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Outline

• Motivation
• Ensemble Sensitivity
• Typhoon Nuri (2008)

• Experimental Design
• Sensitivity Results
• Summary
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: \( J \))

\[
\delta x_t = M \delta x_o = M_t \cdots M_o \delta x_o
\]

\[
\delta J = \left[ \frac{\partial J}{\partial x_t} \right]^T \delta x_t
\]

\[
\delta J = \left[ M^T \frac{\partial J}{\partial x_t} \right]^T \delta x_o
\]

\[
\frac{\partial J}{\partial x_o} = M^T \frac{\partial J}{\partial x_t} = M_o^T \cdots M_t^T \frac{\partial J}{\partial x_t}
\]

adjoint sensitivity to IC

adjoint or transpose of TLM
Sensitivity Analysis

• adjoint approach is deterministic
• consider $\delta J$ and $\delta x$ as random variables

$$
\delta J = \left[ \frac{\partial J}{\partial x_o} \right]^T \delta x_o
$$

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

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

$$
\left[ \frac{\partial J}{\partial x_o} \right]^T = cov(\delta J, \delta x_o) A^{-1}
$$
Ensemble Sensitivity

• compute sensitivity from ensemble output

\[ \delta J \approx \frac{\partial J}{\partial x_j} \cdot \sigma_{x_j} \approx \frac{\text{cov}(J, X_j)}{\text{var}(X_j)} \cdot \sigma_{X_j} \]

• 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)
Typhoon Nuri (2008)

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
Typhoon Nuri (2008)
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

850 hPa heights, and vorticity valid 2008081700
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
  \[ X_j^p = X_j^a + \frac{\partial x_j^a}{\partial J} \cdot \alpha \]

  \[ \frac{\partial x_j^a}{\partial J} = \frac{\text{cov}(X_j^a, J)}{\text{var}(J)} \]

  - independent variable is the forecast metric
  - dependent variable is the analysis
  - apply for a range of scales (\( \alpha \))

- Run full non-linear model w/ perturbed IC’s, recompute \( \delta J \)
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

![Graph showing actual change vs predicted change and data points labeled qv, all-qv, and all.](image-url)
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