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Characterization of biologically significant hydrodynamic anomalies on the Florida Reef Tract

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Abstract. The U. S. National Oceanic and Atmospheric Administration (NOAA) Integrated Coral Observing Network (ICON) Project uses artificial-intelligence software to implement heuristic models of coral reef ecosystem response to physical conditions. These models use if-then rules to recognize patterns in environmental data integrated in near real-time from multiple sources. One model is described to detect episodic, biologically significant fluxes acting upon coral reefs in the Florida Reef Tract. Data are gathered from *in situ* sensors and satellites for three sites near the reef crest: Sombrero Key in the Middle Keys, Molasses Reef in the Upper Keys, and Fowey Rocks off Miami. The model recognizes apparent circulation changes that may impact reef ecology. Criteria are *in situ* sea-temperature variability at near-tidal frequencies, wind velocity variability, and color-derived satellite chlorophyll *a* point data. Model ecological forecasts (*ecoforecasts*) are verified using secondary data not input to the model, including satellite ocean-color imagery, radar-derived ocean surface currents, and divers' reports. Events are characterized as being one of wind-driven upwelling; net transport of eutrophic water from outside the FRT; and interaction of Florida Current frontal features with reef topography, possibly modulated by internal wave-breaking. Multiple events are characterized in a 42-month period in 2005-2008.

Key words: coral reef • NOAA • chlorophyll • eddies and vortices • tidal mixing

Introduction

The Florida Reef Tract (FRT) encompasses the third largest barrier reef system in the world (FKNMS, 2001). Offshore, the Florida Current (FC) flows through the Straits of Florida after interacting with marine environments and ecosystems throughout the Caribbean Sea and the Gulf of Mexico. Meanders of the FC and mesoscale eddies interact with sloping topography in and offshore of the FRT (Lee et al. 2002). Smaller-scale vortices and coastal waves inshore of the FC front (Shay et al. 2007), and various upstream rivers (Hu et al. 2004, 2005) are also observed to interact with the reef as well. Finally, the Keys island chain is crosscut from the north by shallow channels, which episodically admit waters onto the back reef of the FRT from the West Florida Shelf (WFS) and outer Florida Bay (Smith and Pitts 2002; Lee et al. 2006).

The dynamics of circulation between the WFS, the FRT, and the terraces and deeper waters of the Straits can be highly complex, as are the biological responses of the reef ecosystem to the resulting fluxes of allochthonous water. These complex interactions can impact water quality as well as the marine ecology of the Keys, with important implications for coastal resource management within the region. Improvements in the characterization of these interactions are critical to the scientific understanding of nutrient dynamics and larval recruitment on the FRT. These processes, in turn, have important economic and ecological consequences, with potentially significant impact on tourism and commercial fishing interests.

An important tool for understanding this complex system is the Sustained Ecological Research Related to Management of the Florida Keys Seascape (SEAKEYS; Ogden et al. 1994) network of automated monitoring stations. These stations are installed upon navigational structures along the length of the FRT, providing a permanent infrastructure for continuous monitoring of meteorological and hydrographic environmental conditions. Three of these SEAKEYS stations, Sombrero Key, Molasses Reef, and Fowey Rocks, are located immediately inshore of the outer reef crest in the Middle and Upper Keys, providing a valuable base from which to observe physical interactions between the FC front just offshore, and the shallow basin of the back reef just inshore. Furthermore, two of these stations, at Sombrero Key and Molasses Reef, are also suitably positioned to monitor hydrographic and ecological effects due to fluxes from the WFS and outer Florida Bay through the bridge channels of the Florida Keys.

Data

All SEAKEYS stations transmit data hourly in standard C-MAN format, via NOAA geosynchronous operational satellites. These transmissions are archived by the NOAA National Data Buoy Center (NDBC), and are analyzed in near real-time at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML). The data reported by each SEAKEYS station includes hourly mean wind speed and direction, depth-averaged *in situ* sea temperature, and in some cases, *in situ* salinity, tidal height, or sea-surface Photosynthetically Active Radiation (PAR). The archived SEAKEYS data provide a nearly continuous record of these environmental variables, stretching in some cases as far back as 1987 (NDBC 2008).

