The Mediterranean ocean Forecasting System

State of development and progress up to date

N.Pinardi,

University of Bologna, Ravenna Campus

and

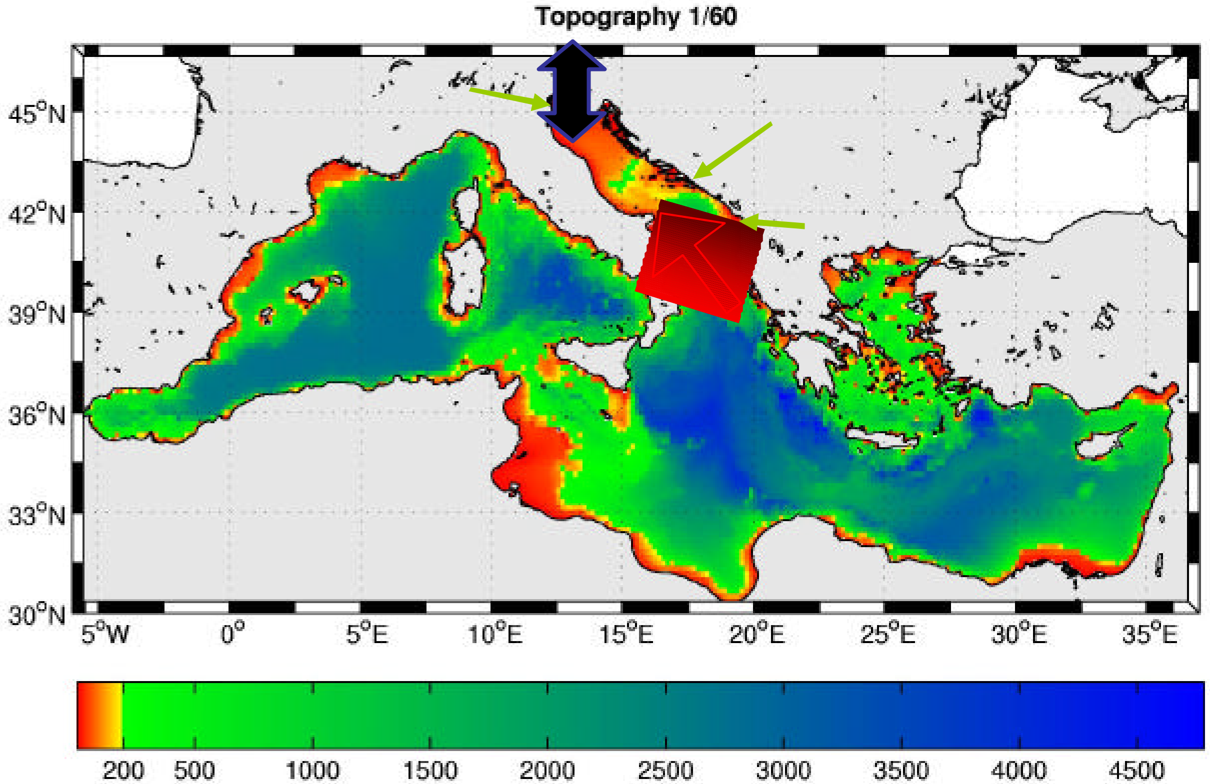
INGV, Bologna, Italy

Outline

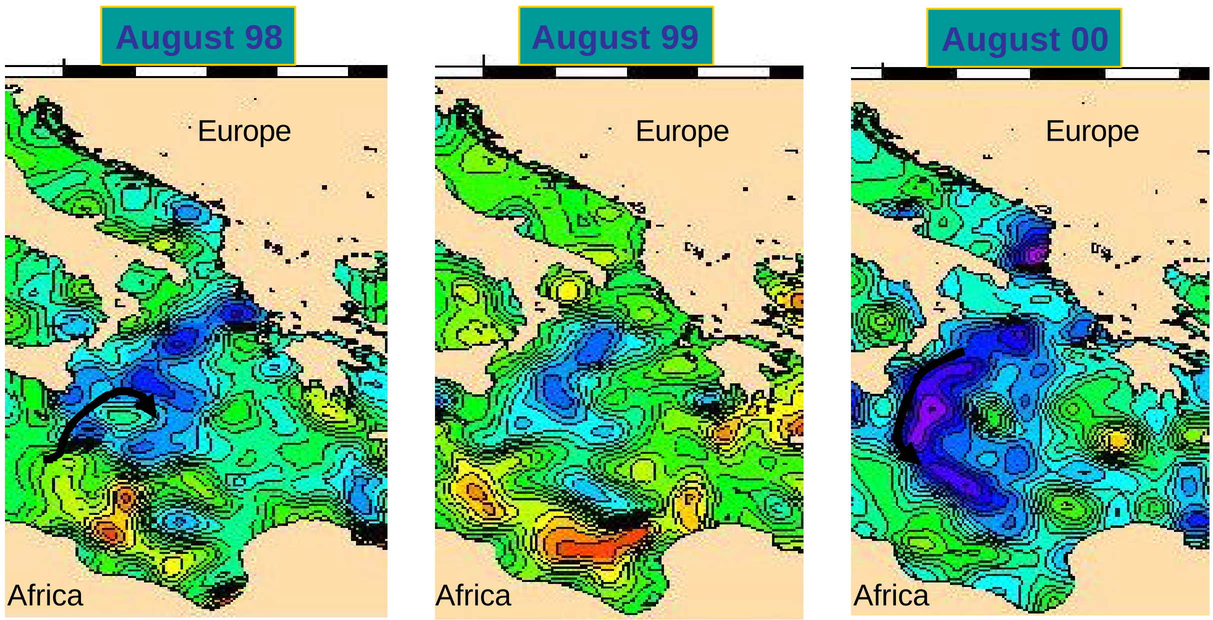
- The Mediterranean Sea variability and the scientific approach to environmental monitoring and predictions
- The Mediterranean ocean Forecasting System: multivariate analysis and 10 days forecasts
- System assessment
- Conclusions and future outlook

The Mediterranean shelf areas:

forced by large air-sea interactions, deep ocean currents variability and river runoff changes

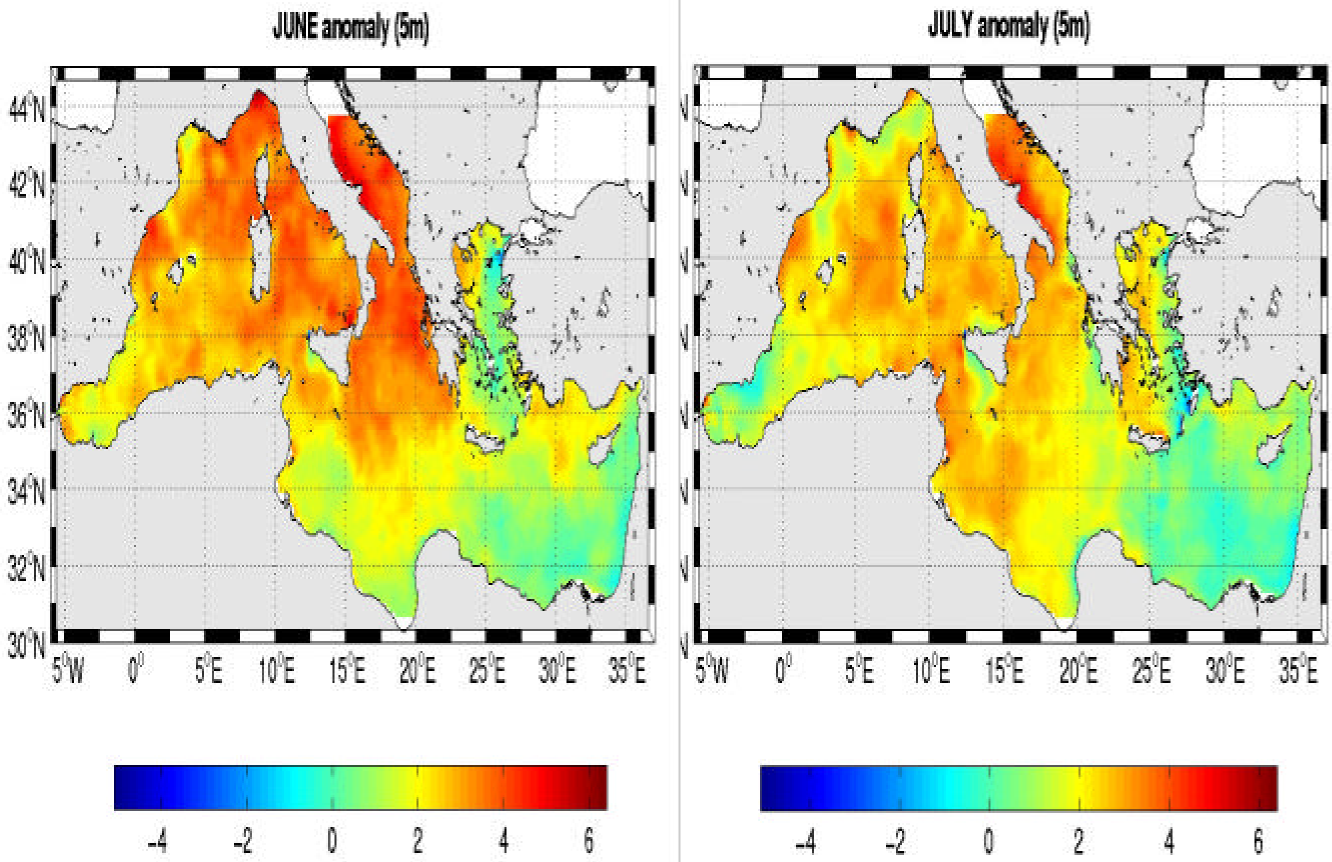


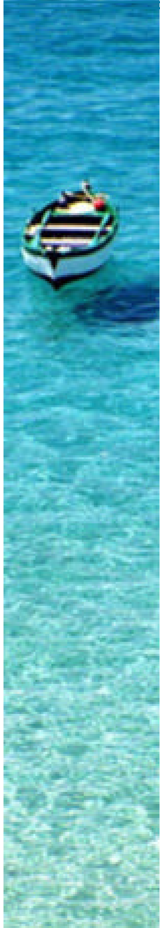
The known large scale variability



Sea Level Anomalies from combined analysis of T/P and ERS2 data (blue negative anomalies/ -20 cm, green-red positive anomalies/ +20 cm

The exceptional summer of 2003: SST anomalies





How do we build predictive capabilities?

- Three phases of knowledge are required (Robinson, 1986):
  1. Descriptive/phenomenological with observations
  2. Dynamical and calibration/validation with observations and models
  3. Assessment of predictive skills and re-formulation of the problem
- Practically develop a Marine Environmental Prediction System

Marine Environmental Prediction System

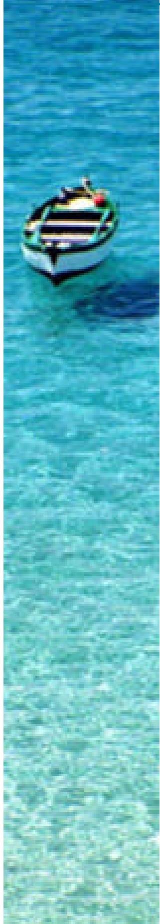
Multidisciplinary Multi-platform Observing system (sustained and relocatable)

Numerical models of hydrodynamics and ecosystem, coupled asynchronously to atmospheric forecast

Data assimilation for optimal field estimates and parameter estimation

Continuos production of nowcasts/forecasts of relevant environmental state variables

The MFS approach:
from large to coastal space scales,
weekly to monthly time scales,
nesting approach for physical and ecosystem processes



LARGE SCALE

- MOORED BUOY ARRAYS
- VOS XBT AND ONDULATING INSTRUMENTS
- SATELLITE: SEA LEVEL, SEA SURFACE TEMPERATURE, SURFACE WINDS, SEA SURFACE SALINITY, COLOR,
- DRIFTING BUOYS (SURFACE AND SUBSURFACE)
- GLIDERS
- AIRPLAINE SURVEYS WITH AXBT

SHELF SCALE

- REPEATED MULTIPARAMETRIC SECTIONS ACROSS SHELF*
- SATELLITE: SAME AS FOR THE LARGE SCALE
- FERRY SURVEYS OF SURFACE PARAMETERS
- BUOY STATIONS
- MESOSCALE SURVEYS
- COASTAL RADAR
- AUTONOMOUS UNDERWATER VEHICLES
- RIVER RUNOFF AND LOADING MONITORING
- SEDIMENT ANALYSIS

OBSERVING SYSTEM

MODELING SYSTEM

LARGE SCALE

MODEL PHYSICS

- PRIMITIVE EQUATION (Ê 5 KM)
- INTERACTIVE OCEAN ATMOSPHERE COUPLING

DATA ASSIMILATION

- OPTIMAL INTERPOLATION AND/OR KALMAN FILTER

ECOSYSTEM MODELS

- PELAGIC COMPARTMENT
- BENTHIC CLOSURE

ATMOSPHERIC FORCING

- OPERATIONAL ANALYSES FROM LARGE SCALE MODELS
- ENSEMBLE FORECASTS

SHELF SCALE

MODEL PHYSICS

- PRIMITIVE EQUATION (Í 5 KM)
- INTERACTIVE OCEAN ATMOSPHERE COUPLING
- TURBULENCE AND LIGHT RAD. TRANSFER SUBMODELS

DATA ASSIMILATION

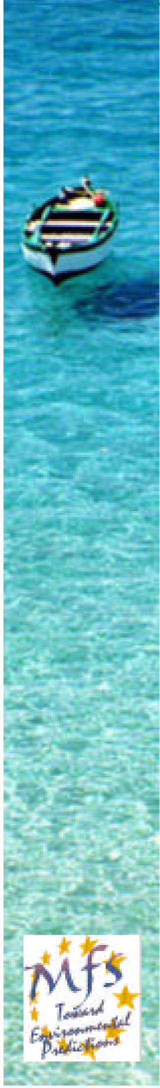
- OPTIMAL INTERPOLATION AND/OR KALMAN FILTER
- ADJOINT MODELS

ECOSYSTEM MODELS

- PELAGIC COMPARTMENT
- BENTHIC-PELAGIC COUPLING
- SEDIMENT DYNAMICS

ATMOSPHERIC FORCING

- OPERATIONAL ANALYSES FROM LARGE SCALE MODELS
- LAM and MESOSCALE MODEL OUTPUT



Phases

First phase: 1998-2001

MFSPP - Mediterranean Forecasting System Pilot Project: implementation of observing system backbone, pre-operational forecast experiments at basin scale

