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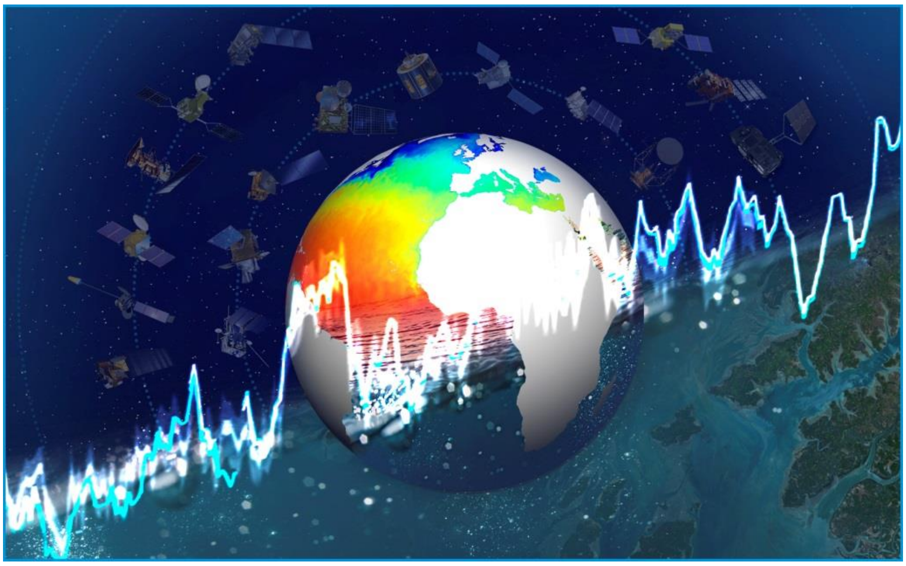

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POSTER ABSTRACTS

POSTER 2: FORECAST OF SST: CALIBRATION OF OCEAN FORCING WITH SATELLITE FLUX ESTIMATES (COFFEE)

Charlie N. Barron(1), Jan M. Dastugue(1), Jackie May(1), Clark Rowley(1), Scott R. Smith(1), Peter L. Spence(2), and Silvia Gremes-Cordero(3)

(1) Naval Research Laboratory, Code 7321, Stennis Space Center, MS, 39529, (USA),
Email: charlie.barron@nrlssc.navy.mil

(2) Vencore, Stennis Space Center, MS, 39529, (USA)

(3) University of New Orleans, Stennis Space Center, MS, 39529, (USA)

ABSTRACT

While satellite observations provide a solid basis to form a global analysis of recent sea surface temperature (SST), they are only part of the solution to ensure accurate SST forecasts. These observations can re-center SST from ocean models at the start of each forecast cycle, but subsequent evolution depends on estimates of surface heat fluxes and upper-ocean processes over the forecast period. A more complete application of satellite remote sensing not only informs the initial ocean state but also anticipates errors in surface heat flux and model representations affecting the distribution of heat in the upper ocean. The COFFEE project (Calibration of Ocean Forcing with satellite Flux Estimates) endeavors to correct ocean forecast bias through a responsive error partition among surface heat flux and ocean dynamics sources. A suite of experiments in the southern California Current demonstrates a range of COFFEE capabilities, showing the impact on forecast error relative to a baseline three-dimensional variational (3DVAR) assimilation using Navy operational global or regional atmospheric forcing. COFFEE addresses satellite-calibration of surface fluxes to estimate surface error covariances and links these to the ocean interior. Experiment cases combine different levels of flux calibration with different assimilation alternatives. The cases may use the original fluxes, apply full satellite corrections during the forecast period, or extend hindcast corrections into the forecast period. Assimilation is either baseline 3DVAR or standard strong-constraint 4DVAR, with work proceeding to add a 4DVAR expanded to include a weak constraint treatment of the surface flux errors. Covariance of flux errors is estimated from the recent time series of forecast and calibrated flux terms. While the California Current examples are shown, the approach is equally applicable to other regions. These approaches within a 3DVAR application are anticipated to be useful for global and larger regional domains where a full 4DVAR methodology may be cost-prohibitive.