The ICON Project has worked with collaborators at University of South Florida's College of Marine Science, Institute for Marine Remote Sensing (USF 2008) to integrate remote sensing data from the satellite-borne MODIS and AVHRR instruments. These products are geo-located and subsetted to each individual monitoring station location, to allow direct integration in time and space with *in situ* data. They provide high spatial resolution (order of 1km) data on sea surface temperature (SST) and ocean-color derived chlorophyll *a* concentrations, downloaded to NOAA AOML within 12 to 24 hours of measurement and indexed to individual reef sites.

Methodology

These integrated data streams are analyzed by AOML. They are evaluated using expert-systems software and heuristic if-then rules developed at AOML (Hendee et al. 2001, 2008) for both quality control, and for the presence of environmental conditions that may have an impact on the coral reef ecosystem, on the marine environment, and on important maritime economic activities in the region. The outputs of these if-then models are ecological forecasts (called *ecoforecasts*). This suite of data-integration, quality control, and near real-time monitoring techniques is the basis for the present study.

Statistical processing is then applied to the raw environmental variables, to derive time series of indices that can be used to directly assess certain hydrodynamic and biological conditions at the monitoring site. The primary index used to indicate increases in biological productivity on the reef over periods of one to three days is chlorophyll *a* concentration (chl_a). The USF-CMS chl_a product provides numerical estimates in $mg{\cdot}m^{-3}$, based on near real-time analysis of Terra and Aqua MODIS ocean color measurements. In this complex environment there is large uncertainty in the absolute value of chl_a, but here it is used as a relative index to show spatial and temporal patterns. High spatial-resolution time series of satellite chl_a for each of the three SEAKEYS sites have been derived for the sample period of 2005-2008. These time series are then filtered using quality control procedures similar to those used by the ICON Project for other types of *in situ* data. Peaks of this quality-controlled chl_a that fall above the 80^{th} percentile for the entire record at each site are then flagged as indicators of change in biological productivity at that site.

For each hourly average sea temperature value in the SEAKEYS *in situ* record, a simple subsample of the values from the prior 24 hours is collected, and the standard deviation of this sample is calculated. A 3-day simple moving average is applied to smooth this *sea temperature variability* time series. This procedure is intended to filter for episodes of sustained variance in sea temperature near inertial and dominant tidal frequencies. Such events include sustained anomalies, where either unusually cold water (Fig. 1) or unusually warm *and* cold waters (Fig. 2) are circulated onto the reef. One possible cause for near-tidal period, high-variance, *cold* events is the breaking of baroclinic tides (internal waves) on the reef slope (Leichter et al. 1996, 2003). When a meander or vortex associated with the FC has previously transported cooler waters to the base of the reef slope, such internal waves can transport and mix those waters up the reef slope. A likely cause of horizontal-mixing (warm *and* cold-anomaly) events is action of the barotropic tide interacting with shallow reef-crest topography. Periods of high chl_a (see above) that do not also correspond to periods of high sea temperature variability are flagged by the expert system as being of particular interest, as these may indicate instances where nutrients of more localized origin are causing a spike in productivity.

Wind velocity is also analyzed to distinguish events of anomalously high chlorophyll *a* concentration and/or high sea temperature variability that can be attributed to wind-forcing, as opposed to other proximate causes such as tidal mixing and frontal interaction with reef topography. Individual zonal and meridional wind vector components are derived from each hourly *in situ* wind-speed and direction measurement. Three-day subsamples of these U_{10} and V_{10} component values are then collected for each hour of the record, and a standard deviation of those subsamples is calculated. The result is intended to provide an hourly index for *impulses* of substantial wind stress forcing that are of sufficient magnitude and duration to produce anomalously high wind-driven (shallow-water) currents in the back-reef, and/or wind-driven upwelling events on the fore-reef slope and reef-crest.

