Mesoscale Ensemble Analysis and Prediction of High-Impact Weather

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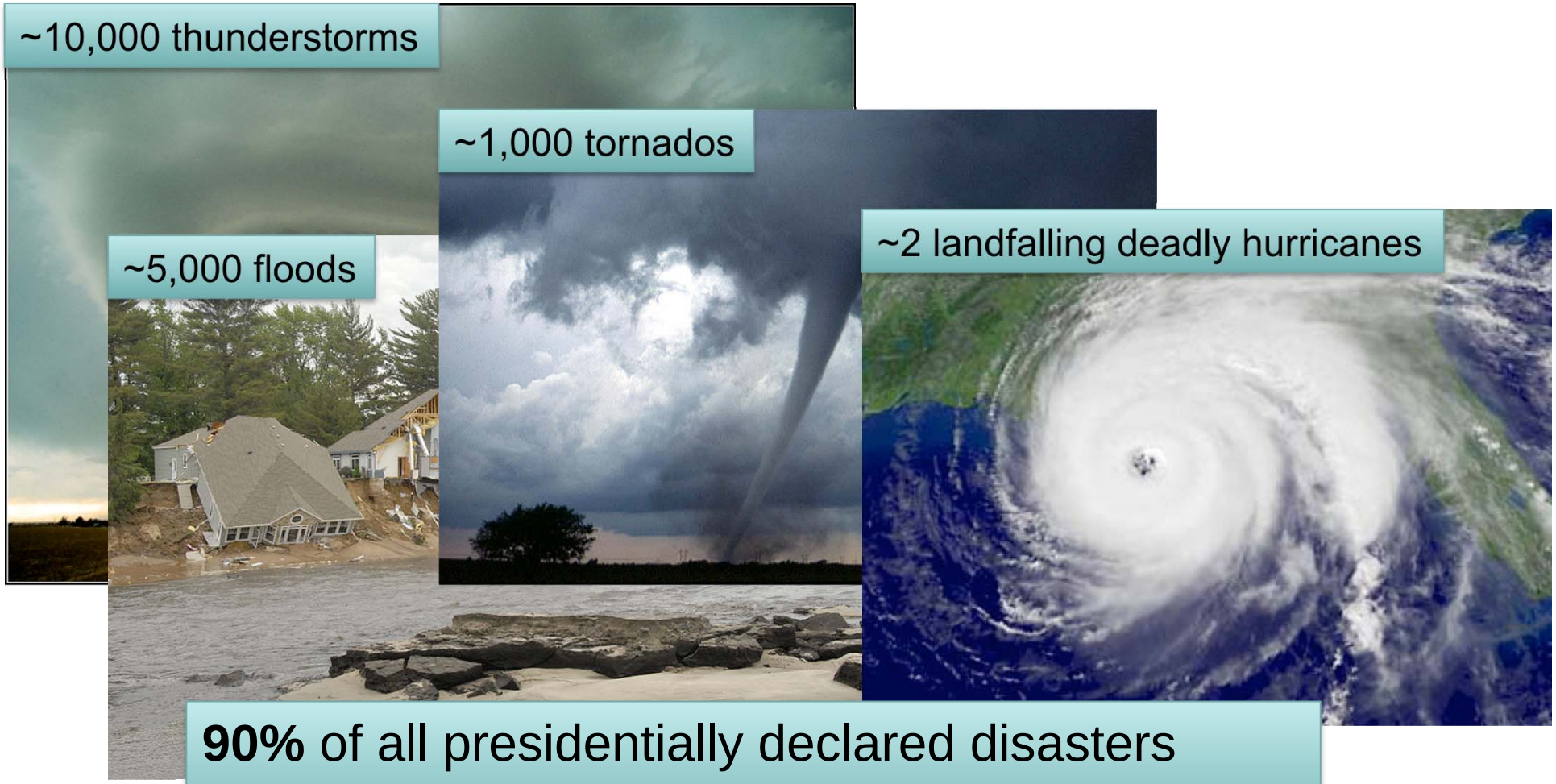
redefine THE POSSIBLE.

Hurricane Ike (2008) viewed

Weather Impact

Each year, Americans cope with …



90% of all presidentially declared disasters
are weather related causing billions in damage !

Weather Impact

For Canadian …

Ice storms

Snow blizzards

High-Impact Weather

- Weather phenomena that have significant impact on socio-economic well-being
- Moist processes are often very important
- Across multiple scales
  - Tropical cyclones
  - Mid-latitude cyclones
  - Convective storms
  - Heat, drought, and fire weather

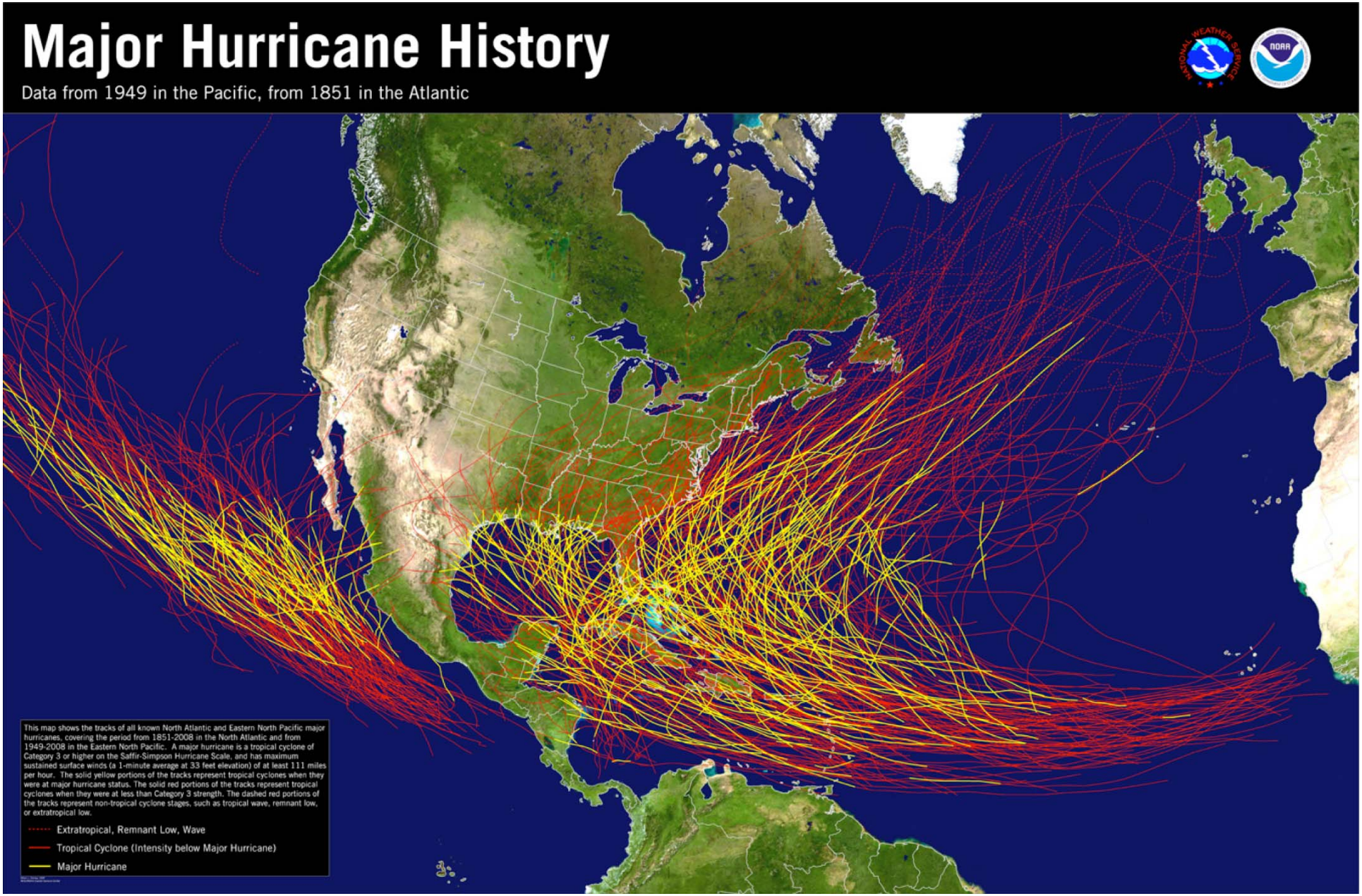


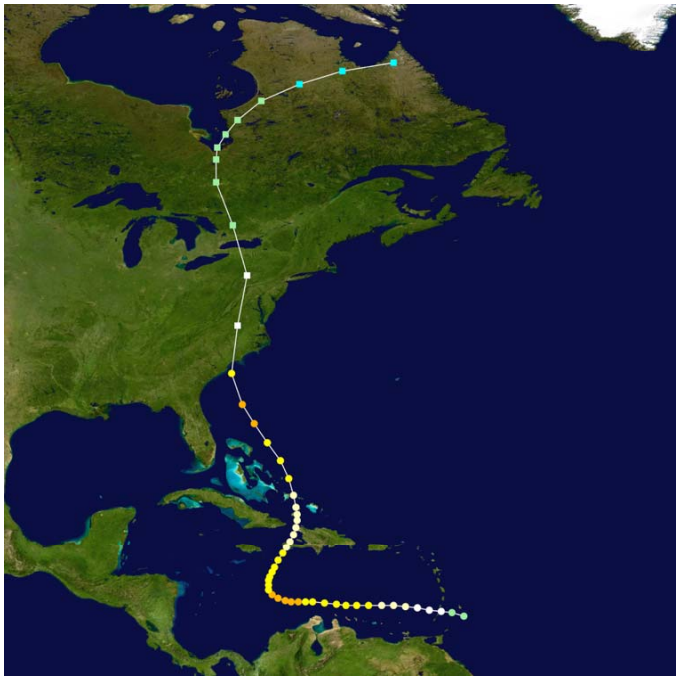
Image courtesy of NOAA

Hurricanes that Canada Remembered …

- **1775 – The Newfoundland Hurricane (also called the Independence Hurricane)**
  - 4000 sailors, mostly from England and Ireland, were lost off the coast of Newfoundland
  - turning point in the American Revolution?

Hurricanes that Canada Remembered …

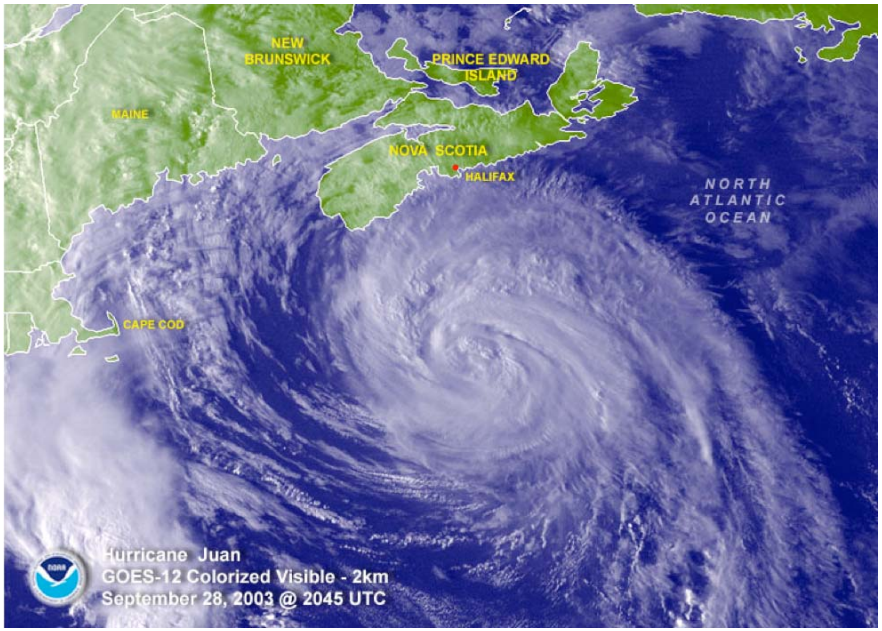
- **1954 – Hurricane Hazel**
  - claimed the lives of 81 people in southern Ontario (mostly Toronto) from the flooding rainfalls



