Measurements of the local energy balance over a coral reef flat, Heron Island, southern Great Barrier Reef, Australia

Hamish A. McGowan,[1] Andrew P. Sturman,[2] Melissa C. MacKellar,[1] Andrew H. Wiebe,[1] and David T. Neil[3]

[1] Coral reefs are thought to face significant threat from global warming due to increased water temperatures and ocean acidity. However, research into the surface energy balance of coral reefs and their associated micrometeorology is rare. Here we present, through a case study approach, the first direct in situ measurements of the surface energy balance of Heron Reef, a small platform coral reef in the southern Great Barrier Reef, Australia. Surface energy exchanges were measured using the eddy covariance method and show that during winter and spring an estimated 80–98% of net radiation goes into heating of the water overlaying the reef and reef substrate. As a result, cloud cover is considered the dominant control on heating of the reef flat environment. Change in cloud cover may therefore significantly affect the thermal environment of coral reefs and their ecology. Sensible and latent heat fluxes reached their highest values during wintertime advection of dry and cool continental air blowing from mainland Australia. This resulted in a net loss of energy from the reef flat and a decreasing trend in water temperature. Turbulent fluxes otherwise remained small, with sensible heat flux often close to zero. Results indicate that coral reefs may act as heat sinks during winter and as heat sources during spring, thereby affecting local water and atmosphere heat budgets and associated thermodynamics.

Citation: McGowan, H. A., A. P. Sturman, M. C. MacKellar, A. H. Wiebe, and D. T. Neil (2010), Measurements of the local energy balance over a coral reef flat, Heron Island, southern Great Barrier Reef, Australia, *J. Geophys. Res.*, *115*, D19124, doi:10.1029/2010JD014218.

1. Introduction

[2] Partitioning of the surface energy balance between sensible, latent and ground heat fluxes over terrestrial surfaces determines local temperature, pressure and moisture gradients across different types of terrain. These in turn influence regional weather and climate, and under the influence of prevailing weather patterns define a site's climate. Not surprisingly, a plethora of studies has documented the surface energy balances of a range of land surface types (e.g., grasslands [*Castellvi et al.*, 2008], desert claypan [*Sturman and McGowan*, 2009], forests [*Shi et al.*, 2008; *Barr et al.*, 2006], and snow and ice [*Schneider et al.*, 2007; *Ishikawa et al.*, 1992]. By comparison, in situ studies of the surface energy balance of marine environments are much less common, with a scarcity of research over the most fragile of these: coral reefs.

[3] Numerous studies comment on the likely impacts of anthropogenic climate change and associated sea level rise on coral reefs, often drawing the conclusion that higher air temperatures due to anthropogenic global warming and increase in sea surface temperatures will threaten the very existence of coral ecosystems [*Hoegh-Guldberg et al.*, 2007]. However, in the absence of data on the surface energy balance of coral reefs accurate predictions of future change of coral reef environments due to temperature change are not possible. Accordingly, there is urgent need to accurately quantify the surface energy balance of coral reef environments so that informed predictions of future environmental change can be made.

[4] Coral reefs cover ~2.8 to 6.0×10^5 km^2 of Earth's tropical and subtropical oceans and are among the most biologically diverse and economically important ecosystems on the planet [*Hoegh-Guldberg et al.*, 2007]. Hoegh-Guldberg et al. concluded that by 2050 to 2100, with atmospheric CO_2 concentrations predicted to be >500 ppm and mean global temperature 2°C above current values, many coral reefs would be reduced to "crumbling frameworks with few calcareous corals" [*Hoegh-Guldberg et al.*, 2007, p. 1741]. The likely impacts of higher concentrations of CO_2 and temperature increases of >3°C were considered likely to result in effects too devastating to consider. However, these are the conditions predicted to occur by the

[1]Climate Research Group, School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Queensland, Australia.
[2]Centre for Atmospheric Research, University of Canterbury, Christchurch, New Zealand.
[3]School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Queensland, Australia.

Intergovernmental Panel on Climate Change (*IPCC*) [2007] under their fossil fuel-intensive A1FI scenario, possibly by 2070 [*IPCC*, 2007]. Predictions of how such climate change may influence coral reefs cannot be made with confidence until the meteorology of coral reefs is known. This is primarily dependent on improved knowledge of the surface energy balance and its partitioning into the turbulent fluxes of latent heat (Q_E), sensible heat (Q_H) and heat storage (ΔQ_S) in the water and reef substrate.

[5] Over the open deep ocean at macroscale, latent heat (Q_E) flux dominates over sensible heat (Q_H), except during intense cold air advection, and in general the heat storage factor in the energy budget equation can be assumed to be zero on a mean annual basis and, therefore, ignored. On this understanding, *Oke* [1978] stated that 90% of net radiation (Q^*) is partitioned into Q_E over the open ocean, resulting in annual Bowen ratio (Q_H/Q_E) values of ~0.10. At regional scale, ocean currents may influence the energy balance through advection of heat which in turn will influence the relative partitioning of the convective fluxes. In comparison, studies conducted over shallow water bodies (primarily lakes) have shown that there is a much greater range in values of heat storage in the water (ΔQ_S) than in the ocean, as a result of the lower thermal mass of shallow water. The heat flux between the water and substrate (Q_G) obviously plays a much greater part in the partitioning of energy than in deeper oceanic environments [*Lenters et al.*, 2005; *Fennessey*, 2000; *Venäläinen et al.*, 1999].

[6] Shallow water reef environments, because of their lower thermal mass, are subject to greater heating and higher sea surface temperatures (SST) than adjacent deeper oceanic sites. The resulting warm waters along tropical and subtropical coasts are a principal source of heat and moisture to the lower atmosphere, affecting cloud processes, precipitation and local winds. They therefore provide moist enthalpy (i.e., latent and sensible heat flux) to the boundary layer which may, for example, intensify tropical cyclones [*Krishna and Rao*, 2009]. Quantification of surface layer turbulent fluxes over reefs is therefore important for establishing the correct lower boundary conditions in atmospheric global circulation and regional forecasting models so that more accurate predictions of weather are available for marine and coastal locations.

[7] In situ measurements of surface energy exchanges over or near coral reefs are rare and have typically been made using towers located on adjacent shorelines during onshore winds [see *Hicks et al.*, 1974; *Kjerfve*, 1978; *Francey and Garratt*, 1979; *Smith*, 2001; *Tanaka et al.*, 2008]. *Hicks et al.* [1974] used a tower mounted platform to make measurements of surface energy exchanges over a coral reef about 300 m offshore south of Port Moresby, Papua New Guinea. Their results from a short measurement period in September 1971 showed a much lower Stanton number over the reef/water surface than would have been expected over the open ocean, indicating an aerodynamically smooth state, although no time series of turbulent flux exchanges were presented. The measurement height above the water/reef surface varied by up to 2.5 m during the tidal cycle.

[8] *Garratt and Hyson* [1975] measured Q_H and momentum fluxes using a 10 m tower in 4 m of water 400 m from the shore at Hentona in the South China Sea as part of the Air Mass Transformation Experiment (AMTEX). Here the focus was on calculation of bulk transfer coefficients and not the detail of diurnal variability in energy flux transfers. Calculation of bulk transfer coefficients for heat and moisture are dependent on robust measurement of surface roughness and calculation of a bulk drag coefficient. *Frederickson et al.* [1997] state that this is often subject to uncertainty as the computed drag coefficient describes an average sea state at the time measurements were made. Therefore, bulk drag coefficients are typically site specific for a given time and errors may arise when applied to other locations under different air-sea conditions. As a result measurements from many sites under the widest possible range of weather and wave conditions are required.

[9] *Kjerfve* [1978] computed the diurnal energy balance of a barrier reef in Belize from measurements of water temperature and Q^* over the water, and air and surface temperature from a site on an adjacent cay. Latent heat was interpreted as the residual flux, accounting for 78% of Q^* over the water, which is similar to that stated by *Oke* [1978] for the open ocean. It is also similar to that reported by *Kondo* [1976] for coastal areas in the western Pacific Ocean and East China Sea using bulk transfer coefficients. However, these results differ considerably from *Tanaka et al.* [2008]. Using the eddy covariance method with instruments mounted on a tower adjacent to the shoreline, they found Q_E and Q_H accounted for 27% and 2.5% of total Q^* over water, respectively. Roughly 70% of Q^* went into ΔQ_S, either heating the water overlying the reef flat and/or the reef substrate. Accordingly, there exists considerable uncertainty as to even the relative partitioning of the surface energy balance over coral reefs which cover vast expanses globally.

