State Estimates and Forecasts in the Gulf of Mexico

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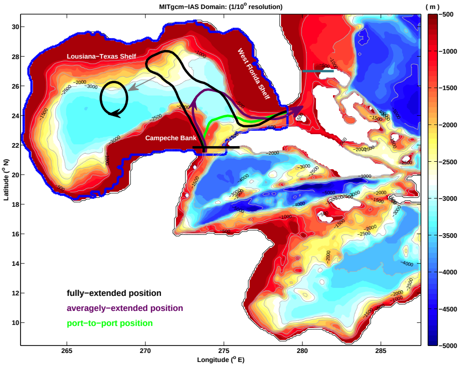
Outline

Motivation

- Energetic Loop currents (LC) and eddy shedding
- LC eddy vacillation and resulting eddy shedding and its westward propagation
- Forecasting LC evolution and eddy shedding with lead times of one or more weeks
  - Advising operational decisions of the Oil and Gas industry
  - Ecosystem monitoring and emergency response
  - Supporting Navy and Government's diverse ocean explorations



Intra Americas Seas showing GoM, LC, and eddy shedding processes

Main focus of the present study

- An ocean state estimation by fitting the model to satellite observations of SSH and SST over a longer time range of two months to obtain a dynamically-consistent hindcast for physical analysis
- Prediction of the circulation in the GoM including LC evolution and eddy shedding
- Duration of validity of the linearization used in the adjoint model
- Assessment of LC predictability with a long forecast horizon of $4 \sim 8$ weeks: Beneficial for public and private stakeholders in the GoM

MITgcm and its adjoint: 4D-VAR assimilation

- Strong constraint 4D-VAR: Based on the Estimating the Circulation and Climate of the Ocean (ECCO) system
- Minimization of a "cost function" ($\mathbf{J}$) penalizing the weighted sum of squared misfits between model and observations ($\mathbf{J}_{data}$) plus the weighted sum of squared control adjustments ($\mathbf{J}_{control}$) between the initial time (t_0) and the final time (t_f) of the assimilation window constrained by the non-linear model equations subject to a set of control variables

$$\mathbf{J}(u) = \underbrace{\sum_{t=t_0}^{t_f}[\mathbf{y}(t) - \mathbf{H}_t(\mathbf{x}(t))]^T\mathbf{R}^{-1}(t)[\mathbf{y}(t) - \mathbf{H}_t(\mathbf{x}(t))]}_{\mathbf{J}_{data}} + \underbrace{\sum_{t=t_0}^{t_f}[\mathbf{u}(t) - \mathbf{u}^b(t)]^T\mathbf{Q}^{-1}(t)[\mathbf{u}(t) - \mathbf{u}^b(t)]}_{\mathbf{J}_{control}}$$

Observations

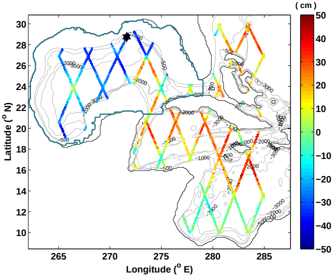
This study focused on near-real-time observations in the GoM, and were limited to satellite derived data of

- SSH along-track anomalies from the Radar Altimetry Database System (RADS: http://rads.tudelft.nl/rads/index.shtml). SSH anomalies from three satellites: Jason-1 (J1), Jason-2 (J2), and Envisat (N1) were used
- SST data from the daily optimally interpolated product derived from the TMI- AMSRE, produced by the Remote Sensing Systems Inc. (http://www.remss.com/)

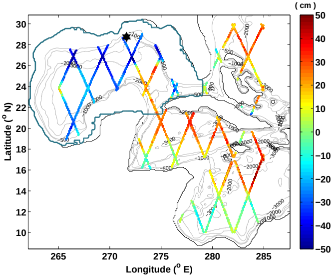
Used inverted barometer correction (*local - global mean pressure*) and the geoid correction (*DNSC08 mean sea surface*) along with RADS default corrections

Used time mean DOT calculated from the difference between DNSCMSS08 [*Andersen and Knudsen (2009)*] and EGM08 (DNSCMSS08-EGM08)

