Impact of Diurnal Warming on Assimilation of Satellite Observations of Sea Surface Temperature

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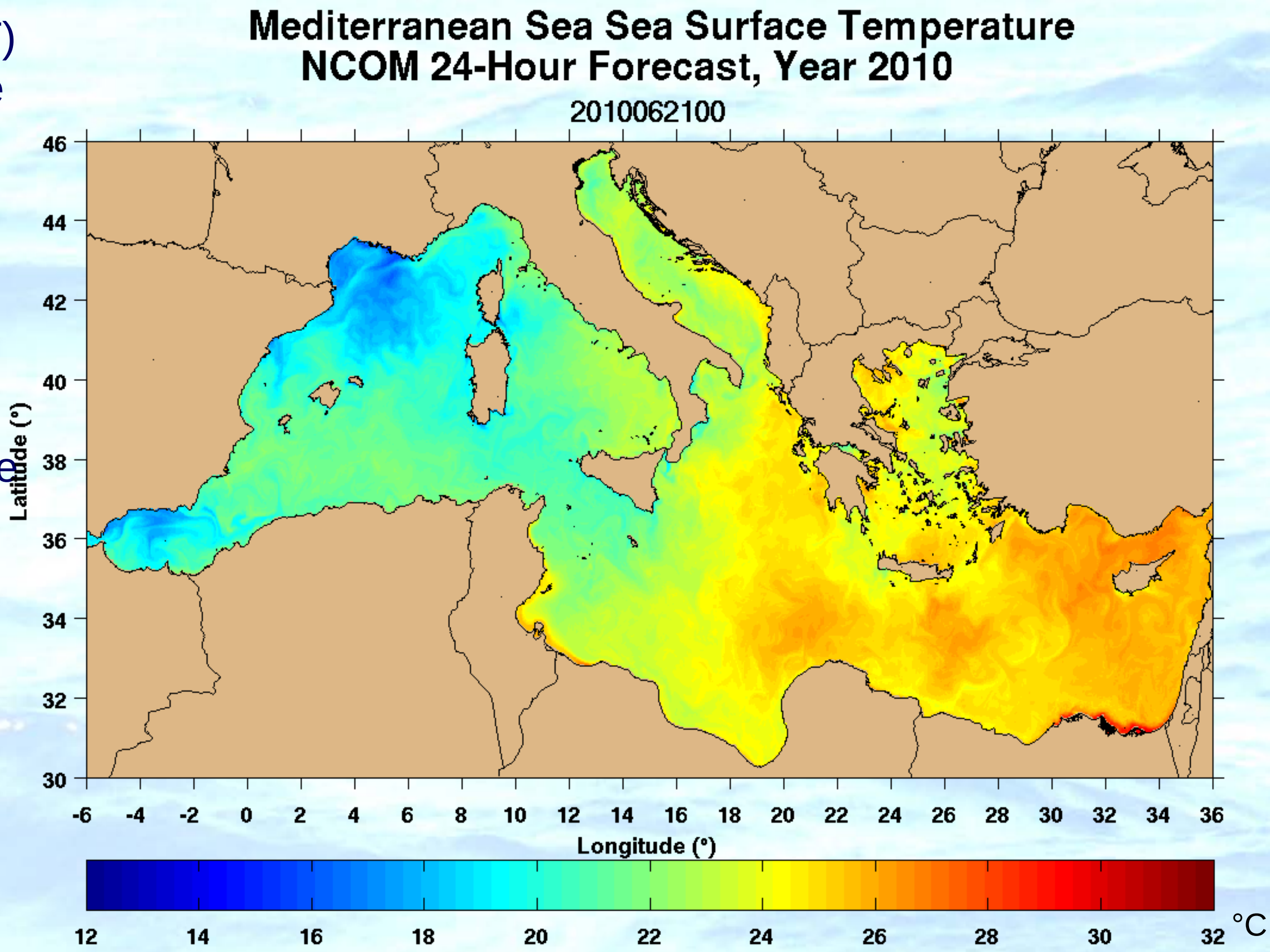
Sea surface temperature (SST) and thermal stratification in the Mediterranean and Gulf of Mexico exhibit variability on diurnal to seasonal scales

We assume that forecasts of SST will be improved by more satellite data streams and more capable assimilation approaches

Compare assimilative cases:

- Using polar orbiting vs geostationary vs both
- USING 3DVAR with and without First Guess at Appropriate Time approach



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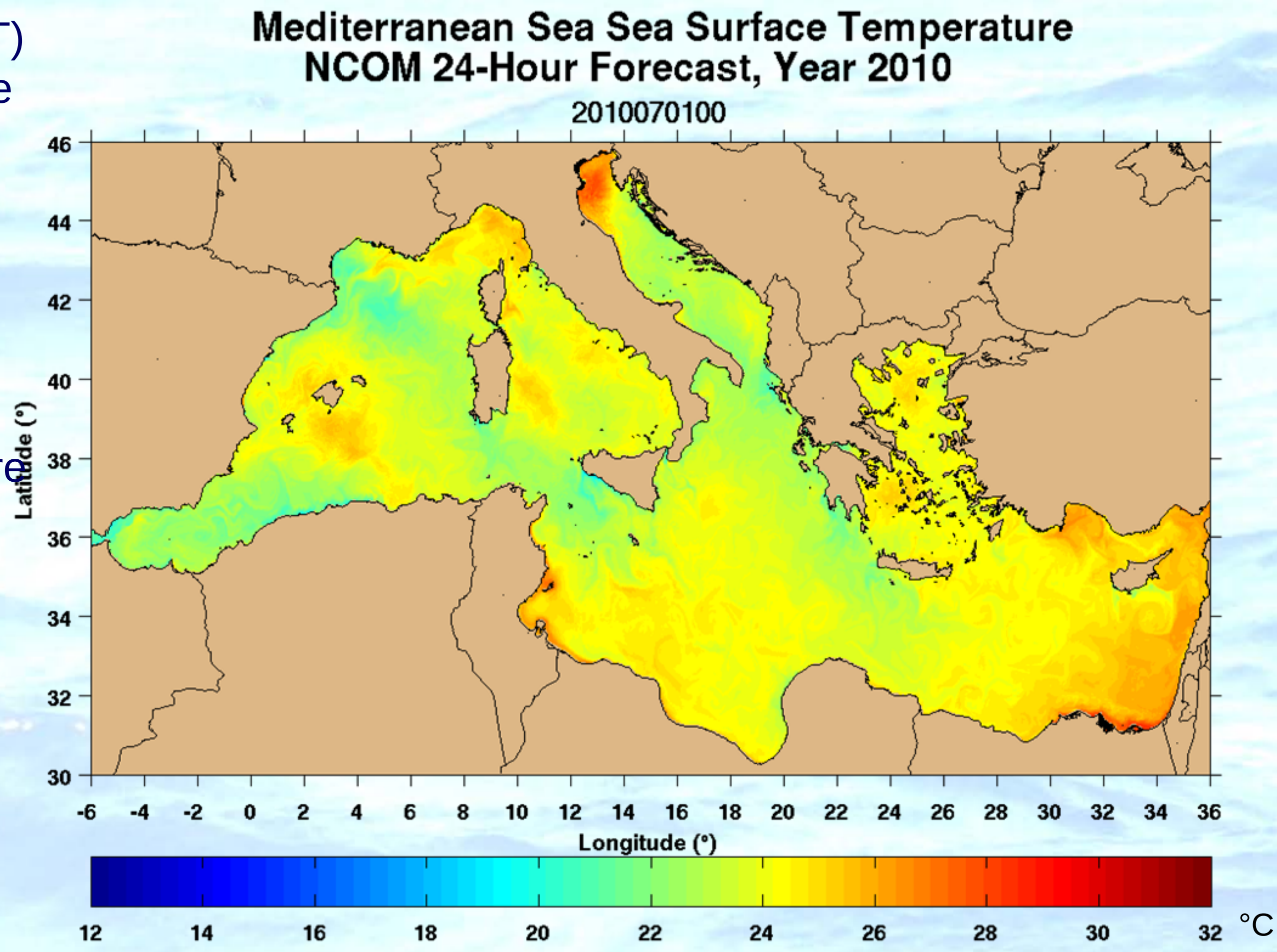
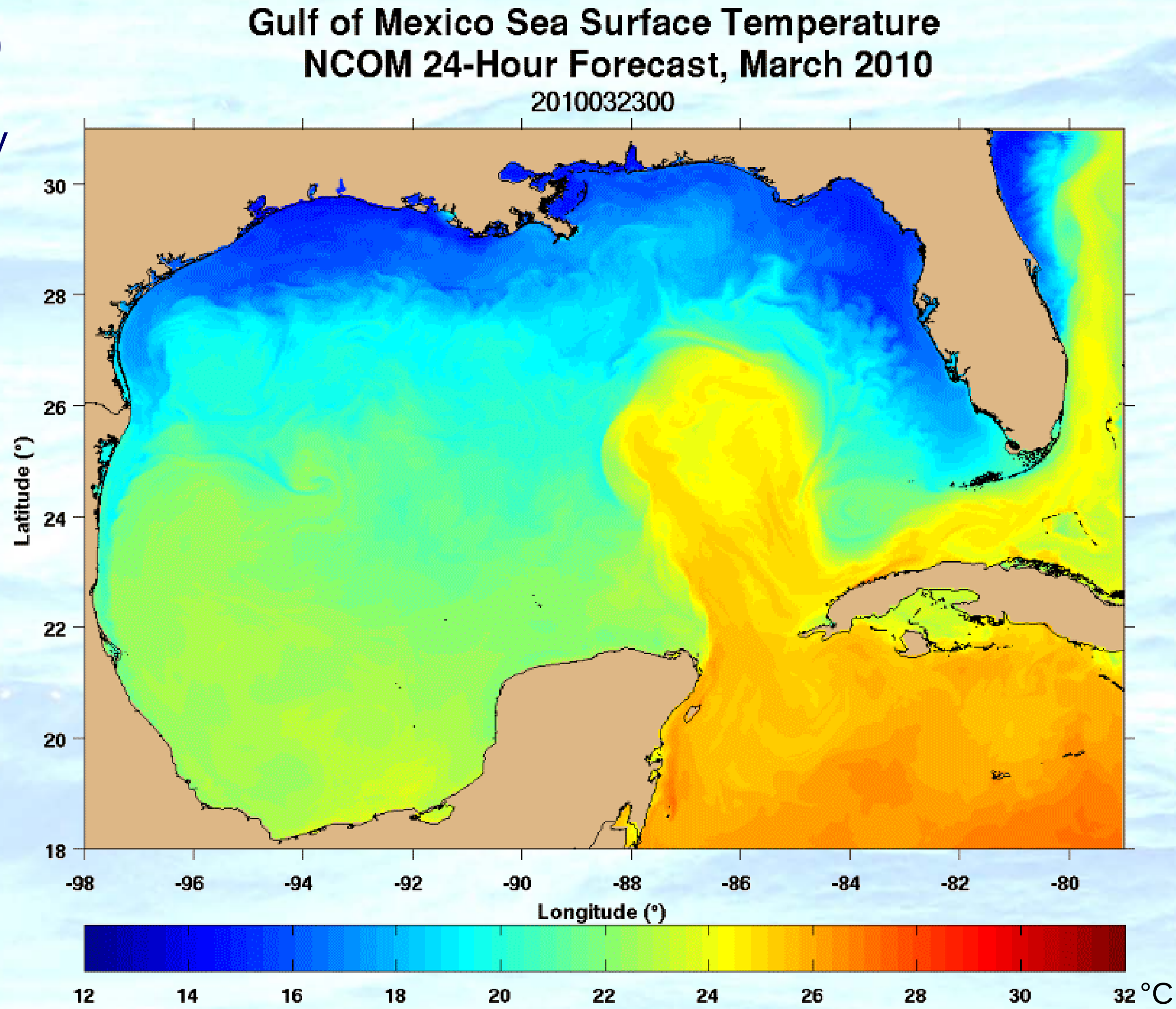


