Towards an Optimal Representation of Model Uncertainty to Enhance Ensemble-based Probabilistic Forecasts

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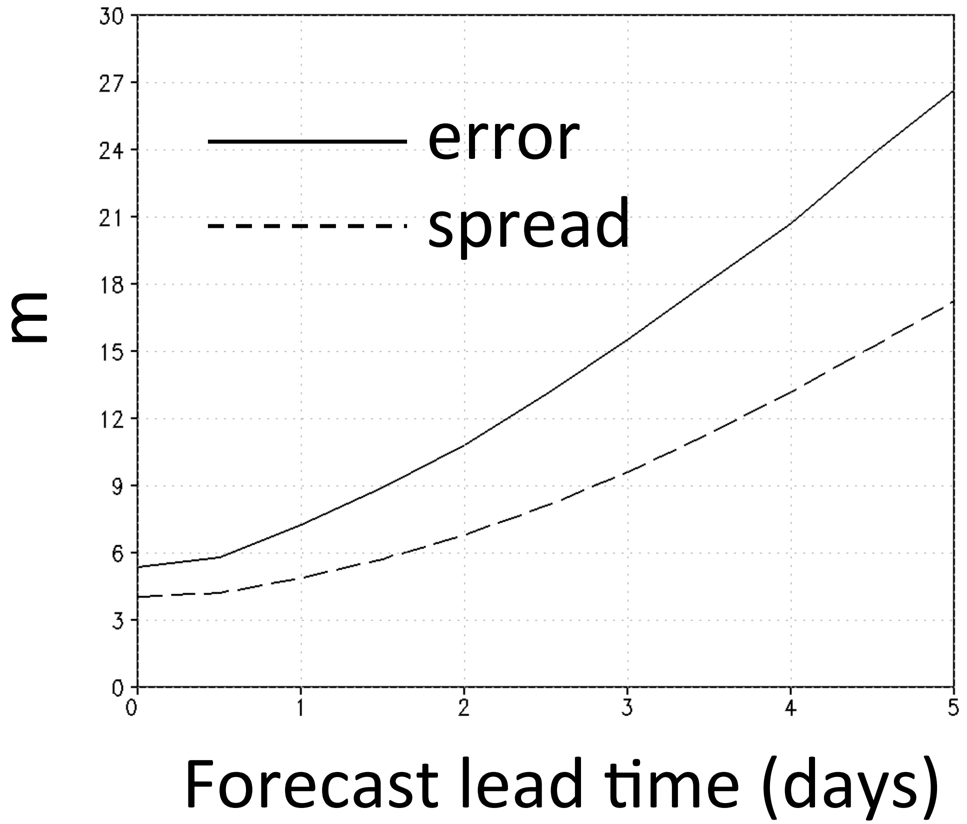
Introduction

- Ensemble forecasts from initial perturbations are under-spread especially in 2-meter temperature, low level winds, and precipitation
- Need to account for model uncertainty (e.g. deterministic physical parameterization, and finite resolution of model)
- Operational centers have embraced approaches that increase spread, but sometimes lack rigorous theoretical basis.
- Want to develop collaborative relationships with parameterization developers to formulate physically based stochastic parameterizations

Example of Under-spread forecasts

20-member GEFS forecast

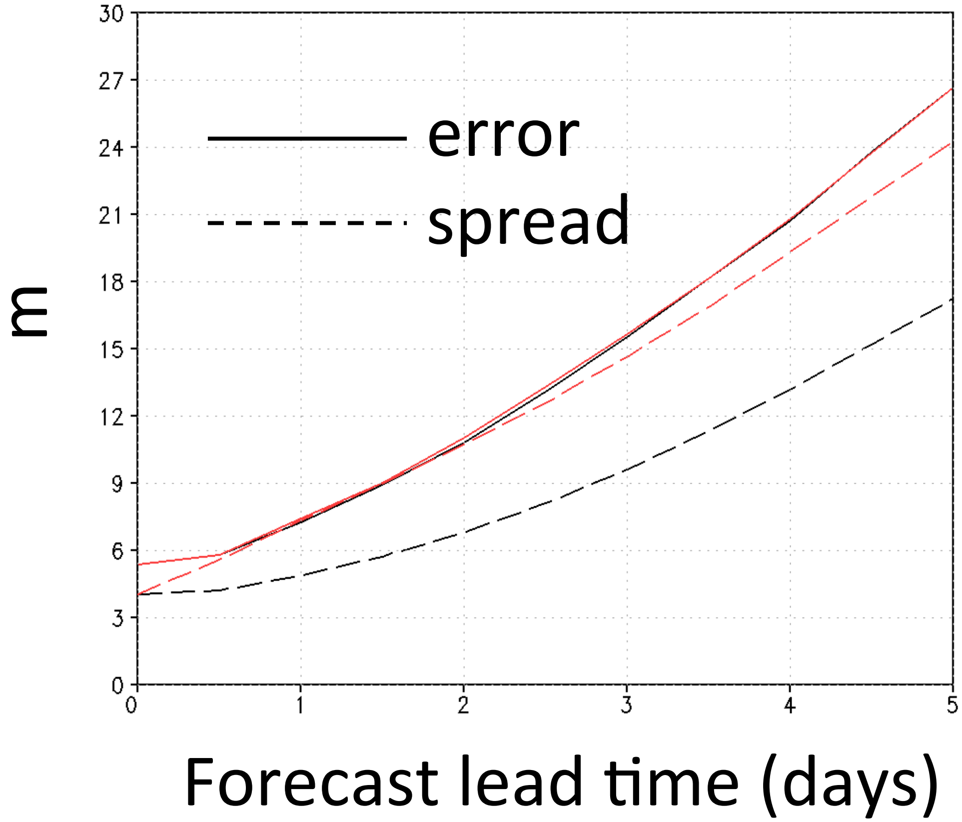
Southern Hemisphere z500



Example of Under-spread forecasts

20-member GEFS forecast

Southern Hemisphere z500



Model uncertainty in the operational GEFS

- Stochastic Total Tendency Perturbations (STTP)

$$\frac{\partial X_i}{\partial t} = T_i(X_i;t) + \gamma \sum_{j=1,\ldots,N} w_{i,j} T_j(X_j;t)$$

