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Weather and hydrographic conditions associated with coral bleaching: Lee Stocking Island, Bahamas

Abstract Thermograph, current-meter, and coastal-weather data from Lee Stocking Island, Exuma Cays, Bahamas, are used to investigate hydrographic and meteorological conditions preceding and during a bleaching event in August 1990. Shelf water temperatures recorded at three locations rise to just over 30 °C. Weather data provide estimates of local heating and cooling by insolation, net outgoing long-wave radiation, and sensible and latent heat fluxes. Weather data do not indicate a period of unusually clear skies during the days and weeks preceding the bleaching event. Rather, calculations suggest that low wind speeds during late July and early August reduced evaporative cooling. A tidal channel near the bleaching site provided a source of hyperpycnal 31 °C water that had been heated in the shallow waters of Great Bahama Bank. Current-meter data suggest an along-shelf transport of water from the mouth of the tidal channel to the bleaching site. A comparison of wind-stress and water-temperature data suggests that a downwelling pattern contributed to heating at the reef by flooding the shelf with warm surface water. Results suggest that heating at the reef was a combination of local warming, enhanced by reduced evaporation, and advective warming resulting from both an along-shelf transport of bank water and a landward across-shelf transport of warm surface water.

Keywords Local heat flux · Advective heat flux · Coral bleaching · Bahamas

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Introduction

The subject of coral bleaching has received considerable attention over the past decade, both within and outside of the scientific community. The global extent of and recent increase in coral reef bleaching have been summarized by Brown (1987) and Glynn (1993) and documented for specific regions by Brown et al. (1996), Hoegh-Guldberg and Salvat (1995), and Cook et al. (1990) among many others. Aside from the direct impact that bleaching has on coral, it has been suggested that coral bleaching is an indicator of global warming (Glynn 1991; Hoegh-Guldberg 1999).

Coral bleaching has been documented throughout the Caribbean (Ogden and Wicklund 1988; Williams and Bunkley-Williams 1988; Zea and Duque Tobon 1989), for reefs of Puerto Rico (Goenaga and Canals 1991), Colombia (Zea and Duque Tobon 1989), Jamaica (Goreau 1990), and in the Florida Keys (Hudson 1981). In the Bahamas, Dennis and Wicklund (1994), Lang et al. (1988), and Anthony et al. (1996) all reported bleaching in bank and shelf waters in the vicinity of Lee Stocking Island in the Exuma Cays.

Many studies of coral bleaching have suggested that elevated temperature is one of the most likely causes (Glynn 1993; Brown 1997; Winter et al. 1998). The objective of this paper is to examine weather conditions that coincided with near-bottom heating in shelf waters off Lee Stocking Island in July and August of 1990, and to describe local and advective heating at a time when coral bleaching was reported (Dennis and Wicklund 1994). Data needed to quantify local heating and cooling processes are available from a land-based weather station less than 0.5 km from shelf waters of Exuma Sound. Current-meter and hydrographic data indicate warm hyperpycnal water leaving Great Bahama Bank on the ebb tide, and both wind direction and along-shelf flow are downwelling-favorable. The observational database supports the hypothesis that bleaching in shelf waters was the result of an along-shelf transport of warm bank water, combined with a downwelling of surface-layer water, at a time when light winds reduced evaporative cooling.

The study area

The Exuma Cays of the Central Bahamas extend for 130 km along the western side of Exuma Sound from Norman Cay south to Great Exuma Island, and they provide a leaky barrier between the deep waters of Exuma Sound and the shallow waters of Great Bahama Bank (Fig. 1). The continental shelf on the east side of the Exuma Cays is generally less than 2 km wide, and the along-shelf alignment is approximately 310–130°. The shelf break occurs at a depth of 25–30 m along the top of a "wall." The bottom drops nearly vertically to a depth of about 200 m, then continues with a slope of approximately 60° to the basin floor at about 2,000 m. A fringing reef runs parallel to the coast, with the top of the reef at about the 10-m isobath. Patch reefs are common both landward and seaward of the fringing reef, and coral is common along the top of the wall (Kendall et al. 1989).

The climate of the region is subtropical, with relatively subtle seasonal variations in temperature and wind conditions (Pitts et al. 1993). Two seasons can be defined in terms of wind patterns and air temperature. Winter weather begins as early as November or as late as January, and continues through March or April. Monthly mean air temperatures decrease to 24–25 °C, but temperature can be substantially lower for brief periods following the passage of cold fronts. Monthly resultant wind directions are out of the northeasterly quadrant from October through February, although northerly and northwesterly winds occur following the passage of cold fronts. Two to three cold fronts per month pass through the central Bahamas in January and February.

