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Climatic trends of the equatorial undercurrent: A backup mechanism for sustaining the equatorial Pacific production

Raffaele Ruggio [a,b,*], Marcello Vichi [b,c], Francesco Paparella [d], Simona Masina [b,c]

[a] Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, Università del Salento, via Arnesano km. 1.2, 73100 Lecce, Italy
[b] Centro Euro-Mediterraneo sui Cambiamenti Climatici, Viale Aldo Moro 44, 40127 Bologna, Italy
[c] Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy
[d] Dipartimento di Matematica e Fisica E. De Giorgi, Universitá del Salento, via Arnesano km. 1.2, 73100 Lecce, Italy

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ABSTRACT

The Equatorial Undercurrent (EUC) is the major source of iron to the equatorial Pacific and it is sensitive to climatic changes as other components of the tropical Pacific. This work proposes a methodology based on a Lagrangian approach aimed at understanding the changes in the transport of iron rich waters to the EUC in a future climate change scenario, using climate model data from an Earth system model. A selected set of regions from the northern and southern extra-equatorial Pacific has been chosen. These regions are characterized by the presence of iron sources from continental shelf processes like the Papua New Guinea region and atmospheric deposition like the northern subtropical gyre. The trajectories that reach the EUC during the 20th and the 21st century departing from these areas have been analyzed using a set of statistics designed to determine variations in the amount of transport and in the travel times of the water masses. The transport of waters to the EUC from the north Pacific subtropical gyre and from the Bismarck Sea is projected to increase during the 21st century. The increase is particularly significant for water masses from the northern subtropical gyre, with travel times lower than 10 years in the second half of the 21st century. This increased interaction between the extra-tropics and the EUC may bring additional iron-rich waters in the high-nutrient low-chlorophyll region of the equatorial Pacific compatibly with the significant increase of the simulated net primary production found in the biogeochemical model, thus partly offsetting the anticipated decrease of production implied by the surface warming.

1. Introduction

The Equatorial Undercurrent (EUC) is one of the major circulation patterns in the equatorial Pacific, flowing within the thermocline at around a 180 m depth and outcropping in proximity of the Galapagos Islands (Kessler, 2006). Maintained by intense zonal pressure gradients, it originates in the western equatorial Pacific between 120 and 320 m of depth (Fine et al., 1994). The origin of the EUC waters has been identified by means of modeling studies (Goodman et al., 2005; Grenier et al., 2011; Gu and Philander, 1997; Rodgers et al., 2003), which have revealed the contributions both from northern and southern sources off the equator (Goodman et al., 2005) with a little role played by recirculation in the sub-surface equator (Rodgers et al., 2003).

The EUC plays a major role in controlling the biogeochemistry of the equatorial Pacific (Pennington et al., 2006), via changes in the supply of dissolved iron (e.g. Christian et al., 2002; Coale et al., 1996; Mackey et al., 2002; Slemons et al., 2010). The area of upwelling in the eastern equatorial Pacific is a high nutrient low chlorophyll region where productivity is limited by iron. The iron found in the current has been shown to mostly originate in the western basin and its lithological characteristics have suggested its association with sedimentary sources from the Papua New Guinea shelves (Mackey et al., 2002). Coupled physical and biogeochemical model studies (see for instance Vichi et al., 2008) have confirmed that by inserting a source of iron derived from shelf data profiles by Mackey et al. (2002) in this area there is a drastic increase of the iron concentration in the center of the equatorial Pacific and a corresponding increase in the net primary production in the eastern equator. Slemons et al. (2010) recently presented further data supporting the continental origin of the EUC iron as the result of enrichment processes along the New Guinea Coastal Undercurrent (NGCU) and the New Ireland Coastal Undercurrent (NICU), where the former provides roughly three times the water volume of the latter to the EUC (Butt and

* Corresponding author at: Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, Università del Salento, via Arnesano km. 1.2, 73100 Lecce, Italy. Tel.: +39 01 4043881110.
E-mail addresses: raffaele.ruggio@unisalento.it (R. Ruggio), marcello.vichi@bo.ingv.it (M. Vichi), francesco.paparella@unisalento.it (F. Paparella), simona.masina@bo.ingv.it (S. Masina).

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Lindstrom, 1994). Their data support the hypothesis that direct river input or sediment resuspension shelf processes are necessary sources to attain the concentration observed in the core of the EUC beyond the date line, because the contribution from local atmospheric deposition could provide less than half of the observed concentration (Slemons et al., 2010).

Notwithstanding the increasingly recognized role of continental sources to the ocean iron budget (Moore and Braucher, 2008), atmospheric deposition is also an important iron input to the surface ocean, especially because it involves large areas of the ocean. Given the fact that the water mass transport to the EUC is about two thirds from the south and one third from the northern subtropical gyre (Goodman et al., 2005) it is likely that a non-negligible fraction of the iron may also be provided by northern sources. In the northern subtropical Pacific the wind-driven meridional circulation maintained by the easterly winds allows for a link of the surface waters of almost the whole area between 20°N and 40°N to the EUC (Gu and Philander, 1997), and this zone is characterized by a large soil dust deposition from both the Californian desert in the east and the Gobi desert in the west (Jickells et al., 2005) that enriches the surface waters of the northern gyre. The subduction of iron-replete waters, that are unlikely to be affected by biological consumption processes along their pathways to the equator, may thus add to the iron flux entering the EUC.

