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Impact of Satellite Observations on SST Forecasts via Variational Data Assimilation and Heat Flux Calibration

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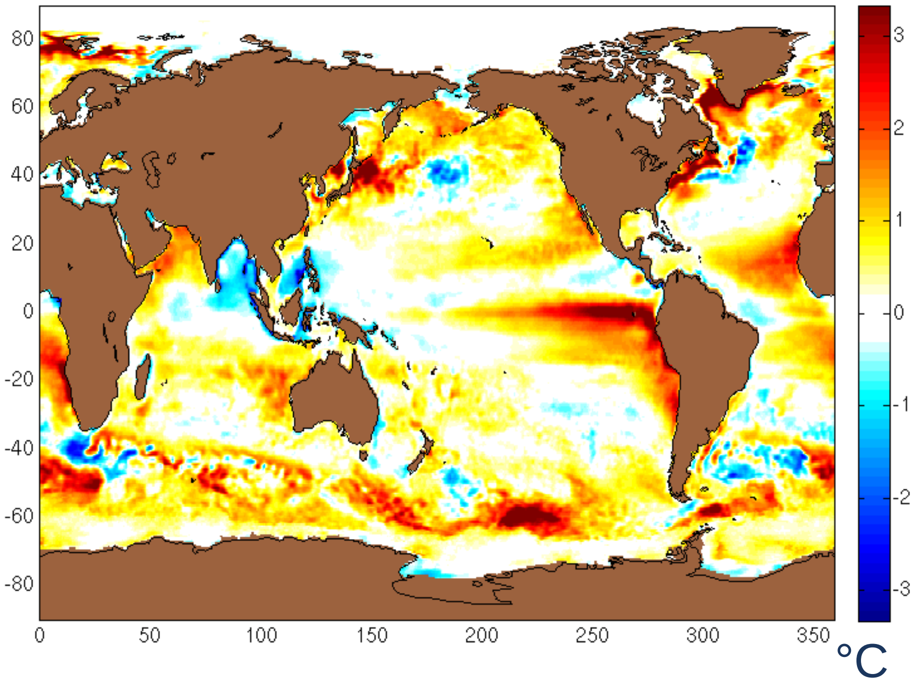
Motivation: Non-assimilative ocean simulations have temperature bias

Calculate bias by running the global ocean model for an extended period, using forcing from the global atmospheric model.
Compare to observed mean SST.

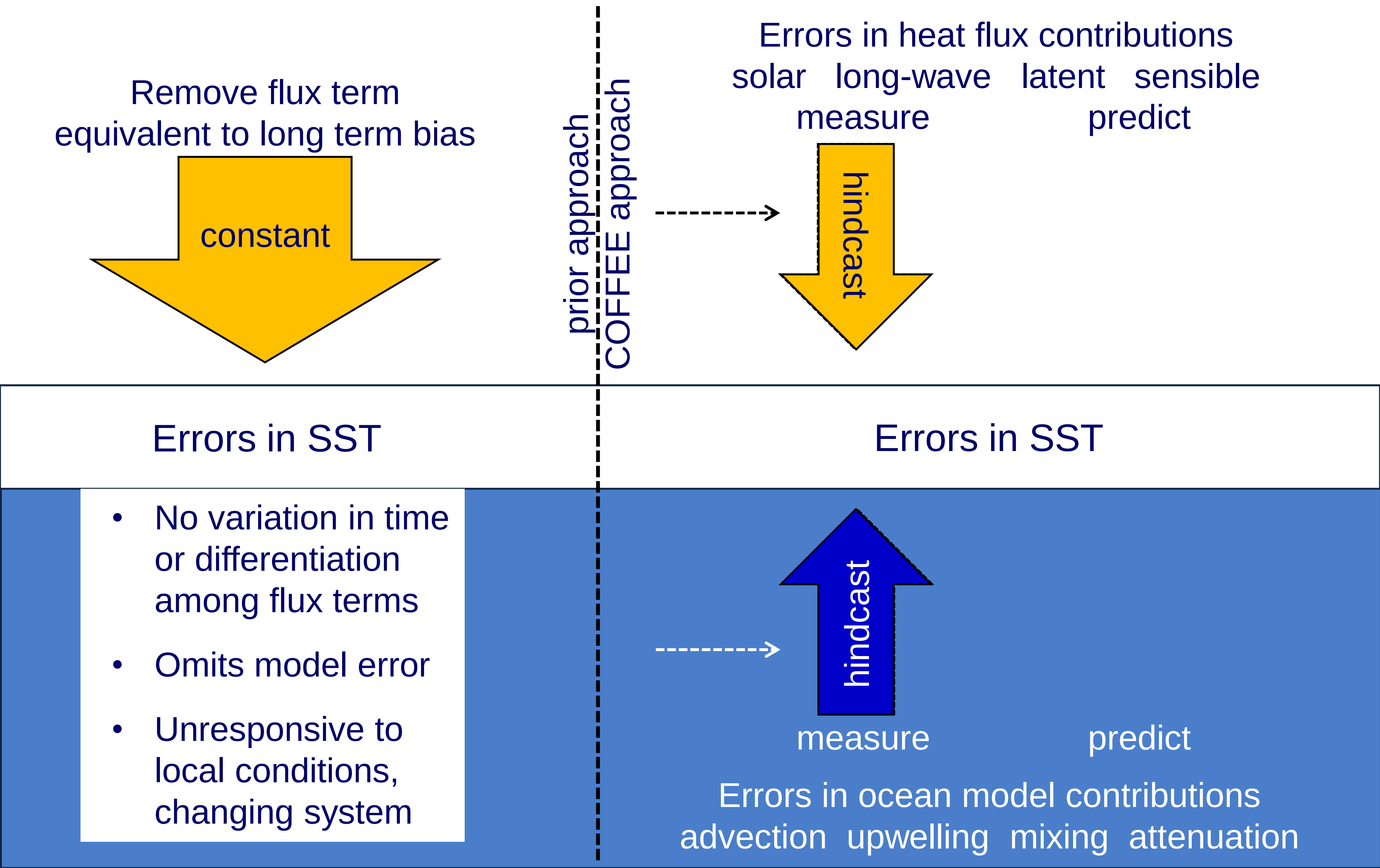
annual Sea Surface Temperature (SST) bias



Without assimilation, simulations exhibit a significant SST bias

We could change the mean heat flux to account for the long term bias, but this would be unrealistic …

