



NATO
+
OTAN

***NURC** - Partnering for Maritime Innovation*



A review of recent super-ensemble multi-model challenges, developments, results, and perspectives for the coastal ocean

M. Rixen & ... all collaborators

MREA10 conference

18-22 October

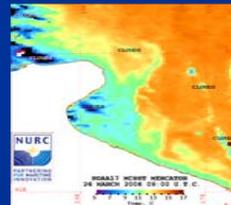
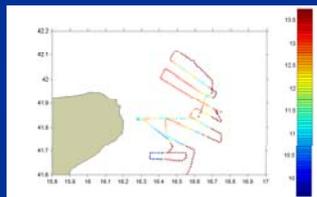
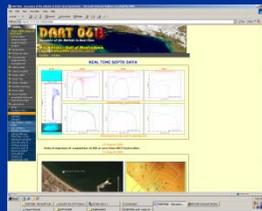


Super-ensembles (SE)



MONITORING

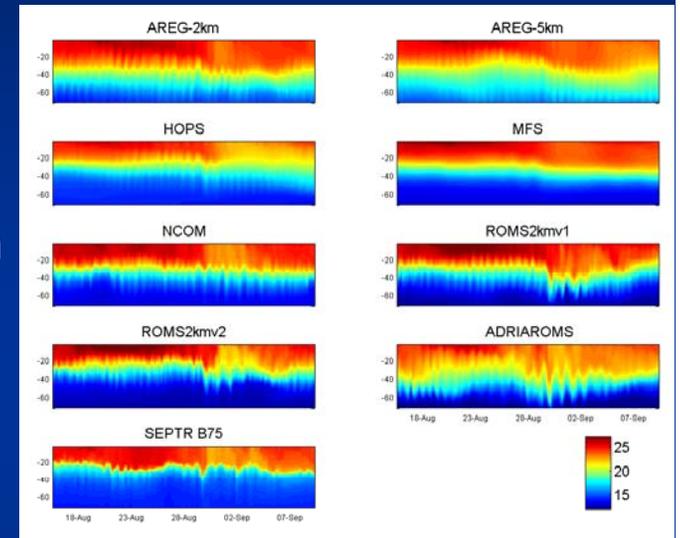
moored towed remote



Data assimilation



PREDICTION models



Which model is best?

SE = model-data fusion =
 improved prediction by
 optimal combinations of predictions and data



Super-Ensembles (SE)...

- Simple ensemble-mean
- Individually bias-corrected ens.-mean
- Linear regression (least-squares)+bias
- EOF regularization
- Non-linear regression (least-squares)
 - Neural networks
 - Genetic algorithms
- Dynamic regression
 - Kalman Filter
 - Particle filter
- Hyper-ensembles: combination of ocean/wave/atmosphere (e.g. surface drift)
 1. compute optimal combination from past model-data regression
 2. use in forecast-mode

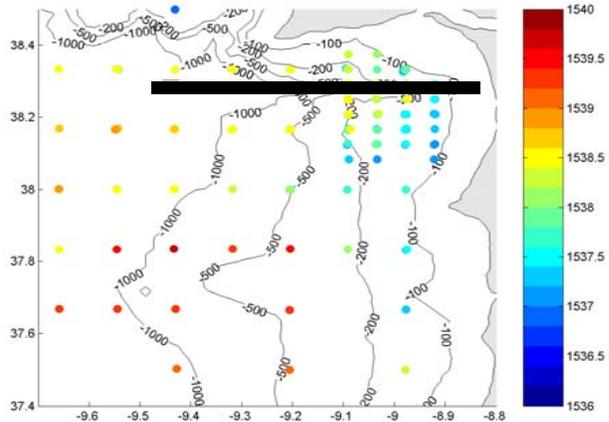
Models	Weights	Data
$F_{1,1}$	w_1	d_1
..
..
..
..
..
..
$F_{M,1}$	w_N	d_M

$$\min_w \left\| \sum_{i=1}^N w_i F_i - d \right\|^2$$

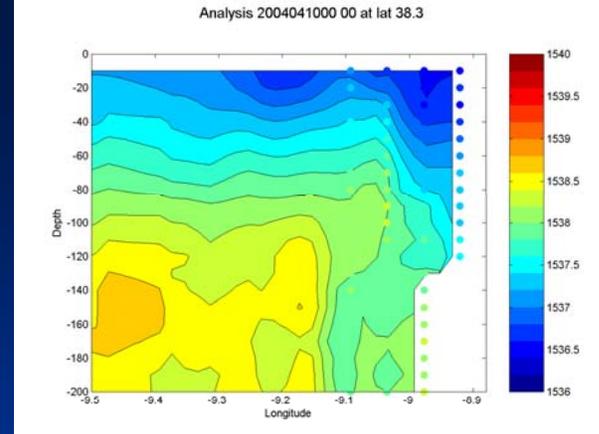
$$F_{SE} = \sum_{i=1}^N w_i F_i$$



Errors on SVP 24h forecast: MREA04

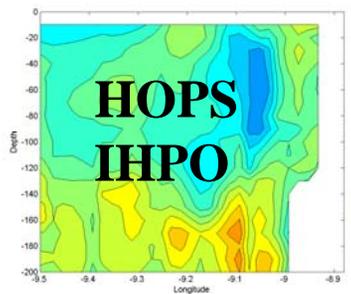


Analysis
(truth)

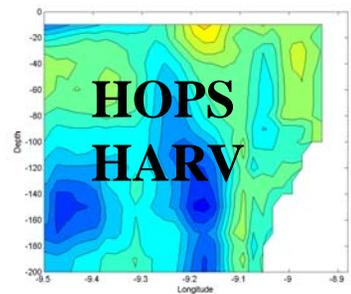


Errors (single models)

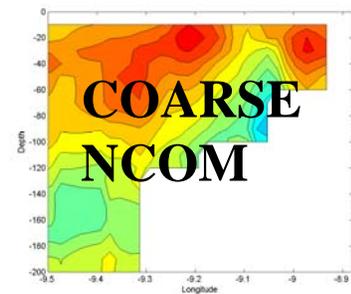
a) HOPS-IHPO forecast error 2004040900 24 at lat 38.3



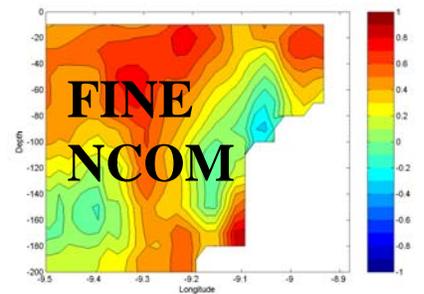
b) HOPS-Harvard forecast error 2004040900 24 at lat 38.3



c) Coarse NCOM forecast error 2004040900 24 at lat 38.3

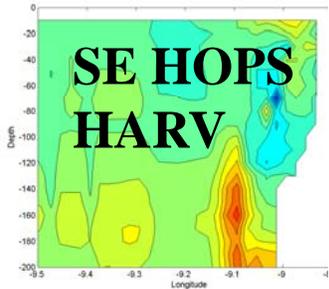


d) Fine NCOM forecast error 2004040900 24 at lat 38.3

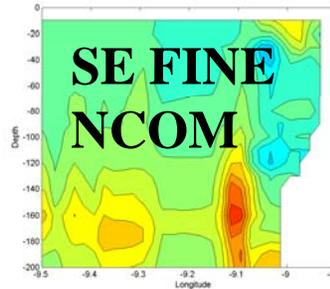


Errors (SE)

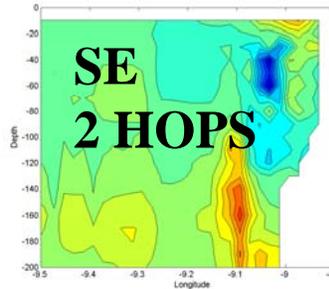
a) SE forecast error 2004040900 24 at lat 38.3 (HOPS-Harvard)



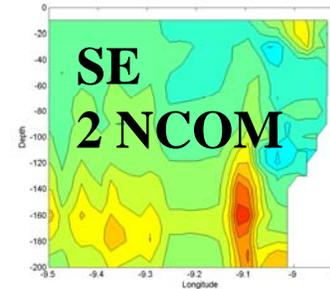
b) SE forecast error 2004040900 24 at lat 38.3 (Fine NCOM)



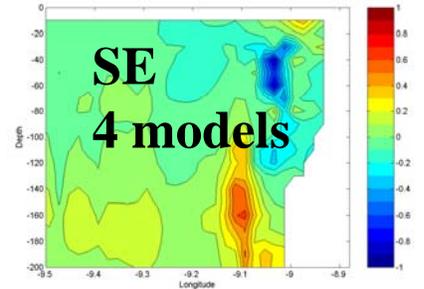
c) SE forecast error 2004040900 24 at lat 38.3 (HOPS-IHPO,HOPS-Harvard)

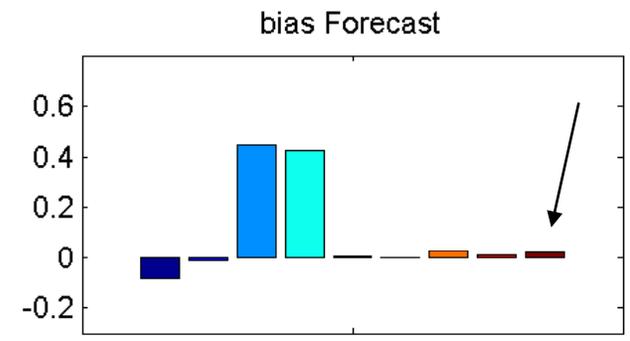
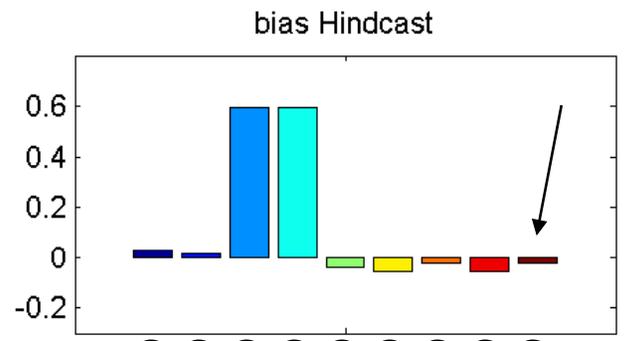
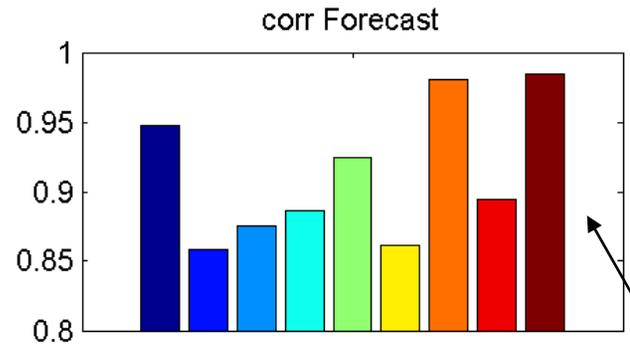
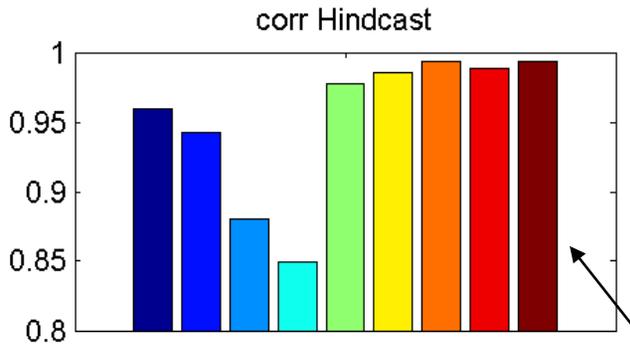
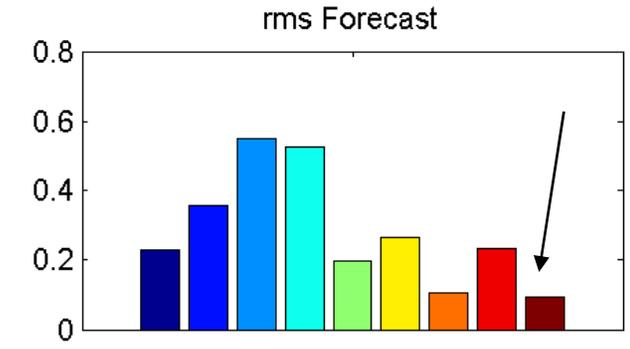
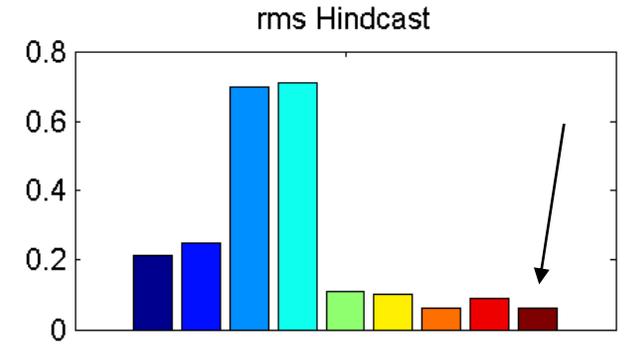


d) SE forecast error 2004040900 24 at lat 38.3 (Coarse NCOM,Fine NCOM)



e) SE forecast error 2004040900 24 at lat 38.3 (HOPS-IHPO,HOPS-Harvard,Coarse NCOM,Fine NCOM)





HOPS-IHPO (1)
HOPS-Harv. (2)
Coarse NCOM (3)
Fine NCOM (4)
SE (2)
SE (4)
SE (1, 2)
SE (3, 4)
SE (1 to 4)

HOPS-IHPO (1)
HOPS-Harv. (2)
Coarse NCOM (3)
Fine NCOM (4)
SE (2)
SE (4)
SE (1, 2)
SE (3, 4)
SE (1 to 4)