Sea Surface Temperature (SST) varies on a range of temporal scales

Sea surface temperature (SST) and thermal stratification in the Gulf of Mexico exhibit variability on diurnal to seasonal scales due to interactions among a variety of factors:

- Solar angle
- Clouds/atmospheric conditions
- Upwelling
- Smaller fronts and eddies
- River plumes
- Biophysical modification of solar attenuation
- Loop Current variation
- Warm core rings



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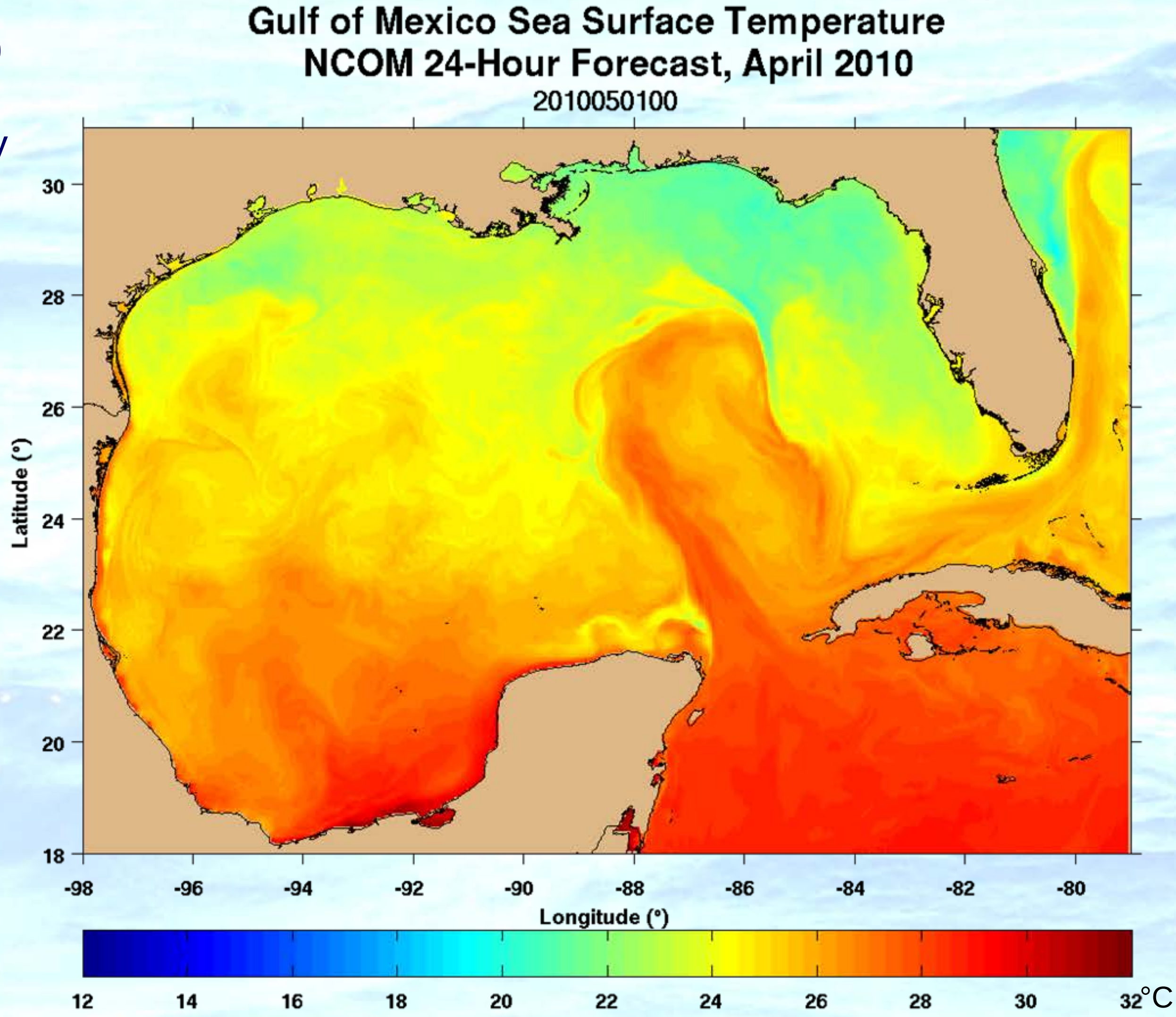


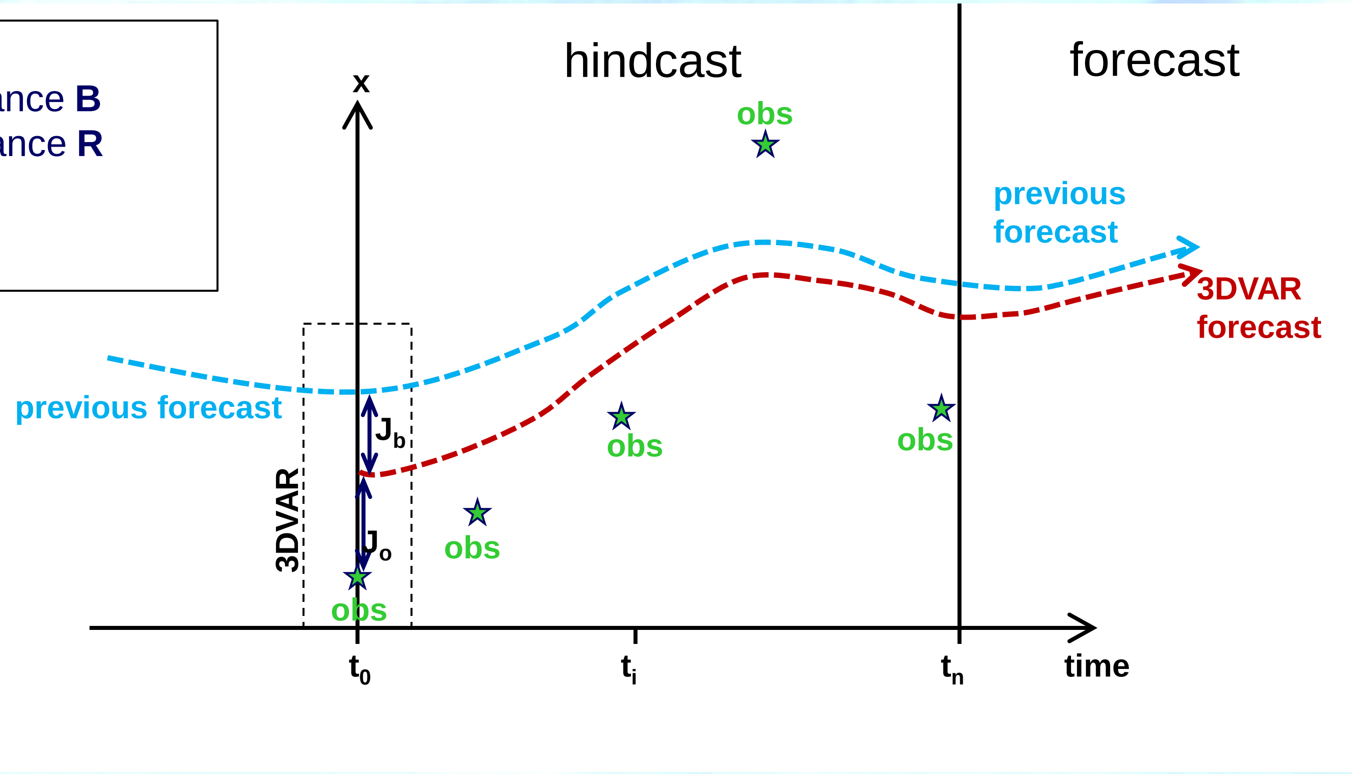
3DVAR SST analyses adjust daily initial conditions toward satellite observations

What is the best estimate of the ocean state **x**? Variational assimilation finds it by balancing estimated errors to minimize a cost function *J*(**x**).

$$J(\mathbf{x}) = \underbrace{(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)}_{J_b} + \underbrace{(\mathbf{Hx}-\mathbf{y})^T \mathbf{R}^{-1}(\mathbf{Hx}-\mathbf{y})}_{J_o}$$

Provide estimates of

- Background error covariance **B**
- Observation error covariance **R**



3DVAR SST – define innovations between the background and observations

What is the best estimate of the ocean state **x**? Variational assimilation finds it by balancing estimated errors to minimize a cost function $J(\mathbf{x})$.

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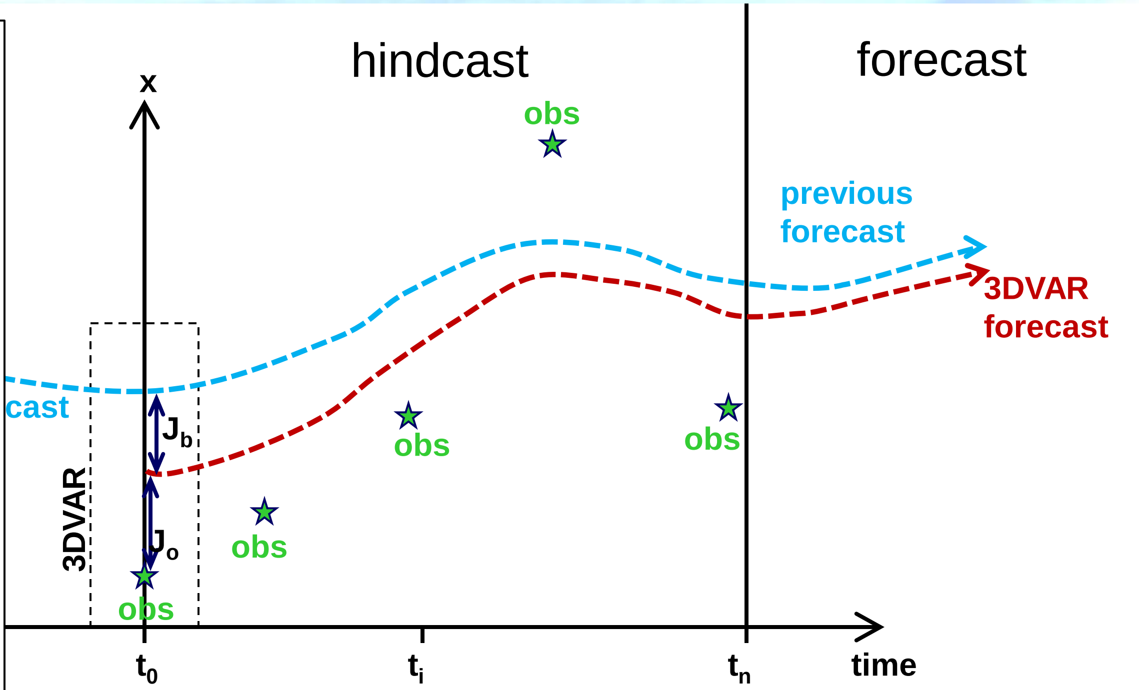
What is the innovation (**Hx – y**), the difference between the observation **y** and the corresponding model state **Hx**?