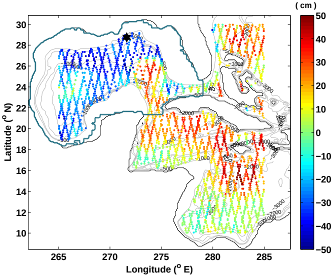
Daily and spatially bin-averaged along-track SSH observations were separated into time mean and anomalies and were separately fit to the model assimilation window mean SSH and daily mean SSH anomalies, using larger uncertainty for the mean SSH and identical space and time averaging



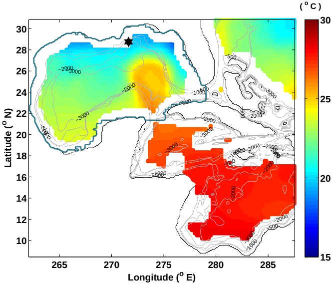
Jason-1



Jason-2



Envisat-1

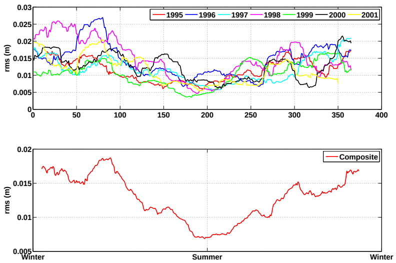


SST

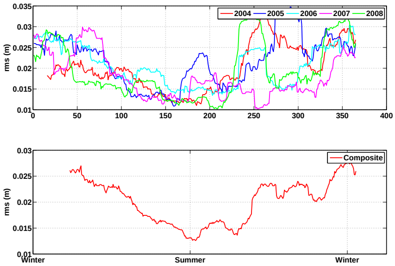
Barotropic model correction

The RADS data used in this study were not corrected for the fast barotropic SSH variation.

SSH *rms* signal from the fast barotropic waves in the GoM computed from the global models GECCO and HYCOM are seasonally varying but small: $< 1\,cm$ usually, and $< 2\,cm$ always.



