

On the climate impacts of atolls in the central equatorial Pacific

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24 **Abstract**

25 Contrary to the above title, a more typical question might be “How does climate
26 variability and change impact atolls (and associated ecosystems and civilizations)?” While
27 several studies have focused on the effects of island topography on local circulation, equatorial
28 currents and their dynamics play a vital role in the tropical heat balance and therefore global
29 climate through atmospheric teleconnections. The Gilbert Islands, which straddle the equator in
30 the western Pacific, block 55% of the corridor between 2°S–2°N. Here we explore the potential
31 role of relatively small open–ocean topographic features, in particular equatorial atolls such as
32 the Gilbert Islands, on the large–scale climate system. Observations and high–resolution ocean
33 model simulations spanning the full width of the Pacific basin indicate that, while the Gilbert
34 Islands have only a local impact on the Equatorial Undercurrent (EUC), the South Equatorial
35 Current (SEC) is substantially reduced downstream of the islands, resulting in a surface warming
36 and freshening over a ~1,000–km wide region along the sharp temperature and salinity front
37 defining the eastern edge of the Indo–Pacific warm pool (IPWP), the heat engine that is a critical
38 player in global climate processes. The simulated mean thermohaline structure in the central and
39 western Pacific, which has previously been shown to be crucial for El Nino–Southern Oscillation
40 (ENSO) dynamics, is improved by including the Gilbert Islands. Implications for coupled model
41 biases, ENSO simulation, and paleoclimate are discussed.

1. Introduction

With the exception of a single volcano on Isla Isabela, Galápagos, the entire equatorial Pacific from Indonesia to mainland South America (16,666 km or 42% of Earth's circumference) is continuous open water (Fig. 1). Nevertheless, previous studies have shown that small islands, if close enough to the equator, can profoundly influence physical and biological processes from local (Hendry and Wunsch, 1973; Cane and DuPenhuet, 1982; Rowlands et al., 1982; Gove et al., 2006; Karnauskas et al., 2010) to regional and basin scales across the equatorial Pacific (Eden and Timmermann, 2004; Karnauskas et al., 2007; 2008; 2014; Karnauskas and Cohen, 2012).

The equatorial Pacific region has long been known to be a significant driver of the Earth's atmospheric circulation and climate variability (Ropelewski and Halpert, 1987), yet fundamental questions about the large-scale ocean-atmosphere coupling and overall tropical heat balance remain (Sun and Liu, 1996; Liu and Huang, 1997). The disproportionate amount of control that equatorial islands can potentially exert on a spatial scale much larger than their own is made possible by the very dynamics that make the equatorial waveguide unique. In particular, the trade winds drive a westward surface current (the South Equatorial Current, or SEC) and the resulting pressure gradient drives an eastward flowing Equatorial Undercurrent (EUC) below the surface that is trapped to the equator by the Coriolis force (Fig. 1).

The Gilbert Islands, Republic of Kiribati, are comprised of 16 low-lying atolls and reef-top islands in the western equatorial Pacific Ocean situated upon volcanic rock hundreds of meters beneath the surface (Fig. 2). The volcanoes upon which the Gilbert Islands have developed are thought to have been active between 10–50 million years ago and are now trending northwest and slowly subsiding (Gillie, 1993; Sharma and Krüger, 2008). The Gilbert

Islands present a fundamentally different climatic problem than that of the Galápagos because they are situated at the boundary between the Indo–Pacific Warm Pool (IPWP) and the Pacific cold tongue. Furthermore, each of the individual atolls comprising the Gilbert Islands are an order of magnitude smaller than the Galápagos and are therefore that much farther from being resolvable in even the latest generation of global climate models with their average horizontal ocean grid spacing of order 100 km (Solomon et al., 2007; Karnauskas et al., 2012). Despite their small individual sizes and the fact that none actually intersect the equator, nine of the major atolls together block 55% of the total north–south distance between 2°S and 2°N—a potentially formidable obstacle to the westward–flowing SEC that also lies within the corridor through which the EUC flows. The Gilbert Islands have been included in several recent assessments of historical and future climate impacts on tropical island ecosystems and civilizations (Donner et al., 2011; Karnauskas and Cohen, 2012; Karnauskas et al., 2015a; 2015b). In the present paper, we reverse their questions and ask whether the Gilberts, like the Galápagos, can have a significant influence on the ocean and climate system at scales beyond that of an individual island or archipelago.

2. Approach

In situ observations of ocean currents at depth across the tropical Pacific have been made for decades (Johnson et al., 2002; Keenlyside and Kleeman, 2002), but are likely too sparse to resolve the detailed response of the mean velocity field to a chain of small islands. To test the hypothesis that the Gilbert Islands have an effect on the large–scale zonal currents in the equatorial Pacific Ocean, including the SEC and EUC, we ran a high–resolution ocean model with and without the Gilbert Islands (as represented in Fig. 2) and analyzed the differences

therein. The impacts on temperature, salinity and stratification are also investigated with the model and observations.

Our high-resolution numerical ocean model simulations were based on the widely-used Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005), distributed along with the pre/post-processing MATLAB toolbox (Penven et al., 2008) by the French group L'Institut de recherche pour le développement (IRD). Designed specifically for high-resolution simulations of regional domains, ROMS is a free-surface, terrain-following coordinate ocean model that solves the primitive equations in an Earth-centered, rotating frame of reference.

