An Equatorial Ocean Bottleneck in Global Climate Models

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ABSTRACT

The Equatorial Undercurrent (EUC) is a major component of the tropical Pacific Ocean circulation. EUC velocity in most global climate models is sluggish relative to observations. Insufficient ocean resolution slows the EUC in the eastern Pacific where nonlinear terms should dominate the zonal momentum balance. A slow EUC in the east creates a bottleneck for the EUC to the west. However, this bottleneck does not impair other major components of the tropical circulation, including upwelling and poleward transport. In most models, upwelling velocity and poleward transport divergence fall within directly estimated uncertainties. Both of these transports play a critical role in a theory for how the tropical Pacific may change under increased radiative forcing, that is, the ocean dynamical thermostat mechanism. These findings suggest that, in the mean, global climate models may not underrepresent the role of equatorial ocean circulation, nor perhaps bias the balance between competing mechanisms for how the tropical Pacific might change in the future. Implications for model improvement under higher resolution are also discussed.

1. Introduction

A suite of 23 global coupled general circulation models associated with the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) was used to project the future state of Earth's climate system, detailed in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4). Realism of their mean and time-varying climate simulations varies. To minimize individual model errors in mean climate, multimodel ensemble means are often used (e.g., Solomon et al. 2007; Clement et al. 2010). Multimodel ensemble means often yield a more realistic solution than any single model (Reichler and Kim 2008). However, assessments often do not consider subsurface ocean characteristics of relevance to climate change.

Strong regional coupling between the ocean and atmosphere implies that climate change over the coming decades and centuries will depend on spatial variations in sea surface warming (Saravanan 1998; Hurrell et al. 2005), particularly in the tropics (Alexander et al. 2002; Barsugli et al. 2006). The eastern equatorial Pacific is a key region where sea surface temperature (SST) variations have a particularly strong relationship with ocean dynamics and are known to exert a powerful influence on global atmospheric circulation and climate (Bjerknes 1969). The Equatorial Undercurrent (EUC) is a vital component of the tropical Pacific circulation as it transports massive amounts of cold, nutrient- and carbon-rich water to the surface there, where their upwelling feeds the cold tongue (e.g., Bryden and Brady 1985), reinforces the zonal SST gradient, and plays an important role in global biogeochemical cycling (e.g., Feely et al. 2002) at seasonal and longer time scales.

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More than a decade of in situ oceanographic observations has allowed detailed description and analysis of the EUC and other aspects of the tropical Pacific circulation (e.g., Johnson et al. 2001, 2002; Karnauskas et al. 2010), providing observational benchmarks for models. Here we present a model-data intercomparison, focusing on the EUC—a key component of the tropical ocean circulation with a relatively high observational signal-to-noise ratio. We assess the realism of the EUC in 23 CMIP3/AR4 models, diagnose a systematic bias, and investigate the implications for model projections of future climate changes in the tropical Pacific. We also discuss avoiding future biases in mean state with higher model resolution.

2. Model EUC assessment

Longitudinal profiles of peak EUC velocity from direct measurements (Johnson et al. 2002), an ocean reanalysis that does not assimilate any velocity data [Carton and Giese 2008; Simple Ocean Data Assimilation (SODA)], and two forced ocean general circulation model (OGCM) experiments (Karnauskas et al. 2007) are in remarkable agreement except for the coarser-resolution OGCM experiment (Fig. 1a) (the contrasting OGCM experiments are discussed in the following section). However, the EUC in 22 out of 23 CMIP3/AR4 models is notably slower than observed (Fig. 1b).[1] This slow bias increases toward the east; the multimodel median EUC is 47% as fast as the observed EUC at 125°W and only 33% as fast by 95°W.

While the velocity of the EUC is important for dynamics (e.g., advection of temperature and vorticity, shear and mixing, and ENSO via thermocline depth and strength, and the Bjerknes feedback; Karnauskas et al. 2007, 2008) as well as upwelling, it alone does not gauge whether a model's total EUC volume transport is realistic; a coarse-resolution, high-diffusivity model EUC may be expected to be slower but also perhaps wider than the observed EUC, hence maintaining a more realistic volume transport than peak velocity. EUC transports in CMIP3/AR4 models are also systematically weak but generally closer to observations than peak velocities; the multimodel median EUC transport is 84% as large as the observed EUC at 125°W and 66% as large at 95°W [not shown; for reference, the observed EUC transport at 95°W is 21 Sv (1 Sv ≡ 10^6 m^3 s^{-1})].

