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Characterising primary productivity measurements across a dynamic western boundary current region

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ABSTRACT

Determining the magnitude of primary production (PP) in a changing ocean is a major research challenge. Thousands of estimates of marine PP exist globally, but there remain significant gaps in data availability, particularly in the Southern Hemisphere. In situ PP estimates are generally single-point measurements and therefore we rely on satellite models of PP in order to scale up over time and space. To reduce the uncertainty around the model output, these models need to be assessed against in situ measurements before use. This study examined the vertically-integrated productivity in four water-masses associated with the East Australian Current (EAC), the major western boundary current (WBC) of the South Pacific. We calculated vertically integrated PP from shipboard ^{14}C PP estimates and then compared them to estimates from four commonly used satellite models (ESQRT, VGPM, VGPM-Eppley, VGPM-Kameda) to assess their utility for this region. Vertical profiles of the water-column show each water-mass had distinct temperature–salinity signatures. The depth of the fluorescence-maximum (f_{max}) increased from onshore (river plume) to offshore (EAC) as light penetration increased. Depth integrated PP was highest in river plumes (792 ± 181 mg C m^{-2} d^{-1}) followed by the EAC (534 ± 116 mg C m^{-2} d^{-1}), continental shelf (140 ± 47 mg C m^{-2} d^{-1}) and cyclonic eddy waters (121 ± 4 mg C m^{-2} d^{-1}). Surface carbon assimilation efficiency was greatest in the EAC (301 ± 145 mg C (mg Chl-a)$^{-1}$ d^{-1}) compared to other water masses. All satellite primary production models tested underestimated EAC PP and overestimated continental shelf PP. The ESQRT model had the highest skill and lowest bias of the tested models, providing the best first-order estimates of PP on the continental shelf, including at a coastal time-series station, Port Hacking, which showed considerable inter-annual variability (155–2957 mg C m^{-2} d^{-1}). This work provides the first estimates of depth integrated PP associated with the East Australian Current in temperate Australia. The ongoing intensification of all WBCs makes it critical to understand the variability in PP at the regional scale. More accurate predictions in the EAC region will require vertically-resolved in situ productivity and bio-optical measurements across multiple time scales to allow development of other models which simulate dynamic ocean conditions.

1. Introduction

Marine primary production (PP) is a fundamental measure of the ocean's capacity to convert carbon dioxide to particulate organic carbon at the base of the food-web and sets the upper limit for ocean productivity (Eppley and Peterson, 1979). Microscopic phytoplankton is primarily responsible for marine primary productivity, with 29% of total ocean PP estimated to occur within continental shelf seas (coastal waters), comprising only 11% of the ocean's surface area (Longhurst et al., 1995).

Direct measurements of PP are undertaken using a variety of methods including ^{14}C (Steemann-Nielsen, 1952), ^{13}C (Hama et al., 1983), chlorophyll *a* (Chl-a) fluorescence (Lawrenz et al., 2013) and oxygen isotopes (Juranek and Quay, 2010). These measurements can be time-consuming and are inherently variable over short temporal and spatial scales (Chassot et al., 2010). They are also spatially and temporally limited and require multiple depth (or integrated) sampling (Kahru et al., 2009). Scaling these relatively sparse discrete measurements to regional, let alone basin-scale or global projections, remains a significant challenge, particularly if we are to understand the consequences of projected changes in coastal and basin-scale ocean circulation (Wu et al., 2012).

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While thousands of measurements of marine primary productivity have been made throughout the world's oceans (e.g. ClimPP; see Friedrichs et al., 2009), there remain significantly under-sampled regions, including much of the temperate Southern Hemisphere. In many cases it is unreasonable to wait for large, replicated in situ datasets in order to investigate variability in regional PP. Scaling up over space and time therefore requires numerical models that quantitatively relate readily measured parameters to primary productivity. For some regions, this necessarily involves estimating primary production from satellite-derived estimates of bio-optical properties such as Chl-a (Behrenfeld and Falkowski, 1997b; Behrenfeld et al., 2005).

Coastal regions affected by western boundary currents (WBC) are of particular physical and biological significance. WBCs move oligotrophic waters poleward, displacing cooler waters, generating mesoscale eddies (Everett et al., 2012) and inducing coastal-upwelling which increases near shore nutrient stocks (Roughan and Middleton, 2002; Suthers et al., 2011). WBCs therefore set up steep cross-shelf gradients in resources for phytoplankton growth and are highly dynamic, further enhancing the need for relatively frequent, synoptic assessments of PP.

In this study, we undertake a spatial survey of PP in temperate coastal waters affected by the East Australian Current (EAC) and use a range of modelling approaches to estimate PP in different water masses. First we use shipboard ^{14}C measurements collected in spring to estimate the vertically-integrated productivity of different water masses associated with this WBC. We then scale up measurements of PP using four different satellite models. PP estimates from models such as the vertically generalised production model (VGPM) described by Behrenfeld and Falkowski (1997a) have typically been validated in the North Atlantic and North Pacific waters (Saba et al., 2010; Friedrichs et al., 2009; Carr et al., 2006). PP model assessments have not yet been undertaken in the Western Tasman Sea, a hotspot for global warming (Wu et al., 2012). In order to apply these models to a range of scientific questions including fisheries management (Chassot et al., 2011), identifying fisheries hotspots (Zainuddin et al., 2006) and characterising ocean ecosystems (Chassot et al., 2010), we need to understand their limitations as a first step to their application in Southern Hemisphere waters.