6-hr tendency

Rescaling factor

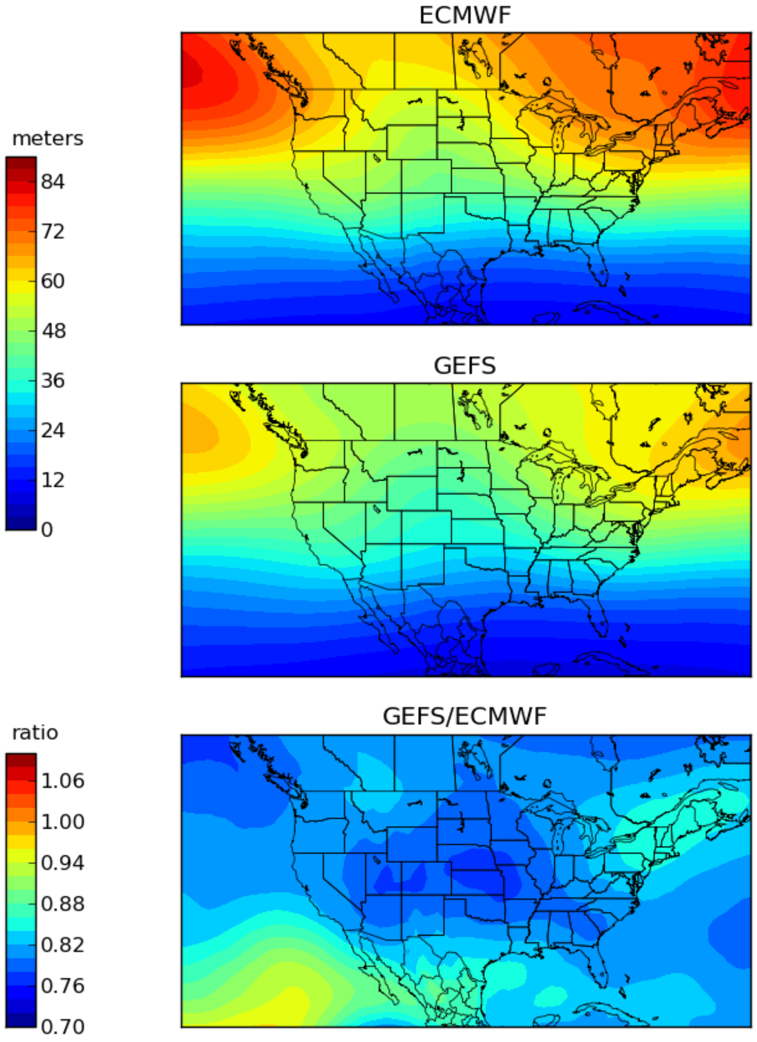
Evolving combination matrix

  - Random linear combinations of 6-hour tendency perturbations from the ensembles are applied to a given member during the model integration
  - *Reference:*
    - *Hou and et al, 2008*

Changes of NCEP Ensemble Spread (STTP)

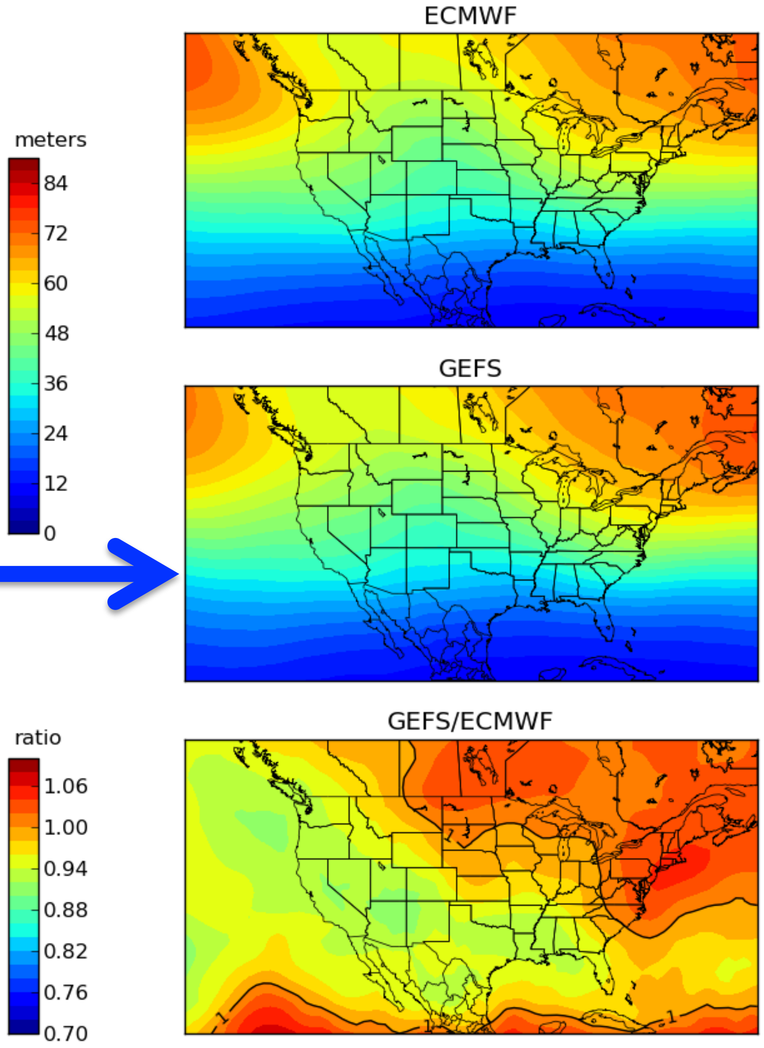
Then

Average 00Z Ensemble Spread (Mar 2007 - Mar 2009)
168-h Forecasts of 500-mb Geopotential Height (n=745)



Now

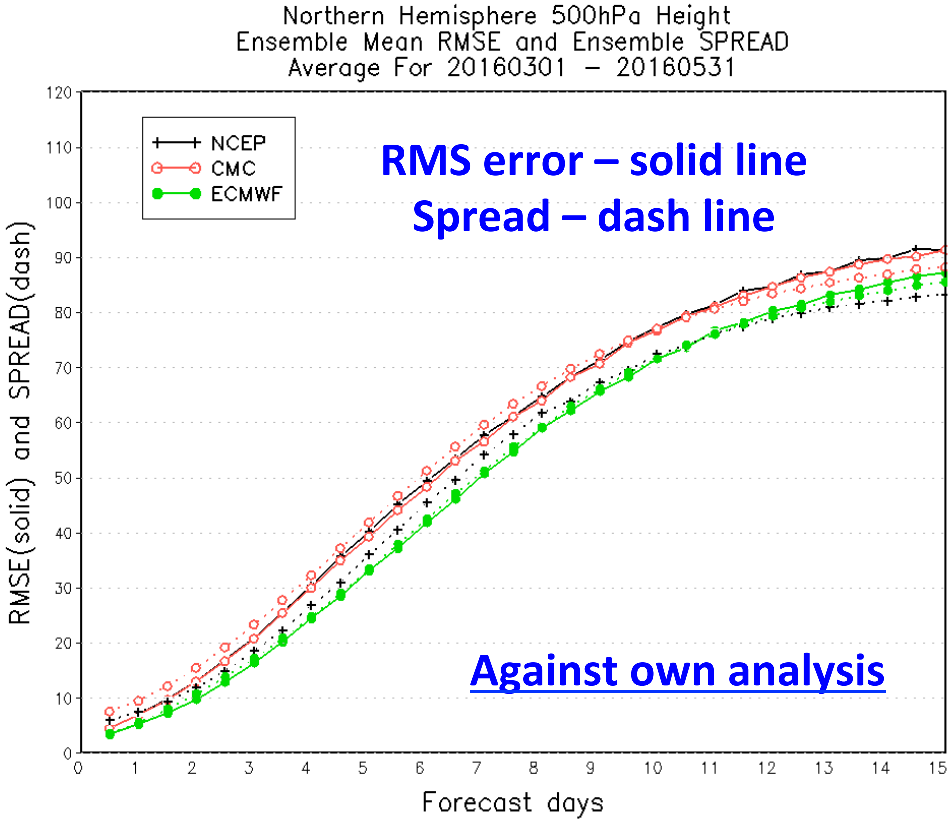
Average 00Z Ensemble Spread (Mar 2012 - Mar 2013)
168-h Forecasts of 500-mb Geopotential Height (n=360)



