Assimilation of satellite and in-situ data in a coastal ocean forecast model off Oregon

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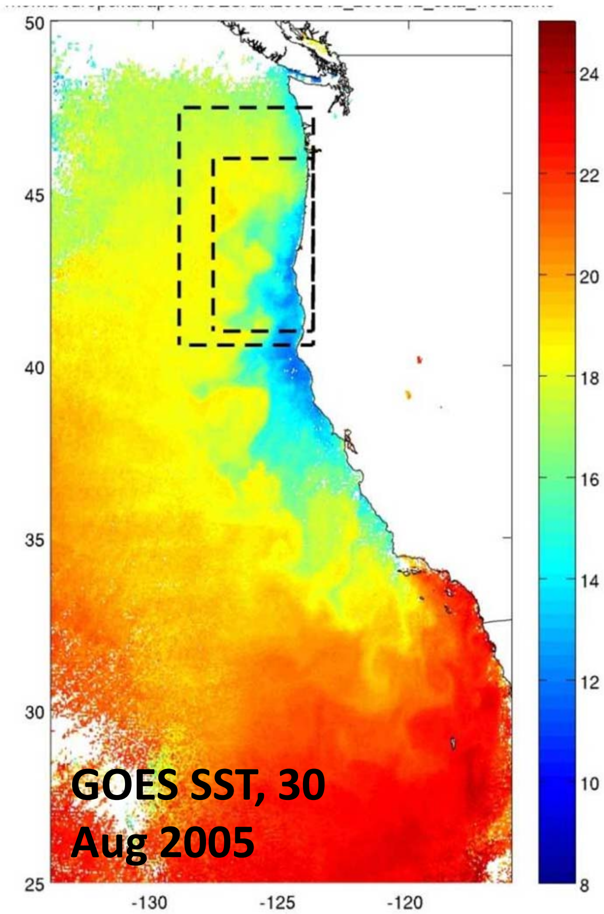
D. Foley (NOAA-CoastWatch), L. Miller (NOAA)



GOES SST, 30 Aug 2005

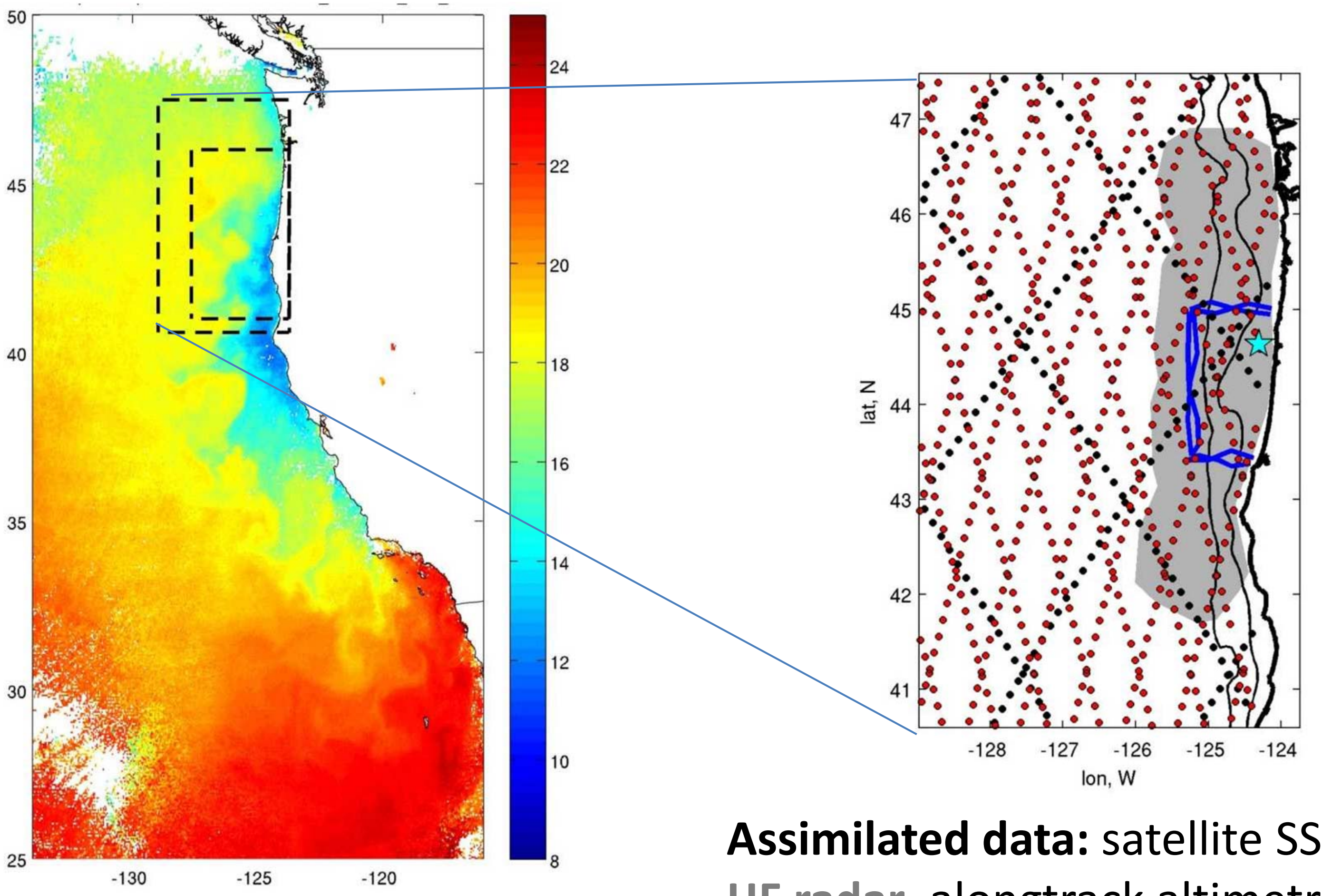
ONR (DA methods in the coastal ocean)

NOAA (IOOS-NANOOS: real-time forecast model; CIOSS: utility of RADS SSH, GOES SST)

NSF (influences of tide- and wind-driven flows, interior - coastal ocean interactions)

Data assimilation

Model + Data = Improved Ocean State Estimate
(in particular, initial conditions for forecasts)



Assimilated data: satellite SST,
HF radar, alongtrack altimetry

Model details:

Regional Ocean Modeling System (ROMS)
3-km horizontal resolution,
40 vertical layers

Atmospheric fluxes: NOAA –NAM forecasts

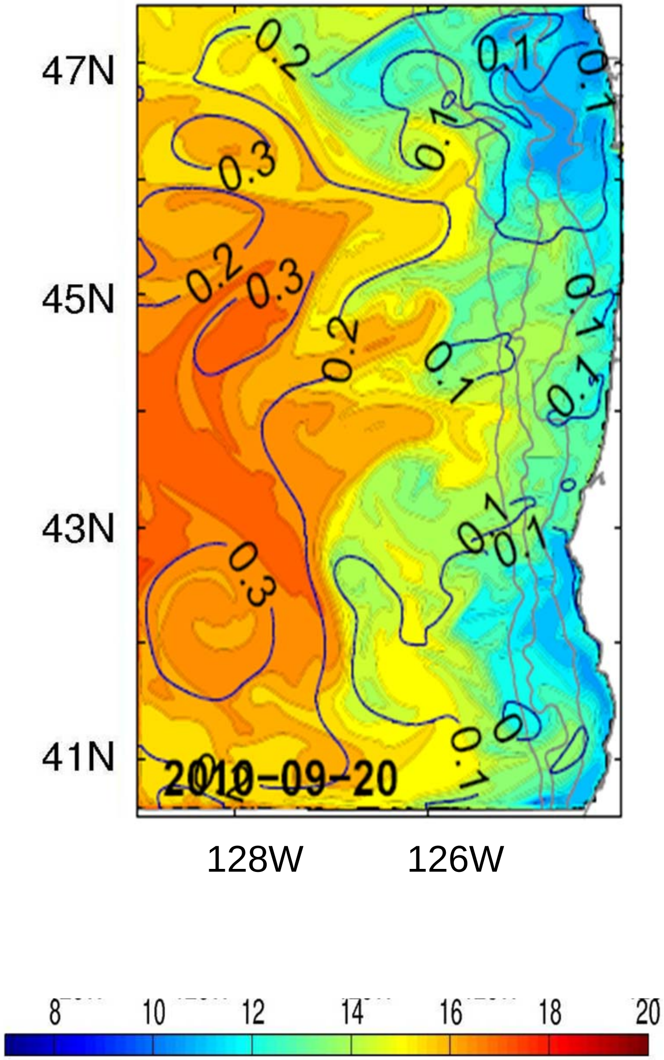
Boundary conditions: NCOM-CCS climatology

- Since 8/2010:
assimilation of HF radar surface currents
\+ hourly GOES SST

- Since April 2011:
assimilation of HFR currents
+GOES SS
+RADS alongtrack SSH

(assimilate at 6-km resolution, correction then interpolated to the 3-km grid)

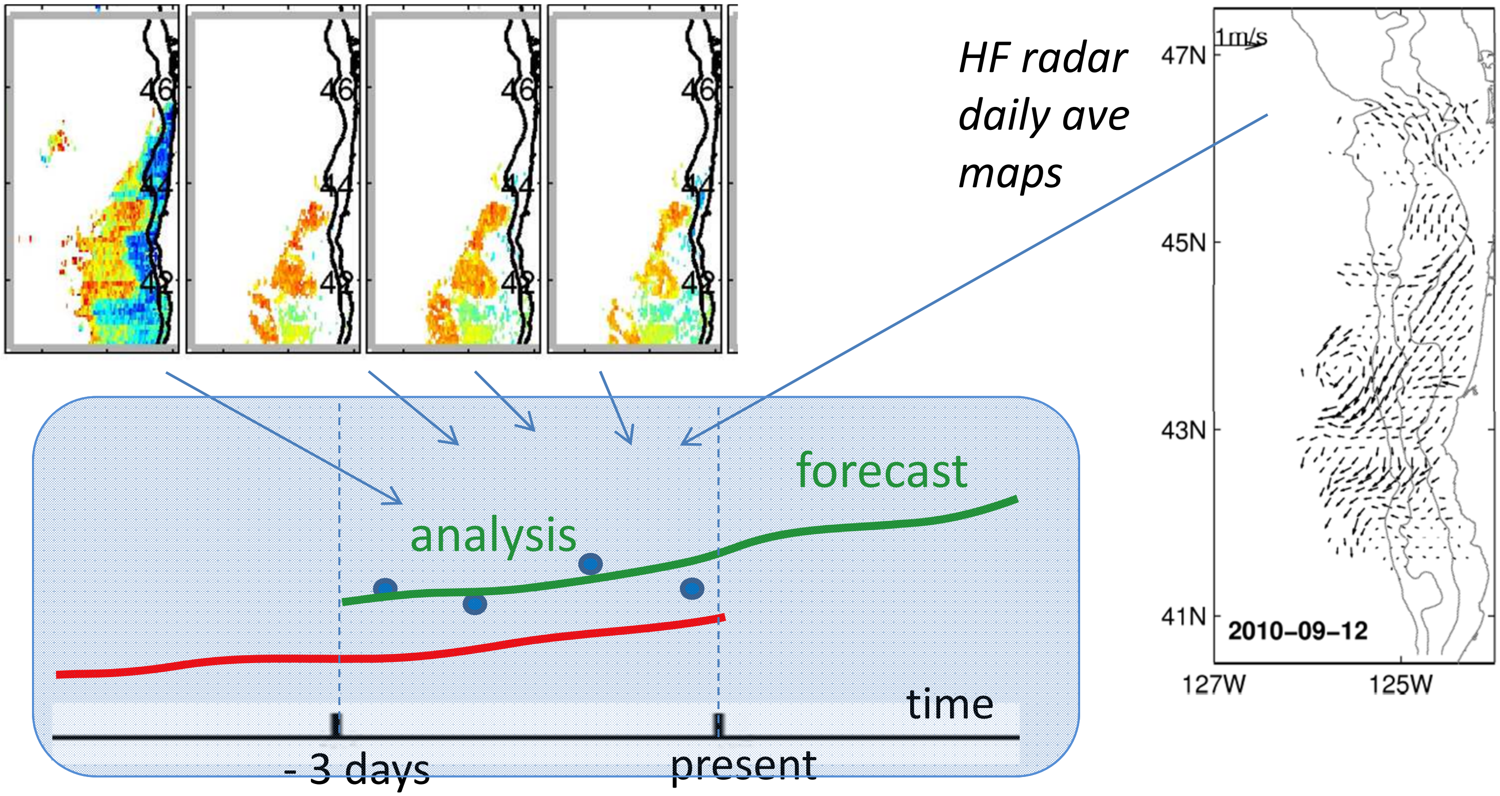
(shown: forecast SST & SSH, Sept. 20, 2010)



4DVAR = dynamically based time- and space- interpolation of data

GOES hourly data

HF radar daily ave maps

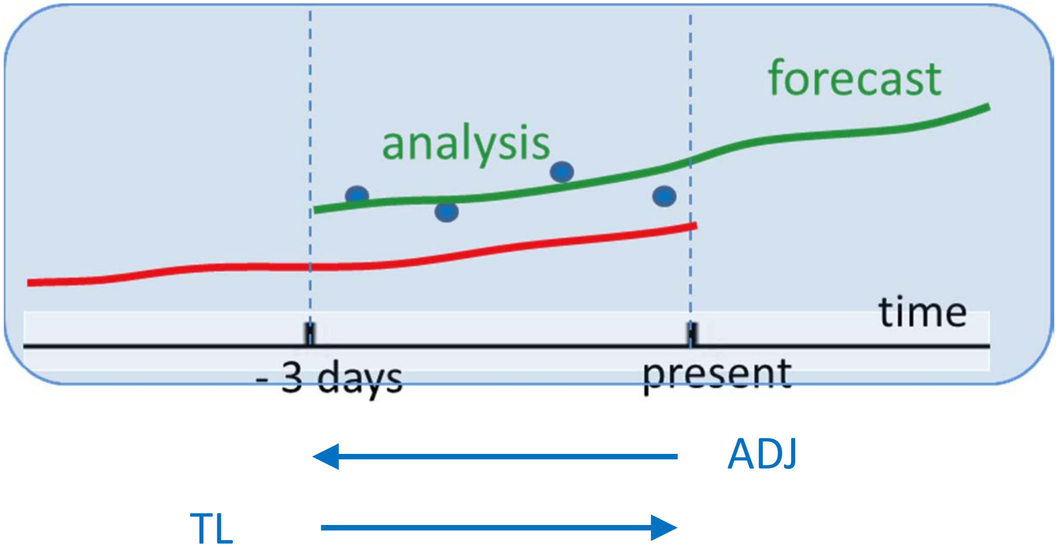


$$J(u) = (u(0) - u_0^B)^T C_0^{-1} (u(0) - u_0^B) + (d - Lu)^T C_d^{-1} (d - Lu) \rightarrow \text{min}$$

$u(0)$ = {SSH, u, v, T, S}
u^B : prior (background) state
d : data vector

C_0 : the initial condition error covariance
C_d : the data error covariance
L : operator matching model output and the data (data functionals)

Minimization algorithm:
indirect representer method (Bennett, 2002; Kurapov, JGR 2007, Kurapov et al., JGR, 2011)



Repeated implementation of the tangent linear (TL) model and its adjoint (ADJ)

TL model: the model for the linear perturbation of the ocean state near a given ocean state

ADJ model: sensitivity of the TL model outputs to inputs (generally, initial conditions, forcing, boundary conditions, parameters)

```
NL:  rhs=u*u

TL:  tl_rhs=2*u*tl_u

ADJ:
ad_u=ad_u+2*u*ad_rhs
ad_rhs=0.d0
```

AVRORA

(**Advanced Variational Regional Ocean Representer Analyzer**)

- Our own tangent linear (TL) and adjoint (ADJ) model, numerically and algorithmically consistent with ROMS
- Flexibility designing data functionals, model error covariances
- MPI

- Indirect representer method
- Preconditioning to accelerate convergence (Egbert et al., 1994)

Computational cost of minimization:

Preconditioner: 100-300 representers (each representer: 1 ADJ+ 1 TL run) – *massively parallel task*

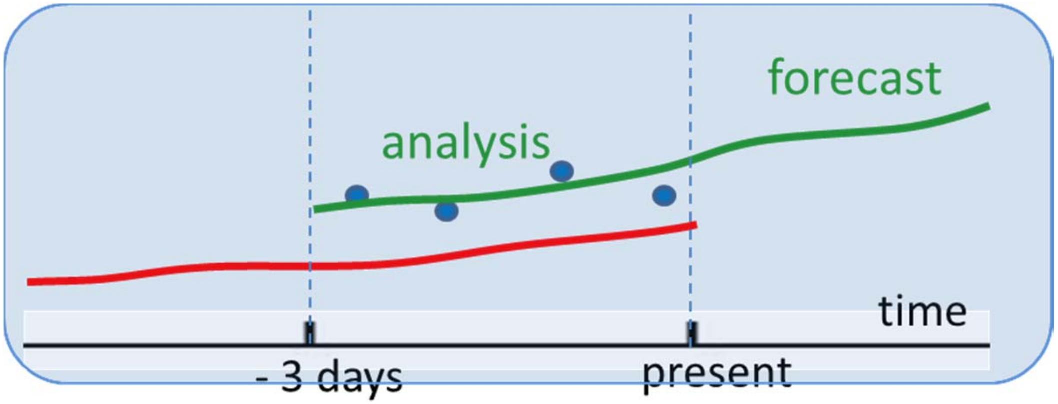
Then: minimization using the conjugate gradient method (5-20 ADJ-TL iterations)