[10] The Great Barrier Reef (GBR) is the world's largest emergent reef system covering ~345,950 km^2 and consisting of more than 2900 reefs [*Woodroffe*, 2003]. It generates >$6.9 billion of economic activity annually [*Access Economics*, 2007], primarily through tourism and fishing industries. Accordingly, knowledge of the surface energy balance of the GBR is essential to understanding the role of the GBR in local and regional weather and climate along its ~2000 km length. It is also required for establishing benchmark data against which effects of natural and anthropogenic forced climate change can be referenced and robust predictions of the impacts of future climate change made.

[11] *Weller et al.* [2008] presented a 10 year climatology of satellite derived ocean-atmosphere heat flux estimates for the GBR and Coral Sea. Sensible and latent heat flux values were derived from existing global data sets adjusted using local station measurements from buoys and island-based meteorological stations of air temperature and specific humidity. Radiation fluxes were modeled from satellite imagery and surface data, including surface temperature, cloudiness and near-surface air temperature [*Weller et al.*, 2008]. They concluded that net turbulent heat fluxes for Heron Island and reef during winter (July) and spring (September) were approximately $-140\,\mathrm{W\,m^{-2}}$ and $-125\,\mathrm{W\,m^{-2}}$, while Q^* was ~65 and 175 W m^{-2}. Heron Island was also found to experience the largest variability in net surface heat flux within the GBR/Coral Sea region, which they argued was due to greater seasonality of climate in this more southern region of the GBR. They concluded that more research was needed to investigate surface energy exchanges

Figure 1.   Location map of Heron Reef showing the study site off the eastern shoreline of Heron Island.

and their relationship to SST, particularly in the shallower regions of the GBR.

[12] In this paper, we present the first in situ measurements of the surface energy balance from Heron Reef on the southern GBR, Australia using the eddy covariance method. Heat transfer into and out of the water and underlying coral and sand substrate is calculated as the residual of a simplified energy balance equation.

2.   Physical Setting

[13] Heron Reef (Figure 1) is located 80 km northeast of Gladstone on the southern GBR and covers ~27 km^2. It is a typical lagoonal platform reef, having developed on an antecedent karst platform with episodes of growth corresponding with higher sea levels during Holocene sea level fluctuations [*Hopley et al.*, 2007]. Heron Island is located on the northwest margin of Heron Reef and is 800 m long and 280 m wide. It is one of over 300 coral cays to have formed on the GBR since the onset of a relatively stable sea level during the late Holocene. Vegetation cover on the island is dominated by *Pisonia grandis* forest, while a research station and resort are located on the western third of the island.

[14] Annual rainfall at Heron Reef is ~1050 mm, with the majority of precipitation occurring in summer from December to February and in autumn from March to May. June to September is the driest period of the year, as anticyclones that track east across the Australian continent at this time bring mostly calm and settled conditions to Heron Reef. The wind regime of Heron Reef is dominated by the southeasterly trade winds, while a more westerly component develops during winter following the passage of cold fronts over southern Australia. Wind direction becomes more variable in summer with the occurrence of occasional strong northeasterlies, although southeasterly winds still dominate. The strongest winds are associated with the passage of tropical cyclones during the summer. Maximum air temperature occurs in January at 29.8°C, with the lowest minimum air temperature occurring in July at 16.7°C [*Australian Bureau of Meteorology*, 2007].

[15] *Masiri et al.* [2008] reported that the southern GBR including Heron Reef has experienced a small but statistically significant increase in solar radiation of ~1% per decade and that coral bleaching during 2002 showed a strong association with the region of maximum insolation [*Masiri et al.*, 2008]. This increase is most likely the result of a southward expansion of the subtropical high-pressure belt and associated reduction in cloud cover. This is believed to have caused the marine climate zone to have migrated south by ~300 km at Heron Island since 1950. A sea surface temperature warming of 0.16°C per decade for the period 1950 to 2007 has also been measured [*Lough*, 2008].

[16] The benthic cover of Heron Reef is characterized by distinct morphological and ecological zones of coral and mixed sediments [*Ahmad and Neil*, 1994]. The coral zonation is dependent on hydrodynamic (waves, tides and currents), geomorphic and ecological processes. The different zones include the outer coral zone, algal rim, and rubble zone on the inside of the reef crest, the coral zone and an inner sandy zone. The hydrodynamic processes of Heron Reef are characterized by semidiurnal tides with a spring tidal range of 2.28 m and a neap tidal range of 1.09 m. At low tide, water depth over much of the reef flat is 0.3–1 m, while in the deeper part of the lagoon it averages 3.5 m [*Chen and Krol*, 1997]. As the tide falls below the reef rim, pooling of water occurs on the lagoon resulting in a higher low tide level than the surrounding ocean [*Gourlay and Hacker*, 1999]. Wave action on the reef flat is generally minimal with wave heights generally less than 0.5 m owing to the limited water depth and protection from ocean generated wave action by the reef rim.

3.   Instrumentation and Methods

[17] Surface energy exchanges over Heron Reef were measured using eddy covariance (EC) instrumentation mounted on a pontoon (Figure 2). The pontoon was anchored ~100 m southeast of Heron Island at 151°55.203E; 23°26.573S so that measurements under the prevailing winds were not influenced by the island (Figures 1 and 2).

Figure 2. Photograph of the pontoon mounted eddy covariance system taken during the July 2007 case study.

The measurement footprint of the EC unit was estimated using the footprint model of *Kljun et al.* [2004]. This showed that 90% of the measurement footprint lay within $\approx$350 m upwind of the EC unit, while using the equilibrium height rule [*Schmid*, 1994] we estimated the measurement footprint was $\approx$215 m upwind of the EC unit. This variability is not unexpected given the inherent limitations of flux footprint calculators [see *Vesala et al.*, 2008]. Importantly, the benthic cover of mixed live coral, coral rubble, sand and algae under our measurement footprint did not show any notable change in density, form or type for at least 600 m upwind of the measurement site. As a result, our flux measurements are representative of energy exchanges over this surface type, which covers ~10% (2.7 km^2) of Heron Reef.

[18] Energy flux transfers over the reef flat were measured in September 2005 and July 2007. During the 2005 measurement campaign instrumentation consisted of a Campbell Scientific CSAT-3 sonic anemometer, KH20 Campbell Scientific krypton hygrometer and REBS Q7 net radiometer. In 2007, the EC unit included a Campbell Scientific CSAT-3 sonic anemometer, while a Li-Cor CS7500 open path H_2O and CO_2 analyzer and NR-LITE-L Kipp and Zonen net radiometer were used in place of the KH20 and REBS Q7, respectively. The EC units were connected to Campbell Scientific CR10X or CR23X data loggers with measurements made at 10 Hz and average values logged either every 10 or 15 min, from which mean half hourly values were calculated. All equipment was serviced daily to ensure that there was no buildup of salt on sensors. Measurements of energy fluxes presented here were made from 21 to 23 September 2005 (spring) and 3–7 July 2007 (winter).

[19] Water depth during September 2005 was monitored using an Ocean Sensor Wave Gauge OSSI-010-003B, while in July 2007 water depth was monitored with a HOBO U20-001-02 water level logger with a resolution of 0.41 cm. Water temperature was monitored using a HOBO Water Temp Pro V2 sensor with an accuracy of ±0.2°C and resolution of 0.02°C attached to the pontoon at ~25 mm below the water surface.

[20] The pontoon frame onto which the EC units were mounted consisted of two 2.5 m crossbars with a 120 dm^3 drum attached at each end (Figure 2). The sensors were attached to a mast suspended above the center of the pontoon by a gimbal mounted on a supporting frame. The gimbal was designed to lessen the influence of wave action on the position of the sensors so that they remained near level at a constant height of ~2.15 m above the water surface. The pontoon was held in position on the reef flat using four mooring lines attached to the end of each crossbar. This meant that the pontoon was able to rise and fall with the tides while maintaining its orientation.