In the standard 3DVAR approach, we treat the observations as if they are representative at the analysis time $\mathbf{t}_0$:

Either use only observation nearest to $\mathbf{t}_0$ or average observations in a window around $\mathbf{t}_0$



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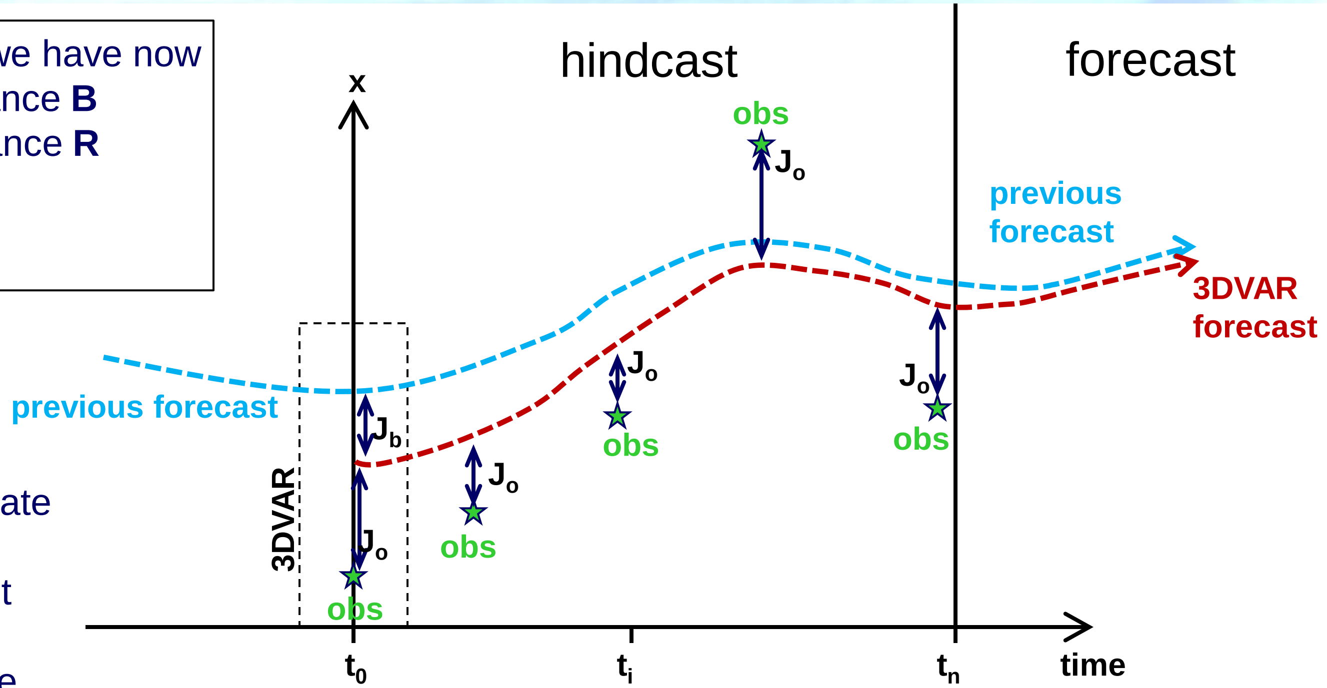
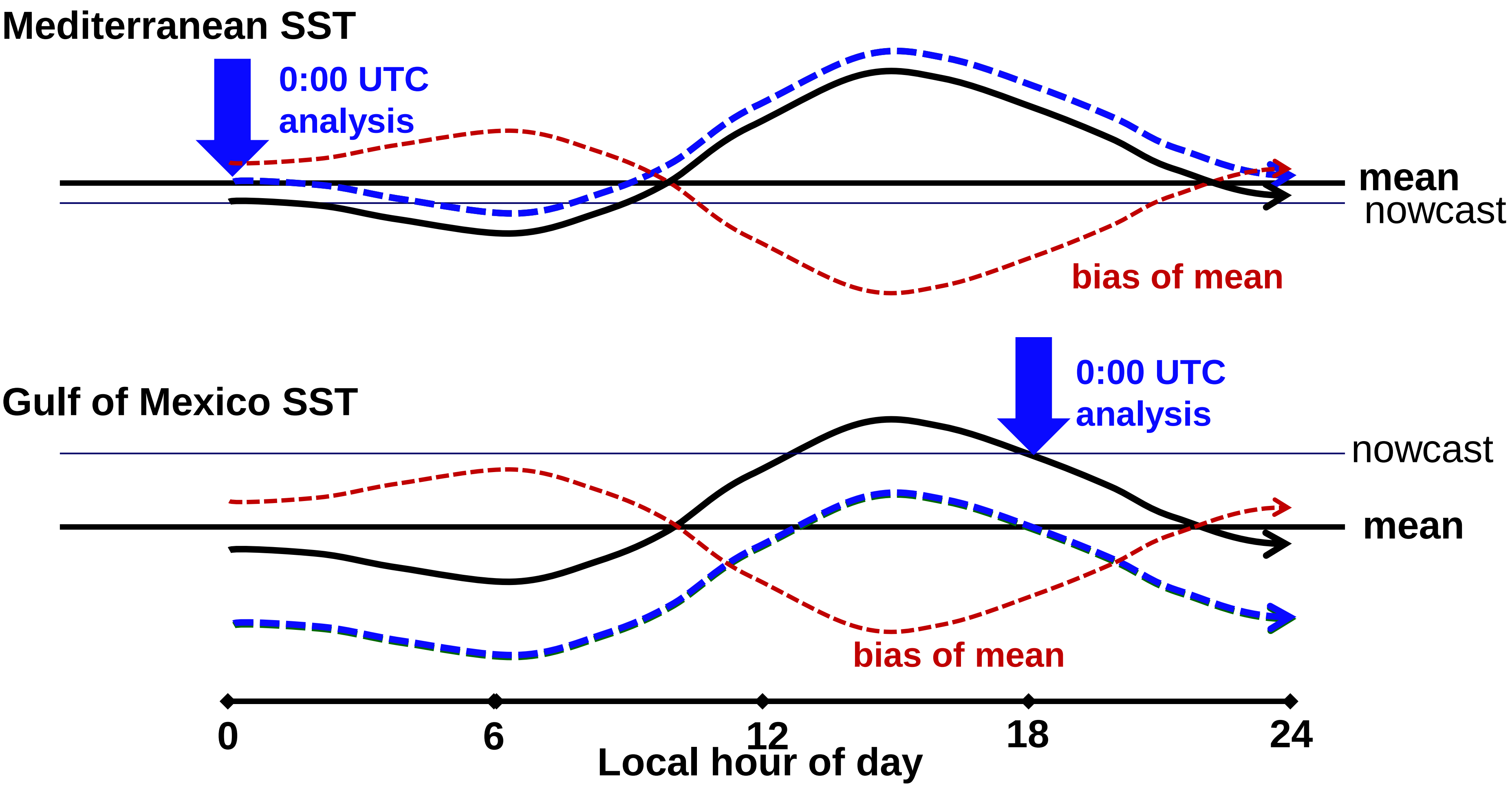
ocean covariances, models we have now

- Background error covariance **B**
- Observation error covariance **R**



FGAT (first guess at appropriate time) calculates increments-background over the hindcast window and applies the increment at the nowcast time

Effect of diurnal cycle + FGAT on assimilative ocean model forecasts



Basic 3DVAR aliases diurnal SST into a bias (mean-nowcast SST).
First Guess at Appropriate Time (FGAT) option eliminates this aliasing.

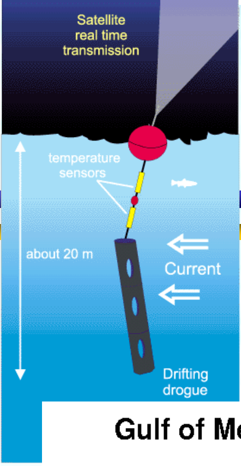
Experiments focus on role of FGAT and geostationary versus polar orbiting sources

	Gulf of Mexico		Mediterranean	
	FGAT on	FGAT off	FGAT on	FGAT off
Polar only	AVHRR (NOAA 18, 19 GAC and LAC; NAVO)			
Geostationary only	GOES-E (GOES-12, 13; NAVO)		MSG (Meteosat-9; IFREMER)	
Both Polar and Geostationary	AVHRR & GOES-E		AVHRR & MSG	

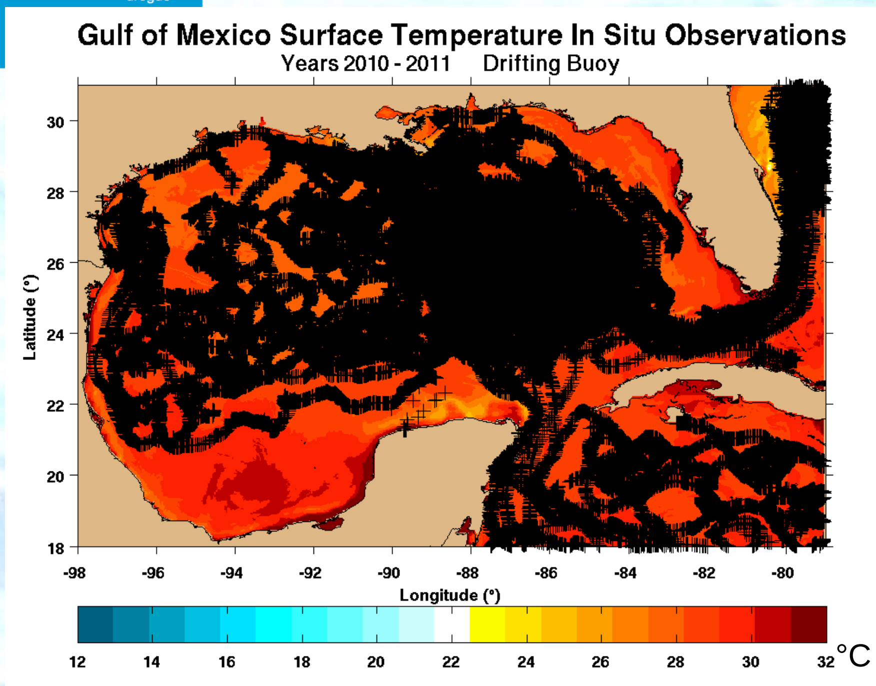
- NCOM/3DVAR NCODA run from 01 Dec 2009 – 31 Dec 2011
- Boundary conditions from GOFS 2.6
- Forcing from COAMPS
- OCNQC ship observations are excluded from the assimilation data stream to serve as a basis for independent validation
- Seasonal breakdown:

