NOAA Earth System Research Laboratory

# Review of developments in ensemble prediction research for weather-climate

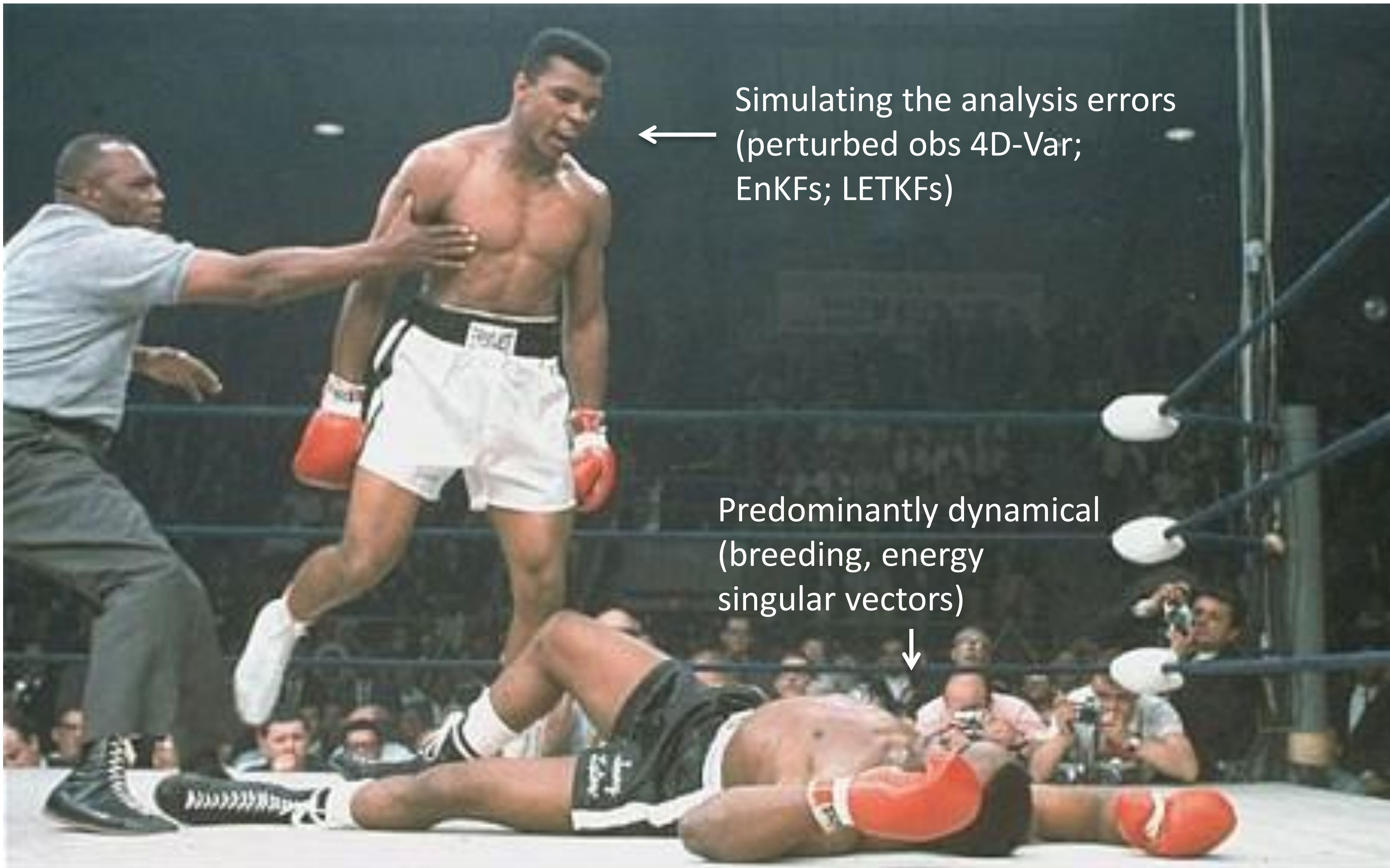
Tom Hamill

*NOAA ESRL, Physical Sciences Division*

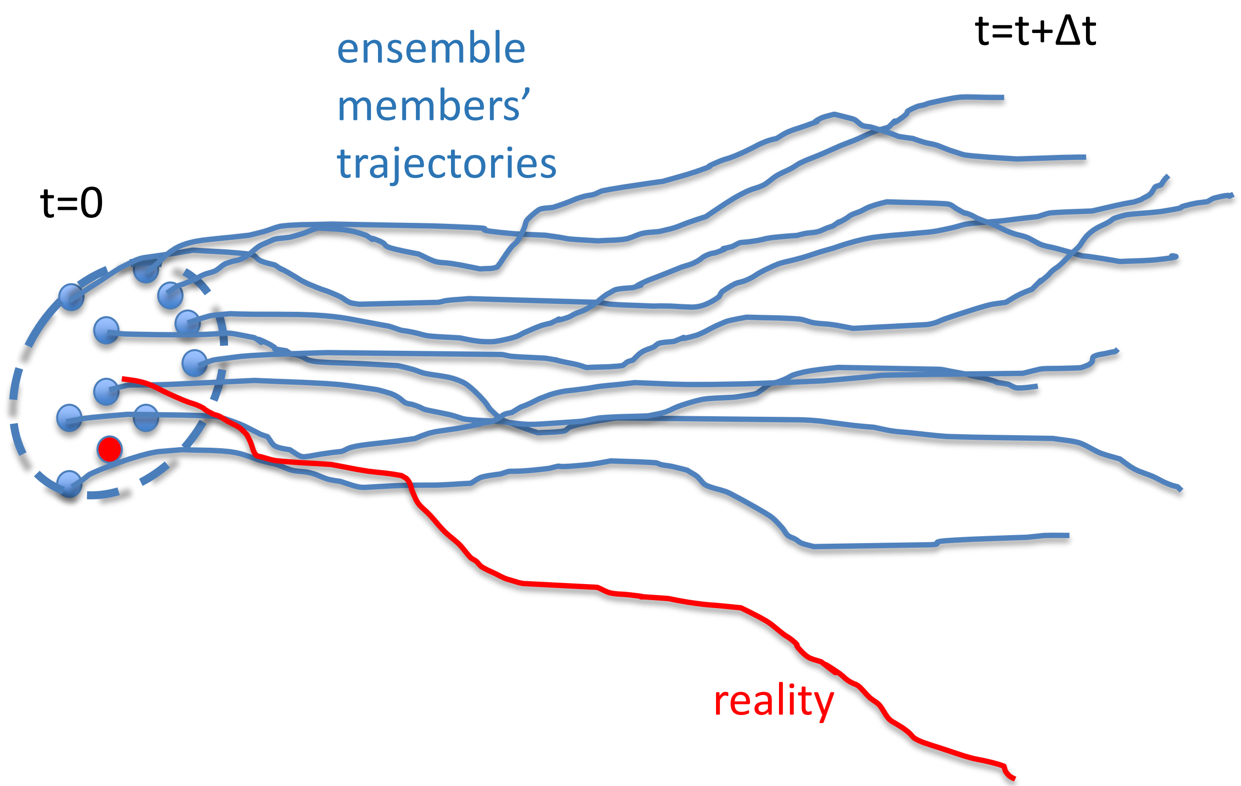
tom.hamill@noaa.gov

also: Jeff Whitaker, Gary Bates, Don Murray, Francisco Alvarez, Mike Fiorino, Tom Galarneau

# Methods for generating initial conditions for weather ensembles



# Model uncertainty is where the most interesting stuff is going on.



# Model uncertainty testing in global ensembles

- Compare NCEP's operational STTP method against:
  - ECMWF's "SPPT" (stochastically perturbed physical tendencies)
  - UK Met Office "VC" (vorticity confinement)
  - Our perturbed boundary-layer relative humidity.

# NCEP operational scheme (STTP)

Stochastic Total Tendency Perturbation

Scheme (*Hou, Toth and Zhu, 2006*)

**NCEP operation – Feb. 2010**

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

**Simplification: Use finite difference form for the stochastic term**

**Modify the model state every 6 hours:**

$$X_i' = X_i + \gamma \sum_{j=1}^{N} w_{i,j}(t)\left\{\left[(X_j)_t - (X_j)_{t-6h}\right] - \left[(X_0)_t - (X_0)_{t-6h}\right]\right\}$$

Where w is an evolving combination matrix, and $\gamma$ is a rescaling factor.

random linear combinations of ensemble tendency perturbations added to state every 6-h (entire ensemble must be run concurrently).

# Schemes we tested

- Stochastically-perturbed **physics** tendencies (SPPT) – operational ECMWF scheme.
- Vorticity confinement (VC) – under development at UKMET and ECMWF.
- Stochastically-peturbed boundary-layer humidity (SHUM).

# ECMWF method (SPPT)

Stochastically Perturbed Physics Tendency

- Perturbed Physics tendencies

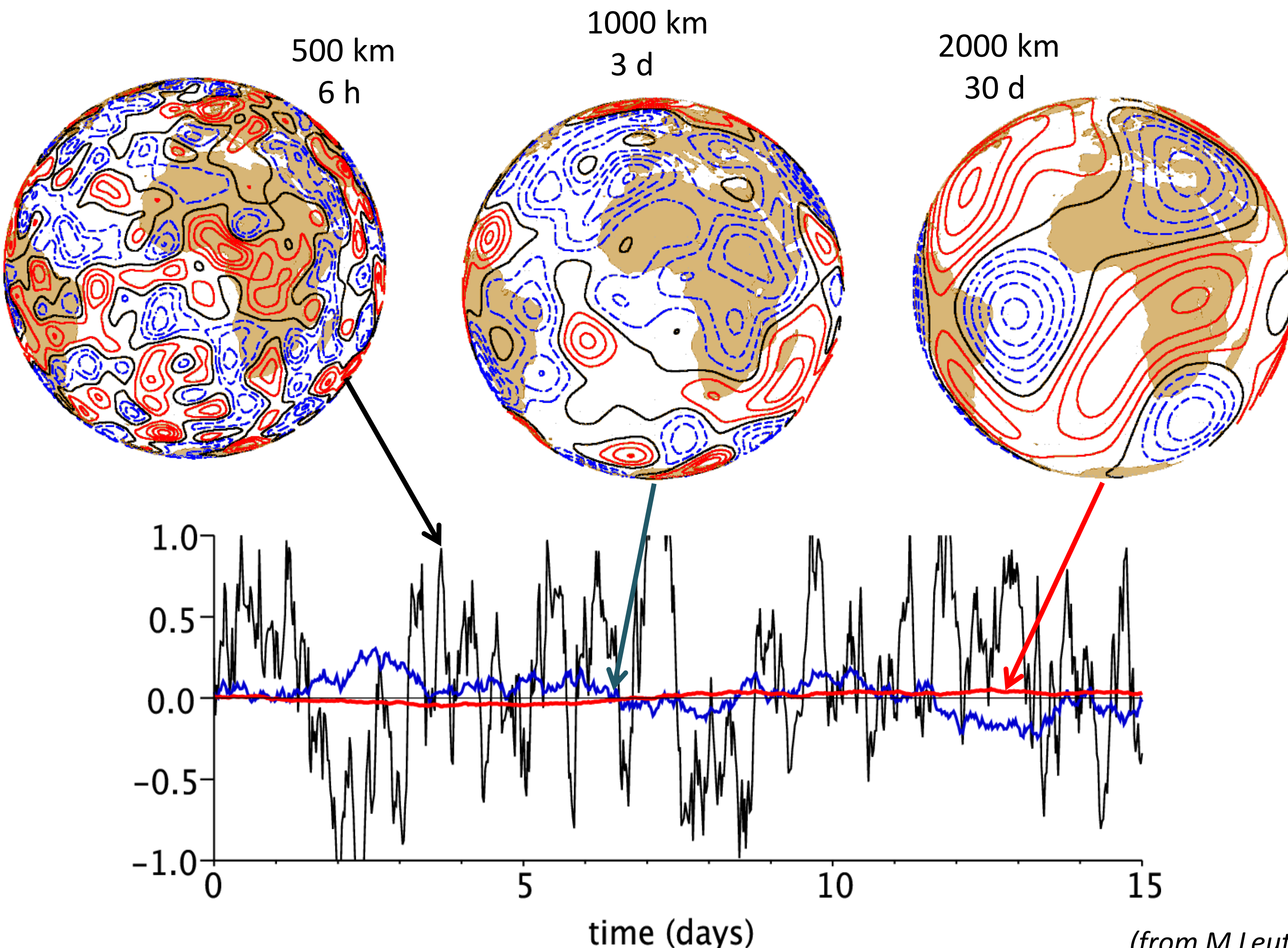
$$X_p = (1 + r\mu)X_c$$

μ- vertical weight: 1.0 between surface and 100 hPa, decays to zero between 100 hPa and 50 hPa.

r- horizontal weights: ranges from -1.0 to 1.0, a red noise process with a

- Temporal timescale of 6 hours
- e-folding spatial scale of 500 km

# Examples of stochastic patterns




*(from M Leutbecher)*

# Vorticity confinement

(Sanches, Williams and Shutts, 2012 QJR doi 10.1002)

$$\frac{D\mathbf{V_H}}{Dt} + f\mathbf{k} \times \mathbf{V}_H + \nabla\phi = \mu\nabla^2\mathbf{V}_H + \epsilon\hat{\mathbf{n}} \times |\zeta|\,\widehat{\mathbf{k}}$$

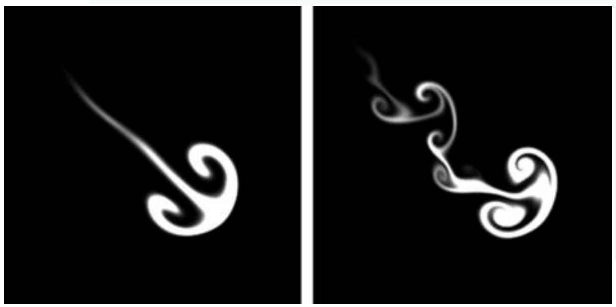
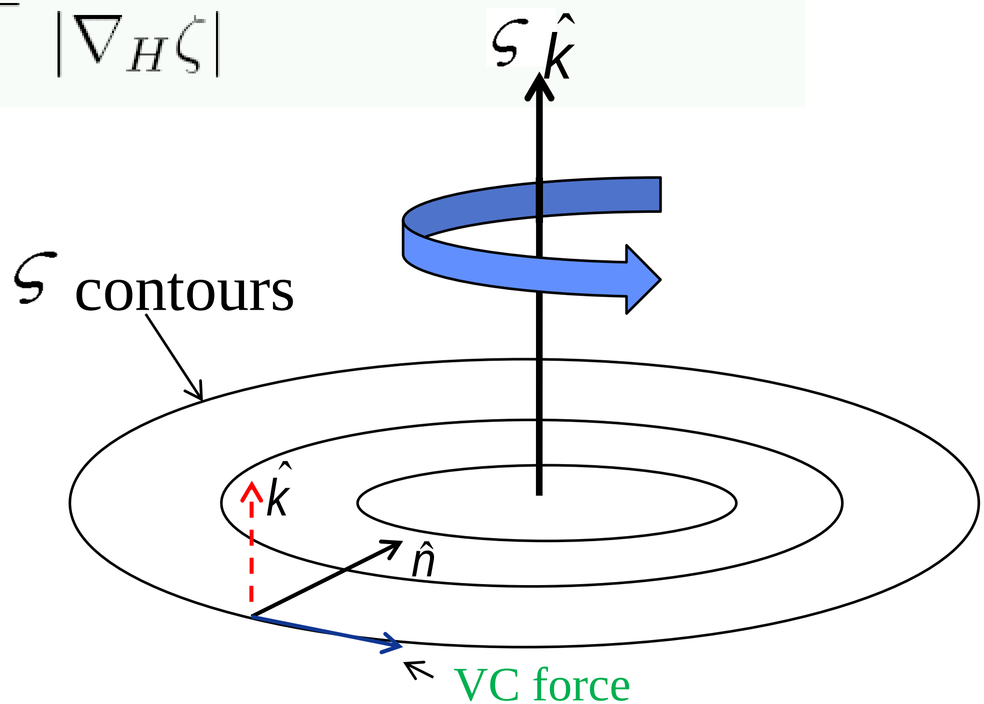


Figure 6: Two frames of animation from two mpeg movies created using `flowanim` and `mpeg2encode`. Both frames depict the 60th frame of the movie. The left animation is created without vorticity confinement, the one on the right with vorticity confinement and a *relatively* high force factor

$$\hat{\mathbf{n}} = \frac{\nabla_H \zeta}{|\nabla_H \zeta|}$$




acts as an advective velocity

ε=0.6 in our experiments

# Stochastic boundary-layer humidity

- SPPT only modulates existing physics tendency (cannot change sign, trigger new convection).
- Triggers in convection schemes very sensitive to BL humidity.

