Coral Reefs (2010) 29:975–985
DOI 10.1007/s00338-010-0644-z

REPORT

The Capricorn Eddy: a prominent driver of the ecology and future of the southern Great Barrier Reef

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Received: 27 July 2009 / Accepted: 22 May 2010 / Published online: 10 June 2010

Abstract This study focuses on a mesoscale eddy feature, the 'Capricorn Eddy', that typically forms within an indentation of the continental shelf in the southern GBR system. Satellite data at moderate resolution (1 km) are used to examine relevant mesoscale and sub-mesoscale sea surface dynamics. Available in situ measurements and model data are used to validate the satellite observations and to specify the nature of the processes occurring within the water column itself. The characteristic features are identified and physical theory employed to develop an understanding of associated processes. In particular, the effect of the eddy in raising cooler, nutrient-enriched oceanic subsurface water and transporting it to the reef zone, and eventually into the lagoon, is shown. This study demonstrates that the linkages between large-scale oceanography and the meso- and sub-mesoscale patterns are crucial to determining biologic responses on the scale of reef communities and may be key to understanding climate change impacts at the relevant spatial scales.

Communicated by Environment Editor Prof. Rob van Woesik

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Keywords Coral reefs · Capricorn Eddy · East Australian Current · Great Barrier Reef · Mesoscale processes · Upwelling

Introduction

Tropical oceans have undergone rapid warming and acidification on a scale not seen for at least 720,000 years if not 20 million years (Hoegh-Guldberg et al. 2007). The rapidity with which these environmental changes have occurred appears to have exceeded the ability for biologic systems to keep up through changes in distribution and genetic structure. If current rates of change in atmospheric carbon dioxide are not reduced, many analysts predict widespread species extinction and ecosystem collapse (Myers and Knoll 2001; Veron 2008; Wake and Vredenburg 2008).

While broad characteristics of these changes have been documented, the finer temporal and spatial scales remain uncharted, representing a challenge for the research and ecosystem management community. As waters have warmed, for example, coral reefs have seen an increasing frequency and intensity of mass bleaching events, with expectations that sea temperatures will soon exceed the threshold for mass bleaching and mortality on a yearly basis (Hoegh-Guldberg 1999; Sheppard 2003; Hoegh-Guldberg et al. 2007). It is apparent, however, that no two bleaching events are identical in terms of their temporal and spatial scales, and their overall intensity (Oliver et al. 2008). Variability in the timing of stress (Weeks et al. 2008), the physical conditions in a particular location, as well as the communities and their resilience (Berkelmans and Willis 1999; Brown et al. 2002; McClanahan et al. 2007), will drive significant differences from site to site in the ecological impacts and responses required from natural resource managers.

Currently, the underlying reasons for this variability have been poorly described and are much less well understood. One can assume, however, that the small-scale variation may ultimately arise from patterns in causative physical factors and mechanisms. Certainly, cooling influences, such as upwelling of cooler waters from greater depths, are important in understanding how other factors (changes in salinity, solar radiation, sedimentation, nutrients) may influence the outcome of primary stresses such as temperature. These coinciding factors may determine ultimately the resilience of reefs to the rapid environmental changes expected in an enhanced greenhouse world. In this respect, understanding the dynamics of ocean processes from global to local scales becomes imperative within the goal of understanding and predicting the impacts of global change. Such predictability would guide the design of process-oriented investigations of key issues, as well as the projection of local effects of climate change based on climate change projections of the larger scale ocean and atmosphere dynamics. These local projections and understandings of change are critical to any effective natural ecosystem management response.

The present project sets out to improve our understanding of the oceanography of the southern Great Barrier Reef (GBR) and to seek explanations of the broad phenomena associated with our changing climate. While we may understand the essential physics of the relevant processes, we need to observe the meso- and sub-mesoscale patterns in order to define and model the processes at relevant scales. In this study, we make use of available observational coverage offered by established satellite systems. Satellite measurements at moderate resolution (1 km) can potentially recognize sea surface expressions of relevant mesoscale and sub-mesoscale dynamic processes. We identify characteristic features and use physical theory and comparative pattern-recognition with respect to similar features studied elsewhere to develop a level of initial understanding of these processes. We use concurrent in situ