This is fast enough to do assimilation in near-real time

C_0 is the initial condition error covariance:

- Smoothing (filtering of small scale perturbations)
- Dynamical balances (multivariate covariance, Weaver et al., 2005, Kurapov et al. 2011)

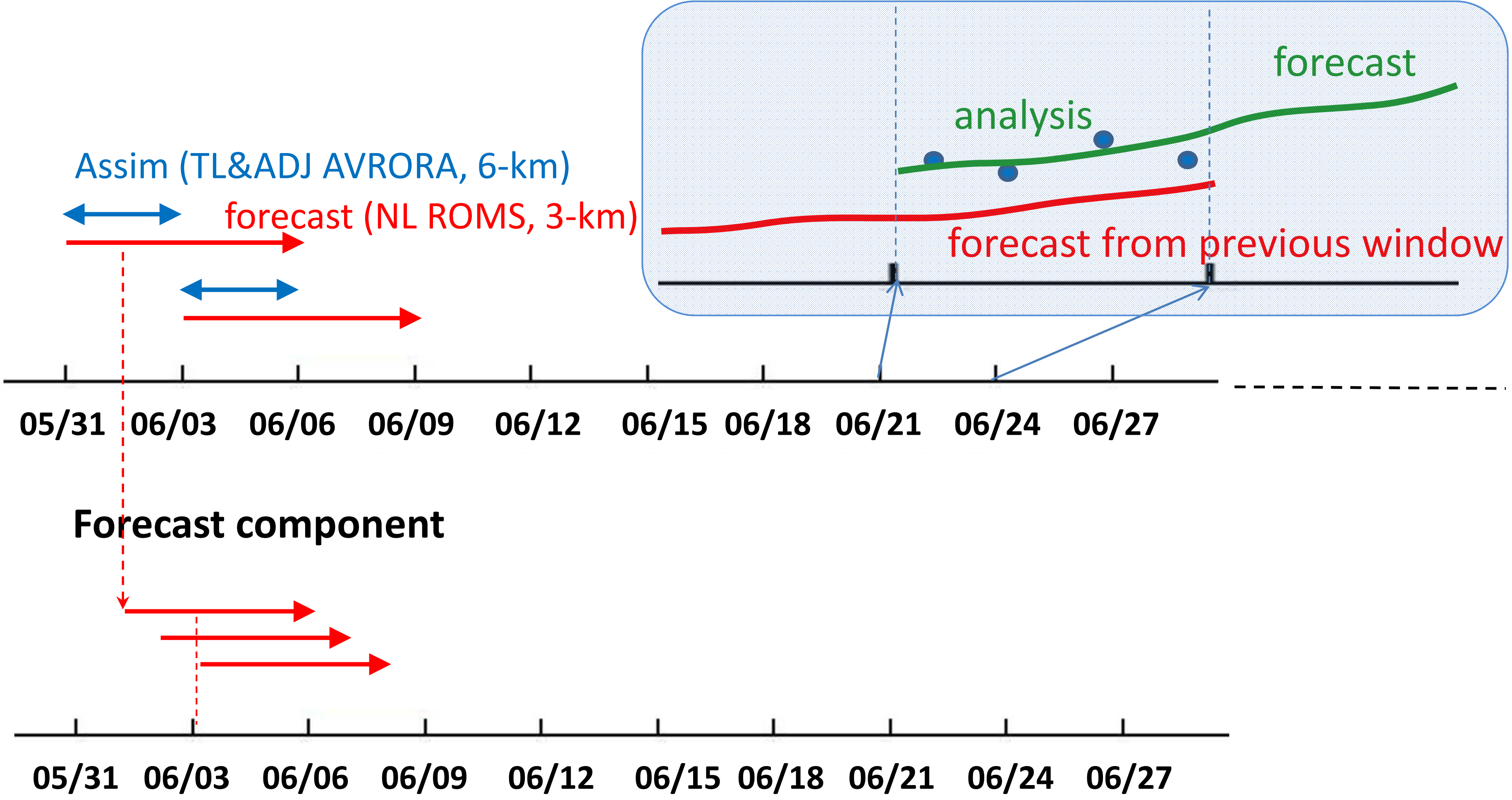
$$J(u) = (u(0) - u_0^B)^T \boxed{C_0^{-1}} (u(0) - u_0^B) + (d - Lu)^T C_d^{-1} (d - Lu)$$



$\lambda(0)$ ADJ

$C_0\lambda(0)$ TL

Real-time coastal ocean forecast model: variational DA in a series of sliding time windows



Assim (TL&ADJ AVRORA, 6-km)

forecast (NL ROMS, 3-km)

analysis

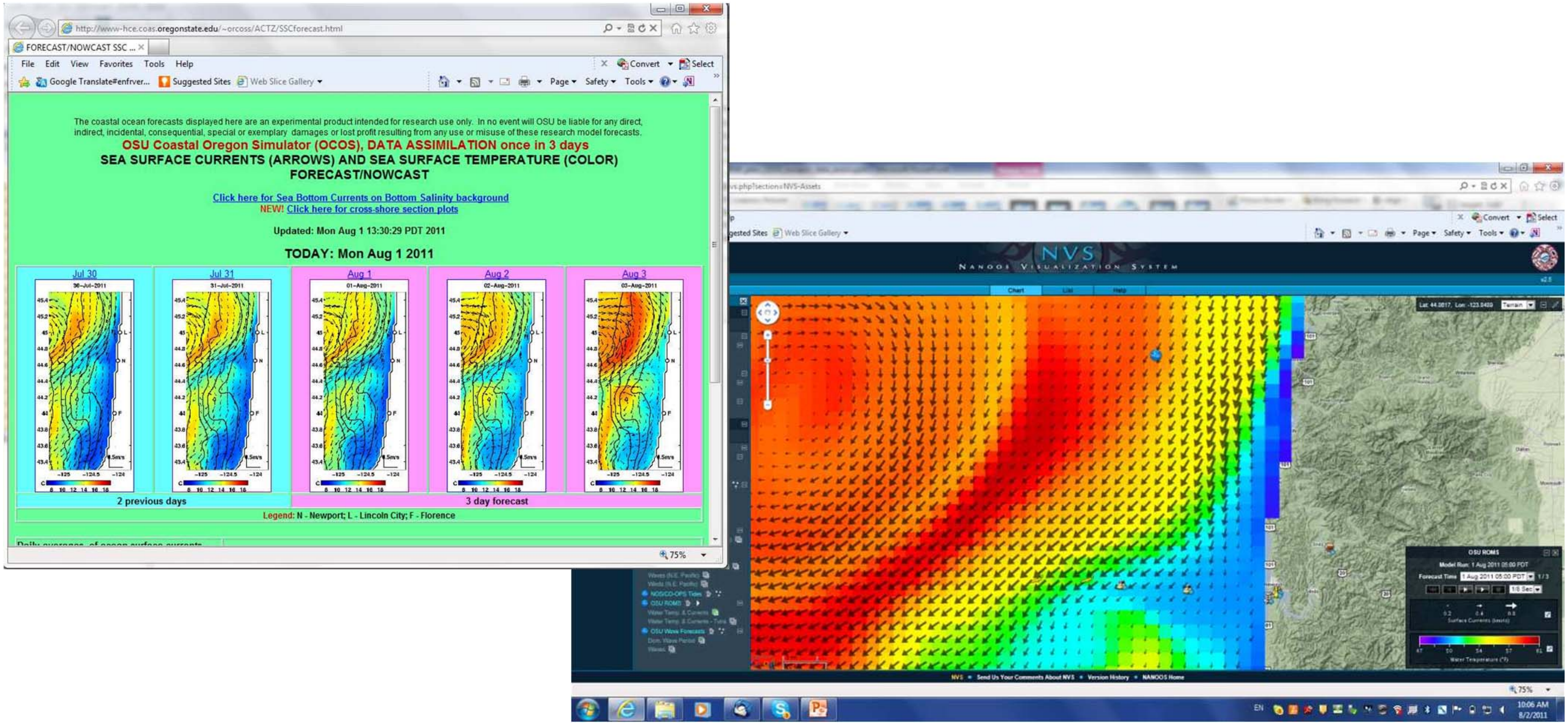
forecast

forecast from previous window

Forecast component

Forecasts online:

http://www-hce.coas.oregonstate.edu/~orcoss/ACTZ/SSCforecast.html
www.nanoos.org



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OSU Coastal Oregon Simulator (OCOS), DATA ASSIMILATION once in 3 days

SEA SURFACE CURRENTS (ARROWS) AND SEA SURFACE TEMPERATURE (COLOR)
FORECAST/NOWCAST

Click here for Sea Bottom Currents on Bottom Salinity background
NEW! Click here for cross-shore section plots

Updated: Mon Aug 1 13:30:29 PDT 2011

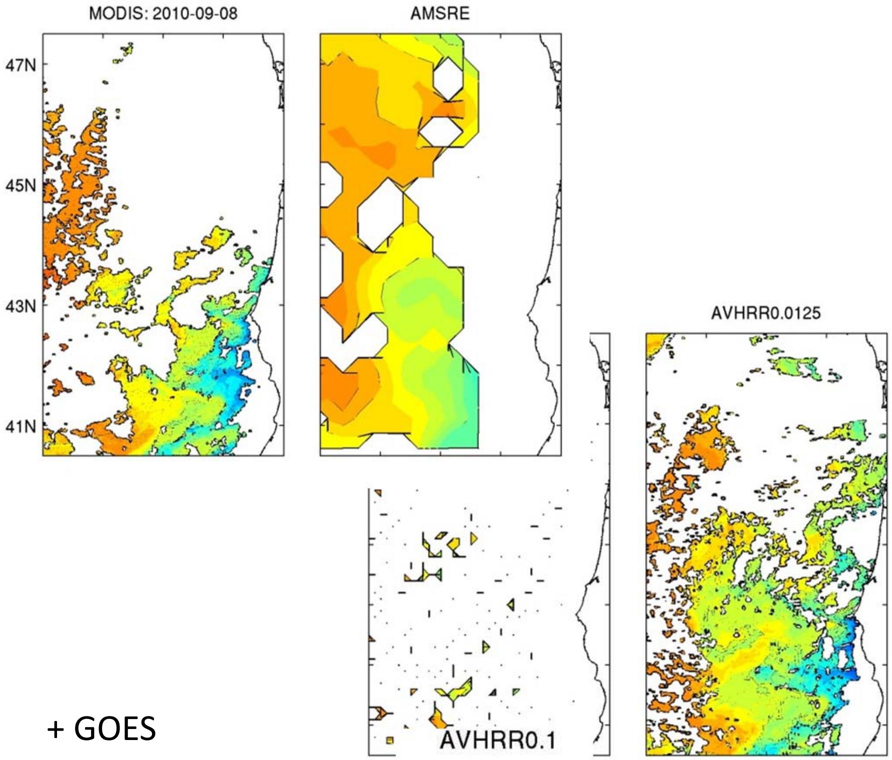
TODAY: Mon Aug 1 2011

Legend: N - Newport; L - Lincoln City; F - Florence

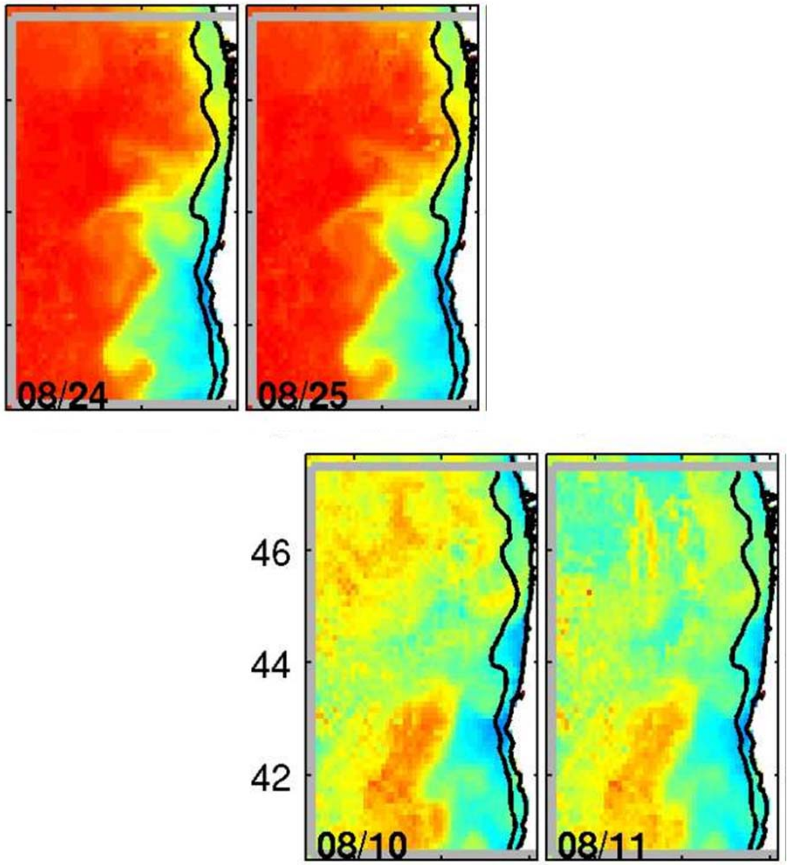
Assimilation of SST: use multi-satellite maps or more original data ?

Original data (GOES, AVHRR, MODIS, etc.)
- gaps, noisy

Multi-satellite blended maps (e.g., 5-day Coastwatch product)
- (mostly) no gaps, can still be noisy