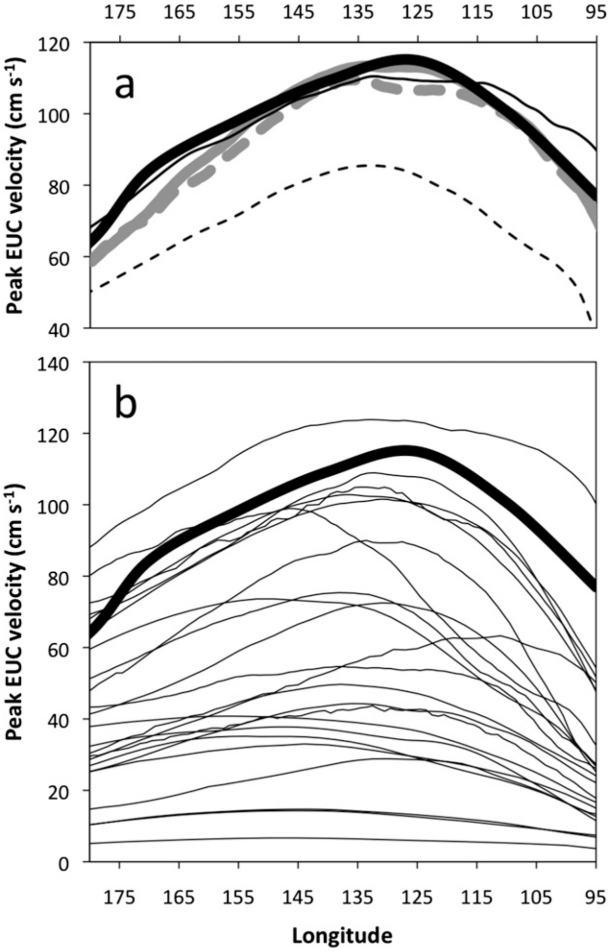

FIG. 1. (a) Longitudinal profiles of peak EUC velocity (cm s^{-1}; defined as the annual mean of maximum monthly climatological zonal velocity between 2°S and 2°N, 0–400 m) from direct observations (Johnson et al. 2002; thick solid black), SODA 1958–2006 (thick solid gray), SODA 1990–99 (thick dashed gray), OGCM-fine (thin solid black), and OGCM-coarse (thin dashed black). (b) Thick black line as in (a), but thin lines represent CMIP3/AR4 models.

3. Diagnosing the model EUC bias

The sole difference between the two OGCM experiments mentioned above (Fig. 1a) is horizontal resolution; the "coarse" experiment was run at ⅓° meridional resolution near the equator and the "fine" at ¼°. Increased model resolution increases peak EUC velocity from 83 to 109 cm s^{-1} at 125°W and from 40 to 90 cm s^{-1} at 95°W. The generally weak and widely varying EUC among CMIP3/AR4 models may therefore be at least partially explained by their generally coarse and widely varying meridional resolution. Comparing peak EUC velocity at any longitude with meridional resolution near the equator yields a positive and significant linear correlation (e.g., $r^2 =$ 0.66 at 125°W) that improves toward the east and is even

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[1] The model means are taken from the 1990s "Climate of the Twentieth Century" simulations.

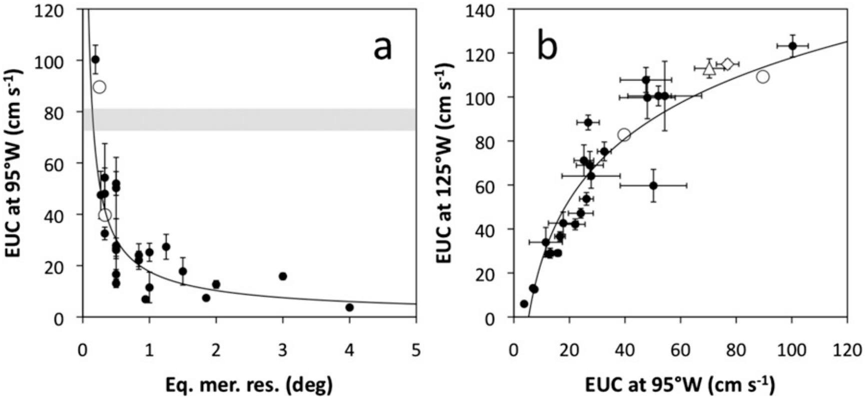

FIG. 2. (a) Equatorial ocean meridional resolution (°) vs peak EUC velocity at 95°W (cm s^{-1}) for CMIP3/AR4 models (filled circles) fit to a power function (solid line; $r^2 = 0.63$), OGCM experiments differing only in horizontal resolution (open circles), and a direct observational estimate (Johnson et al. 2002; gray bar). (b) As in (a), but comparing peak EUC velocities at 95°W vs 125°W for CMIP3/AR4 models fit to a logarithmic function ($r^2 = 0.85$) in addition to SODA values (open triangle) and the direct observational estimate (open diamond). Gray bar in (a) and all error bars in (a) and (b) indicate 95% two-tailed confidence limits assuming a Student's *t* distribution of individual annual means for the models and SODA but number of direct velocity measurements for the observations.