GECCO



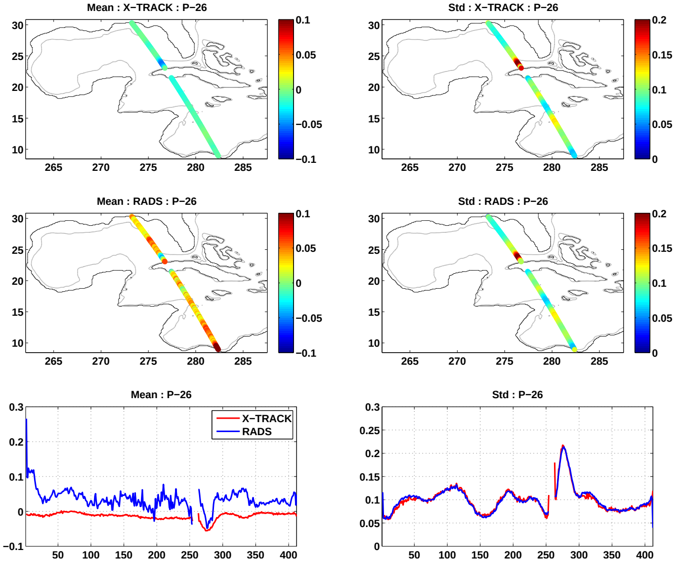
HYCOM

X-TRACK Data

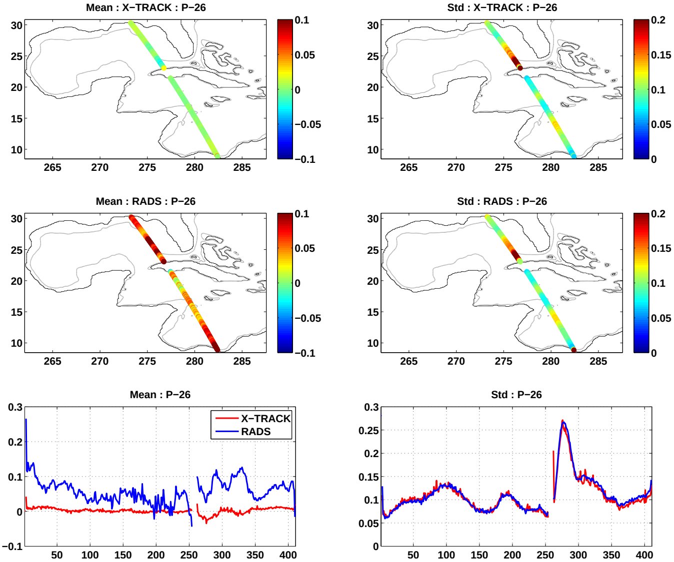
X-TRACK data were kindly provided by CTOH/LEGOS, France (http://ctoh.legos.obs-mip.fr/products/coastal-products)

Special thanks to Rosemary Morrow, Florence Birol, Caroline Delebecque, and Laurent Roblou, LEGOS

X-TRACK 1 *Hz* SLA data were compared with RADS data for Jason-1 (for cycles 73-259) and Jason-2 (for cycles 1-90) for passes in the GoM basin



X-TRACK and RADS comparison for Jason-1, Pass-26, Cycles: 73-259



X-TRACK and RADS comparison for Jason-2, Pass-26, Cycles: 1-90

Model controls

- Initial conditions (T, S), atmospheric forcings, and open boundary conditions (T, S, U, V)

Observation/Background Uncertainties

- SSH anomaly and geoid uncertainty was assumed to be spatially-invariant: 5 *cm* for Jason-1 and Jason-2, 10 *cm* for Envisat, 10 *cm* for geoid
- Used high SST observational uncertainty, especially near the coast
- Initial and boundary conditions uncertainties were computed from the standard deviation (over time) of the model variability over 2004 – 2008 forward integration
- Surface forcing uncertainties are from the standard deviation of NCEP/NCAR Reanalysis-1 over 2004 – 2010
- ECCO system enforces 2D and 3D smoothness of control variables following [*Weaver (2003)*] with decorrelation scales of 50 *km* for atmospheric forcings and initial conditions

The gradient of the cost function obtained by integrating the adjoint of the tangent linear model backward in time [*Le Dimet and Talagrand (1986)*] determines the descent directions toward the minimum of the cost function and is solved iteratively using conjugate-gradient algorithm

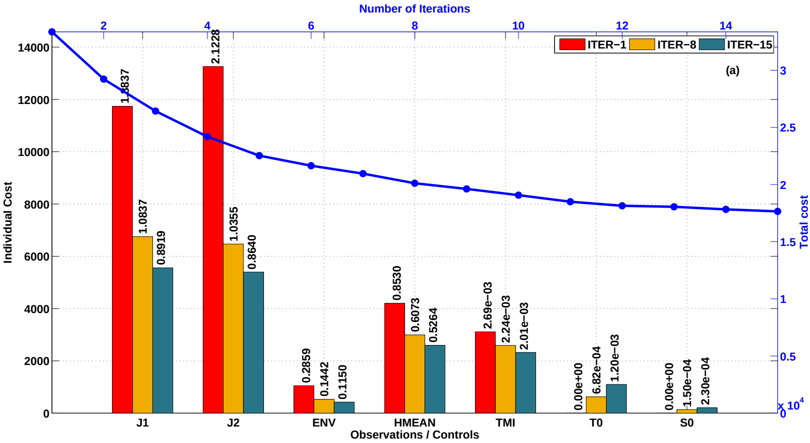
MITgcm-Intra Americas Seas Model

- $1/(10^{\circ})$ Horizontal resolution
- 40 vertical z-levels ($\sim$ 5m near surface)
- NCEP/NCAR Reanalysis-1 surface forcing/fluxes: bulk formulation [*Large and Pond (1981)*]
- HYCOM + NCODA global ($1/12^{\circ}$) analysis initial and boundary conditions [*Chassignet et al (2007)*], (`http://hycom.org/dataserver/glb-analysis`)
- Monthly climatological run-off fluxes