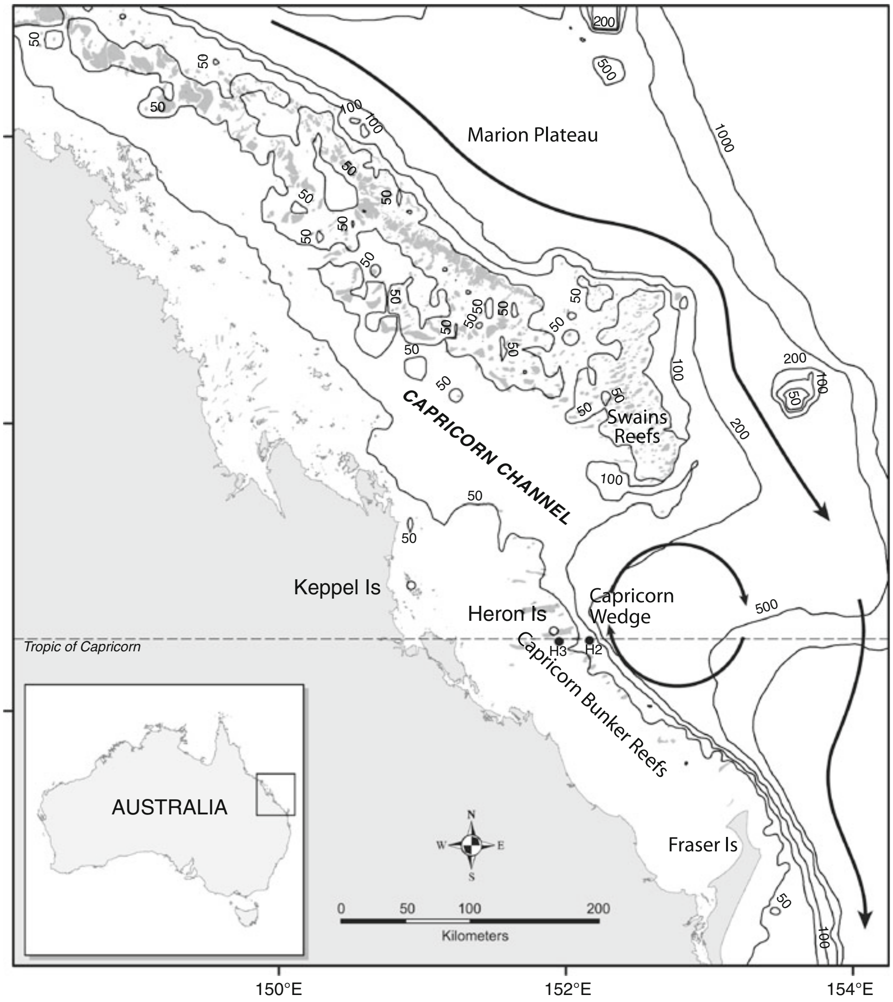

Fig. 1 A schematic map of the study area in the southern GBR, illustrating key bathymetric features, islands and coral reefs. The *solid dark arrows* represent the southward flow of the East Australian Current. The *dark circular arrows* show the location of the Capricorn Eddy within an indentation of 200-m isobath, referred to as the Capricorn Wedge. The *dark circular* markers along the Tropic of Capricorn, H2 and H3, show the location of the long-term moorings used in the study. The landmass and coral reefs are shaded in *light gray*

and model observations where available to validate the satellite observations and to observe the processes within the water column itself.

One of the most significant features that we have identified is a mesoscale eddy feature, which we herein identify as the 'Capricorn Eddy'. This oceanographic feature typically forms within an indentation (approximately 150 km across) of the continental shelf configuration that is located directly off the mouth of the Capricorn Channel, a major channel feature of the southern GBR (Fig. 1). In order to facilitate the discussion, we refer to the "plateau"-like zone situated within the westward arc of the 200-m contour toward the Capricorn Channel between the Swains Reefs and the north of Fraser Island, as the "Capricorn Wedge". (Fig. 1: This lies on the southern slope of the Marion Plateau.)

The Capricorn Eddy

The presence of an eddy in the region adjacent to the mouth of the Capricorn Channel was first noted in 1970 in a surface drifter study (Woodhead 1970). The formation of a stable cyclonic eddy in the lee of the shelf bathymetry was later postulated as contributing toward north-westward flow in the Capricorn Channel region (Griffin et al. 1987). Subsequent oceanographic deployments and satellite sea surface temperature studies have shown these cyclonic features to trigger upwelling along the continental shelf (Kleypas and Burrage 1994; Middleton et al. 1994; Burrage et al. 1996).

Satellite imagery

For this study, a sequence of early spring satellite images (Fig. 2) serves to identify the eddy. The satellite data were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS; modis.gsfc.nasa.gov). Time series of weekly mean sea surface temperature (SST) and chlorophyll-a images were generated at 1 km spatial resolution for the period 2002–2008. Standard SST (Brown and Minnett 1999) and chlorophyll-a concentration (O'Reilly et al. 2000) algorithms were used. Chlorophyll concentrations of >1 mg m^{-3} are used in a qualitative sense only, since it is recognized that bottom reflectance or the presence of scattering particles may contaminate the signal in very shallow or turbid waters, respectively.

In the sequence presented, the poleward-flowing East Australian Current (EAC) waters are easily identified along the continental shelf margin (200 m isobath) in the northern halves of the images as relatively warm in sea surface temperature (Fig. 2a, c, e) and lower in chlorophyll concentration (Fig. 2b, d, f) than the continental shelf waters. The shallow shelf waters in the southern portions of the images are seen as notably cool in the first panel of the sequence (18–21 September, Fig. 2a), as would be expected in this late winter—early spring period. In general, the shallow GBR shelf waters experience a far greater seasonal fluctuation in temperature than do the oceanic EAC waters, being both warmer in summer and cooler in winter than the waters offshore.

Notable in these early spring SST images is the offshore advection of cooler shelf water eastward along ~22.5°S and then southward at ~153°E, and the entrainment of warm EAC waters from the south following the continental shelf edge into the Capricorn Wedge. The advection of these waters in a clockwise manner in the lee of the shelf bathymetry is clearly indicative of a cyclonic eddy, apparent in the thermal signature. This rotational flow is also evident in the chlorophyll signal throughout the image sequence (Fig. 2b, d, f), albeit most clearly defined in the latter period (Fig. 2f). Intrusions of low chlorophyll waters are seen to extend up the Capricorn channel and to a lesser extent, onto the shelf to the south and the north of the Capricorn Bunker group of reefs.

In situ measurements

A number of in-line long-term moorings have been deployed in the vicinity of Heron Island since August 2004 in order to observe shelf/ocean exchanges in the region. These were initially deployed by the Australian Institute of Marine Science (AIMS) and have been upgraded substantially through the Great Barrier Reef Ocean Observing System (GBROOS) regional node of the Australian Government's Integrated Marine Observing System (IMOS). For the present study, we use observations from two moorings positioned to the east of One Tree Island and south of Heron Reef in the Capricorn Bunker group of reefs (sites marked H2 and H3 in Figs. 1 and 3c), located in 55 and 48-m water depth, respectively, between May and October 2008. At site H3, four temperature loggers were placed at set intervals through the water column; three temperature loggers were deployed at site H2.

