NOAA Earth System Research Laboratory

Advances in ensemble weather prediction, 2008-2009

Tom Hamill
NOAA Earth System Research Lab
Boulder, Colorado, USA
tom.hamill@noaa.gov

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Highlights

- Improved stochastic treatments of model errors in ensemble predictions
- Growing maturity of ensemble Kalman filter for improved data assimilation, ensemble initialization.
- Convection-permitting ensembles
- Facilitation of research and model comparisons with new TIGGE data set
- Reforecasts and ensemble post-processing

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(1) Improved stochastic treatments of model errors in ensemble predictions

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SPPT: Stochastically Perturbed Physical Tendencies (ECMWF TM 598)

$$\forall\ X \in \{u, v, T, q\}, \quad X_p = (1 + r\mu) X_c \qquad \mu \in (0,1]$$

r is random number, μ used for reducing the perturbation amplitude near surface and in stratosphere. Random numbers generated through spectral pattern generator of Berner et al. (2009).

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SPPT, continued.

$$\psi^{'}(\phi,\lambda,t)=\sum_{n=0}^{N}\sum_{m=-n}^{n}\psi^{'m}(t)P_n^m(\cos\phi)e^{im\lambda}$$

Ψ' = streamfunction forcing; λ = longitude, ϕ = latitude, t = time;
m = zonal wavenumber, n = total wavenumber,
$\Psi'_n{}^m(t)$ = the random perturbation for this wavenumber,
$P_n{}^m$= Legendre polynomial.

$$\psi^{'m}(t+\Delta t)=(1-\alpha)\psi^{'m}(t)+g_n\sqrt{\alpha}\varepsilon(t)$$

$(1-\alpha)$ = linear autoregressive parameter, $0 < \alpha \le 1$;
g_n = wavenumber-dependent noise amplitude,
$\varepsilon(t)$ = Gaussian white-noise process with zero mean, variance σ_z^2

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SPPT: example of time series of r

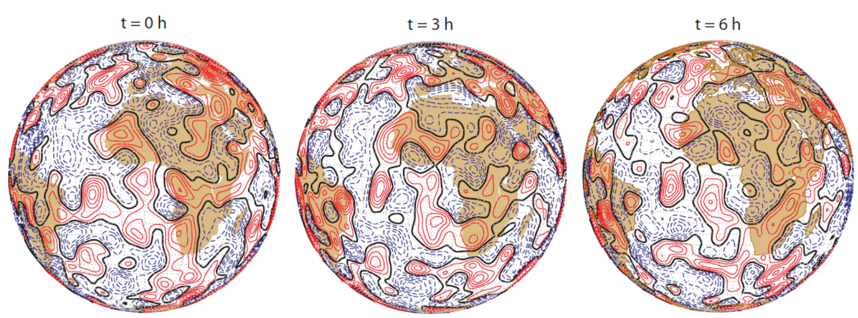

Figure 1: Example of the pattern r used in the revised scheme; contour interval 0.25; red (blue) contours correspond to positive(negative) values.

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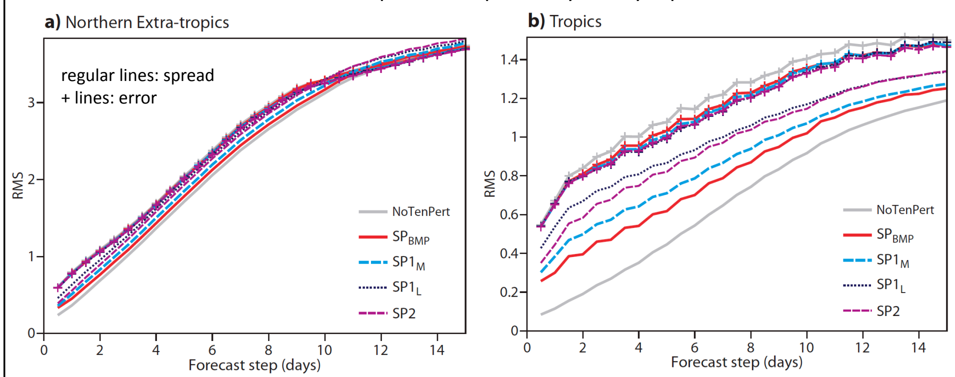
SPPT: T850 RMS error, NH & tropics

NoTenPert: No stochastic tendencies
SP_{BMP}: Buizza, Miller, Palmer blocky stochastic tendencies
SP1M: SPPT, 500 km, 6 h, σ(r)=0.5
SP1L: SPPT, 500 km, 6 h, σ(r)=0.75
SP2: Two independent r, planetary and synoptic scales



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Precipitation Brier scores (lower is better)

