1.1 EDDY COVARIANCE MEASUREMENTS OF THE SURFACE ENERGY BALANCE ASSOCIATED WITH A LOCALISED CORAL BLEACHING EVENT, HERON REEF, GREAT BARRIER REEF, AUSTRALIA

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ABSTRACT

Despite the widely claimed association between climate change and coral bleaching, a paucity of data exists relating to exchanges of heat, moisture and momentum between the atmosphere and the reef-water surface. We present *in situ* measurements of reef-water-air energy exchanges made using the eddy covariance method during a summer coral bleaching event at Heron Reef, Australia. Under settled, cloud-free conditions and light winds, daily net radiation exceeded 800 W m^{-2}, and up to 95% of the net radiation during the morning was partitioned into heating the water column, substrate and benthic cover, including corals. Heating was exacerbated by a mid-afternoon low tide when shallow reef flat water reached 34°C and near-bottom temperatures 33°C, exceeding the thermal tolerance of corals, causing bleaching. Results suggest that local to synoptic scale meteorology, particularly clear skies, solar heating, light winds and the timing of low tide were the primary controls on coral bleaching.

1. INTRODUCTION

While their ecological, economic and societal values are irrefutable, an uncertain future exists for coral reefs due to coastal development, mining, unstainable fishing practises and pollution. Anthropogenically forced climate change has also been increasingly linked to degradation of coral reefs with the number and scale of reported coral bleaching episodes trending upward with global temperature, most notably over the past 30 years. Between 1979 -1990 there were at least 60 reports of major coral bleaching events compared to only three in the preceding 103 years (Glynn, 1993). Six mass bleaching events have affected coral reefs globally since 1979, with over 50% of the reefs in the Great Barrier Reef, Australia, the World's largest emergent reef, being affected (Hoegh-Guldberg, 1999). An increase in bleaching events may result in significant loss, damage or composition change to coral reefs (Baker et al., 2008). Despite the association between climate change and coral reef health being made by many researchers, a paucity of data exists relating to the key reef-atmosphere energy exchanges that take

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place during a bleaching event. Previous studies on energy exchanges over tropical oceans have focused on the development of bulk formulas for estimating air-sea energy fluxes (Fairall et al., 1996; Tanaka et al., 2008; Tsukamoto et al., 1995), rather than the link to water temperature and coral bleaching. As stated by Weller et al. (2007, p3854), “there is a need to examine the heat budget of the water mass (of coral reefs)” in order to understand the processes that underpin coral reef climates and by association coral bleaching events.

In this paper, we present direct *in situ* measurements of surface energy exchanges over Heron Reef, in the southern Great Barrier Reef, Australia, associated with a case of extreme high water temperatures that triggered localised coral bleaching. Exchanges of sensible and latent heat, and heat transfer into the water overlying Heron Reef were measured using the eddy covariance (EC) method from the 18-22 February 2009. While measurements were only made at one location on the reef flat they provide a unique insight in to energy exchanges across the reef-water-air interface that resulted in coral bleaching.

2. PHYSICAL SETTING

Research was conducted at the 27 km^2 Heron Reef, a lagoonal platform reef located approximately 80 km northeast of Gladstone (Figure 1) near the Tropic of Capricorn. Heron Island is located on the western end of the reef, while to the southwest a deep channel separates Heron Reef from Wistari Reef. Tides at Heron Reef are semi-diurnal with a spring and neap tidal range of 2.28 m and 1.09 m respectively (Chen and Krol, 1997). Under an average wind speed of 5 m s^{-1} and wave height of 0.5 m, the mean maximum current velocity at Heron Reef is 0.3 m s^{-1} (Gourlay and Hacker*,* 1999). [5] Mean air temperature at 1500 Eastern Standard Time (EST) varies from 28.3°C in January to 20.1°C in July (Bureau of Meteorology, *2007*). Mean annual rainfall is 1050 mm, with the majority falling during

