Coastal and shelf seas physical data assimilation: a (very) brief overview of scientific challenges

P. De Mey-Frémaux and N. Ayoub, LEGOS, Toulouse, France

(with material from GOV COSS-TT colleagues)

OceanPredict '19

GODAE OceanView Symposium | 6-10 May 2019 Halifax, Canada

Advancing the science and application of ocean predictions

Outline

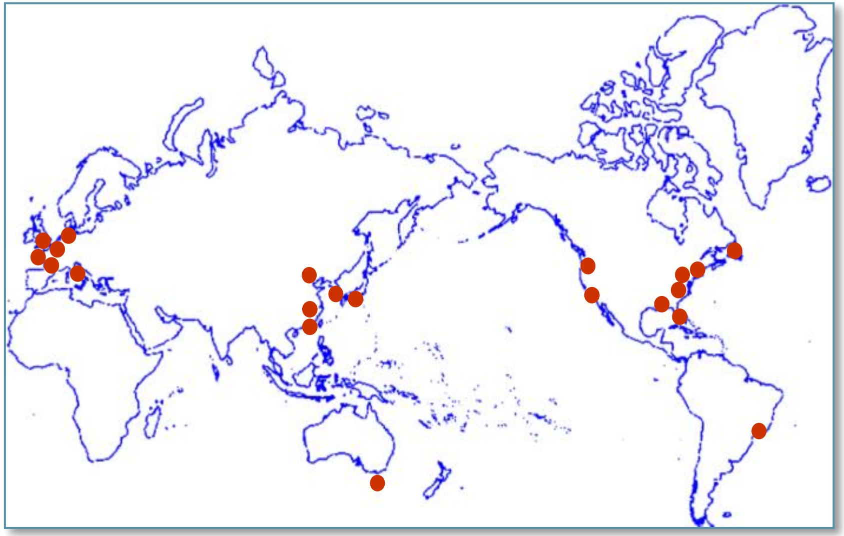
1. Introduction
2. Downscaling considerations
3. Statistical properties of uncertainties in CSS
4. Ensemble generation in CSS
5. Salinity and river plumes
6. Formulation of coastal DA problem
7. Topics not covered (because of time)

Coastal DA – preliminary remarks & TL; DR

- A recent and now very active area of science, with a wealth of relevant studies and papers to choose from
- Def. of coastal ocean? C. Mooers: From coast to shelf break + O(Ri), incl. estuaries.
- Many coastal DA studies are actually regional (for several reasons)
- Specific chalenges wrt. open ocean DA :--
  - Information forcing (=DA) in coastal areas is competing with other forcings: lateral (obc, rivers/plumes and associated freshwater and matter fluxes, coastal waves), surface (wind, pressure, fluxes, extreme events), subgrid scale (submeso, IW)
  - Tides cannot be easily eliminated from the DA problem like in deep ocean, because of the coastal presence of nonlinear constituents, rectification of currents, etc.
  - Coastal DA methods fall in the “advanced” category – OI is out unlike deep oc. DA
- Since 2006, GODAE OceanView has had a WG, then a TT, on coastal modelling and forecasting: the Coastal and Shelf Seas TT (COSS-TT), co-chaired by Villy Kourafalou (U. Miami, USA) and Pierre De Mey-Frémaux (LEGOS, France) – discussions and presentations on Coastal DA at every meeting (open to all).

OceanPredict's Coastal Ocean and Shelf Seas Task Team

First name	Surname	Affilation	Country
Bjorn	Backeberg	CSIRO	South Africa
Alexander	Barth	University of Liege	Belgium
Lucy	Bricheno	NOC	UK
Choi	Byoung-Ju	Chonnam National University	South Korea
Yi	Chao	RSS and UCLA	USA
Guillaume	Charria	Ifremer/Previmer	France
Mauro	Cirano	REMO	Brazil
Pierre	**De Mey**	**LEGOS**	**France**
Claire	Dufau	CLS	France
Chris	Edwards	UC Santa Cruz	USA
Ivan	*Federico*	*CMCC*	*Italy*
Marcos	Garcia Sotillo	Puertos del Estado	Spain
Rouying	He	NCSU	USA
Mike	Herzfeld	CSIRO	Australia
Naoki	Hirose	Kyushu University	Japan
Lars	Hole	Met.no	Norway
Gan	Jianping	Hong Kong Univsersity	China
Villy	**Kourafalou**	**University of Miami**	**USA**
Alexander	Kurapov	Oregon State University	USA
Bruno	Levier	Mercator Ocean	France
Guimei	Liu	NMEFC	China
Youyu	Lu	DFO	Canada
Paolo	Oddo	INGV	Italy
Enda	O'Dea	Met Office	UK
Ananda	Pascual	IMEDEA	Spain
Nadia	Pinardi	University of Bologna / INGV	Italy
Julie	Pullen	Stevens Institute of Technology	USA
James	Richman	NRL	USA
Yeqiang	Shu	South China Sea Institute of Oceanography, CAS	China
Emil	Stanev	HZG	Germany
Joanna	Staneva	HZG	Germany
Nguyen Ba	Thuy	NHMS	Vietnam
Andre	Van der Westhuysen	NOAA/NWS/NCEP	USA



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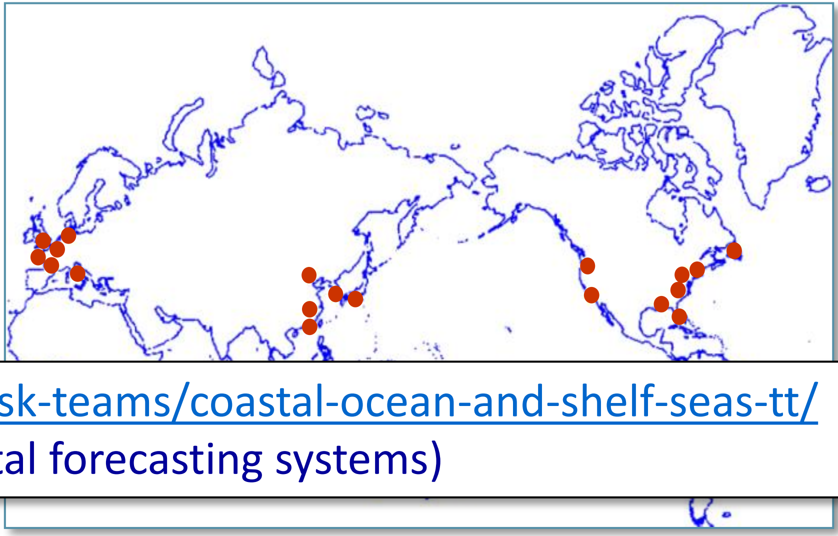


https://www.godae-oceanview.org/science/task-teams/coastal-ocean-and-shelf-seas-tt/

(includes a table with coastal forecasting systems)

US West Coast Ocean Forecast System (WCOFS)

Implementing Organization: NOAA National Ocean Service
Project Lead: A. Kurapov
Real-time implementation: Jiangtao Xu
Visualization tools: Z. Burnett

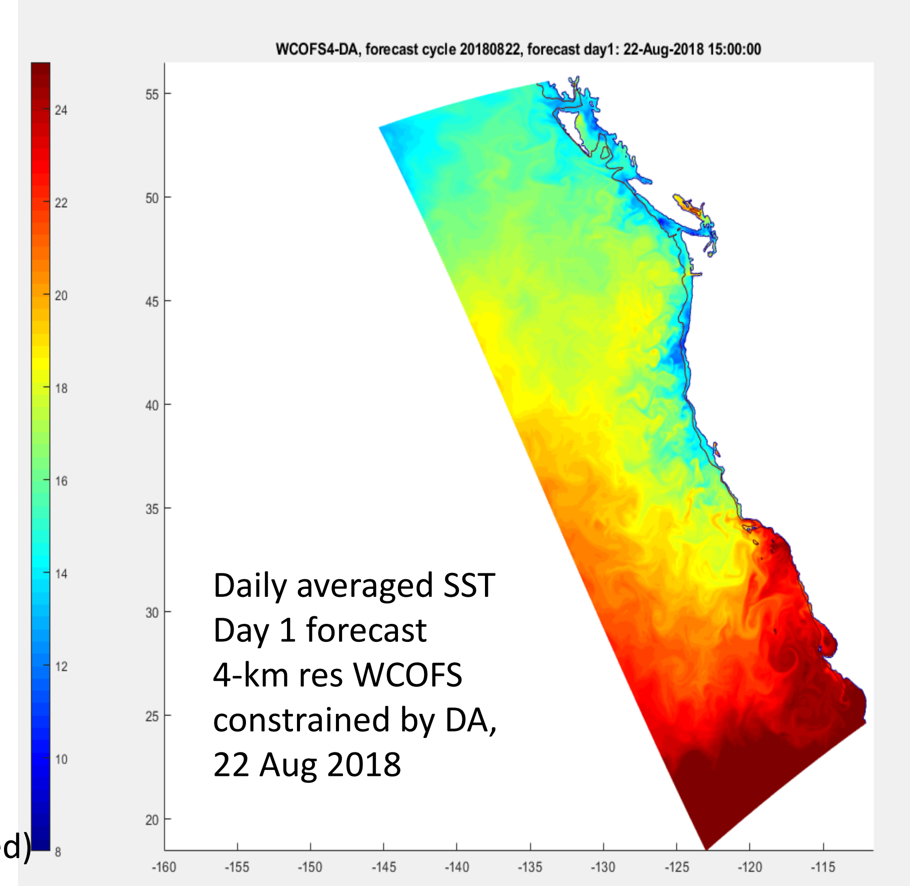
DA: daily, ROMS 4DVAR in 3-day windows
Forecasts: daily updates of 3 day forecasts

