The GMAO Ocean EnKF and Application to the Assimilation of Altimetry Data

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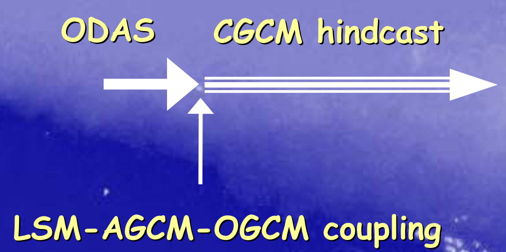
GMAO Ocean Data Assimilation System (ODAS-1)

Algorithms:
- Univariate optimal interpolation (UOI): functional error covariances
- Multivariate OI (MvOI): steady-state ensemble based error representation
- Multivariate EnKF

Model:
- Poseidon v4 OGCM (Schopf and Loughe, 1995) :

•Quasi-isopycnal vertical coordinate
•Prognostic variables are *h, t, s, u* and *v*
•Sea surface height (SSH) is diagnostic: $\eta = \Sigma_i \text{buoyancy}(t_i, s_i)h_i/g$
•538 x 572 x L27 ((1/3° x 5/8° x L27): About 30 million prognostic variables

Observations:
- UOI: T, S
- MvOI: T, S, SSH
- EnKF: T, S, SSH



ODAS-2

Algorithms:
- UOI: tested
- MvOI: tested
- EnKF: upcoming

Models:
- Poseidon v5: tested
- MOM v4: development
- MITGCM: upcoming

Why a new system?:
- Adherence to ESMF gridded component paradigm
- Model independent & enhanced portability
- Main new features:

•Faster analysis
•Analysis conducted at any arbitrary resolution
•Supports multi-model, multi-resolution ensembles
•OMF calculation at observation time
•4-D (x, y, z, 1/t) error-covariance specification
•No code changes required to include new data types

Ocean EnKF (MWR 130, 2951-2965, 2002; JMS 40-41, 363-380, 2003; NPG 12, 491-503, 2005)

- Multivariate compactly supported background covariances: updates T, S, u & v
- Massively parallel
- System noise representation:
  - Random linear combinations of model-state EOFs to simulate model errors
  - Forcing perturbations to simulate forcing errors (colored spectrum in space and time)
- Online bias correction (used in SSH assimilation)

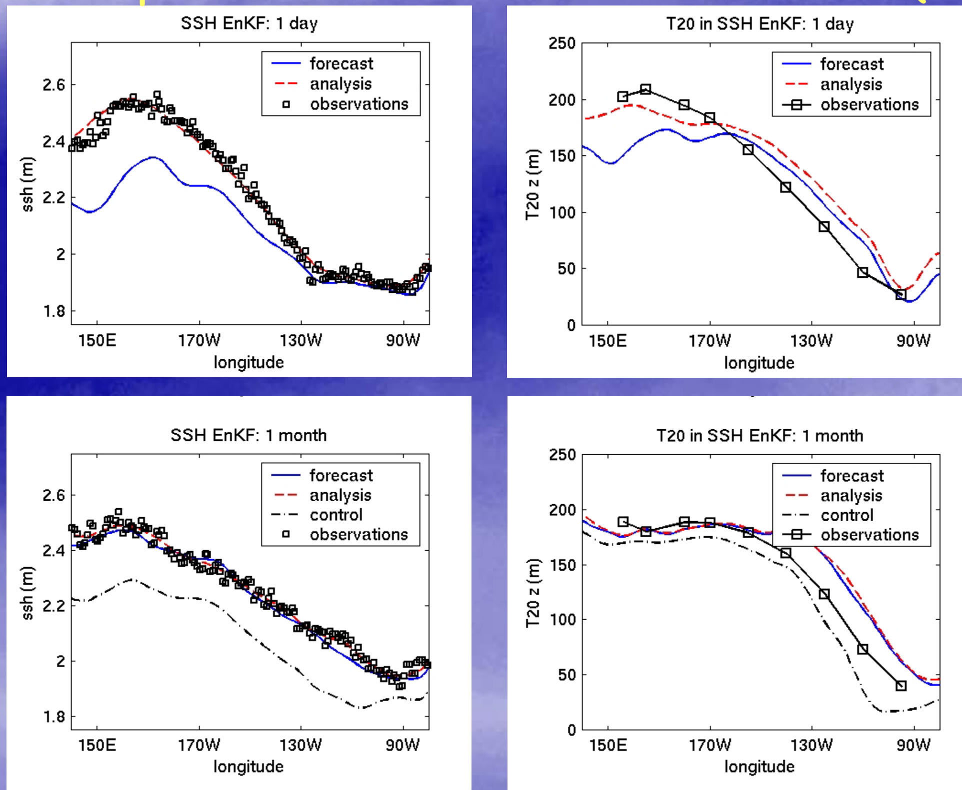
Challenge: Transit EnKF from R&D status to a production application

- *Match the performance/outperform production ODAS*
- *Good performance with very small ensembles*