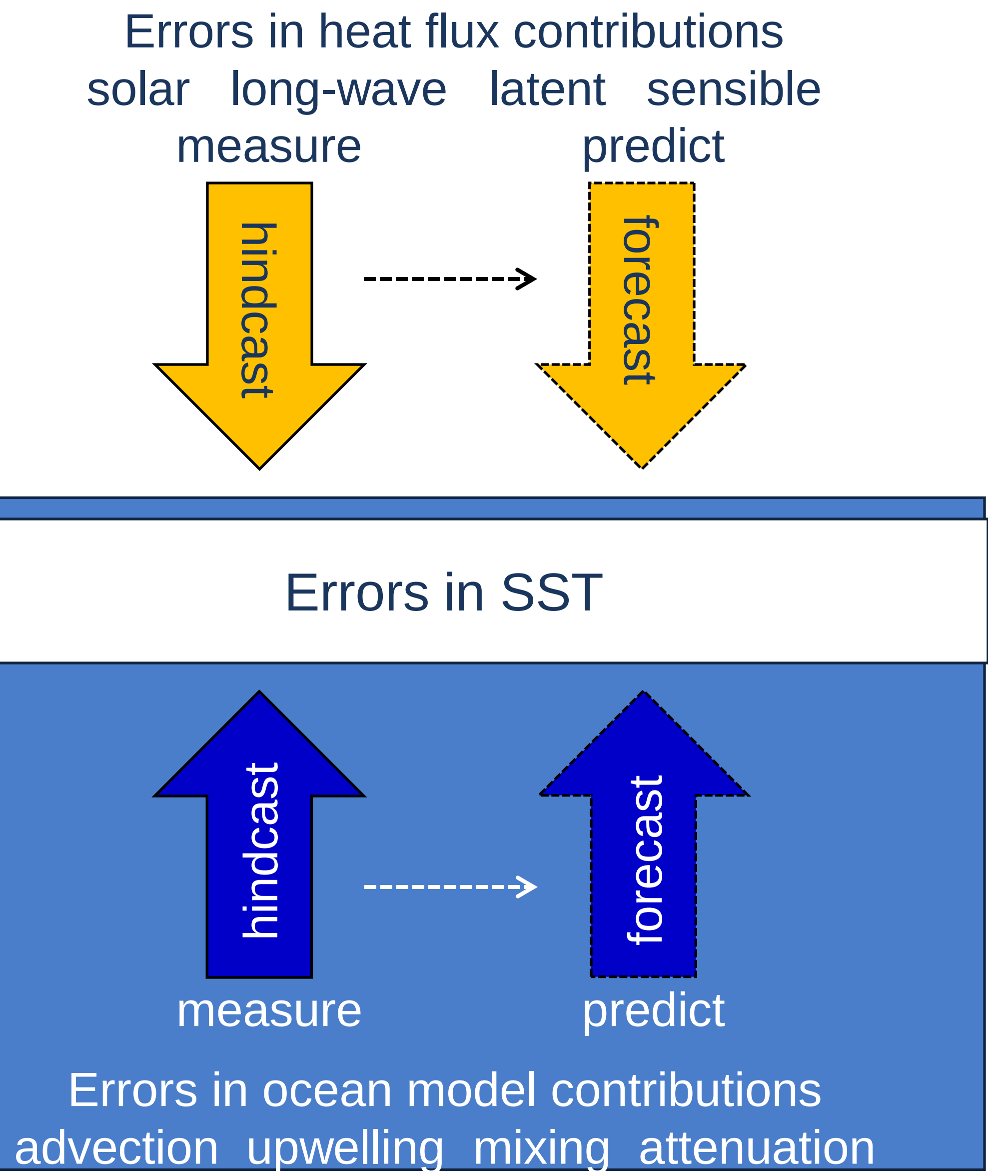
Paradigm shift: from constant bias to time-dependent partition



Use satellite observations, 4DVAR to estimate flux error, guide correction

Use satellite observations to estimate flux values and errors

Relate mismatches with ocean observations to errors in the surface flux and ocean state



Heat Flux Components

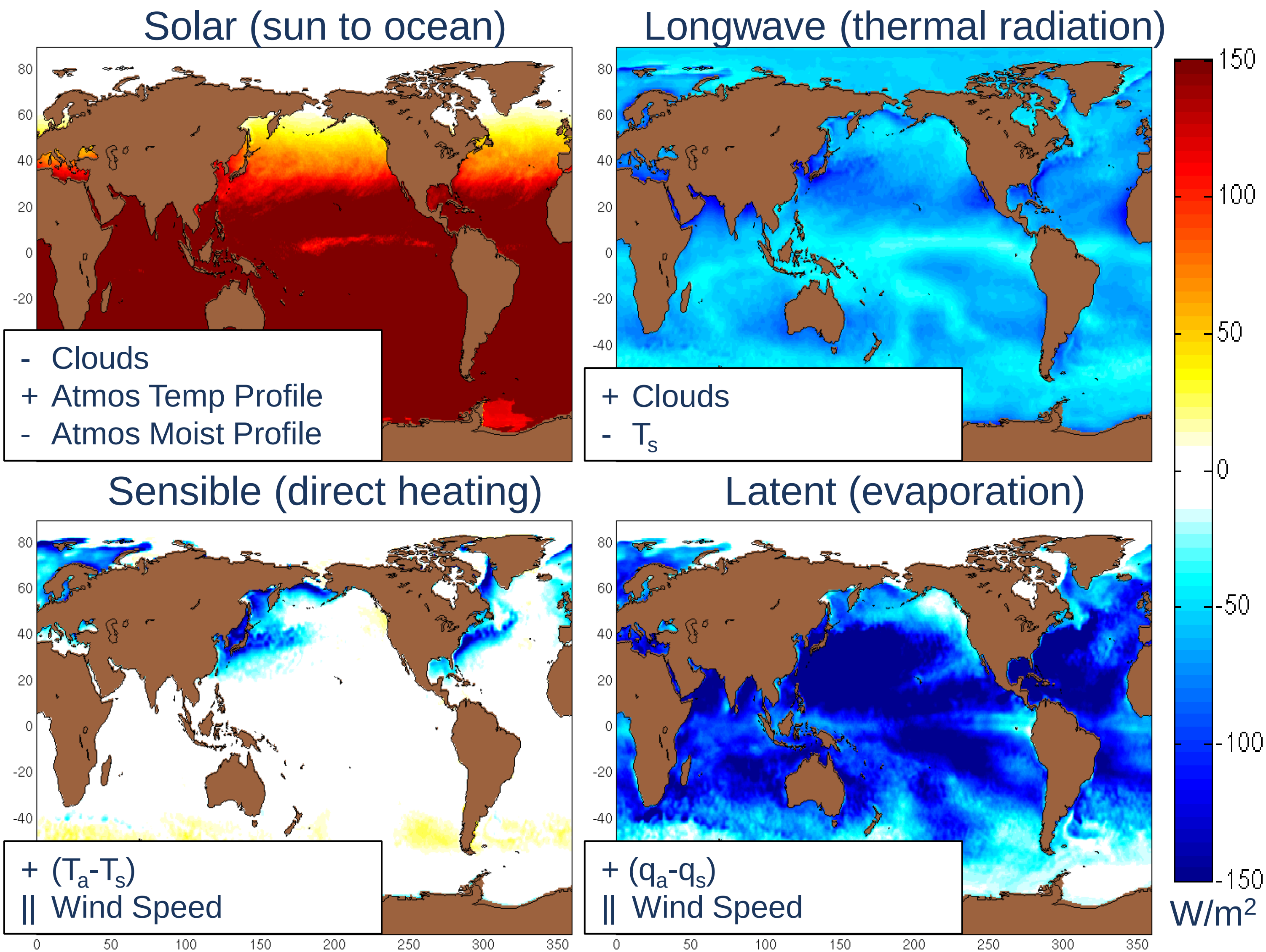
Mean January surface heat flux

Use convention that positive flux is atmosphere→ocean

Positive (red) warms ocean; (blue) cools ocean

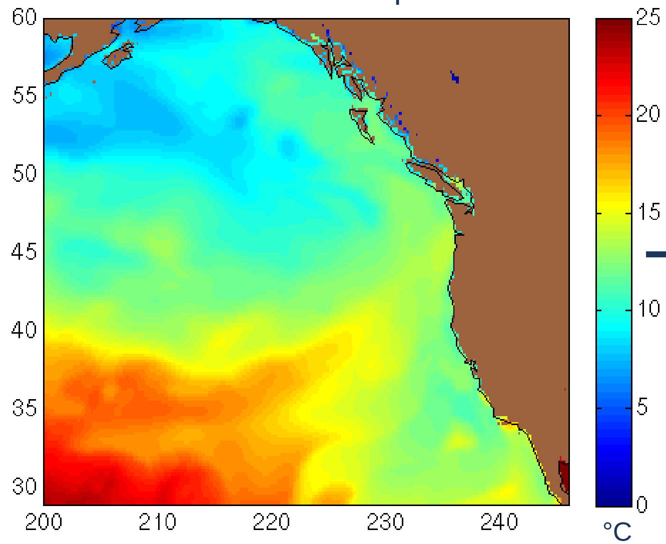
Quantify sensitivity of flux errors to errors in ocean, atmospheric properties

