Ensemble Sensitivity Analysis Applied to the Genesis of Typhoon Nuri (2008)

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Outline

- Motivation
- Ensemble Sensitivity
- Typhoon Nuri (2008)
- Experimental Design
- Sensitivity Results
- Summary

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Motivation and Goal

- Key issues regarding Tropical Cyclones:
  - Dynamical understanding
    - Genesis and Structure
  - Predictability
    - Track and Intensity
- Apply ensemble sensitivity analysis to identify relationships between dynamical processes that control genesis
- Test hypothesis based on sensitivities, modify initial conditions to speed-up or stop genesis

Sensitivity Analysis

- relates change to an input (*state*: x) to changes in the output (*metric*: J)

$$\left.\begin{aligned} \delta\mathbf{x}_t = \mathbf{M}\delta\mathbf{x}_o = \mathbf{M}_t \cdots \mathbf{M}_o \delta\mathbf{x}_o \\ \delta J \doteq \left[\frac{\partial J}{\partial \mathbf{x}_t}\right]^T \delta\mathbf{x}_t \end{aligned}\right\} \quad \delta J = \left[\mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}_t}\right]^T \delta\mathbf{x}_o$$

$$\boxed{\frac{\partial J}{\partial \mathbf{x}_o} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}_t} = \mathbf{M}_o^T \cdots \mathbf{M}_t^T \frac{\partial J}{\partial \mathbf{x}_t}}$$

adjoint sensitivity to IC

adjoint or transpose of TLM

Sensitivity Analysis

- adjoint approach is deterministic
- consider δJ and $\delta \mathbf{x}$ as random variables

$$\delta J = \left[\frac{\partial J}{\partial \mathbf{x}_o}\right]^T \delta \mathbf{x}_o$$

$$\left\langle \delta J \delta \mathbf{x}_o^T = \left[\frac{\partial J}{\partial \mathbf{x}_o}\right]^T \delta \mathbf{x}_o \delta \mathbf{x}_o^T \right\rangle$$

$$cov(\delta J, \delta \mathbf{x}_o) = \left[\frac{\partial J}{\partial \mathbf{x}_o}\right]^T \mathbf{A}$$

$$\boxed{\left[\frac{\partial J}{\partial \mathbf{x}_o}\right]^T = cov(\delta J, \delta \mathbf{x}_o)\mathbf{A}^{-1}}$$

Ensemble Sensitivity

- compute sensitivity from ensemble output

$$\delta J \approx \frac{\partial J}{\partial x_j} \cdot \sigma_{\mathbf{X}_j} \approx \frac{cov(\mathbf{J}, \mathbf{X}_j)}{var(\mathbf{X}_j)} \cdot \sigma_{\mathbf{X}_j}$$

- linear regression
  - dependent variable is forecast metric
  - independent variable is element of state vector
- can apply confidence testing using ensemble statistics
- no adjoint or tangent linear model required
- no assumptions about on/off or moist processes
- can evaluate rapidly for any J

Typhoon Nuri (2008)

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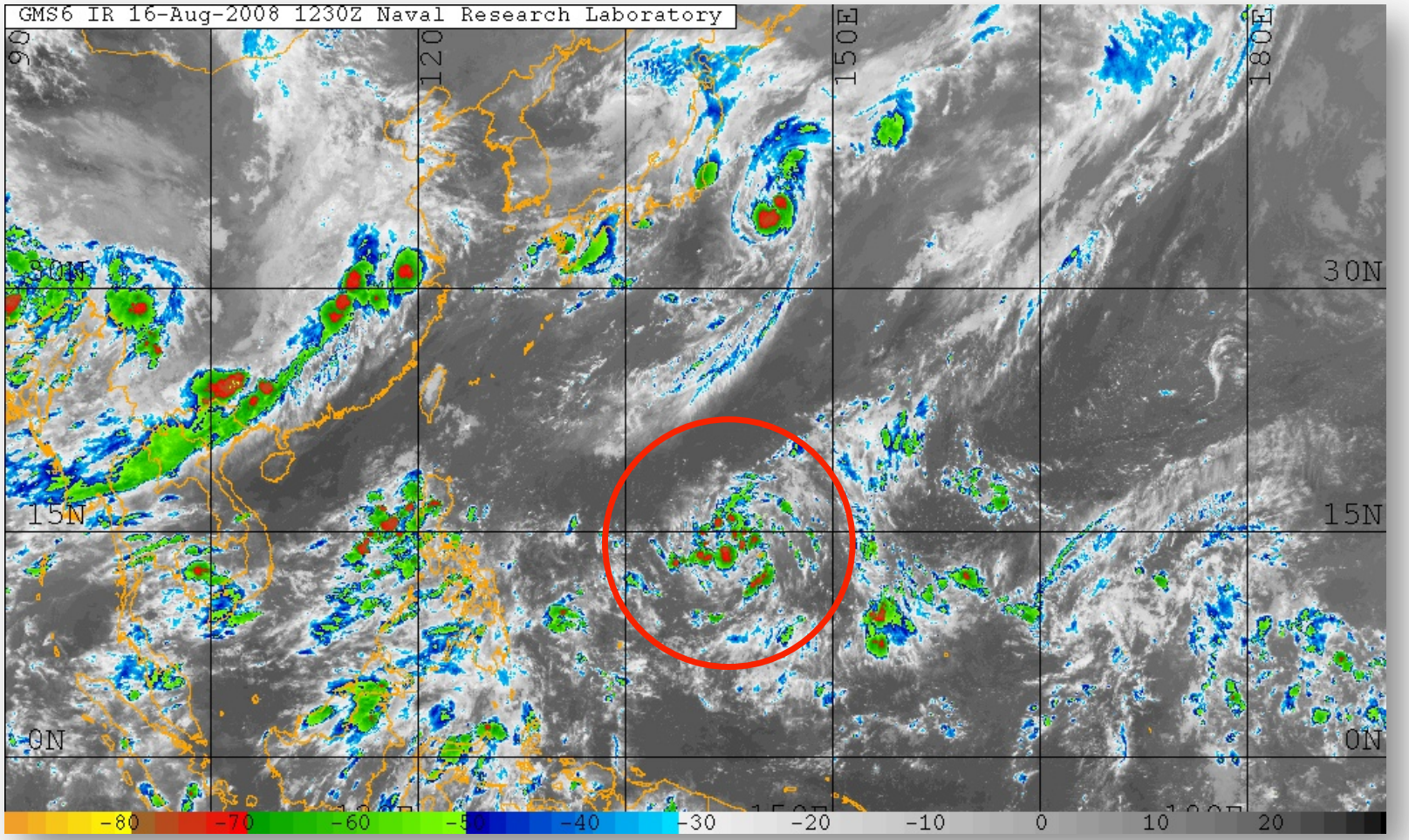
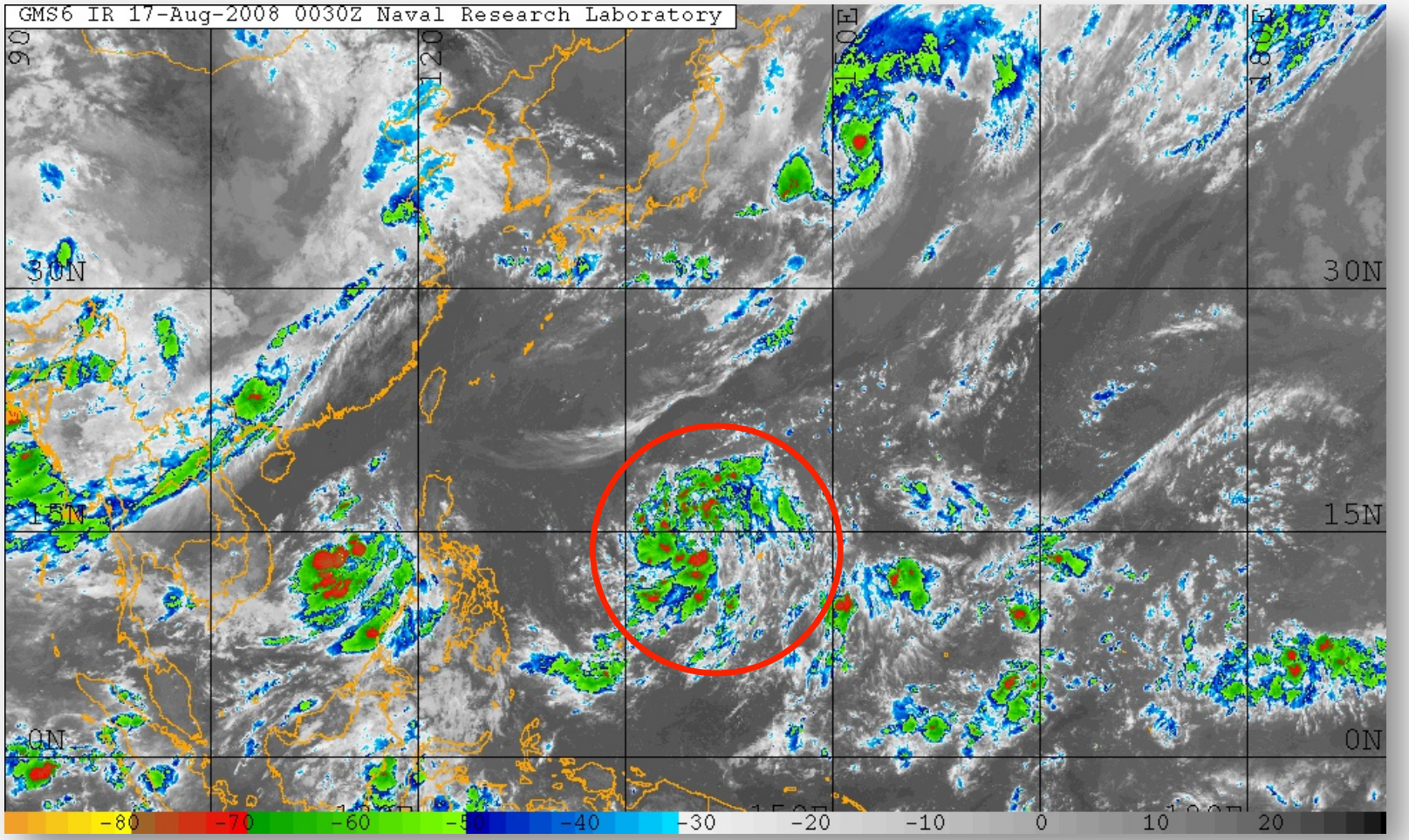