Summer weather patterns are characterized by a dominance of maritime tropical air and frequent development of thunderstorms. Winds are predominantly easterly at speeds of 2–8 m s^{-1}. Wind direction can deviate significantly from mean values, veering into the southeast more commonly than backing into the northeast. Wind speed is at the lower end of the range more often than it is at the upper end.

The annual temperature cycle in shelf waters includes a summer maximum of approximately 29–30 °C which can occur on one or more occasions between mid-July and late September (Pitts and Smith 1993). Winter minimum temperatures of about 24 °C occur intermittently between late December and mid-March. The shallow waters of Great Bahama Bank are more responsive than are the deeper waters of Exuma Sound to seasonal and sub-seasonal heating and cooling cycles. Thus, water temperatures on Great Bahama Bank are higher than water temperatures in the sound in summer and lower in winter, and low-frequency temperature fluctuations are more prominent.

Similarly, bank water salinity is higher than sound water salinity during the dry season and lower during the wet season. Salinities as high as 40 psu have been reported by Smith (1995), while Exuma Sound salinity is generally around 37 psu (Hickey et al. 2000). Bank water ebbing through tidal channels separating the Exuma Cays can impact corals on the shelf by forming density currents. Even in summer months, when higher water temperatures act to reduce density, warm bank water can be hyperpycnal during periods of low rainfall and thus relatively high salinity. Lang et al. (1988) suggested that warm density currents were implicated in coral bleaching that occurred in the southern Exuma Cays in 1987. Smith (1996) documented hyperpycnal water leaving Great Bahama Bank on the ebb tide throughout the year, but especially in spring and summer months.

Extensive bleaching started in mid-August of 1990 along the shelf edge at a depth of 25 m (Dennis and Wicklund 1994). By mid-September, bleaching was occurring from the inner shelf to the upper part of the wall. North Perry Reef (station 3 in Fig. 1) is a section of the fringing reef that is mentioned as a site of extensive bleaching. Bleached organisms included stony corals, gorgonians, and sponges.

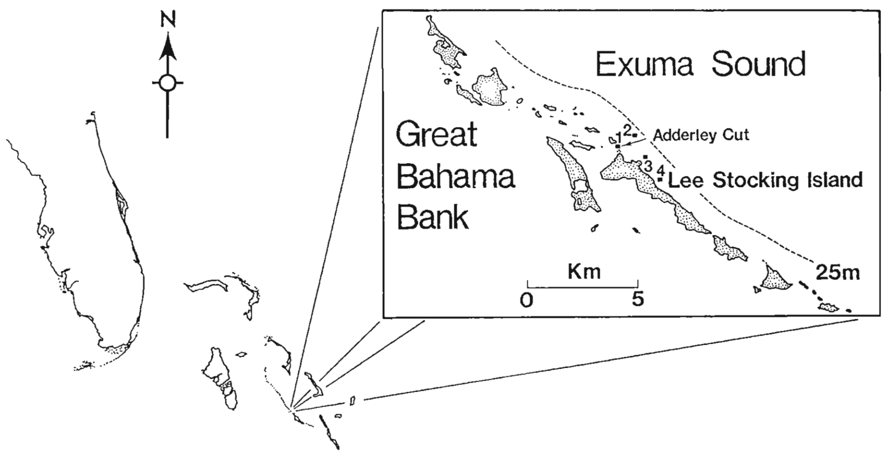

Fig. 1 Map of study sites in vicinity of Lee Stocking Island, Bahamas, along southwest side of Exuma Sound and eastern side of Great Bahama Bank. Thermographs were located at the mouth of Adderley Cut (station *1*), on shelf seaward of Adderley Cut (*2*), and on fringing reef near midpoint of Lee Stocking Island (*4*). Bleaching was reported at North Perry Reef (*3*)

Data

Meteorological data needed to quantify wind forcing, sensible heat fluxes, solar heating, and both radiative and evaporative cooling are available from July and August 1990. A Campbell weather station recorded weather conditions from a study site on Lee Stocking Island, approximately 350 m from Exuma Sound at its closest point. The weather station is located on the southwest side of a landing strip, and when winds are out of the northerly to southeasterly quadrants, speed and direction measurements are minimally influenced by topography or vegetation. During this 2-month period, 75% of wind directions were landward within the 180° arc from 310° clockwise to 130°. Small hills lying southwest of the weather station can impact wind measurements when winds are out of the southwesterly and northwesterly quadrants. The blocking effect of topography, both at the weather station and in nearshore waters, serves more to reduce wind speeds than to alter wind directions. Air temperature is recorded with an accuracy of ±0.5 °C. Relative humidity, in percent saturation, and solar radiation, in calories per centimeter (langleys), are recorded with an accuracy of 5%. The relative humidity sensor was calibrated approximately bimonthly using a sling psychrometer. Wind speed and direction are recorded with accuracies of ±0.11 m s^{-1} and ±5°, respectively.