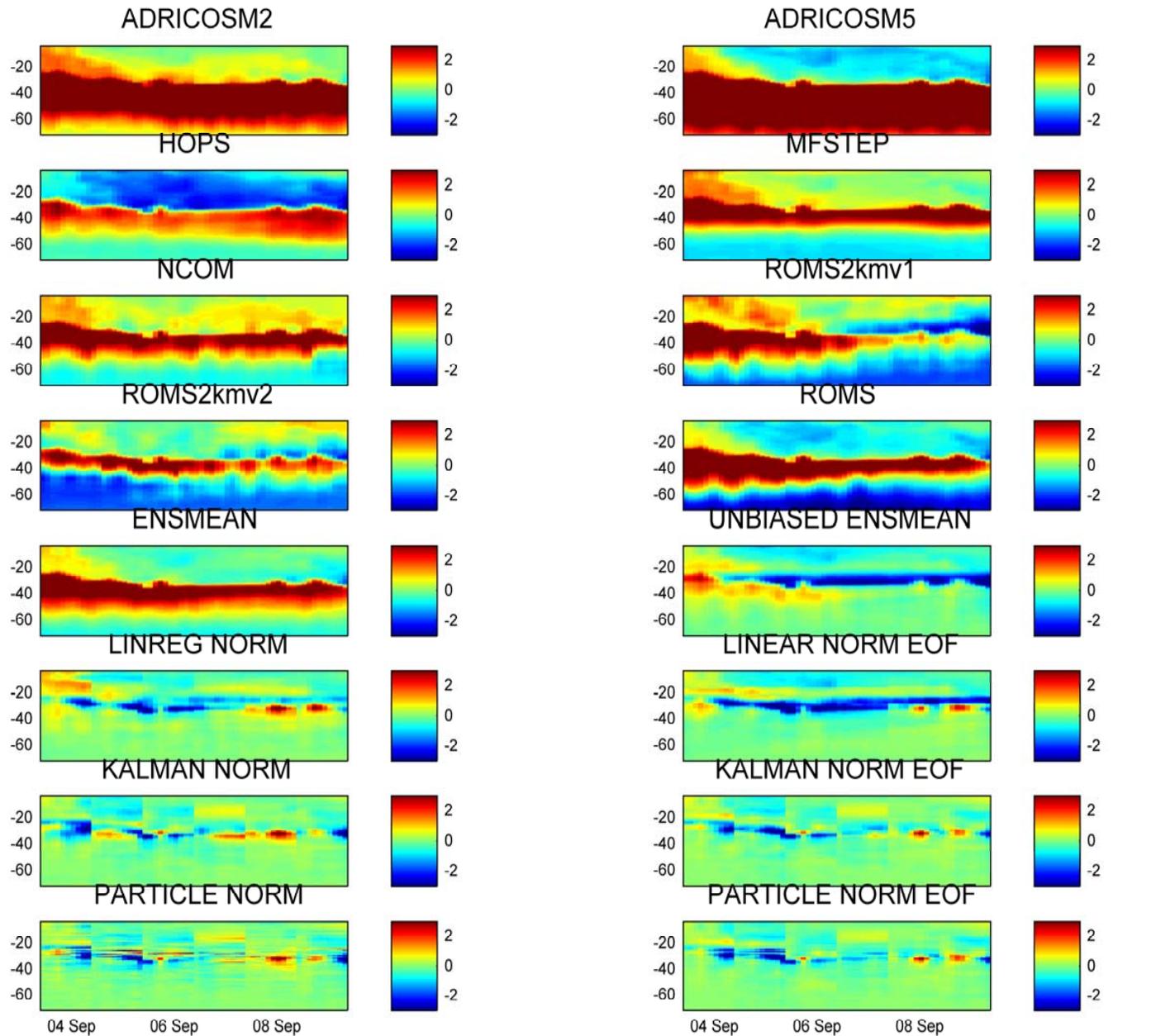


DART06: Forecast error at 24 hrs



Models

SE

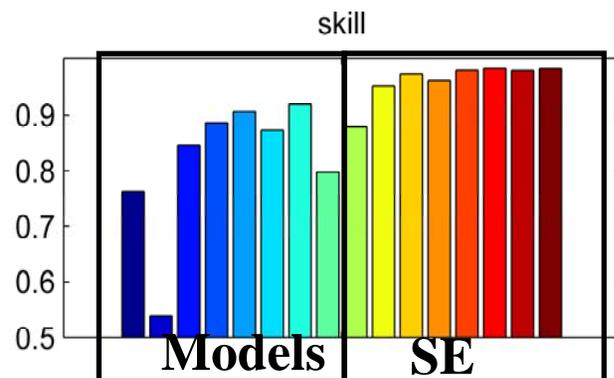
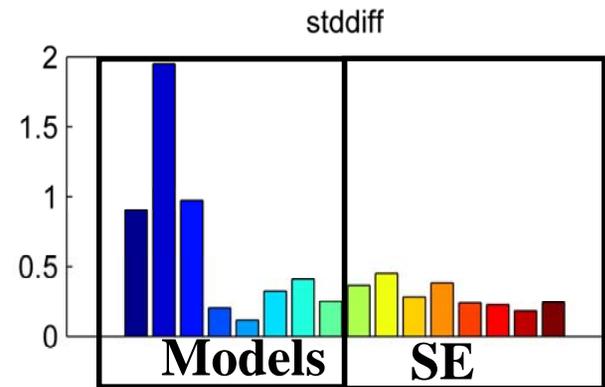
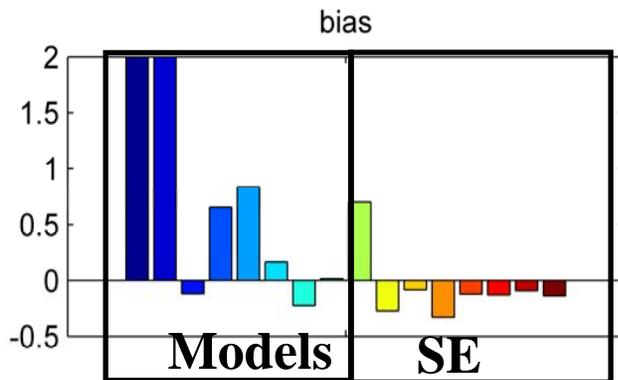
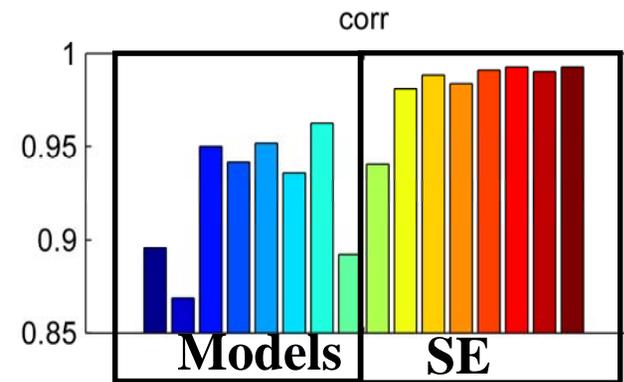
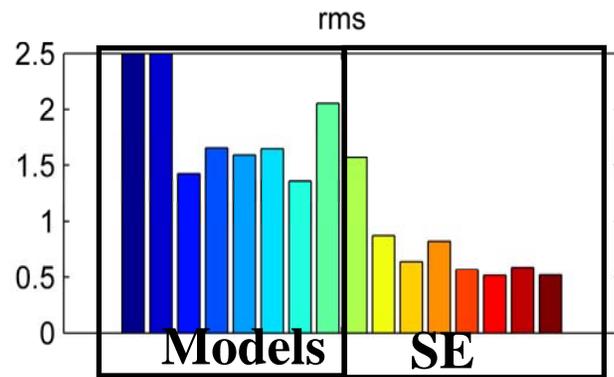


Models

SE



Forecast error statistics (24 hrs)

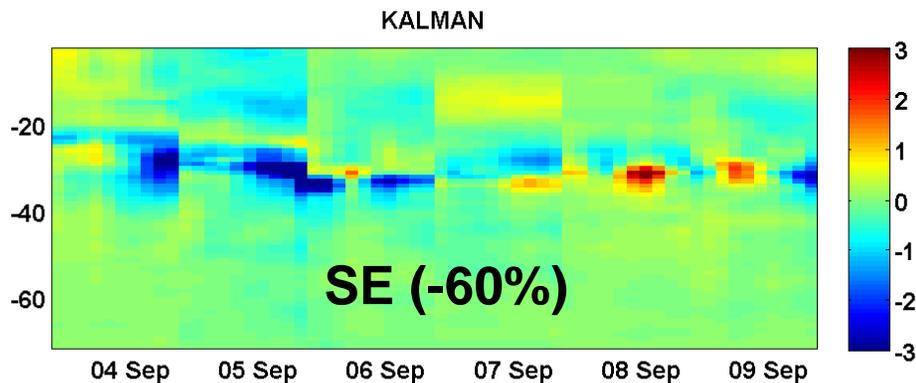
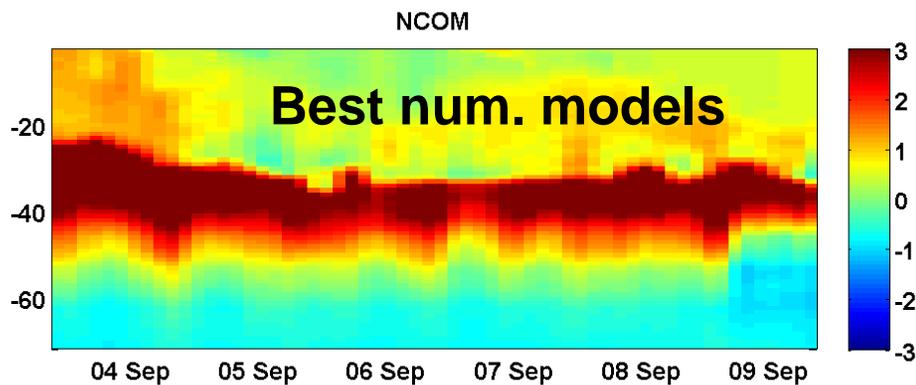




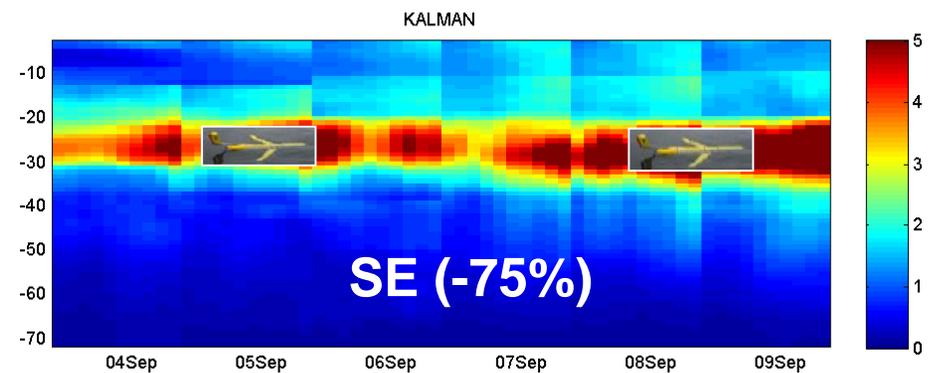
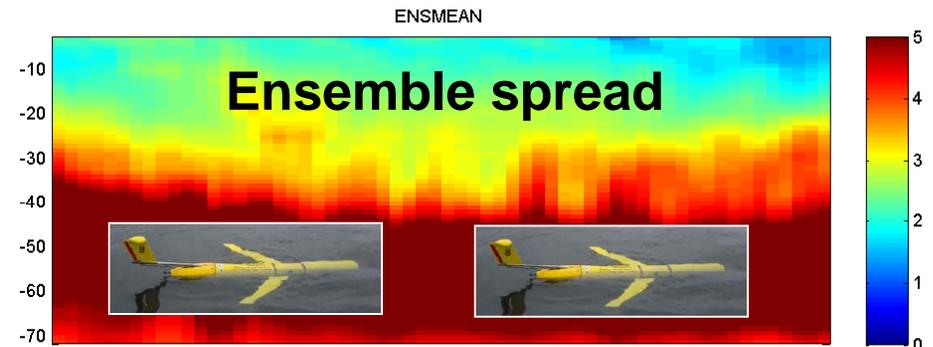
Optimal allocation of assets



Prediction error



Uncertainty

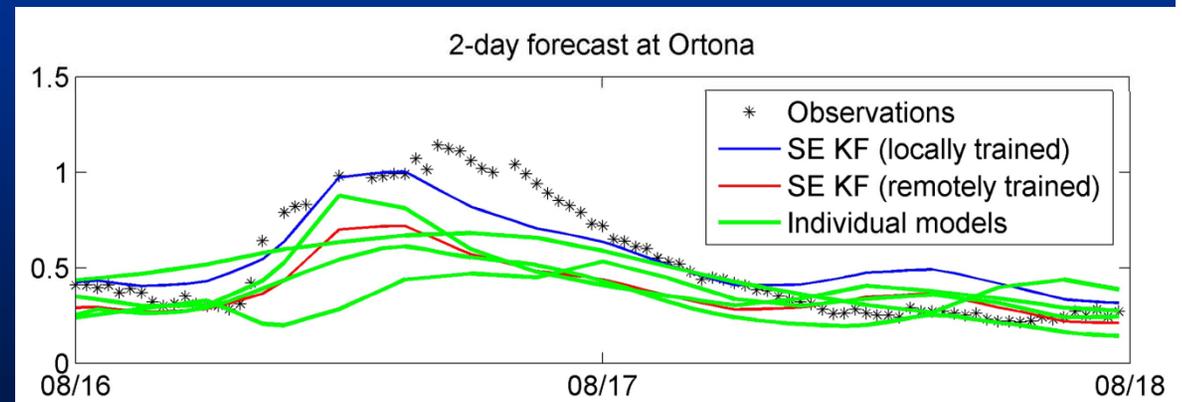
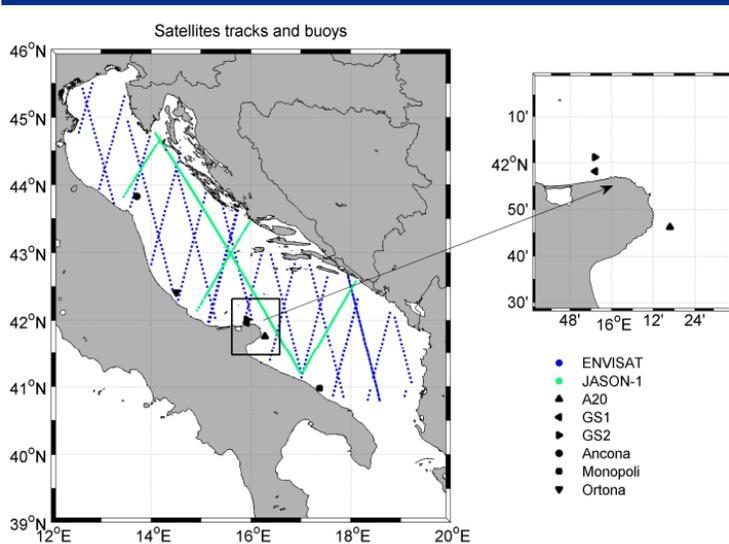
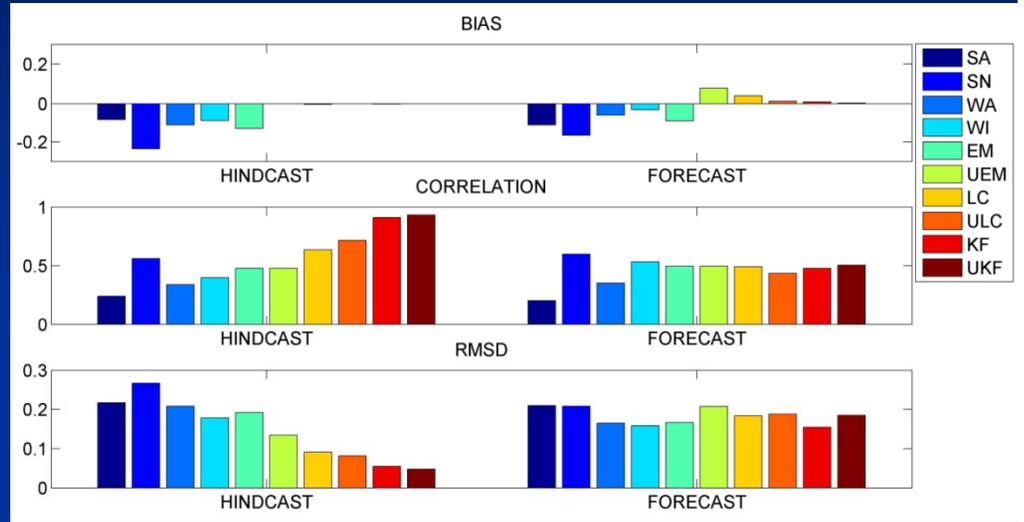
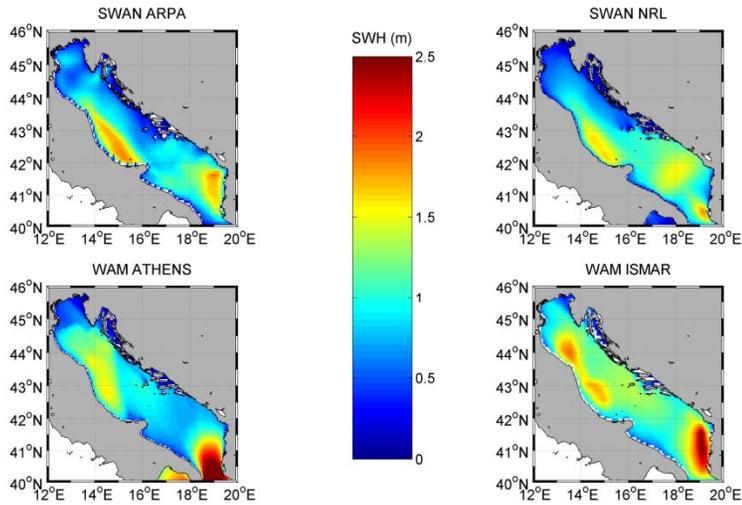