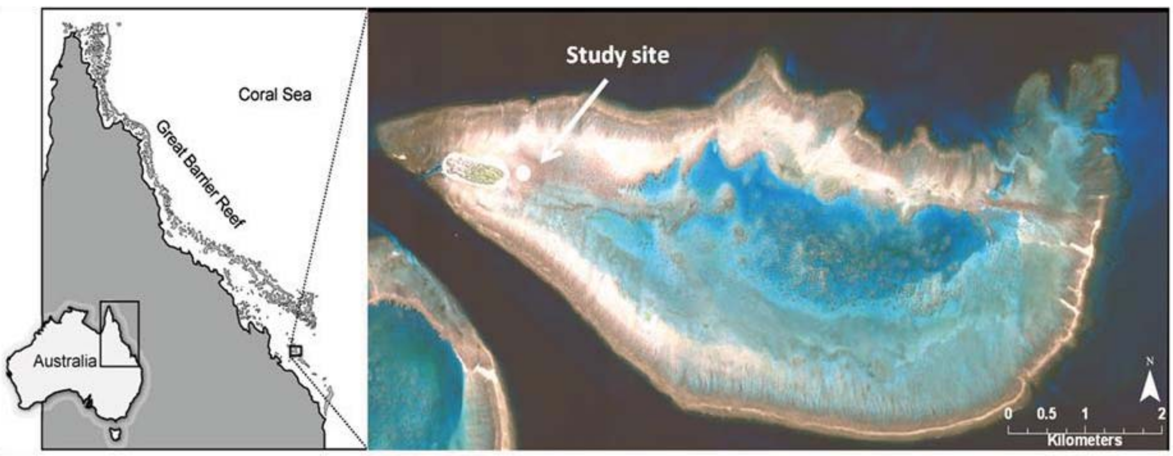

Figure 1. Heron Reef location map (Quickbird-2 image at 00:28:20 hrs UTC 3 August 2006 provided by DigitalGlobe).

summer and autumn. Southward dips in the Intertropical Convergence Zone during summer can result in periods of torrential rainfall at Heron Reef associated with convectively unstable air masses (Sturman and McGowan, 1999). The south-east trades are the dominant winds at Heron Reef, with a winter westerly component associated with the repositioning of the prevailing synoptic weather systems. Wind direction becomes more variable in summer with increased northerly winds as reported in the present study

3. METHODS

The surface energy balance and associated micrometeorology were monitored at Heron Reef from 18-22 February 2009 by an eddy covariance (EC) system mounted on a floating pontoon (see McGowan et al 2010). The pontoon EC system was located approximately 100 m offshore from the eastern end of Heron Island (23.443° S, 151.921° E) (Figure 2) where the benthic cover was dominated by an assemblage of sand, algae, rubble and live coral which was representative of approximately 10% of the total reef (Phinn et al., 2010). This paper used the methods and study site outlined in the paper by McGowan et al., (2010) to quantify the surface energy balance at Heron Reef with the exception of using a CNR1 net radiometer to measure the individual components of the radiation budget.

The EC unit consisted of a Campbell Scientific CSAT-3 sonic anemometer, Li-Cor CS7500 open path H_2O and CO_2 analyser, a Kipp and Zonen CNR1 net radiometer, while a Vaisala HMP45A sensor recorded ambient air temperature and humidity. All instruments were fixed at a constant height of 2.2 m above the surface, were connected to a CR23X data logger with measurements made at 10 Hz and block averages logged every 15 minutes. Water level was recorded using HOBO U20-001-01 water level monitors and near-surface water temperature at a depth of 0.05 m below the surface was monitored using a HOBO water temperature PROV2 logger.

Figure 2. Pontoon mounted Eddy Covariance unit at Heron Reef

Wave action was minimal during the observation period and the pontoon was fitted with a weighted central beam, and gimbal ring system which facilitated levelling of the pontoon arms and minimized dynamic influences. Over the averaging period used here, the effect of small scale perturbations of wave-induced motion on the EC measurements are not considered to affect flux measurements (see Weibe et al,. (2010)). Accordingly, calculations of sensible and latent heat flux can be considered to accurately reflect turbulent energy fluxes over the reef-water surface at Heron Reef (McGowan et al*.,* 2010).

The surface energy balance for a coral reef can be written as:

$$Q^* = Q_E + Q_H + \Delta Q_S + \Delta Q_A + Q_R + Q_G \qquad \text{(Equation 1)}$$

where Q^* = net all wave radiation, Q_E = latent heat flux, Q_H = sensible heat flux, ΔQ_S = change in heat storage of the layer of water overlying the coral reef, ΔQ_A = net horizontal advection of heat in the water by currents, Q_R = addition or loss of heat associated with rainfall, and Q_G = heat transfer via conduction and radiation transfers into or out of the reef substrate (McGowan et al., 2010). No precipitation was recorded during the measurement period reported here, so Q_R can be removed from Equation 1. As measurements of horizontal advection of heat over the reef by currents and the partitioning of heat into the reef benthos and substrate were not made, for the purpose of this study, these energy budget parameters are grouped (ΔQ_{Swr}) and collectively determined as the residual of the energy balance equation. This approach is used when direct measurement of energy transfer through the water column and/or underlying substrate, including coral, is not practical (Kurasawa et al., 1983; Tsukamoto et al., 1995; McGowan et al., 2010). As a result, the surface energy balance equation for Heron Reef can be rewritten as:

$$Q^* = Q_H + Q_E + \Delta Q_{Swr} \qquad \text{(Equation 2)}$$

The measurement footprint of the pontoon mounted EC system was determined using Kljun's online footprint calculator (Kljun et al., 2004). Ninety percent of the along wind footprint for the 18-21 February was calculated to include an area extending to 67.4 m upwind of the site, with the area of maximum influence on measurements located at approximately 24.6 m from the pontoon. Accordingly, the EC measurement footprint was confined to the reef flat surface type previously described and was not influenced by Heron Island or the open ocean under predominantly light northeast to east-north-easterly winds. Post processing data corrections were performed for frequency attenuation (Massman, 2000), density effects (Webb et al., 1980) and spike removal (Liu et al*.,*2009). Missing cross product data meant that correction for coordinate rotations were performed using empirical functions based on a dataset collected during similar conditions in February 2010 where multivariate correlation analysis produced correction functions with R^2 values of 0.84 and 0.94 for Q_E and Q_H respectively. Rainfall on the 22 February 2009 meant that the turbulent flux data was erroneous and not used for this day.

4. RESULTS

The period 18-21 February 2009 was characterised by predominantly cloudless skies, light northeast and east-northeast winds with an average wind speed of 2.63 m s^{-1}. Air temperatures ranged from 24.8°C to 29.2°C (Figure 3a). The near surface layer over the water surface throughout the study period was classified using the Obukhov length stability parameter (Launiainen, 1995) as unstable during the daytime and for most of the night. Leading up to the bleaching event, on the afternoon of the 18 February 2009, Q_E was approximately 80 W m^{-2} resulting in minimal evaporative cooling of the water surface overlying the reef. Sensible heat flux was near zero. with the water surface and water bottom temperatures varying between 26°C and 28°C (Figure 3b).

The surface energy balance from the 19-21 February was characterised by Q* and Q_{Swr} becoming positive shortly after sunrise at 0700 EST and rising steadily throughout the mornings with the falling tide. Low wind speeds meant that wave action was minimal and the friction velocity u* averaged 0.13 m s^{-1}. This contributed to low Q_E values during the mornings (Figure 3c). Incoming and outgoing shortwave radiation (K↓ and K↑ respectively) and incoming longwave radiation (L↓) peaked around midday, coinciding with maximum solar altitude. Spikes in L↓ on the 21-22 February were due to infrequent isolated cumulus cloud. Outgoing longwave radiation (L↑) peaked when the water surface temperature reached its maximum around 1500 EST each day (Figure 3d). Q_{Swr} accounted for up to 93-95% of Q* during the mornings and peaked at between 786 W m^{-2} - 887 W m^{-2} around 1200 EST daily. This coincided with the higher low water in the early afternoon that ranged from 0.45 m at 1200 EST on the 19 February to 0.35 m at 1500 EST on the 21 February. As a result, water temperature over the