[21] A key challenge to the measurement of the surface energy balance over a reef flat (or any water surface) is to account for the effect of wave action on measurement of turbulent fluxes. A. Wiebe et al. (Wavelet analysis of atmospheric turbulence over a coral reef flat, submitted to Journal of Atmospheric and Oceanic Technology, 2010) used wavelet analysis to establish whether wind-wave-induced vertical velocities affected measurement of turbulent exchanges of sensible and latent heat over the water/reef surface from the detailed analysis of two periods of EC measurements made at Heron Reef in February 2007. Vertical wind-wave-induced water velocities were measured adjacent to the EC pontoon by a Nortek Vector (NO-1351 RUD) velocimeter. These data were then analyzed with the vertical velocities measured by the CSAT-3 sonic anemometer mounted on the pontoon. While the spectra of w' (vertical wind velocity fluctuations) and p' (vertical (water) pressure/velocity fluctuations) did show regions of common high power they were not coherent, the interaction between the two spectra was more than an order of magnitude below the measured fluctuations. As a result, over the averaging period of 30 min used here, the effect of small-scale perturbations of wave-induced motion on the EC measurements are believed to be filtered out. The floating pontoon EC system therefore appears to be a sound and robust method for investigating the surface energy exchanges at the reef-ocean-atmosphere interface. This conclusion is also supported by Figure 3 which shows that the variation of sensible heat flux measured by the pontoon EC system compared to a tripod mounted EC system positioned at the shoreline for a period in February 2007 when the winds were onshore (so that both systems were measuring fluxes over the reef flat) is very similar. Accordingly, calculations of Q_H and Q_E can be considered to accurately reflect turbulent energy fluxes over the water/reef surface at Heron Reef (Wiebe et al., submitted manuscript, 2010).

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

$$Q^* = Q_E + Q_H + \Delta Q_S + \Delta Q_A + Q_R + Q_G$$

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 over the reef 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.

[23] In this study, measurements of horizontal advection of heat over the reef by currents and partitioning of heat into
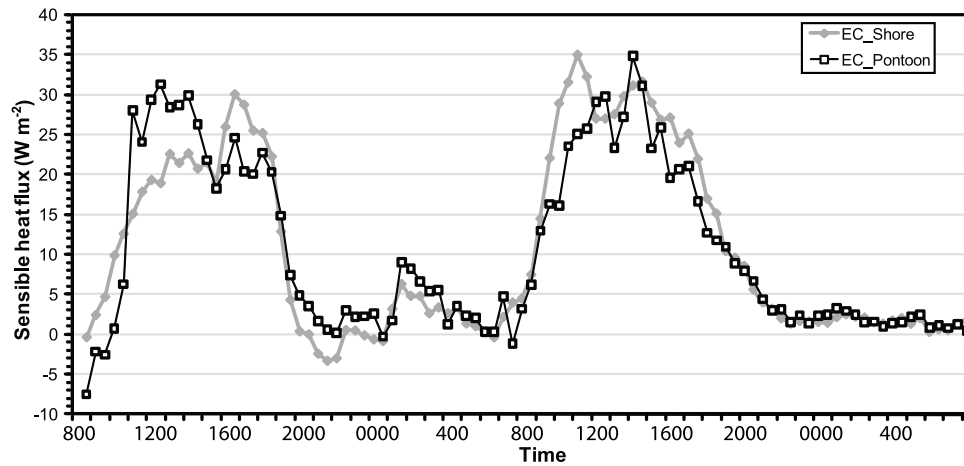
Figure 3. Comparison of sensible heat flux measured by eddy covariance systems on the shore (eastern end of Heron Island adjacent to pontoon) and offshore on the pontoon at the study site shown in Figure 1 on 9–11 February 2007.

the reef substrate and water column were not possible, while no rainfall occurred during the measurement periods. As a result, the surface energy balance equation for Heron Reef can be rewritten as:

$$\Delta Q_{Swr} = Q^* - Q_E - Q_H$$

where Q^*, net all wave radiation; Q_E, latent heat flux; Q_H, sensible heat flux; and ΔQ_{Swr}, change in heat storage of the layer of water overlying the coral reef and the reef substrate. It is calculated here as the residual of the energy balance equation. Accordingly, it also includes advection of heat by currents over the reef flat and measurement errors. These limitations are acceptable where it is not possible to make direct measurement of ΔQ_{Swr} [see *Tsukamoto et al.*, 1995; *Kurasawa et al.*, 1983; *Kondo and Miura*, 1985].

4. Results

4.1. Winter Case Study

4.1.1. Synoptic Setting of 2–7 July 2007

[24] Daily 1000 EST synoptic analyses for 2 to 7 July 2007 are presented in Figure 4. The study site was under the influence of a broad ridge of high pressure over the 6 day period which resulted in clear skies and southwesterly winds blowing from the continent. The maps for the 5 and 6 July (Figures 4d and 4e) show an increase in the synoptic pressure gradient over southern Queensland, with the isobars displaying a more southwesterly orientation over southeastern Australia. This was associated with the formation of a low-pressure system and cold front in the Tasman Sea, which collectively produced moderate to strong cool and dry southwesterly winds at Heron Reef. The ridge then strengthened on 7 July, as shown in Figure 4f, and winds gradually eased.

4.1.2. Surface Energy Balance of 2–7 July 2007

[25] Surface energy balance measurements are presented in Figure 5a along with local meteorological and water depth and water temperature data (Figures 5b and 5c). Net radiation peaked daily at ~400 W m^{-2}, with up to 80% of available Q^* partitioned into ΔQ_{Swr}. Sensible heat flux

changed little over the study period, ranging from −20 W m^{-2} to a maximum of 82 W m^{-2} recorded at 1130 EST on 6 July (Figure 5a). This maximum value of Q_H coincided with moderate to strong southwesterly winds which peaked at 10 m s^{-1} and a minimum water depth on the reef flat at the study site of 0.21 m. Latent heat flux also reached a maximum for the 6 day measurement period of 263 W m^{-2} or 64% of Q^* at midday on 6 July. These observations highlight the ability of southwesterly winds blowing offshore from the continent during winter to evaporate moisture from shallow reef waters and exposed reef flats. This we believe contributed to the lower daytime maximum water temperature recorded on 6 July.

[26] Daily minimum net radiation values of approximately −100 W m^{-2} were recorded at sunset with little change monitored throughout night until sunrise, when values increased quickly. Estimated heat storage in the water overlying the reef and reef substrate reached minimum values between 1730 and 1800 EST daily, corresponding to minimum Q^* values and low tide. During the evening of 2 July and early on 3 July ΔQ_{Swr} ranged between −40 W m^{-2} and −266 W m^{-2}, with no obvious trend until sunrise when it increased quickly. On 3–4 July and 5–6 July ΔQ_{Swr} increased gradually through the night until it became positive after sunrise. Corresponding to this trend in ΔQ_{Swr} was a decrease in Q_E on 5–6 July, while Q_H displayed little change, remaining below 20 W m^{-2}. This is believed to reflect the influence of a decrease in wind speed from about 2100 EST to soon after midnight on 5 July, followed by an extended period of low wind speed until around 0900 EST on 6 July and an increase in humidity. An increase in humidity on the night of 3–4 July was associated with a decrease in Q_E also. Daily minimum ΔQ_{Swr} values in the late afternoon on 5 and 6 July were associated with increases in air temperature at the pontoon. These correspond to near maximum daily Q_E values and almost calm winds at low tide indicating evaporation from exposed coral heads on the reef flat.