Temperature–time series from the loggers located in the GBR lagoon south of Heron Island for the period 15 September to 15 October 2008 (Fig. 3a), concurrent with the sequence of satellite imagery (Fig. 2), shows that near surface temperatures (at 13 and 17 m depth) gradually warmed from 21 to 23°C with tidal variations of up to 1°C during spring tides. Temperature observations from deeper in the water column (44 m depth) show a similar warming trend initially, however with significant cooling relative to surface waters between September 20 and 24, and gradual overall warming again for the period up until October 12. Interrupting this is a short period during September 25 to

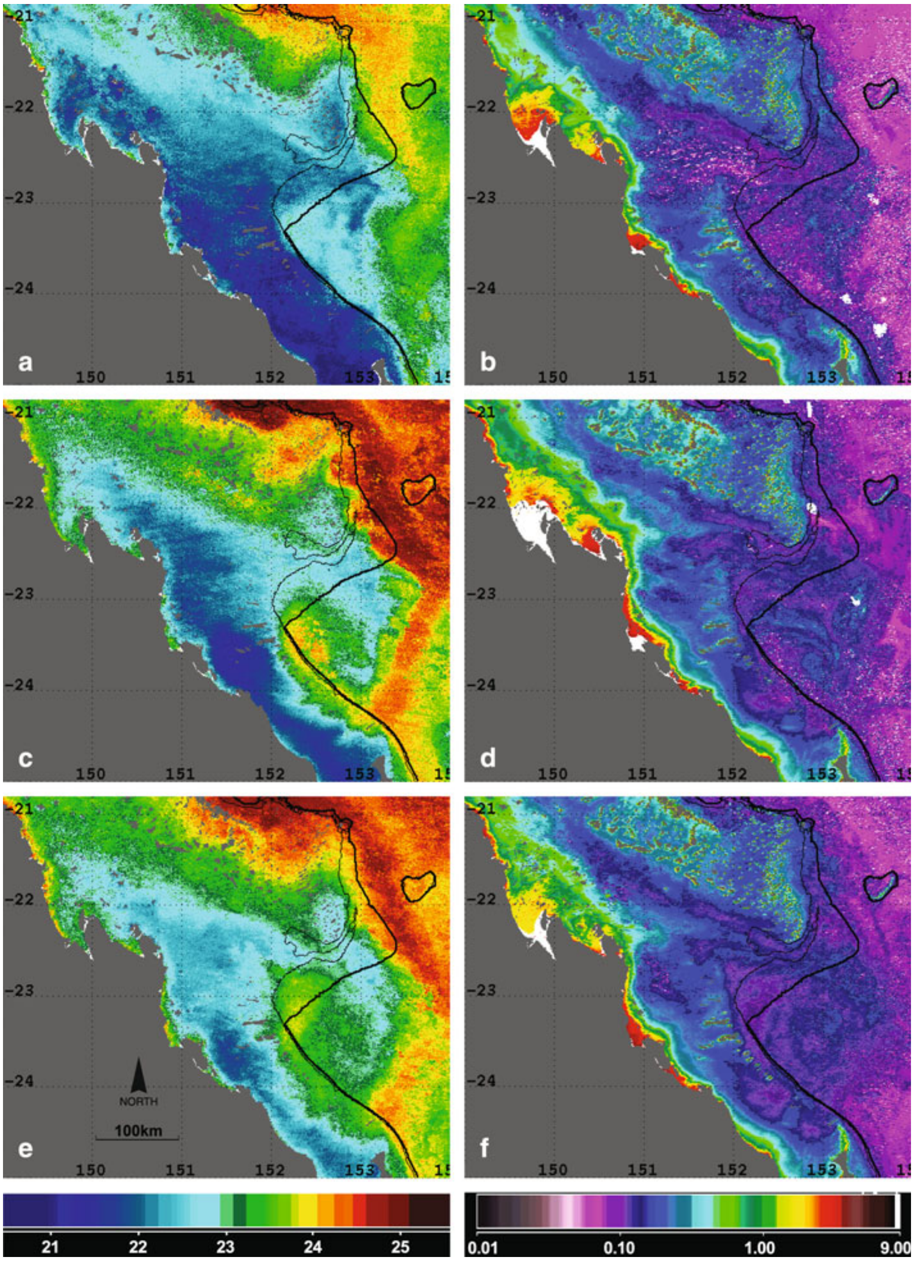

Fig. 2 Weekly mean SST (°C) and chlorophyll-a (mg/m^3) MODIS satellite images for the southern GBR region (21°S-25°S; 149°E-154°E) during the period 18 September to 6 October 2008. **a** SST for 18–21 September 2008; **b** chlorophyll for 18–21 September 2008; **c** SST for 27–30 September 2008; **d** chlorophyll for 27–30 September 2008; **e** SST for 3–6 October 2008 and **f** chlorophyll for 3–6 October 2008. The 100-m (*thin black*) and 200-m (*thick black*) isobath lines are overlain

26 where the water column is de-stratified and cooled due to mixing by strong southerly winds associated with an offshore trough (see Fig. 3). The time series shown in Fig. 3a coincides with periods of satellite imagery shown in Fig. 2 and provides insight into the subsurface processes accompanying the horizontal eddy circulation inferred from the remotely sensed data. During periods of enhanced eddy formation (Fig. 2), the water column in the GBR lagoon south of Heron Island becomes stratified as cool water intrudes onto the shelf. During the period of increased wind stress, the stratification breaks down as the entire water column becomes mixed and cools.

