A Climatology of Ocean–Atmosphere Heat Flux Estimates over the Great Barrier Reef and Coral Sea: Implications for Recent Mass Coral Bleaching Events

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ABSTRACT

A regional-scale estimate of the surface heat budget of the Great Barrier Reef and Coral Sea (10°–26°S, 142°–155°E) has been developed for the period 1995–2005 in the hope of understanding the trends of sea surface temperatures and the surface heat balance. This report describes the methodology to acquire input parameters from satellite observations, the resultant individual components of the surface heat budget, and their validation with existing datasets and surface measurements.

The accuracy of individual flux components of the heat budget were analyzed with an array of surface measurements. Derived monthly averaged latent and sensible heat flux estimates show RMS errors of approximately 25.2 and 3.4 W m$^{-2}$, respectively. Monthly averaged longwave and shortwave radiation flux estimates show RMS errors of approximately 6.7 and 13.3 W m$^{-2}$, respectively. These improved estimates allow a higher confidence in studies that examine recent sea surface temperature (SST) trends and observed mass coral bleaching for the region.

It is proposed that the greatest uptake of heat occurs over the spring/summer period in the central and southern regions of the Great Barrier Reef, agreeing well with areas where anomalously high sea surface temperatures are observed and where the most significant coral bleaching has occurred, and not in the most northern, more tropical region, as might be expected. The surface heat budget climatology was used to examine the mass bleaching episode that occurred in 2002. Results show that areas of maximum and minimum bleaching are better discriminated by the anomaly from mean seasonal values in the net surface heat flux ($Q_{\text{NET}}$), with accuracy of 86% and 79%, respectively, than by absolute $Q_{\text{NET}}$, absolute SST, or SST anomaly. Possible reasons for this are discussed.

1. Introduction

Coral reefs, including the Great Barrier Reef (GBR), are under threat because of such factors as coral bleaching and thermal stress as a result of climate change. It has been shown that events of coral bleaching principally result from elevated ocean temperatures for an extended period of time (e.g., Hoegh-Guldberg 1999; Berkelmans et al. 2004), and there has been an increased frequency of such mass bleaching events worldwide since the mid-1970s (Glynn 1996). The GBR has been impacted by numerous mass bleaching events, most notably the 1998 and 2002 summers. Apart from
studies of sea surface temperature (SST) measurements and thermal stress indices on the GBR for example, there have been few studies that examine the underlying causal factors behind SST patterns. To answer this there is a need to examine the heat budget of the water mass.

Understanding surface heat storage requires information both on ocean dynamics and ocean–atmosphere exchanges of heat, but direct measurement of the heat exchange at the air–sea interface is difficult. Yu et al. (2004a) states that the need to develop high-quality, gridded, time-dependent, and basin- to global-scale air–sea turbulent (latent and sensible) heat fluxes and radiative (shortwave and longwave) heat fluxes has been widely recognized (e.g., Nunez 1988; Godfrey et al. 1991; Taylor 2000). Despite its potential importance, there are few studies that comprehensively examine all the components of the heat balance and their effect in raising ocean temperatures. A heat budget in the upper ocean can give insight into the roles of the atmosphere and ocean in SST; heat content anomalies (Dong and Kelly 2004), or feedback with changing climate.

To achieve the required accuracy of (approximately) 10 W m$^{-2}$ (World Climate Research Programme 1990) in the estimation of net surface heat fluxes for climate forecasting, differences in the various heat budget components must be identified and minimized (Godfrey et al. 1991; Josey et al. 1999). Currently there are numerous global ocean surface heat and radiative flux datasets available, based mainly upon surface parameters derived from satellite and the use of extensively developed empirical formulas (e.g., Clark et al. 1974; Kondo 1975; Chou 1993; Smith 1988). As intercomparison studies have shown, large uncertainties exist (Kubota et al. 2003; Chou et al. 2004) between datasets, and there is need to critically examine these global datasets for application on a regional scale (Yu et al. 2004a, b).

In the present study we have developed a surface heat budget for the GBR and Coral Sea region (10°–26°S, 142°–155°E) and relate it to past mass coral bleaching events. Our method uses a suite of the best available satellite, global, and surface datasets for the period January 1995 to December 2004. Parameterizations that we derive are checked with surface measurements directly obtained from meteorological stations. Section 1 introduces the topic, and section 2 provides a summary of the theories and the data that were collected for the study region and used in analyses and model development. Section 3 presents the resultant heat budget, and past mass coral bleaching episodes are examined within a heat budget perspective. Section 4 discusses various observed bleaching scenarios with the need to critically examine these global datasets for application on a regional scale (Yu et al. 2004a, b).

Table 1. In situ data used in validation of input parameters and heat flux components of the present study. Data were acquired daily but frequency of acquisition varied with station. All data were averaged on a daily basis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>No. of sites</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed (m s$^{-1}$)</td>
<td>$U_a$</td>
<td>30</td>
<td>BOM stations</td>
</tr>
<tr>
<td>SST (°C)</td>
<td>$T_s$</td>
<td>5</td>
<td>AIMS stations</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>$T_a$</td>
<td>30</td>
<td>BOM stations</td>
</tr>
<tr>
<td>Air specific humidity (g kg$^{-1}$)</td>
<td>$Q_e$</td>
<td>16</td>
<td>BOM stations</td>
</tr>
<tr>
<td>Incoming solar radiation (W m$^{-2}$)</td>
<td>$K_{↓}$</td>
<td>2</td>
<td>BOM stations</td>
</tr>
<tr>
<td>Downward longwave radiation (W m$^{-2}$)</td>
<td>$L_{↑}$</td>
<td>2</td>
<td>BOM stations</td>
</tr>
</tbody>
</table>

including exchanges of heat between the ocean and the atmosphere and flux divergence of oceanic heat transport with terms defined below. Validation was done using surface measurements (Table 1); a series of products summarized in Table 2 and described below were used to estimate individual components of the heat flux.