Courtesy of Dr. Trevor Alcott

Current Status of Global Ensembles

Spring 2016 – NH 500hPa height

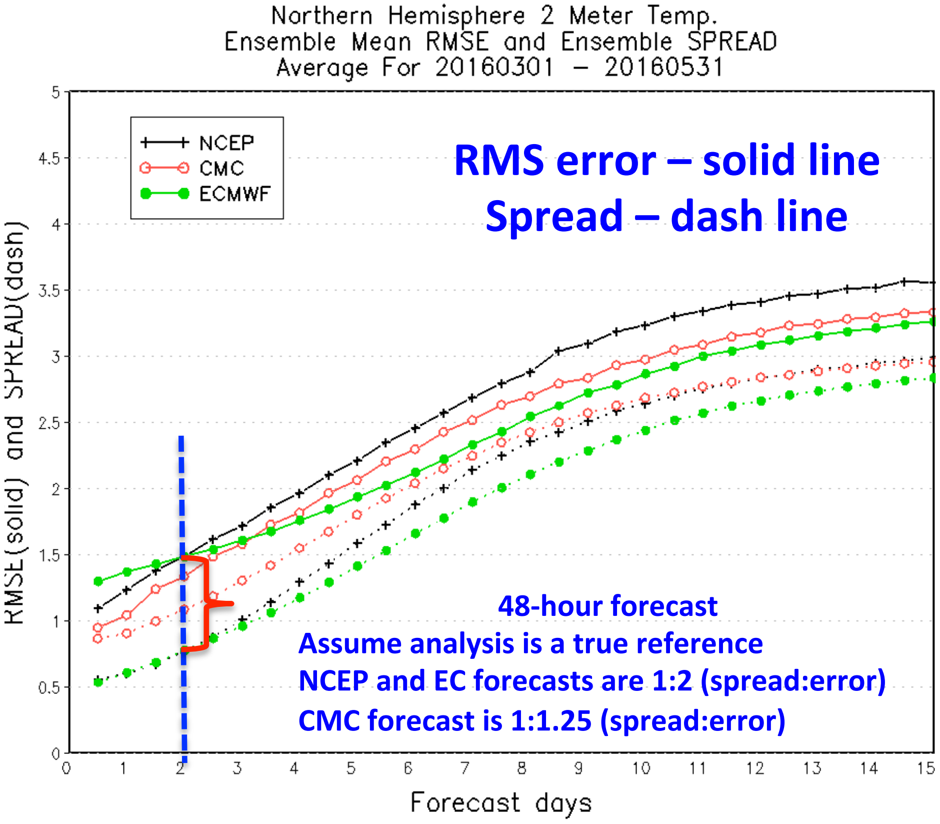


RMS error – solid line

Spread – dash line

<u>Against own analysis</u>

Spring 2016 – NH 2-m temperature



RMS error – solid line

Spread – dash line

48-hour forecast

Assume analysis is a true reference

NCEP and EC forecasts are 1:2 (spread:error)

CMC forecast is 1:1.25 (spread:error)

Upper atmosphere:

- Apply stochastic schemes and/or multi-physics
- All ensemble forecasts have reasonable spread compared to the errors

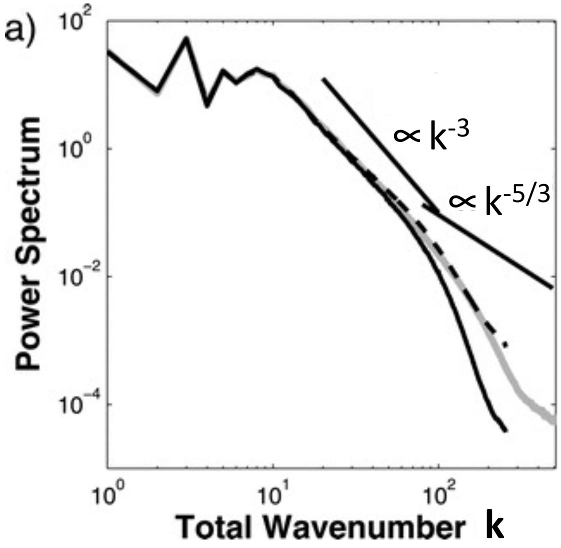
Surface elements:

- Does not apply stochastic schemes for surface
- All ensemble forecasts have more/less under dispersion (over confident)

Model uncertainty in the GFS DA (EnKF) cycle

- **Dynamics**: Due to the model's finite resolution, energy at non-resolved scales cannot cascade to larger scales.
  - Approach: Estimate energy lost each time step, and inject this energy in the resolved scales. a.k.a stochastic energy backscatter (SKEB; Berner et al. 2009)
- **Physics**: Subgrid variability in physical processes, along with errors in the parameterizations result in an under spread and biased model.
  - Approach: perturb the results from the physical parameterizations, and boundary layer humidity (Palmer et al. 2009), and inspired by Tompkins and Berner 2008, we call it SPPT and SHUM
- *Above schemes have been tested for current operational GEFS (spectral model)– plan to replace STTP for next implementation*

Kinetic Energy Spectrum

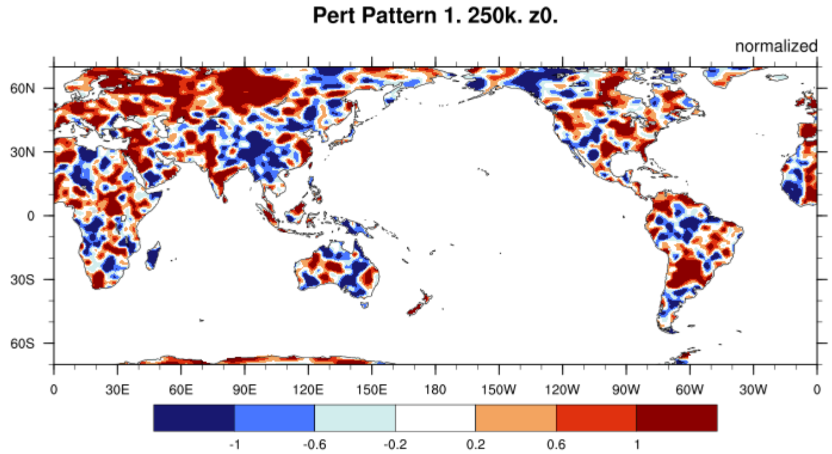


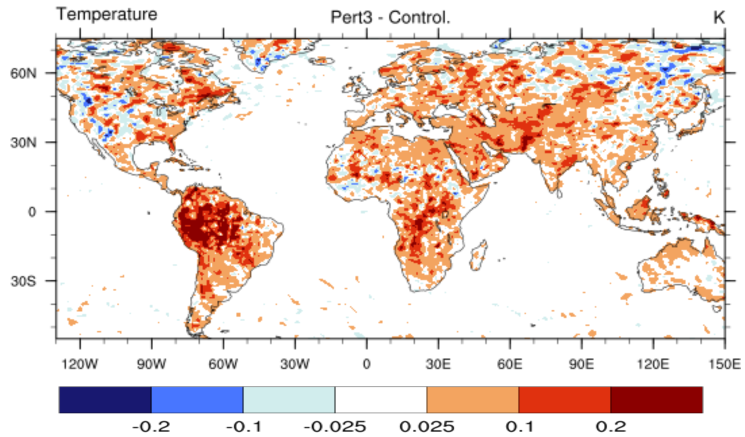
Berner et al. (2009)

Addressing errors in the land surface

Surface Perturbations

- There is error associated with the lower boundary conditions
  - in atmosphere only runs, damp the SST anomalies toward climatology during the forecast
  - Errors associated with land surface mode and initial conditions (not addressed here)
- Perturb SST with random pattern
- Perturb surface momentum roughness length (Z0), thermal roughness lenghth (zt) and soil hydraulic conductivity (SHC).
- And leaf area index (LAI)
- z0’ = z0*10^a, where a is the random pattern

