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Primary production in the tropical continental shelf seas bordering northern Australia

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ABSTRACT

Pelagic primary production (^{14}C uptake) was measured 81 times between 1990 and 2013 at sites spanning the broad, shallow Northern Australian Shelf (NAS; 120–145°E) which borders the Australian continent. The mean of all areal production measurements was 1048 ± 109 mg C m^{-2} d^{-1} (mean ± 95% CI). Estimates of areal primary production were correlated with integral upper-euphotic zone chlorophyll stocks (above the 50% and 20% light penetration depths) accessible to ocean color remote sensing and total water column chlorophyll standing crop, but not surface (0–2 m) chlorophyll concentrations. While the NAS is subject to a well characterized monsoonal climate regime (austral summer-NW monsoon -wet: austral winter- SE monsoon -dry), most seasonal differences in means of regional-scale chlorophyll standing crop (11–33 mg Chl m^{-2} for 12 of 15 season-region combinations) and areal primary production (700–1850 mg C m^{-} day^{-1} for 12 of 15 season-region combinations) fell within a 3–fold range. Apart from the shallow waters of the Torres Strait and northern Great Barrier Reef, picoplankton (< 2 μm size fraction) dominated chlorophyll standing crop and primary production with regional means of picoplankton contributions ranging from 45 to > 80%. While the range of our post-1990 areal production estimates overlaps the range of production estimates made in NAS waters during 1960–62, the mean of post-1990 estimates is over 2-fold greater. We regard the difference to be due to improvements in production measurement techniques, particularly regarding the reduction of potential metal toxicity and incubations in more realistic light regimes.

1. Introduction

The northern margin of the Australian continent is bordered by a broad, shallow (< 200 m), continental shelf that connects it to the island of New Guinea and spans much of the distance between the Australian coast and the Indonesian archipelago (Fig. 1). The Northern Australian Shelf (NAS) forms part of the greater Australasian-Sunda shelf system, the largest low-latitude continental shelf system (Longhurst, 2007), with a hydrodynamically diverse and productive pelagic ecosystem. While long used by indigenous, artisanal and industrial fishers (e.g. Cane, 2013; Davis, 1989; Edwards, 1983; Fry and Milton, 2009), the underlying pelagic ecology, biogeochemistry and broad-scale primary productivity of the Northern Australian Shelf has been less studied (e.g. CSIRO, 1963a;b; CSIRO, 1964a;b; Alongi et al., 2013; McKinnon et al., 2011; Burford and Rothlisberg, 1999; Rothlisberg et al., 1994; Condie, 2011) than other large global shelf systems. General statistical characteristics of NAS water masses, including seasonally averaged nutrient levels, chlorophyll concentrations and mixed layer depths, have been summarized from archival hydrographic data by Rothlisberg et al. (2005) and Condie and Dunn (2006).

Water masses of the NAS to the west of the shallow Torres Strait (142°E) are primarily derived from the Indonesian Throughflow (ITF), while those to the east are part of the northern Coral Sea gyre. The NAS is characterized by high water temperatures (23° to 32 °C) and high levels of insolation 35–60+ mol Q m^{-2} d^{-1}; Furnas, unpublished data) throughout the year. The region has a monsoonal climate (e.g. Du et al., 2005; Kawamura et al., 2002), alternating between a generally cloudy and rainy austral 'summer' (NW monsoon; Dec-Mar) and a less-cloudy, drier austral 'winter' (SE monsoon; Jun-Aug). Episodic cyclonic disturbances can occur between December and April in all parts of the NAS save the far-northern Great Barrier Reef and the Gulf of Papua.

The islands of archipelagic Indonesia and New Guinea to the north of the NAS are characterized by steep emergent terrains and volcanic tectonics which, in combination with high rainfall and freshwater runoff, supports high levels of erosion and mineral exports into the ITF, Arafura Sea and Gulf of Papua (Milliman et al., 1999; Milliman and Farnsworth, 2011). The northern margin of the Australian con-

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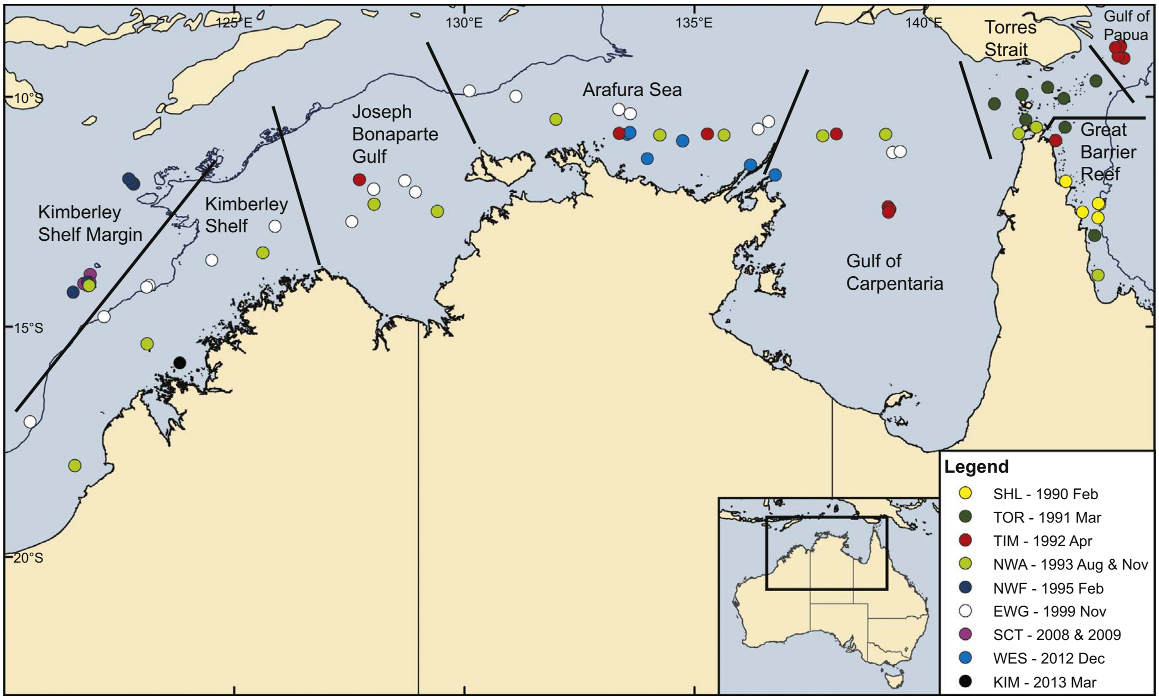