DART06: wave SE

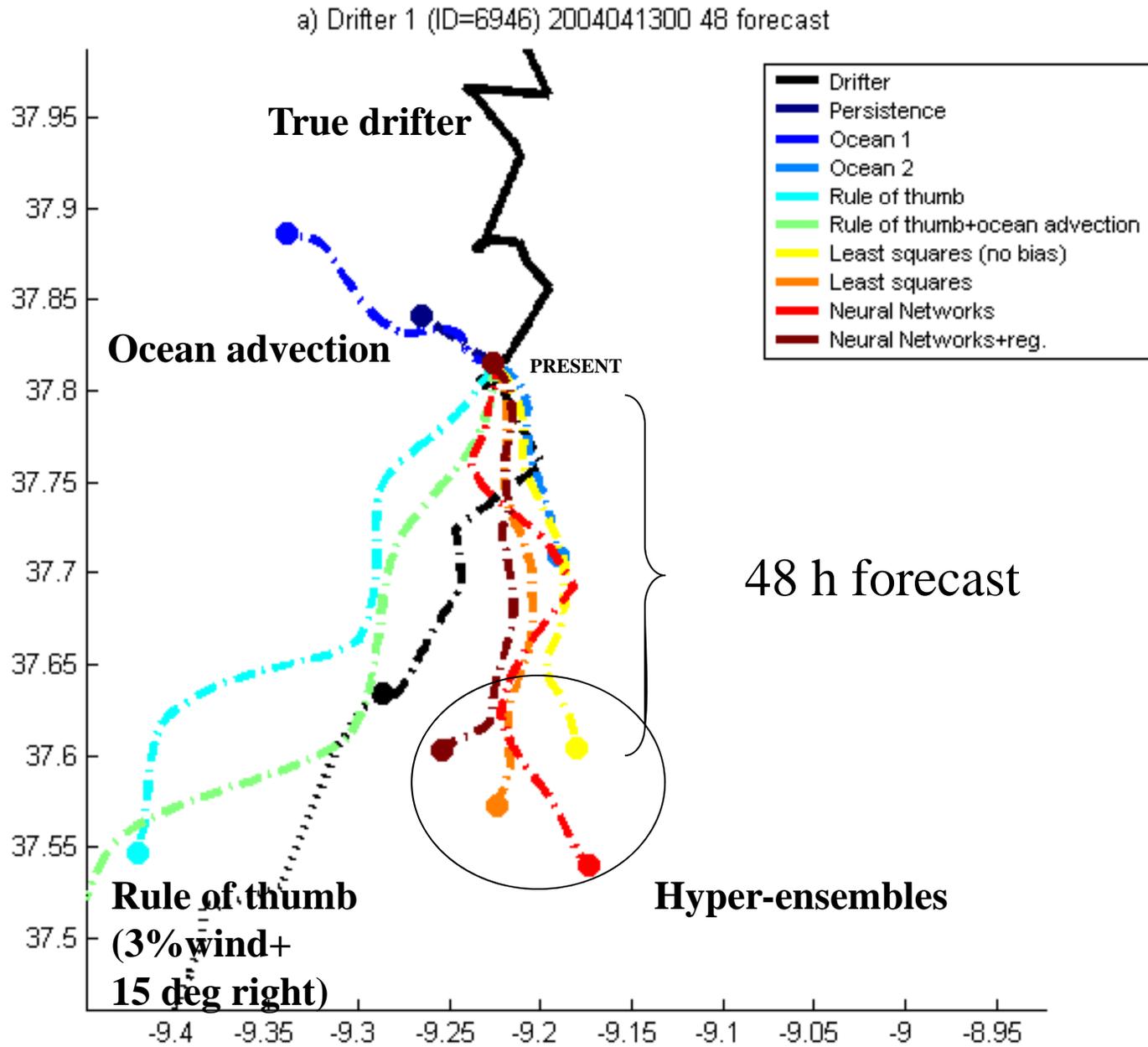


Wave forecasts for 2 August 2006 at 18:00 UTC in the Adriatic Sea.





MREA04: Drifter tracks



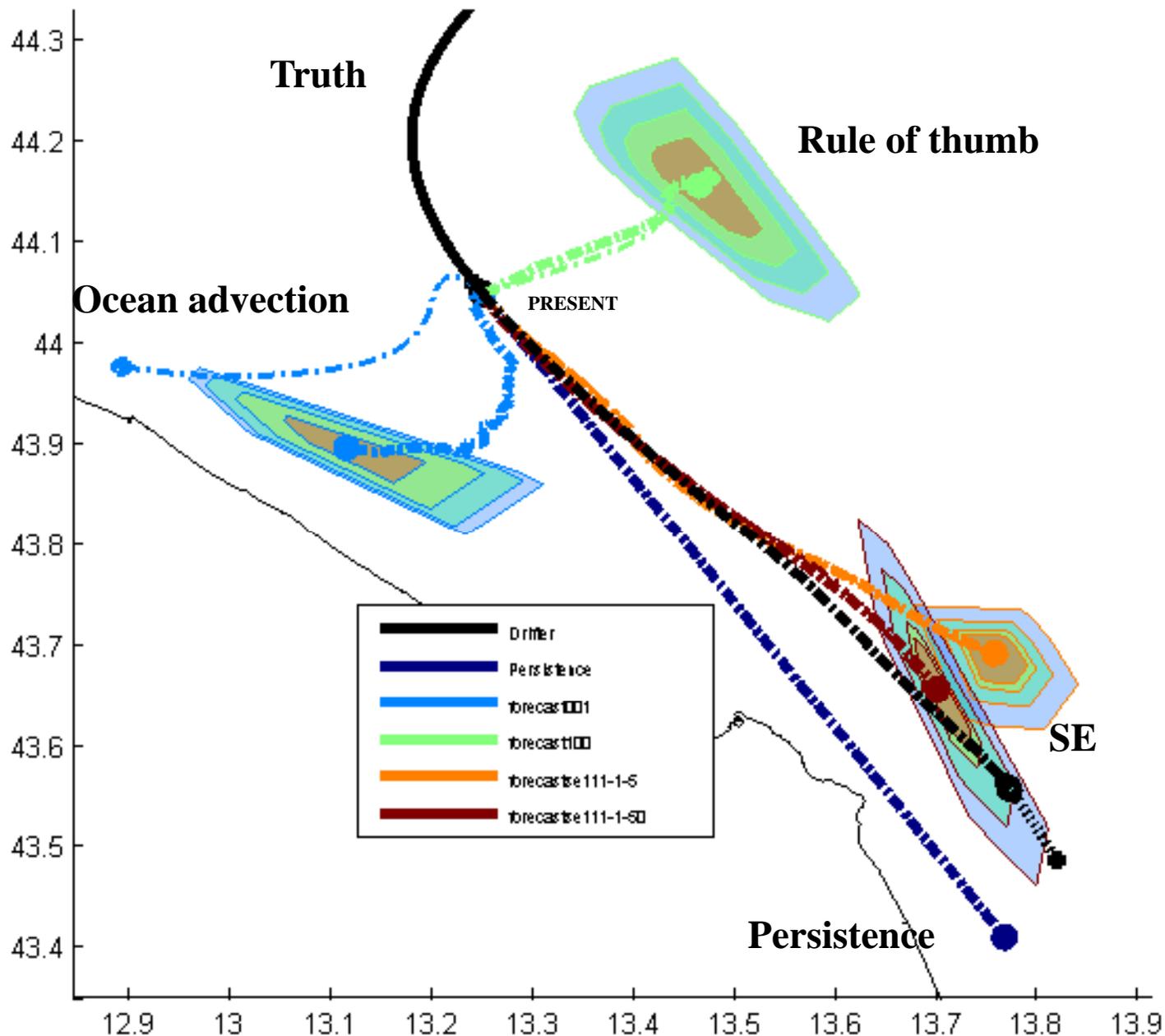


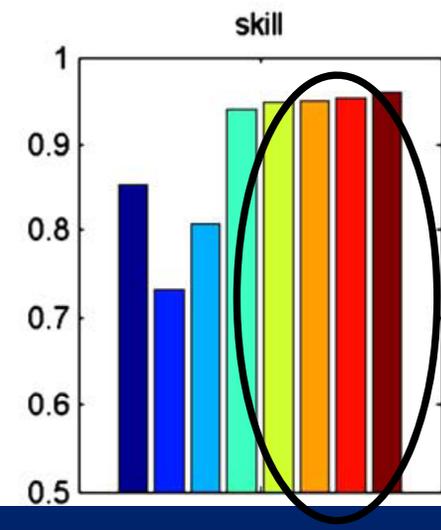
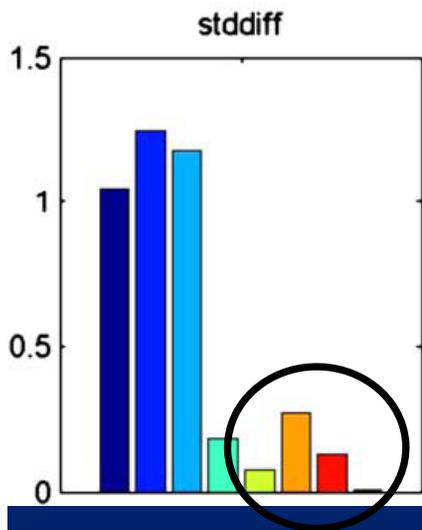
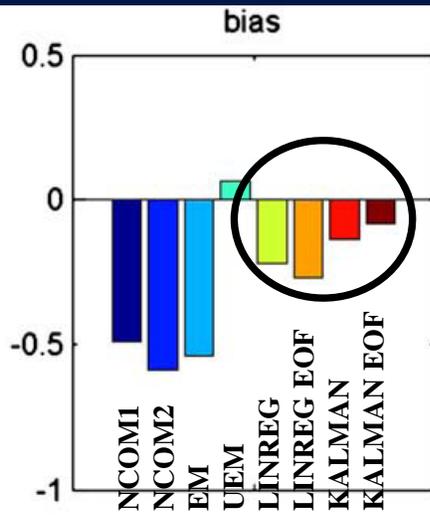
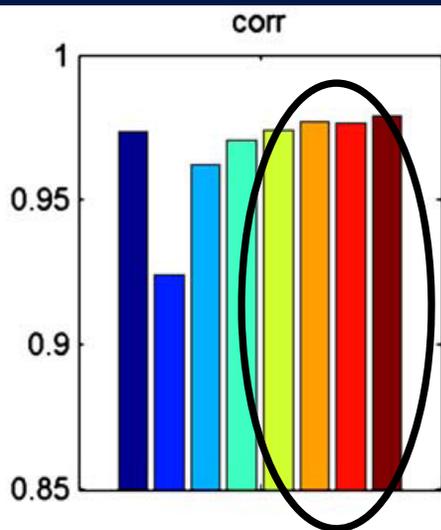
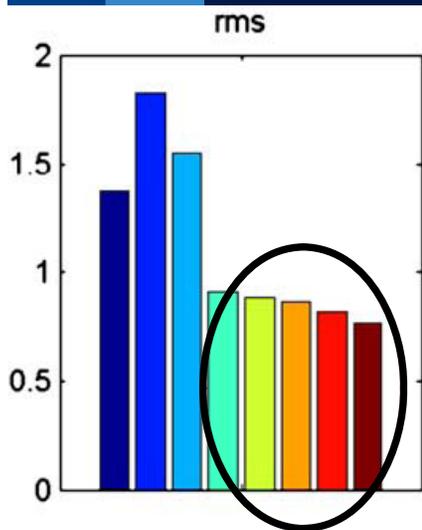
DART06: Probability distribution maps

NURC

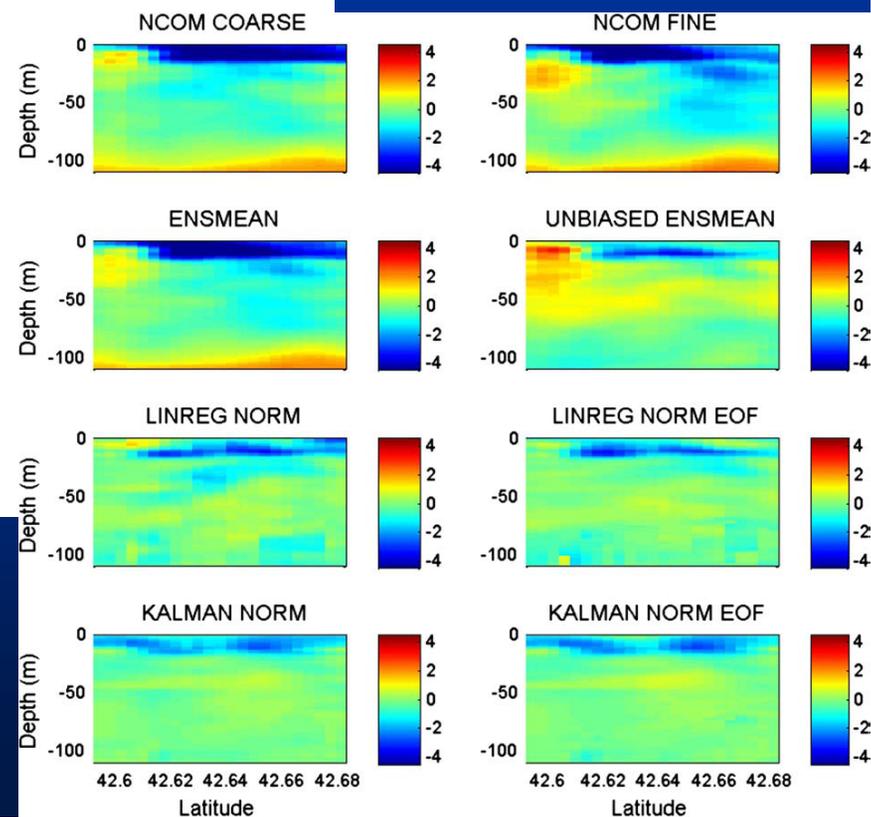


1) Drifter 83 (ID=37696) 2003021400 72 forecast





SE



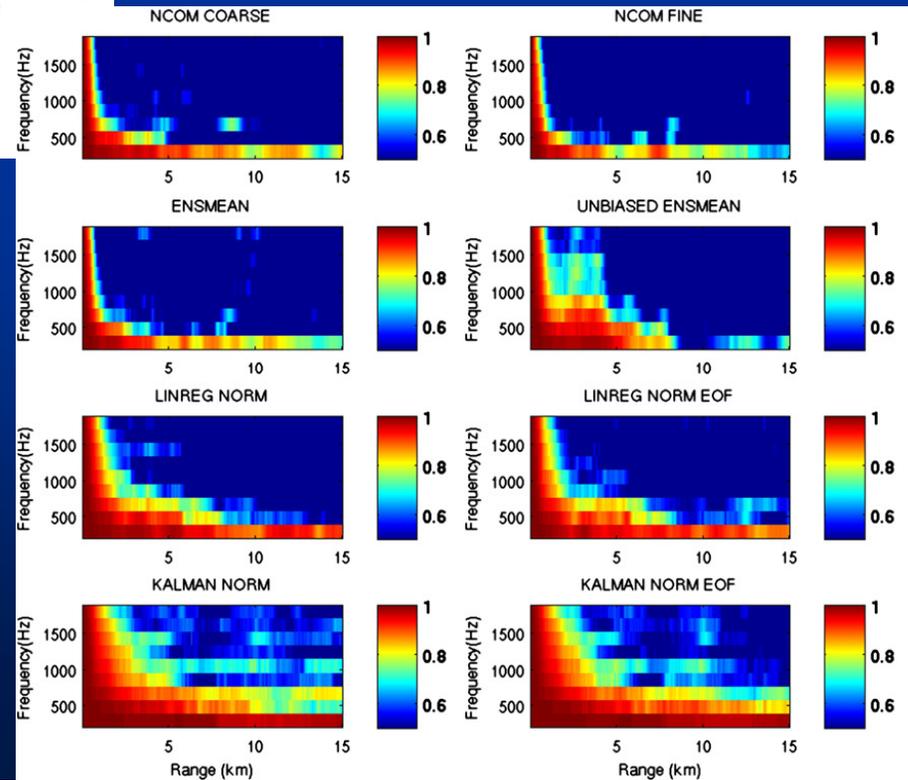
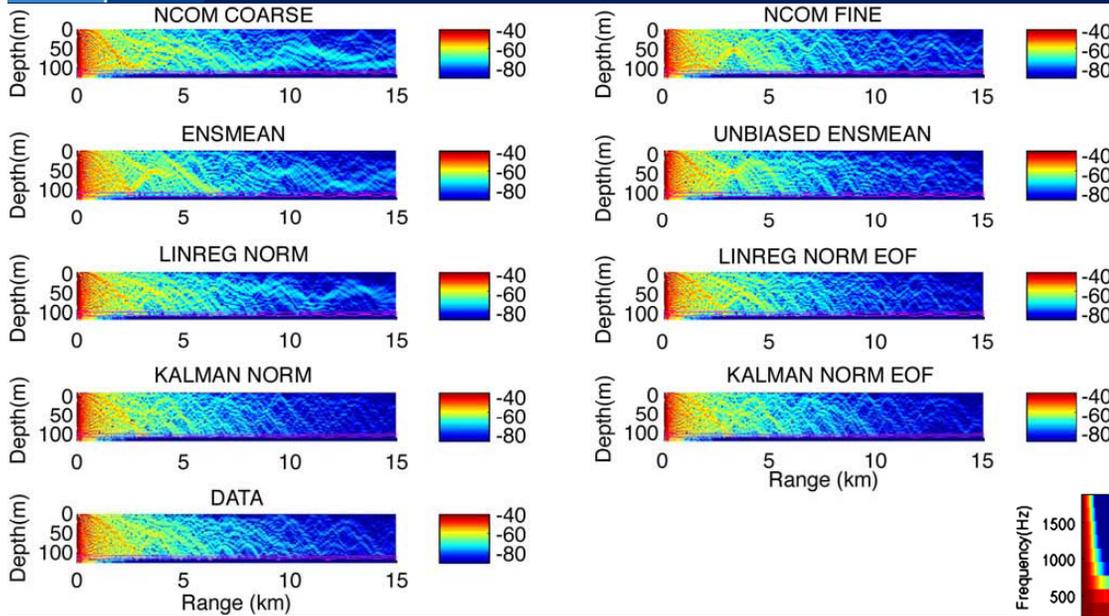
BP07
temp forecast error:
20070430+24 hrs