Water temperature records were collected from 1 July through 31 August in Adderley Cut near the mouth of the channel (station 1 in Fig. 1) and at a mid-shelf study site, 400 m seaward of the mouth of Adderley Cut (station 2). Both time series were provided by General Oceanics Mark II current meters. In Adderley Cut, the current meter was 1 m above the bottom in 4 m of water; at the mid-shelf study site, the current meter was 4 m above the bottom in 21 m of water. The accuracies of the current speeds and directions are ±1 cm s^{-1} and ±2°, respectively, and the accuracy and resolution of the temperature readings are ±0.25 and 0.02 °C, respectively, all according to instrument specifications. The Adderley Cut current meter also recorded conductivity. The accuracy and resolution of the conductivity readings are ±2.5 and ±0.1 mS cm^{-1}. Conductivity and temperature readings were used to calculate salinity (Lewis 1980) with a resolution of ±0.1 psu, and density (Millero and Poisson 1981) with a resolution of ±0.07 kg m^{-3}. Hydrographic data from station 1 at the mouth of Adderley Cut describe Exuma Sound water on the flood and Great Bahama Bank water within one tidal excursion of the channel mouth during the ebb.

Water temperatures on the fringing reef near the midpoint of Lee Stocking Island (station 4) were recorded during a 6-week period prior to, during, and following a coral bleaching event in mid-August 1990. Data were recorded 15 m below the surface from 1 July through 18 August using a Sea Data TDR-3 pressure recorder. The accuracy of the readings is ±0.1 °C, according to instrument specifications.

Methodology

Pyranometer readings, P, were corrected for surface reflection to estimate the incoming solar radiation available for heating, Q_S:

$$Q_S = P[0.623\exp(-0.0851A) + 0.0377] \quad (1)$$

where A is the sun angle. Values calculated with Eq. (1) reproduced tabular data (Payne 1972) with an r^2 of 0.987.

The latent, Q_E, and sensible, Q_H, heat fluxes, in cal cm ^{2} s ^{1}, were quantified using bulk aerodynamic formulas:

$$Q_E = \rho_a L_v C_e U \Delta_q \quad (2)$$

and

$$Q_H = \rho_a\, c_p\, C_h U \Delta_T \quad (3)$$

(Pond and Fissel 1974; Hsu 1978), where ρ_a is the density of air; L_v is the latent heat of vaporization; c_p is the specific heat of air; C_e and C_h are the bulk aerodynamic coefficients for moisture and heat, respectively; U is the 3-m-level wind speed measured at the weather station; and ΔT is the air water temperature difference. The specific humidity difference, Δq, was estimated from the water temperature, assuming the air was saturated at the sea surface, and from the air temperature and relative humidity.

Net outgoing long-wave radiation, Q_B, was estimated using Efimova's formula and corrected for cloud cover, S:

$$Q_B = \varepsilon\sigma T_w^4(0.254 - 0.00495e)(1 - 0.7S) \quad (4)$$

where T_w is the water temperature in degrees Kelvin, ϵ is the emissivity of sea water, σ is the Stefan-Boltzmann constant, and e is the vapor pressure of the overlying atmosphere. Cloud cover was estimated by comparing pyranometer data with the expected clear-sky insolation (Reed 1977); nighttime cloud cover was obtained by interpolation from daytime values.

Current vectors recorded at station 2 were decomposed into the local along- and across-shelf components, defined to be those for which the correlation coefficient became zero. This occurred for headings of 329 149° (along-shelf) and 059 239° (across-shelf). Along-shelf components were low-pass filtered (Bloomfield 1976) to show whether water leaving Adderley Cut was deflected northwestward or southeastward after leaving the mouth of the channel. To characterize along-shelf flow as a response to wind forcing, wind stress was calculated using the drag coefficient suggested by Wu (1980), then low-pass filtered to remove fluctuations at tidal and diurnal periodicities. Current meter data from station 2 were not used to characterize across-shelf flow, because the study site was directly off the mouth of Adderley Cut. There, currents measured 4 m above the bottom in 21 m of water would be some unknown combination of tidal and nontidal exchanges through the cut and a return flow responding to across-shelf transport in surface layers.

