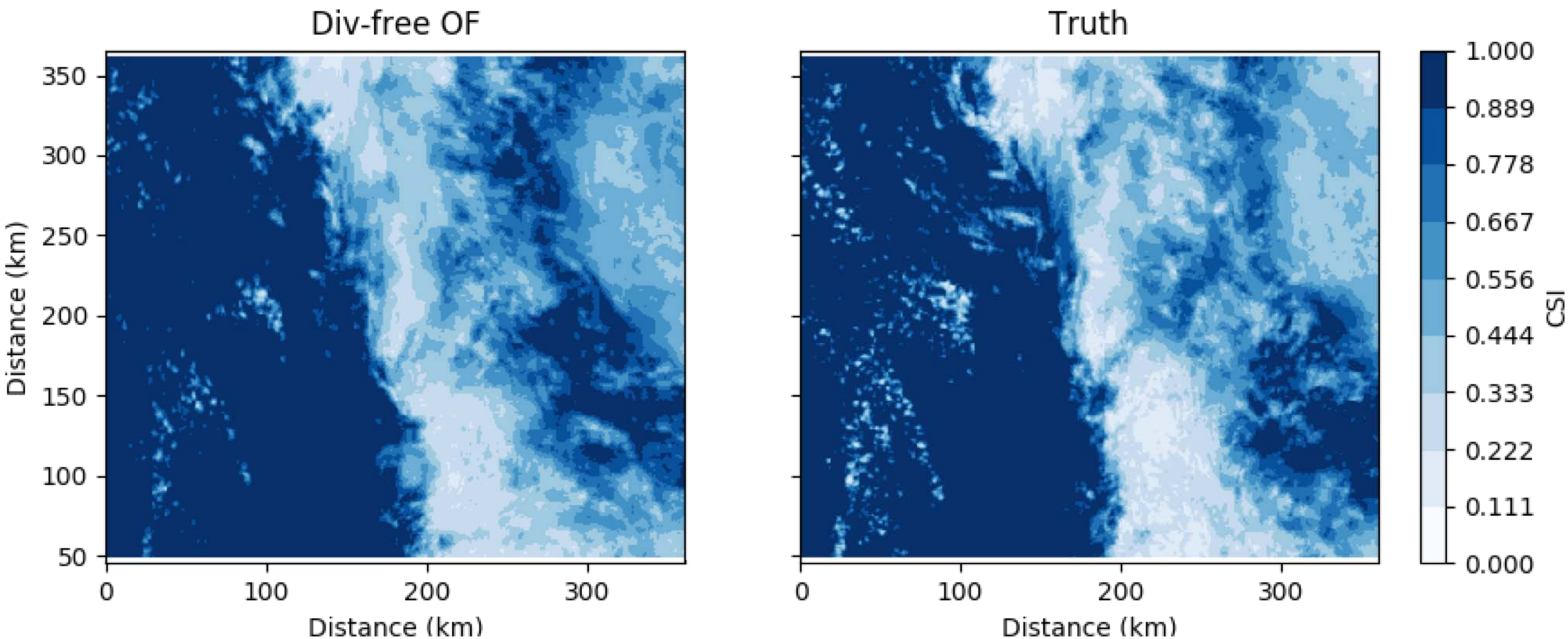
Forecasting with optical flow



- Assimilate optical flow to improve wind field
- Removal of divergence further reduces error and improves

Forecasting with optical flow



- Assimilate optical flow to improve wind field
- Removal of divergence further reduces error and improves