Second phase: 2001-2005

ADRICOSM - ADRIatic Sea integrated COastal areaS and river basin Management system Pilot Project: a coastal prediction system integrated with MFSPP and coupled with a river basin management system

MFSTEP - Mediterranean Forecasting System Toward Environmental Predictions: integration and extension of observing system at basin scale, trial forecasts in the shelf areas and ecosystem model implementation

Third phase: 2003-2008

MERSEA – Marine EnviRonment and Security for the European Area - integration in an European effort

MOON : Mediterranean Operational Oceanography Network –development of applications

MFSTEP components

Mediterranean Forecasting System Toward Environmental Predictions

RT Observing System
satellite SST, SLA, VOS-XBT, moored multiparametric buoys, ARGO and gliders

Upgrade of present basin scale operational system
New model and assimilation

Ecosystem Models
Validation/calibration of Coupled physical and biochemical numerical models

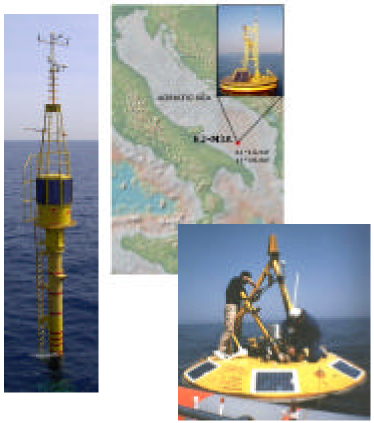
Marine forecast downscaling
Regional and shelf models nesting

End-User applications
Development of modules for oil spill monitoring, ICZM and fishery management

Meteorological forecast downscaling
10 km LAMs and 4 km N.H. mesoscale models

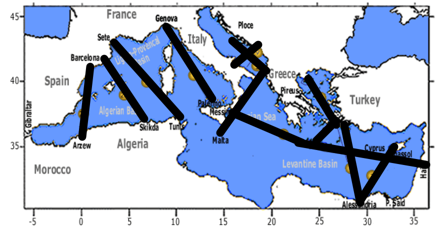
15 nations involved, 48 institutions

Overall Basin Scale Observing System

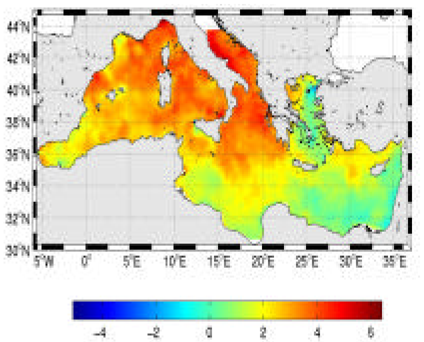


3 multiparametric buoys into: Ligurian Sea, Adriatic Sea and Creatan Sea

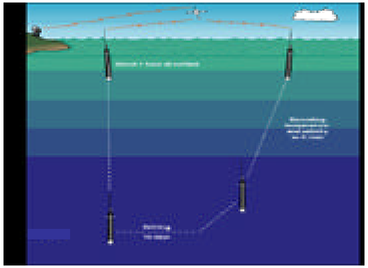
Open ocean monitoring by gliders



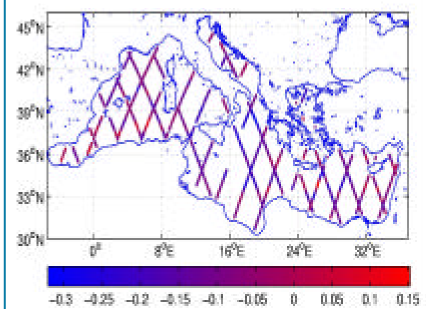
XBT VOS high resolution system (12 nm along track and full profile transmission)



Daily satellite SST interpolated in RT on model grid



25 ARGO floats deployed from VOS



JASON-1, GFO, ENVISAT, T/P Sea Level Anomalies RT products

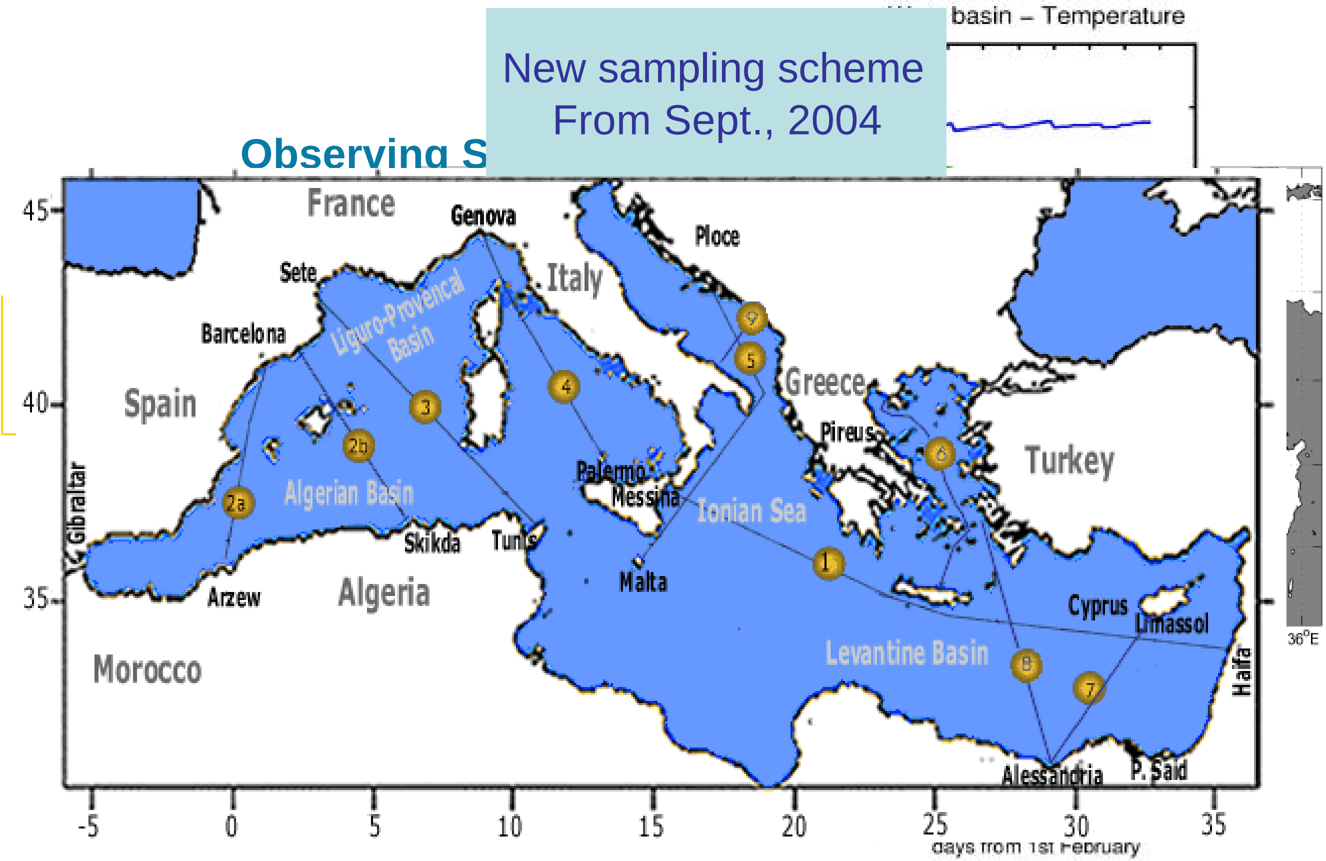
The key: the combination of the different ocean data sets

- In situ data are sparse but they give detailed information about the system (i.e. profiles of field state variables): they have a smaller Real Time data delivery delay
- Satellite data have good coverage but they are only surface and they are available only 48 hr after last collection
- Satellite and in situ data have different error models and very different observation models (satellite have more complicated ones)
- In situ data need to be optimized because expensive in terms of maintenance and they should be developed to extend the value of satellite data to increase predictive capabilities

The VOS system: full temperature profiles in RT (12 hrs delay), 12 nm horizontal resolution