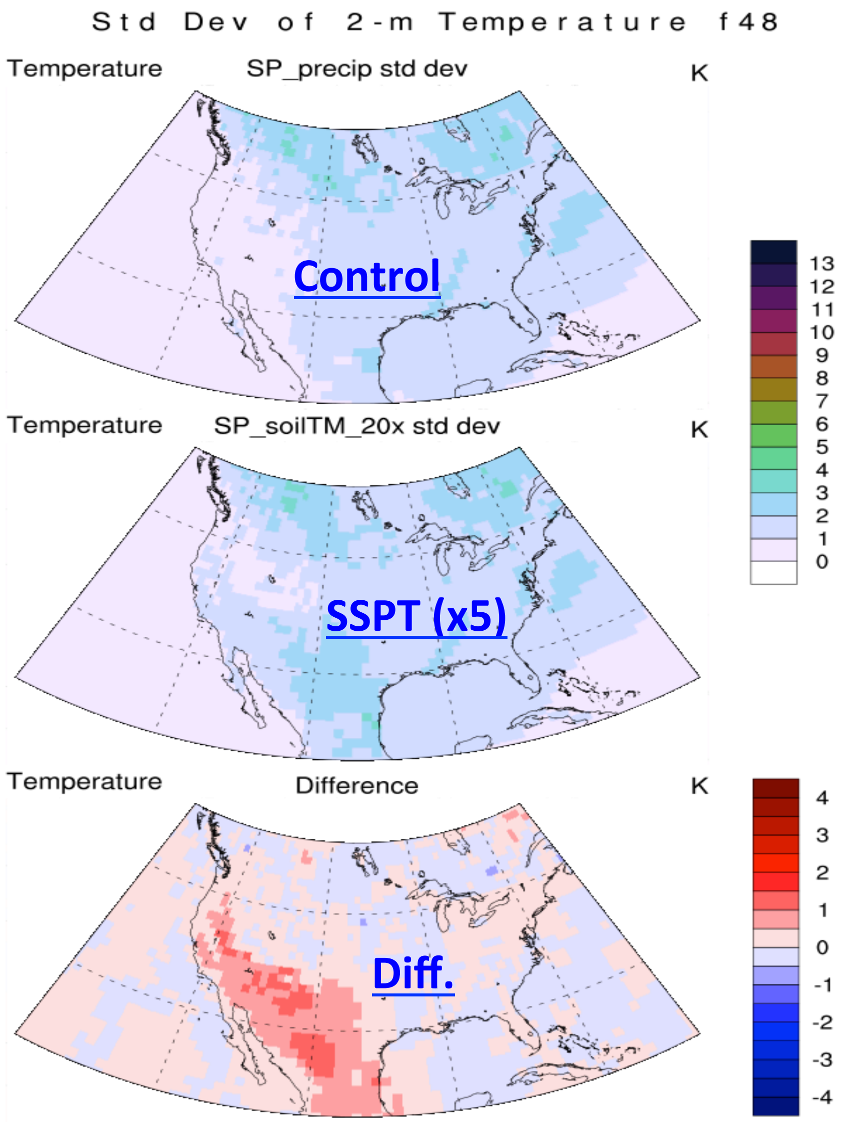




Limitations: many parameters in land model are still deterministic, but very important.

Surface Stochastic Physics Tendency

- Random perturbations for soil temperature and moisture tendency (all 4 model levels)
- Use the same random weights as SPPT scheme
- Sensitivity tests for one summer week and one winter week



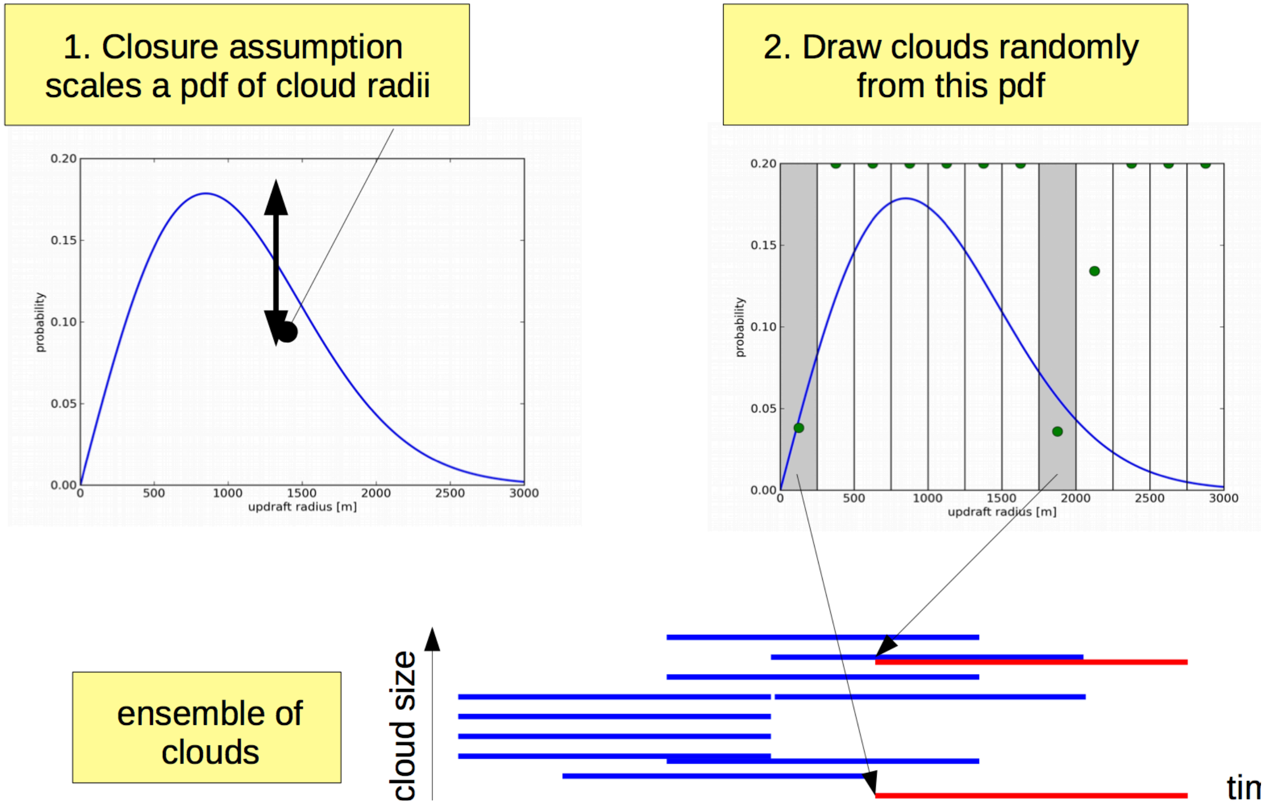
7 cases of winter – 48 hours

Towards physically based stochastic physics/parameterization

- ECMWF: New scheme, SPP: Stochastically Perturbed Parameterizations (starting with cloud/radiation interaction)
- Enviro Canada: In development: Plant-Craig stochastic deep convection, cloud model is adopted from the Bechtold scheme (closure is still deterministic, plume generation is stochastic)
- UK Met is testing random parameters in physics schemes. Parameters include droplet number in microphysics, entrainment rate, turbulent mixing rates.