Remove divergence with Poisson's equation

Isolate portion of vector field with non-zero divergence

$$\vec{V} = -\nabla\phi + \tilde{V}$$

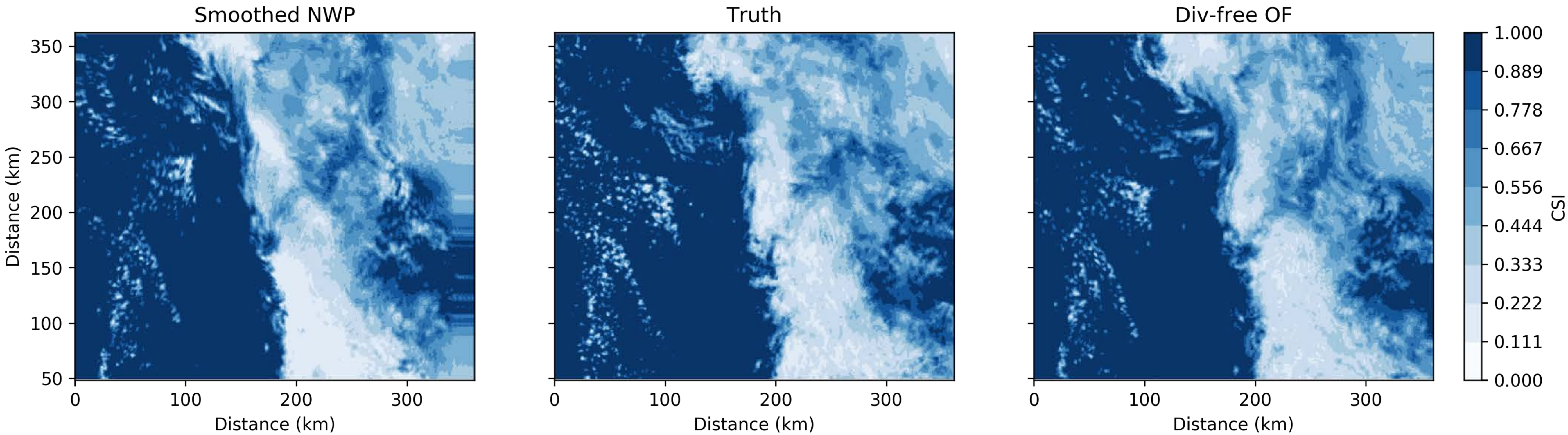
$$\nabla \cdot \vec{V} = -\nabla^2\phi$$