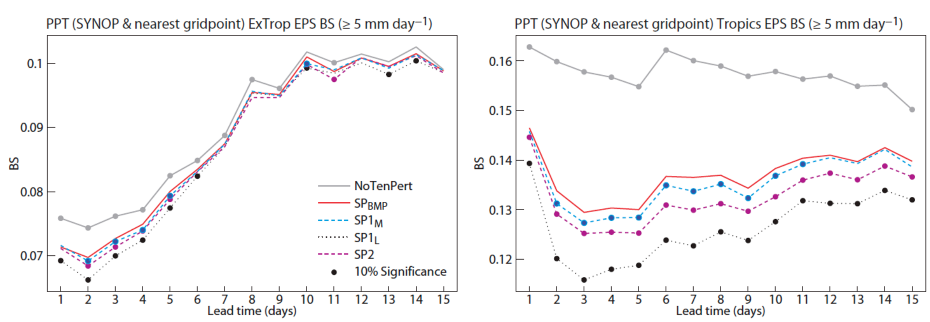

Figure 6: Brier score for 24-hour precipitation accumulations for events of 5 mm/d^{-1}. Left: Northern Extra-tropics (30 °N–90 °N), right: Tropics (30 °S–30 °N). The lead times at which the score differences (between an experiment and SP_{BMP}) are statistically significantly different from zero at the 10% level are marked with a dot. Verification against SYNOP data, joint sample of 40 cases.

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SPPT: incidence of heavy rain in old and new stochastic tendency schemes

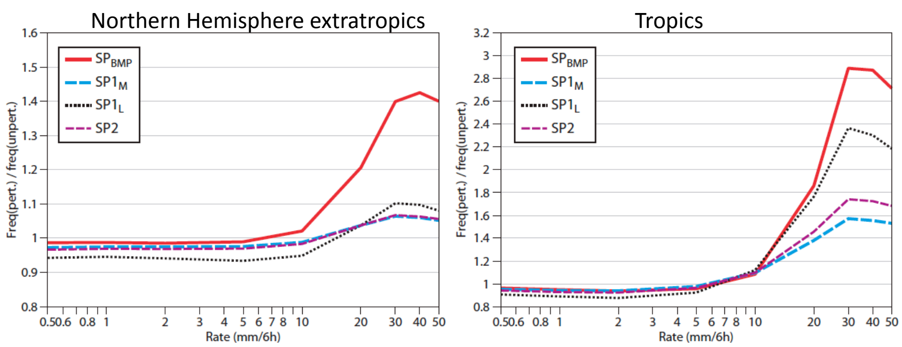

Figure 5: Precipitation frequency ratios between forecasts using tendency perturbations and forecasts without tendency perturbations. Northern Extra-tropics (left), Tropics (right).

old Buizza et al. scheme overpredicted heavy events; this much reduced.

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Similar cautionary tale with stochastic convection

- Tompkins and Berner (2008) perturbed humidity inputs to convective parameterization scheme.

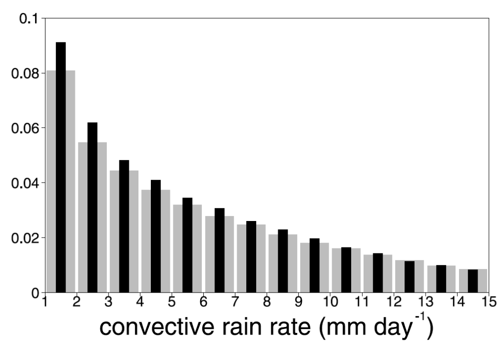

Figure 11. Normalized PDF of convective rain rates in an unperturbed forecast (wide gray) and a perturbed (narrow black) forecast from the IN-SUBGRID-FULLPROF case.

Since CP was tuned originally to give acceptable results, introduction of stochasticity produced a change in the distribution of precipitation forecasts, which in this case had undesirable consequences to the forecasts.

Ref: Tompkins and Berner, 2008, JGR, D18101

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Spectral Stochastic Backscatter (SPBS)

- Total dissipation rate is computed on all model levels; 3 components:
  - Numerical dissipation, from bi-harmonic diffusion and interpolation error in the semi-Lagrangian scheme.
  - KE dissipation due to orographic gravity wave drag and flow blocking
  - Rate of kinetic energy export from sub-gridscale deep convection into the resolved flow.
- Found that must inject energy not just at truncation limit, but also at sub-synoptic scales of motion.
- Note: FURTHER DETAIL to be ADDED.

