Stochastic Physics Perturbations For Ensemble Forecast

Yuejian Zhu
Ensemble Team
Environmental Modeling Center
NCEP/NWS/NOAA

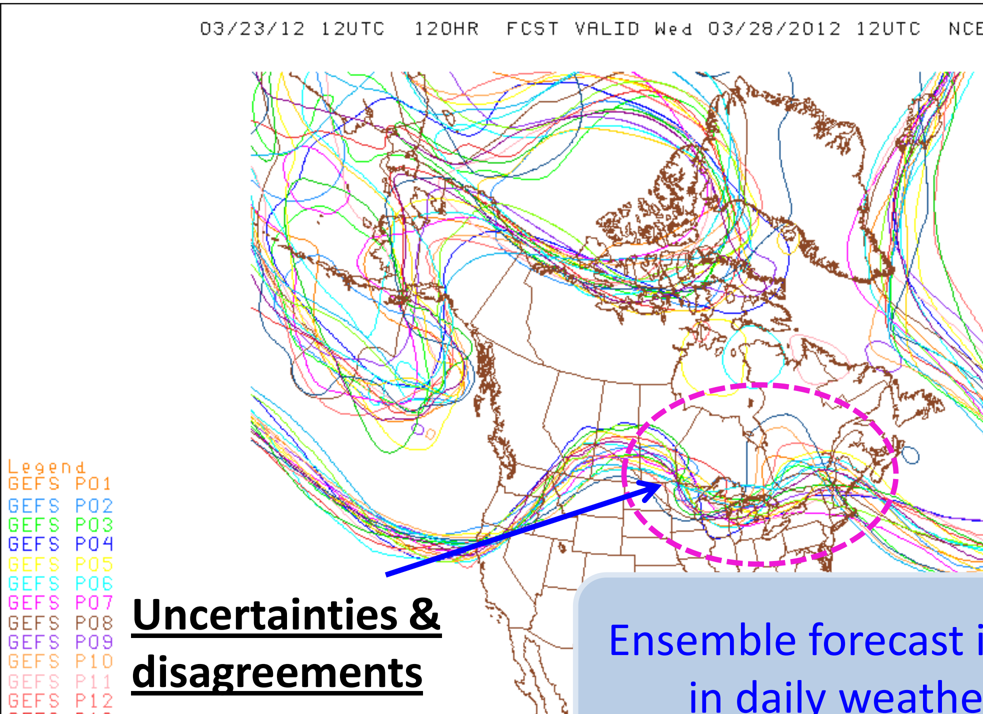
Acknowledgements: Philip Pegion, Walter Kolczynski, Dingchen Hou and Xiaqiong Zhou

Special thanks to IITM and Dr. Mukmopadhyay

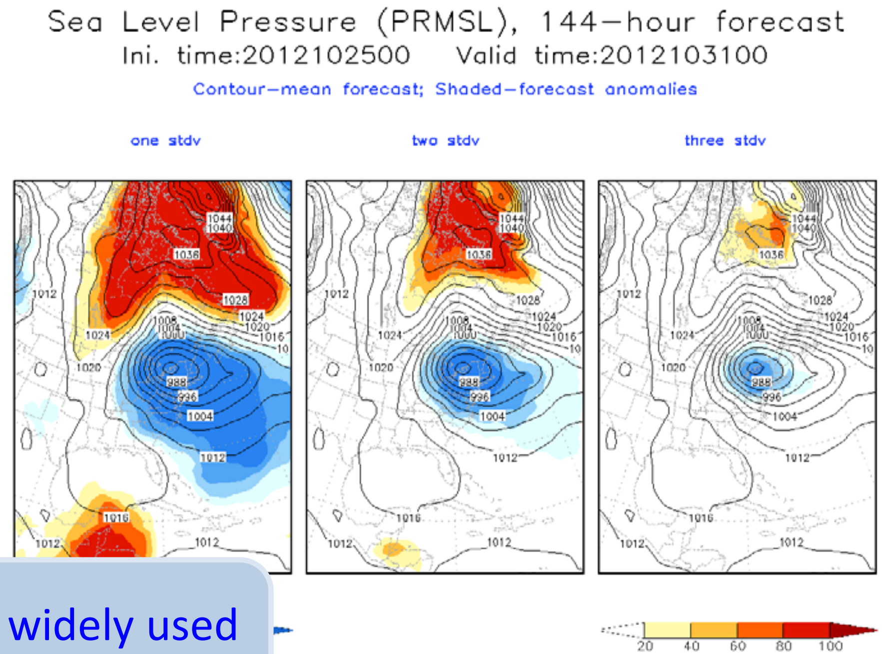
Highlights

- Introduction
- Current status of global ensemble
- Testing of stochastic physics
- Next NCEP GEFS
- Where to go from here?

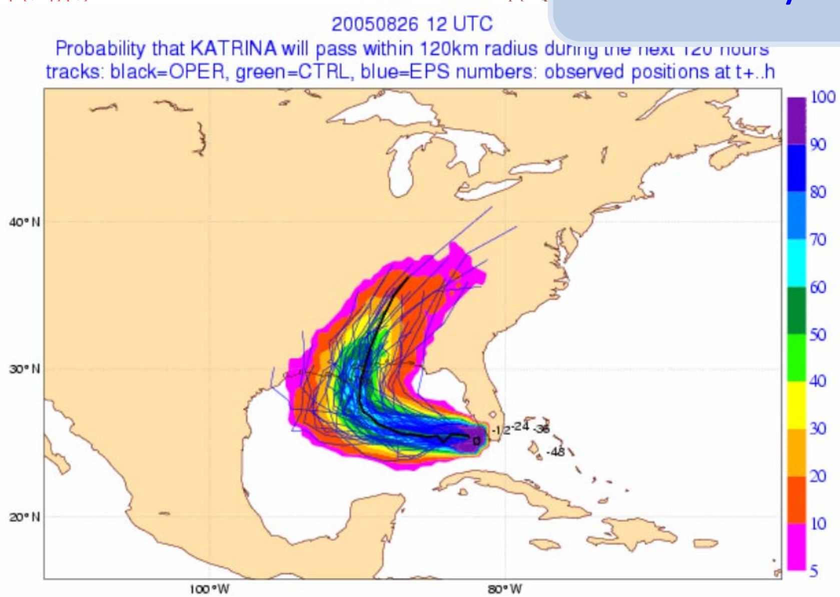
Introduction (1)

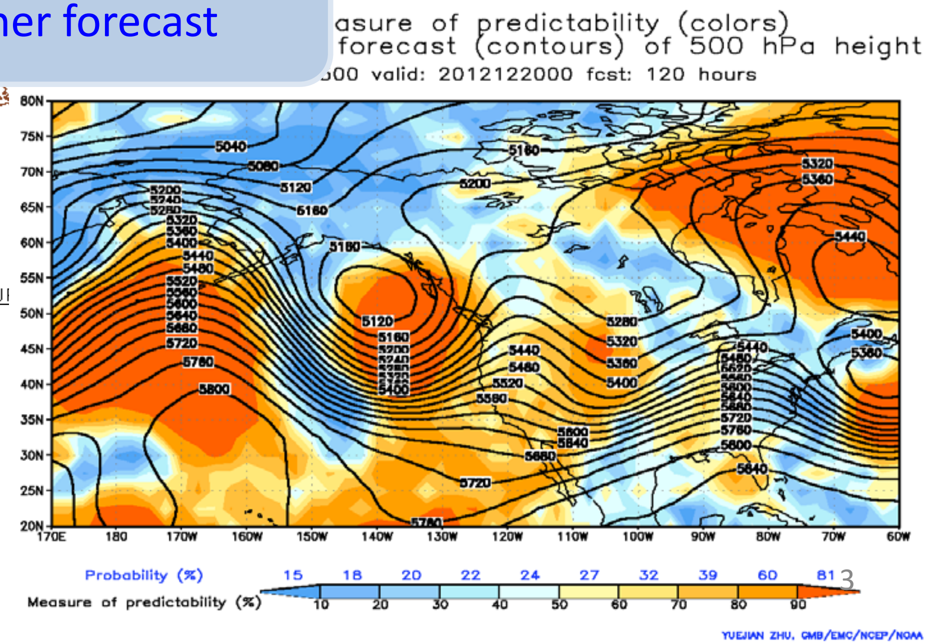


Uncertainties & disagreements



Ensemble forecast is widely used in daily weather forecast





Introduction (2)

2017 was 25th anniversary of both NCEP and ECMWF global ensemble forecasts into operational implementation

Introduction (3)

Description of the ECMWF, MSC and NCEP systems

Each ensemble member evolution is given by integrating the following equation

$$e_j(T) = e_0(0) + de_j(0) + \int_{t=0}^{T} [P_j(e_j,t) + dP_j(e_j,t) + A_j(e_j,t)]dt$$

Initial uncertainty

Model uncertainty

where $e_j(0)$ is the initial condition, $P_j(e_j,t)$ represents the model tendency component due to parameterized physical processes (model uncertainty), $dP_j(e_j,t)$ represents random model errors (e.g. due to parameterized physical processes or sub-grid scale processes – stochastic perturbation) and $A_j(e_j,t)$ is the remaining tendency component (different physical parameterization or multi-model).

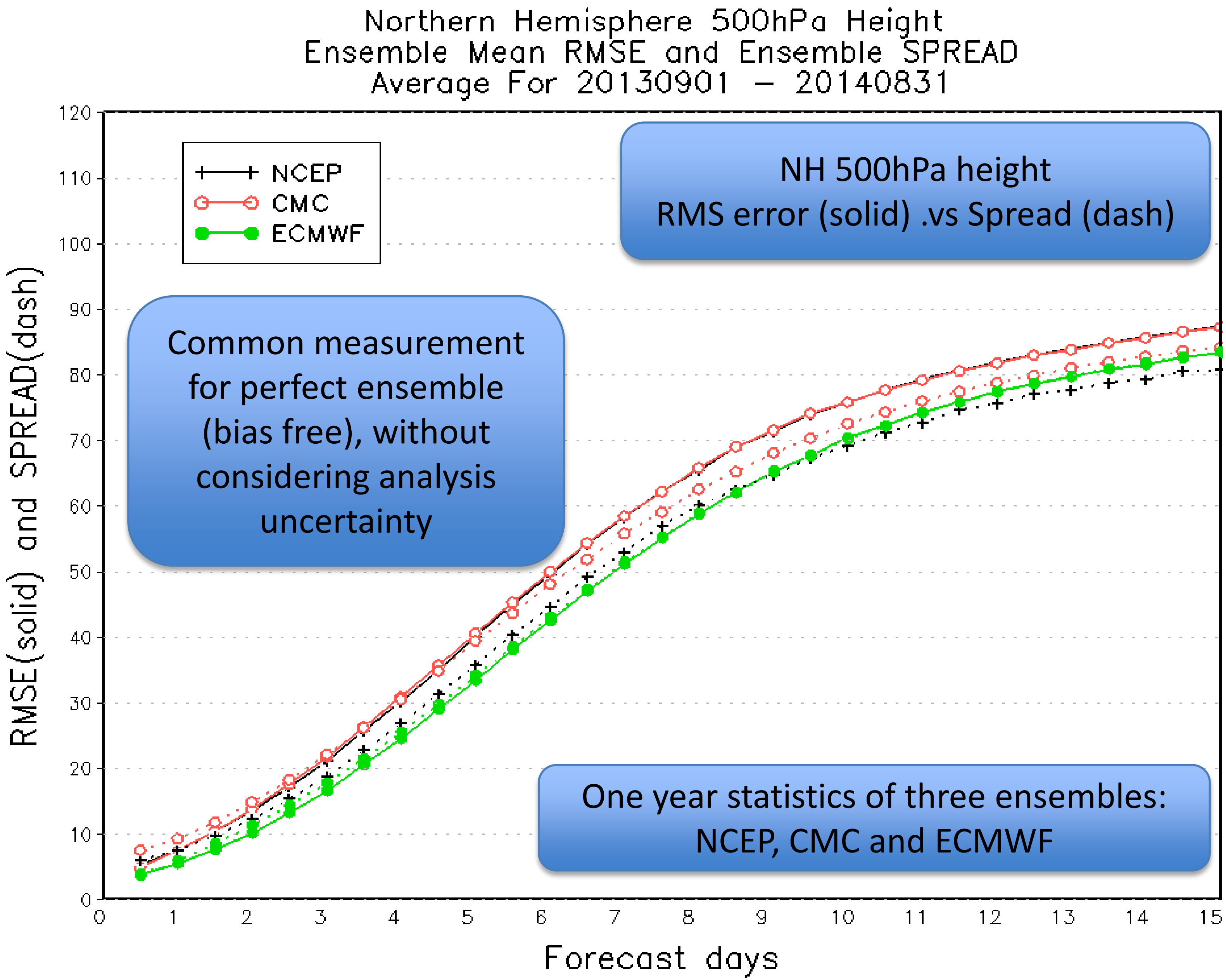
Operation: ECMWF-1992; NCEP-1992; MSC-1998

Reference: - first global ensemble review paper

Buizza, R., P. L. Houtekamer, Z. Toth, G. Pellerin, M. Wei, Y. Zhu, 2005:

"A Comparison of the ECMWF, MSC, and NCEP Global Ensemble Prediction Systems" Monthly Weather Review, Vol. 133, 1076-1097

Introduction (4)



Evolution of NCEP GEFS configuration (versions)

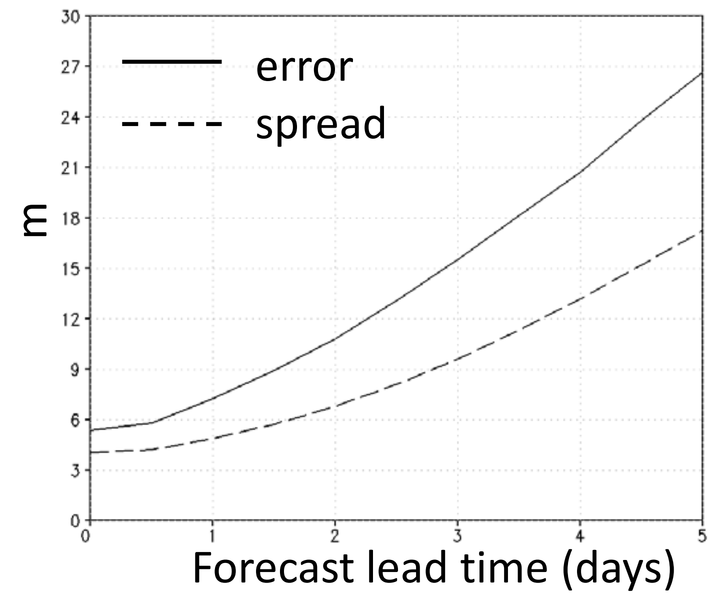
Version	Implementation	Initial uncertainty	TS relocation	Model uncertainty	Resolution	Forecast length	Ensemble members	Daily frequency
V1.0	1992.12	BV	None	None	T62L18	12	2	00UTC
V2.0	1994.3				T62L18	16	10(00UTC) 4(12UTC)	00,12UTC
V3.0	2000.6				T126L28(0-2.5) T62L28(2.5-16)		10	
V4.0	2001.1				T126(0-3.5) T62L28(3.5-16)			
V5.0	2004.3				T126L28(0-7.5) T62L28(7.5-16)			00,06,12, 18UTC
V6.0	2005.8		TSR		T126L28			
V7.0	2006.5	BV- ETR					14	
V8.0	2007.3						20	
V9.0	2010.2			STTP	T190L28			
V10.0	2012.2				T254L42 (0-8) T190L42 (8-16)			
V11.0	2015.12	EnKF (f06)			**T_L574L64 (0-8)** **T_L382L64 (8-16)**			

Introduction (5)

- An ensemble forecasting system should provide information on how much we can trust the forecast.
- This comes in the form of ensemble spread, which ideally would be close to the average error of the forecasts.
- Initial perturbed single modeling ensemble systems (e.g. NCEP and ECMWF) are generally over confident (under dispersion) on their forecasts

20-member GEFS forecast

Southern Hemisphere z500

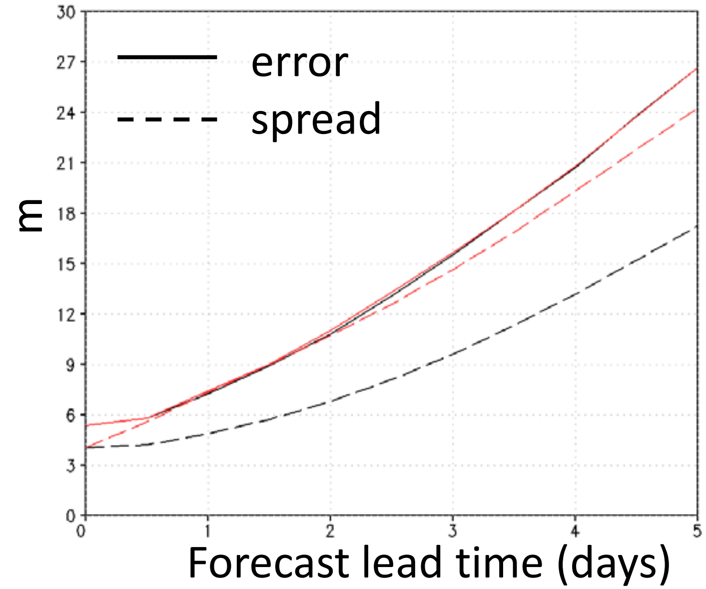


Introduction (5)

- An ensemble forecasting system should provide information on how much we can trust the forecast.
- This comes in the form of ensemble spread, which ideally would be close to the average error of the forecasts.
- Initial perturbed single modeling ensemble systems (e.g. NCEP and ECMWF) are generally over confident (under dispersion) on their forecasts
- Stochastic Physics could improve this relationship

20-member GEFS forecast

Southern Hemisphere z500



Stochastic Representation of Physical Uncertainty

$$T = D + (1+e)\sum_{i=1}^{N} P_i$$

Today

$$T = D + \sum_{i=1}^{N} (1+e_i) P_i$$

Future

$$T = D + \sum_{i=1}^{N} P_i(r_j(1+e_{i,j}), j=1,m)$$

T – total tendency

D – dynamical tendency

P – physical tendency

e – random pattern (4-d)

r – physical parameter

Major physical schemes:

- Convection (shallow and deep)
- Clouds
- Radiation
- Gravity wave drag
- PBL
- Land-surface
- Others ?