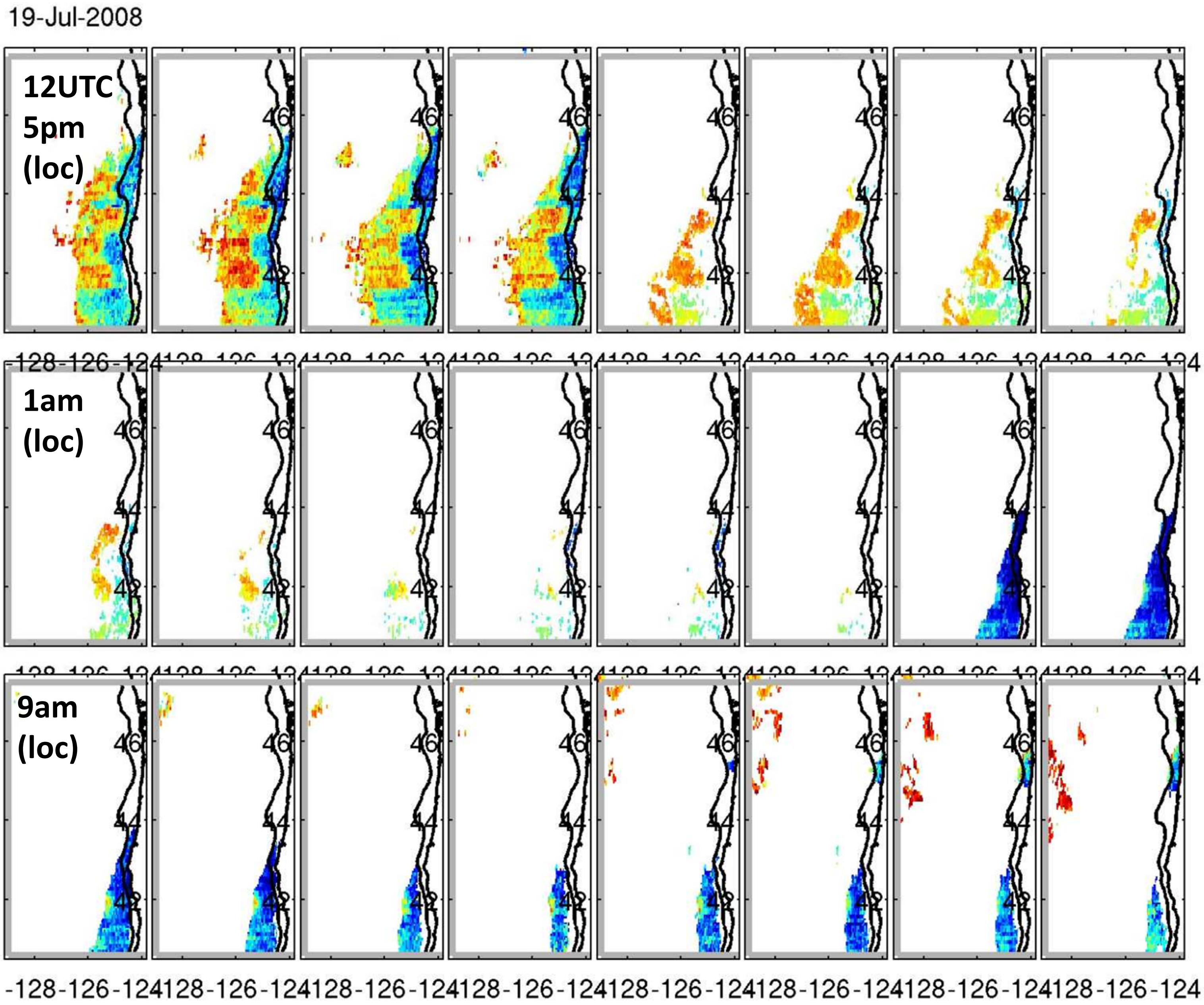


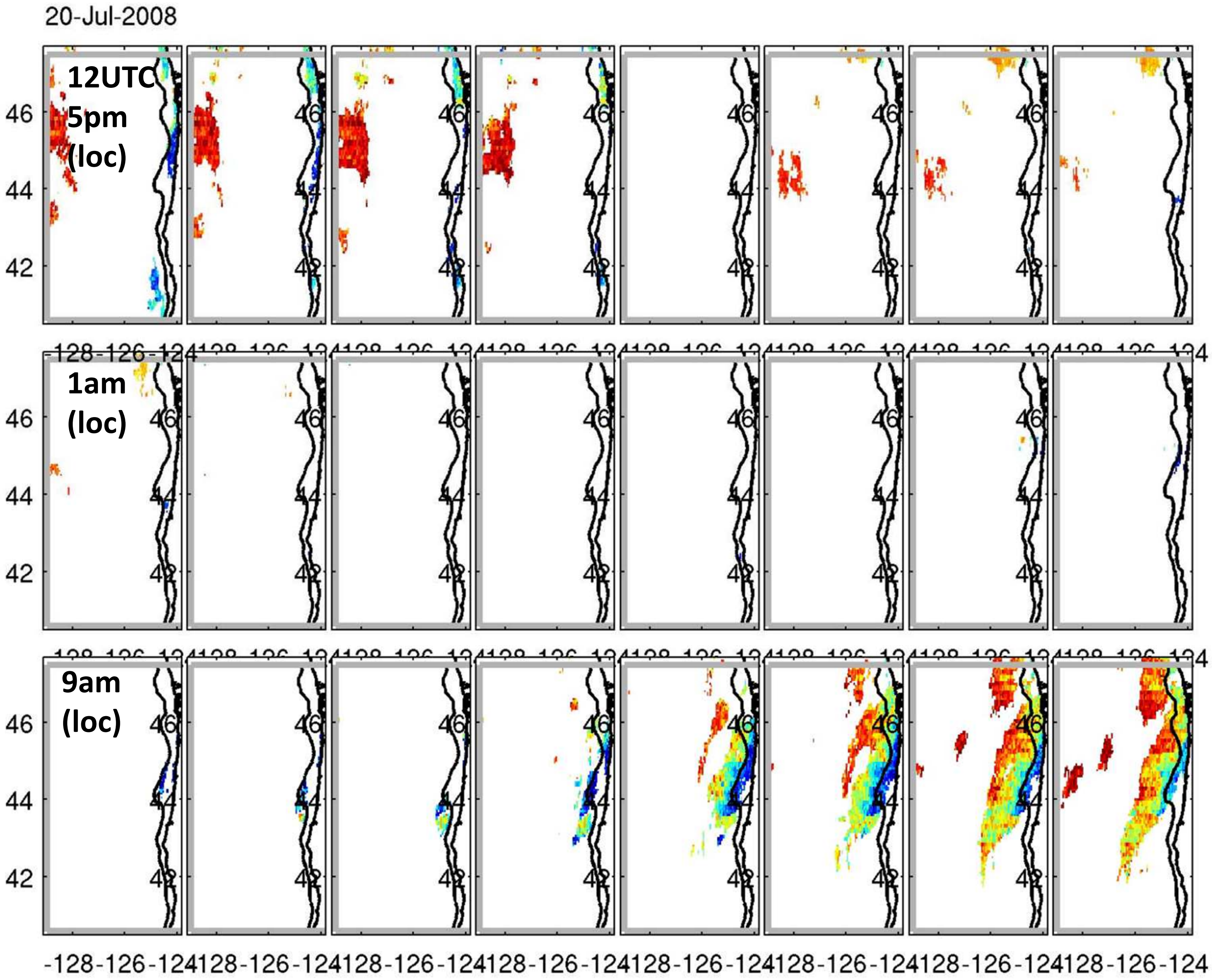
+ GOES



Our choice: assimilate original data

GOES hourly data, 19 – 21 Jul, 2008: *we will assimilate these*





12UTC
5pm
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(loc)

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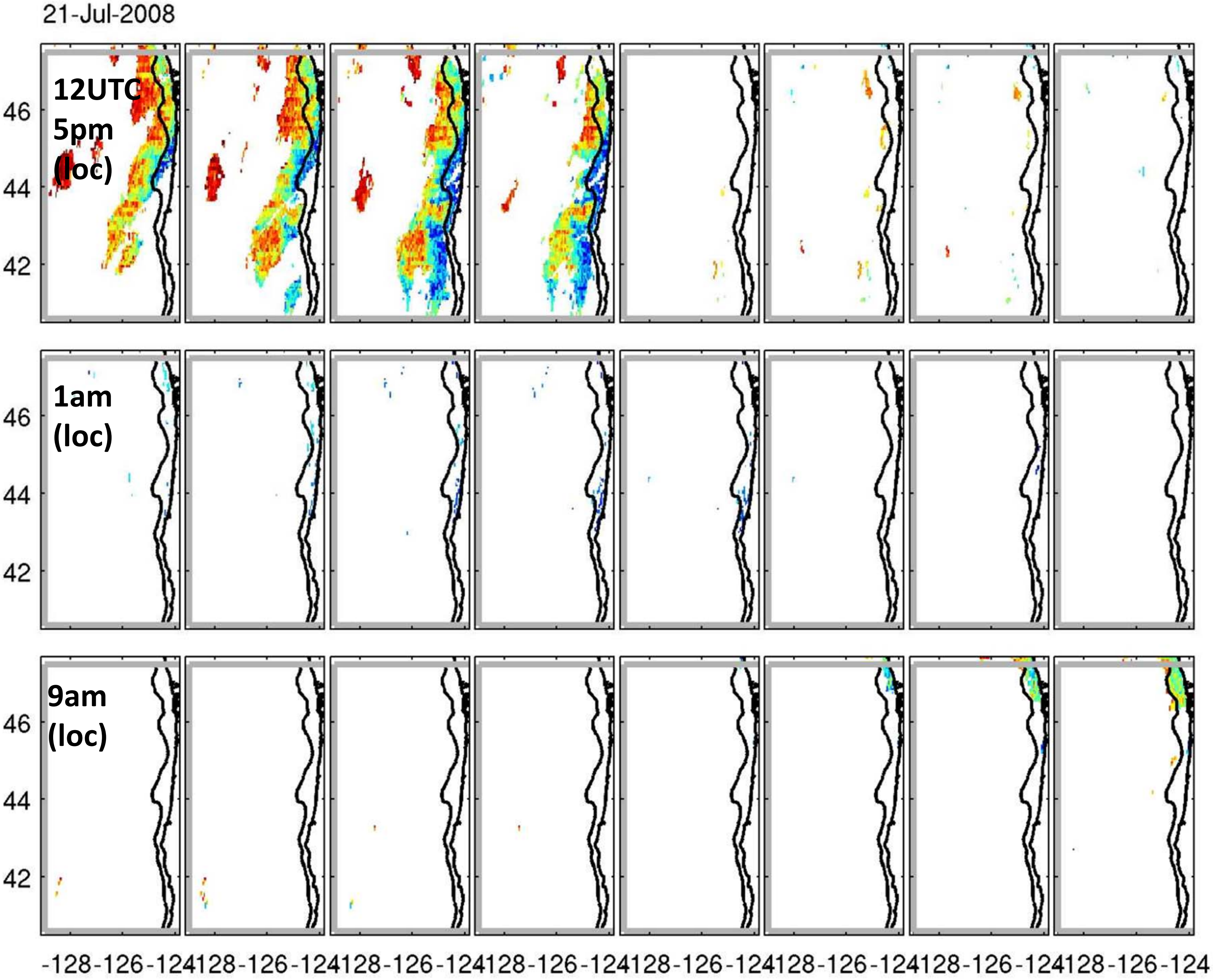
(loc)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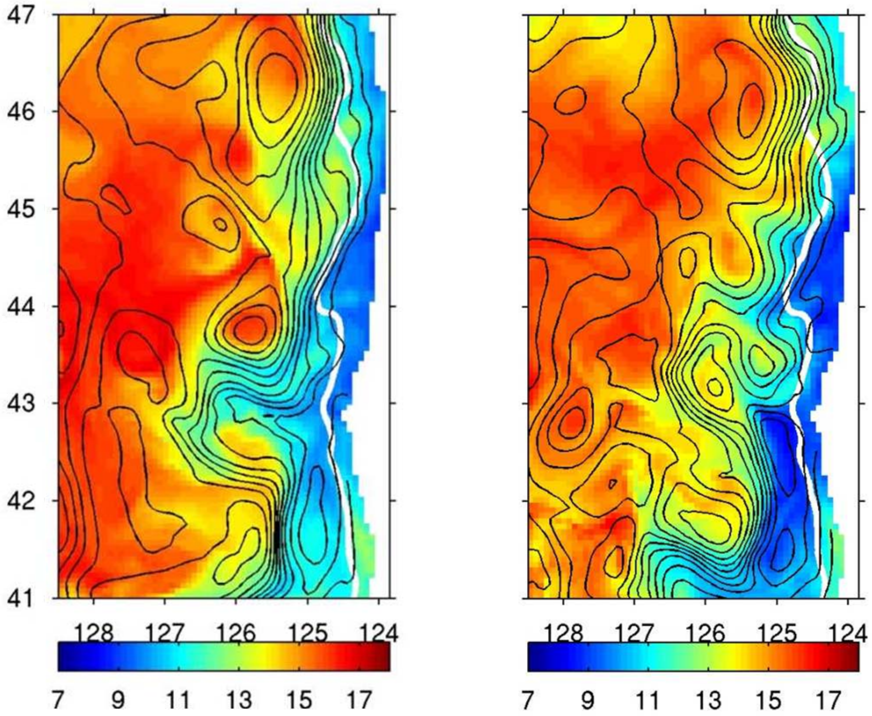
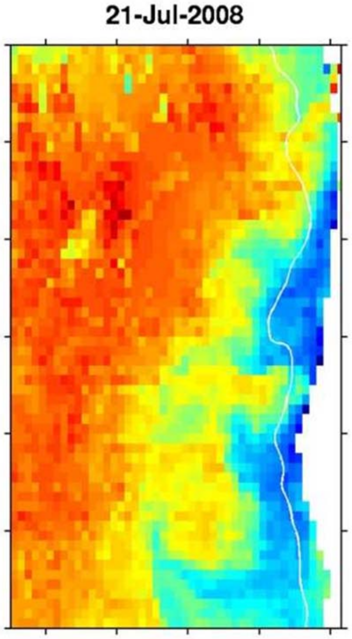
Assimilation of GOES SST affects SSH (and the geostrophic component of the surface currents):



ROMS before / after GOES SST assimilation



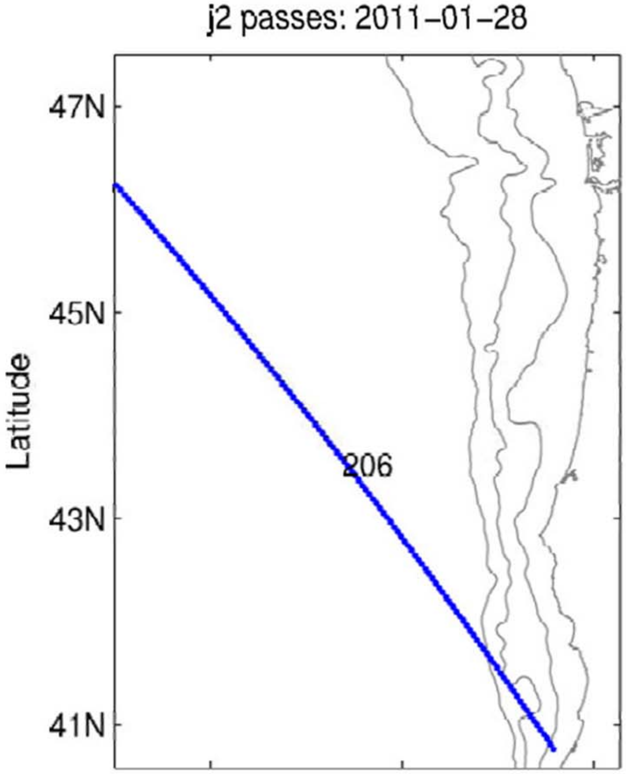
21-Jul-2008

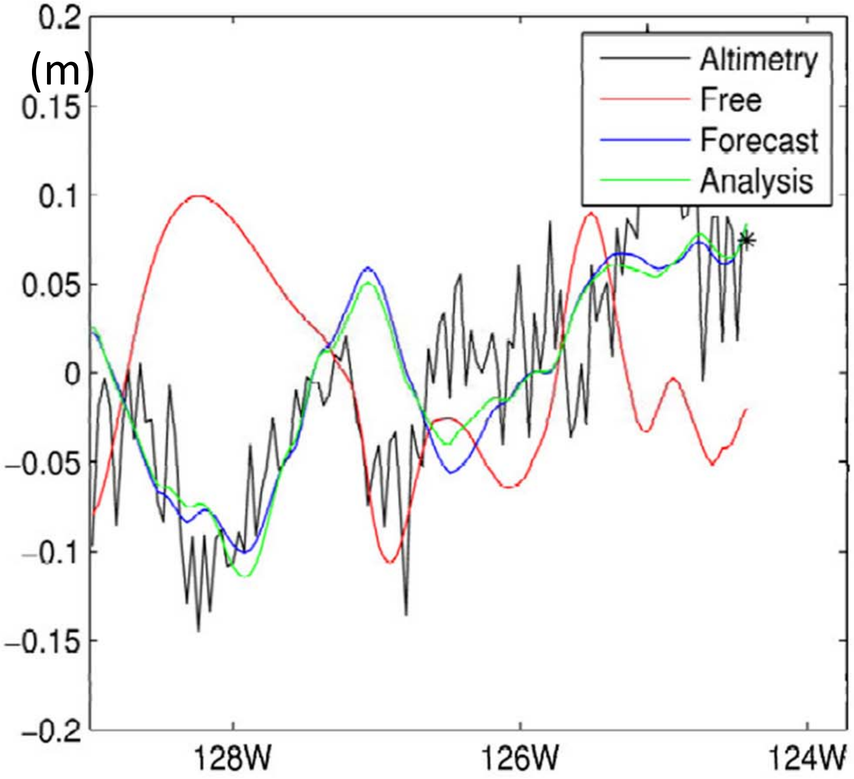
For verification: Multisatellite blended SST (D. Foley, CoastWatch)

SST (color),
SSH (contours, every 2.5 cm)

(note: alongtrack SSH slope data was also assimilated in this case)

Assimilation of hourly GOES SST helps to improve the SSH slope, as verified against the RADS alongtrack SSH data:

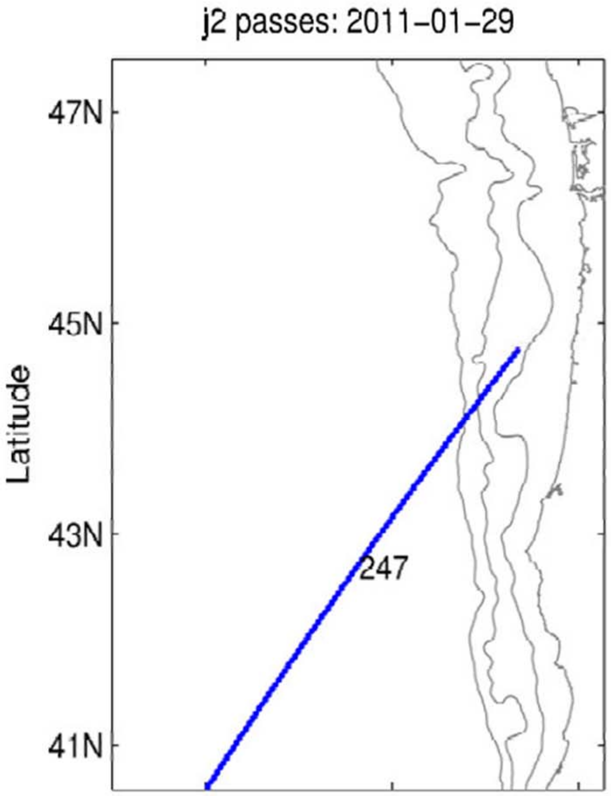


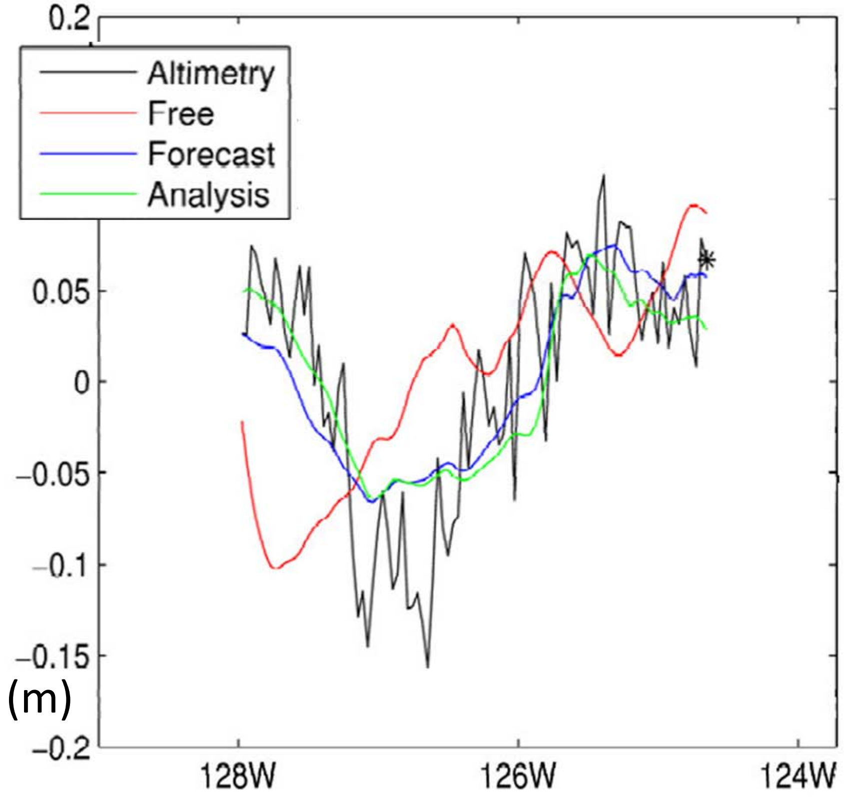


(This example: real-time DA system, assimilates HF radar surface currents and GOES SST)