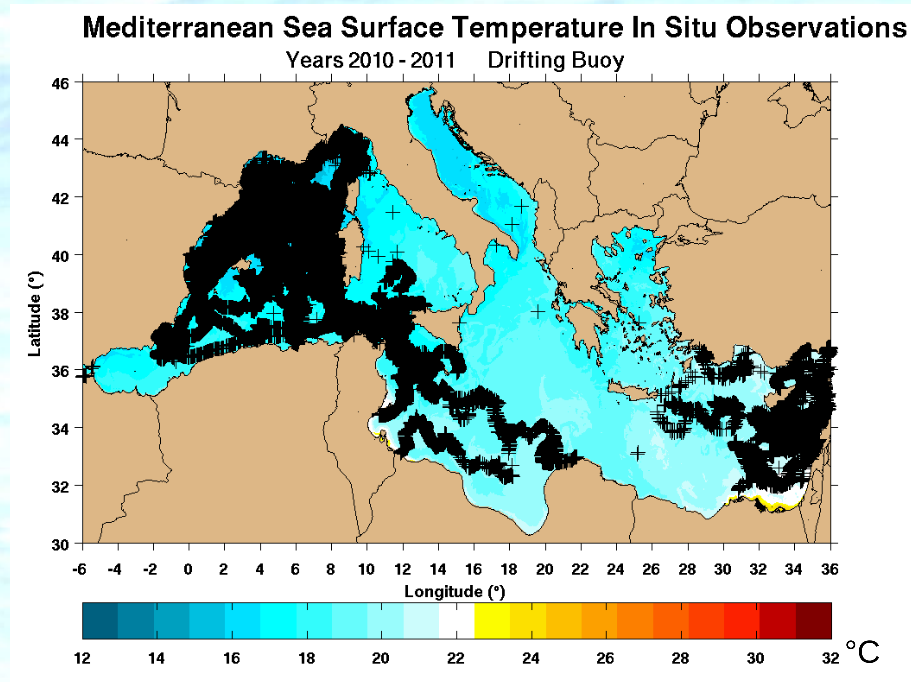
Winter	Spring	Summer	Autumn
21 Dec-20 Mar	21 Mar-20 Jun	21 Jun-20 Sep	21 Sep-20 Dec

Two years of matchup SST data from drifting buoys



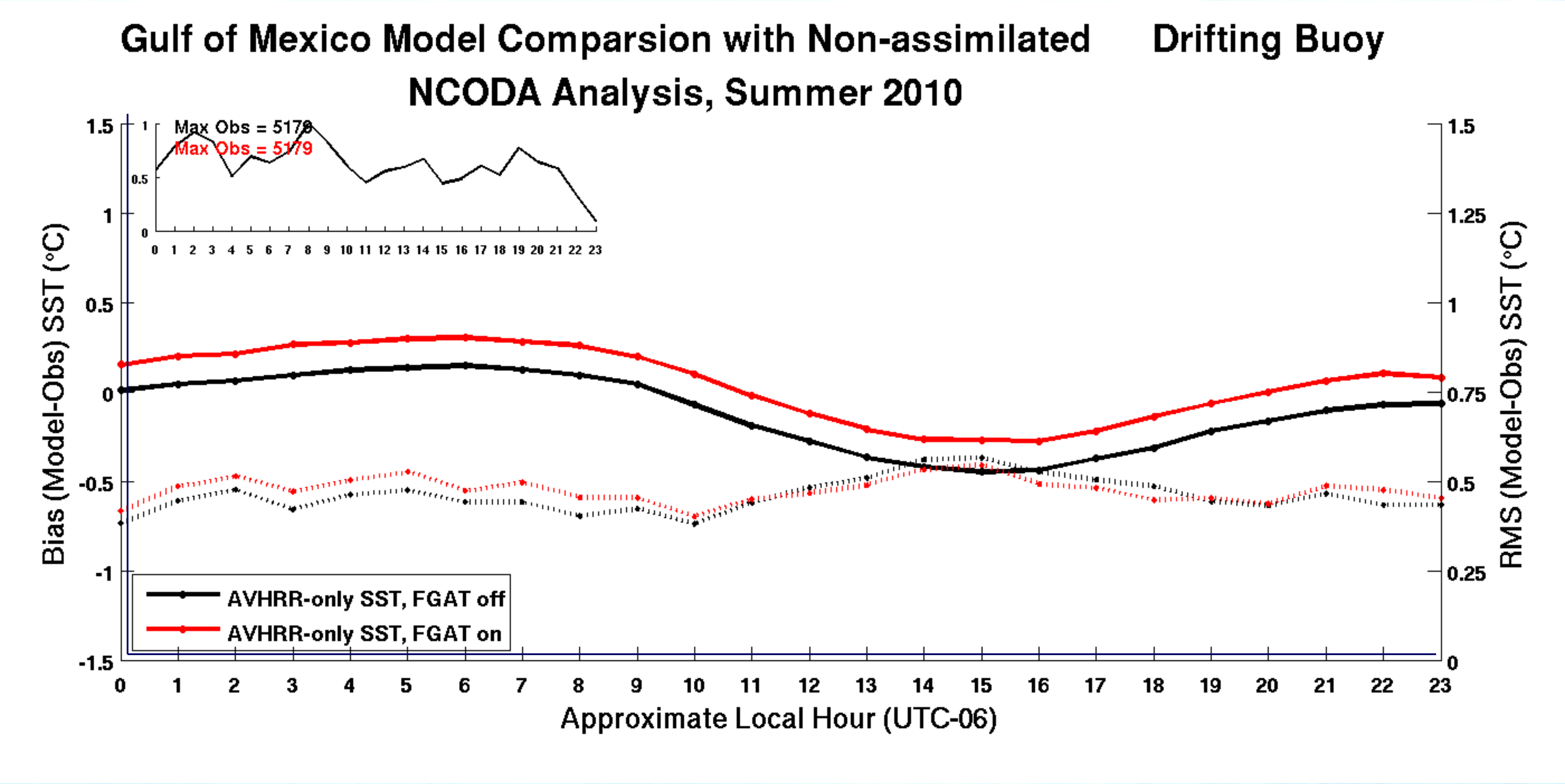
Matchup data is irregularly distributed in space and time





Analyses and forecasts from models assimilating satellite observations are compared with independent SST measurements from drifting buoys

Evaluations show variations in skill over different regions, seasons, and time scales



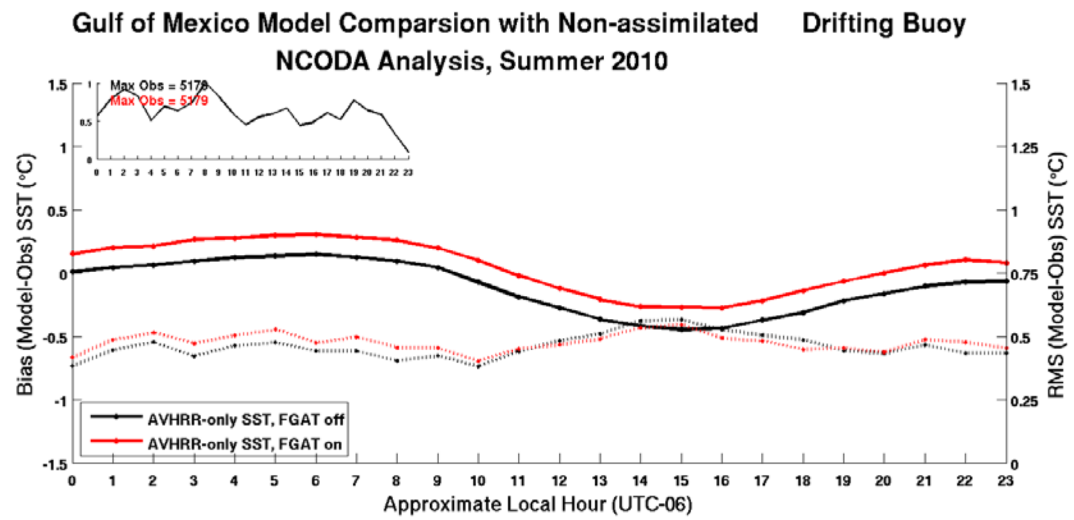
Evaluations show variations in skill over different regions, seasons, and time scales

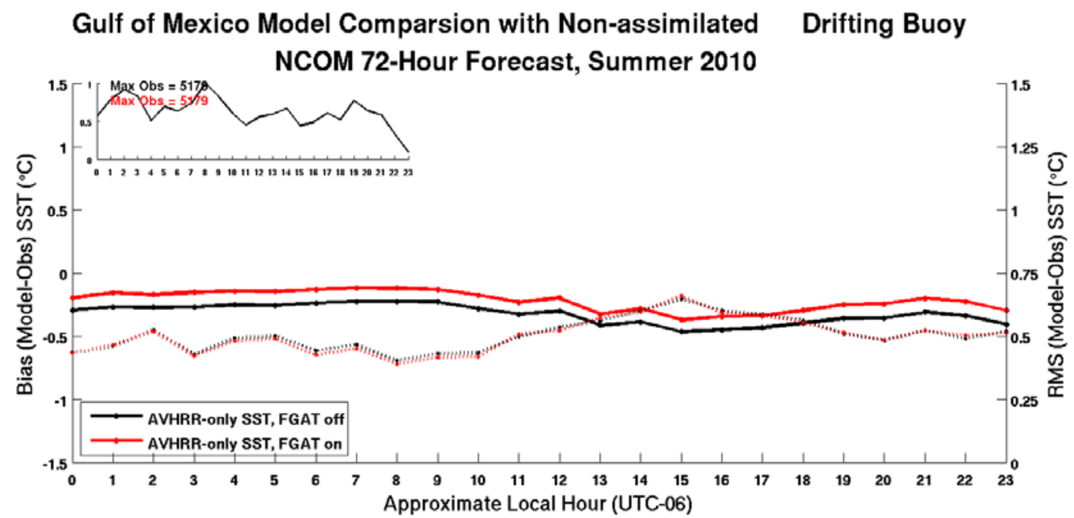
SST analyses show a diurnal variation in bias as a function of local time of day, particularly in summer. This signal is not evident in the forecast bias, indicating that the models sufficiently simulate diurnal variations.

The models exhibit a cold forecast bias, particularly in the Gulf of Mexico, These biases are corrected at forecast time by 3DVAR assimilation. 3DVAR fails to correct the forecast trend.