Model uncertainty in the operational GEFS

- Stochastic Total Tendency Perturbations (STTP)

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

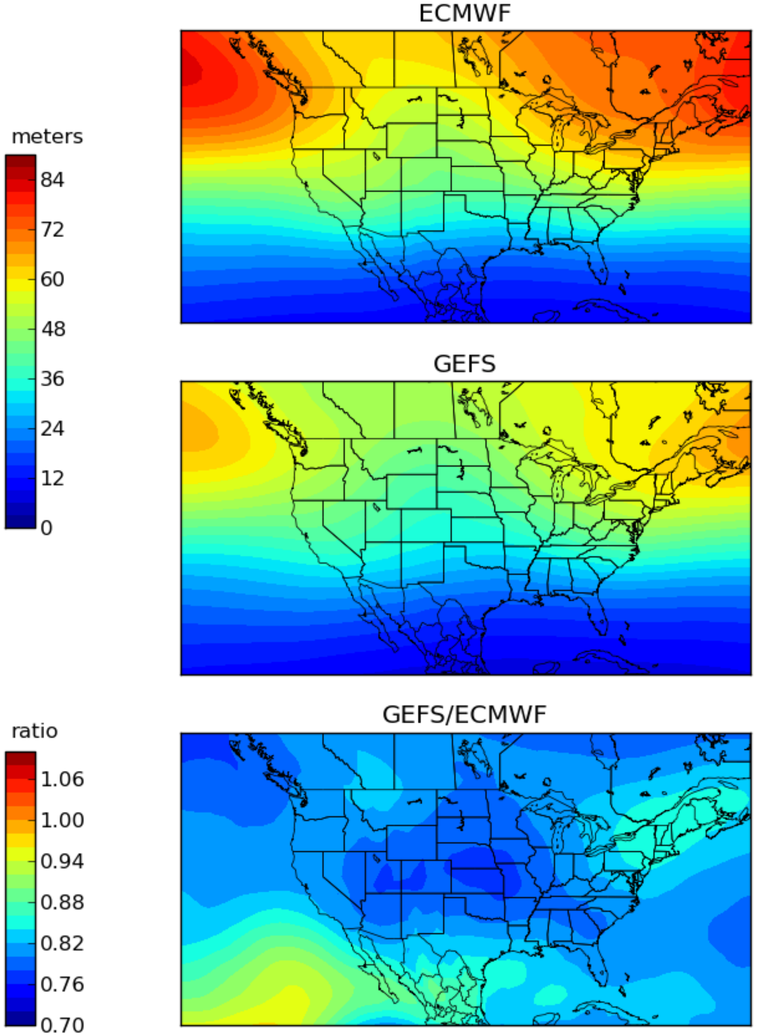
6-hr tendency **Rescaling factor** **Evolving combination matrix**

  – 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*
  – *STTP has less impact to tropical area*

Changes of NCEP Ensemble Spread (STTP)

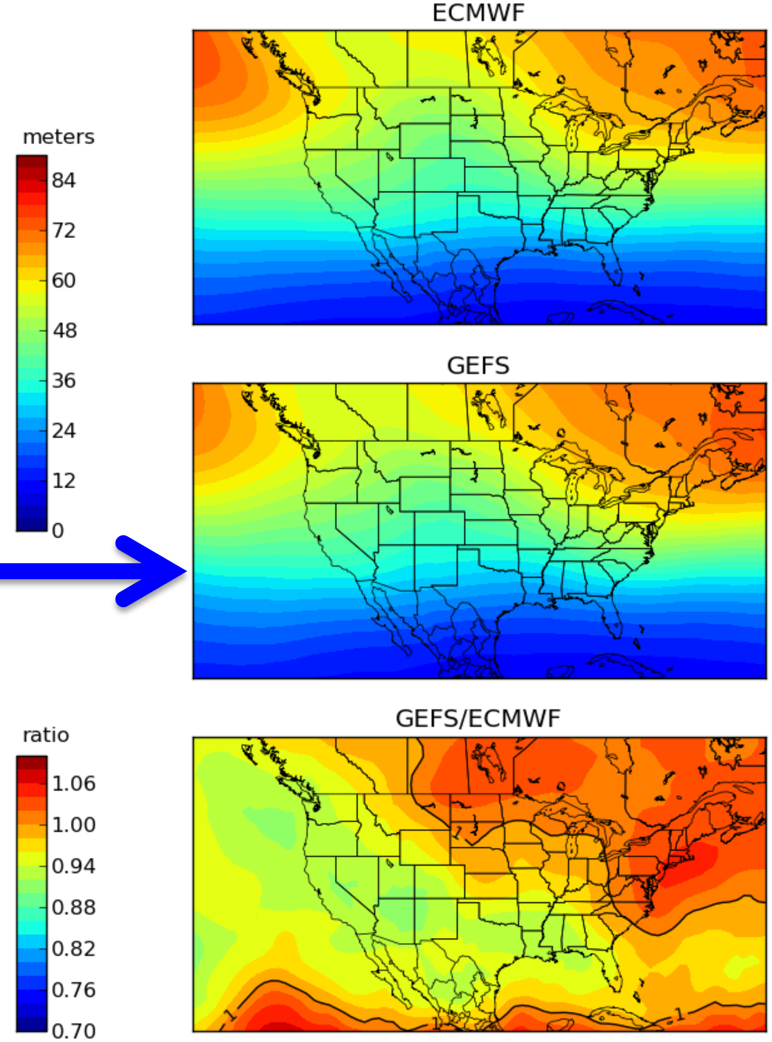
Then

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)

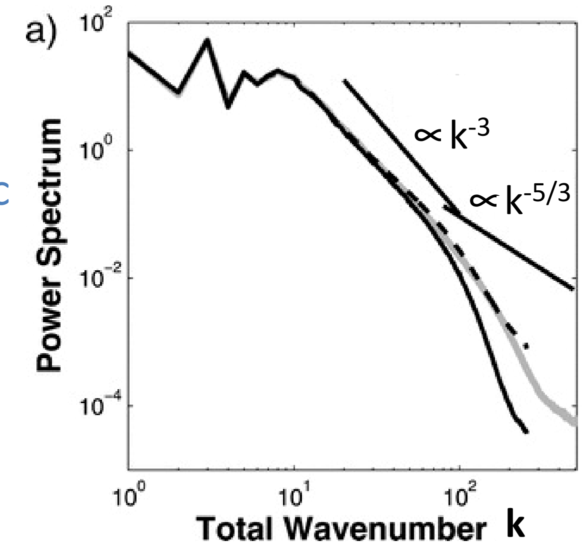


Courtesy of Dr. Alcott Trevor

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 has been tested for current operational GEFS (spectrum model) with positive response – plan to replace STTP for next implementation*

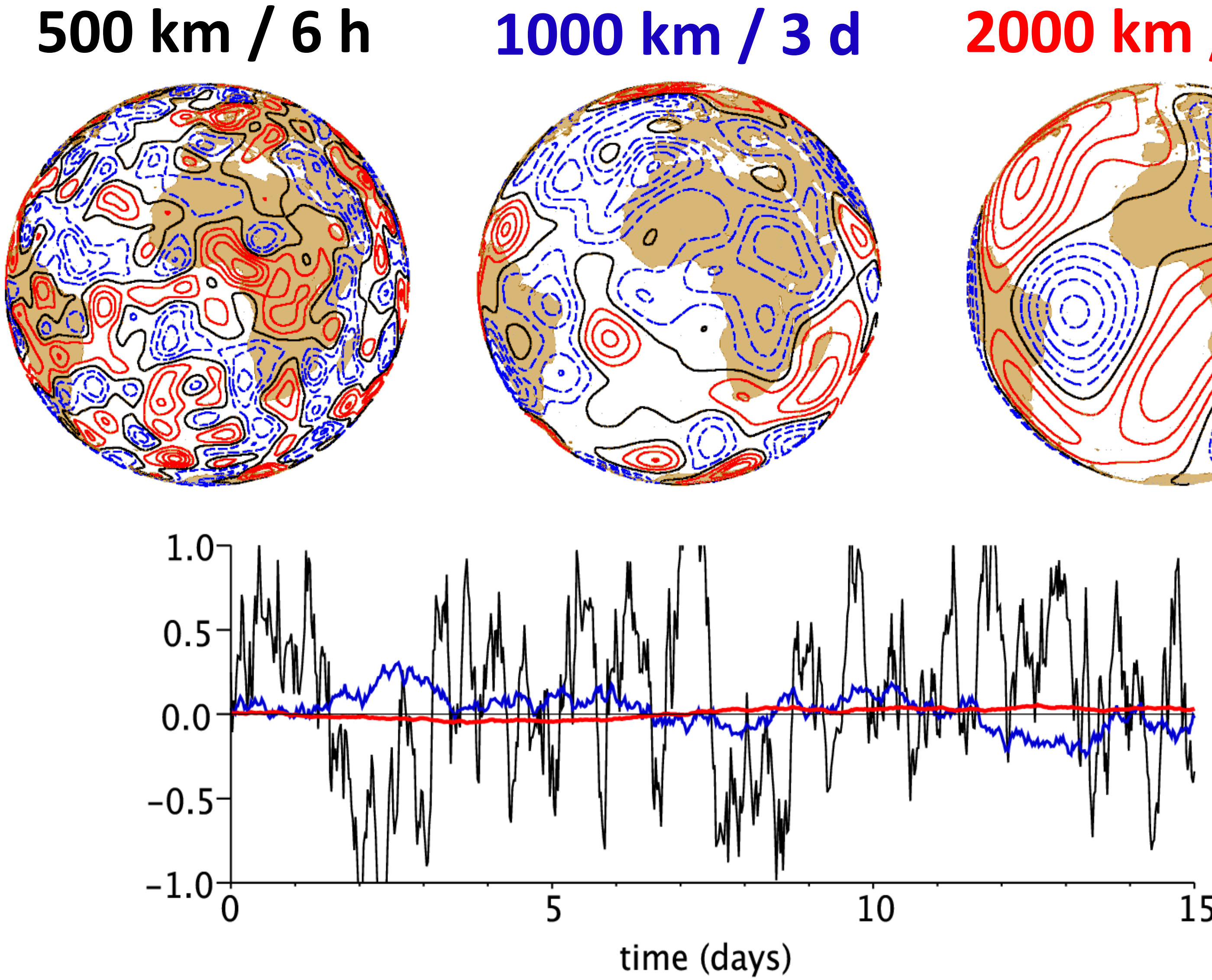
Kinetic Energy Spectrum



Berner et al. (2009)

See next slide for the example of random pattern

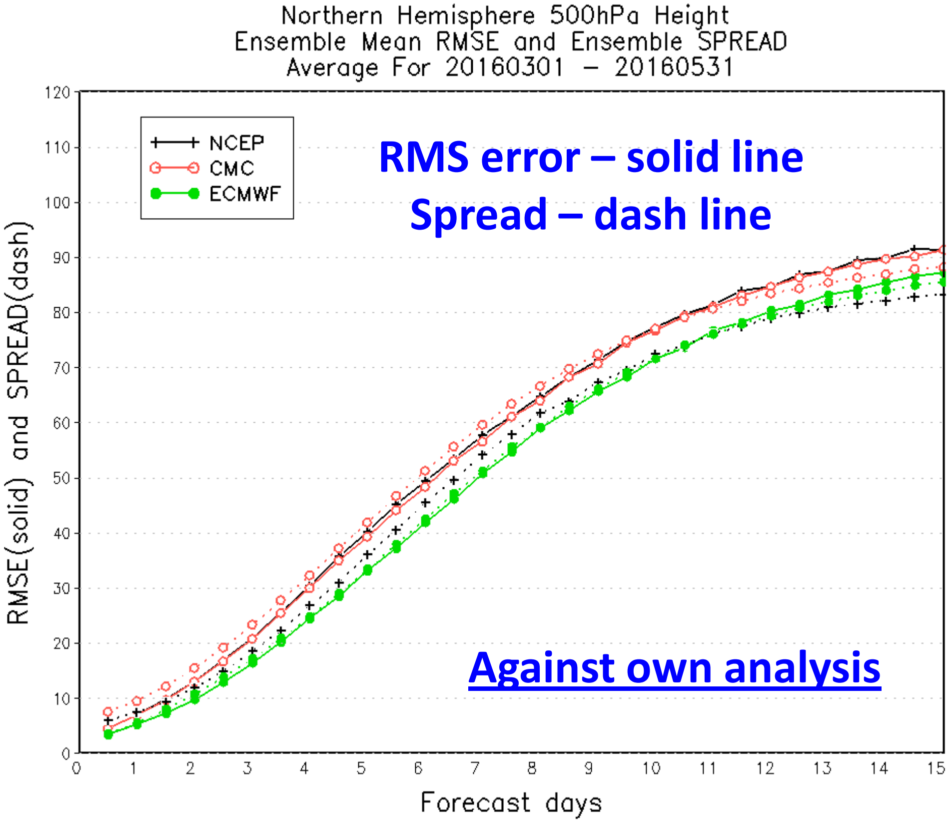
Examples of stochastic patterns



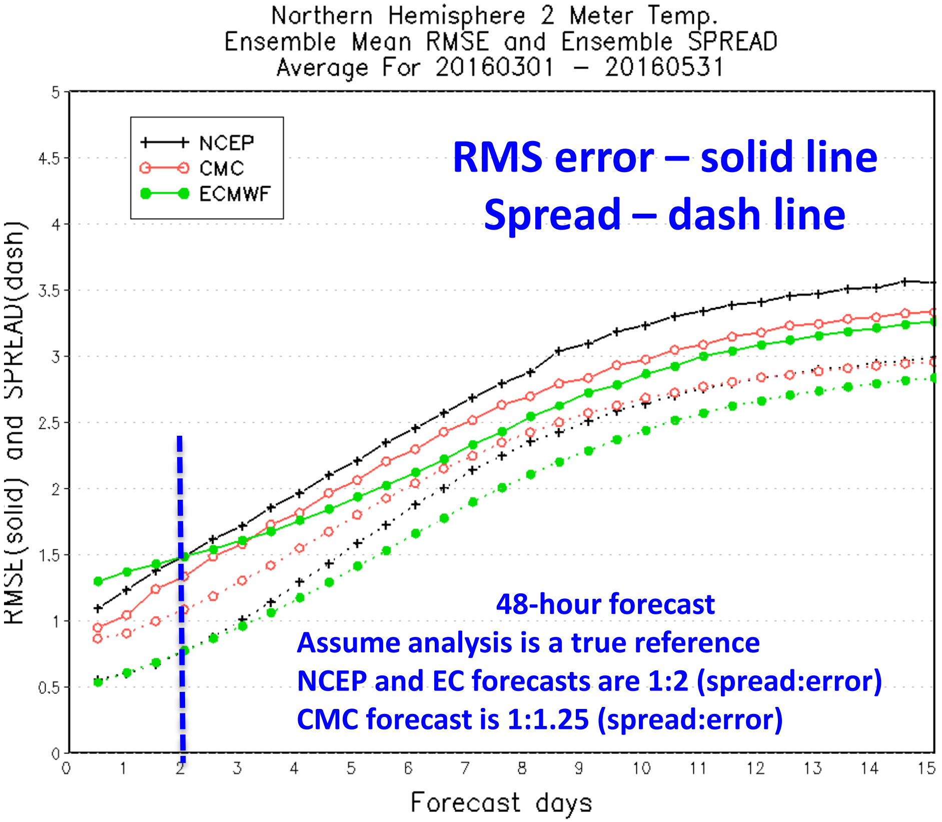
(adapted from M. Leutbecher)

