

Non-tropical Sources of Equatorial Pacific Ocean Heat Content

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Article

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Non-tropical Sources of Equatorial Pacific Ocean Heat Content

Abstract

Ocean heat content in the equatorial Pacific (OHC_{EPac}) is fundamental to ENSO and the associated variations in global weather, marine ecosystems, and the planetary energy budget. While canonical theory focuses on tropical dynamics, non-tropical waters subducted and advected equatorward over years to decades also contribute to OHC_{EPac} but remain poorly constrained. Here, using twenty years of Lagrangian back-trajectories within observationally-constrained ocean data, we identify four non-tropical source regions and decompose the subduction-advection-upwelling pathway linking them to the equatorial Pacific. The dominant subduction process organizes with latitude in a manner that sets the isopycnal pathway and transit time. The net thermal contribution is hemispherically asymmetric: Northern Hemisphere sources cool the equatorial thermocline, whereas Southern Hemisphere sources warm it. Most strikingly, the Southern extratropics – despite subducting at the coldest temperatures of any region – arrive as the warmest contributor. These non-tropical contributions are of comparable magnitude to local ENSO-driven heating. Decomposing the pathways reveals not only a thermally conservative, traceable fraction but also a non-conservative majority, whose transformation along each pathway is structurally predictable. This suggests non-tropical sources may enable predictability of OHC_{EPac} on timescales of years to decades beyond that set by local equatorial forcing.

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1 Introduction

El Niño and the Southern Oscillation (ENSO) is the dominant mode of inter-annual climate variability, with far-reaching consequences for global precipitation patterns, extreme weather events, and ecosystem stability [e.g., 1–3]. The recent 2023–2024 El Niño was driven by an exceptionally strong buildup of ocean heat content in the tropical western Pacific that was independent of the classical tropical Bjerknes feedback [4, 5]. This underscores the need to better understand the physical drivers of the equatorial heat budget, particularly as climate models project such events may become more frequent under continued global warming [4, 5]. More generally, while equatorial Pacific ocean heat content (OHC_{EPac}) is traditionally associated with deep tropical processes [e.g., 6–8], non-tropical sources are known to contribute on inter-annual to decadal timescales [9–12]. Here we apply a Lagrangian backward trajectory framework to assess this remote contribution and characterize the pathways through which it operates.

The equatorial Pacific meridional overturning cells recirculate water within approximately $\pm 10^\circ$ latitude on sub-annuals to inter-annuals timescales [13, 14]. Within this band, equatorial Pacific ocean heat content variability is concentrated in a narrow area (defined here as 5°S – 5°N and 150°E – 275°E ; Figure 1), where inter-annual anomalies in thermocline temperature are largest. Local contributions to these variations are primarily attributed to dynamical mechanisms in the West Pacific Warm Pool region [6]. Anomalous westerly winds in this region intermittently force downwelling equatorial Kelvin waves that propagate eastward and depress the thermocline, producing rapid, sub-annual heat content anomalies [7]. This wind-forced adjustment is one expression of the recharge-discharge oscillator paradigm of ENSO, in which equatorial heat content anomalies build up and decay over the course of the ENSO cycle in response to basin-scale wind stress forcing [8]. Other sub-annual local processes, such as vertical mixing, surface heat flux variability, and zonal advection, also shape OHC_{EPac} [15–17].

Remote contributions to OHC_{EPac} variability arise through oceanic teleconnections between non-tropical subduction regions and the equatorial thermocline, operating on annual to decadal timescales, and have been proposed to modulate equatorial Pacific variability [10, 18–21]. This remote connection operates through a subduction-advection-upwelling pathway, illustrated schematically in Figure 1. Specifically, water parcels are subducted at the base of the seasonal mixed-layer into the permanent thermocline, advected equatorward in the ocean interior along three-dimensional pathways over periods of years to decades, and ultimately upwell into the equatorial thermocline [18, 20]. Heat anomalies imported to the equatorial thermocline by this subduction-advection-upwelling pathway have the potential to directly influence OHC_{EPac} [18, 20]. However, the efficiency and trajectory-dependence of these remote contributions remain incompletely understood.