The Lawrence Avenue bridge was washed out by the Humber River

Hurricanes that Canada Remembered …

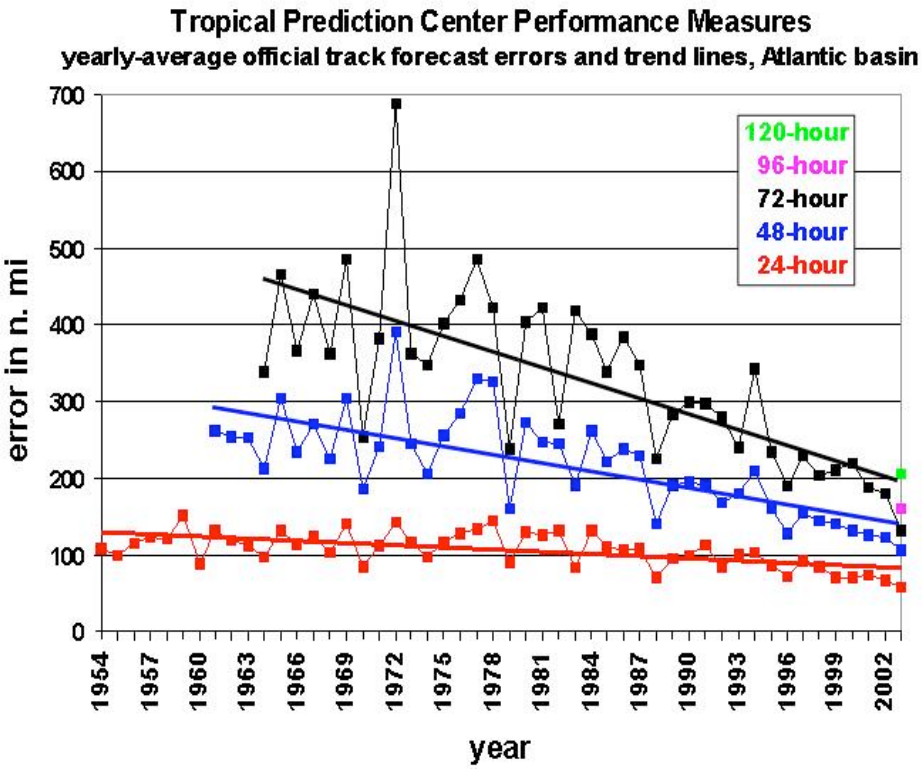
- **2003 – Hurricane Juan**
  - 50–100 million trees came down in Nova Scotia in two hours (one million in Halifax alone)



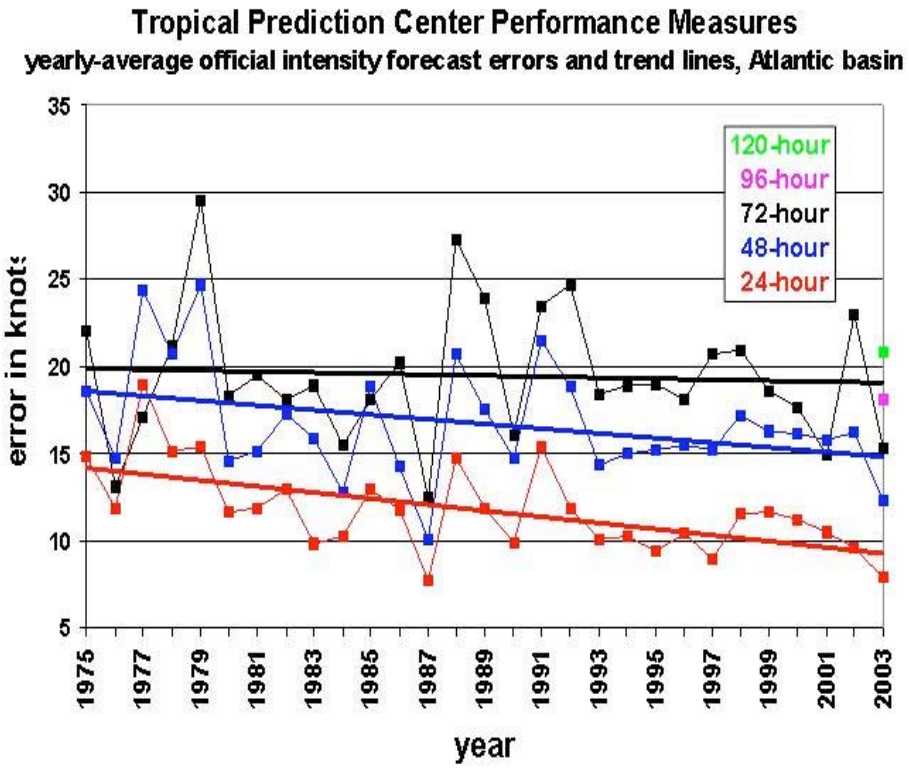
90% of the mature growth of Halifax's Point Pleasant Park came down

Hurricane Prediction Skills

Track



Intensity



Landsea and Lawrence (2004)

Key Issues in Hurricane Prediction

- Improve forecast skill
  - Yearly-average 24-h track forecast error ~ 150 km
  - Intensity forecast - top-priority task for NHC
  - Need ***advanced models*** & ***data assimilation method*** (making use of existing and future remotely sensed ***observations***)
- Advanced models
  - High resolution -- less sub-grid scale parameterization
  - Accurate physics - microphysics, turbulence, surface waves, upper ocean feedback, …
- Better data assimilation method
  - Weak correlations among variables in mesoscale
  - Observations (e.g. Doppler radar) may be very dense locally, but usually not directly in model space

These also apply to other high-impact weather prediction!

What is Data Assimilation?

- A process to obtain an analysis (or estimate) of the atmospheric state at certain time, given
  - heterogeneous (in space and time) observations of some atmospheric quantities, and
  - additional information, such as climatology or previous forecasts,

  according to physical laws, empirical or statistical rules.

Hand analysis is the original form of data assimilation. – Subjective and time consuming!

Objective Analysis

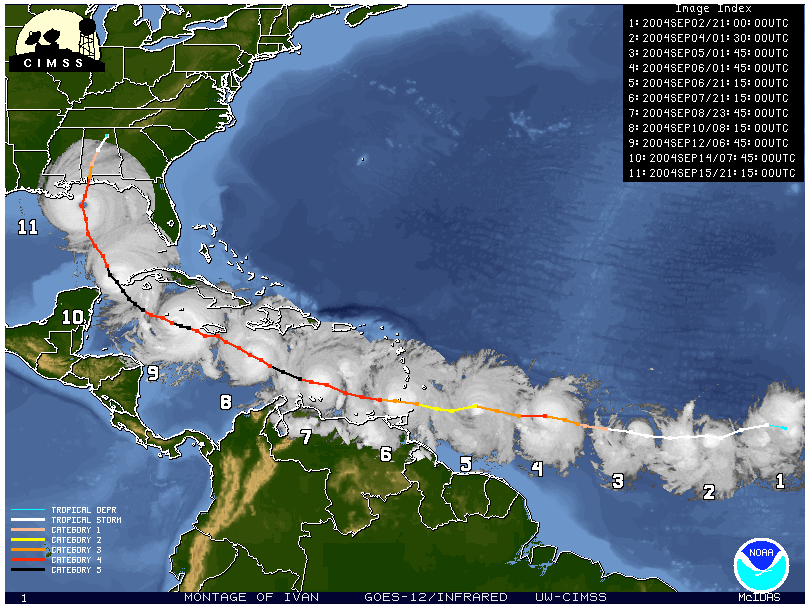
- Function fitting
- Successive corrections
- Statistical interpolation
- Variational methods (3DVAR, 4DVAR)
- Ensemble Kalman filter
  - Efficiently spreading flow-dependent information
  - “Effortless” use of nonlinear observation operators
  - Rapid prototyping for easy experimentation & tuning

Ensemble Kalman Filter

$$\overline{\mathbf{X}}^{a} = \overline{\mathbf{X}}^{f} + \mathbf{K}(\mathbf{y} - \mathbf{H}\overline{\mathbf{X}}^{f})$$

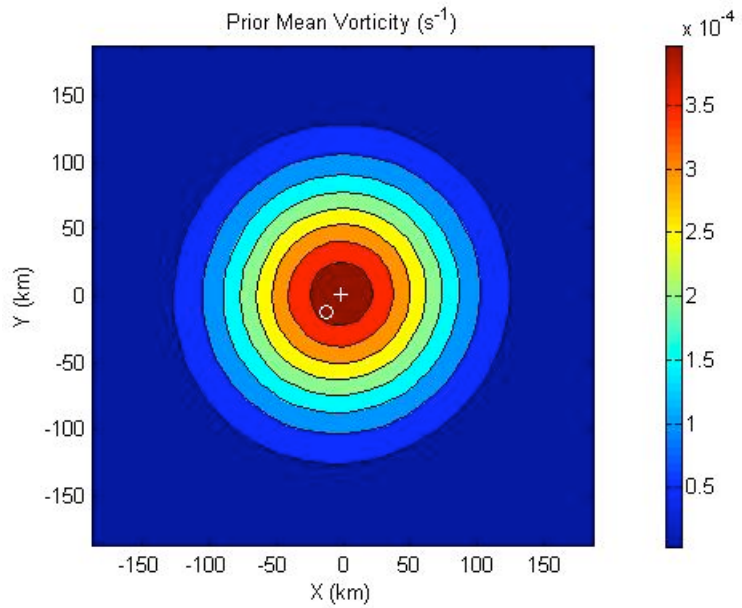
Analysis Forecast Correction

- Kalman Gain **K** ~ Cov (**X**,**HX**)
  can be computed directly from the ensemble
- Observation operator **H**: project **X** to **y**

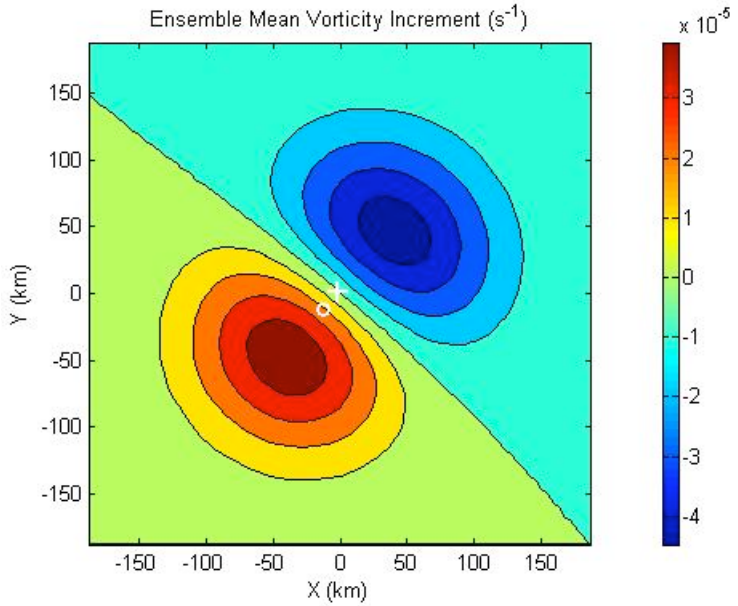


y=vortex position
H=(find vortex position from **X**)

Assimilating Center Position – A Simple Example



+



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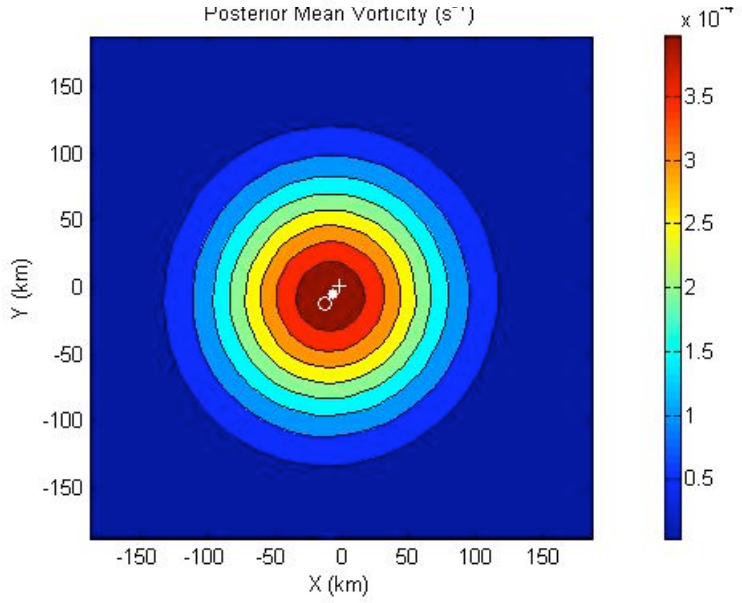


+	prior mean center
o	observed center
dot	posterior mean center

Ensemble Analysis and Forecast System -- WRF/DART

- WRF -- Weather Research and Forecasting model
  - ARW dynamical core: non-hydrostatic, mass-coordinate
  - Two-way nesting and moving nests
  - Various physics packages
  - WRF-DA data assimilation system (3DVar, 4DVar, Hybrid)

- DART -- Data Assimilation Research Testbed
  - Ensemble adjustment filter
  - Parallel and model-independent implementation
  - Interfaces for several simple and complex models, including CAM and WRF
  - Observation operators implemented include conventional obs, GPS occultation, radar obs, and *satellite radiances* (with WRF-Var)
  - Updates multiple nests simultaneously
  - Covariance localization, adaptive inflation

- WRF/DART has been used to simulate tropical cyclones and convective storms, to produce regional re-analysis, etc.

