Data assimilation methods based on the Kalman Filter

Operational implementations in oceanography

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Operational Oceanography: the backbone for **regular** and **routine provision of data and information** for the Ocean
Operational Oceanography: the first steps

WOCE « estimating the ocean state »
GODAE « ocean monitoring and prediction »

Quasi-Geostrophic models
(OPA, MICOM/HYCOM, ROMS, MITGCM, …)

Primitive-Equation models
(NEMO/HOME)

TOPEX-POSEIDON
ERS
ENVISAT
G
F
O
ARGO

MERSEA

90 91 92 93 94 95 96 97 98 99 00 01 02 03 04 05 06
GODAE Global Ocean Data Assimilation Experiment

GODAE Modelling/Assimilation Centers

- **Australia** (BLUELINK): Regional Australian seas to Global Ocean
- **Japan**: N.Pacific to Global Ocean
- **US** (ECCO, HYCOM-US projects, …): N.Atlantic and Global Ocean
- **Europe** (Mersea Consortium)
  - **France** (MERCATOR): N.Atlantic & Med Sea to Global Ocean
  - **Norway** (TOPAZ): North Atlantic to Arctic
  - **UK** (FOAM): N.Atlantic / Global ocean to Northern Shelves
Objective: development of a European system of systems for operational monitoring and forecasting of the ocean physics, biogeochemistry, and ecosystems, on global and regional scales

Funded by E.U. (FP6) 2004-2008

Mersea Executive Committee (Y. Desaubies, P. Bahurel, M. Bell, E. Buch, J. Johannessen, P.-Y. Le Traon, G. Manzella N. Pinardi, S. Poulquen, R. Rayner, H. Roquet, U. Send, J.Verron)

and many partners ....
The MERSEA Integrated System

- NE Atlantic
- ARCTIC
- BALTIC SEA
- MED SEA
- GLOBAL OCEAN
OUTLINE of this talk

- The MERCATOR Ocean Prediction System
  - Objectives and components
  - SAM: a hierarchy of Assimilation Schemes
  - Applications

- Assimilation Challenges for MERSEA
  - Assimilating observations at the air/sea interface
  - New perspectives for SMOS-type measurements
  - Integration of marine ecosystem models
Joint initiative of French agencies for Global/Regional Operational Ocean Monitoring and Forecasting

Providing real-time Ocean Services since 2001, to a wide variety of users

Participating to the E.U MERSEA integrated project

Next objective: the Fast Track Marine Service for GMES (Global Monitoring for Environment and Security)

MERCATOR

a new player in oceanography since 1995
From observations to end-users

Decision Makers
Validation Assessment
Research
Science Working Team

Application Center
Research
Public Service
Comm. Serv.

Data Centers
SATELLITE

In SITU

NWP ...

Assimilation
OCEAN MONITORING AND FORECASTING
Toulouse, France

Validation Assessment
Research

Science Working Team
Ocean data assimilated in operational systems

AVHRR - SST
August 19-26, 1993

Climatological SSS

ALTIMETRY - SLA
August 19-26, 1993

T/S climatological fields

in situ (e.g. ARGO floats)

A scientific challenge:
combining surface with sub-surface data
Ocean domains

Mediterranean Sea (MFS)

1/16°

North-Atlantic basin

1/15°

Global ocean

1/4°

See poster by Marie Drévillon for more details
The MERCATOR global $\frac{1}{4}^\circ$ model developed in liaison with a science project (CLIPPER)

Barnier et al., 2006: Impact of partial steps and momentum advection schemes in a global ocean circulation model at eddy-permitting resolution, *Ocean Dynamics*, *in press (online first)*.
The Mercator Assimilation System (SAM)
from research to real-time operations

Brasseur et al., 2006: Data assimilation for marine monitoring and prediction: the MERCATOR operational assimilation systems and the MERSEA developments, QJRMS, in press.

Incremental implementation strategy
The SAM-2 scheme (derived from SEEK) for mesoscale data assimilation in MERCATOR

South Atlantic hindcast (Penduff et al., 2002)
- OPA model 1/3°, 1993-1996, 6h ECMWF
- Assimilation of SLA (T/P, ERS), SST (AVHRR)
Real-time assimilation cycle: how does it work?