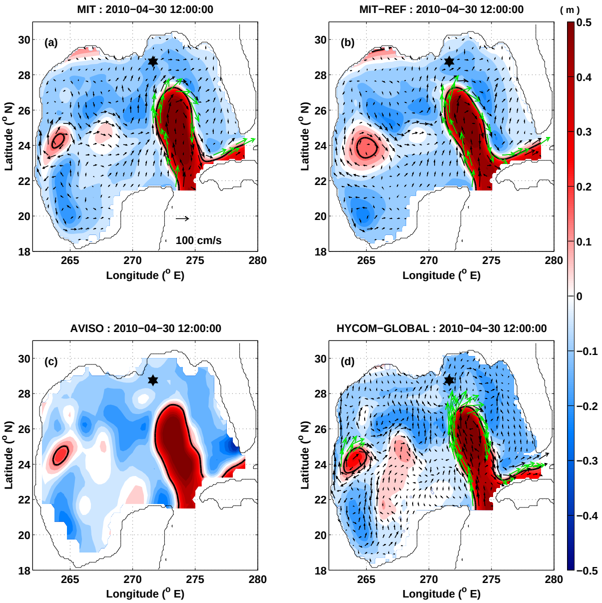
The adjustments to the starting guess controls were penalized in the cost function

SSH and SST data in the GoM were assimilated for a period of two months (March 1 - April 30, 2010)

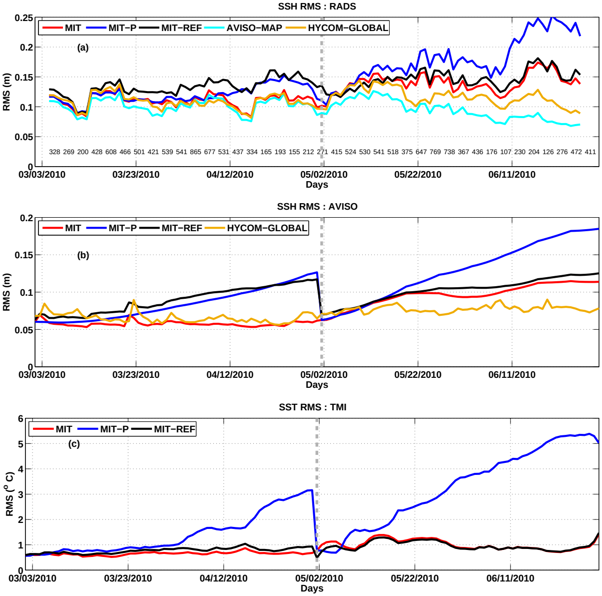
The optimized state is cross-validated by using it as initial conditions for predicting the ocean state including LC eddy separation (Eddy-Franklin) event in late May 2010, after the Deepwater Horizon blowout on April 20, 2010



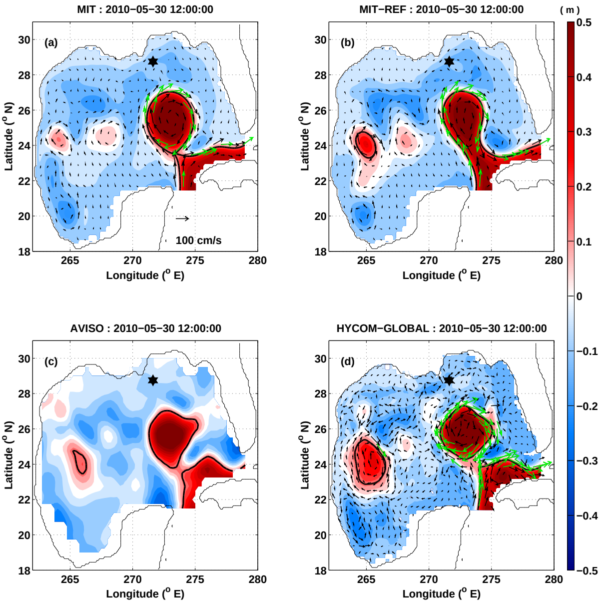
Cost descent after 15 iterations (Total cost function is reduced by 47% after 15 iterations)