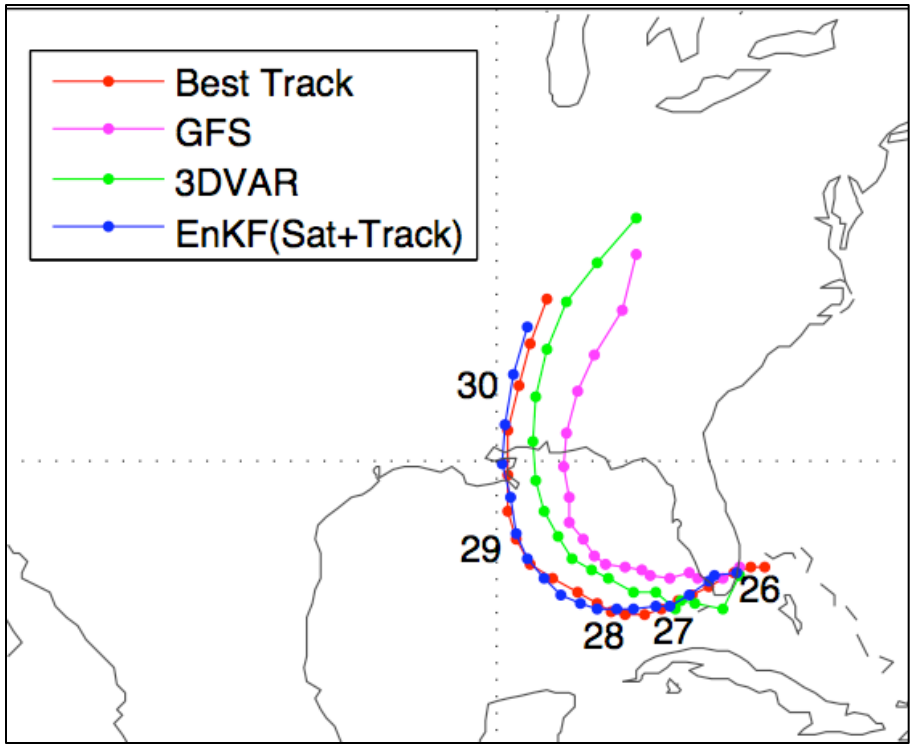
Hurricane Analysis and Forecast Experiments using WRF/DART

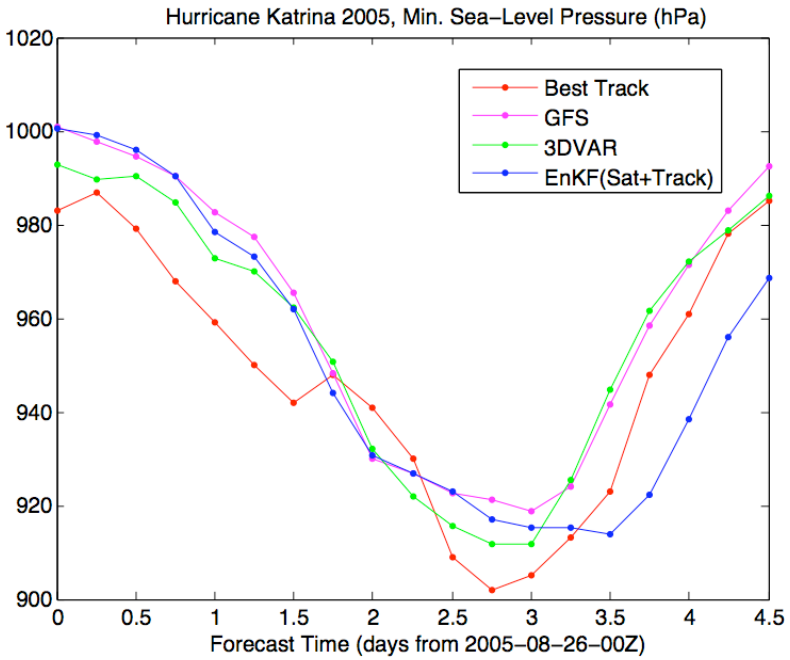
- Ensemble initial and boundary conditions are generated by perturbing GFS analysis/forecast with WRF-Var error statistics

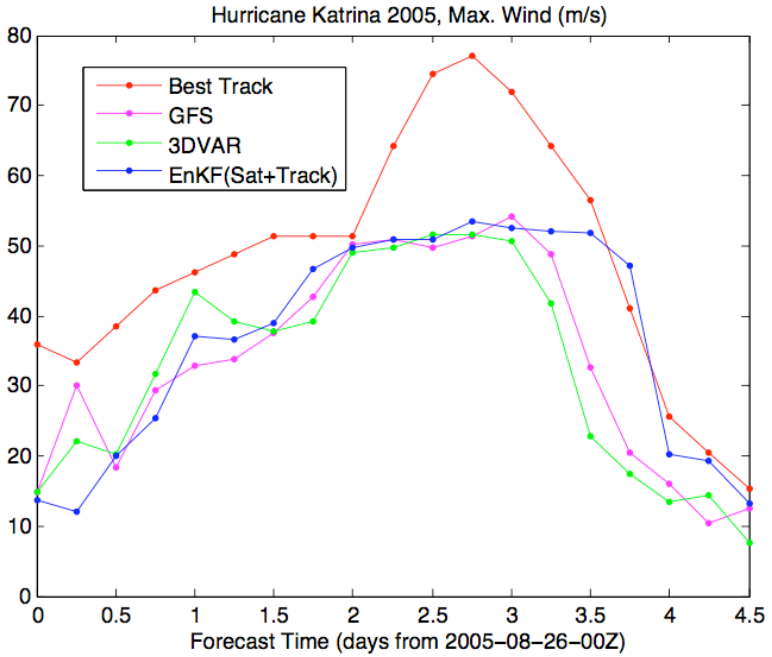
- Assimilated observations:
  - hurricane track (center position and minimum sea level pressure from NHC advisories)
  - conventional observations (radiosondes, surface obs, satellite winds, etc.)
  - GPS occultation
  - satellite radiances

- Perform a deterministic forecast (at the same or higher resolution) and ensemble forecasts initialized from the EnKF mean and ensemble analyses respectively, and compare with forecasts without data assimilation

Hurricane Katrina 2005

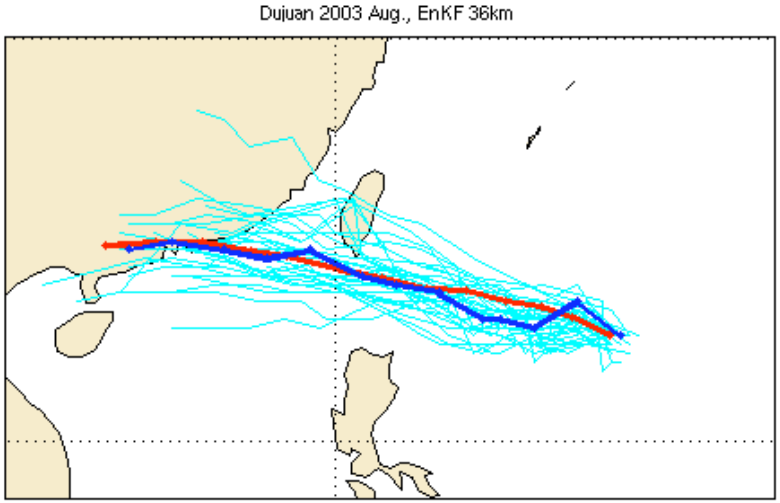


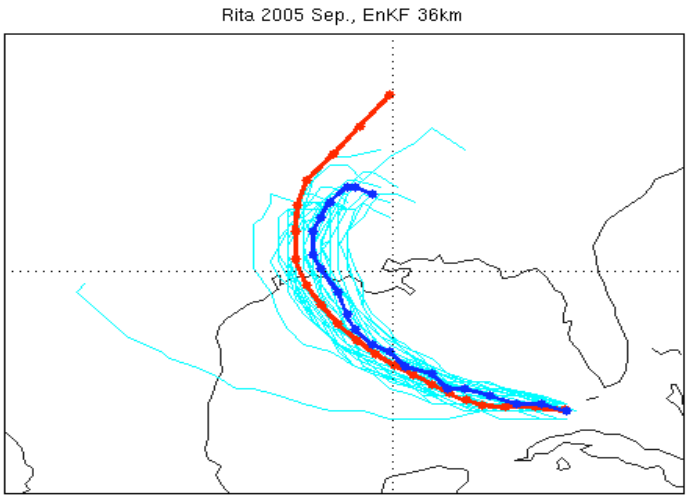


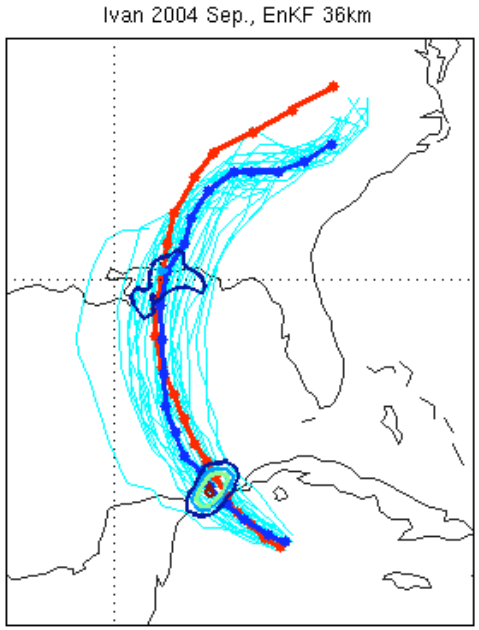


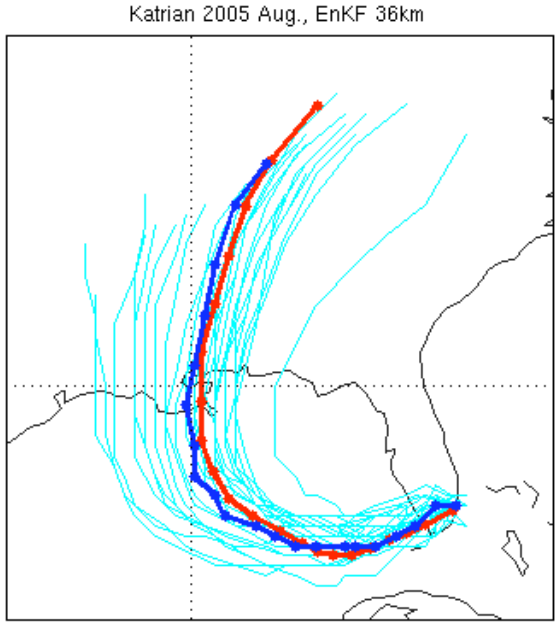
- Analysis: 36-km horizontal resolution, 26 ensemble members
- Assimilate position, intensity, and satellite winds every hour for a total of 12 hours
- Compare forecasts with 36-12km nested domains initialized from the EnKF analysis, WRF-3DVAR analysis and from the GFS forecasts.