The results indicate importance of

- minimizing bias in the satellite data streams
- ocean forecast skill for diurnal signal and forecast bias





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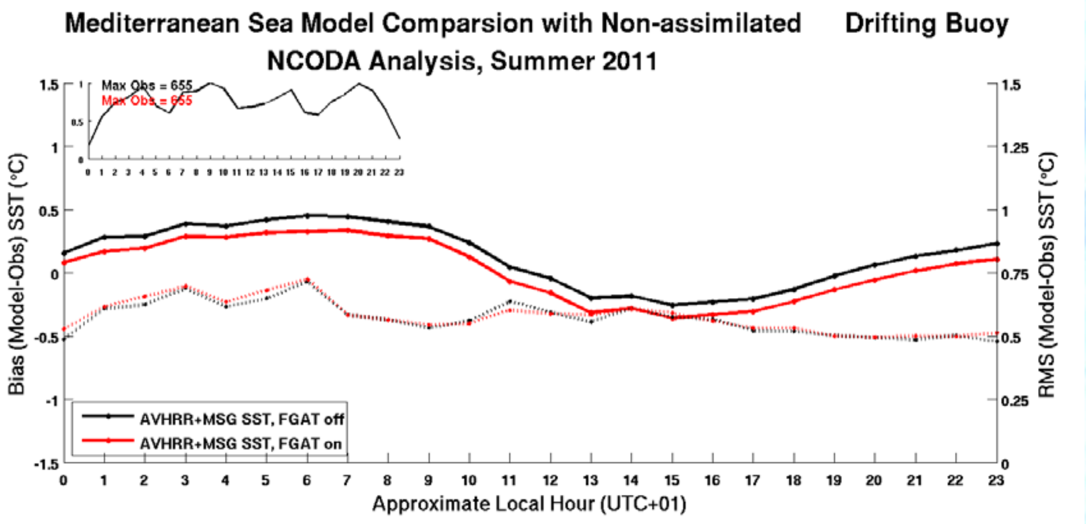

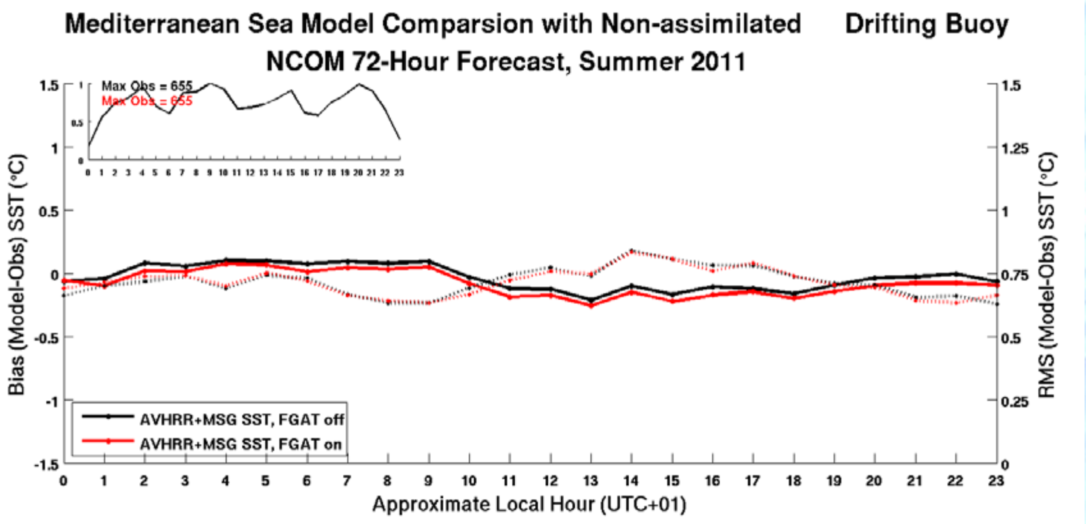

Gulf of Mexico SST Validation 2010-11

Large cold bias when including GOES-E data

FGAT removes 0.1˚C from cold bias

72-hour forecast has cold bias, adds bias of -0.23 ˚C

Nowcast 196,740 obs	Bias °C		RMS Error °C	
	FGAT on	FGAT off	FGAT on	FGAT off
Both Polar and Geostationary	-0.11	-0.21	0.54	0.50
Polar only	0.03	-0.07	0.54	0.51
Geostationary only	-0.17	-0.26	0.54	0.52

72-hr forecast 196,740 obs	Bias °C		RMS Error °C	
	FGAT on	FGAT off	FGAT on	FGAT off
Both Polar and Geostationary	-0.34	-0.41	0.57	0.55
Polar only	-0.25	-0.30	0.57	0.55
Geostationary only	-0.39	-0.46	0.57	0.57

Mediterranean SST Validation 2010-11

Moderate warm bias when including MSG data

FGAT warms bias ~0.05˚C

72-hour forecast has cold bias, adds bias near -0.1 ˚C

Nowcast 95,179 obs	Bias °C		RMS Error °C	
	FGAT on	FGAT off	FGAT on	FGAT off
Both Polar and Geostationary	0.04	0.10	0.70	0.70
Polar only	-0.03	0.03	0.71	0.71
Geostationary only	0.15	0.18	0.72	0.72

72-hr forecast 95,179 obs	Bias °C		RMS Error °C	
	FGAT on	FGAT off	FGAT on	FGAT off
Both Polar and Geostationary	-0.06	-0.01	0.82	0.82
Polar only	-0.12	-0.07	0.82	0.84
Geostationary only	0.04	0.06	0.82	0.83

Seasonal impact of data sources, FGAT treatment on Gulf of Mexico SST nowcasts

Season/years	Satellites	FGAT	Bias	# obs
Winter 2010	AVHRR	same	±0.03	5174
Spring 2010	AVHRR	off	-0.01	3113
Summer 2010	AVHRR	on	0.07	7653
Autumn 2010	AVHRR	same	-0.03	28960
Winter 2011	GOES	off	-0.07	19100
Spring 2011	GOES	off	0.00	11340
Summer 2011	AVHRR	on	-0.15	11490
Autumn 2011	AVHRR+GOES	on	-0.16	8561
2010	AVHRR	same	±0.06	46714
2011	AVHRR	on	-0.04	48465
2010-2011	AVHRR	on	0.03	95179

Using AVHRR only generally leads to smaller bias than GOES or GOES+AVHRR. FGAT helps overall but less benefit in Winter and Spring (weak diurnal signal).

Seasonal impact of data sources, FGAT treatment on Gulf of Mexico SST forecasts

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Winter 2010	AVHRR+GOES	off	-0.12	5174
Spring 2010	AVHRR	on	-0.17	3113
Summer 2010	AVHRR	on	-0.21	7653
Autumn 2010	AVHRR	off	-0.25	28960
Winter 2011	AVHRR+GOES	off	-0.25	19100
Spring 2011	AVHRR	on	-0.05	11340
Summer 2011	AVHRR	on	-0.52	11490
Autumn 2011	AVHRR+GOES	on	-0.38	8561
2010	AVHRR	on	-0.24	46714
2011	AVHRR	on	-0.28	48465
2010-2011	AVHRR	on	-0.25	95179

The 72 hour forecast shows a cold bias. FGAT helps overall but less benefit in Winter (weak diurnal signal). Focusing on heat flux as contributor to cold bias.

Seasonal impact of data sources, FGAT treatment on Mediterranean SST nowcasts

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Autumn 2011	MSG	off	-0.09	8561
2010	AVHRR	on	-0.01	46714
2011	AVHRR+MSG	on	0	48465
2010-2011	AVHRR	on	-0.03	95179

Biases are small using AVHRR and MSG separately or in combination. FGAT helps overall with largest benefit in summer when the diurnal signal is largest.

Seasonal impact of data sources, FGAT treatment on 72-hr Med. SST forecasts

Season/years	Satellites	FGAT	Bias	# obs
Winter 2010	MSG	off	-0.01	5174
Spring 2010	MSG	off	0.03	3113
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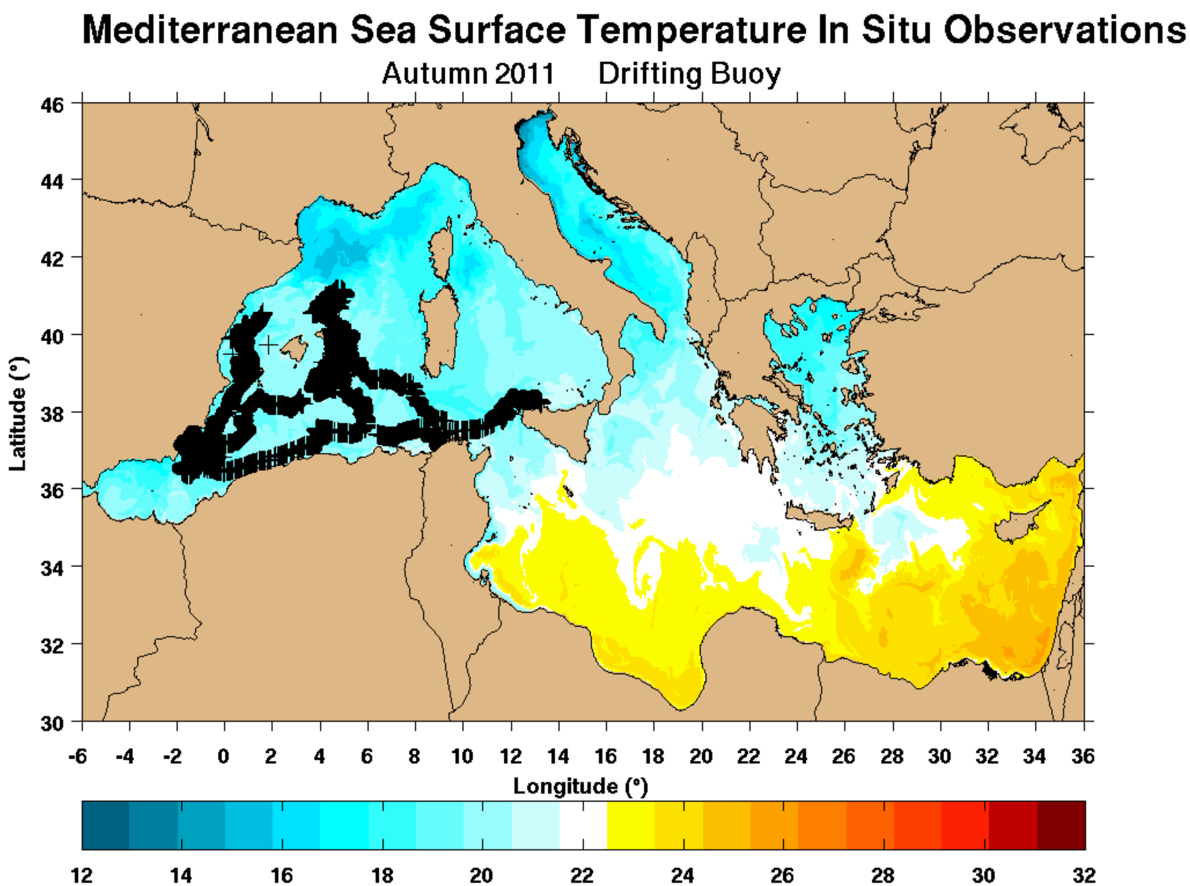
Winter 2011	AVHRR	same	±0.01	19100
Spring 2011	AVHRR+MSG	off	-0.05	11340
Summer 2011	MSG	same	±0.02	11490
Autumn 2011	MSG	off	**-0.29**	8561
2010	AVHRR+MSG	on	-0.03	46714
2011	MSG	off	-0.01	48465
2010-2011	AVHRR+MSG	off	-0.01	95179

Biases are small using AVHRR and MSG separately or in combination. FGAT does not show a strong influence in forecast skill. Autumn 2011 stands out as large bias.