Every week on Tuesday night / Wednesday morning:
- Most recent data are collected from data centres (SSALTO/DUACS & CORIOLIS)
- Forcing fields are downloaded (ECMWF)
- We go 2 weeks back in time and perform a run from \( T_{i-14} \) to \( T_i \)
  - Hindcast: forecast the past, perform analysis at \( T_{i-7} \):
    - best MERCATOR estimate from \( T_{i-14} \) to \( T_{i-7} \)
  - Nowcast: forecast the present, perform analysis at \( T_i \):
    - Temporary results (not all the obs available), will be updated next week
- We perform a 2-week forecast -> applications, …
Files created by MERCATOR: full fields - daily

Hindcast  Nowcast  Forecast

Week 1

Week 2

Week 3

Week 4

4 files each day

First prediction

Best analysis
14-day forecast, valid August 1\textsuperscript{st}, 2006
Global ocean at 1/4° resolution

SST

SSS

Currents
300 m
Oceanic bulletin web page:
http://www.mercator-ocean.fr/
... operations against Oil Pollution
(serving Météo-France, ...)

Oil spill model alone
Oil Spill model, forced by Mercator

Météo-France Oil Drift Forecast
(courtesy of P.Daniel)
June 2002
Scientific Cruise (OVIDE)
Salinity Field

Mercator PSY2

CLIM
Mercator PSY1
CTD

... supporting field campaigns
... monitoring « ocean climate »
and looking back to extreme events

- Hot weather event during summer 2003

Mercator SST
(reanalysis PSY2)
28 July 2003

Mercator SST
(real time PSY2)
28 July 2004
... monitoring « ocean climate »
and looking back to extreme events

- hot weather event during summer 2003

Mercator Mean SST
(reanalysis PSY2)
July 2003

Mercator Mean SST
(real time PSY2)
July 2004
MERSEA R&D in Data Assimilation

**DA objectives**
- to improve our capacity to assimilate data from different sources (satellite altimetry, SST, SSS, in situ profiles, sea-ice param., ocean colour, ...) in ocean circulation models;
- to develop the prototype of a coupled physical biological assimilative system, with the objective to demonstrate the capacity to routinely estimate and forecast biogeochemical variables.

**Participants**
- NERSC, Norway (L. Bertino)
- AWI, Germany (J. Schröter)
- UU, The Netherlands (P.J. van Leeuwen)
- CNRS, France (J. Verron)
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« Augmented » state vector estimation (Skachko et al., 2006)

Uncertainties on forcings

Ocean model
- temperature
- salinity
- currents

Evaporation, wind, heat fluxes

Forcings

T S U V
Uncertainties on forcings

Surface observations (SST, SSS, wind, ice, …)

Ocean model
- temperature
- salinity
- currents

« Augmented » state vector

C_i
T
S
U
V

expected benefits:
- Reduction of uncertainties on oceanic forcings (parameterizations)
- Improved control of mixed layer properties
« Augmented » state vector estimation including « bulk » coefficients (Skachko et al., 2006)

Assimilation of simulated data (0-200 m) in global OPA 2°x2°

RMS error on latent heat flux coef
(x 10^3)

\[ Q_{\text{lat}} = \tilde{n}_{\text{air}} L_w C_w W_{\text{max}} (\theta, q_{\text{srf}} - q_{\text{air}}) \]

RMS error on SST

RMS error on temperature
« Augmented » state vector estimation including « bulk » coefficients (Skachko et al., 2006)

Assimilation of simulated data (0-200 m) in global OPA 2°x2°

RMS error on heat flux (computed *a posteriori*, in W/m²)

Generic approach: to be generalised to other observations at O/A interfaces

In the Tropical Pacific, SSS is potentially useful to
(i) compensate errors arising from ocean/atmosphere interactions (E-P)
(ii) better understand / forecast (?) seasonal climate variability.
The ESA SMOS Mission
(Soil Moisture and Ocean Salinity, 2007)

• **The MIRAS sensor:** an L-band Y-shape interferometric radiometer (1.4 GHz)

![Artist view of SMOS](image1)

![Field of view (FOV)](image2)