Real-time implementation (quasi-operational):
Horizontal resolution: 4 km
Vertical resolution: 40 terrain-following layers
Atm Forcing: 12 km res NOAA NAM forecasts
(winds, heat flux – bulk flux, evaporation& precipitation)
Boundary conditions:

- Tidal: 8 constituents (TPXO Pacific / Egbert & Erofeeva)
- Non-tidal: Global HYCOM (NOAA RTOFS, 1/12th degree)

Assimilated data: HF radar surf currents, SST, SSH (being tested)

In addition, the 2-km resolution non-DA WCOFS has been run for multiple years for skill assessments and scenario simulations



(courtesy of A. Kurapov)

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Real-time imple

https://tidesandcurrents.noaa.gov/ofs/dev/wcofs/wcofs.html

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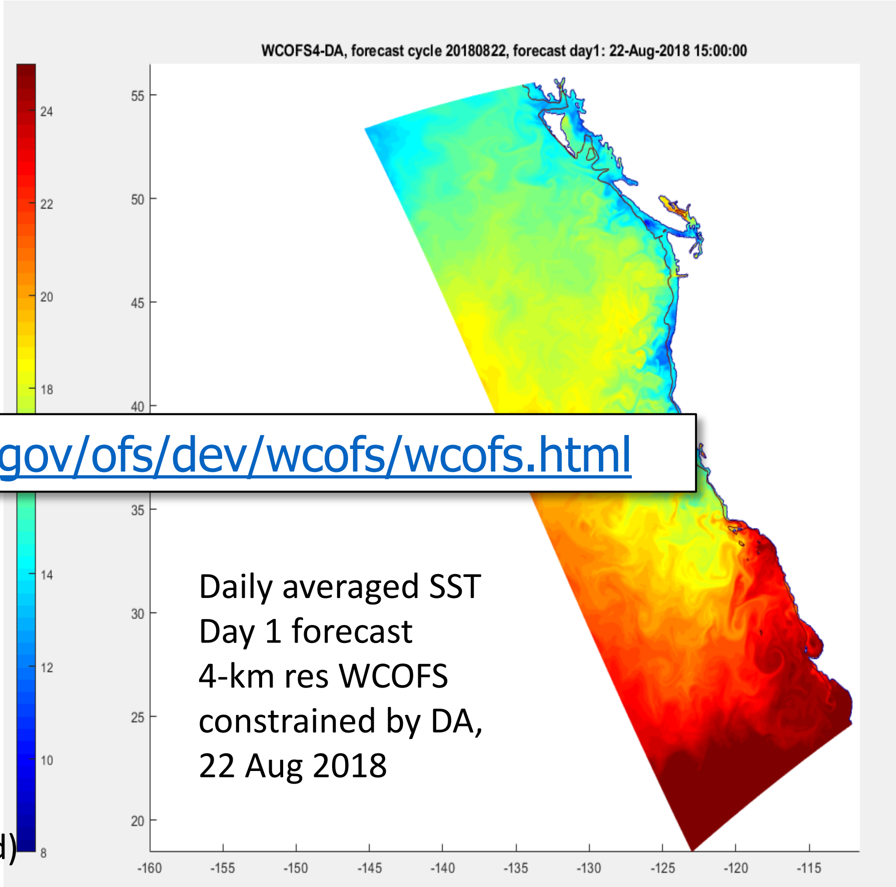

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(courtesy of A. Kurapov)

2. Downscaling considerations

Scale-sensitive downscaling with spectral nudging

Getting tides right

Sources of uncertainties: downscaled + local

Ocean Modelling 104 (2016) 54–72

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Ocean Modelling

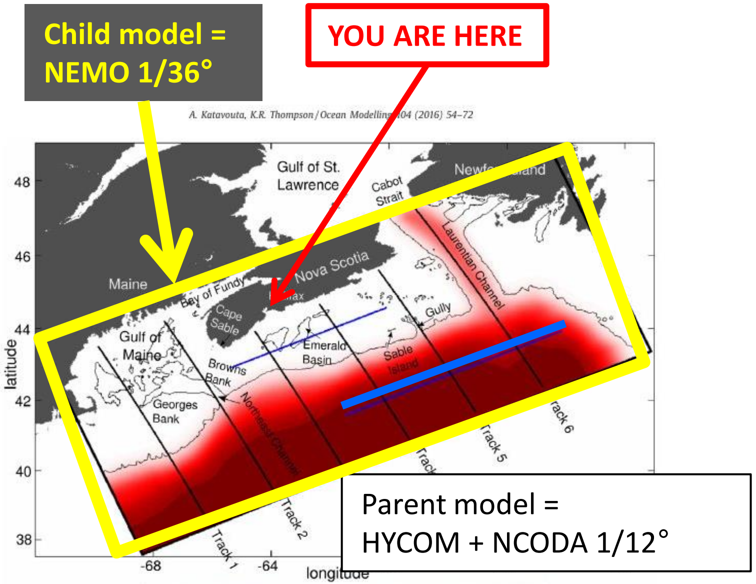
journal homepage: www.elsevier.com/locate/ocemod

Downscaling ocean conditions with application to the Gulf of Maine, Scotian Shelf and adjacent deep ocean

Anna Katavouta*, Keith R. Thompson

Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

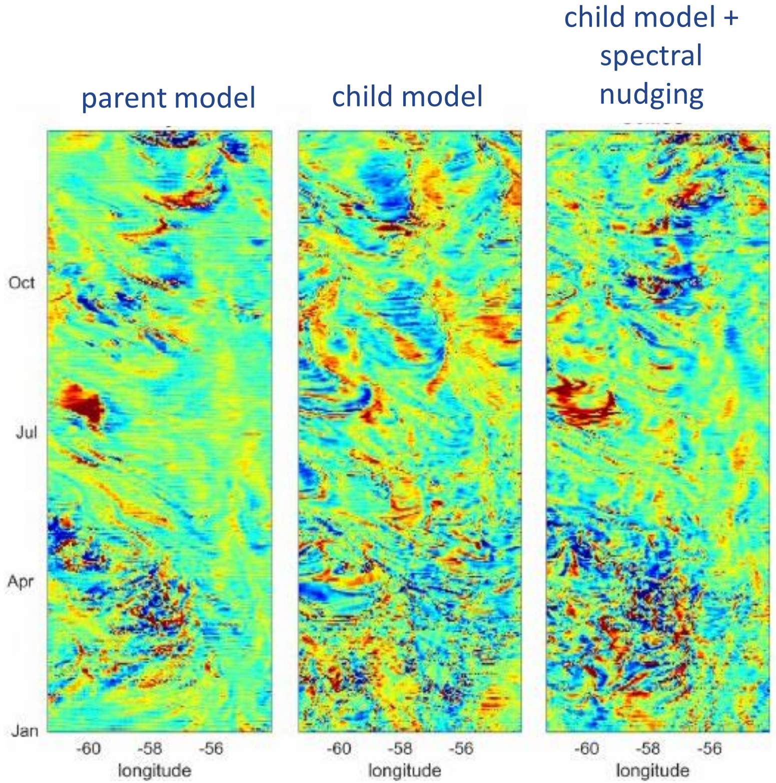
Scale-sensitive downscaling with spectral nudging



In the solution with spectral nudging:

- The front btw. the shelf and deep waters and the associated eddies and meanders are located consistently with observations
- The unrealistic patterns close to the OB are eliminated.

Relative vorticity



(Katavouta and Thompson, 2016)


Eternity begins and ends
with the ocean's tides.

Downscaling tides: why is it important for DA?

What is the quality of the forcing tidal solution in a nested domain ?

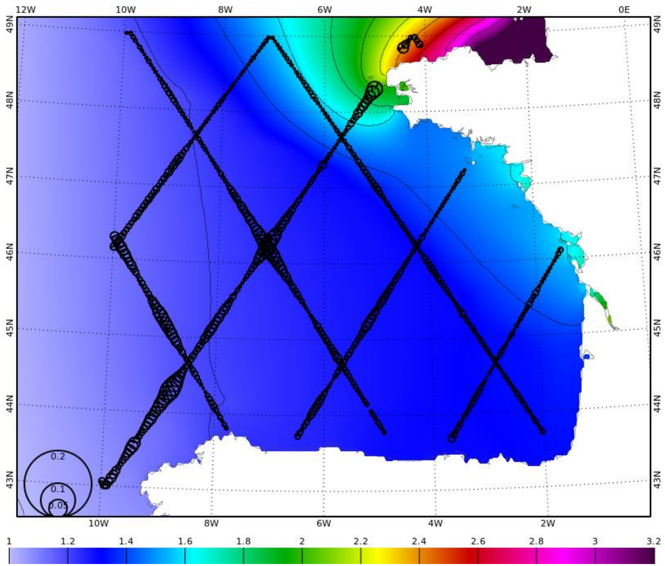
→ Usually very good if one uses global atlases such as FES2012 or FES2014 (FES201x = TUGO model + DA) →

If such solutions are prescribed at the OB, are they consistent with the interior solution ?