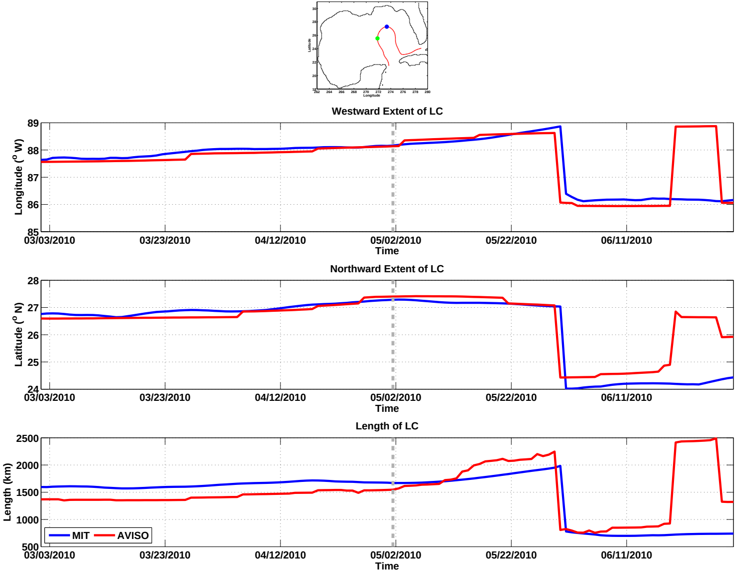
SSH fields at the end of the assimilation period (Hindcast)



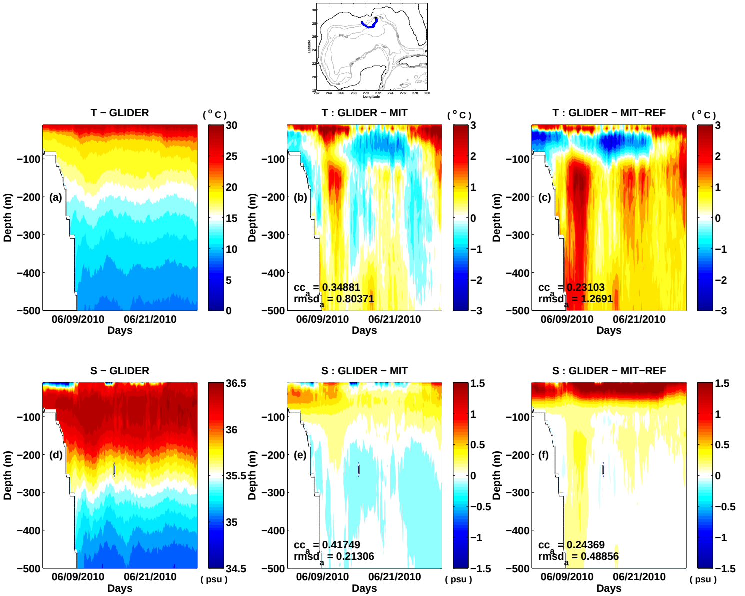
Model-data *rmsd* for hindcast/forecast for SSH and SST



SSH fields at the end of first month of the model forecast



Time-series of Loop Current indices based on 17 *cm* SSH isoline [*Leben (2005)*] for the model hindcast/forecast



Model forecast comparison with glider data for June 2010

Summary

- A 4D-VAR assimilation system has been developed for the Intra-Americas Seas producing a dynamically consistent ocean state for analysis and forecasts
- This assimilation/forecast system has been cross-validated by forecasting the LC and eddy shedding events in the GoM for 2010, as well as for the years 2005, 2006, and 2007
- This system demonstrates that the model physics were adequate and the adjoint gradients calculated over the assimilation period of two months were still useful
- The skill metrics for the forecast generally outperformed persistence and reference (unadjusted) model runs during LC eddy shedding events for a longer forecast horizon of $4 \sim 8$ weeks