$$\vec{n} \cdot \nabla\phi = 0 \text{ on } \partial\Omega$$

Advect only using the portion of the vector field with zero divergence

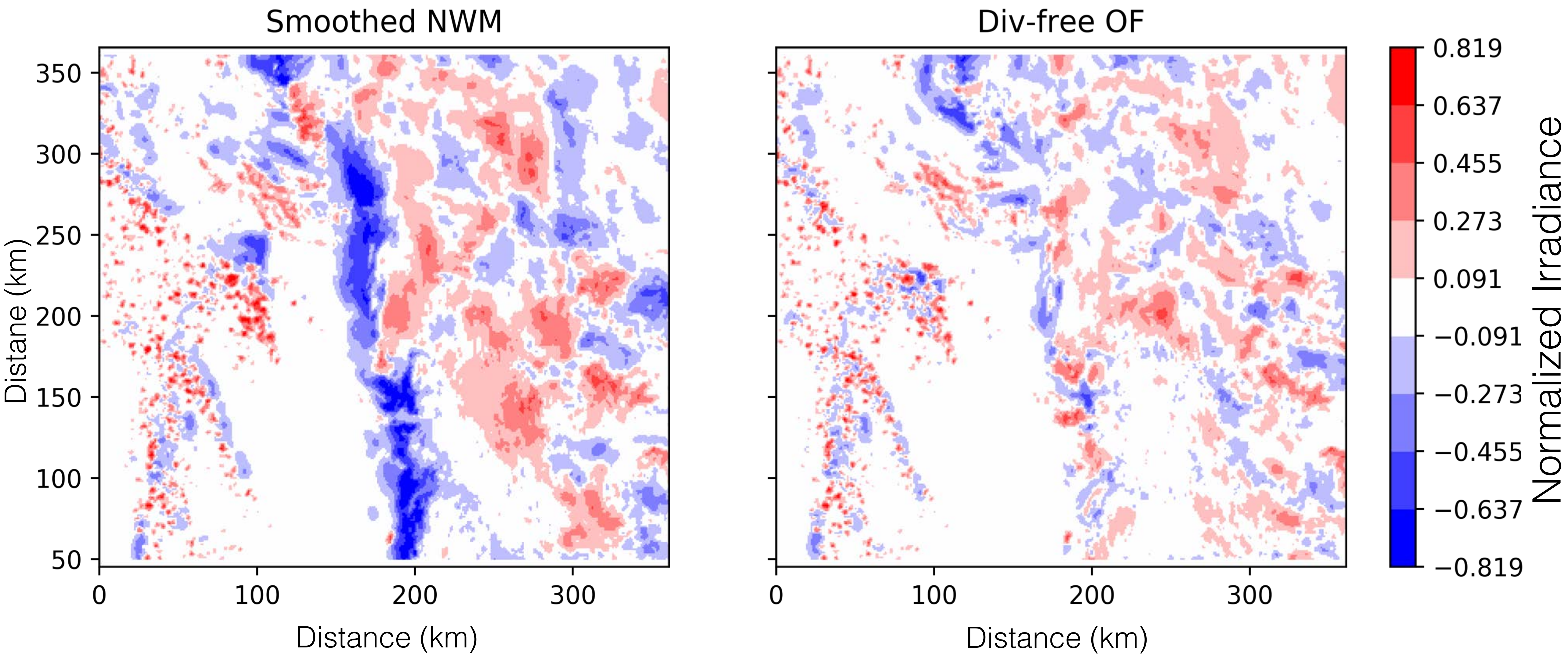
$$\tilde{V} = \vec{V} + \nabla\phi$$

Forecasting with and without assimilation



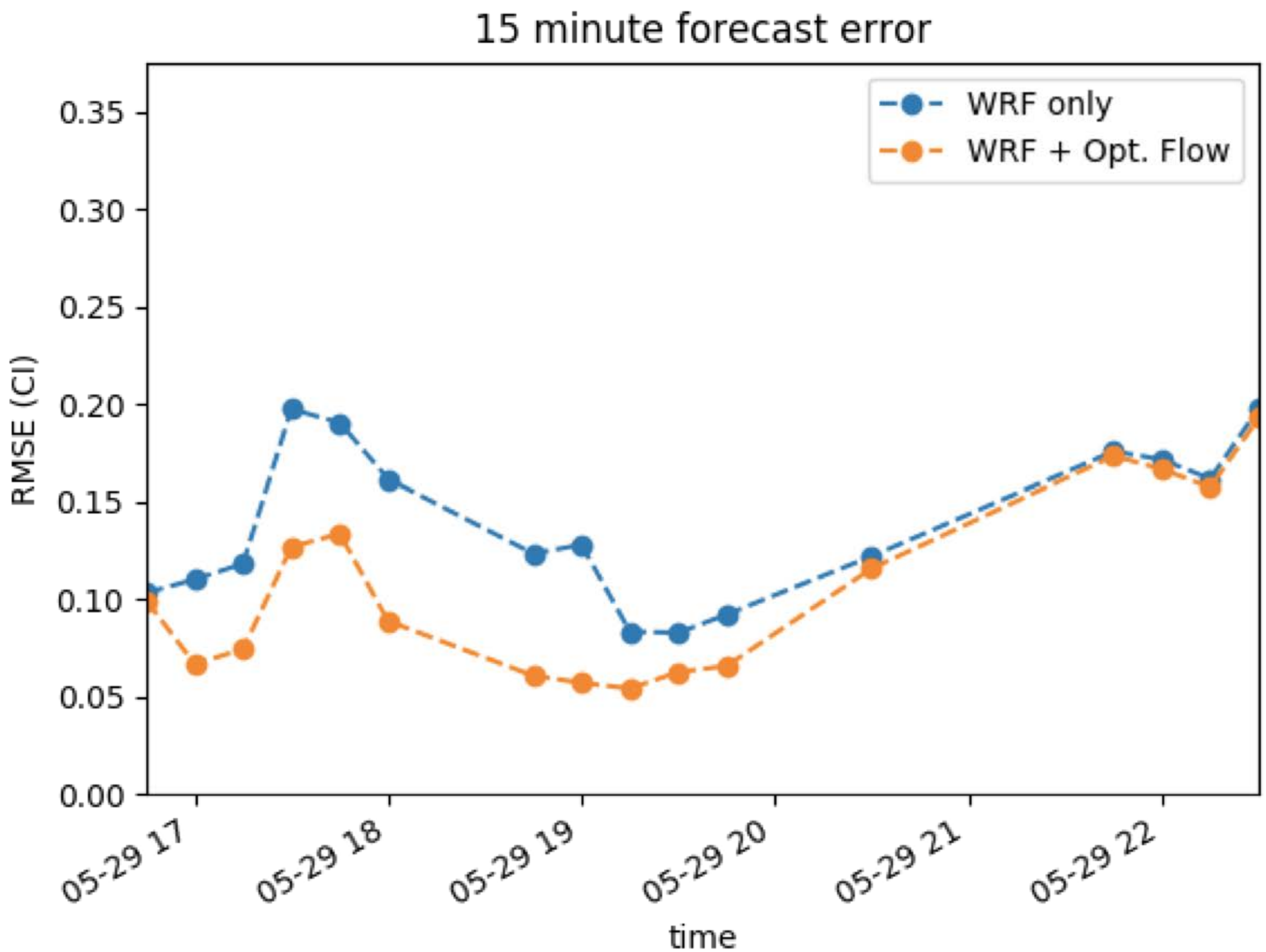
- Comparison of forecasts derived from Numerical Weather Prediction cloud motion and with optical flow vectors assimilated.
- Error is reduced when optical flow vectors are assimilated
- A large portion of error reduction come from correct cloud front position