Stochastic Deep convection

The Plant-Craig stochastic convection scheme



1. Closure assumption scales a pdf of cloud radii

2. Draw clouds randomly from this pdf

ensemble of clouds

Short-term activities

- Integrate all developed (tested) surface perturbation schemes (include initial uncertainties) to see if we could have significant impact to enhance surface temperature spread.
- Collaborate all stochastic physics developments with NGGPS efforts:
  - Diagnose observational (wind profiler) and LES simulation characteristics to inform the shape and size of the distribution of convective plumes assumes in the deep convection scheme and PBL mixing.
  - Adapt SHOC to include representation of model uncertainty, use prognostic sub-grid scale TKE to perturb profiles other physics parameterizations sees
  - Scale aware stochastic convection parameterization, and sub grid cloudiness.

Towards physically based stochastic parameterization (discussion)

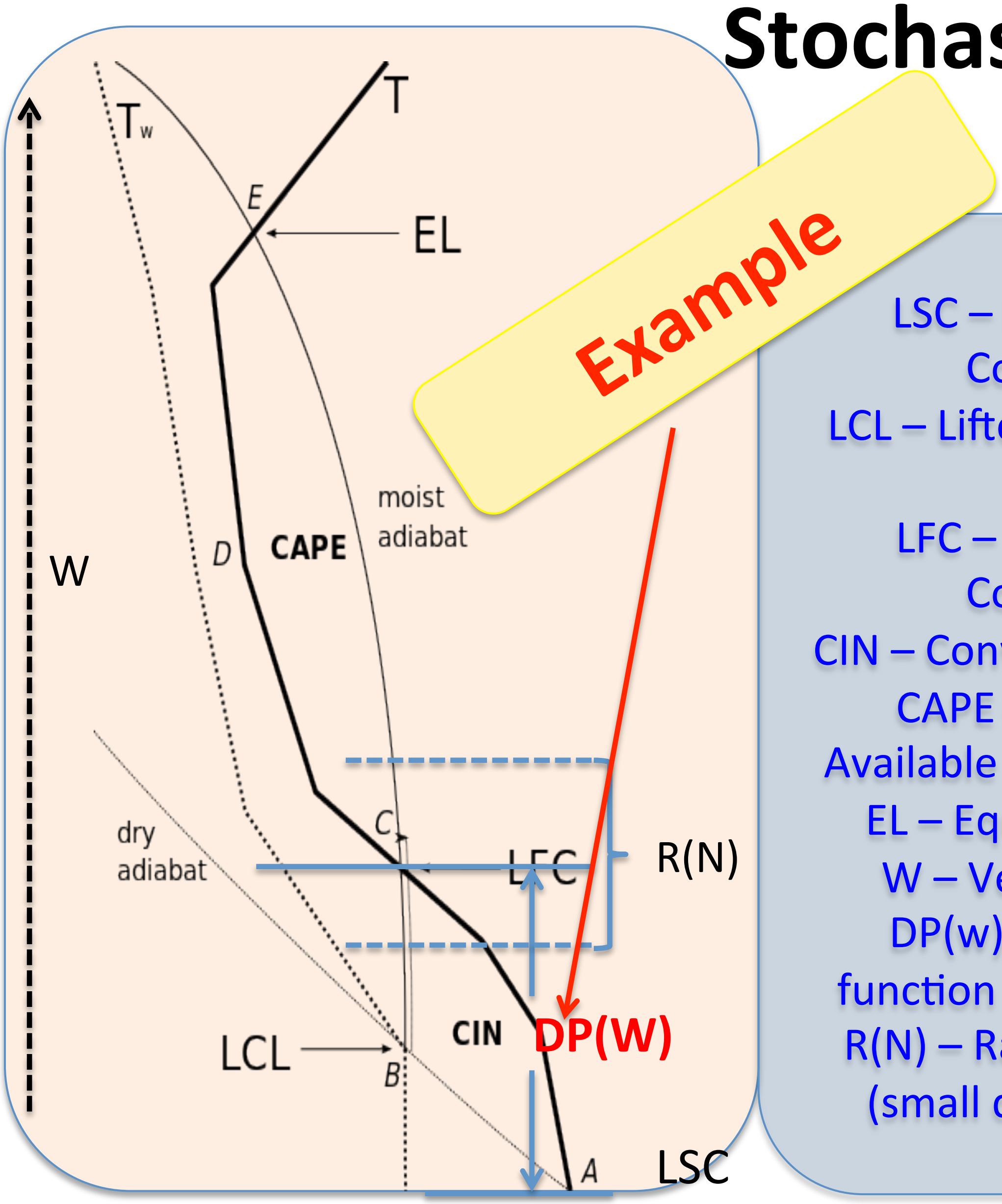
- Direction of future model physics development
  - Physically based stochastic parameterization
  - Not deterministic solution, but full representation of model uncertainty
  - Generates ensemble realizations of tendencies including realistic space-time correlations.
- Closed coordination (or work together) between model physics and ensemble development.
  - Connection through NGGPS CCPP (Common Community Physics Package)
  - Verify new stochastic parameterization in terms of ensemble metric (GMTB - Global Modeling Testbed)
- Identify (and/or understand) source of uncertainty, the key parameters to produce model errors (for different scales?), such as:
  - Convective trigger?
  - Rate of entrainment (updraft)/Detrainment (downdraft)?
  - Turbulence and convection parametrizations? - EDMF
  - Parameters in the microphysics? See next schematic plot
- Physically based scheme should be appropriate for all time scales (scale aware - hourly to seasonal) and spatial resolutions (convective scale the climate model resolutions; e.g. ~100 km)

Towards physically based stochastic parameterization (discussion)

- More discussions on:
  - Avoid to spend major resources on:
    - Multi-model or multi-physics approach?
    - Ad-hoc stochastic physics process?
  - Pay attention to:
    - Land surface process (important to improve surface elements of forecast)
    - Ocean surface (SST) (important to extend forecast, week 2, 3, &4)
    - Tropical storm forecast (could be related issue, not only for stochastic physics, but also initial perturbation)

Stochastic Parameterization

"Convective trigger"



