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4A Water motion, abiotic and biotic processes on coral reefs

Heat budget for Florida reefs: Reef-scale thermal stress via satellite

Lewis J. Gramer [1], Arthur J. Mariano [2], James C. Hendee [3]

[1] U. of Miami, Cooperative Inst. for Marine and Atmospheric Studies, Miami, FL USA
[2] U. of Miami, Div. Meteorology and Physical Oceanography, Miami, FL USA
[3] NOAA's Atlantic Oceanographic and Meteorological Laboratory, Miami, FL USA
Corresponding author: lew.gramer@noaa.gov

Abstract. Variability in multi-decadal records of hourly mean *in situ* sea temperature at shallow water sites in the Florida reef tract (FRT) is analyzed. Tidal, diurnal, and annual periodicities generally dominate, with both "weather-band" and inertial-period variability apparent at different sites. An ocean heat budget is estimated for an 11-year period based on these data, atmospheric reanalysis, satellite sea-surface temperature fields, an operational surface wave model, and estimates of heat exchange with the seafloor substrate. Coincident *in situ* meteorological data were used to estimate errors in the budget. A term for a sub-kilometer scale dynamic process, so-called horizontal convection or *the thermal siphon* is found to be necessary to balance the heat budget. Results are also very sensitive to the assumed rate of shortwave radiation absorption in the water column. Applications for improved remote sensing of benthic thermal stress at topographically complex coral reefs are briefly outlined.

Key words: thermal stress, reef heat budget.

Introduction

The Florida reef tract (FRT) is a large coral reef system that is less than 10 km offshore of southeastern Florida and the Florida Keys. It stretches over 300km from the Dry Tortugas west of Key West, to Martin County north of Palm Beach. The ecological and economic importance of the FRT is considerable (Causey 2002, Causey et al. 2002). The FRT may also represent a critical refugium for corals and associated organisms of the Caribbean and Gulf of Mexico, under scenarios of rapid and complex climatic change (Riegl et al. 2009).

Thermal stress – anomalously high or low near-bottom temperature that can cause reduced coral growth, bleaching (expelling of symbiotic algae), and even mortality – is a major factor influencing the health and management of coral reef ecosystems. Observations of and physical insights into sea temperature variability inform FRT managers (Keller et al. 2009), and may offer a way to identify reefs or larger areas within the FRT that are less prone to temperature extremes, and associated coral bleaching and potential mortality, under varying light and weather conditions (Yee et al. 2008; Lirman et al. 2011).

In the present paper, sea temperature variability from autonomous long-term monitoring stations in the FRT is analyzed. In order to understand this variability better, an ocean heat budget is constructed for each station. Meteorological data for each station from atmospheric reanalysis (model) outputs is combined with horizontal temperature gradients from satellite-derived sea surface temperature (SST), model outputs for sea state, and with simple models of light attenuation and seabed-water heat exchange.

Data and Methods

Meteorological and Oceanographic Data

A network of autonomous reef monitoring stations has been jointly maintained by Florida Institute of Oceanography and the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) within the FRT. For over two decades, these Keys - Coastal Marine Automated Network (SEAKEYS/C-MAN) stations at shallow sites both near shore and on the reef crest of the FRT, measured hourly wind speed and direction, barometric pressure, air and sea temperature, and at some sites dew-point temperature and tide height. Quality control of these data was performed by NDBC (Gilhousen 1998). Incident light both above the surface and near the seafloor have also been measured at one site since 2008; these light data were quality controlled by the Coral Health and Monitoring Program / Integrated Coral Observing Network (CHAMP/ICON) at NOAA Atlantic Oceanographic and Meteorological Labs (AOML). Table 1 and its accompanying map summarize the station locations discussed in this text.

