Tidal mixing around the Maritime continent: implications for paleoclimate simulations

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Abstract

Tidal mixing provides an important source of mechanical energy for the ocean circulation and as such is being incorporated into state-of-the-art climate models. Calculation of the tidal energy flux depends on high-resolution topographic datasets, not available for paleoclimate simulations. In this study we demonstrate that changes in the tidal mixing may have significant impacts on ocean circulation, sea surface temperatures, and hence climate. Using a coupled climate model, we test the system's sensitivity to plausible perturbations in the tidal mixing surrounding the Maritime continent and show that an increase in such mixing would cause significant changes in the ocean thermal structure, including a ~1^{o}C warming of the ocean surface in the eastern equatorial Pacific and a similar cooling in the west. The mechanism of these changes involves mixing the relatively cold waters of the Equatorial undercurrent with warmer surface waters. The reduction of the zonal temperature gradient is amplified by ocean-atmosphere interactions associated with a weakening of the atmospheric Walker circulation. Potential implications of this study concern the Pliocene (an epoch characterized by a reduced zonal temperature contrast along the equator) and other past climates. While the actual strength of tidal mixing during the Pliocene is uncertain, our study assesses the bounds on how much tidal mixing may have contributed to maintaining its climate state. We conclude that, on geological timescales, changes in tidal mixing are an important dynamical factor together with ocean bathymetry and continental configuration.

1. Introduction

Previous warm episodes of the Earth's history are useful in assessing the performance of models used for projections of future climate change (Solomon et al., 2007). A striking observation from one geologically recent warm episode, the Early Pliocene, is the dramatic reduction in the equatorial surface temperature gradient in the Pacific (Wara et al., 2005; Fedorov et al., 2006). This state has been given the moniker a "permanent El Niño" or a permanent El Niño-like condition, which refers to the mean climate state, rather than the climate variability of which El Niño is a feature. The cause of the alteration in equatorial surface temperature gradient is still debated, however one possibility is that the vertical mixing in the upper ocean was different in the Early Pliocene (Brierley et al., 2009; Fedorov et al., 2010).

The addition of stronger vertical mixing to the upper ocean can cause a deepening of the ocean tropical thermocline and a reduction in the equatorial surface temperature gradient (Brierley et al., 2009). While the source of this increased mixing is uncertain, two possible candidates deserve discussion: tropical cyclones (Fedorov et al., 2010) and changes in ocean internal tides (the subject of the present study). Whereas a change in the tropical cyclone activity during the Early Pliocene could be attributed to the larger extent of the tropical warm pool, changes in tidal dissipation (or tidal mixing) would be associated with changes in the ocean bathymetry. Clearly, these two potential causes of enhanced mixing would have different geographical distributions – the off-equatorial open ocean for tropical cyclones and shallow seas and continental shelves for tidal mixing. These two factors could potentially have different behaviors under climate change as well.

Barotropic tides occur when the gravitational fields of the Moon and the Sun force the ocean with a periodicity related to Earth's rotation and orbital motion (Jayne & Laurent, 2001; Pugh, 2001). When a barotropic tide occurs over rough bottom topography, it generates internal gravity waves (or an internal tide) that may break and lead to energy dissipation and strong vertical mixing. Tidal motion is estimated to input 3.5TW of work into the global ocean (Munk & Wunsch, 1998), of which roughly three quarters is believed to dissipate on shelves or in shallow seas (Wunsch & Ferrari, 2004). These values may have changed over the course of the several million years that separate the present time and the early Pliocene, implying different rates of vertical (diapycnal) mixing in the regions of the ocean affected by the tides.

In this study we explore the sensitivity of the Pacific and global climate to ocean vertical mixing in the seas surrounding the Maritime continent of the tropical Indo-Pacific. The Maritime Continent is a vast region of Southeast Asia, which comprises the Islands of Indonesia, Papua New Guinea, and the Philippines, and many smaller islands, peninsulas and seas (Fig. 1). This region is crucial for the atmospheric general circulation, as it comprises a significant portion of the Indo-Pacific warm pool - the region of the warmest sea surface temperatures on Earth. The Indo-Pacific warm pool is the center of the atmospheric deep convection and uplift that forms the ascending branch of both the Hadley and Walker circulations.

This region is also crucial for ocean dynamics, for instance because it contains the only tropical link between the Pacific and Indian oceans – the Indonesian throughflow. There are strong western boundary currents (Zhang & McPhaden, 2006) flowing towards the equator and carrying, at depths of 100-200m, the relatively cold waters from the subtropics and mid-latitudes that feed the Equatorial Undercurrent, see (Gu & Philander, 1997). [An approximately equal amount of water reaches the undercurrent through interior ocean pathways, e.g. Zhang & McPhaden (2006)]. Any changes in the ocean mixing rates should affect the properties of waters carried by these many currents.