The domain of our simulations included the full width of the equatorial Pacific Ocean from 130°E–75°W, from 9°S–9°N, with 32 vertical levels. For simplicity, open boundaries were used along the western, southern, and northern boundaries of the domain, and a realistic representation of the American continental coastline closed off the eastern boundary. The Indonesian Throughflow (ITF) region likely has profound effects on ocean circulation and climate, and has been the subject of several modeling studies (*e.g.*, Murtugudde et al., 1998; Valsala et al., 2011; Santoso et al., 2011). However, our choice of lateral boundary condition should not influence the main results concerning the sensitivity to the Gilbert Islands because all experiments were conducted using identical model configurations in all other respects. Moreover, the Gilbert Islands (174°E) are 4,840 km east of the western boundary in our model domain, which is sufficiently far from the boundary condition for the solution to be dominated by model dynamics. The horizontal resolution in our simulations was a uniform 1/22° latitude by longitude, or 5 km². The total size of our domain was thus 3,411 x 399 x 32, or ~44 million grid points. Parallel processing was implemented through the MPI protocol on a distributed-memory

Linux cluster. Our domain was partitioned into 42 x 6 tiles, which were integrated simultaneously on 21 nodes (252 cores).

Initial conditions of the model simulations were given by climatological state variables from the 1° monthly World Ocean Atlas (Locarnini et al., 2006; Antonov et al., 2006) and initial velocities determined by geostrophy. Boundary forcing (surface fluxes) was given by the 0.5° monthly COADS climatology (Da Silva et al., 1994), repeating year after year. Our simulations did not use heat flux correction, which is a scheme that adjusts heat fluxes so as to relax the model SST field toward observed values. For each simulation, a total span of 7 years (4 years spin-up, 3 years for analysis) was simulated with a 5-minute model time step, saving monthly average output fields. With this configuration, each 7-year simulation required roughly 4.7 days to complete.

Recent high-resolution bathymetric surveys (Sharma and Krüger, 2008) were referenced for defining the islands within the model grid (Fig. 2). The treatment of the Gilbert Islands as cuboids extending from the surface to the seafloor, as shown in Fig. 2, is well justified by the general characteristics of mid-ocean atolls as well as high-resolution bathymetric surveys (Sharma and Krüger, 2008). There is a shallow submarine flank connecting the two islands within box 2 (Abaiang and Tarawa), thus the 7.5 km stretch of sea separating them was filled such that box 2 is a single, continuous island. Since atolls typically grow in size beneath the surface, this island implementation scheme is considered conservative.

The observed zonal velocity data and their processing is described in (Johnson et al., 2002) and the observed seasonal salinity sections are from an Argo climatology (Johnson et al., 2012).

3. Results

The large-scale structure of the equatorial zonal currents is well simulated by the model compared to an analysis of shipboard ADCP observations (Fig. 3). In the simulation with the Gilbert Islands (Fig. 3b), the islands act to slow the EUC locally upstream and in the close vicinity of the islands, which results in upwelling and has implications for the near-surface marine environment and ecosystems of the Gilbert Islands (Karnauskas and Cohen, 2012). A remarkable impact of these islands on the ocean chlorophyll response at the termination of the 1997–98 El Niño was captured by the SeaWiFS (McClain et al., 2014) ocean color satellite (Murtugudde et al., 1999; Messié et al., 2006). While there is a significant amount of EUC transport through each of the gaps between model islands, the EUC flows preferentially through the gap between Aranuka and Nonouti (islands 4 and 5 in Fig. 2). This is the nearest gap to the equator as well as the widest gap between 2°S–2°N. The maximum EUC velocity through this gap is 41.5 cm s^{-1} , which exceeds the greatest EUC velocity upstream of the Gilbert Islands (37.1 cm s^{-1}). This acceleration is an example of Bernoulli's principle in concert with the dynamical requirement that the EUC remain trapped to the equator. The total EUC transport through this gap is 3.4 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$), which is equivalent to about 25% of the maximum total EUC transport upstream of the Gilbert Islands (13.5 Sv). While the impact is very significant locally, there is only modest upstream influence and no noticeable downstream influence of the Gilbert Islands on the simulated EUC (Fig. 3d).

Compared to the EUC, the influence of the Gilbert Islands on the westward surface current (SEC) is larger, with greater downstream reach, and has clear climatological consequences. Between the islands and at the surface, the maximum westward speed through each gap scales approximately linearly with distance from the equator, and the maximum speed

through several of the gaps exceeds the maximum modeled SEC speed at its swiftest point upstream of the Gilbert Islands (60 cm s^{-1}). While the gap through which most of the EUC flows also corresponds to a strong westward acceleration of the SEC, the swiftest westward surface flow is between Tarawa and Maiana (islands 2 and 3 in Fig. 2). This gap is the narrowest and is purely zonally oriented. The acceleration of the SEC through this gap can also be described as a Bernoulli effect, with the distinction that the SEC is *not* dynamically constrained to the equator.

On a larger scale, the SEC is reduced downstream (west of the Gilbert Islands) by over 20 cm s^{-1} . The mechanism for this steady state circulation change is as follows (see schematic in Fig. 4): The obstruction of the EUC by the Gilbert Islands drives topographic upwelling immediately west of the islands, which lifts the thermocline. The resultant change in the sea level slope, which mirrors the thermocline, implies a stronger eastward pressure gradient force and hence reduces the westward flow of the SEC given the same prescribed winds. Below, we address the climatological consequences of these island-induced circulation changes and associated zonal and vertical advections.