Flux sensitivity:
- + positive
- - negative
- || magnitude only

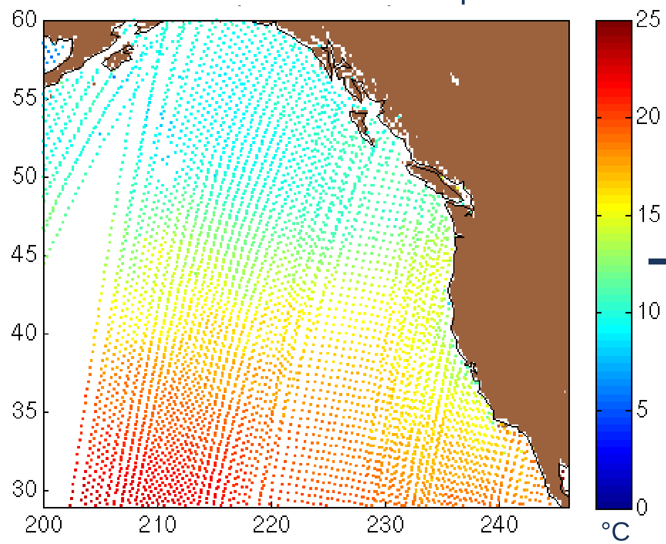


Use satellite measurements to correct estimates of contributing fields

Forecast air temperature

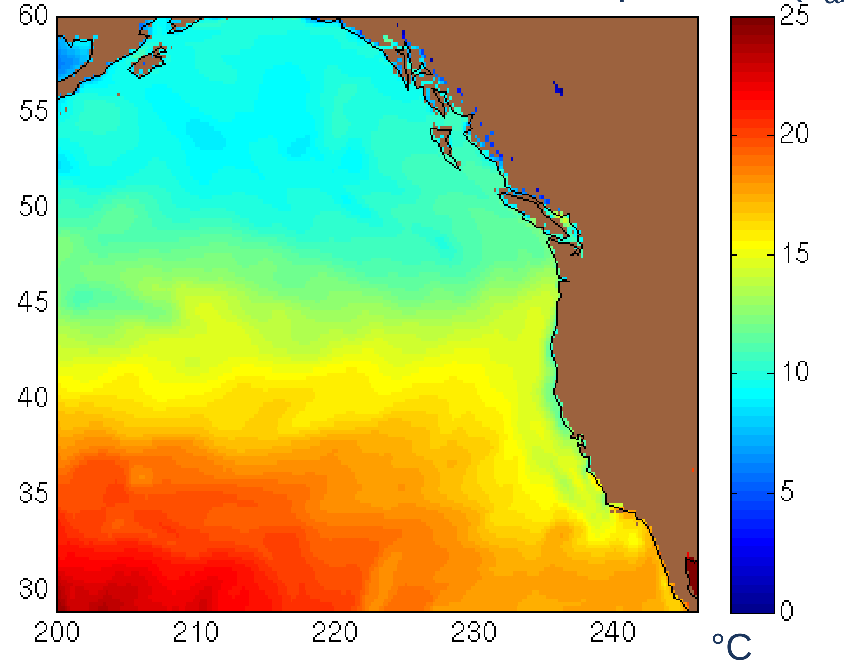


Satellite-observed air temperature



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)

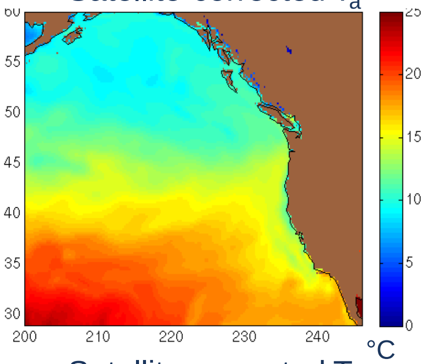


1 July 2010 12Z

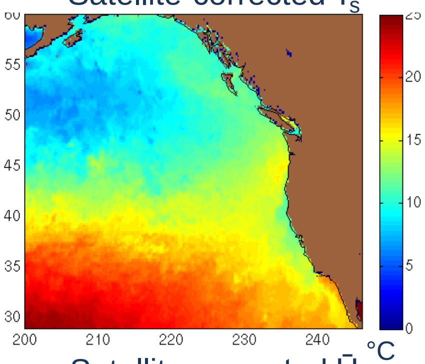
Use satellite measurements to correct estimates of contributing fields, heat flux