The Maritime continent and surrounding regions have undergone significant tectonic reorganization throughout late Cenozoic time, including a northward movement of New Guinea and general land uplift (Hall, 2002). In addition, the sea level was ~25m higher during the Pliocene (Haywood et al., 2009), but there is large uncertainty in this estimate (Sosdian & Rosenthal, 2009). It is not clear how all these changes would affect tidal mixing. Therefore, our goal here is solely to conduct a sensitivity study with a coupled climate model (CCSM3) to investigate the potential consequences for the local ocean thermal structure and to determine whether one can expect any large-scale climate impacts.

In particular, we will show that increasing ocean mixing in this region throughout the water column leads to a deepening of the tropical thermocline in the Indo-Pacific region, an associated warming of a vast part of the Indo-Pacific, and a local cooling in the region of enhanced mixing. The effect of the deeper thermocline on SST is transmitted across both adjacent oceans leading to remote surface warming. Although most impacts occur in the tropical Pacific and Indian oceans, there are other climate impacts across the globe.

2. The Maritime continent and tidal mixing

The shallow seas surrounding Indonesia and the Maritime continent represent one of the regions of the globe in which dissipation of tidal energy is known to have important consequences (Fig. 1). It has been suggested that this region has twenty times the dissipation per unit area than the average ocean value (Koch-Larrouy et al., 2007). As the Indonesian throughflow connects the Pacific and Indian oceans, waters are forced through several different deep straits from the North Pacific into an internal area (formed by the Java, Flores and Banda Seas). They then flow into the Indian Ocean, spreading along 10^{o}S. There is significant mixing of the waters within the internal area, estimated as equivalent to a vertical diffusivity of 1.5 cm^2/s (Koch-Larrouy et al., 2007).

Despite the importance of this region for climate many coupled climate models have large systematic biases in precipitation over the Maritime continent, which have persisted throughout model development (e.g. within CCSM3). One attempt to eliminate these biases increased the background vertical ocean mixing by an order of magnitude uniformly in the internal seas of the Maritime continent, including the Banda Sea (Jochum & Potemra, 2008). They found a local temperature decrease of 0.3^{o}C and precipitation reduction of 1 mm day^{-1}. They did note some slight impacts away from Indonesia, but saw no impacts on climate variability. Koch-Larrouy et al. (2010) used two different climate models to perform a similar experiment, although they use a heterogeneous vertical diffusivity field derived from a global tide model. They find that their tidal mixing parameterization slightly alters ENSO properties in the models and strengthens local impacts on the mean climate (SST cooling of 0.5^{o}C and rainfall reduction of 1.5 mmday^{-1}). Both of these experiments increase the mixing only within the internal seas of the region, leaving the Pacific western boundary currents unaffected.

Overall, the amount of tidal mixing in this region is strongly dependent on local bathymetry. Jayne & Laurent (2001) describe a simple parameterization of ocean internal wave drag over bottom topography. It is a scaling relationship that is analogous to the “mountain drag” parameterization in atmospheric models. The energy flux lost by the barotropic tide to internal waves is calculated as

$$E_f \sim \frac{1}{2}\rho_0 k h^2 N \underline{u}^2 \qquad (1)$$

where (k,h) are the wavenumber and roughness amplitude that characterize the bathymetry, $\underline{u}$ is the barotropic tidal velocity, N is the buoyancy frequency and ρ_0 is the density of seawater. The wavenumber in (1) is set to k = 2π/125km by comparing the results of a barotropic tide model incorporating this parameterization to observed tides (Jayne & Laurent, 2001). In general, the parameters h, N and $\underline{u}$ are functions of latitude and longitude. The roughness amplitude, h, is determined from the ETOPO2 satellite-derived topography (Smith & Sandwell, 1997) as a residual between the climate model’s low-resolution bathymetry and the high-resolution observations (Jayne & Laurent, 2001). Incorporating a vertical diffusivity derived from this energy flux into a climate model has been shown to increase the fidelity of ocean simulations (Jayne, 2009).

The exact bottom topography of this region for the Pliocene and earlier epochs is not known. There were likely changes in the bathymetry around Indonesia, including changes in the pathways of the Indonesia throughflow (Cane & Molnar, 2001), changes in the locations of big and smaller islands and in the overall ocean depth (Hall, 2002). Nevertheless, we can estimate the sensitivity of the energy flux to plausible bathymetric changes.

The three rightmost variables in Eq. (1) may have differed in the Pliocene, whilst the characteristic wavenumber, as a global parameter, is unlikely to have changed. Calculation of the changes in the tidal velocity, $\underline{u}$, would require high-resolution knowledge of the ocean bathymetry, which is unavailable and is unlikely to ever be known. Knowledge of changes in the buoyancy frequency requires knowledge of the past ocean density structure. As this study aims to investigate the sensitivity of the ocean structure to tidal energy changes, we are uncertain of the magnitude these variations at this stage. Therefore, for this sensitivity study, we choose to alter the roughness amplitude, *h*, by an arbitrary 5m in a region encompassing the Maritime Continent, whilst all other variables in Eq. (1) are kept at their modern values. The chosen changes of either 5m or 20m are rather small in comparison to average roughness amplitude of 245m over the region.