Data were collected from a series of stations belonging to the Commonwealth Bureau of Meteorology (BOM) and the Australian Institute of Marine Science (AIMS). There were a total of 30 BOM meteorological stations and 5 meteorological stations/buoys (AIMS) located in the present study area (Fig. 1). The span of data used in the study was 1995–2004, inclusive.

The majority of data were collected from a network of BOM stations that record near-surface air temperature, humidity, pressure, vapor and saturated vapor pressure, and wind speed and direction, in most cases at least several times a day, but daily averages were processed for all data. These observations were used to assess the accuracy of the satellite estimates of the wind speed, air temperature, and humidity fields. Downward longwave radiation is measured at only two places of value for this study, namely the Cairns (16.5°S, 145.3°E) and Rockhampton (23.3°S, 150.4°E) BOM sites, avail-
able at half-hourly intervals, and the data were further processed into hourly, daily, and monthly time series. These observations were used to assess the accuracy of the calculation of downward longwave radiation from selected algorithms for the present study. AIMS weather station data were used to assess the accuracy of SST derived from satellite estimates.

Daily data from each station and the global datasets (presented below) were time averaged into monthly values for specific months for compilation of the primary data. Monthly in situ primary data were compared with primary data from global datasets. This comparison yielded optimum primary datasets.

Having determined optimum primary datasets, various algorithms/methods were examined to determine optimum heat fluxes to apply on a monthly basis. From the literature, the most appropriate bulk coefficient derivation was used with measured data.

### a. Wind speed

Updated Special Sensor Microwave Imager (SSM/I) data (version 5) \( F8, F10, F11, F13, F14, \) and \( F15 \) satellites; additional information is available online at www.ssmi.com were acquired and processed to extract wind speed for error analysis and use in obtaining the heat fluxes. Wind speed and direction not only varies greatly on a daily basis, but can be entirely different on an hourly basis over the GBR and Coral Sea (e.g., Pickard et al. 1977), and therefore to acquire a time-averaged value is extremely difficult. The Wentz (1997) SSM/I \( U_{10m} \) from 1987 to 1997 have been extensively evaluated with those of the Tropical Atmosphere Ocean (TAO) and National Data Buoy Center (NDBC) buoys of Mears et al. (2001), and those of the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis and National Centers for Environmental Prediction (NCEP) by Meissner et al. (2001). Meissner et al. (2001) pointed out that both global analysis did not assimilate the Wentz wind products and that the SSM/I wind speeds incorporated in NCEP were derived using a neural network algorithm and were different from those of Wentz (1997). Mears et al. (2001) found that the mean difference between SSM/I and buoy winds was typically \(<0.4 \text{ m s}^{-1}\) and the standard deviation (SD) error was \(<1.4 \text{ m s}^{-1}\). The analysis of Goddard Satellite-Based Surface Turbulent Fluxes, version 2 (GSSTF2), wind speeds yielded an RMS error and SD of 1.43 and 1.38 m s\(^{-1}\), respectively (Chou et al. 2003). Evaluation of SSM/I winds with surface measurements over the present study area for the period 1995–2004 yielded comparable accuracy with past findings, with an RMS error of 0.79 m s\(^{-1}\) and SD of 1.1 m s\(^{-1}\).

### Table 2. Input parameters used to estimate heat flux components, showing source and the error analysis for each parameter and heat flux component for the present study. All data except solar radiation were acquired on a daily basis. Solar radiation was acquired as an average for a specific month. RMS and mean bias errors, correlation coefficient, and samples sizes \((N)\) are indicated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Source</th>
<th>RMS</th>
<th>Bias</th>
<th>Correlation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_a )</td>
<td>SSM/I (V5) (Wentz 1997)</td>
<td>0.7909</td>
<td>0.0028</td>
<td>0.8762</td>
<td>3600</td>
</tr>
<tr>
<td>( T_s )</td>
<td>Pathfinder (V5)</td>
<td>0.3005</td>
<td>0.0884</td>
<td>0.9745</td>
<td>388</td>
</tr>
<tr>
<td>( Q_e )</td>
<td>Adjusted ICESST ANN</td>
<td>0.8742</td>
<td>-0.0257</td>
<td>0.9747</td>
<td>3600</td>
</tr>
<tr>
<td>( Q_l )</td>
<td>Adjusted ICESST ANN</td>
<td>0.9741</td>
<td>-0.0759</td>
<td>0.9400</td>
<td>1020</td>
</tr>
<tr>
<td>( L_\downarrow )</td>
<td>GMS (Masiri et al. 2008)</td>
<td>0.8681</td>
<td>0.0377</td>
<td>0.9688</td>
<td>240</td>
</tr>
<tr>
<td>( K_d )</td>
<td>Cloud GMS</td>
<td>13.3344 ( \text{W m}^{-2} )</td>
<td>0.1229</td>
<td>0.9815</td>
<td>240</td>
</tr>
</tbody>
</table>
The University of Miami’s Rosenstiel School of Marine and Atmospheric Science (RSMAS) and the National Oceanic and Atmospheric Administration’s (NOAA) National Oceanography Data Center (NODC) have developed a reanalysis of the Advanced Very High Resolution Radiometer (AVHRR) data stream to produce a 4-km AVHRR Pathfinder, version 5.0, SST Project (Pathfinder V5; additional information is available online at www.nodc.noaa.gov/sog/pathfinder4km). Daily SSTs were acquired and quality flagged satellite passes (ascending and descending) were used for the SST field in error analysis and in obtaining the heat fluxes. The analysis of the Pathfinder V5 SST used in the model involved the required visual detection of erroneous patches of SST; however, no such errors were found and pixel analysis showed excellent agreement with surface measurements for SST, yielding an RMS error of (approximately) 0.3°C and a correlation of 0.9745 between the two sources for the area.