Fig. 1. Australia's northern continental shelf and locations of ^{14}C primary production stations occupied in open shelf waters between 1992 and 2013. Major regional zones are identified. The thin blue line shows the 200 m isobath in the study area. (For interpretation of the references to color in this figure legend,the reader is referred to the web version of this article.)

tinent to the south also experiences heavy summer rainfall and runoff, but is relatively low-relief and highly weathered (Wasson et al., 1996; Alongi et al., 2013). Surface waters in all parts of the NAS, and particularly those inshore, are subject to local in situ modification by high evaporation rates and direct monsoonal rainfall. The SE monsoon drives seasonal upwelling in the adjacent Banda Sea (Kinkade et al., 1997) that has a significant effect on local primary production. Dissolved nutrient concentrations and phytoplankton biomass (median surface chlorophyll =0.11 µg L^{-1}; Furnas, unpublished data) are generally very low in surface waters throughout the NAS (e.g. Condie and Dunn, 2006; McKinnon et al., 2011), but regional increases may occur during periods of strong vertical mixing or in coastal areas directly influenced by land runoff (e.g. McKinnon et al., 2007; Condie, 2011). Extensive surface and near-surface blooms of *Trichodesmium* and other N-fixing bacteria occur seasonally throughout the NAS, particularly the Arafura Sea (Montoya et al., 2004) and Gulf of Carpentaria (Burford et al., 2009).

In addition to its dynamic climate and weather forcing, the NAS is characterized by continuous high levels of tidal energy dissipation (Egbert and Ray, 2001; Condie, 2011) forced by surface and internal tides. The largest surface tides occur along the northwestern margin of the continent (e.g. > 10 m spring tides on the southern Kimberley coast, > 8 m in the southern Joseph Bonaparte Gulf). These tides generate energetic internal waves and tides on the Kimberley Shelf and shelf margin (Katsumata et al., 2010; Rayson et al., 2011). While surface tidal amplitudes in the eastern NAS are not quite as large (to ca. 4 m), tidal height differences across the shallow (35 m) Torres Strait generate strong currents through the Strait (> 1 m s^{-1} ; e.g. Wolanski et al., 1988; Harris, 1991) and in the adjoining reef matrices of the far-northern Great Barrier Reef and western Gulf of Papua (e.g. Wolanski and Thomson, 1984).

Despite the relatively small number of biological oceanographic studies of the NAS, a fairly large number of primary production measurements have been made in NAS waters since the early 1960s. Most were made by CSIRO oceanographers during 1960–62 (CSIRO, 1963a,1963b; 1964a, 1964b) as part of a wide-ranging oceanographic campaign in the eastern Indian Ocean. These early results have been broadly summarized in historical reviews of primary production in the wider Indian Ocean (e.g. Kabanova, 1967; Cushing, 1973; Krey, 1973). Motoda et al. (1978) and Rothlisberg et al. (1994) presented smaller sets of ^{14}C-based surface productivity measurements from the Gulf of Carpentaria and eastern Arafura Sea. Most recently, McKinnon et al. (2007, 2011, 2013) reported oxygen-based estimates of pelagic photosynthesis and respiration at stations in the Gulf of Papua, on the Sahul Shelf and in the northern Great Barrier Reef.

Here, we present a new regional estimate of pelagic primary production across the full extent of the NAS between the far northwestern Australian continental margin (120°E) and the Gulf of Papua (145°E) using consistent ^{14}C uptake methods. These production estimates are considered in relation to the general hydrography of NAS waters, the size structure of primary producers and phytoplankton biomass at depths accessible to current optical remote sensing technologies.

2. Methods

The primary production measurements presented herein are based on experiments carried out during thirteen (13) cruises to various parts of the NAS between 1990 and 2013 using the same or very similar experimental methods. Twelve sets of measurements were made by one group from the Australian Institute of Marine Science (AIMS: MF, AM) and one set by a group from the San Francisco State University (SFSU: EC, PH). Individual cruises lasted between 7 and 30 days and were usually within a consistent seasonal and weather setting. We have therefore combined the results from multiple cruises to build a composite picture of regional and seasonal productivity.

For convenience, we have divided the NAS into eight geographic regions (Fig. 1) with similar bathymetric, hydrographic, circulation and mixing characteristics. Hydrographic properties in all of these regions fluctuate on a seasonal basis in response to changes in insolation, monsoonal wind stress, rainfall and freshwater runoff; however, all experience very similar temperature and insolation conditions. Accordingly, measurements are seasonally assigned to one of the two dominant seasonal modes of northern Australia: the austral ‘summer’