There are locations where the tidal energy flux is very sensitive to a small change in roughness amplitude (Fig. 1). Most regions where the energy flux is more than doubled (a 100% increase) are shallow, however there are also deep locations of strong sensitivity. From measurements in the Atlantic we know that ocean vertical diffusivity can be affected up to several thousand meters above rough bottom topography increasing 1 to 2 orders of magnitude as compared to typical background values (Polzin at al., 1997). The exact increase in vertical diffusivity is difficult to determine as it depends on the bathymetry, the local stability of the ocean and the upward propagation of internal waves excited by the flow above a rough topography amongst other factors (Polzin et al., 1997; Jayne, 2009). If the only change were a doubling of the energy flux (as shown in Fig. 1), then the vertical diffusivity would also double as they are linearly proportional to each other (Simmons et al., 2004; Jayne, 2009).

Climate Impacts

We have performed several numerical experiments to test the sensitivity of the global climate to the possible differences in internal wave energy flux shown in Fig 1. The model used is NCAR's community climate system model, version 3 (CCSM3; Collins et al., 2006). It couples the POP ocean general circulation model to atmosphere, sea ice and land surface models. Two simulations were integrated for 200 years; one a sensitivity run and the other a control run with 1990 forcing conditions. This is a sufficient time for the adjustment of the tropical, upper ocean, however small climate drift will remain at depth. The only difference between the perturbed and control simulations is that the sensitivity run includes increased vertical diffusivity around Indonesia (defined as the region colored in Fig. 1). As both Jochum & Potemra (2008) and Koch-Larrouy et al. (2010) find values of $1cm^2/s$ in the modern Banda Sea, we incorporate an additional constant vertical diffusivity of $1cm^2/s$ into the ocean model to simulate the doubling of the energy flux. For this simple sensitivity study, the additional diffusivity does not have a vertical profile and extends from the ocean floor to the surface.

The additional diffusivity has a cooling impact on the local sea surface temperature (SST) around the Maritime continent on the order of 1^oC (Fig. 2a). The strongest cooling occurs in the Indian Ocean ($\sim 1.5^oC$) as the downstream impacts from the mixing of the Indonesian throughflow combine with the increased local mixing. There are also non-local SST impacts, with the strongest being a warming approaching 1^oC in the eastern equatorial Pacific and a weaker warming (0.5^oC) in the western Indian Ocean. Previously only a slight warming in the east has been noted in response to Indonesian tidal mixing (Koch-Larrouy et al., 2010).

The mechanisms of the warming in our sensitivity study involve both oceanic and coupled ocean-atmosphere effects. The enhanced ocean mixing in the west Pacific warm pool brings colder waters to the surface from about 100m depth and at the same time induces a warming below this depth as the increased vertical mixing draws heat downwards (Fig. 3a). This warm anomaly is then transported by the western boundary currents and then by the Equatorial Undercurrent (EU, located at ~150m in the west Pacific in the control simulation) to the eastern equatorial Pacific (Fig. 3c) where it leads to a surface warming. We envisage this initially causing just a small warming, which is then enhanced by a positive coupled ocean-atmosphere feedback.

The strength of the atmospheric Walker cell depends on the magnitude of the SST gradient along the equator (Bjerknes, 1969). The cooling of the west Pacific and the warming of the east Pacific described above would weaken the Walker circulation and the surface easterly winds associated with it. As the surface easterlies weaken, so do the surface equatorial currents (Fig. 3b,c), which are strongest in the central Pacific. The weaker surface currents allow the Equatorial Undercurrent to encroach further towards the surface thus entraining warmer subsurface waters. There is also some weakening of the EU in the east Pacific in the perturbed experiment. These effects together would further increase the east Pacific SST, reducing the Walker circulation and strengthening the initial warming.

We can also understand the aforementioned changes in the ocean thermal structure from the perspective of the ocean heat budget since SST changes in our experiments are followed by significant changes in the heat flux into the ocean (Fig. 2b). The enhanced vertical mixing around the Maritime continent increases ocean heat uptake there and leads to the deepening of the equatorial thermocline across the Indo-Pacific region (Fig. 3) and even in the Atlantic ocean. As the ocean adjusts, this thermocline deepening reduces ocean heat gain in the regions not affected directly by the mixing, including in the eastern equatorial Pacific and coastal upwelling regions. When a new steady state with a deeper thermocline is reached, the ocean re-establishes a heat balance such that any changes in heat gain and loss have been compensated, in agreement with the balanced heat budget argument of Boccaletti et al. (2004) and Fedorov et al. (2004).