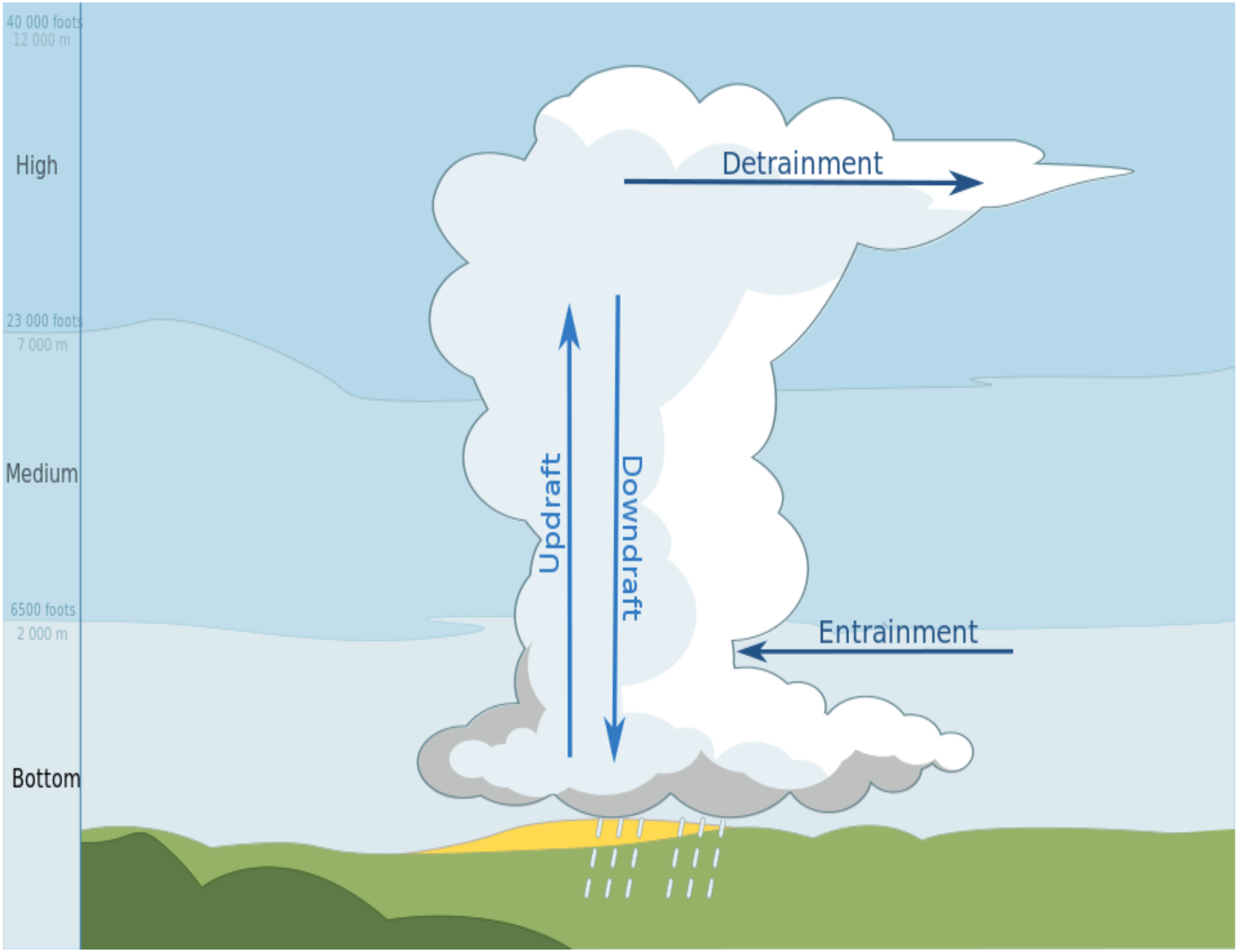
LSC – Level of Start Convection
LCL – Lifted Condensation Level
LFC – Level of Free Convection
CIN – Convective Instability
CAPE – Convective Available Potential Energy
EL – Equilibrium Level
W – Vertical Motion
DP(w) – SAS trigger function (delta pressure)
R(N) – Random function (small delta pressure)

Convective Trigger function in most cumulus parameterization scheme (SAS: Simplified Arakawa-Schubert)

P_{LSC}-P_{LFC} <= DP(w)
Convection is triggered,

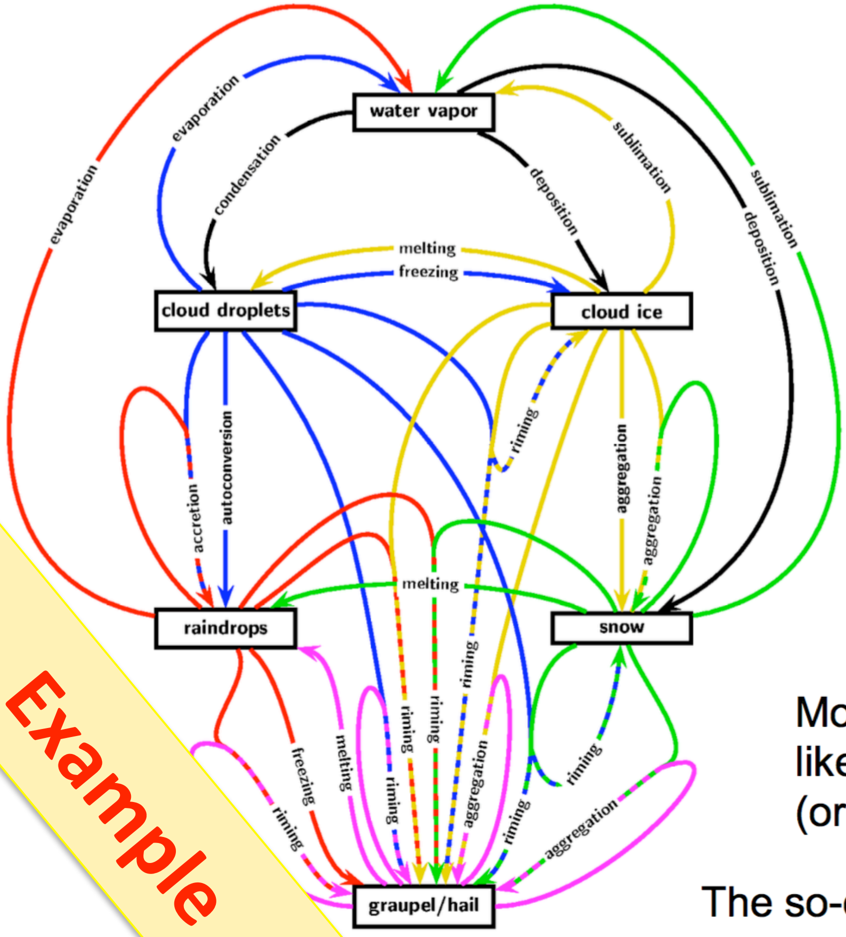
P_{LCS}-P_{LFC} > DP(w)
No sub-grid convection

Figure: Schematic diagram showing an air parcel path when raised along B-C-E compared to the surrounding air mass Temperature (T) and humidity (Tw)


40 000 foots
12 000 m
High
23 000 foots
7 000 m
Medium
6500 foots
2 000 m
Bottom
Detrainment
Updraft
Downdraft
Entrainment

Model error at mesoscale:

Example: cloud microphysical processes



Example

from Axel Seifert presentation to NCAR ASP summer colloquium

Conversion processes, like snow to graupel conversion by riming, are very difficult to parameterize but very important in convective clouds.

Especially for snow and graupel the particle properties like **particle density** and **fall speeds** are important parameters. The assumption of a constant particle density is questionable.

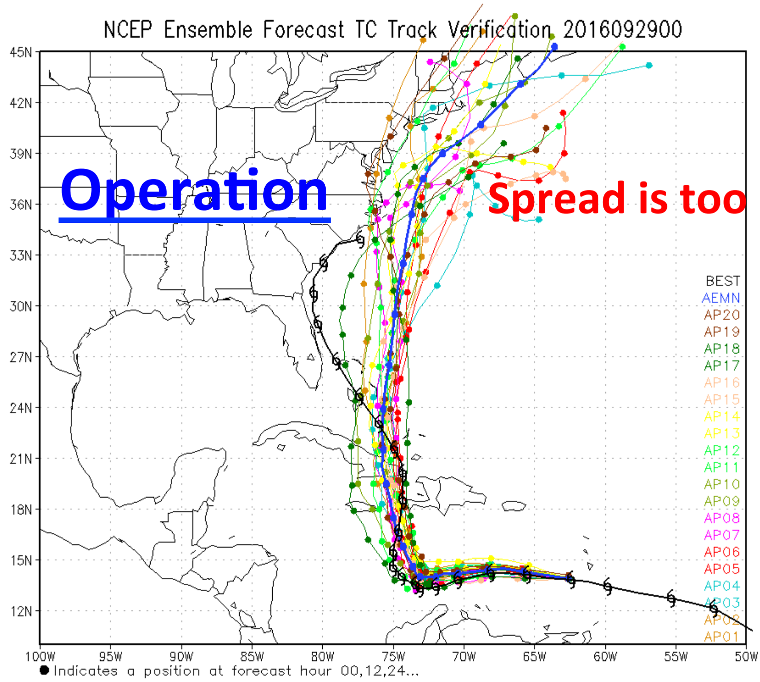
Aggregation processes assume certain collision and sticking efficiencies, which are not well known.