→ Inconsistencies may arise due to different bathymetries and resolutions

→ A good solution may not be a good forcing solution!

→ Because of the amplitude of the tidal signal in CSS, and its dynamical couplings, this can jeopardize assimilation.



M2 SSH amplitude (m)
FES2012 (Lyard et al., 2012)
vs. LEGOS/CTOH altimetric data

(Toublanc et al., OcMod, 2018)

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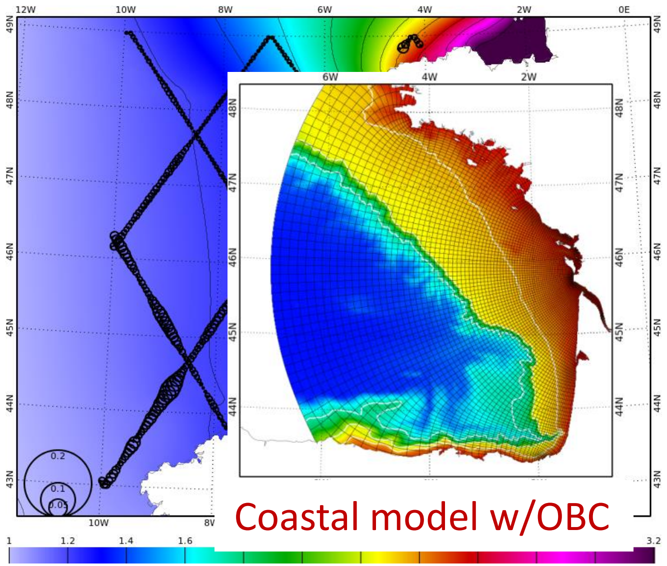

M2 SSH amplitude (m)
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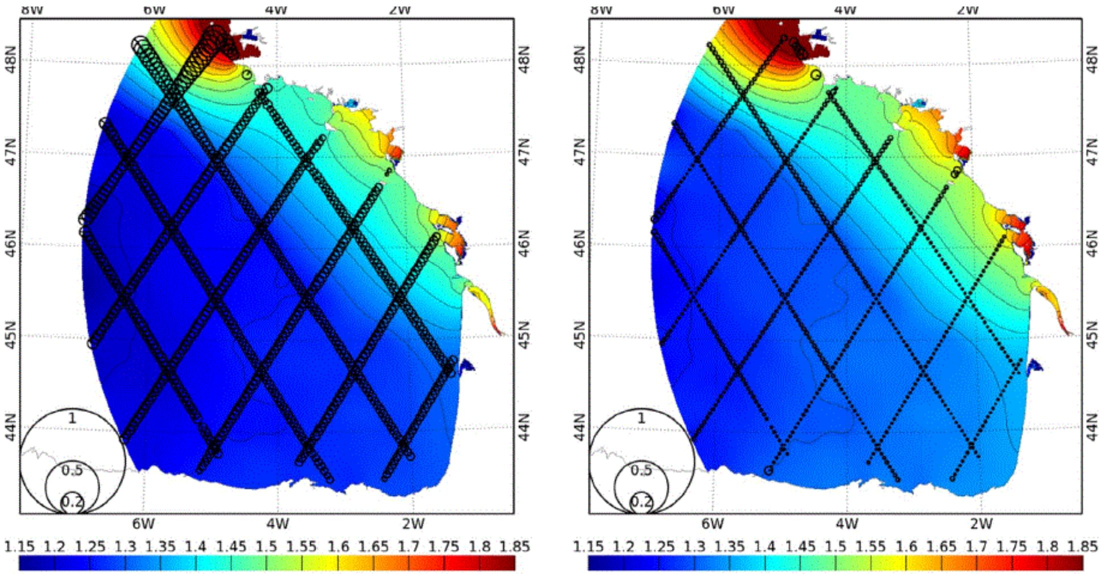
vs. LEGOS/CTOH altimetric data

(Toublanc et al., OcMod, 2018)

A new method for downscaling tides

1. Run the tidal model on the nested 3D coastal model grid and bathymetry
2. Calculate tidal harmonics; use these harmonics to force the 3D model

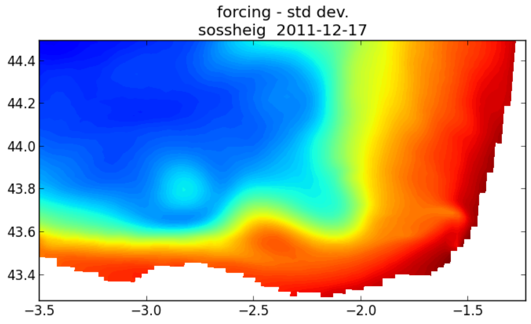
M2 SSH amplitude vs. LEGOS/CTOH altimetry data (m)



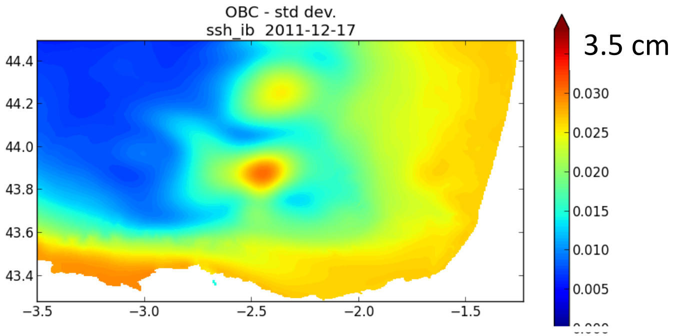
Circles = complex error (cm)

(Toublanc et al., OcMod, 2018)

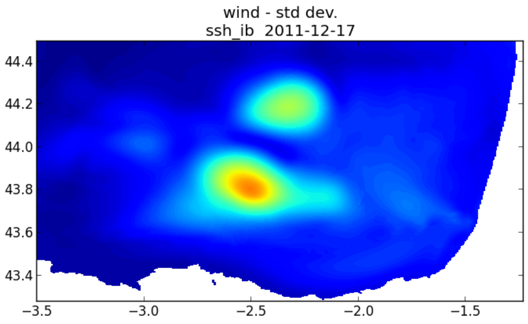
Sources of uncertainties: downscaled + local



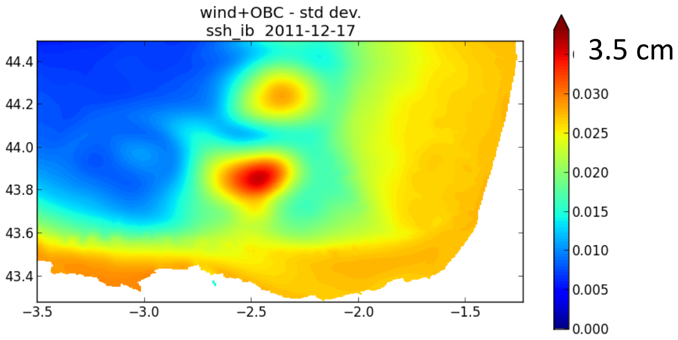
"Parent" Ensemble



Downscaled Ensemble (perturbed OBC)



Local perturbations



Downscaled + local

SSH Ensemble st.dev. (m) on Dec. 17, 2011

(Ghantous et al., submitted, 2019)