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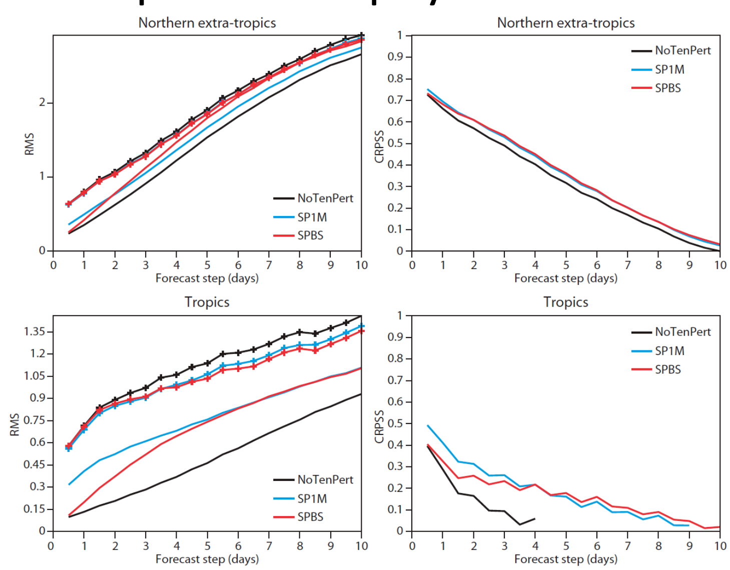
Backscatter comparison with perturbed physical tendencies



SP1M is perturbed physical tendency

SPBS is stochastic backscatter

NoTenPert is no tendency perturbations

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(2) Maturity of ensemble Kalman filter for data assimilation, ensemble prediction

- Operational for last several years at Canadian Meteorological Centre.
  - Progress toward 4D-Var/EnKF hybrid.
- Used with high-resolution (T382) global models for NOAA's Hurricane Forecast Improvement Project.
- Approximations:
  - LETKF used operationally at UK Met Office
  - ET (Ensemble Transform) used operationally at NCEP for medium-range ensemble
  - Experiments with parallel 4D-Vars & perturbed obs at ECMWF.

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Key issues with EnKFs

- Treatment of model (system) errors in appropriate ways.
- Methods of stabilization/dealing with limited ensemble size introduces consequences.
  - Covariance localization in vertical ill-defined with non-point observations such as radiances.
  - As shown, additive noise to account for model error constrains forecast spread growth.
- Best way to hybridize with variational schemes
- Replicating variational QC.

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Canonical EnKF equations

$$\mathbf{x}_i^a = \mathbf{x}_i^b + \mathbf{K}\left(\mathbf{y}_i - H\mathbf{x}_i^b\right)$$

$$\mathbf{K} = \mathbf{P}^b H^{\mathrm{T}}\left(H\mathbf{P}^b H^{\mathrm{T}} + \mathbf{R}\right)^{-1}$$

$$\mathbf{P}^b = \left\langle \left[\mathbf{x}_i^b(t) - \overline{\mathbf{x}}_i^b(t)\right]\left[\mathbf{x}_i^b(t) - \overline{\mathbf{x}}_i^b(t)\right]^T \right\rangle$$

$$\mathbf{P}^a = \left\langle \left[\mathbf{x}_i^a(t) - \overline{\mathbf{x}}_i^a(t)\right]\left[\mathbf{x}_i^a(t) - \overline{\mathbf{x}}_i^a(t)\right]^T \right\rangle$$

$$\mathbf{x}_i^b(t+1) = M\mathbf{x}_i^a(t) + \eta_i, \qquad \left\langle \eta_i \eta_i^T \right\rangle = \mathbf{Q}$$

⇧

how are we estimating the model-error?

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Model-error representations in CMC EnKF (Houtekamer et al. July 2009 MWR)

~ 250 hPa wind speed analysis spread

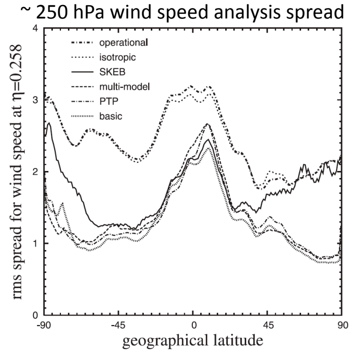

FIG. 7. The rms ensemble spread for the wind speed (m s^{-1}) at η = 0.258 for different EnKF configurations. The latitudinal rms values have been computed for the analyses valid between 0000 UTC 1 Jul 2006 and 1200 UTC 10 Jul 2006.