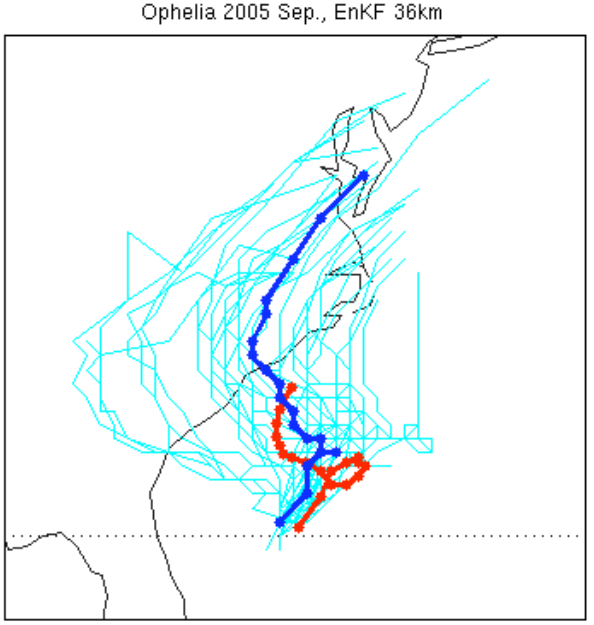
Ensemble Forecast



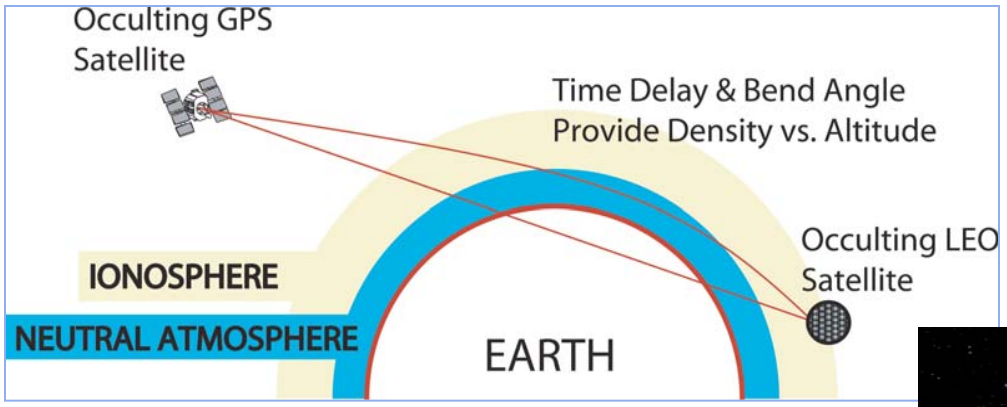


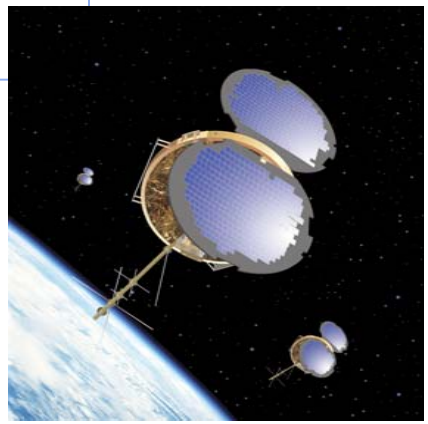


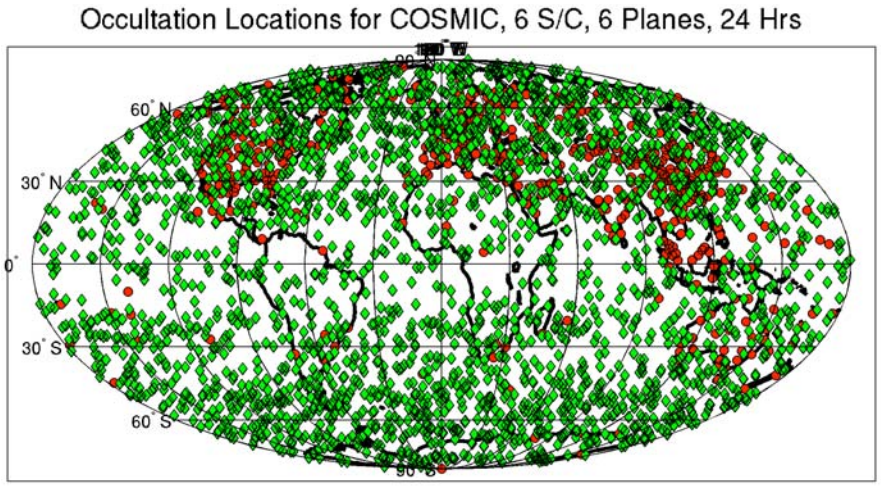




Impact of GPS Reflectivity Assimilation on Cyclogenesis



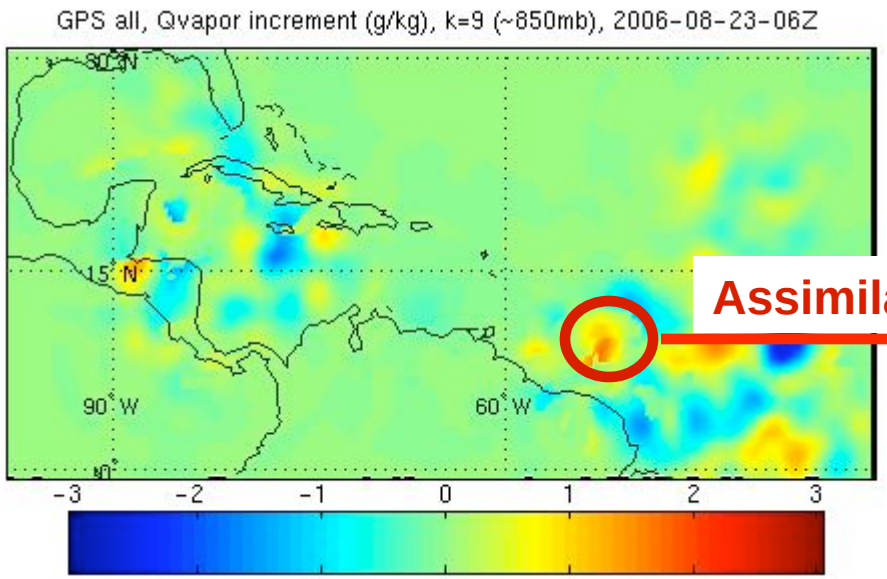




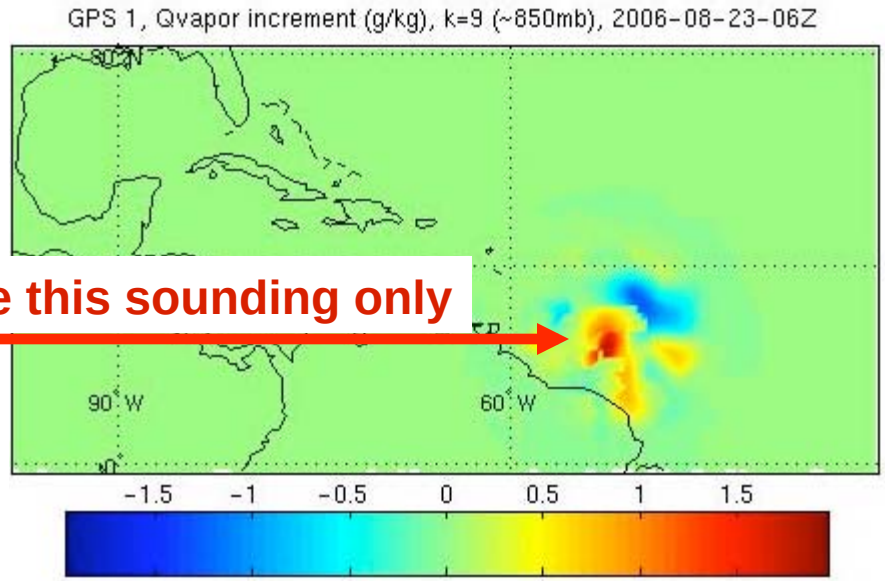
(Illustration courtesy Bill Schreiner UCAR, Broad Reach Engineering, and Orbital Sciences Corporation)

Low-level moisture change by assimilating GPS

GPS all



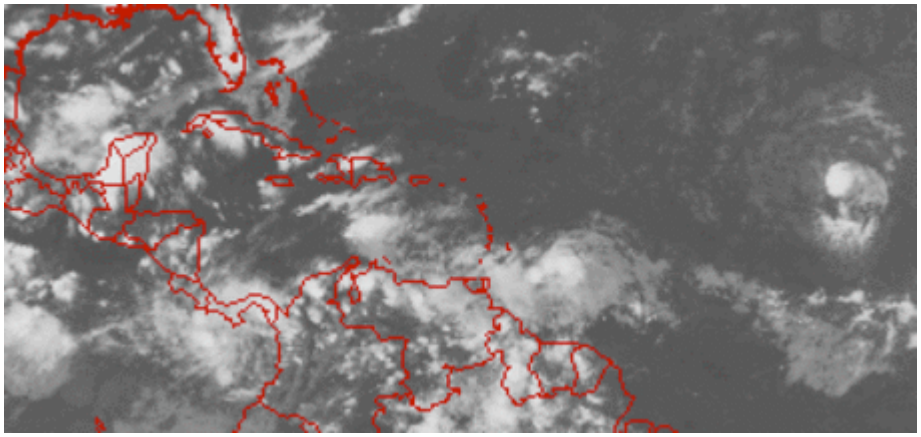
GPS 1



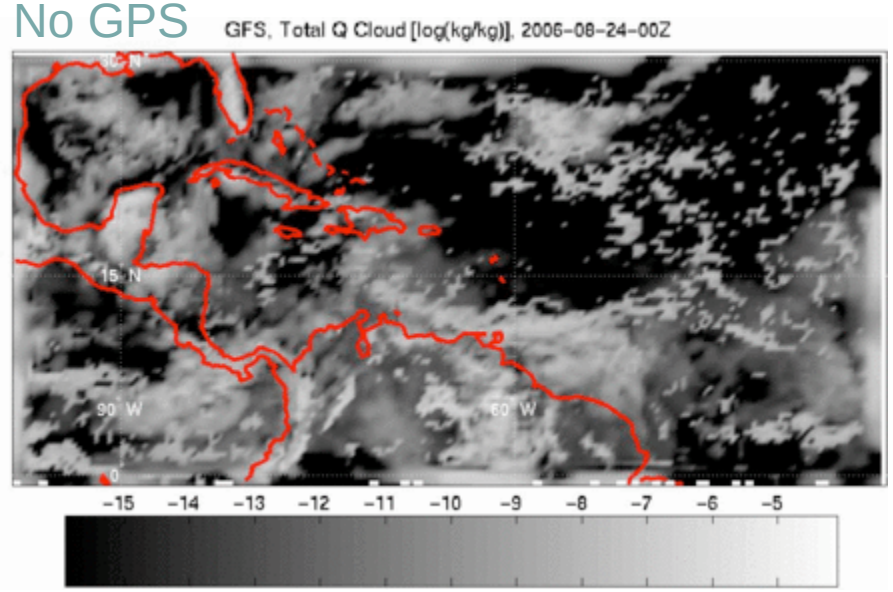
Assimilate this sounding only

2006-08-24-00Z (18h forecast)