nonlinear at 95°W (modeled in Fig. 2a as a power function; $r^2 = 0.63$).[2] For the range of parameters used in CMIP3/AR4 simulations, a meridional resolution of ~¼° or finer appears essential to reproduce the observed EUC velocity.

The difference in EUC velocity between the OGCM experiments (differing only in resolution) increases from west to east and the CMIP3/AR4 bias is most pronounced in the east (Fig. 1), pointing to a mechanistic connection between resolution and EUC velocity. While the dominant acceleration term in the zonal momentum budget of the EUC in the central Pacific is the zonal pressure gradient, it is the nonlinear zonal and meridional terms that dominate to the east of ~110°W (Kessler et al. 2003; Wacongne 1990; Maes et al. 1997), sufficiently high resolution being necessary to capture them (Brown et al. 2007). Eastward advection of cyclonic relative vorticity, a nonlinear term in the vorticity balance, appears to contribute as strongly to the EUC in the east as does wind stress (Kessler et al. 2003). Nonlinear advection is important because of the large meridional gradient of vertically integrated zonal momentum flux across the eastern equator. Meridional resolution much finer than 1° is necessary to resolve this important term (Kessler et al. 2003, their Fig. 7b), with insufficient resolution slowing down the EUC in the eastern Pacific. A substantially weakened EUC in the east could create a bottleneck for the EUC to the west (Fig. 2b): As the EUC at 95°W strengthens, so too does the EUC upstream at 125°W—until the EUC at 95°W approaches a realistic velocity, beyond which the EUC upstream levels off near observed values.

Equatorial circulation is also sensitive to other model parameters, such as mixing (Yu and Schopf 1997), diffusion (Maes et al. 1997; Cravatte et al. 2007; Jochum 2009), viscosity (Jochum et al. 2008), and biophysical feedbacks (Murtugudde et al. 2002). Changing one or more of these parameters independent of resolution would likely have a significant impact on the EUC (Large et al. 2001; Pezzi and Richards 2003). Intermodel differences in these parameters are difficult to assess objectively; nonetheless, meridional resolution, with its role in the zonal momentum balance in the eastern equatorial Pacific, appears to exert a first-order control over the strength and hence bias and intermodel spread of the EUC.

4. Implications for climate change projections

Since the CMIP3/AR4 models have a systematically weak EUC compared to observations, and the EUC is a vital component of the three-dimensional circulation of the tropical Pacific Ocean (e.g., Izumo 2005; Cravatte et al. 2007), one might hypothesize that the current

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[2] Models with higher meridional resolution also tend to have higher zonal and vertical resolution; the correlation between meridional and zonal resolution for the 23 models is 0.81. The correlation between meridional resolution and the number of vertical levels is 0.65.

generation of climate models assigns an unrealistically small role for ocean circulation in determining the response of the tropical Pacific to rising concentrations of greenhouse gases. One relevant mechanism—the ocean dynamical thermostat (ODT; Clement et al. 1996; Seager and Murtugudde 1997)—posits that the greenhouse-forced warming of SST in the eastern equatorial Pacific could be initially mitigated by the mean upwelling and transported away from the equator by the surface branches of the subtropical cells (STCs; McCreary and Lu 1994; Schott et al. 2004). Although the mean upwelling would be reduced given a weakening of the trade winds, its efficiency for cooling the mixed layer could be maintained by increased vertical stratification (DiNezio et al. 2009). The initially strengthened zonal SST gradient would be amplified by the strengthening of the zonal winds in response.

