Ensemble forecasting and initial condition sensitivity for hurricanes

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Where tropical cyclone forecasts go wrong

Why do forecasts possess errors? How do we reduce errors and understand uncertainty?

1. **Errors in the initial conditions**
2. Errors in the model physics and boundary conditions
The assimilation-forecast cycle

Adaptive sampling strategy?

1-12 hr forecast ‘first guess’ for data assimilation

New observational data

Data Assimilation

Model / Ensemble initial conditions

End product: Deterministic and Probabilistic Forecast
Outline of Seminar

A. Typhoon Sinlaku (2008)
   1. Sensitivity to direct environmental perturbations
   2. How do Singular Vectors govern ensemble spread?

B. Hurricane Ike (2008)
   1. Ensemble probabilistic prediction
   2. Sensitivity to remote perturbations

C. Hurricane Irene (2011)
   1. Influence of assimilating special soundings
   2. Ensemble prediction of tropical cyclogenesis
One Goal: Advancing knowledge and improving the short-range prediction of tropical cyclones over eastern Asia and the western Pacific.
Typhoon Sinlaku (2008)
Snilaku: Hypotheses

1. TC forecasts are sensitive to perturbations in the synoptic environment.

2. The spreading in TC track forecasts is due to instabilities in the storm and its environment.
Vorticity perturbation within WRF

Komaromi et al. (2011, MWR)
JTWC Best Track
Control simulation
$-0.75\;\zeta$ at S1
$+0.75\;\zeta$ at S1
$-0.23\;\zeta$ at S1
$+0.23\;\zeta$ at S1
$-0.25\;\zeta$ at S2
$+0.25\;\zeta$ at S2
$-0.75\;\zeta$ at S2
$+0.75\;\zeta$ at S2
$-0.15\;\zeta$ at S2
$+0.15\;\zeta$ at S2
$-0.55\;\zeta$ at S2
$+0.55\;\zeta$ at S2

Komaromi et al. (2011, MWR)
S1: Impact of weakening mid-latitude trough

Komaromi et al. (2011, MWR)
Some ETKF targets demonstrate sensitivity. However, ranking of targets is inconsistent with ranking of targets made by direct perturbations.

Komaromi et al. (2011, MWR)
Sinhalku: Results 1

H: TC forecasts are sensitive to perturbations in the synoptic environment

• Yes, even to perturbations of modest strength.

• Moderate weakening of (S1) mid-latitude trough and (S2) neighbouring upper-level low lead to avoidance of premature recurvature → features initialized too strongly?

• More direct method than adaptive sampling methodologies; however, not applicable in real-time.
Snlaku: Hypotheses

1. TC forecasts are sensitive to perturbations in the synoptic environment.

2. The spreading in TC track forecasts is due to instabilities in the storm and its environment.
Ensemble prediction systems

NCEP: use Ensemble Transform to initialize ensemble.
ECMWF: use Singular Vectors to initialize ensemble.

What mechanisms cause the spreading of the ensemble members?
0 h

Asymmetric propagation

12 h

Background steering

Yamaguchi and Majumdar (2010, MWR)
Singular Vectors

Solve “analysis error covariance optimals” via

\[(GL)^*(P^v)^{-1}(t_v)(GL)v_i(t_a) = \sigma_i^2(P^a)^{-1}(t_a)v_i(t_a)\]

Result: perturbation structures that grow, in a linear sense, to maximize total energy within a verification region around the tropical cyclone.

Add these structures to the ECMWF analysis to obtain a spreading in the forecast tracks.
Asymmetric propagation

Yamaguchi and Majumdar (2010, MWR)
Baroclinic instability centered on the vortex

Theory

Ensemble perturbation

Shading: Streamfunction
Contour: Temperature

Perturbation draws eddy available potential energy from mean flow

Yamaguchi and Majumdar (2010, MWR)
Hypothesis: Eddy APE is converted into EKE → wind perturbation grows where radial heat flux is positive

Yamaguchi and Majumdar (2010, MWR)
Sinlaku: Results 2

H: The spreading in TC track forecasts is due to instabilities in the storm and its environment.

- Growth of advection flow of Sinlaku is larger in ECMWF than NCEP.

- Perturbation growth in ECMWF ensemble associated with
  - 1) baroclinic energy conversion in a vortex,
  - 2) baroclinic energy conversion in midlatitude waves,
  - 3) barotropic energy conversion in a vortex.
Zonal flow over CONUS amplified as two tropopause disturbances moved into western North America on 9 Sep.

Upper-level ridging developed downstream over SE U.S.

