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An assimilative ocean forecast model encompassing the southern tip of Africa is examined to evaluate the impact of alternate satellite data streams and to demonstrate the use of such forecast systems to understand the processes and evolution of regional ocean environments. Assimilative ocean forecast systems are a product of three pillars of oceanographic research: models, observations, and data assimilation. A regional model on a 3-km grid portrays evolving conditions around the southern tip of Africa in response to boundary, atmospheric, and riverine inputs. It is guided by satellite observations, comparing its performance when provided NOAA 18/19 AVHRR and/or Suomi-NPP VIIRS SST. Guided by assimilation of these observations, a model provides one avenue to understand the balances and processes controlling the African ocean environment; the degree to which such simulations correspond to reality is assessed in part by comparisons with independent ocean observations. In situ and remote observations provide irregularly distributed glimpses of the true ocean state. As in situ observations are fairly sparse in the region around southern Africa, particularly in real time, relatively greater reliance is placed upon satellite SST and other types of remote observations. A system of data assimilation uses the varied observations to guide the ocean forecasts, transforming the realistic ocean simulations into forecasts of likely conditions in the real ocean with accompanying estimates of forecast uncertainty. Assimilative ocean forecast around South Africa are evaluated from January to April 2014, investigating the impact of alternative SST data streams and reserving in situ observations of SST as an independent reference for validating the forecast ocean state.

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## TIME SERIES OF SST ANOMALIES OFF WESTERN AFRICA

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### ABSTRACT

An assimilative ocean forecast model encompassing the southern tip of Africa is examined to evaluate the impact of alternate satellite data streams and to demonstrate the use of such forecast systems to understand the processes and evolution of regional ocean environments. Assimilative ocean forecast systems are a product of three pillars of oceanographic research: models, observations, and data assimilation. A regional model on a 3-km grid portrays evolving conditions around the southern tip of Africa in response to boundary, atmospheric, and riverine inputs. It is guided by satellite observations, comparing its performance when provided NOAA 18/19 AVHRR and/or Suomi-NPP VIIRS SST. Guided by assimilation of these observations, a model provides one avenue to understand the balances and processes controlling the African ocean environment; the degree to which such simulations correspond to reality is assessed in part by comparisons with independent ocean observations. In situ and remote observations provide irregularly distributed glimpses of the true ocean state. As in situ observations are fairly sparse in the region around southern Africa, particularly in real time, relatively greater reliance is placed upon satellite SST and other types of remote observations. A system of data assimilation uses the varied observations to guide the ocean forecasts, transforming the realistic ocean simulations into forecasts of likely conditions in the real ocean with accompanying estimates of forecast uncertainty. Assimilative ocean forecast around South Africa are evaluated from January to April 2014, investigating the impact of alternative SST data streams and reserving in situ observations of SST as an independent reference for validating the forecast ocean state. In addition to a regional overview, we consider in more detail time series of SST anomalies, primarily off western Africa, examining the evolution within sections through upwelling zones and predicted instances of relatively large diurnal warming. The prominent band structure evident in diurnal warming is found to appropriately correspond with regions of high insolation and low wind stress aligned with atmospheric fronts. SST variability off the west coast is highest on the edges of the persistent upwelling. On the east coast, SST shows the signals of episodic upwelling in the southeast and possible combined upwelling trends and riverine effects farther north in Maputo Bay.

### 1. Introduction

An assimilative ocean forecast model encompassing the southern tip of Africa is examined to evaluate the impact of alternate satellite data streams and to demonstrate the use of such forecast systems to understand the processes and evolution of regional ocean environments. Demonstrated agreement between the forecasts and independent ocean observations bolsters confidence in the insights drawn from the modeled dynamics and provides a reference for assessing model fidelity.

Assimilative ocean forecast systems are a product of three elements: models, observations, and data assimilation. Ocean models endeavor to numerically represent the physical processes that maintain or change the ocean state. A model quantifies how an ocean would be expected to transition from an initial state under the influence of specified constraints and exchanges with the surrounding environment. The model can be expected to deviate from the real ocean due to errors in the initial state, errors in the constraints, and processes that are non-deterministic on the scales resolved. While the model gives a consistently complete view that approximates a real ocean, in situ and remote observations give irregularly distributed glimpses of the true ocean state. Data assimilation unites these two elements, endeavoring to draw the simulated ocean toward a more accurate representation of its true state.