c. Air temperature and specific humidity

A new methodology in analysis of SSM/I and NCEP–National Center for Atmospheric Research (NCAR) parameters, developed by the Institute for Computational Earth System Science (ICESS) at the University of California (Jones et al. 2003, hereafter JPG03), has improved the accuracy of air temperature ($T_a$) and specific humidity ($Q_a$) estimation. The ICESS tropical
product derives estimates of turbulent heat fluxes by utilizing trained artificial neural networks (ANN) to produce surface fields of \( T_a \) and \( Q_a \) required in calculating the turbulent heat fluxes (JPG03). With an accuracy of 0.53°-0.56°C and 0.93–1.0 g kg\(^{-1}\) when compared to TAO and Pilot Research Moored Array in the Atlantic (PIRATA) buoys, the latent heat flux is found to be an improvement upon NCEP–NCAR surface field’s accuracy (43–47.7 W m\(^{-2}\) compared to 43.5–52.9 W m\(^{-2}\); JPG03). The accuracy of the ANN approach is among the best currently available satellite method to estimate \( T_a \) and \( Q_a \) with high temporal (daily) and spatial (0.25° latitude/longitude) resolutions. However our regional analysis showed that the accuracy of \( T_a \) and \( Q_a \) fields deteriorate for the GBR and Coral Sea.

Figures 2a,c compare monthly average \( T_a \) and \( Q_a \) surface fields from the ICESS method with in situ measurements from the BOM weather stations, displaying large positive biases with an RMS error of 1.42°C and 2.05 g kg\(^{-1}\), respectively; an increase in error from the original evaluation from JPG03. It may be observed that large errors occur for smaller values of \( T_a \) and \( Q_a \). These smaller values were found to correspond mainly with the winter months in the GBR and Coral Sea region, and are thought to be due to an influence of the colder, drier land. Jones et al. (1999) found this discrepancy also, stating that the western boundary currents are characterized by intense atmospheric synoptic variability when cold and dry continental air masses flow over the warm ocean currents. This was even true for surface measurements taken 460 km east of the reef and only about 8 m above sea level, representing open-sea conditions with little topographic interference (Figs. 2e,f). Figures 2e,f show time series of ICESS data for the location of Willis Island (16.29°S, 149.97°E) and the surface measurements at Willis Island. It may be observed that the difference in datasets is greater in the winter months in the GBR and Coral Sea region.

To quantify seasonal errors, monthly measured \( T_a \) (or \( Q_a \)), as a dependent variable, was plotted versus the corresponding ICESS estimate of monthly \( T_a \) (or \( Q_a \)). This was performed for all stations included in Figs. 2a,c. This yielded 12 linear regressions, 1 for each month. These linear regressions were then applied to correct the monthly ICESS \( T_a \) and \( Q_a \) data (Figs. 2a,c), with very high correlation as a result.

Comparison of surface measurements with rendered surface fields found that the error was greatly reduced, to 0.80°C and 0.83 g kg\(^{-1}\) for \( T_a \) and \( Q_a \), respectively (Figs. 2b,d). These results were still not comparable with the accuracy of the initial findings of JPG03 for \( T_a \) (0.53°–0.56°C), but is an improvement on the accuracy of \( Q_a \) (0.93–1.0 g kg\(^{-1}\)). It is also more accurate than the technique of Singh et al. (2004) who also use ANN to estimate \( T_a \) and \( Q_a \) from satellite data (1.0°C and 1.1 g kg\(^{-1}\), respectively) and more accurate than GSSTF2 surface fields (0.9°C for \( T_a \) and 1.4 g kg\(^{-1}\); Chou et al. 2003, 2004). Therefore these reanalyzed surface fields of \( T_a \) and \( Q_a \) are the best available for use in the calculation of the turbulent heat fluxes over the GBR and Coral Sea region.

d. Cloud

Geostationary Meteorological Satellite (GMS) imagery, operated by the Japan Meteorological Agency, obtained from BOM, was used to calculate parameters such as surface albedo and cloud fraction for use in determining radiative heat fluxes. However, because of technical problems with the main imaging instrument on GMS, the last two years of the study period (2000–04) was covered by the backup of the GMS with the Geostationary Operational Environmental Satellite (GOES), operated by NOAA. Cloud fraction was obtained by using an improved cloud fraction calculation which uses surface albedo (As) and maximum cloud-top albedo (Ac) for corresponding zenith angles calculated from GMS satellite reflectivity (Koelemeijer and Stammes 1999) in the form

\[
C = \frac{\alpha_{ea} - As}{Ac - As},
\]

and \( \alpha_{ea} \) is the satellite reflectivity for each pixel.