Current Status of Global Ensembles

Spring 2016 – NH 500hPa height



Spring 2016 – NH 2-m temperature



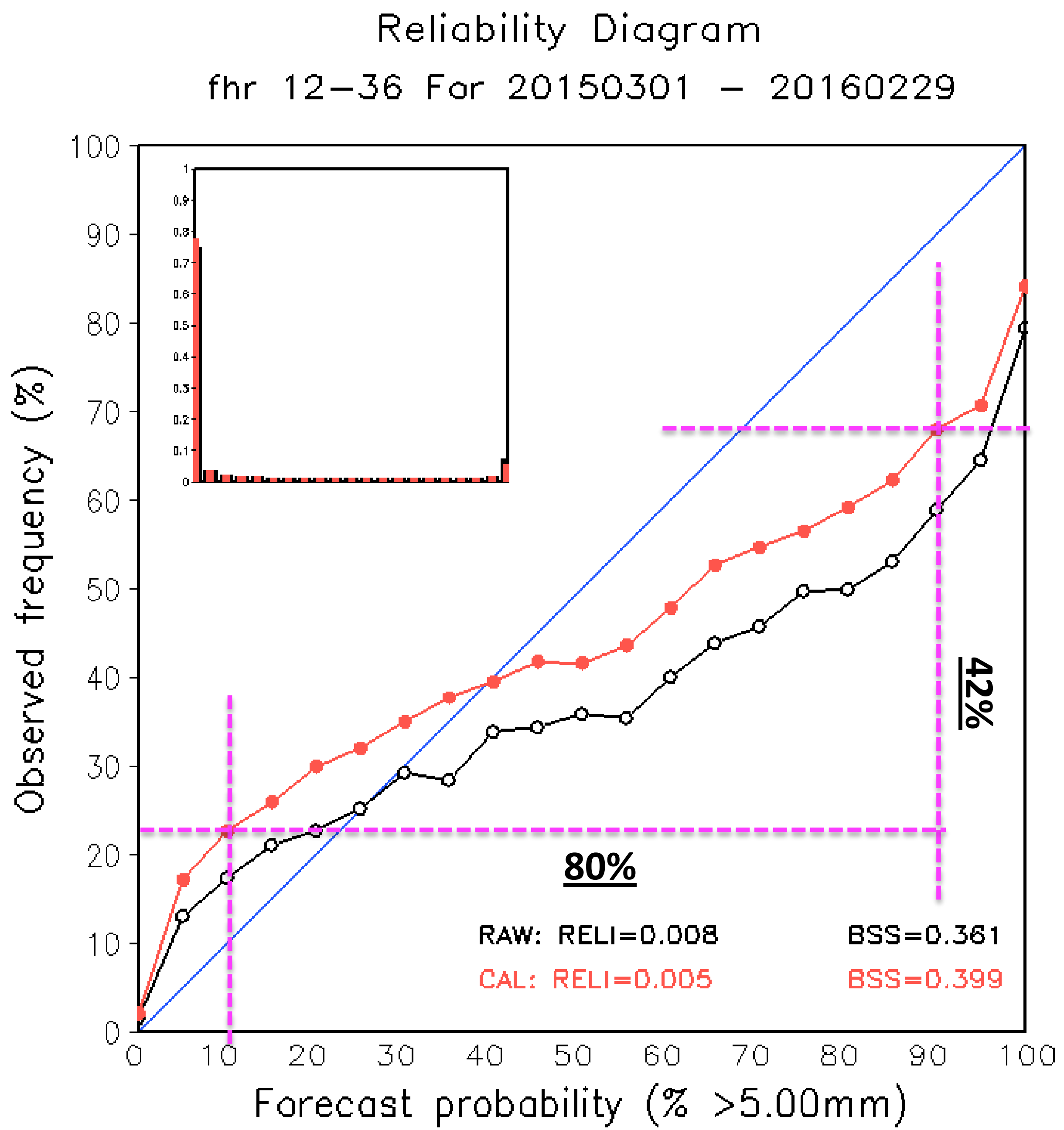
Upper atmosphere:

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

Surface elements:

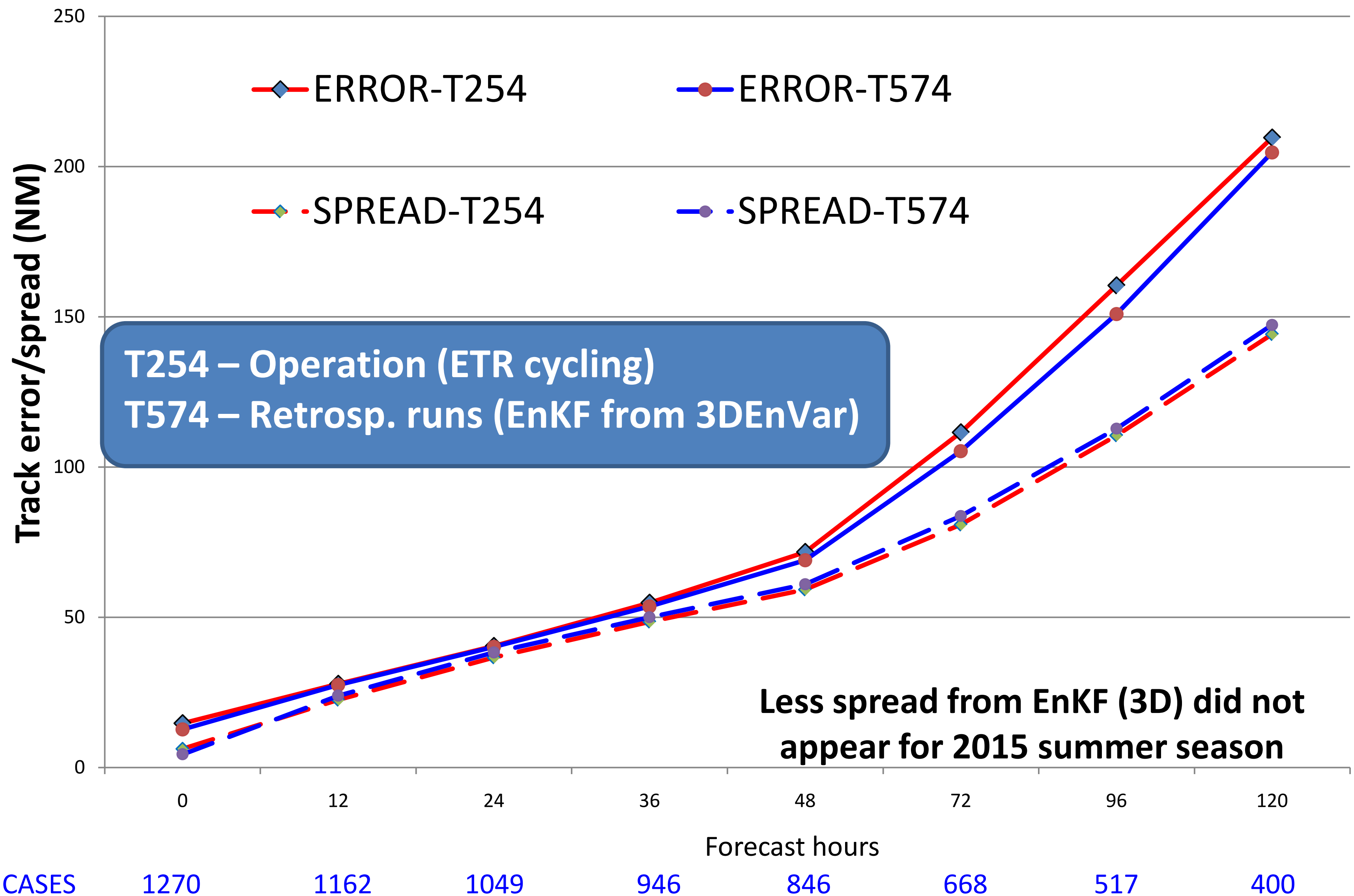
- Does not apply stochastic schemes
- All ensemble forecasts have more/less under dispersion (over confident)

Precipitation Forecast (1 year; 12-36hr; >5mm/24hr)



Spread-Error relationship

2015 TC track AL/CP/EP/WP

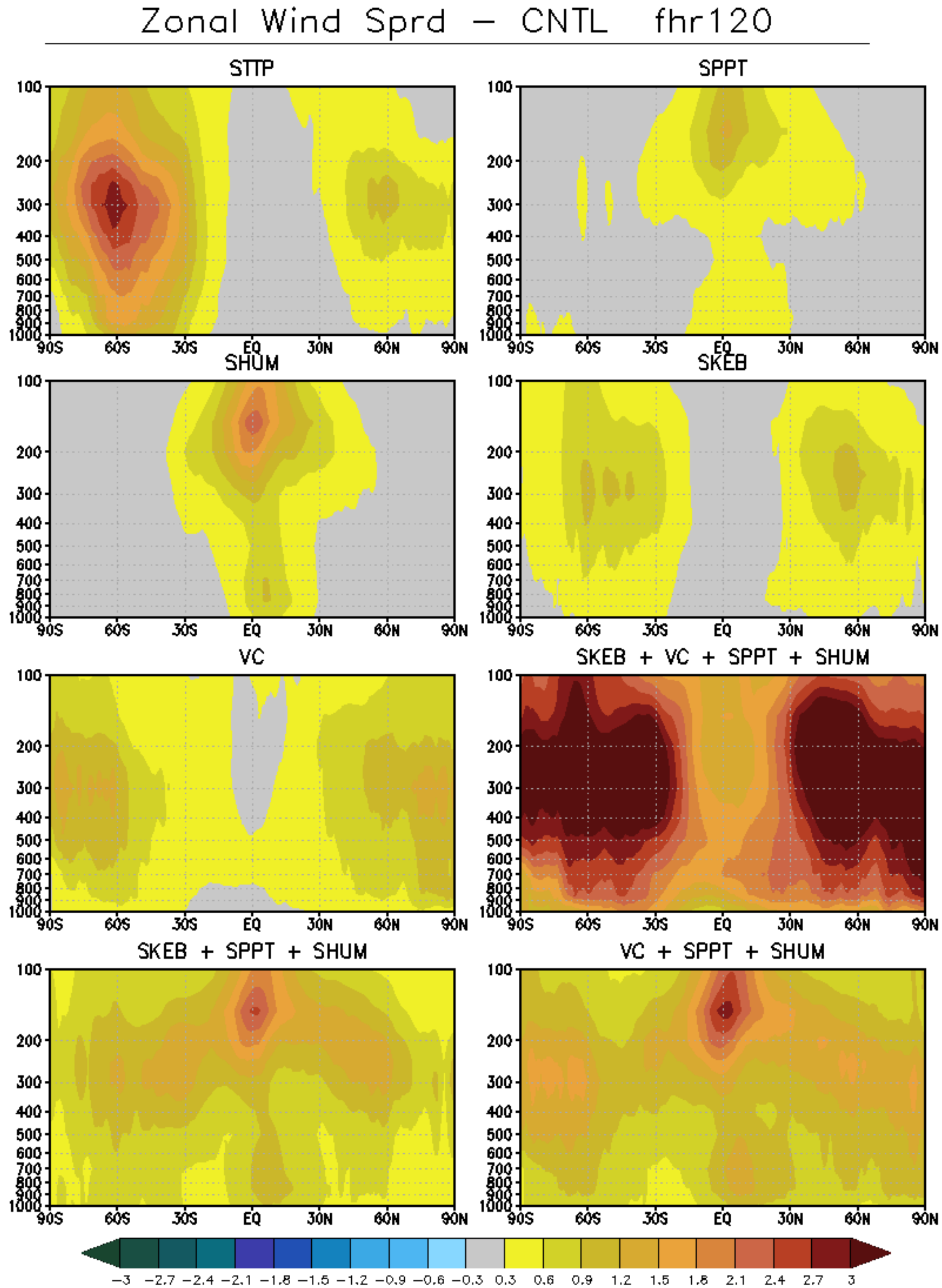


Stochastic Schemes for Atmosphere
- Testing for GEFS

- **Stochastic Kinetic Energy Backscatter (SKEB)**
  - Represents process absent from model
  - Stream function is randomly perturbed to represent upscale kinetic energy transfer (Berner et al., 2009)

- **Stochastic Perturbed Physics Tendencies (SPPT)** – (ECWMF tech memo 598)
  - Designed to represent the structural uncertainty (or random errors) of parameterized physics
  - Multiplicative noise used to perturb the total parameterized tendencies (Palmer et al., 2009)
  - Biggest impact on tropic

- **Stochastically-perturbed boundary layer HUMidity (SHUM)**
  - The same formula as SPPT
  - Designed to represent influence of sub-grid scale humidity variability on the the triggering of convection (Tompkins and Berner 2008)
  - Biggest impact on tropic



Characteristics of one summer month test

STTP → strong at winter hemisphere

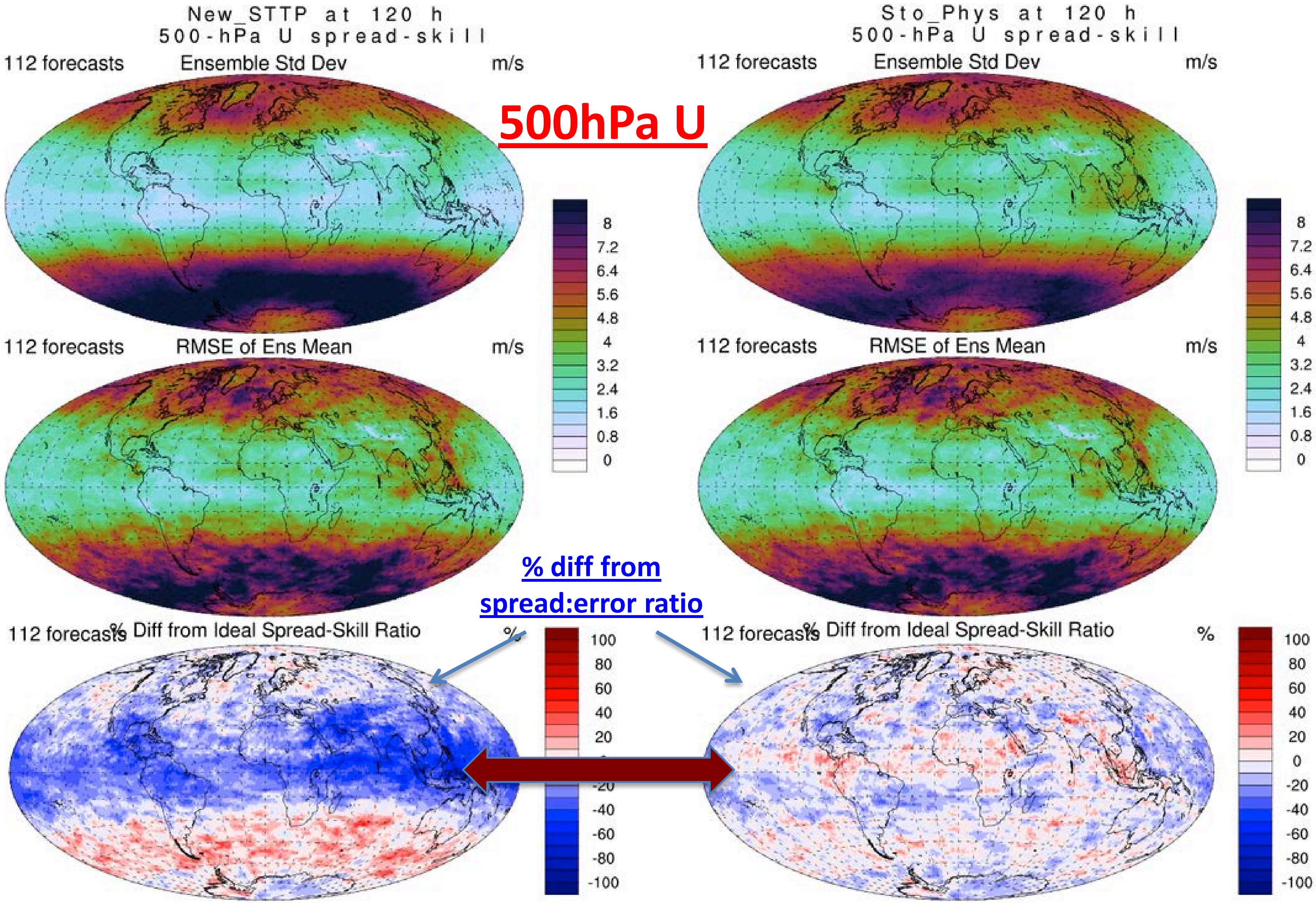
SKEB → similar to STTP, but for large scale

SPPT → big impact is tropical, not mid-latitude

SHUM – big impact is tropical, duplicate to SPPT

VC – big impact is high latitude

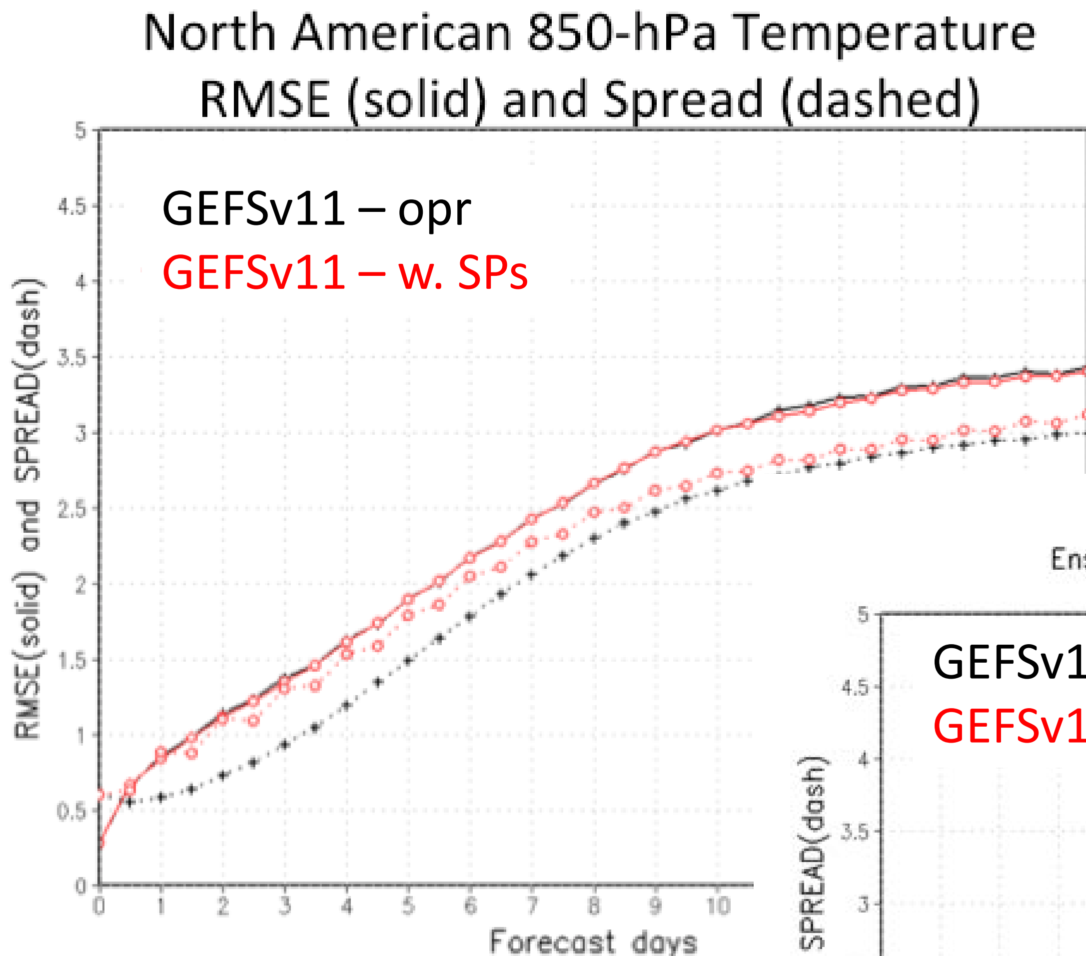
Change of ensemble spread from introducing new stochastic physics