$$q_{perturbed} = (1 + r\,m)q$$

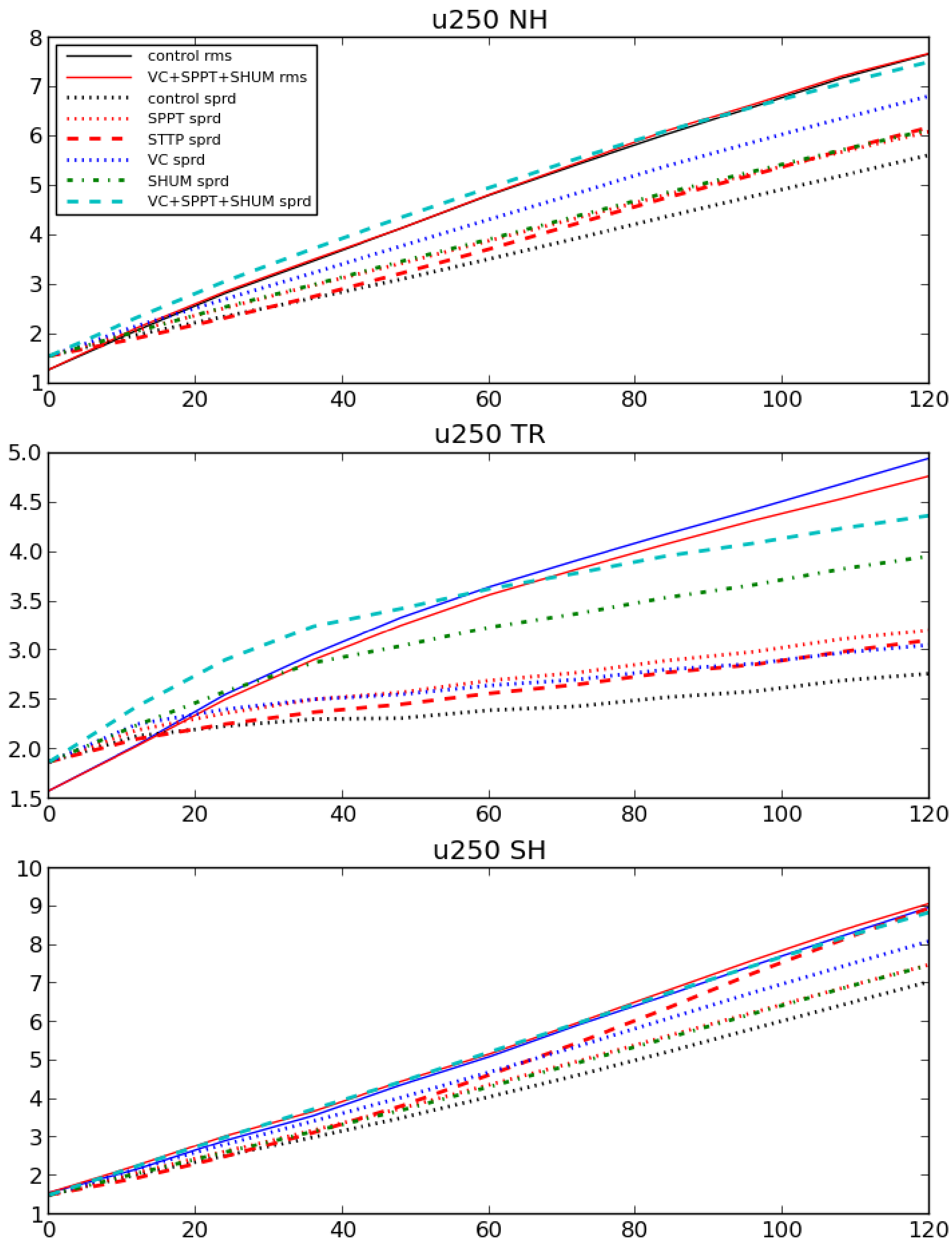
- Vertical weight **r** decays exponentially from surface. Added every time step after physics applied. Random pattern *μ* has a (very small) amplitude of 0.00375, horizontal/vertical scales (250 km, 3-h).

# U250 spread/error growth (July 2012)

RMS error (solid lines) reduced in tropics

STTP (NCEP) only adds much spread in winter hemisphere.

Much faster spread growth with SHUM in tropics.



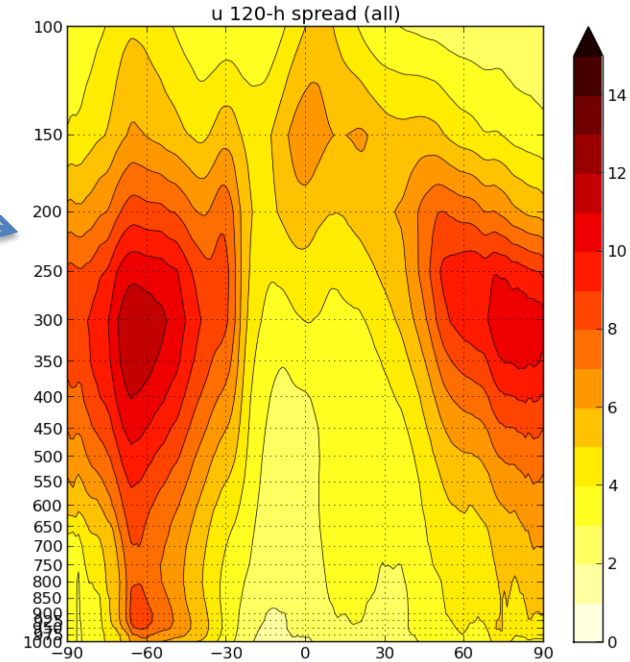

VC+SPPT+SHUM
VC
SHUM
STTP
control

VC+SPPT+SHUM
SHUM
SPPT
VC
STTP
control

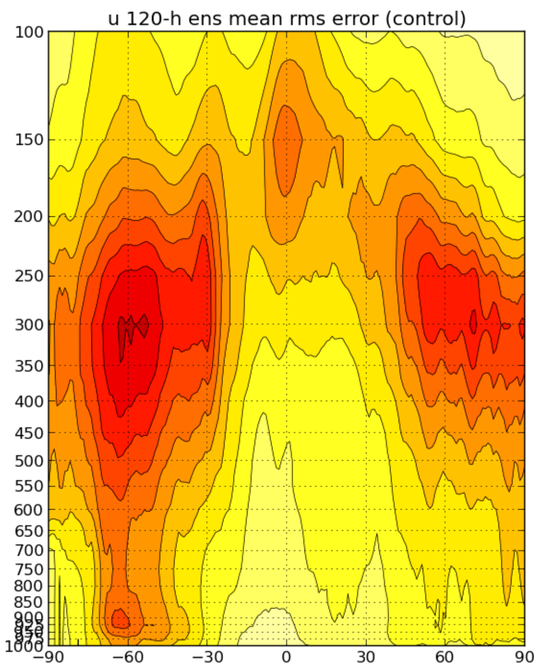
VC+SPPT+SHUM
STTP
VC
SHUM
SPPT
control

# Zonal Wind Spread

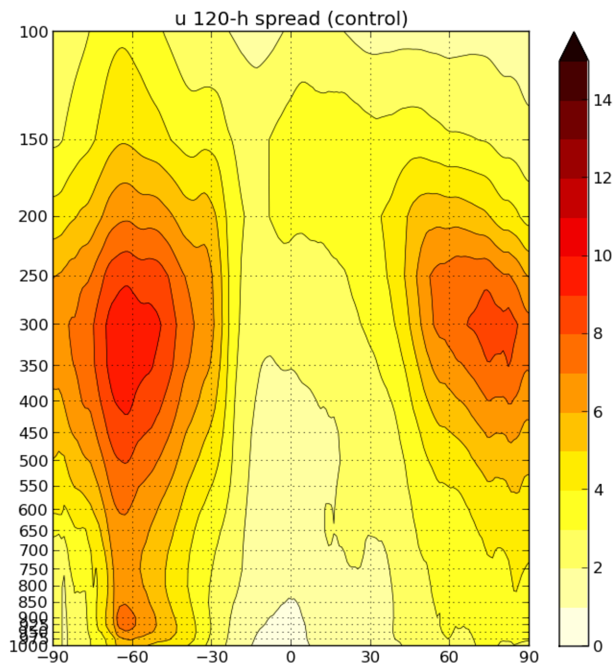
Ensemble Spread
(SPPT+SHUM+VC)



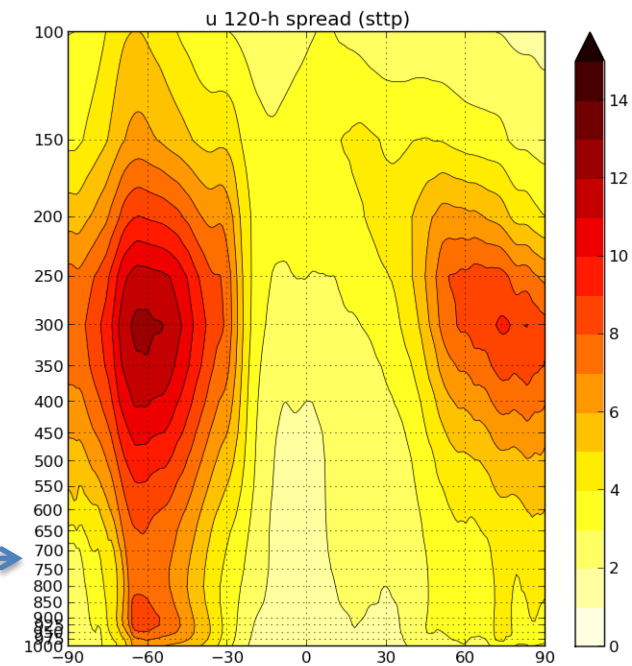

Ensemble Mean Error
(control)



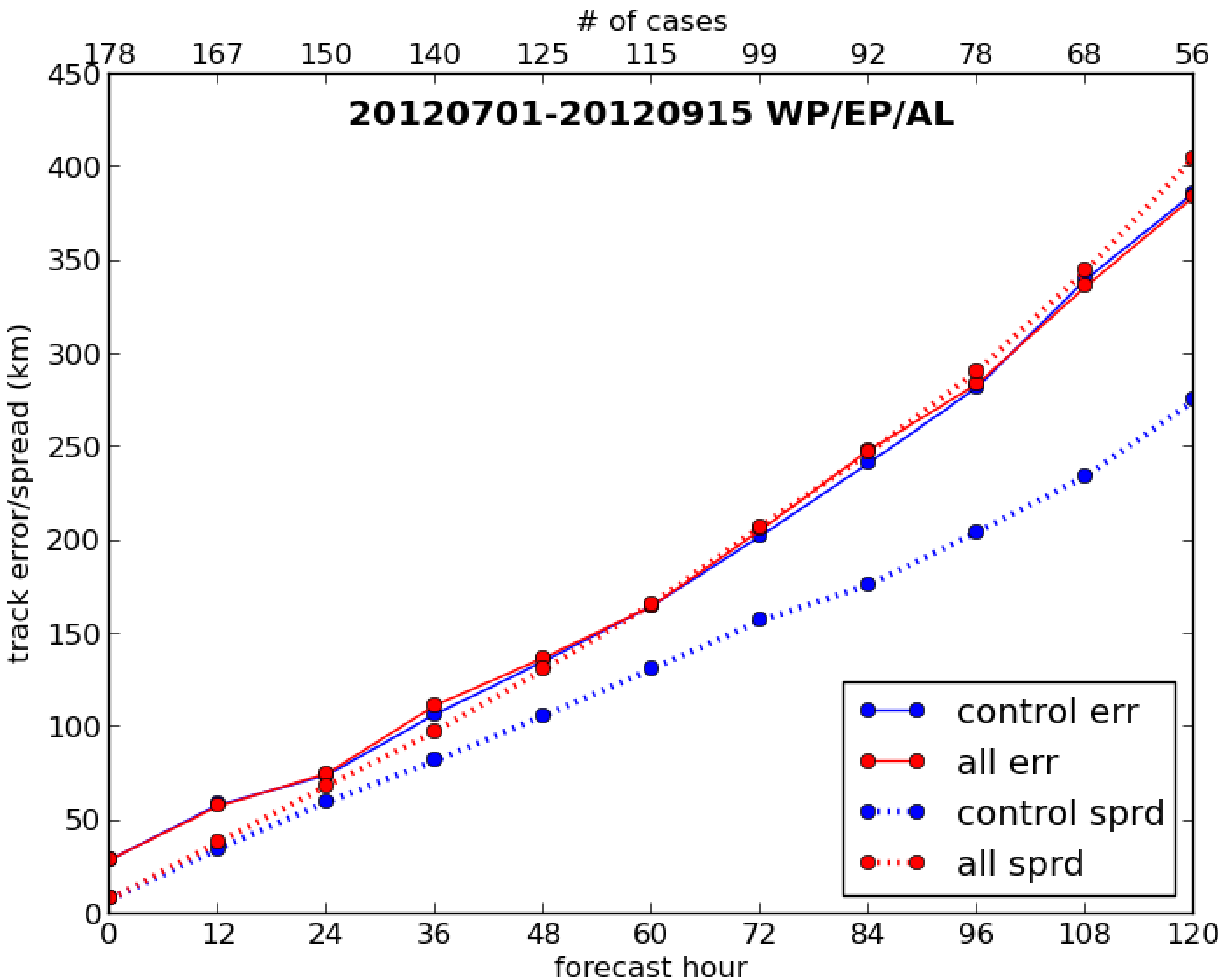

Ensemble Spread
(control)




Ensemble Spread
(STTP)

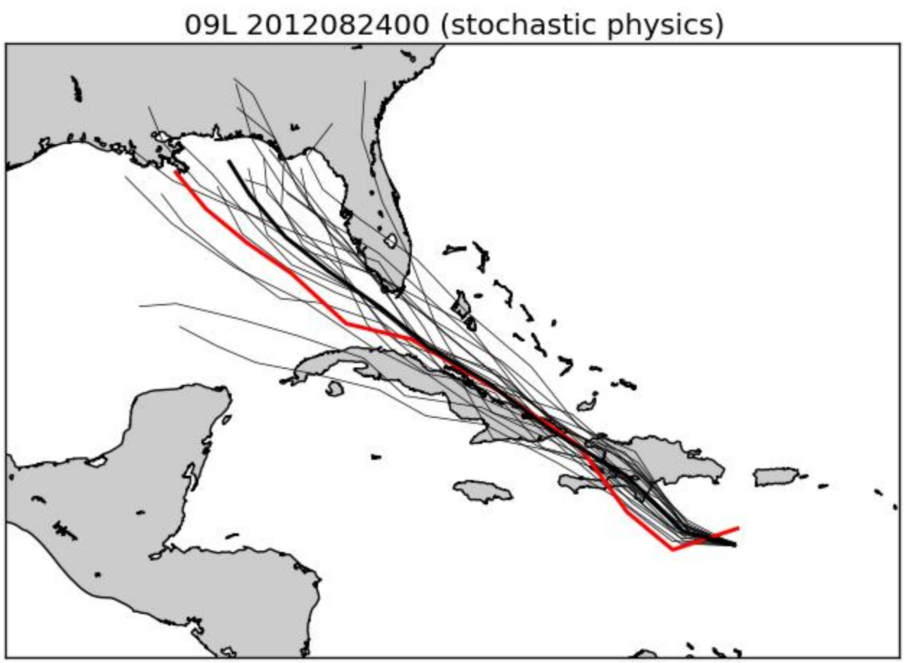


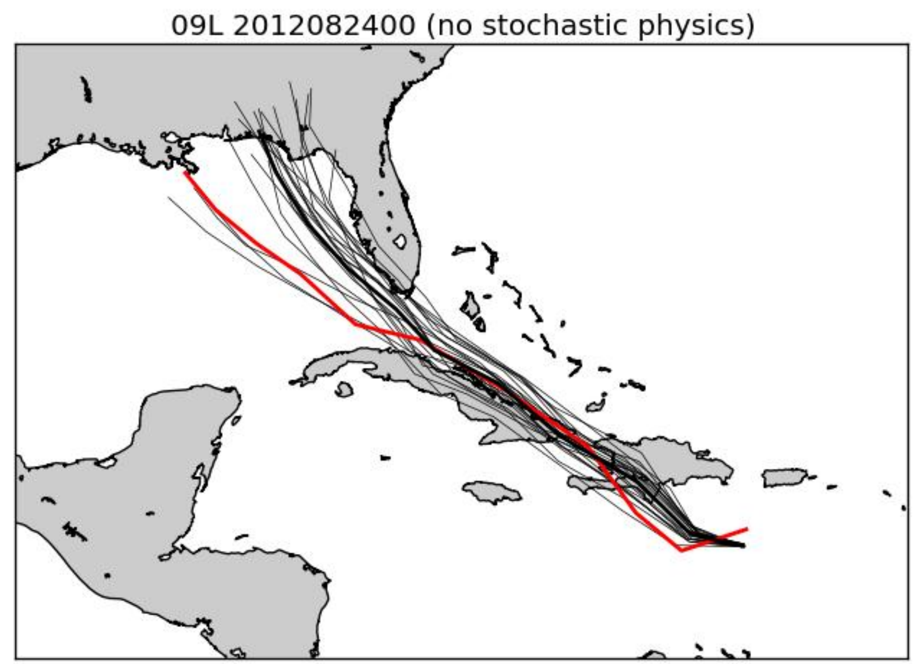
# TC track error/spread




Combination of 3 schemes produces calibrated track forecasts, but does not reduce ensemble mean error.

# Example (Isaac)



# Reforecasts:
# what are they good for?

Using multi-decadal reforecasts from the NCEP Global Ensemble Forecast System.