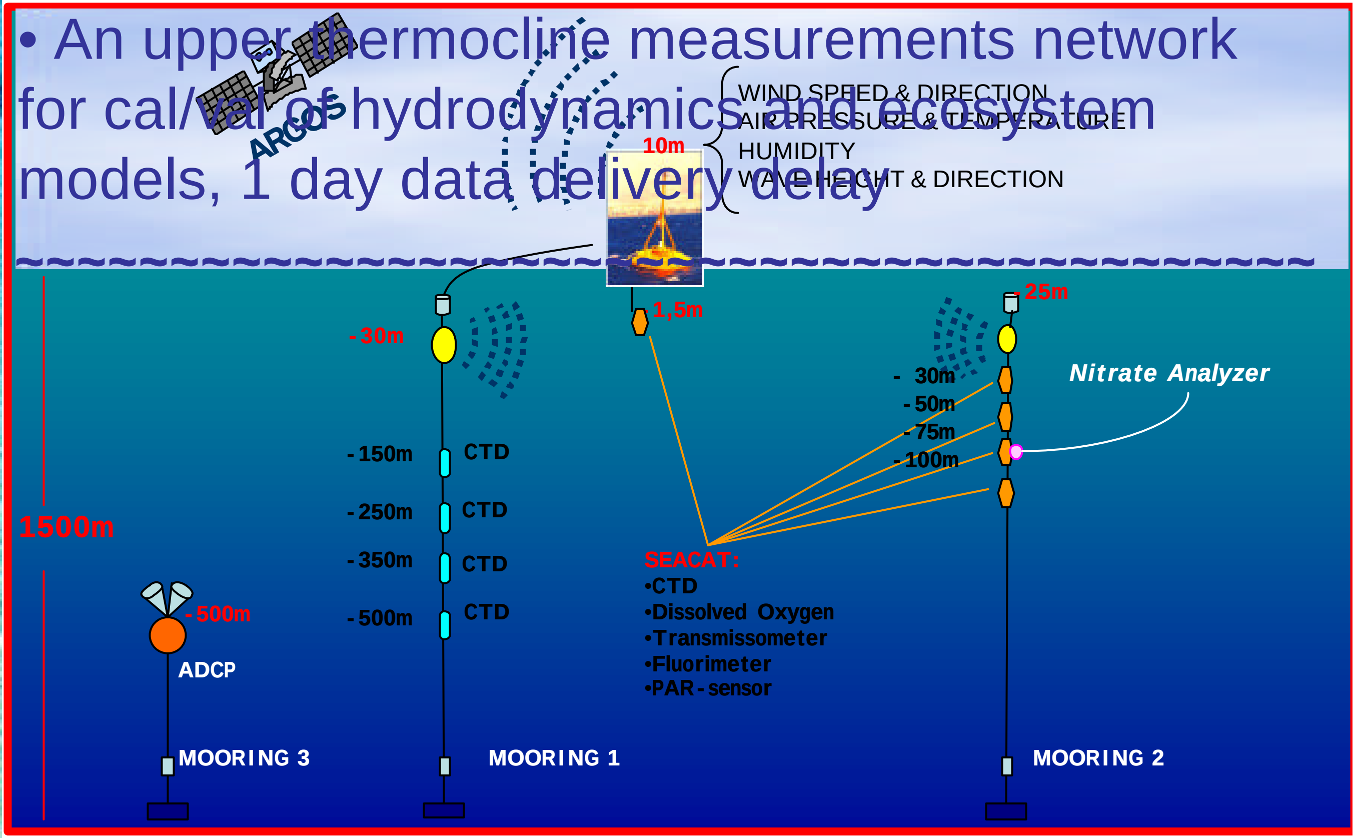
New sampling scheme
From Sept., 2004

Observing S

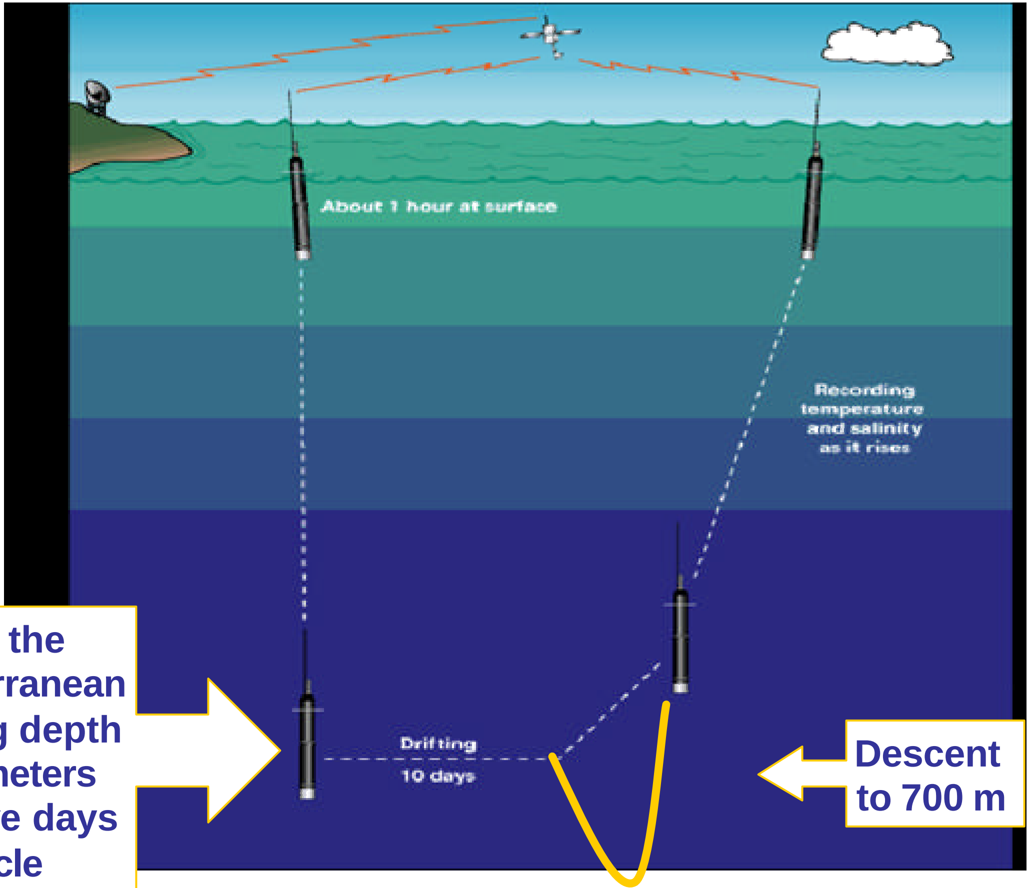


The fixed buoy array: Mediterranean Multisensor Moored Array-M3A

• An upper thermocline measurements network for cal/val of hydrodynamics and ecosystem models, 1 day data delivery delay



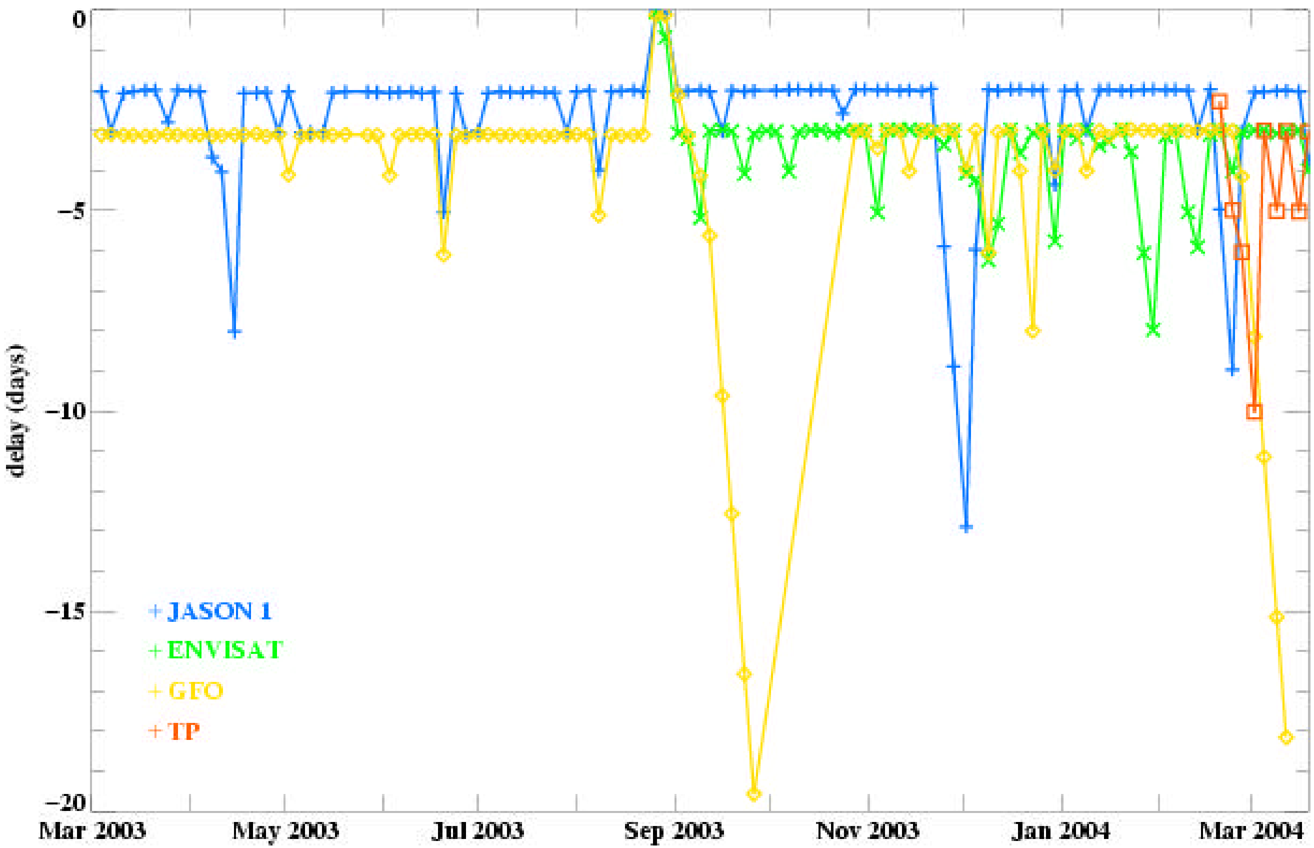
The MedARGO experiment: 25 floats unevenly launched from VOS, 1 day data delivery delay



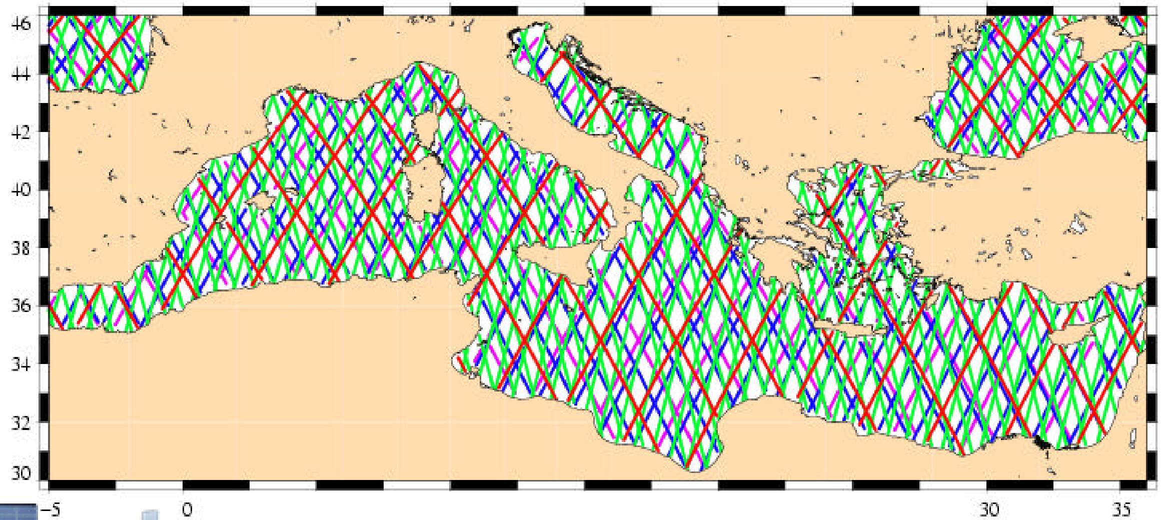
For the Mediterranean drifting depth 350 meters and five days cycle

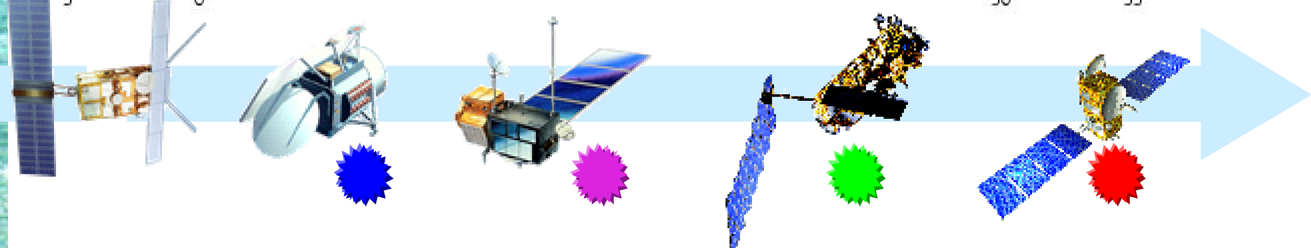
Descent to 700 m

RT Altimeter Data Acquisition (CLS, Toulouse)



JASON, GFO, ENVISAT and TP$_{interlaced}$ coverage

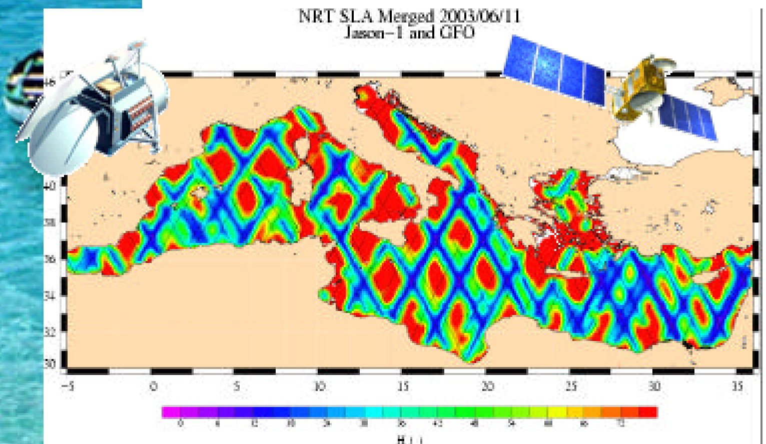


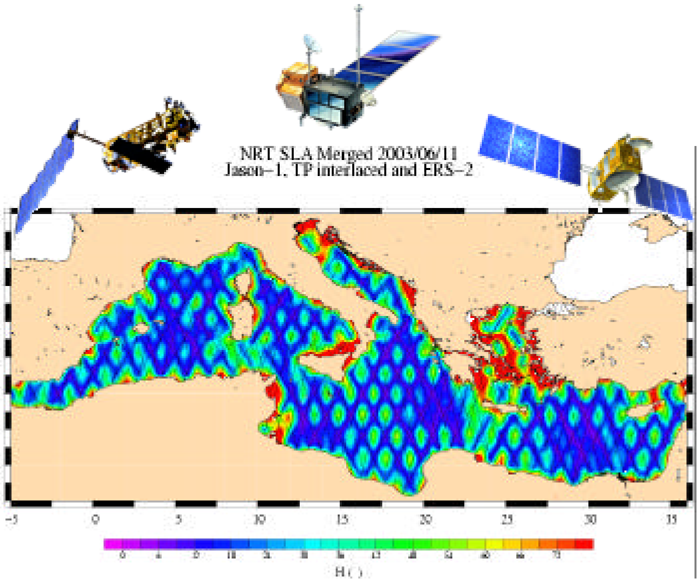


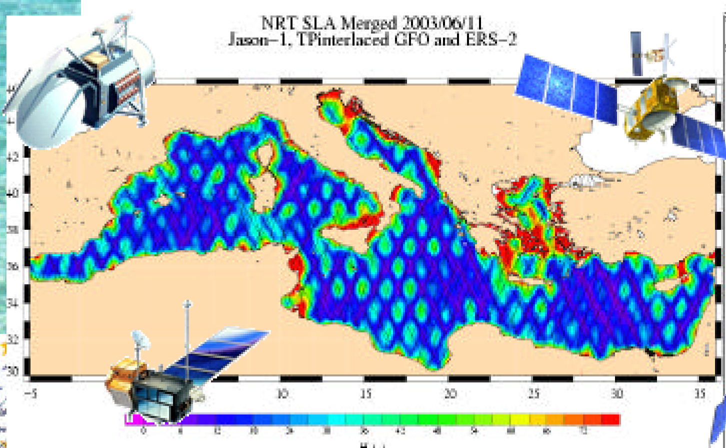
GFO TP ENVISAT JASON

MFS availability

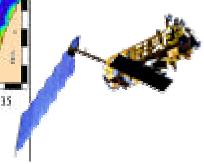
Jason-1/GFO / ENVISAT / TP$_{interlaced}$ integration