Results

Ecoforecasts were produced by the heuristic model independently for each of the three monitoring sites, for each day between 2005 Jan 01 and 2008 Jun 30 when statistically significant high sea temperature variability was indicated. Output for each ecoforecast included three components: 1) all antecedent data values (chl_a in $mg{\cdot}m^{-3}$, sea temperature variability index, wind impulse index); 2) a numerical indicator of the relative intensity of the forecast ecological response, called a Stimulus/Response Index (S/RI; Hendee et al. submitted); and 3) a series of symbolic codes indicating the attempted classification of each ecoforecast according to *dynamical mechanism* (wind-forced or non-wind forced), and *productivity* (sea-temperature variability coincident with high chlorophyll, or not).

Second, where a significant ecoforecast was produced for multiple days in a row at a given site, ecoforecasts were grouped together into an extended *event*. An attempt was then made to verify the dynamical mechanisms forecast for each event using synoptic satellite imagery of the Straits of Florida (Fig. 3), and where available, 1km-resolution ocean surface current vector fields derived from WERA High-Frequency radar (Shay et al. 2007). These images and fields were then further examined to characterize the regional scale of such events and any translational motions apparent in the associated phenomena, such as visible vortices offshore of the reef crest, or extended plumes of high chlorophyll *a* and turbid water inshore in the back-reef.

At Sombrero Key Reef, 44 such events were confirmed in the sample period, comprising 273 individual days of high sea temperature variability. At Molasses Reef only 28 events totaling 108 days were observed. Finally, at Fowey Rocks, the site furthest downstream relative to the FC, 38 events comprising 133 days of high sea temperature variance occurred.

The dynamical mechanism indicated by the ecoforecasts also showed significant variability between sites, with wind velocity variability strongly indicated as a forcing mechanism for 32% of all events at Molasses Reef, but only 21% of events at both Sombrero Key and Fowey Rocks. Overall, sea temperature variability events were at least partially coincident with high chlorophyll *a* concentrations 80% of the time across the three sites. Finally, although it was beyond the scope of the present study, periods of high chl_a concentration were also noted where there was *no* significant sea temperature variability. These also showed variability of incidence between sites – but with Sombrero Key showing significantly lower correlation between sea temperature variability and chl_a than the other two sites did.

Discussion and Conclusion

The pattern of spatial variability in the results is suggestive of possible differences in the dynamical regimes operating at each reef site. Sombrero Key is a site that is believed to be subject to periodic, persistent and significant influence from WFS, due to its proximity to the relatively large Moser Channel beneath Seven Mile Bridge. It is also a site where mesoscale vortices, long-period surface wave activity, and dominant wind forcing during much of the year may all be favorable to upwelling and up-mixing of nutrients from deeper FC waters offshore.

Molasses Reef by contrast is a site where the angle of the reef-crest isobaths to wind stress forcing differs by approximately 45^{o} from that at Sombrero (Lee et al. 2002). This cyclonic bend in topography, together with horizontal broadening in offshore isobaths, may also explain why this and other Upper Florida Keys sites are subject to relatively less mesoscale and sub-mesoscale cyclonic vorticity than Lower Keys sites (Fiechter et al. 2008). This is significant as such vorticity is also a potential forcing mechanism for upwelling of cool water and nutrients when it interacts with steep reef slope bottom topography.

The angle between reef crest isobaths at Fowey Rocks and the wind vector is shifted still further, by approximately 90^{o} relative to Sombrero Key. Compared to the isobaths at Molasses, however, bottom topography offshore of Fowey is also relatively steep, more like that at Sombrero. These facts are represented in our results, both by the intermediate frequency of events, and by the relatively low incidence of those events where wind was implicated as a dominant forcing mechanism.

Overall, the heuristic modeling approach is a powerful mechanism for monitoring and interpretation of both historical and near real-time environmental data on coral reefs. Furthermore, the indices chosen for the ecoforecast model described in this text, while kinematical and categorical, still appear to provide some valuable insights into the dynamical regimes operating on and affecting those reefs. Future work using these tools, coupled with additional data such as radar-derived surface currents, ship data, and numerical models of the mesoscale and sub-mesoscale circulation patterns on the reef, should bear still richer fruits.