# GEFS reforecast v2 details

- Seeks to mimic GEFS operational configuration as of February 2012.
- Each 00Z, 11-member forecast, 1 control + 10 perturbed.\
- Reforecasts produced every day, for 1984120100 to current (actually, working on finishing late 2012 now).
- CFSR (NCEP's Climate Forecast System Reanalysis) initial conditions (3D-Var) + ETR perturbations (cycled with 10 perturbed members). After ~ 22 May 2012, initial conditions from hybrid EnKF/3D-Var.
- Resolution: T254L42 to day 8, T190L42 from days 7.5 to day 16.
- Fast data archive at ESRL of 99 variables, 28 of which stored at original ~1/2-degree resolution during week 1. All stored at 1 degree. Also: mean and spread to be stored.
- Full archive at DOE/Lawrence Berkeley Lab, where data set was created under DOE grant.

# Status

- 00Z reforecasts 1985-2010 completed and publicly available.
- 2011- Sep 2012 reforecasts are being processed, available within weeks.
- Within a month or two, we will be pulling real-time GEFS data over from NCEP and putting it in our archive.
- Web sites are open to you now:
  - NOAA/ESRL site: fast access, limited data (99 fields).
  - US Department of Energy: slow access, but full data set
- Soon: experimental probabilistic precipitation forecast graphics in real time.

# Data that is readily available from ESRL

**Table 1:** Reforecast variables available for selected mandatory and other vertical levels. Φ indicates geopotential height, and an X indicates that this variable is available from the reforecast data set at 1-degree resolution; a Y indicates that the variable is available at the native ~0.5 degree resolution. AGL indicates "above ground level."

| Vertical Level | U | V | T | Φ | q | Wind Power |
|---|---|---|---|---|---|---|
| 10 hPa | X | X | X | X | | |
| 50 hPa | X | X | X | X | | |
| 100 hPa | X | X | X | X | | |
| 200 hPa | X | X | X | X | | |
| 250 hPa | X | X | X | X | | |
| 300 hPa | X | X | X | X | X | |
| 500 hPa | X | X | X | X | X | |
| 700 hPa | X | X | X | X | X | |
| 850 hPa | X | X | X | X | X | |
| 925 hPa | X | X | X | X | X | |
| 1000 hPa | X | X | X | X | X | |
| $\sigma \cong 0.996$ | X | X | | X | | |
| $\sigma \cong 0.987$ | X | X | | X | | |
| $\sigma \cong 0.977$ | X | X | | X | | |
| $\sigma \cong 0.965$ | X | X | | X | | |
| 80m AGL | X,Y | X,Y | | | | X,Y |

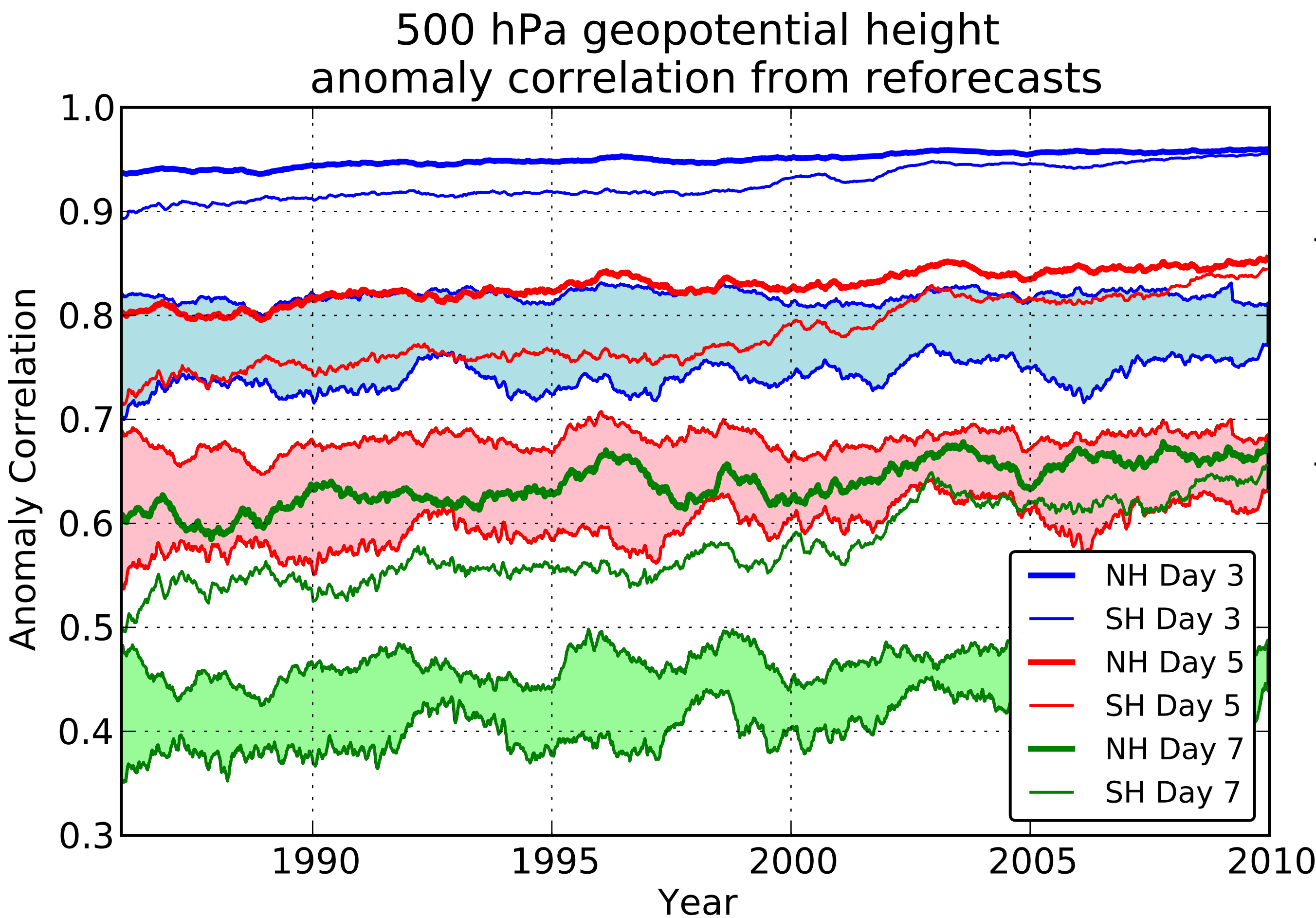
Also: hurricane track files

# Data that is readily available from ESRL

**Table 2**: Single-level reforecast variables archived (and their units). Where an [Y] is displayed, this indicates that this variable is available at the native ~0.5-degree resolution as well as the 1-degree resolution.

| **Variable (units)** |
|---|
| Mean sea-level pressure (Pa) [Y] |
| Skin temperature (K) [Y] |
| Soil temperature, 0.0 to 0.1 m depth (K) [Y] |
| Volumetric soil moisture content 0.0 to 0.1 m depth (fraction between wilting and saturation) [Y] |
| Water equivalent of accumulated snow depth (kg $m^{-2}$, i.e., mm) [Y] |
| 2-meter temperature (K) [Y] |
| 2-meter specific humidity (kg $kg^{-1}$ dry air) [Y] |
| Maximum temperature (K) [Y] |
| Minimum temperature (K) [Y] |
| 10-m u wind component ($ms^{-1}$) [Y] |
| 10-m v wind component ($ms^{-1}$) [Y] |
| Total precipitation (kg $m^{-2}$, i.e., mm) [Y] |
| Water runoff (kg $m^{-2}$, i.e., mm) [Y] |
| Average surface latent heat net flux (W $m^{-2}$) [Y] |
| Average sensible heat net flux (W $m^{-2}$) [Y] |
| Average ground heat net flux (W $m^{-2}$) [Y] |
| Sunshine |
| Convective available potential energy (J $kg^{-1}$) [Y] |
| Convective inhibition (J $kg^{-1}$) [Y] |
| Precipitable water (kg $m^{-2}$, i.e., mm) [Y] |
| Total-column integrated condensate (kg $m^{-2}$, i.e., mm) [Y] |
| Total cloud cover (%) |
| Downward short-wave radiation flux at the surface (W $m^{-2}$) [Y] |
| Downward long-wave radiation flux at the surface (W $m^{-2}$) [Y] |
| Upward short-wave radiation flux at the surface (W $m^{-2}$) [Y] |
| Upward long-wave radiation flux at the surface (W $m^{-2}$) [Y] |
| Potential vorticity on $\theta$ = 320K isentropic surface (K $m^2$ $kg^{-1}$ $s^{-1}$) |
| U component on 2 PVU (1 PVU = 1 K $m^2$ $kg^{-1}$ $s^{-1}$) isentropic surface ($ms^{-1}$) |
| V component on 2 PVU isentropic surface ($ms^{-1}$) |
| Temperature on 2 PVU isentropic surface |
| Pressure on 2 PVU isentropic surface |

# 500 hPa Z anomaly correlation
## (from deterministic control)

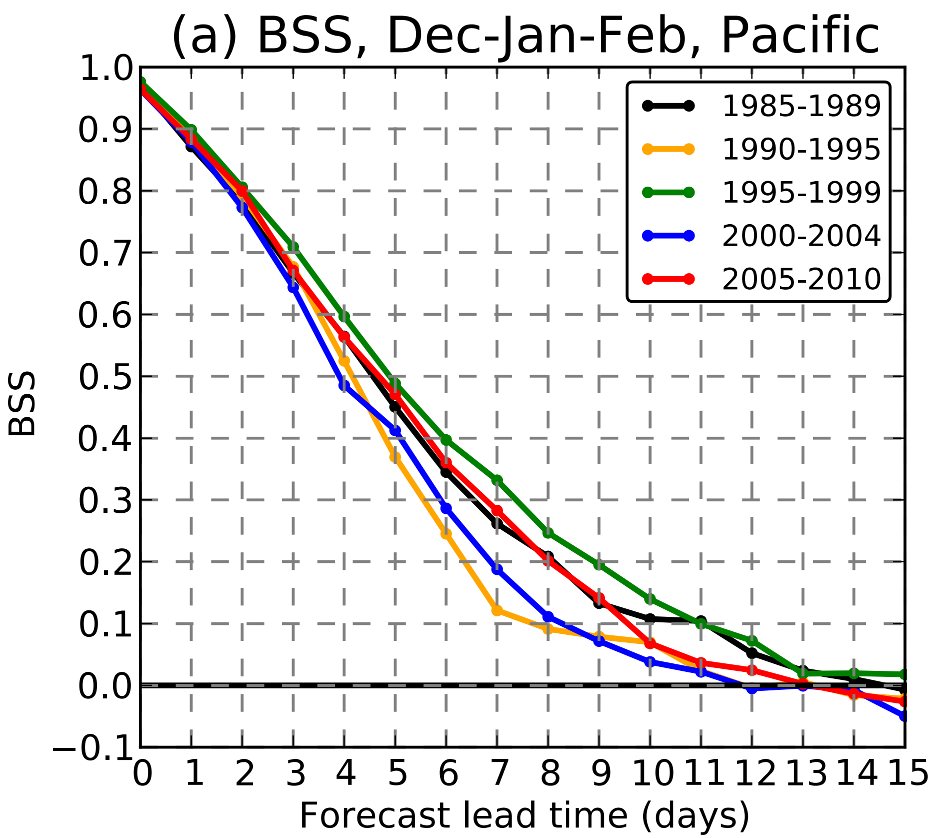


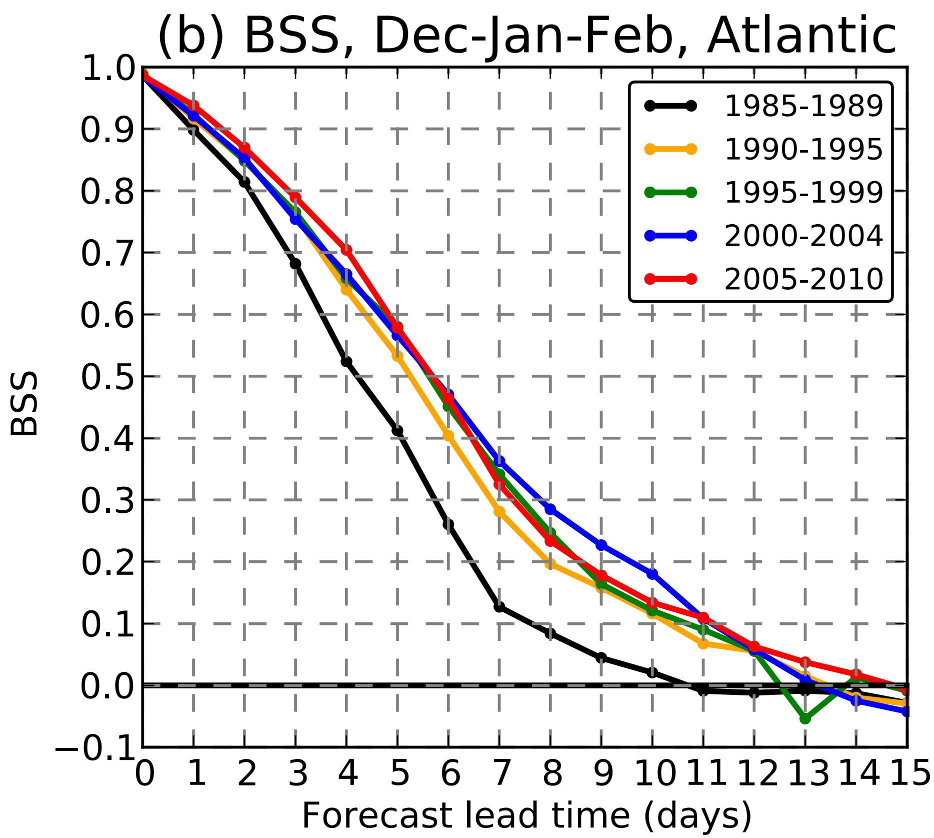

Lines w/o filled colors for second–generation reforecast (2012, T254)

Lines with filled colors for first-generation reforecast (1998, T62).

Perhaps a 1.5-2.5 day improvement.

# GEFS blocking skill by half decade



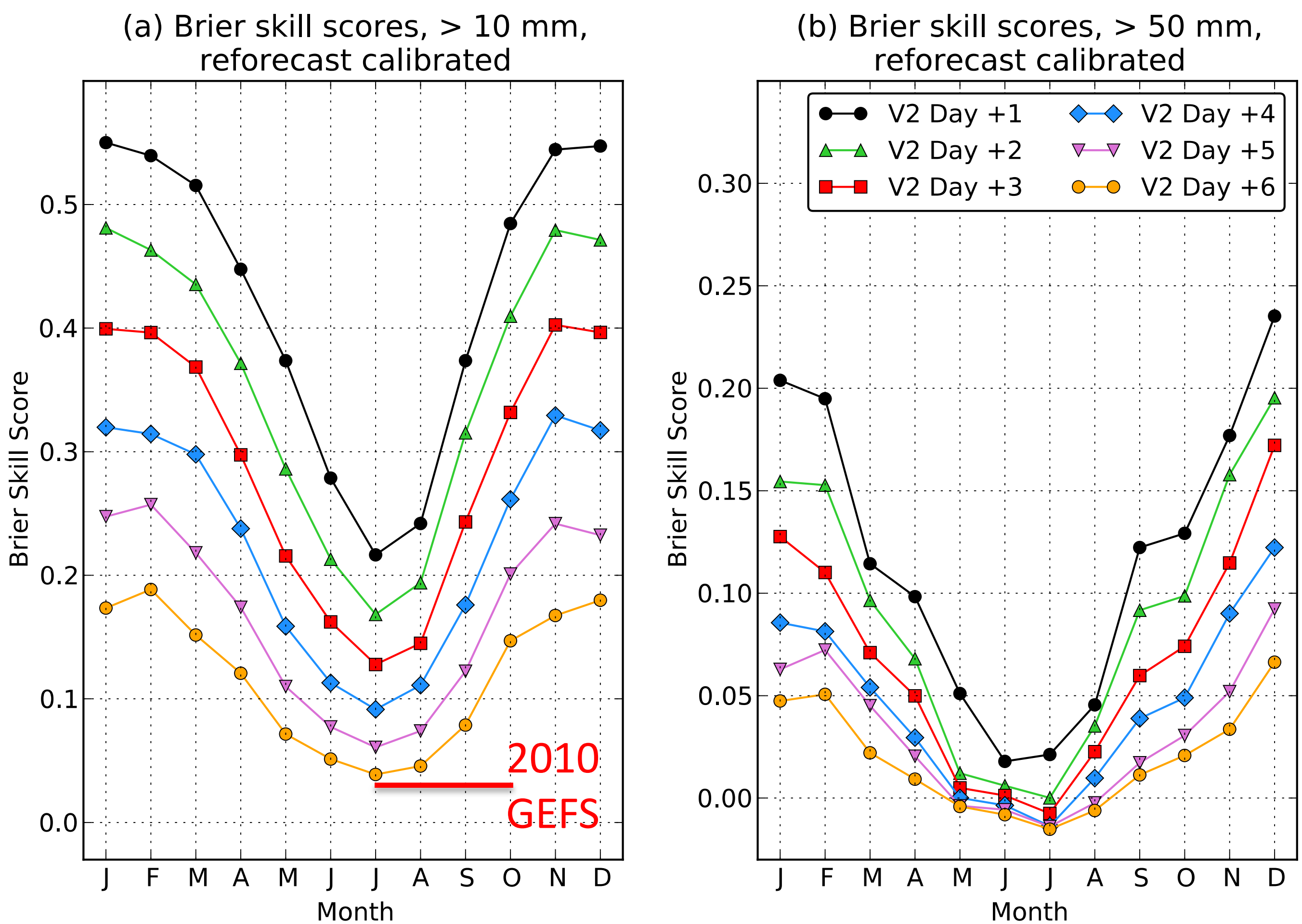




Blocking is evaluated using Tibaldi-Molteni algorithm for every longitude, every day. Skill of the ensemble in predicting blocking is then evaluated.