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

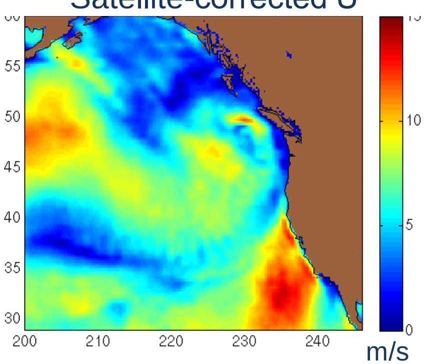
Satellite-corrected T_a



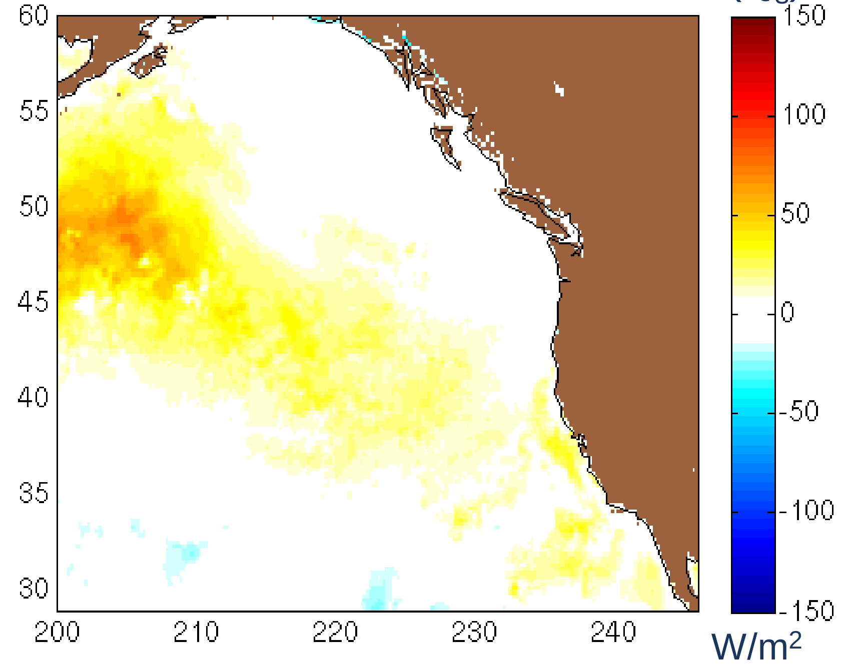
Satellite-corrected T_s



Satellite-corrected $\bar{U}$



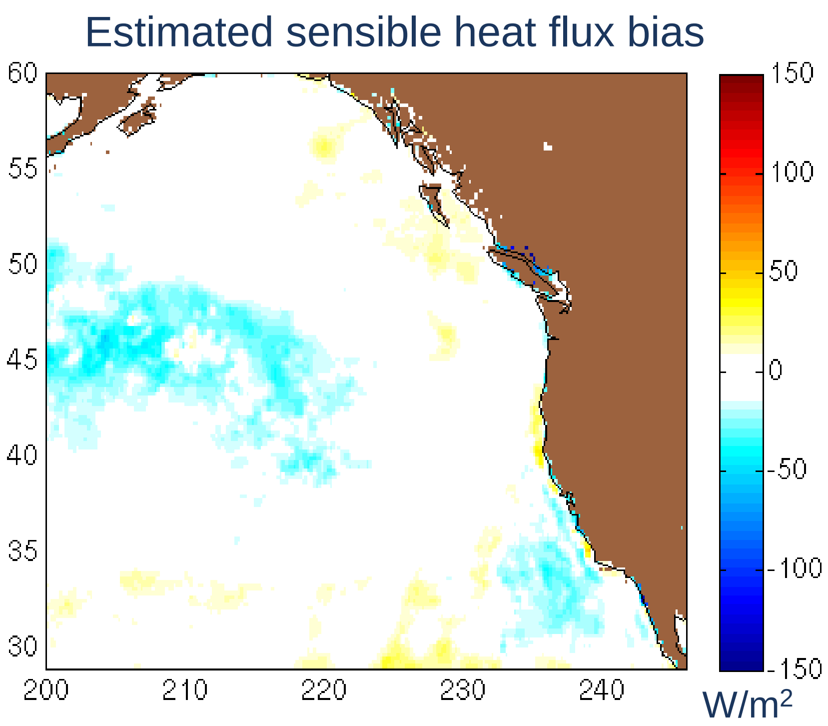
Satellite-corrected sensible heat flux (Q_s)

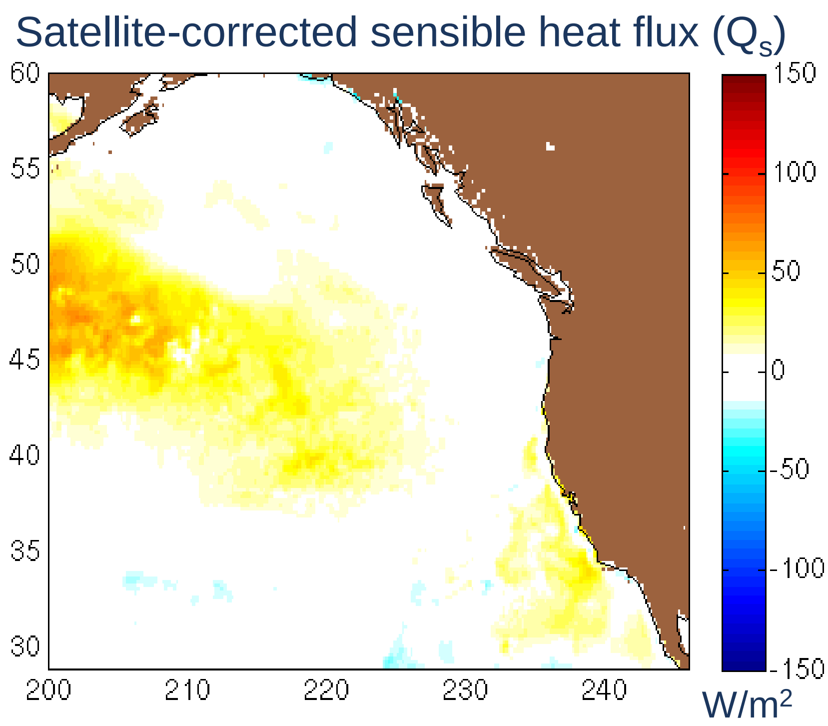


1 July 2010 12Z

Prepare a time series of satellite corrected heat fluxes to estimate error covariance

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

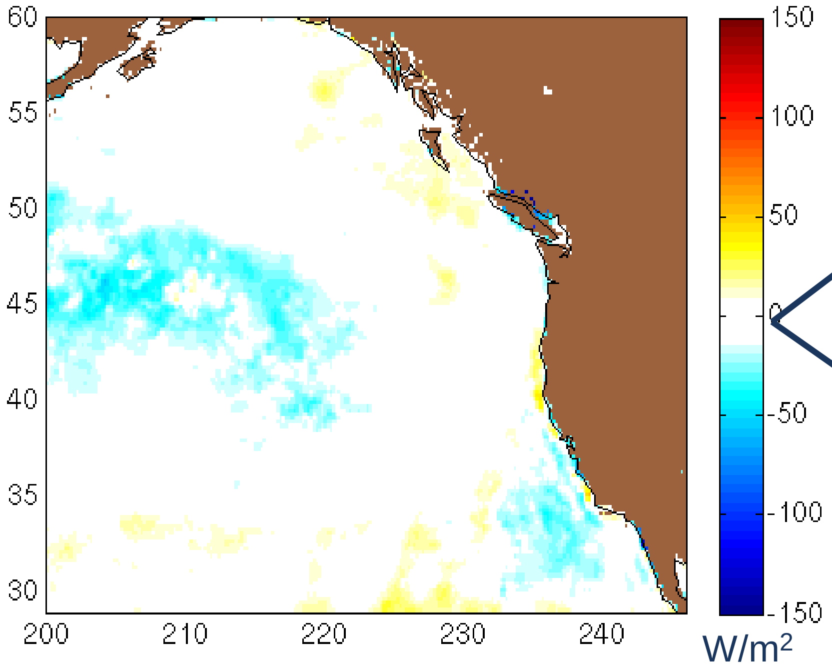




Use flux error covariance to relate hindcast observations to flux corrections

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

Estimated sensible heat flux bias



Decompose hindcast corrections into persistent and transient modes to inform forecast corrections

- Persistent bias correction
- 20-day running average
- Apply in full over forecast

- Transient bias correction
- Daily running average of remaining bias
- Weight by decorrelation scale

NFLUX reduces turbulent flux errors

Flux or Constituent		Bias	St. Dev.	RMSE	R^2	N
Air temp T_a (°C)	NFLUX	0.24	1.22	1.24	0.98	199,944
	NAVGEM	-0.30	1.21	1.25	0.98	
Humidity q_a (g kg^{-1})	NFLUX	0.25	1.18	1.21	0.96	117,298
	NAVGEM	-0.50	1.19	1.29	0.96	
Wind speed $\overline{U}$ (m s^{-1})	NFLUX	0.21	2.06	2.07	0.64	194,649
	NAVGEM	-0.33	2.14	2.17	0.63	
Latent Flux Q_{LH} (W m^{-2})	NFLUX	-17.41	59.31	61.81	0.49	15,707
	NAVGEM	14.28	62.70	64.30	0.49	
Sensible Flux Q_{SH} (W m^{-2})	NFLUX	-2.06	19.21	19.32	0.48	15,707
	NAVGEM	2.28	19.71	19.84	0.51	
Shortwave Flux Q_{SW} (W m^{-2})	NFLUX	23.98	150.00	151.90	0.74	10,066
	NAVGEM	25.58	153.98	165.96	0.69	
Longwave Flux Q_{LW} (W m^{-2})	NFLUX	-5.41	28.75	29.25	0.75	17,138
	NAVGEM	-10.72	33.05	34.75	0.72	

Sat-estimated heat flux: NFLUX prepared daily; similar NASA products are delayed

NFLUX is prepared daily

- for operational short-medium forecasts
- real-time satellite data
- See May *et al.*, *Applied Meteorology and Climatology*, 2016

NASA products are delayed weeks-months

- for long-term climatological forecasts
- use delayed-mode satellite data
- CERES (Kratz et al., 2010) delayed 6+ months
- FLASHFlux (Kratz et al., 2014) delayed 1 week

NFLUX gives us the capability to use satellite observations to estimate flux values and errors

4DVAR data assimilation gives us the capability to relate mismatches with ocean observations to errors in the surface flux and ocean state