Finally, these ecoforecasting tools are seen to have the potential to serve up useful information on marine conditions and reef ecology – to researchers, natural resource managers, and the public. Such information, made available in near real-time via the Web (ICON, 2008), can represent a unique perspective on the fragile ecosystem of the reef, and human use of it.

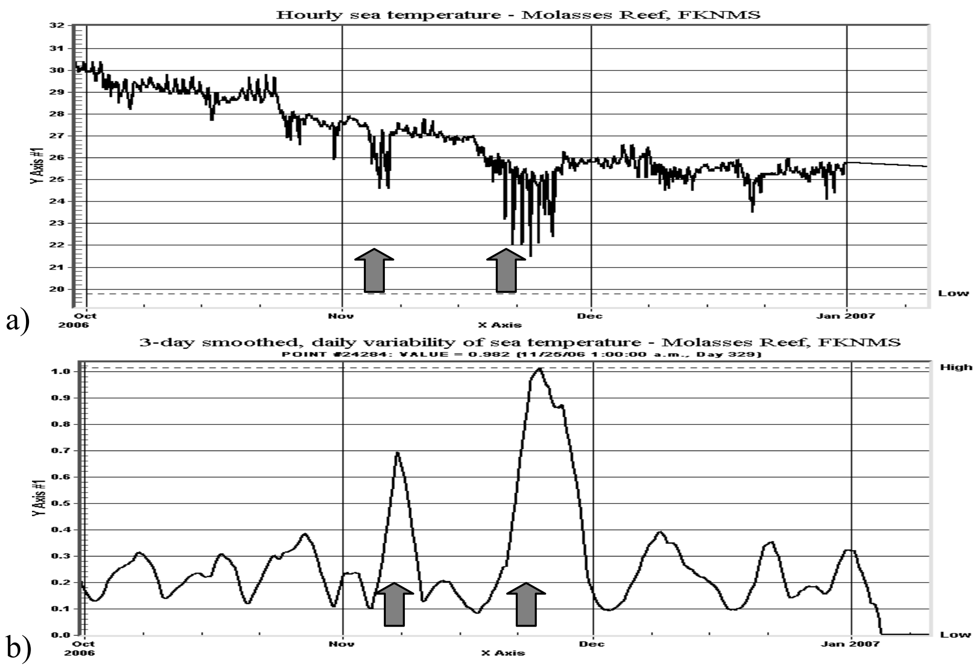

Figure 1: Cold-water anomaly (panel a) and associated peak in sea temperature variability index (b) associated with a likely upwelling event. Note that use of a realizable time-series filter in the variability index means it may lag raw sea temperature changes by one or more days.