[27] Tidal fluctuations appeared to influence humidity with rapid increases in absolute humidity recorded on 3, 4, and 6 July corresponding to low tide at sunrise. Maximum
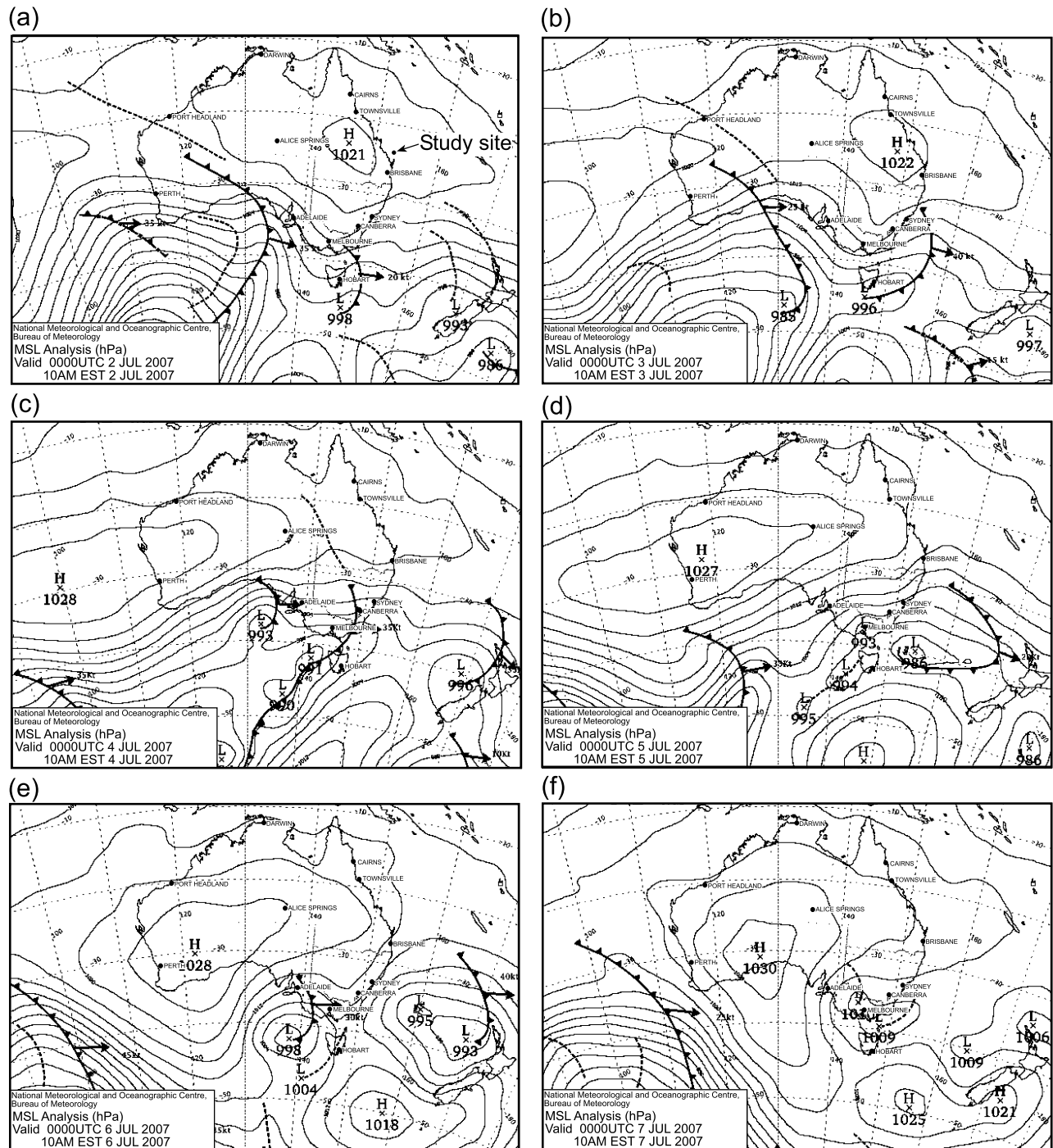
Figure 4. Mean sea level synoptic analyses at 1000 EST on 2–7 July 2007.

daily air temperature correlated with low tide just before sunset (Figure 5), which may be explained by the release of heat (and evaporation) from the reef substrate that had accumulated during the day as water levels reached a minimum and some coral became exposed to the air. These effects are also evident in the EB flux time series (Figure 5a) and are similar to a land signature.

[28] Table 1 presents a summary of daily energy budget components for three 24 h periods for which complete records

of energy balance measurements were available. Total Q^* ranged from 3.37 to 3.99 MJ m^{-2} d^{-1} with the dominant flux being Q_E which ranged from 5.81 to 8.56 MJ m^{-2} d^{-1}. The maximum Q_E value of 8.56 MJ m^{-2} d^{-1} computed for 5 to 6 July was associated with gradient southwesterly winds and the highest wind speeds recorded during the measurement period. Total daily Q_H remained below 1 MJ m^{-2} d^{-1}, while ΔQ_{Swr} ranged from −3.01 to −5.54 MJ m^{-2} d^{-1}. This net loss of energy from the shallow reef flat waters and underlying
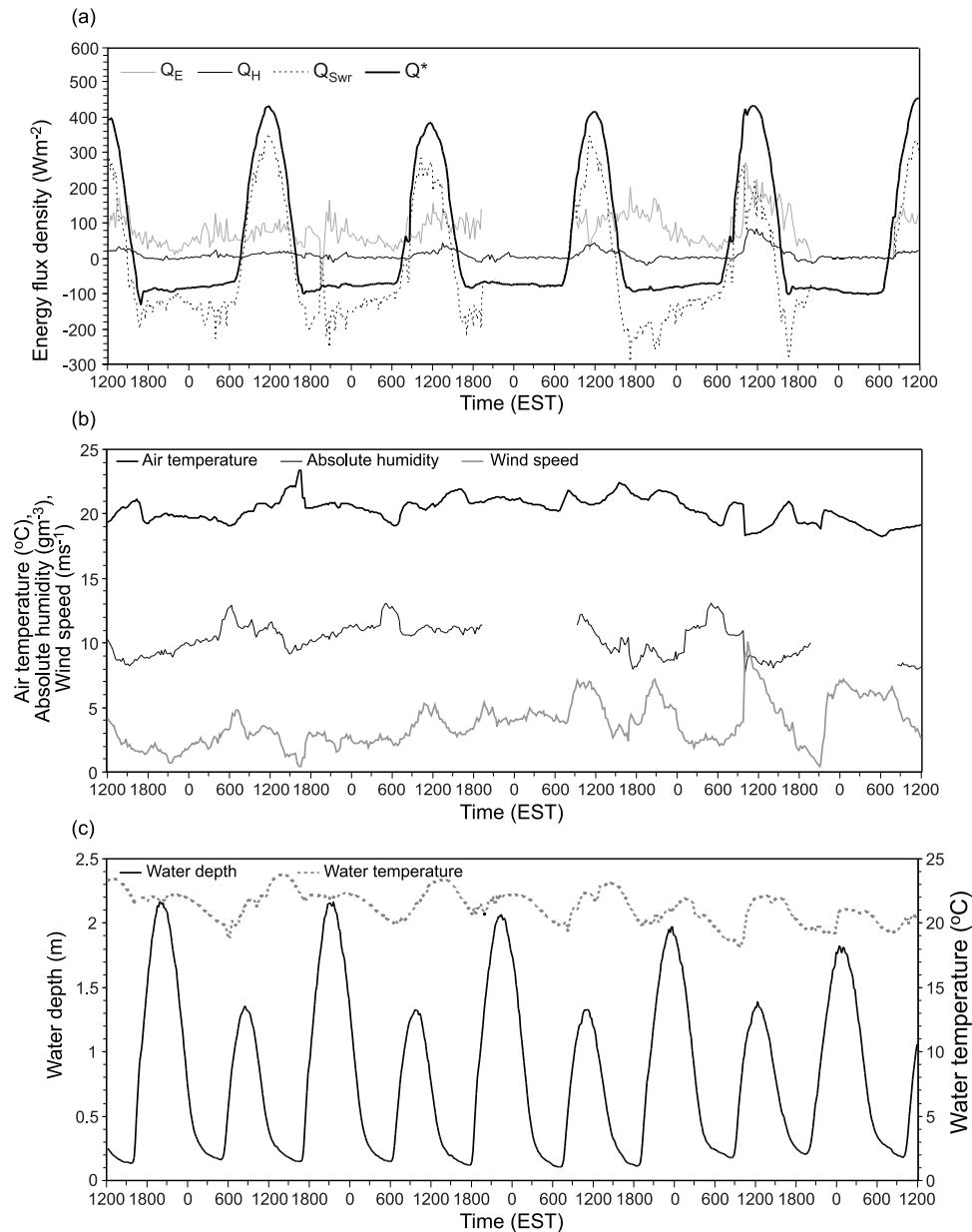
(a)

(b)

(c)

Figure 5. Micrometeorological measurements made from 2–7 July 2007 (a) surface energy balance measurements, (b) supplementary meteorological measurements, and (c) water depth and temperature.

substrate on Heron Reef is likely to have resulted in the gradual decreasing trend in water temperature (Figure 5c). It highlights the ability of cool and cloudless southwesterly continental air masses to significantly influence energy transfers and reef flat water temperature on the southern GBR at 80 km offshore. The Bowen ratio values ranged from 0.11 to 0.14 (Table 1).