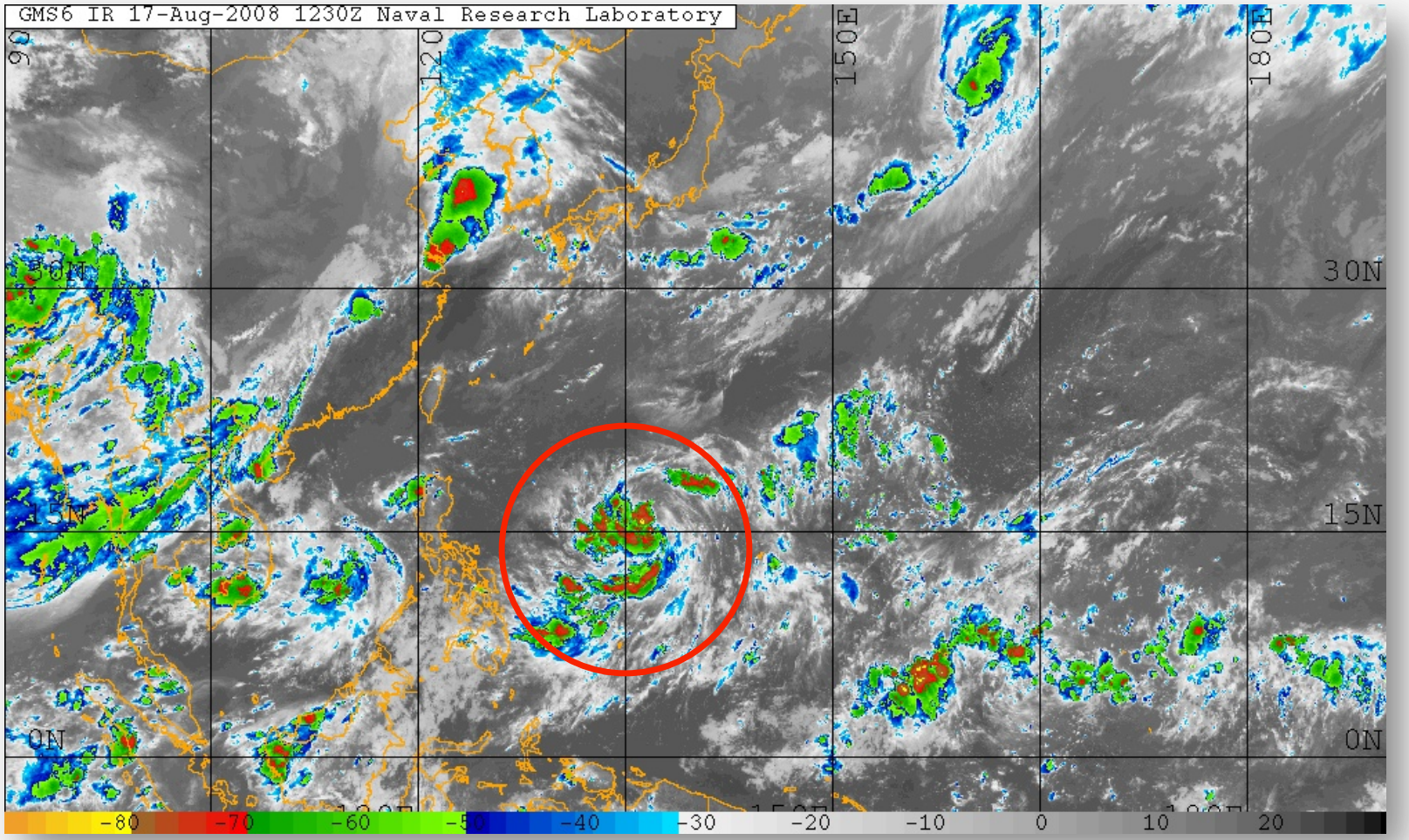
Genesis -24 hrs 1230Z 16 August 2008

Typhoon Nuri (2008)



Genesis -12 hrs 0030Z 17 August 2008

Typhoon Nuri (2008)



Genesis 1230Z 17 August 2008

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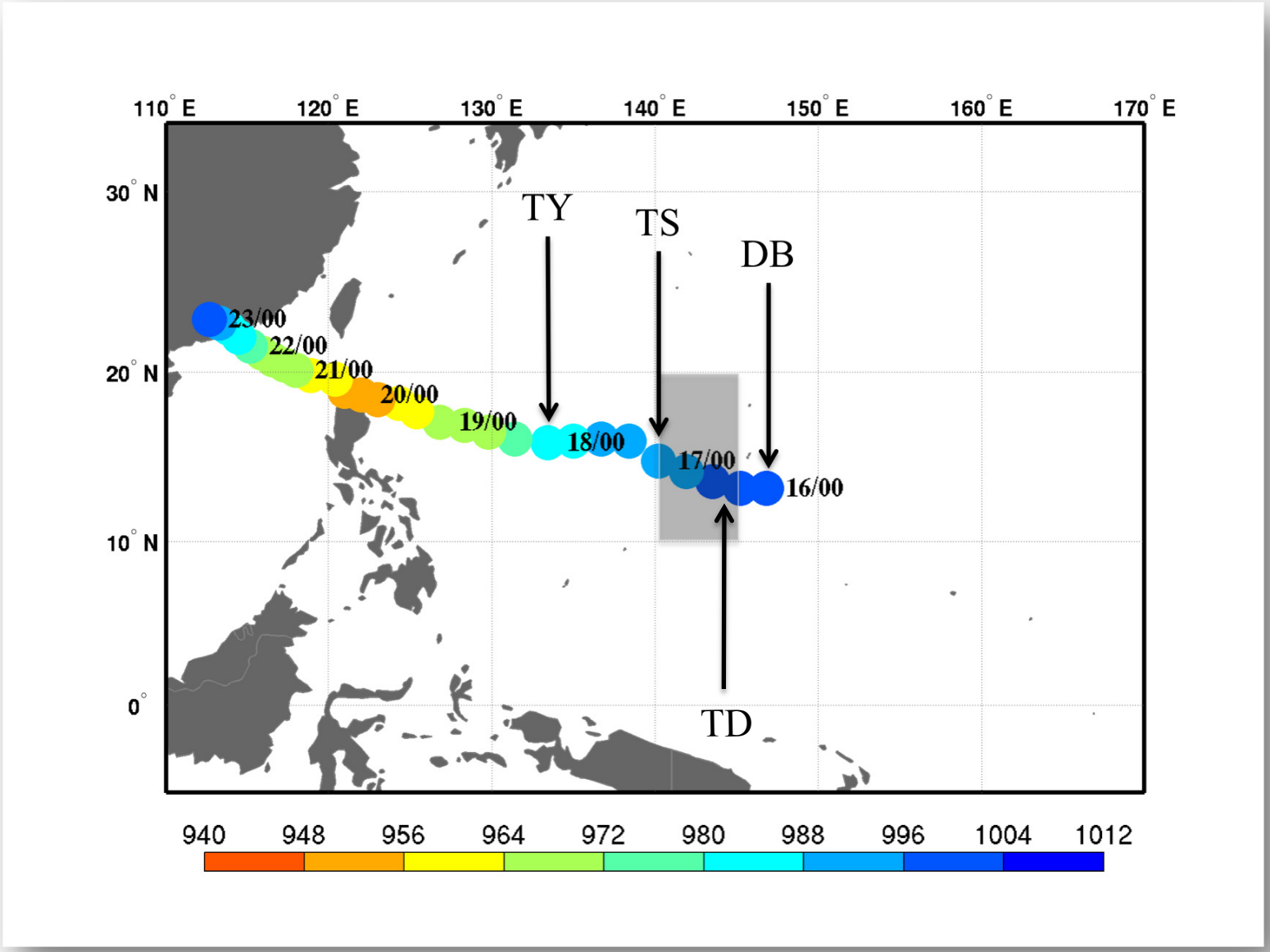