Station Code	***Name, type of installation***	***Lat, Lon °***	***Isobath orient-ation***	***Depths: Tidal avg. water column, sea temp. sensor***	***Max btm. slope (β)***	***Dates of* in situ *data***
FWYF1	Fowey Rocks, reef crest lighthouse	25.590, -80.097	2ºT	12m, 2.0m	4%	1991-2012
MLRF1	Molasses Reef, reef crest light.	25.010, -80.380	54ºT	11m, 2.7m	3%	1987-2012
LONF1	Long Key, Bay side shallows day marker	24.840, -80.860	(0ºT)	2m, 1.3m	0.2%	1992-2012
SMKF1	Sombrero Key Reef, crest light	24.628, -81.111	65ºT	9m, 2.0m	2%	1988-2008

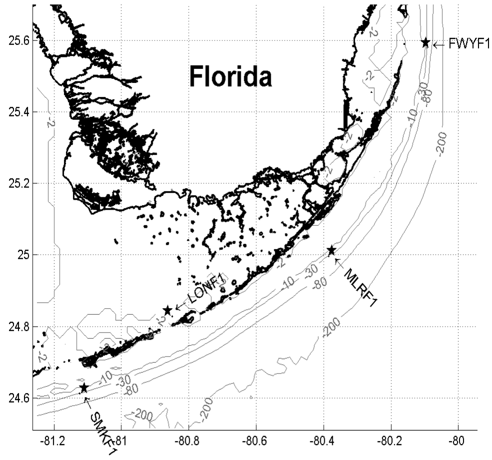

Table 1, Figure 1: Monitoring station locations, bathymetry, and dates for which hourly in situ data are available.

In order to evaluate the ability to estimate heat budgets at sites where no *in situ* meteorological data are available, six-hourly atmospheric forecast and radiative analysis fields from the European Centre for Medium-range Weather Forecasting (ECMWF) Reanalysis – Interim ("ERAI", Dee et al. 2011) were extracted. ERAI data were used for these variables: air temperature, wind speed and direction, specific humidity, barometric pressure, downward shortwave (insolation) and longwave radiative fluxes, total cloud cover, and atmospheric planetary boundary-layer height. Horizontal sea temperature gradients were estimated around each site from a 1 km-resolution weekly composite produced by University of South Florida (USF) of satellite SST from the Advanced Very-High Resolution Radiometer (AVHRR, e.g., Hu et al. 2009). Bilinear spatial interpolation and cubic spline time interpolation were used to produce hourly time series specific to each site from all gridded data sets described in the present study.

Surface wave state was required in the present study to estimate both Stokes drift (residual surface transport forced by waves), and sea-surface roughness (affecting both sea surface albedo and turbulent heat flux rates). For this study, output of the NOAA operational multi-grid Wave Watch III model (WW3, Tolman 2008) was chosen. Sea temperature sensors at all sites were fixed to structures on very shallow promontories, with water depths from 1 to 3m. However, mean water column depth for this study was chosen to encompass a reasonable daily tidal excursion for a local water parcel according to the NGDC 3-arcsecond resolution Coastal Relief Model (CRM, Divins and Metzger 2008), as the mean of the seven grid-point square (~650x650m) surrounding each site. A 1x1km subset of CRM around each site was also used to estimate maximum slope of the sea-floor topography, and to choose angle to true north of the isobath contours (Table 1). Hourly water height was then varied and tidal currents estimated using a Oregon State University Gulf of Mexico tidal solution (e.g., Egbert and Erofeeva 2002) for each site.

All data sources provided data beginning in the late 1980s or early 1990s, with two exceptions: horizontal gradients from USF AVHRR SST were only available from 1993 onward, and outputs from the WW3 operational wave model were only available from mid-1999 on. Due to these limitations, heat budget calculations (below) were only carried out from January 1st, 2000 through December 31st, 2011.