Long-time series of temperature data capturing 8 months of the austral spring/summer for the period September 2007 to May 2008 (Fig. 3b, d) indicate that bottom water temperature fluctuations near the shelf break (site H2) are seen as more frequent and more intense than at the relatively sheltered mooring south of Heron Island (site H3). In addition, the surface water temperature response often decouples from that of the cooler temperatures deeper in the water column, warming significantly during the periods of cold bottom intrusions, presumably due to enhanced surface warming and reduced tidal range and/or wind-driven vertical mixing. This enhanced

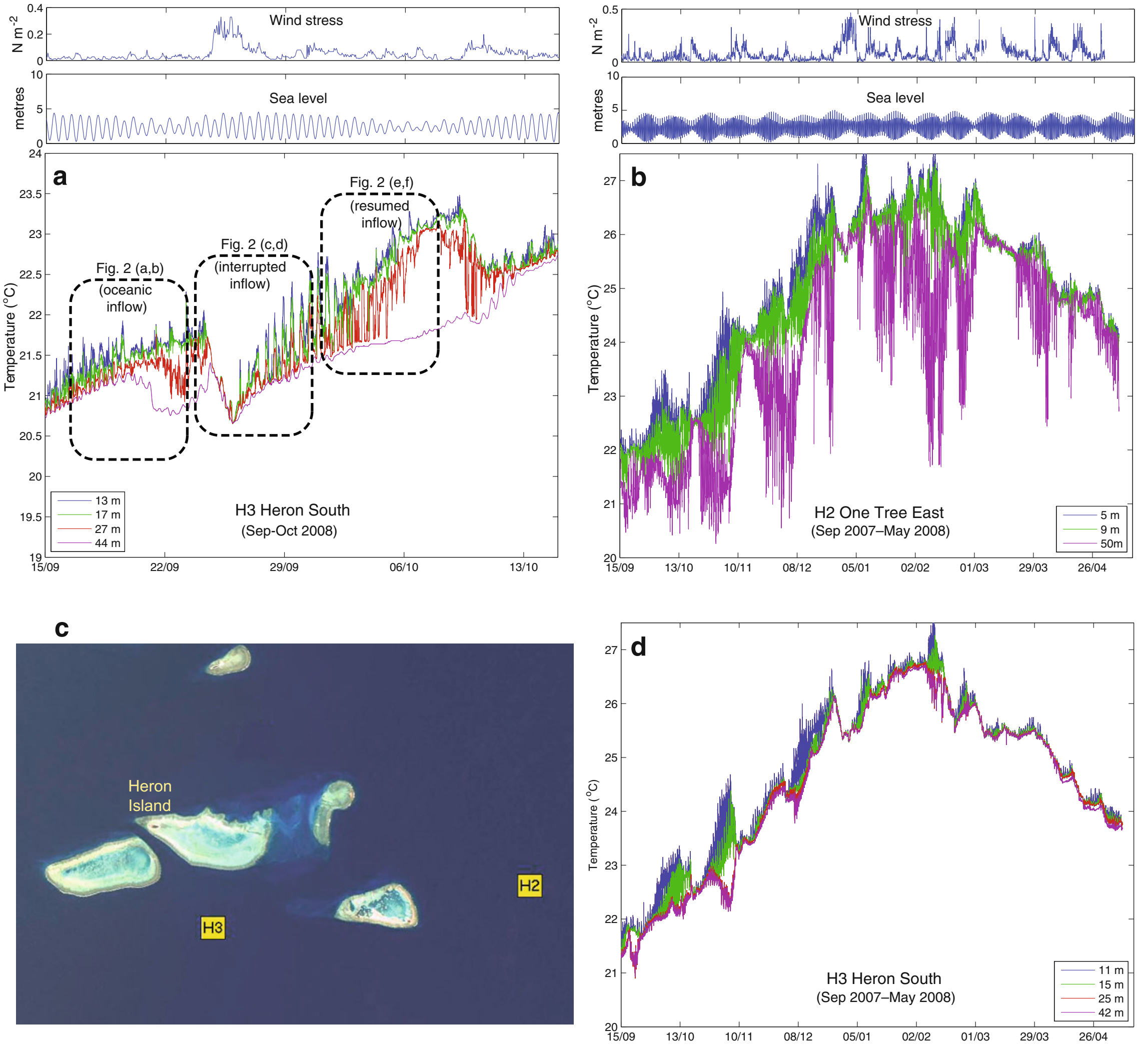

Fig. 3 Plots of temperature observed on in-line moorings located at H2 and H3 near Heron Island, wind data from the weather station at Heron Is. and sea level data from Rosslyn Bay on the coast near Keppel Is. **a** *Upper panels* show wind stress and sea level for the period 15 September to 15 October 2008. The *bottom panel* shows concurrent temperature traces from loggers located on mooring H3 at depths 13, 17, 27 and 44 m out of a total water depth of 48 m. **b** *Upper panels* show wind stress and sea level for the period 15 September 2007 to 15 May 2008. The bottom panel shows concurrent temperature traces from loggers located on mooring H2 at depths 5, 9 and 50 m out of a total water depth of 58 m. **c** The locations of moorings H3 on the shelf south of Heron Is. (23°30.79′S, 151°57.31′E) and H2 on the shelf edge east of One Tree Is. (23°28.988′S, 152°10.432′E). **d** Concurrent temperature traces from loggers located on mooring H3 at depths 11, 15, 25 and 42 m out of a total water depth of 46 m

stratification has implications for potentially more severe coral bleaching events occurring near the surface.