Impact on acoustics : RAM



20070430 - T=21h



Correlation of predicted complex LF
acoustical pressure fields



Conclusions: super-ensemble



- Improved predictions
- Reduced uncertainties
- Objective+automated fusion of model
- Reconciles contradicting forecasts
- Many (inter-disciplinary) applications

- See also presentation by B. Mourre



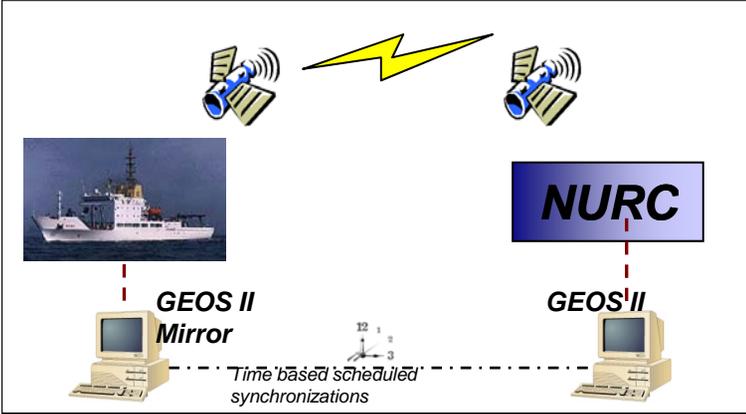
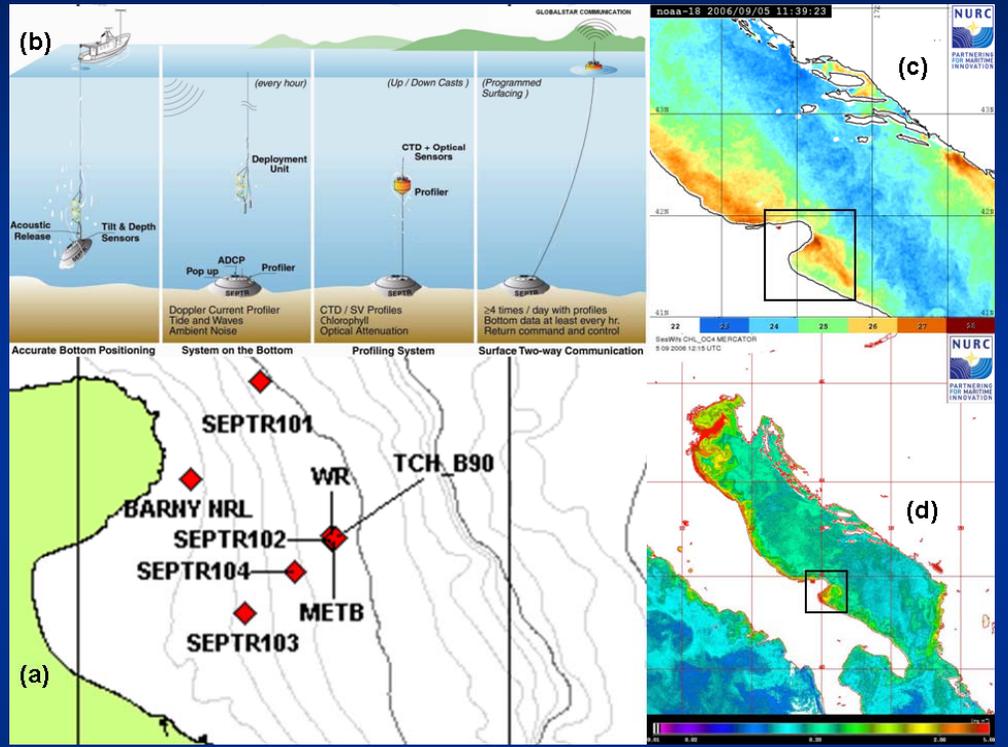
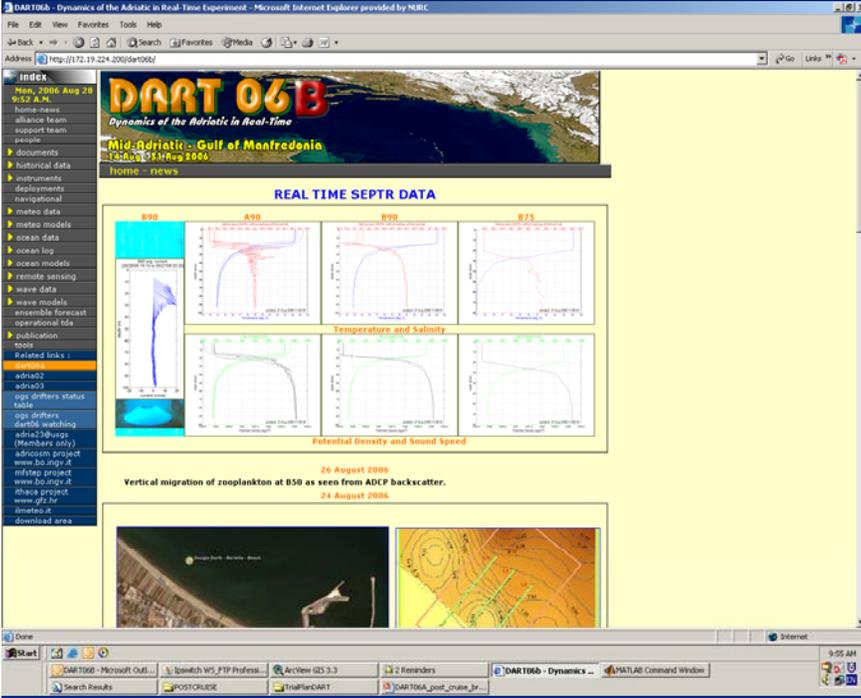
Perspectives



- **Multivariate & coupled ocean-wave-atmosphere covariances**
- **Dynamical constraints**
- **Analytical models**
- **Multi-scale/processes level SE**
- **Non-Gaussian/Particle Filter SE**
- **Re-initialization of numerical models**



DART06 (Dynamics of the Adriatic in Real-Time) SEPTR data in NRT on the web High bandwidth Ship-NURC satellite link



NATO UNCLASSIFIED

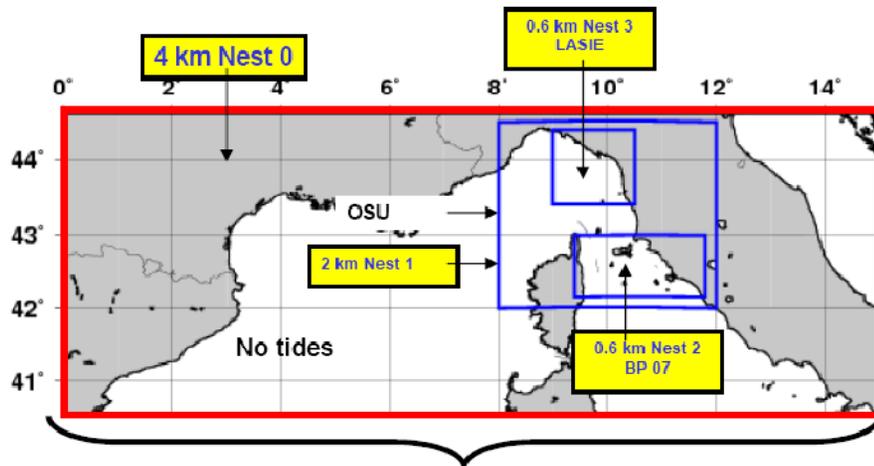


BP07

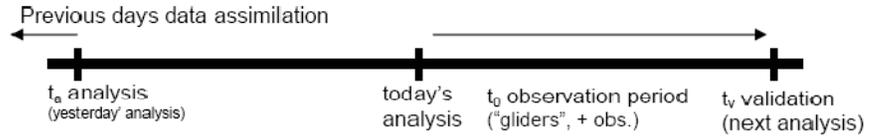


Multiple NCOM nests

NCODA DA

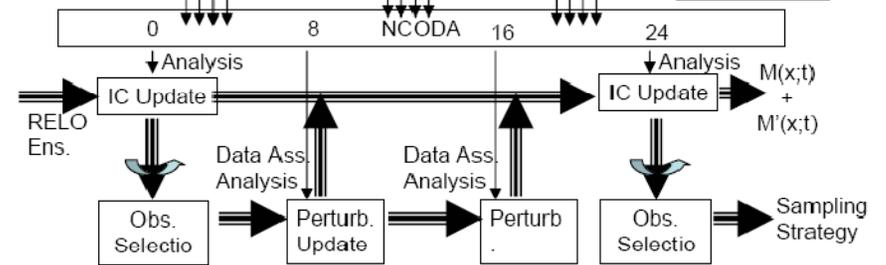


Courtesy G. Peggion GI_NCOM on boundary



IMPROVE ANALYSIS AND FORECASTING SKILLS
BY IDENTIFYING BEST OBSERVATIONS
TO MINIMIZE NEXT ANALYSIS ERRORS

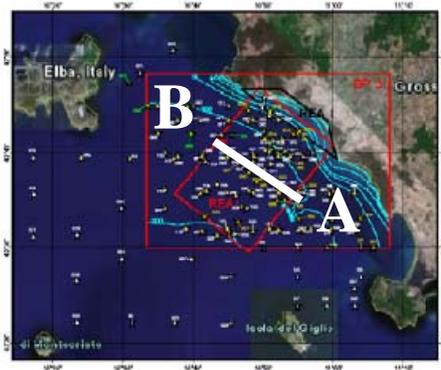
Cummings J., 2006
Rowley C., 2006



CTD (3 ships)

MVP (SNELLIUS)

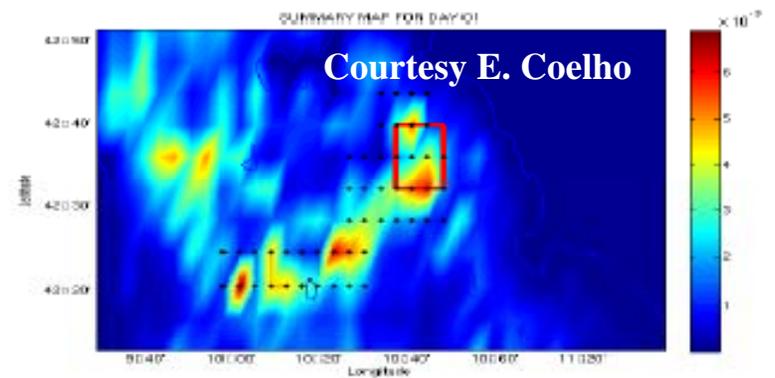
ETKF, GA - OSSE



★ CTD Arvane
★ CTD Lomandi
★ CTD Snellius



Snellius S
25 A
24 A
23 A
22 A
21 A
20 A
19 A



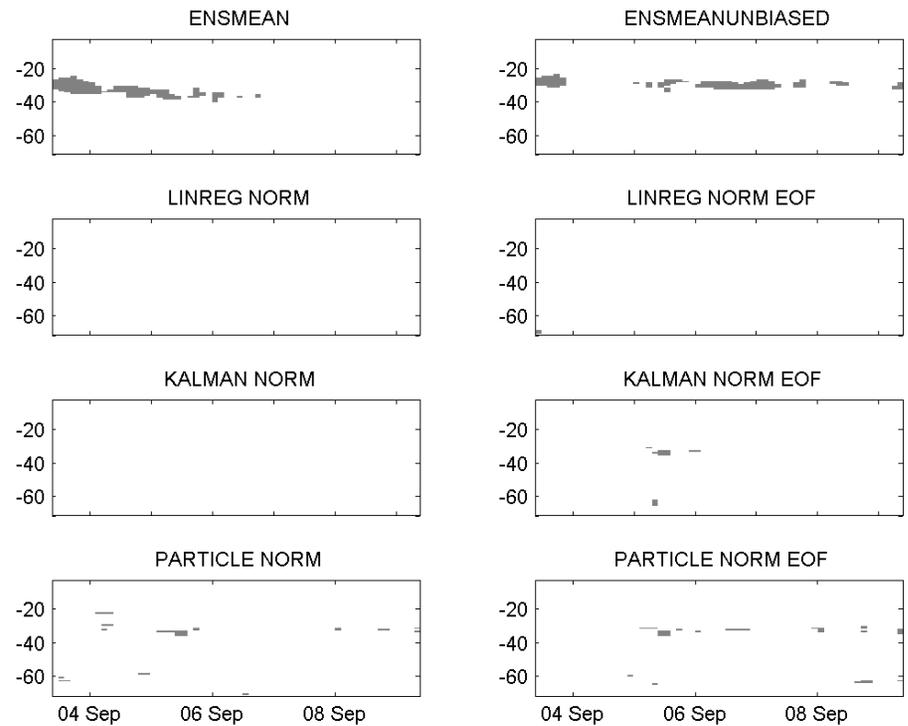
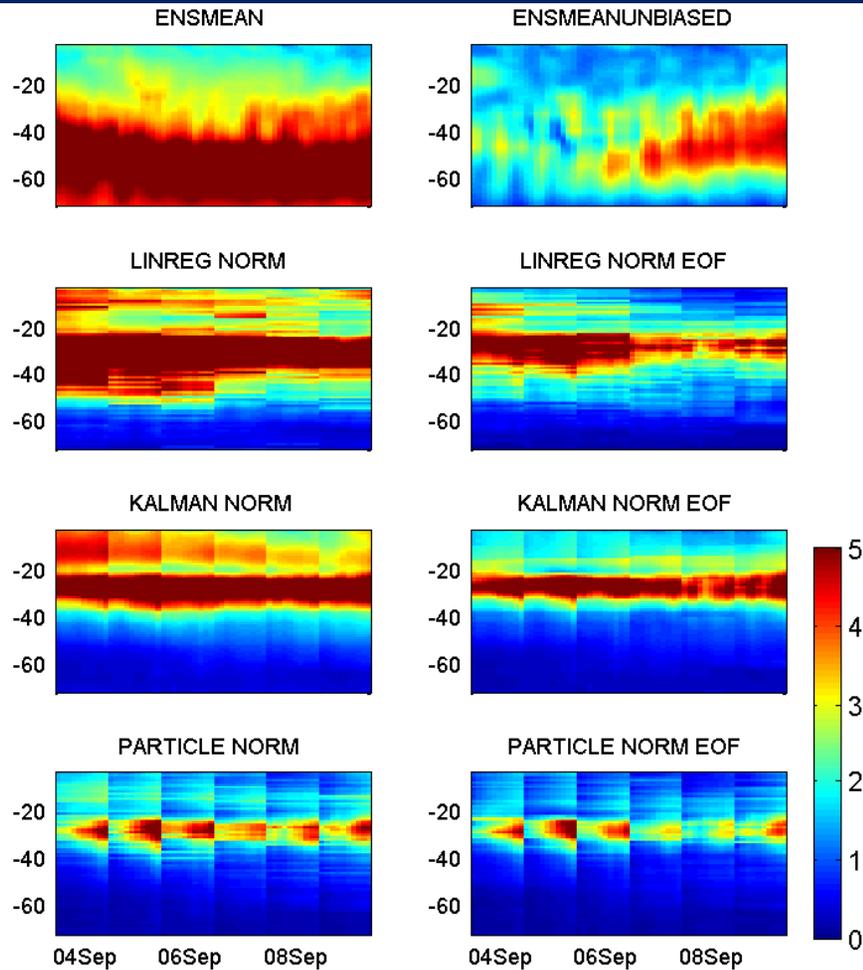