Seasonal impact of data sources, FGAT treatment on 72-hr Med. SST forecasts



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±0.01	19100
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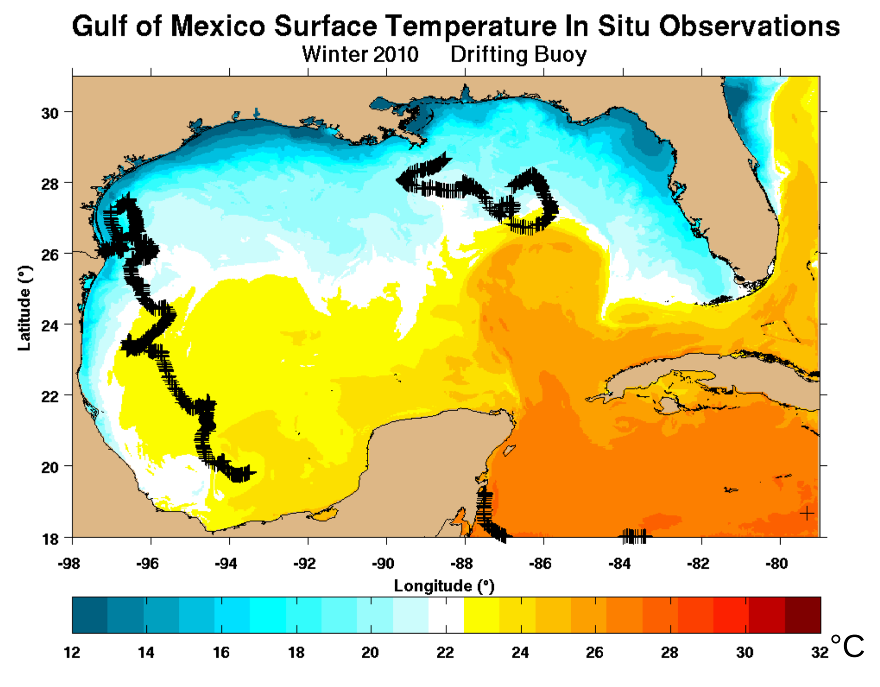
±0.02	11490
-0.29	
-0.03	
-0.01	48465
-0.01	95179

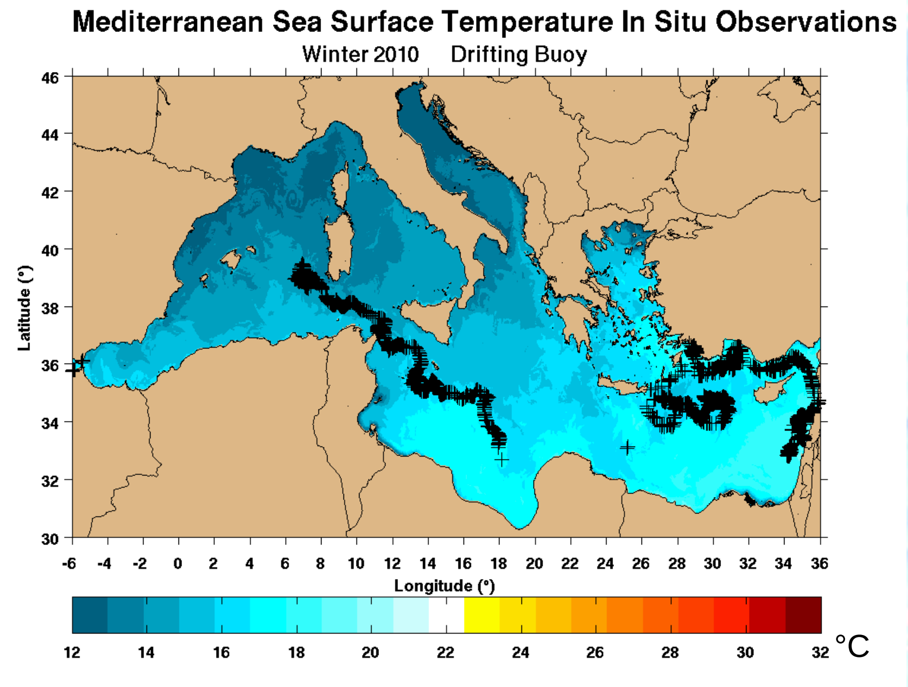
Excessive upwelling along Algerian coast

Biases are small using AVHRR and MSG separately or in combination. FGAT does not show a strong influence in forecast skill. Autumn 2011 stands out as large bias.

Seasonal matchup SST data from drifting buoys

Matchup data is irregularly distributed
in space and time

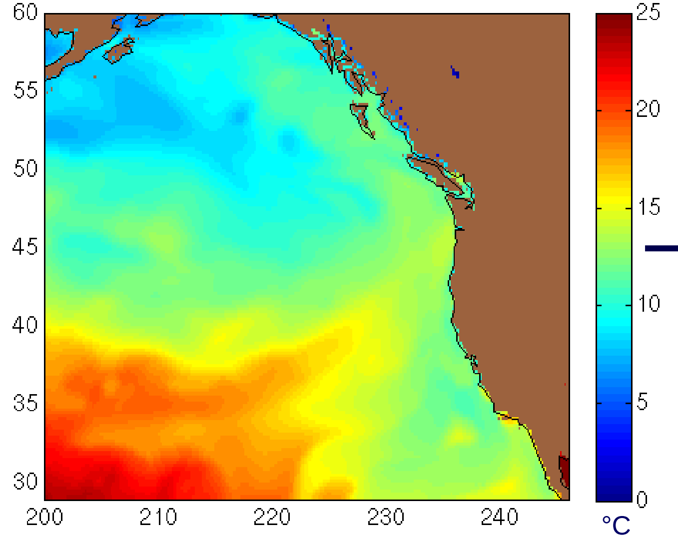




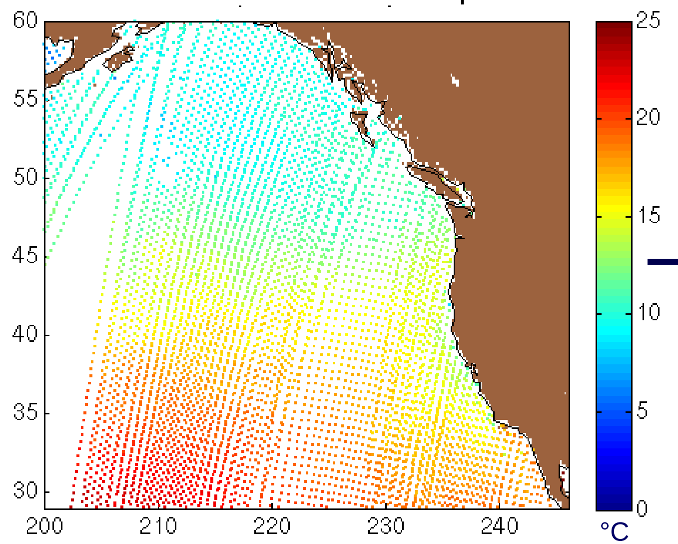
Analyses and forecasts from models assimilating
these satellite observations are compared with
independent SST measurements from drifting buoys

Use satellite measurements to correct estimates of fields contributing to heat flux

Forecast air temperature

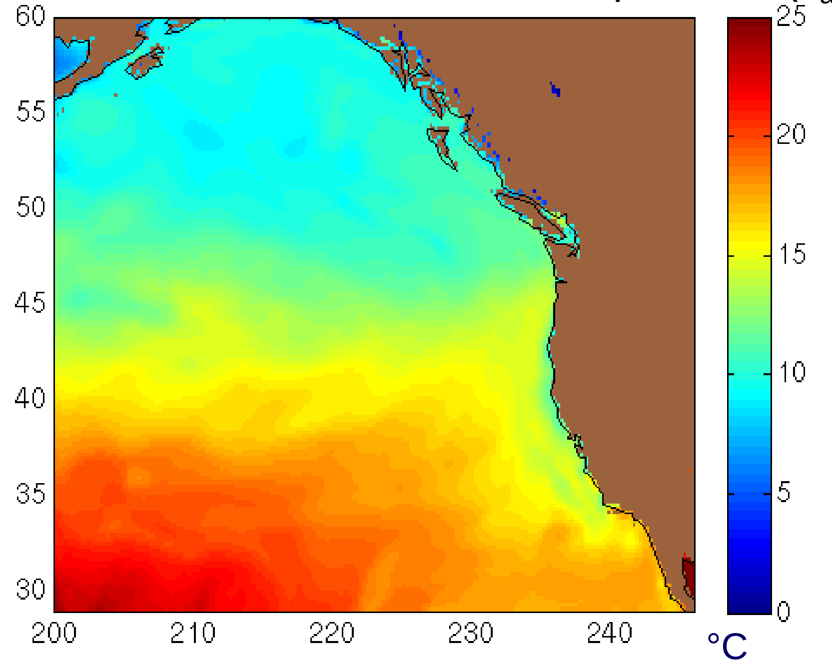


Satellite-observed air temperature



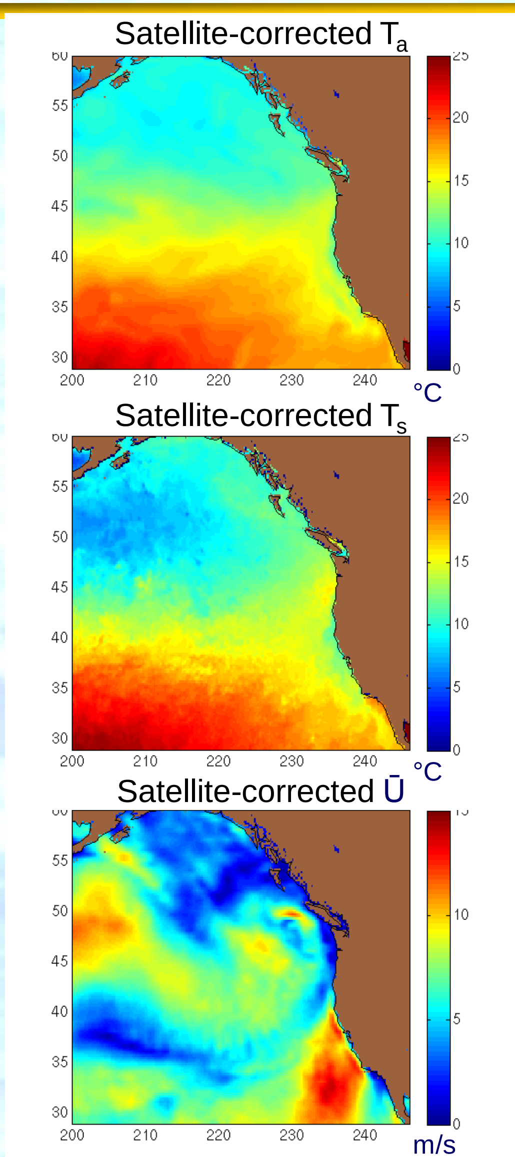
Combine satellite, in situ, and model data to make satellite-corrected estimates of properties used to calculate heat flux: temperatures, humidity, wind speed, etc.