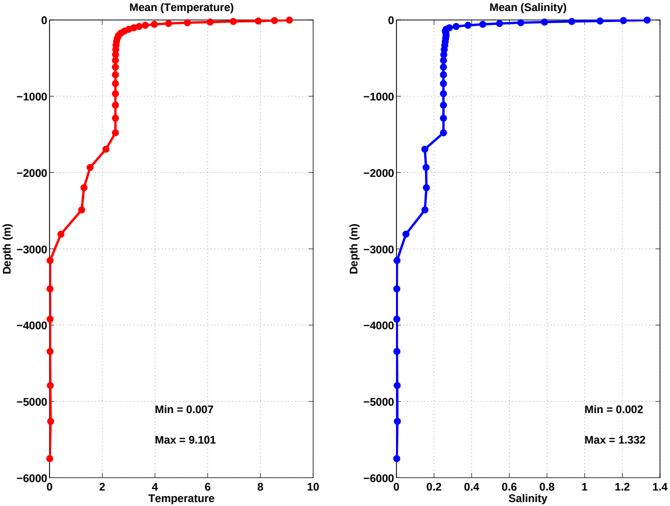
Ongoing work

- Assimilating Glider and other *in situ* data along with the SSH and SST data
- Analyze and quantify the effect of Glider data assimilation on the LC forecast
- Increasing the model grid resolution and assimilating coastal altimetry products

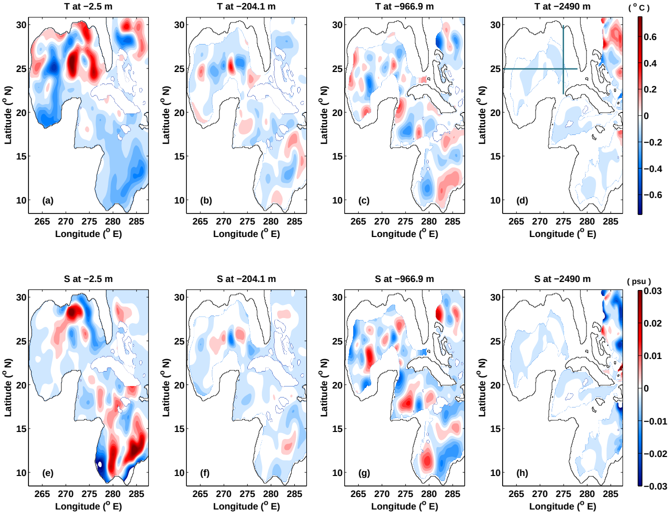
Acknowledgments

- Travel grant award from the Cooperative Institute for Oceanographic Satellite Studies (CIOSS) and the National Oceanic and Atmospheric Administration (NOAA)
- Several data sources: the Radar Altimetry Database System (RADS), AVISO, NCEP/NCAR Reanalysis-1, the HYCOM consortium, Remote Sensing Systems, Inc, and the ECCO consortium, including MIT, JPL, and the University of Hamburg

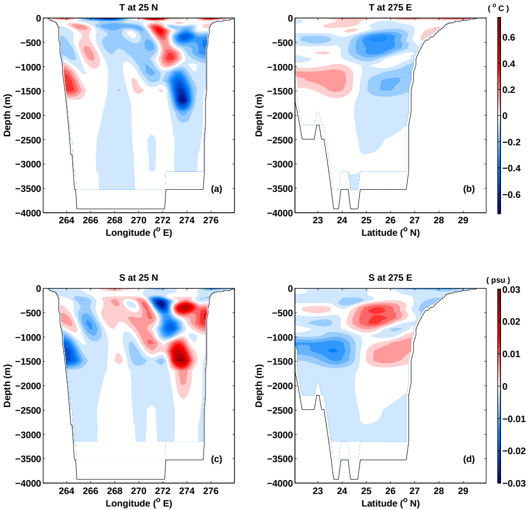
Thank You



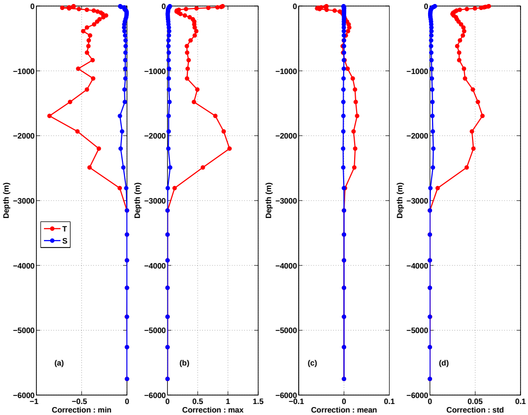
Square root of the horizontal mean over the model domain of background uncertainty variances used for initial temperature *T0* and salinity *S0* conditions as a function of depth. Temperature in $^\circ C$ and salinity in *psu*