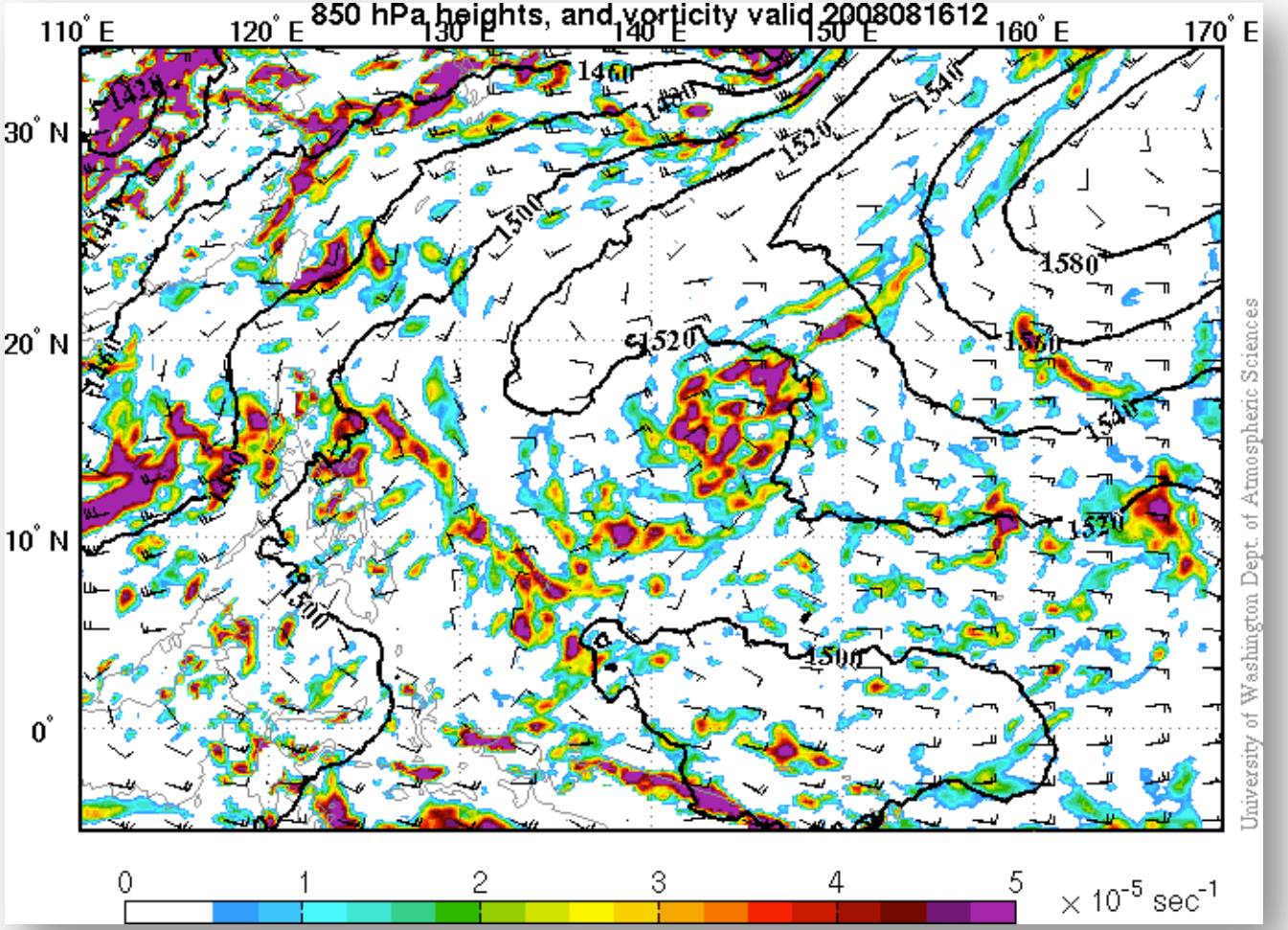
Experiment Setup

- Model
  - Weather Research and Forecasting (WRF V3.1)
  - 27km horizontal resolution domain over west Pacific
  - 38 vertical levels, 10 hPa model top
- Data Assimilation
  - Ensemble Square Root Filter
  - 90 ensemble members
  - Covariance Relaxation, Gaspari-Cohn localization
  - assimilate observations every 6 hrs
    - *Conventional observations*:
      - rawinsondes, ACARS, surface stations, buoys, ships, cloud track winds
    - *Field observations from T-PARC / TCS08*:
      - dropsondes and flight level data

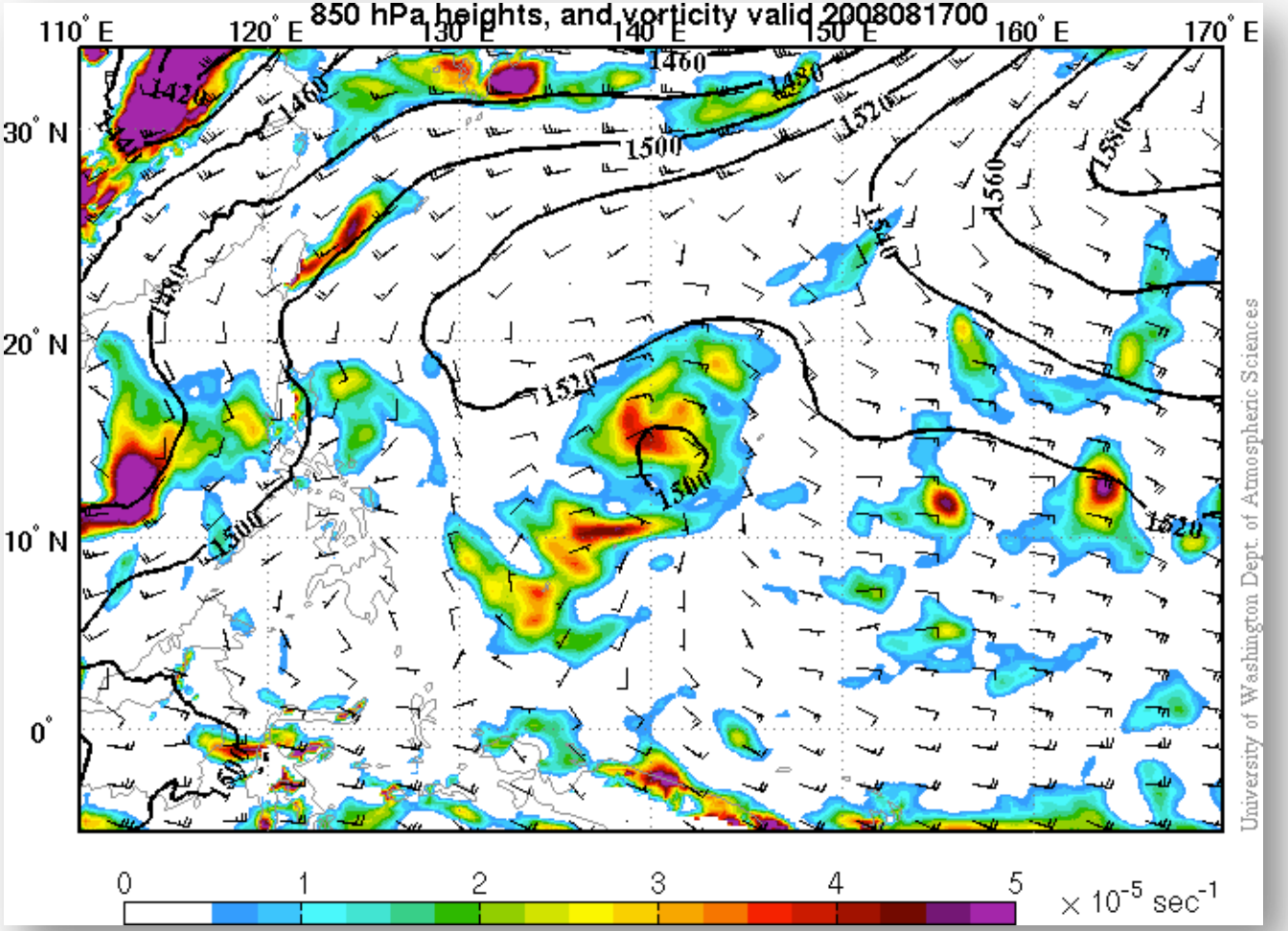
Procedure

- Cycle EnKF from pre-depression to maximum intensity of typhoon Nuri
- Generate ensemble forecast out to 24 hours from pre-depression to tropical storm strength (16/12Z – 17/12Z)
- Compute sensitivity of metrics at forecast time to analysis state at initialization time