3. The statistical nature of uncertainties differs in the coastal ocean wrt. deep ocean

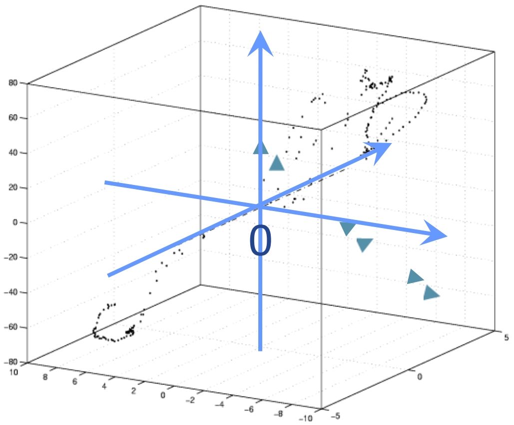
Climatology is not a mean

Uncertainties are not Gaussian

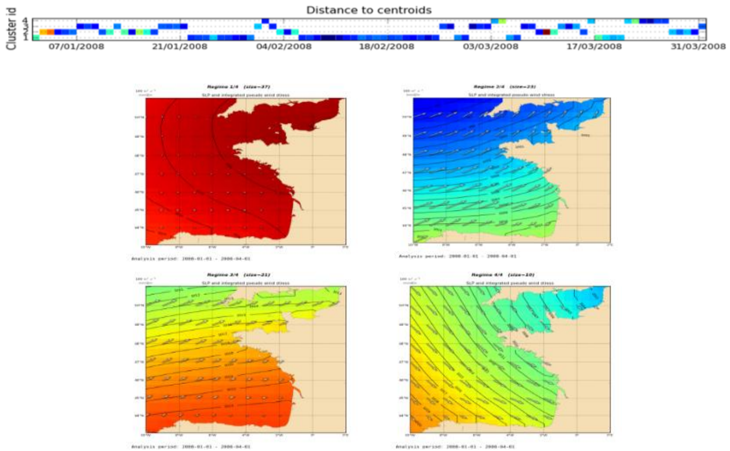
Geostrophy does not rule

Error growth on either side of shelf break differs

The coastal ocean: a multi-stable dynamical system



Phase transition along 3 EOFs in response to Northern wind burst in NW Med



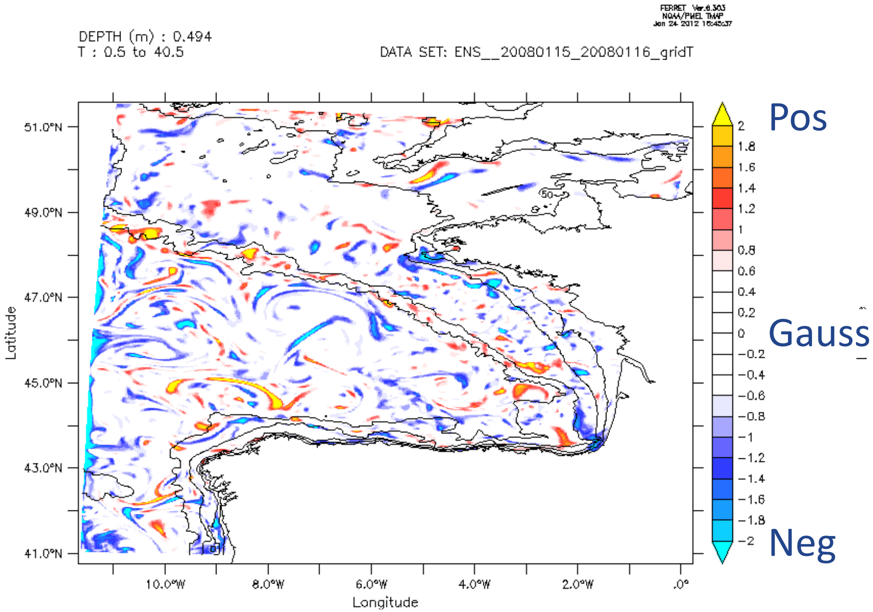
K-means cluster analysis of surface wind + SLP in Bay of Biscay

- Multiple forcings (lateral obcs, air/sea fluxes incl. waves, rivers)
- "Basins of attraction" in phase space instead of a "mean behavior"

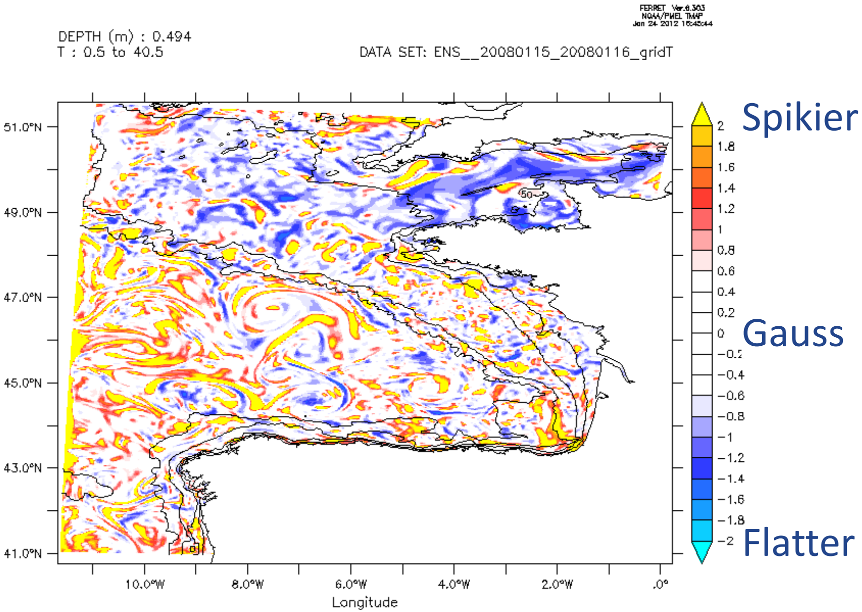
(Auclair, Marsaleix & De Mey, DAO 2003)

(Raynaud et al., pers.comm. 2012)

Uncertainties: departures from Gaussian pdf



Distribution skewness (order 3)



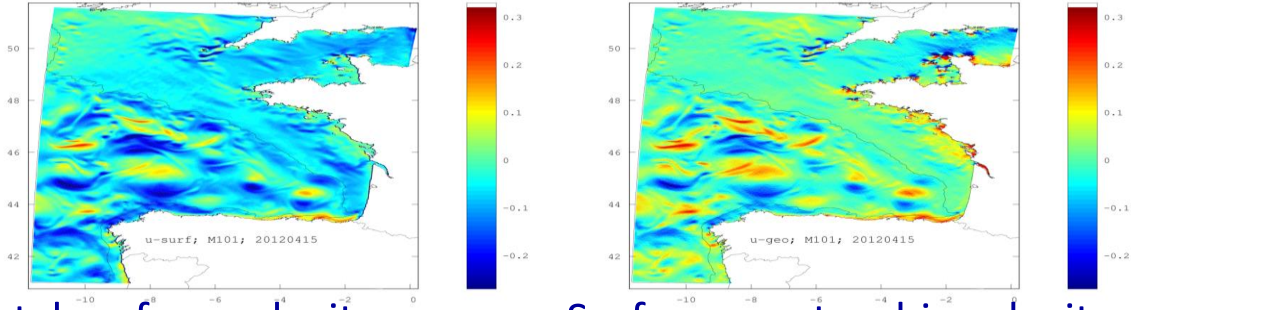
Excess kurtosis (order 4)

SST, Bay of Biscay (100 samples)

(Quattrocchi et al., JOO, 2014)

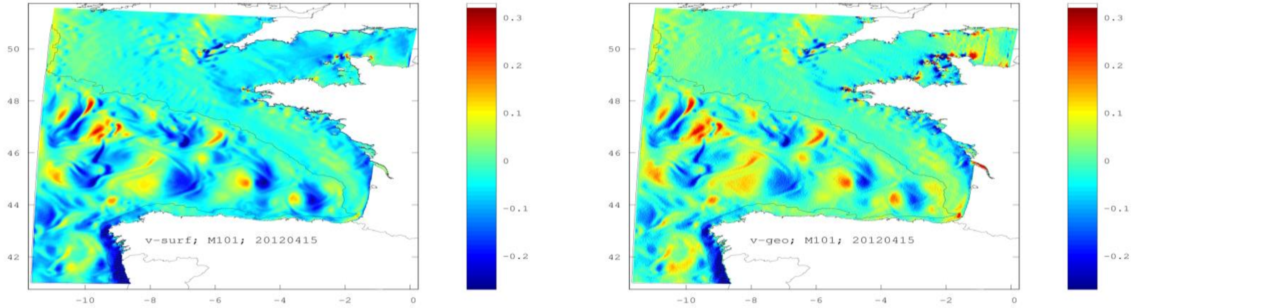
Uncertainties: departures from geostrophy

u



Total surface velocity $\mathbf{u}_{TOT}$ Surface geostrophic velocity $\mathbf{u}_G$

v

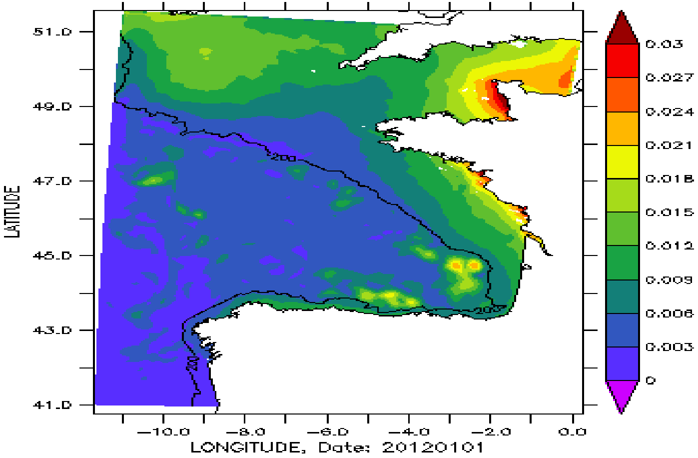


(u,v) Spring 2012, BISCAY36 (member 101)

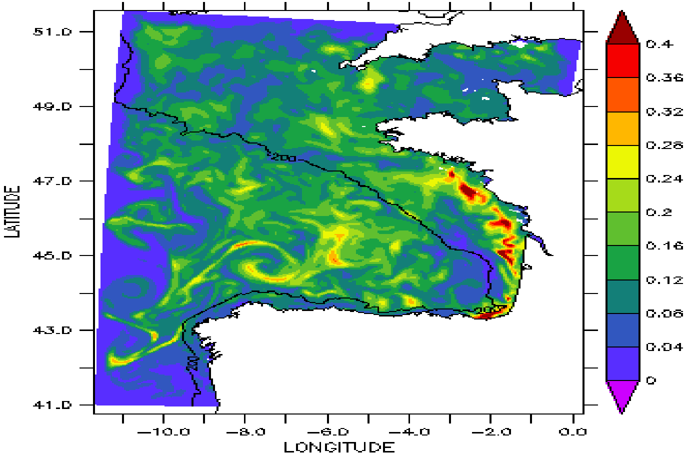
- Can have $\|\mathbf{u}_G\| \gg \|\mathbf{u}_{TOT}\|$ ($\mathbf{u}_G$ meaningless unless time-averaged)

(Vervatis et al., OcMod, 2016)

Error growth on either side of shelf break differs



SSH (m) ensemble spread



SST (°C) ensemble spread

NEMO 1/36° response to wind pert., Jan-June 2012

(Quattrocchi et al., 2015; Vervatis et al., 2016)

3. Ensemble generation in coastal and shelf seas

Use *samples* (members, particles) to represent complex pdf’s (as in the coastal ocean)

Generate Ensembles

Verify Ensembles empirically

→ Basis for use in Ensemble/Hybrid filters

Ensemble generation and consistency analysis in SCRUM

1. Ensemble generation – Sources/scales of uncertainties:

Atm Forcing

wind σ=0.3, τ=3 days, $\sigma_{x,y}$=1°, Gauss

T_{air} σ=0.1, τ=15 days, $\sigma_{x,y}$=2°, Gauss

SLP σ=0.01, τ=5 days, $\sigma_{x,y}$=3°, Gauss

AR1 processes

Elliptic Gaussian eq.