The hypothesis might then be that the EUC, hence the tropical ocean circulation, in CMIP3/AR4 models is simply too weak to represent the ODT mechanism. Surprisingly, we find little evidence to support this hypothesis when we consider just the mean states. One observational study estimates peak equatorial upwelling to be 1.9 (± 0.9) $\times 10^{-3}$ cm s^{-1} and poleward volume transport divergence by the surface limbs of the STCs (northward transport at 5°N minus southward transport at 5°S) to be 57 (± 26) Sv in the central and eastern Pacific Ocean (Johnson et al. 2001). Of the 15 CMIP3/AR4 models that provided both vertical and meridional ocean velocity output, 13 simulate both equatorial upwelling and poleward volume transport divergence within the error bars of observed estimates, large as they are (Fig. 3). Grouping the models based on simulated upwelling and poleward transport within the error bars as being stronger or weaker than observed, we find no apparent association with EUC strength (average 30 Sv at 125°W in both groups). The remaining two models lying outside the error bars (a third group) do indeed have a very weak EUC (17 Sv at 125°W, compared to 36 Sv observed). Transport-weighted EUC temperatures computed for several CMIP3/AR4 models (not shown) are not systematically biased relative to observational estimates, so this potentially important aspect of the large-scale mean circulation is well reproduced by the models.

We only consider mean quantities. Variability at interannual and longer time scales may have hysteresis or low-frequency rectification effects in nature, whereas models may be able to capture ODT dynamics via pathways different than in nature. Sparse observations, especially in the crucial eastern tropical Pacific, leave the actual strength of the ODT relatively uncertain, making attribution of model deficiencies difficult (Vecchi et al. 2008; Karnauskas et al. 2009).

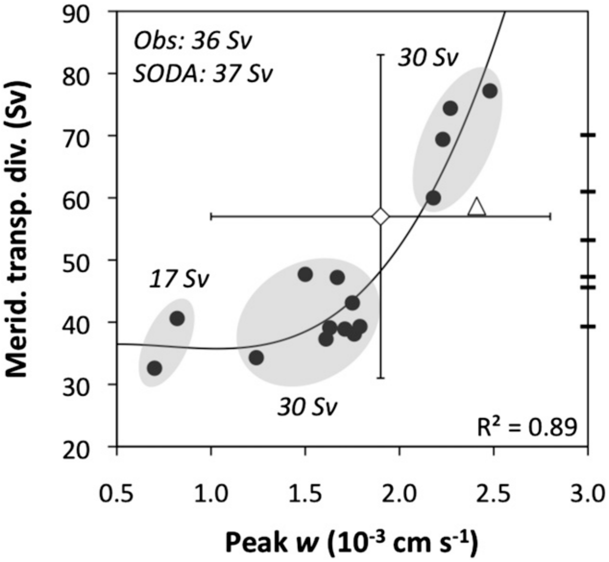

FIG. 3. Peak vertical velocity w (10^{-3} cm s^{-1}; defined as the maximum w between 2°S and 2°N, 0–100 m of the annual mean w field zonally averaged from 170° to 95°W) vs meridional transport divergence (Sv; defined as northward transport through the plane 170°–95°W, 0–100 m at latitude φ_N minus southward transport through the same plane at latitude φ_S of the annual mean meridional velocity field). For the observed estimate, φ_N and φ_S are 5°N and 5°S, respectively, but must be adjusted model by model (and for SODA) to accommodate the spatial structure of the subtropical cells, which varies considerably from model to model. The quantities φ_N and φ_S vary between 0.9 and 3.7°N and between 1.5 and 4°S, respectively. All other choices of geographical bounds on model calculations were made to match those of published observations. Symbol conventions follow Fig. 2b. Error bars on the observed estimates follow Johnson et al. (2001). Italicized values near shaded groupings of data points represent the group mean 125°W EUC transport. Hash marks on the right side of the graph indicate the meridional transport divergence calculations for six models that provided v output but not w output. A third-order polynomial (solid line) is fit to only the CMIP3/AR4 model values (closed circles) and r^2 value indicated (lower right corner).

5. A caution regarding the impact of resolution

The prospect of increased model resolution, hence faster and more realistic model EUCs, implicates the importance of resolving the Galápagos Archipelago. The mean EUC in CMIP3/AR4 models is slower than observed by approximately the same absolute velocity at 110°W, and 95°W (Fig. 4). In contrast, at 85°W (east of the Galápagos), the EUC in CMIP3/AR4 models is in close agreement with observations. However, the model EUC velocities at 95°W are similar to those at 85°W, in sharp contrast with the observations, which show a marked decline in EUC velocities across the Galápagos Archipelago (92°W).

In models and observations, the Galápagos Archipelago has a significant effect on the EUC (Eden and Timmermann 2004; Karnauskas et al. 2007, 2008, 2010).