Changes in SSTs caused by the adjustment of the ocean-atmosphere system to the enhanced ocean mixing are felt throughout the tropics. The largest precipitation changes are co-located with the SST changes, however there are statistically significant impacts across the globe (Fig. 2c). There is a substantial drying across the majority of the Maritime Continent of around 2 mm day^{-1}. The Java Sea is the only part showing an increase in rainfall, which is also the only part with a slight increase in SST. The east Pacific, east Atlantic and west Indian ocean all see increases in rainfall approaching 1mmday^{-1}. These are all regions of cold SSTs, atmospheric subsidence and therefore little convection, so these changes indicate a 50% increase rainfall. These precipitation changes bear similarities to those observed from El Niño events in this model (Deser et al., 2006).

In addition to the main perturbed experiment, another sensitivity experiment was also performed, where 1cm^2/s of additional background vertical diffusivity was placed only in the top 200m of the ocean, rather than throughout the water column. This modification acts to amplify the previously noted climate impacts (fig. 4), with the SST warming in the east equatorial Pacific increasing to 1.5^{o}C. The deepening of the thermocline and changes in the EUC become more visible in this simulation. Along with the changes in the mean climate state of the Equatorial Pacific, there are detectable changes in the climate variability in the shallow-mixing simulation - the activity of ENSO is reduced. The results of this experiment demonstrate that for the tidal mixing to be effective, it should be able to reach the upper ocean (note that in the observations of mixing by Polzin et al. (1997) the effect of rough bottom topography was noticeable at distances up to 4000m above the ocean floor).

Discussion

This study has investigated possible consequences of changes in ocean mixing produced by the tidal energy dissipation for past climates. In this instance, we chose a geologically recent climate with relatively well-constrained continental position and concentrated on a region known to have significant tidal mixing impacts at present. A number of state-of-the-art coupled models are now incorporating tidal dissipation into their ocean simulation, which requires knowledge of the bathymetric roughness (Jayne, 2009). For paleoclimate simulations, however, accurate knowledge of the model-resolution bathymetry, let alone the bathymetric roughness critical for tidal dissipation, is not available. Here we show that modifying the bottom roughness and hence ocean vertical diffusivity in a particular region (around the Maritime continent in our study) may lead to significant differences in climate with strong remote effects.

Previously, past changes in tidal energy have been considered for the climate of the Last Glacial Maximum (Montenegro et al., 2007). The main reason for changes in bathymetry at this time, as compared to the present, is the drop in sea level caused by the storage of large amounts of water in continental ice sheets: tectonic changes at the ocean bottom are assumed relatively small in comparison. These authors did find higher diffusivities at the Last Glacial Maximum from tidal mixing, however the exposure of additional land (such as in the Java Sea) dominated the climate response. The early Pliocene situation is different in that tectonics, rather than sea level variations, would be expected to dominate the change in tidal energy.

The ocean bathymetry of the Maritime continent has changed over the past five million years (even though the timing and extent of the changes remain uncertain). Previous studies have largely focused on the effect of changes in land configuration on ocean circulation. Cane & Molnar (2001) suggested that as a result of the tectonic movement of Indonesia over the past 5 million years the Indonesian throughflow switched from a south Pacific source to a north Pacific source around 3 to 4 Ma, which would have altered ocean temperatures. In an ocean-only model, this leads to a warming of several ^{o}C at 100-150m depth in Pacific and a cooling in the Indian Ocean at the same depths (Rodgers et al., 2000; Cane & Molnar, 2001). A more recent study with a comprehensive coupled model found the sea surface temperature impacts of changes in the position of Indonesia to be much weaker, with a maximum of 0.3^{o}C in the central equatorial Pacific (Jochum et al., 2009). They conclude that although the "details of the ITF can influence tropical variability, but they seem unlikely to affect the mean global climate directly".

Our study shows that changes in ocean vertical mixing on geological timescales can potentially be more effective than the modest changes in land configuration that occur since the early Pliocene. In particular, we show that an increase in the mixing around the Maritime continent can generate a warm temperature anomaly of ~1^{o}C in the eastern equatorial Pacific. Together with local cooling in the western equatorial pacific, this effectively reduces the zonal SST gradient along the equator in the Pacific by some 2^{o}C. In our simulations, a decrease in the zonal temperature gradient occurs in the Indian ocean as well.

It is important that the relatively local increase in mixing can involve far reaching remote effects. For example, we observe a broad thermocline deepening in all three tropical oceans and corresponding warming (a few ^{o}C) in coastal upwelling regions. This result is consistent with the conclusion of Fedorov et al. (2006) that a deeper tropical thermocline is an important element of the Pliocene climate. In parallel, changes in global SSTs lead to pronounced changes in precipitation analogous in principle to those simulated by Barreiro et al. (2006) and Brierley & Fedorov (2010) in the tropical region for the Pliocene climate.

Note that looking at the effect of ocean vertical mixing within the internal seas of the Maritime continent in an experiment somewhat similar to ours, Jochum & Potemra (2008) did not find non-local

SST changes. The main differences between our and their experiments that explains this disagreement is the expanse of the region with enhanced tidal mixing – in the present study this region extends to the seas around the Maritime continent, so that enhanced mixing can directly affect the western boundary currents in the Pacific and the eastern boundary currents on the other side of this continent in the Indian ocean.

