IMPACT OF SATELLITE OBSERVATIONS ON SEA SURFACE TEMPERATURE FORECASTS VIA VARIATIONAL DATA ASSIMILATION AND HEAT FLUX CALIBRATION

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ABSTRACT

Satellite observations are used to guide forecasts of sea surface temperature (SST) through variational data assimilation and heat flux calibration. In the experiments considered, assimilation is conducted using the Navy Coupled Ocean Data Assimilation (NCODA) in either a standard 3D variational (3DVAR) or an alternative 4DVAR formulation. Heat flux for the forecasts follows the original operational highest-quality time series or modifies the flux-determining fields using the Naval Research Laboratory ocean flux (NFLUX) capability. These alternatives are evaluated relative to independent, unassimilated in situ sea surface temperature (SST) observations in two sets of year-long experiments, sets based on atmospheric fields from either the global or the regional operational atmospheric model. Each set begins with a control run with standard forcing and standard 3DVAR assimilation, and the experimental variants employ the various combinations of 4DVAR assimilation and NFLUX-modified forcing. Results in the California Current region demonstrate that the combination of 4DVAR assimilation with NFLUX-modified forcing tends to produce forecasts in best overall agreement with independent in situ observations.

1. Introduction

Satellite observations support a variety of avenues to improve sea surface temperature (SST) forecasts. The upwelling visible, infrared and microwave radiation intensities integrated across various wavelength bands or channels are sensitive to various physical properties of the atmosphere and ocean. In this way satellite instruments can offer information not only on SST itself but also on other ocean and atmospheric properties that influence heat flux and therefore the evolution of SST over the forecast. Among these properties are atmospheric temperature, relative humidity, temperature and humidity from the upper atmosphere to the ocean surface, and cloud cover. Use of these satellite observations is categorized either within systems to modify heat fluxes or as assimilation to refine the ocean and possibly boundary layer states.

Brief overviews of the Naval Research Laboratory Ocean Surface Flux (NFLUX) and 3D and 4D variational (3DVAR/4DVAR) data assimilation in the Navy Coupled Ocean Data Assimilation (NCODA; Cummings, 2005) are in Section 2, with greater detail available in the references and in the GHRSST XVI proceedings (Barron et al., 2016). Section 3 reports on experiments in the California Current and northern Arabian Sea regions. Section 4 summarizes our conclusions to date and projects future developments relating to NFLUX and the COFFEE project.

2. Methods

The experiments examining the effectiveness of heat flux correction and variational ocean data assimilation for reducing forecast errors of SST rely on two capabilities recently developed and introduced for use in U.S. Navy ocean forecast systems: NFLUX (May et al., 2016, 2014; Van de Voorde et al., 2015) and NCODA 4DVAR (Smith et al., 2015). NFLUX combines satellite observations or retrievals related to wind speed, air and sea surface temperature, atmospheric temperature and moisture profiles, and cloud conditions with other operational products or databases of aerosols, trace gases, and other properties to provide more accurate estimates of the ocean and atmospheric properties related to various components of heat flux. Heat flux is partitioned into its constituent components of shortwave (or solar), longwave, sensible, and latent heat flux. Flux estimates are expressed in terms of COARE 3.0 bulk flux algorithm (Fairall et al., 2003; Wallcraft et al., 2008) for coupling with ocean models. Radiant heat flux components are estimated using the Rapid Radiative Transfer Model for Global circulation models (RRTM-G; Iacono et al., 2000). NFLUX can produce estimates of flux fields using swath-level observations from satellites; these are interpolated to produce full-field estimates using 2DVAR assimilation with background fields from regional Navy Coupled Ocean Atmosphere Prediction System (COAMPS) or global Navy Global Environmental Model (NAVGEM) forecasts.

The second capability evaluated in these experiments is data assimilation of satellite altimeter or SST observations and subsurface observations of temperature and salinity using NCODA 3DVAR (Smith et al., 2012) or 4DVAR capabilities. NCODA 3DVAR has been the standard assimilation in Navy ocean prediction systems, and 4DVAR is a recently-introduced capability that is anticipated to provide greater forecast skill in priority regions. A primary difference between these capabilities is that 3DVAR only modifies the initial model state at nowcast time, while 4DVAR modifies the model trajectory over a recent hindcast period, typically 3 days, to adjust not only the nowcast state but also the trajectory and dynamic balance of the model in the window leading up to the nowcast. It is anticipated that the increased computational cost of 4DVAR assimilation will reduce forecast error by not only correcting the nowcast but also the dynamic balance leading into and during the forecast.