~850 hPa T analysis spread

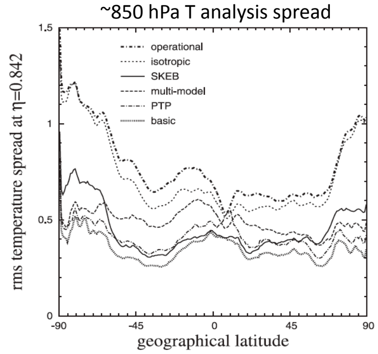

FIG. 8. The rms ensemble spread for the temperature (K) at η = 0.842 for different EnKF configurations. The latitudinal rms values have been computed for the analyses valid between 0000 UTC 1 Jul 2006 and 1200 UTC 10 Jul 2006.

isotropic additive noise dominates in EnKF.

operational = multimodel + SKEB + PTP
isotropic = additive noise to streamfunction and unbalanced T
SKEB = stochastic kinetic energy backscatter
PTP = perturbed physical tendencies (like ECMWF's SPPT)
multi-model = 4 different CPs, 2 LSMs; 2 mixing length; 2 inverse Prandtl numbers
basic = no model error simulation

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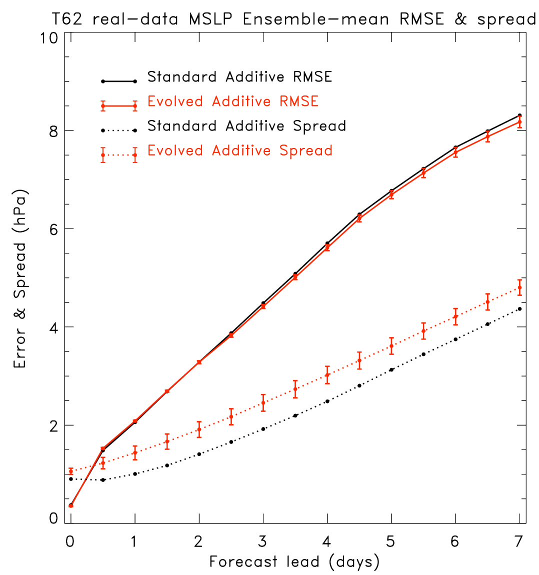
A problem with isotropic additive noise



the standard additive noise results in a slow growth of spread in the early hours of the forecast. Introducing the additive noise earlier (here, 24 h earlier) and evolving it forward in time before using in the data assimilation improves the rate of growth of spread in the forecasts.

Ref: Hamill and Whitaker, 2009 MWR, submitted.

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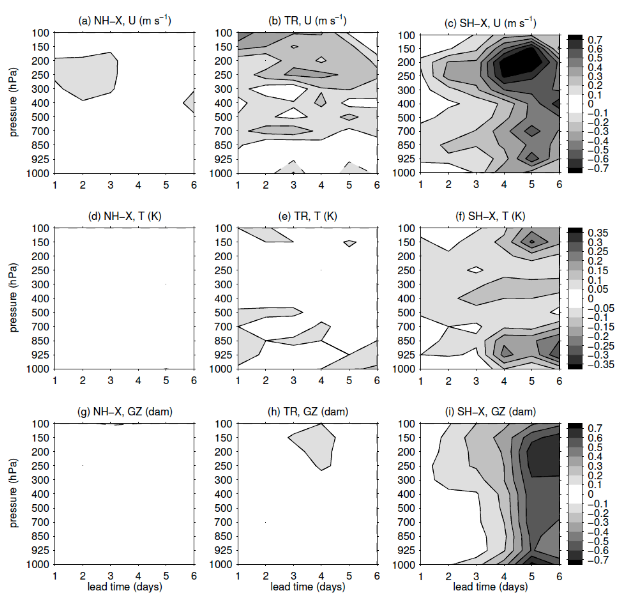
EnKF / 4D-Var hybrids?



from Buehner et al., MWR, accepted/minor.

Impact of CMC's 4D-Var using EnKF covariances relative to using static initial covariances. Impact measured in terms of reduction/increase in error standard deviation. Negative impact where contours are dashed.

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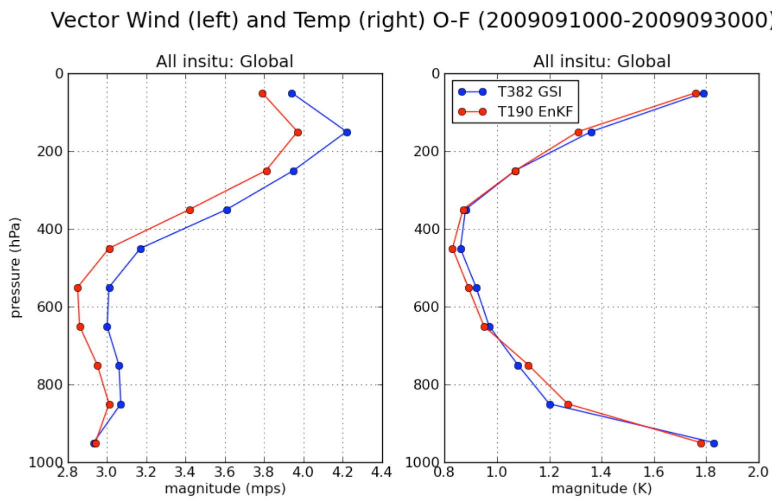
NOAA EnKF vs. NCEP operational 3D-Var



EnKF at half the resolution fits temp. obs as well as operational 3DVar, but shows large improvement for winds.

