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Thermal History of Reef-Associated Environments During a Record Cold-Air Outbreak Event

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Received 5 November 1981; accepted 18 November 1981

Summary. Several polar continental air masses intruding into the south Florida/northern Bahama Bank region during January 1981 caused record low air temperatures and rapid chilling of extensive shallow-water carbonate systems. Numerous "coral kills" along the Florida reef tract and massive fish mortalities in Florida Bay were attributable to unusually cold waters generated at this time. Thermal evolution of Florida Bay/Florida reef tract and northern Bahama Bank waters from 8 to 21 January was assessed from thermal infrared data acquired by the NOAA-6 environmental satellite, in situ water temperatures, local meteorological data, and a computerized heat flux model. Field observations and laboratory experiments identify 16 °C as a thermal stress threshold for most reef corals (Mayor 1915; Davis 1981). Temperature-corrected digital satellite data indicated that water temperatures below 16 °C were generated in Florida Bay and on Little and Great Bahama Banks during a 10-day period in January. Lowest temperatures on the Florida reef tract resulted from offshore transport of Florida Bay water through major tidal channels. Offshore movement of bay water is driven primarily by strong northerly winds, density gradients, and tidal pumping. Absence of reef development opposite major tidal passes along the Florida reef tract (Ginsburg and Shinn 1964) and aperiodic coral kills along bank margins can be attributed to this process, which has probably had a limiting influence on Holocene reef development in these areas.

Introduction

Field observations following harsh winter-weather events have provided insight into the role of cold-water stress as a limiting factor to coral growth in high latitudes. During 1969–1970 Hen and Chickens patch reef (Florida reef tract) experienced 80%–90% mortality (Voss 1973), which was attributed to cold waters generated during the winter months (Hudson et al. 1976a). Recent research based on sclerochronology has shown a close correlation

between years of "stress band" deposition in *Montastrea annularis* along the Florida reef tract and low air temperatures recorded at Key West (Hudson 1981; Hudson et al. 1976a, b). Abnormally cold outbreaks of polar air in January 1977 investigated by Roberts et al. (1982) proved detrimental to reef corals in the northern Bahamas and Florida reef tract. At Dry Tortugas in 1977 more than 90% of the dense *Acropora cervicornis* was killed to a depth of 15 m as a result of thermal shock. Water temperatures of 14–16 °C were recorded by minimum-maximum thermometers placed under coral heads 1 m from the surface (Davis 1981). Similar widespread mortality of *Acropora* sp. in the Persian Gulf was attributed by Shinn (1976) to cold waters generated during a severe cold-air outbreak.

Although temperature tolerance is species dependent, Mayor (1915) identified a critical thermal stress threshold by showing that reef-building hermatypic corals lose the ability to capture food at 16 °C. His laboratory experiments had already indicated that exposure to a water temperature of 14 °C for only a few hours would exterminate the principal Florida reef corals (Mayor 1914). Vaughan and Wells (1943) concluded, however, that reefs do not grow where minimum water temperatures fall below 18 °C, and that optimum growth occurs at 25 °C to 29 °C.

Reef development in the Florida/Bahama region is primarily along the windward (eastern) bank margins owing to favorable conditions provided by warm oceanic currents and an active wave climate. These ideal conditions can be interrupted by extreme southerly intrusions of polar continental air masses. Shallow bay and bank waters, having a limited heat storage capacity, experience rapid heat loss, chilling below the 16 °C thermal stress threshold sometimes for several days (Roberts et al. 1982). Exceptionally cold, dense waters generated in bay and bank areas can move into deeper adjacent environments, thereby subjecting shelf reefs to cold-water stress.

Three cold-air outbreaks from 8 to 21 January 1981 created abnormally chilled waters in the south Florida/Bahama Bank region. Massive fish kills in Florida Bay

(J. Parks, personal communication) and several coral mortalities observed along the Florida reef tract (Hudson, USGS; E. Davidson, Audubon Soc. Pres.; and P. Moore, captain, Underseas, Inc., personal communications) provided evidence of the effects of this dramatic cold-air event. This paper is a report on the thermal response of Florida Bay and northern Bahama Bank waters to atmospheric forcing and resultant impacts on proximate reef systems.