Heat Budget

The overall ocean heat budget consists of terms for heat storage, surface and bottom vertical fluxes, and horizontal advection and diffusion. It is modeled by the following equation (e.g., Reed and Halpern 1975; Wilson-Diaz et al. 2009; Davis et al. 2011).

$$\partial_t T = \frac{Q_0 + Q_b}{\rho C_p h} - \vec{u} \bullet \nabla T - \vec{u}_{hc} \bullet \nabla T(Q_0, h, \beta) + K\nabla^2 T$$

Here T is depth-averaged sea temperature as reported by NDBC, $\partial_t T$ Eulerian time rate of change in temperature, Q_0 net heat flux at the water surface from all sources, Q_b net heat flux at the sea floor, h tidally varying water depth of each site, β maximum local grade of the sea-floor, and ρ and C_p are density and heat capacity of sea water, resp. Heat advection $\mathbf{u}\cdot\nabla T$, and Fickian diffusion $K\nabla^2 T$ were calculated from satellite SST gradient, with an annually varying eddy diffusivity K, and depth-averaged currents **u** estimated from hourly wind and wave state using an empirical relationship in Ardhuin et al (2009).

Sea-surface heat flux has terms, resp. for (absorbed) shortwave and longwave radiative fluxes, sensible and latent turbulent heat fluxes, and heat flux due to rainfall: $Q_0=\gamma Q_{SW}+Q_{LW}+Q_{SH}+Q_{LH}+Q_{RH}$. The latter three (turbulent) air-sea fluxes were estimated using the method of Fairall et al. (2003) with cool-skin adjustment. Downward radiative fluxes were derived from ERAI, sea-surface albedo was estimated using the method of Jin et al. (2011), and upward longwave flux was estimated assuming sea-surface emissivity 0.97. Insolation absorption factor γ was estimated hourly from the fraction of insolation in penetrative (visible and ultraviolet) wavelengths, solar zenith angle, a seasonally varying light attenuation coefficient K_d, chosen to balance both the climatological and net accumulated heat budgets, and estimates of local seabed reflectivity in visible/UV.

Horizontal Convection

Finally, a smaller (sub-km) scale heat-advection term was found to be necessary to balance the heat budget at all of these sites (see Fig. 3c below). This is horizontal convection, $\mathbf{u}_{hc}\cdot\nabla T(Q_0,h,\beta)$, which is estimated from surface net heat flux, varying water depth, and local seabed slope β=rise/run. The reef-crest rise or reef promontory on which SEAKEYS stations FWYF1, MLRF1, and SMKF1 lie represents a local peak in the cross-shore profile of sea depth. If spatially invariant heating is applied at a shallow site with a pronounced gradient in bottom depth, down-slope buoyancy-driven flows or "gravity currents" may be expected (Mao et al. 2010b; Mao et al. 2010a). Cases considered in prior studies include uniform surface cooling (e.g., Bednarz et al. 2008; Mao et al. 2010b), and periodic heating and cooling, where all heat flux is directly absorbed in the water column (e.g., Bednarz et al. 2009). The case where penetrative solar radiation is absorbed by the seabed and re-radiated has also been considered by numerical and theoretical studies (ibid.; Chubarenko 2010).

Such thermal exchange currents are referred to in literature as "horizontal" convection or the thermal siphon (Monismith et al. 2006). For the present study, horizontal convective exchange velocity $\mathbf{u}_{hc}$ was calculated from *characteristic convective velocity* u_f, which was estimated directly from low-pass filtered air-sea flux, using the scaling for steady (periodic) thermal forcing and viscous/unsteady momentum balance described by Monismith et al. (ibid). An empirical relationship between $|u_{hc}|$ and u_f was estimated based on the study by Monismith et al. in the Gulf of Eilat, Red Sea (slope 3.0, bias -0.026, ibid., their Fig. 10a). In an upcoming manuscript, the present authors analyze a six-year record of data from a nearby acoustic Doppler current profiler deployment to validate these parameters. To the knowledge of the authors, horizontal convection has not been previously reported within the FRT.

Results

Sea temperature variability

Analysis of variability in hourly mean *in situ* sea temperature was done for periods from 6 hours up to interannual. Spectral analysis of sea temperature from SEAKEYS sites allows some immediate conclusions about temperature variability (Fig. 2): The dominant low-frequency variability at all sites is annual (365-day period), with no apparent semi-annual variability. Sea temperature at Sombrero Key Reef station SMKF1 offshore in the Middle Keys, for example (Fig. 2a), clearly shows both the dominant diurnal and annual periods over the entire 20-year time series, as well as a smaller response at the local inertial period (≈27.5h). Periods between diurnal and annual are also significant at the site with the shallowest, flattest topography, Long Key station "LONF1" (Fig. 2b). This suggests that synoptic variability in atmospheric forcing, e.g., due to passage of cold fronts or easterly waves ("weather" band), may play a greater role at this flat site than it does at other sites of similar depth that lie near steep topography, e.g., on the reef crest.