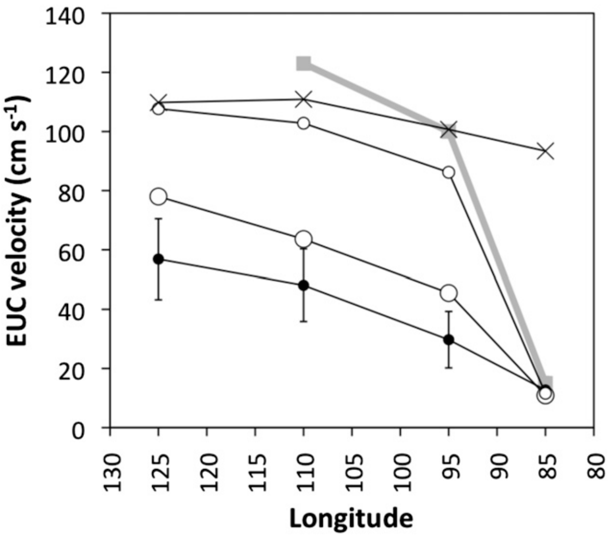

FIG. 4. Peak EUC velocity (cm s^{-1}) as a function of longitude from moored ADCP (Karnauskas et al. 2010; gray squares), CMIP3/AR4 models (filled circles and error bars indicate multimodel mean and ±2 standard errors, respectively), and three OGCM experiments (Karnauskas et al. 2007). Large (small) open circles indicate a coarse (fine)-resolution OGCM experiment with the Galápagos Islands, and crosses indicate a fine-resolution OGCM experiment without the Galápagos Islands. See section 5 of main text for discussion and further details.

In most CMIP3/AR4 models, the EUC is not fast enough by the time it reaches 92°W for the presence or absence of these islands to have any noticeable impact on its zonal evolution. This circumstance is reproduced in the relatively coarse-resolution ($3/4°$ zonal × $1/3°$ meridional) OGCM experiment (Fig. 4). The EUC strength in this experiment is only slightly reduced from its already weak state between 95° and 85°W. In contrast, for a pair of OGCM experiments with finer resolution ($1/4$ zonal and meridional; Fig. 4), the EUC is stronger (and more similar to the observed EUC) between 125° and 95°W, but much too fast east of 95°W without the Galápagos Islands. As climate model resolutions increase, equatorial ocean dynamics (and the EUC) are likely to improve; however, consideration of details such as the influence of the Galápagos Islands on the EUC will become crucial for avoiding new model biases.

6. Discussion

We have identified and diagnosed a striking bias in one critical component of the tropical Pacific Ocean circulation, the EUC. While its strength should be coupled to that of adjoining components of the circulation, such as equatorial upwelling and the STCs, we find little evidence that they are biased, given observational uncertainties. Therefore, CMIP3/AR4 models may include a realistically strong ODT mechanism. This finding leaves much to be reconciled, as most of the CMIP3/AR4 models predict a weakening of the zonal SST gradient and Walker circulation in the equatorial Pacific by the end of this century (e.g., Solomon et al. 2007; Vecchi and Soden 2007), while recent analyses of instrumental datasets offer conflicting results on whether the zonal SST gradient has been strengthening or weakening (Cane et al. 1997; Vecchi et al. 2008; Karnauskas et al. 2009; Bunge and Clarke 2009; Compo and Sardeshmukh 2010; Kumar et al. 2010; Deser et al. 2010; Tung and Zhou 2010; W. Zhang et al. 2010; An et al. 2011; L. Zhang et al. 2011).

The magnitude of future drying in southwestern North America and the sign of precipitation–evaporation in northern South America appear to depend on whether the zonal SST gradient strengthens or weakens (Seager and Vecchi 2011). In these models, a weakening Walker circulation in response to global warming (Vecchi and Soden 2007) weakens the zonal SST gradient and leads to enhanced equatorial warming. Could this mechanism be too strong in models? Are the Walker circulation and zonal SST gradient coupled on global warming time scales as they are on seasonal and ENSO time scales? Will error bars on observed tropical ocean circulation shrink, allowing a stricter assessment of the ODT strength in models?

Fortuitous error cancellation leading to realistic-looking ODT mechanisms is possible, considering the biases and deficiencies in model renditions of ENSO, monsoons, and their interactions. Moreover, beyond the context of the ODT mechanism, other potential dynamical implications of a slow EUC (advection of temperature and vorticity, shear, etc.) may be important to how the equatorial Pacific will respond to radiative forcing, warranting further study. Furthermore, finer model resolution in the future would appear to necessitate explicitly and accurately resolving the Galápagos Archipelago, currently excluded from most CMIP3/AR4 models—even those with sufficient resolution. All AR5 simulations are being run not only at higher resolution but also in Earth system model configuration, that is, with ecosystems and biogeochemistry, including the biophysical feedbacks. Clearly, it will be of great interest to revisit the EUC and its role in the ODT mechanism and the crucial issue of the response of the tropical Pacific to increased radiative forcing.

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