The considerable reduction of the SEC downstream (west) of the Gilbert Islands occurs at the onset of the equatorial Pacific zonal sea surface temperature (SST) gradient (Fig. 5a) and the sharp salinity gradient defining the eastern edge of the IPWP (Fig. 6). Thus, the Gilbert Islands act to reduce the westward advection of cold SST along the boundary between the Pacific cold tongue and the warm, fresh IPWP. To quantify this effect, we calculated the anomalous surface zonal temperature advection ($-u' \partial T / \partial x$) by applying the anomalous zonal velocity due to the Gilbert Islands (u') to the mean zonal SST gradient ($\partial T / \partial x$) estimated from high-resolution satellite observations (Esaias et al., 1998). The result is a warming effect up to 0.3°C per month over a $\sim 1,000$ -km wide stretch between 160°E and the Gilbert Islands at 173°E (Fig. 5b), which

is equivalent to 34–41% of the mean zonal SST advection in that region. The Gilbert Islands therefore act to maintain a more eastern climatological warm (and fresh) pool boundary than would otherwise be possible or, equivalently, a less expansive cold tongue. Nearly all global climate models (none of which resolve the Gilbert Islands) have a Pacific cold tongue that extends too far west (Solomon et al., 2007; Reichler and Kim, 2008). Since the mean SST in this region is high ($\sim 29^{\circ}\text{C}$) and therefore at or near the convective threshold (Palmer and Mansfield, 1984), this model bias has serious consequences for atmospheric circulation, precipitation, as well as El Niño–Southern Oscillation (ENSO) dynamics (Picaut et al., 1996) both in nature and in the model rendition of global climate (Neale et al., 2008).

The impact of the Gilbert Islands on the horizontal and vertical salinity distribution in the western equatorial Pacific is also considerable and has important consequences for interannual variability. Comparing the simulated salinity changes (Fig. 6a) with observed seasonal salinity sections (Fig. 6b–c) provides two key insights. Firstly, while the model does not capture the steepness of the zonal and vertical salinity gradients relative to observations, the net result of the Gilbert Islands is to improve both of these biases. Within the upper 50 m, the Gilbert Islands act to reduce the mean annual salinity by ~ 0.09 PSS–78 up to 3,000 km west of the islands, increase salinity by ~ 0.06 east of the islands, and increase salinity by ~ 0.04 near the barrier layer at ~ 100 m depth (Fig. 6a). While the local salinity anomalies are relatively small, they translate into very significant changes in gradients, including a 23 (17%) increase in the maximum zonal (vertical) salinity gradient between the simulations without and with the Gilbert Islands. Secondly, while the observed sections indicate broad seasonal displacements of the near–surface salinity field in other regions, *e.g.*, the east–central equatorial Pacific, the sharp salinity front is kept immediately west of the Gilbert Islands throughout the year with limited zonal displacement. Therefore, the

Gilbert Islands appear to contribute to the sharpness of both the zonal and vertical salinity gradients as well as the maintenance of the climatological position of the eastern edge of the IPWP.

4. Discussion

Our model-based evidence in support of the hypothesis that the Gilbert Islands play an important role in defining the warm pool-cold tongue complex motivates at least three lines of inquiry that must be pursued. (1) High-resolution observations of the velocity and thermohaline structure near the Gilbert Islands by way of, *e.g.*, ocean gliders or shipboard ADCP surveys may provide critical observational support of this hypothesis. (2) While the computational requirements may be onerous, a global coupled model with adequate oceanic resolution in the tropics to resolve the Gilbert Islands ($\sim 5 \text{ km}^2$) is necessary to account for all of the feedbacks and fully understand the local and remote impacts of equatorial islands like the Gilberts on the atmospheric circulation. Finally, since our results provide insight into the expected oceanographic and climatic fingerprint of the Gilbert Islands, (3) developing a timeline of the geologic origin and evolution of the Gilbert Islands, particularly in terms of their spatial extent and distribution relative to the equator, would allow informed comparison with paleoclimate records and thus an assessment of their role as drivers of climate change over the past several millions of years, especially for the East African drying that is hypothesized to be related to changes of Indo-Pacific pathways in the deep tropics (Cane and Molnar, 2001). As we live in an era of measured global climate change with low-lying tropical islands such as the Gilberts facing multiple threats—not the least of which is the loss of habitat due to rising global mean sea

level—it is worth pointing out that they themselves also have important effects on productivity and global climate (Murtugudde et al., 1999; Messié et al., 2006; Karnauskas and Cohen, 2012).

It is also an interesting accident of the Earth's evolution that this important region for the coupled climate system, vis-à-vis, the tropical Pacific is constrained by relatively tiny islands on either end of its zonal contrast, presumably the most critical aspect for the ENSO phenomenon. Fundamental to the ENSO growth phase is the zonal advection (Picaut et al., 2001) as well as the vertical structure (Maes et al., 2005) of salinity gradients along the eastern edge of the IPWP. Clearly, large-scale coupled ocean-atmosphere processes take over once the ENSO onset occurs (Bjerknes, 1969) but the eastern edge of the warm pool is a virtual boundary during the recharge phase and its position is likely critical for the entire recharge-discharge process underpinning the ENSO cycle (Wyrtki, 1985; Jin, 1997). Accurate simulation of this feature can thus be expected to be critical for coupled climate process studies or prediction/projection efforts.