During summer, visible surface gradients tend to be masked by a highly stable warmed surface layer. Accordingly it is much more difficult to evaluate the eddy characteristics via satellite remote sensing, and the direct in situ measurements provide insight into the complexity of the outer shelf circulation. Time series of subsurface temperature (Fig. 3b, d) clearly portray episodes of buildup and breakdown of stratification in the spring/summer season, the onset the result of intruding waters onto the shelf and the conclusion either through withdrawal of the water body, or mixing due to spring tides and/or strong wind forcing. It is reasonable to conclude that these stratification events are related to fluctuations in Capricorn Eddy activity.

Hydrodynamic model

The Australian Ocean Model Analysis and Prediction System (OceanMAPS), an operational ocean forecast model of the BLUElink project (Brassington et al. 2007) has been employed to provide independent confirmation and further insight into the existence of the Capricorn

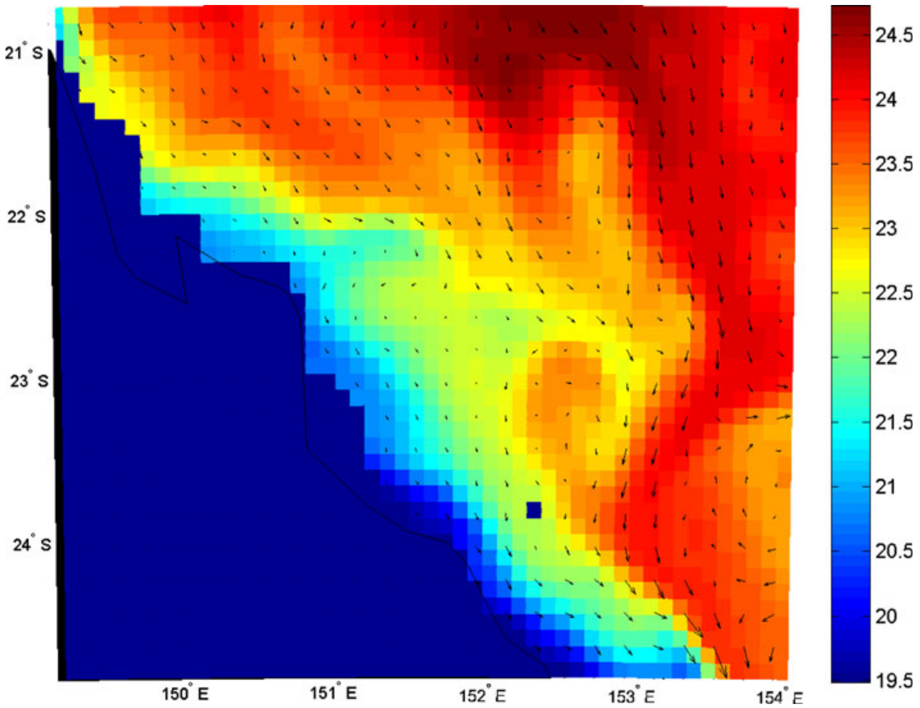

Fig. 4 A snapshot of the OceanMAPS modeled surface layer (0–10 m) temperature data with current vectors overlain for 20 September 2008

Eddy. This model has an ~10 km horizontal resolution and 10 m vertical resolution in the surface waters (Oke et al. 2008). While a limited number of higher resolution models do exist for sections of the GBR (Webster et al. 2007; Lambrechts et al. 2008), these do not provide coverage of the continental slope and Marion Plateau where the Capricorn Eddy forms.

Daily OceanMAPS results generally correlate well with the satellite imagery shown in Fig. 2, despite the relative coarseness of the model (resulting for example in EAC leakage across the Swains Reefs and Fraser Island not being resolved as an emergent island). Figure 4 shows the modeled Capricorn Eddy on 20 September 2008 developing as an entrainment of warm EAC water from the south into the Capricorn Wedge, coincident with Fig. 2a. Although the surface currents on the northern and western edges appear weak due to surface wind masking of the eddy strength, the model results at 50–60 m depth reveal a much stronger cyclonic eddy circulation unaffected by the surface circulation.

Mechanistic description

Magaldi et al. (2008) explore the various conditions that determine the nature of the turbulent flow pattern that exists in the lee of a coastal “cape” feature. Within their classification hierarchy, the Capricorn Eddy reflects an “eddy-attached regime”. But the dynamics of the eddy are inherently turbulent and exhibit a good deal of variability. Thus, the simplified heuristic diagrams that we present in this section should be viewed more as aggregate means rather than as precisely representative of any one situation at any particular time.

Frictional forcing of a cyclonic “lee eddy”

When a strong current such as the EAC flows along the edge of a continental shelf, the frictional effects exerted by the shallowing sea floor and the nearby land boundary retard the flow at the inner (coastal) edge of the current, producing a frontal zone of strong velocity shear. Where a “lee” is created by a very large cape-like coastal feature in the upper continental shelf topography, such as by the Swains Reefs, the main current flow may track the deeper continental slope and thus skirt across the shallower lee zone rather than tracking into its interior. Turbulent momentum exchanges with the swiftly flowing offshore current produces a lateral stress on the mass of water in the lee zone, effectively exerting a cyclonic torque on it. That torque drives (“spins up”) a cyclonic (clockwise) eddy circulation within the lee zone (Fig. 5a), thereby generating centrifugal and coriolis forces directed radially outward from the eddy center toward its periphery. These forces act to induce surface water flow outward from the eddy center producing upwelling within the resulting zone of surface flow divergence.