Uncertainties prediction



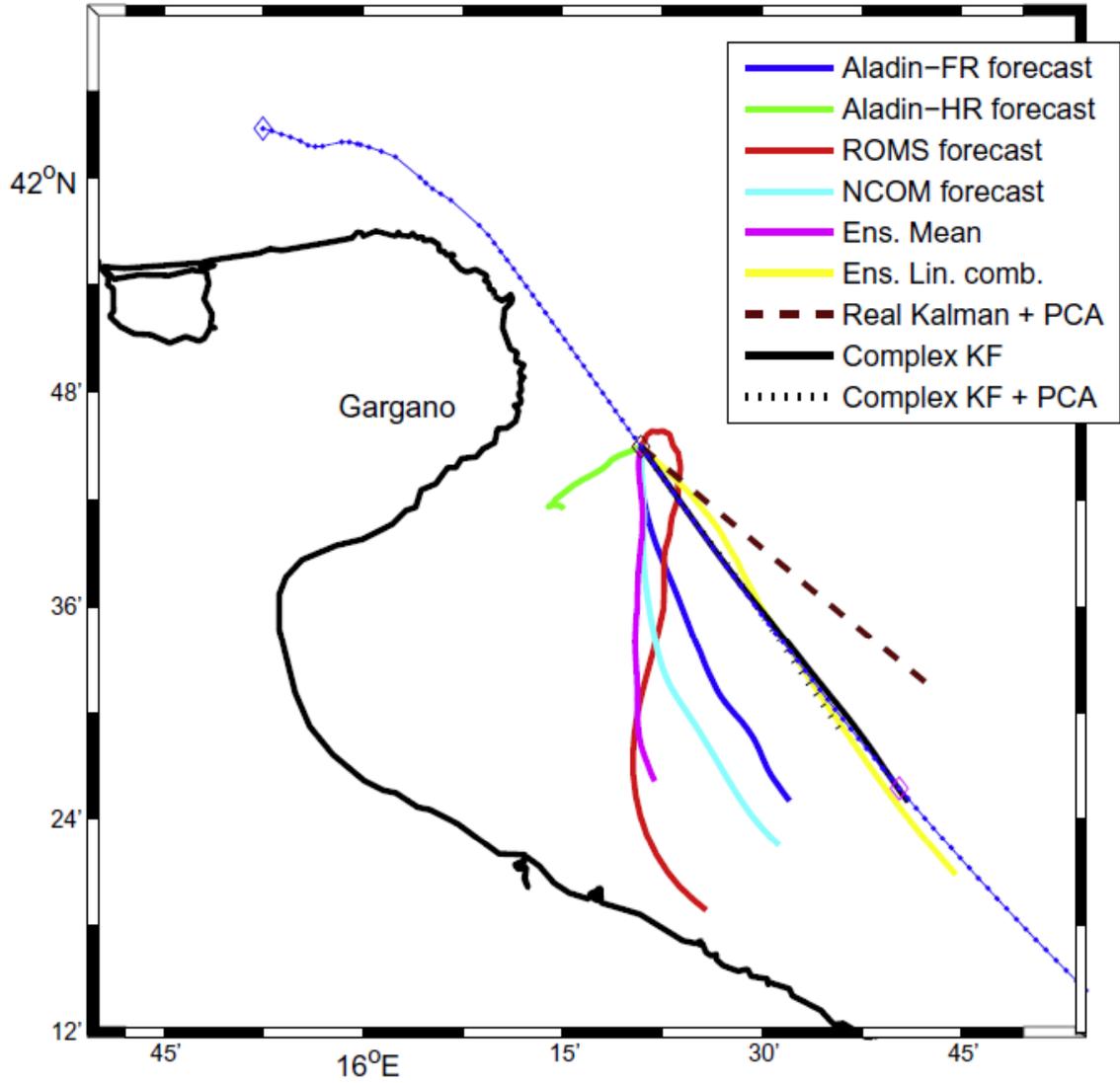
Uncertainty (99.7% conf.)

Posterior verification

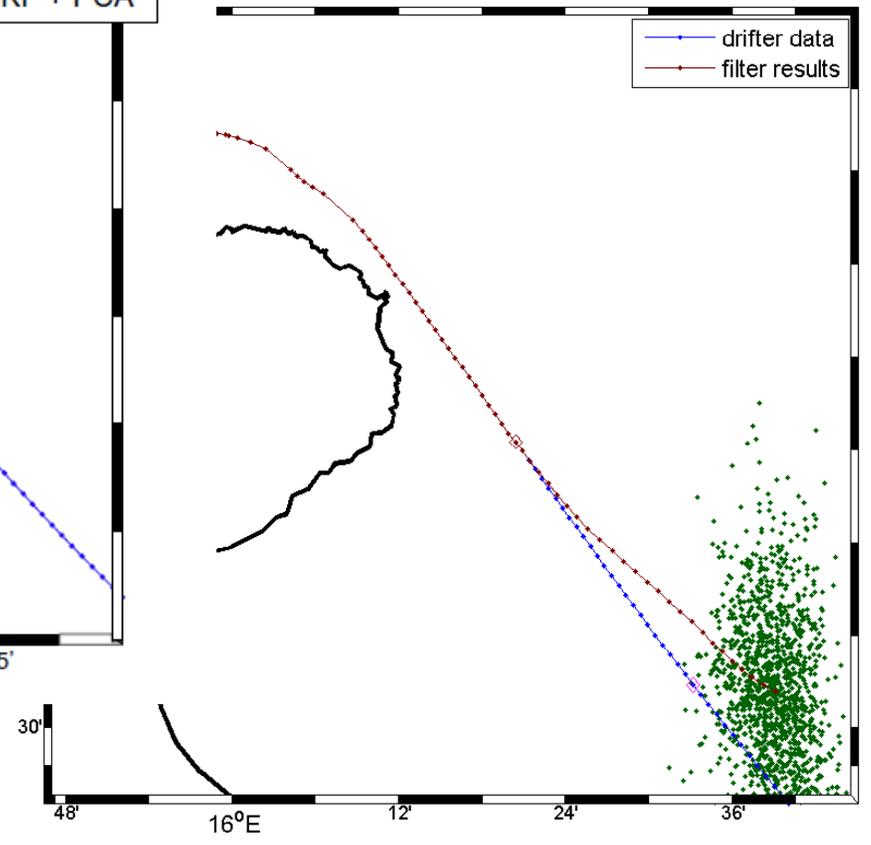




DART06: Kalman and Particle Filter SE



SE SIR (real)





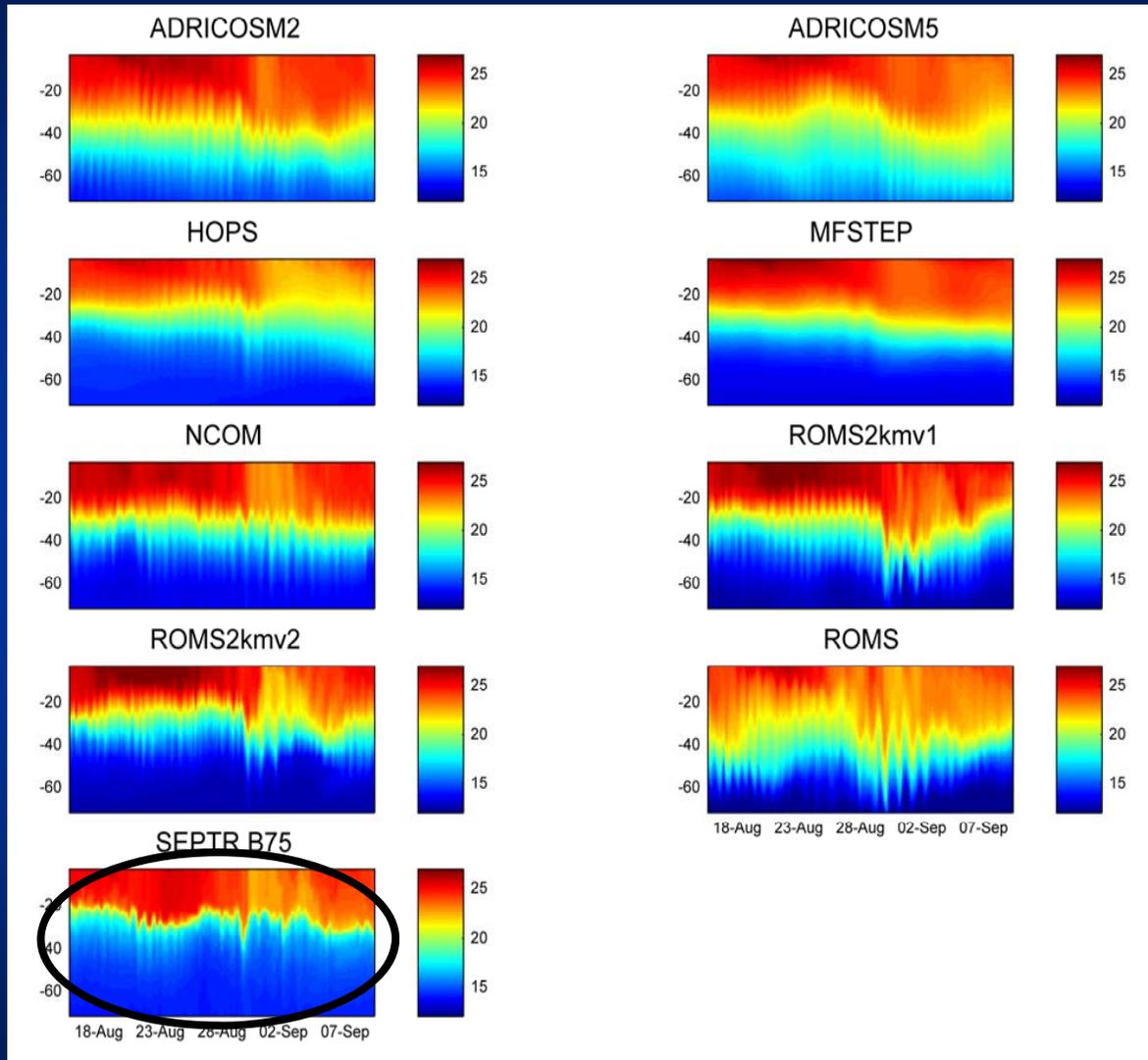
Which forecast (24 hrs) is best?



Models

Models

Data



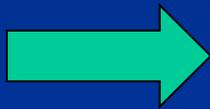


Can we do better?



What if we have multiple predictions?

- Select the best prediction?
- Fuse all predictions:



multi-model super-ensembles

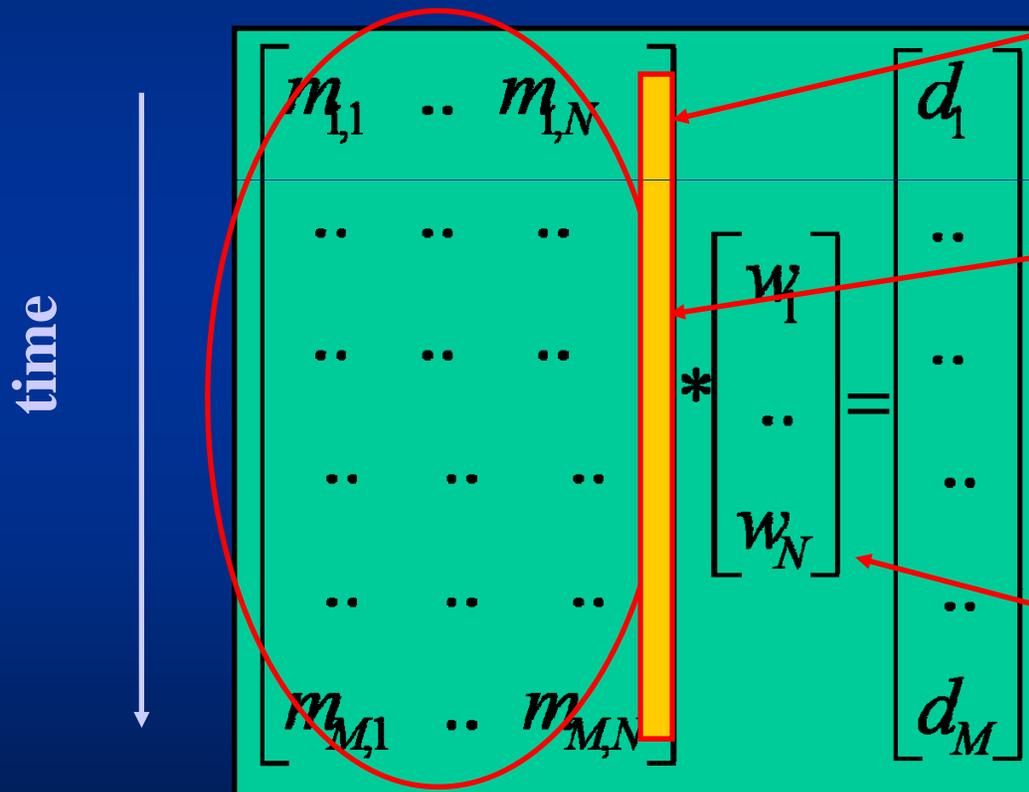
- Some existing applications in climate/meteorology
- NURC: pioneered work for the ocean
 - poor skills of models
 - lack of real-time data
 - few operational models
- General aim: improved
 - forecast
 - uncertainty/confidence estimation (PDF)



SE 'tricks'



Models Weights Data



Independent term
add a bias column

Regularize (PCA/EOF)
e.g. 95% of variance
helps generalization

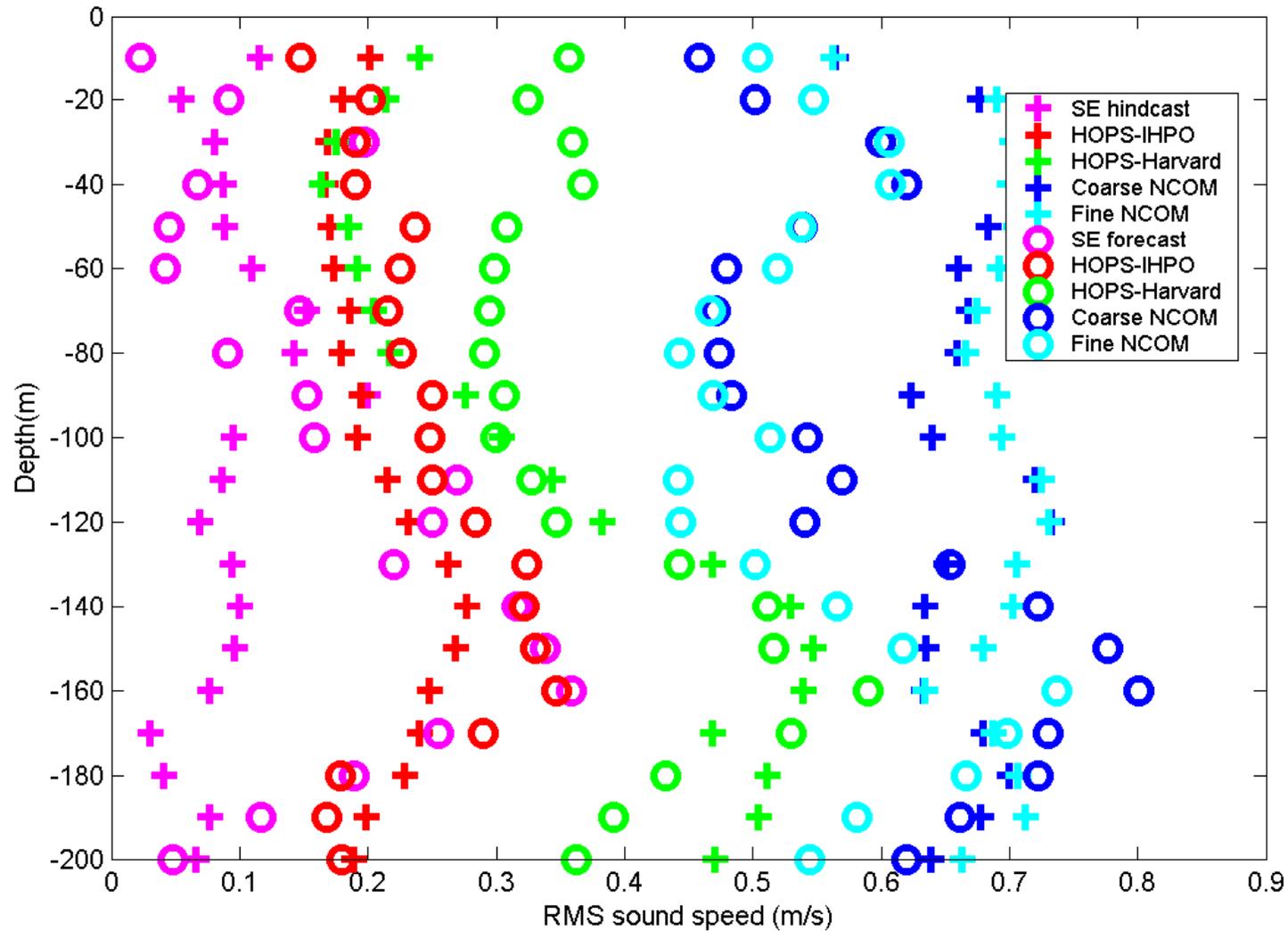
Complex weights
Magn: stretch
Phase: rotate