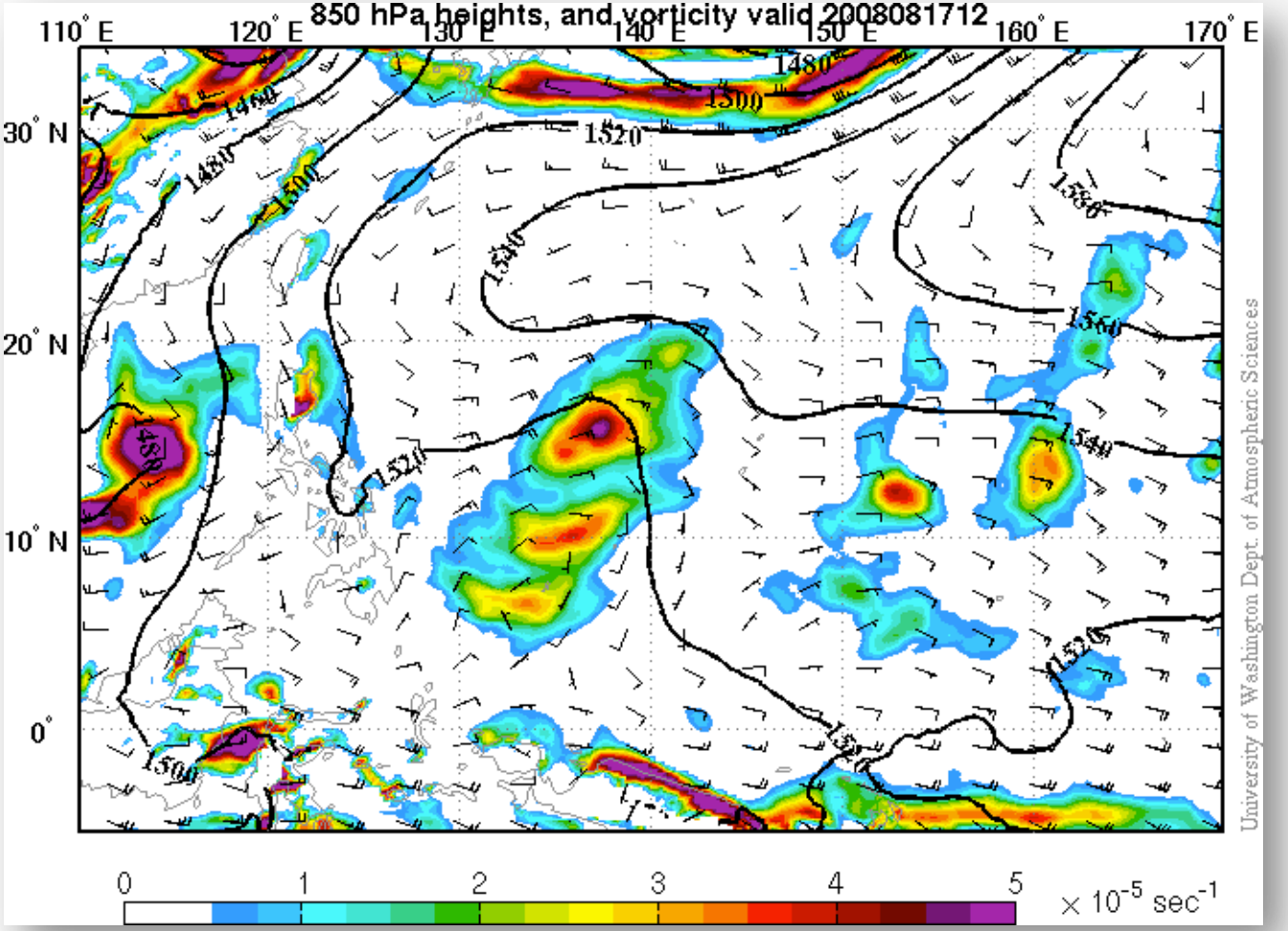
Nuri analysis 16/12 (00hr forecast)