It should be also noted that model used for this experiment significantly underestimates the percentage of cold water entering the Equatorial Undercurrent in the Pacific through the western boundary currents, known as the exterior pathways, rather than through interior pathways (Zhang & McPhaden, 2006). An even stronger effect of the enhanced ocean mixing would be expected in a model with a larger fraction of water entering the EU from the west.

Using geochemical proxies, Karas et al. (2009) assessed long-term changes in the mixed layer temperature at ODP site 214 located in the Indian Ocean side of the Indonesian throughflow (Fig. 1). A change in water properties occurs during the mid-Pliocene (~3.5 - 3 Ma), most likely associated with changes in the Indonesian throughflow. These authors state these changes are consistent with the hypothesis of Cane & Molnar (2001). However, here we have shown that the Indian Ocean thermal structure is also dependent on the amount of tidal mixing within [agreeing with the earlier studies of Jochum & Potemra (2008) and Koch-Larrouy et al. (2010)] and especially around the Maritime continent. Thus, the observed temperature changes could arise in part from changes in the tidal mixing.

In summary, changes in tidal mixing appear to be an important potential driver of climate change on geological timescales. Even though accurate knowledge of even the sign of changes in tidal mixing in the deep past is currently not attainable, our study suggest that paleoclimate modeling studies should consider at the very least the uncertainty associated with these changes when interpreting their results, but also investigate potential climate changes related to this phenomenon.

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Figure Captions

Figure 1. The Maritime Continent: (top) Land and ocean bottom topography from the ½ degree data set of (Smith & Sandwell, 1997). Topographic features referred to in the text are labeled. **(bottom) Percentage change in energy flux from tidal dissipation** as a result of the uniform increase of roughness

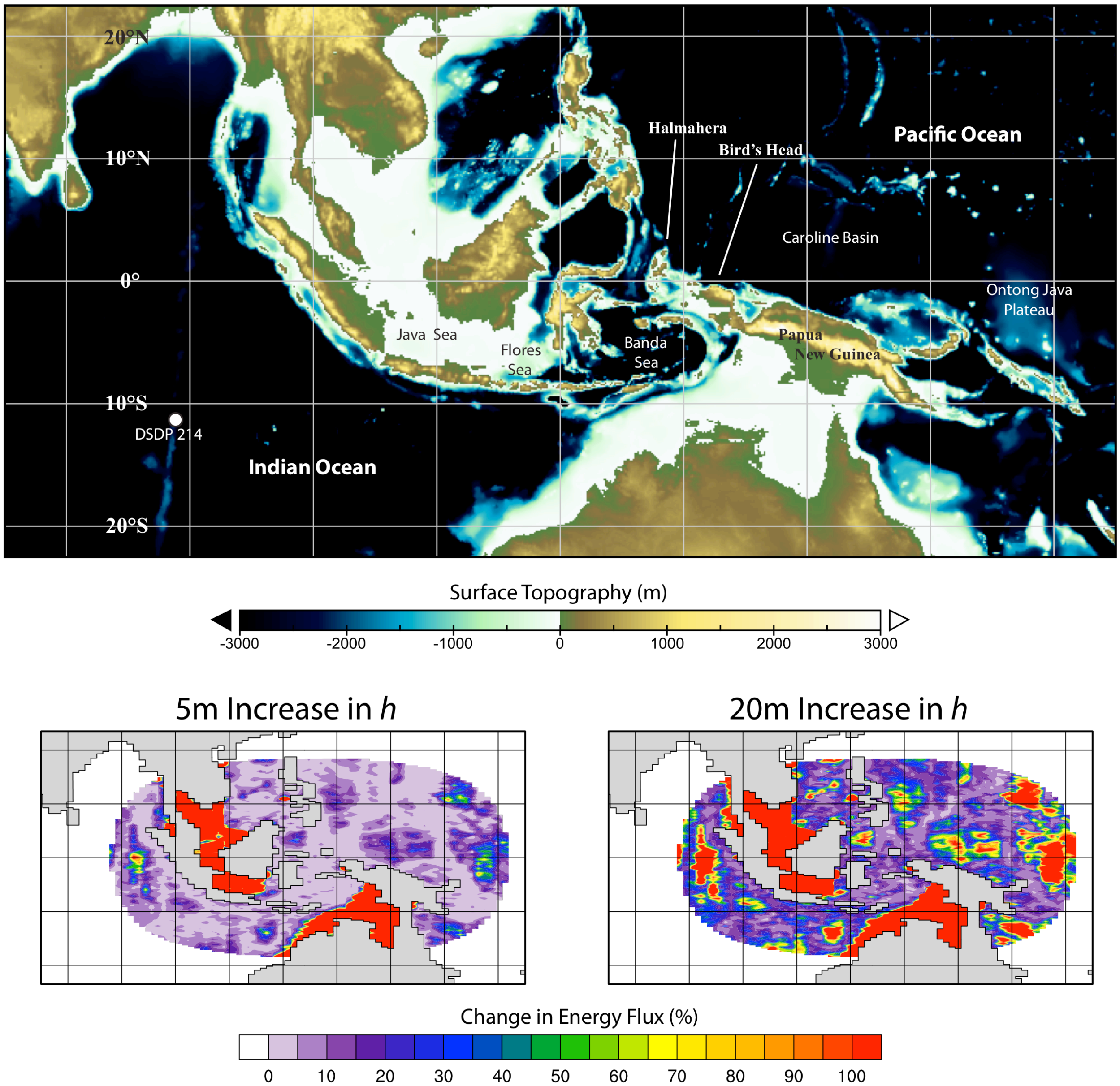
amplitude *h* from its modern local values by 5m and 20m (calculated from Eq. 1). Red indicates the energy flux has at least double, in some places the energy flux actually increases by two orders of magnitude. The calculation is performed on the ocean model grid – the gray area indicates the model's land mask.

