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Climate change projection for the western tropical Pacific Ocean using a high-resolution ocean model: Implications for tuna fisheries

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ABSTRACT

The Western Pacific Warm Pool is a region of high tuna catch, and how future climate change might impact the tuna fisheries is an important regional issue. By using a high-resolution ocean model forced by the simulated climate of the 2060s, we investigate whether enhanced spatial resolution and bias correction of the mean state could alter the climate change projection for the western tropical Pacific and examine the consequences this might have for tropical tuna distributions. For most of the physical environmental variables, enhanced resolution and bias correction had only a minor impact on the projected changes. The climate projections showed a maximum surface warming east of the Warm Pool, a shoaling of the thermocline in the Warm Pool, and an eastward expansion of the Warm Pool. In the Warm Pool, the shoaling of the thermocline raises the nutricline into the photic zone and increases phytoplankton and primary productivity, a feature that is most evident in the high-resolution model projection but also weakly present in the coarse-resolution projection. The phytoplankton and primary productivity response to climate change was where ocean model resolution produced a clear difference. With enhanced resolution, the simulation had stronger and better-defined zonal currents, which were more consistent with observations. Along the equator, the high-resolution model enabled vertical current shear mixing to generate a sub-surface phytoplankton maximum both inside and outside the Warm Pool, which is an observed phenomenon. With climate change, the enhanced-resolution model projected enhanced vertical shear mixing, increased vertical supply of nutrients to the photic zone, and increased sub-surface phytoplankton concentrations. The increase in sub-surface phytoplankton concentrations helps to offset the decline in surface phytoplankton concentrations and results in a projection of almost no change in the western tropical Pacific primary productivity. In contrast, the low-resolution model projected a substantial reduction in phytoplankton concentrations and primary productivity; such a response is typical of climate change projections for the region. Importantly, enhanced resolution dramatically altered the projected response of phytoplankton and primary productivity to climate change. Using the enhanced-resolution model, the projected increase in the size of the Warm Pool with little change in primary productivity and in suitable habitat for skipjack tuna suggest that by the 2060s climate change will not have a large impact on skipjack tuna fisheries.

1. Introduction

The upper waters of the equatorial Pacific Ocean are divided into two regions, which have distinct physical, biogeochemical and ecosystem characteristics. In the central and eastern Pacific, there is an equatorial upwelling system with relatively cold, salty, macronutrient-rich water, where primary production is iron-limited (Christian et al., 2002). In the western tropical Pacific, the water is warm, fresh and oligotrophic, and encompasses a prominent oceanographic region called the Western Pacific Warm Pool (Le Borgne et al., 2002). The Warm Pool has some of the warmest surface water in the ocean (McClain et al., 1999), and this warm water is fundamental to the large-scale deep atmospheric convection in the western Pacific region, the circulation and stratification of the upper ocean, and El Niño Southern Oscillation (ENSO) variability (Maes et al., 2010).

The zonal movement of the eastern edge of the Warm Pool appears to be important for the onset of the ENSO phases (Picaut et al., 1996), with the eastern edge moving westward during La Niñas and eastward during El Niños (Maes, 2008; Bosc et al., 2009; Maes et al., 2010). The location of the Warm Pool's eastern edge

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also seems to modulate the distribution of tuna in the equatorial Pacific (Lehodey et al., 2011). For example, the skipjack tuna catch appears to move with the large zonal displacement in the Warm Pool that occurs during ENSO events (Lehodey et al., 2011). Tuna fisheries contribute significantly to the livelihoods and economies of many Pacific Island Countries and Territories (Bell et al., 2013), so the way in which future climate change might impact tuna populations is a critical issue for this region.

Under the influence of climate change, the mean climate of the western tropical Pacific will probably undergo significant changes, with potentially important consequences for ENSO variability (Collins et al., 2010) and for tuna distributions (Lehodey et al., 2011). Coupled global circulation models (CGCMs) have common spatial biases in the western tropical Pacific, such as a Warm Pool eastern edge that is too far west (Brown et al., 2013a), which can potentially affect their future climate projections for the tropical Pacific (Brown et al., 2013b). To investigate the impact of climate change on the western tropical Pacific, we use simulations from a high-resolution ocean model (HOM) that gives a good representation of the present-day western tropical Pacific ocean state to make a climate projection for the 2060s (Chamberlain et al., 2012). The simulations are configured to determine the change in the mean ocean state. They also include the lower levels of the food web (i.e. phytoplankton and zooplankton). A previous study used the same simulations to predict future climate change in the Western Boundary Current region of the Southwest Pacific (Matear et al., 2013); the study showed that by resolving mesoscale features (e.g. the East Australian Current and its eddies), the oligotrophic water of the Tasman Sea is projected to have increased primary productivity, because of increased eddy activity. By comparing our climate projections with previously generated CGCM projections (e.g. Ganachaud et al., 2013), we investigate whether climate projections of the ocean state will be modified by a less-biased ocean state with enhanced model resolution. For this study, we focus on the western tropical Pacific because of its importance for tuna. In particular, we are interested in whether enhanced resolution can significantly alter the projection of primary productivity and suitable thermal habitat for skipjack tuna.