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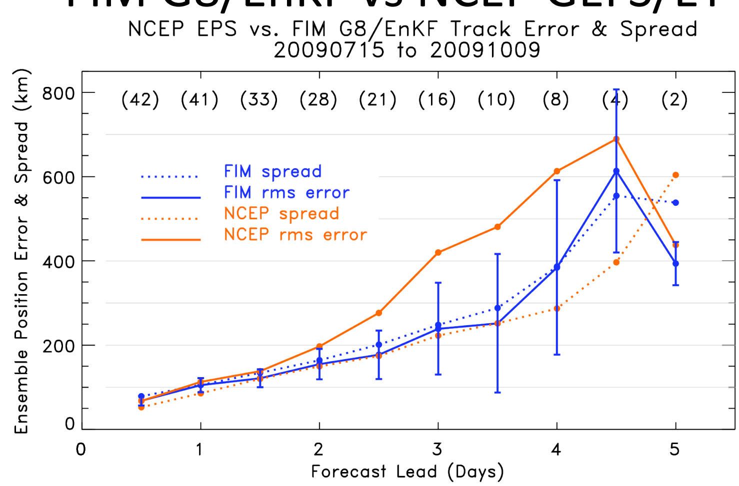
TC position error and ensemble spread FIM G8/EnKF vs NCEP GEFS/ET



FIM is NOAA/ESRL's experimental global icos grid model.
Error bars are 5th and 95th percentiles from paired block bootstrap.
Numbers in parentheses are the sample size at this lead.

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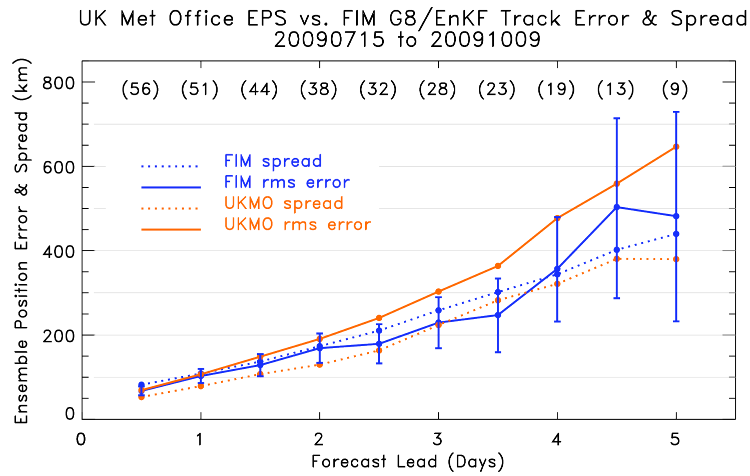
TC position error and ensemble spread FIM G8/EnKF vs UK Met Office



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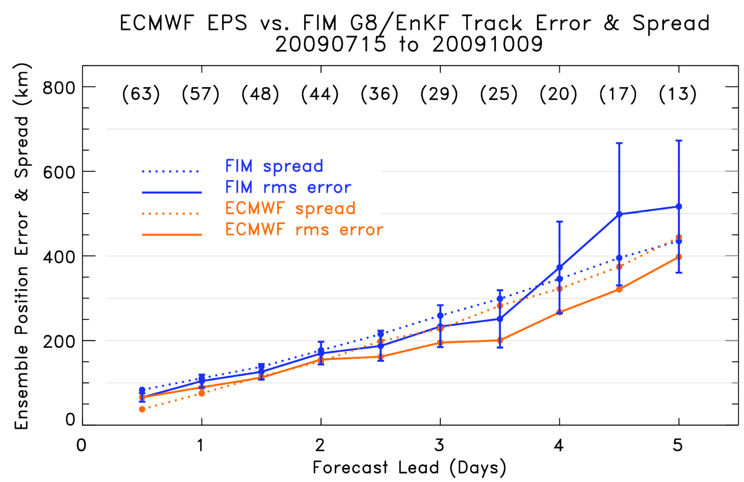
TC position error and ensemble spread FIM G8/EnKF vs ECMWF