EnKF validation experiments

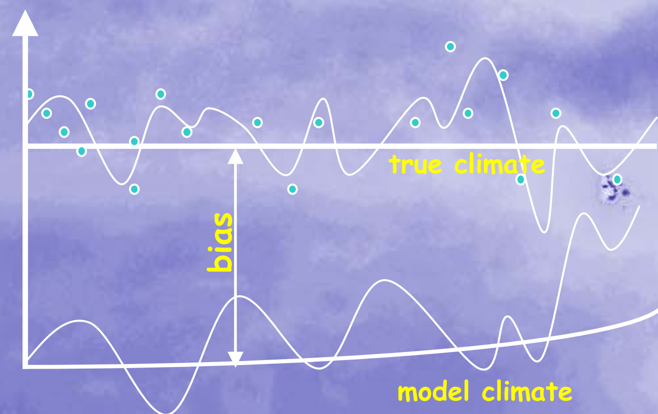
- Assimilate T/P SSH anomalies + TAO & XBT temperature profiles 1/1/2001-12/31/2001
- Online bias estimation in SSH assimilation
- 4 runs: 9, 17, 33 & 65 member EnKF
- Compare with
  - no-assimilation control
  - Production ODAS (temperature OI + S(T) correction)

First attempt to assimilate T/P anomalies with ENKF (2001)

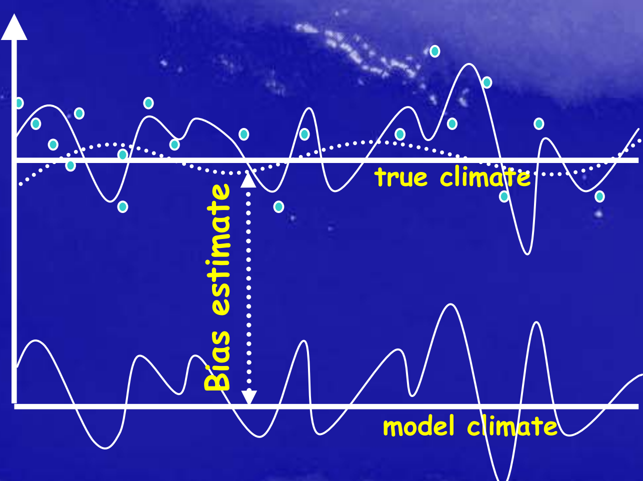


T/P altimetry data are anomalies
Hence bias must be accounted for when assimilating SSH

a) Standard assimilation



b) Assimilation with online bias estimation (OBE)



Side by side estimation of:
- Unbiased error
- Climatological error (bias)

Compactly supported EnKF (bias estimation omitted)

Time filter: $$\boldsymbol{x}^{\Phi}_{i,k} = (1-\beta)\boldsymbol{x}^{\Phi}_{i,k-1} + \beta \boldsymbol{x}^{f}_{i,k} \qquad , i = 1,\ldots,n,$$

$$\boldsymbol{x}^{f}_{i,k} = \boldsymbol{M}(\boldsymbol{x}^{a}_{i,k-1}, \boldsymbol{f}_{k-1}) + \boldsymbol{N}_{i,k-1}, \qquad E(\boldsymbol{N}_{i,k-1}\boldsymbol{N}^{T}_{i,k-1}) \approx \boldsymbol{Q}_{k-1}, \qquad i = 1,\ldots,n, \quad (1a)$$

$$\boldsymbol{S} = \{\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_n\} = \{\boldsymbol{H}(\Phi(\boldsymbol{x}^{f}_{1} - \overline{\boldsymbol{x}}^{f})), \boldsymbol{H}(\Phi(\boldsymbol{x}^{f}_{2} - \overline{\boldsymbol{x}}^{f})), \ldots, \boldsymbol{H}(\Phi(\boldsymbol{x}^{f}_{n} - \overline{\boldsymbol{x}}^{f}))\}, \quad (1b)$$

↑ Spatial filtering operator

$$\boldsymbol{HP}^{f}\boldsymbol{H}^{T} = \frac{1}{n-1}\boldsymbol{SS}^{T}, \quad (1c)$$

$$\boldsymbol{a}_i = [\boldsymbol{C} \bullet (\boldsymbol{HP}^{f}\boldsymbol{H}^{T} + \boldsymbol{R})]^{-1}(\boldsymbol{y} + \boldsymbol{e}_i - \boldsymbol{H}(\boldsymbol{x}^{f}_{i})), \qquad E(\boldsymbol{e}_i\boldsymbol{e}^{T}_{i}) \approx \boldsymbol{R}, \qquad i = 1,\ldots,n, \quad (1d)$$

$$\boldsymbol{x}^{a}_{i,l} = \boldsymbol{x}^{f}_{i,l} + \frac{1}{n-1}\sum_{j=1}^{n}(\Phi(\boldsymbol{x}^{f}_{j,l} - \overline{\boldsymbol{x}}^{f}_{l}))\boldsymbol{s}^{T}_{j}(\boldsymbol{c}_l \bullet \boldsymbol{a}_i), \qquad i = 1,\ldots,n. \quad (1e)$$

Improving the performance for small ensembles

Spatio-temporal filtering of background-error covariances

- Temporal filter applied to X^f integration (exponential moving average)
- Spatial filter applied to (X^f -<X>) deviations (Gaussian filter)

Effect of time filtering

β	1 (no time filter)	0.01	0.005	0.0025	0.00125
RMS OMF (K)	1.174	1.165	1.161	1.164	1.177

Table 1. RMS OMF difference for T as a function of the time-filtering parameter β in 30 day 17-member EnKF runs assimilating TAO and XBT observations (model timestep: 1200s).