NEMO model *2D parameterized coeff.*

c_d c_e c_h σ=0.1, τ=3 days, $\sigma_{x,y}$=0.5°, Gauss

K_{PAR} σ=0.2, τ=15 days, $\sigma_{x,y}$=0.5°, Logn.

c_b σ=0.2, τ=30 days, $\sigma_{x,y}$=0.2°, Lap. flt

PISCES model

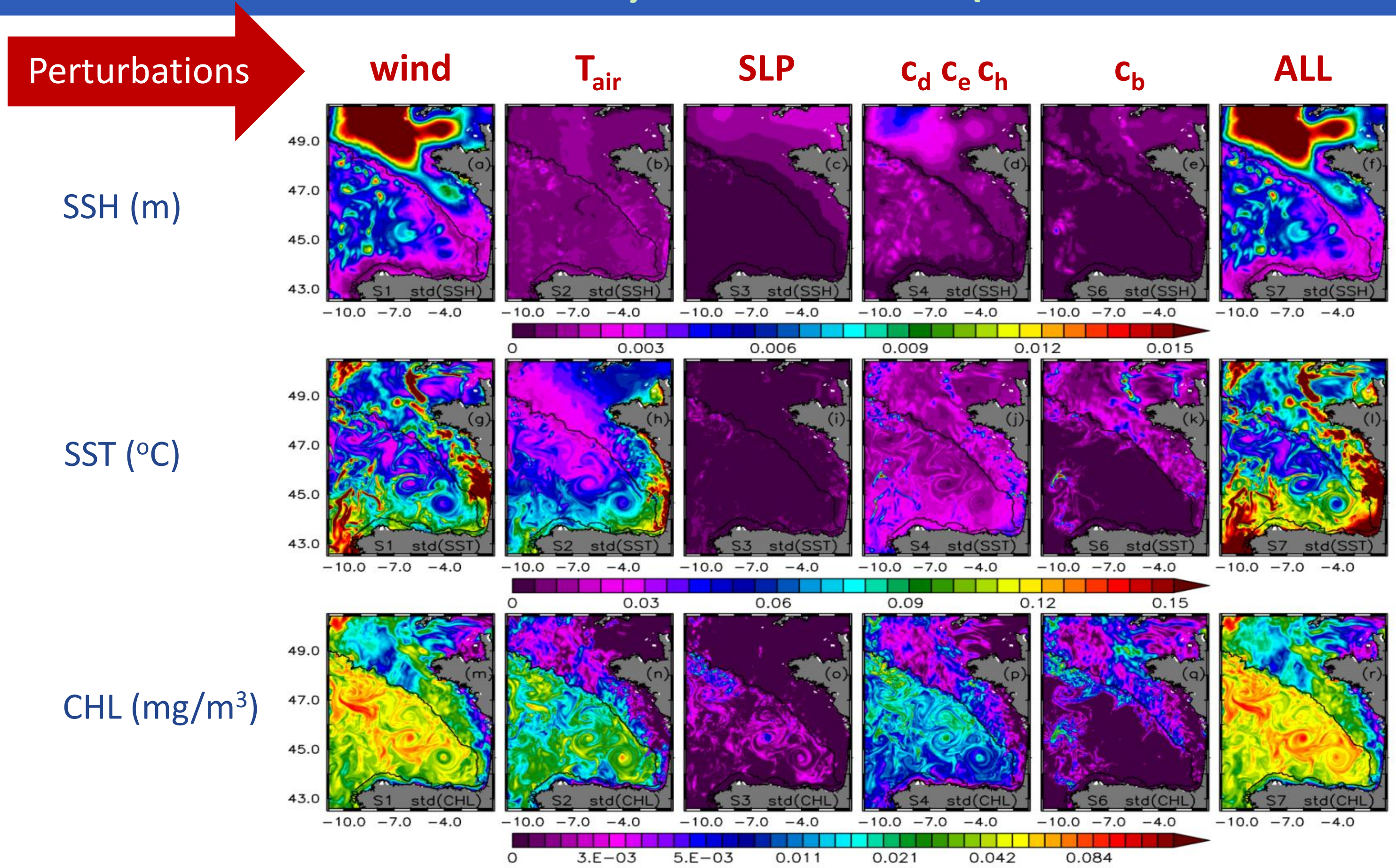
Sources Minus Sinks (SMS)

σ=0.6, τ=10 days, $\sigma_{x,y}$=0.5°, Logn.

2. Ensemble consistency analysis vs. CMEMS TAC data
   - Rank histogram analysis
   - Array modes analysis.

(Vervatis et al., submitted, 2019)

Prior uncertainty estimates (Ensemble st.dev.)



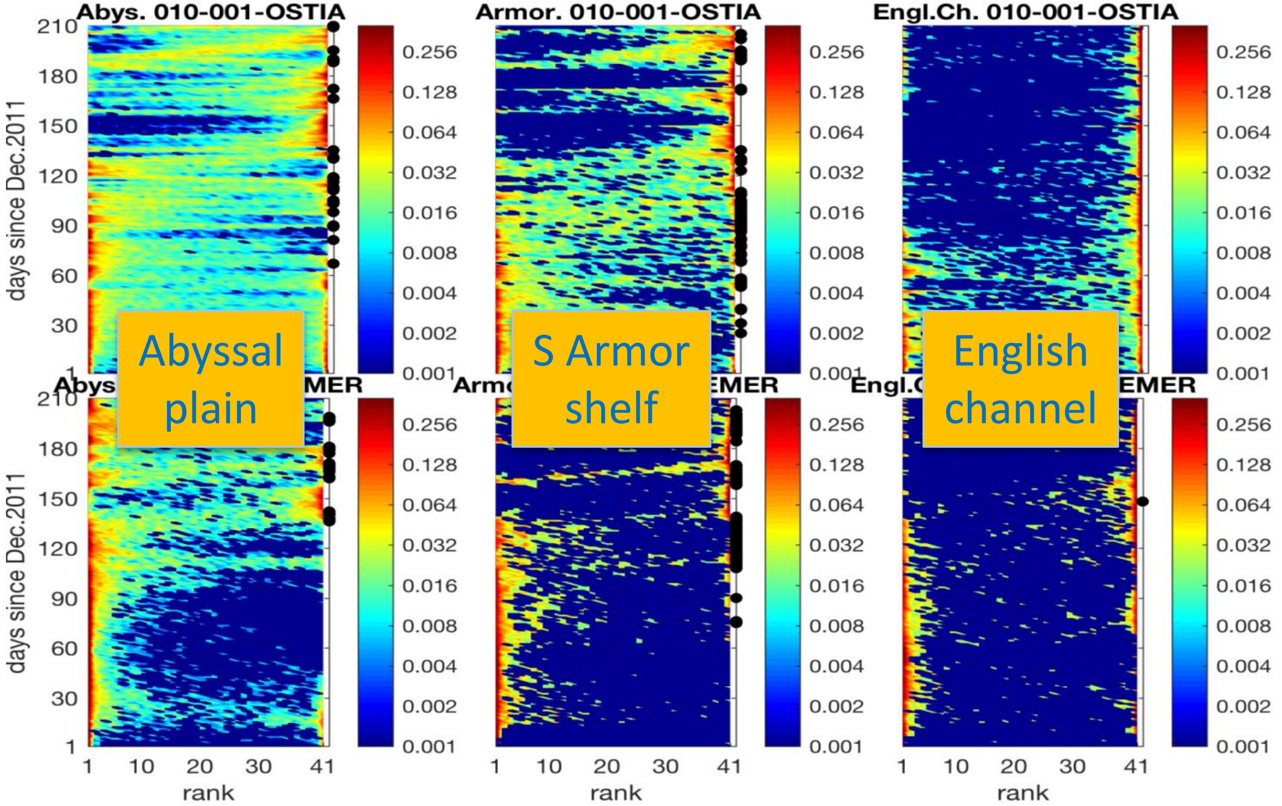
(Vervatis et al., submitted, 2019)

Verifying prior uncertainty estimates

SST Ens-1 Rank Histograms wrt. two CMEMS/TAC products in 3 regions

OSTIA L4 SST

IFREMER SST



Colorbar = pdf[0 1]

Dots = flatness criterion verified

(Vervatis et al., in prep., 2019)

4. Salinity and river plumes

The coast is where seawater meets freshwater!