Forecasting with and without assimilation



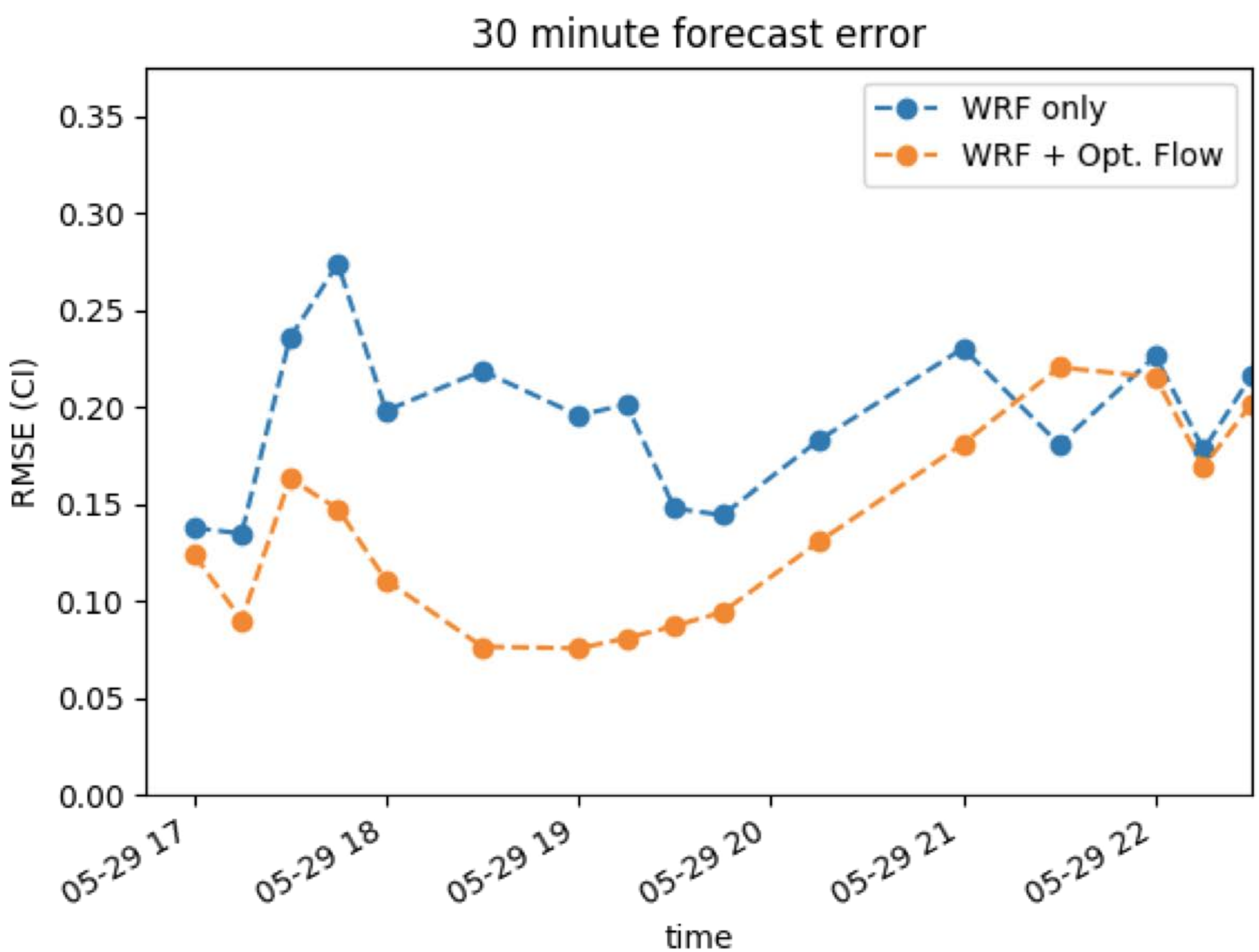
- Comparison of forecasts derived from Numerical Weather Prediction cloud motion and with optical flow vectors assimilated.
- Error is reduced when optical flow vectors are assimilated
- A large portion of error reduction come from correct cloud front position