Effect of spatial filtering

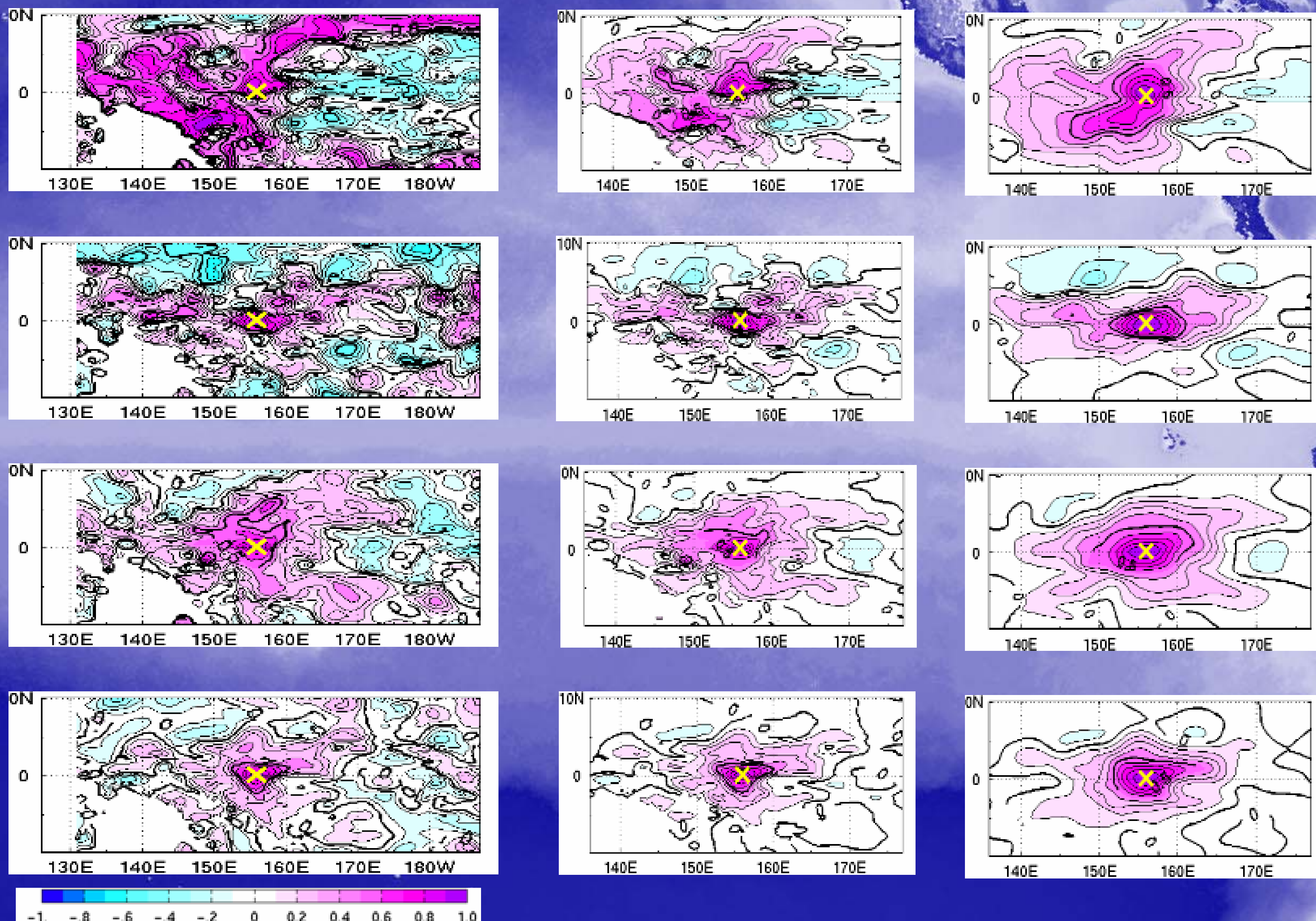
Example of marginal Kalman gain: T obs @(0n,156E,150m) on 12/31/01
horizontal section through <T',T'> covariances