Around the periphery of the eddy, except in the sector that is directly driven by the boundary current, the eddy circulation is slowed by the increasing frictional drag

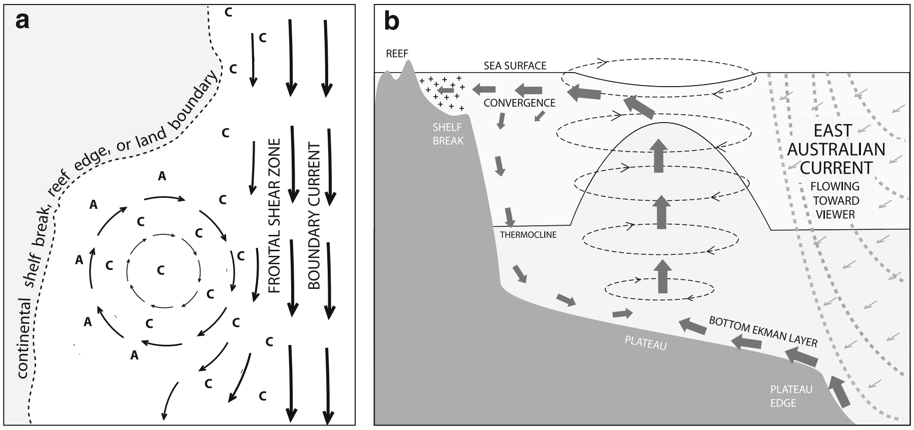

Fig. 5 **a** Schematic diagram of the gross distribution of vorticity input in a vigorously forced cyclonic lee eddy. *Arrow symbols* signify the near-surface current flow pattern. 'C' symbols identify zones of clockwise lateral turbulent frictional torque generation (i.e., via lateral diffusion of vorticity). 'A' symbols identify zones of anti-clockwise torque generation. The sizes of the 'A' and 'C' symbols are not quantitatively indicative. **b** Schematic diagram of the Capricorn Eddy configuration showing upwelling of cooler, nutrient-enriched water in the interior of the eddy, which then flows coastward in the near-surface upper layer causing surface water accumulation ('+' symbols) in the vicinity of the reefs themselves. Water from within the thermocline of the EAC is forced up the continental slope toward the vicinity of the eddy to feed the upwelling circulation in the eddy interior. (Adapted from Bakun 2006)

associated with the abruptly shallowing sea floor and nearby land mass or with momentum exchanges with the surrounding mass of water. This represents an anti-cyclonic (anti-clockwise) torque being exerted by the rotating eddy on the less rapidly rotating waters beyond the zone of maximum circumferential velocity around the eddy (Bakun 2006). In this zone, the outwardly directed centrifugal and coriolis forces are declining rapidly with increasing distance from the eddy center, producing convergence and associated downwelling in the induced water flow.

Upwelling and downwelling

With a vigorously forced cyclonic eddy such as illustrated in Fig. 5a, there will be upwelling occurring in the clockwise-torqued sectors (identified by the 'c' symbols in Fig. 5a) and downwelling in the anti-clockwise-torqued sectors (identified by the 'a' symbols in Fig. 5a). Accordingly, the frontal shear zone and the interior of eddy center will be characterized by upwelling. The eddy periphery, beyond the zone of maximum tangential velocity, will be characterized by downwelling and convergence.

Thus, in the "Capricorn Eddy" configuration, one can expect upwelling to dominate in the eddy interior as well as in the frontal shear zone that lies between the eddy and the EAC. However, beyond the band of maximum circumferential velocity of the eddy in the sectors that are not driven by direct frictional coupling to the EAC, a band of downwelling will typically exist due to flow convergence (Bakun 2006). This is in response to progressive reduction from the eddy center of the outward-directed coriolis and centrifugal forces in the coastward (outer) zone where frictional retardation is increasing.

As a result, we can expect upwelling of cooler, relatively nutrient-enriched water in the interior of such an eddy, which then flows coastward in the near-surface upper layer (Fig. 5b). In the case of the Capricorn Eddy, which is nestled in an indentation of the shallow continental slope topography, this coastward flow might be expected to extend to the vicinity of the reefs themselves. Here, the shallowing sea floor may inhibit downwelling through the bottom layer, causing surface-layer water accumulation ('+' symbols in the upper left part of Fig. 5b) and forcing water originating from the eddy toward and into the reef channels.

Supply of EAC subsurface waters to the eddy-driven system

In addition to driving the eddy circulation via turbulent momentum transfers (lateral friction), the EAC also experiences frictional drag due to contact with the shallowing continental slope. This reduces the EAC flow velocity in a thin frictional boundary layer, thus reducing the Coriolis force that opposes the coastward-directed pressure force with which the current is in geostrophic balance. This unbalanced coastward pressure force in the bottom frictional boundary layer (bottom Ekman layer) forces water originating within the thermocline of the EAC up the continental slope toward the eddy to feed the upwelling circulation in the eddy interior (Fig. 5b). Thus, in summer, the eddy system as a whole serves as a direct conduit of cooler, relatively denser, waters with enhanced nutrient content from the thermocline-nutricline zone of the EAC to the upper layer zone of water near the reefs. It is important to note that the cooler temperature character of these waters may be obscured in satellite SST images in summer due to solar heating of the surface "skin" layer. (Hence, the sequence of satellite images used to depict the eddy in Fig. 2 was selected from a late winter—early spring period even though summer is when coral reefs are at greater risk.)