Most schemes do not include **hail processes** like wet growth, partial melting or shedding (or only very simple parameterizations).

The so-called **ice multiplication** (or Hallet-Mossop process) may be very important, but is still not well understood

Extra slides

NCEP Ensemble Forecast TC Track Verification 2016092900

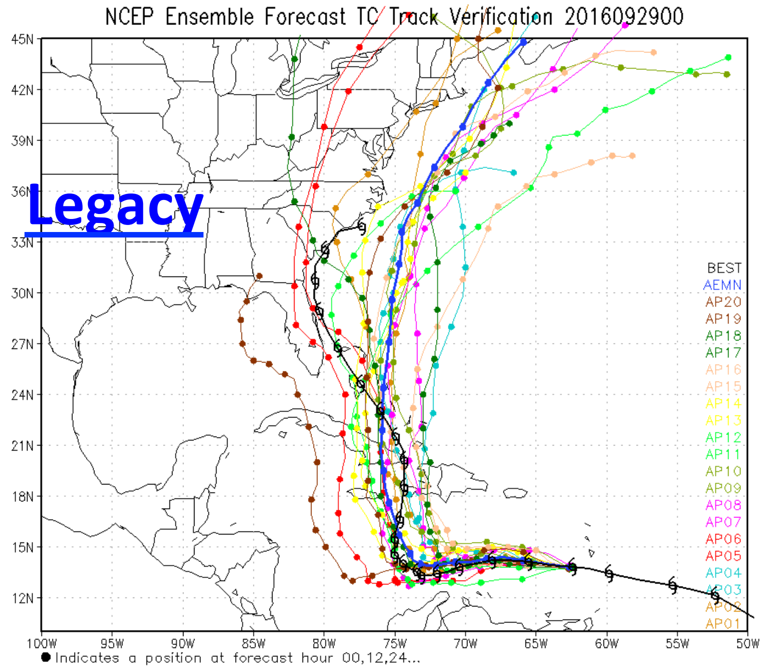


● Indicates a position at forecast hour 00,12,24...

Operation

Spread is too small?

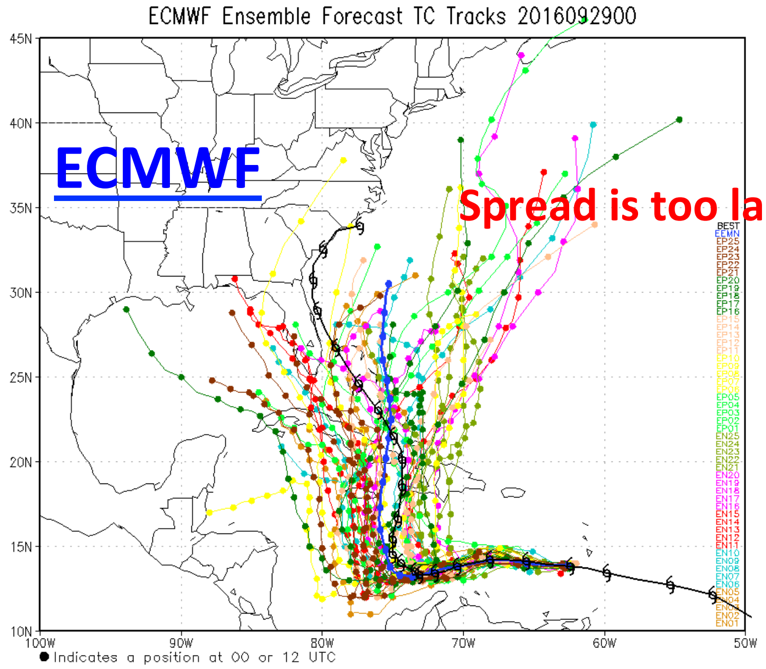
NCEP Ensemble Forecast TC Track Verification 2016092900



● Indicates a position at forecast hour 00,12,24...

Legacy

ECMWF Ensemble Forecast TC Tracks 2016092900



● Indicates a position at 00 or 12 UTC

ECMWF

Spread is too large?

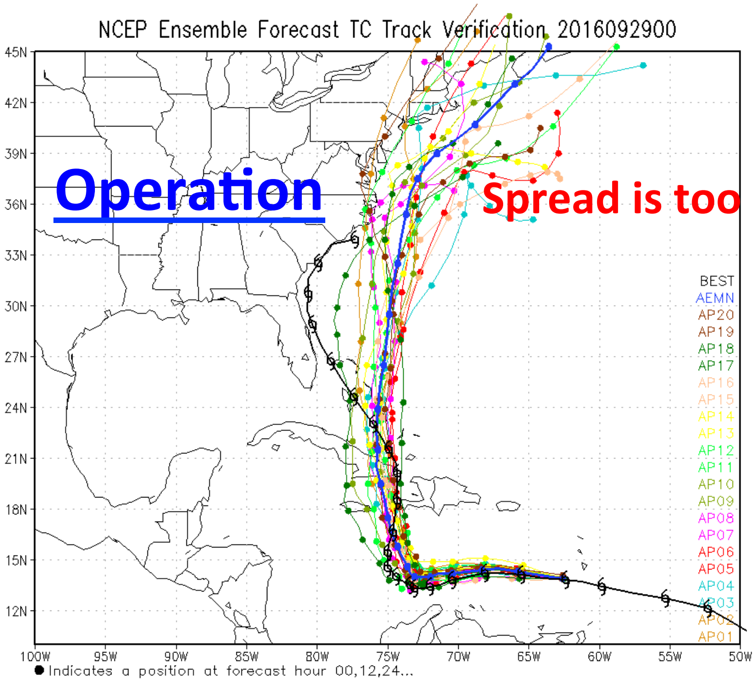
Hurricane Matthew

Initial: 2016092900

Top left – GEFS operation forecast (V11)

Top right – GEFS legacy forecast (V10)

Bottom left – ECMWF forecast

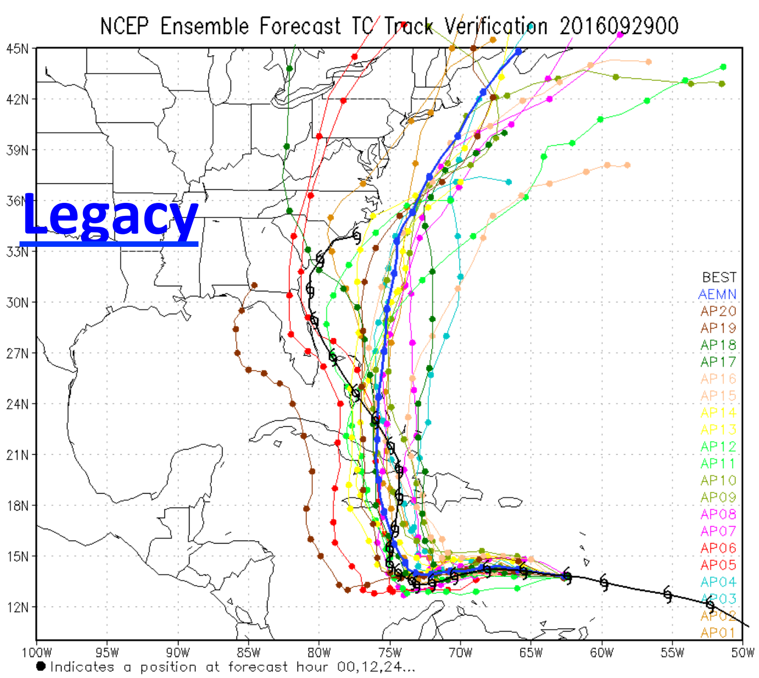


NCEP Ensemble Forecast TC Track Verification 2016092900

Operation

Spread is too small?