Figure 2. Surface impacts of the enhanced vertical diffusivity. (a) Changes in the annual mean sea surface temperature: SST decreases in the region of increased mixing, however there is a substantial warming of the east Pacific, centered over the Niño3.4 region. (b) Changes in the mean heat flux at the ocean surface: ocean gains more heat in the region of enhanced mixing, but there is a reduction in heat gain elsewhere in the tropics. (c) Changes in annual average rainfall: a drying occurs over the Maritime continent, but it rains heavier elsewhere. Green stippling indicates anomalies significant at the 95% confidence level.

Figure 3. Change in the upper ocean thermal structure (temperature along the equator, averaged between 1^{o}N to 1^{o}S is shown). (a) There is a reduction in temperature local to the mixing, and a warming below that extends laterally across the basins and upward in the upwelling regions. The solid and dashed lines show the location of the 20^{o}C isotherm (a proxy for the thermocline depth) with and without the mixing respectively. (b) - (c) The zonal velocities in the enhanced mixing and control simulations, respectively, that show the Equatorial Undercurrent shoals in the perturbed experiment.

Figure 4. Sensitivity to vertical extent of the mixing. (a) The changes in SST when the additional mixing occurs only in the top 200m. (b) The equatorial zonal velocity in a simulation with additional mixing only in the top 200m of the ocean. (b) Changes in the ocean thermal structure along the equator showing the 20^{o}C isotherm (a proxy for the thermocline depth) in the experiments with (solid line) and without (dashed line) the additional shallow mixing.