Data: L. Miller (NOAA)

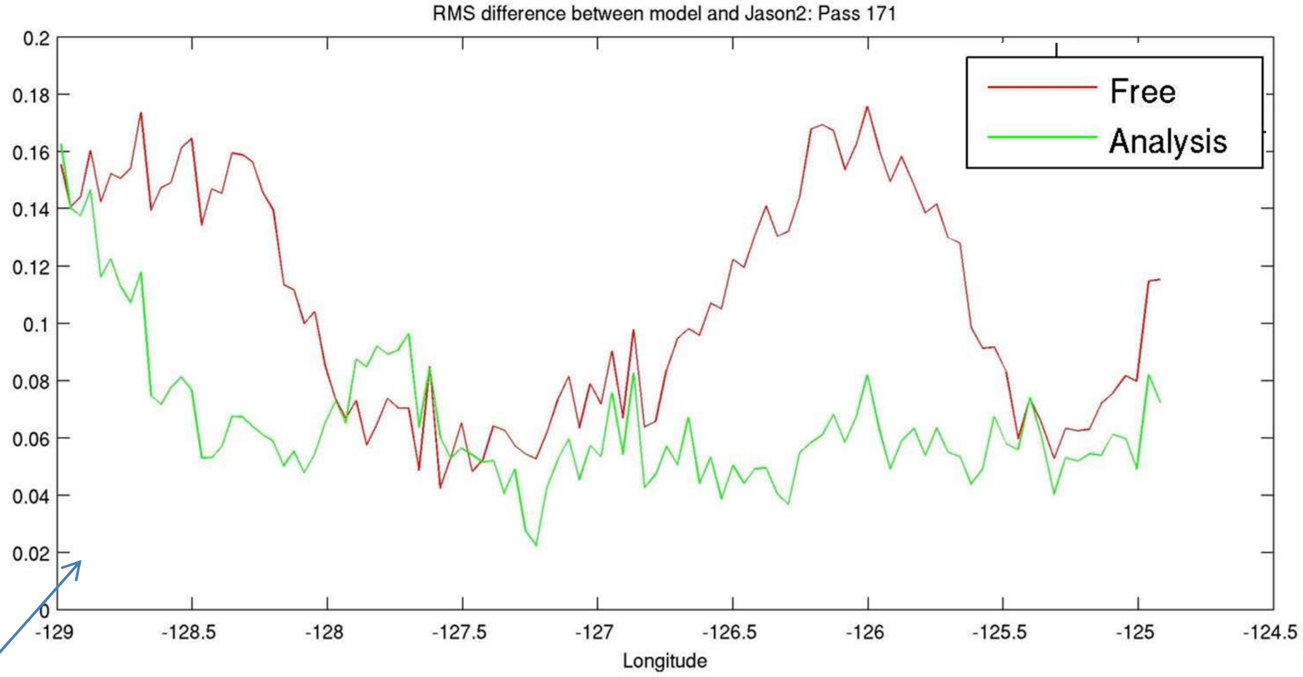
Assimilation of hourly GOES SST helps to improve the SSH slope, as verified against the RADS alongtrack SSH data:

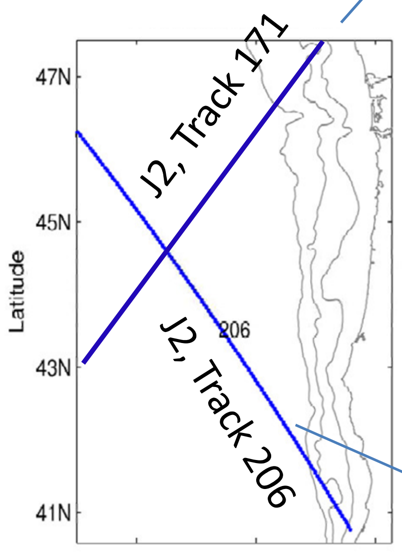


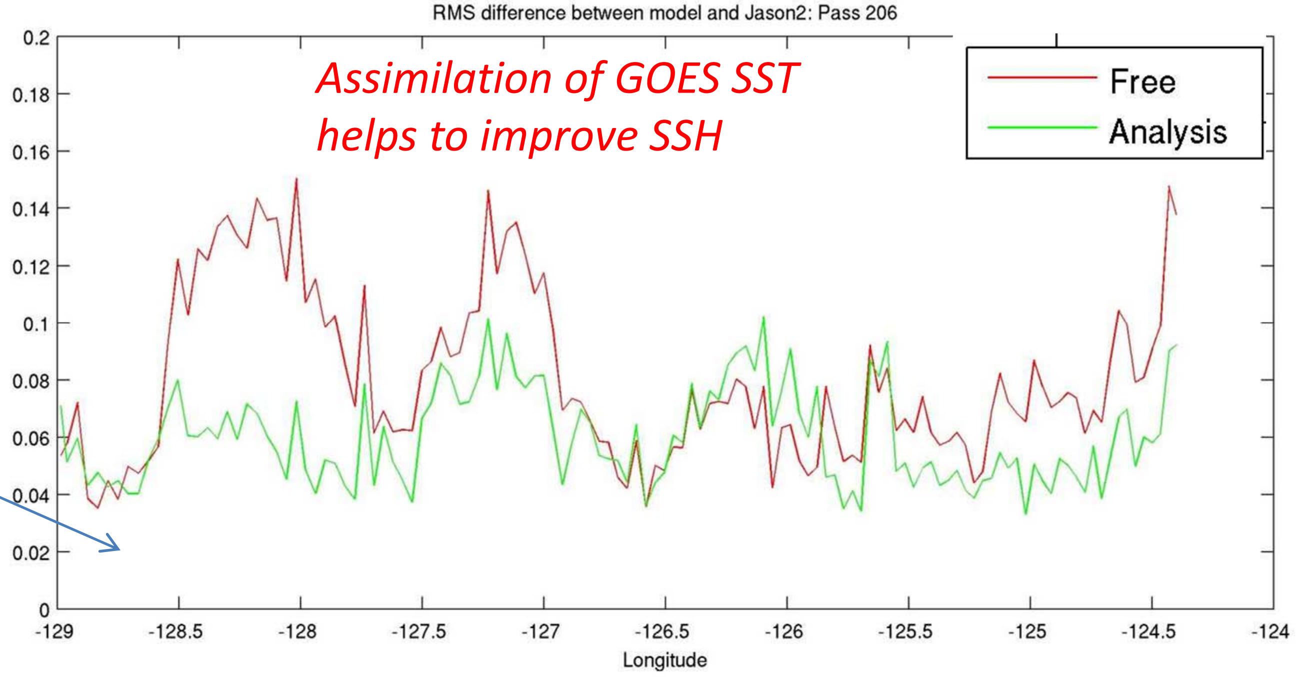


Time-averaged model-data RMS difference for alongtrack SSH (m)
(alongtrack means taken out)

Aug 2010 – Jan 2011







Assimilation of GOES SST helps to improve SSH

Time-averaged model-data RMS difference for alongtrack SSH (m)
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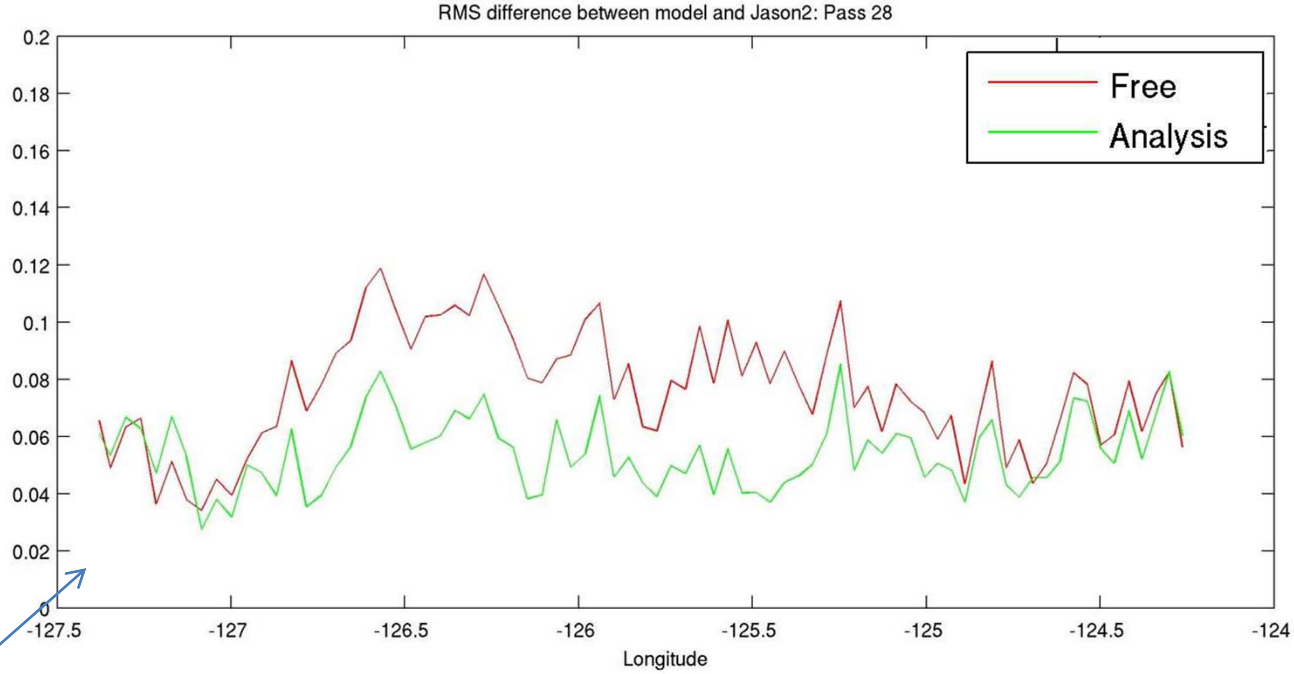
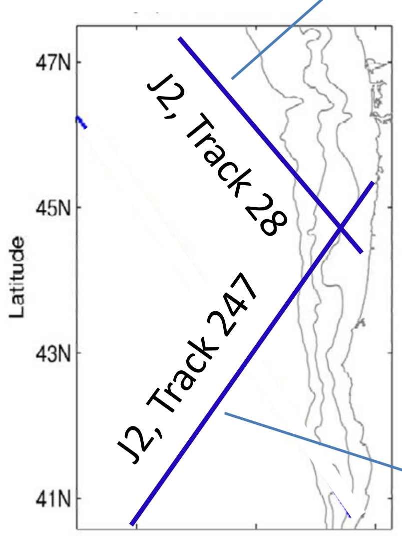
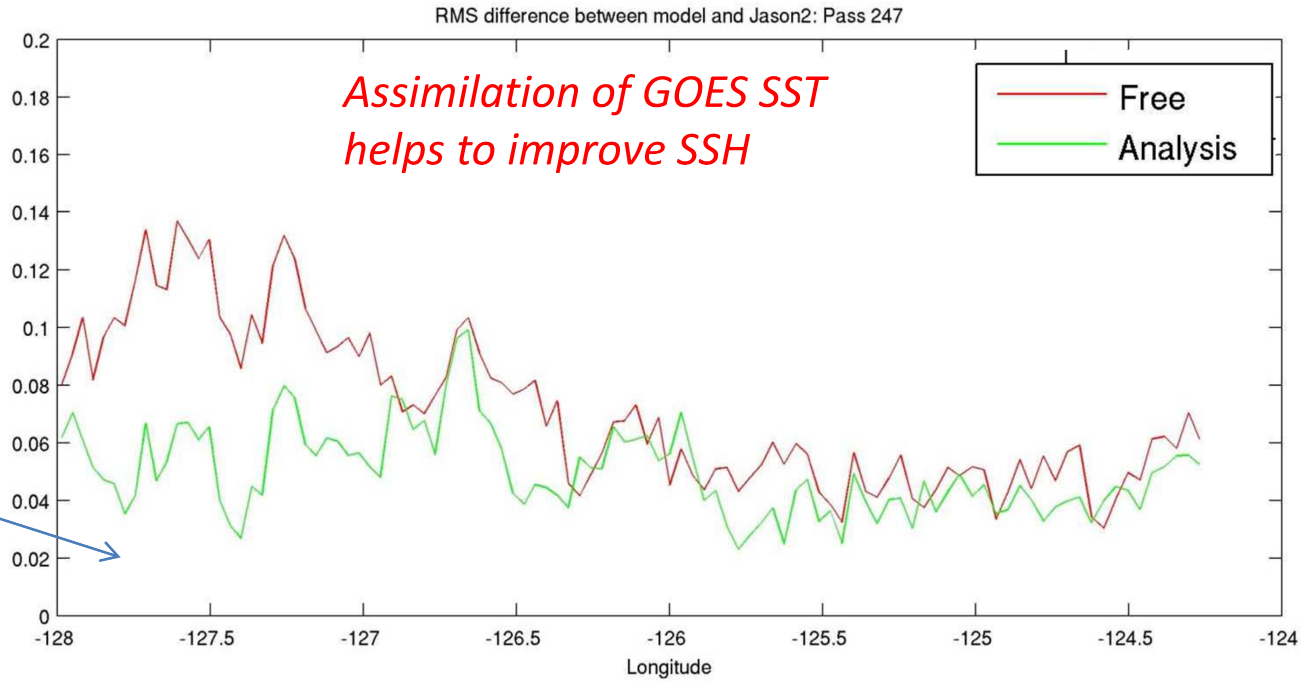






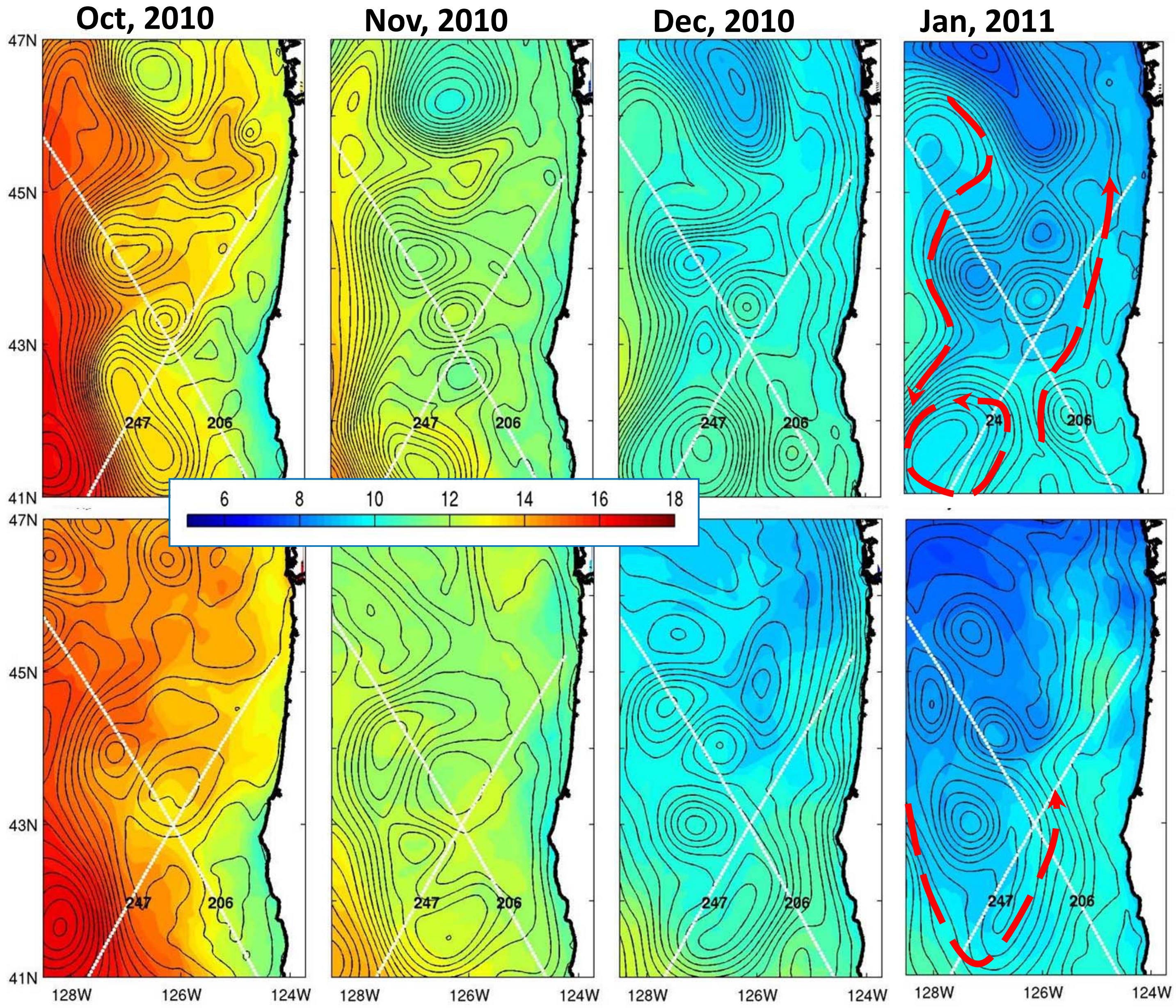
Assimilation of GOES SST helps to improve SSH