1. Introduction

Inaccuracies in forecast SST can be attributed to errors in the initial state and errors in the forecast after the initial state. In the present standard operational approach, recent observations of SST are assimilated within the Navy Coupled Ocean Data Assimilation System (NCODA; Cummings, 2005) using 3D variational assimilation (3DVAR; Smith et al., 2012) to correct the initial state each day, taken to be at 00:00 UTC. A more flexible adjustment of the model is possible with 4DVAR assimilation (Smith et al., 2015), which enables the model trajectory to be also adjusted over the hindcast period leading to the nowcast state. Errors introduced into the forecast evolving from its initial state arise from two sources: (1) errors in the heat flux at the ocean surface, and (2) errors in the redistribution of heat within the ocean model.

The potential impact of errors during the forecast is evident from long non-assimilative, alternatively called free-running, multiyear ocean forecasts using the global Hybrid Coordinate Ocean Model (HYCOM; Chassignet et al., 2007). Evaluation of SST after multiple years of integration using forcing from the real-time operational atmospheric model NOGAPS (Navy's Operational Global Atmospheric Prediction System), reveals a mean annual bias exceeding ±3°C in places. This could be attributed to a proportional bias in the mean surface heat flux, where a mean flux bias of 45 W m^{-2} leads to a mean temperature bias of approximately 1°C. This implies that the net annual heat flux bias is as much as ±150 W/m^2, similar in magnitude to the annual mean of the flux itself.

This simple adjustment has been applied in the past, thereby attributing all of the error in estimating the annual mean SST to mean errors in the incoming heat flux. Such an approach is unrealistic, as it does not allow for variation in time, differentiation among flux terms, or errors in the ocean model. It also requires cumbersome reevaluation periods to account for shifting bias due to changes in components of the atmosphere or ocean prediction systems such as a change from NOGAPS to NAVGEM (Navy Global Environmental Model) or subsequent NAVGEM reformulations (Metzger et al., 2013). COFFEE represents a paradigm shift from this monolithic approach and instead endeavors to determine the time-dependent partition of error contributions among surface heat flux and ocean model contributions. If these errors can be measured and corrected in the hindcast period, then the error covariance should allow a projection and correction of errors into the forecast period. Such an approach is responsive both to changing local conditions and to updates in the overall modeling and assimilation system.

New advances in remote sensing and ocean data assimilation are leveraged to determine appropriate balances between errors in surface heat flux and other ocean factors affecting redistribution of heat. Our first hypothesis is that satellite observations can be used to calibrate heat flux values and determine flux error covariance. This is implemented within the NRL Ocean Surface Flux (NFLUX) system. Our second hypothesis is that variational assimilation can relate mismatches with ocean observations to errors in surface flux and the ocean state. This leads to an approach in which satellite observations enable NFLUX to estimate corrected surface fluxes and error covariance, while ocean observations and error covariances allow variational assimilation to balance error contributions among surface flux and ocean processes. We will extend 4DVAR to have a weak-constraint treatment of the surface flux terms. These will be tested in a matrix of experiments in regional cases of interest, spanning a range of cloud conditions and dominant features. Finally these approaches will be extended to global and broader regional applications where the expense of 4DVAR may be prohibitive. Section 2 reports on NFLUX, while section 3 lays out a set of experiments to diagnose alternate methods to determine and balance error contributions related to the distribution of heat within NCODA and the Navy Coastal Ocean Model (NCOM; Barron et al., 2006). Section 4 summarizes our conclusions to date and projects future developments under the COFFEE project.

2. NFLUX

NFLUX offers a system to process and quality control measurements related to the air/ocean boundary layer in order to provide more accurate satellite-corrected estimates of heat flux over hours prior to the present analysis. Consider mean January surface heat flux from the U.S. Navy's global atmospheric model (Figure 1). Solar, strictly non-negative, is direct warming by shortwave, primarily visible radiation from the sun. The other three terms are mixed but primarily negative: longwave thermal radiation between the ocean and clouds, sensible heating where contact with the air directly warms or cools the ocean, and latent heating where evaporation or condensation produces a heat flux.