EnKF-9

EnKF-17

EnKF-33

EnKF-65



Unfiltered, not compactly supported

Unfiltered, compactly supported

Filtered, compactly supported

Effect of spatial filtering

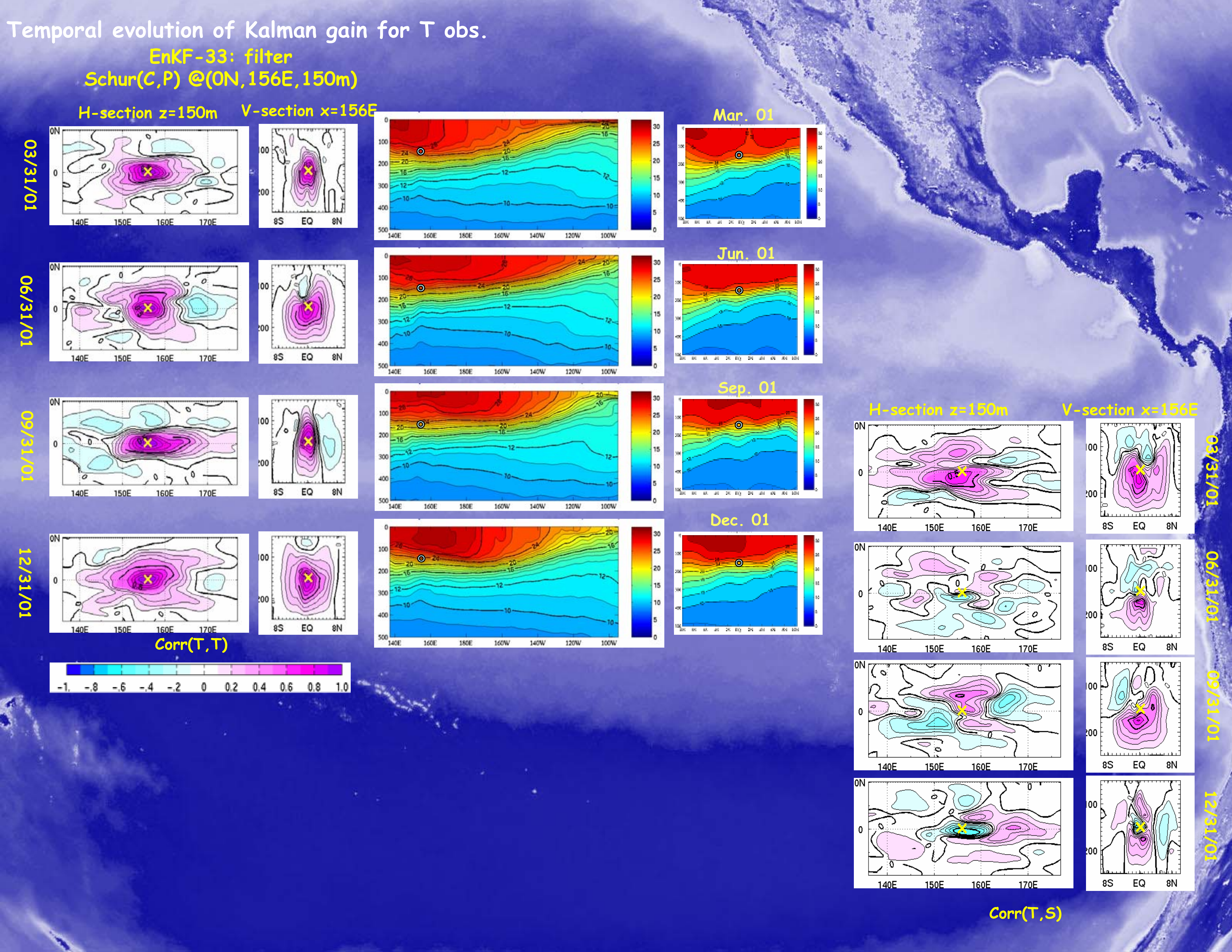
Example of marginal Kalman gain: T obs @(0n,156E,150m) on 12/31/01
horizontal section through <T’,T’> covariances

	EnKF-9	EnKF-17	EnKF-33
Unfiltered, globally supported (UGS)	0.36	0.46	0.67
Unfiltered, compactly supported (UCS)	0.51	0.58	0.75
Filtered, compactly supported (FCS)	0.63	0.70	0.77

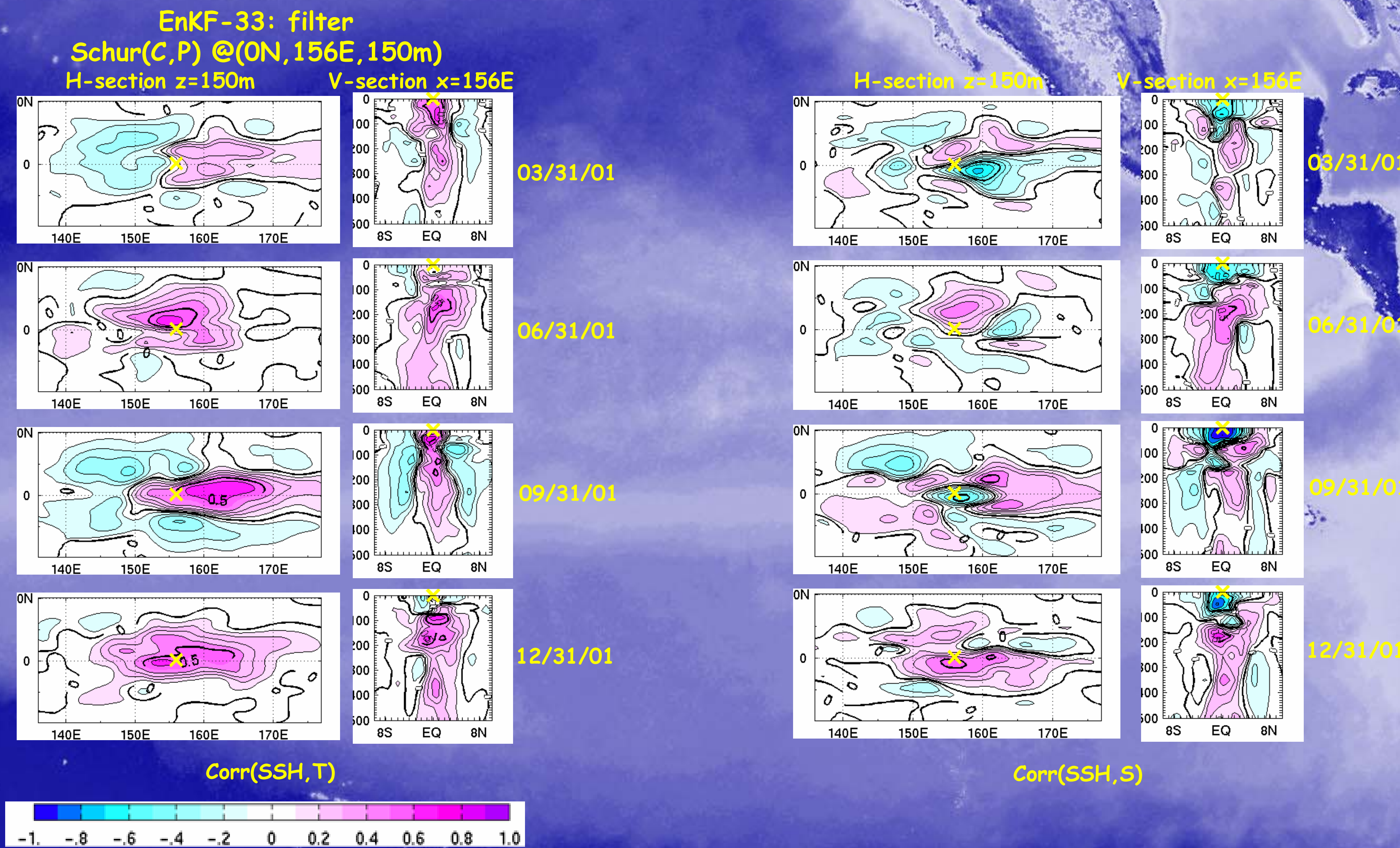
Table 2. Correlation of the horizontal section through the unfiltered globally supported (UGS) marginal gain for *T* in the EnKF-65 run with the corresponding UGS, unfiltered compactly supported (UCS) and filtered compactly supported (FCS) horizontal sections through the corresponding marginal gain in the EnKF-9, EnKF-17 and EnKF-33 runs.