DA constrains connectivity of interior and coastal ocean in winter

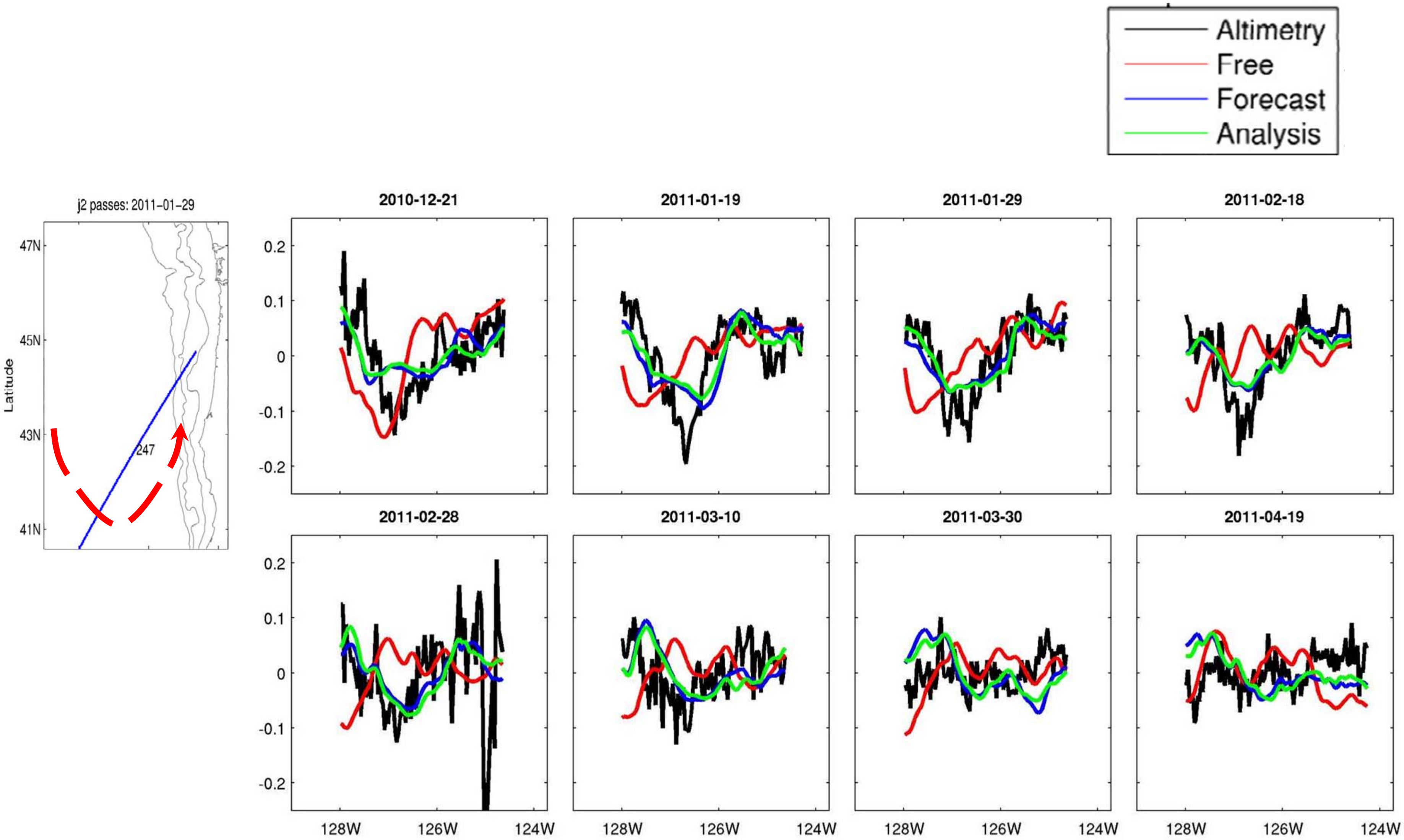
Monthly Mean SST (color) and SSH (contours):

No assimilation

Assimilation: HF radar surface (u,v) and hourly GOES SST



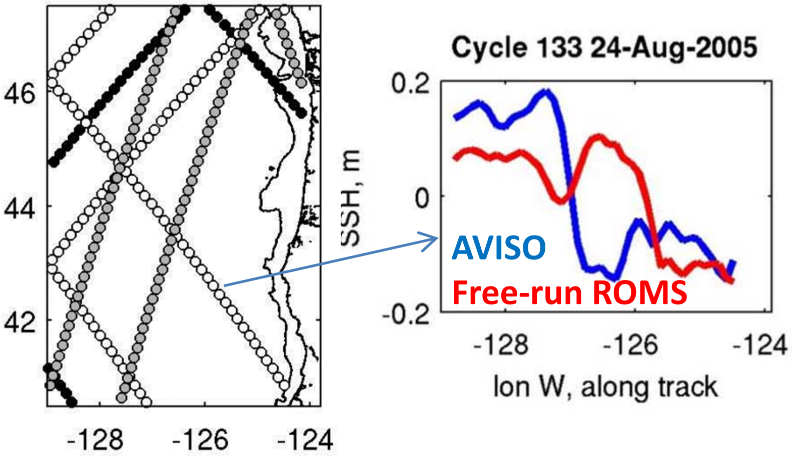
SST contrast and SSH interior-coastal ocean connectivity are associated with the deepening in the alongtack SSH:

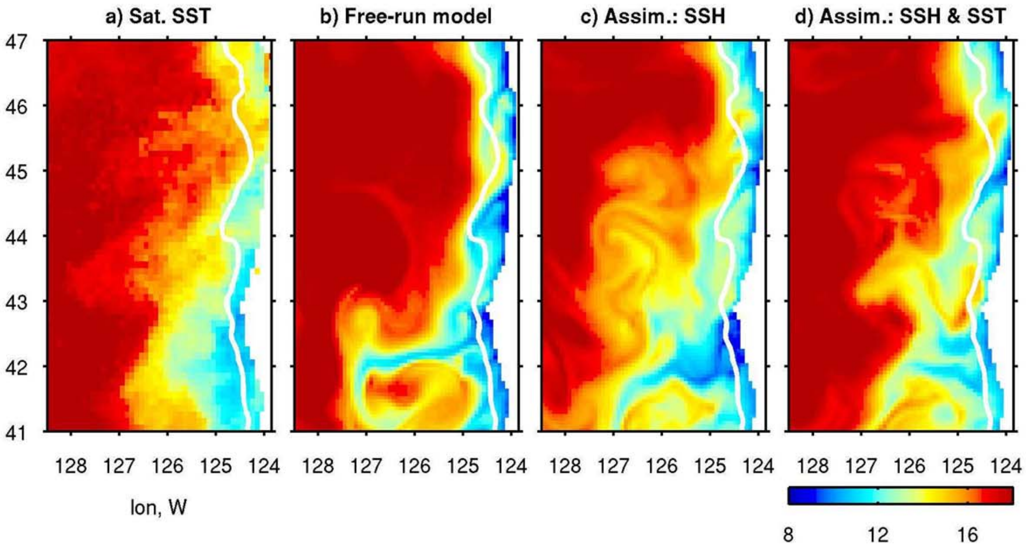


The version of the real-time model that is currently reported online:
HFR currents +GOES SST assimilation

The newest case (at the verification stage):
RADS alongtrack SSH (demeaned) + HFR currents +GOES SST assimilation

Previous experience: assimilation of AVISO alongtrack data (slope of SSH) alone ⇒ improvement in the geometry of the SST upwelling front (Kurapov et al., JGR, 2011)





Area-averaged, 3-day time-averaged model-data RMS differences ("data fit"):

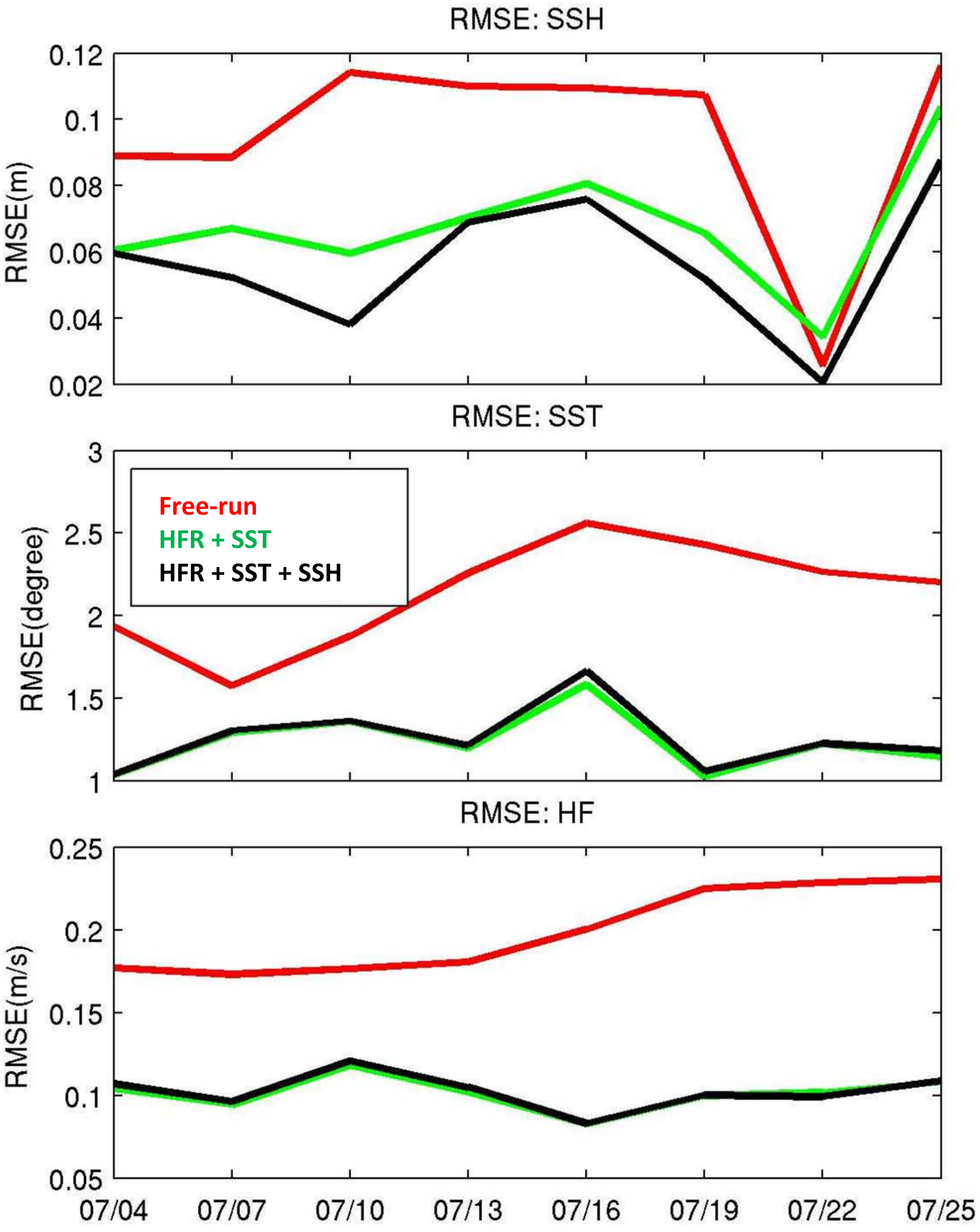
Free-run ROMS
DA: HFR + GOES SST
DA: HFR + GOES SST + RADS SSH

Notes:

1) HFR+SST assimilation improves fit to SSH

2) SSH assimilation additionally improves the fit to SSH

3) SSH assim.: no impact on surface velocity or SST RMSE (which are already constrained by assimilation)



RMS difference between two assimilative solutions: SSH slope (surface geostr. current)

$$\sqrt{\frac{1}{N_{time}}\sum_{j=1}^{N_{time}}(u_j^{(1)}-u_j^{(2)})^2+(v_j^{(1)}-v_j^{(2)})^2}\,,\ u=-\frac{g}{f}\frac{\partial(SSH)}{\partial y}\,,v=\frac{g}{f}\frac{\partial(SSH)}{\partial x}$$

(1) HF+SST
(2) HF+SST+SSH

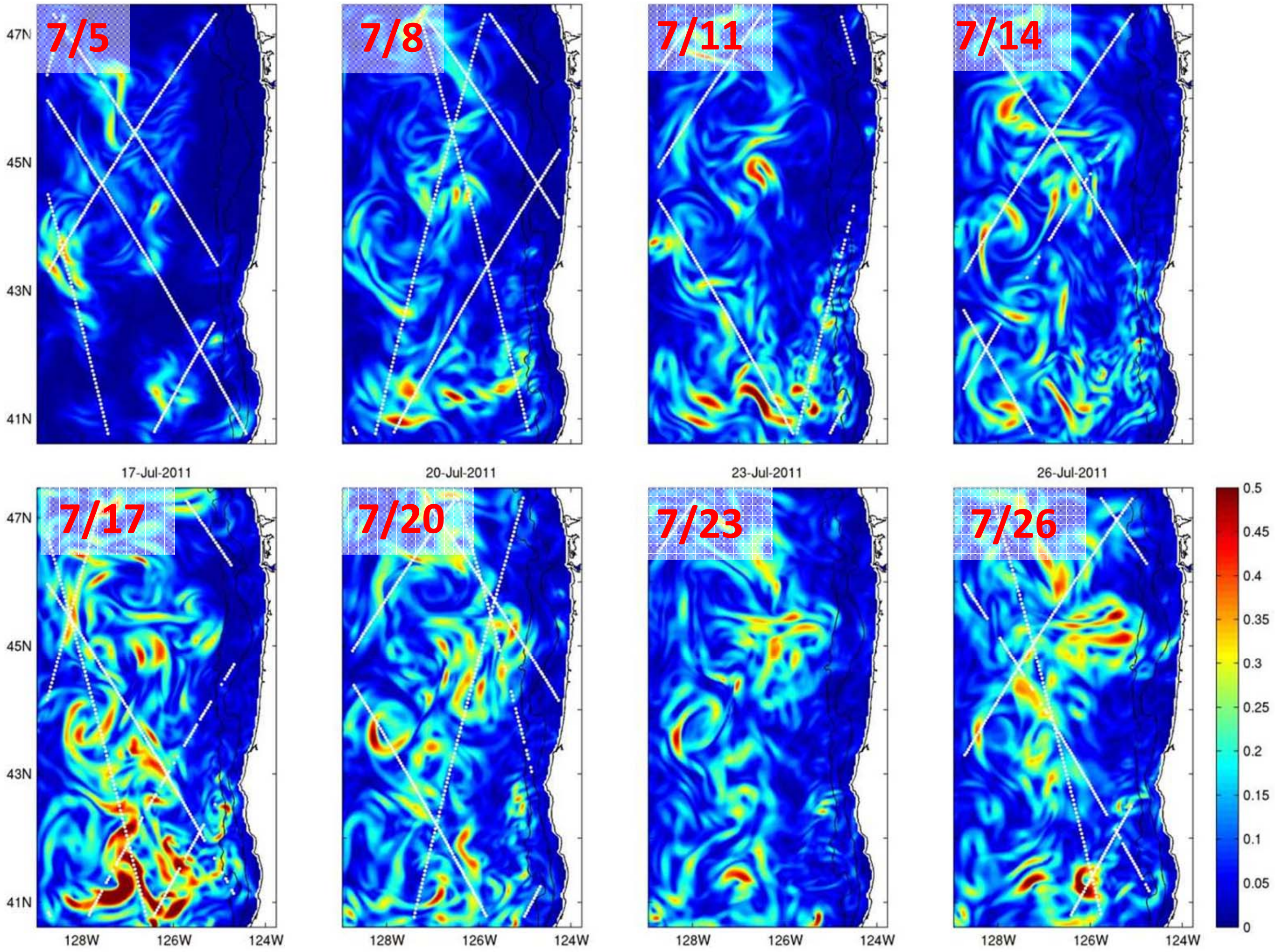
Notes:

- Lower impact in the area of HF radar data

- Appreciable differences in the geostr. currents away from the HF radar data area

- The forecast model has memory of the corrections along the tracks (differences are gradually filling the area)

Consecutive windows (shown is ave. for day 3 in each window): →



Future/ongoing efforts:

Research issues:

- How does assimilation of surface data (SSH, SST, HFR u and v) affect subsurface fields? (source waters, undercurrent, etc.)