Satellite-corrected surface air temperature (T_a)

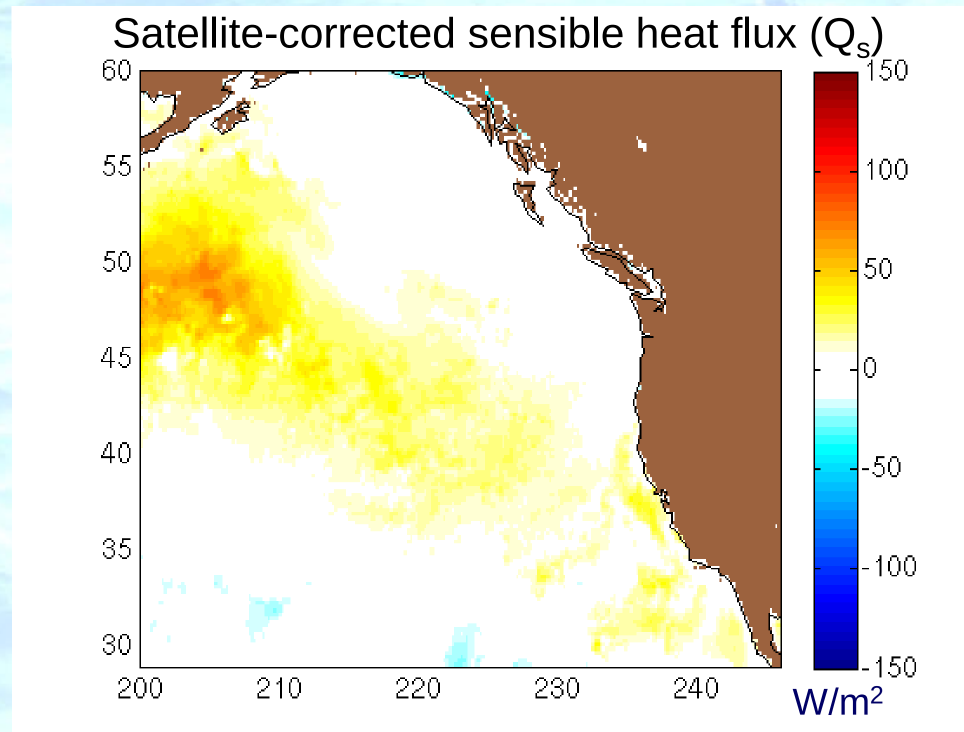


1 July 2010 12Z

Use satellite measurements to correct estimates of fields contributing to heat flux



Satellite-corrections in surface properties lead to satellite-corrected surface fluxes.

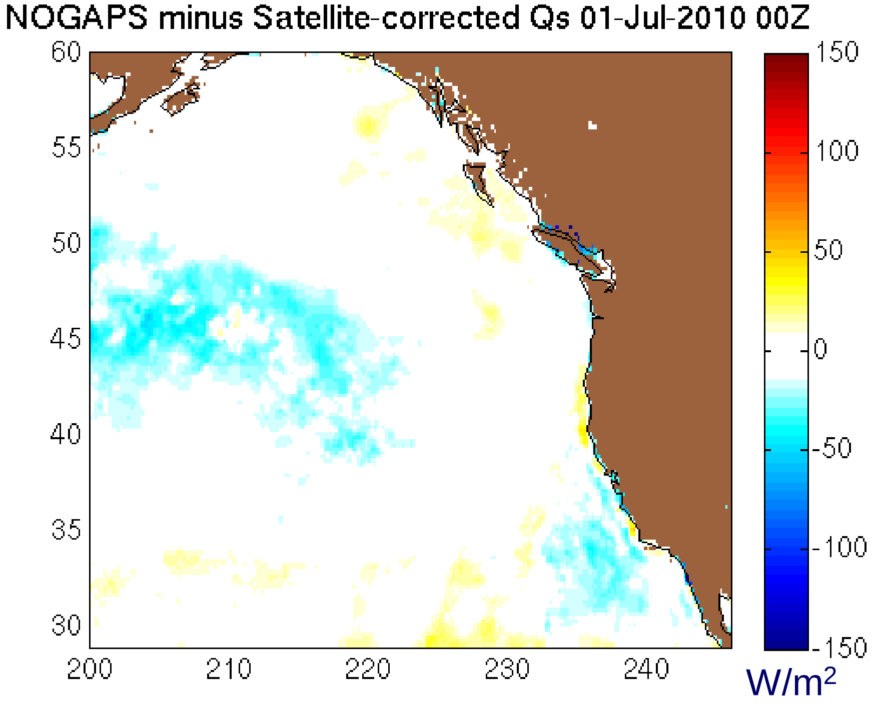


1 July 2010 12Z

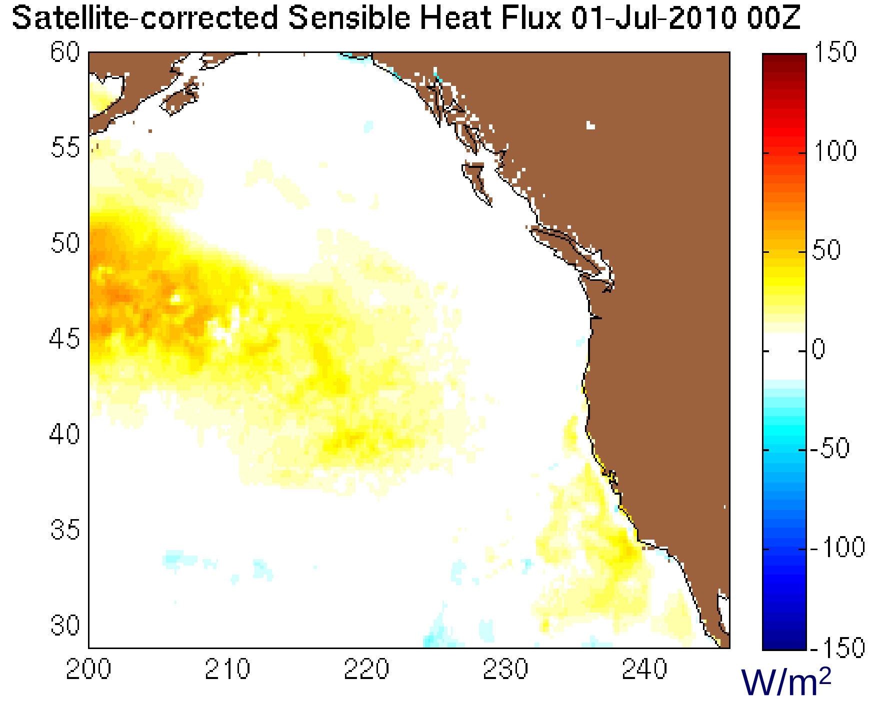
Use satellite measurements to correct estimates of fields contributing to heat flux

The time series of sensible heat flux bias provides a basis for automatically estimating the flux error covariance.

Estimated sensible heat flux bias



Satellite-corrected sensible heat flux (Q_s)



4DVAR adjusts the background state trajectory toward satellite observations

What is the best estimate of the ocean state **x**? Variational assimilation finds it by balancing estimated errors to minimize a cost function *J*(**x**).

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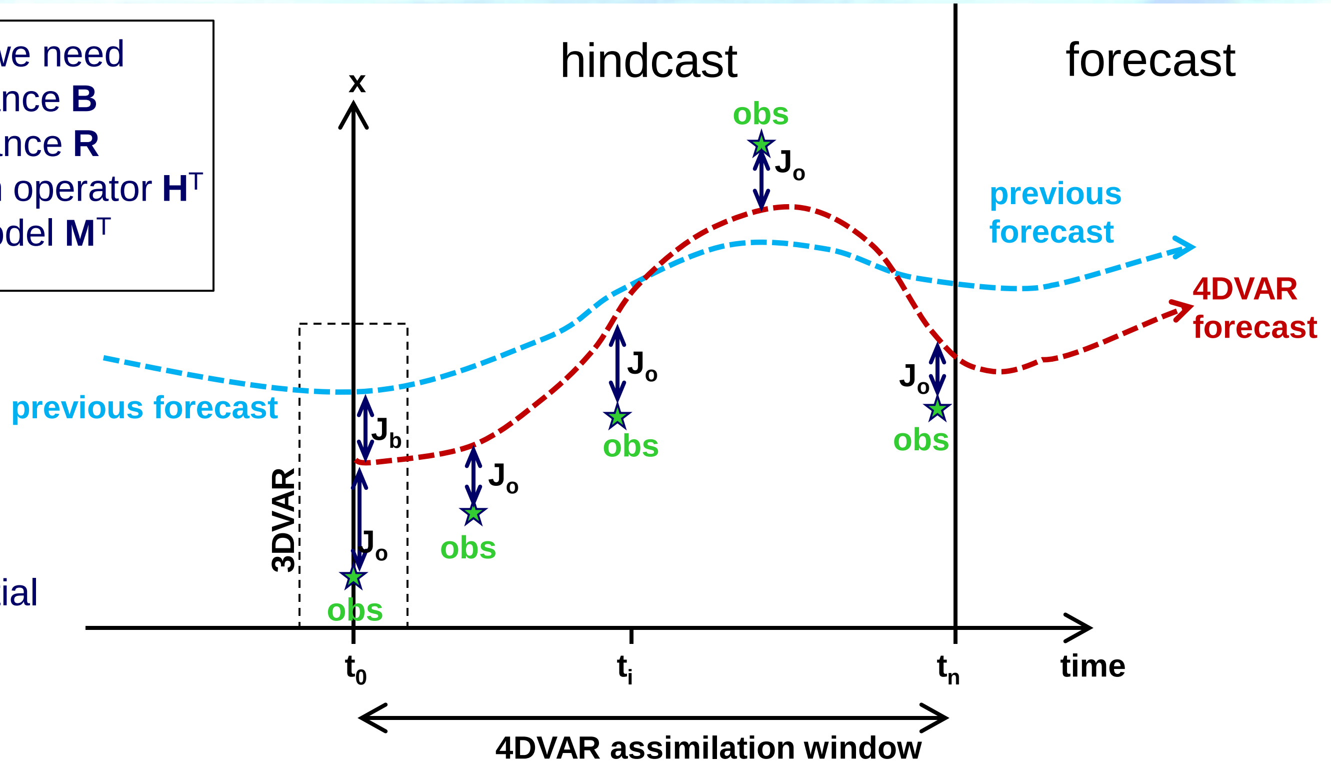
ocean covariances, models we need

- Background error covariance **B**
- Observation error covariance **R**
- Adjoint of the observation operator $\mathbf{H}^T$
- Adjoint of the forecast model $\mathbf{M}^T$



4DVAR uses observation increments over the hindcast window to adjust both the initial condition and model state trajectory

Weak-constraint 4DVAR includes background, observation, flux errors

In weak-constraint 4DVAR, terms associated with the model state are augmented by terms associated with the model system, e.g., surface heat flux.