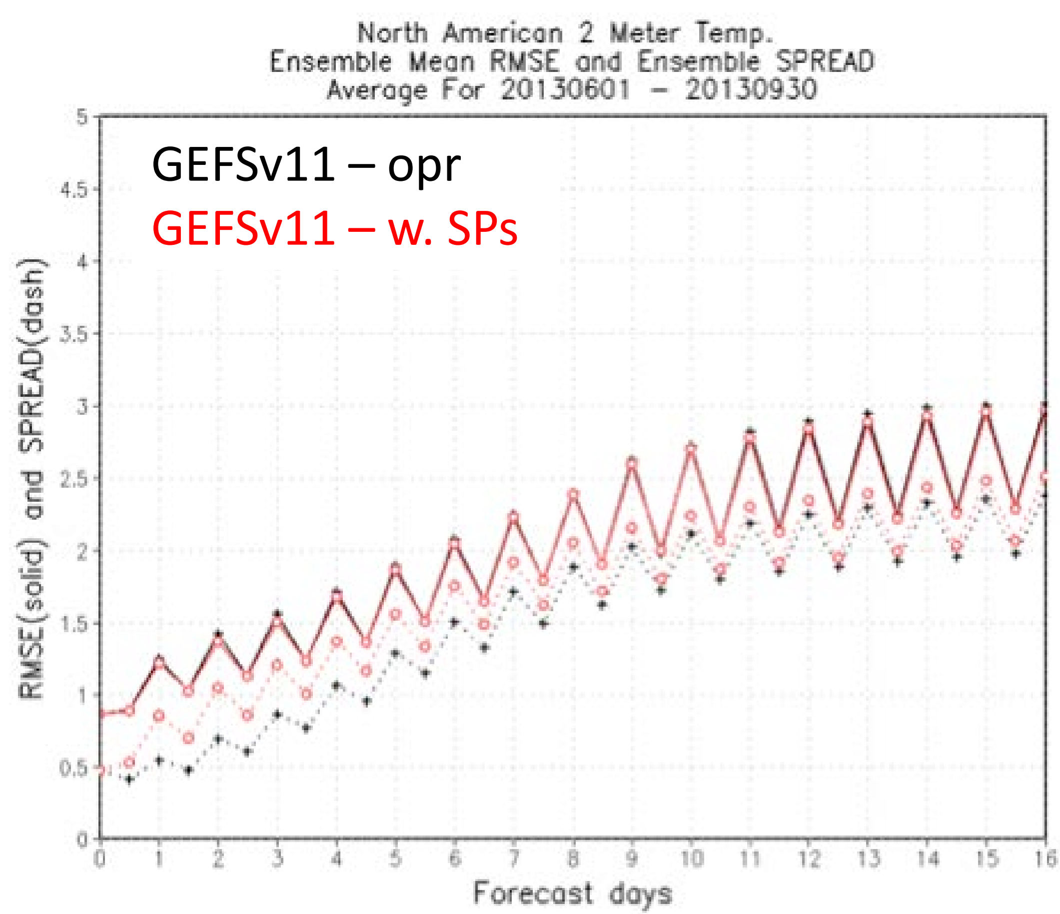


V11 (STTP)

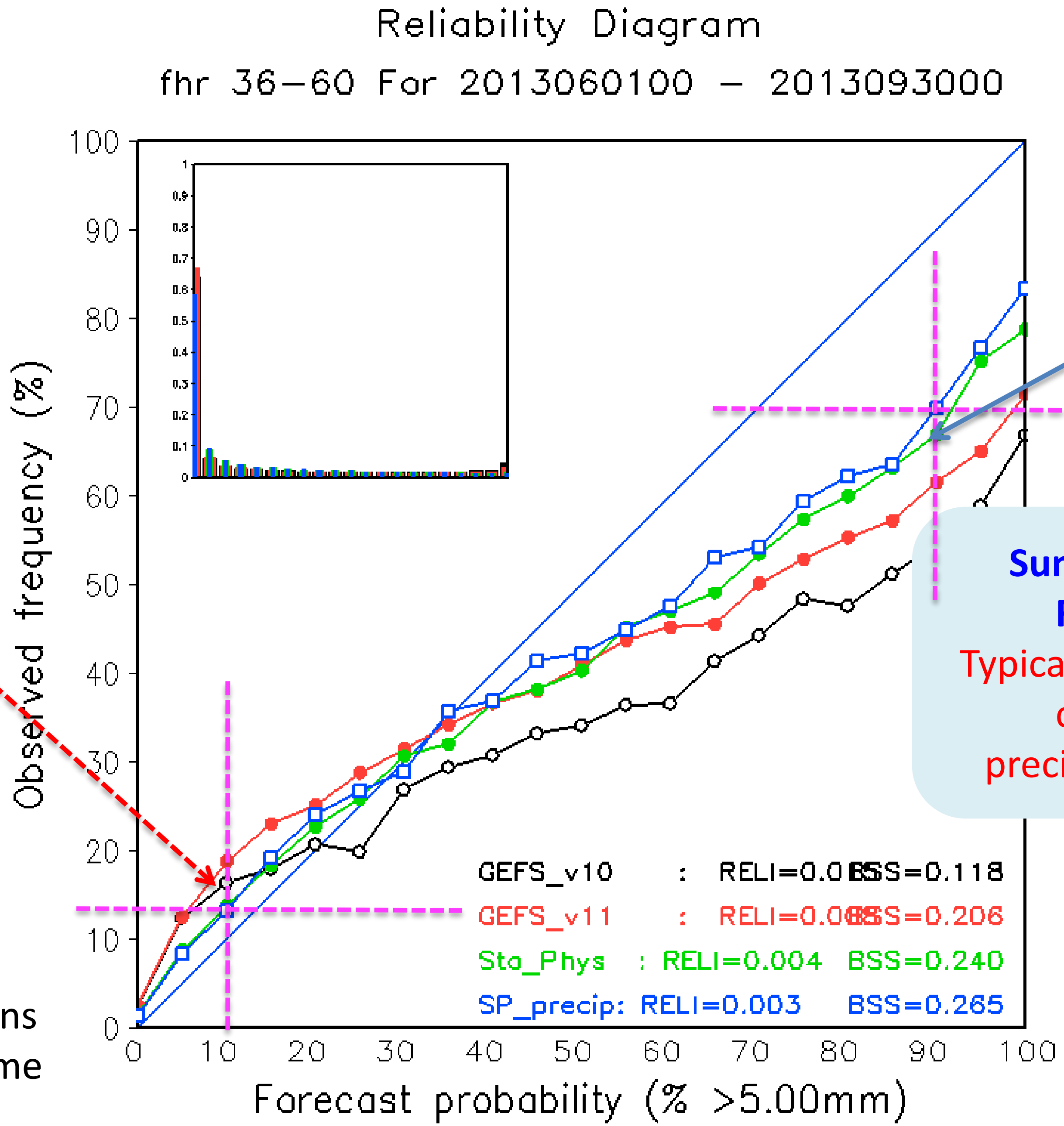
V11 (with new stochastic)

Impact to temperature





<u>10% <-> 14%</u>

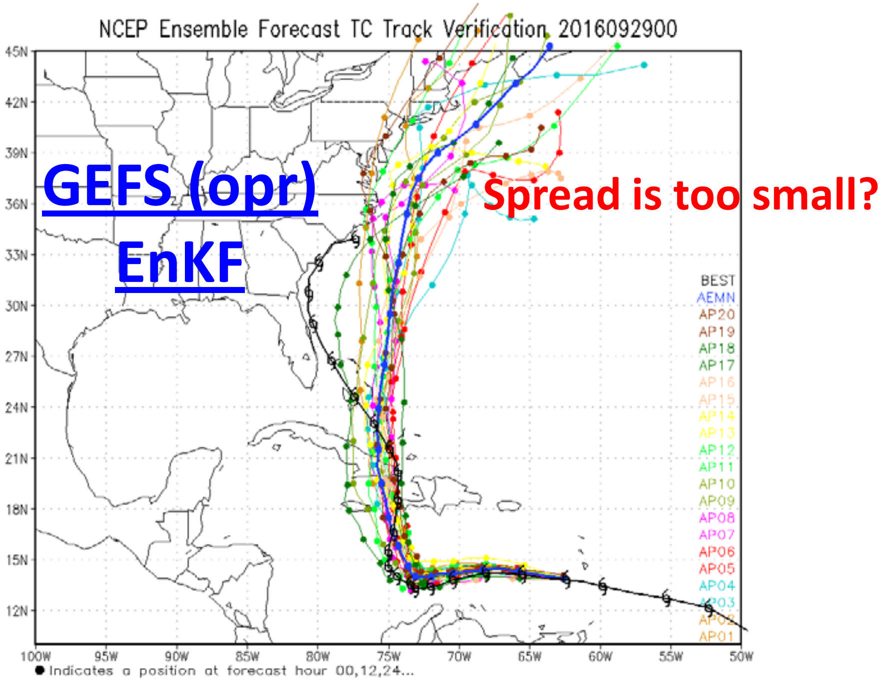


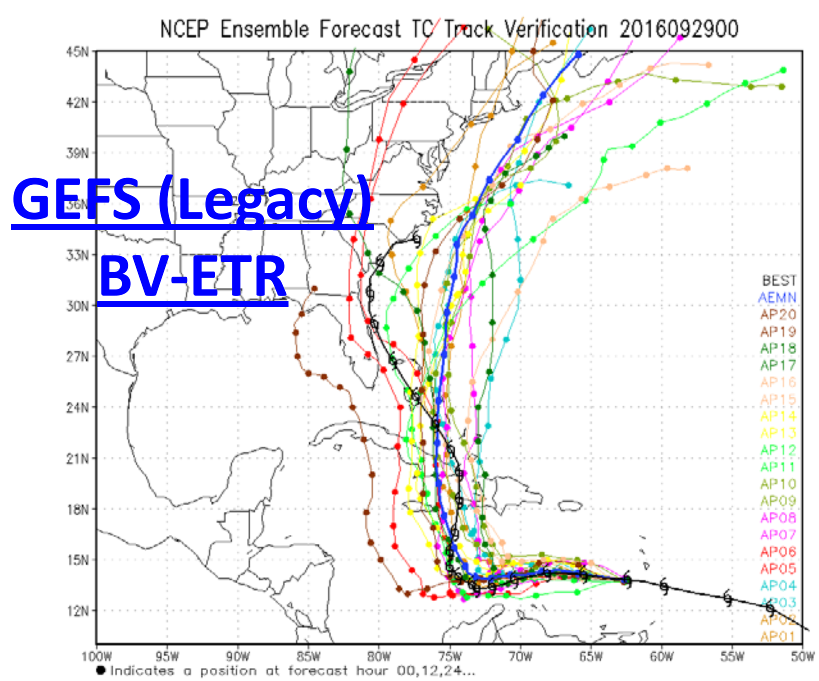
<u>90% <-> 70%</u>

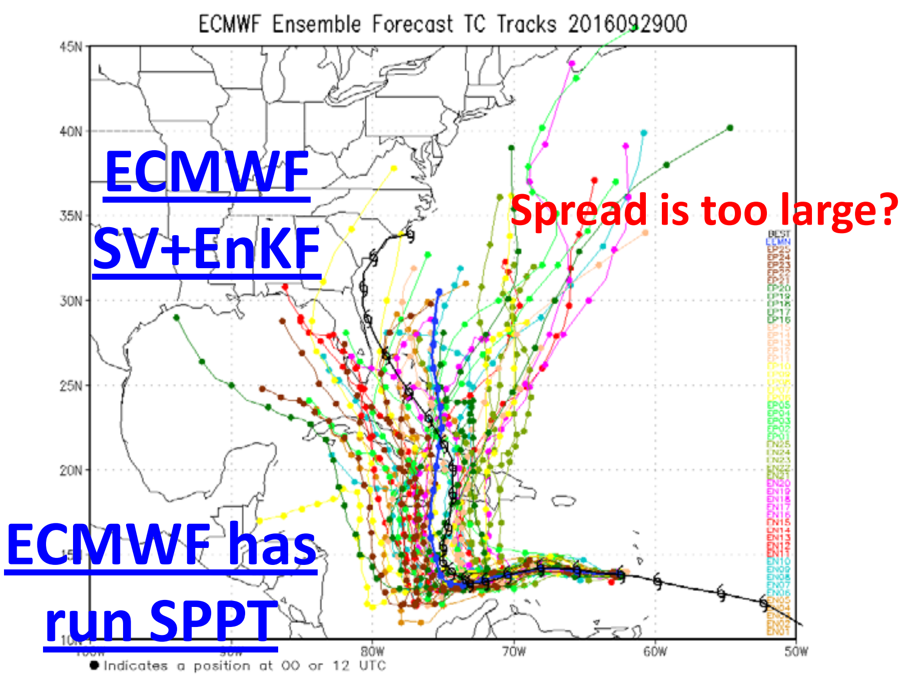
Summer-Fall 2013
Four months
Typical example of over-confident for precipitation forecast