4.2. Spring Case Study

4.2.1. Synoptic Setting of 21–23 September 2005

[29] Throughout this 3 day period (21 to 23 September 2005) Heron Reef was under the influence of a large anticyclone positioned over eastern Australia and the Coral Sea (Figure 6). This produced light southeasterly winds and mostly clear skies at the study site.

Table 1. Summary of Daily Energy Budget Components Over the Reef Flat at Heron Reef, Australia[a]

Date	$Q*$	Q_H	Q_E	ΔQ_{Swr}	Bowen Ratio (Q_H/Q_E)
2–3 July 2007	3.61 (41.78)	0.81 (9.37)	5.81 (67.25)	−3.01 (−34.84)	0.14
3–4 July 2007	3.37 (39.00)	0.65 (7.52)	5.76 (66.67)	−3.04 (−35.19)	0.11
5–6 July 2007	3.99 (46.18)	0.97 (11.23)	8.56 (99.07)	−5.54 (−64.12)	0.11

[a]Occurred daily at 1200–1200 EST. Daily average W m^{-2} values are shown in parentheses. Daily energy budget components are given in units of MJ m^{-2} d^{-1}.
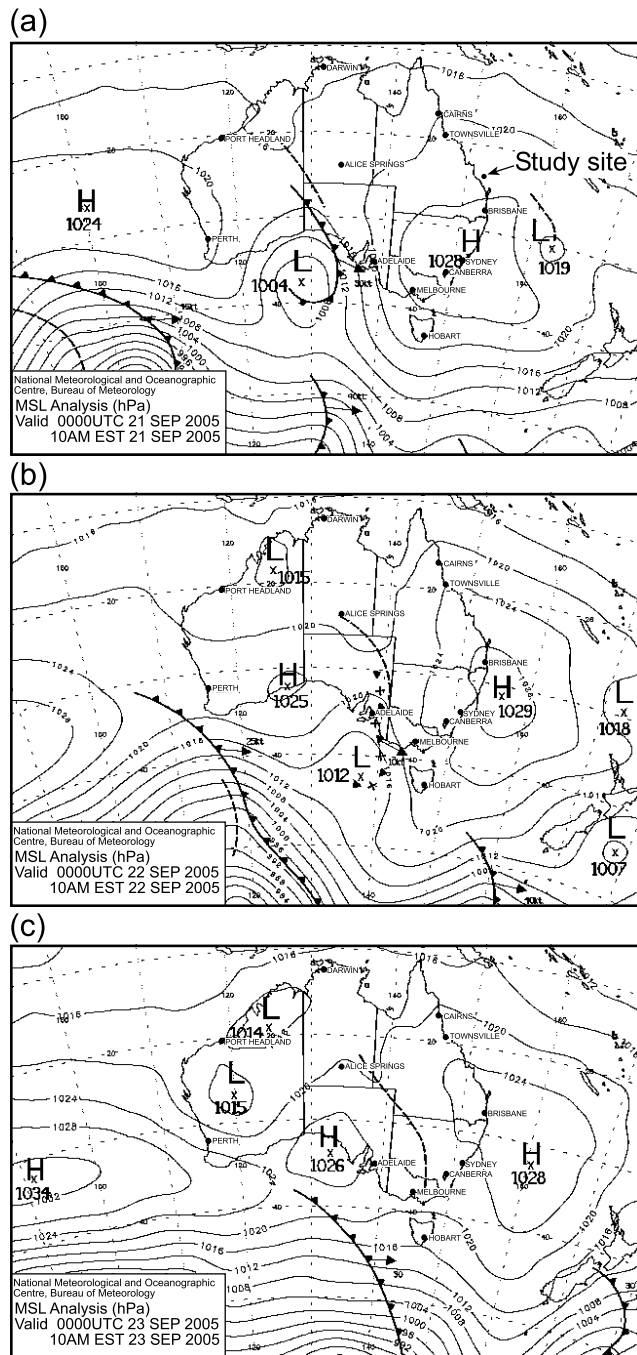
Figure 6. Mean sea level synoptic analyses at 1000 EST on 21–23 September 2005.

4.2.2. Surface Energy Balance of 21–23 September 2005

[30] Surface energy balance measurements for this period are presented in Figure 7a. High tides occurred around midday and midnight (Figure 7c), while wind speeds ranged from almost calm on 21 September to ~7.5 m s^{-1} on 22 September (Figure 7b). Maximum clear sky Q* was 831 W m^{-2} measured on 22 September 2005. Higher peak values of Q* recorded on 21 and 23 September (Figure 7a) were associated with cumulus cloud development over the study site and resulted from multiple reflections of solar radiation from

the surface of the clouds. Sensible heat flux over the 3 day period averaged 4.4 W m^{-2}, which is reflected by the almost constant air temperature (Figure 7b). Latent heat flux ranged from −12.7 to 134 W m^{-2} with an average of 47.6 W m^{-2}. Slight increases in Q_E around late morning and midday during this period appear to be linked to small increases in water temperature (Figure 7c) that are not associated with the tide. This is due to increasing energy input through the day and also the possible influence of local water movement over the reef flat on surface energy exchanges.

[31] During this measurement period the majority of Q* was partitioned into ΔQ_{Swr}, with typically 80 to 98% of daytime Q* going into heating of the water overlaying the reef flat and the reef substrate. This is a larger proportion of Q* than recorded under cloudless wintertime conditions, when the drier prevailing southwesterly airflow was responsible for partitioning more of the available Q* into Q_E and Q_H, as shown in Figure 5a. The development of cumulus cloud on 21–23 September reduced Q*, and in turn ΔQ_{Swr}, highlighting the ability of cloud to moderate the heat budget of shallow reef flat waters.

[32] Nocturnal energy exchanges displayed similar characteristics to those recorded in July 2007, although both Q* and ΔQ_{Swr} did not decrease as much at night. We believe that this reflects the influence of warmer nocturnal air temperatures and a more humid maritime air mass over the study area during the September 2005 period. Absolute humidity during this 3 day period averaged 13 g m^{-3} compared to 10.05 g m^{-3} during the July 2007 measurement program.

[33] A summary of daily energy budget components over the reef flat for 21–23 September 2005 are presented in Table 2. Total daily Q* peaked at 17.45 MJ m^{-2} d^{-1} on 22 September, which is more than 4 times the values recorded during the winter measurement period, while sensible heat flux values were again less than Q_E. Notably, ΔQ_{Swr} accounted for >65% of Q* on a daily basis, resulting in a net gain of energy into the water overlaying the reef flat and underlying substrate compared to the net loss recorded during the winter measurement period. A diurnal signal in water temperature over the reef flat at the pontoon (Figure 7c) appears to be a response to this energy input, although the lack of a warming trend over the measurement period is probably due to the influence of local hydrodynamics on the advection of heat during tidal movement of water on and off the reef flat. The Bowen ratio during this measurement period ranged from 0.04 to 0.12 (Table 2).