Nuri 12hr forecast

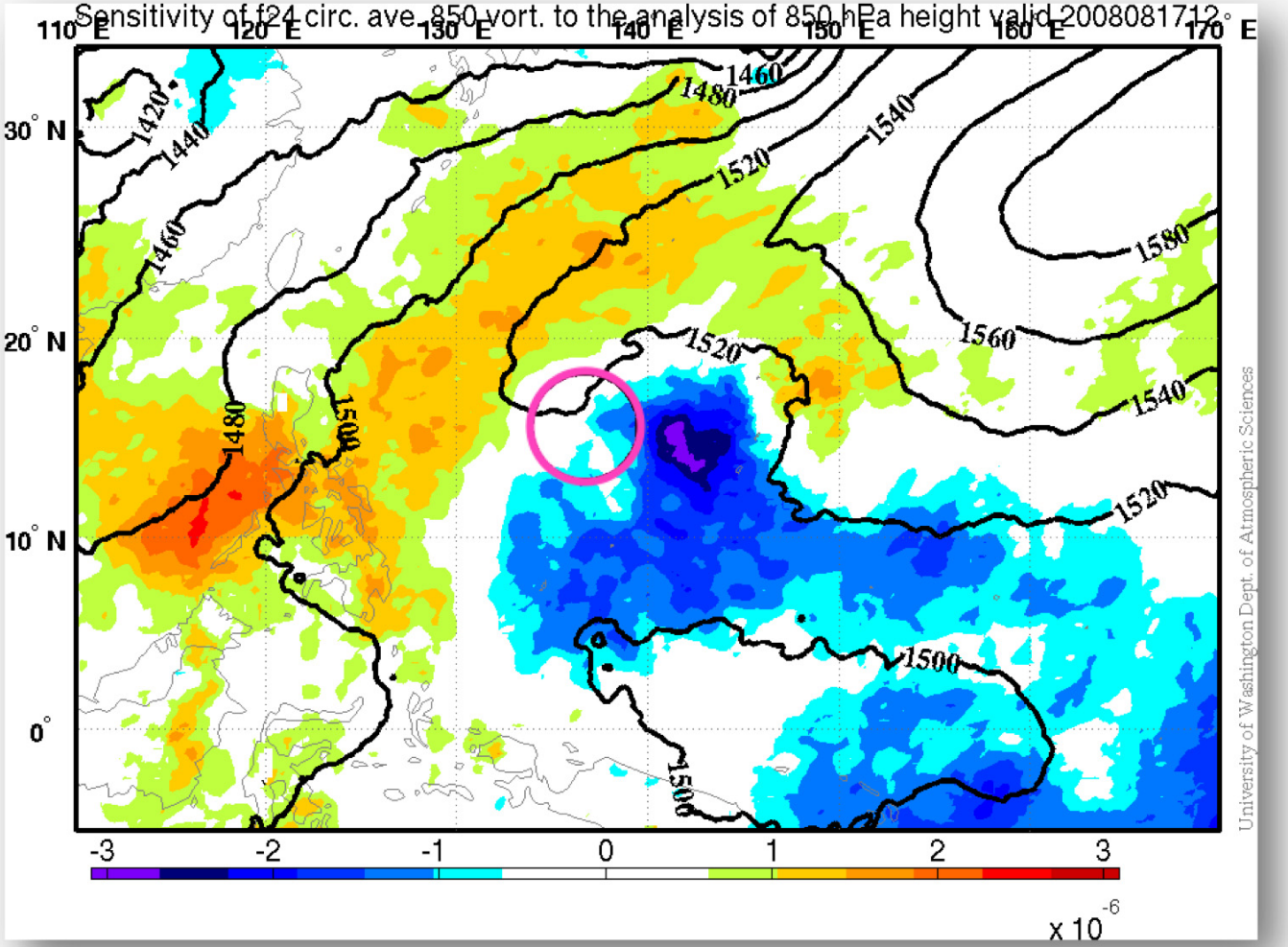


Nuri 24hr forecast

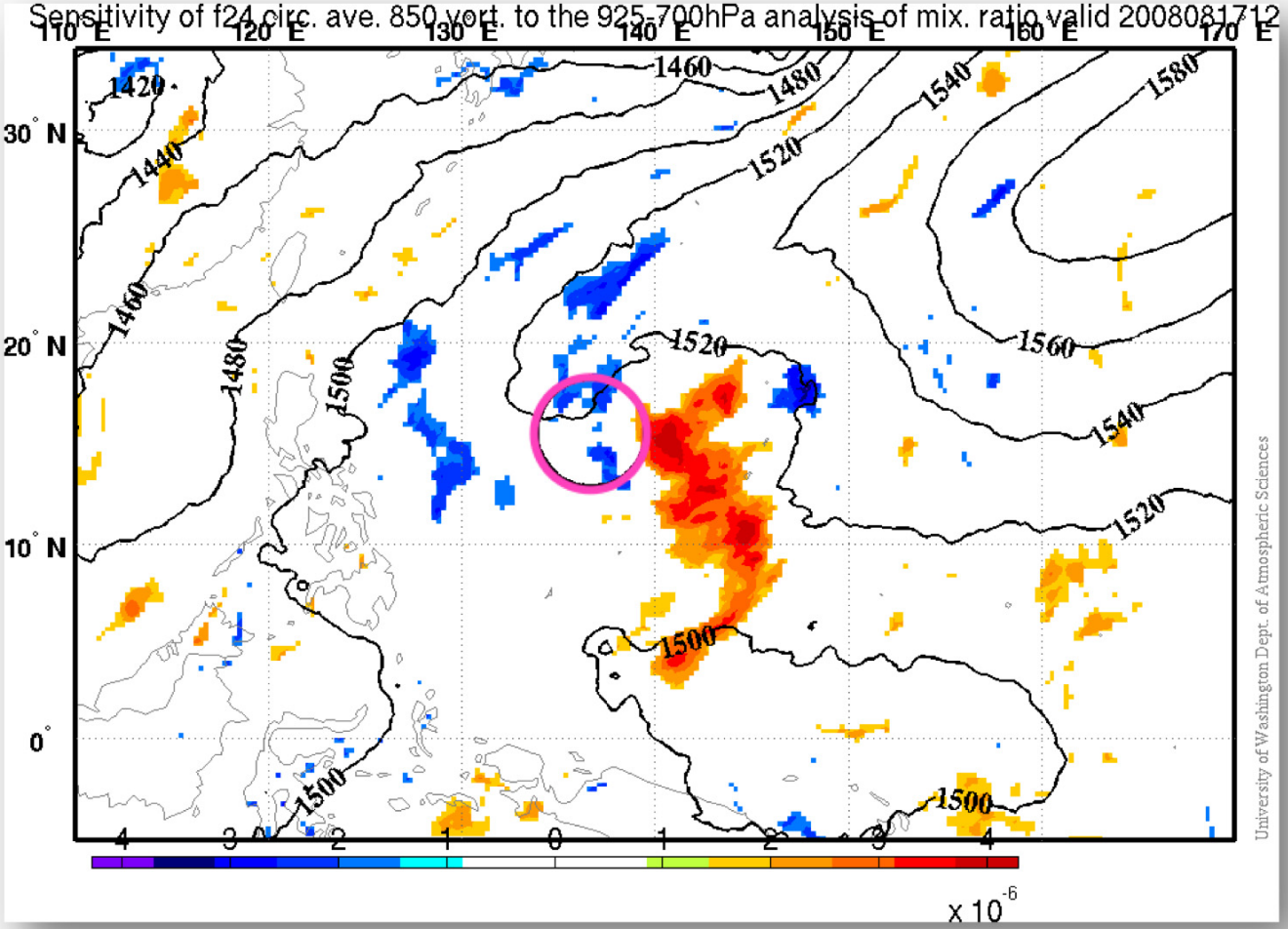


Sensitivity Results

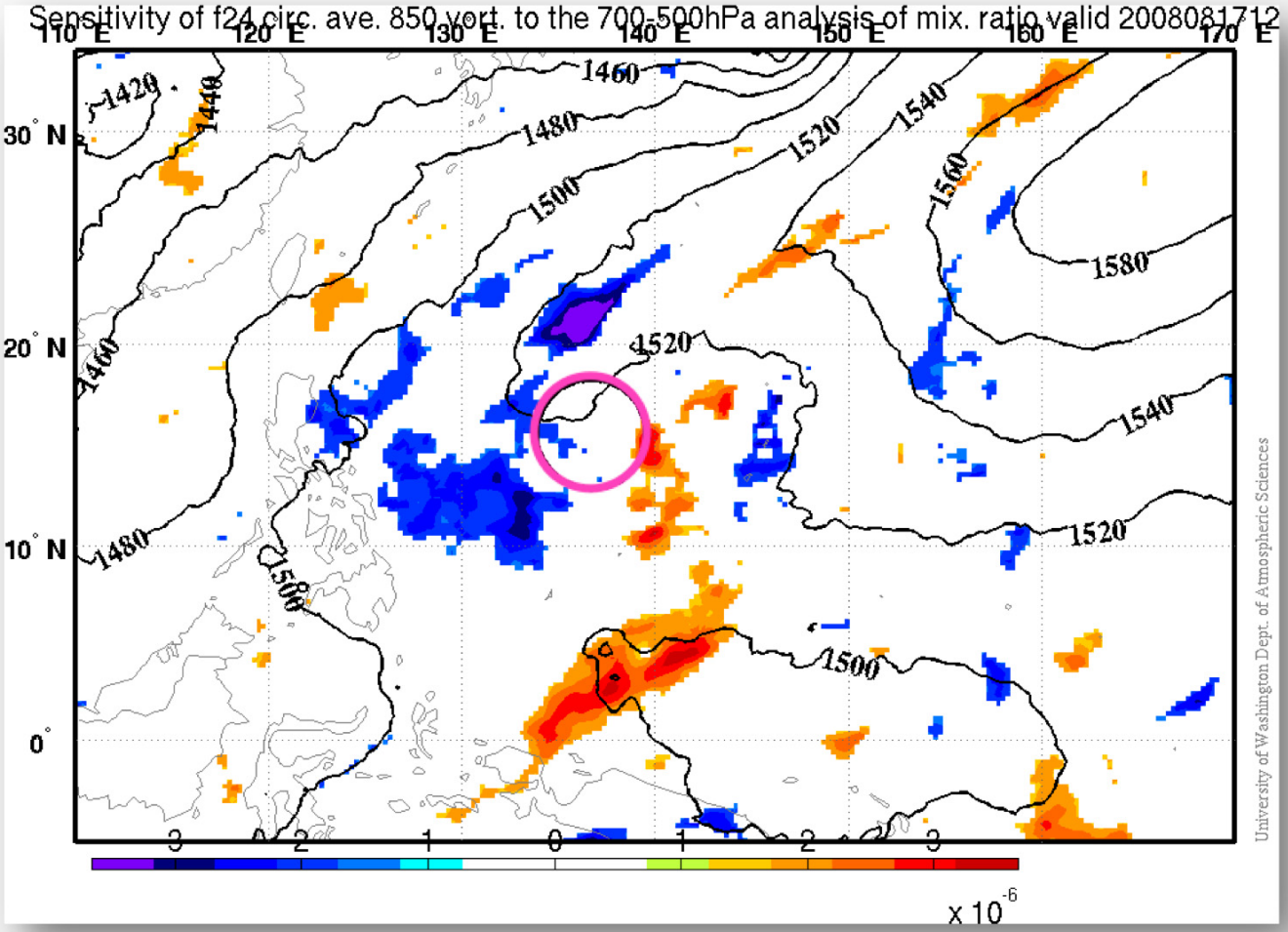
Sensitivity to 850 hPa height analysis



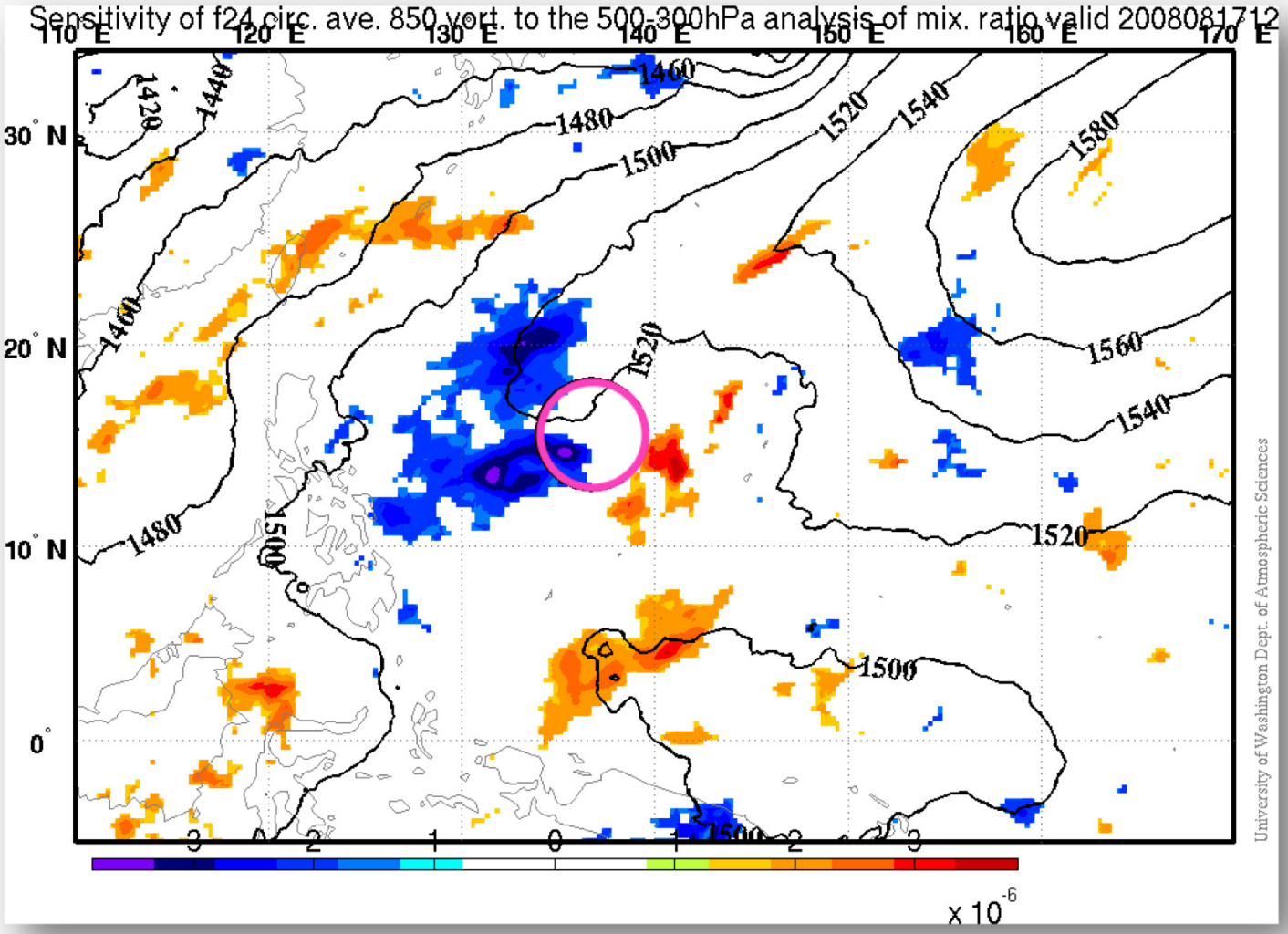
Sensitivity to 925-700 vapor analysis



Sensitivity to 700-500 vapor analysis



Sensitivity to 500-300 vapor analysis