• **The measurements:** for a given pixel in FOV (sizes from ~35km to ~80km), a series of reconstructed L-band **brightness temperature** is measured at several incidence angles (0-60°) and polarization

(Courtesy N. Reul, Ifremer)
Ocean Surface Salinity: measurement principle of SMOS

• For electromagnetic frequencies < 20 GHz, the dielectric constant $\varepsilon$ of sea water follows:

$$
\varepsilon(T, S, f) = \varepsilon_\infty(T, S) + \frac{\varepsilon_o(T, S) - \varepsilon_\infty(T, S)}{1 - j2\pi f \tau(T, S)} + j\frac{\sigma_i(T, S)}{2\pi\varepsilon_0 f}
$$

where $\varepsilon_\infty$, $\varepsilon_o$, $\tau_{sw}$ et $\sigma_i$ are polynomial functions of sea surface salinity $S$ (SSS) and Sea Surface Temperature $T$. Maximum sensitivity to $S$ occurs for low values of $f$ (=1.4 GHz).

• The brightness temperature $T_B$ of the sea surface measured by a radiometer at frequency $f$, incidence angle $\theta_i$, azimuth $\phi_i$ and polarization $p$ is given by:

$$
T_B(\theta_i, \phi_i, f, p) = T \cdot e(\theta_i, \phi_i, f, p, \varepsilon(T, S, f), \vec{U}, X)
$$

where $e$ is surface emissivity and $\vec{U}$ is the wind speed vector.

(Courtesy N. Reul, Ifremer)
2 different approaches:

Ø Calculate the equivalent $T_b$ from the PE model, using the previous formula, and then assimilate $T_b$ in the PE model;

Ø Invert $T_b$ measurements into SSS data (using, e.g. look-up tables), and then assimilate SSS in the PE model.

$T_B(\theta, \phi, f, p) = T \cdot e(\theta, \phi, f, p, \epsilon(T, S, f), \bar{U}, X)$

SSS assimilation impact studies using SAM-2
Tranchant et al., 2006
SMOS
AQUARIUS
1-day sampling
Mean error (t)
Response of marine ecosystems to ocean climate variability?

NPDZ - LOBSTER - PISCES - ?

ASSIMILATION

Gregg et al., 2005, GRL
Assimilation of **SLA+SST** data in coupled models

Surface Chlorophyll$_a$ (mg .m$^{-3}$) – seasonal average (Berline et al., 2006)
A MERSEA demonstration: the BIONUTS/Mercator project
Development of advanced sequential filters: towards non-linear filtering

- Traditional data-assimilation based on linearizations (Kalman Filter, 4D-VAR)
- Models become strongly nonlinear (physics/bio-chemistry, higher resolution)
- Need for nonlinear data-assimilation

→ new « resampling » strategies (SIR, EnKF)
Development of the EnKF: anamorphosis

Model variable: $P$

Statistical variable: $S$

Example: phytoplankton

in situ concentrations

$S = \varphi(P)$

Improves EnKF with 1D ecosystem model [Bertino et al. ISR 2003]
Characteristics
• Sensitive to initial conditions
• Non-linear dynamics

Nutrients

Phytoplankton

*time-depths plots*

Herbivores

Spring bloom model, yearly cycles in the ocean

Anamorphosis: a logarithmic transform

Original
histograms
asymmetric

Histograms of logarithms
less asymmetric

Arbitrary choice, possible refinements (polynomial fit)
EnKF assimilation results
(Bertino et al., 2003)

Gaussian assumption
- Truncated $H < 0$
- Low $H$ values overestimated
- "False starts"

Lognormal assumption
- Only positive values
- Errors dependent on values

RMS errors

Gaussian

Lognormal
Concluding remarks

- **Operational Oceanography is on good tracks**: the progress should continue after GODAE.

- **Satellite altimetry is absolutely vital** for ocean forecasting systems. The expected gap in altimetric missions (post-Envisat, post Jason-1) will not be filled in by alternative observing systems (in space or *in situ*).

- Efforts should be undertaken (at institutional level) to make sure that the ocean research and operational communities are working together in the best possible way (GMES will not solve everything !)
Thank you!