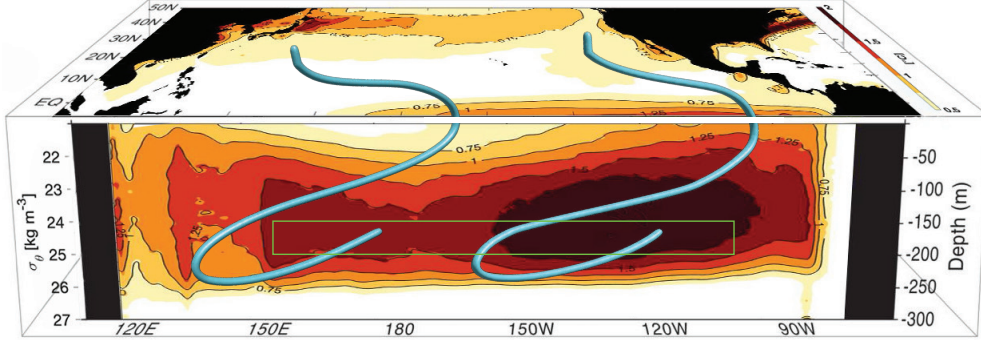


Fig. 1 Inter-annual variability of equatorial thermocline conservative temperature (1980–2018) shown along the horizontal plane (latitude–longitude) and the vertical section (depth–longitude) of the equatorial box (5°S–5°N, 150°E–275°E). 3D subduction-advection-upwelling pathways are illustrated in blue lines. Data taken from SODA3.3.2 reanalysis.

The ventilated thermocline theory provides the theoretical basis for how the main thermocline in subtropical ocean gyres is formed and maintained [18]. Within this framework, we define the subduction flux as the transfer of water parcels from the base of the mixed-layer into the thermocline, representing the primary mechanism by which the ocean interior is ventilated [22]. This flux depends on three main physical processes: (i) wind-driven Ekman pumping, whereby vertical motion is driven by the wind stress curl and modulated by the Coriolis parameter [23]; (ii) the seasonal deepening of the mixed-layer, where predominantly late-winter conditions are permanently subducted into the thermocline as earlier anomalies are erased by spring re-stratification [24]; and (iii) lateral induction over a sloping mixed-layer base, which transports water horizontally from the base of the mixed-layer into the ocean interior [22, 25]. Additional factors, such as bathymetric constraints, boundary effects, and mesoscale eddies, also influence subduction but generally produce only localized effects [22, 25].

Indeed, modeling and observational studies have established that extra-tropical subduction can deliver thermal anomalies to the equatorial thermocline along three-dimensional pathways, as depicted in Figure 1 [e.g., 9–11, 18]. Once in the ocean interior, adiabatic transport is often assumed, whereby water parcels conserve their thermohaline properties along isopycnal pathways [e.g., 9–11, 18–21, 26]. In practice, however, parcels are subject to isopycnal stirring by mesoscale eddies and diapycnal mixing, which can progressively modify their thermohaline properties along the pathway [11, 12, 27].

Despite the theoretical basis connecting extra-tropical subduction to the equatorial region, the extent to which these pathways effectively contribute to the equatorial heat content, and whether the thermal properties of advected parcels are indeed conserved, remain largely unresolved. Because subduction and interior transport are governed by robust, quasi-stationary circulation features [13, 20, 28, 29], we characterize their climatological pathways and thermal signatures as the physical ground through which non-tropical sources could shape OHC_{EPac} variability. We do so using Lagrangian back-trajectory analysis of ocean reanalysis data, addressing the following questions:

1. What mechanisms regulate the subduction flux in non-tropical source regions?
2. How well are the thermohaline properties of subducted parcels conserved along the subduction pathways?
3. What is the contribution of non-tropical subduction pathways to OHC_{EPac} ?

We find strong regional heterogeneity across remote influences on OHC_{EPac} that can fundamentally diverge from canonical theory, with implications for ENSO theory and predictability.

2 Results

The results are organized around the three research questions outlined above. We first identify the key source regions (Section 2.1) and the physical mechanisms regulating subduction flux (Section 2.2). We then examine the validity of the adiabatic transport assumption along subduction pathways (Section 2.3). Finally, we assess the contributions of the non-tropical source regions to OHC_{EPac} (Section 2.4).

2.1 Non-Tropical Source Regions

The source subduction map (SSM), illustrating the origin of water parcels obducting in the equatorial thermocline, is shown in Figure 2a. Consistent with previous works [11, 26, 30], the key remote source regions of upwelled equatorial thermocline water are generally concentrated along the edges of the subtropical gyres, which we separate here into four distinct source regions, as shown in Figure 2b: Northern Extratropics-West (NXW), Northern Extratropics-East (NXE), Southern Subtropics (ST), and Southern Extratropics (SXT). Approximately 60% of the particles that resurface are advected from these gyre-edge regions.