Discussion

In summary, evidence of the transport of oceanic water onto the shelf and toward the reef is seen in Fig. 2b where low chlorophyll oceanic water has moved across the 100-m contour well into the Capricorn Channel. As discussed previously, the inflow into the channel is perhaps less evident 1 week later in Fig. 2d, while it increases in prominence a further week later in Fig. 2f. The low chlorophyll concentrations that are typical of oceanic waters are likewise seen as intruding onto the shelf to the south of the Capricorn Bunker group (Fig. 2b, d, f) where the absence of reef islands results in less of a barrier to intrusion of waters at depth. In the temperature panels (Fig. 2a, c, e) the eddy form is visually identifiable at differing stages of development. However, evidence of inflow into the Capricorn Channel is less apparent, likely due to the satellite thermal signature being representative of surface "skin" temperature and not of the underlying water column.

In the smaller inter-reefal channels of the Capricorn-Bunker group, the shallow bottom depths are likely to have contributed to the enhanced ocean color signal (Fig. 2b, d, f). Hence, caution must be applied in interpretation of higher chlorophyll levels here. However, it is known that the Capricorn-Bunker reefs, located on the shelf edge, are flushed by frequent intrusions of oceanic water (Steinberg 2007). The resultant mixing of relatively cooler deeper water (Skirving et al. 2006) is clearly evident even in the long-term mean temperature distribution (Fig. 6), which composites the summer months (December–February) over a number of years. The relatively cooler thermal signal along the shelf edge and immediately surrounding the Capricorn Bunker reefs themselves (Fig. 6) offers a clear indication of tidal mixing/shelf edge upwelling, evidently

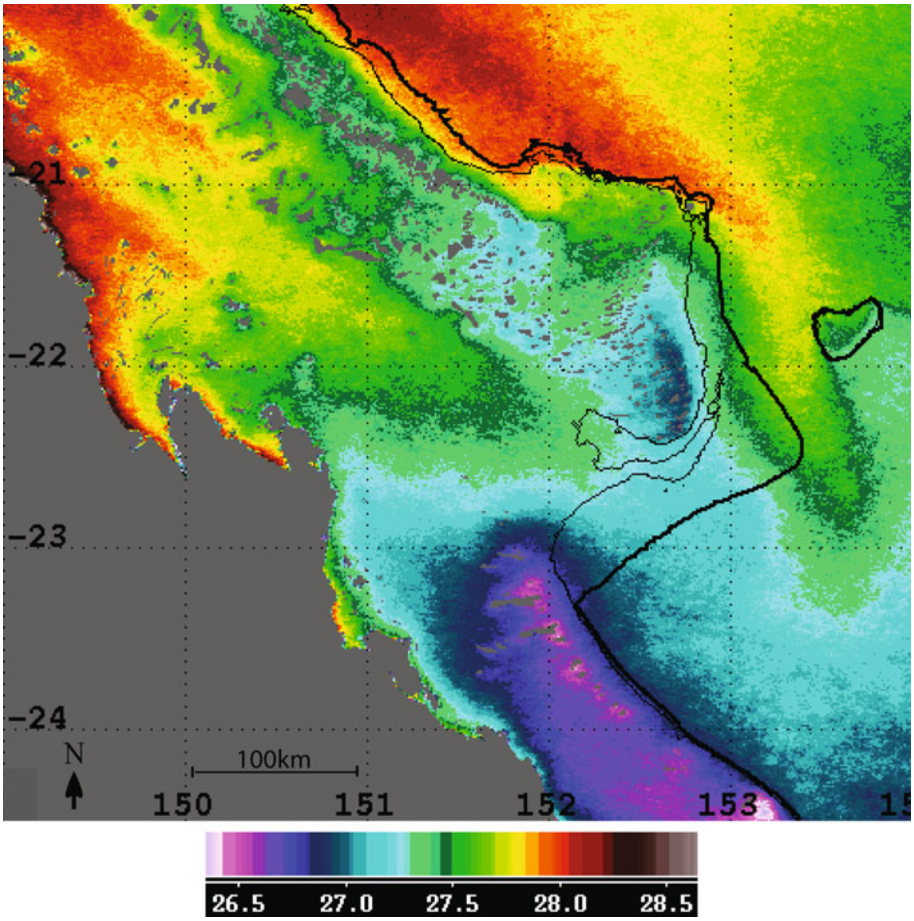

Fig. 6 Long-term summer SST (°C) mean (Dec-Feb 2000-08) for the southern GBR region (20°S-25°S; 149°E-154°E). The 100-m (*thin black*) and 200-m (*thick black*) isobath lines are overlain

leading to generally lower levels of bleaching relative to the shallow coastal Keppel Islands' location inshore. Similarly, the north-westward direction of the intrusions would impinge the north-east aspect of Heron Island to a greater degree. The resulting upwelling and mixed waters lower comparative probability of bleaching here than on the more sheltered south-west aspect of Heron Island Reef, which is consistent with observations published previously (Weeks et al. 2008).

Although we have demonstrated these features using only a small number of images (Figs. 2 and 6) and in situ data segments (Fig. 3), the indications conform to generalities apparent in the examination of a much larger time series of satellite and in situ data. Detailed visual analysis of the weekly mean SST and chlorophyll images (1-km resolution) for the last 2 years (July 2007–June 2009) show the Capricorn Eddy as most clearly defined during spring (September to November). The seasonality and prevalence of the eddy over the July 2007 to June 2009 period was also assessed using the OceanMAPS model. Over the full 2-year period, OceanMAPS confirms the Capricorn Eddy to form most strongly and regularly in the austral spring/summer when the EAC strengthens and the southeast trade winds relax. This springtime acceleration of the EAC has been previously observed in the central GBR (Burrage et al. 1994) and further to the south (Ridgway and Godfrey 1997).