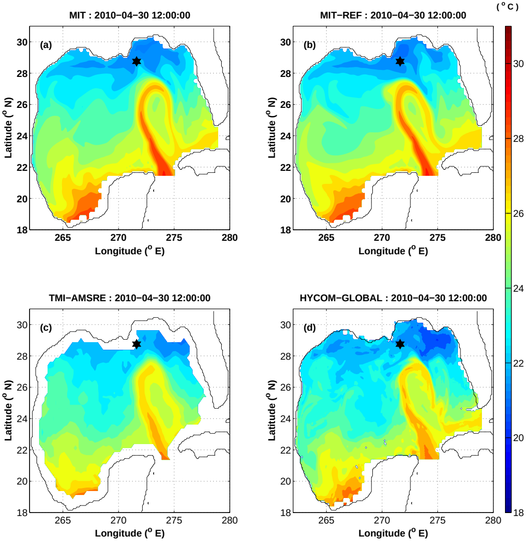
Spatial distribution of adjustments to initial temperature (*T0*: top panels a to d) and salinity (*S0*: bottom panels e to h) conditions at different depth levels. Temperature in $^\circ C$ and salinity in *psu*



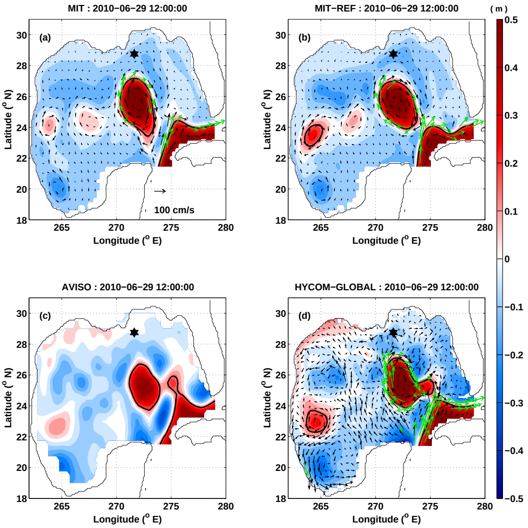
Adjustments to initial temperature (*T0*: top panels) and salinity (*S0* : bottom panels) conditions at zonal (at 25° N: left panels) and meridional (at 275° E: right panels) section in the GoM basin. Temperature in °*C* and salinity in *psu*



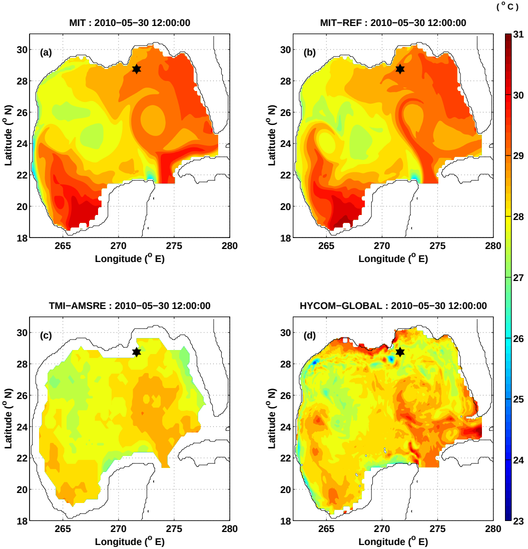
Horizontal minimum, maximum, mean, and standard deviation (panels a to d) over the model domain of the adjustments to initial temperature *T0* and salinity *S0* conditions as a function of depth. Temperature in $^\circ C$ and salinity in *psu*