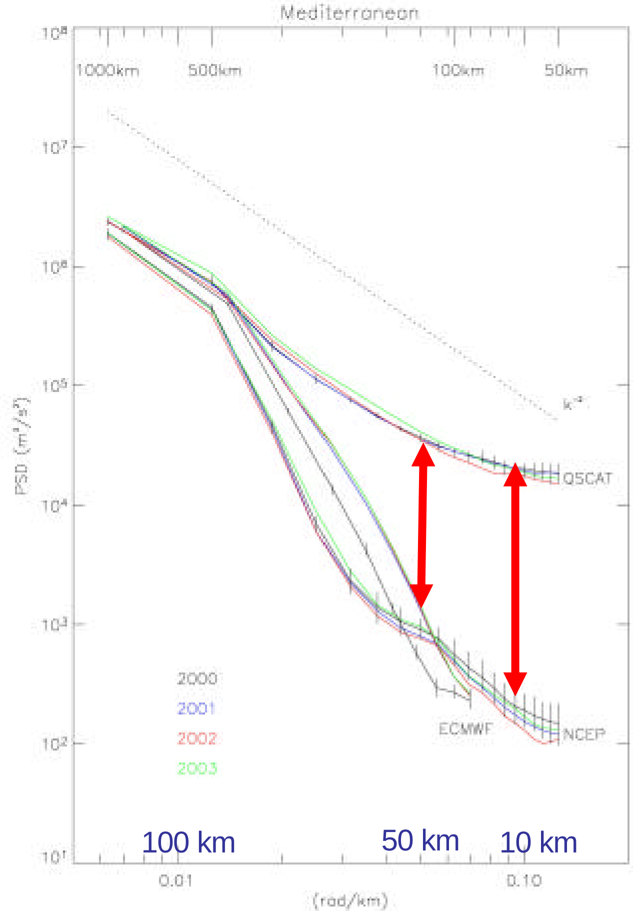


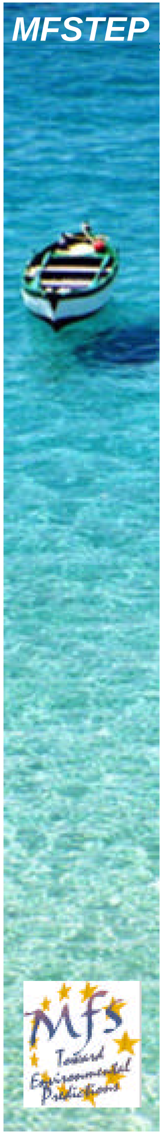
Objective Analysis error map done with different number of satellites



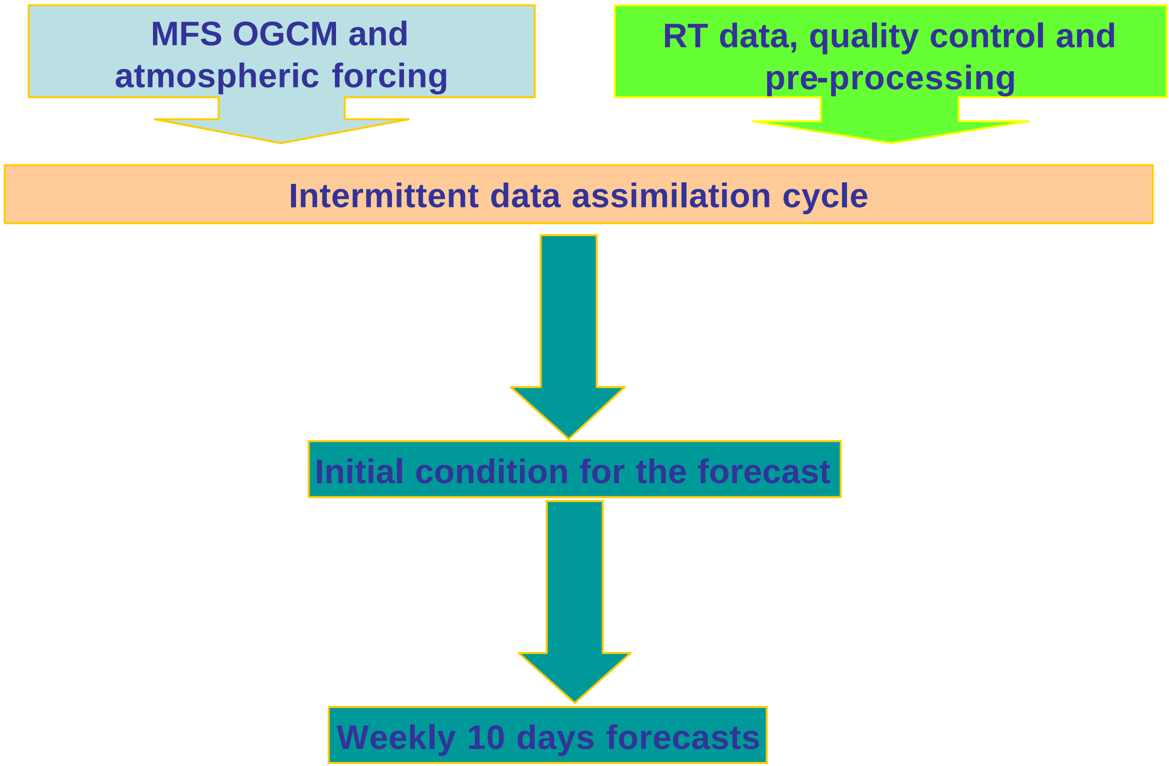
Scatterometer data analysis in RT: blended product with NCEP analyses

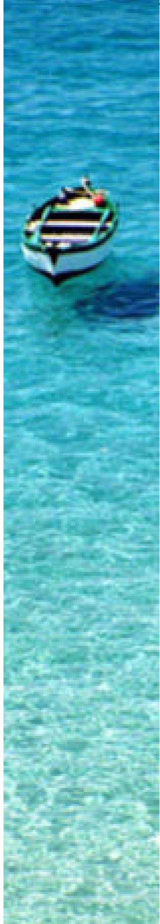
Even the latest
ECMWF forecast model
cannot reproduce the
power in the high
wavenumber range:
Scatterometer
winds needed
to quantify uncertainty
in wind forcing





The MFS operational system





The forecasting system: the OGCM

- **$1/8^0$ x $1/8^0$ x 31 levels unevenly spaced**
- **Atlantic box 3X3 degrees to parametrize Gibraltar inflow/outflow system**
- **Biharmonic horizontal visc. and diff.: A_h=5 10^{17} , K_h=1.5 10^{18} (cgs)**
- **Vertical mixing: A_v=1.5, K_v=0.3 (cgs), conv. adj. passes= 10**
- **full diagnostic computation of sea surface height in rigid lid approximation**

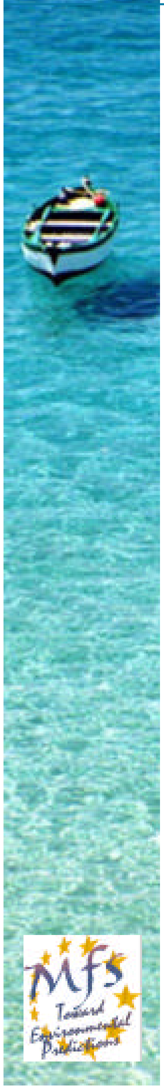
Air-Sea physics

•Heat flux is re-computed using interactive formula with ocean SST and bulk formulas adapted to the Mediterranean case:

$$r_0 K_v \frac{\partial T}{\partial z}\Big|_{z=h} = \frac{1}{C_p}\left\{Q_s(C,a,t) - Q_B(T_a,T_s,C,rh) - LE(T_a,T_s,rh,|\vec{v}_w|) - H(T_a,T_s,|\vec{v}_w|)\right\}$$

Asynchronous atmospheric Forcing

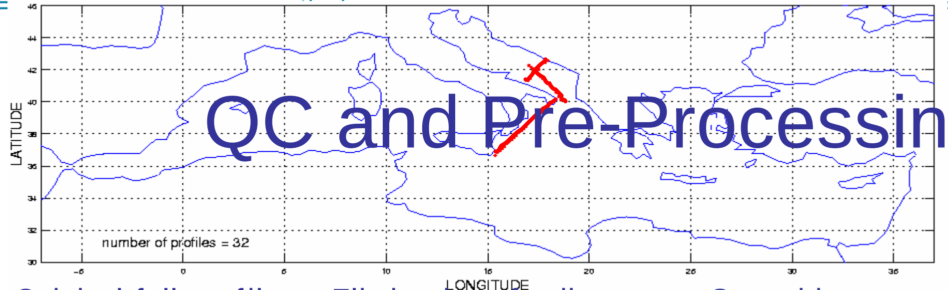
•ECMWF 6 hours analyses and/or forecast parameters: air and dew point temperature, mean sea level pressure, clouds, 10 m winds



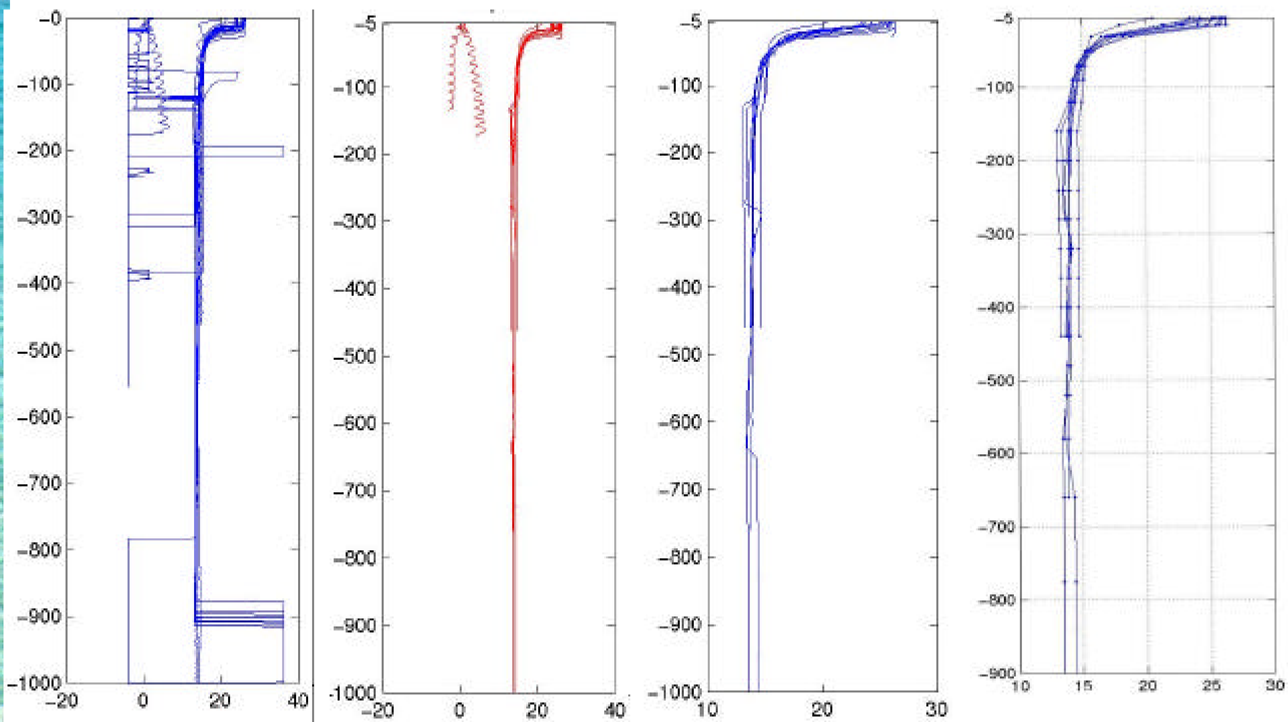
The Forecasting system: the data quality control and pre-processing

- Real Time data sets collected every week: SLA, SST and XBT, ARGO, CTD
- Quality control and pre-processing is applied to XBT, SLA and SST.
  - XBT: new method required for RT data
  - SLA: Mean Sea Level Anomaly (MSLA) subtracted from along track data
  - SST: daily declouding and gap filling with OA
- Model sea surface height pre-processed to get SLA

QC and Pre-Processing XBT

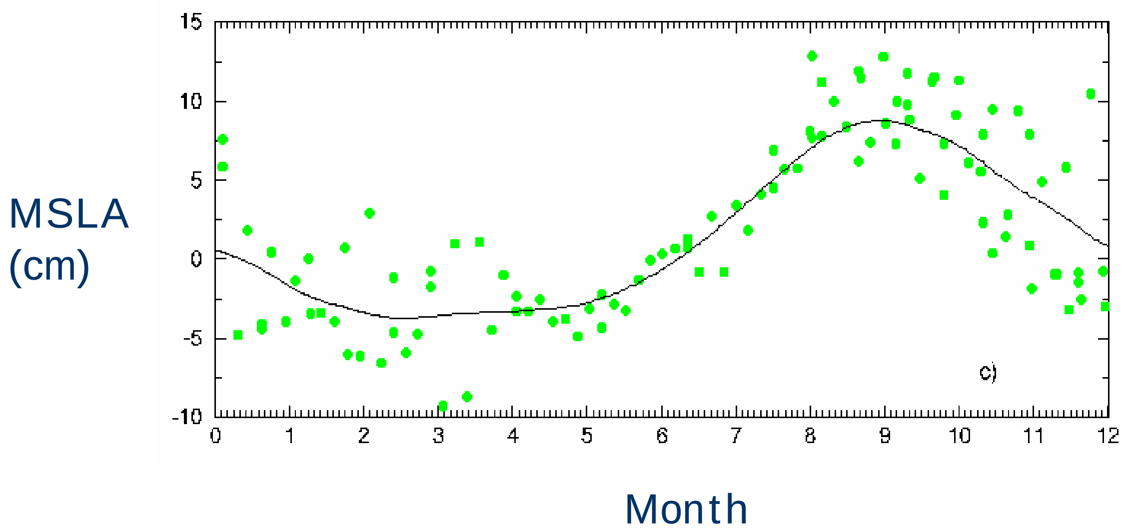


Original full profile | Elimination of spikes | Smoothing | Interpolation on MOM levels