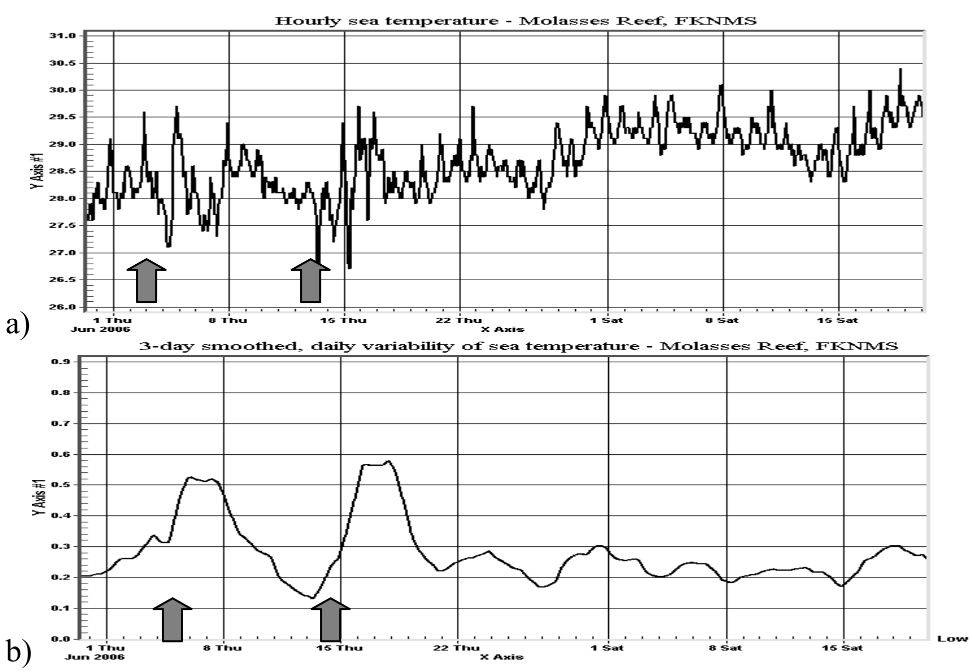

Figure 2: Sea temperature (a) and sea temperature variability index (b), showing a pair of events likely due to horizontal mixing of warmer (back-reef) and cooler (offshore) waters across the reef crest.

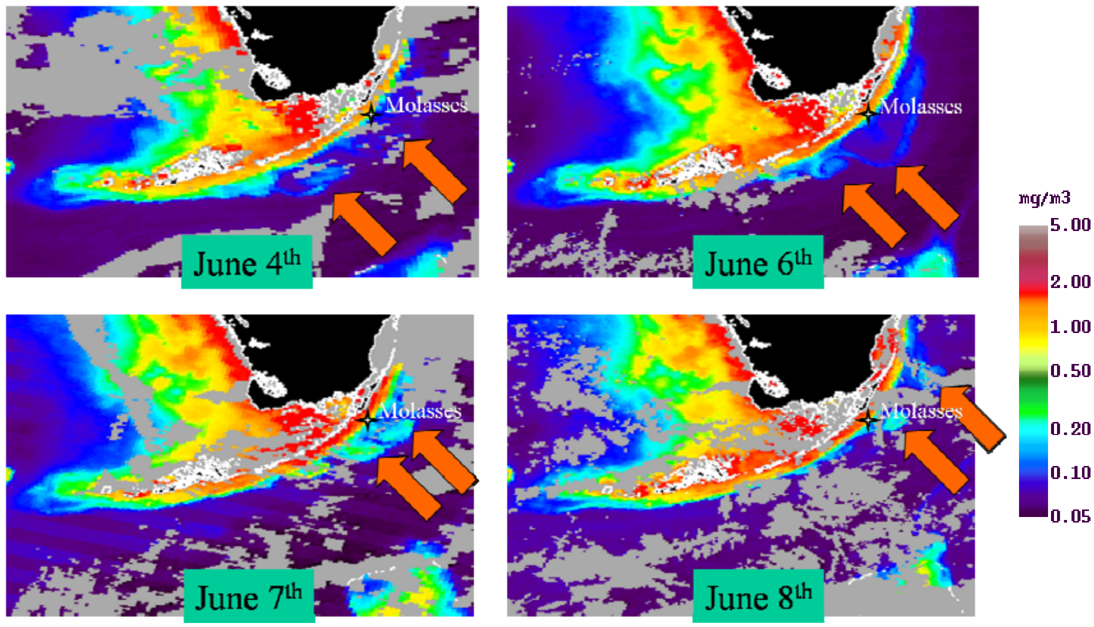

Figure 3: Sequence of MODIS satellite ocean-color images, showing chlorophyll *a* concentrations and associated circulation patterns in the Straits of Florida from 2006. Grey regions indicate cloud cover. Note the pair of vortices (arrows) translating past Molasses Reef over the four-day period, and interacting with one another and the inshore topography as they pass. These were among approximately 800 images examined visually in response to sea temperature variability ecoforecasts produced by the system described in the text, and served as visual confirmation both for the events, and the likely forcing mechanisms associated with each.

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