e. Turbulent heat fluxes

The turbulent heat flux, including latent heat (\( Q_E \)) and sensible heat (\( Q_H \)) fluxes, is dominated primarily by \( Q_E \) and is the key component in removing heat from the ocean surface via evaporation. The fluxes are determined with transfer coefficients that relate the fluxes to the variables measured using the following bulk formulas:

\[
Q_E = \rho L C_E u_a (Q_s - Q_a) \quad \text{and} \quad (3a)
\]
\[
Q_H = \rho C_o C_H u_a (T_s - T_a), \quad (3b)
\]

where \( \rho \) and \( C_o \) are the density and specific heat of air, and \( L \) is the latent heat of vaporization of water; \( u_a, Q_s, \) and \( T_s \) are the wind speed, specific humidity, and temperature at a reference height in the atmosphere surface layer, respectively; and \( Q_s \) and \( T_s \) are the specific humidity and temperature at the surface, respectively. The transfer coefficients for latent and sensible heat (\( C_E \) and \( C_H \), respectively) are primarily functions of height, stability, and wind speed; for this study, the re-
FIG. 2. Analysis of monthly average (a) air temperature and (c) specific humidity between the ICESS ANN with surface measurements; analysis of monthly average (b) air temperature and (d) specific humidity between the corrected surface fields (present study) with surface measurements; and time series of monthly average (e) air temperature and (f) specific humidity estimated by the ICESS ANN and surface measurements at Willis Island (16.29°S, 149.97°E).
lationship found and further discussed by Liu et al. (1979) was used.

There were large differences between various global \( Q_E \) datasets when applied to the GBR, as well as between these sets and surface measurements, but the spatial pattern was similar. The spatial patterns of the GSSTF, versions 1 and 2 (Chou et al. 1997, 2000, 2003), the Japanese Ocean Flux Datasets with Use of Remote Sensing Observations (J-OFURO; Kubota et al. 2002, 2003), and the Hamburg Ocean–Atmosphere Parameters and Fluxes from Satellite Data (HOAPS), versions 1 and 2 (Grassl et al. 2000), are closely related (Kubota et al. 2003; Tomita and Kubota 2003). Estimates from J-OFURO \( Q_E \) were found to be approximately 10 W m\(^{-2}\) higher than GSSTF2, and the difference between the three can vary by about as much 20–30 W m\(^{-2}\). The ICESS satellite estimates of \( Q_E \) over the global tropics (Jones et al. 1999; JPG03) displayed values that were 20–40 W m\(^{-2}\) less in the southern part of the region and up to 20–60 W m\(^{-2}\) higher in the middle and upper regions when compared to the other datasets.

Statistical analysis, with surface measured values of \( Q_E \) for the four reviewed products over the GBR and Coral Sea, revealed that J-OFURO and GSSTF2 have the largest overestimation, with J-OFURO having the largest RMS error and bias (47 and 25 W m\(^{-2}\), respectively). Estimates from GSSTF2 and HOAPS have reasonably small positive bias (12 and 6 W m\(^{-2}\), respectively) but display large RMS errors (42 and 35 W m\(^{-2}\), respectively) and low correlation (0.1986 and 0.2572, respectively). Overall, GSSTF2 errors are similar to those found previously (36 W m\(^{-2}\); Chou et al. 2003). The ICESS product overestimates consistently with a positive bias of approximately 22 Wm\(^{-2}\), but displays the smallest RMS error and higher correlation (31 W m\(^{-2}\) and 0.6722, respectively) than any of the other products.

The ICESS product was found to give the most accurate comparison with measured \( Q_E \) fluxes from weather stations. In a previous section (section 2c) we discussed that primary data from ICESS \( (T_a \) and \( Q_a \)) were also closest to the surface measured values, but they needed adjustment with measured meteorological data.

The final \( Q_E \) and \( Q_H \) product developed in the present study consisted in the adjusted \( T_a \) and \( Q_a \) from ICESS, SST from Pathfinder V5, \( U_r \) from SSM/I, and the Liu et al. (1979) bulk coefficient relationship, with a spatial resolution of 0.044° (~4 km). The monthly estimate for the present developed dataset was found to estimate \( Q_E \) with an RMS of (approximately) 25 W m\(^{-2}\) and a mean bias of 11 W m\(^{-2}\) and therefore is the best

\[ L_{\text{NET}} = \varepsilon a T_s^4(0.39 - 0.05(e_a)^{1/2})F(C) + 4\varepsilon a T_s^3(T_s - T_a) \]

\((4a)\)
where $\varepsilon$ is the emissivity of the ocean surface, $\sigma$ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$), $e_u$ is the near-surface water vapor pressure, and $F(C)$ is the cloud correction factor using Eq. (2) and including a function of latitude.