Local heat fluxes

Weather data used for calculating local heat fluxes are shown in Fig. 2. Incoming solar radiation (insolation), in langleys min^{-1}, is at the top of the plot in Fig. 2a. Midday maximum values commonly reach 1.3 ly min^{-1}. Maximum insolation is slightly reduced in 13 14 July, 28 30 July, and on 4 and 7 August, but there is no indication of a period of unusually high insolation that would produce correspondingly high solar heating.

Air temperature (Fig. 2b) includes diurnal ranges of 3 4 °C throughout the 2-month period. Highest temperatures are approximately 31 °C through the end of July, then increase to as much as 33 °C in early August.

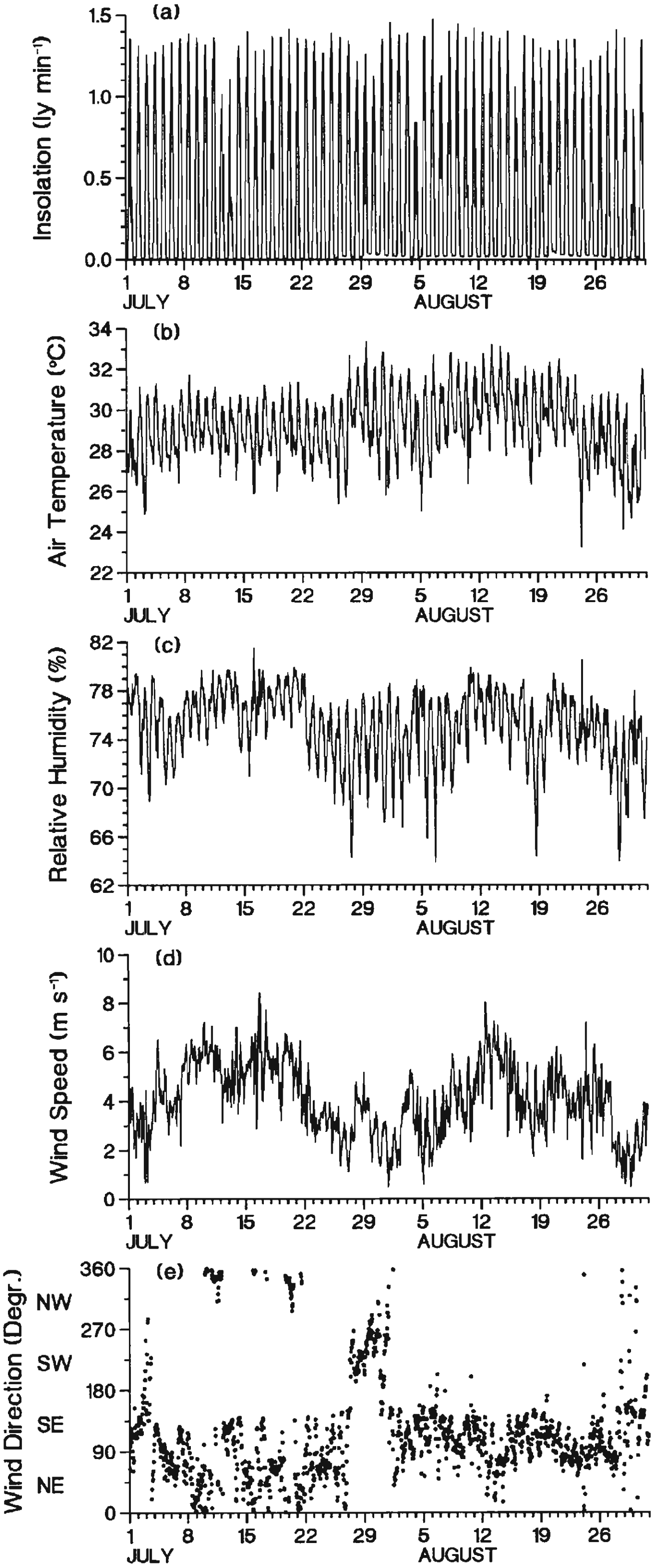

Fig. 2 Weather variables recorded hourly at Lee Stocking Island, Bahamas, 1 July to 31 August 1990

Relative humidity values (Fig. 2c) are generally between 70 and 80% throughout the record, though somewhat higher values were recorded during the first 3 weeks of July, and larger diurnal ranges appear during the final week of July and the first week of August.