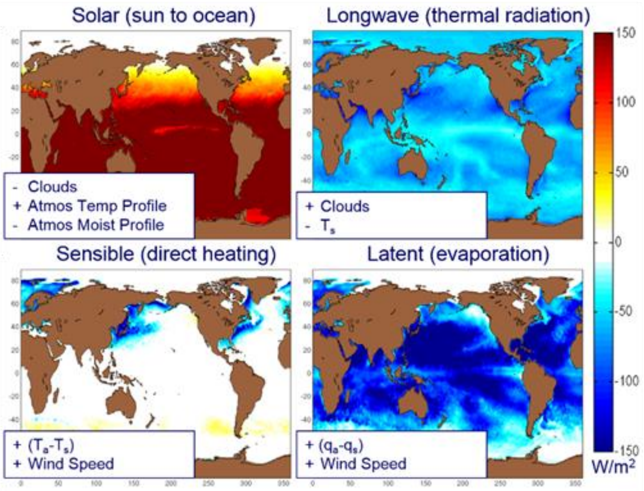
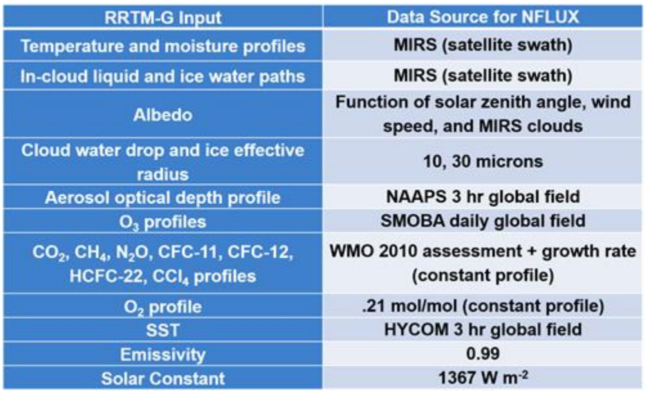


Figure 1: Mean January heat flux from NOGAPS defined such that positive values warm the ocean. Flux values and errors are proportional to ocean and atmospheric properties as indicated in each field's southwest corner.

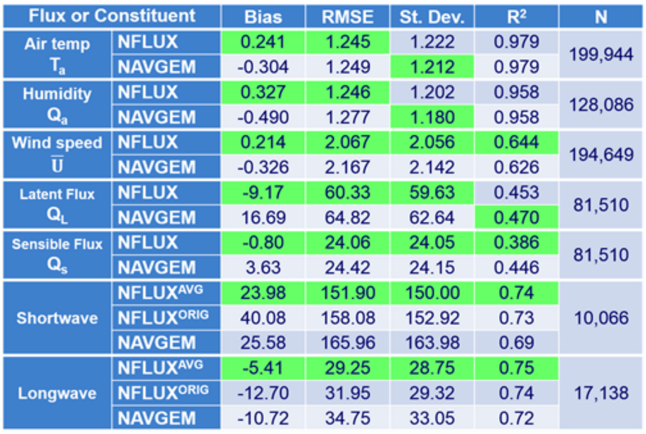
Consider the downward sensible heat flux, proportional to wind speed and the air-sea temperature difference. Satellite observations tell us about wind speed, air temperature, and sea surface temperature over the hindcast period. These are passed to the COARE 3.0 bulk flux algorithm (Fairall et al., 2003; Wallcraft et al., 2008) for coupling with ocean models. Satellite data from the hindcast period can be assimilated into a model background to make satellite-corrected estimates of the terms in the bulk formulae or, for radiant fluxes, terms in radiative transfer models. Radiant heat flux components are estimated using the Rapid Radiative Transfer Model for Global circulation models (RRTM-G; Iacono et al., 2000) using a variety of inputs (Table 1). Preparation and validation of these terms within NFLUX is covered in Van de Voorde et al., 2015, and May et al., 2014.