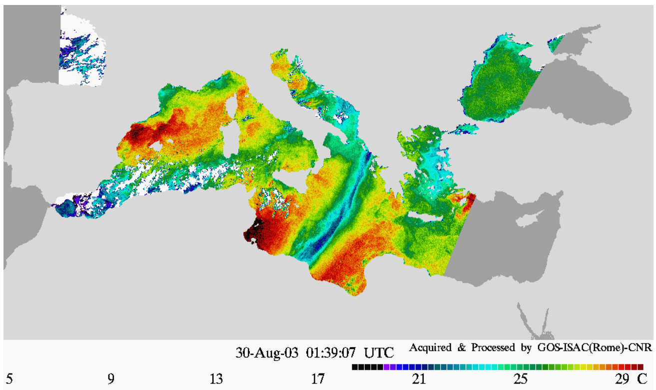
Pre-processing of SLA: de-biasing for volume changes

- A regression curve was found to fit the volume changes in the Mediterranean from T/P data (MSLA)

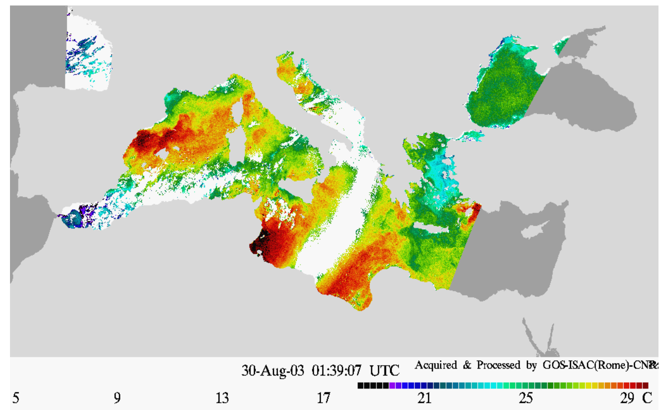


The MSLA is subtracted from along track data before assimilation since model is rigid lid

Satellite daily SST is produced in RT from nightime images with cloud detection: field is interpolated on model grid with objective analysis scheme



Before declouding

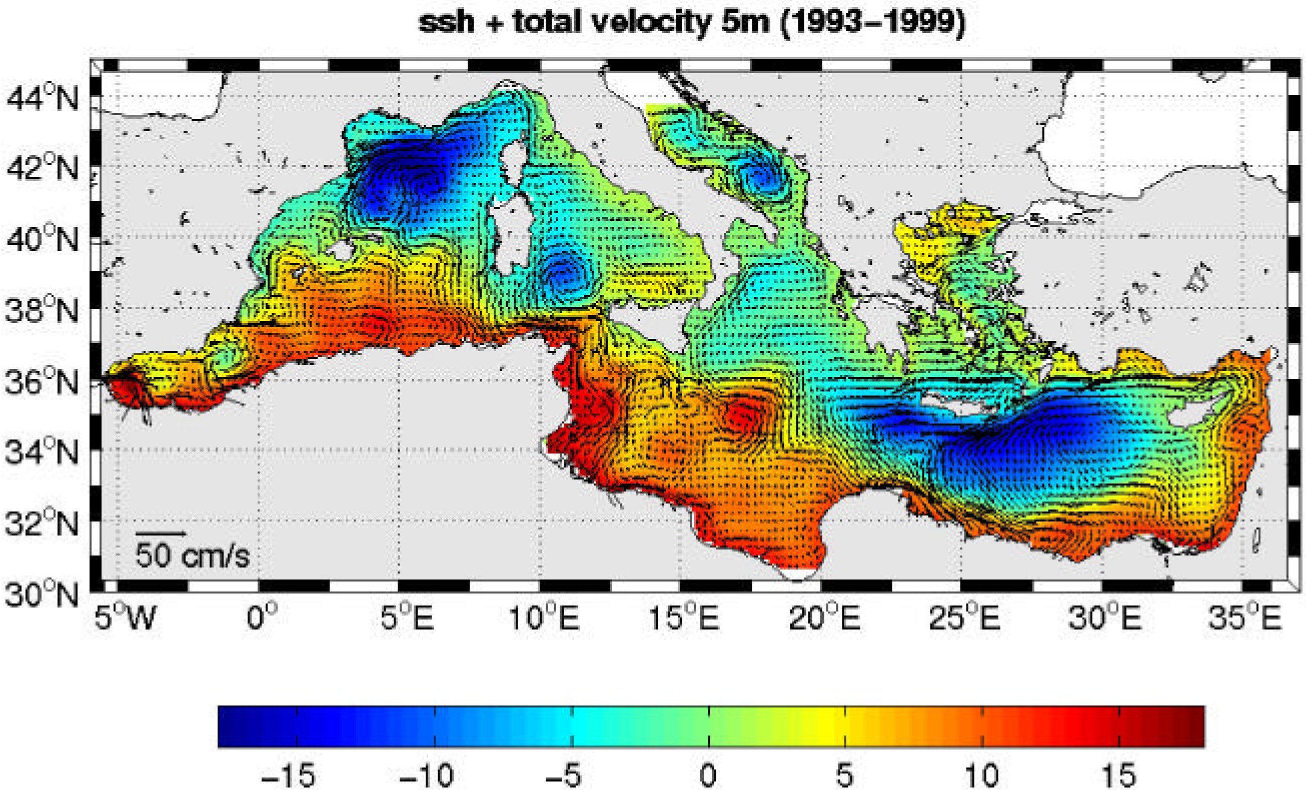


After declouding

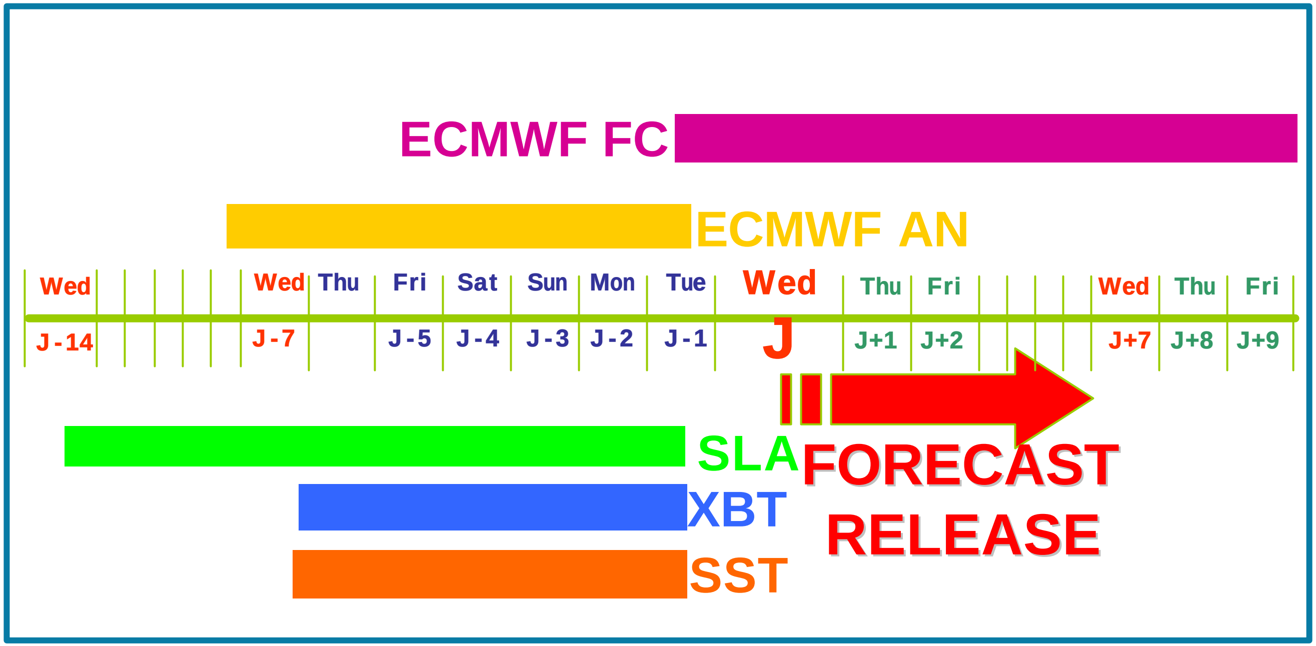
SST is inserted in the model as a heat flux correction

$$Q_{corr} = Q - \left.\frac{\partial Q}{\partial T}\right|_{T=T^*} (T - T^*)$$

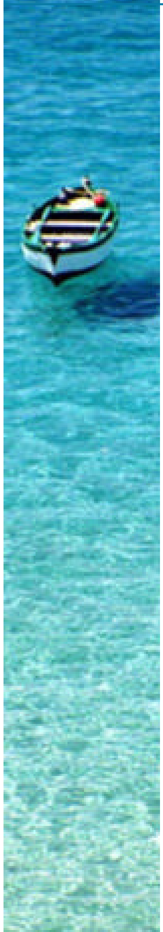
The model data pre-processing: mean sea surface height from simulation



The present day MFS (SYS3) weekly forecasting system



Data are disseminated through a Web/ftp service (www.bo.ingv.it/mfstep)



The MFS system: operational data assimilation system

- MFS uses a Reduced Order Optimal Interpolation scheme that is multivariate (X) and multi-data (Y) in input

$$\mathbf{X}^a = \mathbf{X}^b + \mathbf{K}(\mathbf{Y}^o - H(\mathbf{X}^b))$$

$$\mathbf{K} = \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R})^{-1}$$

$$\mathbf{X} = [T\ S\ U\ V\ h\ y\ \ r]^T$$

- The background error covariance is separated into vertical (S) and horizontal (Br) correlation structures (valid for open ocean)

$$\mathbf{B} = \mathbf{S}\,\mathbf{Br}\,\mathbf{S}^{\mathrm{T}}$$

(De Mey and Benkiran, 2002)

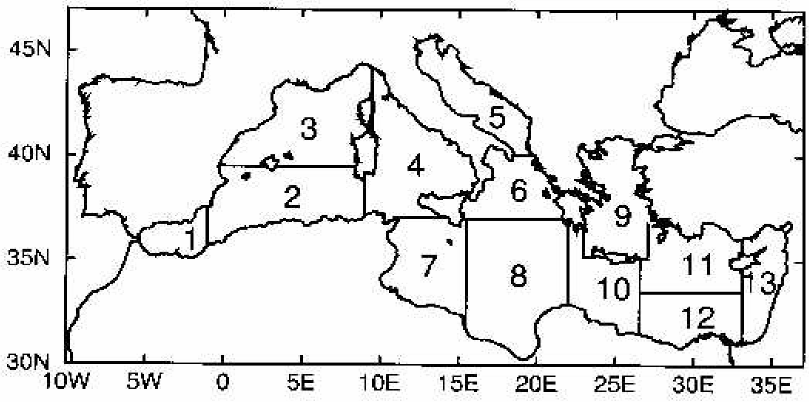
Order reduction procedure for the B matrix

The order reduction is achieved because only a limited number of vertical modes are required in the ocean, thus:

$$\mathbf{K}^{\mathrm{ROOI}} = \tilde{\mathbf{S}}\,\mathbf{Kr}$$

$$\mathbf{Kr} = \mathbf{Br}\,\tilde{\mathbf{S}}^{T}\mathbf{H}^{T}(\mathbf{H}\tilde{\mathbf{S}}\,\mathbf{Br}\,\tilde{\mathbf{S}}^{T}\mathbf{H}^{T} + \mathbf{R}^{*})^{-1}$$

where $\tilde{\mathbf{S}}$ contains a limited number of multivariate vertical EOFs.
For the Mediterranean, the EOFs are calculated for 13 different regions



The multivariate background error covariance matrix

- **How is B defined?**

$$\mathbf{B} = \left\langle (\mathbf{X}^{\mathbf{b}} - \mathbf{X})(\mathbf{X}^{\mathbf{b}} - \mathbf{X})^{\mathbf{T}} \right\rangle$$

But practically $\mathbf{B} = \left\langle (\mathbf{X}^{o,b} - \overline{\mathbf{X}}^{o,b})(\mathbf{X}^{o,b} - \overline{\mathbf{X}}^{o,b})^{\mathbf{T}} \right\rangle = \left\langle \mathbf{X}'\mathbf{X}'^{\mathbf{T}} \right\rangle$

$$\mathbf{B} = \begin{vmatrix} \mathbf{T'T'} & \mathbf{T'S'} & .. & \mathbf{T'?'} \\ \mathbf{S'T'} & \mathbf{S'S'} & \mathbf{S'U'} & \mathbf{S'?'} \\ \mathbf{U'T'} & .. & ... & .. \\ \mathbf{?'T'} & \mathbf{?'S'} & & \mathbf{?'?'} \end{vmatrix}$$