Decreased Atlantic sector skill in 1985-1989 period stands out.

# Skill of raw reforecasts (no post-processing)

# Skill of calibrated precipitation forecasts
## (over US, 1985-2010, "rank analog" calibration method)

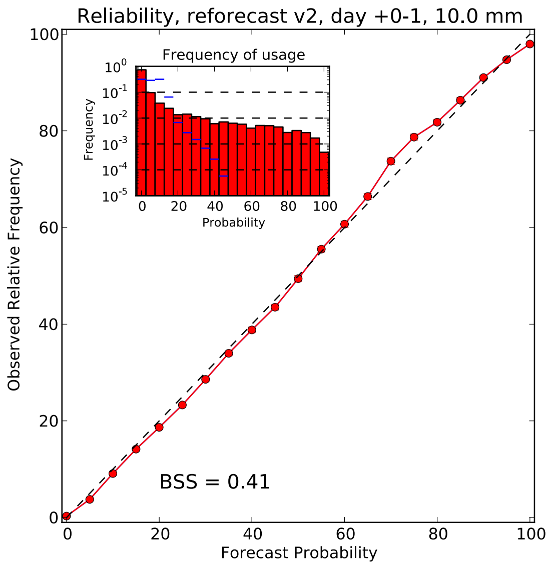



Verification here against 32-km North American Regional Reanalysis (tougher).
Verification in previous plot against 1-degree NCEP precipitation analysis (easier).

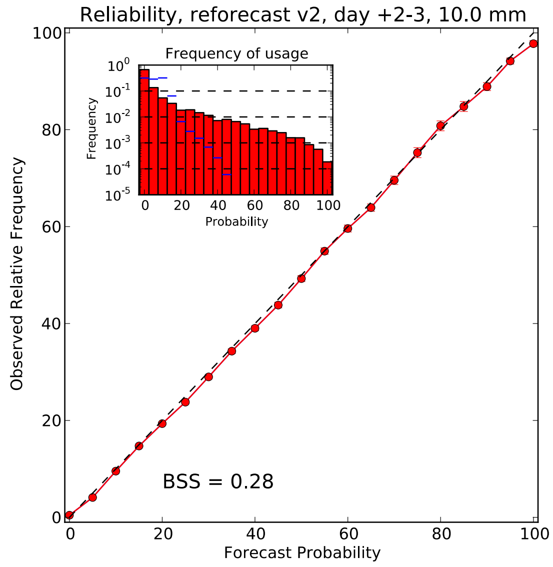
# Reliability, > 10 mm precipitation 24 $h^{-1}$

Version 2 (2012 GEFS)

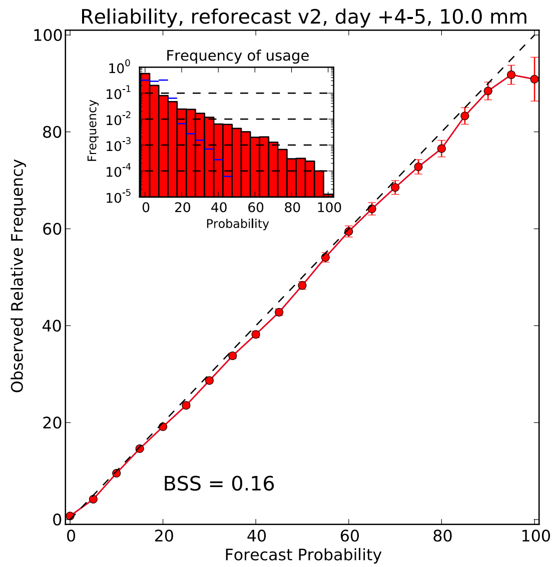
## Day +0-1




## Day +2-3




## Day +4-5

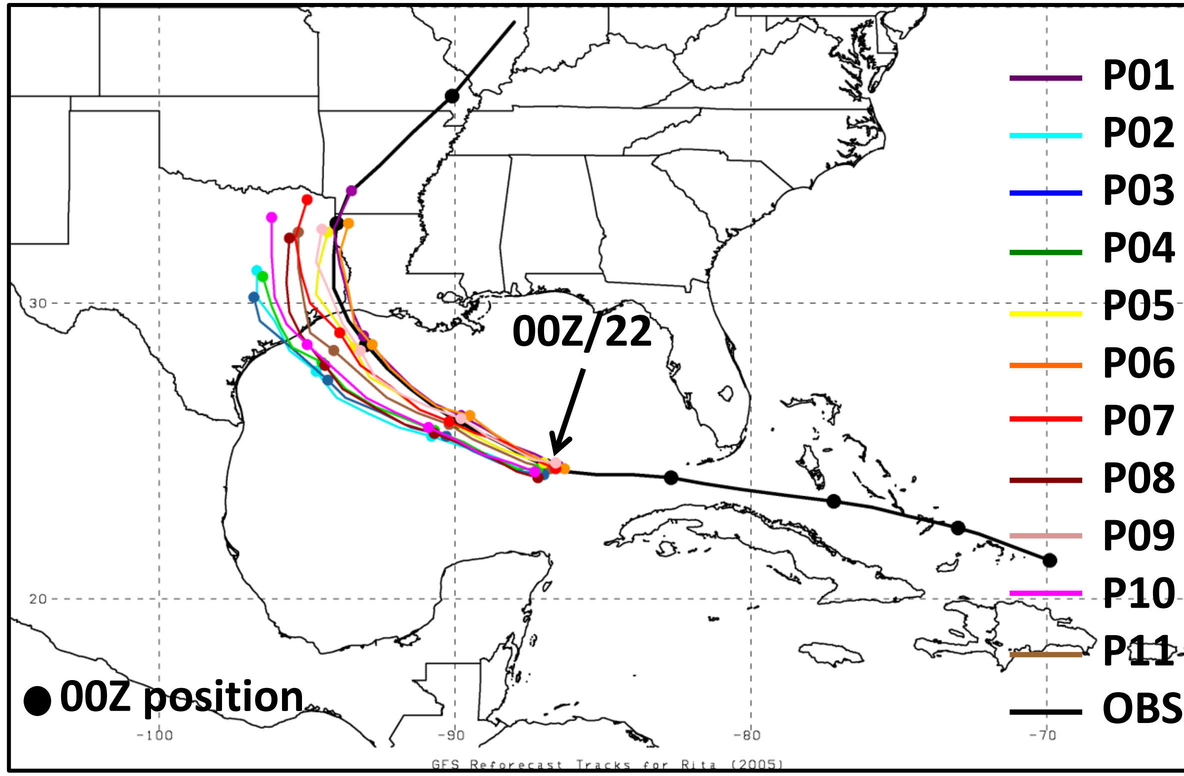


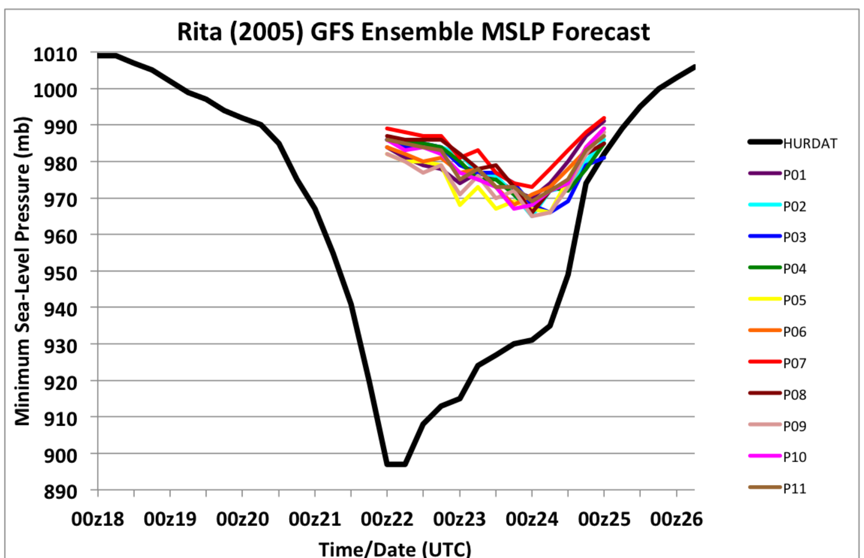

Almost perfect reliability.

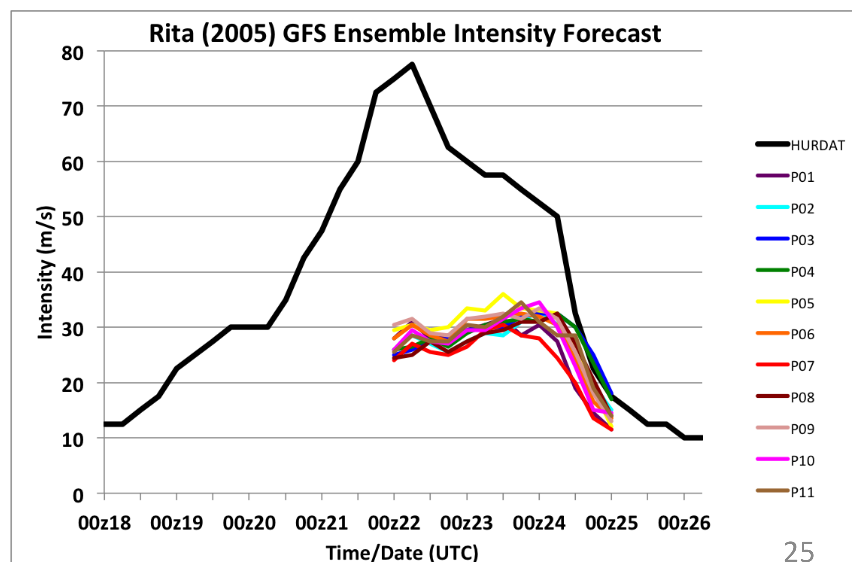
TC Rita (2005)

GFS reforecast ensemble

72-h forecast
initialized at 00Z 22 Sept



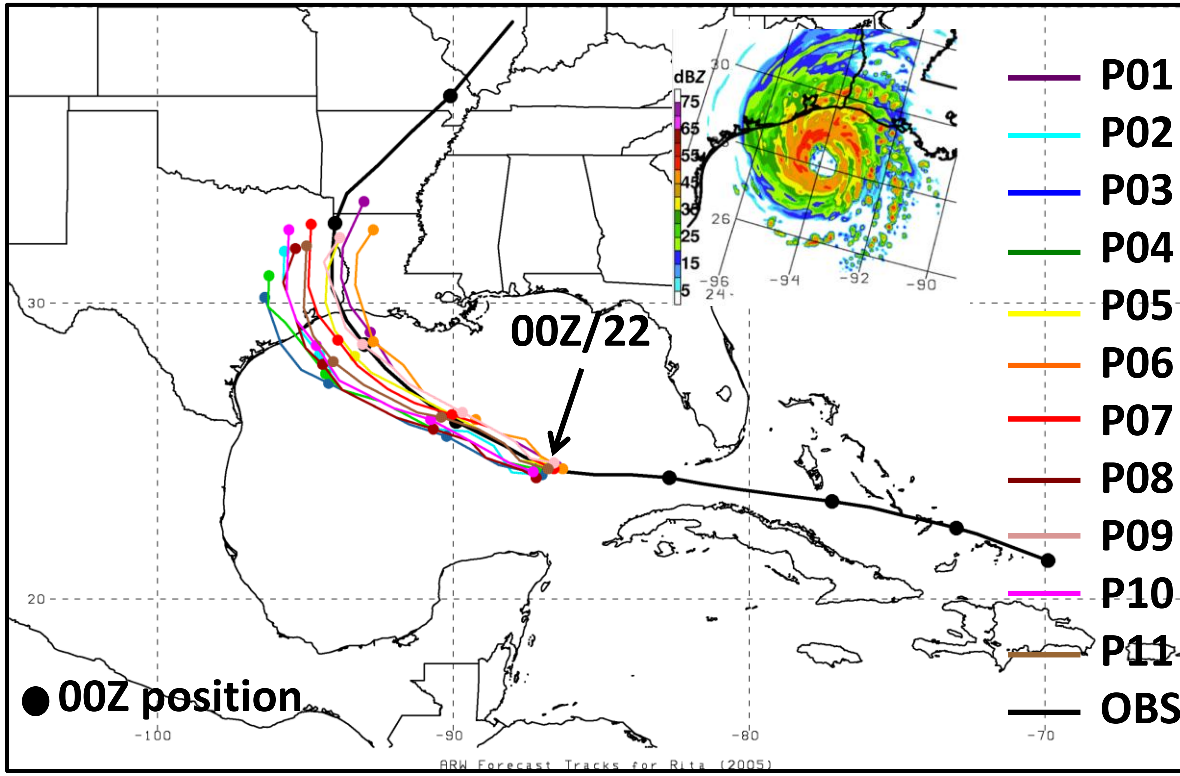



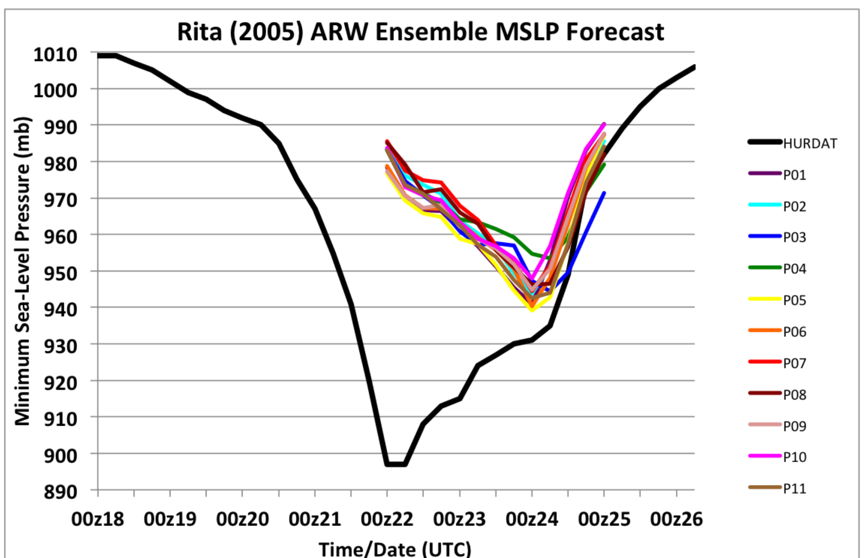



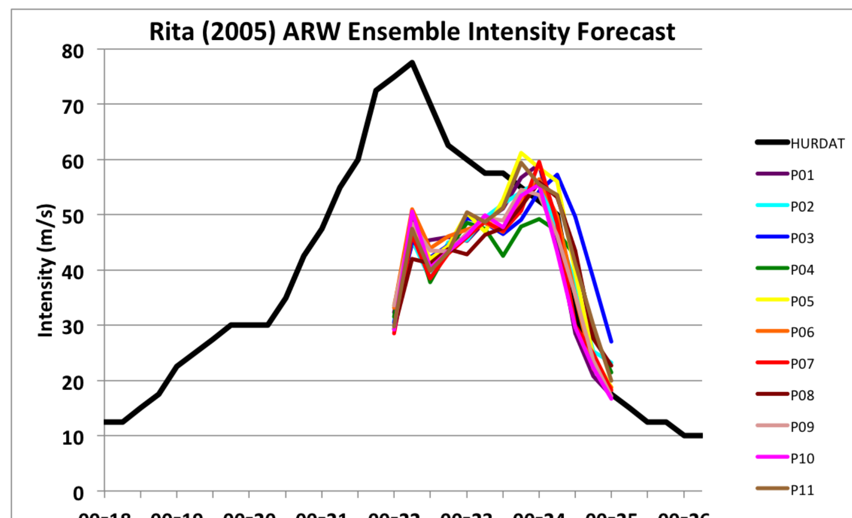
**TC Rita (2005)**

**ARW ensemble with GFS reforecast ensemble as boundary and initial conditions**

**72-h forecast initialized at 00Z 22 Sept**

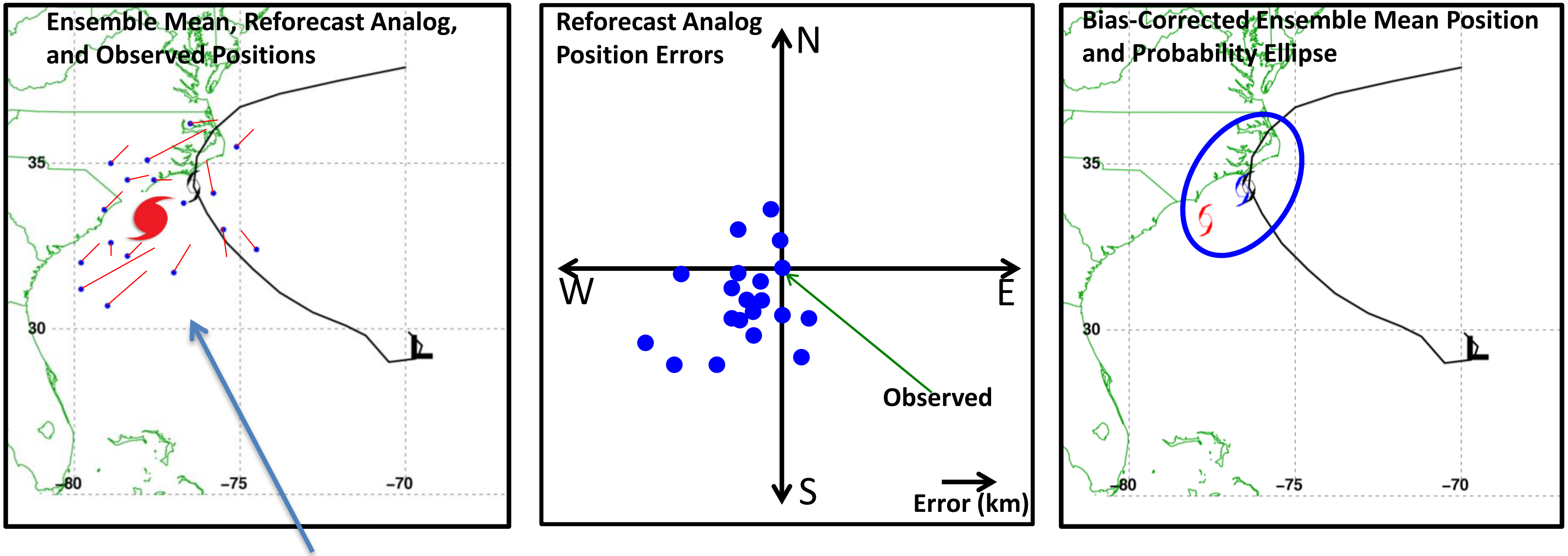


# A synthetic example of using reforecasts to make track error bias corrections

**72-h Forecast Verifying 1200 UTC 9 September**




Red : mean forecast position

Blue dot: forecast positions of +72-h forecast analogs

End of red tail ___ : observed positions at +72 h

# Define BSS for evaluating blocking skill

- The blocking Brier Skill score is calculated after summing forecast and climatological Brier scores over the relevant longitudes in either the Pacific or Atlantic basins, respectively, then averaged. For example (Pac):