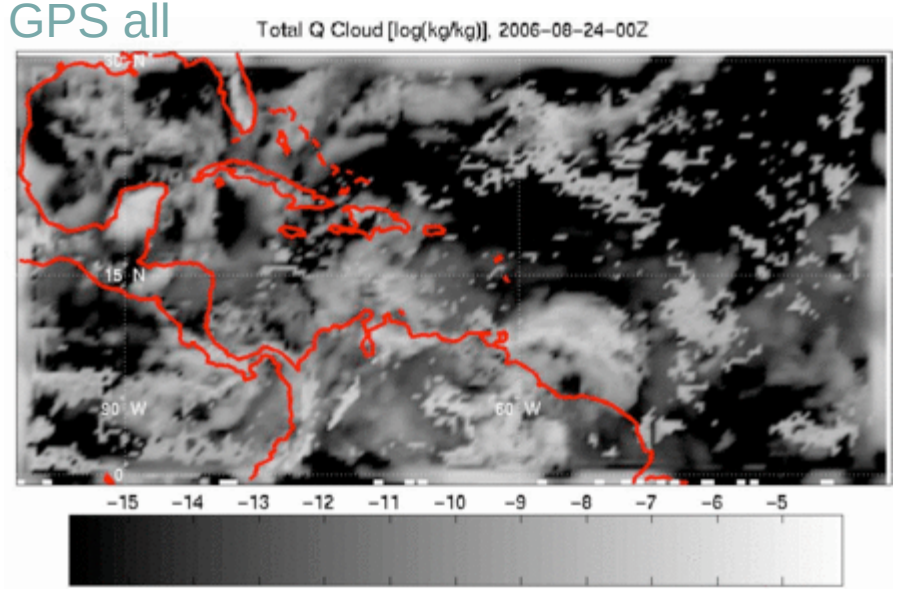
Sat. IR



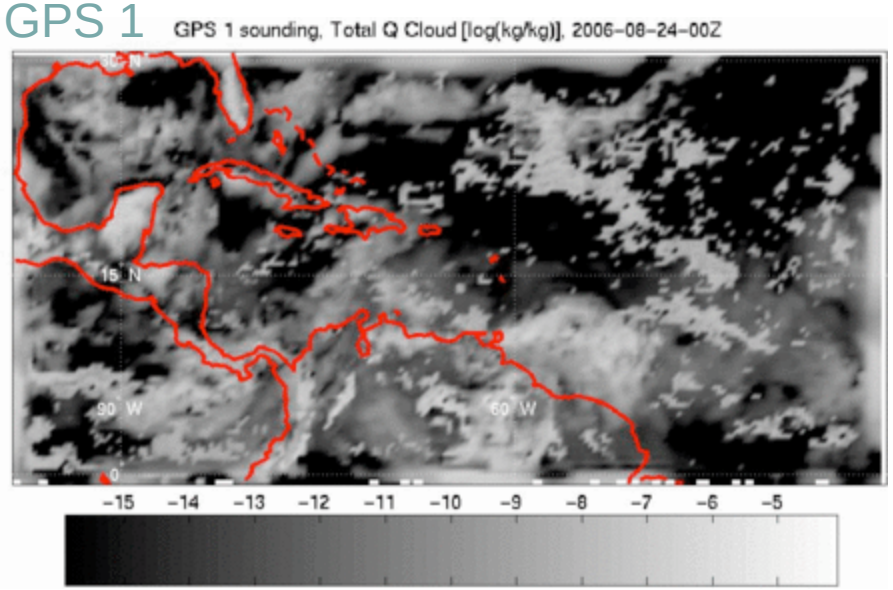
No GPS



GPS all

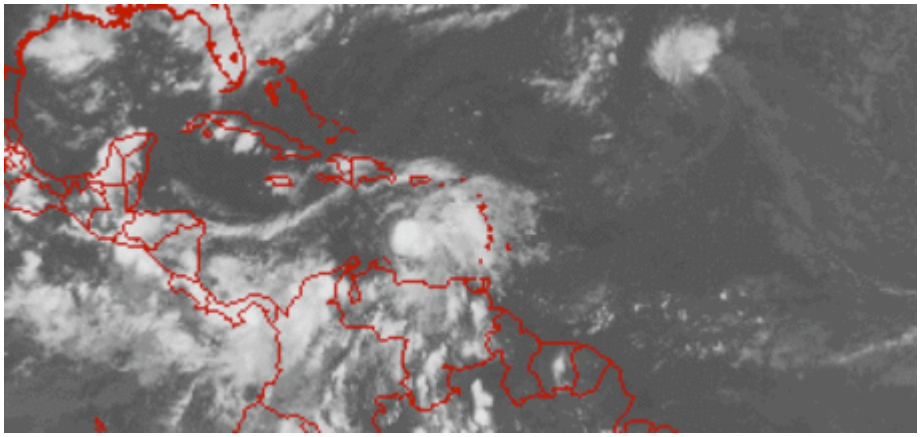


GPS 1

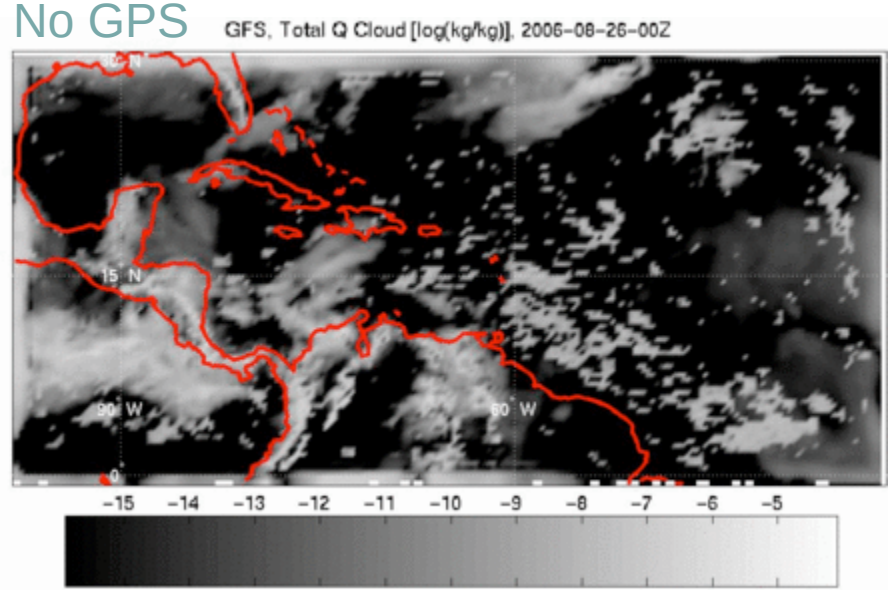


2006-08-26-00Z (66h forecast)

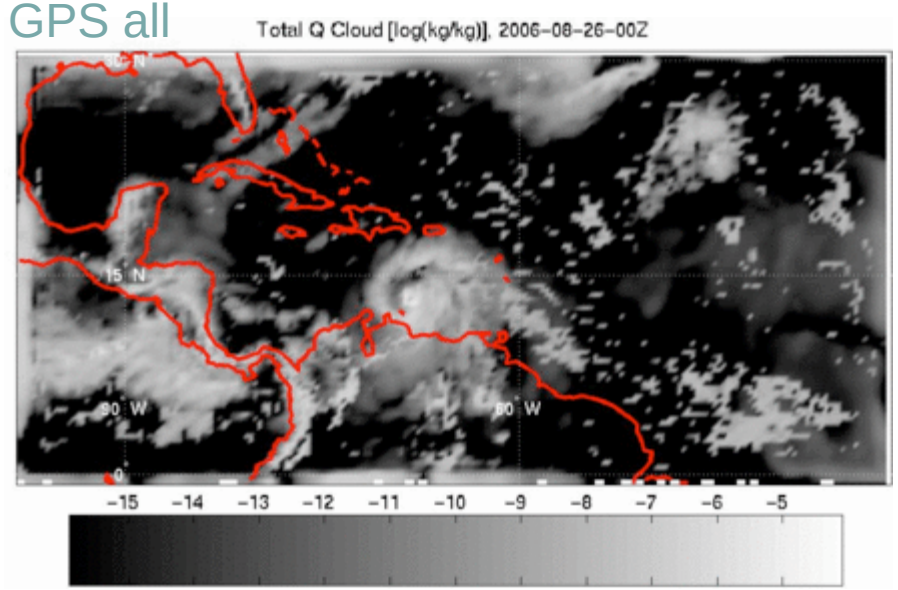
Sat. IR



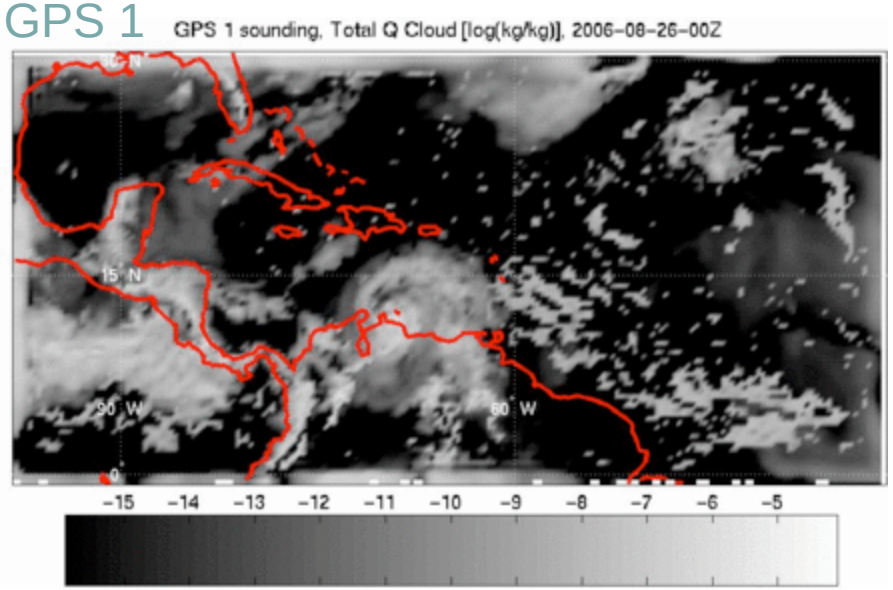
No GPS



GPS all

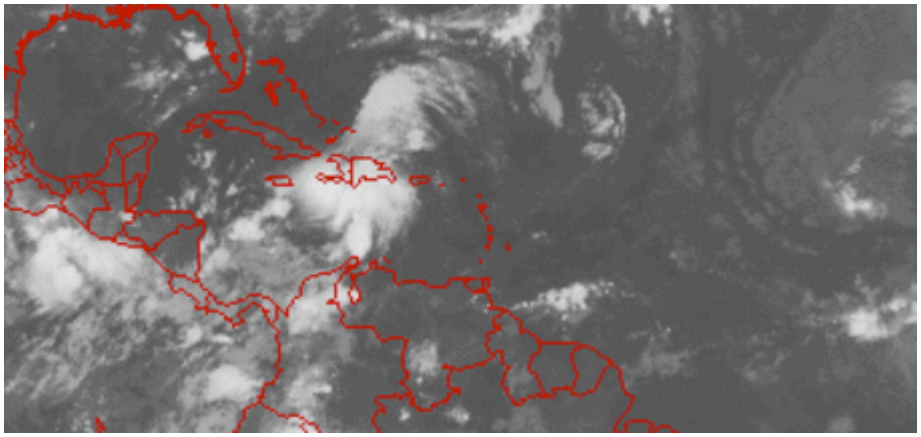


GPS 1

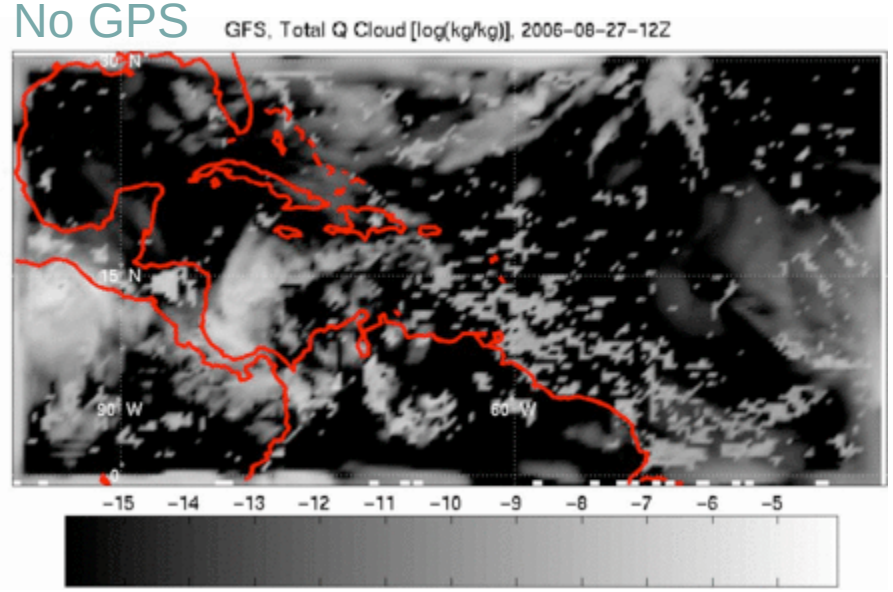


2006-08-27-12Z (102h forecast)