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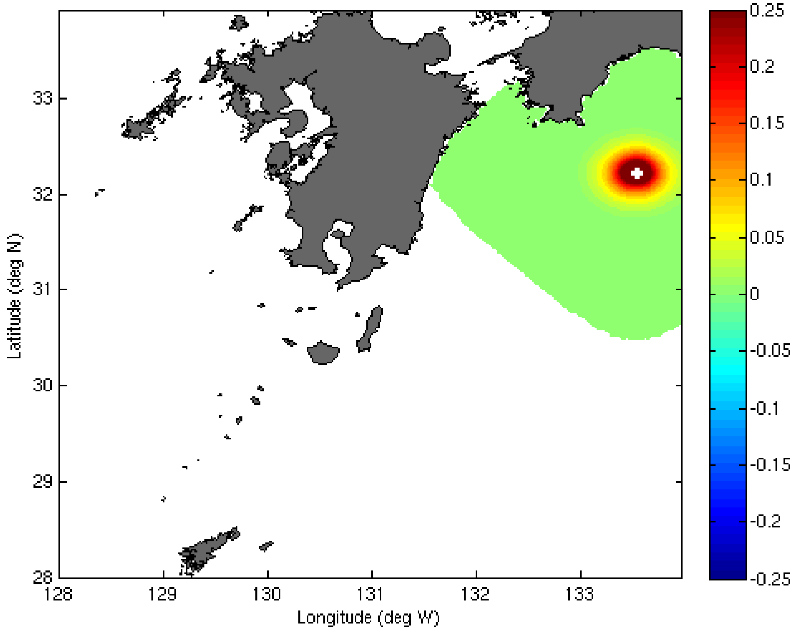
Variational data assimilation: 3DVAR, 4DVAR adjust the model state

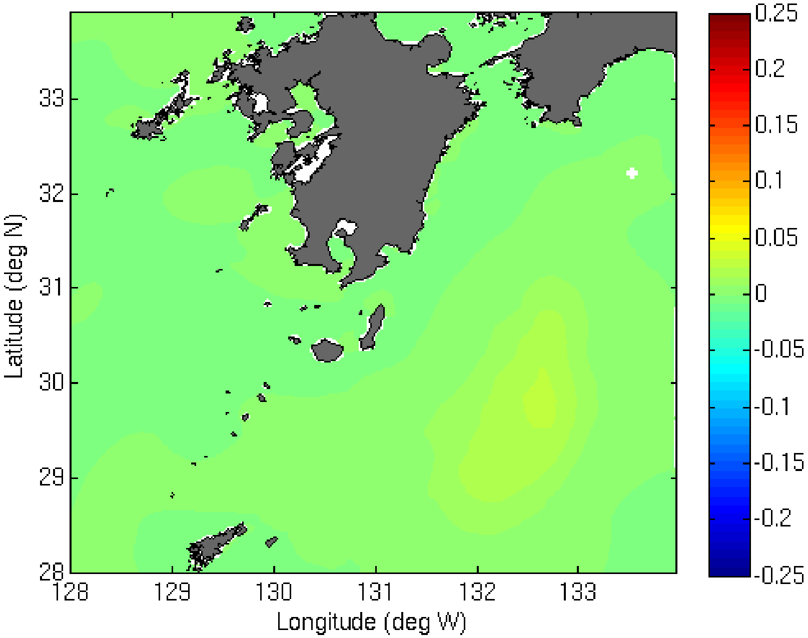
3DVAR corrects the initial state only
4DVAR extends observation correction in time and space along model flow
Extended 4DVAR includes boundary-layer with ocean in adjoint, TLM

3DVAR SST increments (°C)



RELO NCOM: Rowley and Mask, 2014

4DVAR SST increments (°C)



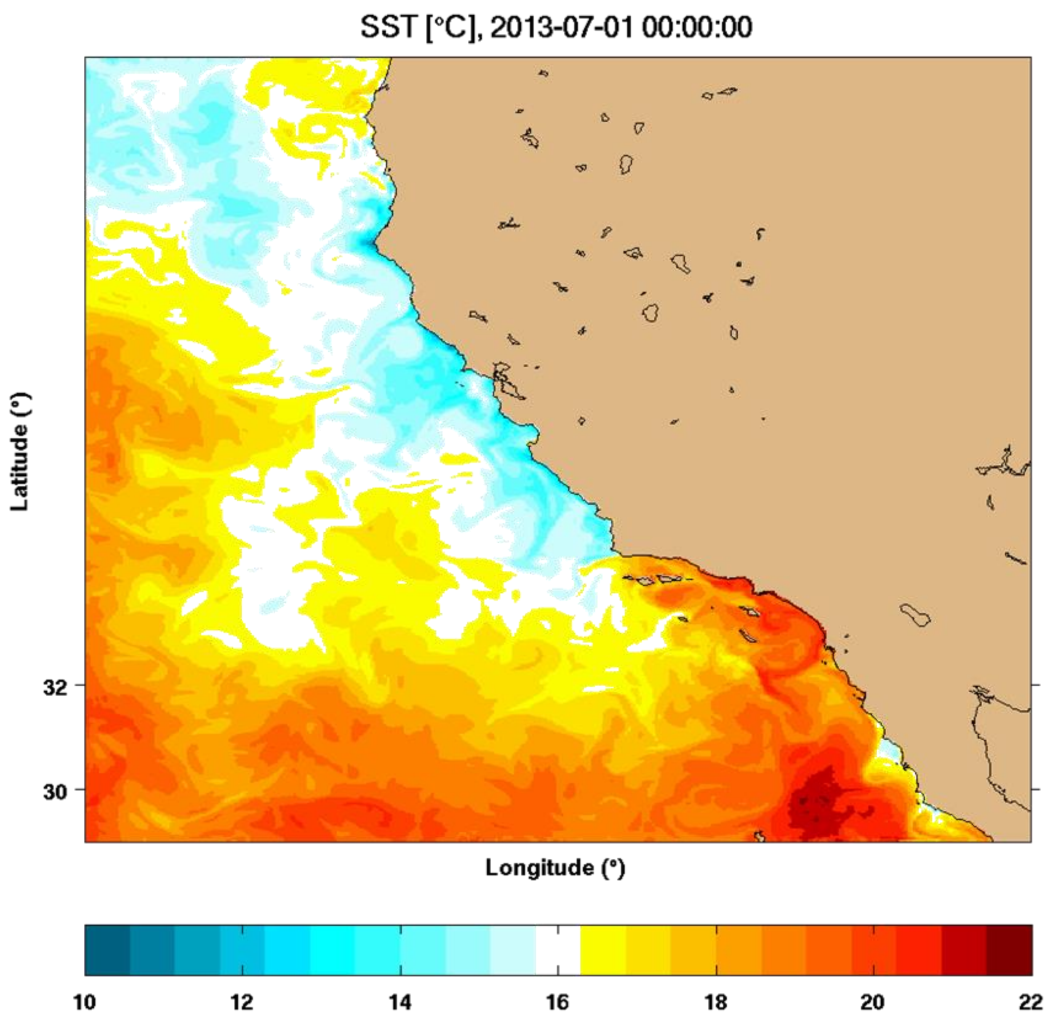
NCOM 4DVAR: Ngodock et al., 2014

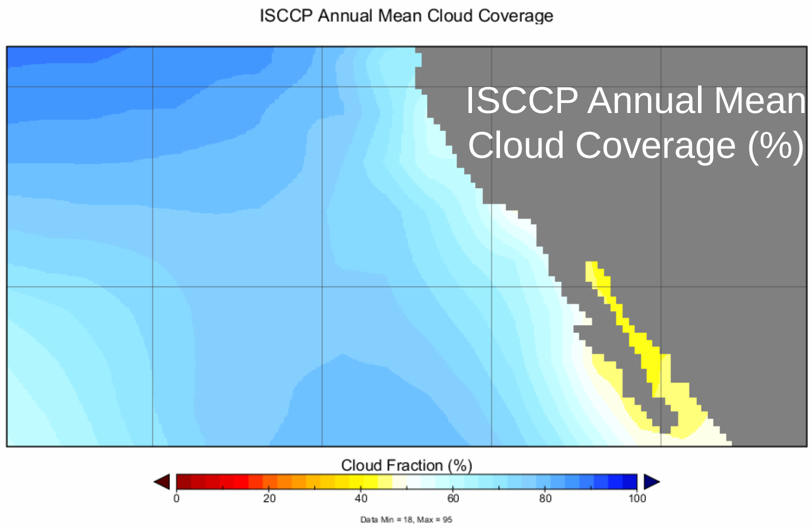
COFFEE experiments using NFLUX and variational assimilation