$$BSS = 1.0 - \frac{BS_{forecast}}{BS_{climo}}$$

$$BS_{forecast} = \sum_{l_p=1}^{nlons} \sum_{i=1}^{ndates} \left( p_i^{forecast}\left(l_p\right) - o_i\left(l_p\right) \right)^2$$

$$BS_{climo} = \sum_{l_p=1}^{nlons} \sum_{i=1}^{ndates} \left( p_i^{climo}\left(l_p\right) - o_i\left(l_p\right) \right)^2$$

$$o_i\left(l_p\right) = \left\{ \begin{array}{ll} 1 & if\ blocked \\ 0 & if\ unblocked \end{array} \right\}$$

$$p_i^{forecast}\left(l_p\right) = ensemble\text{ - }based\ probability\ of\ block\ for\ this\ longitude$$

$$p_i^{climo}\left(l_p\right) = climatological\ probability\ of\ block\ for\ this\ longitude$$

# Methods for representing model uncertainty in ensembles

- Multi-model ensembles
  - Pros
    - Everybody gets to keep working on their own model.
    - Seems to work well for seasonal predictions
  - Cons
    - Heavy maintenance burden – hard to keep all models equally skillful.
    - Addresses uncertainties in model formulation – but not the effects of sub-grid scale variability.

# Methods for representing model uncertainty in ensembles

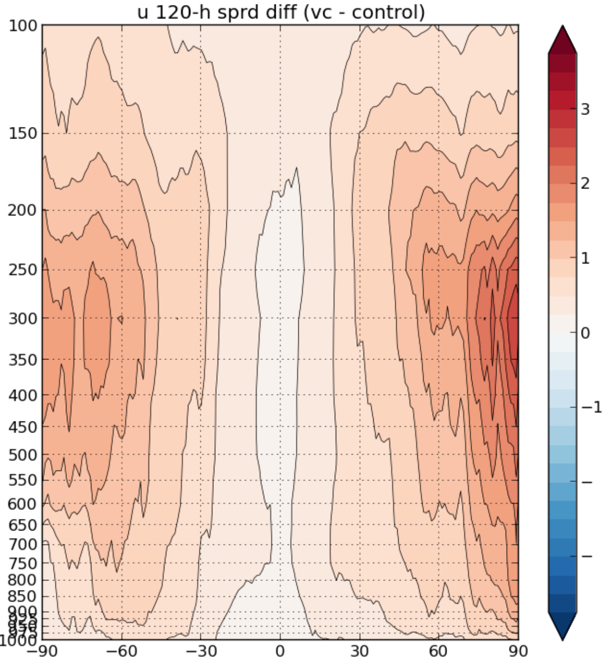
- Parameter perturbations
  - Pros
    - Relatively simple to create (no need to develop new schemes).
  - Cons
    - How to determine the sensitive parameters, what a reasonable parameter range is?
    - Nonlinear interactions between processes (radiation/convection/boundary layer). Easy to push model into an unrealistic regime.

# Methods for representing model uncertainty in ensembles

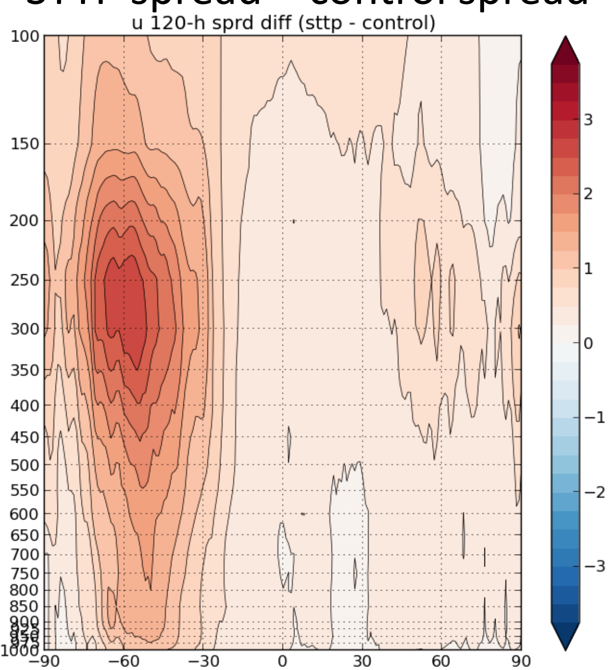
- Stochastic parameterization
  - Pros
    - Potentially a more rigorous approach.
    - They have a deterministic limit – can maintain a single model for deterministic and ensemble prediction.
  - Cons
    - Hard to find observations to inform development (use LES simulations instead?)
    - Should be done from the ground-up, at the process level.

# U spread differences

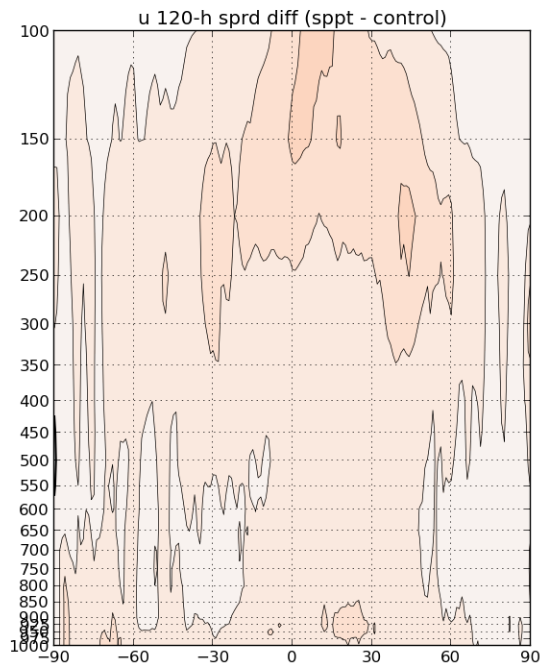
VC spread – control spread



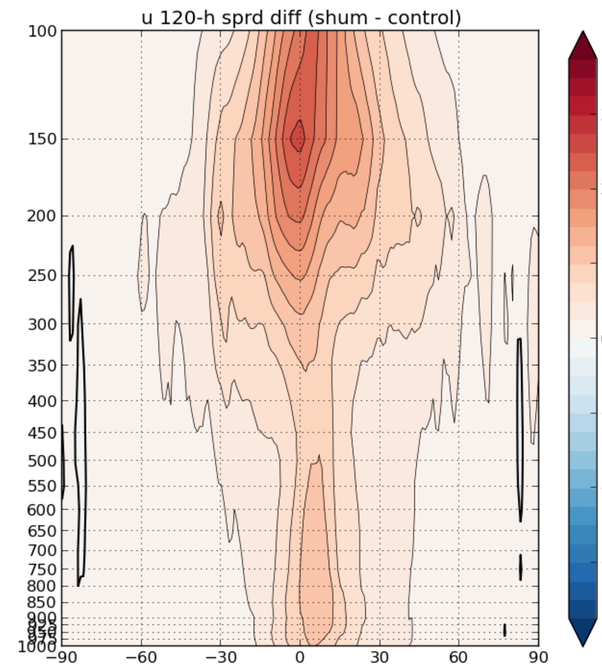

STTP spread – control spread



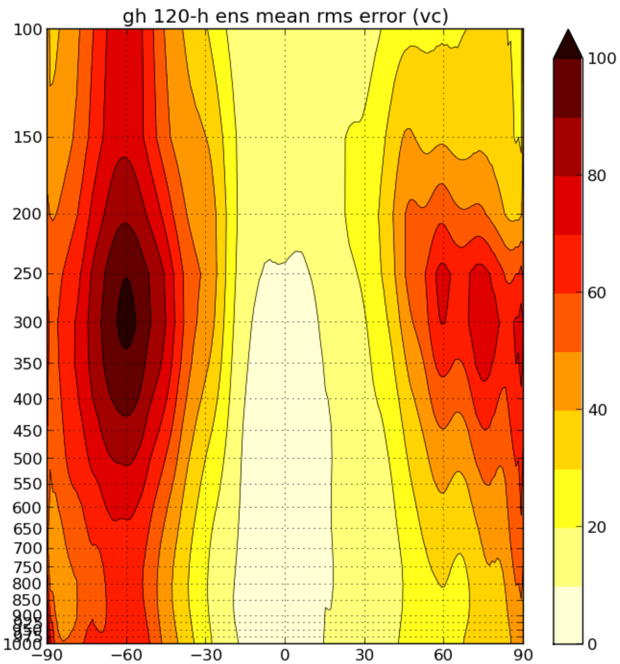

SPPT spread – control spread



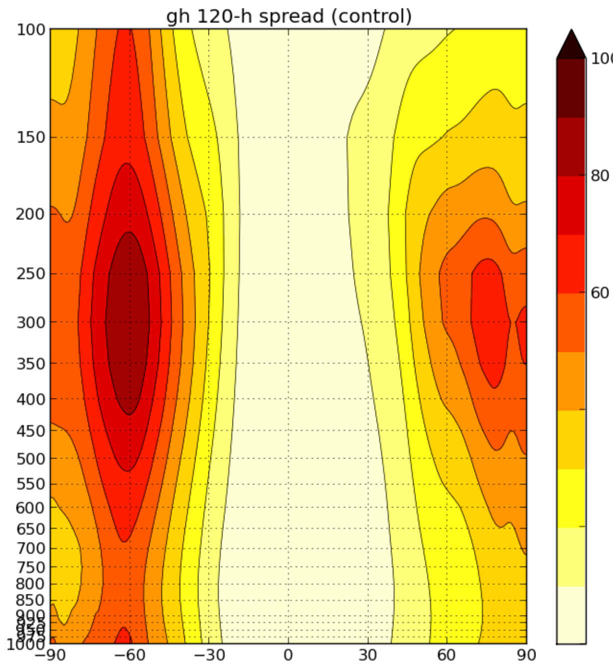

SHUM spread – control spread



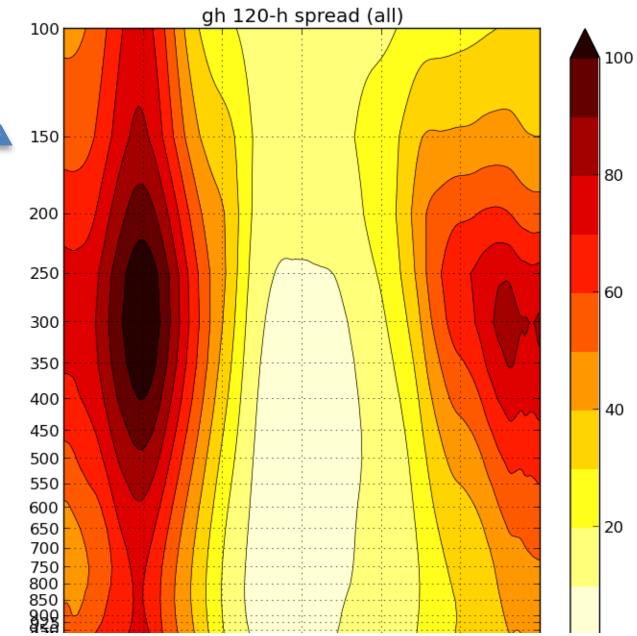
Ensemble Mean Error
(control)




Ensemble Spread
(control)

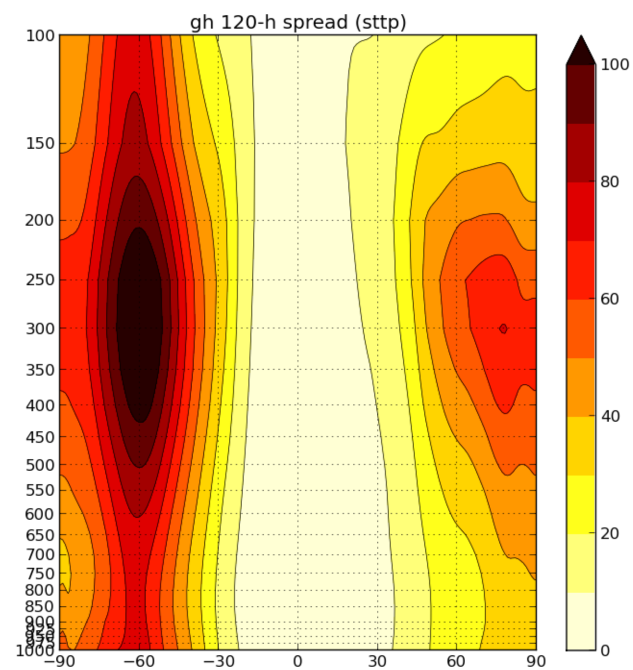



Ensemble Spread
(SPPT+SHUM+VC)



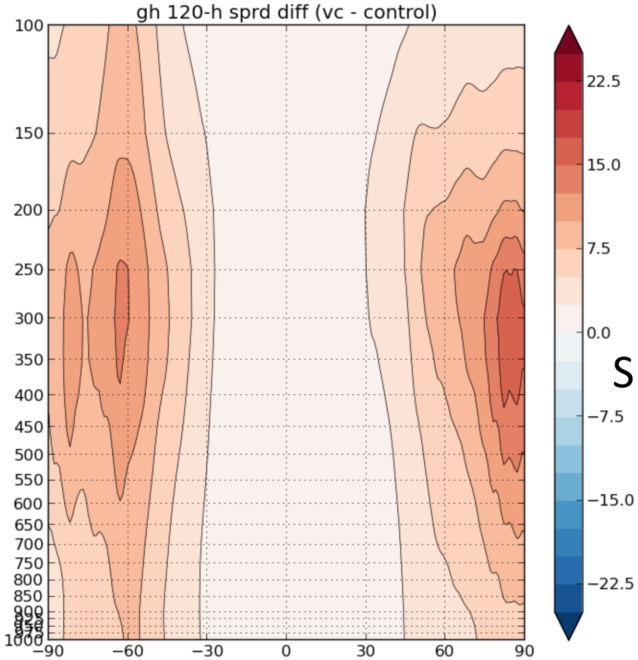

# Geopotential Height Spread

Ensemble Spread
(SPPT)