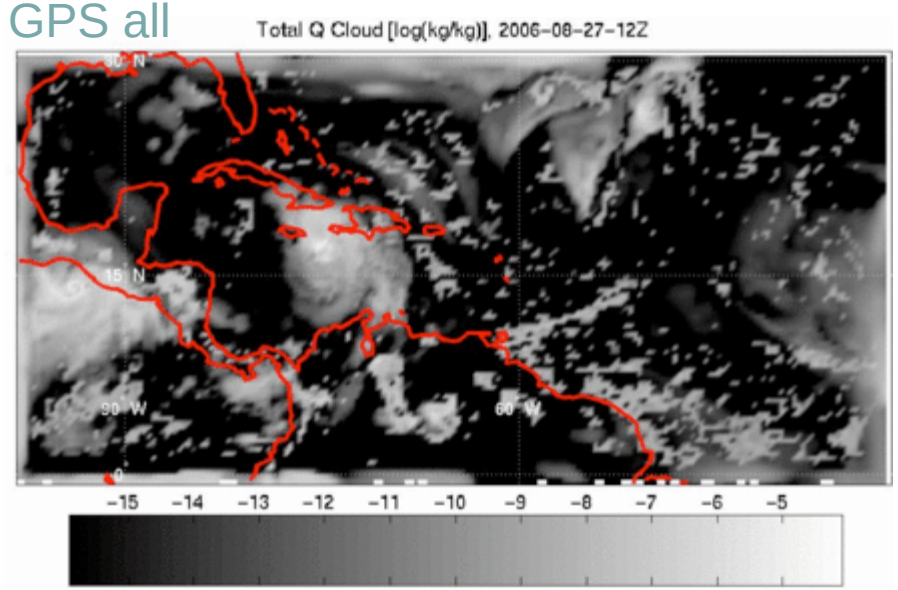
Sat. IR



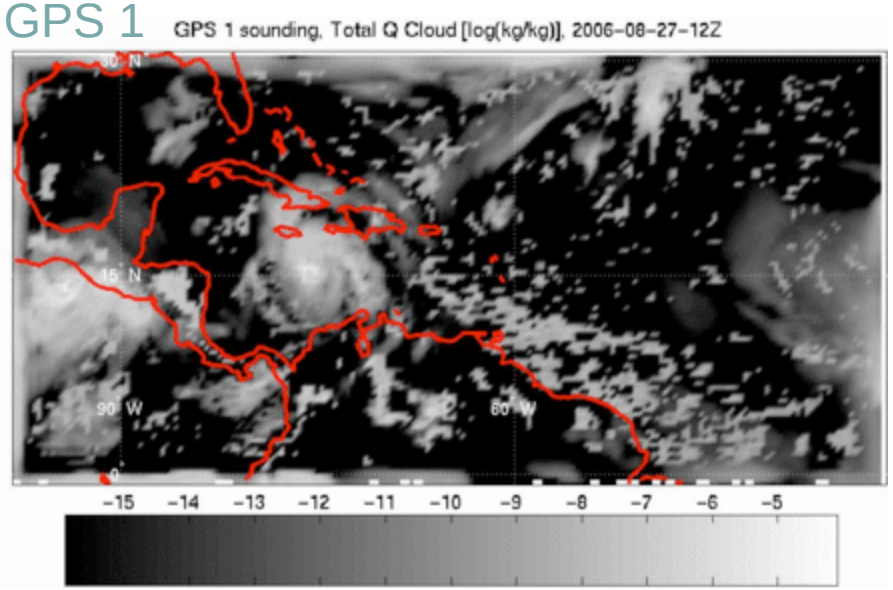
No GPS



GPS all

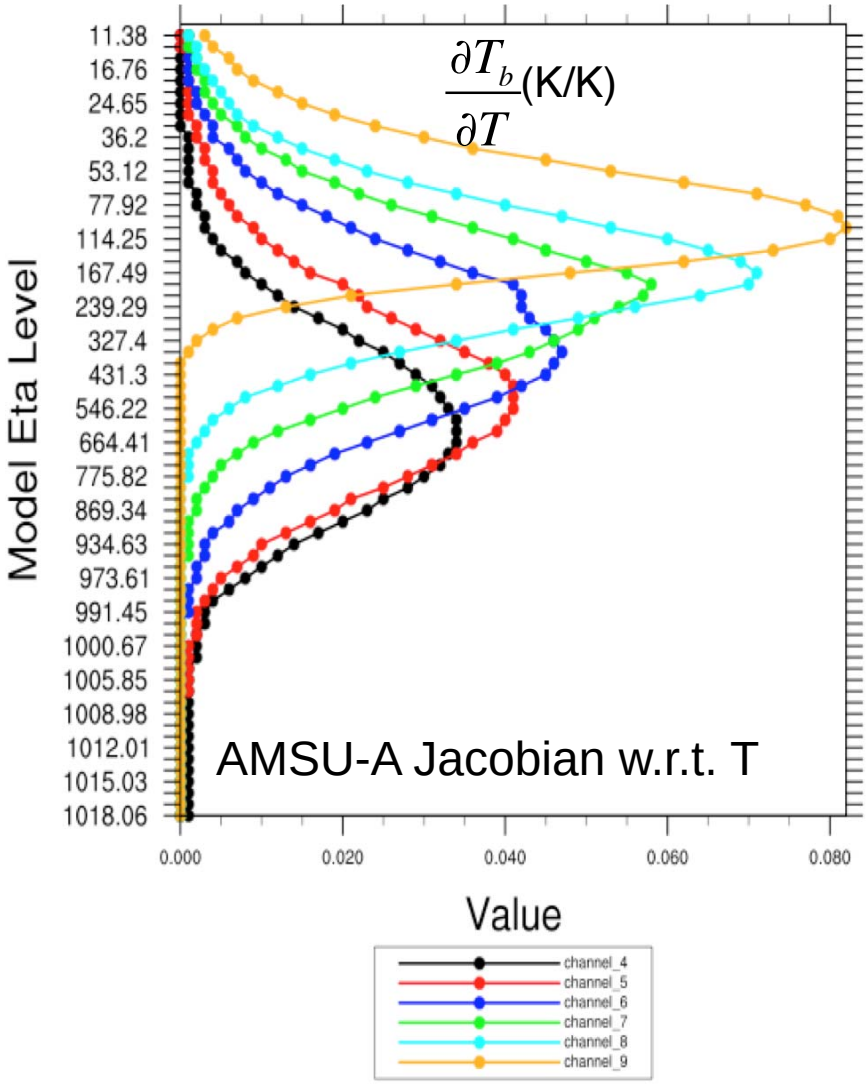


GPS 1



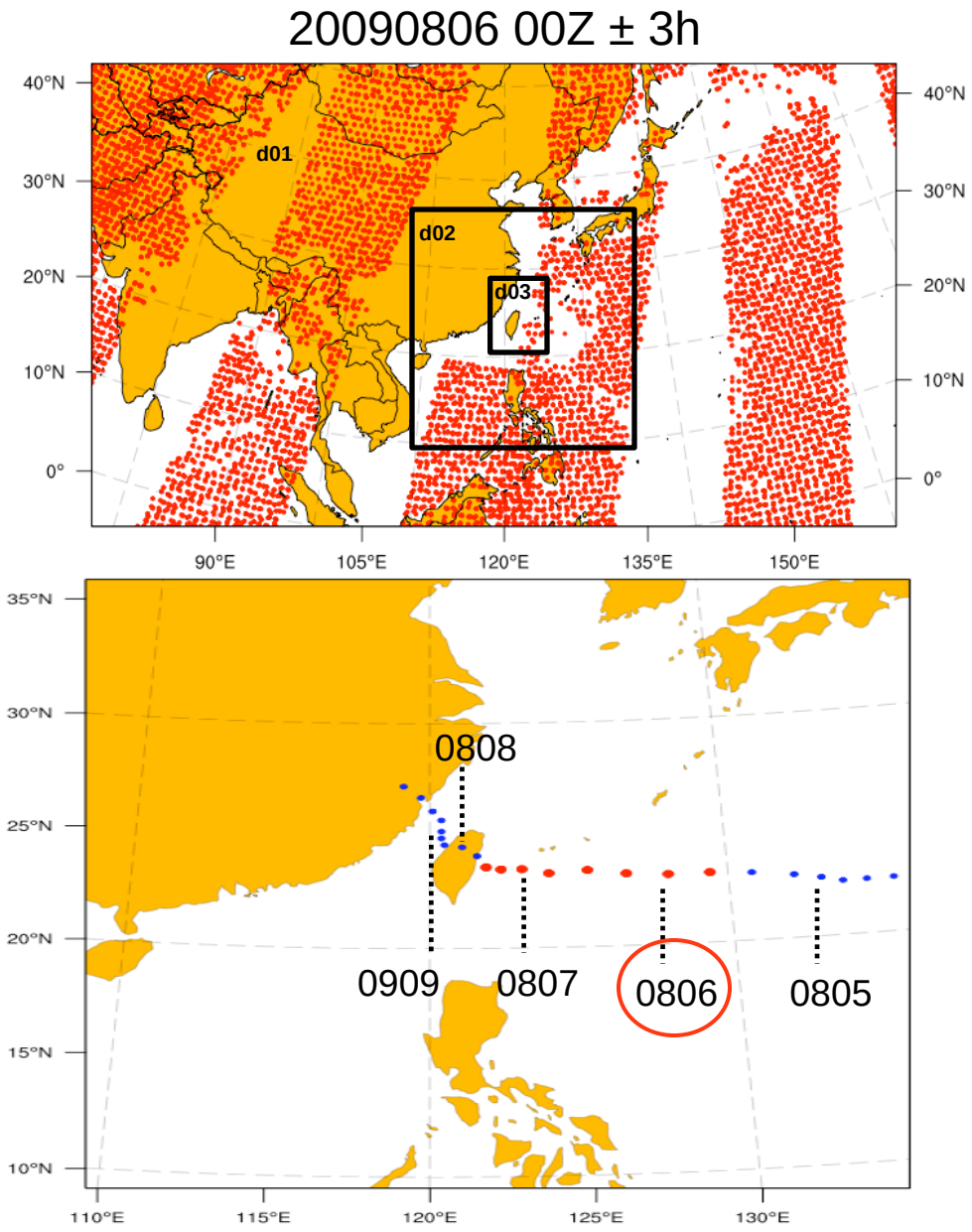
Assimilating Radiance in DART

- Use existing radiance operator and bias correction in WRF-3DVar
- DART ingests pre-computed observations
- Vertical localization centered at the height of peak levels of Jacobian from CRTM

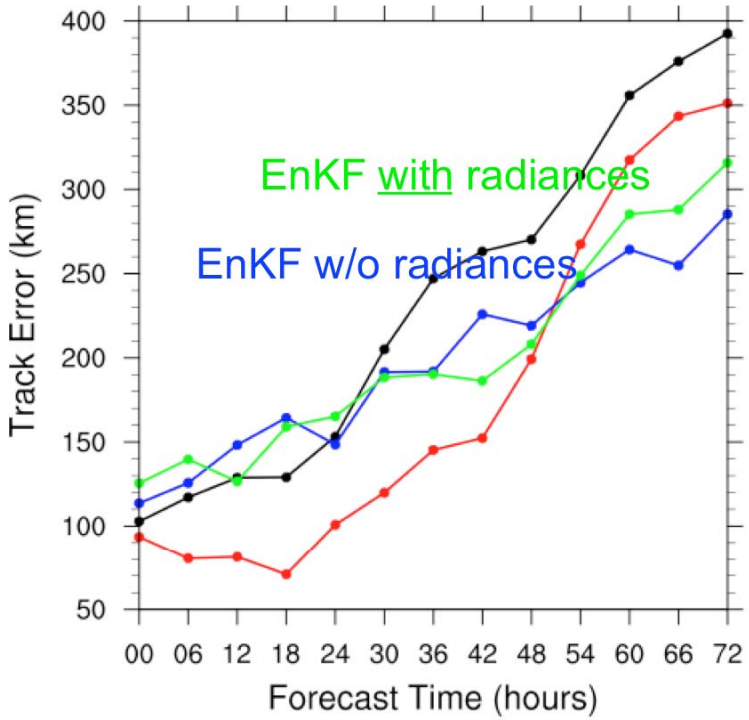


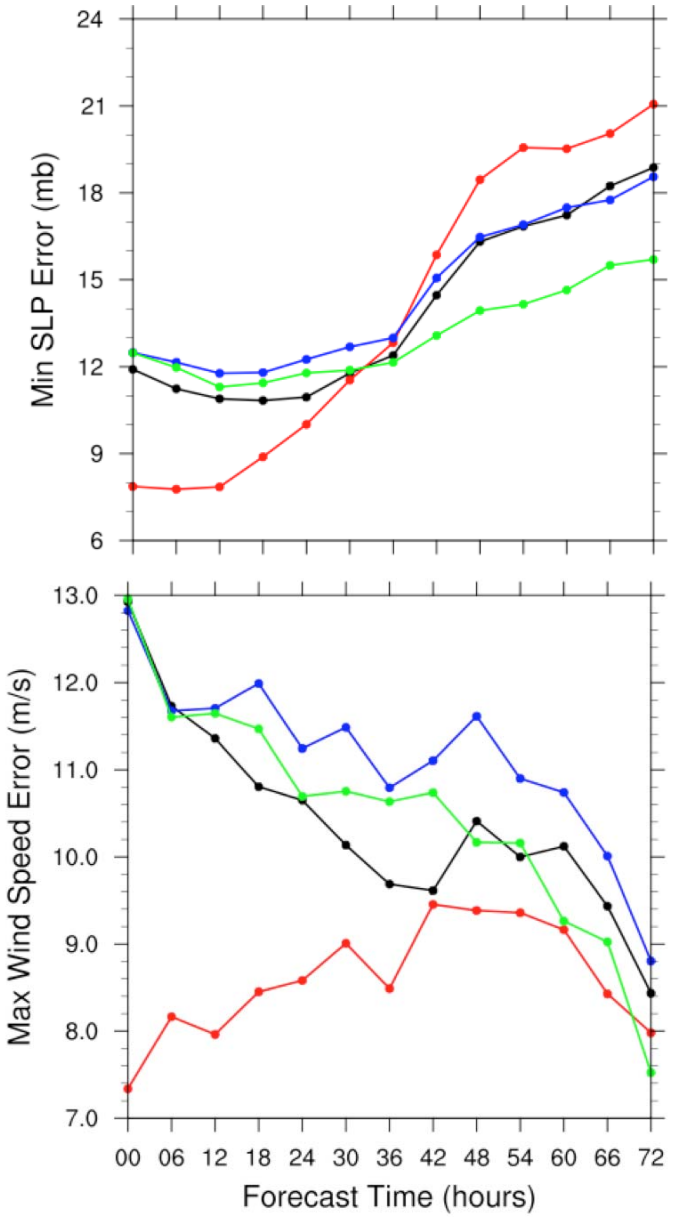
Assimilating Radiance in DART

- Case study: Typhoon Morakot (2009)
- WRF: 45-15-5 km, 45 levels, Ptop=30hPa
- 64 members, 6-h cycling from 08/03 18Z – 08/08 00Z, assimilating conventional and microwave radiances from AMSU-A/B and MHS only in d01
- 72-h forecast initialized from the ensemble mean after each analysis