The paper is structured as follows. First, we briefly discuss the key oceanic features of the western tropical Pacific in Section 2. Then, in Section 3 we summarize how the future climate change projections are performed with our HOM. In Section 4 we present results of the HOM simulation of the present-day ocean state and compare them with observational data and with the low-resolution model that we used to produce the climate change projection. Next, we describe in Section 5 the climate change projection for the 2060s and compare our simulated projections from the high- and low-resolution models. This section also includes a comparison of the projected changes with previous results, discussion of the implications of our projected changes for tuna distributions in the western tropical Pacific, and remarks on the robustness of the projections. Finally, in Section 6, we present a short summary of the limitations of our modelling approach and discuss the direction of our future work.

2. Oceanography of the Western Pacific Warm Pool

The Western Pacific Warm Pool has warm surface water, with a shallow mixed layer (at 30–40 m depth) separated from the thermocline (deeper than 65 m) by a high-salinity-gradient barrier layer (Lukas and Lindstrom, 1991). In the Warm Pool, the phytoplankton are macronutrient-limited, and a deep chlorophyll maximum occurs below the mixed layer (Barber and Chavez, 1991), where most of the primary productivity occurs (Le Borgne et al., 2011). Surface-nutrient depletion in the Warm Pool reflects the lack of upwelling and a deep thermocline, which under average climatic conditions is located near the lower limit (approximately 80 m) at which there is sufficient light for phytoplankton growth (Le Borgne et al., 2011). In addition to the large horizontal movement of the eastern edge of the Warm Pool with ENSO, the vertical structure within the Warm Pool also changes with ENSO phases. During an El Niño, the thermocline can shoal to 40 m, which raises macronutrients into the photic zone and increases primary productivity (Le Borgne et al., 2011).

The tuna fisheries of the tropical Pacific Ocean mostly consist of skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), bigeye (*T. obesus*) and albacore (*T. alalunga*) (Lehodey et al., 2011). In 2009, catches from the western Pacific represented around 60% of the global tuna catch, of which about 70% comprises skipjack (Lehodey et al., 2013). Skipjack are found throughout the equatorial and subtropical Pacific, but catches are highest in the Warm Pool (Lehodey et al., 1997). Sustaining benefits from the tuna resources is a challenge for the Pacific Island Countries and Territories, as the quantity and distribution of the fish catch display large variability from year to year (Lehodey et al., 1997), and a changing ocean (e.g. Durack et al., 2012) will make it even more difficult to maintain catch levels (Bell et al., 2013).

3. Methods

The climate model used in this study is the CSIRO Mk3.5 model of Rotstayn et al. (2010), hereafter referred to as CSIRO35. The CSIRO35 projection of the SRES (Special Report on Emissions Scenarios) A1B scenario (Nakicenovic et al., 2000) for the decade of the 2060s is used to force an HOM (Chamberlain et al., 2012). The selected SRES scenario describes a future world of very rapid economic growth, with a global population peaking in the middle of the century and declining thereafter, and where from mid-century there is also rapid introduction of new and more efficient technologies balanced across fossil and non-fossil energy sources (Nakicenovic et al., 2000). The HOM used in this study is the Ocean Forecasting Australia Model (Brassington et al., 2007; Oke et al., 2008), which is a near-global model (covering latitudes of 70°S–70°N). The HOM has 47 vertical levels, with 10 m resolution in the upper 200 m, while the horizontal grid is variable: eddy-resolving around Australia (with 0.1° resolution between 90°E and 180°E and between 20°N and 70°S) and increasing to a maximum of 2° in the north Atlantic. The HOM also has a simple ocean biogeochemical formulation, namely the Whole Ocean Model with Biogeochemistry And Trophic-dynamics (WOMBAT). WOMBAT is based on Kidston et al. (2011) and has been implemented in the 3D ocean model 'Modular Ocean Model version 4' (Dietze et al., 2009); details of WOMBAT are given in Matear et al. (2013).

The HOM simulations used in this study are briefly summarised below, and Chamberlain et al. (2012) provide a detailed explanation of how the CSIRO35 climate change projection was used to simulate future climate change in the HOM.

To prepare the HOM, an initial spin-up of the ocean physics was performed, where the model was initialised with observed climatological fields (Chamberlain et al., 2012) and forced by atmospheric reanalysis products (i.e. windstresses, heat and freshwater fluxes) from 1991 to 2004 (ERA-40, Uppala et al., 2005), while the surface layer was relaxed to the observed surface temperatures (Reynolds and Smith, 1994) and salinities (Levitus, 2001) on a 30-day time-scale. HOM was then run for a second loop of atmospheric forcings in the same manner as the original spin-up for the period 1991–1994 but with WOMBAT activated. The ocean state at the end of this spin-up period was used as the initial state for the HOM present-day simulation. From the HOM spin-up, the windstresses and the heat and freshwater fluxes from the years 1993–2001 were averaged to produce a monthly