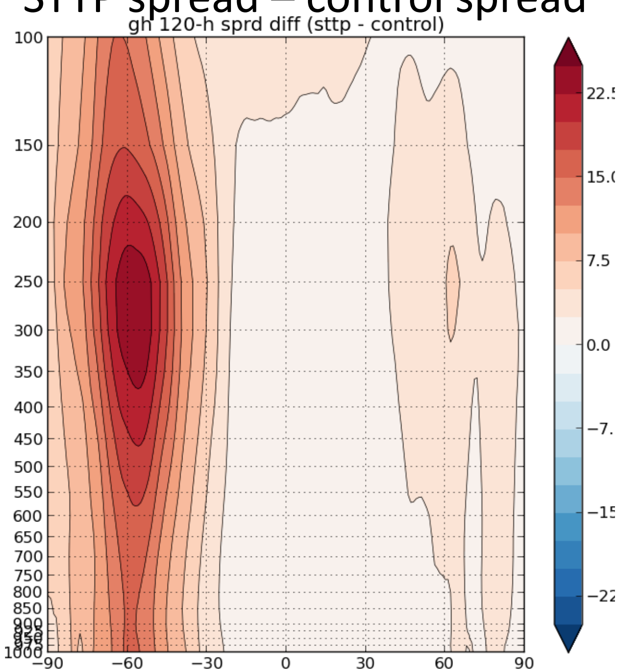


# Z spread differences

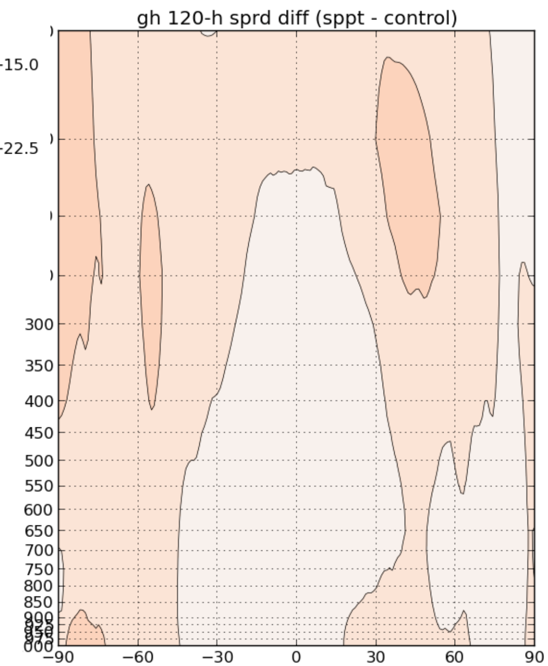
VC spread – control spread



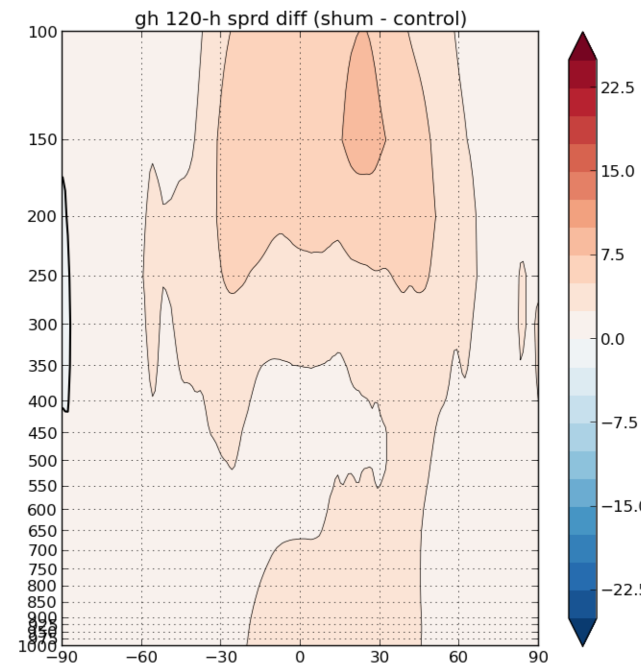

STTP spread – control spread




SPPT spread – control spread



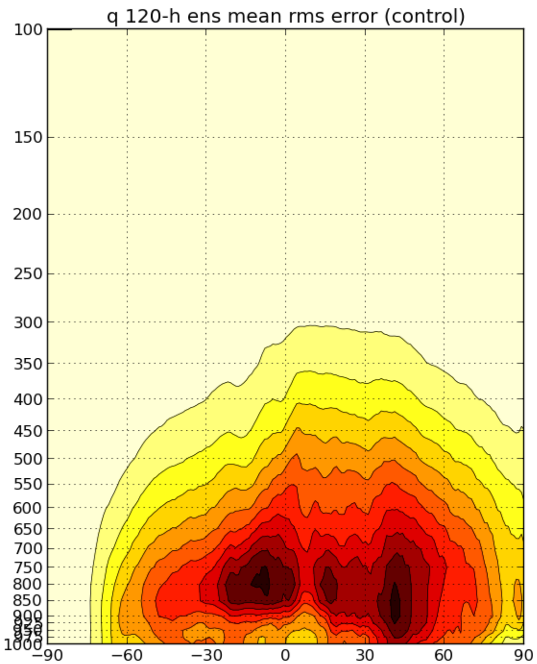

SHUMs pread – control spread



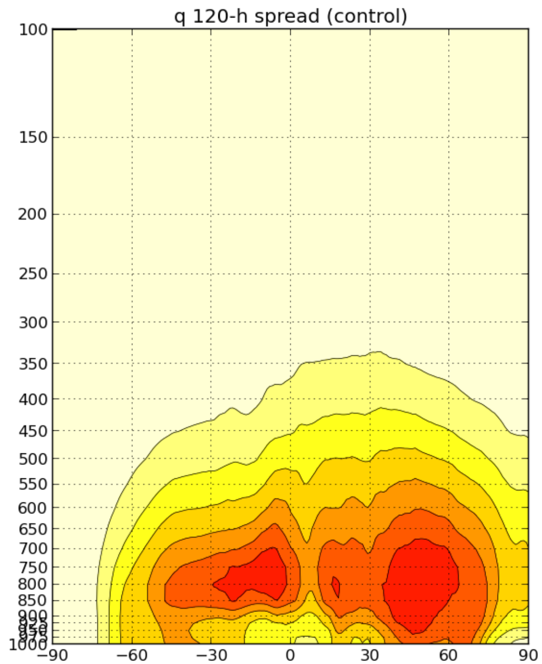
# Specific Humidity Spread

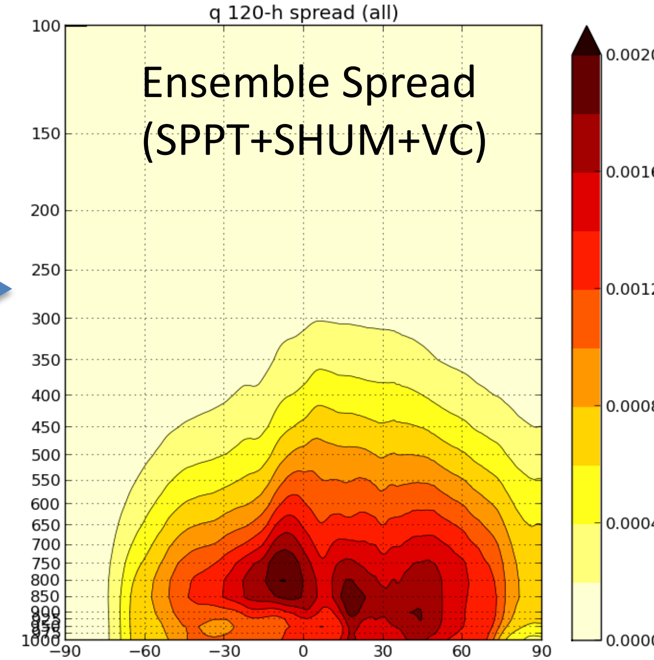
Almost all of the spread increase comes from SHUM

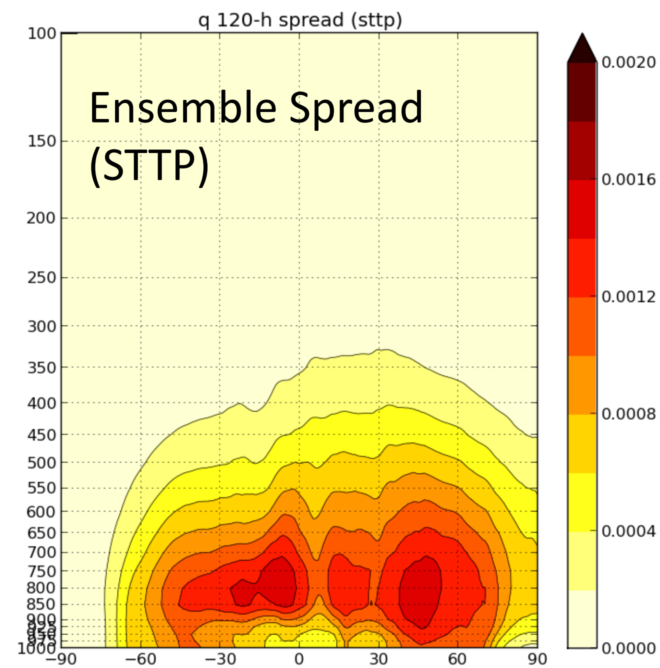
Ensemble Mean Error (control)



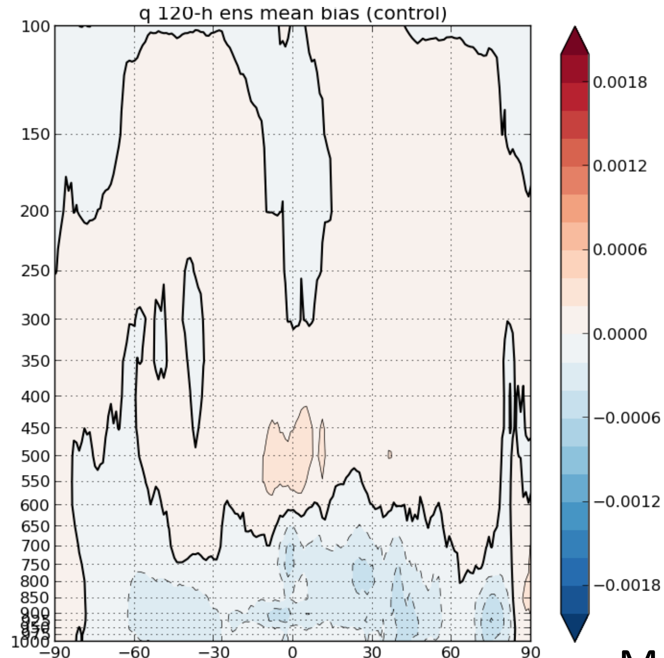

Ensemble Spread (control)