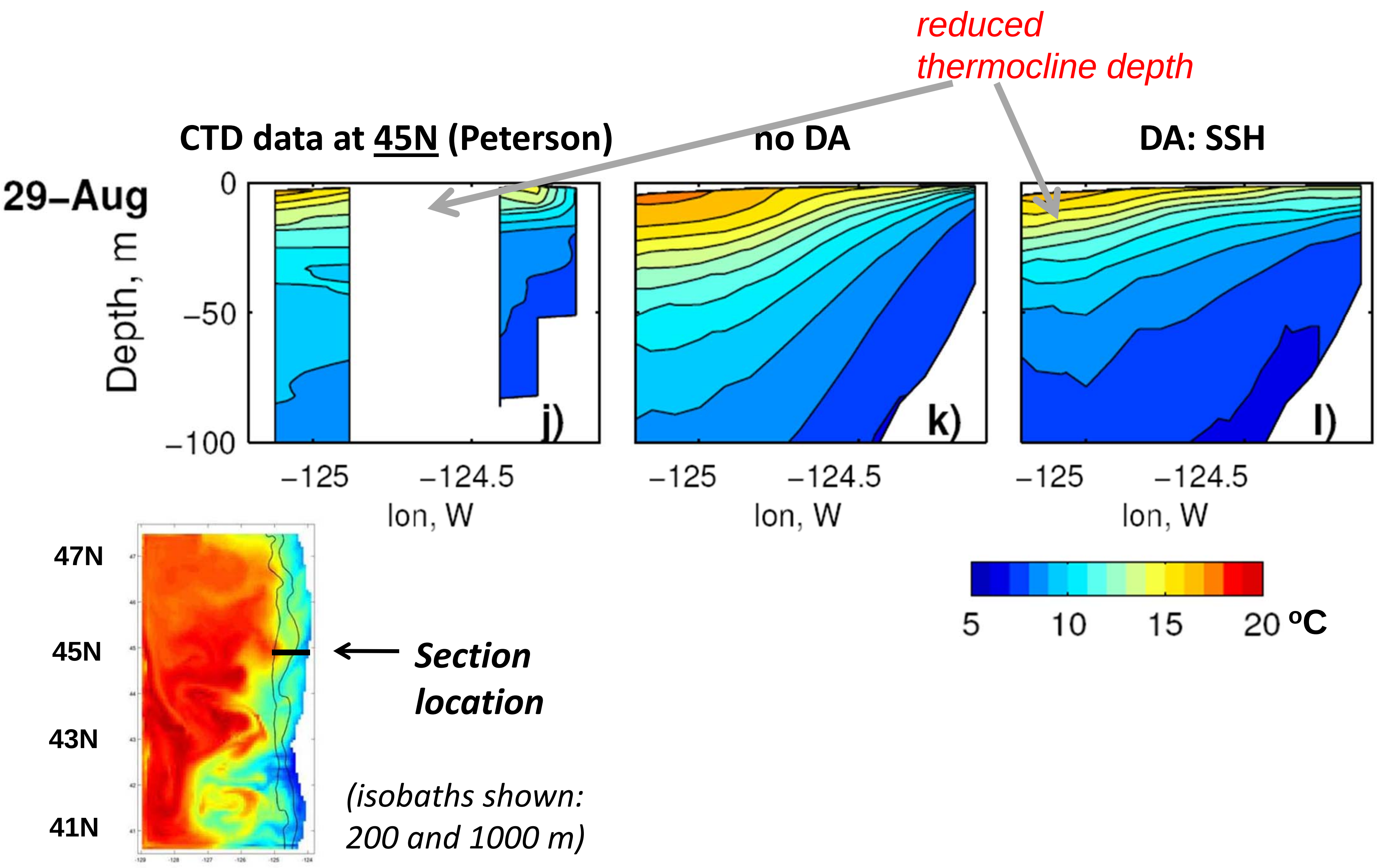
- Assimilation in the presence of the Columbia River water (not only *S*-, but also *T*-anomaly)

Technical tasks:

- Extending the domain

- Coupling with the oil spill/Lagrangian particle software (in collaboration with A. MacFayden, NOAA)

SSH assimilation: effect on subsurface temperature



reduced thermocline depth

CTD data at <u>45N</u> (Peterson)

no DA

DA: SSH

Section location

(isobaths shown: 200 and 1000 m)

Extend the cross-shore section farther west: an outer front is apparent in the DA solution at 126-127N

Shown: cross-shore vertical sections of T and meridional vel. at 45N, 29 Aug 2005

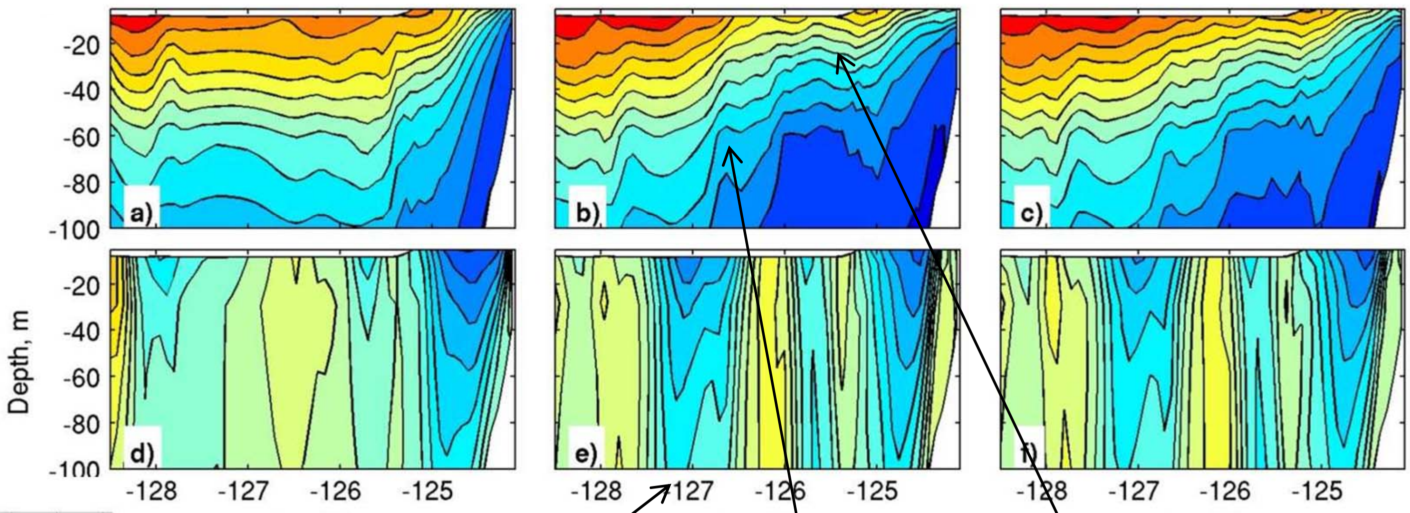
free-run model DA: SSH DA SSH&SST

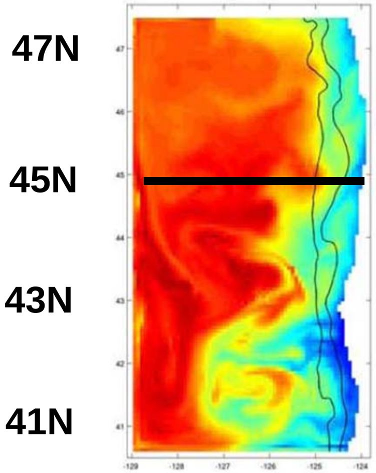
Temp.

Meridional Velocity

ΔT=1°C

Δv=5 cm/s





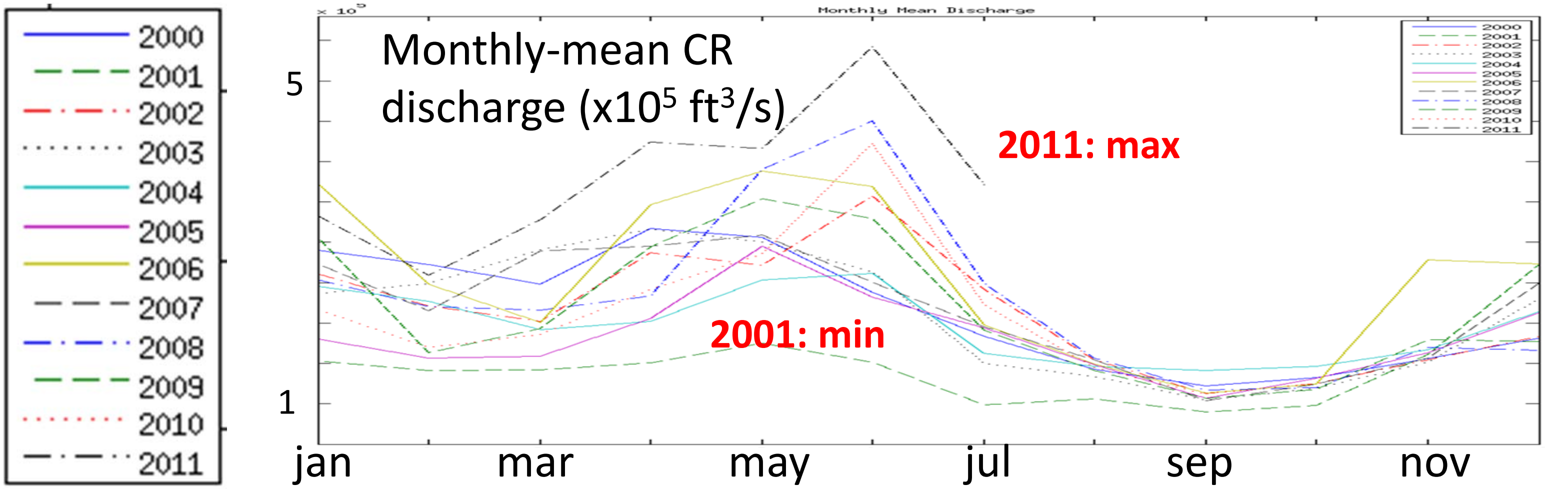
outer front (emerged in part due to SSH assim.)

subsurface temperature front (in thermal wind balance)

stronger temperature stratification inshore of the front

In spring, the Columbia R. waters are warmer than the surrounding ocean

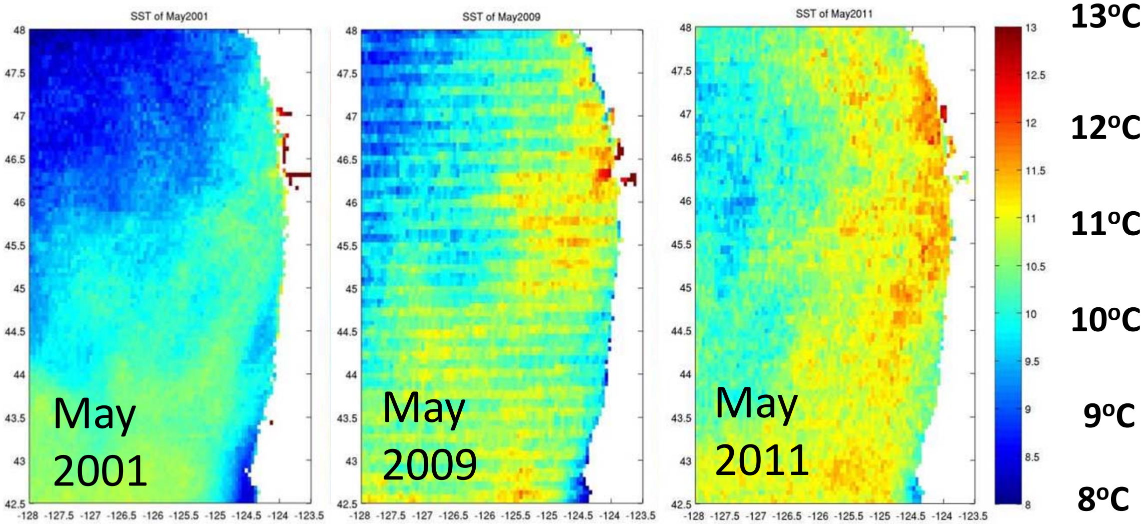
- Challenge for assimilation (a thin water layer with anomalous T-S properties)
- Contribution to inter-annual variability in the coastal ocean


Monthly-mean CR discharge (x10^5 ft^3/s)

2011: max

2001: min

Monthly GOES SST composites, May

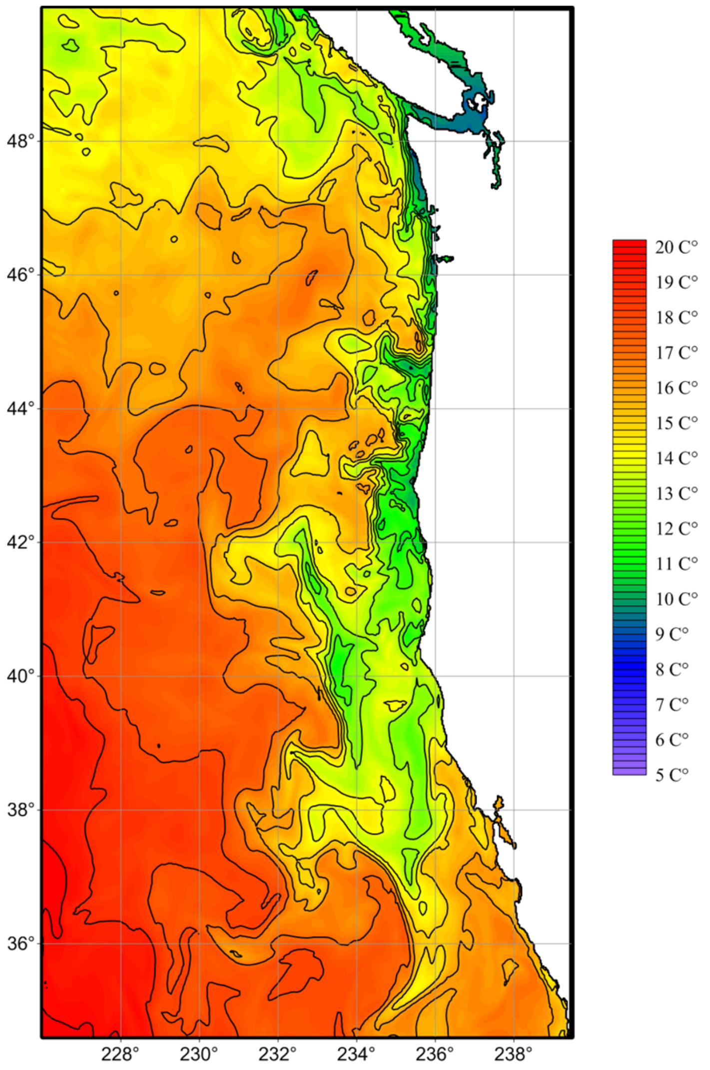


Images courtesy E. Simmons III, the NSF-REU summer intern

Gearing toward modeling and assimilation in a larger domain

- Better utilization of satellite data

- Better focus on interior /coastal ocean interactions and interannual variability



(image courtesy *P. Fayman, OSU*)

HYCOM, 1/12th degr., 18 Sep., 2008

SUMMARY:

Using the variational (4DVAR) approach in the context of the real-time regional ocean forecast model is feasible

Using the variational (4DVAR) approach is advantageous:

- Dynamically-based interpolation in space and time (particularly convenient with GOES SST data… remove noise… fill gaps…)

- Explicit assumptions about the errors in the model can be made

- A tool for synthesis of data from different platforms

Assimilation of SST helps to improve the SSH slope

Assimilation of SSH helps to improve geometry of the upwelling front, impacts subsurface structures

Exercises with the near-real-time assimilation and forecasting are interesting, since they challenge us to explore new areas (e.g., river influences, winter flows)

ADDITIONAL SLIDES:

The balanced C_0:

- provides smoothing (filtering) of the ADJ field
-approximate balance of the initial correction in SSH, u, v, T, and S

(based on Weaver et al., 2005)

Error in *T*

$$\delta\mathbf{u} \equiv \begin{pmatrix}\delta\zeta\\ \delta u\\ \delta v\\ \delta T\\ \delta S\end{pmatrix} = \mathbf{B}\begin{pmatrix}\delta T\\ \delta\Psi\end{pmatrix}$$

Error in the streamfunction of the depth-integrated transport (assumed to be statistically independent from *T*)

balance operator
(numerical code)

$$\mathbf{C}_0\boldsymbol{\lambda}(0) = \underbrace{\langle\delta\mathbf{u}\delta\mathbf{u}'\rangle}_{\langle\rangle=\text{expected value}}\boldsymbol{\lambda}(0) = \mathbf{B}\begin{pmatrix}\mathbf{C}_T & 0\\ 0 & \mathbf{C}_\Psi\end{pmatrix}\mathbf{B}'\boldsymbol{\lambda}(0),$$

(our case: C_Ψ=0)

Balance operator (given δT, δΨ, find δS, δρ, δζ, δu)

simple T-S relationship

$$\delta S = \alpha \delta T, \qquad \alpha = -0.16 \text{ psu C}^{-1}$$

linear eqn. of state

$$\delta\rho = \rho_\circ(-\alpha_T \delta T + \alpha_S \delta S),$$

$\rho_\circ = 1025$ kg m^{-3}, $\alpha_T = 1.7 \times 10^{-4}$ C^{-1}, and $\alpha_S = 7.5 \times 10^{-4}$ psu^{-1}.

geostrophic relation

$$f\,\mathbf{k} \times (\delta u, \delta v) = -g\nabla\delta\zeta - \frac{g}{\rho_\circ}\int_z^0 \nabla\delta\rho\, dz'$$

streamfunction:

$$\mathbf{k} \times \nabla\delta\Psi = -\int_{-H}^{0} (\delta u, \delta v)\, dz,$$