Wind speed (Fig. 2d) shows a well-defined low-frequency variation, with lowest values early in the 2-month period, then again during the last week of July and the first week of August. Wind directions (Fig. 2e) show considerable scatter and are difficult to characterize. For the most part, wind directions are out of the northeast and southeast quadrants, but a several-day period of anomalous westerly winds was recorded in late July.

Local heat fluxes calculated for July and August are shown in Fig. 3. Subsurface insolation corrected for reflection (Fig. 3a) averages 93% of that recorded by the pyranometer. Latent heat fluxes (Fig. 3b) are inversely related to wind speed (Fig. 2d) with a correlation coefficient of –0.415, and periods of relatively low evaporative cooling occur at the start, middle, and end of the record. Sensible heat fluxes vary between ± 0.1 ly min^{-1} (Fig. 3c), and values are centered about a mean value of –0.042 ly min^{-1}. Low-frequency variability is minimal. Net outgoing long-wave radiation averages –0.037 ly - min^{-1}, and individual values vary between about –0.02 and –0.05 ly min^{-1} (Fig. 3d). Comparison of net outgoing long-wave radiation with incoming solar radiation suggests that cloudy skies reduce both solar heating and radiative heat losses.

Water temperature records

Water temperature recorded at station 1 at the mouth of Adderley Cut (Fig. 4a) contains prominent tidal-period "spikes" produced when water from Great Bahama Bank leaves on the ebb tide. Bank water is over 1 °C warmer than sound water in early and late July, which were times of spring tide and thus strongest tidal exchanges. Relatively small spikes appear during 16–20 July and at the end of the month, at times of neap tide. Bank-sound temperature differences are relatively small during most of the final 3 weeks of the study. Two factors may have contributed to this. First, increased wind speeds in mid-August (Fig. 2d) would have cooled bank water more than sound water and therefore reduced the temperature difference. Second, apogean neap tides during the third week of August reduced the tidal excursion needed to bring warm water off Great Bahama Bank.

Near-bottom water temperatures from station 2, the mid-shelf study site seaward of Adderley Cut (Fig. 4b), show many features that are similar to those recorded at station 1, including the temporary maximum in early July, the slow increase during the last half of July and the first week of August, and the highest temperatures on about 5–6 August. High-frequency fluctuations are noticeably less throughout the record. Linear regression of low-pass filtered temperatures from station 2 and low-pass filtered wind stress reveals a well-defined response to wind forcing, and results suggest that wind-