- Filtering increases correlation of Kalman gain with corresponding raw (no filter, globally supported) gain from EnKF-65 run

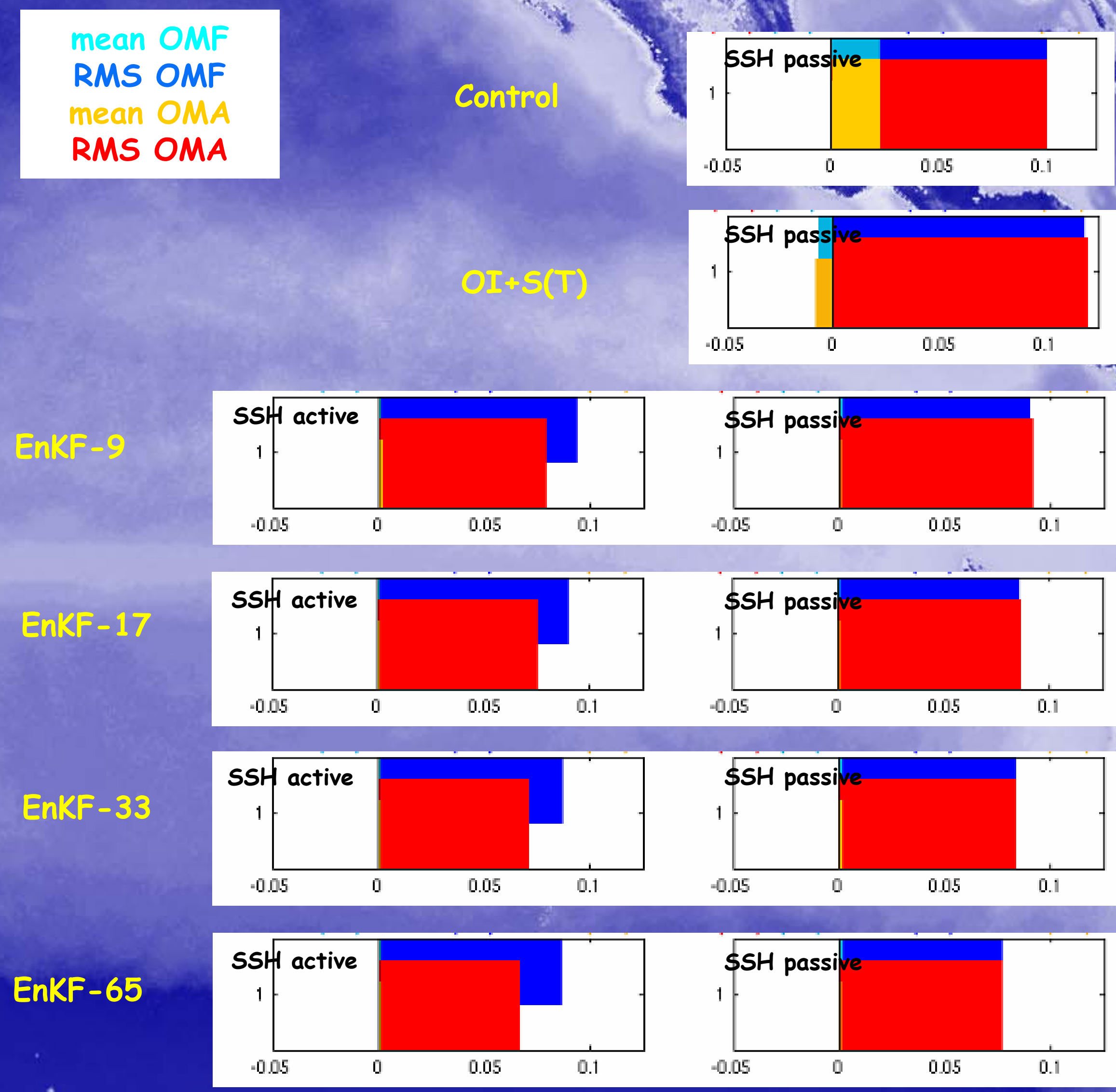
- Especially for very small ensembles, the filter “simulates” the covariances one would get from a larger ensemble