Impact of Radiance Assimilation



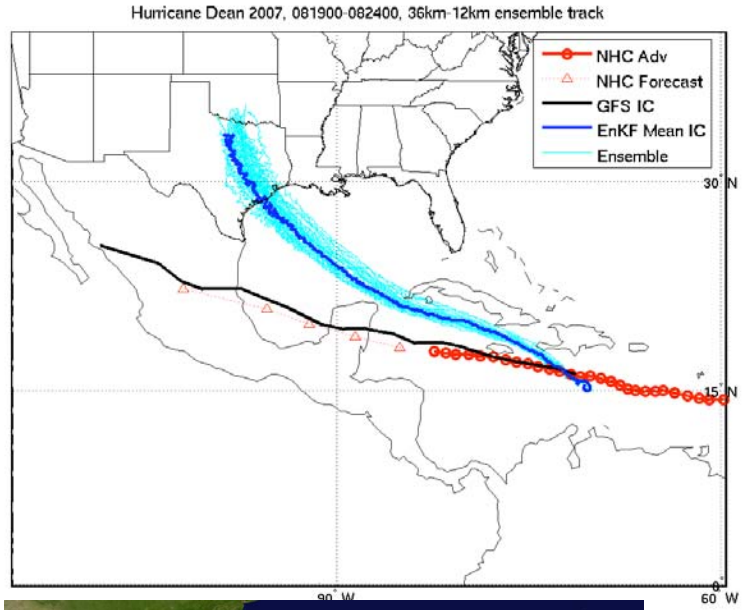


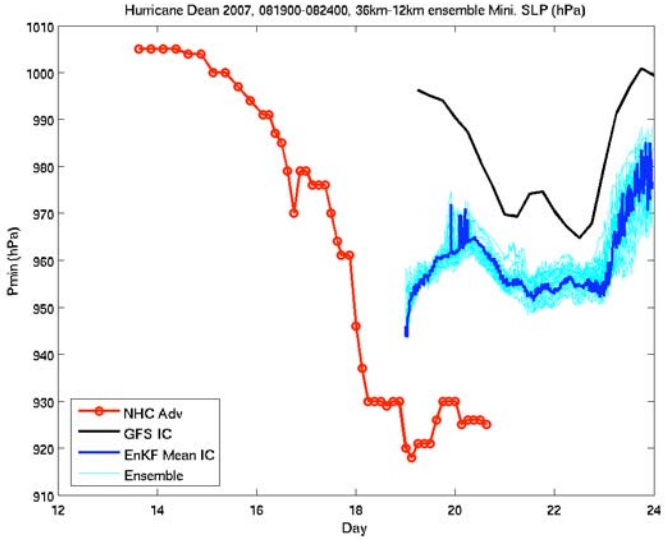
Radiance assimilation

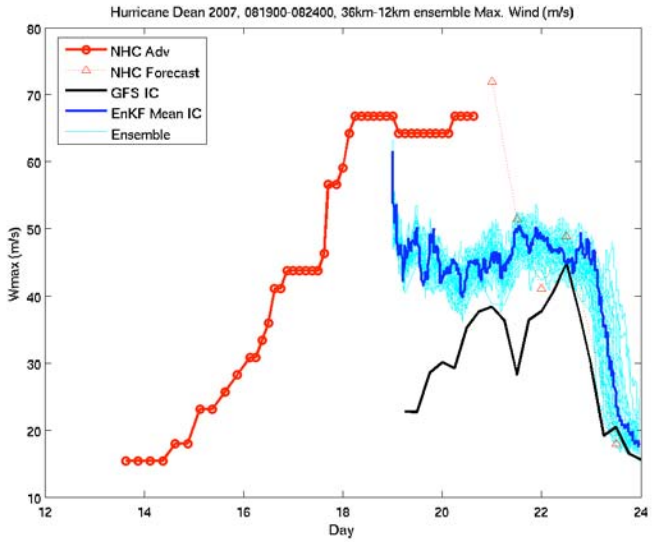
- alters slightly track forecast
- improves intensity forecast

Hurricane Initialization -- Challenge

Hurricane Dean (2007)







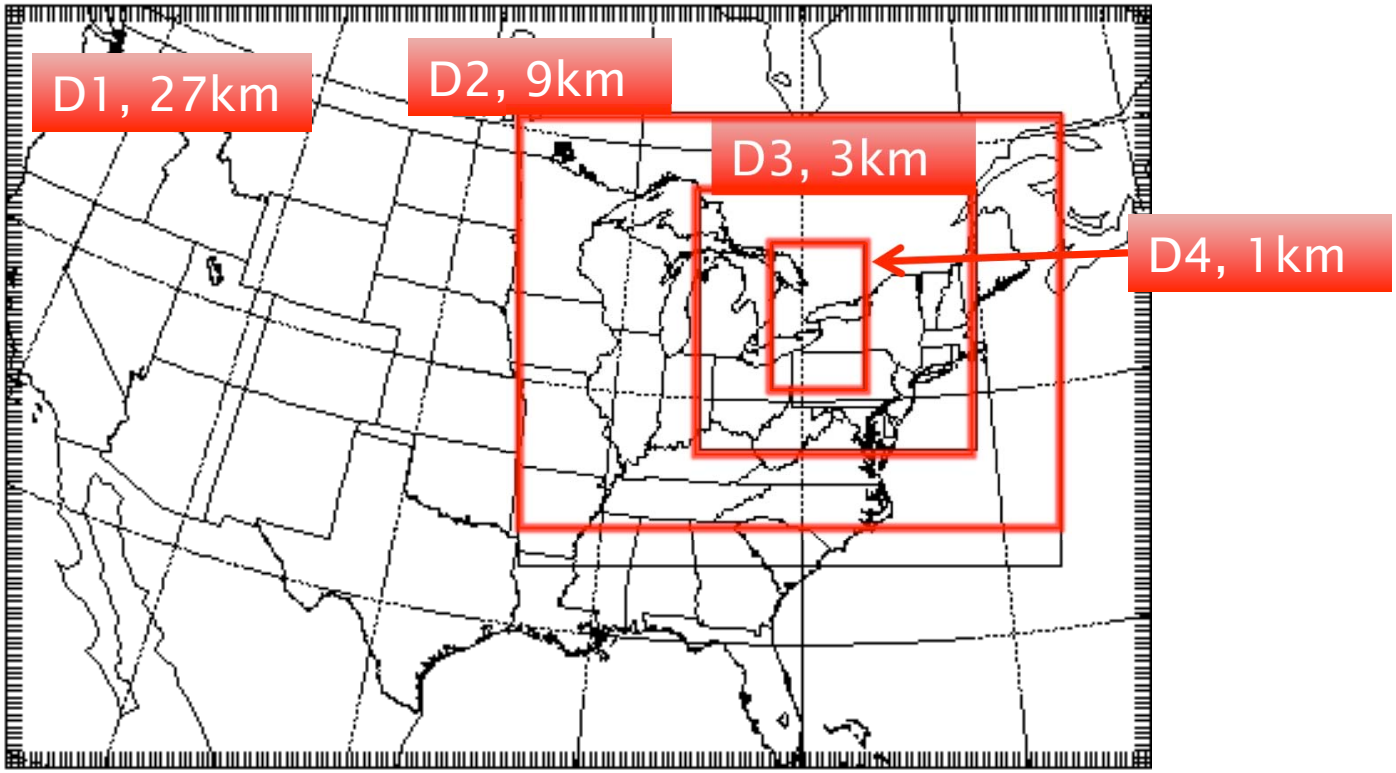
Ensemble Forecast of 2009 Ontario Tornado Outbreak

- A record number of tornadoes occurred during this event – 18 in total
- 4 of these tornadoes were of F2 intensity

Credit: Jim Parsons

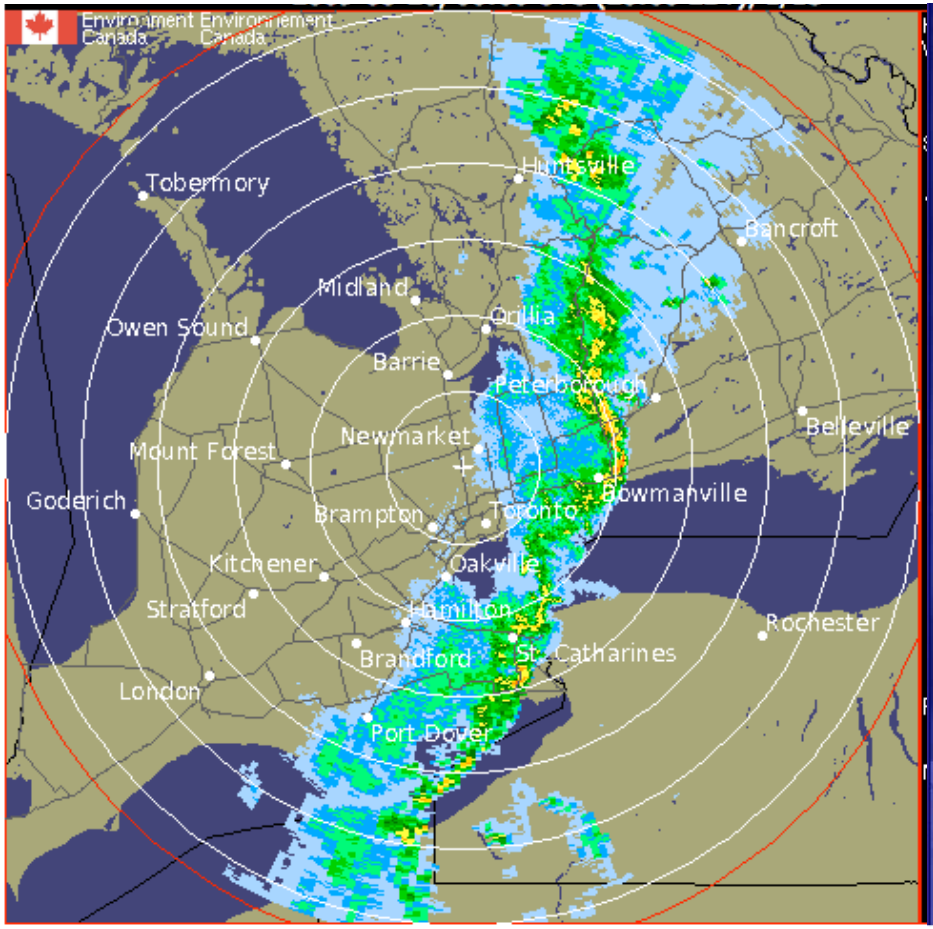
High-Resolution Ensemble Forecast

- Evaluate usefulness of high-resolution ensemble analysis and forecast in severe convective storm
- Use ensemble technique to assess the dynamics predictability and to study the dynamics of convective storm and its environment
- WRF ensemble: 27-9-3 km, 27 levels, 20 members, initialized from GFS analysis + GFS ensemble perturbations
- WRF deterministic: 27-9-3-1 km, initialized from GFS analysis