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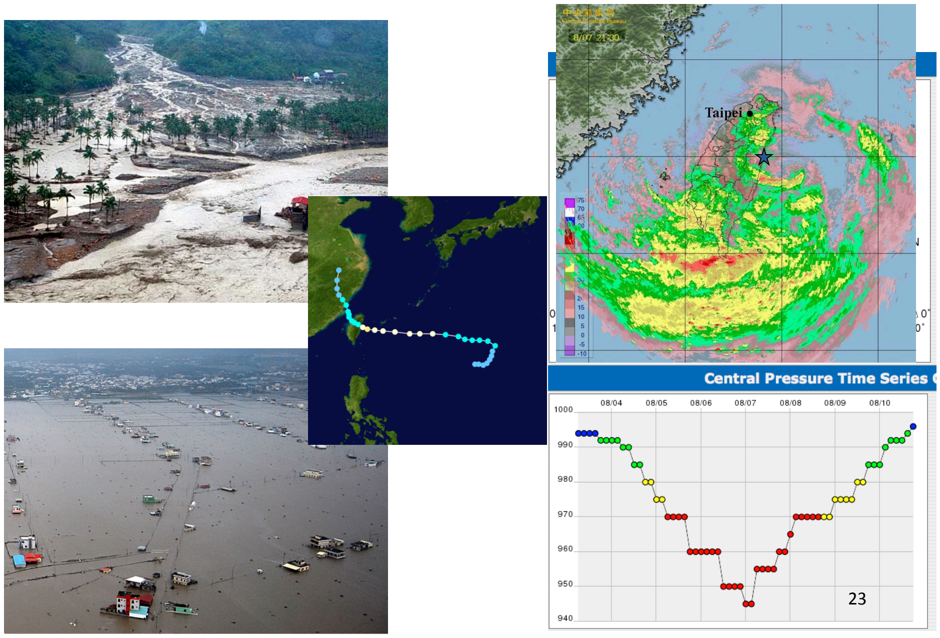
Ensemble predictions for typhoon Morakot, 2009



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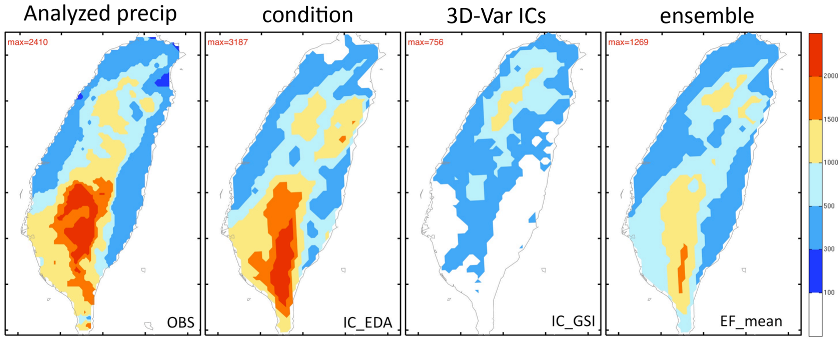
WRF high-resolution regional model precipitation forecasts for Morakot

Analyzed precip | EnKF mean initial condition | NCEP GSI 3D-Var ICs | mean from EnKF ensemble



WRF/ARW, 4.5 km nested inside 13.5 km, initialized 2.5 days before landfall; GFS ensemble used for lateral boundary conditions.

from draft article by Fuqing Zhang et al., 2009

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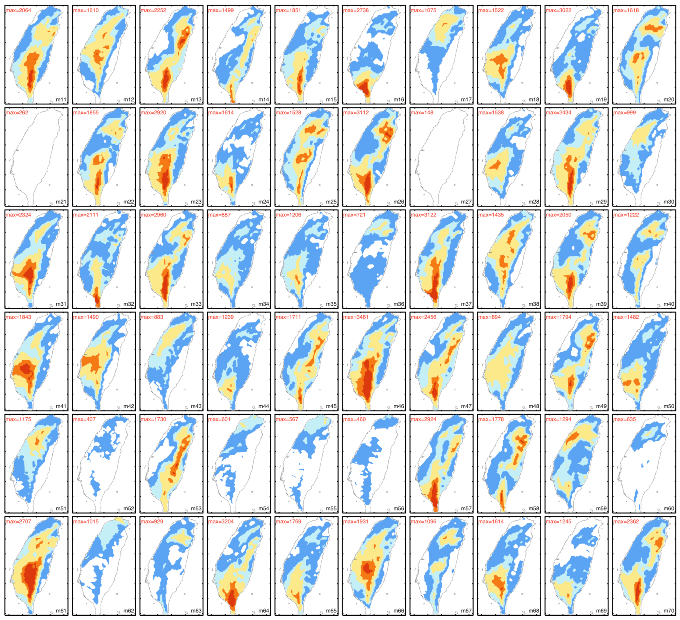
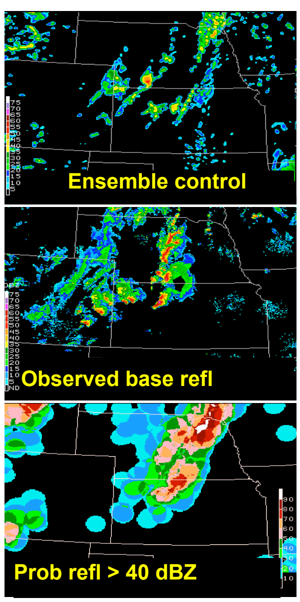
Ensemble precipitation forecasts for Morakot