From the above relationship, the downward longwave radiation ($L_{\downarrow}$) may be obtained as

$$L_{\downarrow} = L_{\text{NET}} - L_{\uparrow}$$

$$= L_{\text{NET}} - [\varepsilon \sigma T_4^4 + L_{\downarrow}(1 - \varepsilon)]$$

$$= \frac{L_{\text{NET}} - \varepsilon \sigma T_4^4}{\varepsilon}.$$  \hspace{1cm} (4b)

The estimation of the downward longwave heat flux was also calculated using the formula of Kondo (1976) (hereafter the formula will be referred to as K76) as a means of comparison with the downward contribution of the net downward longwave heat flux, and also for comparison to surface measurements where only downward longwave radiation is recorded. The C74 and K76 methods agree well with each other in the estimation of downward longwave radiation (0.9843 correlation). When compared to surface measurements, the C74 method agrees marginally better, with a RMS error of 6.7 W m$^{-2}$, bias of $-1.5$ W m$^{-2}$, and correlation of 0.9688.

If this is considered the only error in the net longwave heat flux calculation then it would be comparable with those of Cronin and McPhaden (1997) and Wang and McPhaden (2001), where the measurements of error were (approximately) 6 W m$^{-2}$. However, there are no surface measurements of upward and net longwave radiation in the study region so further analyses cannot be undertaken. However, upward longwave radiation is a function of the surface temperature ($\varepsilon \sigma T_4^4$), which was found to be derived with good confidence. Therefore the C74 method as described in Eq. (4a) was used for the estimation of $L_{\text{NET}}$. Imagery of GMS was reduced to a spatial resolution of 0.044° (~4 km) so that it conformed to the resolution of the turbulent heat fluxes.

3. Results

a. Seasonal heat fluxes

1) Turbulent heat flux

Figure 3 provides the mean net turbulent heat flux of Southern Hemisphere seasons for the period 1995–2004 in the GBR and Coral Sea region. All images show that the maximum transfer of heat out of the sea occurs throughout the four seasons over the GBR at approximately 12°–18°S, and a minimum transfer of heat is out of the sea along the coast in the middle to southern region of the GBR, south of approximately 18°S. Summer and winter months appear to be similar in both pattern and magnitude, with autumn displaying the largest transfer of heat out of the sea on average. These patterns can be in part explained by the wind speed, and, of importance to humidity, the wind direction. The southern section of the GBR is dominated by the southeast trade winds, with winds generally from between east (August–February) and south (rest of the year). North of 15°S, northwest winds are the common from December through to March, being replaced by southeast winds at other times. Synoptic systems in the region of the GBR are highly variable and often transport dry continental air masses eastward, creating periods of high evaporation. Figure 4 shows these processes operating during the autumn season when they are strongest.

2) Radiative heat flux

Figure 5 displays the mean seasonal net radiation heat flux for the period 1995–2004 in the region. Unlike the net turbulent heat fluxes, the net radiation heat flux in summer and winter show large differences. Quantitatively, a positive net radiation flux of about 225–300 W m$^{-2}$ occurs in the summer period, reducing to 50–175 W m$^{-2}$ in the winter period. Generally, the region experiences a north–south latitudinal gradient, that is, decreasing positive net radiation flux with increasing latitude, except summer. Greater positive net radiation flux occurs in the middle to southern region of the GBR and Coral Sea region in the summer period as a result of cloud presence in the north and along the coast, and the high solar elevation at that time of the year.

Comparison with previous studies (Gupta et al. 1999, their Figs. 2 and 3) shows that the net surface radiation budgets yield these similar patterns and results for the GBR and Coral Sea region. To understand this feature, we must examine the influence of both the solar and longwave heat fluxes on the net radiative heat flux. Masiri et al. 2008 found that a distinct maxima in solar radiation is exhibited in the southern end of the study area, between latitudes 18° and 26°S, and decreasing northward of this latitude in summer, autumn, and spring. However, this study found that a larger loss of radiation (net longwave heat flux) occurs in the higher latitudes during autumn, winter, and spring; enough to reverse the solar radiation trend, which results in decreasing positive net radiation flux with increasing latitude, except for the summer period, which still exhibits a distinct maxima in summer south of latitude 16°S.
3) **NET SURFACE HEAT FLUX**

As shown in Eq. (1a), the net surface heat flux ($Q_{NET}$) can be calculated by the net radiation heat flux (heat gain) minus that of the net turbulent heat flux (heat loss). The mean seasonal $Q_{NET}$ for the period 1995–2004 is shown in Fig. 6 with climatological monthly means over the 10-yr period plotted in Fig. 7. Figure 7 also displays the contribution of individual components to $Q_{NET}$. With a larger positive net radiative flux over the summer periods, a gain of about 75–150 W m$^{-2}$ results in $Q_{NET}$, with the winter period displaying a range of about 0–100 W m$^{-2}$ loss to the atmosphere except for a gain of about 25 W m$^{-2}$ in a small area of the north. The climatology plot (Fig. 7) reveals that the maximum mean $Q_{NET}$ is observed toward the end of the year, around November–December. It is also shown for summer and winter values in the net turbulent heat flux over the GBR and Coral Sea region, as it does not appear to fluctuate greatly over the year.

Two distinct regions of heat uptake appear in the
The first one is featured just south of Papua New Guinea; the second one appears over the GBR south of latitude 16°S. The anomaly south of the GBR is particularly strong in spring and summer. The reason for high positive heat flux relates to high solar radiation values during the spring and summer months, as well as the low evaporation over the area. This low evaporation is likely to be related to the high pressure regions on the mid-GBR and the resultant low wind speeds.

Figure 7 shows that the southern region of the GBR experiences larger fluctuations, with Heron Island displaying the highest and lowest \( Q_{\text{NET}} \) over the year on average. This is mainly because the southern GBR stretches to latitude of about ~25°S, which experiences more profound seasonality than the tropics, resulting in greater changes in both air and sea surface temperatures. The mean \( Q_{\text{NET}} \) seems to be well mirrored by Willis Island.