RRTM-G Input	Data Source for NFLUX
Temperature and moisture profiles	MIRS (satellite swath)
In-cloud liquid and ice water paths	MIRS (satellite swath)
Albedo	Function of solar zenith angle, wind speed, and MIRS clouds
Cloud water drop and ice effective radius	10, 30 microns
Aerosol optical depth profile	NAAPS 3 hr global field
O$_3$ profiles	SMOBA daily global field
CO$_2$, CH$_4$, N$_2$O, CFC-11, CFC-12, HCFC-22, CCl$_4$ profiles	WMO 2010 assessment + growth rate (constant profile)
O$_2$ profile	.21 mol/mol (constant profile)
SST	HYCOM 3 hr global field
Emissivity	0.99
Solar Constant	1367 W m^{-2}

Table 1: RRTM-G inputs and data sources. MIRS is NOAA's Microwave Integrated Retrieval System; NAAPS is Navy Aerosol Analysis and Prediction System; SMOBA is NOAA's Stratosphere Monitoring Ozone Blended Analysis; WMO is the World Meteorological Organization.

NFLUX and global/regional forecast NAVGEM/COAMPS (Coupled Ocean/Atmosphere Mesoscale Prediction System) turbulent fluxes and their components are evaluated relative to ship and buoy observations, with the flux validation considering only complete matching sets of data. The COARE 3.0 algorithms are used with NFLUX, the atmospheric models, and the validating observations to calculate the turbulent heat flux components. Radiant fluxes calculated with RRTM-G are evaluated relative to independent benchmark observations automatically logged by vessels participating in the Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) initiative. The green cells on Table 2 highlight the flux or constituent predictors that are in closer agreement with the independent observations (i.e., is satellite-corrected NFLUX better than the NAVGEM forecast). NFLUX provides improved flux estimation overall, particularly when a spatial averaging is applied to the MIRS cloud fields used in RRTM-G. The evaluations with NAVGEM are global; similar regional evaluations are underway using COAMPS as the control estimate.

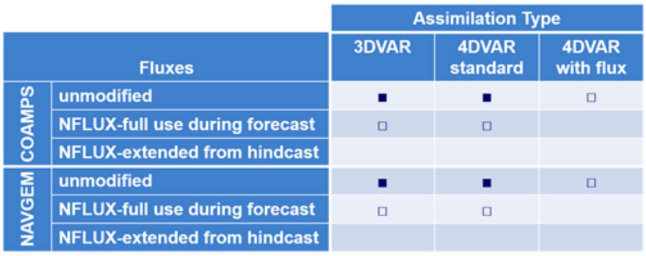


Flux or Constituent		Bias	RMSE	St. Dev.	R^2	N
Air temp T_a	NFLUX	0.241	1.245	1.222	0.979	199,944
	NAVGEM	-0.304	1.249	1.212	0.979	
Humidity Q_a	NFLUX	0.327	1.246	1.202	0.958	128,086
	NAVGEM	-0.490	1.277	1.180	0.958	
Wind speed $\overline{U}$	NFLUX	0.214	2.067	2.056	0.644	194,649
	NAVGEM	-0.326	2.167	2.142	0.626	
Latent Flux Q_L	NFLUX	-9.17	60.33	59.63	0.453	81,510
	NAVGEM	16.69	64.82	62.64	0.470	
Sensible Flux Q_s	NFLUX	-0.80	24.06	24.05	0.386	81,510
	NAVGEM	3.63	24.42	24.15	0.446	
Shortwave	$\text{NFLUX}^{\text{AVG}}$	23.98	151.90	150.00	0.74	10,066
	$\text{NFLUX}^{\text{ORIG}}$	40.08	158.08	152.92	0.73	
	NAVGEM	25.58	165.96	163.98	0.69	
Longwave	$\text{NFLUX}^{\text{AVG}}$	-5.41	29.25	28.75	0.75	17,138
	$\text{NFLUX}^{\text{ORIG}}$	-12.70	31.95	29.32	0.74	
	NAVGEM	-10.72	34.75	33.05	0.72	

Table 2: Model-observation bias, standard deviation, root mean square error, squared correlation, and number of matchups over 13 months from April 2013 to April 2014. For the radiant fluxes, the superscript indicates whether MIRS clouds were used as their ORIGinal value at each time, location or whether spatial AVeraGing was applied.