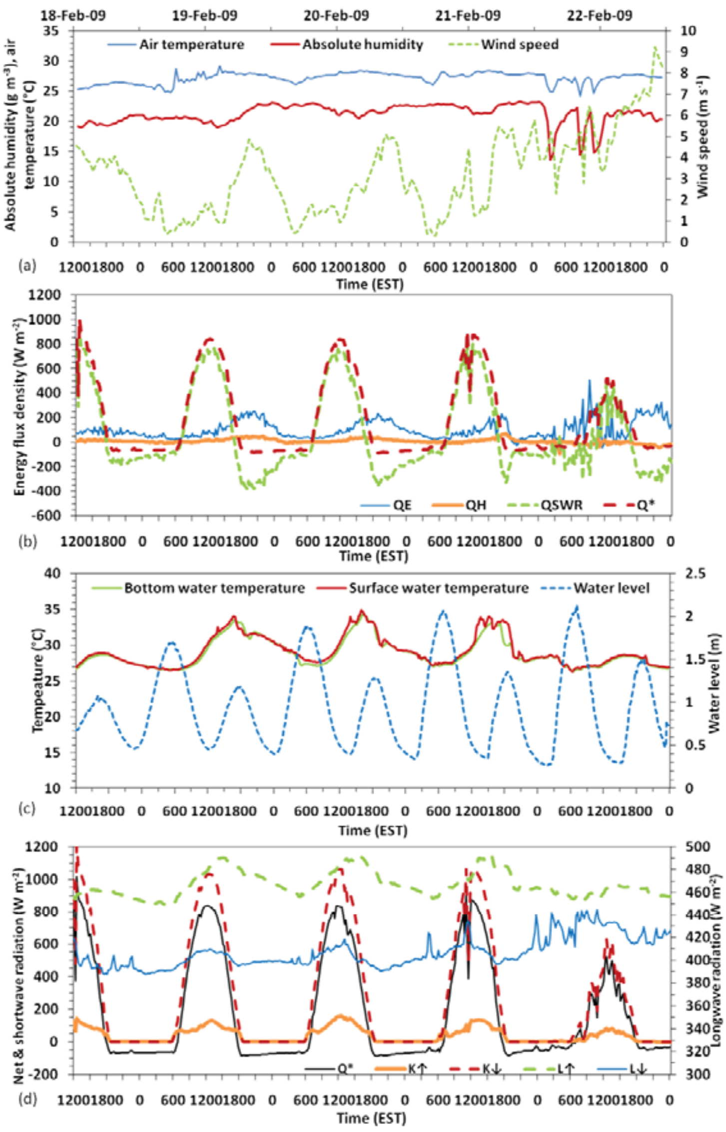

Figure 3 Heron Reef location map (Quickbird-2 image at 00:28:20 hrs UTC 3 August 2006 provided by DigitalGlobe).

reef increased quickly during the morning reaching maximum temperatures of >34°C at the surface and near the bottom from 1500 and 1700 EST (Figure 3b). On the 19 February the total daily heat gain for the near-bottom water temperature was +3.3°C, compared to +0.3°C at the surface. This highlights the ability of warm, northerly air masses, cloud free conditions (and high solar radiation), in conjunction with low water levels around midday to early afternoon, to cause high water temperatures on the reef, with the majority of Q*, which was dominated by positive net shortwave radiation (K*), partitioned into heating of the water overlying the reef.

Table 1 presents the total daily energy flux for the 19-21 February 2009 and shows that K* was 70.55 MJ m^{-2} day^{-1} and net longwave (L*) was -17.73 MJ m^{-2} day^{-1}, highlighting solar radiation as the major cause of radiative heating of the water overlying the reef. On the 19-21 February, 41 - 58% of total Q* (17.97 MJ m^{-2} day^{-1}) was partitioned into Q_{Swr}, with a net gain of heat for the water column and corals. Over the three day period, the surface and near-bottom water temperatures both exceeded the upper thermal range of most corals of 30°C (Hoegh-Guldberg*,* 1999) 27% of the time. This resulted in bleaching of *Acropora aspera* at Heron Reef during this three day period of accumulated heat stress (Figure 4). The bleached corals were located along the western side of the reef flat and adjacent to the boat harbour channel. Here the low tide is prolonged as flooding of the reef flat by the rising tide is delayed by the reef rim and a bund wall running along the edge of the harbour boat channel, thus delaying tidal flushing. Pooling of shallow water over the reef in conjunction with low wind speeds limited horizontal advection of heat away from the site thereby contributing to the very high water temperatures reported here.

Table 1 Total daily energy fluxes (MJ m^{-2} day^{-1})

	19 Feb	20 Feb	21 Feb	22 Feb	Total 19-21 Feb
K↓	27.84	27.74	26.69	12.22	82.26
K↑	3.77	4.35	3.59	1.81	11.72
L↓	34.43	34.61	35.17	36.79	104.22
L↑	40.53	40.83	40.58	39.77	121.94
Q*	17.97	17.17	17.69	7.44	52.82
Q_E	9.11	8.74	6.30	-	24.15
Q_H	1.49	1.26	1.05	-	3.81
Q_{SWR}	7.37	7.16	10.33	-	24.86
Bowen Ratio	0.16	0.14	0.17	-	-

Latent heat flux peaked daily in the late afternoon and evening (as did Q_H), corresponding with daily peaks in wind speed, surface friction velocity and maximum air-sea temperature difference (up to -5 to -6.5°C at around 1600 EST). Evaporative cooling of the water surface may have occurred at this time. However, as it coincided with the afternoon flood tide, which brought cooler oceanic water onto the reef flat, and longwave radiative cooling, separation of the effects is not possible. An increase in wind speed in the evening is believed to have been associated with coupling of the weak north to north-westerly geostrophic flow with the surface, which decoupled from the surface in the early morning. Daily peaks in water surface and near-bottom temperatures lagged maximum Q_{Swr} by 4-5 hours as heating of the water column continued throughout the afternoon, until Q_{Swr} fell below 0 W m^{-2} at approximately 1700 EST. This indicates that there was limited heat loss from the site due to horizontal advection within the water column.