5. Discussion

[34] This paper presents the first in situ measurements of local surface energy exchanges over a coral reef in the GBR. Importantly, Heron Reef in the southern GBR is experiencing significant rapid climate change with the regional marine climate zone in this area having migrated south by ~300 km since 1950 [Lough, 2008]. This latitudinal migration is believed to be driven by an expanding tropical belt which Seidel and Randel [2007] claim expanded by 5 to 8° latitude between 1979 and 2005. The associated change in local to regional-scale meteorology, including winds, cloud, precipitation and radiation transfers, is likely to have caused significant and rapid environmental change. This is
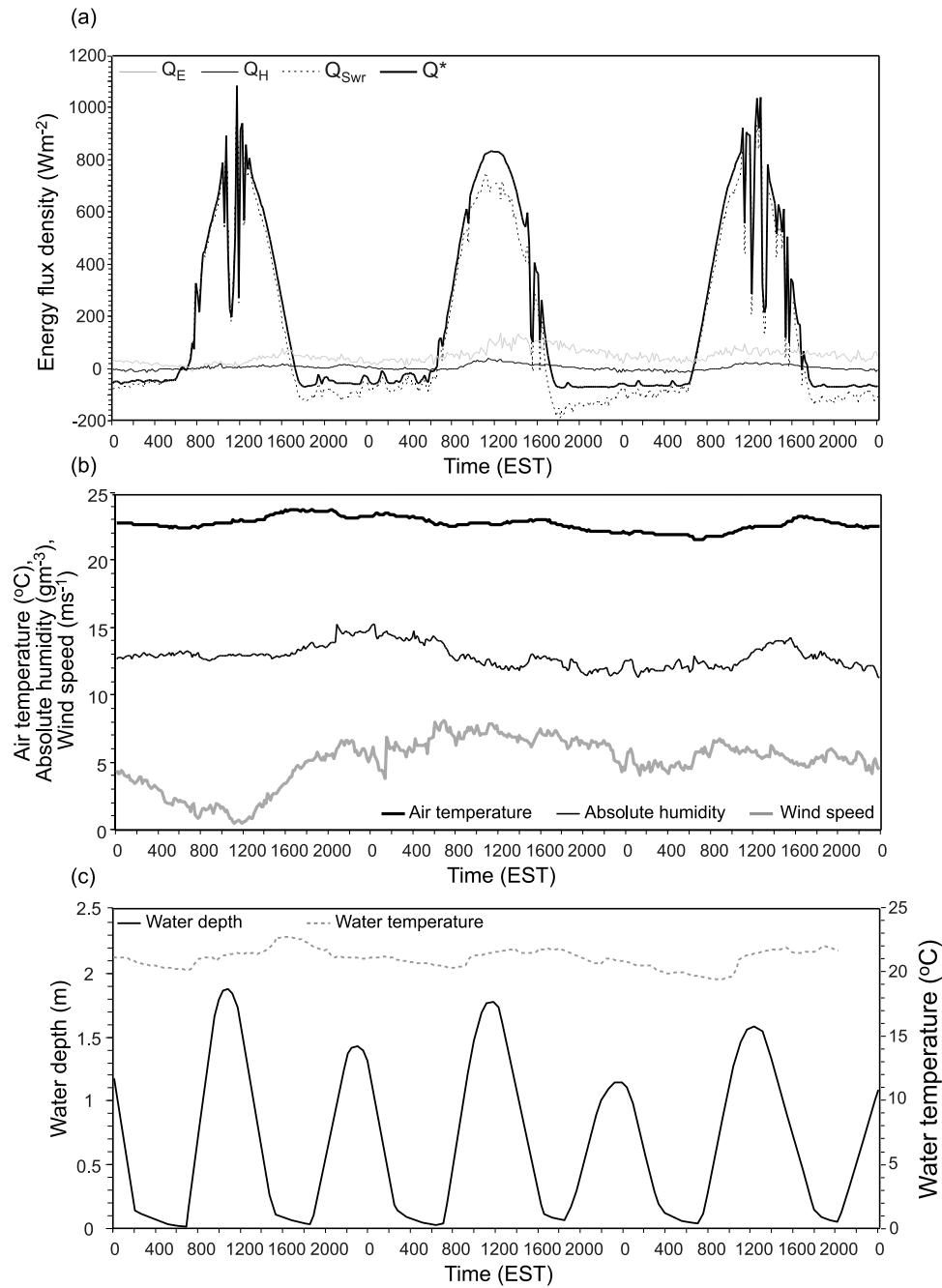
Figure 7. Micrometeorological measurements made from 21–23 September 2005 (a) surface energy balance measurements, (b) supplementary meteorological measurements, and (c) water depth and temperature.

Table 2. Summary of Daily Energy Budget Components Over the Reef Flat at Heron Reef, Australia[a]

Date	Q*	Q_H	Q_E	ΔQ_{Swr}	Bowen Ratio (Q_H/Q_E)
21 September 2005	14.82 (171.52)	0.30 (3.47)	2.47 (28.59)	12.06 (139.58)	0.12
22 September 2005	17.45 (201.96)	0.67 (7.75)	5.50 (63.66)	11.28 (130.06)	0.12
23 September 2005	15.94 (184.49)	0.17 (1.97)	4.38 (50.69)	11.39 (131.83)	0.04

[a]Occurred daily at 0000–2400 EST. Daily average W m^{-2} values are shown in parentheses. Daily energy budget components are given in units of MJ m^{-2} d^{-1}.

set against a backdrop of uncertain future global climate change and effects. Accordingly, there is urgent need to establish understanding of the micrometeorology of coral reefs in the southern GBR and the exchanges of heat, moisture and momentum that occur between these reefs and the lower atmosphere, which is likely to affect local to regional-scale weather and climate.

[35] Results from this investigation of surface energy exchanges over a mixed substrate of coral sand, live coral and algae in water depths of 0.2 to 2.2 m at Heron Reef show that during daytime a significant proportion of Q^* (>80%) in winter and spring may go into heating of water overlaying the reef and the underlying substrate. This was highlighted during the spring case study when ΔQ_{Swr}, albeit calculated as the residual of a simplified energy balance, accounted for >65% of Q^* on a daily basis. This is similar to results presented by *Tanaka et al.* [2008]. They found ~70% of Q^* went into ΔQ_S during late summer, either heating the water overlying the reef flat and/or the reef substrate at Miyako Island, Japan (24.91°N; 125.26°E). During the winter case study at Heron Reef, daily ΔQ_{Swr} was found to be negative, resulting in a net loss of energy and a cooling of the reef flat environment. This is similar to results reported from shallow sea studies [e.g., *Tsukamoto et al.*, 1995]. Clearly, until ΔQ_{Swr} can be quantified through direct measurement caution is needed when interpreting these results as they do not account for the affects of advection associated with tidal movement of water over our study site. Nonetheless, our results show similar partitioning of the energy balance as reported by studies conducted in the marine subtropical setting of southern Japan.

[36] Latent heat was the dominant positive energy flux during the winter case study, as the prevailing southwesterly winds evaporated water from the reef flat. Daytime sensible heat flux values reached a maximum under these conditions on 6 July 2007, but total Q_H was close to zero on a diurnal basis. The authors observed bleaching of corals that had been exposed to the air intertidally during this period, similar to that reported by *Hoegh-Guldberg et al.* [2005] owing to chilling of surface waters and exposed coral. This cooling effect was highlighted by the negative ΔQ_{Swr} values presented in Table 1.

[37] *Agee and Howley* [1977] measured similar marked increases in sensible and latent heat exchange between the sea surface and the lower atmospheric boundary layer during cold air outbreaks over the Kuroshio Current in the East China Sea. The associated air mass transformation was also considered important in the formation of mesoscale cloud clusters (MCC) and cyclogenesis. No research has been conducted on the influence of warm coral reef waters on MCC in the southern GBR region, where nonfrontal cyclonic storms known locally as east coast lows may develop in early winter, often producing heavy rainfall along the central east Australian coast.

[38] During the spring case study, Q_H at Heron Reef displayed little diurnal change, while latent heat flux values peaked during midafternoon, corresponding with low tide indicating higher evaporation rates. Importantly, during this period the majority of Q^* was partitioned into ΔQ_{Swr}, although cloud cover was observed to result in a marked reduction in both Q^* and ΔQ_{Swr} for short periods, with little impact on either Q_H or Q_E. This observation highlights the possible role of cloud cover in moderating ΔQ_{Swr} and, therefore, potentially water temperature, particularly in shallow reef flat waters where radiation transfers and water depth are likely to be the dominant controls on water and substrate temperature.