e.g. when we predict 10% chance of 5+ mm, it happens 13% of the time

Precipitation reliability for 36-60hr and greater than 5mm/day







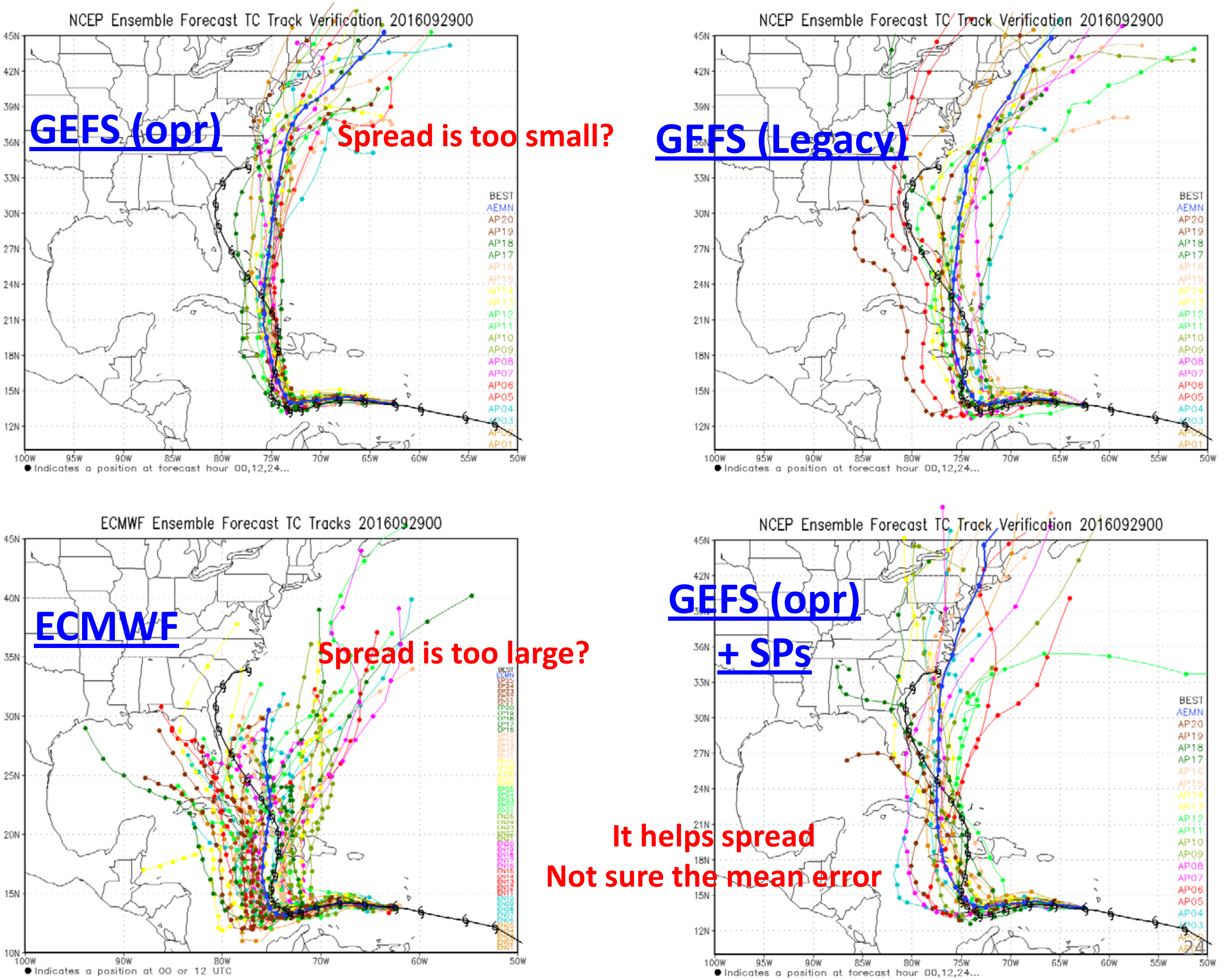
Hurricane Matthew

Initial: 2016092900

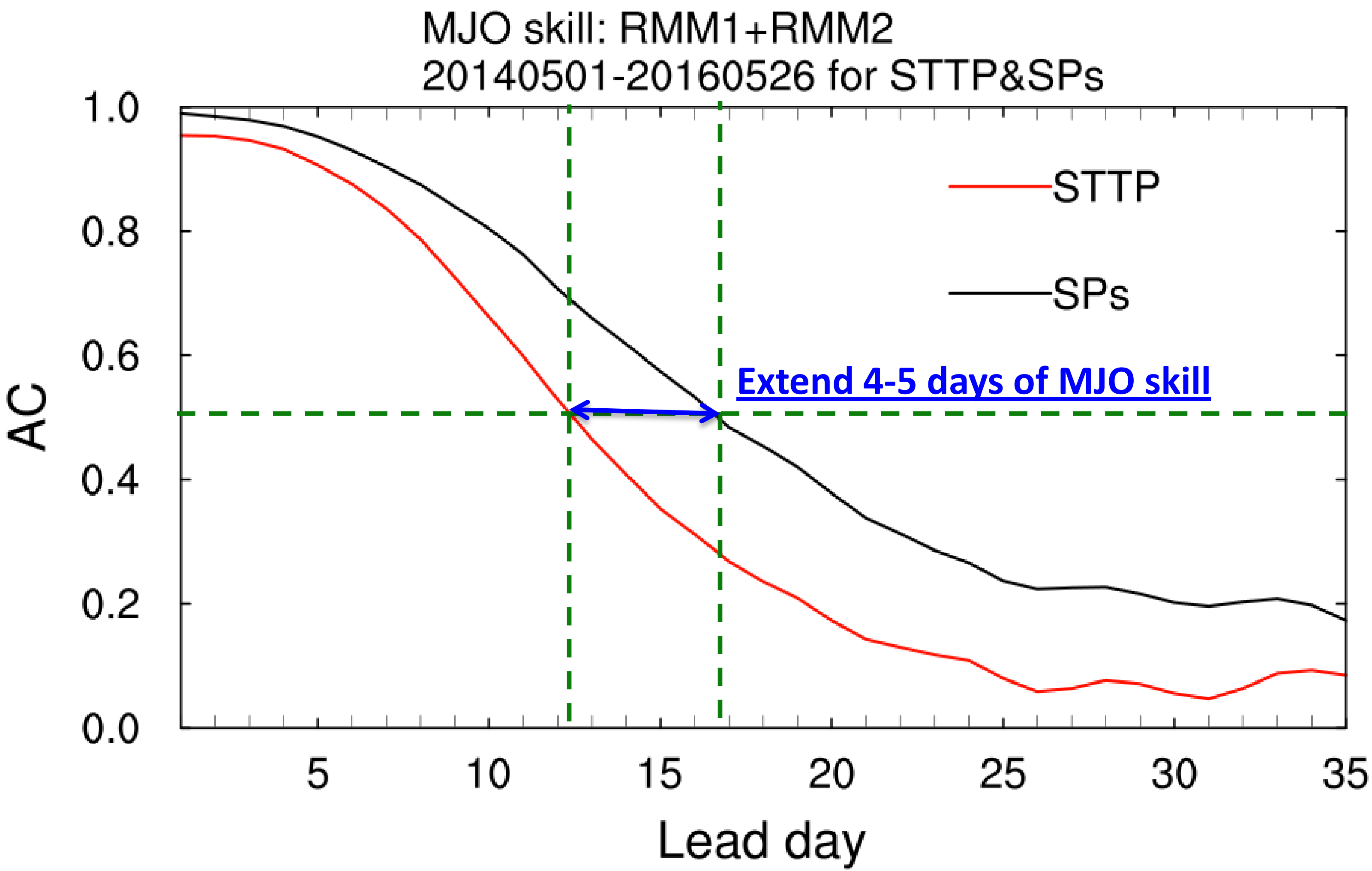
Top left – GEFS operation forecast (V11)

Top right – GEFS legacy forecast (V10)

Bottom left – ECMWF forecast


NCEP Ensemble Forecast TC Track Verification 2016092900
GEFS (opr)
Spread is too small?
NCEP Ensemble Forecast TC Track Verification 2016092900
GEFS (Legacy)
ECMWF Ensemble Forecast TC Tracks 2016092900
ECMWF
Spread is too large?
NCEP Ensemble Forecast TC Track Verification 2016092900
GEFS (opr)
+ SPs
It helps spread
Not sure the mean error
● Indicates a position at forecast hour 00,12,24...
● Indicates a position at 00 or 12 UTC

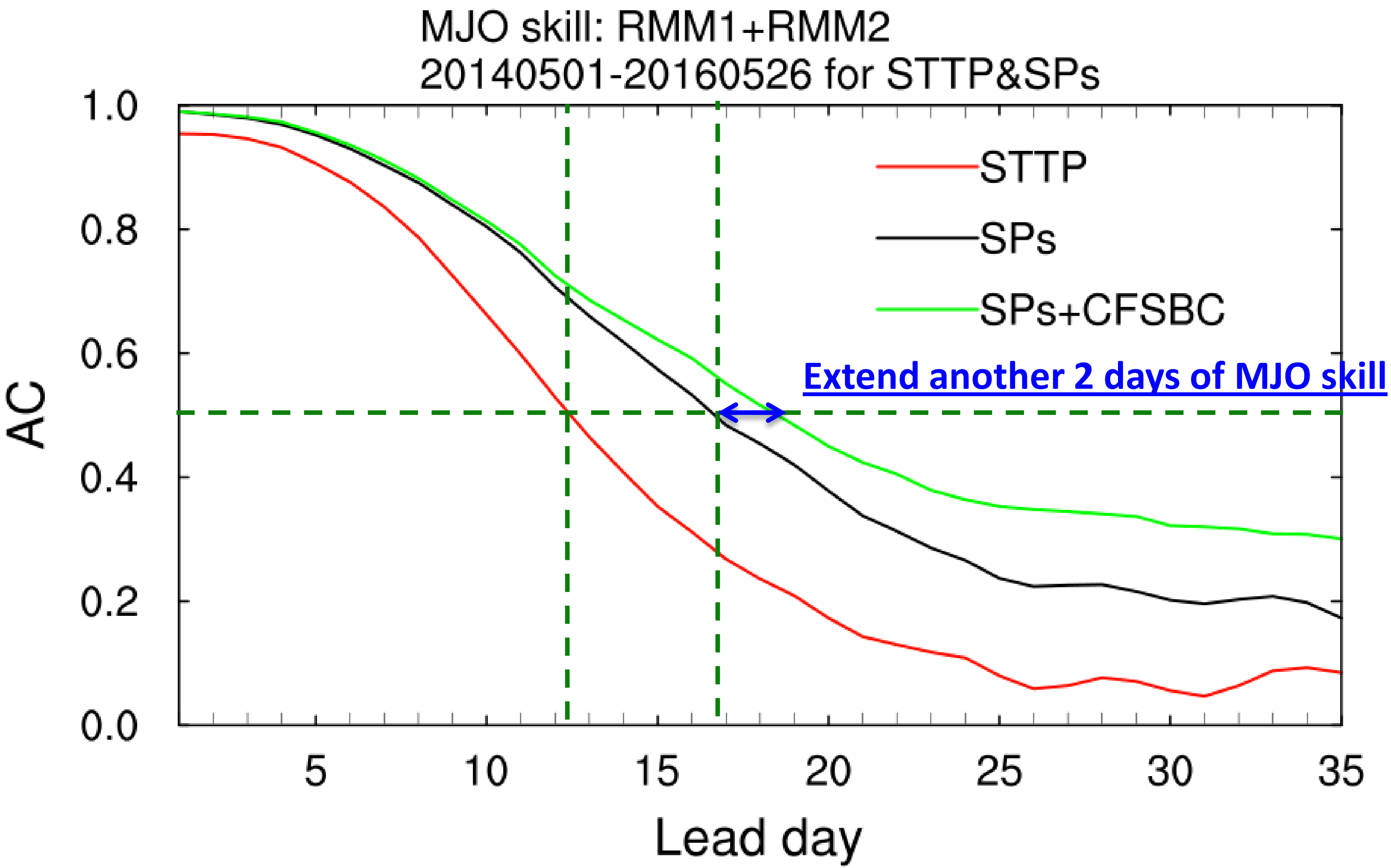
GEFS week 3&4 forecasts (un-coupled)



Period: May 2014 – May 2016

Higher resolution (~50km) for week 3&4 with different SPs

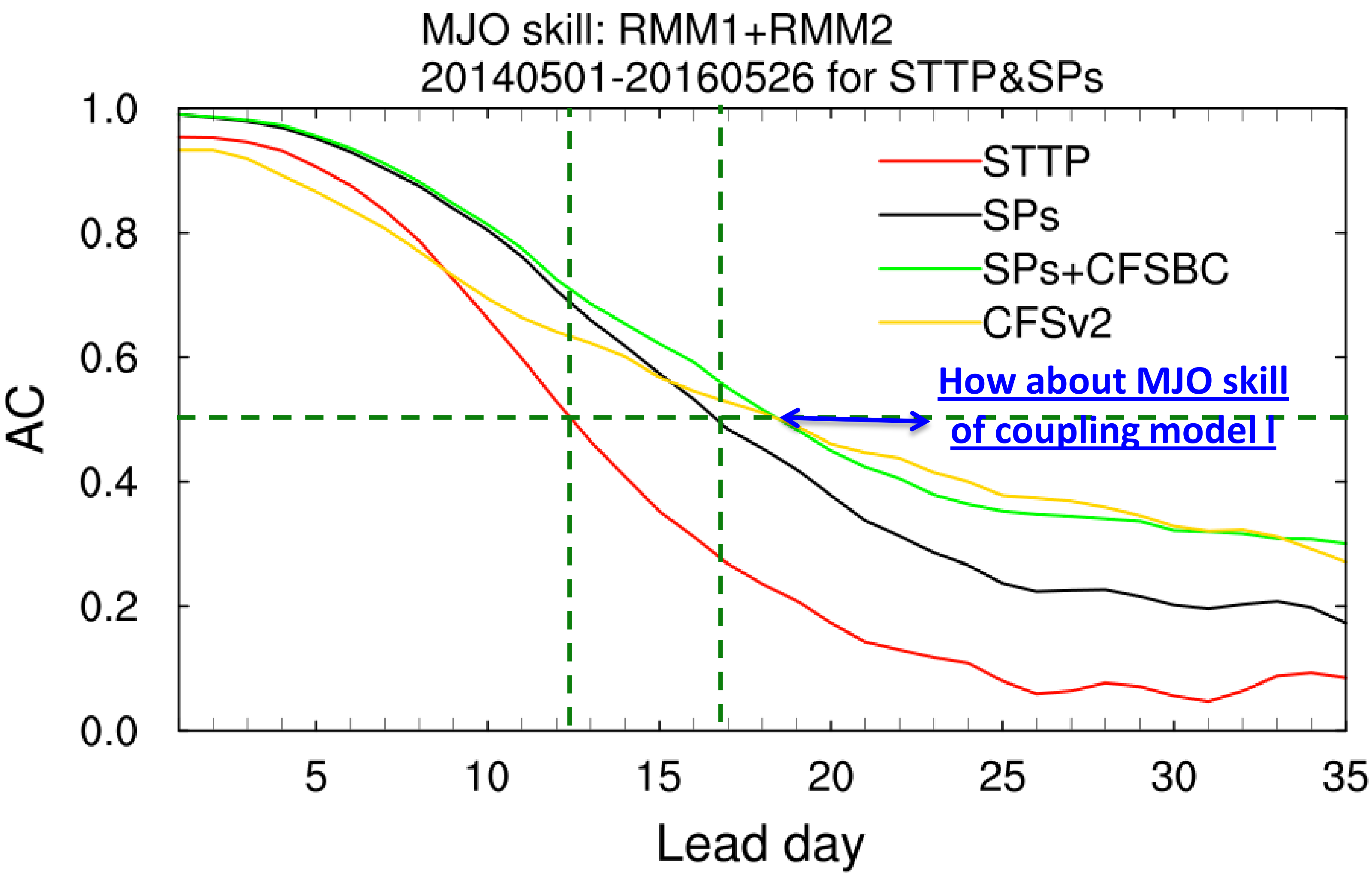
GEFS week 3&4 forecasts (un-coupled)



Period: May 2014 – May 2016

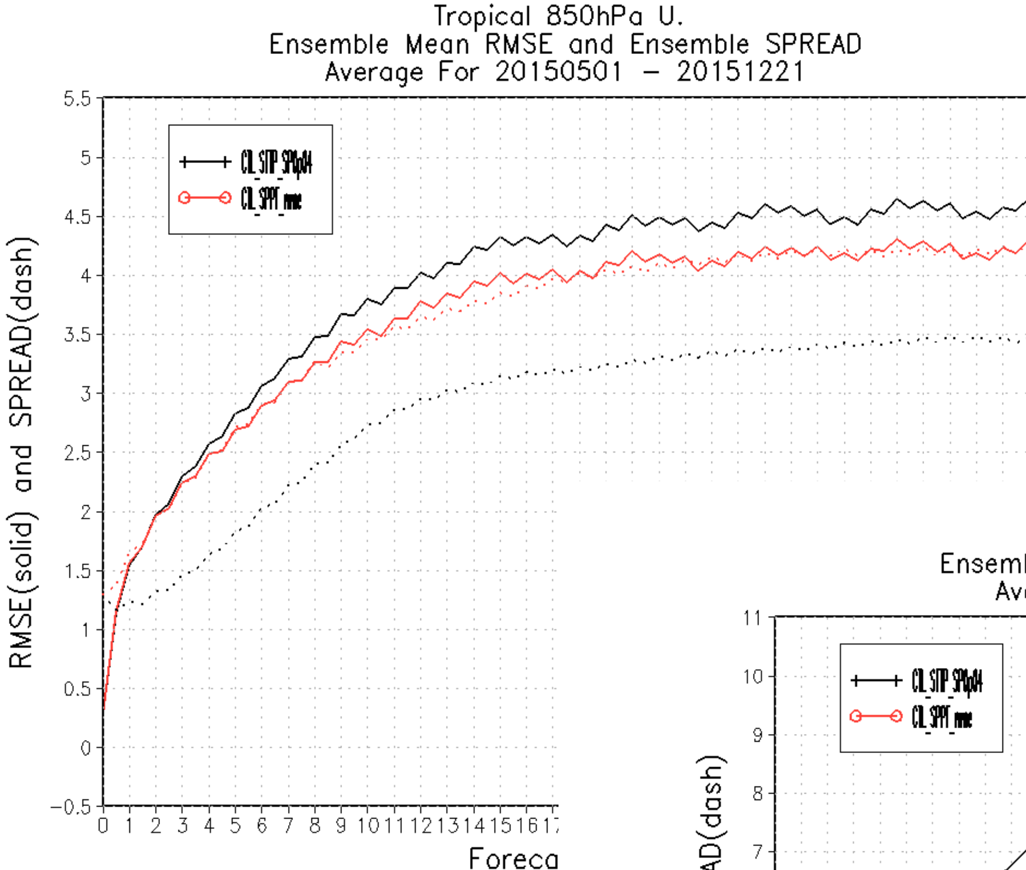
Higher resolution (~50km) for week 3&4 with different SPs

GEFS week 3&4 forecasts (un-coupled)