Strong jet developed over SW U.S. by 13 Sep, setting the stage for Ike’s rapid recurvature after landfall in SE TX.
Ike: Hypotheses

1. Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclone track.

2. Initial condition errors in the ridge and shortwave troughs were a primary reason for the troublesome landfall forecast.
NHC 67% “Cone of uncertainty”
Over the full season, does the actual track fall within the 67% circles 67% of the time?
H: Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclone track.

- For the Atlantic season in 2008, in which the ensemble mean forecast was accurate, the ECMWF probability circles were also accurate. Not the case for NW Pacific in 2008.
Ike: Hypotheses

1. Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclone track.

2. Initial condition errors in the ridge and shortwave troughs were a primary reason for the troublesome landfall forecast.
Low-predictability problem? Red and blue initial GEFS members produced similar 500 hPa Z on Sep 9\textsuperscript{th}, but the red forecast exhibited a much stronger ridge on the 12\textsuperscript{th}.

Brennan and Majumdar (2011, WAF, in press)
NCEP GFS Assimilation experiments

Figure 9. GFS analysis of 200-hPa wind (barbs, kt), 500-hPa geopotential height (solid contours, dam), and 850-hPa relative vorticity (positive values contoured every 4 x 10^5 s^-1) valid at 0000 UTC 9 September 2008. Dots represent the approximate location of observations for GFS perturbation experiments e1-e8.

Figure 10. (a) Temperature perturbation (K) for experiment e1 along a cross section from 30°N 100°W to 30°N 60°W, (b) as in (a) except for geopotential height (m).

Brennan and Majumdar (2011, WAF, in press)
Figure 11. 5-day GFS track forecasts of Hurricane Ike initialized at 0000 UTC 9 September 2008, for the operational forecast (maroon), the eight perturbed analyses e1-e8, and the analysis ‘fl’ from the combined perturbations of the ridge north of Ike and the shortwave off California (see legend). The observed best track of Ike is shown in black. The dots along the tracks correspond to positions every 24 h during the forecast period.
Figure 12. GFS 500-hPa geopotential height (contours, dm) from operational run (black) and perturbation experiment e1 (green) initialized at 0000 UTC 9 September 2008 and difference field e1-operational (shaded, m) for (a) the analysis (b) 24-h forecast, (c) 48-h forecast, and (d) 72-h forecast.
A modest change to the operational analysis can modify the longwave pattern.

Strengthened CA shortwave weakened ridge further, allowing Ike to gain more latitude.

Brennan and Majumdar (2011, WAF, in press)
H: Initial condition errors in the ridge and shortwave troughs were a primary reason for the troublesome landfall forecast.

- Weakening the ridge allowed Ike to gain in latitude, and thereby undergo recurvature.

- The strengthening of upstream troughs acted to modify the longwave pattern, further weakening the ridge adjacent to Ike.

- Some dependence on the model and perturbation method.
Hurricane Irene (2011)
Irene: Hypotheses

1. Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclogenesis.

2. The assimilation of supplementary rawinsonde and dropwindsonde data improved the track forecast – ongoing work.
Seek a reliable quantitative metric for a tropical cyclone

Area ave. rel. vort. > 5 x 10^{-5} \text{ s}^{-1}
Local 200-850 hPa thickness anomaly > 40 m
Local MSLP minima < 1010 mb

w/ Ryan Torn (SUNY at Albany)

http://www.rsmas.miami.edu/personal/smajumdar/predict/
Color: 700–850 hPa AREA-AVG REL. VORT. x 2.5e-5 s^-1 and 200–850 hPa THICK ANOM x 20 m. 50 members.
50-member ECMWF ensemble 108-hour forecast probabilities. Init. 2011081800, Valid 2011082212.

700–850 hPa AVE. REL. VORT.

200–850 hPa THICKNESS ANOMALY

MSLP

w/ Ryan Torn (SUNY at Albany)
H: Global model ensembles are useful for providing dynamical probabilistic forecasts of tropical cyclogenesis.

A quantitative metric for tropical cyclogenesis in numerical models is achievable.

Immediate future: Probabilistic verification of genesis and non-genesis cases, for 0-10 day ensemble forecasts in 2010-11.
Ongoing and further work

• Danielle/Earl (2010): Track forecasting issues.
• Characteristics of forecast errors in genesis / non-genesis cases; quantifying predictability.
• Assimilation of satellite wind data and T and q soundings in global and regional models.
• Targeting strategies for satellite and rawinsonde / dropsonde data, particularly winds and moisture.
• Coordinated motion of unmanned aircraft and ensemble-based serial adaptive sampling.
• Environmental interactions; multiple scales.