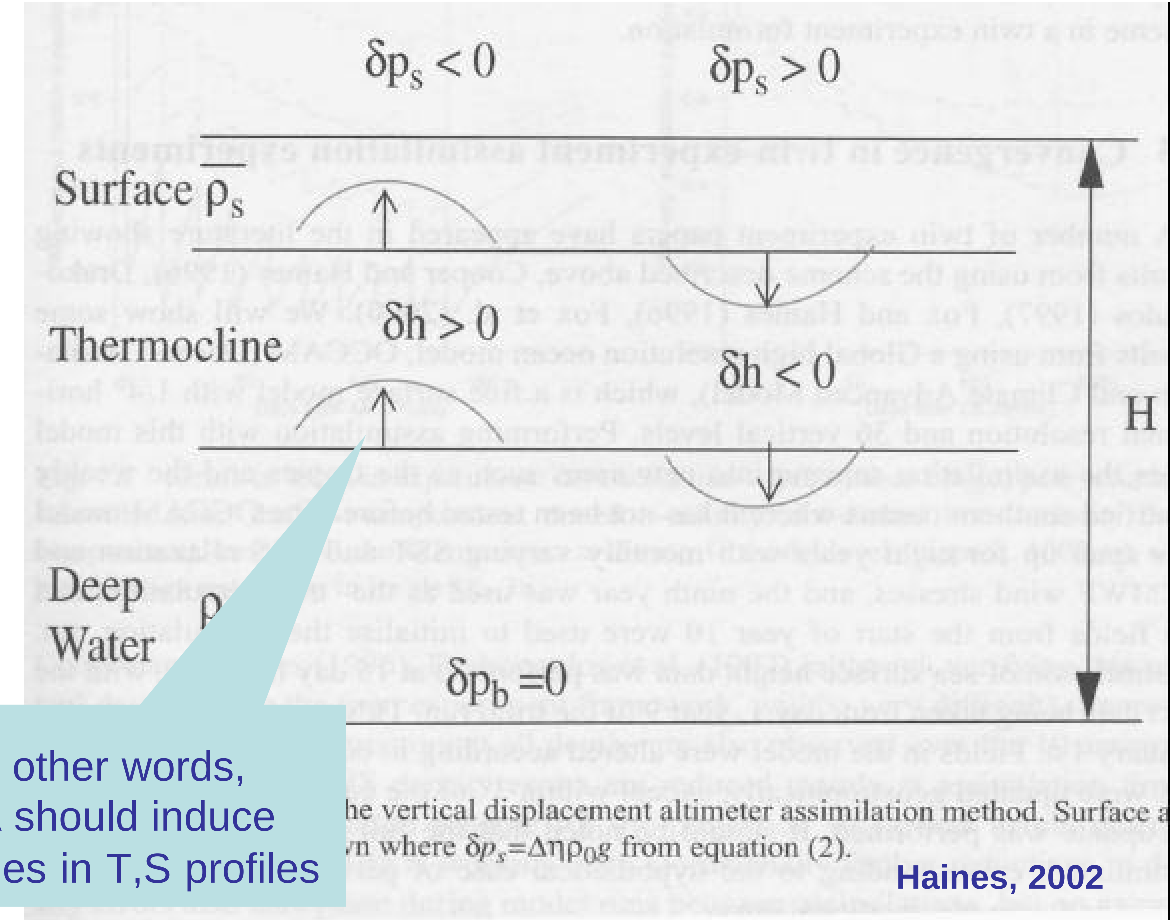
Water mass properties

Important for T,S profiles assimilation

Correlates SLA with thermocline and halocline

Important for SLA Assimilation: extrapolation to T,S corrections

What does it mean to assimilate SLA ?

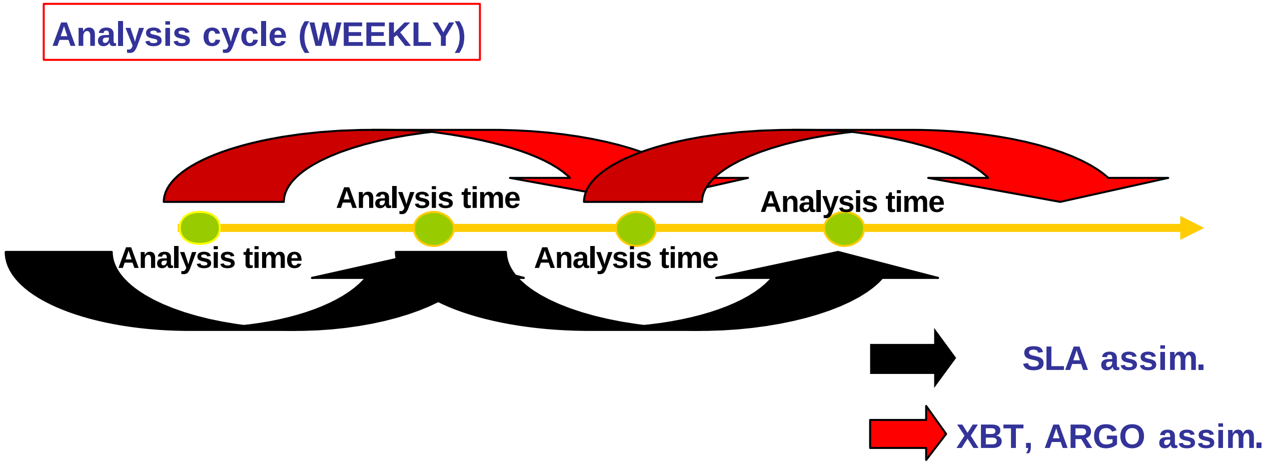


In other words,
SLA should induce
changes in T,S profiles

Haines, 2002

The MFS assimilation system: split of the analysis cycle

- Due to the specific ocean data sets (T,S profiles and SLA) the vertical modes of B, the S matrix, should be considered separately for the two data sets
- Thus the analysis cycle is split into two separate steps: one with the vertical modes for SLA and the other with the vertical modes for XBT, ARGO

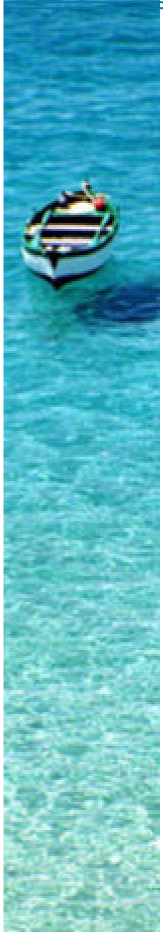


S for XBT and ARGO profiles assimilation

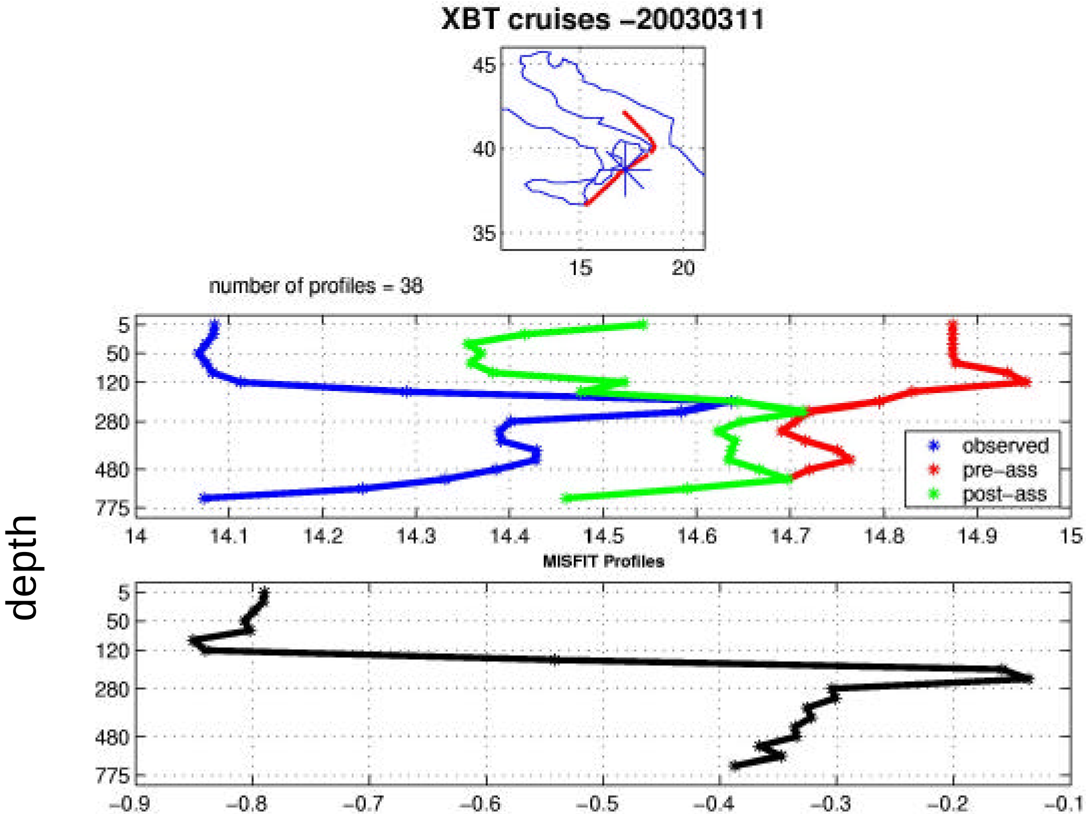
- For XBT, T profiles only, we want to correct the temperature and the salinity by using extrapolation from the multivariate S covariance
- For ARGO T,S profiles we want to use the same T-S error vertical characteristics than for XBT
- The present day operational system for assimilation of XBT and ARGO uses then bi-variate vertical EOFs obtained from a B matrix written simply as:

$$\mathbf{S} = \begin{vmatrix} \mathbf{T'T'} & \mathbf{T'S'} \\ \mathbf{S'T'} & \mathbf{S'S'} \end{vmatrix}$$

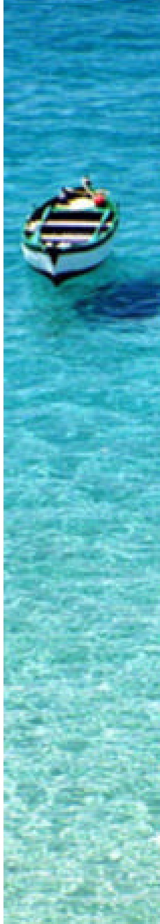
- The anomalies are constructed from an historical climatological data set for T,S profiles. Thus assumption is that error behaves as variance of field



Assimilation of XBT data: balance between model error and measurement error (free parameter)



Misfit= T(model)- T(XBT)



B for SLA assimilation

- On the basis of the a priori knowledge of the relevant physical processes we know that the geostrophic sea level is written as (Pinardi et al., 1995):

$$h = \frac{1}{H_0}\left\{ f\frac{y}{g} - \frac{1}{r_0}\int_{-H_0}^{0} r\ z dz - \frac{H_0}{r_0}\int_{-H_0}^{0} r\, dz \right\}$$

Thus **B** should be:

$$\mathbf{B} = \begin{vmatrix} \mathbf{T'T'} & \mathbf{T'S'} & \mathbf{T'?'} & \mathbf{T'?'} \\ \mathbf{S'T'} & \mathbf{S'S'} & \mathbf{S'?'} & \mathbf{S'?'} \\ \mathbf{?'T'} & \mathbf{?'S'} & \mathbf{?'?'} & \mathbf{?'?'} \\ \mathbf{?'T'} & \mathbf{?'S'} & \mathbf{?'?'} & \mathbf{?'?'} \end{vmatrix}$$

- In this case we need to use the model data

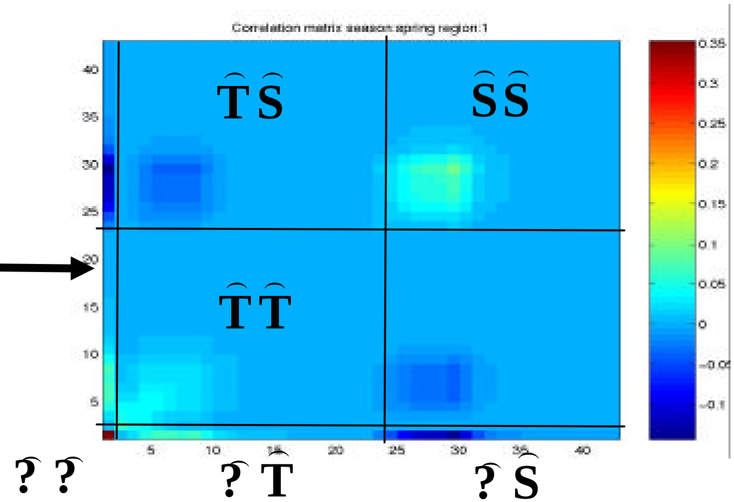
S for SLA assimilation: matrix scaling is needed

$$\mathbf{X} = \begin{bmatrix} \frac{y'}{s_y} & \frac{T'_1}{\bar{s}_T} & \cdots & \frac{T'_m}{\bar{s}_T} & \frac{S'_1}{\bar{s}_S} & \cdots & \frac{S'_m}{\bar{s}_S} \end{bmatrix} \qquad T'_k = T_k - \bar{T}$$

$$\mathbf{G} = \begin{bmatrix} 1 & \sqrt{\frac{dz_T^1}{l}} & \cdots & \sqrt{\frac{dz_T^m}{l}} & \sqrt{\frac{dz_S^1}{l}} & \cdots & \sqrt{\frac{dz_S^m}{l}} \end{bmatrix} \qquad \bar{s}_T = \frac{1}{m}\sum_1^m \sqrt{\frac{1}{n}\sum_1^n \left(T_k - \bar{T}_k\right)^2}$$