SE Sound speed profile errors



e) RMS sound speed (m/s), 2004040900 24

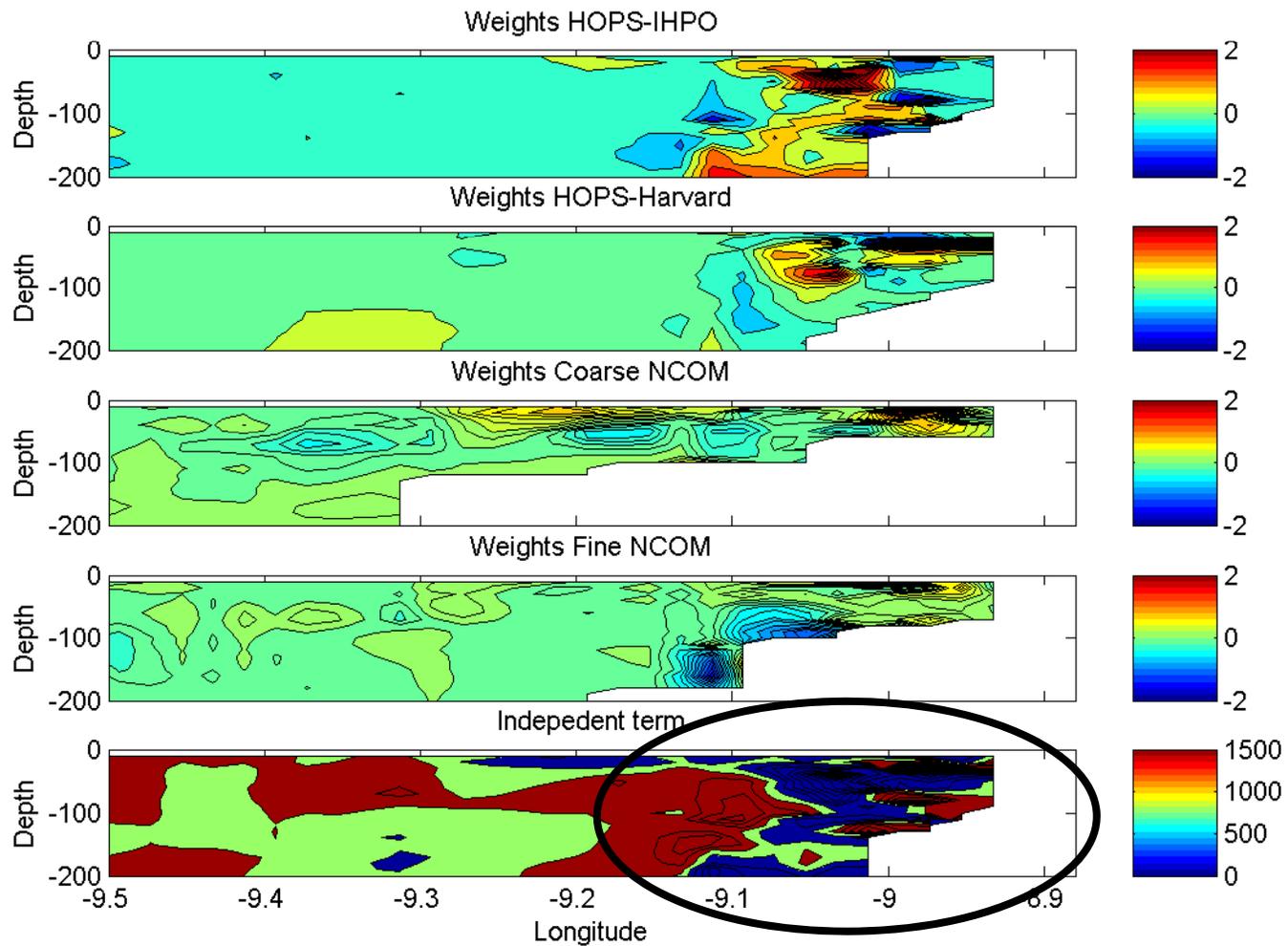




SE Weights

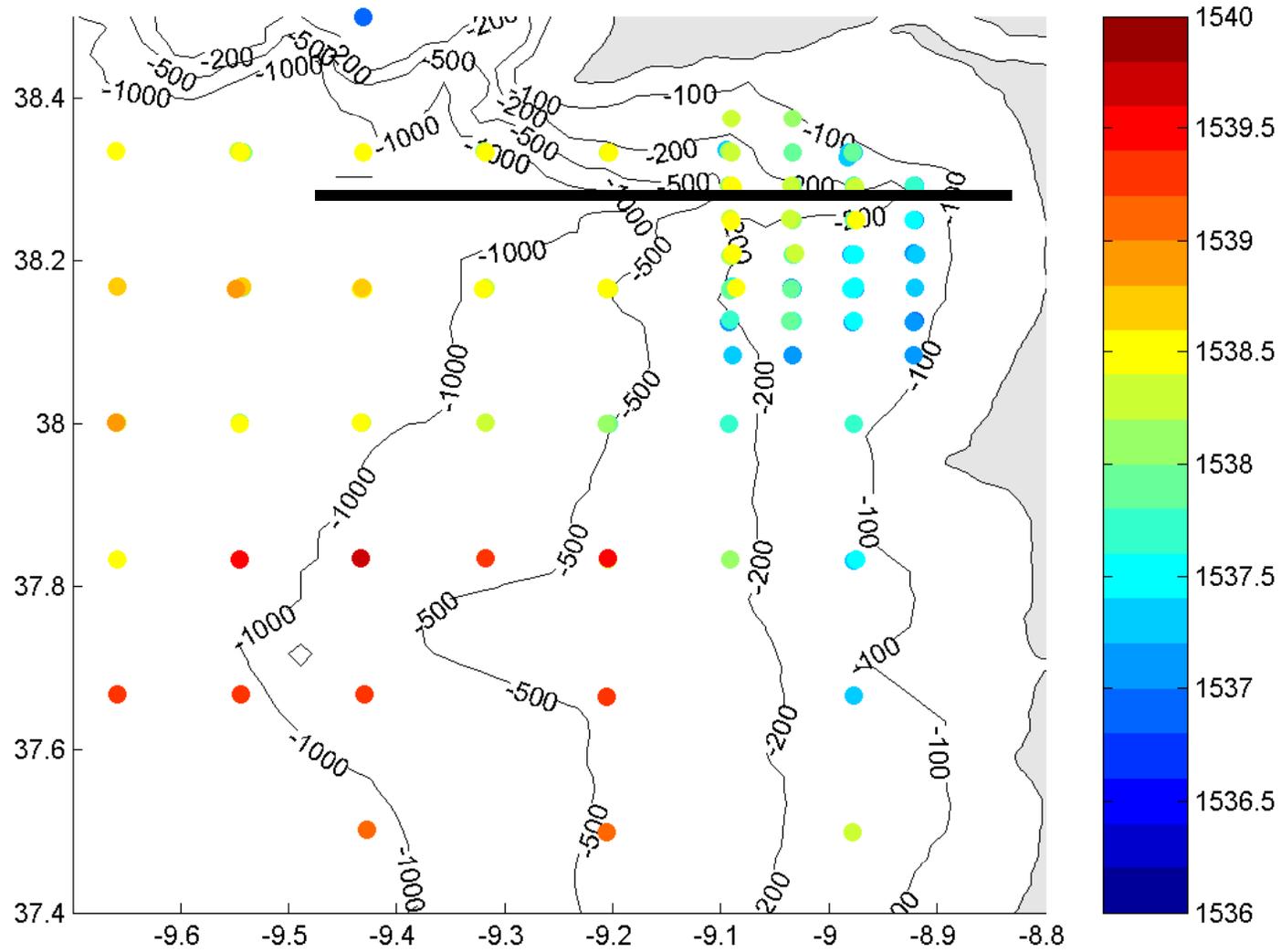


e) Optimal weights at 2004040900 24 at lat 38.3





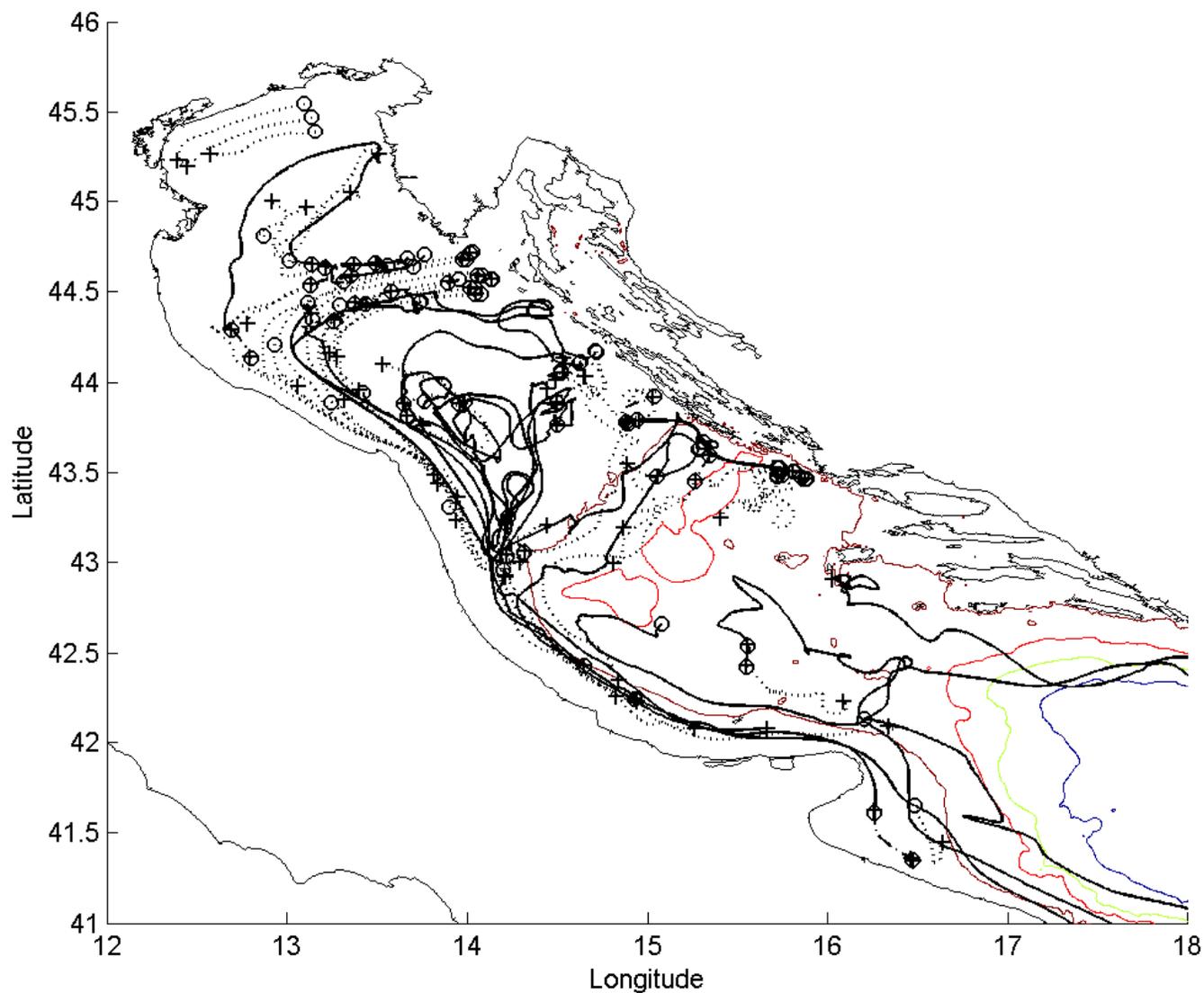
MREA04: sound velocity (100m)





ADRIA02-03 drifters (Jan-Feb)

NURC

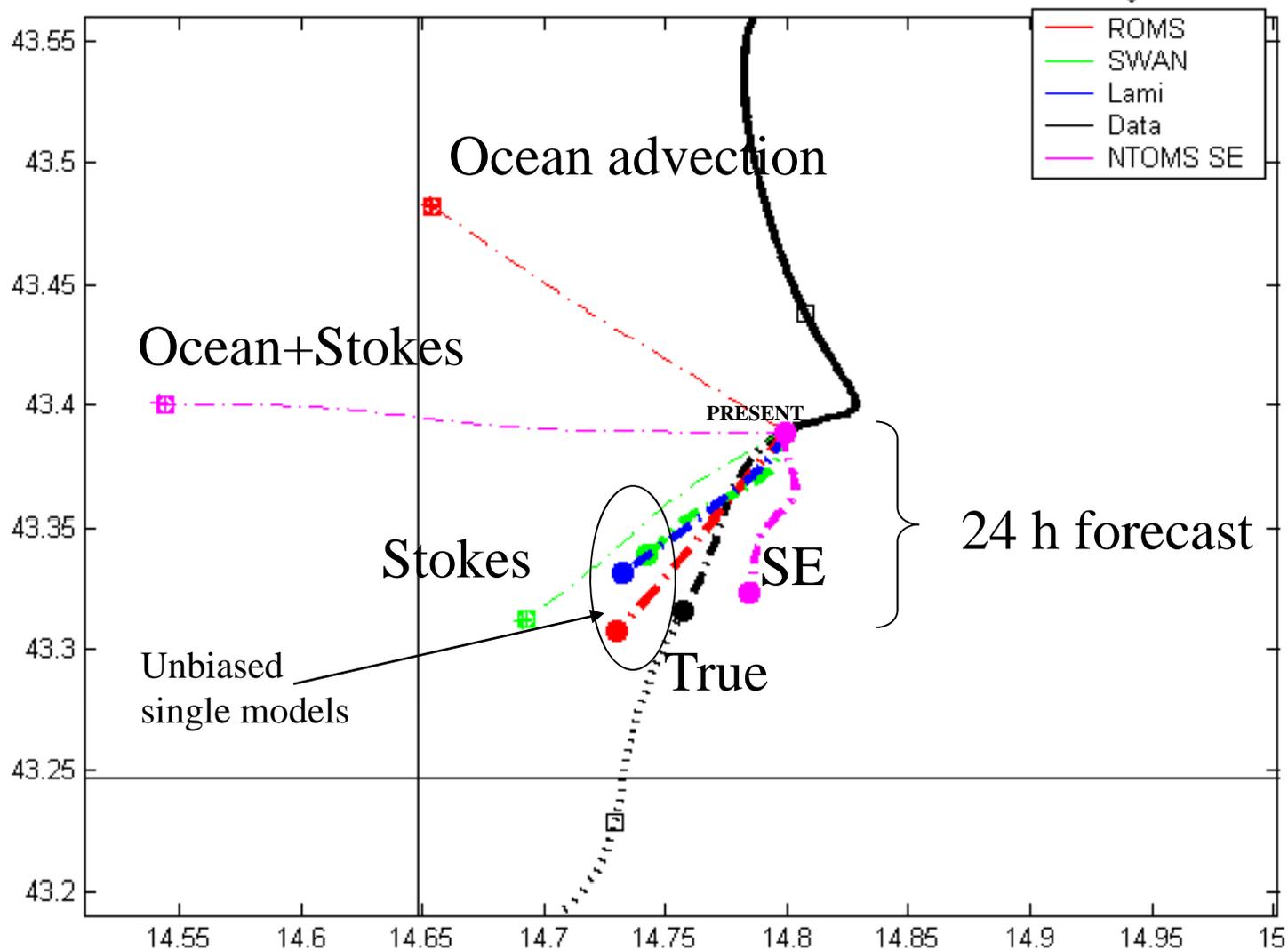




Drifter tracks

Drifter 1 (id=4001,2003020703 to 2003022402)

Simul from 2003021600 to 2003021700 Valid 2003021600 24 forecast mldivide()





Surface drift



Surface drift (air-sea interface) = response to:

- wind forcing
- Stokes drift (waves)
- Ocean advection (+ inertial oscillation, tides, sub-mesoscale, etc)

Not well understood:

- wave-current interaction
- energy dissipation
- very young/very high seas
- spectrum (besides Hs & Ts)
- directional spread

Heuristic approach



Hyper-ensemble (in complex domain) =
combination of wind, current, Stokes



Hyper-ensembles (HE)



Ocean

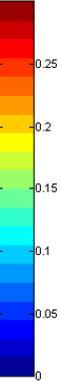
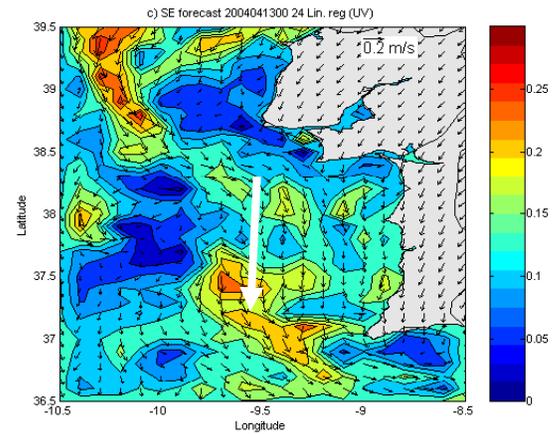
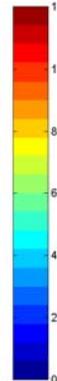
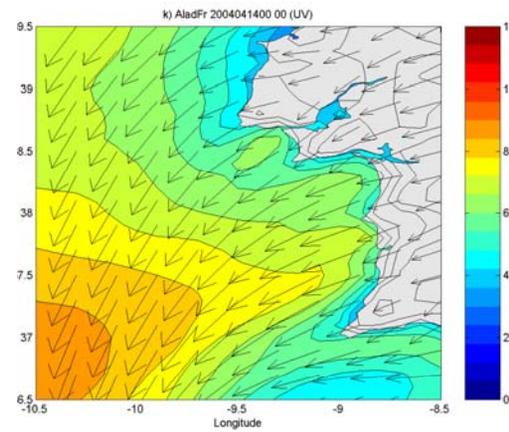
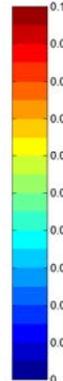
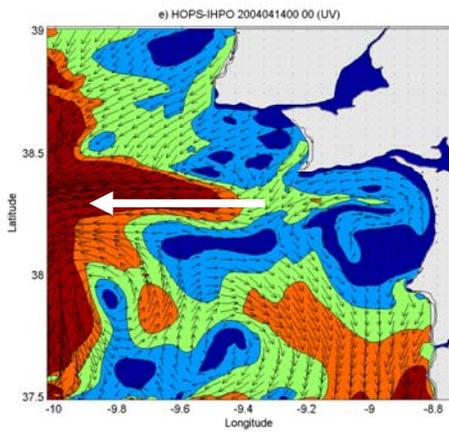
Meteo

Hyper-ens.