Initial Condition Perturbations

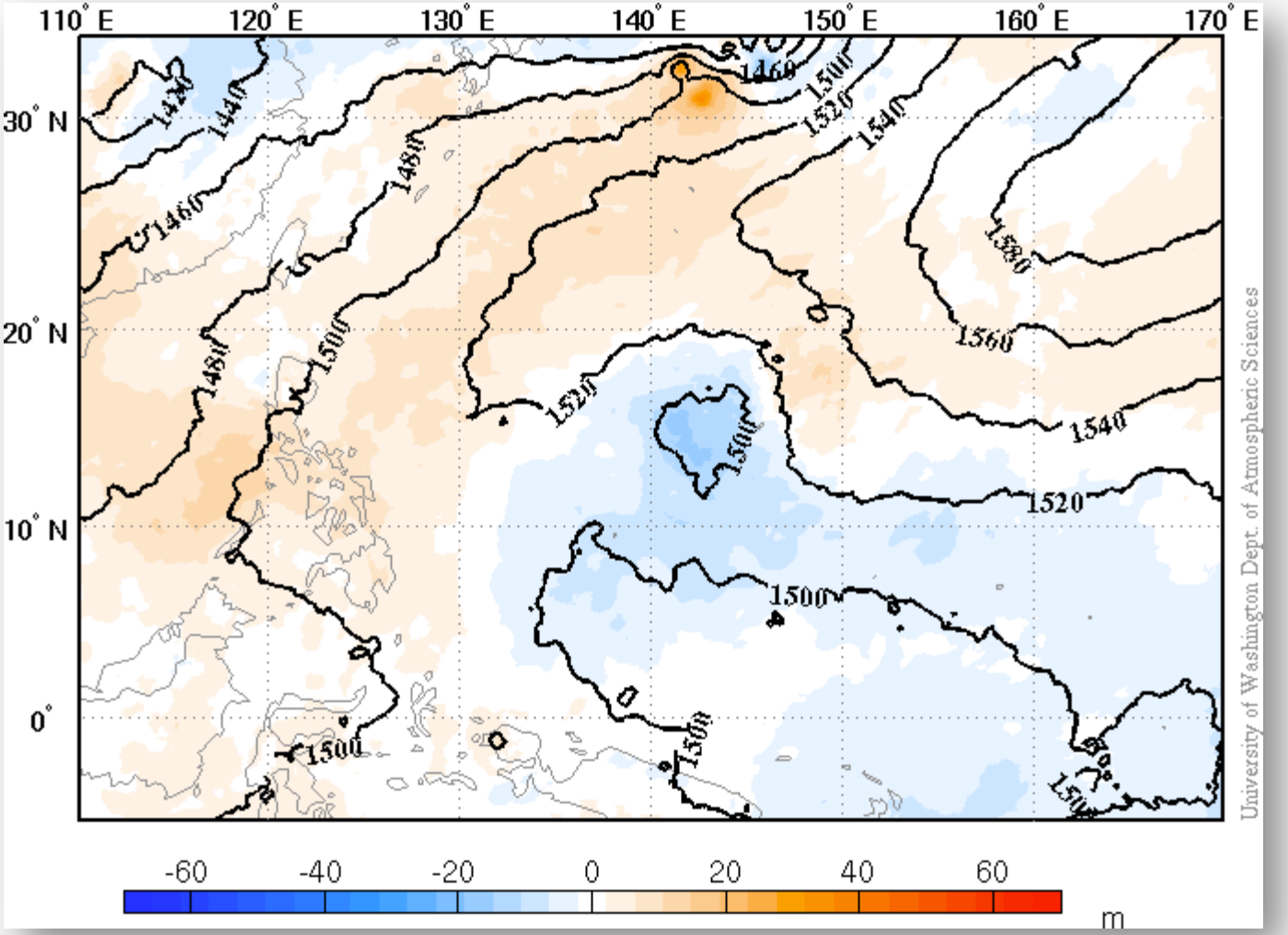
- Test statistical predictions with model response
- Perturb initial state via

$$\mathbf{X}_j^p = \mathbf{X}_j^a + \frac{\partial x_j^a}{\partial J} \cdot \alpha$$

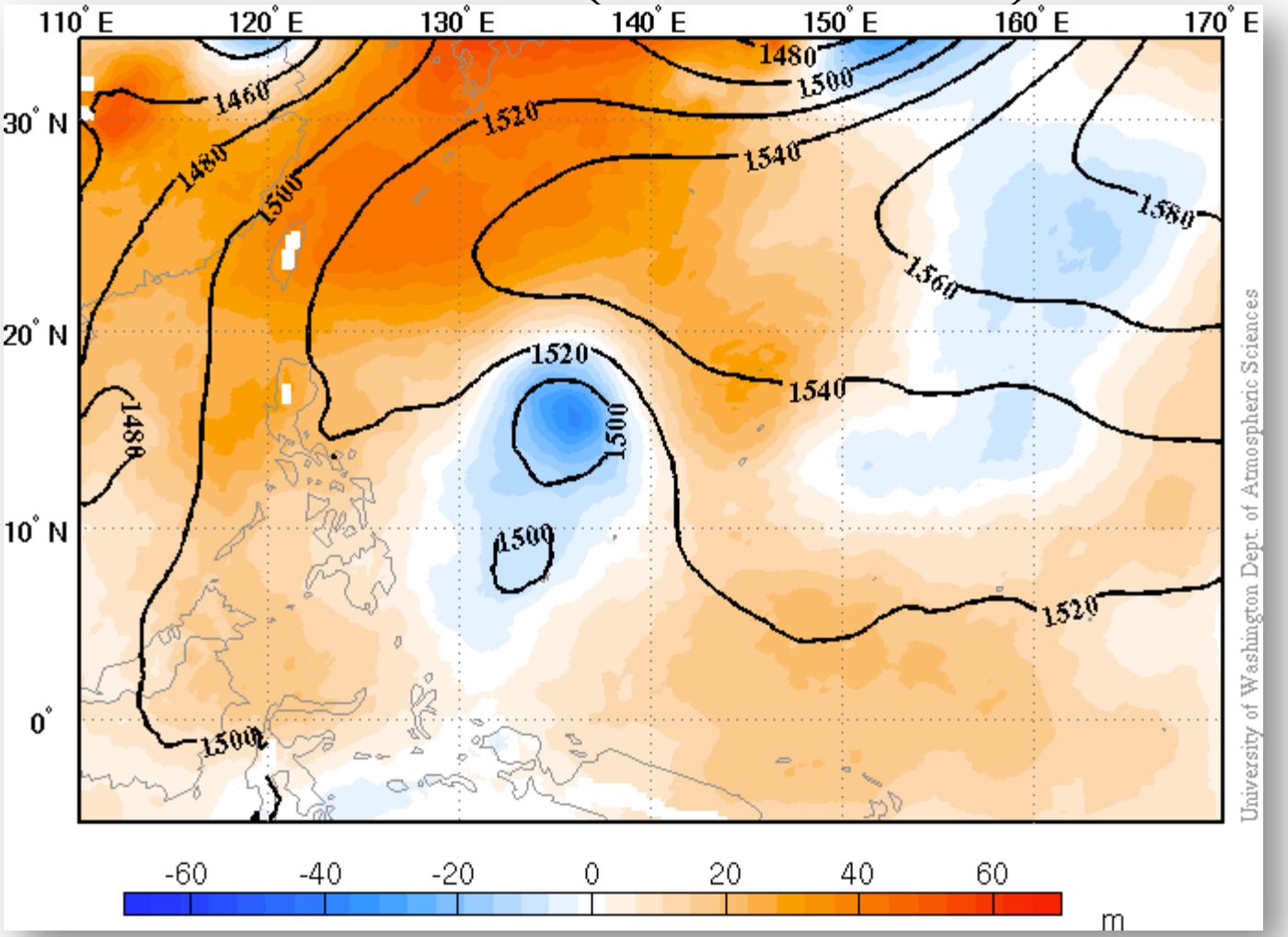
$$\frac{\partial x_j^a}{\partial J} = \frac{cov(\mathbf{X}_j^a, \mathbf{J})}{var(\mathbf{J})}$$