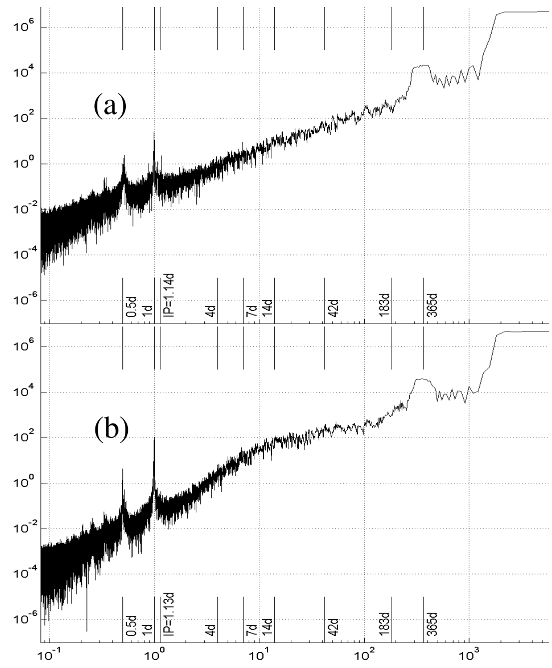

Figure 2: Power spectral density estimates for *in situ* sea temperature [ºC^2/cpd] from the Thomson multi-taper method, for: (a) Sombrero Key Reef (SMKF1) and (b) Long Key (LONF1).

Climatological mean hourly sea temperature for one site, SMKF1, has a peak at year-day 230 (mid-August, 30.5°C) and a low on year-day 35 (February, 23.5°C), for mean annual amplitude 7K. Variation in the median *diurnal* amplitude at SMKF1 with year-day is also observed, with minimum 0.7 in October and a peak over 1.4K/day in January. Other outer reef sites FWYF1 and MLRF1 experience similar annual amplitudes of 7K (Fig. 3a,c), but somewhat weaker seasonality in median diurnal range, with minimum diurnal range at both sites of 0.5 in September-November and peak diurnal range around 1.2 K/day in January. On the Bay side, LONF1 experiences minimum median diurnal amplitude of 1.1K/day in December and a peak in April above 1.7K/day, with an 11K mean annual amplitude (Fig. 3b). Thus, LONF1 is an outlier in both annual and peak diurnal ranges.

Heat Budget

Climatological daily mean sea temperature at each site was compared with the climatological daily mean of the accumulated hourly heat flux from the heat budget, for each calendar day from 2000 to the end of each sea temperature record (early 2008 for SMKF1, the end of 2011 for the other three sites). A mean for each year-day from 1 to 365, for both observed sea temperature and the cumulative heat flux predicted by the budget are shown below (Fig. 3). Days with fewer than 24 hours of quality-controlled data from any source (sea temperature, reanalysis, satellite SST, or wave model) were not included in these results.

The difficulties of closing the heat budget for these shallow reef sites are demonstrated by Fig. 3c: results when horizontal convection are omitted from the budget predict much greater annual amplitude than is actually observed. This is true even when we assume the water column depth is that experienced by a water parcel on a “daily tidal excursion”, rather than the water depth where the actual sensors are deployed (e.g., on a promontory near the outer reef crest). A simple annual air-sea surface flux budget in fact does not close at all for these sites: Water over shallow topography may not absorb all shortwave radiation entering the sea surface, and reflectivity and heat exchanges between the seabed and the water column are found to be important for temperature evolution there (Fig. 3c).