The aims of this study are to: (1) examine how ^{14}C estimates of PP change with depth and water-mass in the western Tasman Sea; (2) compare vertically-integrated shipboard ^{14}C PP estimates with modelled estimates derived from satellite-based measures and (3) use the satellite model with the highest skill to examine the temporal patterns of PP at PH100, a long-term coastal time-series station established south of Sydney in the 1940s. Despite the limited spatial and temporal coverage, this work represents the first assessment of PP model efficiency in these waters and provides critically important PP data from water masses associated with this dynamic WBC.

2. Methods

2.1. In situ measurements and water sampling

The study domain was in the western Tasman Sea (Fig. 1) and extended from 29°S to 36°S and eastward to 155°E, spanning subtropical and temperate latitudes. Sampling was timed to coincide with the spring bloom, when Chl-a biomass is at its highest (Everett et al., 2014). Hydrographic, optical and biogeochemical properties were sampled from 15 to 31 October 2010 on board the *R/V Southern Surveyor*.

Vertical profiles were completed (measuring depth, temperature, salinity (PSS-78) and fluorescence) using a Seabird SBE911 and Chelsea AquaTracker fluorometer mounted on a CTD rosette. Water samples were collected for Chl-a analysis using 10 L Niskin bottles. These samples were taken at the surface, and nominal depths of 10, 25, 50, 75 and 100 m. The closest bottle-depth was adjusted to sample the fluorescence-maximum (f_{max}) based upon the fluorescence profile on the downcast. Water samples were also taken for ^{14}C uptake analysis at the surface and fluorescence-maximum (see details below).

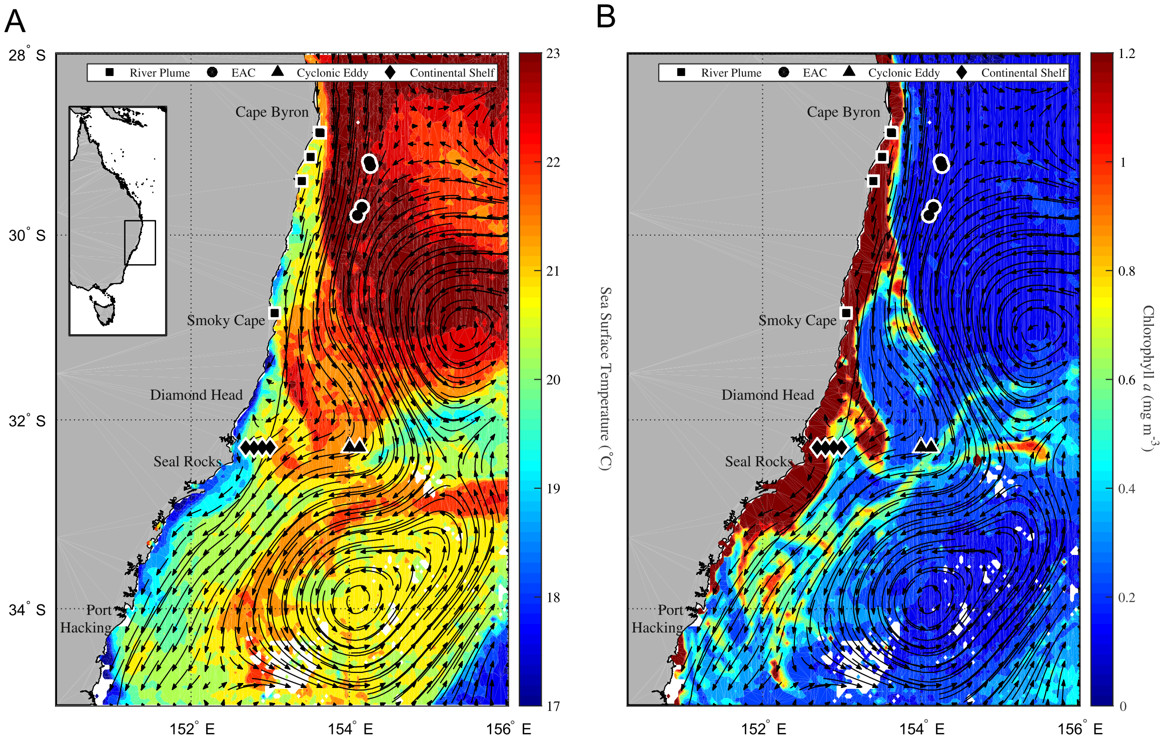

Fig. 1. Location map of southeast Australia showing (A) Sea Surface Temperature and (B) Chl-a biomass from MODIS-Aqua Ocean Colour (L3 OC3). Arrows represent Lagrangian paths for the 24 h leading up to the midday satellite pass. The 200 m isobath is shown as a black line. The black markers denote the sampling locations. See Table 1 for a complete description of station locations and properties.