Figure 1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Banda
Sea
Papua
New Guinea
DSDP 214
Indian Ocean
Surface Topography (m)
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-2000
-1000
0
1000
2000
3000
5m Increase in *h*
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Change in Energy Flux (%)
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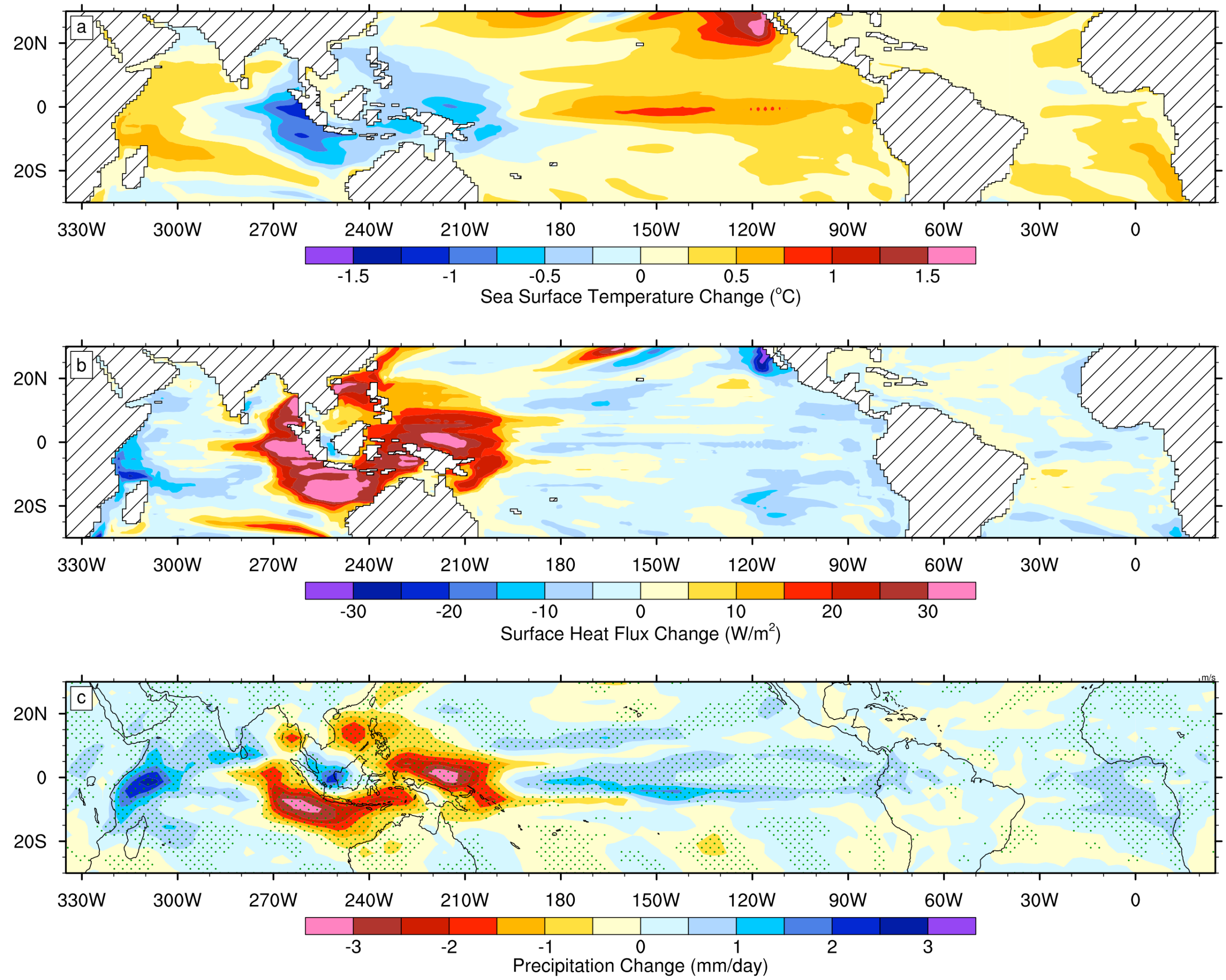
Figure 2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Sea Surface Temperature Change (°C)
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Surface Heat Flux Change (W/m2)
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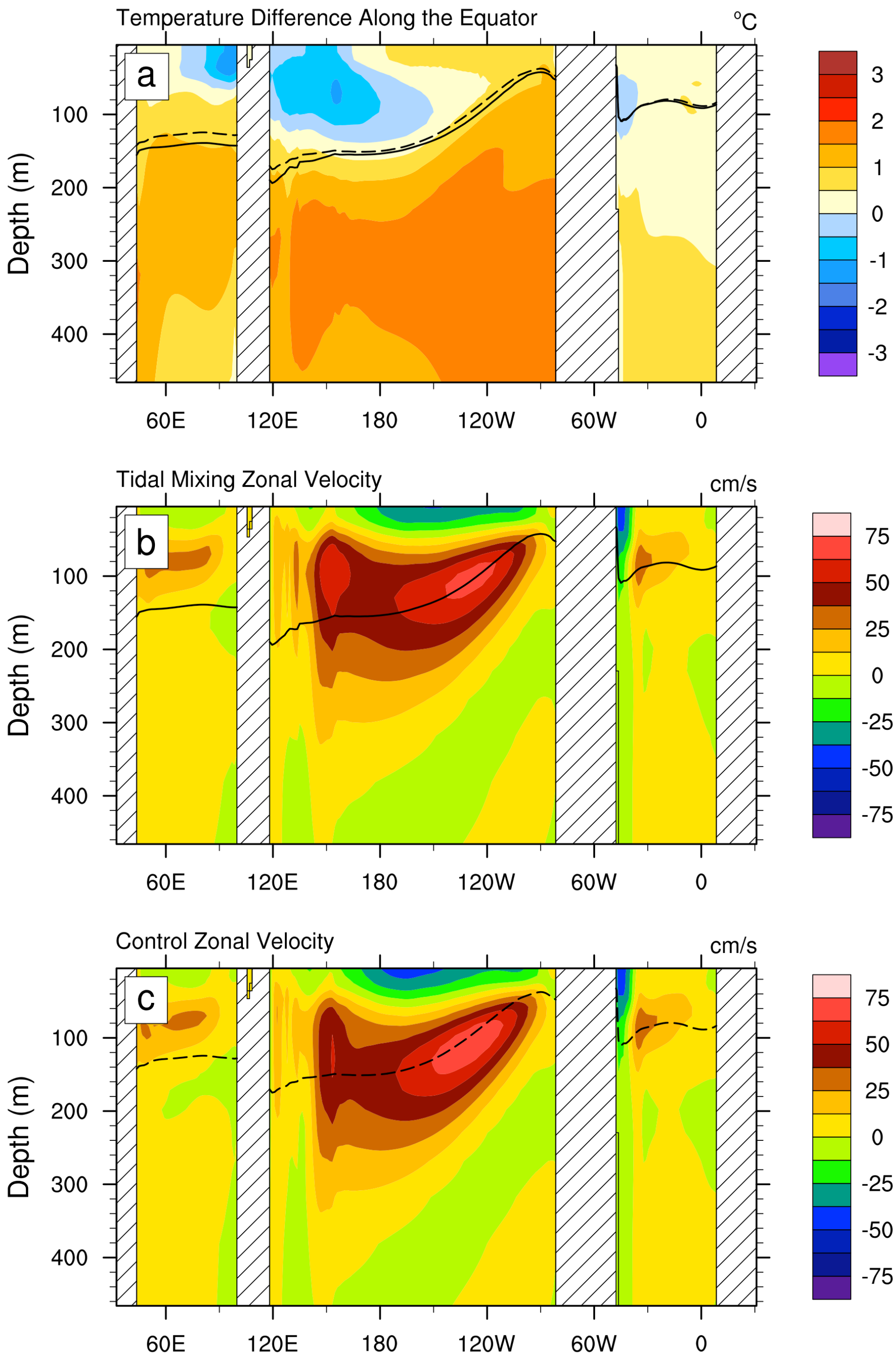
Precipitation Change (mm/day)