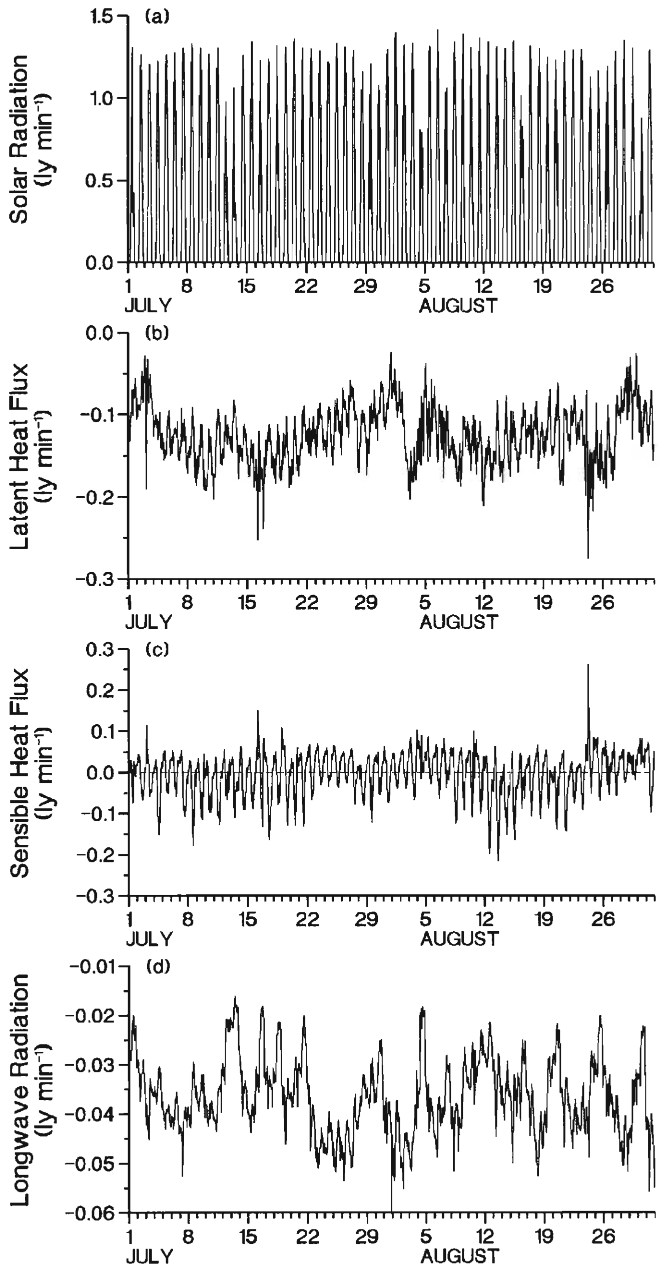

Fig. 3 Local heat flux terms (in ly min^{-1}) calculated from weather data, 1 July to 31 August 1990

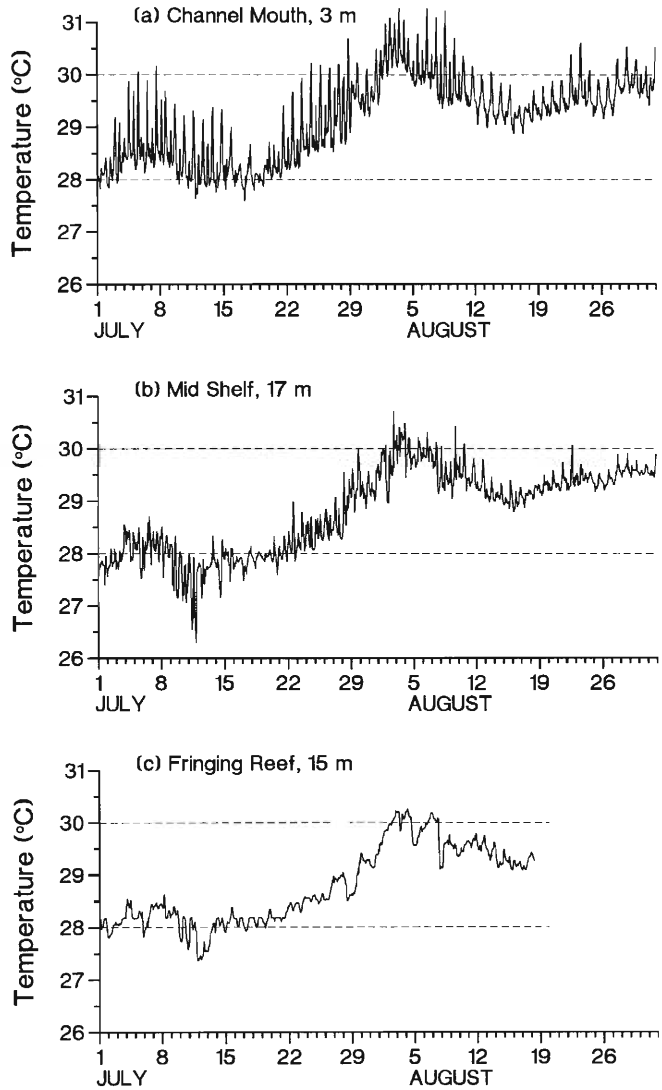

Fig. 4 Water temperatures observed at station 1 in Adderley Cut, station 2 directly seaward of Adderley Cut, and station 4 on the fringing reef; 1 July to 31 August 1990 (19 August at the fringing reef)

driven upwelling and downwelling has an important effect on shelf water temperature. Highest correlation (r=–0.631) occurred when temperatures were paired with the 359–179° component of the wind stress vector and lagged 31 h. Southward wind stress produced higher near-bottom temperatures, suggesting a shoreward-directed Ekman transport that flooded the shelf with warm surface-layer water. Wind directions were in the northeasterly quadrant and thus had a strong southward component for most of the second, third, and fourth weeks of July, when shelf water was warming (Fig. 4b) in spite of relatively strong wind speeds (Fig. 2d) and large latent heat fluxes (Fig. 3b).

Water temperatures recorded on the fringing reef, 1 km southeast of North Perry Reef (Fig. 4c), are similar to those recorded at the mid-shelf study site, though high-frequency fluctuations are greatly suppressed. The subtle rise and fall in temperature throughout the record, and the maximum temperatures just above 30 °C, are features seen in both of the other plots. Temperatures at all three study sites are increasing at the same time that latent heat flux is decreasing in late July.