\( Q_{\text{NET}} \) maps. The first one is featured just south of Papua New Guinea; the second one appears over the GBR south of latitude 16°S. The anomaly south of the GBR is particularly strong in spring and summer. The reason for high positive heat flux relates to high solar radiation values during the spring and summer months, as well as the low evaporation over the area. This low evaporation is likely to be related to the high pressure regions on the mid-GBR and the resultant low wind speeds.

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**b. Heat fluxes during the 2002 mass coral bleaching event**

This section examines a period where high SSTs and solar radiation were observed in early 2002, and that coincided with a period of mass coral bleaching event for the GBR. It may be observed that the interannual variability of the mean \( Q_{\text{NET}} \) and SST for the region (Fig. 8a) shows that the summers of 1997/98 and 2001/02 recorded the highest monthly amounts of positive \( Q_{\text{NET}} \) (or highest heat uptake), and the highest SST. Clearly the years of extensive bleaching correspond to the highest year of net surface heat uptake during the summer period.

Figure 9 displays the average \( Q_{\text{NET}} \) and SST for the summer of 2001/02 as well as the anomalies when compared to the mean seasonal values for the same period. Also shown are aerial survey results of bleaching sites taken from Berkelmans et al. (2004), collected over January–April 2002. For ease of viewing, only a strip along the coast encompassing all the GBR is shown, as well as only two cases of bleaching—with 58 sites recording very high to extreme bleaching (with 30%–100% of its surface being bleached) and 123 sites recording very little or no bleaching (<1% of its surface being bleached). Relevant statistics are shown in Table 3. Reefs that were surveyed from the Berkelmans et al. (2004) study were also partitioned into inshore and offshore types (98 and 83, respectively). It is evident that the majority (83%) of severe bleaching sites coincide with areas of maximum positive heat flux greater than 125 W m\(^{-2}\) along the coast, and that \( Q_{\text{NET}} \) (Fig. 9a) relates the most severely bleached reefs (>60% of surface area being bleached) to a region near the coast with the highest (~150 W m\(^{-2}\)) positive heat flux. Eighty-one percent of inshore unbleached sites were found in a region less than 125 W m\(^{-2}\). For all unbleached sites (inshore and offshore) it was found that \( Q_{\text{NET}} \) anomalies are a better discriminator, with 79% of
unbleached sites in a region less than 20 W m\(^{-2}\) with respect to mean seasonal values. This result is explained in further detail in the discussion.

Bleaching was observed in areas where the summer mean SST was above (approximately) 29\(^\circ\)C, except for the northern section, where these temperatures are quite common (Fig. 9b). It may be observed that the SST has a cold tongue along the offshore unbleached Swains area.

The pattern of the \(Q_{\text{NET}}\) anomalies (Fig. 9c) subtly follow the absolute \(Q_{\text{NET}}\), and it was found that most of the GBR and Coral Sea received greater positive heat flux than the summer climatological average, except north of 14\(^\circ\)S. It can also be seen that the SST anomalies were higher than normal south of this latitude, with temperatures reaching up to 1.5\(^\circ\)–2.0\(^\circ\)C higher than other summers, but mainly between 0.5\(^\circ\)–1.0\(^\circ\)C for most of the region south of 14\(^\circ\)S.

4. Discussion

Now that a reliable estimate of the ocean–atmosphere fluxes over the GBR and Coral Sea region

Fig. 5. Seasonal averages of net radiation heat fluxes (W m\(^{-2}\)) for the period 1995–2004.
It is vital to examine what, if any, patterns exist between SSTs and $Q_{\text{NET}}$. From the investigations of the individual components of $Q_{\text{NET}}$, it was found that the net radiation has a maximum in summer at the middle to southern reef latitudes, and that the turbulent heat fluxes display a slightly higher loss to the atmosphere in the 12°–18°S latitudinal band. The southern region of the GBR also experiences larger fluctuations in $Q_{\text{NET}}$ as a result of more seasonality. This may lead to more stress for the reef systems (Glynn 1996), and any anomalous change in any individual components and $Q_{\text{NET}}$ could have severe impacts on these reefs, as they have lower coral bleaching thresholds.

As suggested by previous studies (e.g., Godfrey et al. 1991), if ocean mixing and advection are too weak to carry away the influx of heat at the surface in a region, an increase in $Q_{\text{NET}}$ should be reflected (possibly with a determinable lag) in surface water temperatures. However, these determinants have not yet been exam-
ined for the GBR and Coral Sea region. It is known that coral bleaching events are most often correlated with temperature stress in conjunction with high light levels (Drollet et al. 1994; Winter et al. 1998; Hoegh-Guldberg 1999; Berkelmans 2002; Done et al. 2005); therefore, a relationship between $Q_{\text{NET}}$ and SST could be vital in the understanding of these episodes.

Figure 7d, representing spatial averages over the entire GBR, qualitatively supports the assumption of $Q_{\text{NET}}$ being the most dominant process in controlling SSTs in the region, as the two curves display excellent agreement in pattern. A monthly time series of the spatial averages for the GBR and Coral Sea region (Fig. 8a) show slightly higher peaks in the mean $Q_{\text{NET}}$ corresponding with slightly higher peaks in the mean SST; the 1997/98 and 2001/02 summers displaying the highest $Q_{\text{NET}}$, and SSTs responding with higher peaks after about a lag of two months, which is mainly a result of the thermal inertia of the ocean.