● Indicates a position at forecast hour 00,12,24...



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Legacy

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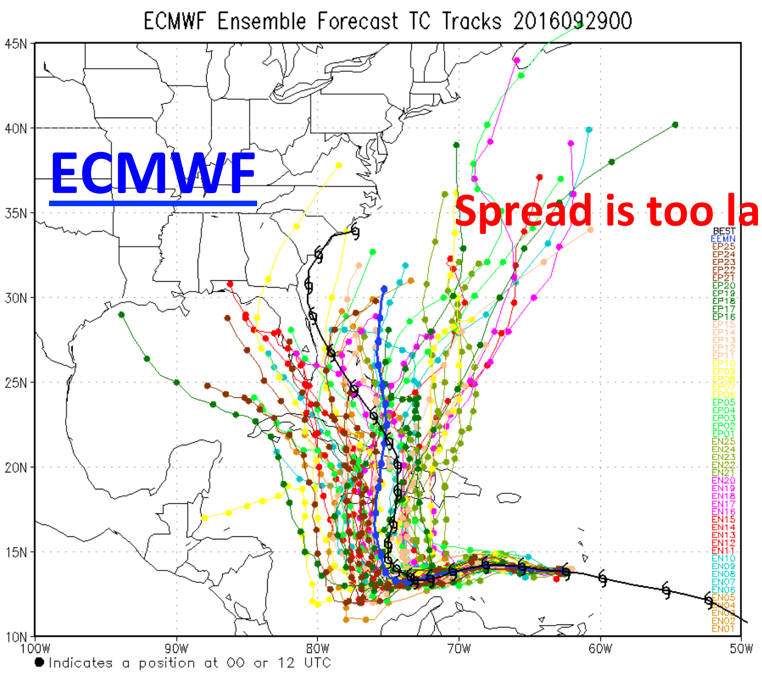
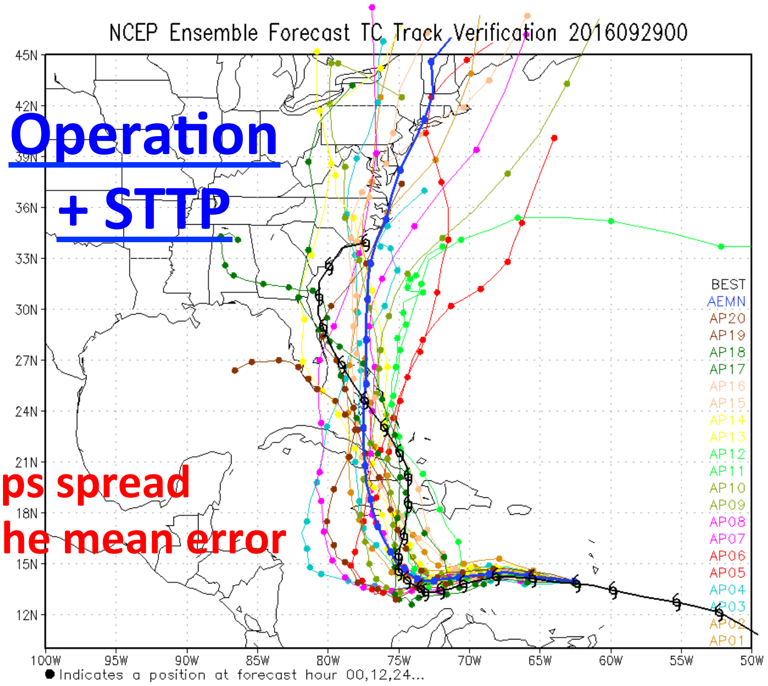


ECMWF Ensemble Forecast TC Tracks 2016092900

ECMWF

Spread is too large?

● Indicates a position at 00 or 12 UTC



NCEP Ensemble Forecast TC Track Verification 2016092900

Operation

+ STTP

It helps spread

Not sure the mean error

● Indicates a position at forecast hour 00,12,24...

Physically-based Stochastic Perturbations (PSP)

Implementation in COSMO model (2.8 km grid length)

- Add random increments to model variables
- Amplitude scaled using turbulence theory
- Rescaled to account for averaging over effective horizontal resolution
- Perturbations are coherent in height and over 10 min in time

$$\left(\frac{\partial\Phi}{\partial t}\right)_{sh}^{stoch} = \frac{\partial\Phi}{\partial t} + \alpha_{sh} \cdot \eta_{sh} \cdot \langle\Phi^2\rangle^{1/2}$$

$\frac{\partial\Phi}{\partial t}$: tendency of Φ of all physical parameterizations

Φ : resolved variable (T, w, q)

α_{sh} : scaling factor

η_{sh} : Gaussian random perturbation

$\langle\Phi^2\rangle$: variances from turbulence parameterization

$$\alpha_{sh} = \alpha_{sh,\Phi} \cdot \frac{\ell_\infty}{5 \cdot dx} \cdot \frac{1}{dt}$$

dt : temporal resolution of model

ℓ_∞ : asymptotic mixing length

dx : horizontal resolution of model grid

$\alpha_{sh,\Phi}$: scaling factor

(Kober and Craig 2016)

Currently in development for the GEFS

- Sensible weather elements (T2M and Precipitation) are still very under dispersion
  - Land surface perturbations at initialization (PSD)
  - Random perturbations to land-model parameters (PSD)
  - Random perturbations to land-model tendencies (EMC)

- TS track forecast (*under investigation?* – EMC)
  - Hurricane track forecast
  - Due to 4DEnVar? Latest EnKF has smaller perturbations
  - Could stochastic perturbation help to improve this?

Short-term plans for GEFS upgrade

- Integrate all developed (tested) surface perturbation schemes (include initial uncertainties) to see if we could have significant impact to enhance surface temperature spread.
- Make stochastic physics packages independent of dynamical core in NEMS for easy maintain and upgrade
- Diagnose observational (wind profiler) and LES simulation characteristics to inform the shape and size of the distribution of convective plumes assumes in the deep convection scheme and PBL mixing.
- Adapt SHOC to include representation of model uncertainty, use prognostic sub-grid scale TKE to perturb profiles other physics parameterizations sees.

Future plans

- Integrate all developed (tested) surface perturbation schemes (include initial uncertainties) to see if we could have significant impact to enhance surface temperature spread.
- Make stochastic physics packages independent of dynamical core in NEMS for easy maintain and upgrade
- Diagnose observational (wind profiler) and LES simulation characteristics to inform the shape and size of the distribution of convective plumes assumes in the deep convection scheme and PBL mixing.
- Adapt SHOC to include representation of model uncertainty, use prognostic sub-grid scale TKE to perturb profiles other physics parameterizations sees.

Where to go from here?

- Need closed coordination (or work together) between model physics and ensemble development.
- Identify (and or understand) the key parameters to produce model errors (for different scales?)
- Develop physics based stochastic parameterization schemes
- Physically based scheme is appropriate for all time scales (scale aware - hourly to seasonal) and spatial resolutions (less Km to ???)
- Multi-model or multi-physics approach?
- Land surface needs more attention
- Ocean surface needs more attention
- Tropical storm needs to investigate (could be related issue, not only for stochastic, but also initial perturbation)