Significance to reef preservation

Understanding the patterns of change that drive stress within coral reef ecosystems is critical to designing effective marine management outcomes. Locating No Take or Marine Protected Areas across areas of reef where thermal stress is likely to drive mass coral bleaching and mortality would reflect a poor choice if the objective is to sustain coral populations. As a result, efforts to locate reserves in less stressful physical environments, such as relatively cool environments that experience high levels of mixing with cooler, deeper water, are critical issues within reserve design (Mumby and Steneck 2008). Also, the associated input of key nutrients to the normally oligotrophic waters bathing coral reefs like those of the Capricorn Bunker islands drive seasonal peaks in productivity (Hatcher 1990), which in turn drive changes in organisms as diverse as macroalgae (Hatcher and Larkum 1983), seabirds (Congdon et al. 2005) and turtles (Chaloupka 2001; Chaloupka and Limpus 2001). For these reasons, a detailed understanding of the oceanography in a particular region at appropriate scales becomes crucial to effective reserve design. Our attempt here to describe mesoscale and sub-mesoscale oceanographic features such as the Capricorn Eddy is a critical step in understanding solutions to protecting coral reefs on the southern GBR. It is important that we develop greater insight into the local scale influences of global phenomena and understand how stress and resilience will vary across reef landscapes at the scale of natural ecosystem management.

The strategy to select resilience areas (e.g., an upwelling zone close to an offshore reef system) and protect them does lead to a number of conundrums, however. For example, under a more traditional conservation paradigm, one might be tempted to increase protection of more vulnerable areas; much as we do when threatened ecosystems or processes are identified today. Clearly, climate change by forcing progressive and continuous change leads to the alternative paradigm of looking for those areas that are likely to survive future change and protect them through shoring up their ecological resilience. In reality, there is probably room for both sets of logic, and most situations, including those of coral reefs, will probably benefit from a blend of the two approaches. While these debates still rage, however, it is clear that an in-depth understanding of the dynamics associated with coastal currents and oceanographic features is destined to play an important role in underpinning decisions of this sort.

The implications of climate change for eddy-related effects

There is a growing consensus among oceanographers and climate model simulators that the Walker Circulation, of which the equatorial trade winds in the Pacific are the surface manifestation, will weaken as atmospheric concentrations of CO_2 continue to increase (Vecchi et al. 2006). Accordingly, the associated trans-Pacific tilt of the near-equatorial oceanic thermocline (Bjerknes 1966) can be expected to lessen, and the coupled Pacific ocean–atmosphere system to become more chronically "El Niño"-like (Quinn 1974; Wyrtki 1975) in its underlying mean background state. Climate change is also predicted to drive a strengthening of the EAC itself and a general southward shift of the South Pacific Gyre (Cai et al. 2005, Steinberg 2007), of which the EAC represents the far western limb. Effects on local ecosystems are expected to be influenced in two potentially opposing ways by an intensification of EAC flow adjacent to the Capricorn Eddy. (1) The complex of eddy mechanisms (depicted in Fig. 5) would tend to operate even more energetically. This would result in greater cooling effects acting to locally counteract thermal stress and bleaching effects on the reefs and associated channels, as well as in lagoon zones directly influenced by associated oceanic inflows. There may also be biologic responses to the greater inputs of nutrient-rich water from below the oceanic thermocline. (2) Increased intensity of the local EAC flow might tend to increase the tendency for the Capricorn Eddy to be episodically shed (Gill and Schumann 1979; De Ruijter et al. 1999) from its quasi-stable position on the Capricorn Wedge, and perhaps to propagate southward along the Australian coast. This would serve, temporarily or chronically, to deprive the local system of the favorable eddy-related effects elaborated earlier, and likely affect those organisms that are highly dependent on the proximity of oceanic productive areas to nesting colonies or beaches (e.g., seabirds and turtles).

Concluding remarks

The EAC circulation and consequent eddy dynamics are primary forcing mechanisms in the southern GBR, with direct impact on the ecology and the future of the ecosystem. Key to understanding climate change impacts is an understanding of the patterns and processes at relevant spatial scales. This has huge importance to projections of the future and to anticipated responses from coral reef ecosystem managers. In this respect, recent mass coral bleaching events in the GBR have been distinct in their regional and local impacts, although the underlying reasons for these patterns have not been clear. This paper has explored the critical linkages between large-scale oceanography and the meso- and sub-mesoscale patterns of physical and biologic conditions that are crucial to determining biologic responses on the scale of reef communities and sections of coral reef. Incorporation of oceanographic variability will provide an understanding of which reefs are more naturally adapted, are more environmentally resilient, are more able to withstand the impacts of our warming seas, and will produce more accurate tools for predicting patterns of mass coral bleaching. Such predictability would guide the design of process-oriented investigations of key issues, as well as the projection of local effects of climate change based on climate change projections of the larger scale ocean and atmosphere dynamics, critical to any effective management response.

Acknowledgments We gratefully acknowledge the NASA Ocean Biology Processing Group for provision of Moderate Resolution Imaging Spectroradiometer satellite data, particularly G. Feldman and J. Wilding. This study was funded by the Australian Government's Marine and Tropical Sciences Research Facility. In situ moorings data was supplied by the Integrated Marine Observing System (IMOS) Great Barrier Reef Ocean Observing System moorings array, funded by the Queensland State Government and the Australian Government's National Collaborative Research Infrastructure Strategy and the Super Science Initiative. Sea level observations were sourced from the Australian National Tidal Centre, and weather and OceanMAPS model data obtained from the Australian Bureau of Meteorology.

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