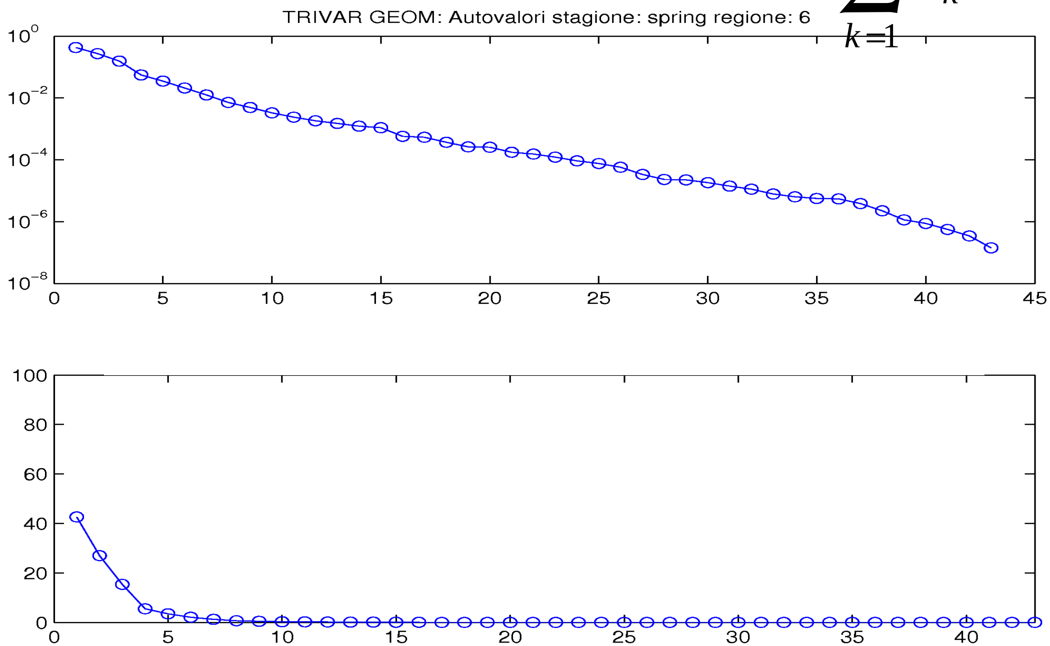
$$\hat{\mathbf{X}} = \mathbf{G}^{-1}\mathbf{X}$$

$$\mathbf{S} = \hat{\mathbf{X}}^{\mathrm{T}}\hat{\mathbf{X}}$$

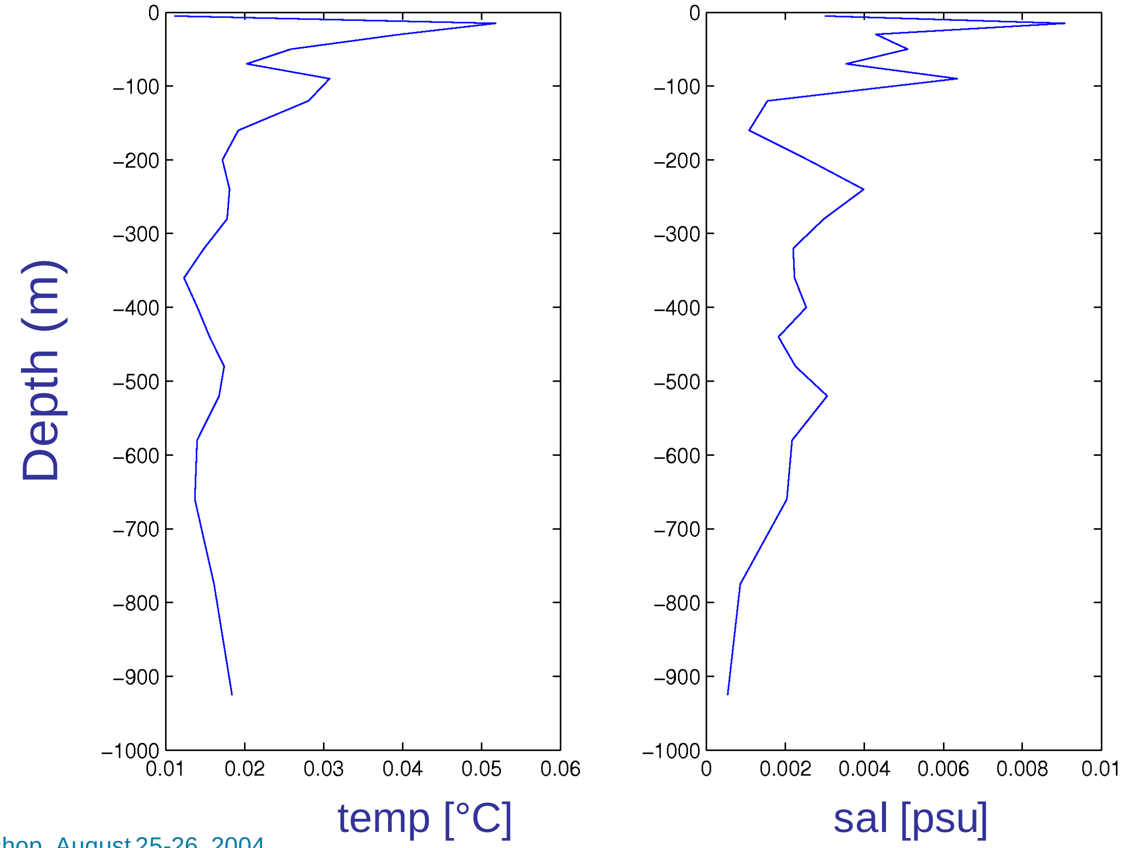


Eigenvalues and Percentage of Variance Explained-PVE

$$\mathbf{S} = E\Lambda E^{T}; \quad \text{?} = l_i d_{ij}; \quad PVE = \frac{100 * l_i}{\sum_{k=1}^{2m} l_k};$$

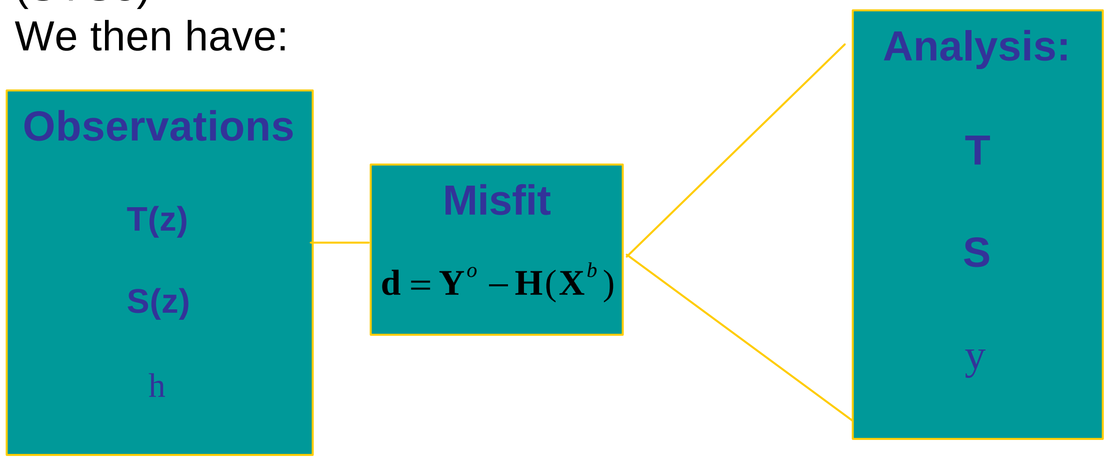


The truncation error with 20 vertical multivariate EOF (over a maximum of 45): root mean square error for temperature and salinity



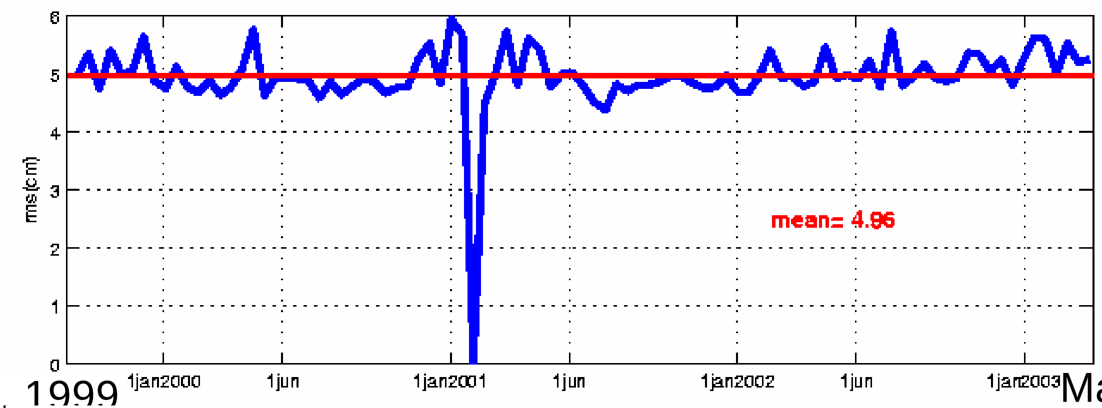
The practical implementation of the ROOI

- The real time observations are: SLA, SST, XBT and ARGO.
- Assimilation of XBT and ARGO is done with 10 seasonal vertical EOFs calculated from (T,S) multivariate statistics from historical data
- Assimilation of SLA is done with 20 seasonal vertical EOFs calculated from (T,S,η,ψ) statistics from model simulations (SYS3)
- We then have:



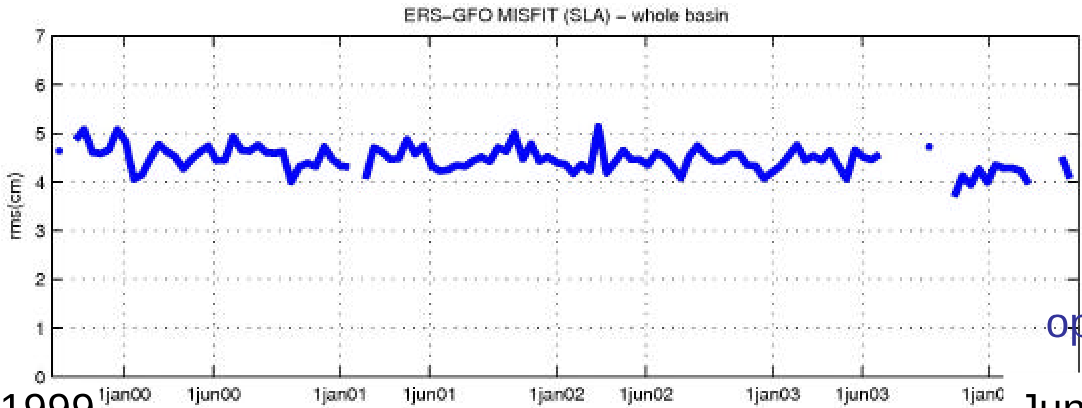
Up to May 2004, MFS had SYS2 system with only one vertical EOF for SLA assimilation

MFS SYS2 versus SYS3 assessment:
SLA rms misfit



Sept, 1999 — May, 2003

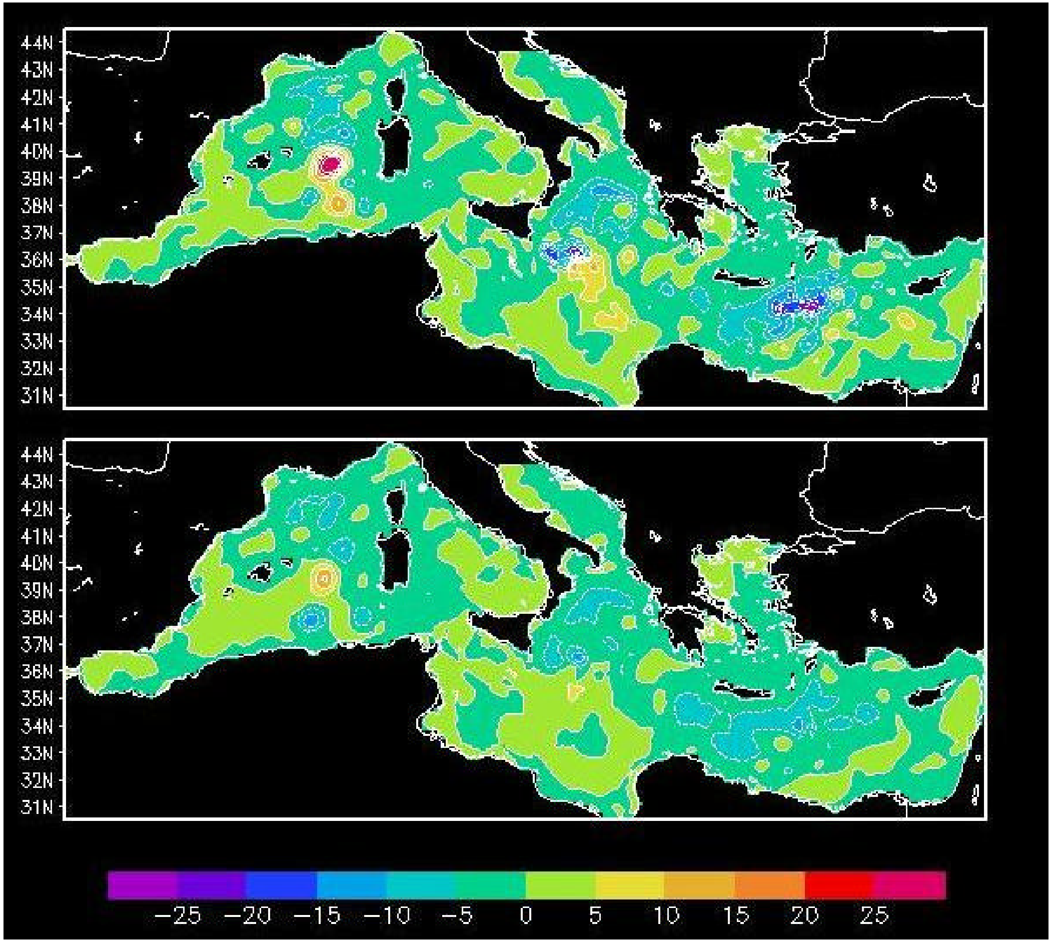
SYS2 (up to May 2004)



Sept, 1999 — June, 2004

SYS3 (now operational)

Comparison between MFS SYS2 and SYS3: 1 vs 20 multivariate EOFs in SLA assimilation