Hyperpycnal ebb tide plumes

Salinity and density calculated from temperature and conductivity measured at station 1 at the mouth of Adderley Cut are shown in Fig. 5. The salinity plot contains ebb tide spikes that rise 0.5–1.5 psu above levels characteristic of Exuma Sound shelf water. Density shows an irregular decrease that occurs as a response to the irregular seasonal warming (Fig. 4a–c). Superimposed onto the more gradual variations in density is a succession of density spikes which represent the net effect of temperature and salinity differences between bank and sound water. In the absence of temperature differences, spikes project upward when ebbing bank water has a higher salinity than sound water. Temperature differences can enhance, suppress, or even reverse spikes produced by salinity differences alone, however. For example, during the second week of July, warm water leaving Great Bahama Bank, combined with minimal salinity differences, results in downward-pointing spikes. Bank-sound density differences indicated by the spikes are an indication of whether ebb tide plumes will be confined to near-surface or near-bottom layers in shelf waters of Exuma Sound. Density reaches 1–1.5 kg m^{-3} above but rarely exceeds 0.25 kg m^{-3} below the levels that represent the density of shelf water in Exuma Sound. Hyperpycnal density spikes are highest in mid-July, when ebb-tide temperature spikes are small (Fig. 4a). They occur intermittently through the last half of July and into the first week of August, then they become more persistent during the second and third weeks of August. Water temperatures everywhere in the study area were reaching their highest values during the first week of August, and this coincides with the start of the bleaching event (Dennis and Wicklund 1994).

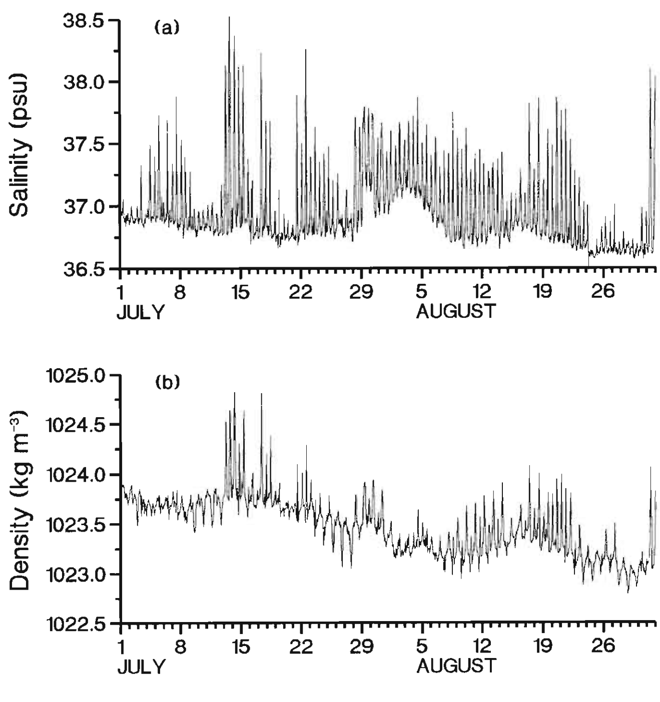

Fig. 5 Salinity and density computed from hydrographic data recorded at station 1 at the mouth of Adderley Cut, 1 July to 31 August 1990

Along-shelf circulation

Low-frequency along-shelf flow recorded at station 2 (Fig. 6) is generally within ± 3 cm s^{-1}, and reversals occur every 2–3 days. Dominant features of the plot include an approximately 2-week period of flow toward the northwest during the second and third weeks of July. This corresponds closely in time with the period of slight cooling noted in all three temperature records (Fig. 4). A 2-week period of mostly southeastward flow in late July and early August coincides with the period of gradual warming and the highest water temperatures recorded during the study, and with the regular occurrence of warm, hyperpycnal water leaving Adderley Cut (Fig. 5). The decrease in shelf water temperature that begins on about 5 August coincides with an increased frequency of northwestward flow.