Error time series



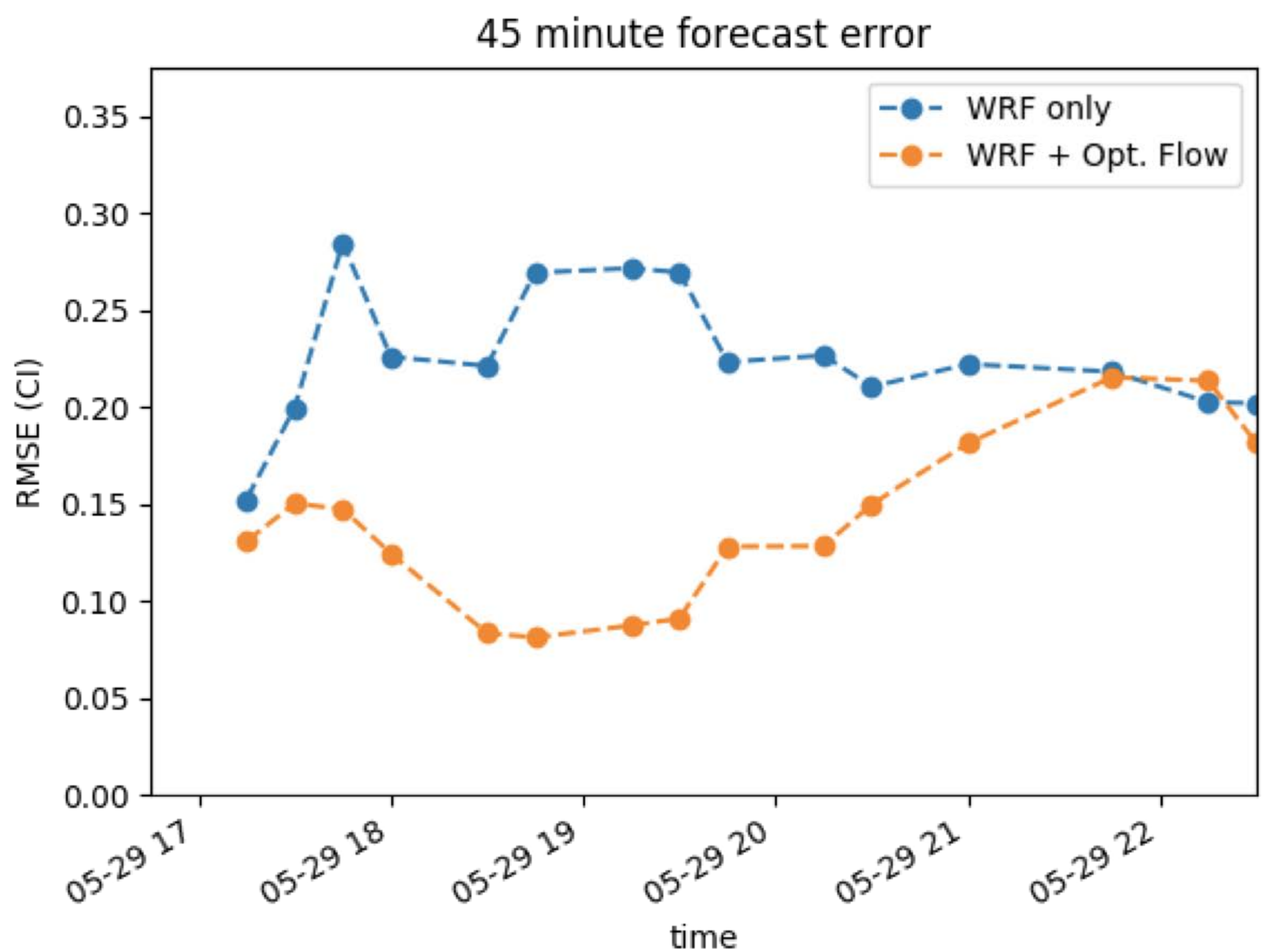
Error is calculated as RMSE between forecasted normalized irradiance and the actual satellite derived normalized irradiance for a 2240 km^2 area over Tucson.