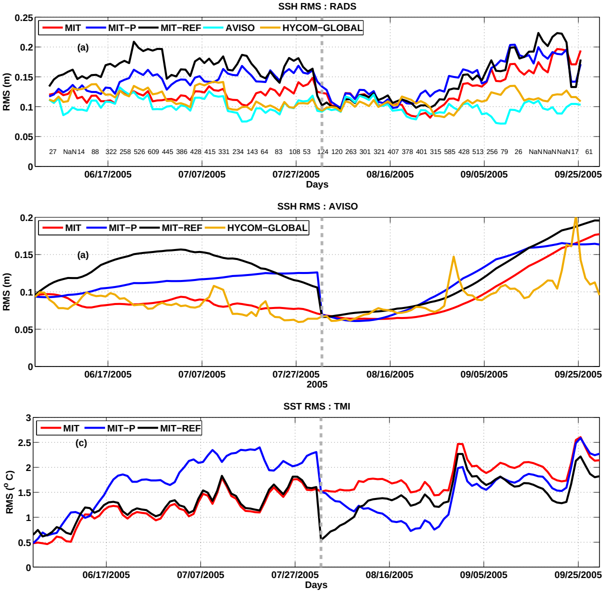
SST fields at the end of the assimilation period (Hindcasts)



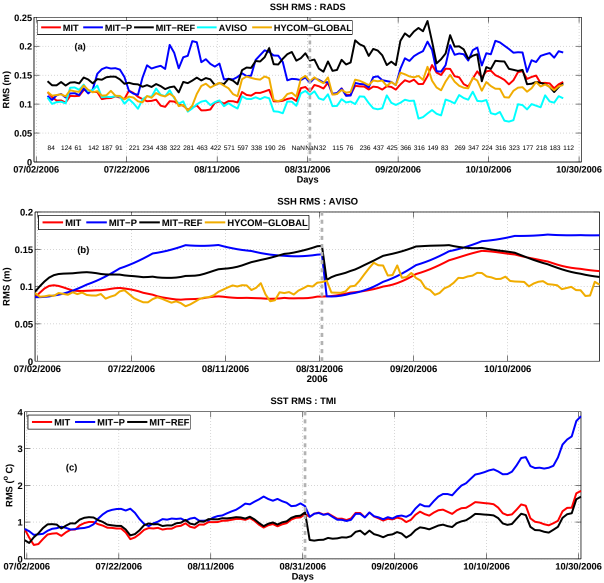
SSH fields at the end of the two-month forecasting period



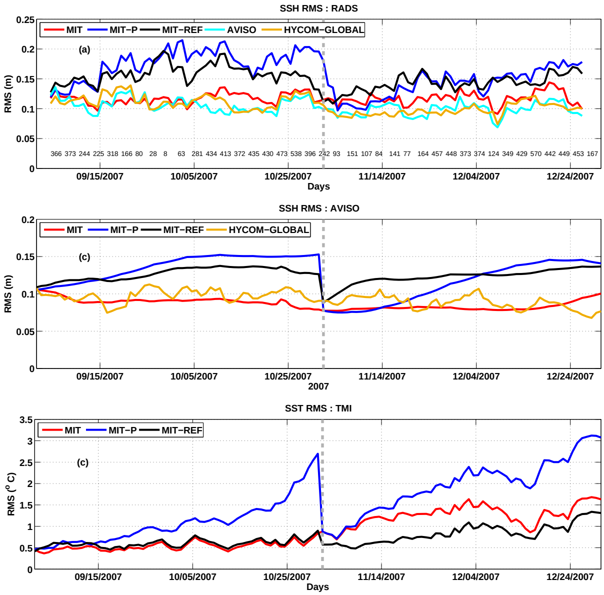
SST fields at the end of first month of the model forecasting period



Model-data *rmsd* for hindcast/forecast for SSH and SST: 2005 (Eddy Vortex)



Model-data *rmsd* for hindcast/forecast for SSH and SST: 2006 (Eddy Yankee)



Model-data *rmsd* for hindcast/forecast for SSH and SST: 2007 (Eddy Albert)