[39] The daily summaries of energy balance components presented in Tables 1 and 2 suggest that significant change occurs in the energy exchanges of the relatively shallow water environment of Heron Reef. During winter (July) a net diurnal loss of energy was found, compared to a significant gain measured during the spring (September) field campaign. Similar relative change in energy transfers between winter and spring were reported by *Tsukamoto et al.* [1995] over the sea south of Japan where the mixed layer was taken to be 150 and 100 m deep. This suggests that significant change in the direction of energy exchanges under different seasons is not confined to shallow (2–3 m deep) coral reef settings, but includes extensive oceanic environments as reported by *Tsukamoto et al.* [1995]. Quantification of the role of water or mixed layer depth in the magnitude of seasonal energy gain or loss from marine environments is required for calculation of ocean and atmosphere heat budgets and associated dynamics. For example, reef environments such as Heron Reef may act as significant sinks or sources of energy, which in turn may influence neighboring ocean and atmosphere temperatures and processes such as regional atmospheric pressure gradients and local winds, convective cloud development including MCC and water currents. This requires further research which is beyond the scope of the current study.

[40] The relative partitioning of surface energy exchanges during spring at Heron Reef is similar to that reported during late summer by *Tanaka et al.* [2008] over a coral reef at Miyako Island. Comparison with other studies such as *Tsukamoto and Ishida* [1995], made as part of the Tropical Ocean and Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE), is difficult as these were conducted aboard ships over the open ocean. Not surprisingly, the partitioning of turbulent fluxes reported was similar to that described by *Oke* [1978] for the open ocean. *Garratt and Hyson* [1975] and *Hicks et al.* [1974], who did make energy balance measurements over coral reefs, only presented bulk transfer coefficients which are site and time specific and do not allow analysis of diurnal variability in the surface energy balance. As a result, the present study makes a valuable contribution to the study of surface energy exchanges between the reef/water surface and lower atmosphere, although further measurements are required under a wider range of weather conditions.

[41] As shown here, cloud cover is a significant control on ΔQ_{Swr} and any reduction in cloud cover due to, for example, change in atmospheric circulation in response to global warming [see *Andrews and Forster*, 2008; *Gregory and Webb*, 2008] is likely to increase average Q^* over coral reefs such as Heron Reef. While warmer atmospheric temperatures may increase evaporation from shallow coral reefs, any increase in Q_E and/or Q_H may not offset increases in ΔQ_{Swr} owing to reduced cloud cover, which would result in additional warming of water overlying coral reefs. Clearly the influence of cloud cover (and aerosols) on the surface energy balance of coral reefs warrants investigation as a matter of urgency.

[42] Comparison with the remote sensing climatology of *Weller et al.* [2008] of surface-atmosphere energy fluxes on the GBR is difficult, given the two very different approaches and scales of observations. Furthermore, *Weller et al.* [2008] "adjusted" their computed Q_E and Q_H fluxes using air temperature and humidity data from island weather stations and buoys, including from Heron Island, but made no correction for the likely effect of warmer air temperatures recorded at island sites on these variables. This in part may explain the difference between modeled and measured specific humidity for Willis Island in the northern GBR of >4 g kg^{-1} and air temperature of approximately $+1°C$ reported by *Weller et al.* [2008]. On Heron Island we have measured air temperature to often exceed near-surface air temperatures over the adjacent reef flat and open ocean by $>4°C$. Importantly, in situ EC measurements have identified temporal variability related to such factors as cloud cover, which would be difficult to determine from once daily remotely sensed measurements. Eddy covariance allows quantification of the surface energy balance over discreet morphological and ecological zones on a reef flat, which may be masked by the large pixel sizes of remotely sensed data, such as the >4 km^2 used by *Weller et al.* [2008]. Accordingly, we now aim to use our surface energy balance measurement approach to calibrate/validate remotely sensed data with the objective of developing more accurate surface energy balance models of the whole GBR region.

6. Conclusion

[43] Quantification of the surface energy balance over coral reefs presents many challenges, but it is essential for obtaining a proper understanding of microscale to macro-scale heat and water balances, cloud formation and precipitation, local winds, marine ecology and improved prediction of the impacts of global warming on coral reefs, their weather and climate. Using a case study approach, this paper reports the first in situ measurements of the surface energy balance of a small area of Heron Reef in the southern GBR.

[44] Results show that during the winter and spring case studies $>80\%$ of available daytime net radiation went to heating of the water overlaying the reef and the reef substrate. As this value was calculated as the residual of a simplified energy balance, this needs to be confirmed through direct measurement of heat flux into the water column overlaying the reef and the reef substrate. Cloud was shown to be the dominant control on the surface energy budget, and therefore, the heat budget of the reef flat. Accordingly, change in cloud cover due to change in synoptic circulation will significantly affect the heat budget of coral reef flats. Of concern are predictions that less cloud cover in the subtropics, as may occur due to change in atmospheric circulation as a result of global warming, would likely increase reef flat temperatures and contribute significantly to coral bleaching episodes. These effects may extend beyond the reef flat, which may act as a significant heat source to affect both marine and atmospheric processes including MCC and tropical cyclogenesis.

[45] Cold air advection during winter associated with cool and dry westerly winds blowing from the Australian mainland had the greatest impact on both Q_H and Q_E, with the highest daytime values of Q_H recorded under these conditions. These winds were able to chill the reef flat, which at Heron Reef is 80 km from the mainland. During spring under more settled anticyclonic conditions, Q_H remained close to zero for the entire 3 day measurement period with little corresponding change recorded in air temperature. The tidal influence on the surface energy balance identified by this study was small, although we acknowledge that measurements are required over a greater range of tidal cycles and at other times during the year. This will be a priority of future studies when we will also conduct measurements over different benthic covers on Heron Reef.

References

Access Economics (2007), Measuring the economic and financial value of the Great Barrier Reef Marine Park 2005/06, Great Barrier Reef Mar. Park Auth., Townsville, Qld., Australia.

Agee, F. M., and R. P. Howley (1977), Latent and sensible heat flux calculations at the air-sea interface during AMTEX 74, *J. Appl. Meteorol.*, *16*, 443–447, doi:10.1175/1520-0450(1977)016<0443:LASHFC>2.0.CO;2.

Ahmad, W., and D. T. Neil (1994), An evaluation of Landsat Thematic Mapper (TM) digital data for discriminating coral reef zonation: Heron Reef (GBR), *Int. J. Remote Sens.*, *15*, 2583–2597, doi:10.1080/01431169408954268.

Andrews, T., and P. M. Forster (2008), CO_2 forcing induces semi-direct effects with consequences for climate feedback interpretations, *Geophys. Res. Lett.*, *35*, L04802, doi:10.1029/2007GL032273.

Australian Bureau of Meteorology (2007), *Climate*, Aust. Bur. of Meteorol., Melbourne, Vic., Australia. (Available at http://www.bom.gov.au.)

Barr, A. G., K. Morgenstern, T. A. Black, J. H. McCaughey, and Z. Nesic (2006), Surface energy balance closure by the eddy-covariance method above three boreal forest stands and implications for the measurement of the CO_2 flux, *Agric. For. Meteorol.*, *140*, 322–337, doi:10.1016/j.agrformet.2006.08.007.

Castellvi, F., R. L. Snyder, and D. D. Baldocchi (2008), Surface energy-balance closure over rangeland grass using the eddy covariance method and surface renewal analysis, *Agric. For. Meteorol.*, *148*, 1147–1160, doi:10.1016/j.agrformet.2008.02.012.

Chen, D., and A. Krol (1997), Hydrogeology of Heron Island, Great Barrier Reef, Australia, in *Geology and Hydrogeology of Carbonate Islands*, vol. 54, *Develop. in Sedimentol. Ser.*, edited by L. H. L. Vacher and T. M. Quinn, pp. 867–884, Elsevier, New York.

Fennessey, N. M. (2000), Estimating average monthly lake evaporation in the northeast United States, *J. Am. Water Resour. Assoc.*, *36*, 759–769, doi:10.1111/j.1752-1688.2000.tb04304.x.