A regional model implemented on a 3-km represents evolving ocean conditions in response to boundary, atmospheric, and riverine inputs. It is guided by satellite observations, and we evaluate the relative effect of assimilating alternative satellite data streams by comparing its performance when provided NOAA 18/19 AVHRR and/or Suomi-NPP VIIRS SST. Since the in situ observations are relatively sparse in the region around southern Africa, particularly in real time, ocean assimilation relies on the more abundant satellite SST and other types of remote observations for guidance and reserves surface in situ samples for validation. Guided by assimilation of the remote observations, the model provides an avenue to understand the balances and processes controlling the African ocean environment. The degree to which such simulations correspond to reality is assessed by comparisons with the independent in situ observations.

## 2. Experiments

The baseline capabilities developed by the Naval Research Laboratory (NRL) for US Navy ocean predictions begin with the global Hybrid Coordinate Ocean Model (HYCOM; Chassignet *et al.*, 2007) within the Global Ocean Forecast System (GOFS 3.0; Metzger *et al.*, 2008; Metzger *et al.*, 2012). With its representation of the ocean on a 9 km grid, GOFS 3.0 is adequate as an initial source of assessment for many applications. In other circumstances where greater detail is needed, the operational forecasters at the Naval Oceanographic Office (NAVOCEANO) will configure a higher resolution nested implementation of the Navy Coastal Ocean Model (NCOM; Barron *et al.*, 2006).

As an example of this rapidly relocatable capability, NCOM is implemented on a 3 km grid to examine the sea surface temperature (SST) around South Africa (Figure 1a). It uses atmospheric inputs from the Navy Global Environmental Model (NAVGEM 1.1; Pauley *et al.*, 2013; Metzger *et al.*, 2013). Assimilation uses 3DVar Navy Coupled Ocean Data assimilation (NCODA; Cummings, 2005) with the FGAT option (Massart *et al.*, 2010). Lateral boundaries are interpolated from GOFS 3.0, and rivers are included following the available climatology (Barron and Smedstad, 2002).

Following standard operational practices, the forecast systems are guided by assimilation of available real-time data streams including satellite altimetry (Altika, Jason-2, Cryosat), satellite SST, and in situ observations. In the three cases shown here, the standard satellite SST observations are limited to three sources produced by NAVOCEANO: 1) Advanced Very High Resolution Radiometer (AVHRR) on NOAA 18, 19; 2) Visible/Infrared Imager Radiometer Suite (VIIRS) on Suomi-NPP; and 3) combined AVHRR and VIIRS. Of the variety of in situ observations that would be assimilated under standard operational conditions, only profile observations, those extending below the surface (i.e. Argo, gliders, XBT, etc.) are assimilated; surface ship and buoy observations are reserved as a source of independent confirmation data. Assimilation distributes insertion of analysis increments over a 24-hour update cycle for daily 00:00 UTC nowcasts and three-hourly forecasts extending to 72 hours. For the matchup comparisons, model SST is interpolated in space and time to match corresponding independent SST observations from drifting buoys.

Figure 1b shows matchup locations of the validating surface drifting buoys from January-April 2014 superimposed over SST. The collective data set extends from the warm Mozambique Channel and Agulhas Current into the cool Antarctic Circumpolar Current. Unfortunately, the drifters cover neither the upwelling zones nor diurnal warming bands off western Africa that are the focus of this paper. Extension of the in situ matchups to include ship engine intake or hull sensor would broaden coverage, but the high standard errors and potential biases of these additional data cause us to restrict matchups to the relatively high quality surface drifter observations.