Methods

Thermal infrared imagery from the Advanced Very High Resolution Radiometer (AVHRR) of the NOAA-6 environmental satellite provided the means for detecting temperature variability on a regional scale. Radiometric data obtained from the National Climatic Center were in the form of black-and-white photographic images and in digital format on computer-compatible tape. Digital data acquired on the morning pass of 19 January (0800 EST) provided optimum dry-air, clear sky conditions over Florida and the Bahama Banks on one of the coldest days during the study period. Spatial resolution of the data is 1.1 km at nadir (Kidwell 1979) with a thermal quantization interval of 0.25 °C (DiRosa and Huh 1980). Data were calibrated to yield radiometric temperatures and were computer processed at the Remote Sensing and Image Processing Laboratory, College of Engineering, Louisiana State University. Radiation temperatures were extracted from the 10.5–11.5 μm channel along transect lines and within polygonal areas of uniform temperature structure to quantify shallow-water thermal responses. Time-series satellite imagery was used to detect possible transport routes for unusually cold waters.

Satellite-measured radiation temperatures can provide accurate measurement of surface water temperatures if calibrated with "surface truth" temperatures acquired within the study area. Water temperatures monitored at Lignumvitae Key, northeast Florida Bay (Fig. 1), throughout the 1981 winter and surf temperatures from Naples, Florida (National Weather Service), provided these in situ measurements. Air temperatures measured at Lignumvitae Key were entered in a computerized heat flux model that hindcasts water temperature evolution from local meteorological parameters. Required model inputs include hourly air temperature, relative humidity, air pressure, wind speed, solar radiation, and cloud cover. The model accuracy was tested with Florida Bay water temperature data during a cold-air event in January 1977. Predicted hourly water temperatures were found to be within 0.03 °C of measured temperatures, with a standard deviation of 0.3 °C over an 8-day observation period (Walker, in preparation). The model was used in this study to determine time-series water temperature changes from 8 to 21 January 1981 for Florida Bay water.

Results

Evolution of Stress-Inducing Water Temperatures

The three cold-fronts that moved through the area in rapid succession during Stress Phase I (Fig. 2) introduced two high-pressure systems with accompanying strong northerly winds. Two lows (9 and 10 January) were followed by a minor cold-air outbreak that chilled Florida Bay water from 18.8 °C to slightly below 16 °C. The passing front on the night of 11 January was followed by an abnormally cold air mass. Wind speeds close to 15 m/s and the intrusion of cold, dry, arctic air caused rapid heat loss from Florida Bay, resulting in an episodic low water temperature of 8.7 °C on 13 January. This was 4.0 °C lower than water temperatures recorded in northeast Florida Bay during the severe January 1977 cold-air outbreak episode

(Roberts et al. 1982). In the northern Bahamas, an air temperature minimum of 5.6 °C was experienced at Freeport (Little Bahama Bank) on the morning of 14 January (Bahama Meteorological Office 1981).

Relaxation of the high-pressure systems was accompanied by diminished wind speed, directional shift to the southeast, and rapid rise in air temperatures, which indicated the return of maritime air. Measured temperatures showed rapid response to the warming trend, whereas model-predicted temperatures did not. This discrepancy reflects the proximity of the thermograph site to a major tidal pass connecting Florida Bay and the Florida reef tract.

Stress Phase II was initiated late on 16 January as two fronts merging over south Florida caused a wind shift to the northwest and a dramatic increase in wind speed. Florida Bay chilled rapidly, reaching minima of 11.0 °C and 10.7 °C on 18 and 19 January, respectively.

Water temperatures measured at Lignumvitae remained below 16 °C, a thermal stress threshold, for 4 days during Stress Phase I and 2½ days during Stress Phase II and thus indicate the residence time of chilled waters near tidal passes. The heat flux model, which does not incorporate tidal influence, demonstrates that the mass of Florida Bay water remained below 16 °C for at least 10 days, from 11 to 21 January 1981.

Satellite Observations

The thermal infrared satellite data acquired by the NOAA-6 satellite provided an excellent data base for monitoring surface temperature features of Florida Bay, Little and Great Bahama Banks. Absorption and reemission of sea-surface temperatures primarily by atmospheric water vapor cause satellite-measured radiation temperatures to be colder than in situ measurements. Cold, dry air conditions characteristic of outbreak events minimize the radiation temperature depression. Hsu et al. (1976) found a temperature offset of 2.0 °C or less in the 10.5–12.5 μm range under cloud-free, dry-air conditions following an advancing cold front. Comparisons of "surface truth" temperatures with radiation temperatures on 19 January confirmed an offset of 2.0 °C.