3. Experiments

Regional NCOM California Current experiments start in April 2013, the beginning of the MIRS data, and after a one-month spin-up enter a 12-month validation period from May 2013 through April 2014. The forecasts cycle with a daily 3DVAR or 4DVAR (Smith et al., 2012; 2015) assimilation of satellite SST (GOES, AVHRR, VIIRS), altimeter (Jason, Altika), and in situ temperature and salinity profile observations. Surface-only in situ data are not assimilated; these are a means of independent validation. Other observations are independent when used to evaluate the forecast period, as the daily assimilation includes no data measured after the 00:00 UTC analysis.



		Assimilation Type		
Fluxes		3DVAR	4DVAR standard	4DVAR with flux
COAMPS	unmodified	■	■	□
	NFLUX-full use during forecast	□	□	
	NFLUX-extended from hindcast			
NAVGEM	unmodified	■	■	□
	NFLUX-full use during forecast	□	□	
	NFLUX-extended from hindcast			

Table 3: Planned COFFEE experiments in each region. The rectangle symbols track progress in the California Current region, solid symbols indicating completed runs while open symbols indicate cases in preparation.

Eighteen experiments are envisioned for each of the COFFEE regions, distributed as shown in Table 3. The cases differ on the background atmospheric forcing, the modification applied to heat fluxes, and the assimilation methodology. The International Satellite Cloud Climatology Project reveals the range of conditions within the various regions. Over the California Current, mean cloud cover decreases from annual highs above 80% toward the northern central Pacific to lows below 50% along the coast and toward the Gulf of California. Such variations in cloud distribution are one challenge in predicting heat flux and SST.

In situ observations from buoys, whether fixed or drifting, provide the most reliable estimate of SST at a particular time and location. However, both sets of buoy observations poorly sample the whole domain. Drifting buoys are concentrated in a small number of trajectories while fixed buoys oversample the shelf nearest the coast. Satellite observations offer more complete coverage with vastly more observations than in situ, but the accuracy of the retrievals may be subject to the same uncertainty sources affecting flux determination.

Figure 2 shows results of an evaluation of the monthly and annual averages of forecast-observation bias and RMS errors. Bias is small relative to AVHRR but up to 1.0°C warm relative to in situ and 1.0°C cool relative to GOES. Comparisons with GOES and fixed buoys give the largest RMS errors. The error and bias trends shown here are representative of those found in the nowcast and other forecast intervals in the various experiments run to date. Work to diagnose such discrepancies and their relation to surface forcing or assimilation continues.

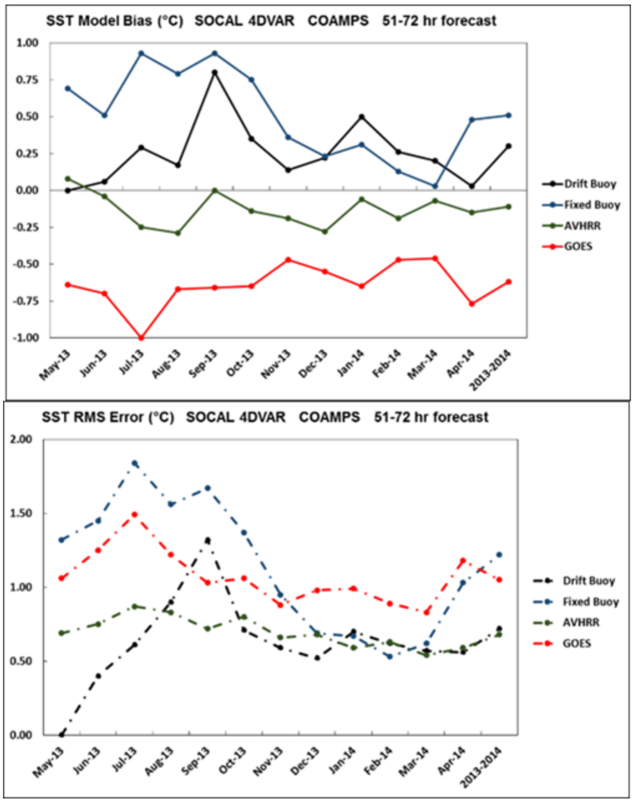


Figure 2: Monthly and annual average forecast-obs SST bias (top) and RMS errors (bottom) for the 51-72 hour forecast from the standard 4DVAR California Current experiment using unmodified NAVGEM forcing.