Figure 4. Bleached colony of *Acropora aspera* on Heron Reef, 23 February 2009.

On the 22 February 2009 strengthening easterly onshore winds brought convectively forced showers to Heron Reef throughout the day (total of 9.2 mm rain). The associated cloud cover limited Q* to a maximum of 519 W m^{-2}, approximately 38% lower than the preceding three days. The total daily heat flux of K* was 10 MJ m^{-2} day^{-1}, <50% of the previous day's totals. Reduced solar heating in conjunction with such factors as rainfall and higher wind speeds meant that the pronounced peak in water temperatures seen on the 19-21 February was absent on the 22 February and a net temperature decrease over the day of 1.5°C was recorded.

5. DISCUSSION

The results presented in this paper are the first quantitative observations of the surface energy balance over a reef flat made during a summertime coral bleaching event by direct *in situ* measurement using an EC system. Importantly, they begin to shed light on meteorological controls of coral bleaching in response to reef-water-air energy exchanges. This knowledge is required to improve prediction of future impacts of natural and anthropogenic climate variability on the thermal environment of coral reefs.

Results show that clear sky settled summertime conditions were an important factor in this coral bleaching event as K* peaked at > 900 W m^{-2} and was not moderated by cloud. Cloud cover has been highlighted as a key control of the surface energy balance of coral reefs (McGowan et al., 2010) and radiative stress during coral bleaching events (Mumby et al., 2001). Under cloud-free conditions with daytime low tides, 41 to 58% of daily total Q* was partitioned into heating the water overlying the reef and the coral and reef substrate (Q_{Swr}). This resulted in three days of very high water surface and near bottom water temperatures and highlights the ability of warm, northerly air masses and clear cloudless summer conditions to cause extreme heating of the reef flat at Heron Reef, causing localised coral bleaching. These results are consistent with Smith (2001) and Lough (2001) who found that bleaching events are common during periods of low wind speeds and low latent and sensible heat fluxes, which inhibit local evaporative cooling and result in accumulation of heat by the reef water column. Bleaching thresholds for corals differ geographically, although short term bleaching has been observed to occur when corals are exposed to temperatures 3-4°C above mean maximum summertime temperatures for that region for 1-2 days only (Jokiel and Coles, 1990). In February 2009, this occurred at Heron Reef where the mean February water surface temperature at the measurement site is 27.4°C and the mean daily maximum is approximately 29.6°C.

Importantly, our results highlight the critical role of cloud in controlling the thermal environment of coral reefs. As a result, change in synoptic circulation patterns whether in response to natural variability such as El Niño – Southern Oscillation or climate change that alter the cloud field properties (spatial coverage, height, thickness, cloud type) over coral reefs will significantly influence the thermal environment on reef flats. The greatest impact will occur at low tide under light winds when shallow waters are likely to pool over coral reefs. Andrews and Forster (2008) investigated climate forcing and feedbacks from seven slab-ocean GCMs for a doubling of CO_2. All models showed a rapid response to CO_2 (via tropospheric adjustment) and that under a "doubling of CO_2" scenario cloud typically appeared to decrease, thereby enhancing warming. This conclusion was also reached by Gregory and Webb (2008). Combined with recent expansion of the subtropical high pressure belt as reported by Seidel and Randel (2007) reduced cloud cover over coral reefs seems likely, thereby presenting a potentially greater threat than gradual upward trending oceanic sea surface temperatures due to climate change. Further research will include the parameterisation of the energy budget in the water column in order to better understand hydrodynamic controls of Q_{Swr} (e.g. currents, benthic cover) through *in situ* measurements and modelling.

6. CONCLUSION

Eddy covariance measurements of surface energy exchanges of heat and moisture between the coral reef-water surface and the atmosphere were made during February 2009. Over the three day period weak synoptic pressure gradients prevailed, resulting in clear skies and low wind speeds.

Under these conditions, turbulent exchanges of sensible and latent heat fluxes were low, with up to 95% of Q* partitioned into heating the water, substrate and benthic cover during the daytime. Clear sky conditions through this period were the dominant factor on the surface radiation budget and in-turn Q*. This sustained heating of the coral reef waters in conjunction with pooling of water at the site resulted in localised coral bleaching.

Results show that reduced evaporative cooling due to low Q_E under settled, cloud-free conditions in conjunction with a low tide during daily maximum solar heating, promotes the accumulative heating of the coral reef waters, creating a thermally intolerable environment, causing coral bleaching. This study presents a rare insight into the local and micrometeorological controls of a coral bleaching event and highlights the need for more comprehensive study of the reef-water surface-atmosphere energetics under different weather patterns and locations.

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