$$J(\mathbf{x}) = \underbrace{(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b)}_{J_b} + \underbrace{(\mathbf{Hx}-\mathbf{y})^T \mathbf{R}^{-1}(\mathbf{Hx}-\mathbf{y})}_{J_o} + \underbrace{(\mathbf{b}-\mathbf{Mx})^T \mathbf{Q}^{-1}(\mathbf{b}-\mathbf{Mx})}_{J_q}$$

ocean covariances, models we need

- Background error covariance **B**
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- Adjoint of the observation operator $\mathbf{H}^T$
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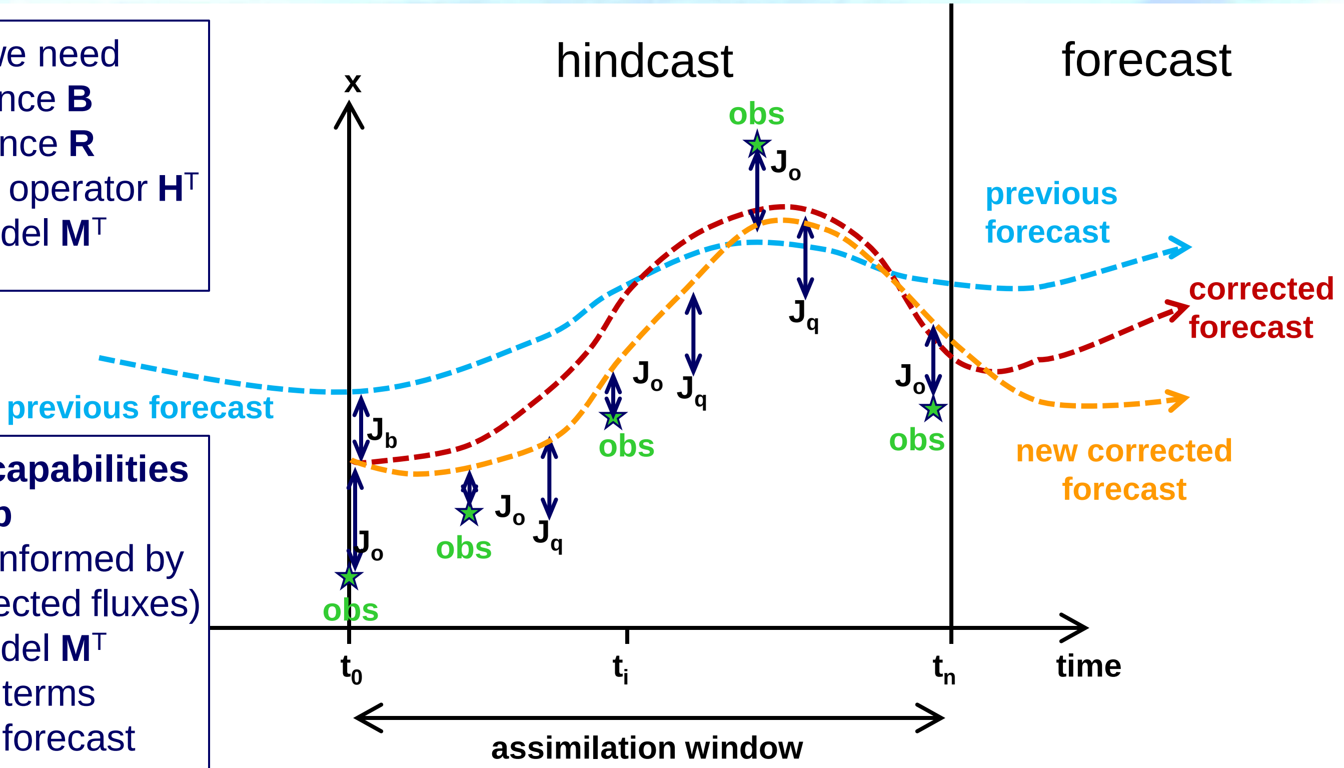


S&T Challenges in new capabilities

- Corrected flux estimates **b**
- Flux error covariance **Q** (informed by analysis of satellite-corrected fluxes)
- Adjoint of the forecast model $\mathbf{M}^T$ extended to include flux terms
- Correction of flux into the forecast period; reshaping the **trend** in addition to shifting the start

Summary

Model forecasts sufficiently simulate diurnal variations to account for mean diurnal signal.

The models exhibit a cold forecast bias

- 3DVAR accounts for biases are corrected at nowcast time
- 3DVAR is not designed to correct the forecast trend
- **Forecast bias can counteract use of best data, methodology.**

Weak constraint 4DVAR provides an avenue to use satellite-observed SST and heat flux factors to correct model nowcast and forecast skill

Results confirm the importance minimizing bias, bias inconsistencies among satellite data streams and importance of ocean model forecast skill for diurnal and longer time scales

New visitor to Stennis Space Center, MS
19 June 2013

Official guidance: do not feed the alligators or bears; leave them alone

Abstract

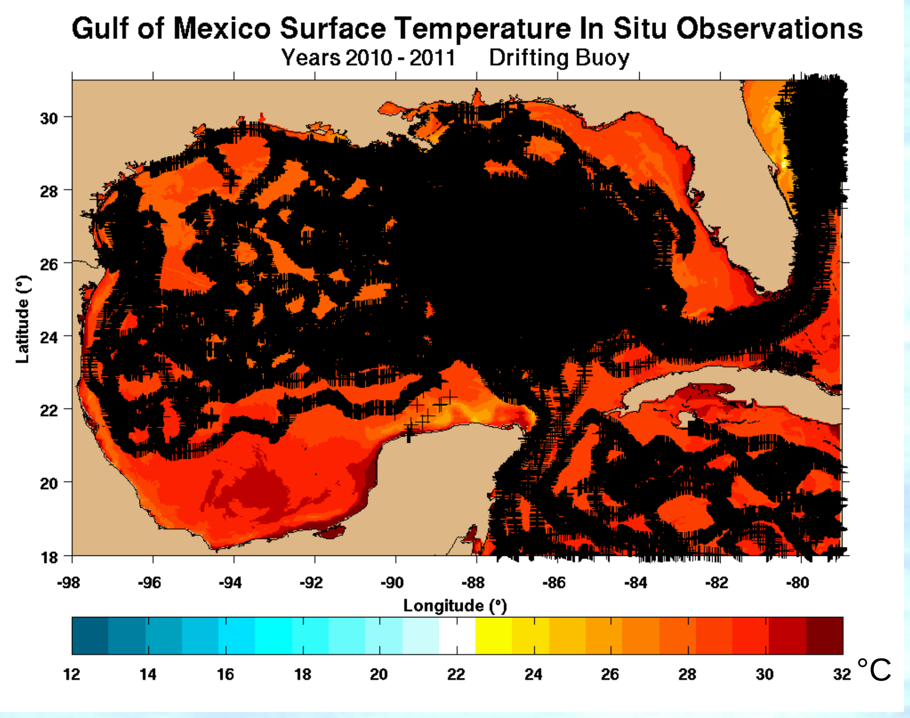
Sea surface temperature (SST) and thermal stratification in the Gulf of Mexico exhibit variability on diurnal to seasonal scales due to the interactions of surface heat fluxes, Loop Current intrusion, eddy shedding, and biological modification of solar attenuation. Variational treatment of mismatches between forecasts and observations of these conditions can be used to diagnose and mitigate model errors that lead to consistent biases. The impacts of various satellite data streams and alternative assimilation methodologies are evaluated in this context by comparing model analyses and forecasts to unassimilated ship and buoy observations. Seasonal and diurnal trends in the forecast errors identify low SST biases during the summer and local afternoon, periods of peak solar radiation. Assimilative model studies are used to estimate the relative contributions of errors in heat flux/total energy input and errors in solar attenuation/thermal stratification/vertical energy distribution.

Backup Slides

Impact of polar and geostationary satellite data on assimilative forecasts

Infra-red observations of Gulf of Mexico SST are available from the polar-orbiting NOAA and MetOp satellites and geostationary GOES

- NOAA 18 Global Area Coverage (GAC)
- NOAA 19 GAC and LAC (local area coverage)
- Sun-synchronous, mid-afternoon orbits
- AVHRR/3 imager
- 1.1 km pixels, GAC processed to ~4 km at NAVOCEANO; 2 per day per satellite
- IR is obscured by clouds



- Geostationary Operational Environmental Satellite
- GOES 12 Jan-Apr 2010
- GOES 13 June 2010+
- Geostationary
- GOES Imager
- 4 km pixels, every 30 minutes
- SST processed by NAVOCEANO
- IR is obscured by clouds

Analyses and forecasts from models assimilating these satellite observations are compared with independent SST measurements from drifting buoys

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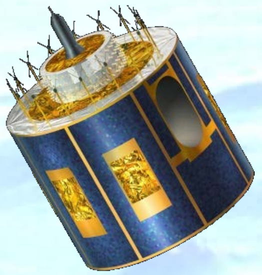
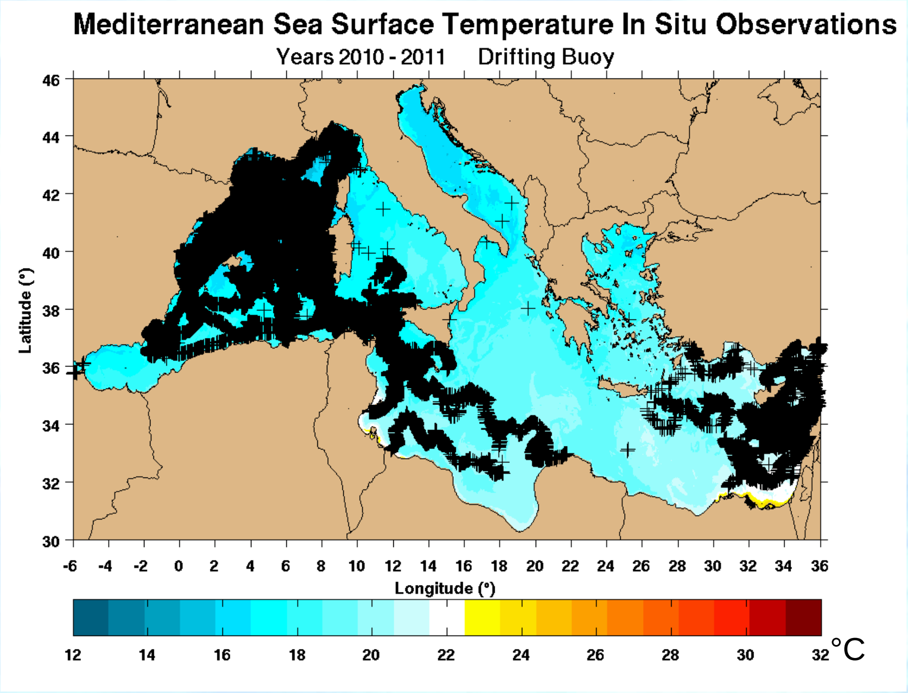


- NOAA 18 Global Area Coverage (GAC)
- NOAA 19 GAC and LAC (local area coverage)
- Sun-synchronous, mid-afternoon orbits
- AVHRR/3 imager
- 1.1 km pixels, GAC processed to ~4 km at NAVOCEANO; 2 per day per satellite
- IR is obscured by clouds



- Geostationary Operational Environmental Satellite
- Meteosat 9 2010-2011
- Geostationary
- SEVIRI Imager
- 3 km pixels, every 15 minutes
- SST processed by IFREMER/METEO-France
- IR is obscured by clouds

Analyses and forecasts from models assimilating these satellite observations are compared with independent SST measurements from drifting buoys