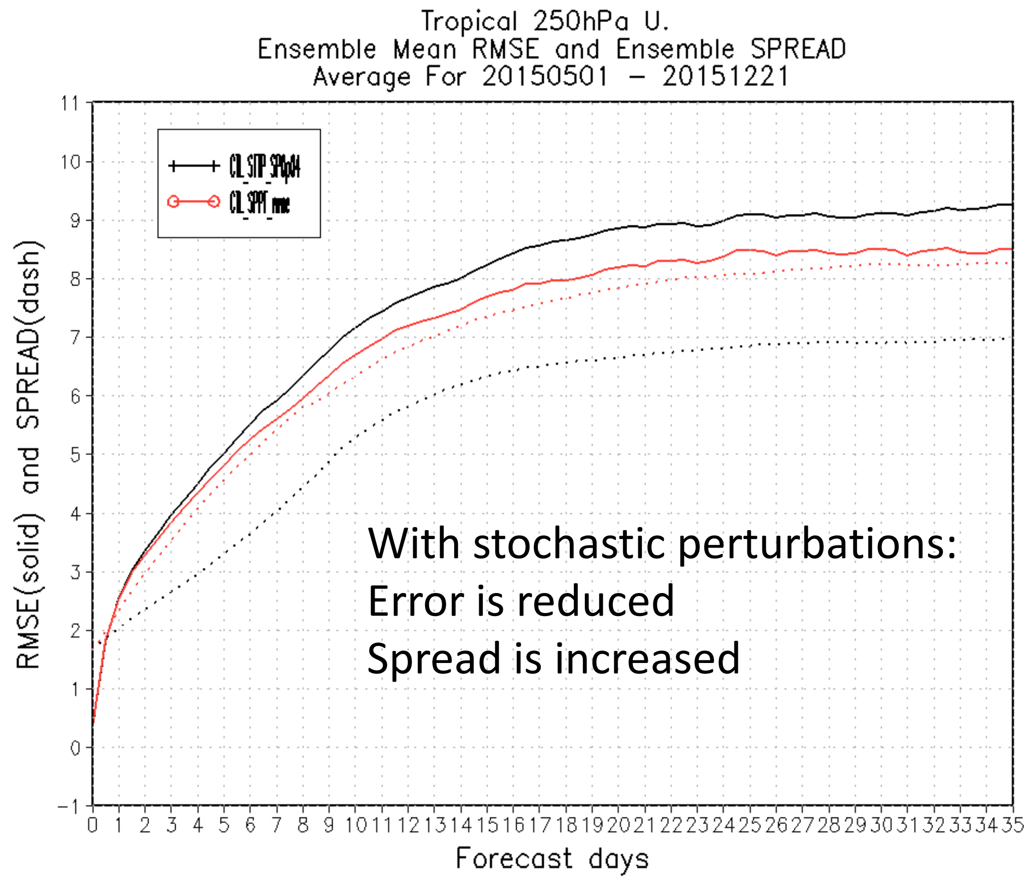


Period: May 2014 – May 2016

Higher resolution (~50km) for week 3&4 with different SPs



850hPa tropical zonal wind



With stochastic perturbations:
Error is reduced
Spread is increased

250hPa tropical zonal wind

New Stochastic Schemes for Land

Under development – test uncertainties for land model

- **Stochastic Perturbed Tendencies of Land (SPTL) - EMC**
  - Designed to represent the uncertainty (and/or random errors) of land surface parameterization
  - Perturbed soil temperature/moisture directly
- **Perturb parameters of land model – PSD/ESRL**
  - Roughness, surface albedo and soil hydraulic conductivity
- **Initial perturbations of soil temperature/moisture – PSD/ESRL**
  - EOF analysis of the difference of NOAH and climate

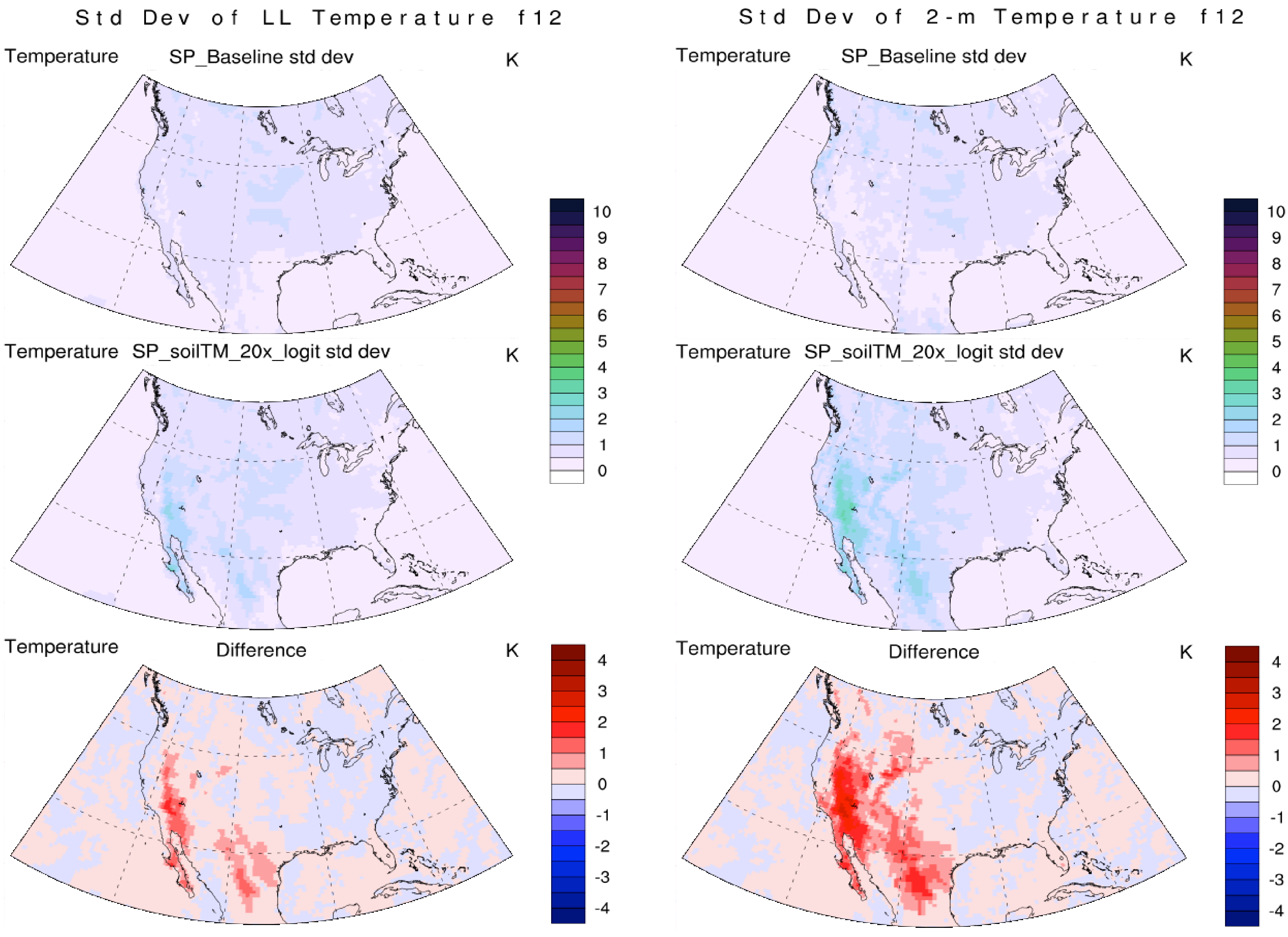
EMC's investigations

- Early investigation – GEFSv9
  - EMC visitor from CMA (Dr. Deng) in 2010
  - Initial Soil temperature/soil moisture perturbations
  - Deng, G., Y. Zhou, L. Zhong, Y. Zhu, R. Wobus, M. Wei, 2012: *"Effect of Initial Perturbation of Land Surface Processed on Tropical Cyclone Forecast"* Journal of Tropical Meteorology, Vol. 18, No. 4, 412-421
  - Deng, G., Y. Zhu, J. Gong, D. Chen, R. Wobus and Z. Zhang, 2016: *"The Effects of Land Surface Process Perturbations in a Global Ensemble Forecast System"* Advances in Atmospheric Science Vol. 33, 1199-1208

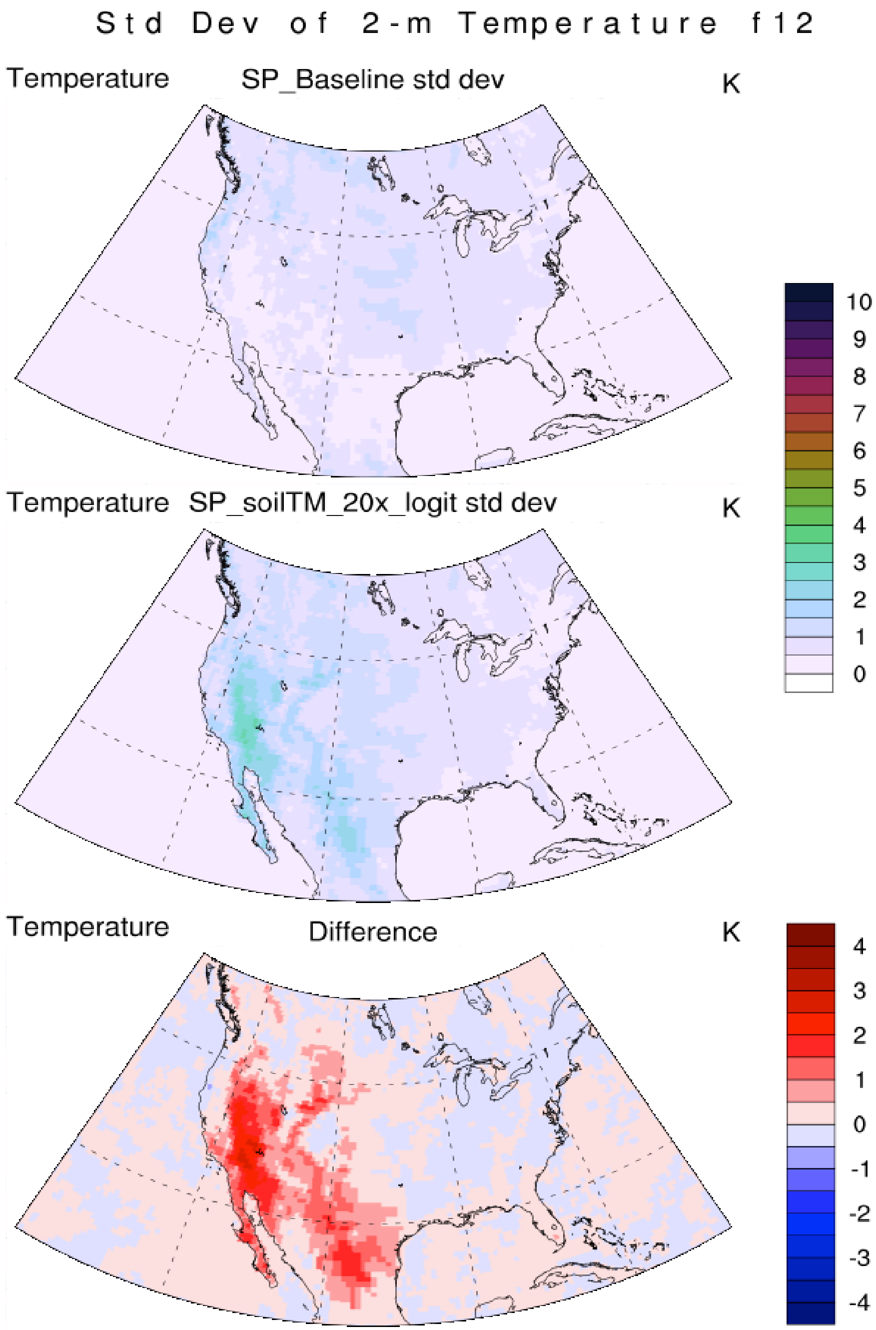
- Current investigation – based on GEFSv11
  - Not initial perturbations, but stochastic physics perturbations.
  - The same stochastic pattern as SPPT
  - Soil temperature – all four layers (1^{st} try)
  - Both soil temperature/moisture

Model Lower Level Temperature

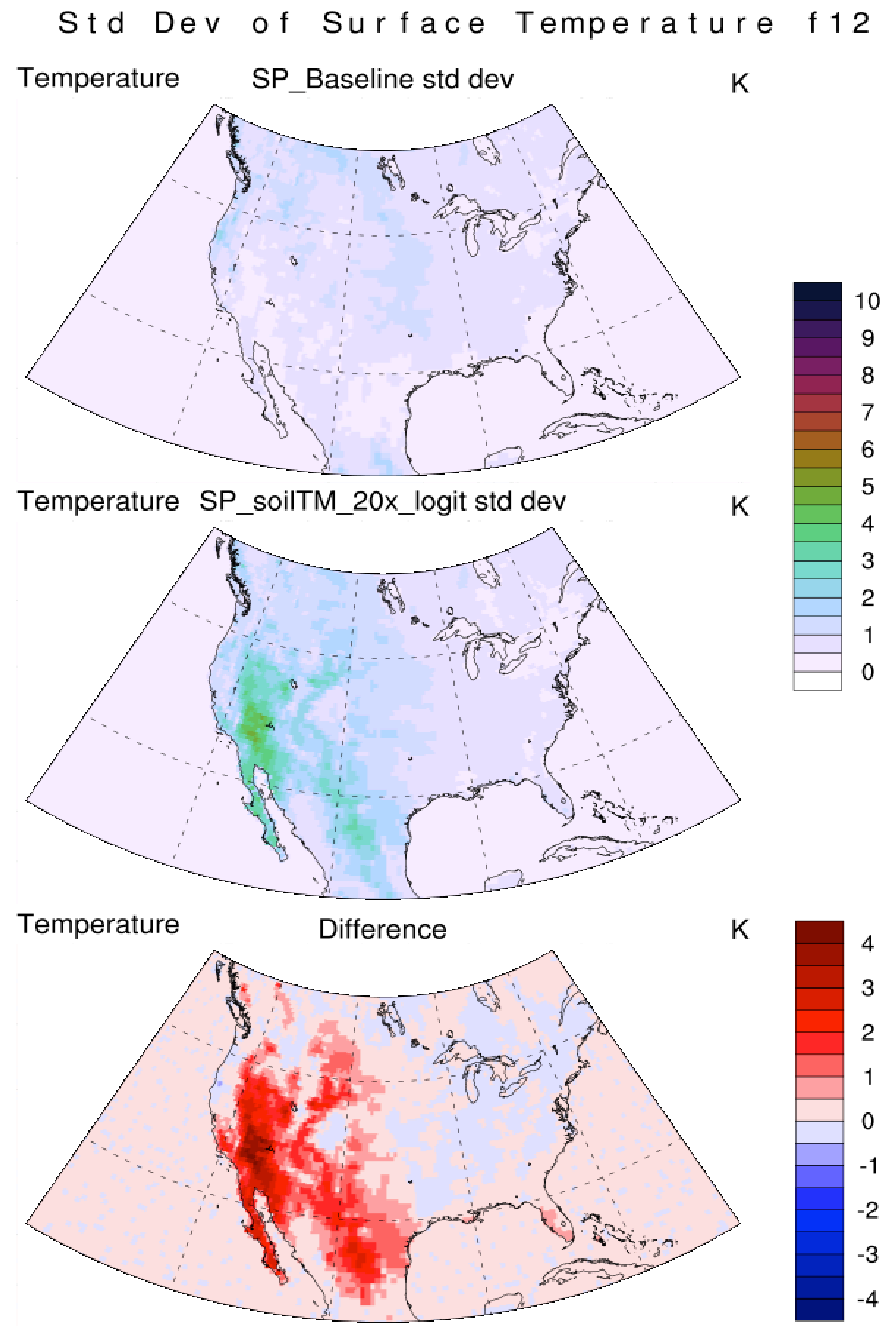
2 Meter Temperature

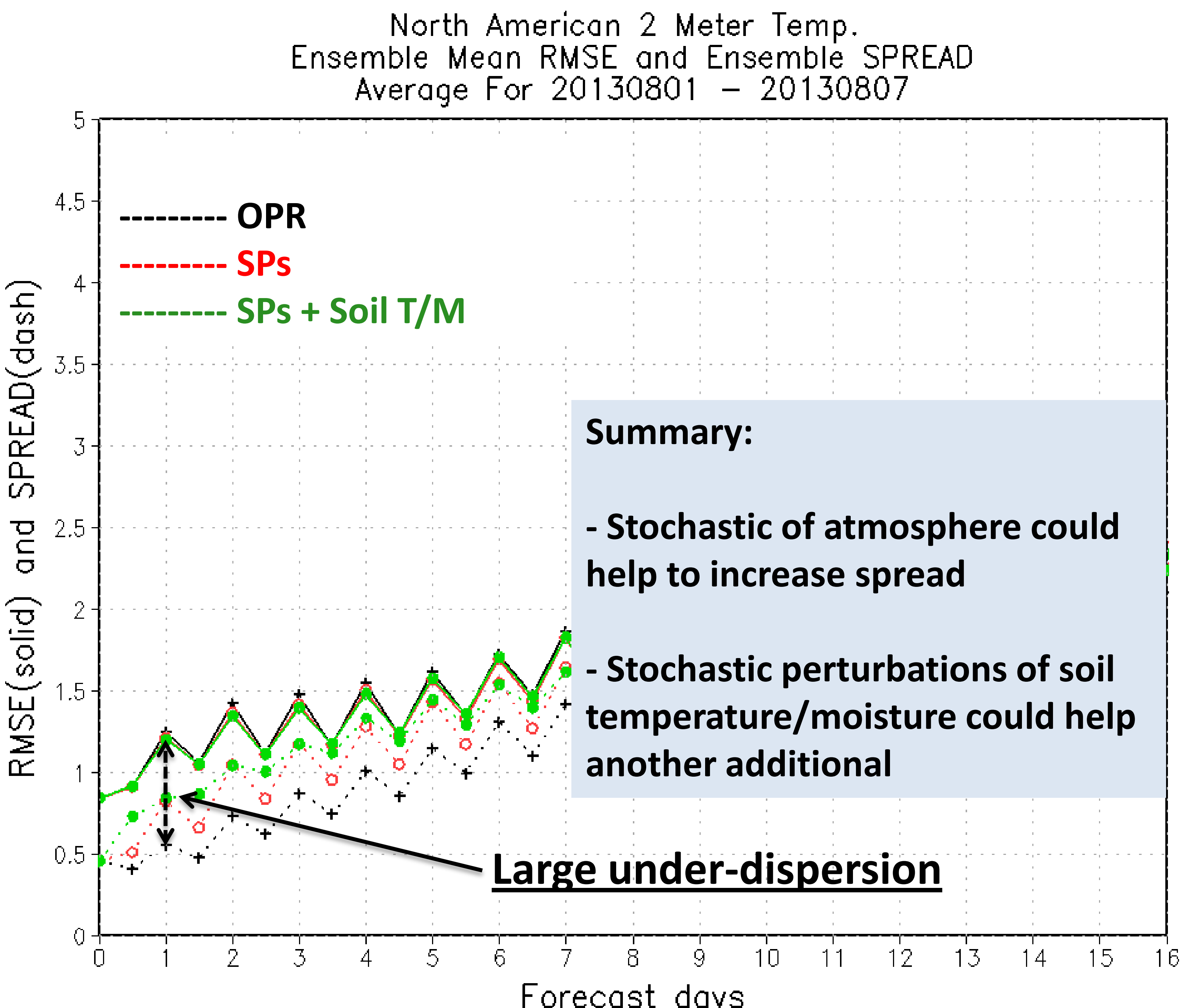


2 Meter Temperature



Skim Temperature





Summary:

