Ensemble Prediction Systems

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Acknowledgements to Michael Brennan
Question 1

What are some current advantages of using single-model ensembles?
A. Estimates of uncertainty
B. TC intensity model spread
C. Alternative TC-track solutions
D. All of the above
E. A & C
Why Aren’t Models Perfect?

- Atmospheric variables cannot be measured to an infinite degree of accuracy or precision (measurement error)
- Models’ initial state never matches the real atmosphere (analysis error)
- Initial condition errors grow with model integration time, most rapidly at smaller scales (error growth)
- Model equations do not fully represent all of the processes in the atmosphere (model error)
- Model grid cannot explicitly resolve all features and processes in the atmosphere (model error)
Options?

• Increase our understanding of physical processes and how models represent them *(research)*

• More accurate and numerous observations with greater coverage *(expensive)*

• Improved data assimilation methods *(4-D Variational Data Assimilation, Ensemble Kalman Filter)*

• Faster computers and more complex models *(many programs competing for resources)*

• *Probabilistic forecasting with ensembles*
Definitions

• **Deterministic Model** - single forecast from one forecast model or method using a single set of initial conditions
  - Examples: GFS, ECMWF, UKMET, GFDL, HWRF, BAMS

• **Ensemble** - collection of “member” forecasts verifying at the same time created from:
  - Different but equally viable initial conditions
  - Different forecasting methods and/or models that (ideally) statistically represent nearly all forecast possibilities
Definitions

- **Dynamical Model Ensemble** – based on perturbation of initial conditions of a single model or different models to create “member” forecasts
  - Examples: NCEP Global Ensemble Forecast System (GEFS), ECMWF Ensemble Prediction System

- **Control Run** – for dynamical model ensembles, the member of the ensemble run with the “best” initial analysis
  - The analysis used by the control run is usually perturbed to produce initial conditions for the remaining ensemble members

- **Spread** – measure of the degree of disagreement (i.e., standard deviation) between ensemble members
Ensemble Use

• Originally used for medium-to long-range forecasting of the large-scale pattern

• Uses have grown to encompass all temporal and spatial scales down to convective storm scale

• Address uncertainty, particularly those leading to rapidly diverging solutions
  – Initial conditions, model physics, resolution, model numerics
Ensemble Use

- Estimate rate of skill loss with time
  - Spread of solutions generally increases with time

- Compute probabilities of occurrence of a particular event or condition
  - 25 mm of precipitation, winds > 34 kt

- Identify regions where the analysis and forecast are sensitive to additional data in the analysis
  - Ensemble Kalman Filter, targeted observations
Ensemble Mean vs. Deterministic

- Deterministic runs (e.g., GFS) usually have more skill than any individual ensemble member due to superior resolution.

- Ensemble mean usually has at least as much skill as an equal-resolution control run.

- Ensemble mean can be more skillful than a higher-resolution deterministic run, especially beyond ~3 days.
Ensemble Mean vs. Deterministic

500-mb height anomaly correlation die-off chart – 30 Jan-16 Mar 2015

GEFS mean provides about 1 day of additional skill compared to the GFS

Courtesy NCEP EMC
Current Global Ensemble Systems that NHC uses most frequently
NCEP Global Ensemble Forecast System (GEFS)

- 4 cycles per day (00, 06, 12, 18 UTC)
- 21 members (1 control + 20 perturbed)
- Forecast extends out to 384 hours (16 days)

180-h forecast of 588 dm 500-mb height contour valid at 1200 UTC 22 March 2010
NCEP GEFS

• Current Configuration (last upgrade 2015)
  – T574 (~ 34 km) through 8 days, T328 (~ 52 km) days 8-16
  – 64 vertical levels

• Ensemble members
  – 20 members generated using Bred Vector and Ensemble Transform methods to address uncertainties in the initial conditions
  – Stochastic (statistical) perturbations try to address model uncertainty
  – Includes vortex relocation to NHC/CPHC/JTWC analyzed position for tropical cyclones in each ensemble member
  – Model physics consistent with GFS

• Deterministic GFS
  – T1534 (~ 13 km) through 10 days, T574 (~ 35 km) days 10-16
  – 64 vertical levels
Improvements to Global Ensemble TC Track with Increasing Horizontal Resolution