  - independent variable is the forecast metric
  - dependent variable is the analysis
  - apply for a range of scales (α)
- Run full non-linear model w/ perturbed IC's, recompute δJ

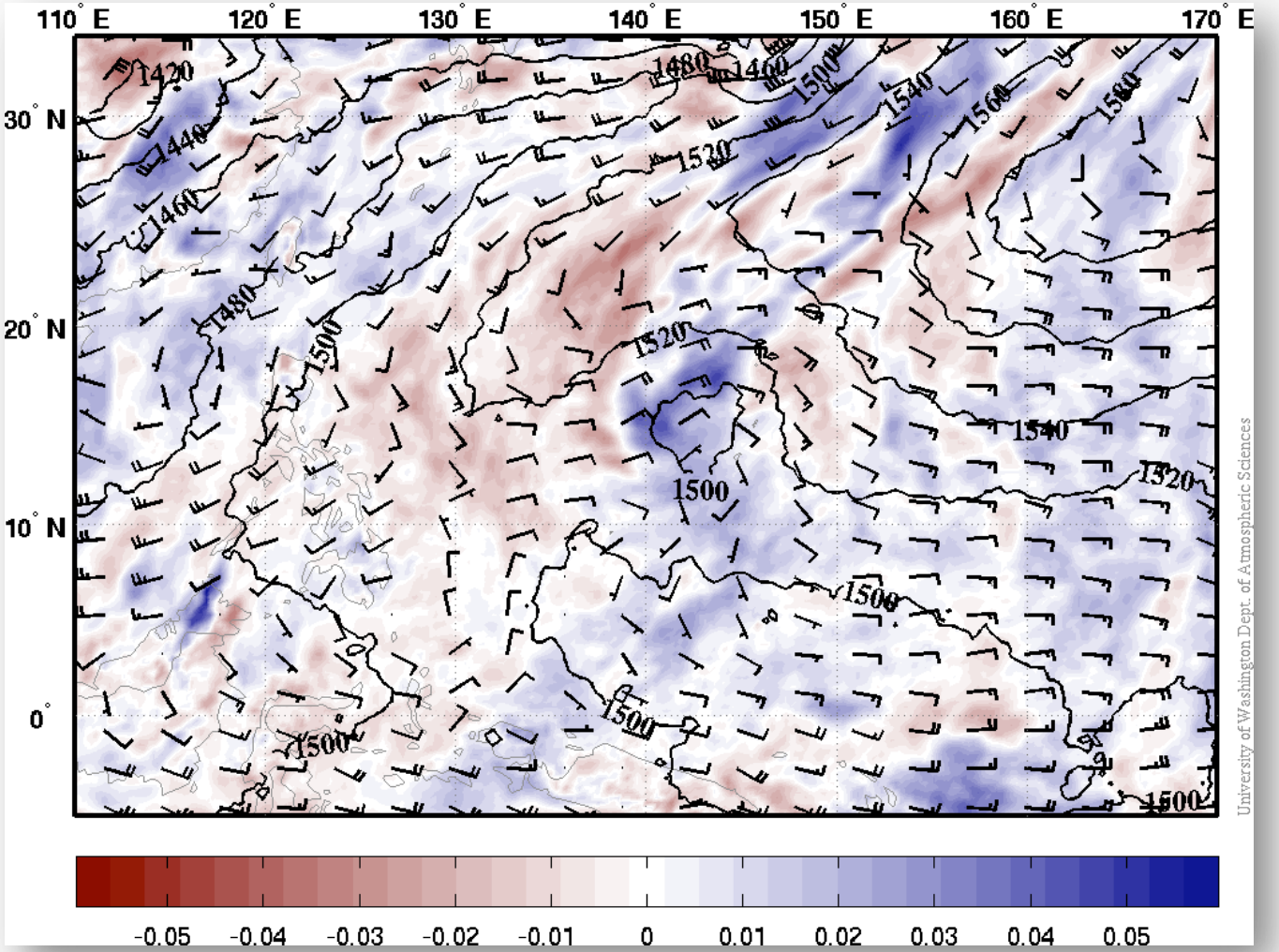
Perturbed Initial Conditions (850 hPa Z)



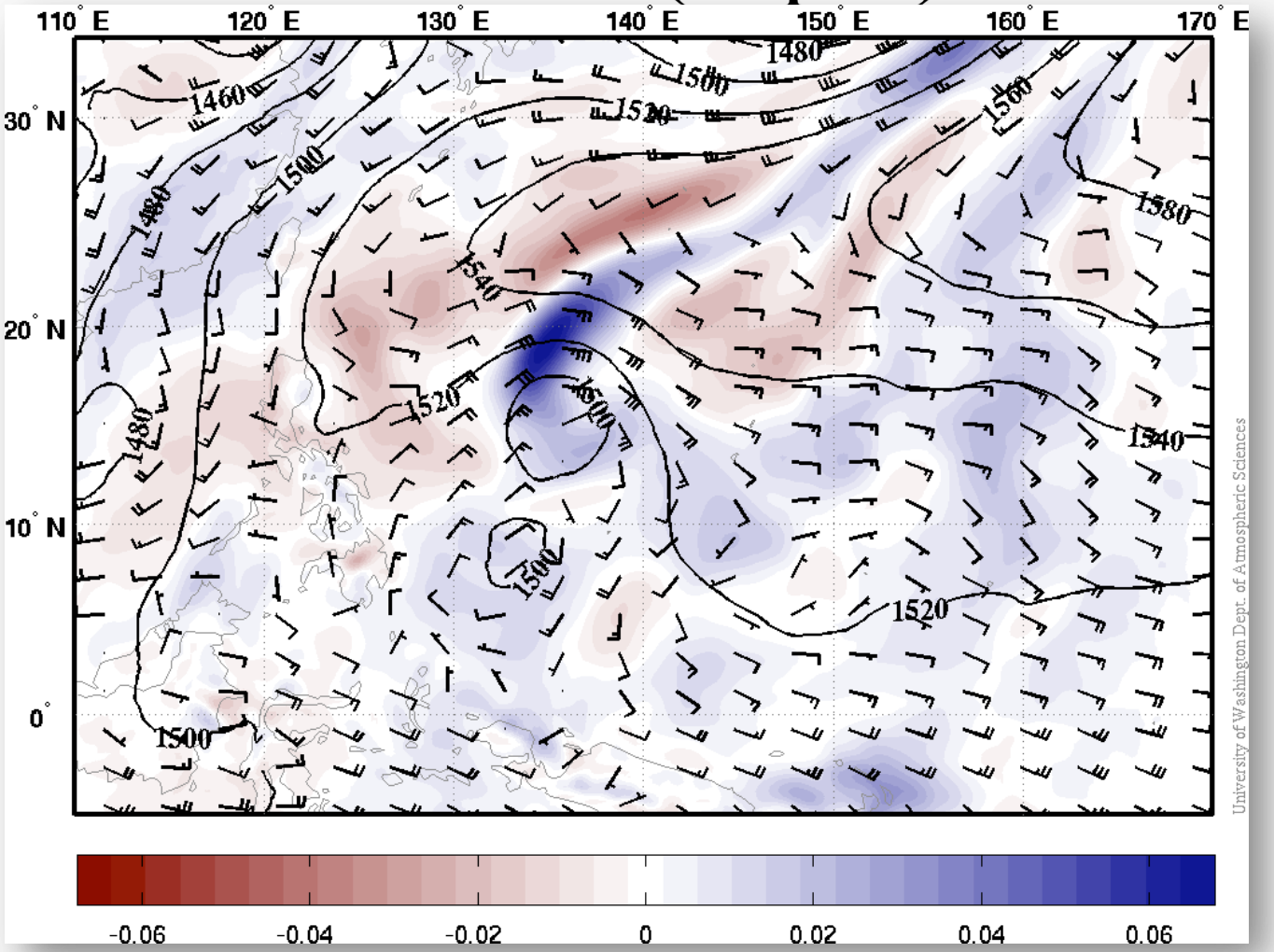
24 hr perturbed forecast and difference(850 hPa Z)