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Figure Captions

Figure 1. Overview map of the tropical Pacific Ocean. Annual mean sea surface temperature (SST; °C) averaged over 1982–2014 (Reynolds et al., 2002) indicating the general boundary of the Indo–Pacific Warm Pool (29°C; white line), Gilbert Islands (see Fig. 2 for detail), South Equatorial Current (transparent solid white arrow), Equatorial Undercurrent (hollow white arrow), and Galápagos Islands (far eastern equatorial Pacific).

Figure 2. Real and model Gilbert Islands. High–resolution Terra/MODIS visible satellite image of the Gilbert Islands, Republic of Kiribati in the west–central Pacific Ocean on May 10, 2006. White boxes indicate the islands as implemented in the 5–km ocean model grid. Credit: Jeff Schmaltz, NASA Visible Earth (<http://visibleearth.nasa.gov/view.php?id=75672>).

Figure 3. Observed and simulated equatorial currents. (A) Zonal (east–west) velocity (cm s^{-1}) along the equator (averaged 2°S–2°N) from *in situ* observations, (B) a model simulation with the Gilbert Islands as implemented in Fig. 2, (C) a model simulation without the Gilbert Islands, and (D) the impact of the Gilbert Islands as (B)–(C).

Figure 4. Schematic diagram of the effect of the Gilbert Islands on the steady–state circulation of the equatorial Pacific Ocean. The Gilbert Islands partially obstruct the Equatorial Undercurrent (EUC), resulting in topographic upwelling to their west. This upwelling lifts the thermocline, which is mirrored by a local depression in sea level. The zonal momentum balance of the South Equatorial Current (SEC) is primarily between the frictional force imparted

by the trade winds and the zonal pressure gradient ($\partial p/\partial x$) due to a sloping sea level. The local sea level depression generated by the islands results in a stronger pressure gradient over a broad area west of the islands, slowing the SEC there.

Figure 5. Impact of the Gilbert Islands on SST advection. (A) Profile of SST ($^{\circ}\text{C}$) along the equator from high-resolution satellite observations. (B) Profile of $-u' \partial T/\partial x$, the surface zonal temperature advection anomaly ($^{\circ}\text{C mo}^{-1}$), along the equator due to the anomalous surface zonal current resulting from the Gilbert Islands. Both (A) and (B) are averaged 2°S – 2°N .

Figure 6. Impact of the Gilbert Islands on salinity. (A) As in Fig. 3d, but for salinity (PSU) differences (colors), and with the mean salinity field from the model simulation without the Gilbert Islands (contours). Climatological salinity observations during (B) February and (C) August from an Argo/historical CTD isopycnal mixed-layer climatology. Colored markers in (B) and (C) indicate the position of the sharp salinity front (blue and red signify low and high values of salinity, respectively).

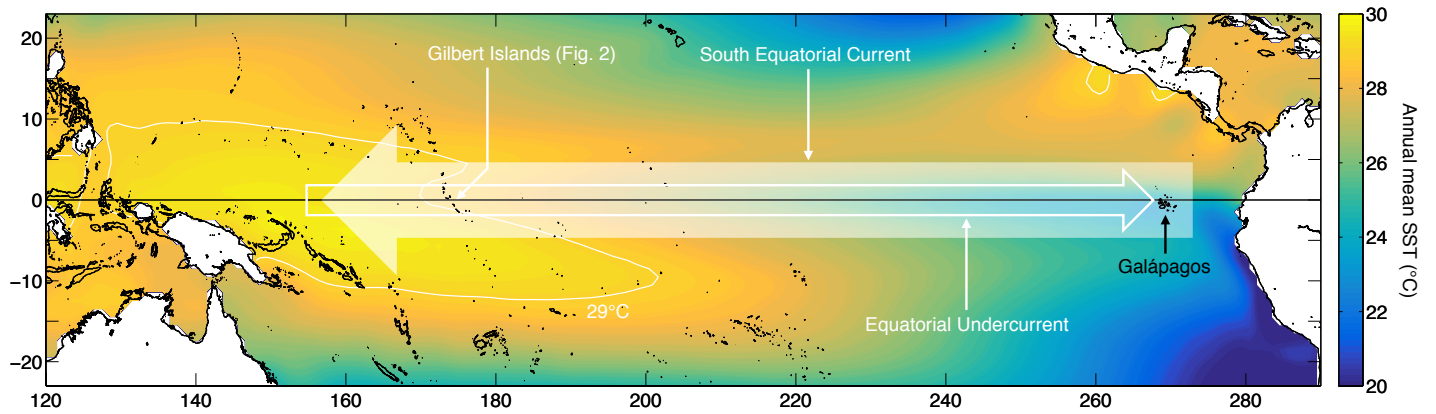


Figure 1. Overview map of the tropical Pacific Ocean. Annual mean sea surface temperature (SST; °C) averaged over 1982–2014 (Reynolds et al., 2002) indicating the general boundary of the Indo–Pacific Warm Pool (29°C; white line), Gilbert Islands (see Fig. 2 for detail), South Equatorial Current (transparent solid white arrow), Equatorial Undercurrent (hollow white arrow), and Galápagos Islands (far eastern equatorial Pacific).