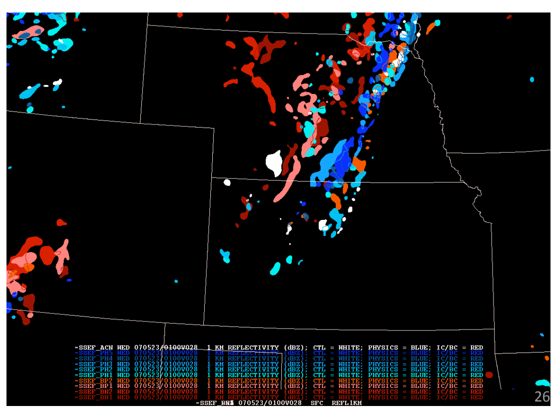


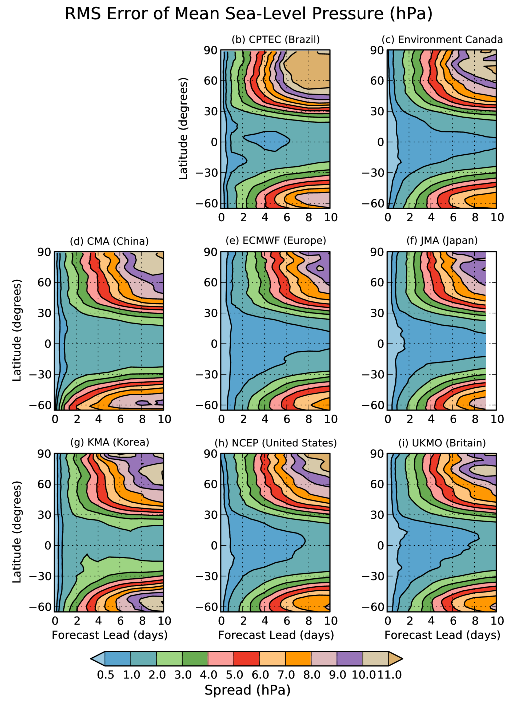
(3) Convection-permitting limited-area ensembles



from 2007 NOAA/SPC “Spring Experiment”
(c/o Jack Kain, Steve Weiss)

“Spaghetti” Plot for Reflectivity $\geq$ 40 dBZ





(4) Exploring ensemble system characteristics with the TIGGE data set

from upcoming Bougeault et al. 2010 BAMS overview of TIGGE

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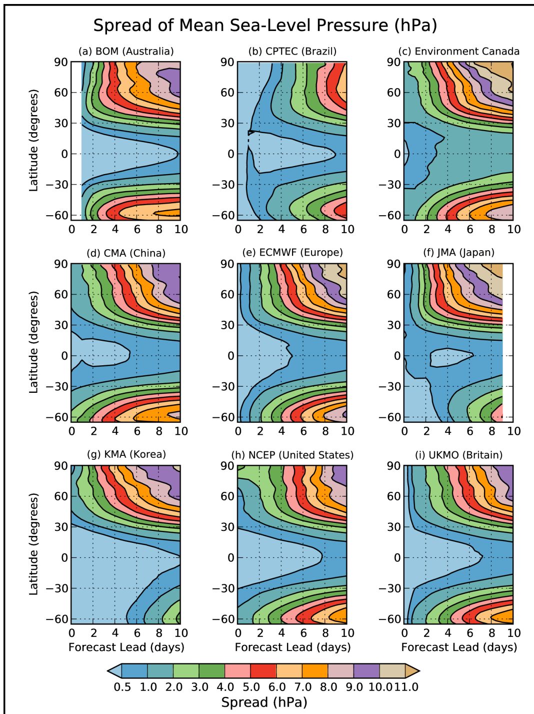