3. Experiments

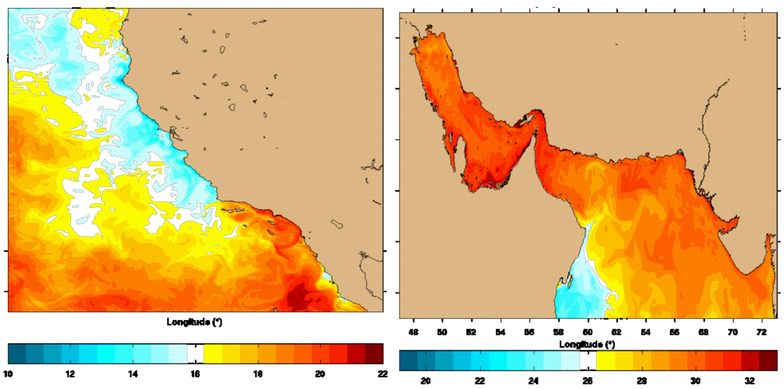

Figure 1: July 1 2017 00:00 UTC forecasts from the 3DVAR NFLUX COAMPS California Current (left) and 3DVAR NFLUX NAVGEM northern Arabian Sea (right) experiment cases.

Experiments are conducted using the Navy Coupled Ocean Model (NCOM; Barron et al., 2006; Rowley and Mask, 2015) from May 2013-April 2014 in two domains (Fig. 1): a California Current region and a northern Arabian Sea region. In each region, a set of four experimental cases is run for each of the atmospheric forcing cases, the regional COAMPS and global NAVGEM. In each set of experiments, the control run uses the original atmospheric forcing and standard 3DVAR assimilation, while the experimental variants use standard or NFLUX-modified heat fluxes combined with 3DVAR or 4DVAR assimilation. The forecasts cycle daily with 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. Each experimental case starts in April 2013 as initialized from the operational global run, allowing a one-month spin-up before the 12-month evaluation.

Table 1 shows evaluation of forecasts out to 96-hours from the California Current experiments using NAVGEM or COAMPS forcing as the background. Matchups are interpolated horizontally and in time from the 3-hourly forecast fields on the ~3.5 km model grids. Temporal interpolation treats the forecast fields as a continuous time series sampled at every three hours; for example, the matchups labeled 24 h are sampled from the time series beginning with the 29 April 2016 24 UTC forecast to the 03-24 hour forecasts from 30 April 2016, 03-24 hour forecasts from 1 May 2013, and continuing in that manner to the 24 UTC forecast field from 29 April 2014. In that way the 24 h forecast time series has three-hourly forecast fields valid at the times from 00 UTC 1 May 2013 through 24 UTC 30 April 2014. In general, the cases using NFLUX modification of the heat fluxes outperform those with the standard unmodified fluxes, and the cases with 4DVAR assimilation have smaller errors than those using 3DVAR assimilation.

		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

Table 1: Evaluation of forecast bias and rms error (°C) relative to subsequent corresponding VIIRS SST observations for the sets of NAVGEM and COAMPS cases in the California Current from May 2013-April 2014. Cases with smallest errors are highlighted in green, most often cases using 4DVAR assimilation with NFLUX. N indicates the number of matchups used in calculating each statistic.

Similar statistics are shown in Table 2 for the 3DVAR assimilation cases in the northern Arabian Sea forecasts over the same time period. While the 57M matchups indicate that the NFLUX cases have accuracy in general similar or superior to the accuracy of cases with standard fluxes, spurious forecasts with matchups errors as large as 12°C cold have been identified very nearshore along the northern coast of Qatar. Such large negative biases appear to be due to errors in the longwave terms where the NFLUX estimates are contaminated surface temperature values appropriate for land regions rather than water cells. This may be a consequence of imprecision in aligning coarser land/sea masks appropriate for atmospheric products with higher-resolution land/sea masks corresponding to the ocean model. Work continues to resolve these discrepancies and complete a corrected set of northern Arabian Sea cases. Additional development is underway to extend NFLUX corrections into the forecast period and extend the 4DVAR assimilation into the atmospheric boundary layer. Examples of using NFLUX in other applications are reported in Rowley et al., 2015.

		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
	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
	3DVAR NFLUX	-0.06	-0.10	-0.11	-0.10	0.44	0.52	0.55	0.57	52156075

Table 2: Evaluation of forecast bias and rms error (°C) relative to VIIRS SST for NAVGEM and COAMPS cases in the northern Arabian Sea, May 2013-April 2014. Cases with smallest errors are highlighted in green, most often cases using NFLUX. The 4DVAR experiments have been interrupted to resolve issues with spurious COAMPS NFLUX corrections perhaps contaminated by longwave values valid for land.

4. Conclusion

COFFEE uses satellite-based heat flux corrections and 3D/4D variational assimilation capabilities to enable more accurate SST forecasts. Year-long results (May 2013-April 2014) in the California Current indicate that forecast skill is generally improved through the use of NFLUX corrections combined with 4DVAR assimilation. Preliminary results in the northern Arabian Sea similarly support the use of NFLUX corrections; issues in longwave flux corrections will be resolved before completing the Arabian Sea cases. Work is proceeding on extending corrections in a forecast mode in short term forecasts, providing a capability that is responsive to environmental and forecast system changes. Demonstration of these capabilities in these regional cases 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.

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