Tropical Storm Fay 00Z – 16 Aug 2008

More members retain the TC and track forecasts are much improved

T126
~100 km

T190
~70 km
ECMWF Ensemble Prediction System

- 51 members (1 control+50 perturbed members)
- Run twice daily (00 and 12 UTC) out to 15 days
  - T639 (~ 18 km) to 15 days
  - 91 vertical levels
- Perturbations:
  - Initial condition: generated using singular vectors and perturbations from an ensemble of data assimilations
  - Physics: generated by two stochastic parameterization schemes
- Deterministic ECMWF
  - Horizontal grid resolution T1279 (~9 km) out to 10 days with 137 vertical levels
Ensemble Display and Interpretation
Displaying Ensembles

If we try to look at every ensemble member at once, it is messy and difficult to interpret.
Displaying Ensembles

**Spaghetti Diagram** – displays one isopleth at a time from each ensemble member.
Displaying Ensembles

**Ensemble Mean** - average of multiple forecast members verifying at same time
Displaying Ensembles

Disagreement, or **spread**, between ensemble members
Displaying Ensembles

- **Black** lines = ensemble mean 500-mb height forecast
- Spread indicated by shading (meters)
  - **Orange/Red** – little agreement between members
  - **Blue** – good agreement between members

Credit: COMET
Displaying Ensembles
Ensemble Mean and Spread

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Displaying Ensembles

Ensemble Mean and Spread

• Advantages
  – Summarizes data in easy to interpret form
  – Information provided for the entire domain
  – Low predictability features smoothed out by the ensemble mean and easily identifiable using spread

• Disadvantages
  – Ensemble mean can be misleading (and may not be the best forecast) if multiple clusters of nearly equal probability forecast outcomes exist (i.e., bi-modal distribution)
  – May not reveal extreme outlier solutions
Interpreting Mean and Spread

Large spread within the ensemble mean feature → **Uncertainty in amplitude of the feature**

- In this case, there is uncertainty in the **depth** (not the location) of this 500-mb trough

- If there were a tropical cyclone located southeast of this trough, would the trough be deep enough to recurve the tropical cyclone?
Interpreting Mean and Spread

Large spread upstream or downstream of an ensemble mean feature → Uncertainty in the location of the feature

• In this case, there are nearly equal chances that the 500-mb trough will be east or west of the position shown by the ensemble mean trough.

• If a tropical cyclone was located southeast of this trough, at what time will the tropical cyclone begin to be influenced by this trough?
Interpreting Mean and Spread

Large spread on one side of an ensemble mean feature → A cluster of ensemble members different from the ensemble mean

• In this case, the spread indicates greater potential for the trough axis to be east of the ensemble mean trough than to the west

• If there was a tropical cyclone located southeast of this trough, at what time will the tropical cyclone begin to be influenced by this trough?
NCEP Short Range Ensemble Forecast System (SREF) plume diagram for total precipitation at Durango, Colorado, starting at 15Z 27 Feb 2015 (courtesy NWS SPC)
Little objective guidance is seen with ensembles now, though they help subjectively.

**In-house product**

shading: combined probability of 70 ensemble members (GEFS + ECENS):
- 850 – 700 hPa RH > 70%
- 200 – 850 hPa vertical wind shear < 20 kt

contours: 850 hPa relative vorticity (8 x 10^{-5} \text{s}^{-1} intervals)
thin green: ECENS members
thick green: ECMWF deterministic
thin yellow: GEFS members
thick yellow: GFS deterministic

Invest AL93
Ensemble Problems

• Need a properly calibrated system
  – GEFS is currently underdispersive
  – This problem results in an overconfident forecast
  – Lower resolution can also hinder a more accurate track forecast (i.e. when track especially dependent on intensity)

• Other issues
  – Ensemble mean can be misleading (and may not be the best forecast) if multiple clusters of nearly equal probability forecast outcomes exist (i.e., bi-modal distribution)
  – May not reveal extreme outlier solutions
Single-Model Ensembles for TC Track Forecasting
NCEP Global Ensemble Forecast System
Tropical Cyclone Track Forecast Guidance

GEMN = GEFS Ensemble Mean
GFS = Deterministic GFS
In the Atlantic, the GEFS ensemble mean track forecast (AEMI) is competitive with the deterministic GFS (GFSI) through day 3 and better afterward.