Error time series



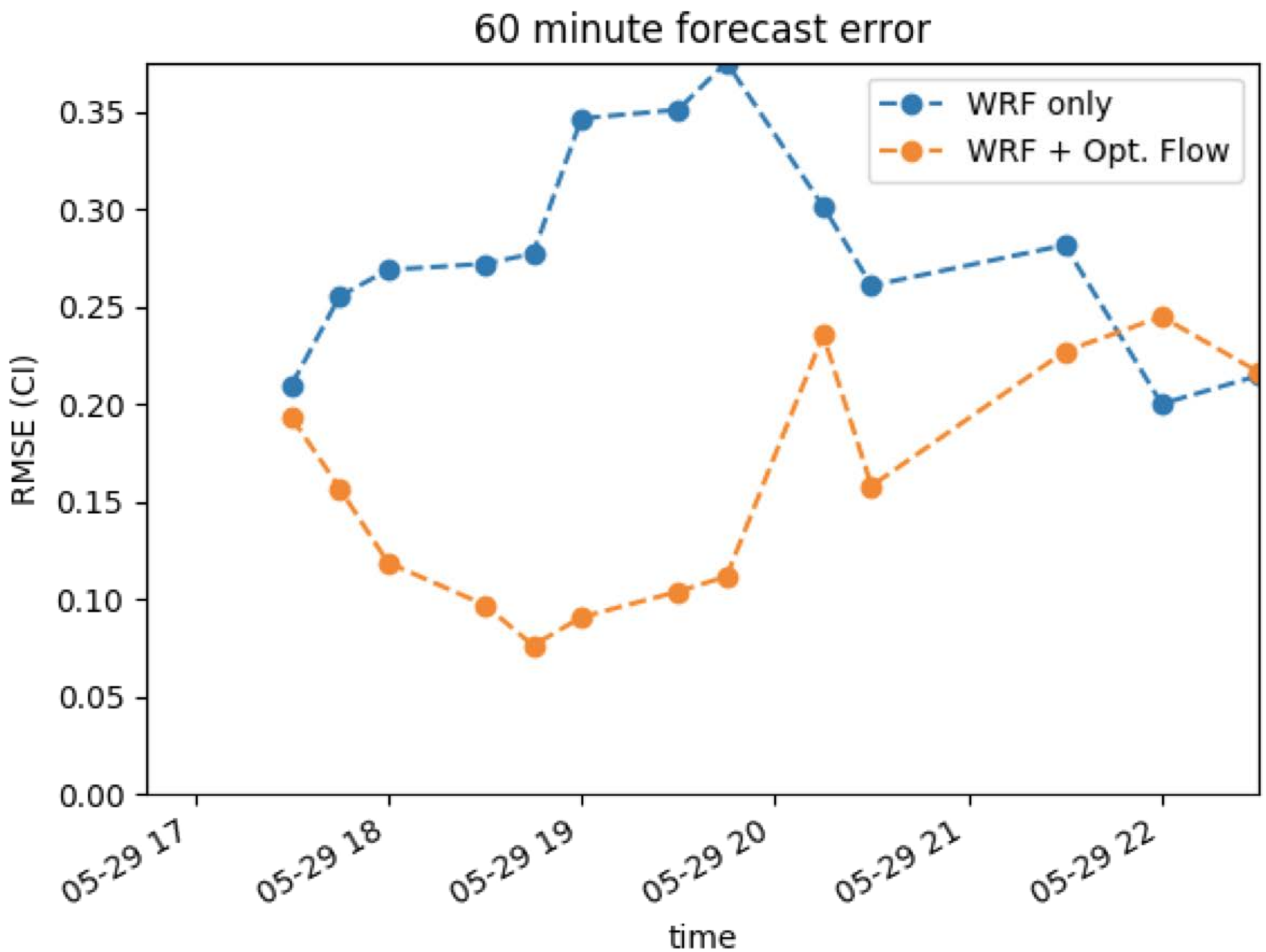
Error is calculated as RMSE between forecasted normalized irradiance and the actual satellite derived normalized irradiance for a 2240 km^2 area over Tucson.