- **Stochastic of atmosphere could help to increase spread**
- **Stochastic perturbations of soil temperature/moisture could help another additional**

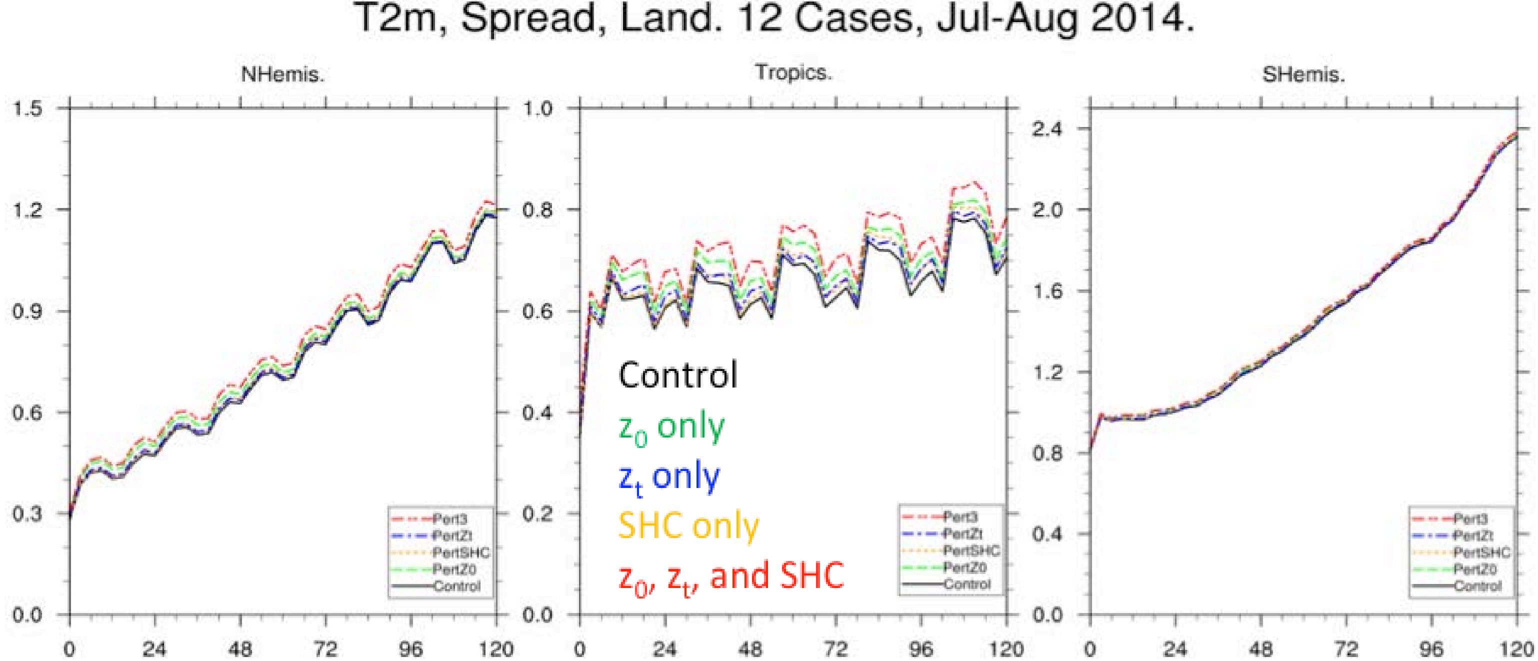
ESRL/PSD's Investigations

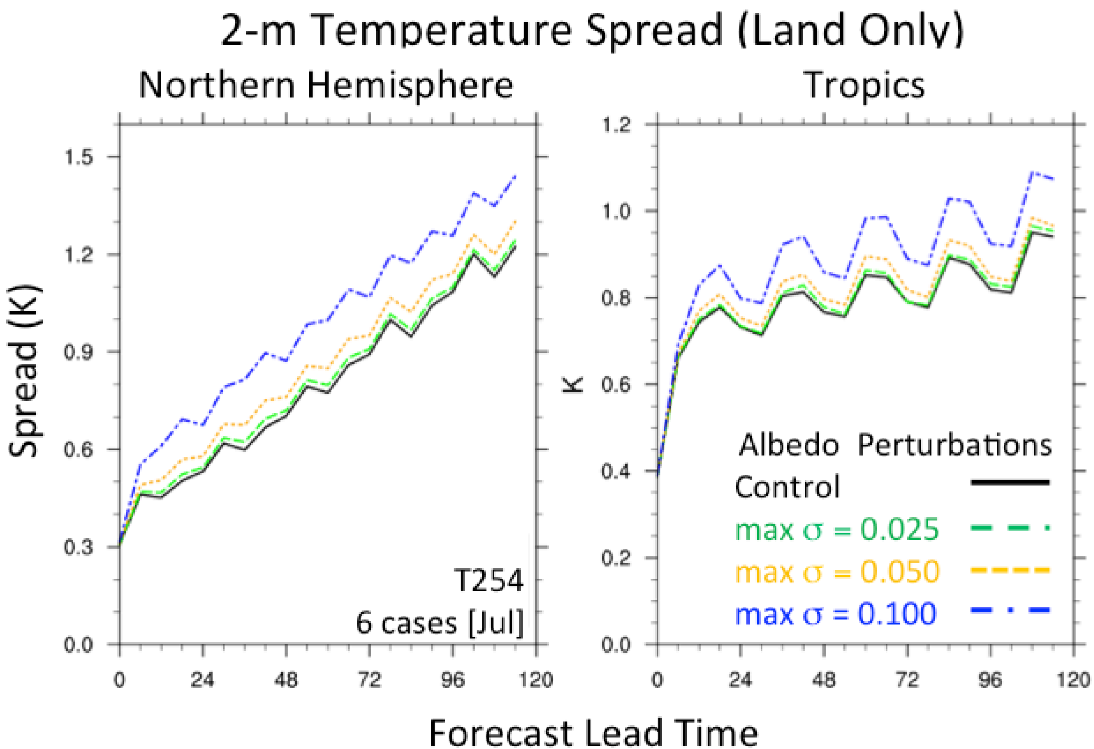
- In land model, perturb surface momentum roughness length (Z_0), thermal roughness lenghth (Z_t) and soil hydraulic conductivity (SHC)

- Test sensitivity of surface albedo

- Parameter values are perturbed using spatially and temporally correlated random patterns, as in SPPT and SHUM.

- Only a slight increase (0.1 K or less) in spread, even when combining SHC and roughness perturbations. Perturbing albedo has a larger effect, but still only ~0.25 K for the largest perturbation.





Sensitivity test for albedo perturbations

Courtesy of Dr. Maria Gehne

Next GEFS (version 12)

- Introduce new dynamic core – FV3
- Integrate current/improved physics
- C384L63 (25km) for day 1-8
- C192L63 (50km) for day 8-35
- 21-31 members per cycle, 4 times per day
- Initial perturbations – EnKF f06
- Model uncertainties
  - Stochastic perturbations for atmosphere
  - Stochastic perturbations for land
- Ocean boundary – SST
  - Introduce bias corrected coupled predictive SST
  - NSST to assimilate diurnal variation of SST
- Reanalysis and reforecast to support downstream application

Where to go from here?

Towards physically based stochastic parameterization - NGGPS

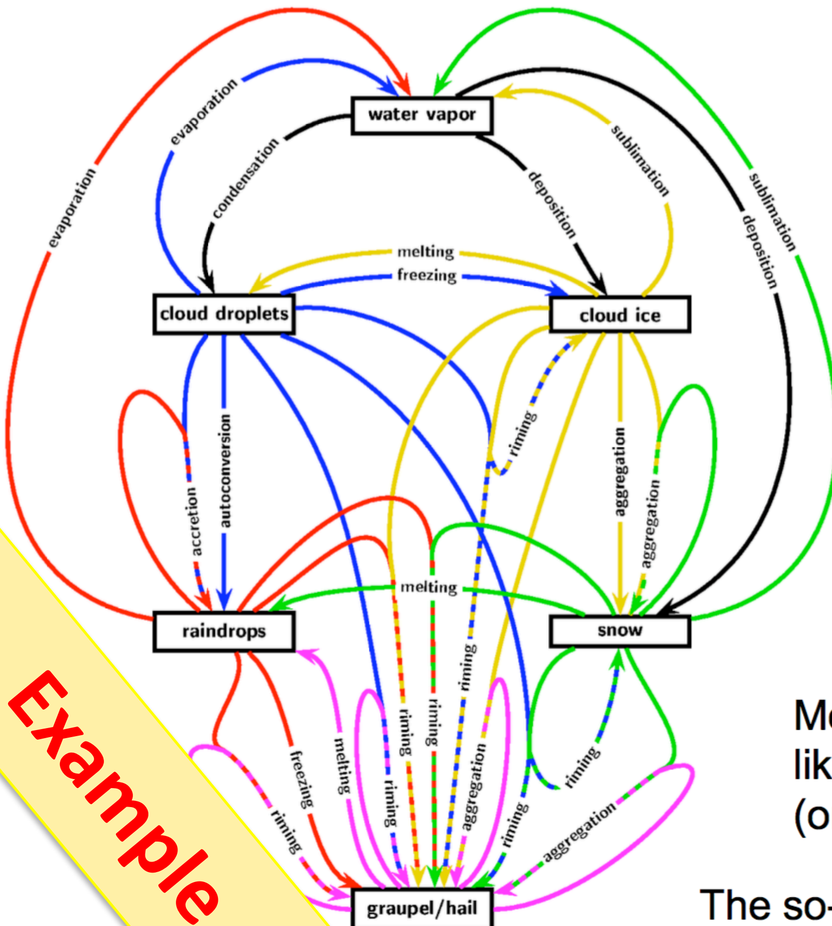
- Direction of future model physics development
  - Physically based stochastic parameterization
  - Not deterministic solution, but full representation of model uncertainty
  - Generates ensemble realizations of tendencies including realistic space-time correlations.
  - From tunable to functional
- 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?
  - Many others???
- Physically based scheme should be appropriate for all scales (scale aware), not only one/two schemes.

Towards physically based stochastic parameterization - NGGPS

- Should we?
  - 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)
    - HIW, such as tropical storm forecast

Model error at mesoscale:

Example: cloud microphysical processes



Example

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).

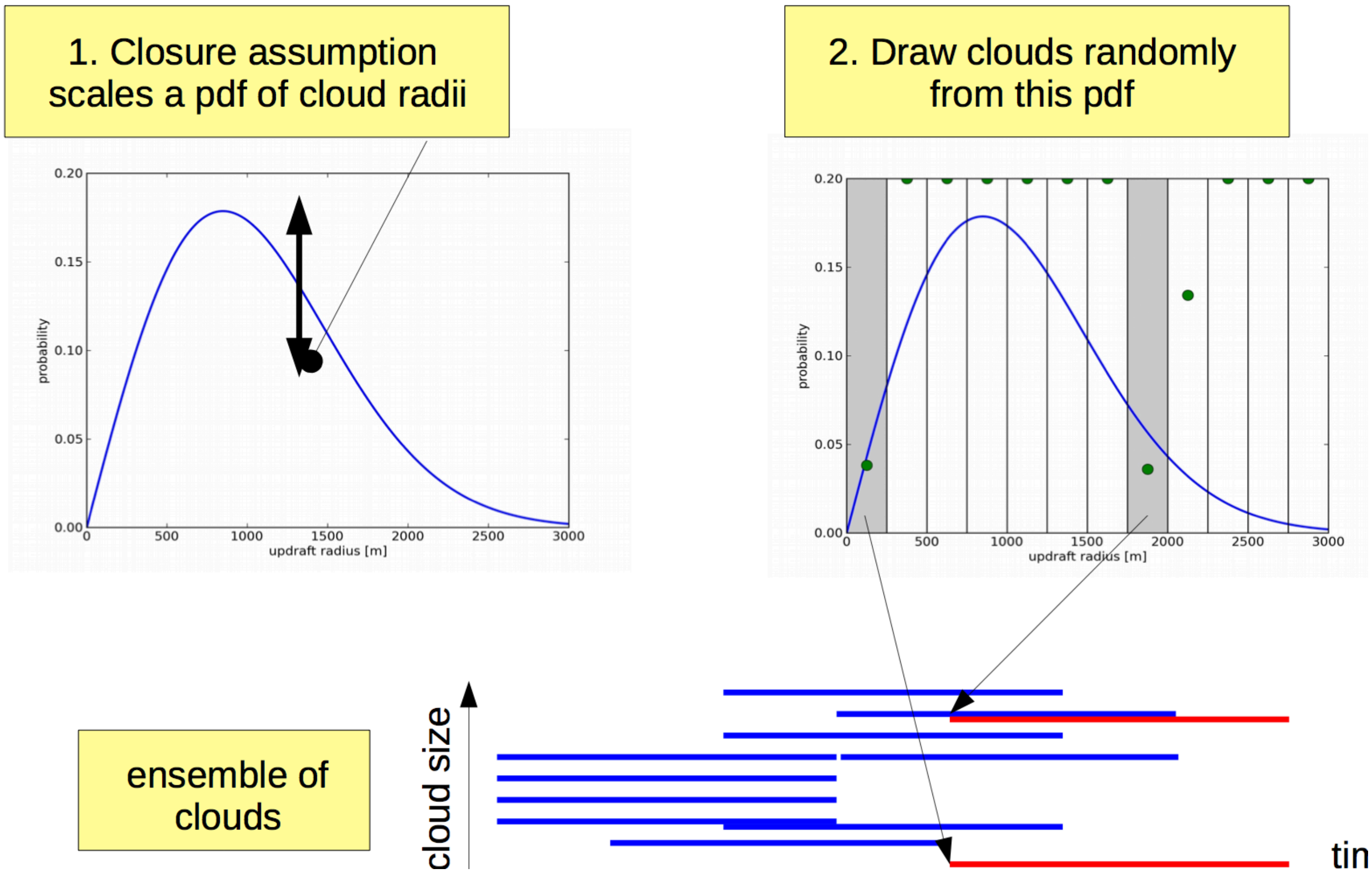
The so-called **ice multiplication** (or Hallet-Mossop process) may be very important, but is still not well understood