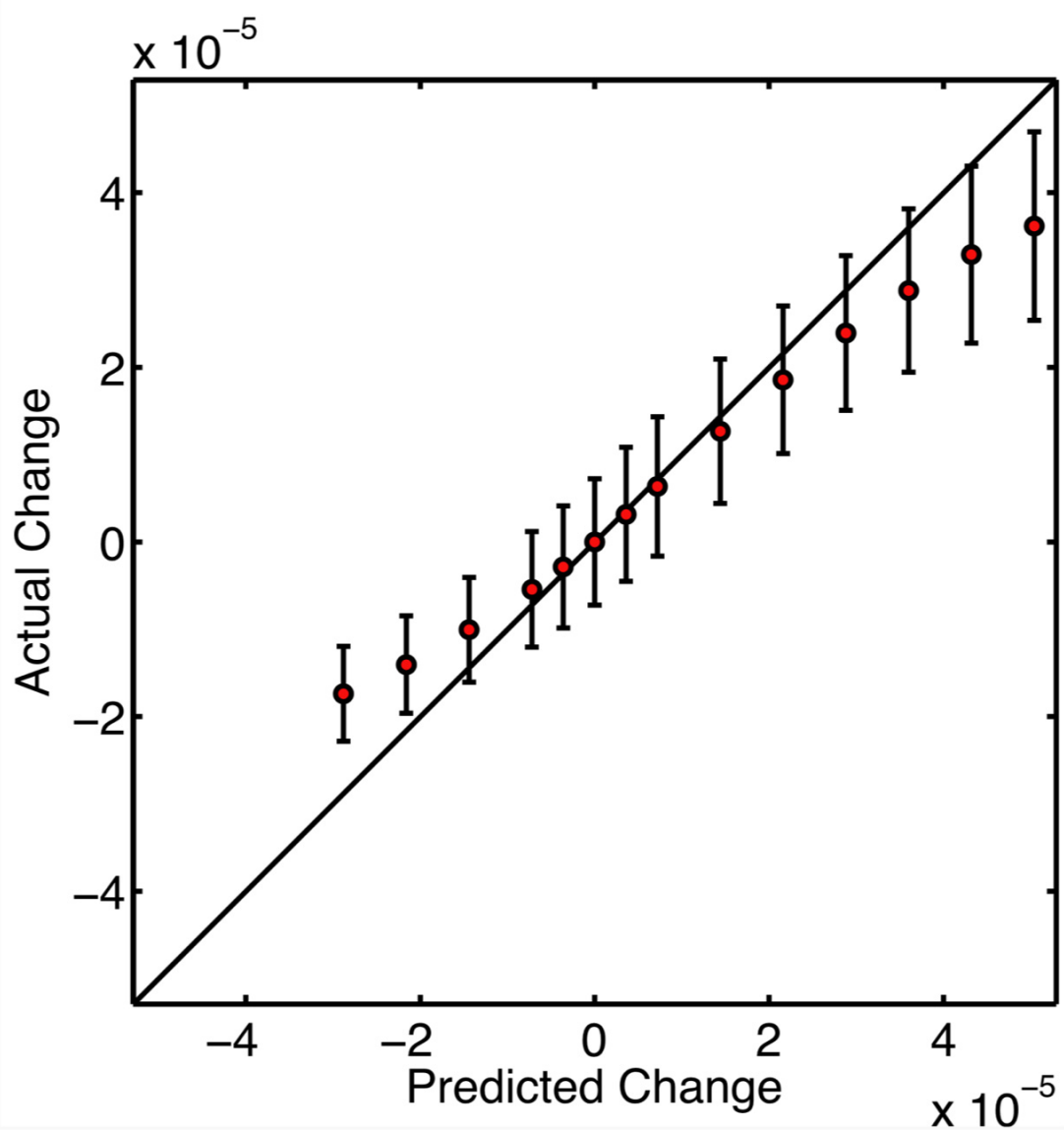
Perturbed Initial Conditions (vapor)



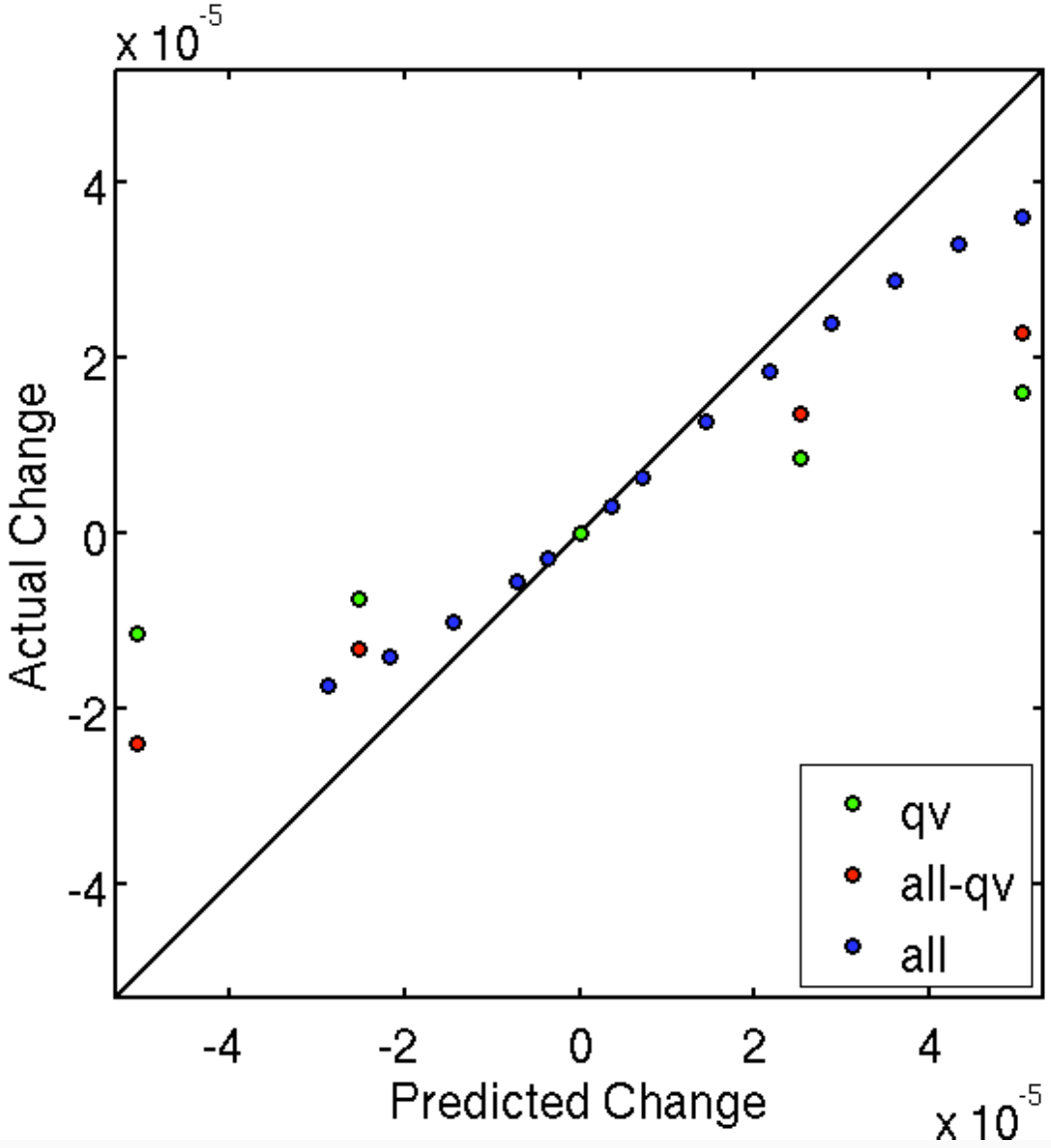
24 hr perturbed forecast and difference(vapor)



Perturbed Forecasts, 850 hPa vorticity



Perturbed Forecasts, moisture



Summary

- Applied ensemble sensitivity analysis to explore tropical cyclogenesis of typhoon Nuri

- Genesis sensitivity associated with
  - initial intensity and downstream ridge
  - moisture near trough and along boundary

- Modified initial conditions with perturbations:
  - small: model response comparable to ensemble predictions
  - large: model response less than the ensemble predictions suggesting non-linear interaction
  - experiments suggest significant contribution from moisture at low levels

- Iterate over different choices of forecast metrics and analysis state variables and increased resolution