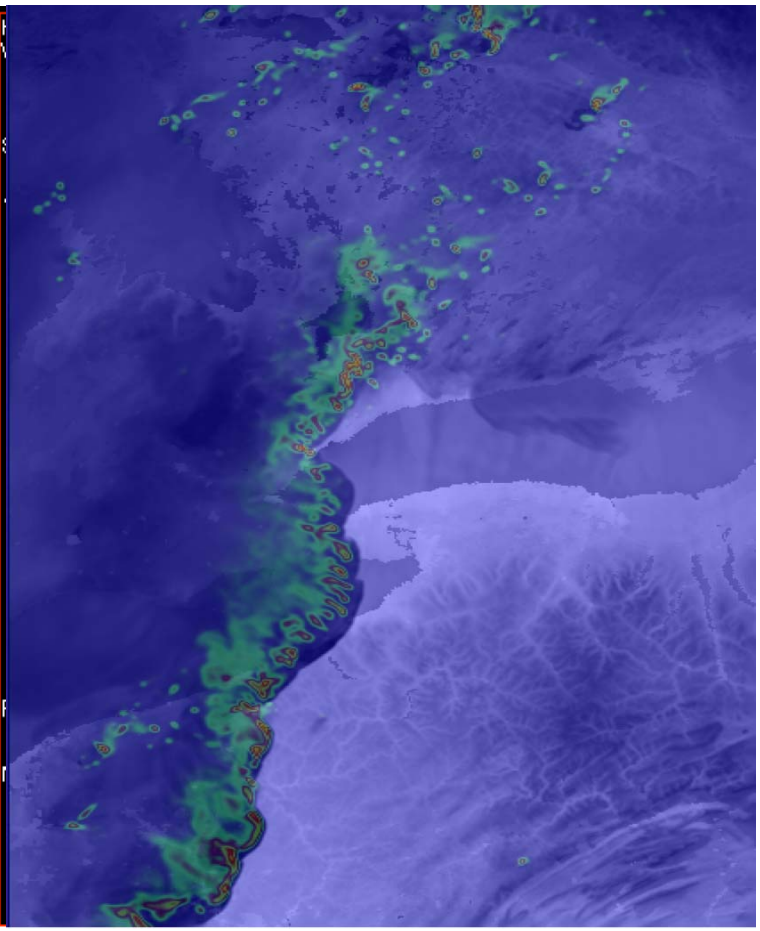


High-Resolution Simulation

Radar Obs, 2009/08/21/00Z

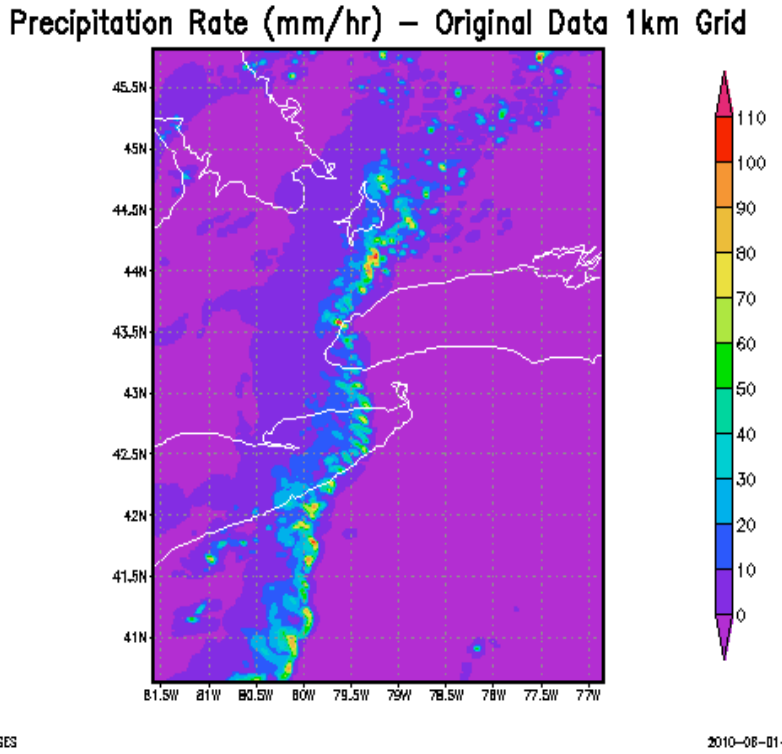


1km Deterministic 24-h f/c

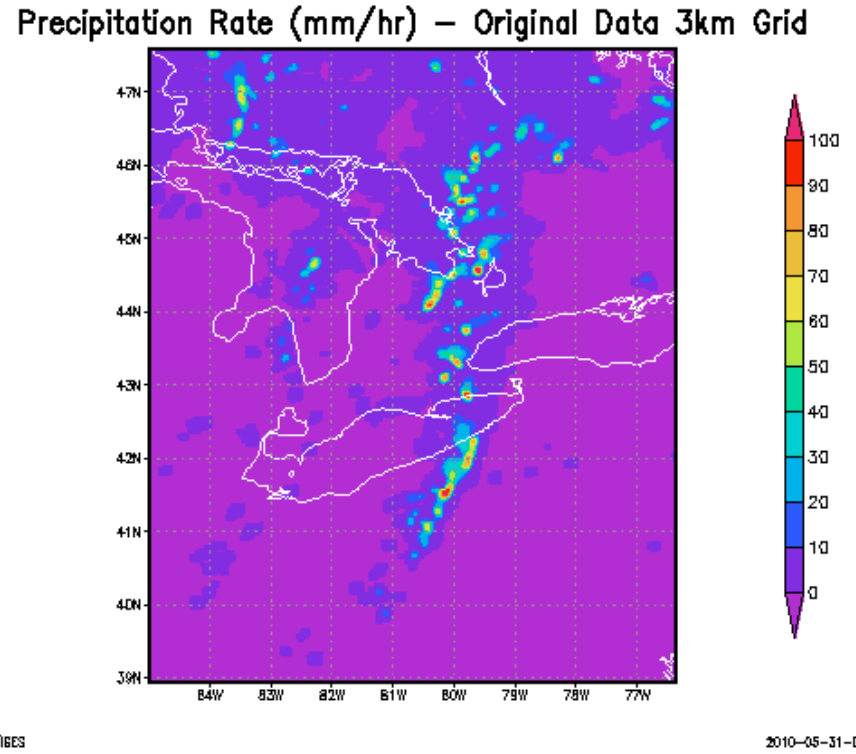


High-Resolution Simulation

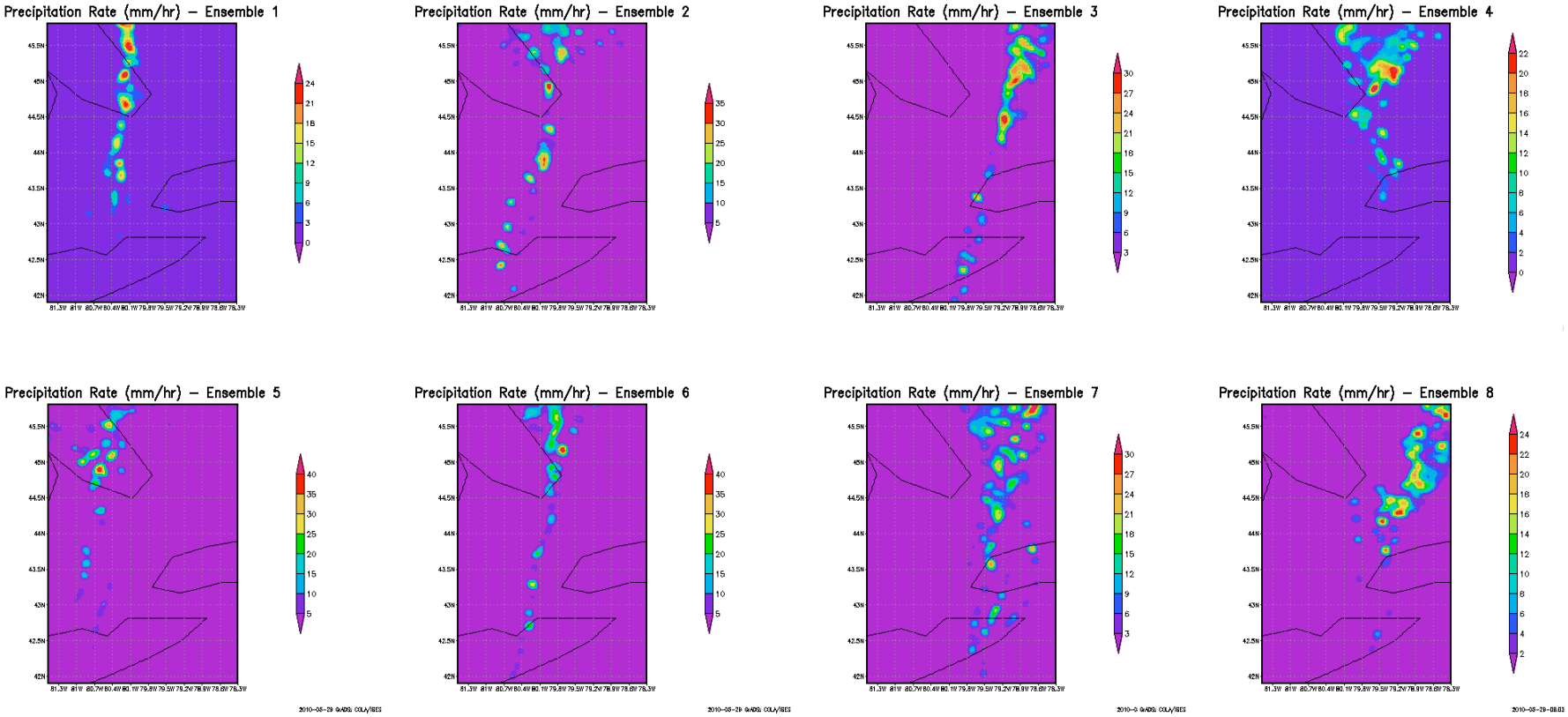
1km Deterministic 24-h f/c



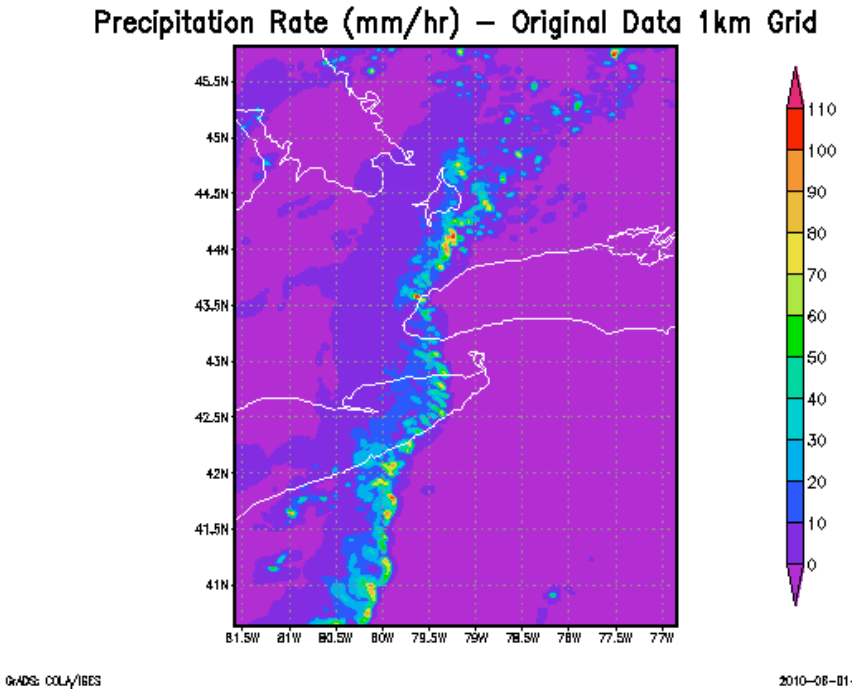
3km Deterministic 24-h f/c

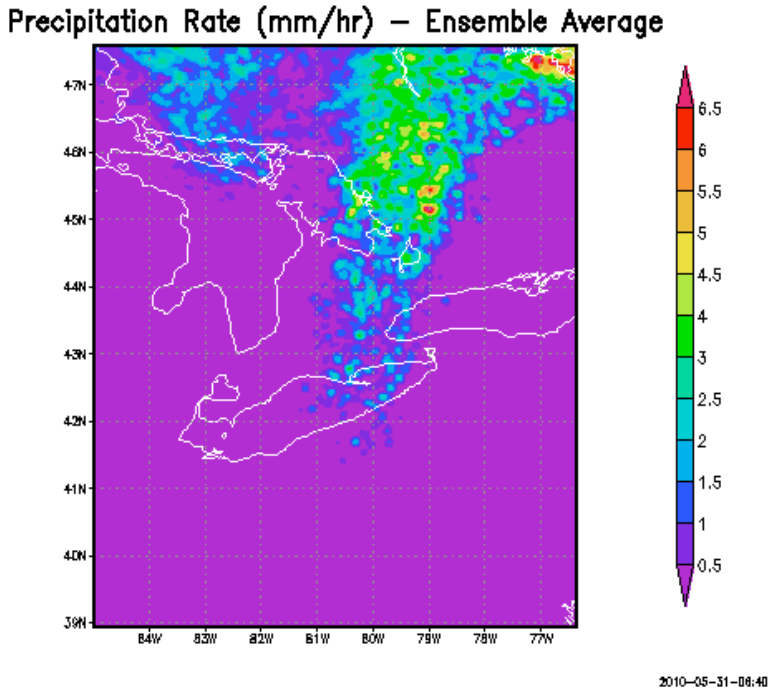


Ensemble members



Ensemble Mean





Summary

- EnKF can be used to build an effective convective weather initialization scheme to potentially improve the prediction
- Ensemble analysis and forecast can provide more information, not just in forecast, but also in dynamics
- Available tool is suitable for research and experimental real-time forecast