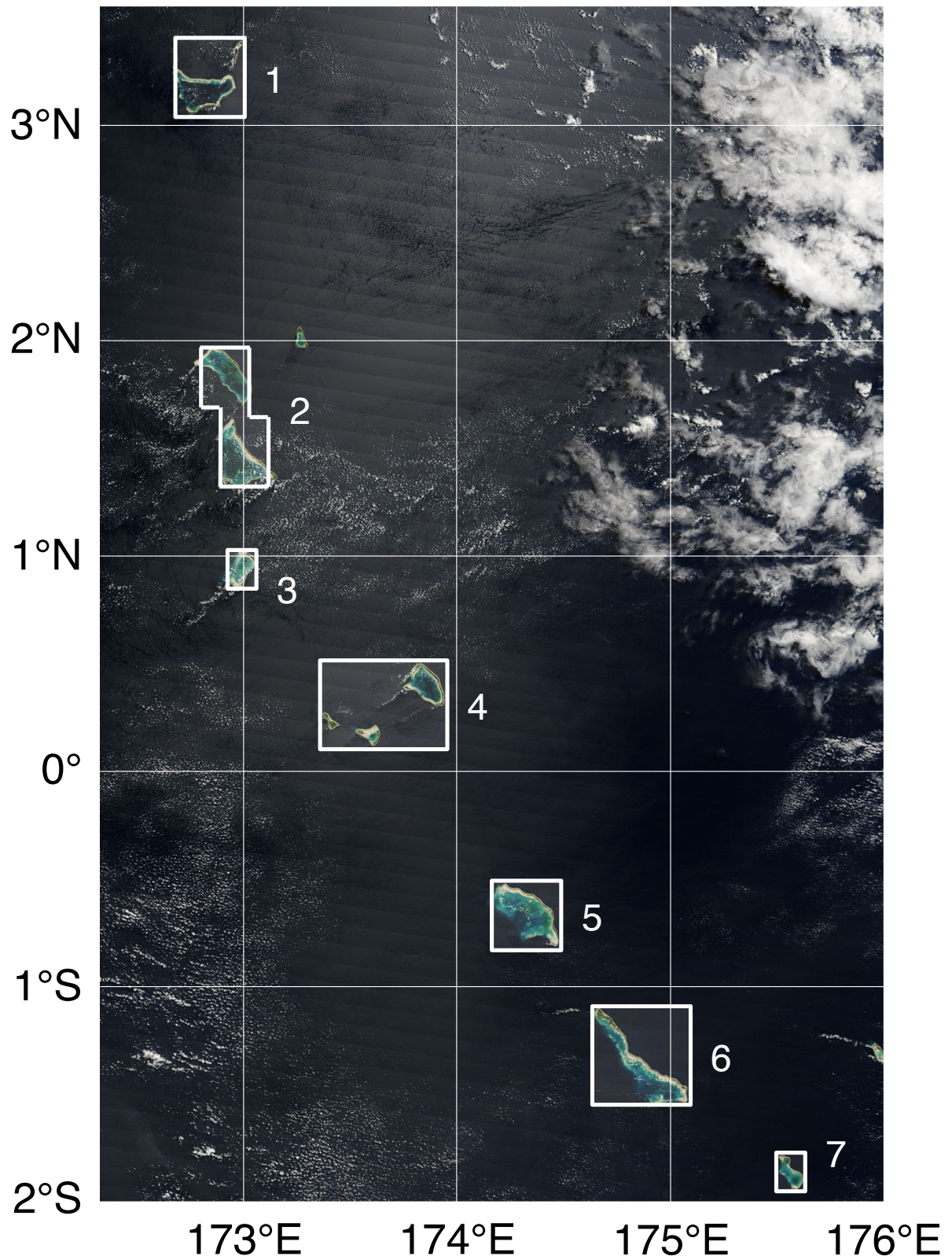


Figure 2. Real and model Gilbert Islands. High-resolution Terra/MODIS visible satellite image of the Gilbert Islands, Republic of Kiribati in the west-central Pacific Ocean on May 10, 2006. White boxes indicate the islands as implemented in the 5-km ocean model grid. Credit: Jeff Schmaltz, NASA Visible Earth (<http://visibleearth.nasa.gov/view.php?id=75672>).