Figure 3


Temperature Difference Along the Equator
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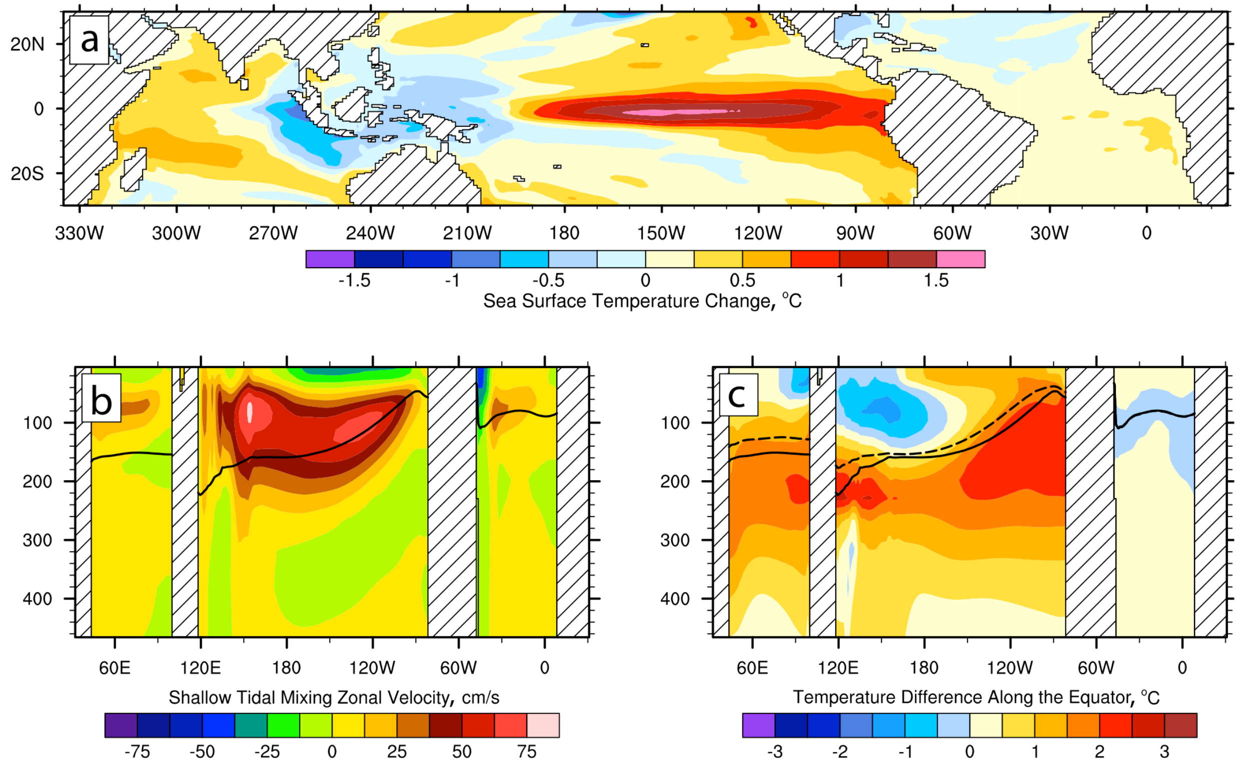
180
120W
60W
0
3
2
1
0
-1
-2
-3
Tidal Mixing Zonal Velocity
cm/s
b
Depth (m)
100
200
300
400
60E
120E
180
120W
60W
0
75
50
25
0
-25
-50
-75
Control Zonal Velocity
cm/s
c
Depth (m)
100
200
300
400
60E
120E
180
120W
60W
0
75
50
25
0
-25
-50
-75

Figure 4



a
20N
0
20S
330W
300W
270W
240W
210W
180
150W
120W
90W
60W
30W
0
-1.5
-1
-0.5
0
0.5
1
1.5
Sea Surface Temperature Change, °C
b
100
200
300
400
60E
120E
180
120W
60W
0
Shallow Tidal Mixing Zonal Velocity, cm/s
-75
-50
-25
0
25
50
75
c
100
200
300
400
60E
120E
180
120W
60W
0
Temperature Difference Along the Equator, °C
-3
-2
-1
0
1
2
3