Temporal evolution of Kalman gain for T obs.
EnKF-33: filter
Schur(C,P) @(0N,156E,150m)
H-section z=150m
V-section x=156E
03/31/01
06/31/01
09/31/01
12/31/01
Mar. 01
Jun. 01
Sep. 01
Dec. 01
Corr(T,T)
-1. -.8 -.6 -.4 -.2 0 0.2 0.4 0.6 0.8 1.0
H-section z=150m
V-section x=156E
03/31/01
06/31/01
09/31/01
12/31/01
Corr(T,S)

Temporal evolution of Kalman gain for SSH obs.

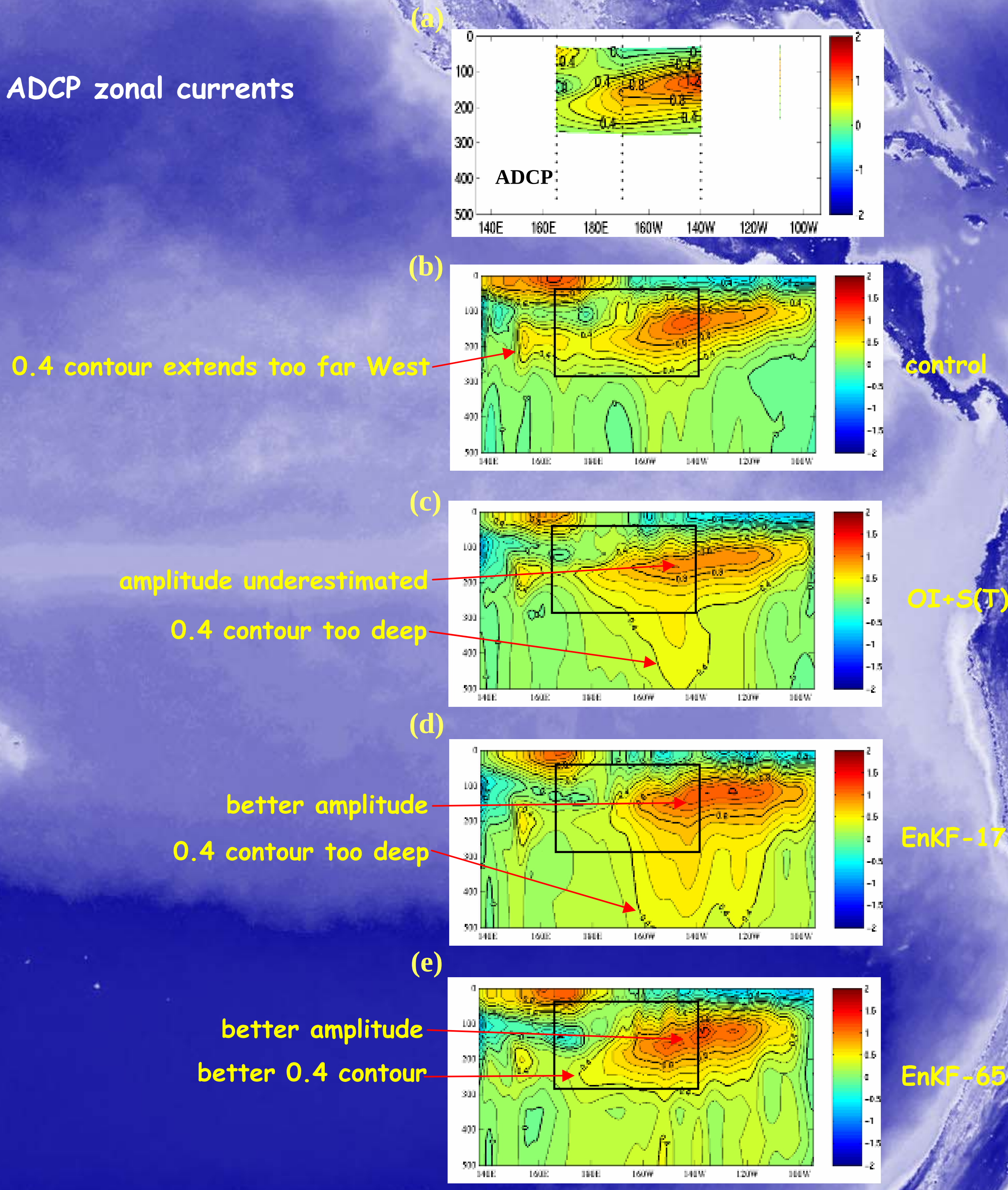


SSH OMF and OMA statistics



- Control is most biased
- OI partly corrects SSH bias but worsens RMS OMF
- EnKF runs have no noticeable SSH bias