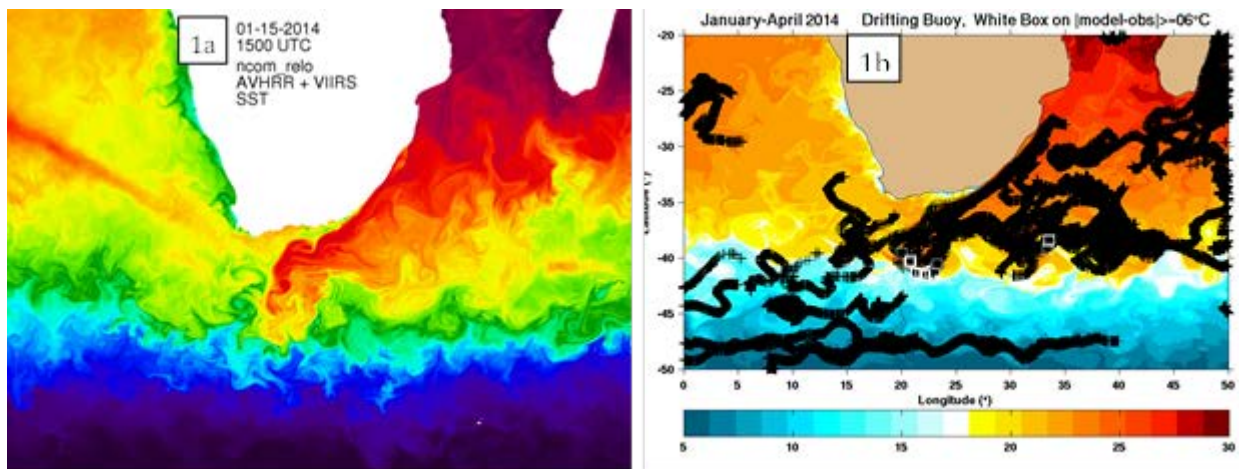


Figure 1: a) Forecast SST valid on 15 January 2014, 1500. Notable features on this day include cool upwelling along much of the western coast and points along the eastern coast in addition to the signature of diurnal warming in a band west of South Africa extending west-northwest from the vicinity of the Cape. b) Locations of surface drifting buoys over January-April 2014 superimposed over SST. These provide the independent in situ SST observations used for validation.

Comparison among the simulations differing by the satellite alternatives show reasonable agreement with the in situ observations, with some improvement gained by using VIIRS over AVHRR and slight additional improvement derived from their combined use. Biases and standard deviations relative to the independent surface drifter observations from January-April 2014 are shown in figure 2. Both the analysis and forecasts have a forecast bias of 0.01°C or less. Root mean squared (RMS) errors are smallest for the case assimilating both AVHRR and VIIRS, increasing from about 0.7°C for the analysis (and 3-24 hour forecasts, not shown) to about 0.9°C in the 72 hour forecasts. Around 2100 matchups are available per local hour, as shown by the inset plots placed in each plots upper right corner. Agreement between the model and observed SSTs in the case assimilating both AVHRR and VIIRS, the most accurate scenario, is further quantified in the scatter plots of Figure 3.

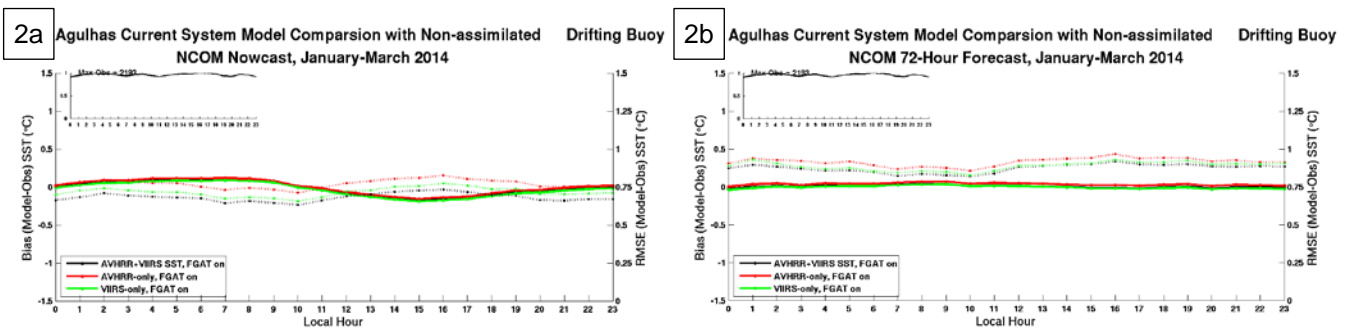


Figure 2: Comparisons of (a) 0000 UTC analysis and (b) 51-72 hour forecast SST analysis fields with corresponding observations valid at the range of local hours over the day. The comparisons with the static analysis nowcast over the same day reveals mean diurnal signal with amplitude of ~0.3°C. This diurnal signal is not evident in comparisons of the forecast fields, indicating that the model is capturing an accurate mean diurnal cycle.