In the east Pacific, AEMI beats GFSI at 48 h and beyond.
ECMWF Ensemble
Sandy example of desirable spread/verification
Joaquin ensemble guidance

- GEFS
- EC Ensemble

MAP OF預測 評述 2023/8/8

KNHC
ECMWF Joaquin ensembles 29 Sep 1200 UTC
A different way to view the data using probabilities
GEFS vs EC Ensemble 29 Sep 0000 UTC
GEFS vs EC Ensemble 30 Sep 0000 UTC
Matthew ensemble guidance 1 Oct 00 UTC

GEFS (blue) too underdispersive, especially in Caribbean

Every single GEFS member also too fast at 5 days

ECMWF (red) has more realistic spreads, albeit potentially too large
ECMWF ensemble colored by intensity
-Stronger members farther right
-Weaker members farther north
Question 2

In which situation(s) is a well-calibrated ensemble system likely to fail?
A. Unusual forecast track cases
B. When TC track is dependent on intensity
C. If deterministic models are in poor agreement
D. All of the above
E. B & C
TC Intensity Ensemble Forecasting

- Little skill above single-model deterministic at present
- Very computational expensive to run high-resolution (<3 km) intensity ensembles
- HFIP is funding efforts to find products that could be operationally useful
Intensity Change Probability Distributions

GPMN 2016093006 MATTHEW (AL14)

00-24 h

24-48 h

48-72 h
Online Access to Ensemble Output and Training Resources
Access to Ensemble Output

NCEP GEFS and NAEFS: http://mag.ncep.noaa.gov/

Access to ensemble mean, spread, and spaghetti plots
Spaghetti diagram of 500-mb 522 and 582 dm height contours

FHR 72 forecast of the probability that the 12 hour accumulation exceeds 2 mm (The 12-h accumulation period immediately precedes the valid time)
Access to Ensemble Output

- ECMWF Ensembles:
COMET Courses
http://www.meted.ucar.edu

• Introduction to Ensemble Prediction:
  http://www.meted.ucar.edu/nwp/pcu1/ensemble_webcast/

• Ensemble Forecasting Explained:
  http://www.meted.ucar.edu/nwp/pcu1/ensemble/

  http://www.meted.ucar.edu/nwp/pcu2/ens_matrix/

• Wave Ensembles in the Marine Forecast Process:
  http://www.meted.ucar.edu/nwp/WaveEnsembles/

• NWP Workshop on WRF and NAEFS:
  http://www.meted.ucar.edu/s_africa_work/
Thank you

Questions?
Case Example
Ensemble Forecast Example

- Initial time: 1200 UTC 11 Sep 2004
  NCEP Ensemble members and operational GFS
- Purple dots = forecast position at 0300 UTC 17 Sep 2004 (FHR135)
- Ensemble forecast shows large uncertainty in ultimate path of Hurricane Ivan
- Tendency for clustering of tracks
  - 5 members east of the GFS track and faster than GFS at 0300 UTC 17 Sep 2004
  - 4 members west of GFS
  - Operational GFS and 1 member in the middle of the ensemble solutions

Credit: COMET
Ensemble Forecast Example

- Forecast: 0000 UTC 16 Sept 2004
- 108-hour NCEP ensemble forecast

- 500-mb 589-dm height (dashed) and 1000-mb PMSL (solid), color coded by ensemble member

- Degree of weakening of western Atlantic ridge over the northeast Gulf of Mexico determines position of Hurricane Ivan
  - Ridge strongest in pink: Ivan near northeastern Mexico, 589-dm height contour in mid-Gulf
  - Ridge weakest in light blue: Ivan over the Georgia coast, 589-dm height contour over the western Atlantic/northwest Caribbean

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Ensemble Forecast Example

- Ultimate path for Hurricane Ivan (black) - not too far from GFS and in the middle of the ensemble envelope of solutions
  - Wide envelope of possible tracks
  - Because of uncertainty in the weakening of the Atlantic ridge, it turned out to be the best solution
  - Typically, one would be wary of using the ensemble mean forecast when there is clustering of the solutions
  - Look at the handling of the ridge by the other dynamical models to determine which “cluster” to lean toward