The investigation of the summer of 2001/02 provided strong evidence that the specific areas of higher-than-normal $Q_{\text{NET}}$ anomalies coincided with areas of observed higher SSTs and the most extreme coral bleaching. It can be seen that over this period $Q_{\text{NET}}$ was approximately 20–60 W m$^{-2}$ above seasonal averages for most of the region (Fig. 9c), especially the GBR south of approximately 14°S, and 86% of bleached sites were in a region greater than 20 W m$^{-2}$. A heat gain of these values (i.e., 20 W m$^{-2}$ for a month) can lead to warming of 0.5°C in such a shallow (i.e., 25 m) water column alone.

It is well documented that some reefs in the middle to southern area of the GBR experienced the most severe mass coral bleaching to date (Berkelmans et al. 2004; Done et al. 2005), and an increase in $Q_{\text{NET}}$ to the water seems likely to have been one probable cause for coral bleaching due to higher water temperatures or high solar radiation (light levels) as a result.

This process may be viewed in more detail by examining the fluxes and SST for Heron Island. Figure 8b shows that the SST anomalies for the 1998, 2002, and 2004 summers are 1.0°–1.5°C above monthly means of the past 10 yr for Heron Island. The 1997/98 summer SST anomalies were the highest for Heron Island. However, all these high SST anomalies have coincided with the observed mass coral bleaching on the GBR.
(Berkelmans et al. 2004), but the reef group including Heron Island (Capricorn Bunker Group) was not observed to be severely bleached in 2001/02, only 1997/98. More so, during the 2001/02 summer, it was observed that most of the offshore Swains area, for example, experienced minimal or no bleaching as well.

Although the absolute positive heat flux (Fig. 9a) appears high in the summer of 2001/02 for these unbleached areas, the positive heat flux anomaly for the period (Fig. 9c) was not high, nor were the SST values much higher (Fig. 9d). This observation provides support that anomalous high values of $Q_{\text{NET}}$ could be instigating bleaching events. Statistical analysis (Table 3) explained this feature, where it was found only 37% of unbleached sites were in a $Q_{\text{NET}}$ region less than 125 W m$^{-2}$. However, the percentage of unbleached sites in a $Q_{\text{NET}}$ anomaly region of less than 20 W m$^{-2}$ increased to 79%, also with 86% of bleached reefs in a region greater than this 20 W m$^{-2}$. This shows that the $Q_{\text{NET}}$ anomaly discriminates between the two cases sufficiently. It also suggests that higher values of $Q_{\text{NET}}$ for the summer of 2001/02 affected inshore reefs more than offshore reefs.

To better understand these features of the area, a transect across the reef at a constant longitude, chosen here to be 22°S to cover inshore and offshore reefs, as well as the area separating them and the continental shelf/sea on either side, was mapped. Figure 10 shows the mixed layer depth estimates (MLD), based on difference criteria (Condie and Dunn 2006; Alory et al. 2006; Brainerd and Gregg 1995) and defined as the minimum depth where temperature is 0.5°C lower than SST. Seasonal MLD was comparable to past study estimates (Condie and Dunn 2006). Also shown are SSTs across this transect, confirming that a deeper MLD exists on both sides of the offshore reefs, allowing the intake of heat to be distributed evenly through a greater mass of water. The MLD for the majority of the GBR was found to correspond to the seafloor, as it is so shallow that SSTs are quite uniform through the water column. This implies that shallower reefs also surrounded by shallower water (i.e., inshore reefs) are more at risk than reefs that are surrounded by deeper water (i.e., offshore reefs).

An interesting feature of the overall results of the seasonal images of $Q_{\text{NET}}$ (Fig. 6) is that, in the spring and summer periods, the greatest positive heat flux is seen along the coast and in the middle to high latitudes.
Fig. 9. The (a) net surface heat flux mean, (b) SST mean, (c) net surface heat flux anomaly, and (d) SST anomaly for summer 2001/02. Also shown are aerial surveys of bleaching sites taken from Berkelmans et al. (2004) and the 200-m isobath. Filled triangles represent severe (30%–100%) bleached sites, and open triangles represent unbleached (<1%) sites.

Table 3. Statistics for the 2002 bleaching episode using seasonal average $Q_{net}$ and SST and anomaly from mean seasonal values. Numbers in parentheses denote the percentage of sites above the threshold for each classification.
of the GBR, instead of the most northern tropical area. These results correlate well with this area experiencing the most significant coral bleaching and high SSTs for the GBR. The northern reef systems of the GBR have not experienced as extensive coral bleaching, and it was found that higher-than-normal $Q_{\text{NET}}$ and SST did not occur in this area as much as in the southern area. The general surface currents for the middle to north region of the GBR are northwest, and the observed high heat uptake in the midlatitudes does not seem to be transported north, as during the summer of 2001/02; average wind speeds were found to be reduced. Therefore this supports the hypothesis of more than local ocean mixing and advection being quite minimal in the GBR and Coral Sea region (Ridgway and Godfrey 1994).