Note: over shelf no ref. depth can be defined. A 2nd order elliptic eqn. has to be solved for SSH (Fufumori et al., 1998). Boundary conditions needed (we use δζ=0)

$$\boxed{g\nabla \cdot (H\nabla\delta\zeta) = \delta F_\Psi - \delta F_\rho}$$

$$\delta F_\Psi = \nabla \cdot (f\nabla\delta\Psi),$$

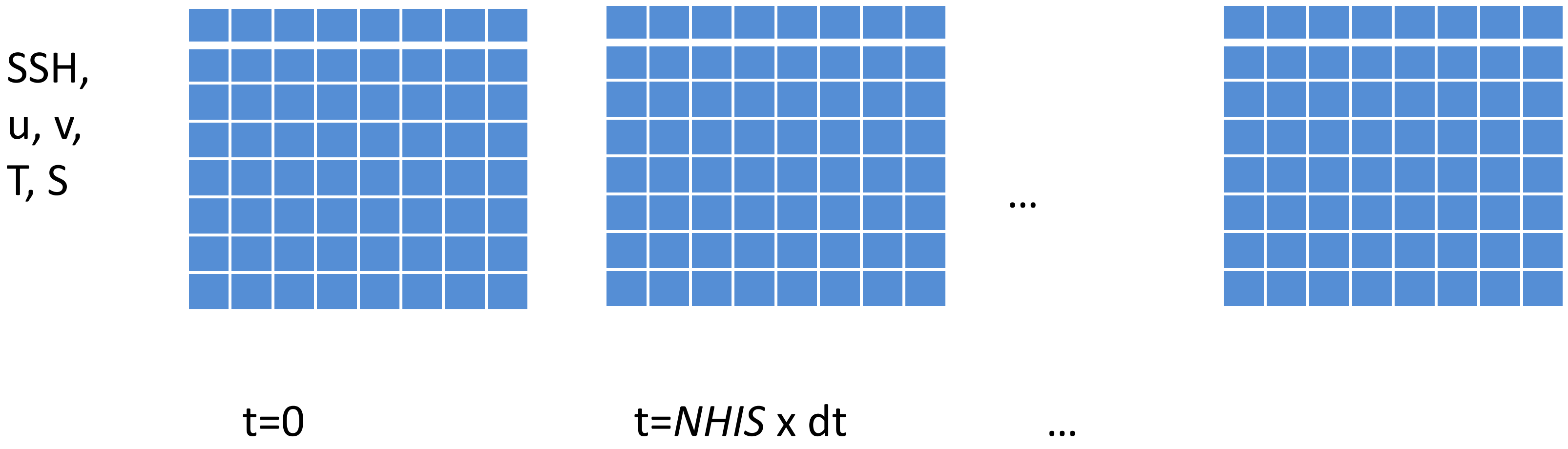
$$\delta F_\rho = \frac{g}{\rho_\circ}\nabla \cdot \left(\int_{-H}^{0} dz \int_z^0 \nabla\delta\rho\, dz'\right).$$

Data functionals: $d - Lu$

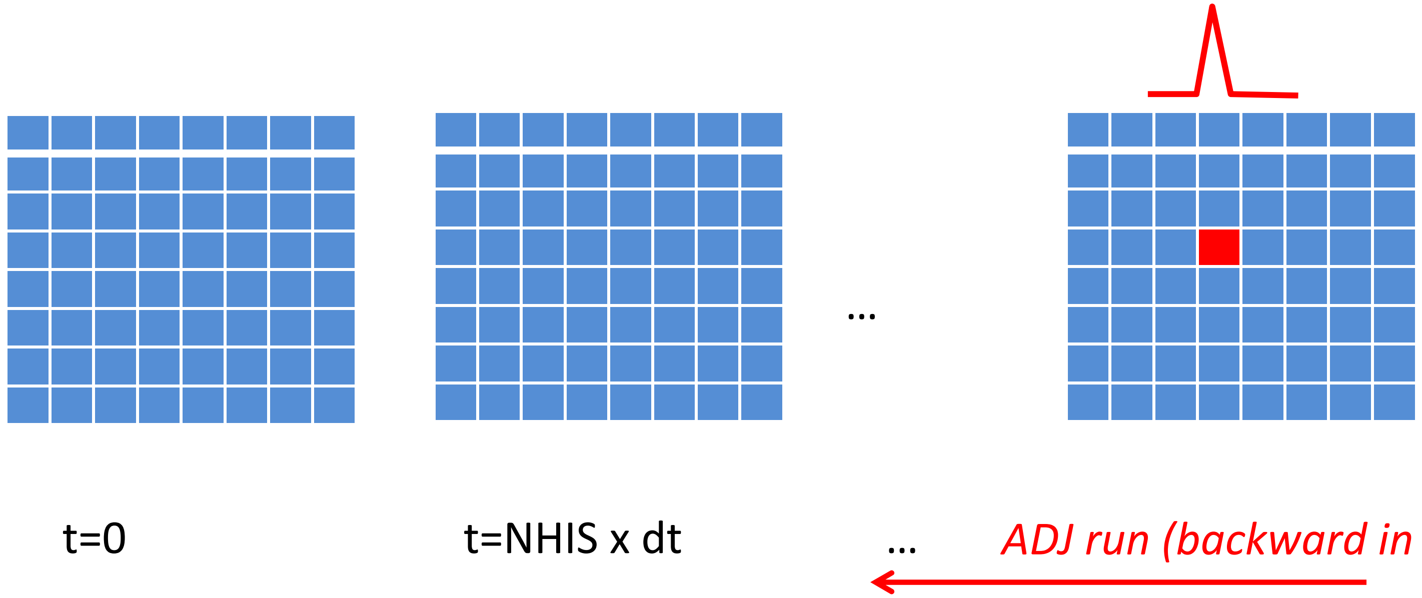
- sample result of TL model
- force ADJ model

Introduction of new data types may require consistent changes in the TL and ADJ codes

Adjoint symmetry in AVRORA: for a general form of a data functional (any linear combination of the state vector)



Assimilation of data local in space and time: impulse at the obs. location/time



t=0

t=NHIS x dt

…

…

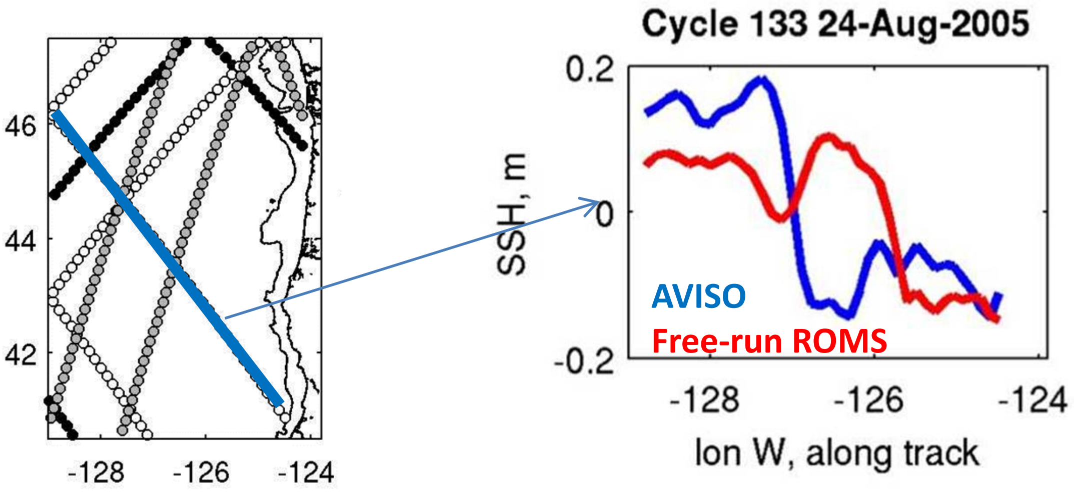
ADJ run (backward in time)

(in practice, ADJ forcing is a linear combination of these impulses;

the technical task is to find an optimal such combination;

the fields of impulses are added to the ADJ variables at the times corresponding to TL output time)

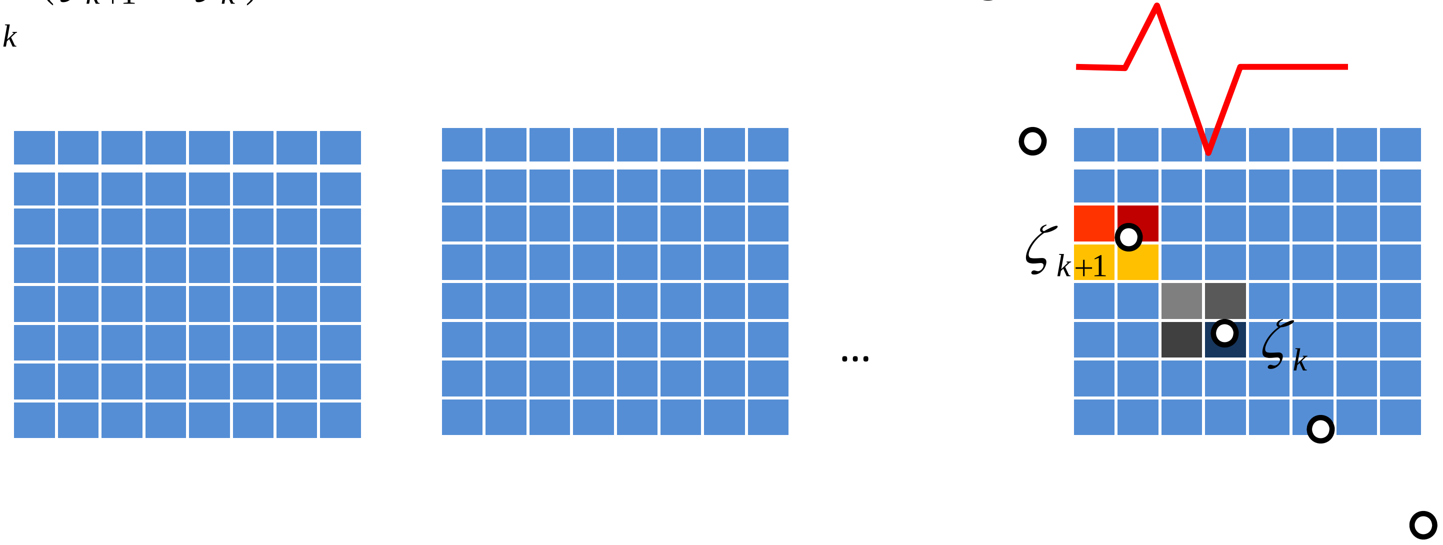
Assimilation of alongtrack altimetry:



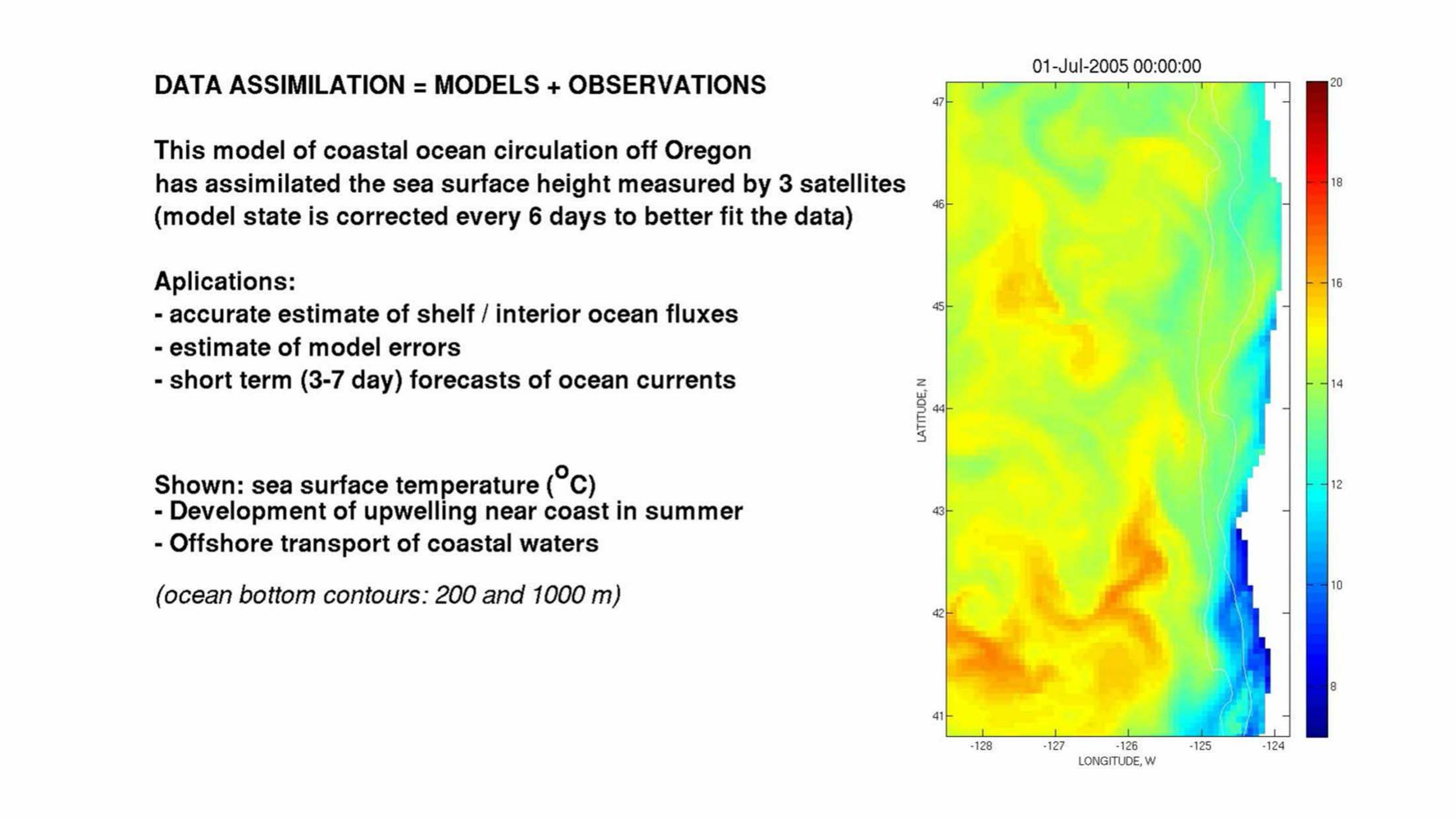
Assimilate slope (information about geostrophic component of surface currents):

$$L\zeta = \frac{g}{f\Delta s_k}\left(\zeta_{k+1} - \zeta_k\right)$$, where *k* is the obs. number along the track

SSH,
u, v,
T, S



A series of analyses is discontinuous:



DATA ASSIMILATION = MODELS + OBSERVATIONS

This model of coastal ocean circulation off Oregon has assimilated the sea surface height measured by 3 satellites (model state is corrected every 6 days to better fit the data)

Aplications:

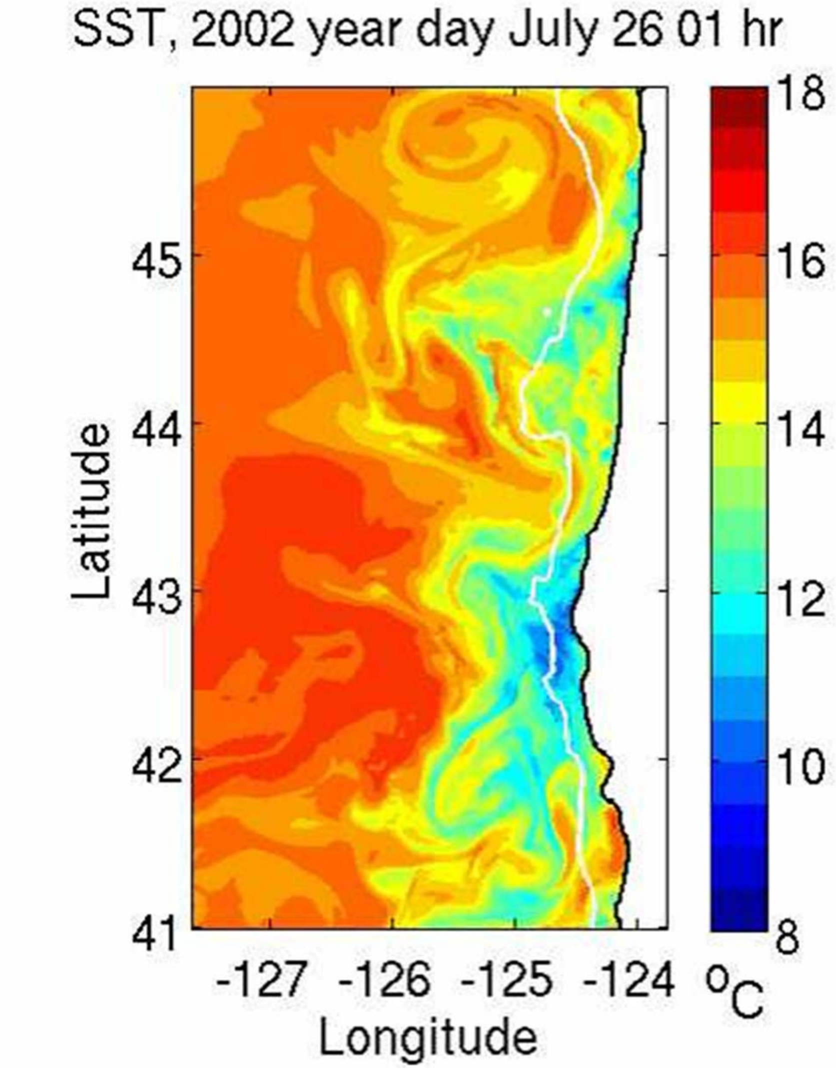
- **accurate estimate of shelf / interior ocean fluxes**
- **estimate of model errors**
- **short term (3-7 day) forecasts of ocean currents**