	Fluxes	Assimilation Type: 3DVAR	Assimilation Type: 4DVAR standard	Assimilation Type: 4DVAR ocn + bdry layer
COAMPS	unmodified	■	■	
COAMPS	NFLUX-corrected hindcast	■	■	
COAMPS	NFLUX-corrected forecast			
NAVGEM	unmodified	■	■	
NAVGEM	NFLUX-corrected hindcast	■	■	
NAVGEM	NFLUX-corrected forecast			

COFFEE has completed year-long May 2013-April 2014 experiments marked with the ■, the period coinciding with the MIRS cloud data.

Southern California Current: cloud gradients, eastern boundary upwelling





- Positive equivalent annual heat flux bias
- High cloud coverage, decreasing shoreward
- Eastern boundary current system with upwelling
- Results from 3DVAR NFLUX COAMPS

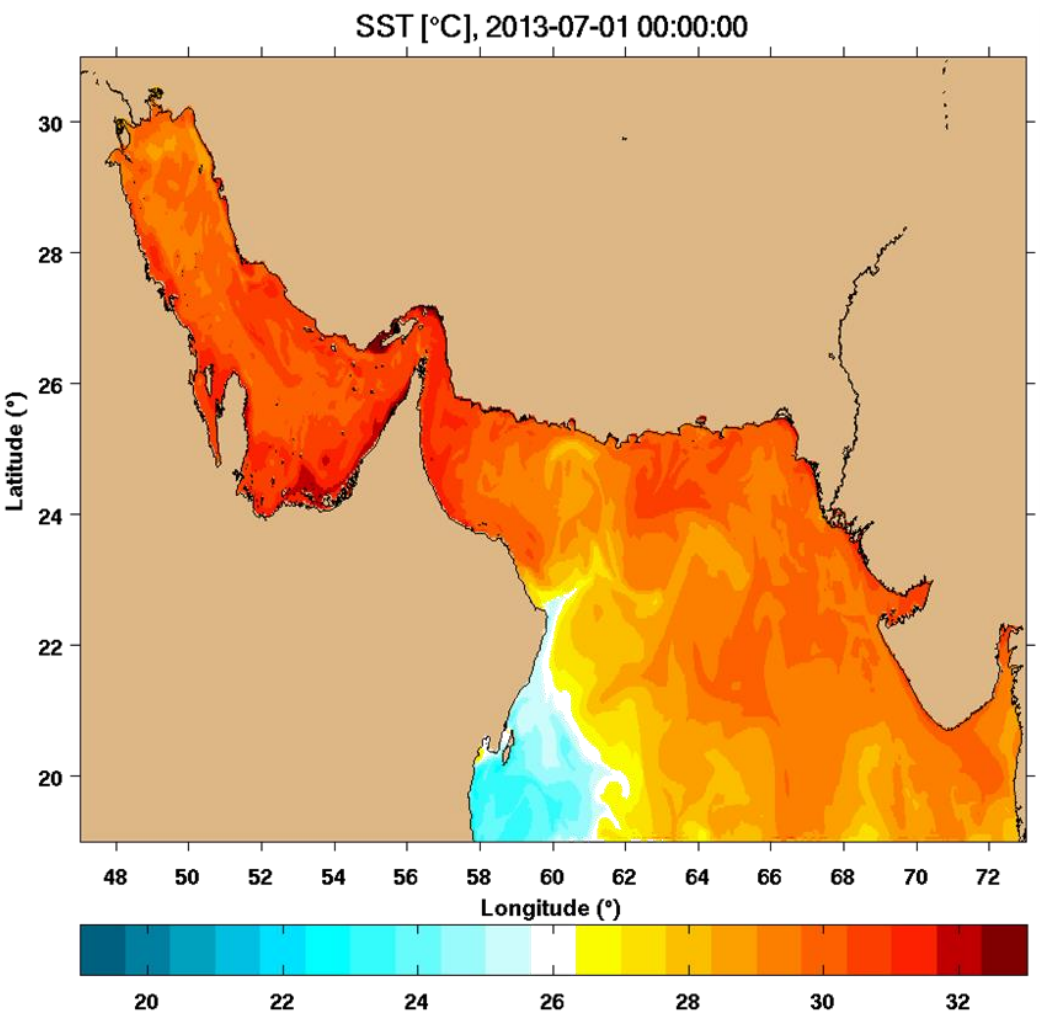
COFFEE experiment results (VIIRS)
California Current May 2013 – Apr. 2014

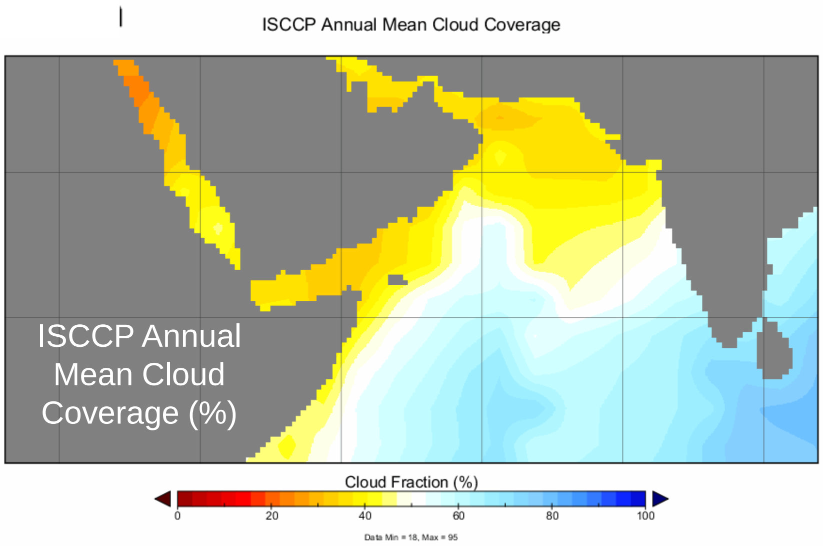
		NAVGEM								
		bias (°C)				rms error (°C)				N
	SOCAL case	24 h	48 h	72 h	96 h	24 h	48 h	72 h	96 h	42123179
VIIRS	3DVAR original	-0.15	-0.15	-0.15	-0.15	0.74	0.79	0.83	0.85	42123179
	3DVAR NFLUX	-0.14	-0.13	-0.12	-0.11	0.77	0.82	0.85	0.88	42123179
	4DVAR original	-0.17	-0.19	-0.20	-0.21	0.64	0.70	0.75	0.78	42123179
	4DVAR NFLUX	-0.13	-0.15	-0.15	-0.15	0.64	0.70	0.74	0.78	42123179

		COAMPS								
		bias (°C)				rms error (°C)				N
	SOCAL case	24 h	48 h	72 h	96 h	24 h	48 h	72 h	96 h	42123179
VIIRS	3DVAR original	-0.28	-0.31	-0.32	-0.31	0.79	0.84	0.88	0.90	42123179
	3DVAR NFLUX	-0.23	-0.25	-0.25	-0.25	0.79	0.84	0.87	0.89	42123179
	4DVAR original	-0.20	-0.25	-0.28	-0.28	0.66	0.73	0.78	0.81	42123179
	4DVAR NFLUX	-0.18	-0.21	-0.23	-0.23	0.65	0.72	0.77	0.79	42123179

NFLUX reduces forecast bias and RMS error.
4DVAR outperforms 3DVAR in 3 of 4 cases, similar in fourth.