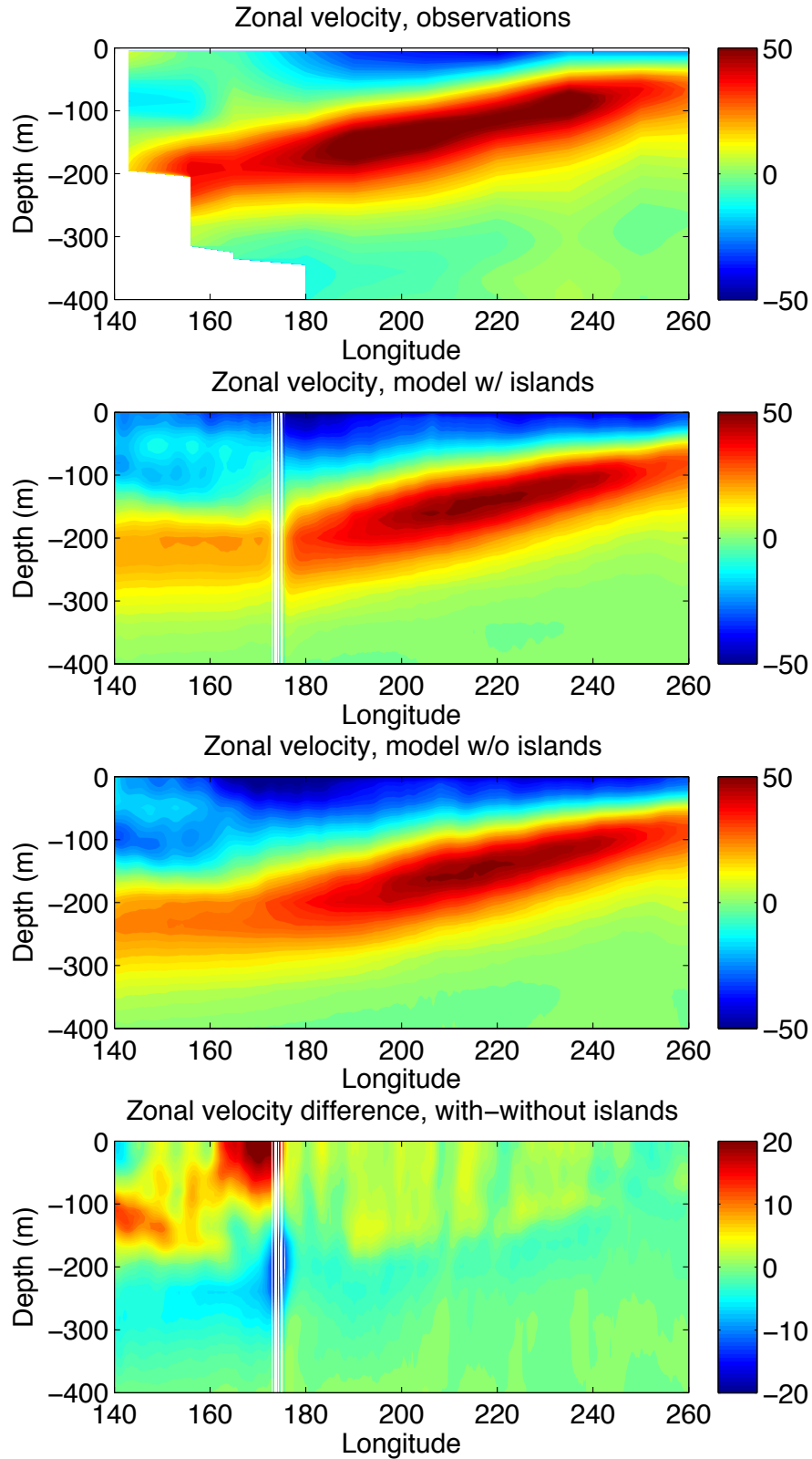


Figure 3. Observed and simulated equatorial currents. (A) Zonal (east–west) velocity (cm s^{-1}) along the equator (averaged 2°S – 2°N) from *in situ* observations, (B) a model simulation with the Gilbert Islands as implemented in Fig. 2, (C) a model simulation without the Gilbert Islands, and (D) the impact of the Gilbert Islands as (B)–(C).