Shown: sea surface temperature (°C)

- **Development of upwelling near coast in summer**
- **Offshore transport of coastal waters**

(ocean bottom contours: 200 and 1000 m)

Qualitatively, westward front propagation in the 6-km DA model is similar to that in the 1-km free-run model



[model described in: ***Osborne, Kurapov et al., JPO, in press***]

Volume-integrated heat equation:

$$c_p\rho_\circ \frac{d}{dt}\int_V T\,dV =$$

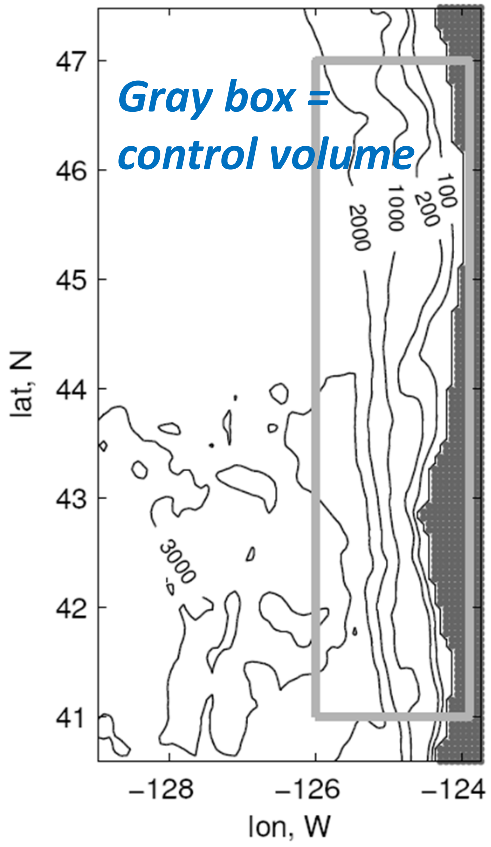
$$-c_p\rho_\circ \int_B T\mathbf{u}\cdot\mathbf{n}\,dB + \int_A Q_{atm}\,dA +$$

advective flux through side boundaries

atmospheric heat flux

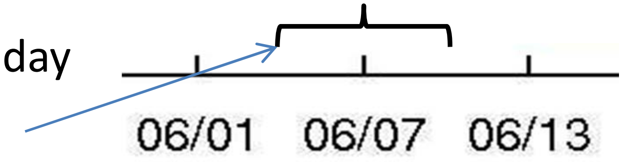
$$+\,c_p\rho_\circ \sum_k \delta(t-t_k)\int_V \delta T_k\,dV,$$

series of instantaneous DA corrections at times t_k



Gray box = control volume

To present these terms, we average the terms over 6 day intervals, each centered on the time of correction

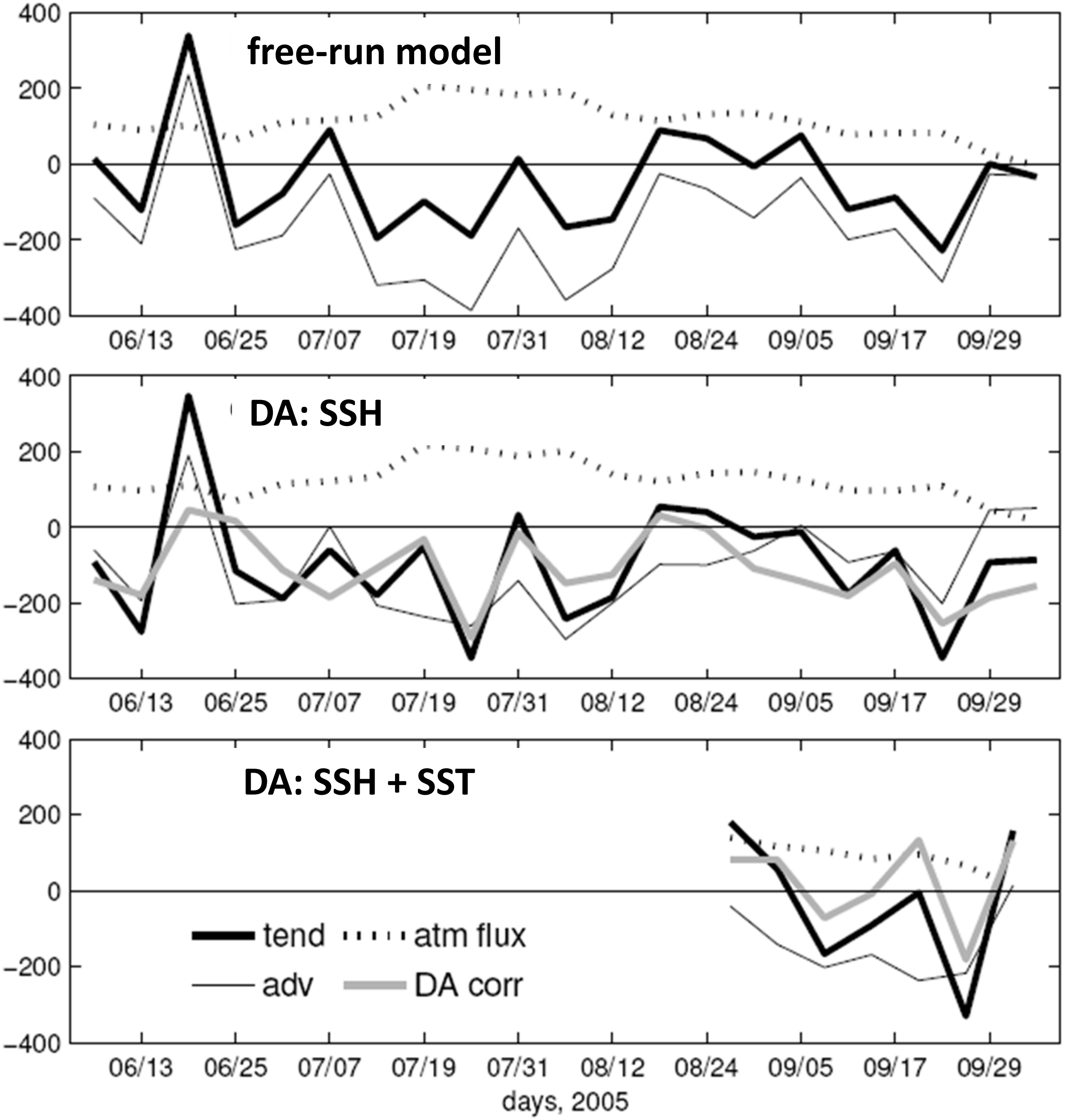


Time-series of volume-integrated terms in the heat equation (*scaled to obtain units of W/m²*)

- Variability in tendency is dominated by advection

-DA correction term is comparable in magnitude to other terms

- Correction term:
DA SSH – cooling
DA SSH+SST closer to 0 on average

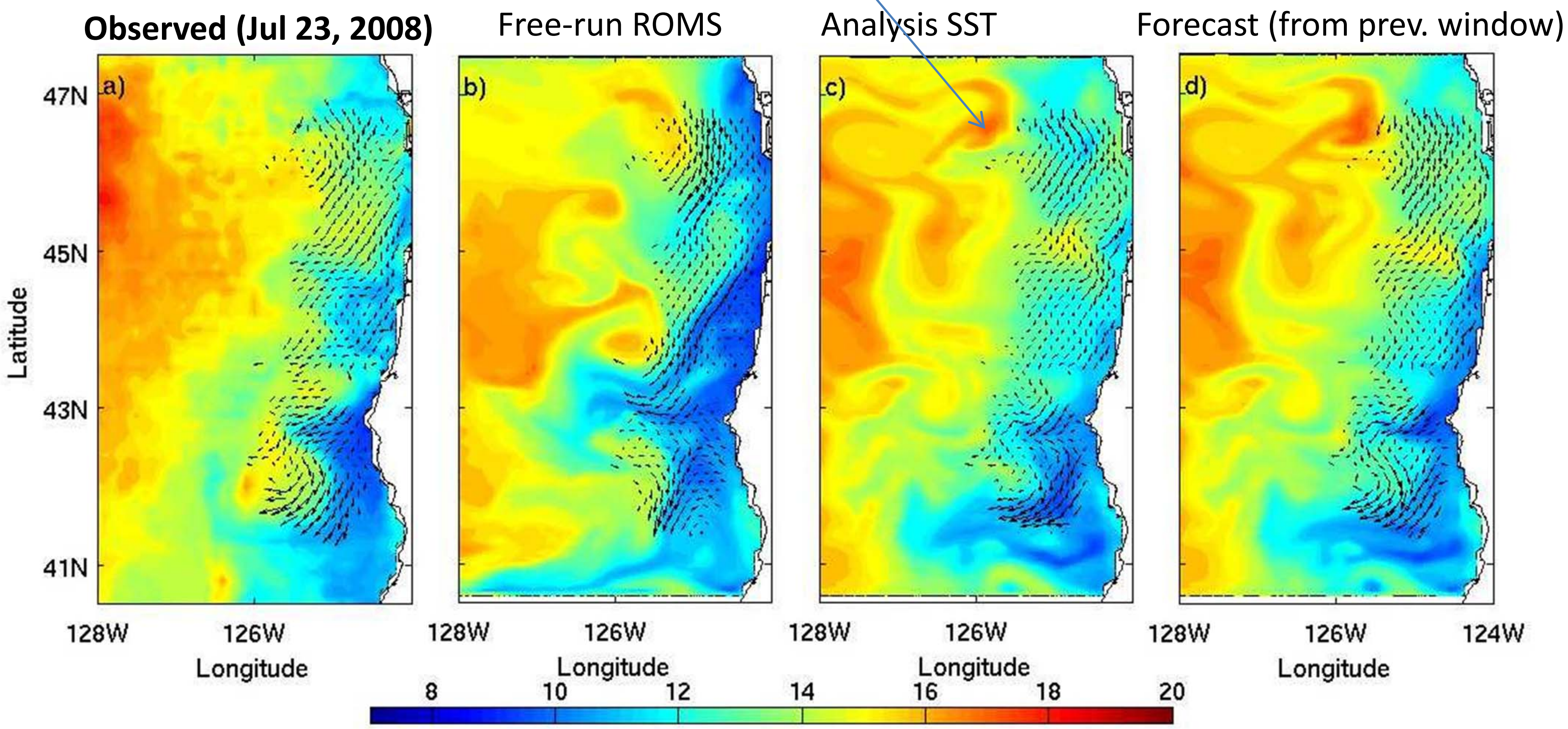


Impact of assimilated HF radar surface current data:

(hindcast study, summer 2008, *Yu et al., ms in prep.*):

- **geometry of the SST front is improved**

(HFR currents are assimilated alone)



Observed (Jul 23, 2008)

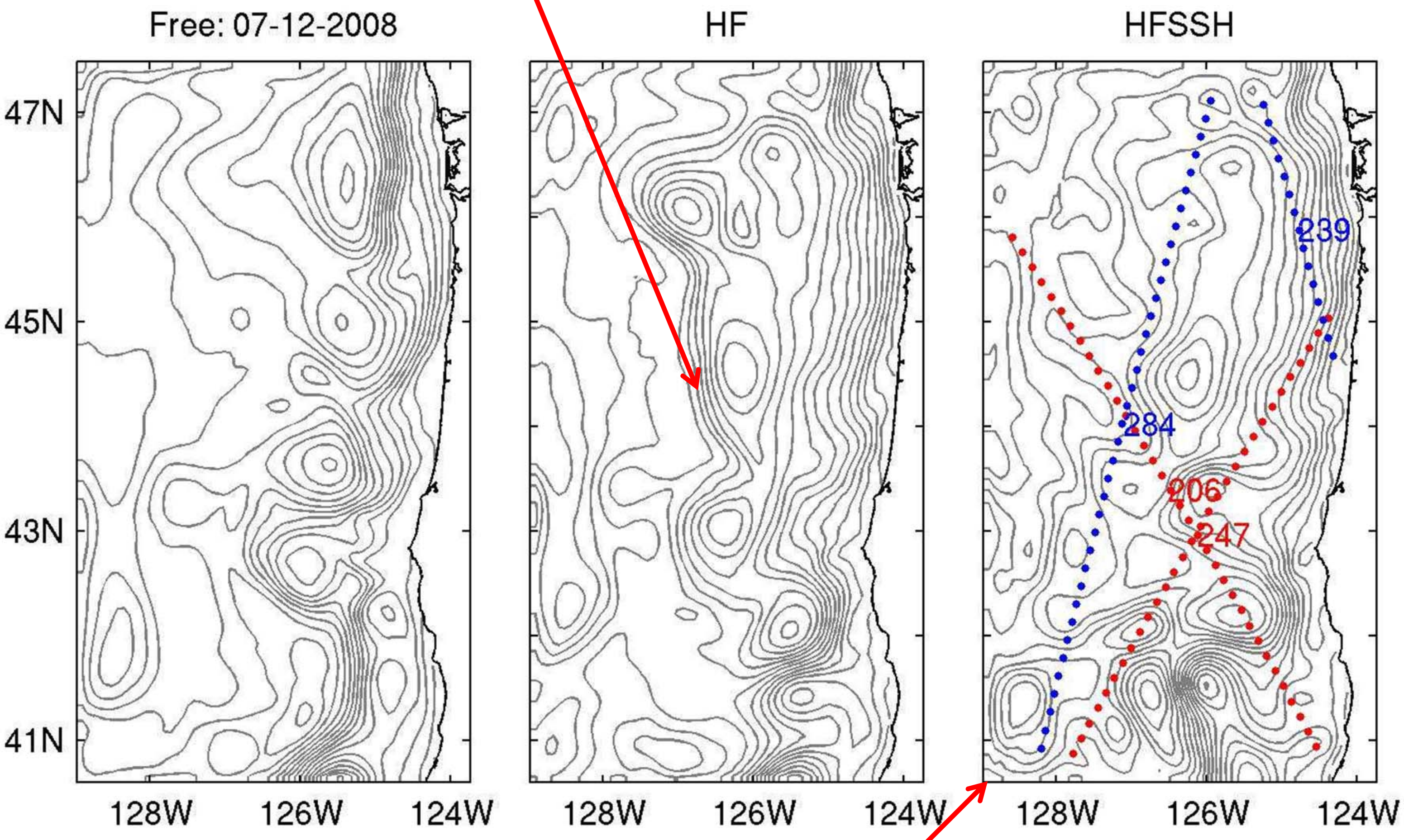
Free-run ROMS

Analysis SST

Forecast (from prev. window)

HF radar data: P. M. Kosro

Bogus strong current was generated by assimilation of HF radar currents alone (west of the area of HF radar coverage, 126W)



Combined HF + alongtrack SSH assimilation helps to improve overall quality of surface currents estimate (only Jason and Envisat used – more sat. data would help better)

The balanced C_0:

- provides smoothing (filtering) of the ADJ field
-approximate balance of the initial correction in SSH, u, v, T, and S

(based on Weaver et al., 2005)

$$\delta\mathbf{u} \equiv \begin{pmatrix}\delta\zeta\\ \delta u\\ \delta v\\ \delta T\\ \delta S\end{pmatrix} = \mathbf{B}\begin{pmatrix}\delta T\\ \delta\Psi\end{pmatrix}$$

Error in*T*

Error in the streamfunction of the depth-integrated transport (assumed to be statistically independent from *T*)

balance operator
(numerical code)

$$\mathbf{C}_0\boldsymbol{\lambda}(0) = \underbrace{\langle\delta\mathbf{u}\delta\mathbf{u}'\rangle}_{\langle\rangle\text{=expected value}}\boldsymbol{\lambda}(0) = \mathbf{B}\begin{pmatrix}\mathbf{C}_T & 0\\ 0 & \mathbf{C}_\Psi\end{pmatrix}\mathbf{B}'\boldsymbol{\lambda}(0),$$

(our case: C_Ψ=0)

Balance operator (given δT, δΨ, find δS, δρ, δζ, δu)

simple T-S relationship

$$\delta S = \alpha \delta T, \qquad \alpha = -0.16 \text{ psu C}^{-1}$$

linear eqn. of state

$$\delta\rho = \rho_\circ(-\alpha_T \delta T + \alpha_S \delta S),$$

$\rho_\circ = 1025 \text{ kg m}^{-3}$, $\alpha_T = 1.7 \times 10^{-4} \text{ C}^{-1}$, and $\alpha_S = 7.5 \times 10^{-4} \text{ psu}^{-1}$.

geostrophic relation

$$f\,\mathbf{k} \times (\delta u, \delta v) = -g\nabla\delta\zeta - \frac{g}{\rho_\circ}\int_z^0 \nabla\delta\rho\, dz'$$

streamfunction:

$$\mathbf{k} \times \nabla\delta\Psi = -\int_{-H}^0 (\delta u, \delta v)\, dz,$$

Note: over shelf no ref. depth can be defined. A 2nd order elliptic eqn. has to be solved for SSH (Fufumori et al., 1998). Boundary conditions needed (we use δζ=0)

$$\boxed{g\nabla \cdot (H\nabla\delta\zeta) = \delta F_\Psi - \delta F_\rho;}$$

$$\delta F_\Psi = \nabla \cdot (f\nabla\delta\Psi),$$

$$\delta F_\rho = \frac{g}{\rho_\circ}\nabla \cdot \left(\int_{-H}^0 dz \int_z^0 \nabla\delta\rho\, dz'\right).$$