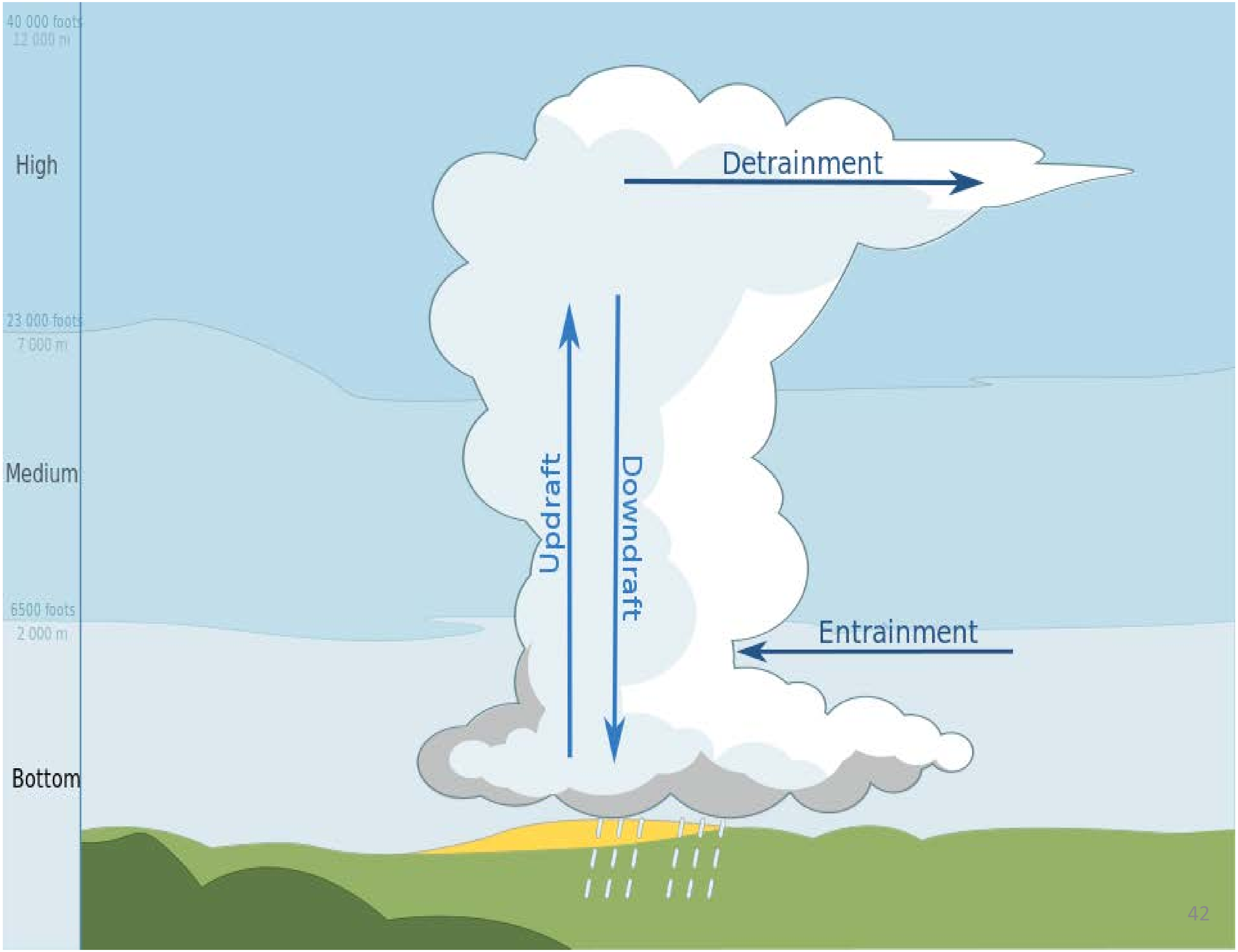
41

from Axel Seifert presentation to NCAR ASP summer colloquium

Stochastic Deep convection

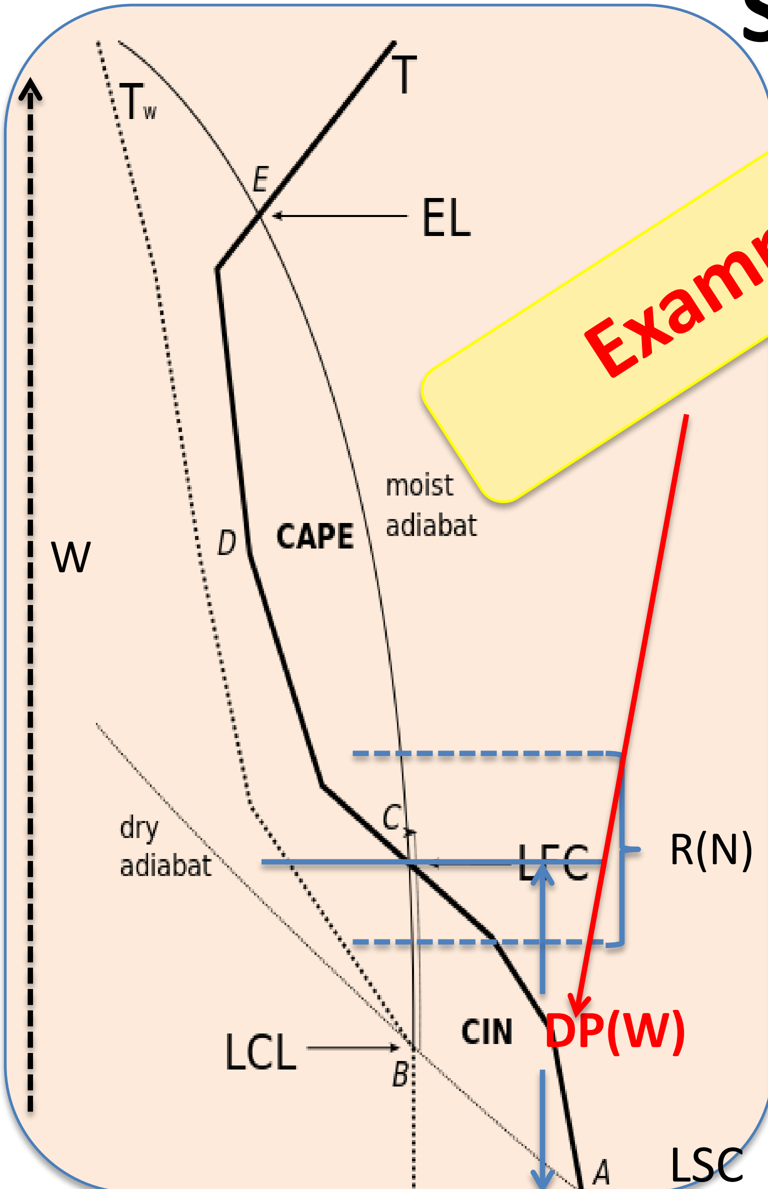
The Plant-Craig stochastic convection scheme





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

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)

Extra slides – may be for discussion?

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.

SKEB - Spectral Kinetic Energy Backscatter

- Rationale: A fraction of the dissipated energy is backscattered upscale and acts as streamfunction forcing for the resolved-scale flow
  (Shutts and Palmer 2004, Shutts 2005, Berner et al 2009)
- Streamfunction forcing is given by:

$$F_\Psi(\lambda,\mu,\eta,t) = \sqrt{b_R D_{tot}}\,F(\lambda,\mu,\eta,t)$$

Streamfunction forcing

Backscatter ratio

Total dissipation rate

Pattern generator

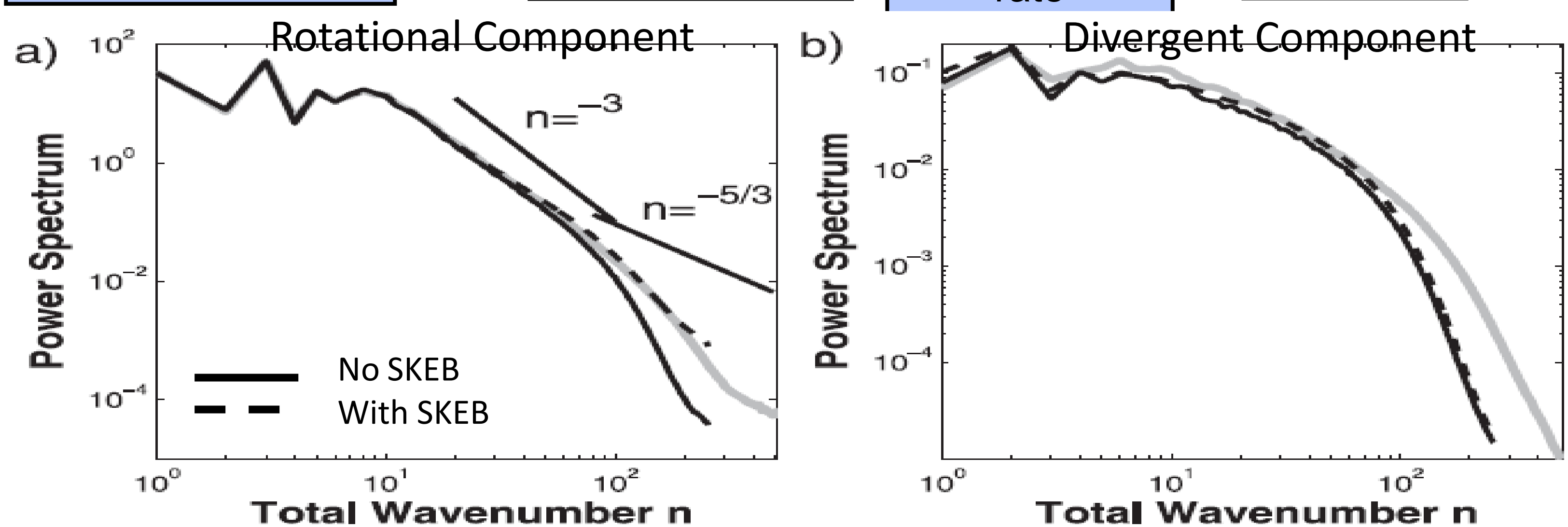
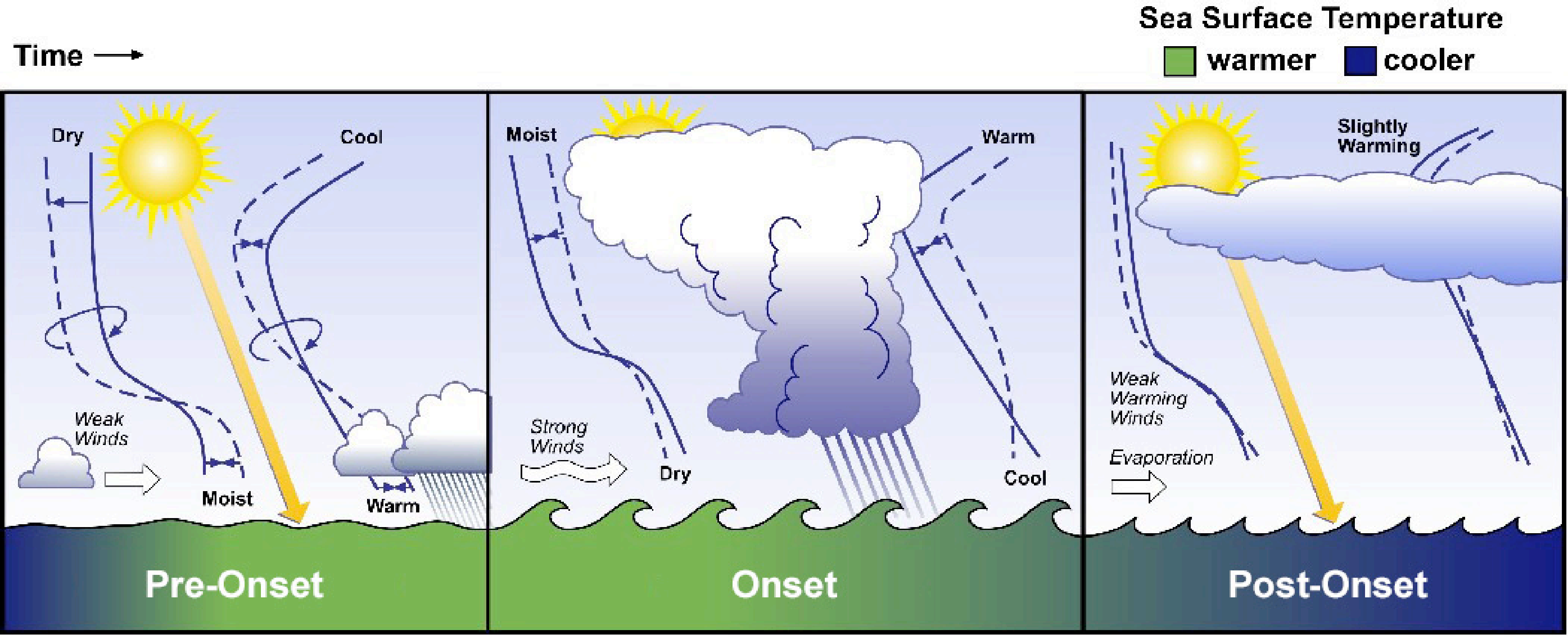
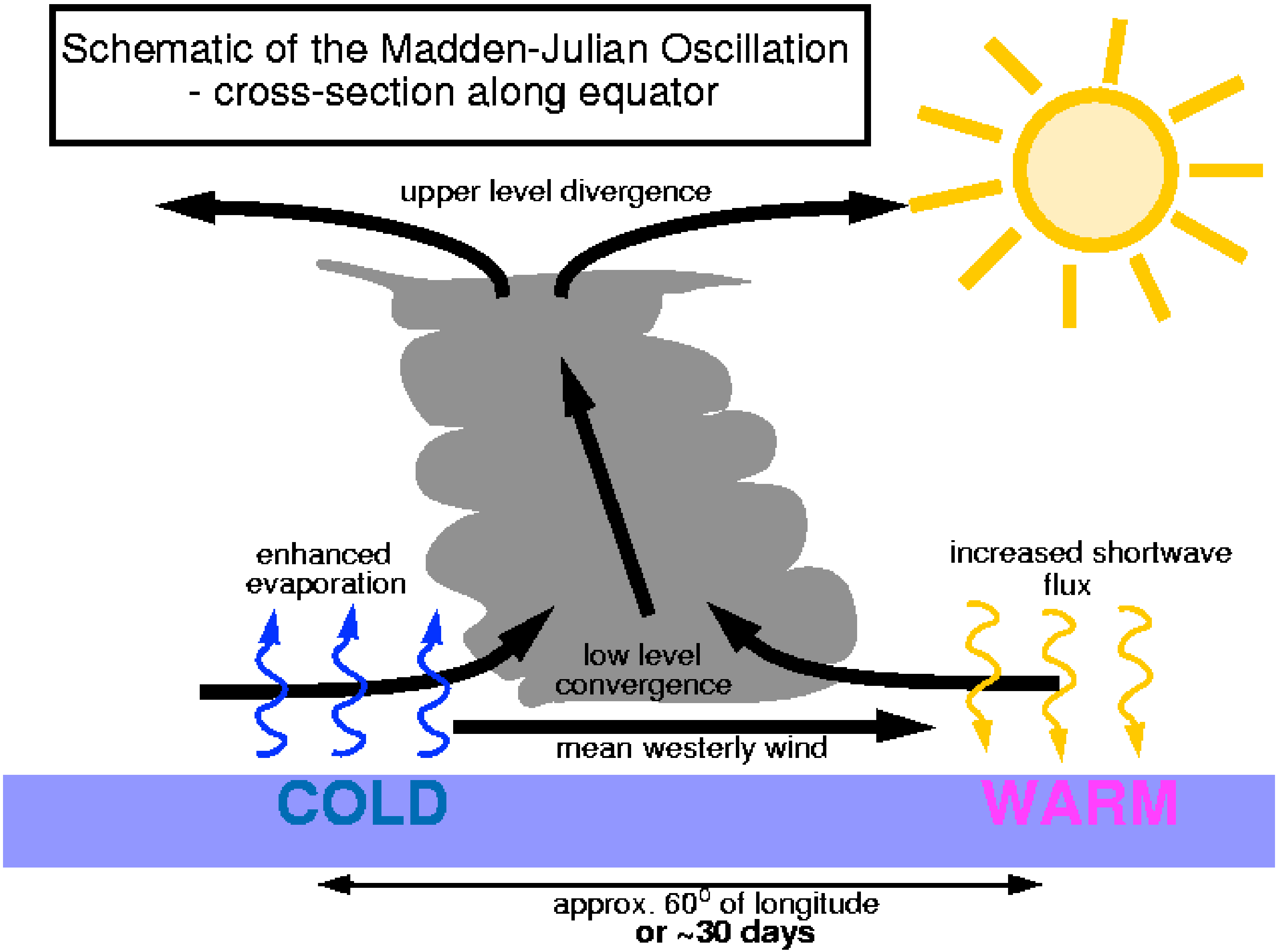


Figure 6 from Berner et al. (2009)


Sea Surface Temperature
warmer
cooler
Time
Dry
Cool
Weak Winds
Moist
Warm
Pre-Onset
Moist
Warm
Strong Winds
Dry
Cool
Onset
Slightly Warming
Weak Warming Winds
Evaporation
Post-Onset


Schematic of the Madden-Julian Oscillation
- cross-section along equator
upper level divergence
enhanced
evaporation
increased shortwave
flux
low level
convergence
mean westerly wind
COLD
WARM
approx. 60° of longitude
or ~30 days

What other global centers are doing?

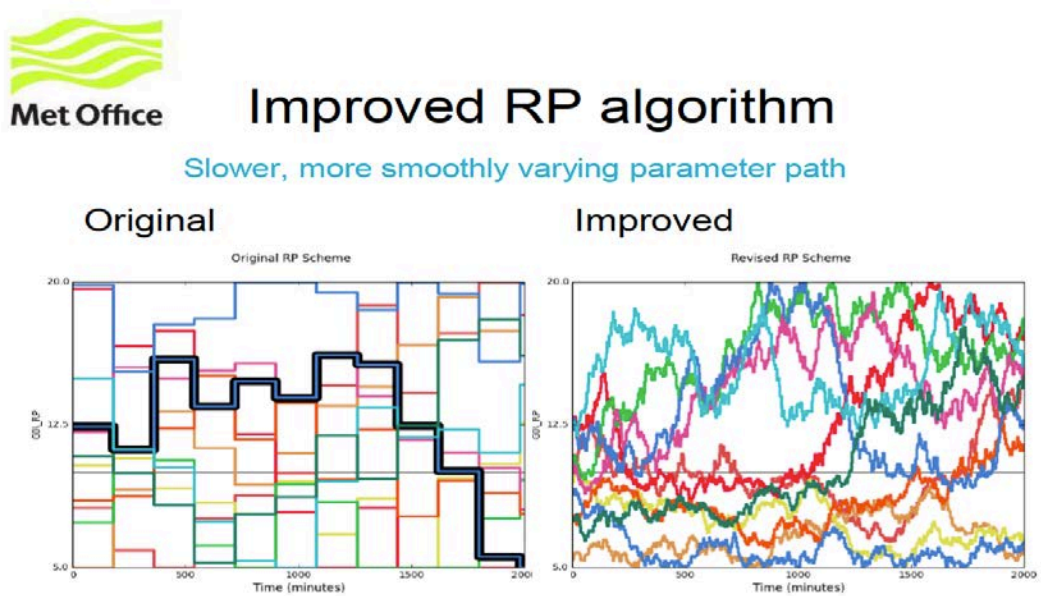
- ECMWF
  - Operational: SPPT and SKEB in the medium/extended range, Ensemble DA only uses SPPT
  - In development: Modifications to SPPT (SPPTi and work on ensuring global integral of tendency perturbations is zero)
  - New scheme, SPP: Stochastically Perturbed Parameterizations (starting with cloud/radiation interaction)

What other global centers are doing?

- Environment Canada:
  - Operational: PTP (similar to SPPT), SKEB and multi-physics
  - In development: Plant-Craig stochastic deep convection, cloud model is adopted from the Bechtold scheme (closure is still deterministic, plume generation is stochastic)

What other global centers are doing?

- UK Met is testing random parameters in physics schemes similar to the land surface perturbations that Maria and Gary are working on
- Parameters include droplet number in microphysics, entrainment rate, turbulent mixing rates.



Increase in spread is small, and ensemble is still under-spread in near surface wind and temperature, but improves fog forecasts. They are also perusing land surface perturbations.

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)

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)

Contribution of Variables