Correcting salinity and river plumes

Volume constraints

Impact of SST observations on Bay of Biscay river plumes

Assim(SST)
Ens. spread in SSS
before analysis

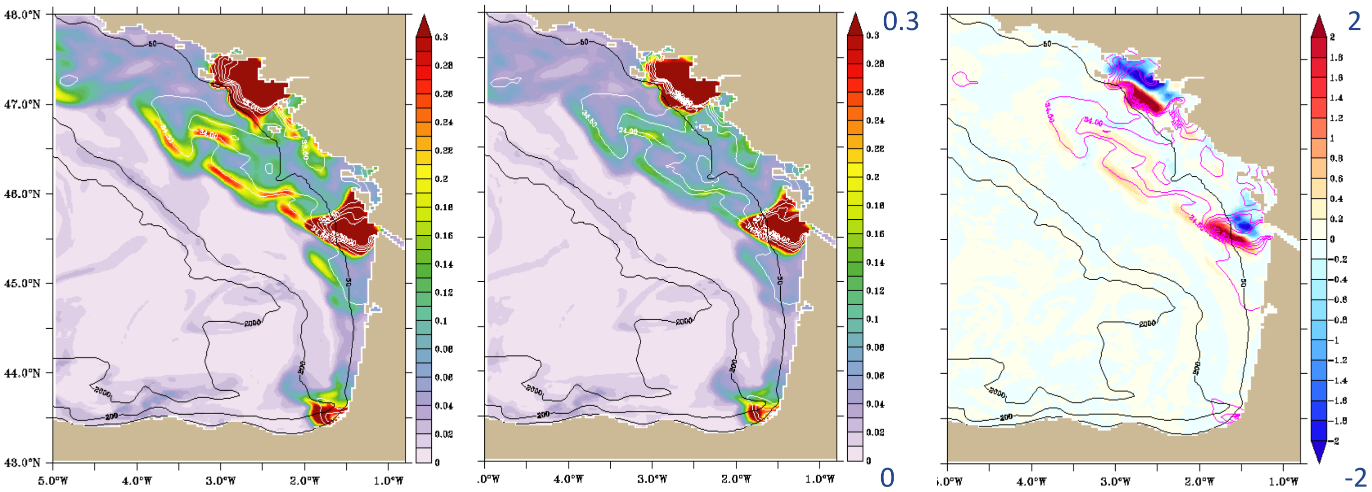
March 20

Assim(SST)
Ens. spread in SSS
after analysis

March 20

Assim(SST)
Correction in SSS
Member #20

March 20

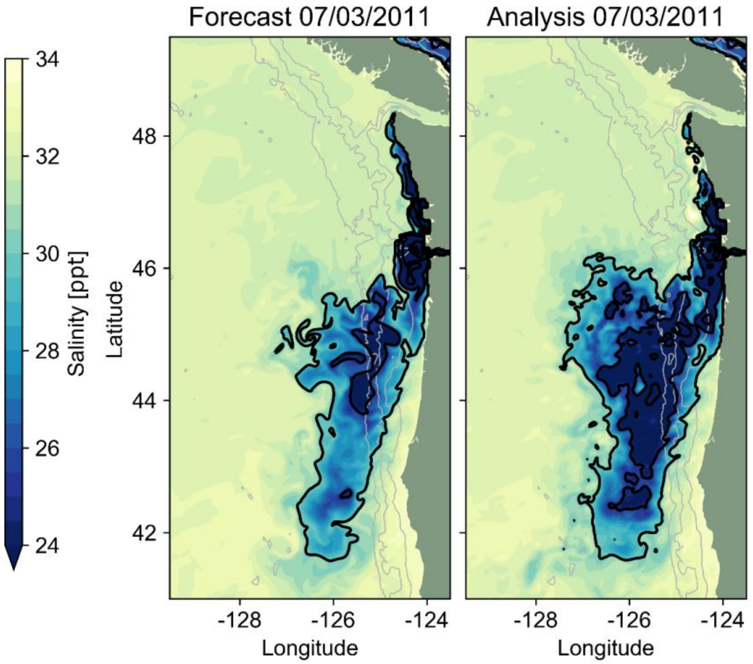


- Multivariate covariances are captured by the prior Ensemble
- Freshwater fronts: spread reduction by EnKF
- Freshwater river plumes: spread reduction + displacement

(Ayoub & De Mey, 2016)

DA can induce large corrections in the plume size

No constraint on salinity



- If one assumes that Evaporation-Precipitation is a minor source of the error, that Columbia River discharge is correct (as measured), and that the model does mixing more less OK, then the assimilation must not change the upper ocean salinity dramatically
- Assimilation with ensemble **B** can instantly increase/decrease the size of the plume

(Pasmans & Kurapov, in prep., 2019)

Constraining DA salinity changes

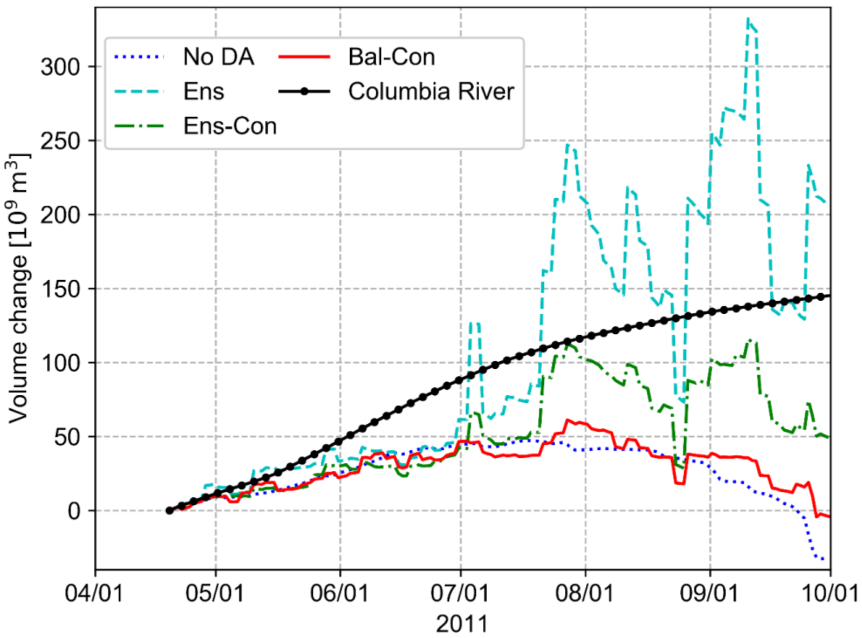
- The constraint on surface salinity is introduced using the prior model solution (in the area-averaged sense)
- This drastically reduces changes in plume water volume introduces by data assimilation.
- Constraining does not completely eliminate the changes to plume water volume by DA.

Find plume water volume per grid cell by solving

$$S_{grid\ cell}V_{grid\ cell} = S_{fresh}V_{fresh} + S_{ocean}(V_{grid\ cell} - V_{fresh})$$

$$S_{fresh} = 0.3\ ppt, S_{ocean} = 32.2\ ppt$$

Plume water volume south of the Columbia River



(Pasmans & Kurapov, in prep., 2019)

6. Formulation of coastal DA problem

Which obs are useful in controlling coastal properties?

Different behaviors of DA on shelf and in deep ocean

Controlling the surface atm. variables on the shelf

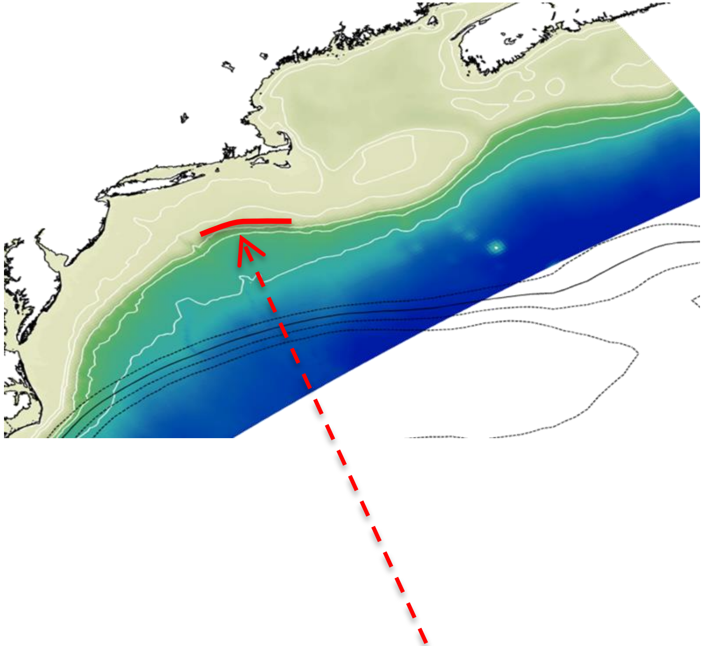
Cross-Shelf Exchange Circulation Metrics

Cross-shelf volume transport:

$$I_1 = 1/\tau \int_0^{\tau} \int_S \int_{-h}^{0} u_n \, dz \, ds \, dt$$

Cross-shelf heat transport:

$$I_2 = \rho c_p / \tau \int_0^{\tau} \int_S \int_{-h}^{0} (u_n - \bar{u})(T - \bar{T}) \, dz \, ds \, dt$$



*Alongshelf-vertical section following the 200 m isobath and passing through **OOI Pioneer Array***

(Wilkin, Moore, Laughlin, Levin, Arango, 2017)

Historical context:

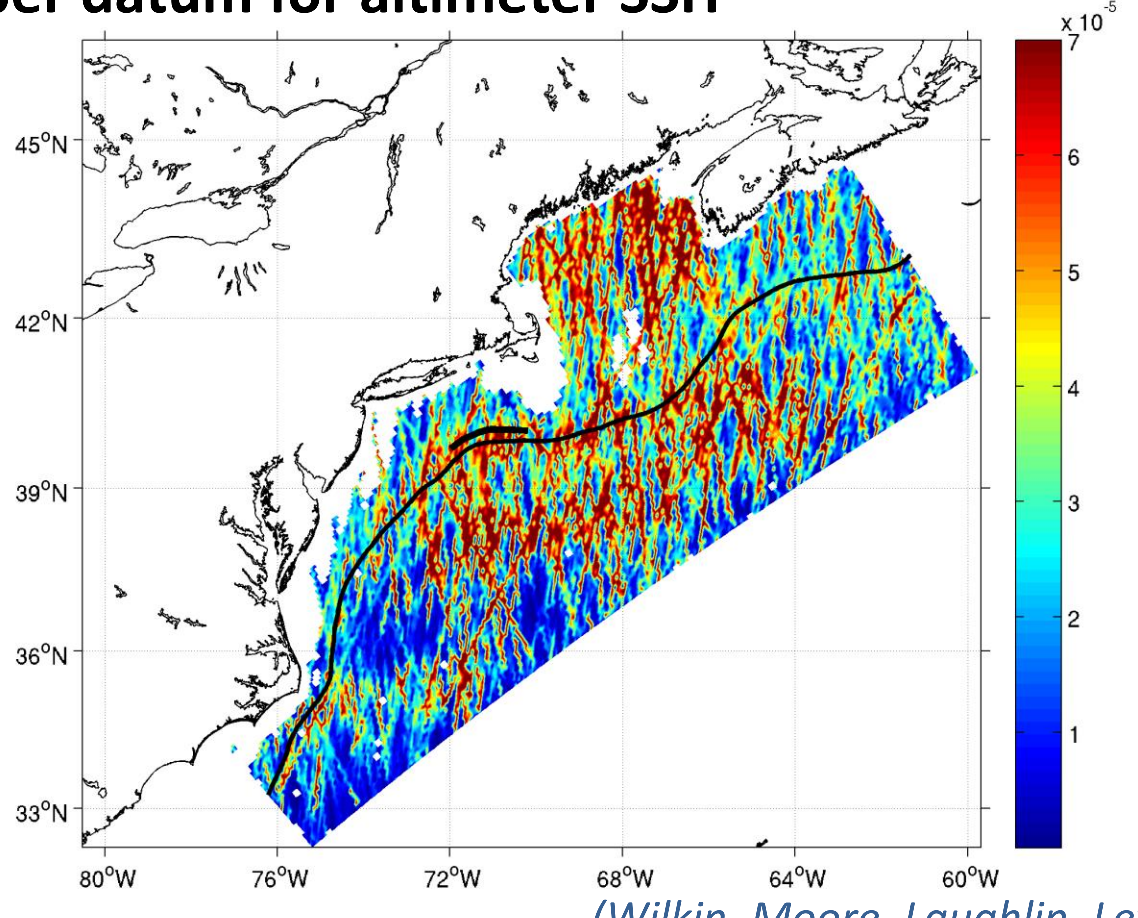
Linder and Gawarkiewicz (1998)

Chen and He (2014)

Zhang et al. (2015)

Cross-shelf volume transport:

RMS impact per datum for altimeter SSH



(Wilkin, Moore, Laughlin, Levin, Arango, 2017)

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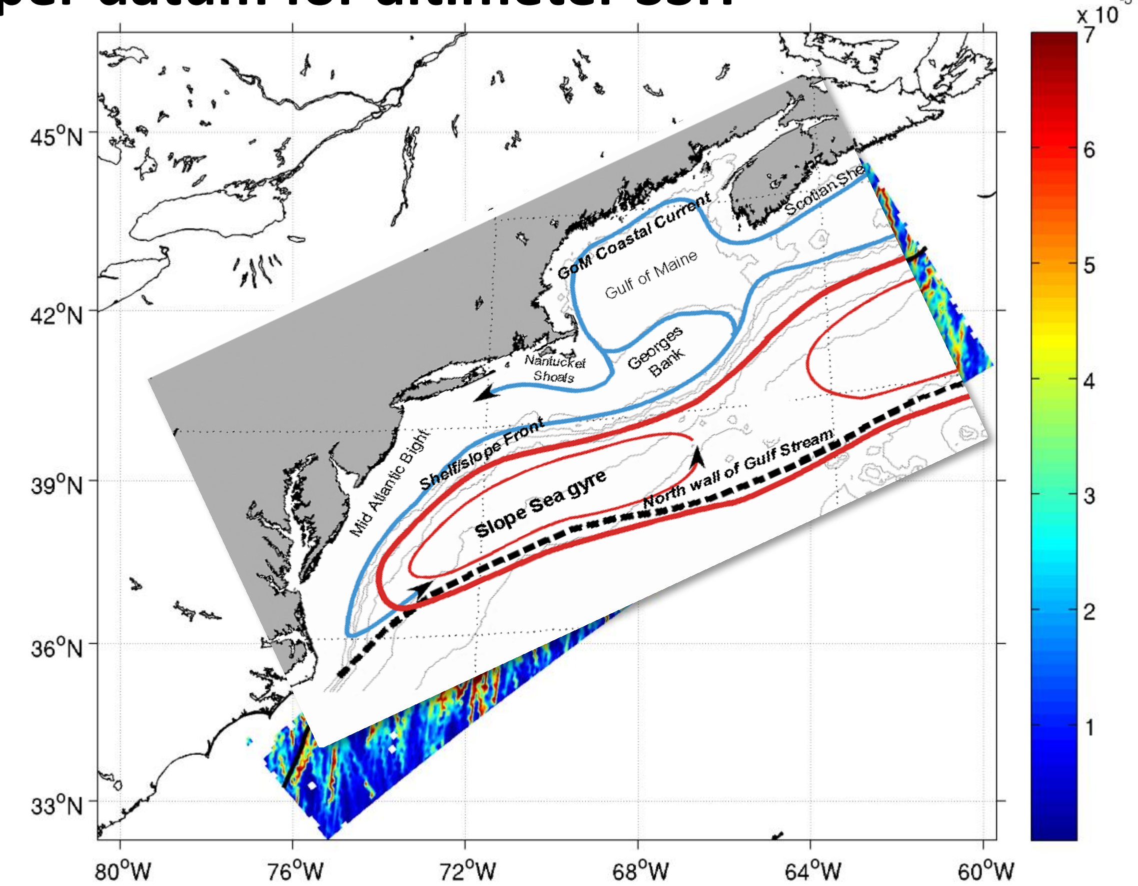
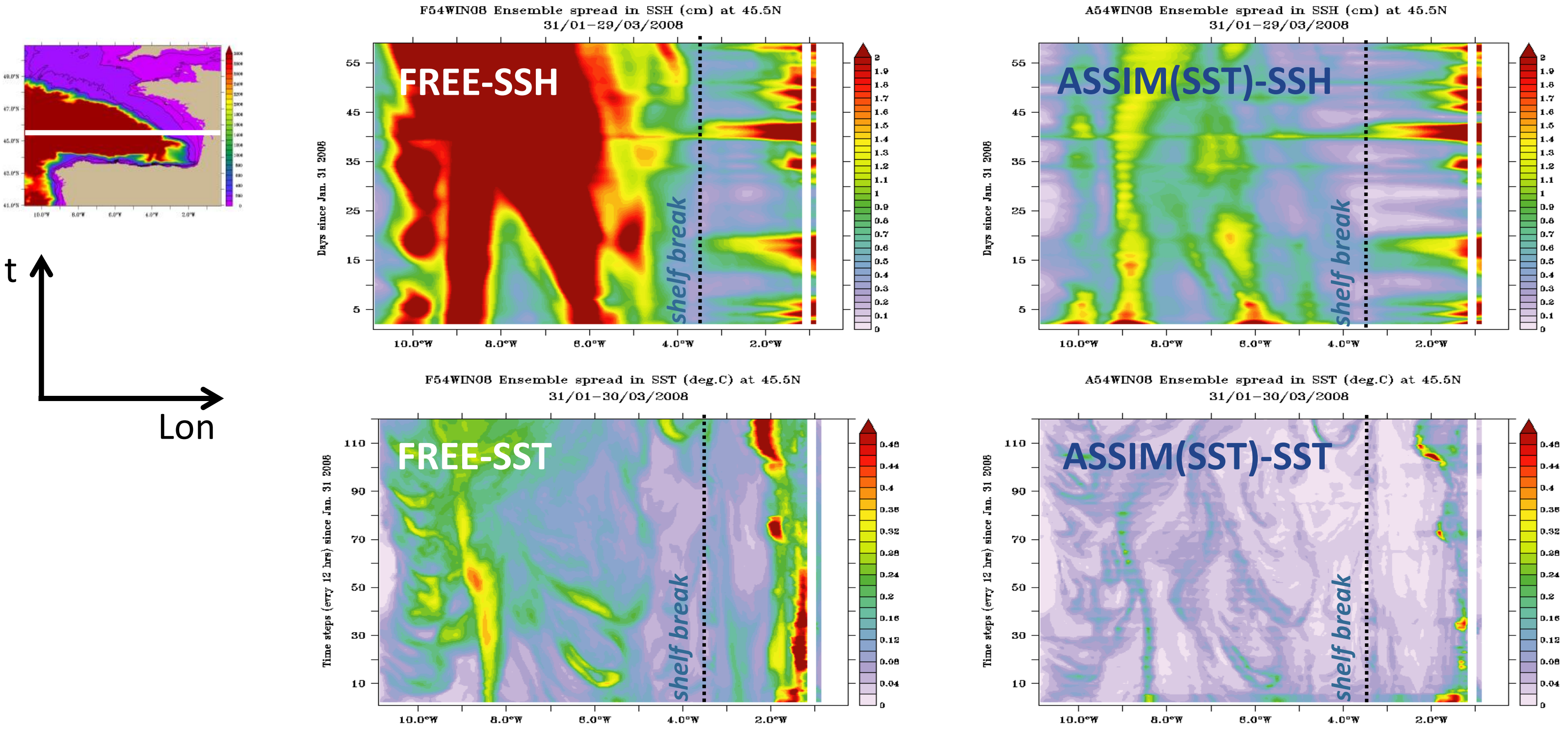