Northern Arabian Sea: Low mean cloud coverage, monsoon effects, upwelling





- Low mean cloud coverage
- Monsoon cycle
- Upwelling east of Oman
- Differences between Persian Gulf and Arabian Sea
- Results from 3DVAR NFLUX NAVGEM

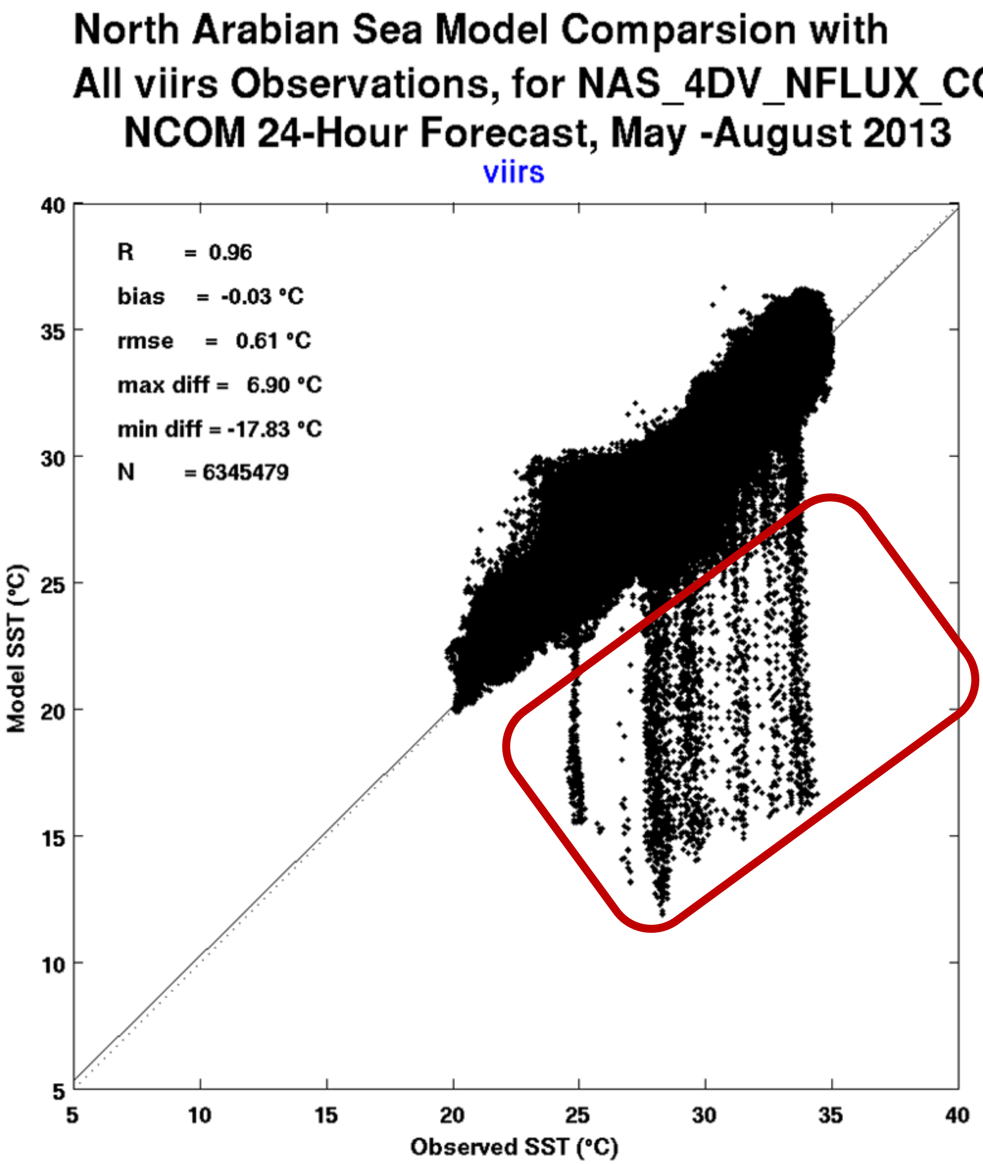
COFFEE experiment results (VIIRS)
North Arabian Sea May 2013 – Apr. 2014

		NAVGEM								
		bias (°C)				rms error (°C)				N
	NAS case	24 h	48 h	72 h	96 h	24 h	48 h	72 h	96 h	52156075
VIIRS	3DVAR original	-0.05	-0.08	-0.09	-0.08	0.43	0.50	0.53	0.55	52156075
VIIRS	3DVAR NFLUX	-0.05	-0.08	-0.09	-0.08	0.42	0.50	0.53	0.55	52156075

		COAMPS								
		bias (°C)				rms error (°C)				N
	NAS case	24 h	48 h	72 h	96 h	24 h	48 h	72 h	96 h	52156075
VIIRS	3DVAR original	-0.08	-0.13	-0.14	-0.14	0.45	0.53	0.57	0.60	52156075
VIIRS	3DVAR NFLUX	-0.06	-0.10	-0.11	-0.10	0.44	0.52	0.55	0.57	52156075

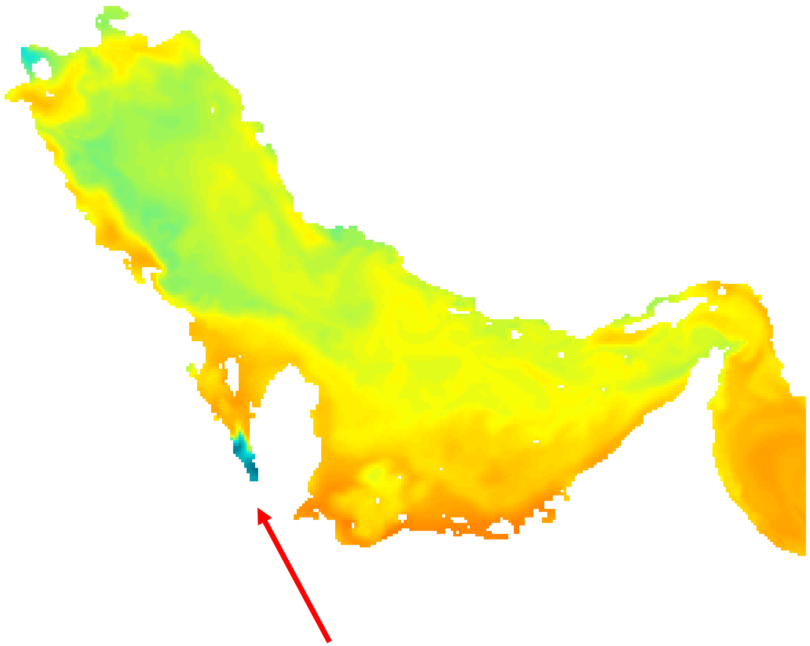
NFLUX reduces forecast bias and RMS error.
12-month 4DVAR results are incomplete.