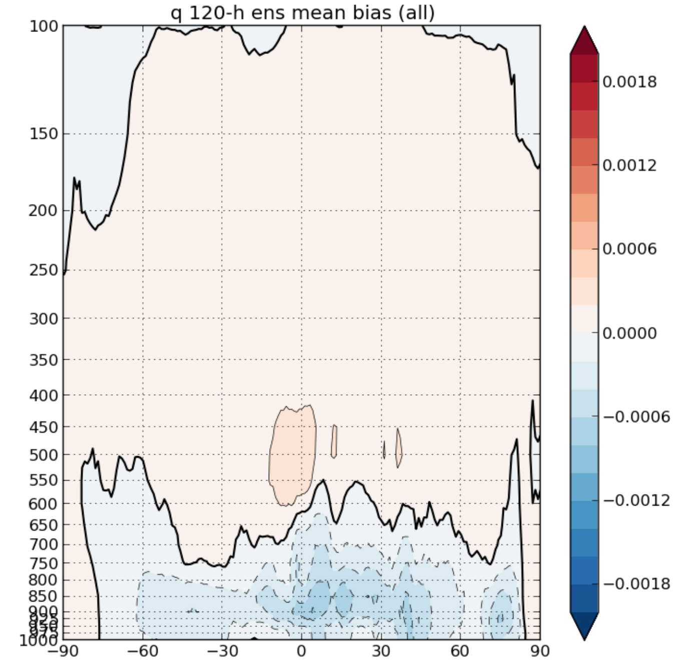
# Bias



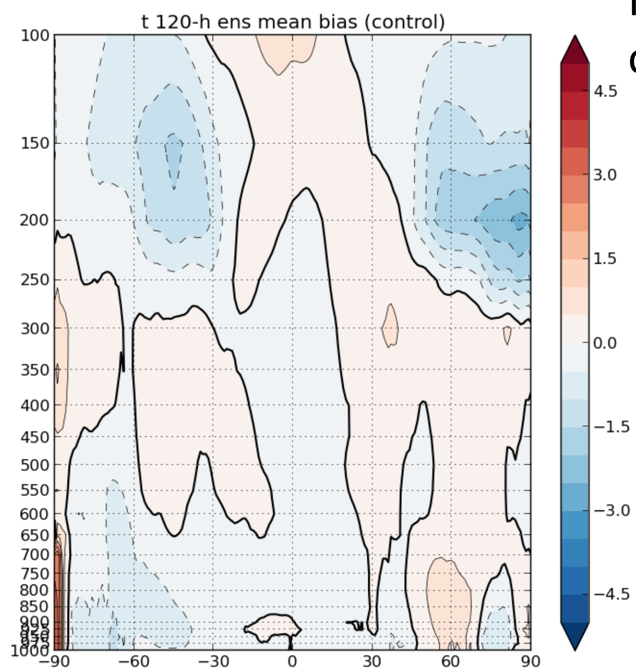

Humidity

← Control

ALL →



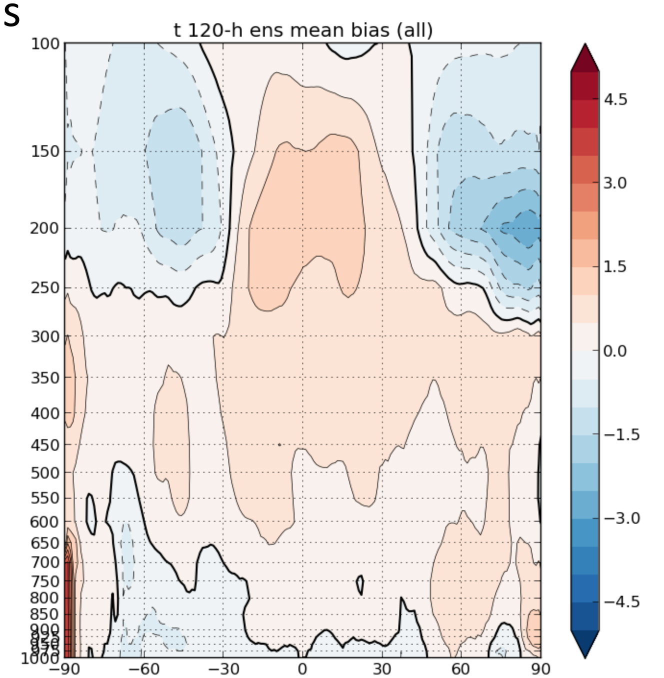

Most of additional bias comes from SHUM




Temperature

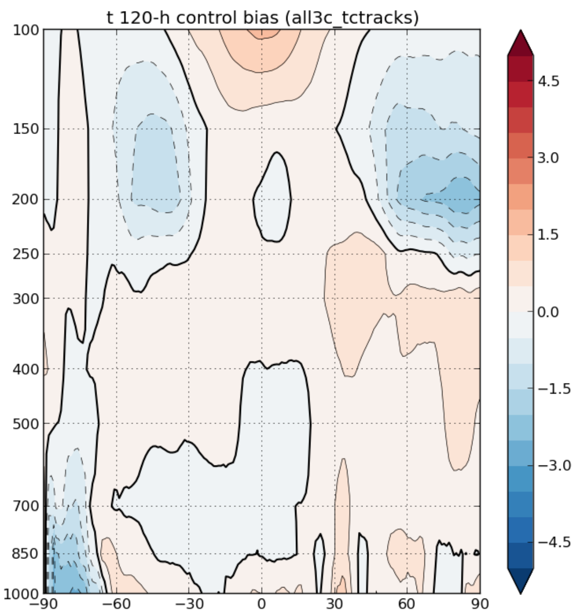
← Control

ALL →

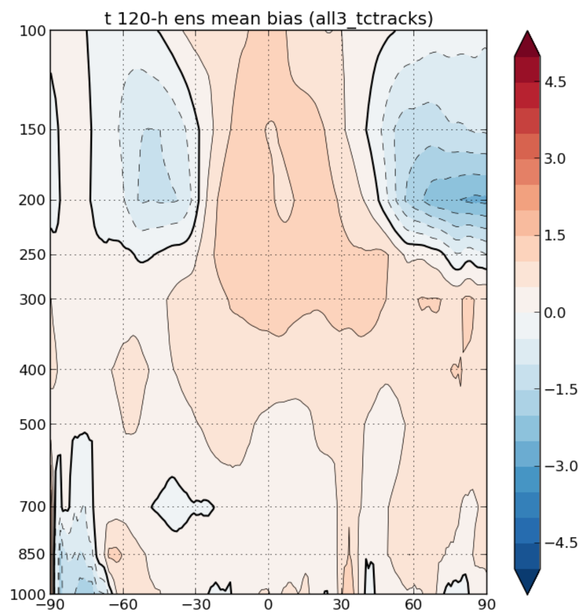


# Zonal mean T bias (120-h) (relative to EC analysis)

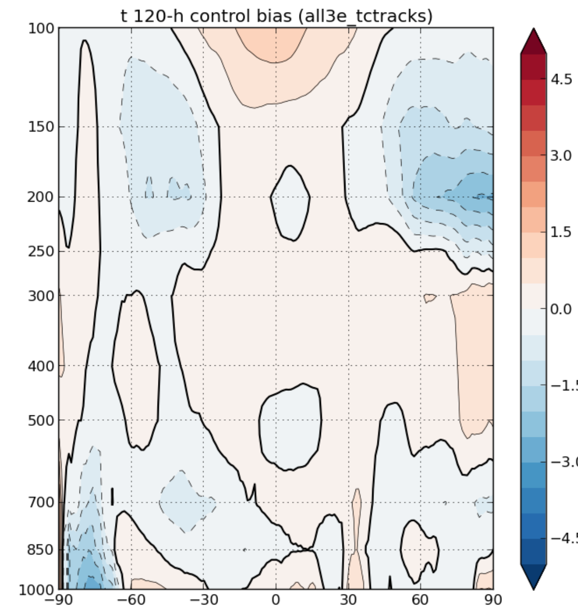
control




VC+SPPT+SHUM

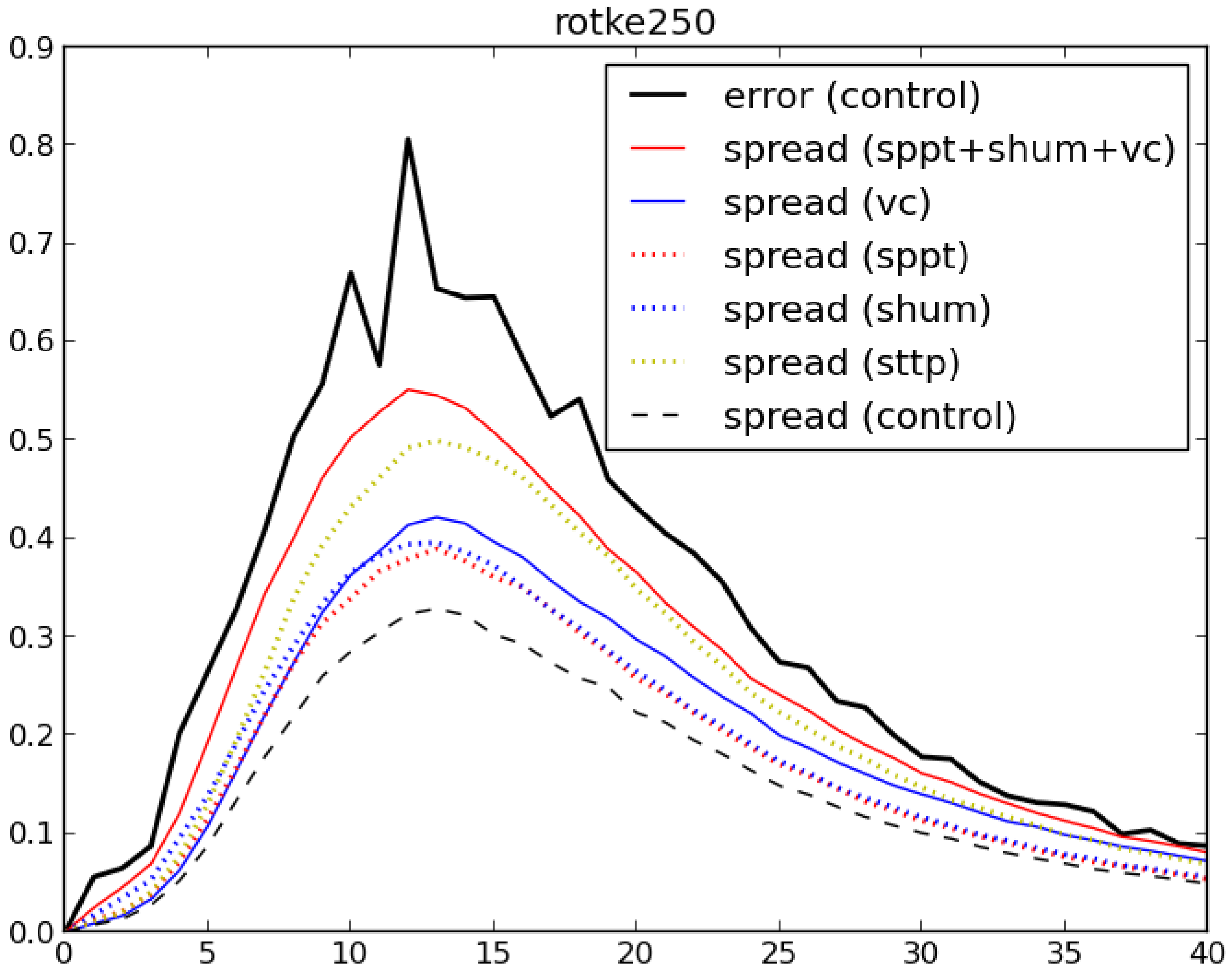



VC+SPPT+SHUM
Modified micro-physics

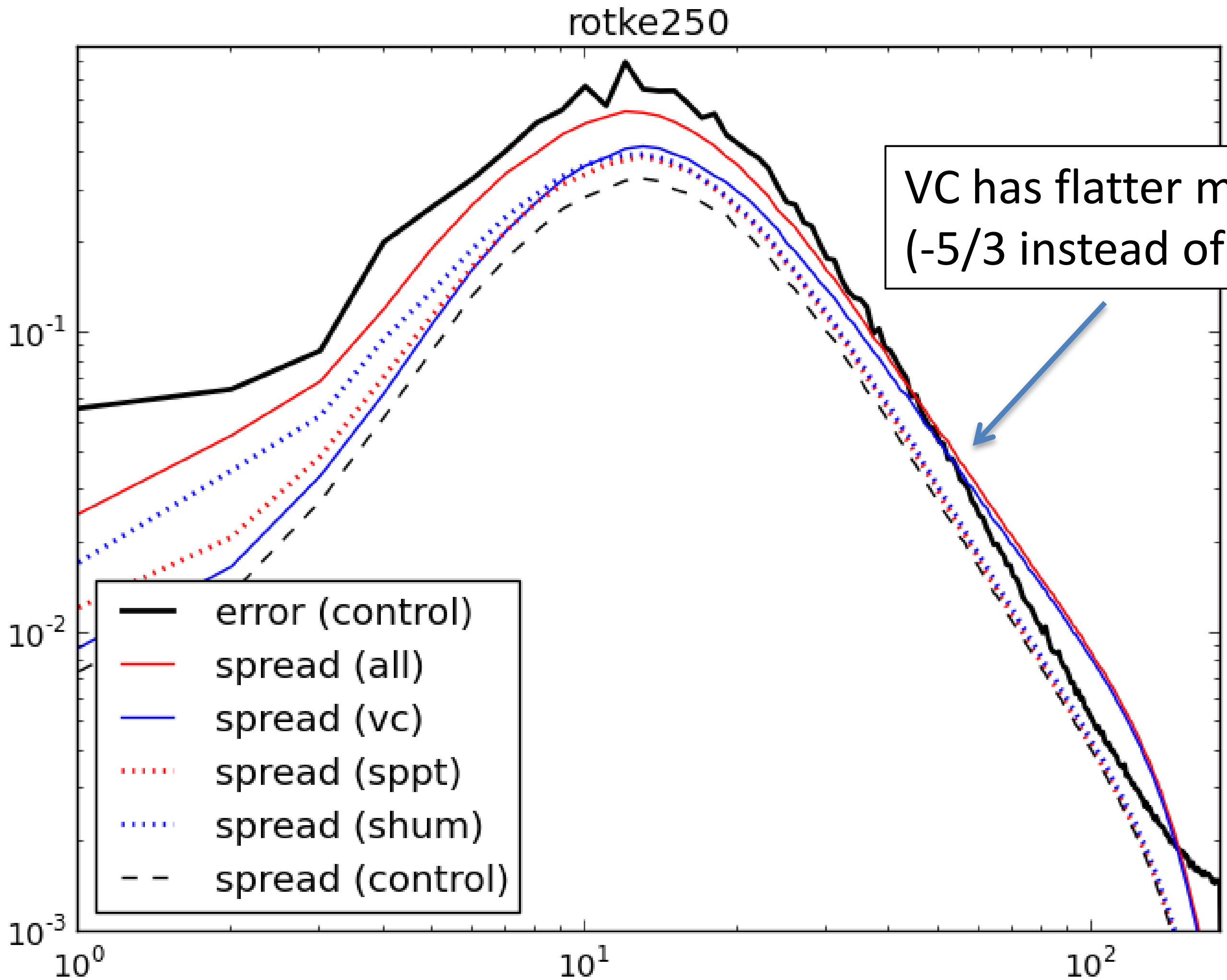



Bias eliminated if microphysics parameters appropriate for higher res GFS used (the model with stochastic physics behaves like a higher resolution model).

# KE spectra

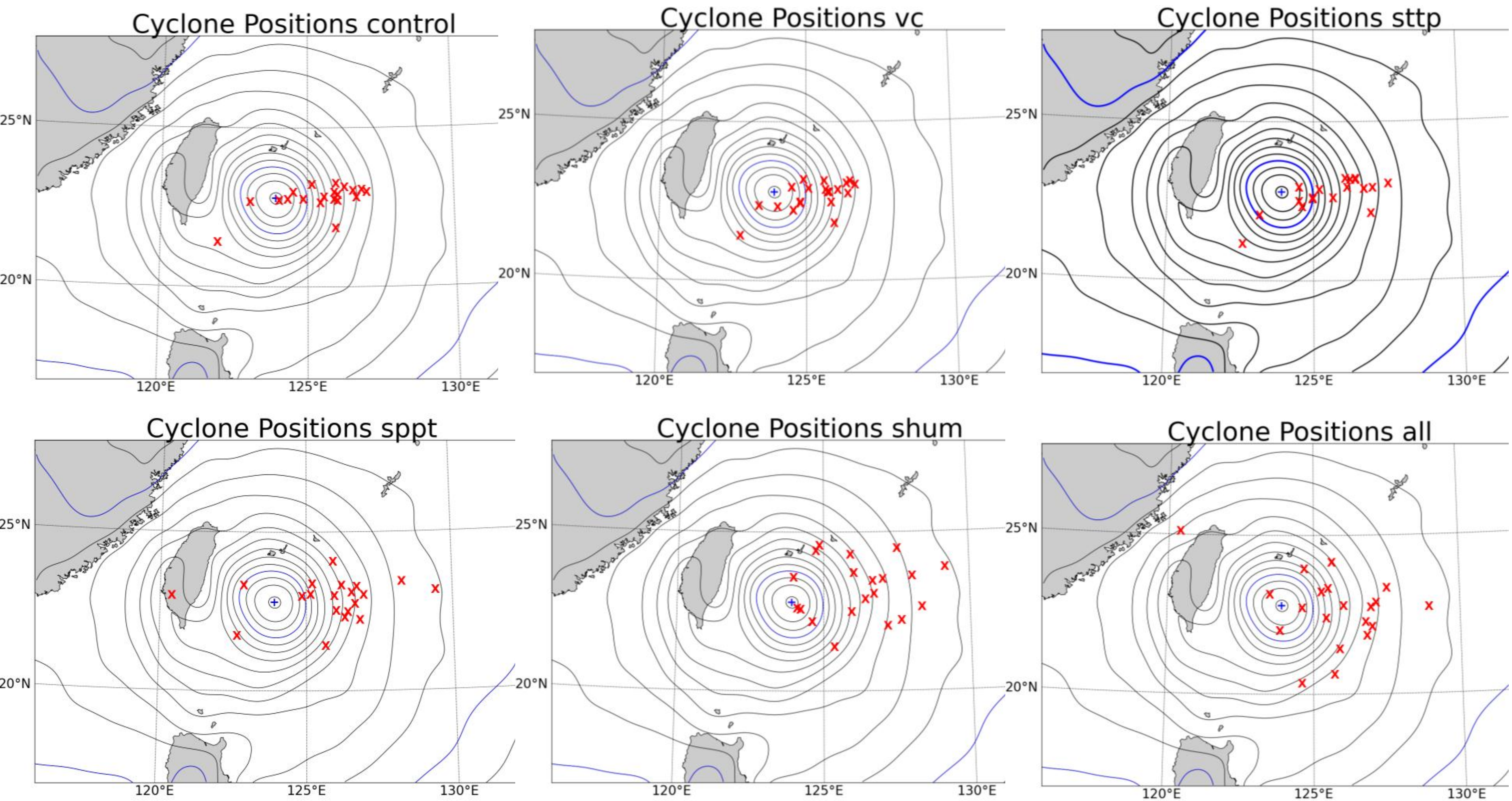

rotke250
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
error (control)
spread (sppt+shum+vc)
spread (vc)
spread (sppt)
spread (shum)
spread (sttp)
spread (control)

# KE spectra (log-log)




VC has flatter mesoscale spectrum (-5/3 instead of -3?)

# Effect on 3-d forecast TC position spread



# esrl.noaa.gov/psd/forecasts/reforecast2/download.html

**Select Desired Variables and Associated Levels:**

**Single Level (1°x1°)** | Pressure Levels (1°x1°) | Hybrid Levels (1°x1°) | Single Level (Gaussian ~.5°)

| | |
|---|---|
| ◯ Total Accumulated Precipitation | ◯ Temperature at 2 meters |
| ◯ U-Component of Wind at 10 meters | ◯ V-Component of Wind at 10 meters |
| ◯ U-Component of Wind at 80 meters | ◯ V-Component of Wind at 80 meters |
| ◯ Convective Available Potential Energy | ◯ Convective Inhibition |
| ◯ Surface Downward Long-Wave Radiation Flux | ◯ Surface Downward Short-Wave Radiation Flux |
| ◯ Surface Upward Long-Wave Radiation Flux | ◯ Surface Upward Short-Wave Radiation Flux |
| ◯ Ground Heat Flux | ◯ Surface Latent Heat Net Flux |
| ◯ Surface Sensible Heat Net Flux | ◯ Mean Sea Level Pressure |
| ◯ Surface Pressure | ◯ Precipitable Water |
| ◯ Volumetric Soil Moisture Content | ◯ Specific Humidity at 2 meters |
| ◯ Total Cloud Cover | ◯ Total Column-Integrated Condensate |
| ◯ Skin Temperature | ◯ Maximum Temperature |
| ◯ Minimum Temperature | ◯ Soil Temperature (0-10 cm below surface) |
| ◯ Upward Long-Wave Radiation Flux | ◯ Water Runoff |
| ◯ Water Equivalent of Accumulated Snow Depth | ◯ Wind Mixing Energy |
| ◯ Vertical Velocity at 850 hPa Surface | ◯ Temperature on 2 PVU Surface |
| ◯ Pressure on 2 PVU Surface | ◯ U-Component of Wind on 2 PVU Surface |
| ◯ V-Component of Wind on 2 PVU Surface | ◯ Potential Vorticity on 320 K Isentrope |

**Select Desired Dates (Available from Dec 1 1984 to Dec 31 2010):**

**From:** ______ **To:** ______

◉ Download all the forecasts within the chosen time period. Help
◯ Download forecasts within the month-days range for the chosen years. Help

**Select Desired Forecast Hour(s):**

**High Resolution:** (Select All or Clear)

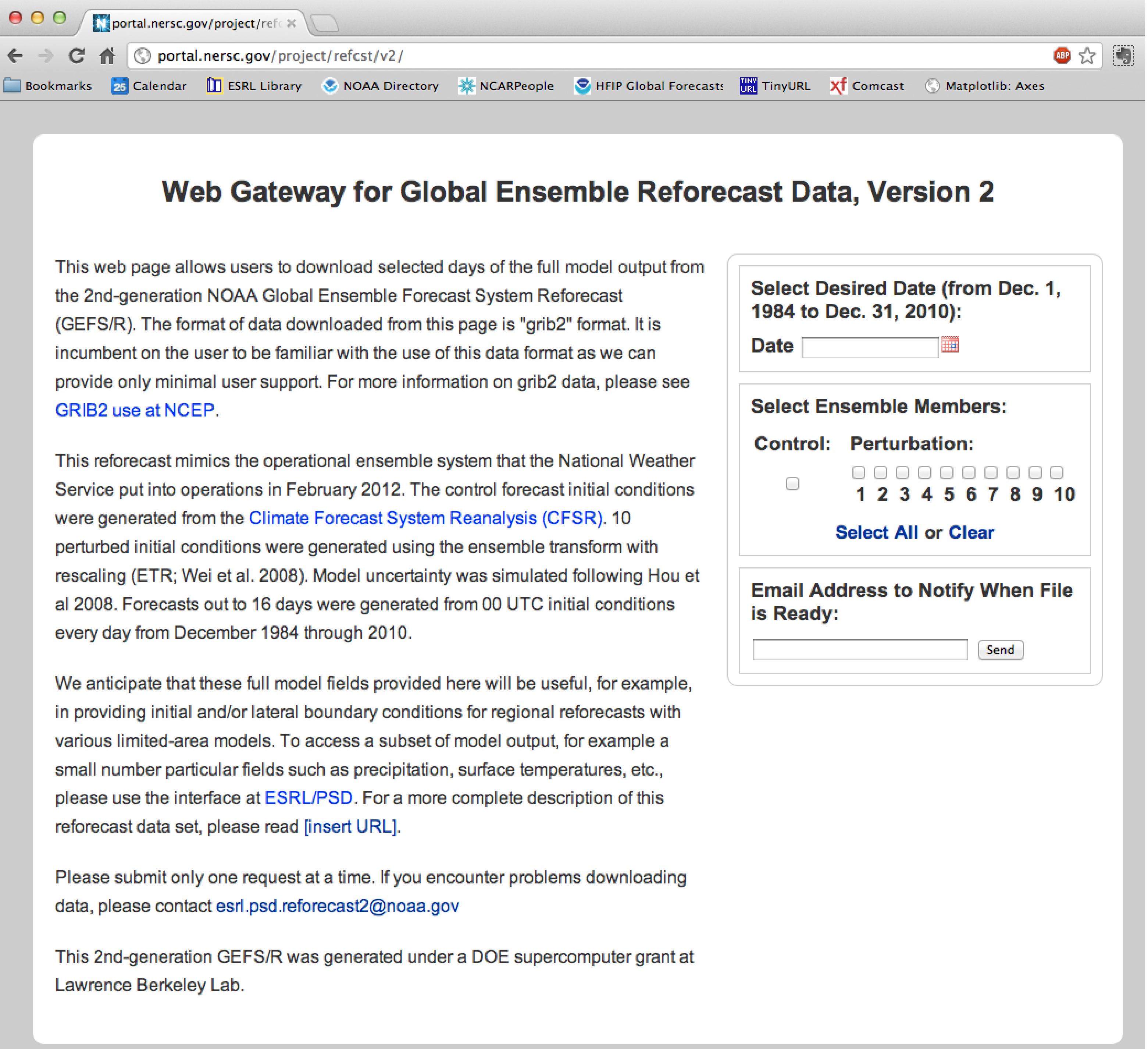
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ☐ 0 | ☐ 3 | ☐ 6 | ☐ 9 | ☐ 12 | ☐ 15 | ☐ 18 | ☐ 21 | ☐ 24 | ☐ 27 |
| ☐ 30 | ☐ 33 | ☐ 36 | ☐ 39 | ☐ 42 | ☐ 45 | ☐ 48 | ☐ 51 | ☐ 54 | ☐ 57 |
| ☐ 60 | ☐ 63 | ☐ 66 | ☐ 69 | ☐ 72 | ☐ 78 | ☐ 84 | ☐ 90 | ☐ 96 | ☐ 102 |
| ☐ 108 | ☐ 114 | ☐ 120 | ☐ 126 | ☐ 132 | ☐ 138 | ☐ 144 | ☐ 150 | ☐ 156 | ☐ 162 |
| ☐ 168 | ☐ 174 | ☐ 180 | ☐ 186 | ☐ 192 | | | | | |

**Low Resolution:** (Select All or Clear)

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| ☐ 186 | ☐ 192 | ☐ 198 | ☐ 204 | ☐ 210 | ☐ 216 | ☐ 222 | ☐ 228 | ☐ 234 | ☐ 240 |
| ☐ 246 | ☐ 252 | ☐ 258 | ☐ 264 | ☐ 270 | ☐ 276 | ☐ 282 | ☐ 288 | ☐ 294 | ☐ 300 |
| ☐ 306 | ☐ 312 | ☐ 318 | ☐ 324 | ☐ 330 | ☐ 336 | ☐ 342 | ☐ 348 | ☐ 354 | ☐ 360 |
| ☐ 366 | ☐ 372 | ☐ 378 | ☐ 384 | | | | | | |

Produces netCDF files.