As average winds were considered to be one of the main causal factors of the 1997/98 bleaching event (Wolanski 2001), it is important to examine the processes leading to the anomalously high values in $Q_{\text{NET}}$ and possibly the high SSTs and mass bleaching for the summer of 2001/02. A previous study (Masiri et al. 2008) found that solar radiation was found to predict inshore bleaching much better than SST, and it may be observed from Fig. 9 that severe bleaching sometimes occurred in areas of minimal changes in SST but with high $Q_{\text{NET}}$ anomalies. This appears to reverse offshore, where high SSTs predicted bleaching better than solar radiation receipt. Our study found that the influence of slackened winds (not shown here), leading to less evaporation and higher SSTs, and combined with higher solar radiation (and light levels) were the main instigating drivers in the mass coral bleaching for the summer of 2001/02 for different areas of the GBR.

To further analyze the degree of influence of $Q_{\text{NET}}$ on SST and the extent to which heat is stored locally in the upper layer in the GBR and Coral Sea, several approaches can be taken. In this study as shown elsewhere (Moisan and Niiler 1998; J.-M. Verstraete et al. 2006, personal communication; Yu et al. 2006), the relationship between $Q_{\text{NET}}$ and the observed change in SST can be statistically represented by calculating the correlation between the two. This allows the significance of the coupling between the two fields to be observed, and an initial statement can be made on the dominant processes in the region, either $Q_{\text{NET}}$ or ocean processes.

Seasonal and interannual variability of the correlation between $Q_{\text{NET}}$ and the change in SST were computed and are shown in Fig. 11. The seasonal variability shows high correlation ($r > 0.9$) for the majority of the GBR and Coral Sea region except two main areas, that is, the northwest and northeast regions, which display relatively low coefficients. The interannual variability displays the same pattern; however, the correlation decreases substantially. This suggests that the seasonal cycle of changes in SST is dominated primarily by the seasonal cycle of $Q_{\text{NET}}$ in the majority of the GBR and Coral Sea except for possible ocean processes (advection due to currents) in the northern area of the region. The interannual variability shows that on the shorter time scale (i.e., monthly) south of approximately 18°S, the GBR variations of local SST is still mainly dominated by the role of $Q_{\text{NET}}$. East of the continental shelf, oceanic processes seem to distribute heat more profoundly in the deeper waters.

Major currents in the region flow into the Coral Sea approximately between 19° and 11°S, namely the South Equatorial Current (SEC), which is broken up into several jets (Ridgway and Dunn 2003; Kessler and Gourdeau 2007) that can be identified in the seasonal correlation figure where lower correlation is observed. This bifurcates at around 15°-18°S along the coast of Australia, creating the East Australian Current (EAC) and the North Queensland Current (NQC), which fluc-
tuates on an annual cycle with a maximum in the second half of the year (Kessler and Gourdeau 2007). This latitude also coincides with the large fluctuations in wind speeds and directions. This fluctuation in strength of the main currents and winds in the region is thought to account for the low correlations that were observed.

5. Summary and conclusions

Intercomparison of both turbulent and radiation heat flux estimates over the GBR and Coral Sea region found that, although similar spatial patterns are observed, significant quantitative differences exist between various global/tropical datasets. This study involved the analysis of the satellite-derived surface fields relating to ocean–atmosphere heat exchanges on a regional scale in order to minimize errors in estimating the net surface heat flux ($Q_{\text{NET}}$) of the GBR and Coral Sea region.

A 10-yr (1995–2004) dataset of monthly individual turbulent and radiation heat flux components has been constructed for the GBR and Coral Sea region, with a 4-km spatial resolution. Turbulent heat fluxes are derived from the surface winds from SSM/I, air temperature, and specific humidity reanalysis from JPG03 and SST provided by the Pathfinder V5 product and the similarity flux model of Liu et al. (1979). Radiation fluxes are also derived from cloud fraction and surface albedo extracted from GMS imagery and the formula of Clark et al. (1974).

Redeveloped surface fields and the resultant heat fluxes were validated with surface measurements in the region over the 10 yr and were found to be an improvement upon previous sources of the turbulent heat fluxes. The comparison of radiation heat fluxes accuracy was found to be comparable with results from similar studies.

The $Q_{\text{NET}}$ in the GBR and Coral Sea region was investigated and appears to be influential on the SSTs observed. The mass coral bleaching events that were observed in the GBR during 1998 and 2002 coincide with an increase in $Q_{\text{NET}}$ and a lagged increase in SST, and coral bleaching levels can be explained in some sense from $Q_{\text{NET}}$ anomalies (including solar and evaporation effects), mixed layer depth and SSTs. This link between the $Q_{\text{NET}}$ and SST may suggest that large-scale ocean mixing and advection in this region does not play a large part in the overall heat balance of the GBR south of approximately 18°S; however, it needs to be investigated in more detail in the thinner regions of the GBR and also the deeper, stronger current (EAC for example) offshore waters, east of the continental shelf.

The accuracy of the $Q_{\text{NET}}$ developed here provides direct input to SST and other thermodynamic stresses (such as solar radiation), which can directly affect coral bleaching. An extension of this dataset into the future could provide an advantage to management and conservation of the GBR, as areas of future mass bleaching may be able to be predicted. Further quantitative

![Fig. 11. Correlation between (a) seasonal and (b) interannual SST variations and net surface heat flux, based on the newly developed dataset. Also shown is the 200-m isobath.](image-url)
analysis of the variations in mixed layer depths and surface currents of the GBR and Coral Sea region could also provide estimation of advective transport allowing calculation of a complete heat balance.

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