Linear regression was used to quantify the correlation of along-shelf flow with periods of warming and cooling. When low-pass filtered temperatures were paired with low-pass filtered along-shelf currents, the correlation coefficients reached a maximum value of –0.397 when temperature was lagged 43 h. Cooling was associated with northwestward currents. This is consistent with a current-induced upwelling pattern of the type modeled by Hsueh and O'Brien (1971) and observed by Smith (1983). Linear regression was also used to investigate along-shelf flow as a response to wind forcing. Wind directions of 218 and 038° were found to be most effective for driving northwestward and southeastward along-shelf flow, respectively. These directions are only 21° from a directly across-shelf heading, and it is likely that the response to wind stress is influenced by nontidal exchanges through Adderley Cut. The correlation coefficient was +0.547 when the current lagged wind stress by 4 h.

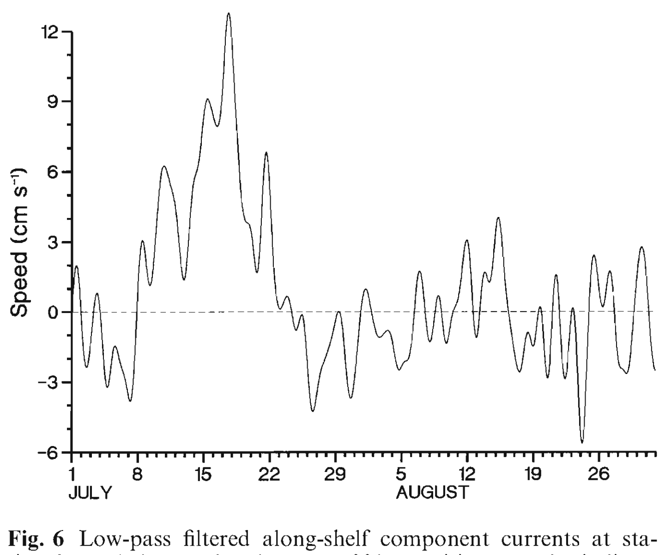

Fig. 6 Low-pass filtered along-shelf component currents at station 2, 1 July to 31 August 1990. Positive speeds indicate northwestward flow

Discussion

The combined meteorological and hydrographic database suggests that the August 1990 bleaching event was a response to both local and advective heating. Pyranometer data indicate that unusually intense or sustained solar heating was not a factor in raising shelf water temperatures. Rather, wind directions were favorable for the shoreward movement and downwelling of warm surface water through much of July. Warming at both shelf sites was recorded while wind speed was relatively high in mid-July, and the wind-driven downwelling would oppose the cooling that would be expected from a current-induced upwelling during a 2-week period of northwestward flow in mid-July.

In late July, wind speed decreased for a period of about 2 weeks, and evaporative cooling was reduced both in shelf waters and in the shallow waters of Great Bahama Bank. Water leaving Adderley Cut on the ebb exceeded 30 °C and reached 31 °C during an approximately 10-day period in early August, but high bank-water salinity kept bank-water density higher than sound-water density. Warming in near-bottom layers was thus a result of both density currents and downwelling. Along-shelf currents became intermittently southeastward, and warm hyperpycnal bank water was carried in the direction of North Perry Reef (station 3), one of the sites at which bleaching was reported. Highest shelf-water temperatures were short-lived for two reasons. Wind speeds increased, thereby increasing evaporative cooling, and wind directions shifted into the southeast quadrant in early August, thereby becoming more upwelling-favorable along this coastline.

The relatively low correlation of along-shelf flow with wind stress, and especially the unexpected maximum correlation with nearly directly landward wind directions, suggest that tidal and nontidal exchanges through Adderley Cut have a significant perturbing effect on along-shelf flow. Ebb tide plumes often extend half-way across the narrow shelf, and they can have a blocking effect on along-shelf flow. Because tidal channels commonly occur every few kilometers along the Exuma Cays, along-shelf flow will be interrupted at regular intervals. It follows that the correlation with local wind forcing would be reduced. Landward or seaward transport in surface layers is not restricted to nearshore waters, however; thus across-shelf heat transport by upwelling and downwelling patterns can play a significant role in the warming and cooling of shelf waters even where along-shelf heat transport is locally interrupted.

Results presented here are consistent with empirical data (Hendee et al. 2001) which suggest that elevated water temperatures during bleaching events coincide with periods of low wind speed, and thus reduced local cooling. The present study suggests also, however, that wind speeds strong enough to produce a wind-driven current can play an important role by influencing advective heat transport. Wind-driven along-shelf transport of warm water can expose a longer section of the inner shelf to warming as water leaves a tidal channel on the ebb tide, and current-induced upwelling and downwelling can raise and lower shelf-water temperatures. Similarly, wind-induced upwelling and downwelling can produce an across-shelf heat transport that influences both the frequency and duration of periods of unseasonable warming.

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