Also: direct ftp access to allow you to read the raw grib files.


portal.nersc.gov/project/refcst/v2/

Bookmarks | Calendar | ESRL Library | NOAA Directory | NCARPeople | HFIP Global Forecasts | TinyURL | Comcast | Matplotlib: Axes

# Web Gateway for Global Ensemble Reforecast Data, Version 2

This web page allows users to download selected days of the full model output from the 2nd-generation NOAA Global Ensemble Forecast System Reforecast (GEFS/R). The format of data downloaded from this page is "grib2" format. It is incumbent on the user to be familiar with the use of this data format as we can provide only minimal user support. For more information on grib2 data, please see GRIB2 use at NCEP.

This reforecast mimics the operational ensemble system that the National Weather Service put into operations in February 2012. The control forecast initial conditions were generated from the Climate Forecast System Reanalysis (CFSR). 10 perturbed initial conditions were generated using the ensemble transform with rescaling (ETR; Wei et al. 2008). Model uncertainty was simulated following Hou et al 2008. Forecasts out to 16 days were generated from 00 UTC initial conditions every day from December 1984 through 2010.

We anticipate that these full model fields provided here will be useful, for example, in providing initial and/or lateral boundary conditions for regional reforecasts with various limited-area models. To access a subset of model output, for example a small number particular fields such as precipitation, surface temperatures, etc., please use the interface at ESRL/PSD. For a more complete description of this reforecast data set, please read [insert URL].

Please submit only one request at a time. If you encounter problems downloading data, please contact esrl.psd.reforecast2@noaa.gov

This 2nd-generation GEFS/R was generated under a DOE supercomputer grant at Lawrence Berkeley Lab.

**Select Desired Date (from Dec. 1, 1984 to Dec. 31, 2010):**

**Date**

**Select Ensemble Members:**

**Control:** **Perturbation:**

**1 2 3 4 5 6 7 8 9 10**

**Select All or Clear**

**Email Address to Notify When File is Ready:**

Send

This DOE site will be ready for access to tape storage of full data (slower).

Use this to access full model state.

# MJO deterministic verification metrics

$$\mathrm{COR}(\tau) = \frac{\sum_{i=1}^{N}[a_{1i}(t)b_{1i}(t) + a_{2i}(t)b_{2i}(t)]}{\sqrt{\sum_{i=1}^{N}[a_{1i}^2(t) + a_{2i}^2(t)]}\sqrt{\sum_{i=1}^{N}[b_{1i}^2(t) + b_{2i}^2(t)]}},$$

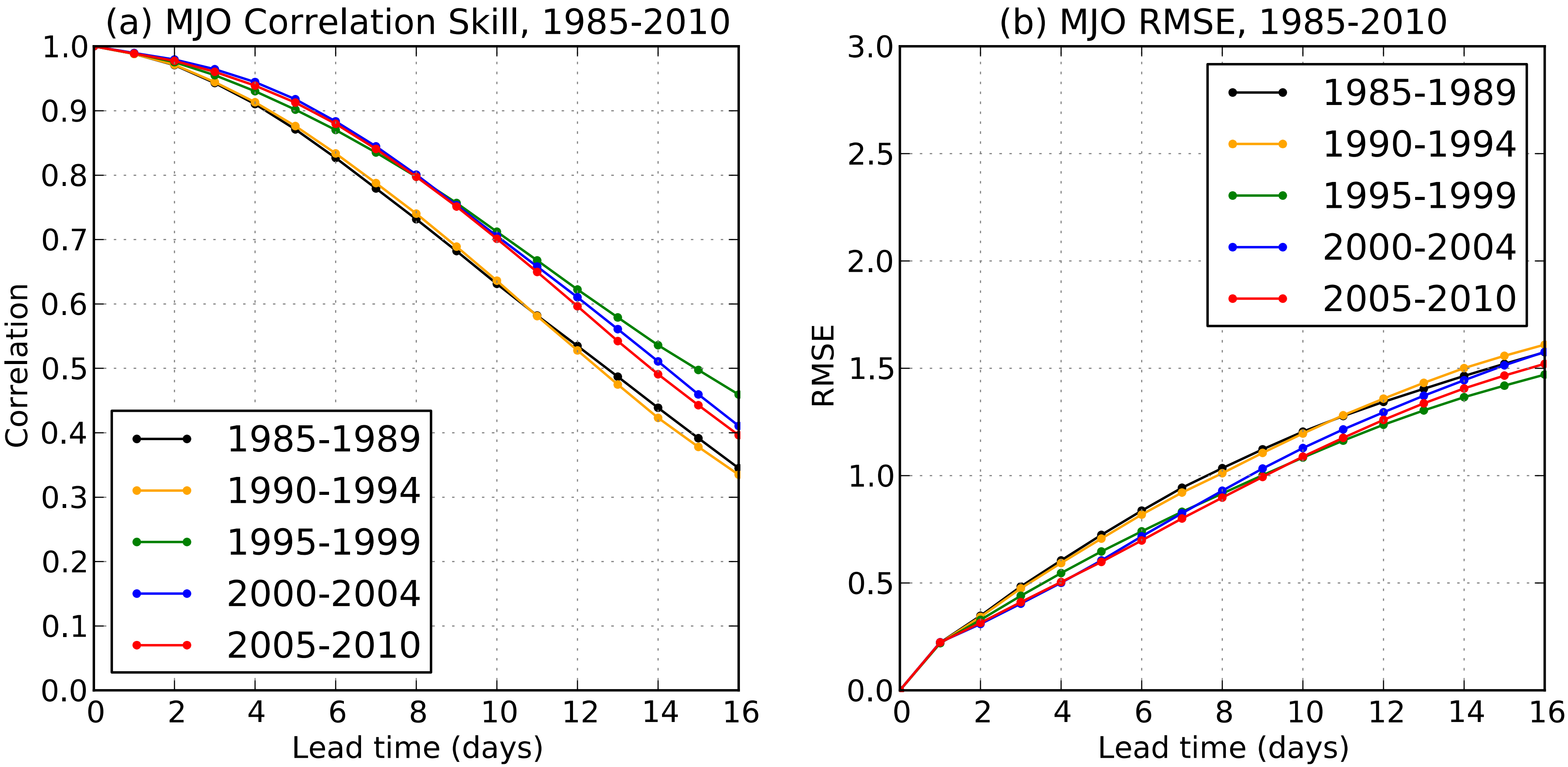
where $a_{1i}(t)$ and $a_{2i}(t)$ are the observed RMM1 and RMM2 at day $t$, and $b_{1i}(t)$ and $b_{2i}(t)$ are their respective forecasts, for the $i$th forecast with a $\tau$-day lead. Here, $N$ is the number of forecasts.

COR($\tau$) measures the skill in forecasting the phase of the MJO, which is insensitive to amplitude errors. COR($\tau$) is equivalent to a spatial pattern correlation between the observations and the forecasts when they are expressed by the two leading combined EOFs.

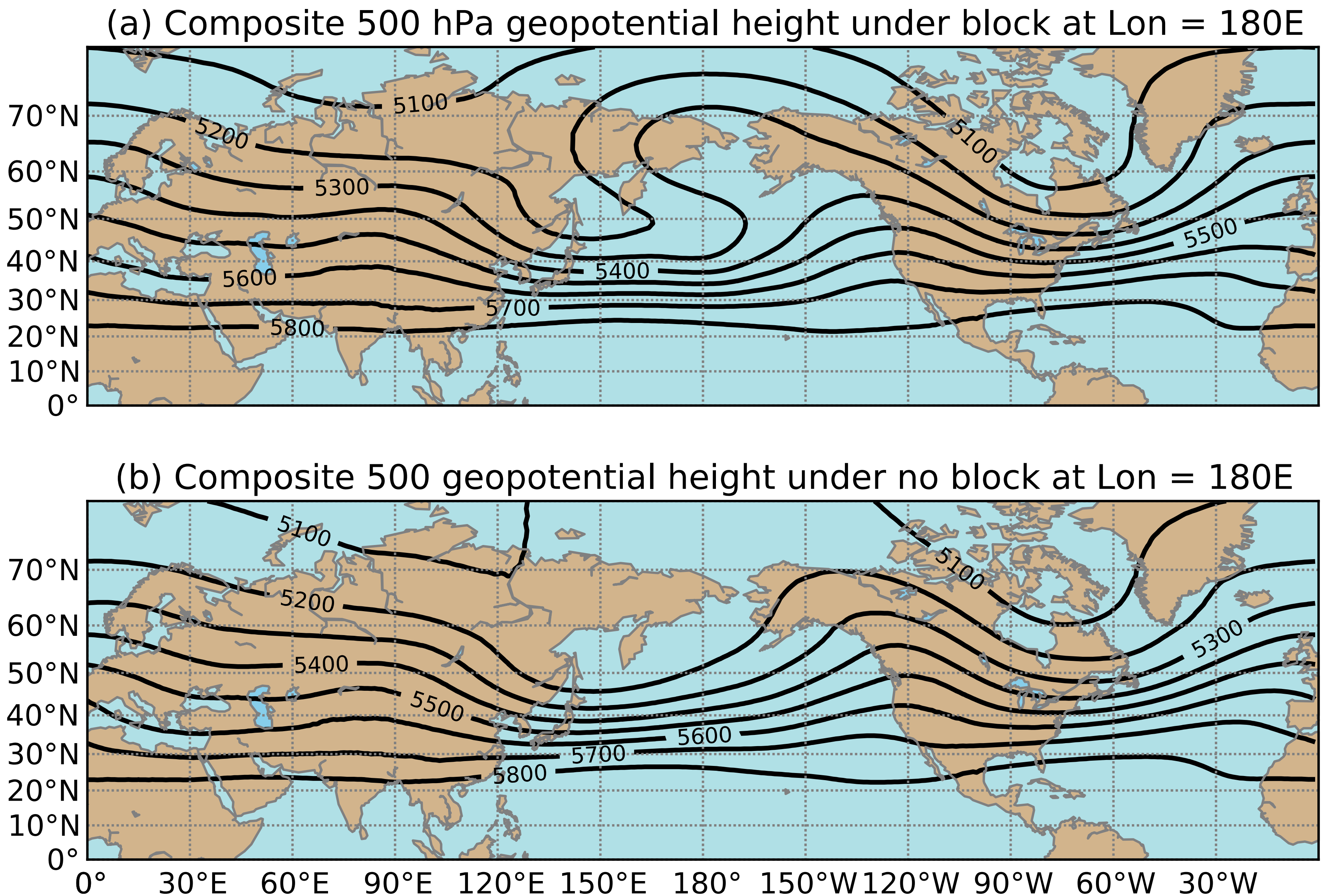
$$\mathrm{RMSE}(\tau) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\{[a_{1i}(t) - b_{1i}(t)]^2 + [a_{2i}(t) - b_{2i}(t)]^2\}}.$$

from Lin et al., Nov 2008 *MWR*.

# Bi-variate RMM1 and RMM2 correlation and RMSE by half decade

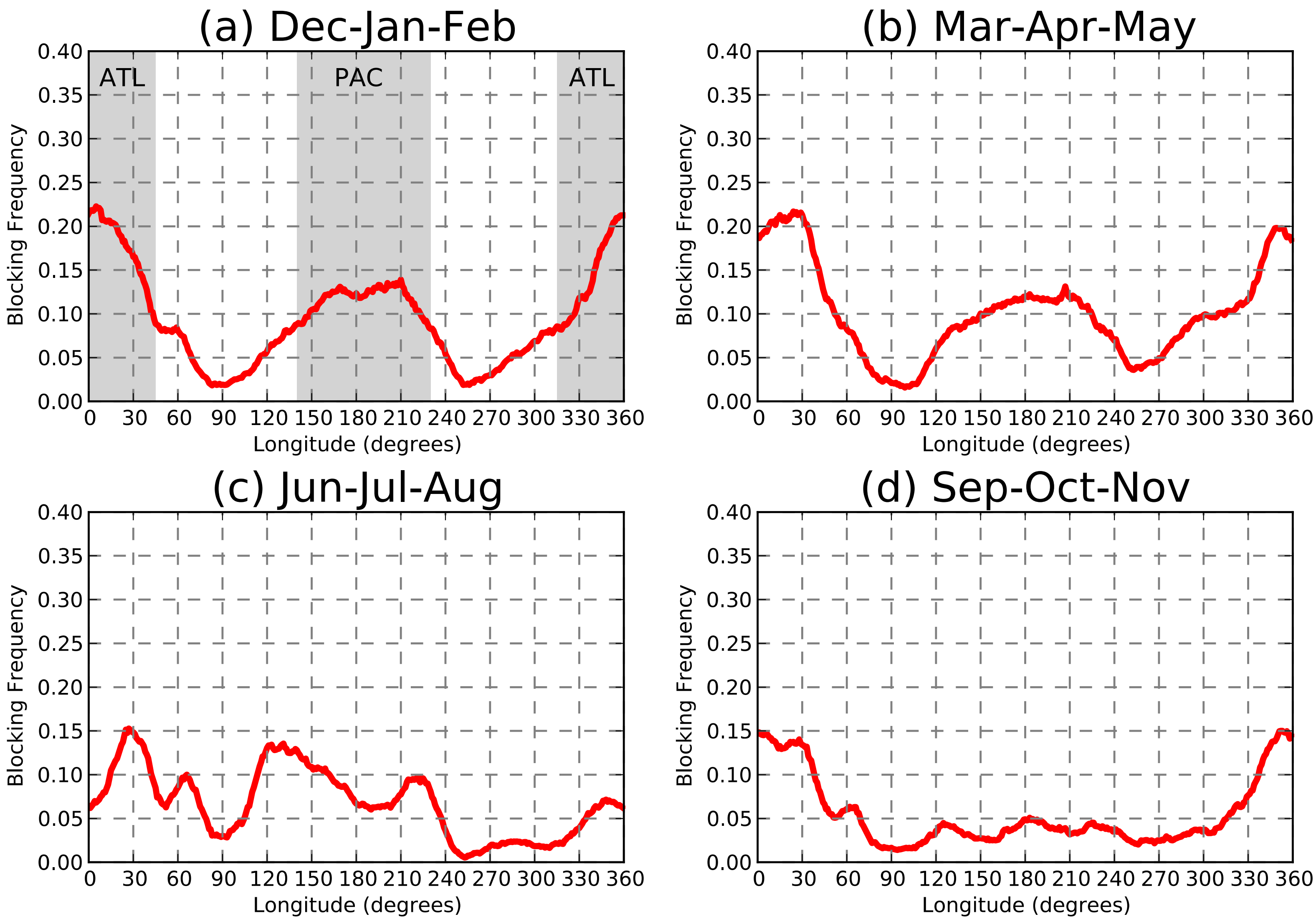



The first 10 years are much less skillful than the subsequent 16.




Dec-Jan-Feb 1985-2010 CFSR data. Blocks defined here by Tibaldi/Molteni algorithm.

# N Hem. blocking: more common in winter, spring




Blocking as defined in Tibaldi and Molteni (1990) using Z500. Hereafter, let's focus on Dec-Jan-Feb. Grey bands defines Euro/Atlantic and Pacific blocking sectors in subsequent plots.