Digital satellite data showed that vast expanses of water on Little and Great Bahama Banks had chilled to below 16 °C by 19 January (Fig. 1). Radiation temperatures extracted from each pixel (picture element) along the transect A–A' are illustrated in Fig. 3. This temperature profile displays the strong temperature gradients between the deep Gulf Stream water mass and the shallow bank and bay water bodies. Water temperatures generated on the Bahama Banks were not as cold as those experienced in Florida Bay owing to modification of the polar air mass by the Gulf Stream and greater mean water depths on the banks (4 m as compared to 1.6 m in Florida Bay).

Digital data allowed a detailed analysis of thermal variability along the Florida reef tract (Fig. 4). Radiation temperatures ranged from 11.2 to 14.2 °C (13.2 to 16.2 °C

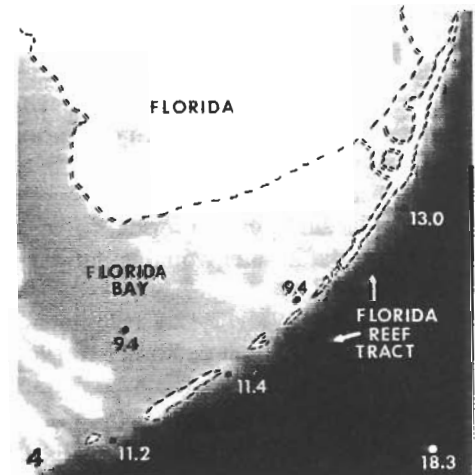
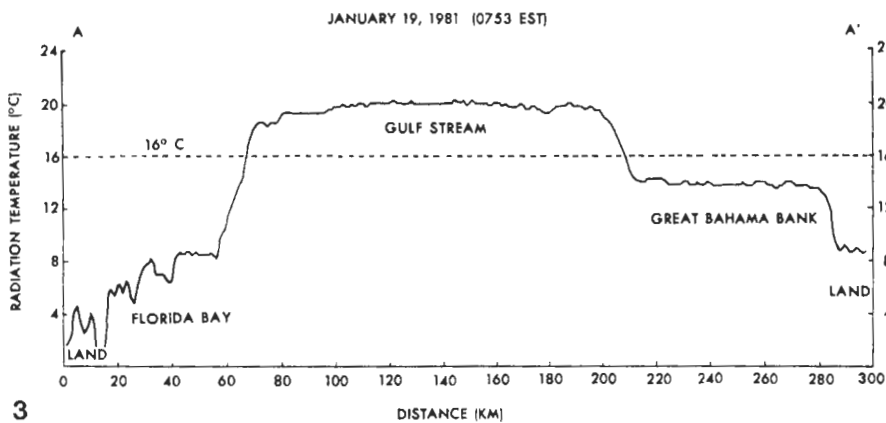
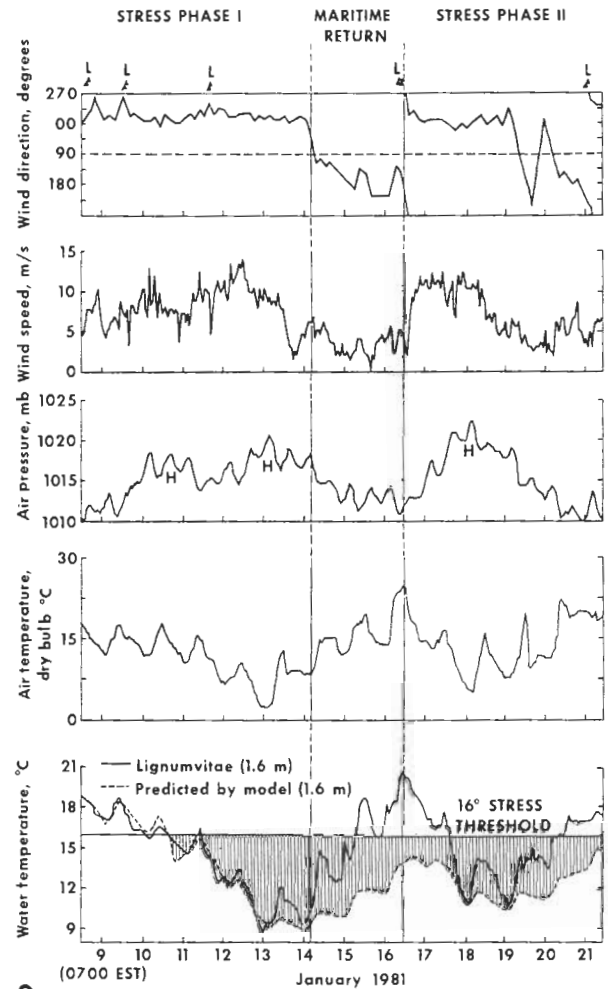
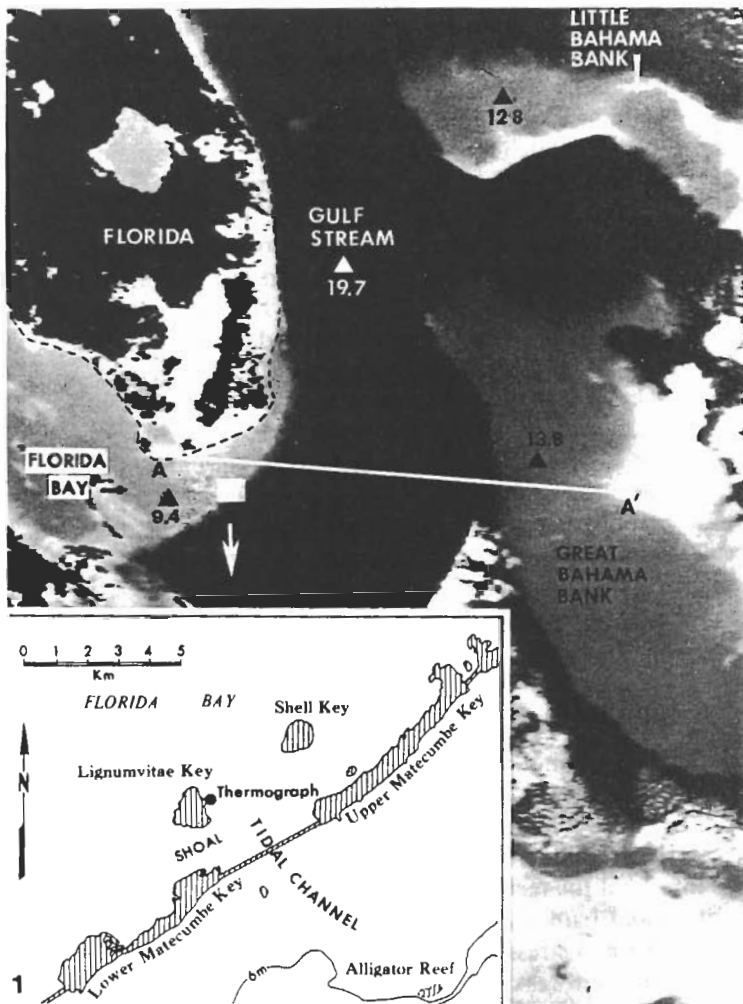