Francey, R. J., and J. R. Garratt (1979), Is an observed wind speed dependence of AMTEX '75 heat-transfer coefficients real?, *Boundary Layer Meteorol.*, *16*, 249–260, doi:10.1007/BF02220485.

Frederickson, P. A., K. L. Davidson, and J. B. Edson (1997), A study of wind stress determination methods from a ship and an offshore tower, *J. Atmos. Oceanic Technol.*, *14*, 822–834.

Garratt, J. R., and P. Hyson (1975), Vertical fluxes of momentum and sensible heat and water vapour during the Air Mass Transformation Experiment (AMTEX) 1974, *J. Meteorol. Soc. Jpn.*, *53*, 149–160.

Gourlay, M. R., and J. L. F. Hacker (1999), Influence of waves and winds on reef-top currents at Heron Island, Southern Great Barrier Reef, paper presented at Coasts and Ports '99, 14th Australasian Coastal and Ocean Engineering Conference and 7th Australasian Port and Harbour Conference, Perth, West. Austr., Australia.

Gregory, J., and M. Webb (2008), Tropospheric adjustment induces a cloud component in CO_2 forcing, *J. Clim.*, *21*, 58–71, doi:10.1175/2007JCLI1834.1.

Hicks, B. B., R. L. Drinkrwo, and G. Grauze (1974), Drag and bulk transfer coefficients associated with a shallow water surface, *Boundary Layer Meteorol.*, 6, 287–297, doi:10.1007/BF00232490.

Hoegh-Guldberg, O., M. Fine, W. Skirving, R. Johnstone, S. Dove, and A. Strong (2005), Coral bleaching following wintry weather, *Limnol. Oceanogr.*, 50, 265–271, doi:10.4319/lo.2005.50.1.0265.

Hoegh-Guldberg, O., et al. (2007), Coral reefs under rapid climate change and ocean acidification, *Science*, 318, 1737–1742, doi:10.1126/science.1152509.

Hopley, D., S. G. Smithers, and K. E. Parnell (2007), *The geomorphology of the Great Barrier Reef: development, diversity, and change*, Cambridge Univ. Press., Cambridge.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry et al., Cambridge Univ. Press, New York.

Ishikawa, N., I. F. Owens, and A. P. Sturman (1992), Heat balance characteristics during fine periods on the lower parts of the Franz-Josef Glacier, south Westland, New Zealand, *Int. J. Climatol.*, 12, 397–410, doi:10.1002/joc.3370120407.

Kjerfve, B. (1978), Diurnal energy-balance of a Caribbean barrier reef environment, *Bull. Mar. Sci.*, 28, 137–145.

Kljun, N., P. Calanca, M. W. Rotach, and H. P. Schmid (2004), A simple parameterisation for flux footprint predictions, *Boundary Layer Meteorol.*, 112, 503–523, doi:10.1023/B:BOUN.0000030653.71031.96.

Kondo, J. (1976), Heat balance of the East China Sea during the Air Mass Transformation Experiment, *J. Meteorol. Soc. Jpn.*, 54, 382–398.

Kondo, J., and A. Miura (1985), Surface heat budget of the western Pacific for May 1979, *J. Meteorol. Soc. Jpn.*, 63, 633–646.

Krishna, K. M., and S. R. Rao (2009), Study of the intensity of super cyclonic storm GONU using satellite observations, *Int. J. Appl. Earth Obs. Geoinf.*, 11, 108–113, doi:10.1016/j.jag.2008.11.001.

Kurasawa, Y., K. Hanawa, and Y. Toba (1983), Heat balance of the surface layer of the sea at ocean weather station T, *J. Oceanogr. Soc. Jpn.*, 39, 192–202, doi:10.1007/BF02070263.

Lenters, J. D., T. K. Kratz, and C. J. Bowser (2005), Effects of climate variability on lake evaporation: Results from a long-term energy budget study of Sparkling Lake, northern Wisconsin, *J. Hydrol. Amsterdam*, 308, 168–195, doi:10.1016/j.jhydrol.2004.10.028.

Lough, J. M. (2008), Shifting climate zones for Australia's tropical marine ecosystems, *Geophys. Res. Lett.*, 35, L14708, doi:10.1029/2008GL034634.

Masiri, I., M. Nunez, and E. Weller (2008), A 10-year climatology of solar radiation for the Great Barrier Reef: Implications for recent mass coral bleaching events, *Int. J. Remote Sens.*, 29, 4443–4462, doi:10.1080/01431160801930255.

Oke, T. R. (1978), *Boundary Layer Climates*, Routeledge, London, doi:10.4324/9780203407219.

Schmid, H. P. (1994), Source areas for scalars and scalar fluxes, *Boundary Layer Meteorol.*, 67, 293–318, doi:10.1007/BF00713146.

Schneider, C., R. Kilian, and M. Glaser (2007), Energy balance in the ablation zone during the summer season at the Gran Campo Nevado Ice Cap in the southern Andes, *Global Planet. Change*, 59, 175–188, doi:10.1016/j.gloplacha.2006.11.033.

Seidel, D. J., and W. J. Randel (2007), Recent widening of the tropical belt: Evidence from tropopause observations, *J. Geophys. Res.*, 112, D20113, doi:10.1029/2007JD008861.

Shi, T.-T., D.-X. Guan, J.-B. Wu, A.-Z. Wang, C.-J. Jin, and S.-J. Han (2008), Comparison of methods for estimating evapotranspiration rate of dry forest canopy: Eddy covariance, Bowen ratio energy balance, and Penman-Monteith equation, *J. Geophys. Res.*, 113, D19116, doi:10.1029/2008JD010174.

Smith, N. (2001), Weather and hydrographic conditions associated with coral bleaching: Lee Stocking Island, Bahamas, *Coral Reefs*, 20, 415–422, doi:10.1007/s00338-001-0189-2.

Sturman, A. P., and H. A. McGowan (2009), Observations of dry season energy exchanges over a desert clay pan, Queensland, Australia, *J. Arid Environ.*, 73, 74–81, doi:10.1016/j.jaridenv.2008.08.008.

Tanaka, H., T. Hiyama, and K. Nakamura (2008), Turbulent flux observations at the tip of a narrow cape on Miyako Island in Japan's southwestern islands, *J. Meteorol. Soc. Jpn.*, 86, 649–667, doi:10.2151/jmsj.86.649.

Tsukamoto, O., and H. Ishida (1995), Turbulent flux measurements and energy budget analysis over equatorial Pacific during TOGA-COARE IOP, *J. Meteorol. Soc. Jpn.*, 73, 557–568.

Tsukamoto, O., H. Ishida, and Y. Mitsuta (1995), Surface energy balance measurements around ocean weather station-T during OMLET/WCRP, *J. Meteorol. Soc. Jpn.*, 73, 13–23.

Venäläinen, A., M. Frech, M. Heikinheimo, and A. Grelle (1999), Comparison of latent and sensible heat fluxes over boreal lakes with concurrent fluxes over a forest: Implications for regional averaging, *Agric. For. Meteorol.*, 98–99, 535–546, doi:10.1016/S0168-1923(99)00100-8.

Vesala, T., N. Kljun, Ü. Rannik, A. Sogachev, T. Tarkkanen, K. Sabelfeld, T. Foken, and M. Y. Leclerc (2008), Flux and concentration footprint modelling: State of the art, *Environ. Pollut.*, 152, 653–666, doi:10.1016/j.envpol.2007.06.070.

Weller, E., N. Manuel, G. Meyers, and I. Masiri (2008), A climatology of ocean-atmosphere heat flux estimates over the Great Barrier Reef and Coral Sea: Implications for recent mass coral bleaching events, *J. Clim.*, 21, 3853–3871, doi:10.1175/2007JCLI2085.1.

Woodroffe, C. D. (2003), *Coasts: Form, Process and Evolution*, Cambridge Univ. Press, New York.

M. C. MacKellar, H. A. McGowan, and A. H. Wiebe, Climate Research Group, School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Qld 4072, Australia. (h.mcgowan@uq.edu.au)

D. T. Neil, School of Geography, Planning and Environmental Management, University of Queensland, Brisbane, Qld 4072, Australia.

A. P. Sturman, Centre for Atmospheric Research, University of Canterbury, Christchurch, 8020, New Zealand.