At higher-relief sites, near the outer reef crest where topographic slopes exceed 1% for example, sea temperature response to air-sea forcing is significantly moderated by convective currents, particularly during rapid air-sea cooling, as shown in Fig. 3c. Furthermore, it should be noted that such horizontal convective currents, where they occur, are likely to do more than merely condition the thermal environment of coral reefs. They may also change availability of nutrients for photosynthesis and respiration (James and Barko 1991), and of prey for filter feeding by corals and other reef organisms (Monismith et al. 2010).

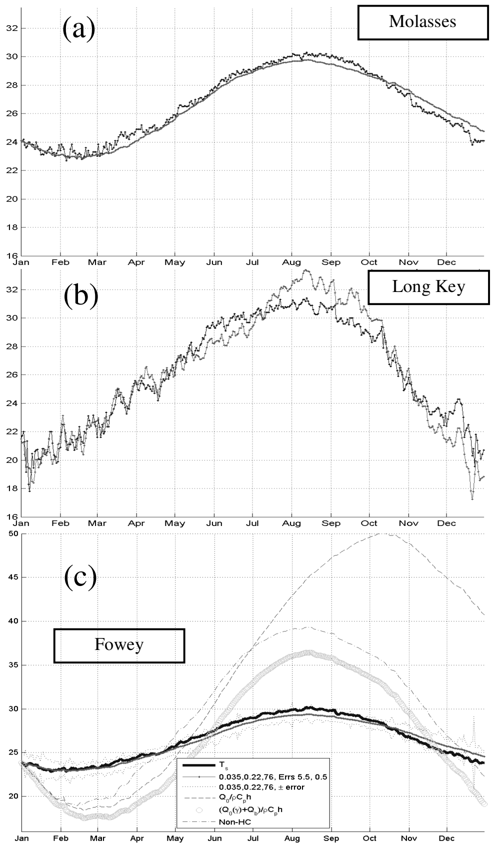

Figure 3: Heat budget results. Climatology (mean for each year-day from 1 to 365, for years 2000-2011) of sea temperature (black dots, °C), cumulative daily temperature change from the budget with all terms (gray lines) at (a) Molasses Reef, (b) Long Key, and (c) Fowey Rocks. Panel (c) also shows results from an air-sea flux budget (dashed line), combined surface and benthic terms (circles), and a budget with all terms except horizontal convection (dot-dash); note ordinate scale on (a) and (b) is 16 to 33 ºC , while that for (c) is 16 to 50ºC.

Discussion

The FRT is a coral reef ecosystem fringing the south and east Florida Shelf. FRT corals and other organisms (incl. Acroporid corals, listed under the US Endangered Species Act) are sensitive to thermal stress. To manage this large, fragile ecosystem, reliable information on thermal stress is needed, including climatological baselines of annual and diurnal variability.

To this end, *in situ* sea temperature and meteorological data have been gathered at reef sites in the FRT by autonomous monitoring stations for over two decades. A heat budget has been developed to model sea-temperature evolution over shallow-water reefs of the FRT using this *in situ* sea temperature, together with kilometer- and regional-scale data from atmospheric reanalysis, surface wave models, and satellite SST.

One aim of such research is to characterize reliably sea temperature variability and extremes on coral reefs, using ***only*** larger-scale data. With access to near real-time model output and remote sensing data, a heat budget can provide resource managers with timely information on thermal stress as it is actually experienced by corals, in protected areas around the world where *in situ* data is not available. However, such a heat budget must adequately account for oceanographic and other processes that may contribute to small-scale variability on coral reefs.

The present work describes a heat budget that compares well with *in situ* sea temperature at topographically diverse sites in the FRT. These results hold out the hope that reliable, remote sensing of reef-scale thermal stress may now be in sight, at least for reefs on continental margins, as in the FRT. A manuscript now in preparation by the authors contains further details of the heat budget methodology described here. That manuscript compares results above with heat budget estimates using *in situ* meteorological data. Upcoming publications will estimate the heat budget for FRT and other sites using gridded "foundation" (sub-surface) sea temperature estimates derived from satellite data ("MISST"; Gentemann et al. 2009).

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