4. Conclusion

COFFEE demonstrates a capability using satellite-based estimates of heat flux and variational balancing of uncertainties among surface heat flux and ocean dynamics sources to provide more accurate forecasts of SST and boundary layer conditions. The NFLUX satellite-corrected estimates of turbulent and radiative heat exchange at the ocean surface have smaller errors than the operational forecast fields, enabling calculation of a flux error covariance that extends into the short-term forecast. Parallel efforts have evaluated the baseline performance of 3DVAR and 4DVAR ocean forecasts in the California Current. Work is proceeding on evaluating the impact of satellite-corrected fluxes in a hindcast scenario and extending them in short term forecasts, providing a capability that is responsive to environmental and forecast system changes. Demonstration of these capabilities in the California Current is a first step in establishing their applicability in other regions and globally. Such a capability is envisioned to play a role in mediating imbalances between components of regional and global coupled modeling systems.

5. Acknowledgements

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6. References

Barron, C.N., A.B. Kara, P.J. Martin, R.C. Rhodes, and L.F. Smedstad, 2006: Formulation, implementation and examination of vertical coordinate choices in the global Navy Coastal Ocean Model (NCOM). *Ocean Modelling* **11**(3-4), 347-375, doi:10.1016/j.ocemod.2005.01.004.

Chassignet, E.P., H.E. Hurlburt, O.M. Smedstad, G.R. Halliwell, P.J. Hogan, A.J. Wallcraft, R. Baraille, and R. Bleck, 2007: The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. *J. Mar. Sys.*, **65**, 60-83.

Cummings, J.A., 2005: Operational multivariate ocean data assimilation. *Quart. J. Roy. Met. Soc.* **131**, 3583-3604.

Fairall, C.W., E.F. Bradley, J.E. Hare, A.A. Grachev, and J.B. Edson, 2003: Bulk parameterization of air sea fluxes: updates and verification for the COARE algorithm. *J. Climate*, **16**, 571-591.

Iacono, M.J., E.J. Mlawer, S.A. Clough, and J.J. Morcette, 2000: Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3. *J. Phys. Oceanography*, **105**(D11), 14,873-14,890.

May, J., N. Van de Voorde, and C. Rowley, 2014: Validation test report for the NRL ocean flux (NFLUX) quality control and 3d variational analysis system. NRL Memorandum Report, NRL/MR/7320--14-9524.

Metzger, E.J., A.J. Wallcraft, P.G. Posey, O.M. Smedstad, and D.S. Franklin, 2013: The switchover from NOGAPS to NAVGEM 1.1 atmospheric forcing in GOFS and ACNFS. NRL Memorandum Report NRL/MR/73-8677-03-5.

Smith, S.R., M.J. Carrier, H.E. Ngodock, J. Shriver, and P. Muscarella, 2015: Validation Testing Report for the Navy Coastal Ocean Model Four-Dimensional Variational Assimilation (NCOM 4DVAR) System, Version 1.0. NRL Memorandum Report NRL/MR/7320-15-9574.

Smith, S.R., J.A. Cummings, P. Spence, S.N. Carroll, C. Rowley, O.M. Smedstad, P. Chu, B. Lunde, J. Shriver and R. Helber, 2012. Validation Test Report for the Navy Coupled Ocean Data Assimilation 3D Variational Analysis (NCODA-VAR) System, Version 3.43. NRL Memorandum Report, NRL/MR/7320-12-9363.

Van de Voorde, N.E., J. May, and C. Rowley, 2015: NFLUX PRE: Validation of new specific humidity, surface air temperature, and wind speed algorithms for ascending/descending directions and clear or cloudy conditions. NRL Memorandum Report, NRL/MR/7320-15-9611.

Wallcraft, A.J., A.B. Kara, H.E. Hurlburt, E.P. Chassignet, and G.H. Halliwell, 2008: Value of bulk heat flux parameterizations for ocean SST prediction. J. Mar. Sys., **74**, doi:10.1016/j.marsys.2008.01.009.

WMO (World Meteorological Organization), 2010: Scientific Assessment of Ozone Depletion. Global Ozone Research and Monitoring Project, Report No. 52, Geneva, Switzerland, 516 pp.