HOPS

ALADIN FR

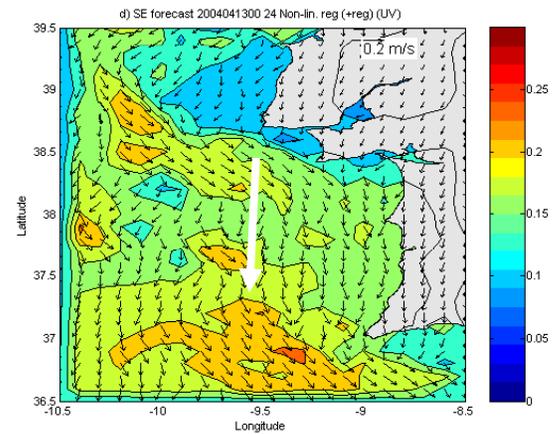
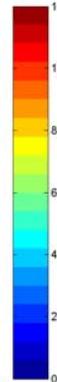
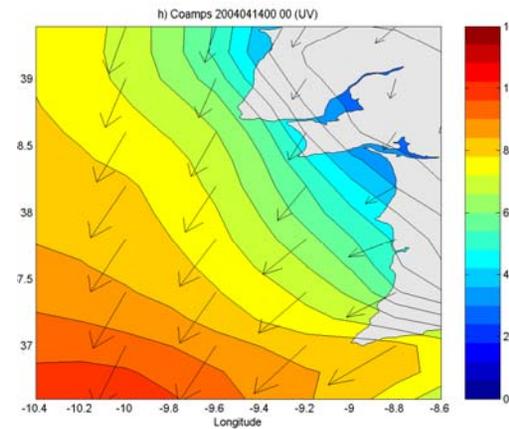
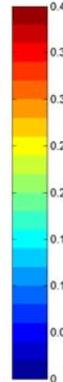
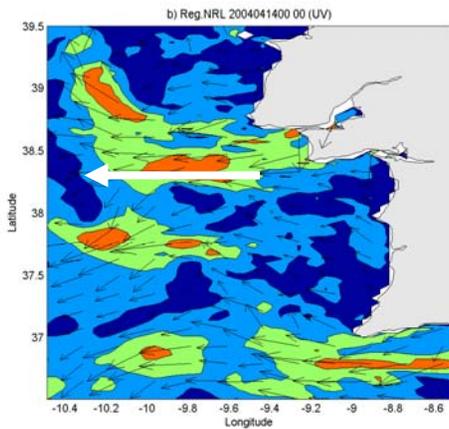
Linear HE



NCOM

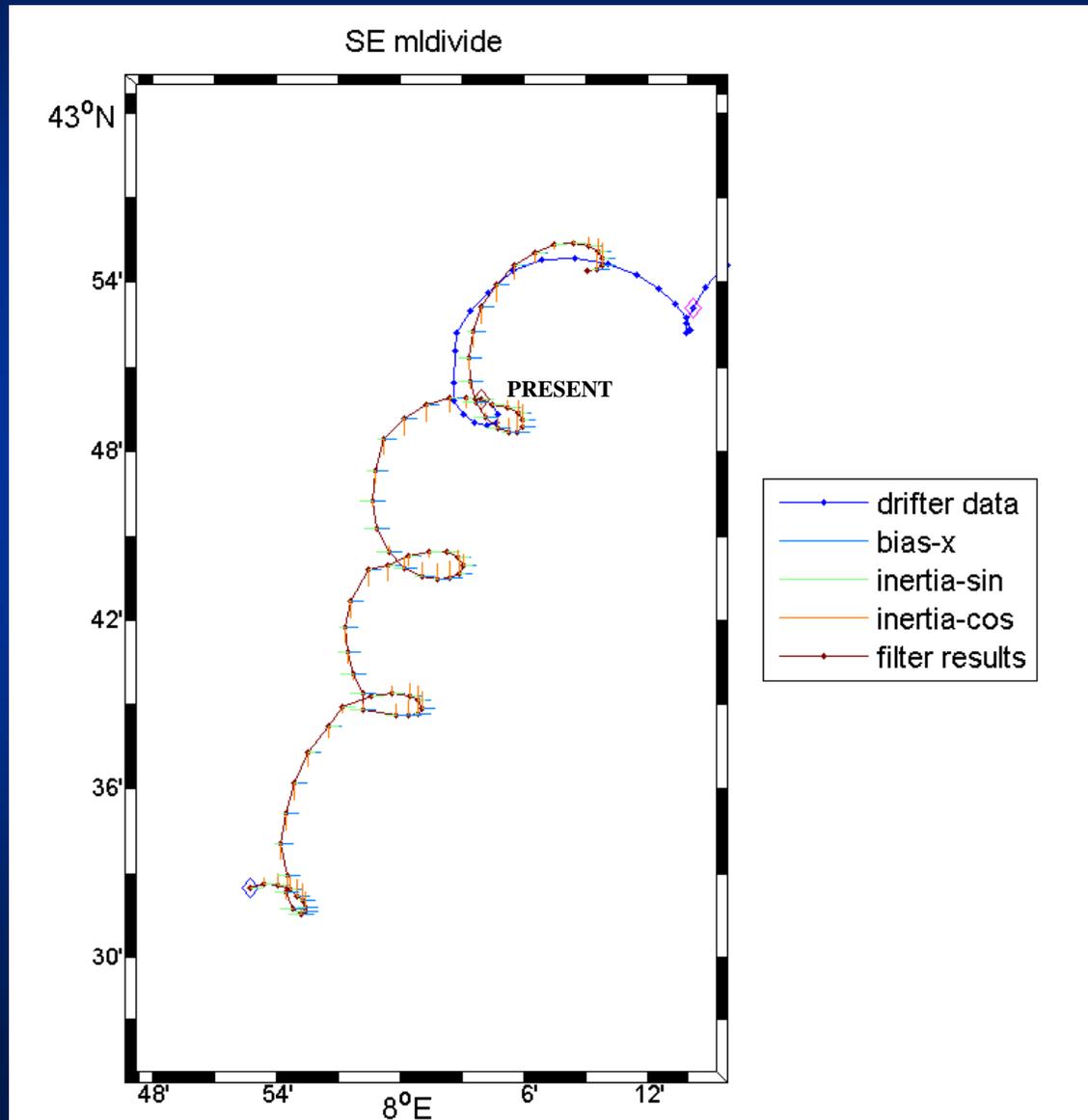
COAMPS

Non-linear HE



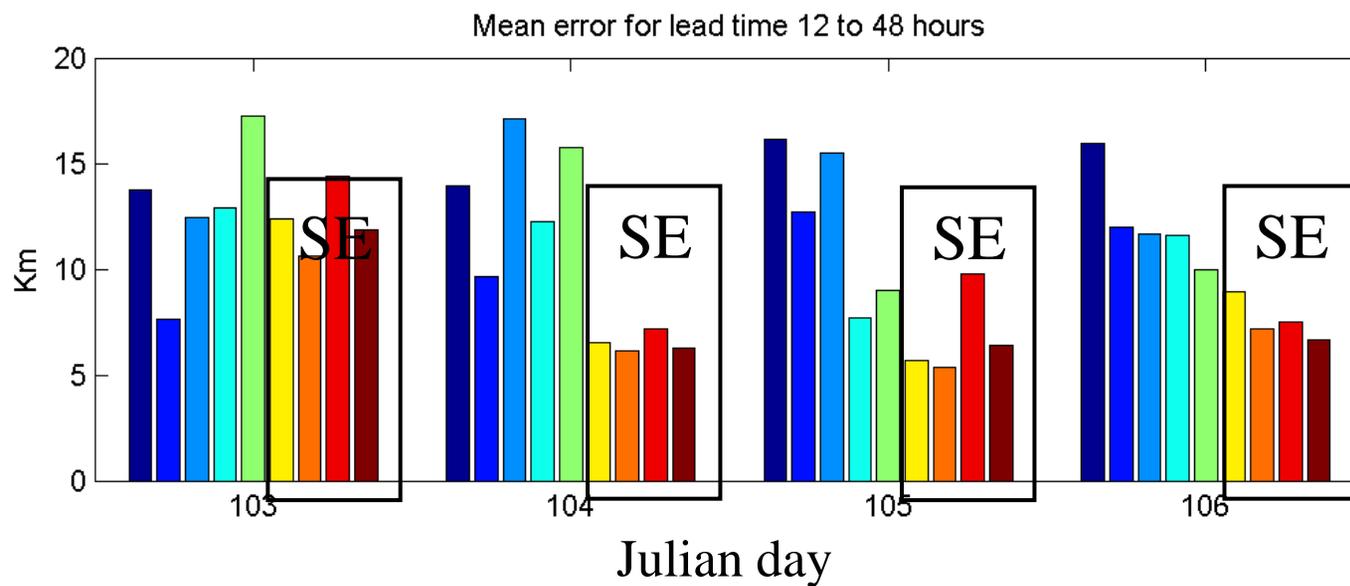
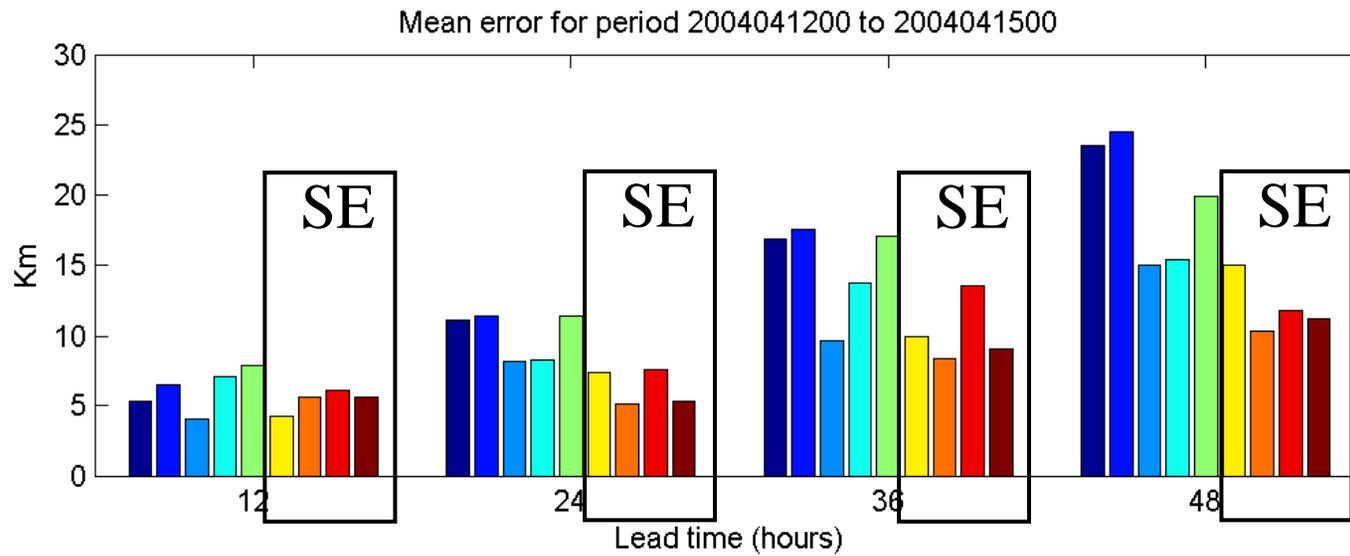