Validation with December 2001 ADCP zonal currents

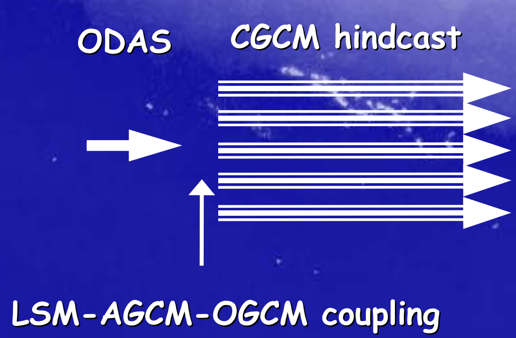


Impact of assimilation on CGCM hindcast skill

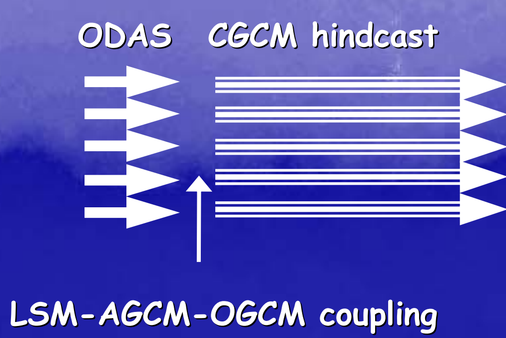
- 17-member EnKF
- Assimilate T + SSH for February-April of each year from 1993 to 2002
- Couple OGCM to AGCM & LSM after running ODAS
- 12-month May start CGCM hindcasts initialized with ocean from EnKF runs
  (to save CPU time, EnKF-initializedCGCM hindcasts have only 5 ensemble member)

- Assess impact of assimilation on SST hindcast skill
- Compare to history of production May-start hindcasts