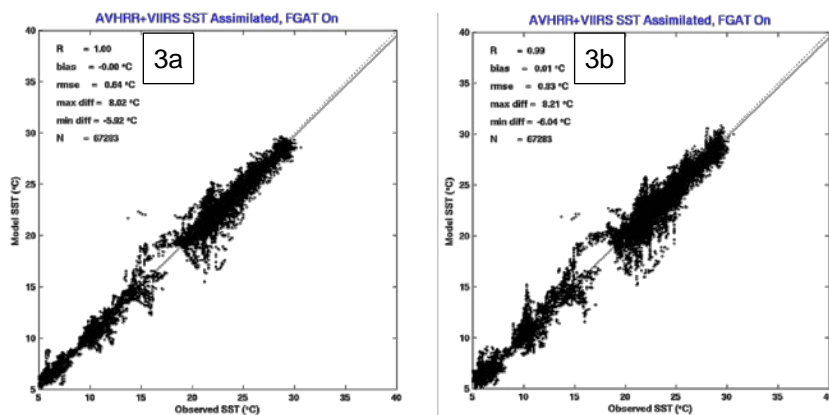


Figure 3: Comparison of SST observations and matching values from NCOM (a) analyses and (b) 51-72 hour forecasts using South Africa regional NCOM assimilating AVHRR and VIIRS. The largest RMSE tend to occur within the interface between bimodal warm and cold distributions. NCOM has a warm bias in this cap. Overall the simulations show little ( $<0.005^{\circ}\text{C}$  amplitude) analysis bias and slightly warm ( $\sim 0.01^{\circ}\text{C}$ ) 72-hour forecast bias

### 3. Results

Simulations from the case assimilating both AVHRR and VIIRS, the case in best agreement with the independent observations, are used to investigate variability in SST around South Africa, particularly on the western side. We focus on two aspects well represented in the region: diurnal warming and upwelling.

The context of diurnal warming events evident on 15 January 2014 in Figure 1 is examined in more detail in Figure 4. Regions of peak diurnal warming are associated with the combined effects of low wind stress over the hours of high solar flux. The low wind stress magnitude allows the heating to be retained within a stratified, near-surface layer rather than distributed over a thicker mixed layer. The narrow swath of high diurnal warming is typical of the forecast events in this region corresponding to regions of low wind stress and high insolation aligned with patterns of atmospheric fronts in this region. Similar diurnal warming patterns were found by Gentemann et al. (2008) through analysis of microwave and infrared SST retrievals around the world. The bands of diurnal warming are a product of the solar flux and wind stress and are not a product of data assimilation, as the bands are not evident in the 00:00 UTC assimilative analyses.

Upwelling is examined in 4 sections off South Africa (Figure 5). Upwelling is strongest to the west, where broad bands of cool water are persistent from St. Helena Bay to Luderitz and farther north. Narrow episodes of upwelling do occasionally emerge along the east coast, leading to a dip in mean SST and a peak in SST temporal standard deviation near the Great Kei River at  $32.5^{\circ}\text{S}$ . Evidence of upwelling is scant moving north along the east coast, and only in April (not shown) are the nearshore temperatures in Maputo Bay ( $26^{\circ}\text{S}$ ) relatively cool. Maputo Bay does have sharply fresher water inshore associated with the climatological inflow from the Limpopo, Incomati, Maputo, and Umbeluzi Rivers in southern Mozambique. As discussed by Smit (2014), riverine and other very nearshore SST can differ significantly from the slightly offshore values observable through satellite remote sensing, further increasing the uncertainty of temperatures applied to model river inflows and their influence on the nearshore temperature forecasts.