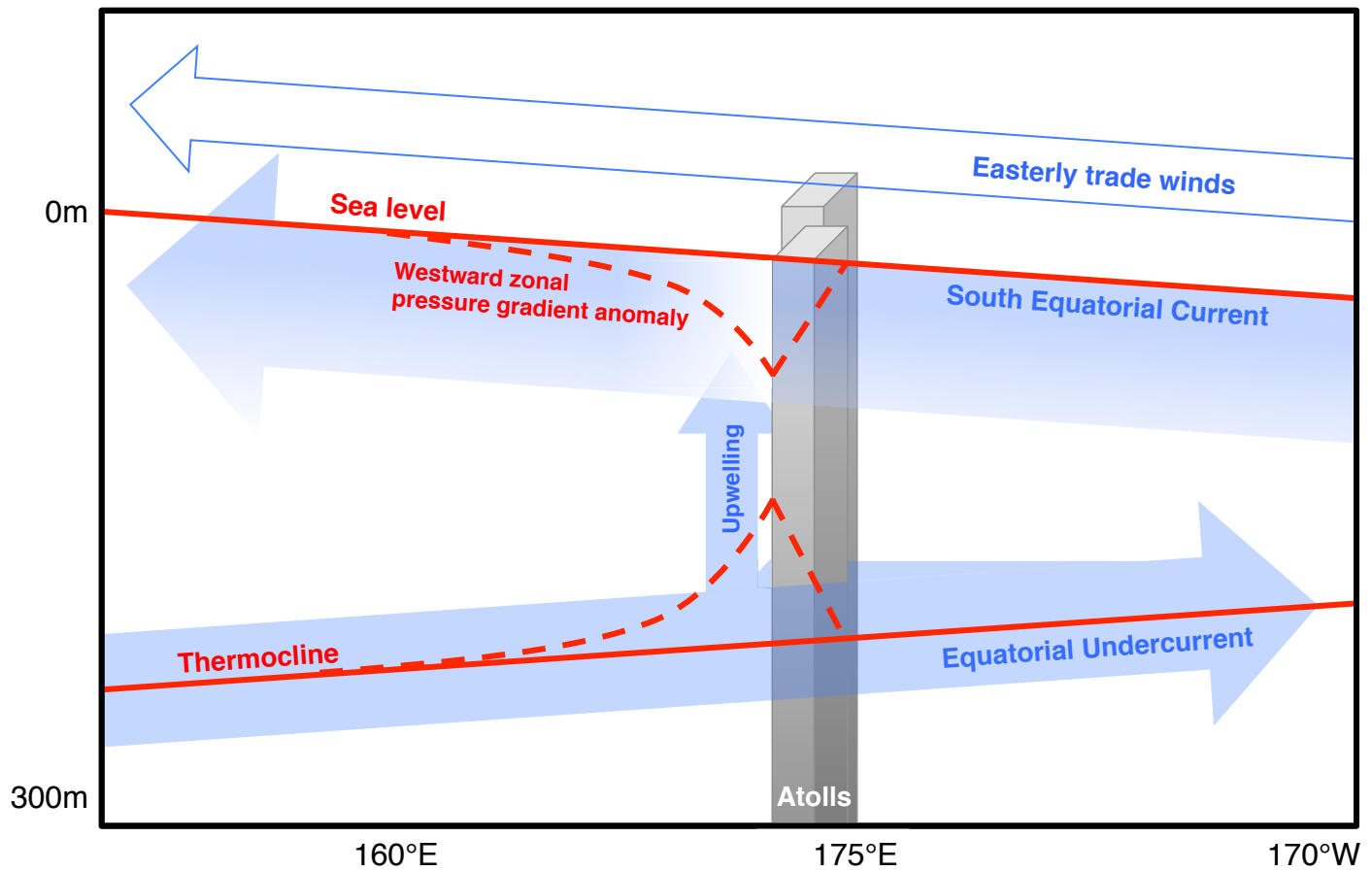


Figure 4. Schematic diagram of the effect of the Gilbert Islands on the steady-state circulation of the equatorial Pacific Ocean. The Gilbert Islands partially obstruct the Equatorial Undercurrent (EUC), resulting in topographic upwelling to their west. This upwelling lifts the thermocline, which is mirrored by a local depression in sea level. The zonal momentum balance of the South Equatorial Current (SEC) is primarily between the frictional force imparted by the trade winds and the zonal pressure gradient ($\partial p / \partial x$) due to a sloping sea level. The local sea level depression generated by the islands results in a stronger pressure gradient over a broad area west of the islands, slowing the SEC there.