COFFEE experiment results (VIIRS)
North Arabian Sea May 2013 – Apr. 2014

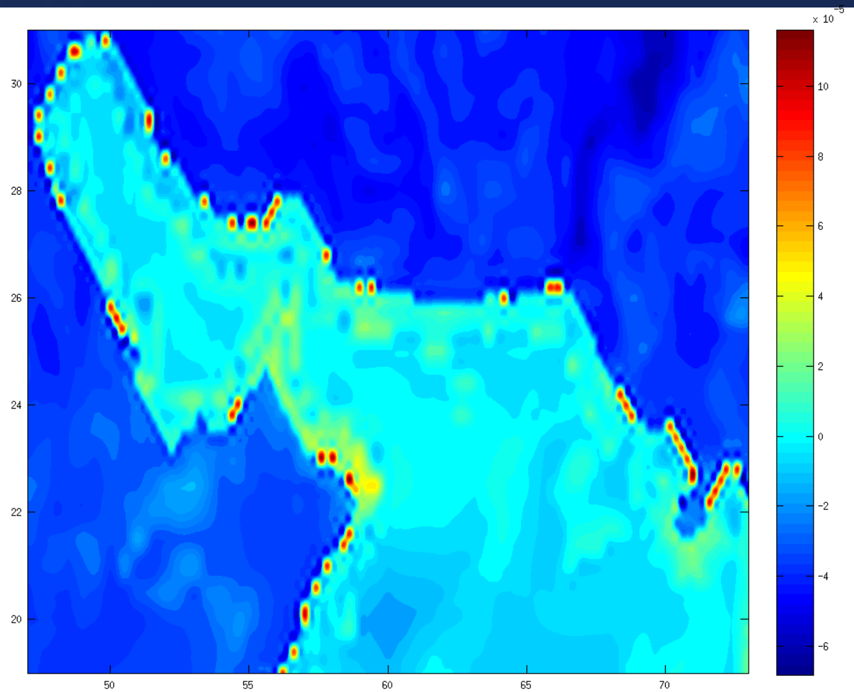


Small bias and RMS error in bulk statistcs over 6M matchups May-August 2016 obscures large errors occurring in a small number of comparisons

Identify nearshore NFLUX COAMPS error apparently due to mismatch in SST/land T



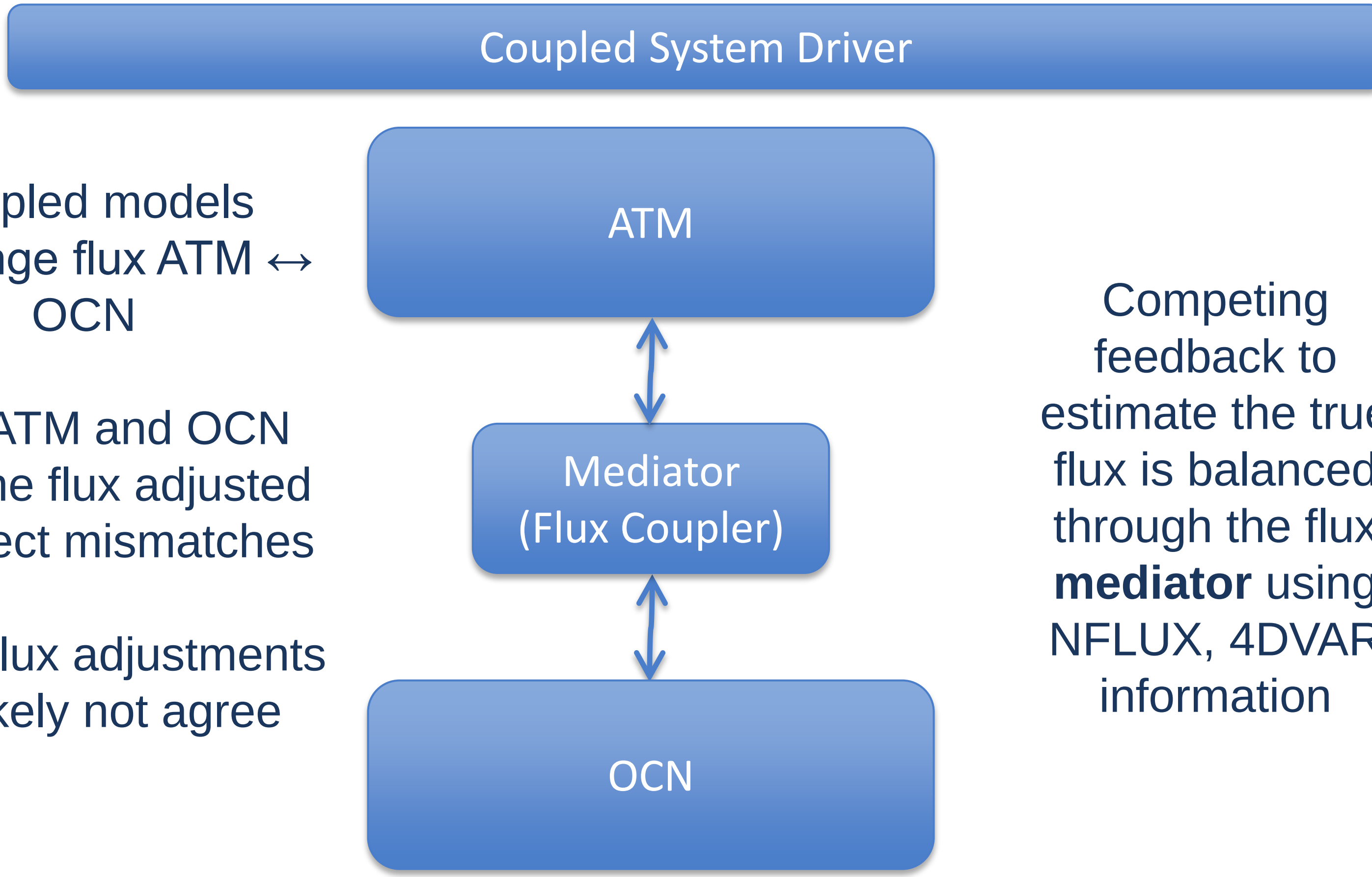
Spurious low values in May 2013, around 12°C



NFLUX_COAMPS longwave – NFLUX_NAVGEM longwave
Isolated discrepancies along the boundaries (including the coast of Qatar where the cold spot is)

Ongoing examination in extrapolating NFLUX longwave corrections nearshore

Payoff for coupled systems: capability to determine errors, balance of fluxes



Coupled models exchange flux ATM ↔ OCN

Both ATM and OCN want the flux adjusted to correct mismatches

These flux adjustments will likely not agree

Competing feedback to estimate the true flux is balanced through the flux **mediator** using NFLUX, 4DVAR information

NRL SSC postdoc opportunities

NRL SSC is recruiting postdocs interested in

- SST/radiance/flux data assimilation in coupled air/ocean/ice/wave forecast systems
- Velocity data assimilation in ocean models
- Automated guidance for unmanned observing systems (floats, gliders, Remus)

More info for postdocs: stipend ~$75K/year

ASEE: https://nrl.asee.org/

NRC: http://sites.nationalacademies.org/pga/rap/

(both open to US citizens or US permanent residents)

COFFEE - Conclusions

Errors in heat flux are significant for ocean forecasts

Assimilation of satellite retrievals relating to air, water temperatures and wind speed near the air-sea interface reduces errors in forecast turbulent heat flux

Assimilation of additional satellite observations reduces errors in forecast radiant heat flux

Using satellite-corrected heat fluxes reduces forecast errors of sea surface temperature

The combination of flux corrections with 4DVAR assimilation reduces errors more than either approach alone

Use of satellite-corrected fluxes or additional satellite retrievals relating to near-surface properties will likely be important in guiding coupled forecast systems