(Wilkin, Moore, Laughlin, Levin, Arango, 2017)

EnKF Ensemble spread(t) at 45.5°N – SST assimilated



(Ayoub & De Mey, 2016)

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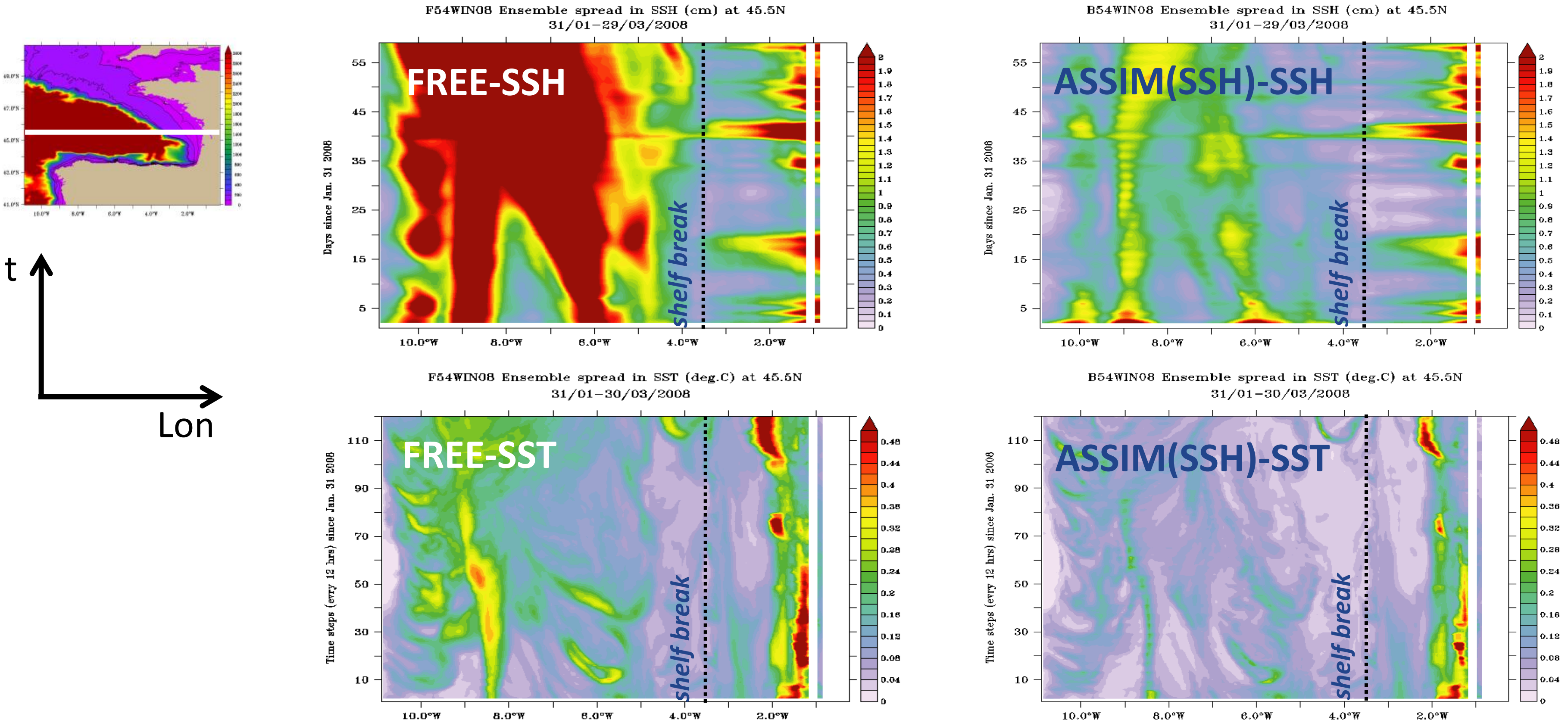
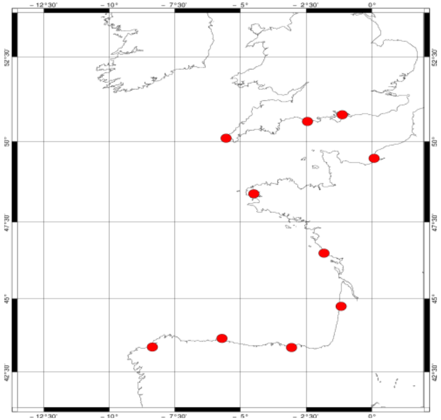
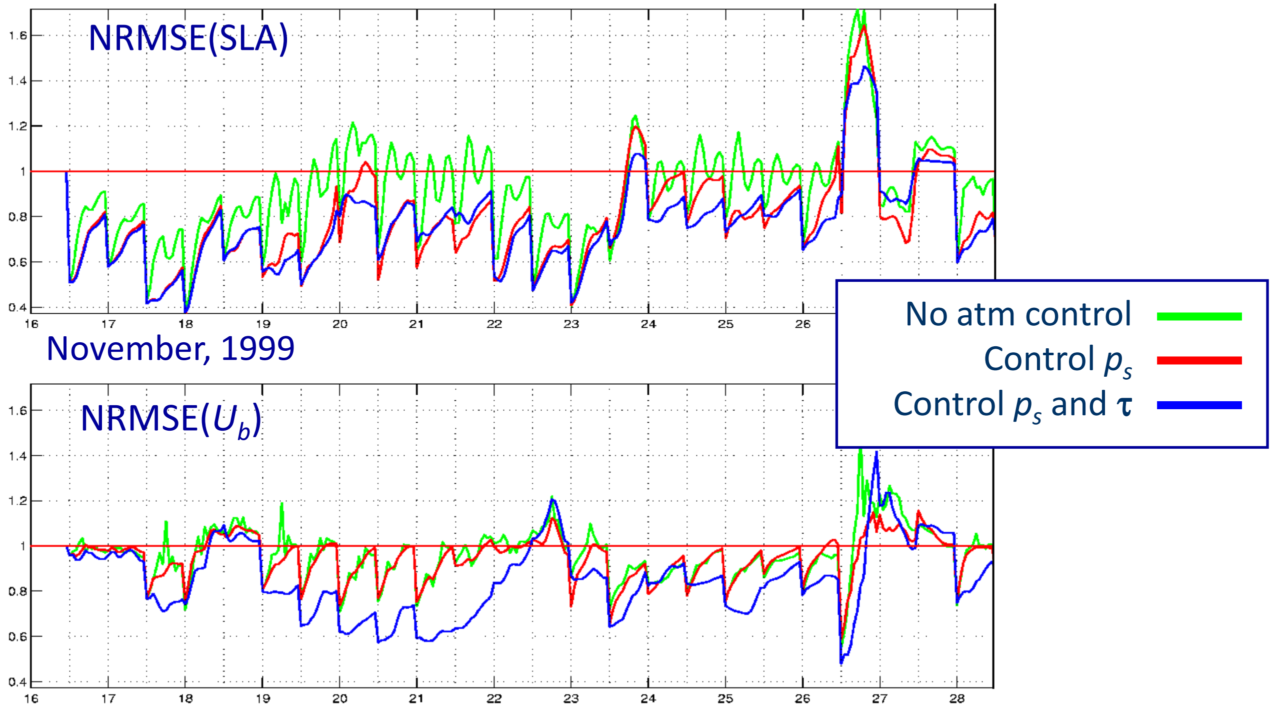


(Ayoub & De Mey, 2016)

Controlling the surface atm variables



10-TG network
obs freq: 1 hour
SDAP EnOI
T-UGOm 2D unstruct.grid
assim cycle: 12 hours
Wind+atm. pressure errors



Normalized *rms* error (<1) – Lower is better

- Controlling atm. pressure improves sea level
- Controlling surface wind stress improves surface velocities

(Lamouroux & De Mey, 2006)

Other important coastal DA science topics (not covered)

- Observability
  - Data types, platforms, coastal observatories
  - …and observation errors
  - Sea-level reference for ALT/TG assimilation
- Localization
- Seamless estimates + upscaling *(e.g. Vandenbulcke and Barth, 2019)*
- Ensemble degeneracy and inflation
- Predictability of the coastal ocean
  - Predictability time scales: shelf vs. deep ocean
  - On shelf, f(predictability of atm.)
  - Probabilistic scores & their verification
  - Machine learning.
- Discussion!