SE+Analytical model

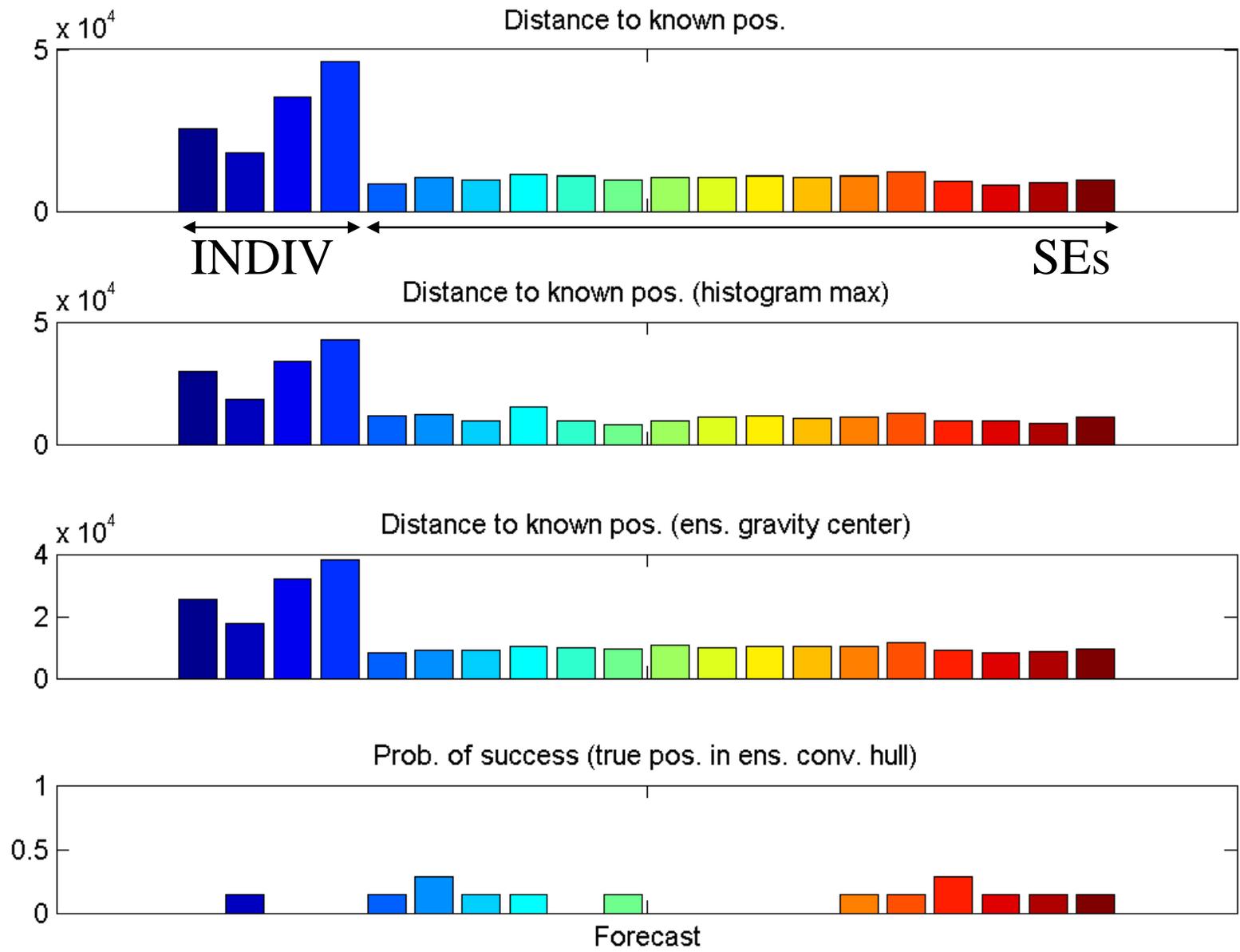




Hyper-ensemble statistics

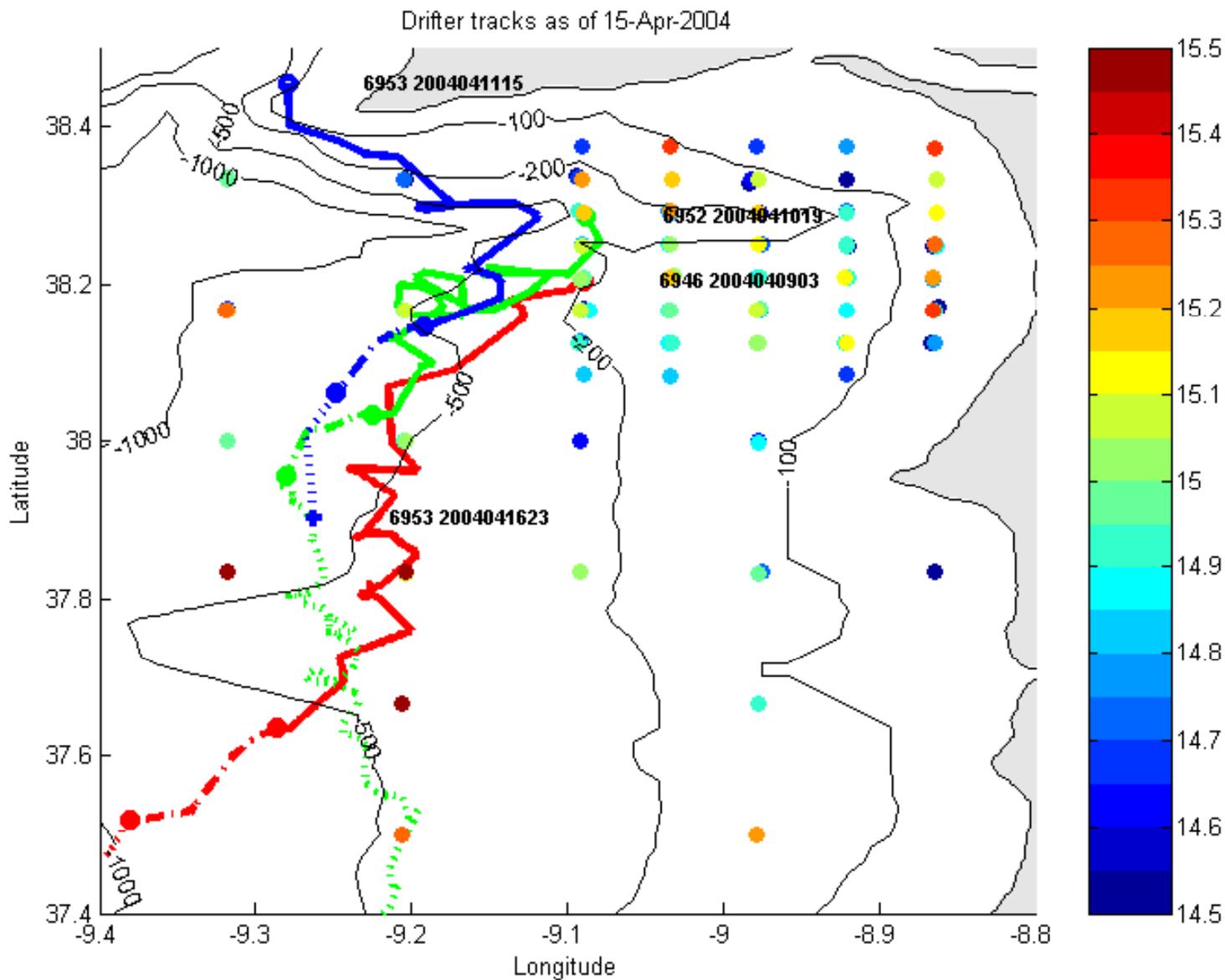


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MREA04: DRIFTERS





Kalman Filter (Gaussian error statistics)



The KF in the super-ensembles paradigm

Forecast :

$$\mathbf{x}_i^f = \mathbf{M}\mathbf{x}_{i-1}^a$$

$$\mathbf{P}^f = \mathbf{M}\mathbf{P}^a\mathbf{M}' + \mathbf{Q}$$

\mathbf{x} contains the weights of the models in the combination

\mathbf{M} is the identity matrix

\mathbf{Q} contains a reasonable error cov. of model weights

Analysis :

$$\mathbf{K} = \mathbf{P}^f \mathbf{H}' [\mathbf{H}\mathbf{P}^f \mathbf{H}' + \mathbf{R}]^{-1}$$

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

$$\mathbf{P}^a = \mathbf{P}^f - \mathbf{K}\mathbf{H}\mathbf{P}^f$$

As \mathbf{x} is the model weights, and

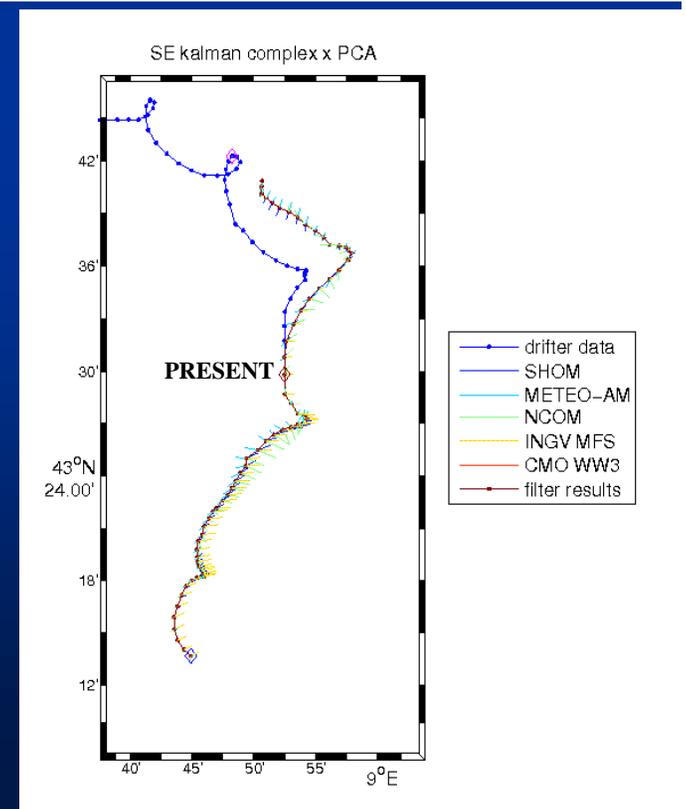
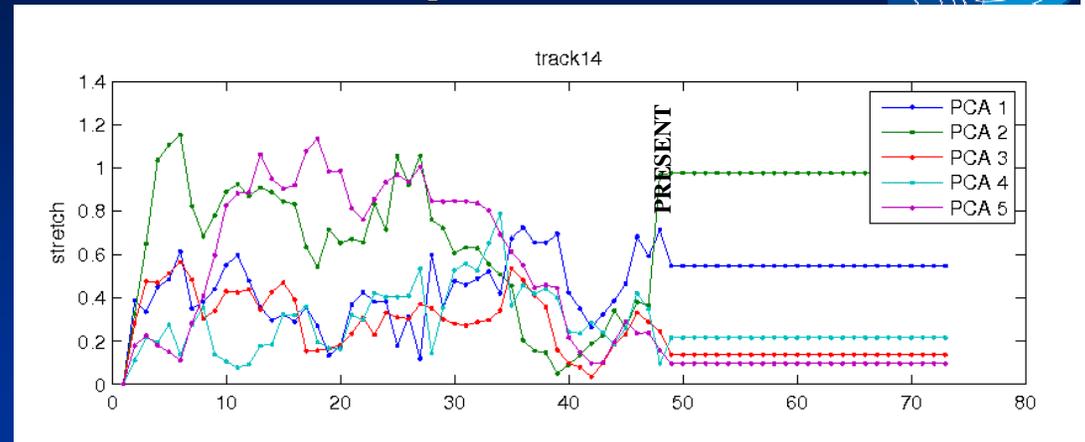
\mathbf{y} , the observation, is the real drifter position,

\mathbf{H} contains the (wind, ocean...) model forecasts !

\mathbf{R} represents the error covariance matrix of \mathbf{y} .

Memory of the system ?

Depends on \mathbf{Q} and relative errors between models and observations





What if not Gaussian & highly non-linear? Particle filter (with sequential importance resampling)

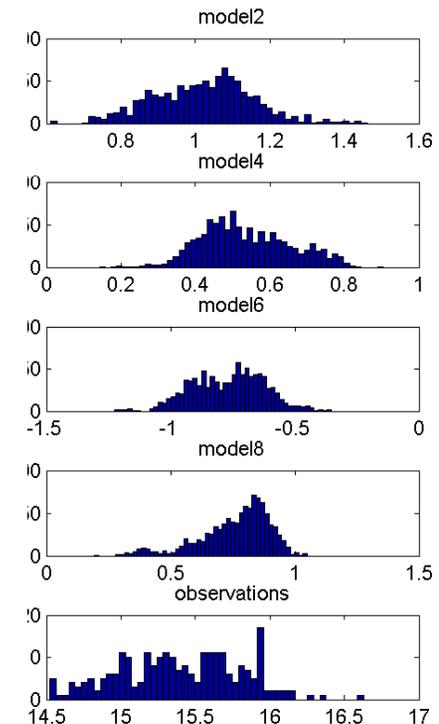
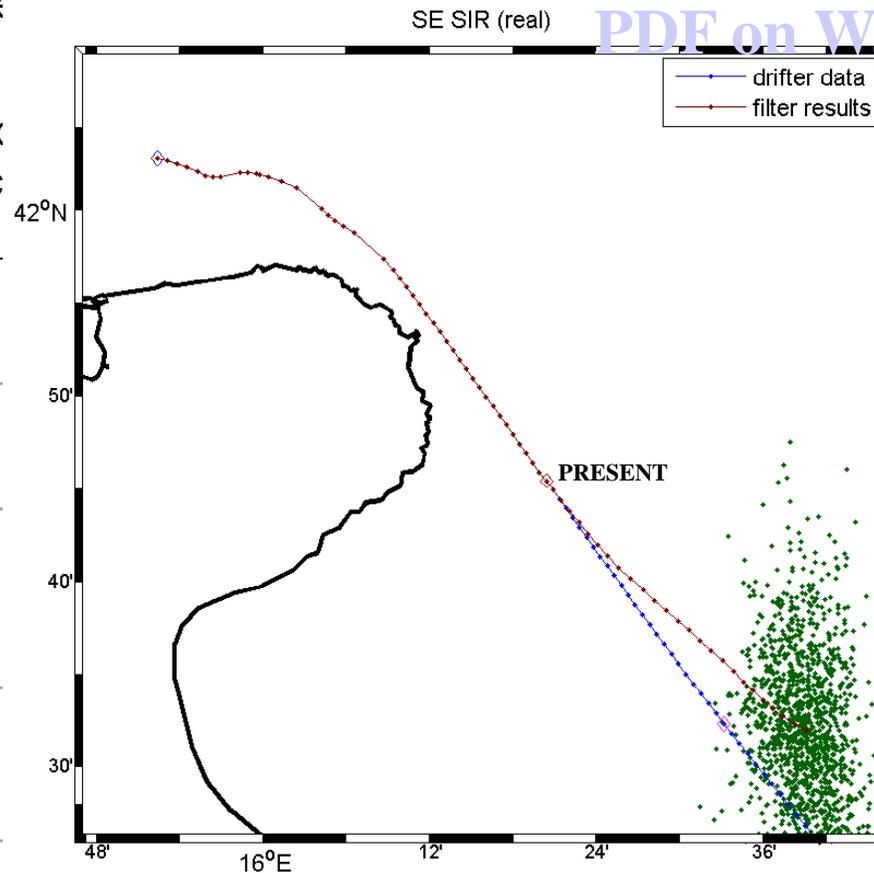
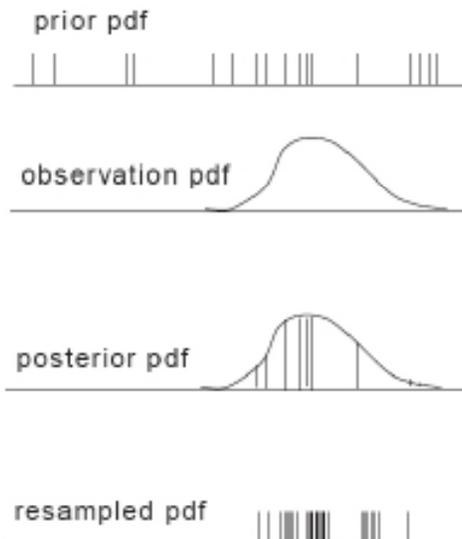


SIR filter

- create hundreds of particles, i.e. combinations of the physical models
- select the ones going in the right direction, replace bad ones
- Continue until no more data are available, then predict ensemble of particles

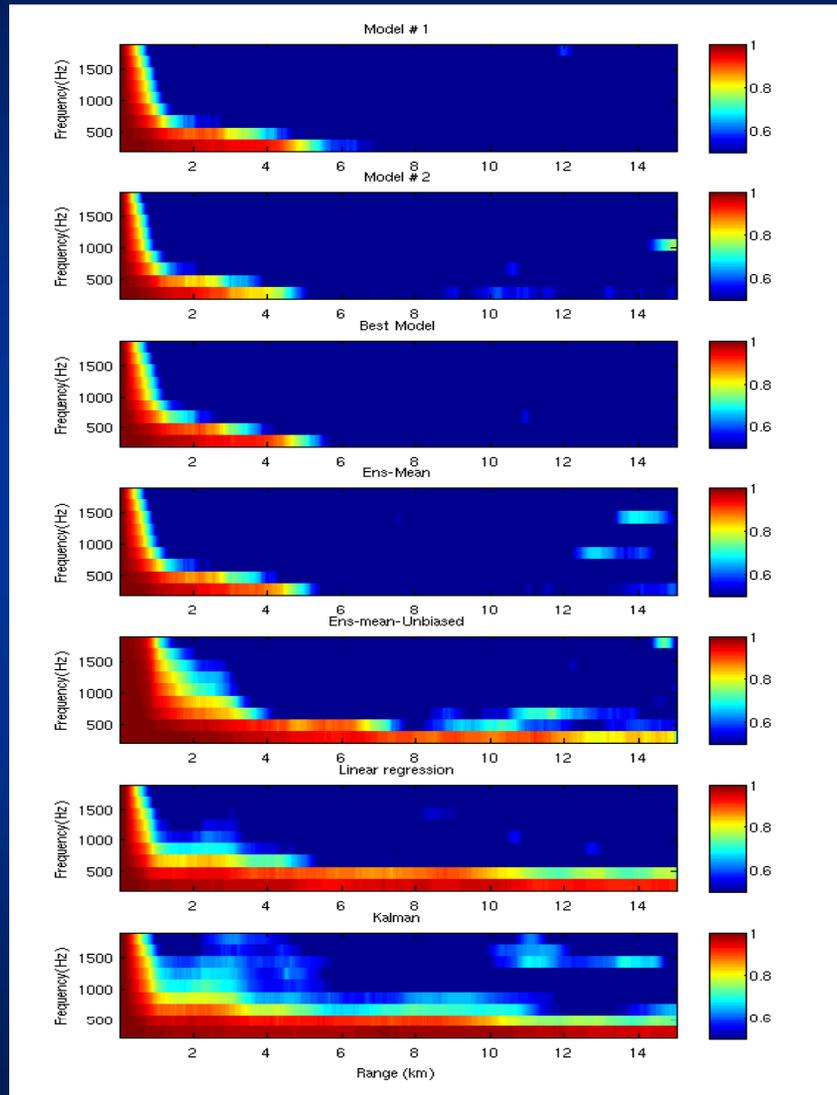
Access to full PDF =
uncertainty + higher moments
(skewness, kurtosis, etc)

PDF on W. DART06B, T, B75





Correlation of predicted complex LF acoustical pressure fields



20070430 – T=21h