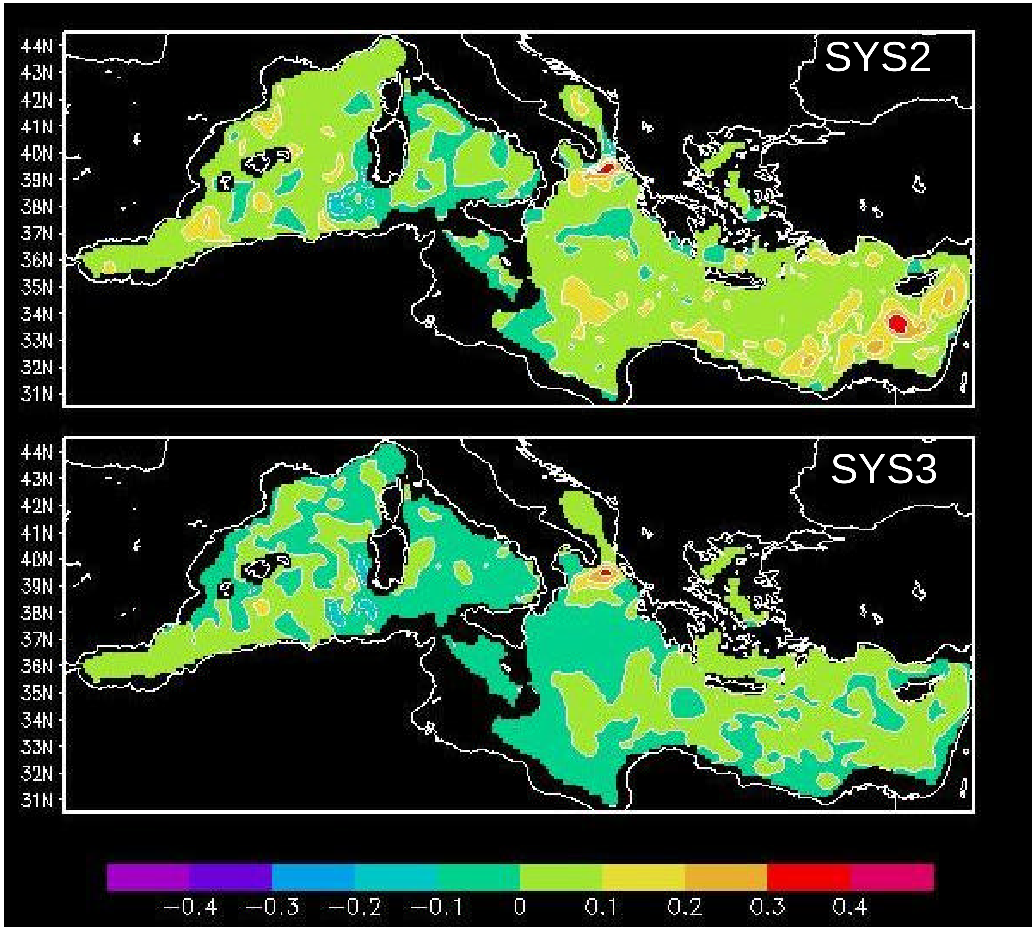


SYS2

Barotropic stream function on 22.08.2000.

SYS3

Comparison between SYS2 and SYS3: 1 vs 20 multivariate EOFs in SLA assimilation

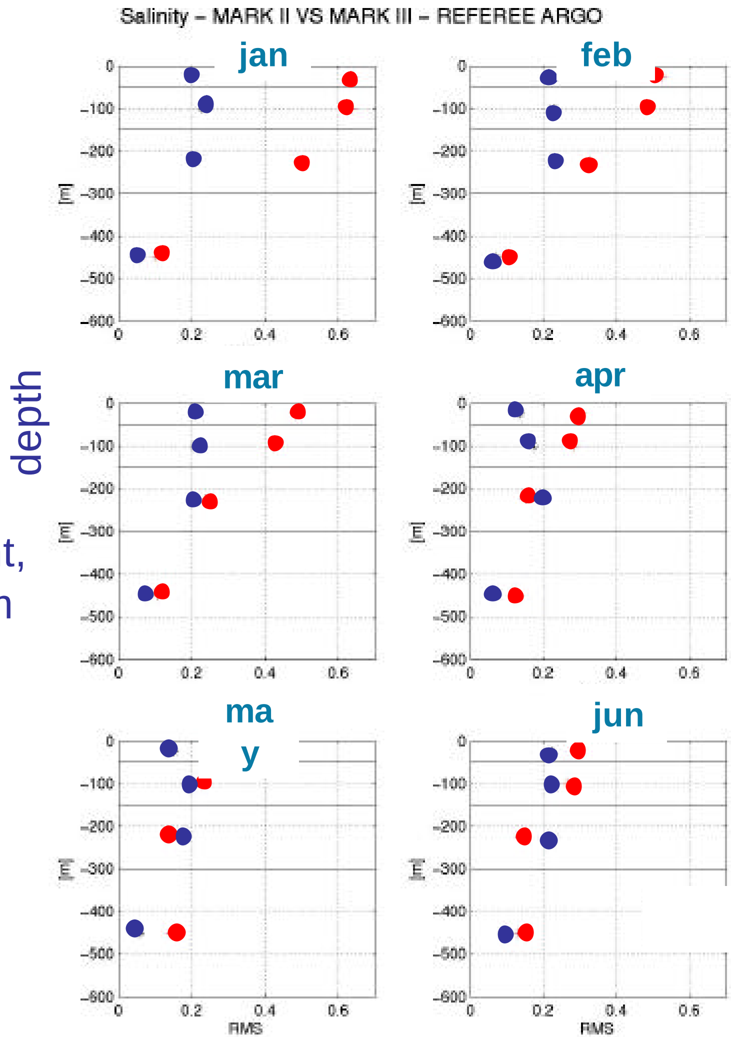


Difference fields between salinity on August 2000. and on August 1999. at 360m

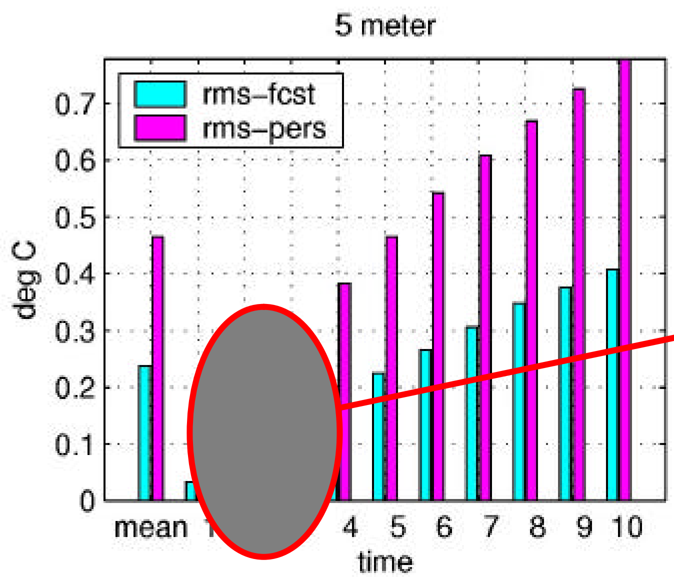
SYS2 was giving drift of model salinities at depth

SYS3 ● vs
SYS2 ●:
RMS error
between ARGO
and analyses

No salinity data
has ever been
assimilated at this point,
only extrapolation from
satellite altimetry



Assessment of the MFS forecast: comparison between root mean square error of forecast and persistence



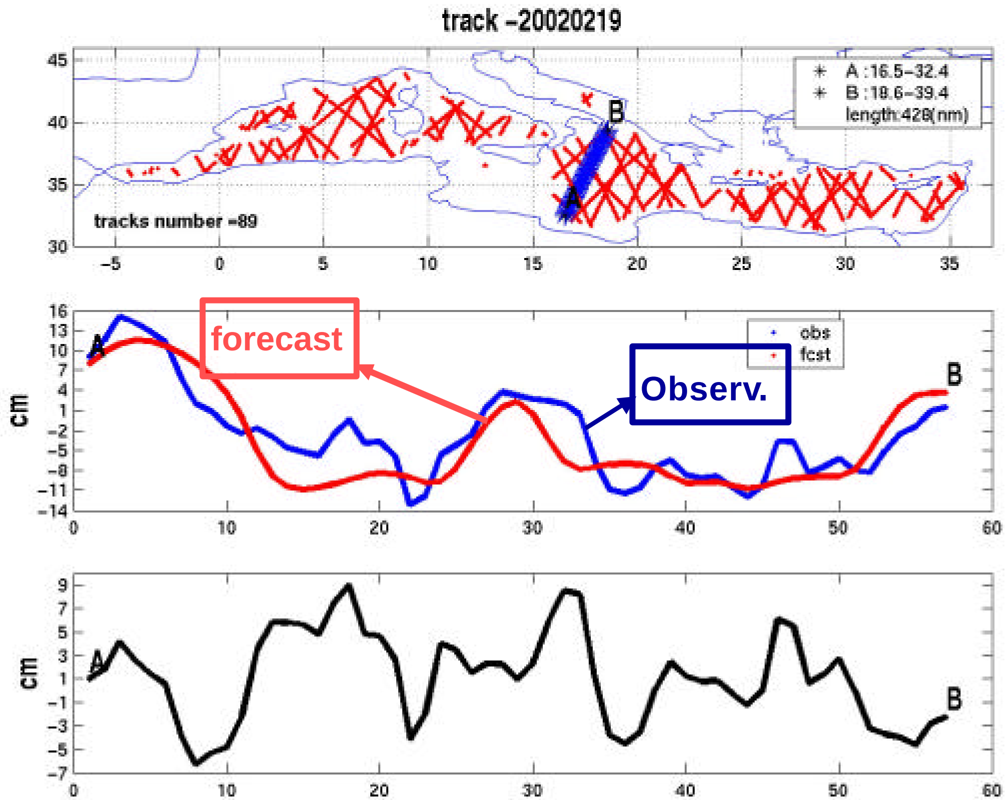
Conclusion: forecast is important from the second day

$$rms(fcst) = \sqrt{\frac{\sum (f_{FCST} - f_{ANAL})^2}{N}}$$

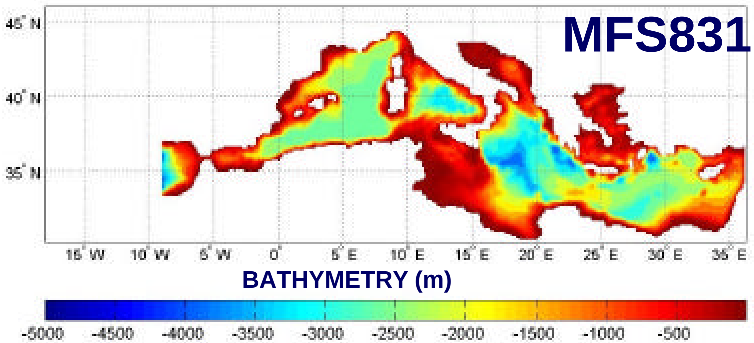
Basin 2002

$$rms(pers) = \sqrt{\frac{\sum (f_{PERS} - f_{ANAL})^2}{N}}$$

Quality assessment: SLA misfit on a single track

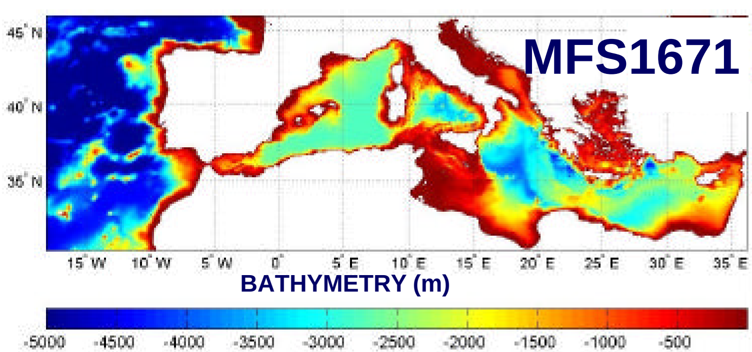


MFSTEP UPGRADE: new basin scale model



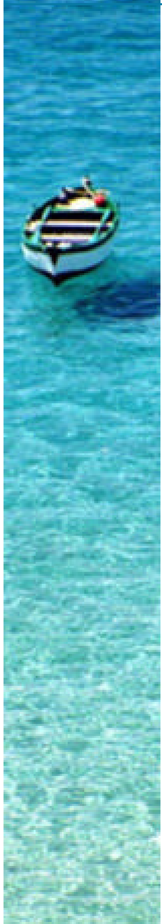
MFSPP OGCM

MOM 1.1, rigid lid
1/8º x 1/8º horizontal grid
31 vertical levels (5-3850m)
9 islands



MFSTEP OGCM

OPA 8.1, implicit free surface
1/16º x 1/16º horizontal grid
71 vertical levels (1.5-5000m)
49 islands



Conclusions and future outlook

- Ten days basin scale forecasting activities are possible with assimilation of combined in situ and satellite data: forecast is quite accurate and RT data delivery is sufficient for weekly assimilation cycle
- Future developments foreseen:
  - Increase the model resolution and the quality of physical parameterizations. In particular: vertical mixing, air-sea interaction physics, etc.
  - Add physical processes to have more realistic hydrodynamics: free surface (water budget), tides, atmospheric pressure forcing, non-Boussinesq effects, etc.
  - Increase temporal and horizontal resolution of meteorological forcing: 10 km, hourly meteorological parameters, use of scatterometer data in assimilation cycle
  - Increase frequency of assimilation cycle: one-two days cycle with plus or minus two days window for repeated data insertion
  - Need to improve satellite data pre-processing algorithms (declouding, MSLA correction, geoid, long wavelength error on the track, etc.)
  - Insert SST in the smoother and filter assimilation cycle controlling the effects of subsurface extrapolation