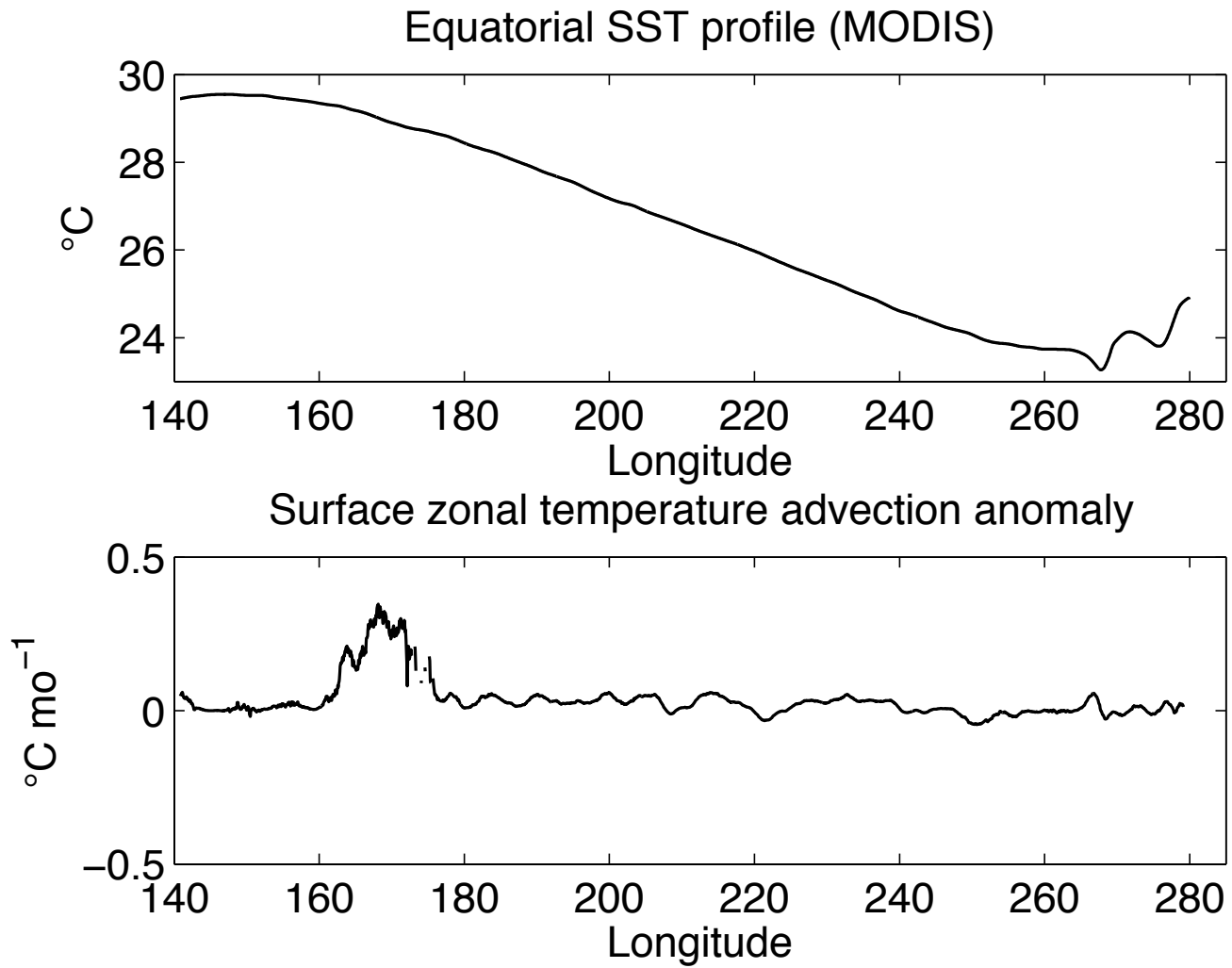


Figure 5. Impact of the Gilbert Islands on SST advection. (A) Profile of SST (°C) along the equator from high-resolution satellite observations. (B) Profile of $-u' \partial T / \partial x$, the surface zonal temperature advection anomaly (°C mo⁻¹), along the equator due to the anomalous surface zonal current resulting from the Gilbert Islands. Both (A) and (B) are averaged 2°S–2°N.

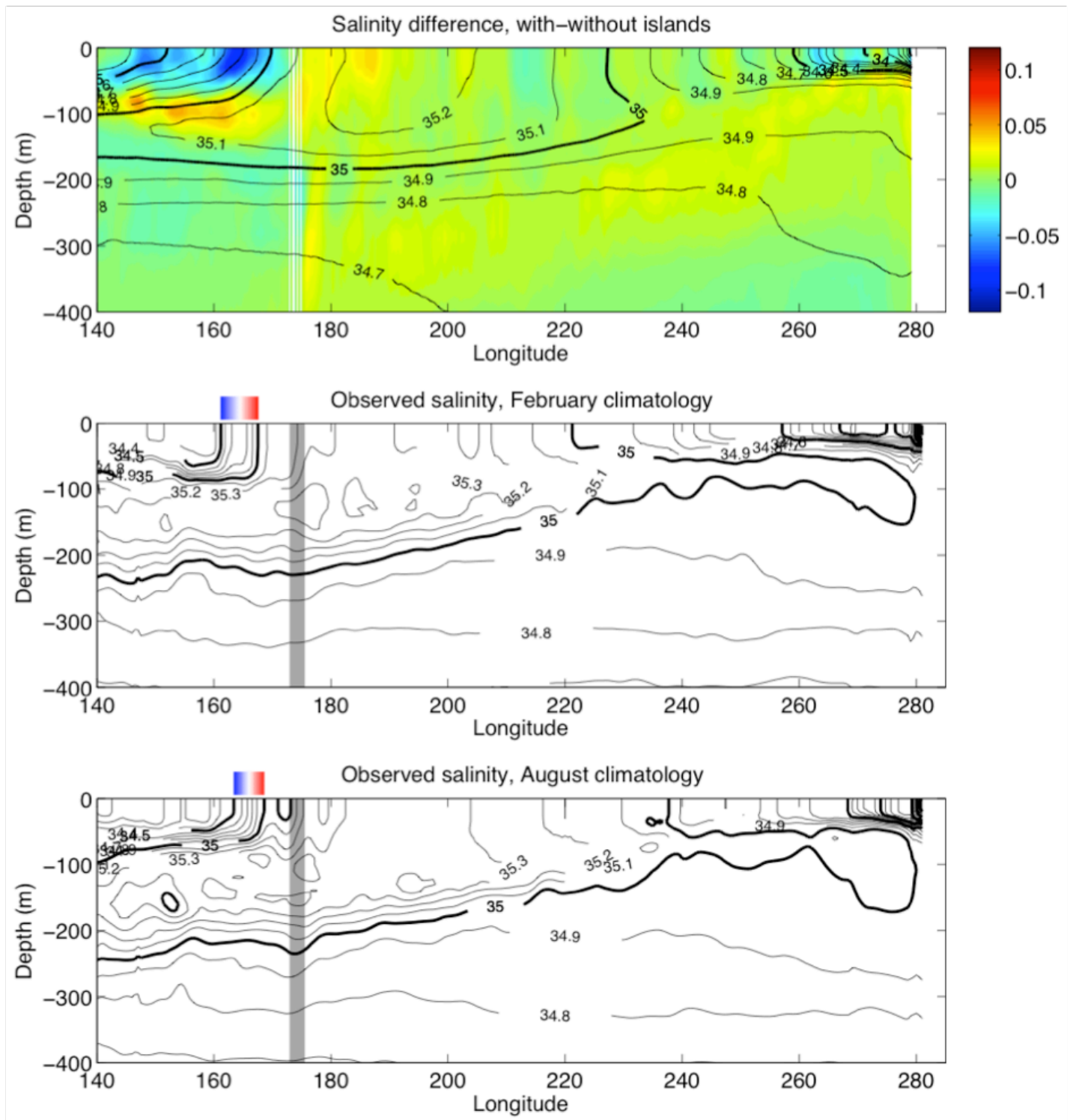


Figure 6. Impact of the Gilbert Islands on salinity. (A) As in Fig. 3d, but for salinity (PSU) differences (colors), and with the mean salinity field from the model simulation without the Gilbert Islands (contours). Climatological salinity observations during (B) February and (C) August from an Argo/historical CTD isopycnal mixed-layer climatology. Colored markers in (B) and (C) indicate the position of the sharp salinity front (blue and red signify low and high values of salinity, respectively).