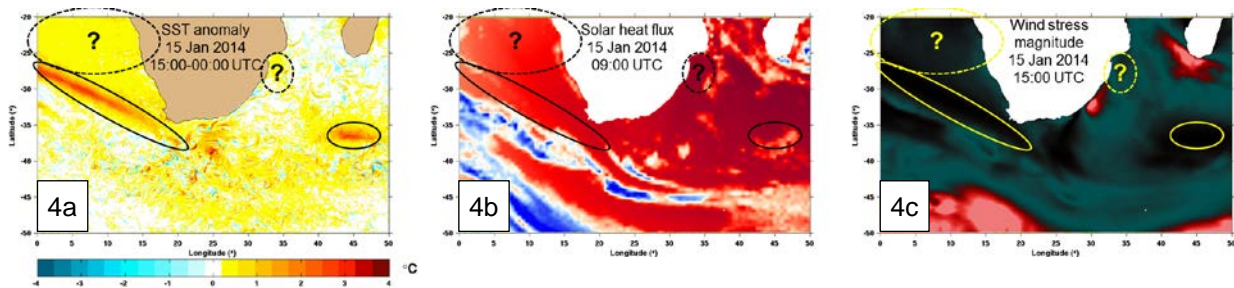


Figure 4: The diurnal warming SST anomaly (a) and corresponding solar flux (b) and wind stress magnitude (c) at various times on 15 January 2014. Peak diurnal warming near 3°C within the solid ellipses is associated with high solar flux and uniformly low wind stress over the preceding hours, while the dashed ellipses identify areas of only moderate diurnal warming where intervals of moderate wind stress have mixed warming associated with similarly high solar flux.

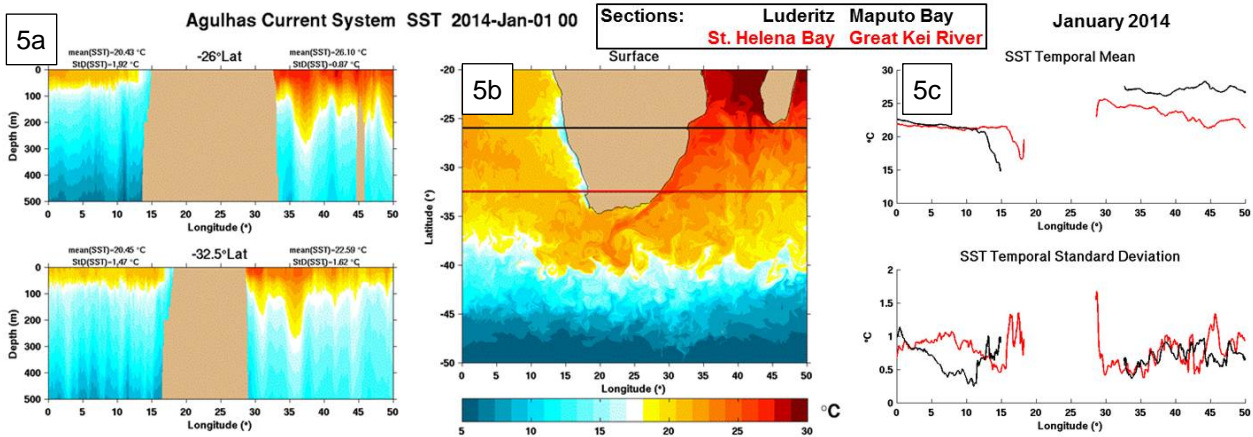


Figure 5: 01 January 2014 0000 UTC snapshot of (a) temperature sections and (b) SST showing cool upwelling regions along the west coast of Africa. (c) January mean and standard deviations of SST reflect episodic upwelling near the Great Kei River through the local nearshore mean SST minimum and high standard deviation.

#### 4. Conclusion

Implementation of relocatable NCOM nest around South Africa provides SST forecasts of low bias and reasonable accuracy. Patterns of diurnal warming and coastal upwelling are consistent with the dominant dynamic balances and similar to observations from remote sensing. The model provides a useful tool for investigating local characteristics and confirms the positive impact of assimilating both AVHRR and VIIRS as processed by NAVOCEANO.

#### 5. Acknowledgements

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