Error time series



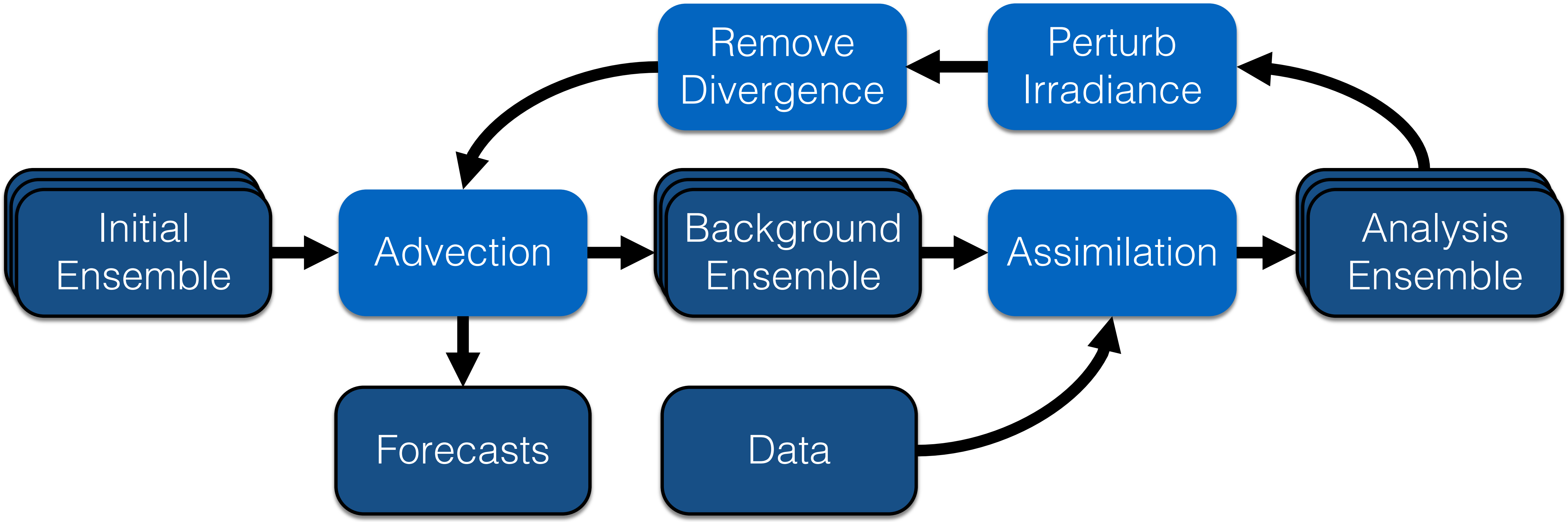
Error is calculated as RMSE between forecasted normalized irradiance and the actual satellite derived normalized irradiance for a 2240 km^2 area over Tucson.

Error time series



Error is calculated as RMSE between forecasted normalized irradiance and the actual satellite derived normalized irradiance for a 2240 km^2 area over Tucson.

Summary



- Short term irradiance forecasts through combining data from satellites, ground sensors, numerical weather prediction, and optical flow
- LETKF allows us to quickly assimilate a large amount of observations
- Assimilation of optical flow introduces convergence which should be removed
- Error is significantly reduced in comparison to using NWP winds alone

Thank you!

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