T OI + S(T) initialization

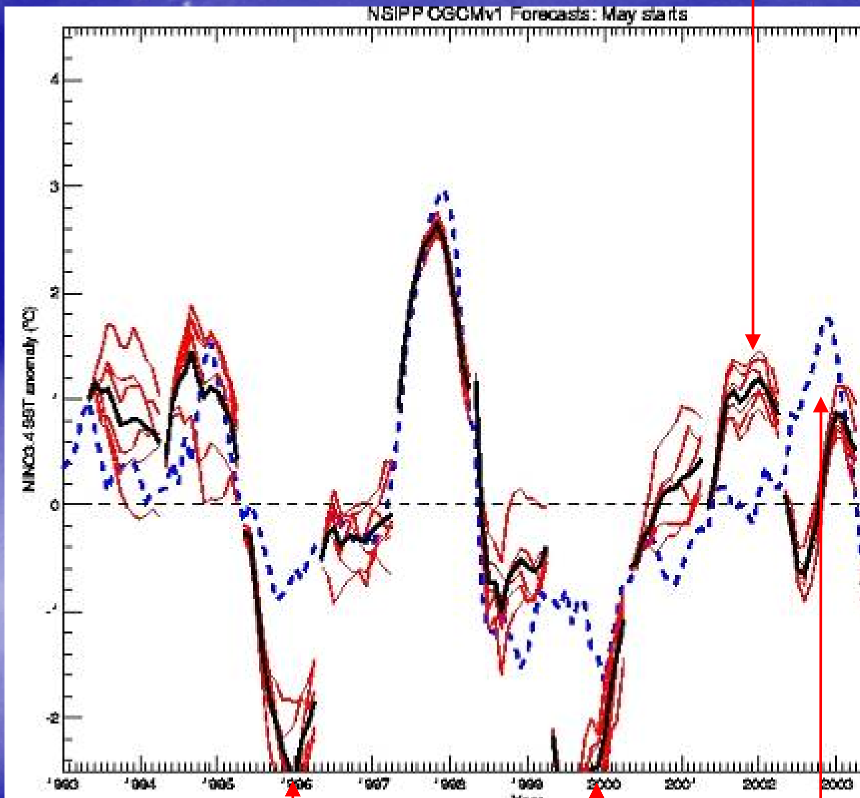


EnKF initialization



OI + S(T) initialization

False EN alert

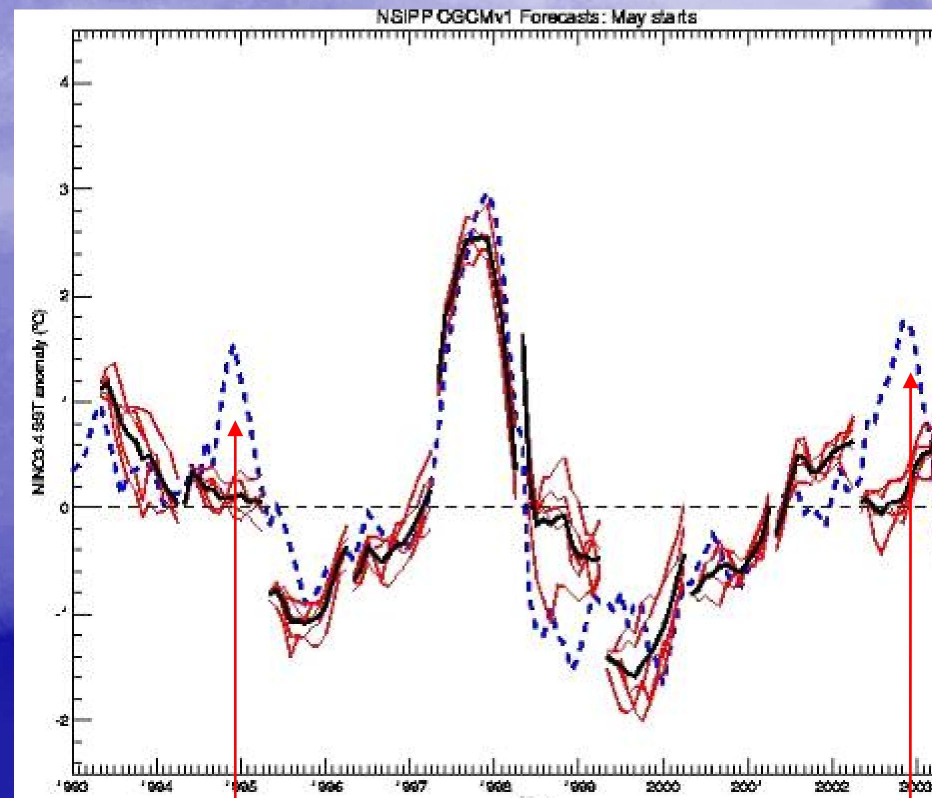


missed EN

false LN alert

false LN alert

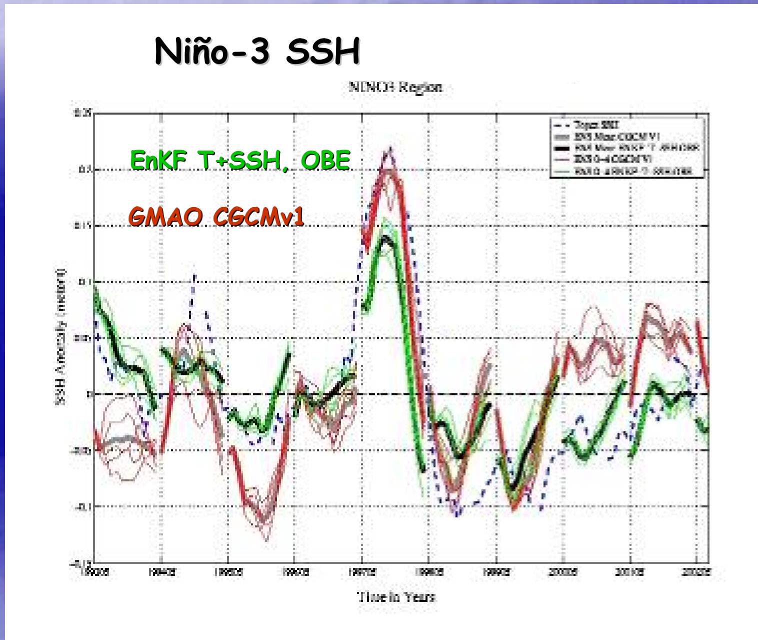
EnKF-17 initialization

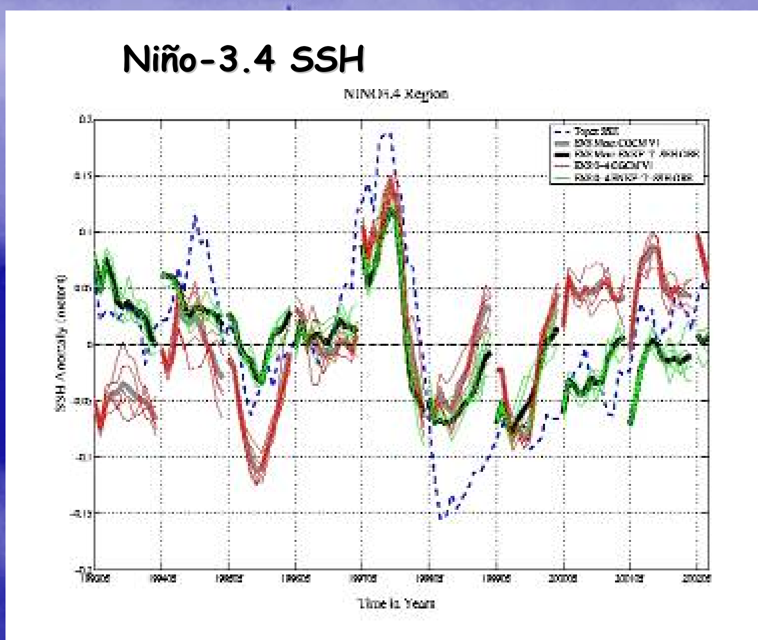


missed EN

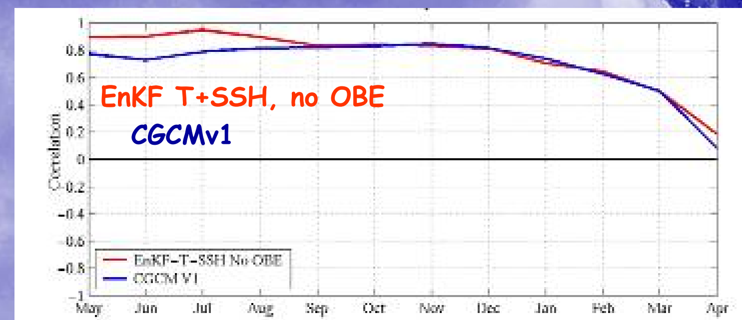
missed EN

May start Niño-3.4 SST hindcasts





hindcast correlations with TOPEX



May start SSH hindcasts

Conclusions

- Analysis speed up makes it practically feasible to use the EnKF in the production forecast initialization
  Small ensemble EnKF can outperform production system provided background covariances are appropriately preconditioned

Ongoing work

- More hindcast experiments with EnKF and Poseidon v4 (Robin Kovach)
- ODAS-2 testing and development: towards multi-model multi-resolution EnKF

- Investigating use of bred vectors (Shu-Chih Yang):
- - in lieu of model EOFs in MvOI
- - in EnKF system noise model and initialization