Fig. 1. Thermal infrared data acquired by the NOAA-6 satellite, 19 January 1981 (0753 EST). Lighter gray tones of water bodies represent colder radiation temperatures, as illustrated by areal temperatures extracted. A correction factor of $+2.0^{\circ}\text{C}$ is necessary for determination of in situ water temperatures. The insert shows location of the northeast Florida Bay thermograph site

Fig. 2. Lignumvitae Key, NE Florida Bay. Meteorological characterization of cold-air outbreak from 8 to 21 January 1981. Shading indicates the extent and duration of chilling below 16°C for Florida Bay water

Fig. 3. Profile of radiation temperatures extracted from digital satellite data along the transect A-A' (location on Fig. 1)

Fig. 4. Enlargement of Florida Bay/Florida reef tract on 19 January. Radiation temperatures extracted from 4-km^2 areas in the Bay and in cold-water "plumes" are shown

corrected) along the reef tract. Coldest temperatures were measured in "plumes" extending from Florida Bay onto the reef tract through major tidal passes. Cloud-free imagery available for 13–19 January indicated the presence of extensive plume features on 13, 18 and 19 January, which corresponded to strong northerly wind occurrences.

Discussion

Comparisons between model-predicted temperatures and in situ measurements at Lignumvitae Key provided evidence of water mass movements through tidal passes during cold-air outbreak events. The close correlation between predicted and measured temperatures that occurred in conjunction with strong northerly winds from 8 January to 13 January (Fig. 2) indicated that tidal flux into the Bay from the reef tract (flood tides) was suppressed. During the Maritime Return Phase, tidal flux resumed, as is shown by the significant difference between predicted and measured water temperatures, which indicates that Lignumvitae temperatures were the result of advection.

Suppression of flood tides is demonstrated again during Stress Phase II. Strong northerly winds can control water movements at major tidal passes along the Florida reef tract. On 13, 18 and 19 January cold-water "plumes" extended from Florida Bay onto the reef tract, as a result of the high northerly wind stress evident in Fig. 2.

Results of this study indicate that offshore movement of cold Florida Bay water is the primary process by which abnormally cold water is introduced to and moved along the Florida reef tract. Strong northerly winds that accompany cold-air outbreak episodes can initiate this offbank flux. Ebbing tides and water mass density differences may augment the rate of transport. Chilled waters generated during cold-air outbreak episodes are significantly denser than adjacent warm oceanic water. This density imbalance implies that once offshore movement of Florida Bay water is initiated it will tend to flow near the bottom until it either mixes with shelf water or reaches its equilibrium depth in the adjacent Strait of Florida. Offshore movement of cold Bahama Bank water would be subject to this same sequence of events.

During January 1981 Florida reef corals were killed along the reef tract at patch and outer-reef locations as a result of this process. In early February, researchers observed numerous dead corals at a frequently studied patch reef (5-m water depth) near Elliot Key, in the northern reef tract (Hudson, USGS, personal communication). *Montastrea annularis* and *Agaricia agaricites* were partly killed, whereas *Porites astreoides* suffered total mortality. Farther south, at Looe Key (southern reef tract), two dense stands of *Acropora cervicornis* (10–15 m in linear extent) and two smaller patches of *Acropora palmata* lost their zooxanthellae and were subsequently overtaken by algae (P. Moore, captain, Underseas Inc., personal communication).

Isolated observations of cold-water-induced stress in south Florida and northern Bahama reef systems in re-

cent years indicate that temperature plays a significant role in controlling coral growth and reef development in high latitudes.

Along the Florida reef tract, outer bank reefs are least developed and patch reefs are virtually absent where major tidal passes connect Florida Bay and the reef tract (Ginsburg and Shinn 1964; Marszalek et al. 1977). Since coldest reef tract temperatures were measured opposite tidal passes, temperature appears to be the important factor limiting coral growth at these sites. During the Holocene transgression, barrier reefs off southeast Florida (Lighty 1977; Lighty et al. 1978) were killed when the flooding of shallow backreef lagoons subjected reefs to detrimental temperature fluctuations. The demise of the Abaco barrier reef (along northeast margin of Little Bahama Bank) and the subsequent establishment of a fleshy algae community have been attributed to the offshore transport of episodically cold water masses (Lighty 1981). Competition between reef corals and fleshy algae in high latitudes may also be related to temperature-induced stresses.

Conclusion

1. Satellite technology is available to study temperature structure of vast shallow-water carbonate areas.
2. Successive cold-air outbreaks can chill Florida Bay and northern Bahama Bank waters below the 16 °C stress threshold for reef corals.
3. Bay and bank water temperatures can remain below the thermal stress threshold for several days owing to cold-air outbreak events.
4. Offshore movement of chilled waters, driven by northerly winds, density gradients, and tidal pumping, can limit coral growth and reef development in high latitudes.

Acknowledgements. This study was supported by the NASA Graduate Student Researcher Program through the Jet Propulsion Laboratory, Pasadena, California. Support was also provided by the Coastal Sciences Program, Office of Naval Research, Arlington, Virginia. Thanks are extended to S. A. Hsu for use of the thermograph and to Jeannie Parks and the staff of Long Key State Recreational Area for operational maintenance of the unit throughout the winter. Don DiRosa assisted in image processing, Kerry Lyle with photography, and Mrs. G. Dunn with graphics.

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