The equatorial Pacific is an important region to be considered for climate change studies, as it is expected to be quite sensitive to future climate change (Vecchi et al., 2006). Multi-model analysis reports an abrupt warming in the eastern Pacific and a reduced east–west sea surface temperature gradient (Vecchi and Soden, 2007) although the response of the vertical structure at the equator is more complex. Most coupled climate models give a robust increase in near-surface stratification associated with a shoaling of the EUC (DiNezio et al., 2009). The maximum projected EUC shoaling and transport increase occur in the west where the increased stratification is primarily due to surface warming and freshening (Ganachaud et al., in press). The intensification of the EUC velocity under a global warming scenario has been studied in the CMIP3 multi-model dataset (Meehl et al., 2007), and more recently also using results from preliminary analysis of CMIP5 climate models (Ganachaud et al., in press) and combination of satellite observations and models (Karnauskas and Cohen, 2012). According to Sen Gupta et al. (2012) the main driver of the projected EUC increase is an intensification of the NGCU due to a strengthening of the south-easterly trade winds south of the equator.

These changes in the oceanic physical features are anticipated to impact the biological production of the equatorial ecosystem, although current model-based studies only partly agree on the changes to be expected in the eastern tropical Pacific, with some models showing a decrease of production and others an increase (Steinacher et al., 2010; Vichi et al., 2011). Earlier model-based studies (e.g. Sarmiento et al., 2004) reported a generalized decrease of primary production due to the reduced upwelling of nutrient-rich waters. The declining production is an overall response of global ocean biogeochemical models to warmed surface ocean conditions. In the equatorial Pacific this is linked to the dominant warming of the area simulated by the first generation of coupled climate models. However, as briefly introduced above, the response of more recent simulations of the physical system does not simply show a generalized warming of the eastern equatorial Pacific, so that unexpected changes in the dynamical features may develop (DiNezio et al., 2010, e.g.). It is thus likely that contrasting biological patterns may occur as well: for instance, Vichi et al. (2011) found a particularly evident increase in the simulated equatorial net primary production at the end of the 21st century using two different emission scenarios, the A1B (Nakicenovic and Swart, 2000) and a 450 ppm stabilization scenario (Lowe et al., 2009) and they suggested a link with changes in the iron transport through the EUC.

It is therefore of interest to investigate whether the intensity of the EUC water mass transport is affected by climate change and how this may impact the supply of iron from the known extra-equatorial sources. This work aims to construct a diagnostic analysis based on a combination of Lagrangian particle tracking and statistical tools that have been applied to the results of an Earth system model (ESM) forced with a climate change scenario. Of all the regions of the Pacific Ocean that have been identified as sources or important pathways of the EUC waters (Goodman et al., 2005), we have considered a subset of those that may also provide a sustained iron input to the ocean, classifying them into regions of shelf (riverine or sedimentary) and atmospheric sources. The diagnostic tool is composed of a two-stage process. Initially, from the selected Pacific regions, a set of water mass trajectories have been evolved over the simulation period using a Lagrangian algorithm, which allows to compare their pathways to previous works on the sources of the EUC. Subsequently, a set of statistics has been designed and applied to the trajectory data to quantify the changes in the mass transport over the 20th and 21st centuries and in other characteristics such as travel times of the water masses. The implications associated to the iron transport are then discussed in light of the simulated impacts on equatorial primary production under a future climate scenario.

2. Methods

2.1. Model description and model data

The model used in this work is the INGV–CMCC carbon cycle Earth system model (Fogli et al., 2009; Vichi et al., 2011), a coupled climate model which represents explicitly the carbon cycle on land and in the ocean with detailed marine biogeochemical processes. The oceanic component of the model is PELAGOS (Vichi and Masina, 2009; Vichi et al., 2007a,b), a coupling between the ocean general circulation model OPA8.2 (Madec et al., 1999) and the biogeochemical flux model (Vichi et al., 2007b). It is solved on the curvilinear grid ORCA2 (Madec and Imbard, 1996), with a resolution of 2° of longitude and a variable mesh of 0.5–2° of latitudes. The vertical grid has 31 levels with variable depth and a constant 10 m step in the top 100 m. The grid is fine enough to resolve the EUC and to track Lagrangian particles flowing into and along this current.

In this study we have used model outputs consisting of monthly averages of the zonal, meridional and vertical velocities as well as temperature and salinity fields for the period from January 1900 to December 2099. The simulation has been spun up for 300 years using only the physical components of the climate model. Ocean biogeochemistry started in year 1765 and continued under pre-industrial CO_2 concentrations until year 1860 when the historical observed CO_2 time series has been applied. The future scenario simulation (2000–2099) has been forced by the SRES A1B emission scenario (Nakicenovic and Swart, 2000) for greenhouse gasses and sulfate aerosols (see also Vichi et al. (2011) for additional details on the spin-up phase and carbon cycle adjustment). Biogeochemical model data at monthly resolution have been used to analyze the iron distribution and the response of phytoplankton production to climate change.

The physical model reproduces the circulation patterns of the Pacific as presented in Fig. 1, averaged over the simulation period 1970–1999. The major pathways to the EUC at a depth of 180 m are all clearly recognizable in Fig. 1, particularly the Northern Equatorial Current (NEC), the Mindanao Current (MC), the New Guinea Coastal Undercurrent (NGCU), the New Ireland Coastal Undercurrent (NICU), the Southern Equatorial Current (SEC) and the Southern Equatorial Counter Current (SECC).

Lagrangian trajectories of water masses have been computed from these physical ocean model data using the ARIANE Lagrangian integrator (Blanke and Raynaud, 1997, http://stockage.univ-brest.fr/grima/Ariane/). ARIANE is based on an efficient mass-conserving integration