Exploring ensemble system characteristics with the TIGGE data set

from upcoming Bougeault et al. 2010 BAMS overview of TIGGE

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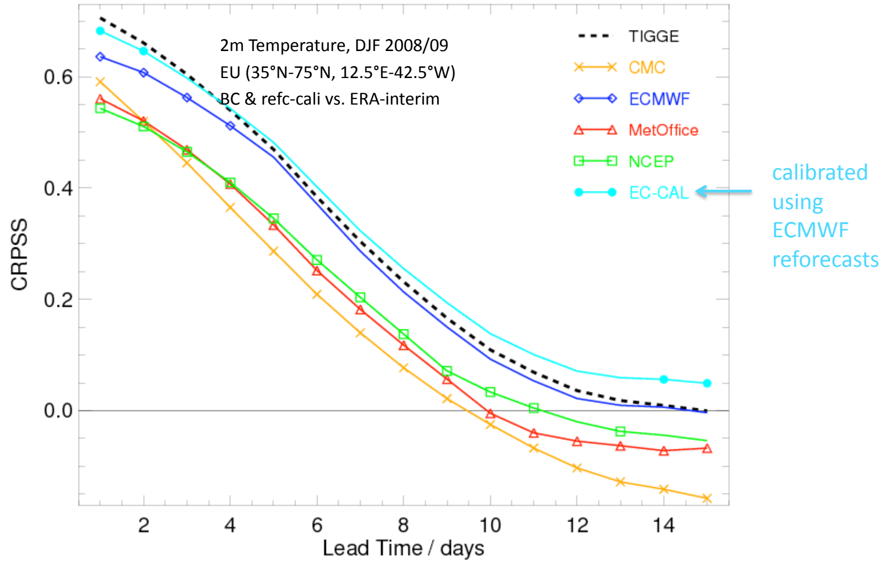
(5) Value of ensemble post-processing



from Hagedorn presentation to 3rd International THORPEX conf., Monterey, CA, Sep 2009.

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Conclusions

- Substantial progress in 2008-2009 on:
  - Model error
  - Ensemble initialization through EnKF.
  - Convection-permitting applications.
  - Exploration of multi-model concepts via TIGGE.
  - Amelioration of systematic errors using reforecasts.

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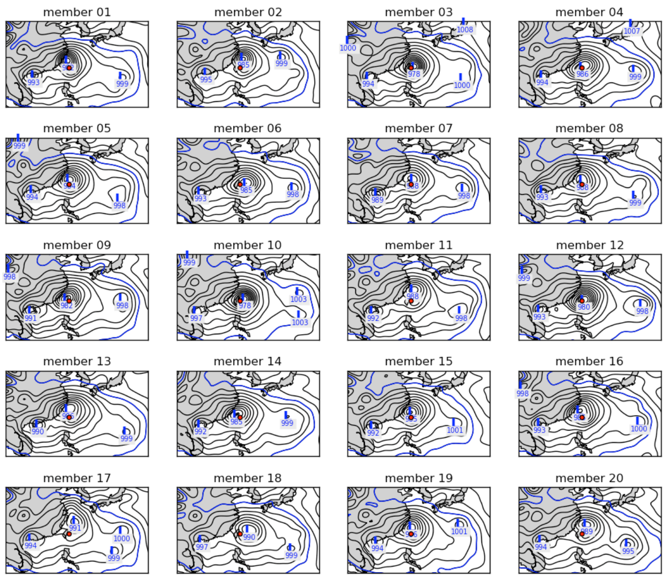
54-h ensembles from T382 GFS & EnKF initial conditions.



Intense vortices in forecasts, with ensembles of forecast positions relatively close to the observed position (red dot).

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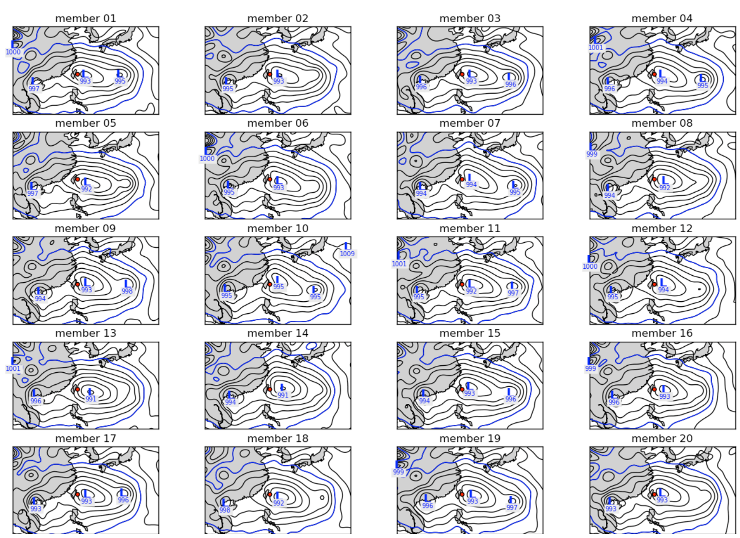
54-h ensembles from experimental T382 GFS & GSI / ET perturbations (operational).

GSI/ET ensemble 54-hr fcst from 2009080500



Note that this GFS model resolution is much greater than current operational, T126

GSI-ET initialized ensemble produces less intense vortices, and forecasts are slow in moving typhoon west.

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