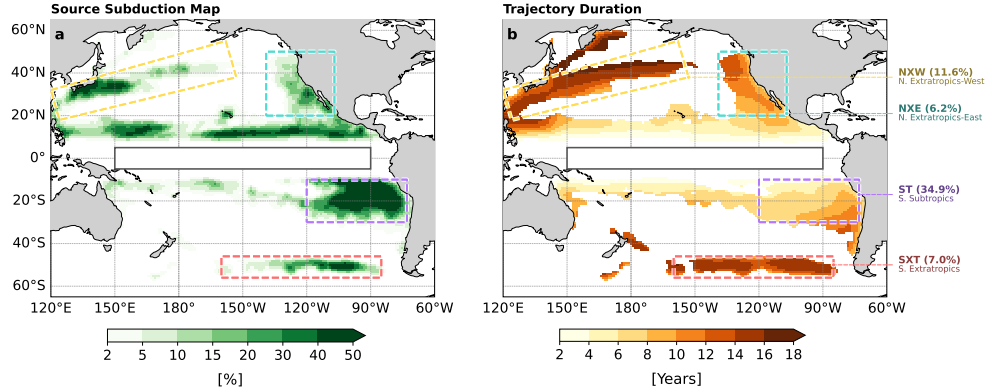


Fig. 2 (a) Source Subduction Map (cumulative probability density function, Eq. 3 in Methods) of source regions for upwelled equatorial thermocline water. Subduction points are binned into a regular $1^\circ \times 1^\circ$ grid and exclude particles not crossing 10° . (b) Mean trajectory duration. Data taken from SODA for 1980–2018.

Among the four regions, ST is the largest contributor, accounting for 34.9% of the particles, consistent with previous studies identifying the eastern subtropical South Pacific as a dominant source of water ventilating the equatorial thermocline [11]. NXW follows as the next largest contributor, at 11.6%, while NXE and SXT each account for a comparatively smaller share (6.2% and 7.0%, respectively). Of the remaining particles, 22% subduct within the northern subtropical band between 10–19°N. However, because this band is identified with the shallow characteristics of the tropical overturning cell rather than a genuine non-tropical source (Supplementary Figure 1), it lies outside the scope of this study’s objective and is therefore not included in our analysis. The remaining contributions are distributed across the basin, concentrated mostly along the equatorward edge of the South Pacific subtropical gyre.

The mean trajectory duration from subduction to equatorial obduction is shown in Figure 2b. Travel times vary systematically across source regions, spanning approximately 3 years for ST to approximately 20 years for SXT and NXW, with intermediate durations of 8–14 years for NXE [cf. 11, 26]. Importantly, travel times are primarily controlled by advection within the anticyclonic subtropical gyre circulation rather than by the meridional distance from the equator, underscoring the role of the large-scale circulation in setting the characteristics of tropical–extratropical ventilation.

2.2 Dominant Mechanisms Regulating Subduction Flux

Having established the spatial distribution of source regions and their associated travel times, we now turn to the key mechanisms driving subduction within each region. The subduction flux (W) is estimated as the entrainment velocity at the base of the mixed-layer (h), summed across its three physical contributions, multiplied by the grid cell weighted area A [25]:

$$W = -\underbrace{\partial_t h \cdot A}_{W_d} + \underbrace{\mathbf{u}_h \cdot \nabla h \cdot A}_{W_{\text{ind}}} + \underbrace{w_h \cdot A}_{W_{\text{Ek}}} \quad (1)$$

where W_d represents the seasonal deepening or shoaling of the mixed-layer associated with the seasonal buoyancy cycle (positive for deepening), W_{ind} represents lateral induction, i.e., the advection of water across a sloping mixed-layer base, and W_{Ek} represents the residual vertical flux at the base of the mixed-layer diagnosed from mass conservation in SODA, and consistent with Ekman pumping computed independently from the wind stress curl [25, 31, 32]. With this convention, W is positive upward for obduction and negative for subduction.

The seasonal thermocline, which forms and erodes within the annual cycle, does not contribute to long-term water mass modifications. Only water subducted into the permanent thermocline, below the maximum mixed-layer depth (MLD), is retained for multi-year transport [18, 24, 33]. Following the Stommel demon framework [24], in which late-winter subduction dominates this permanent ventilation, W is evaluated at the timing of peak MLD, computed independently at each grid cell rather than assumed from a fixed calendar window. Consistent with previous works, this peak was found to occur within January–March and July–September for the northern and southern hemisphere, respectively [11, 26].

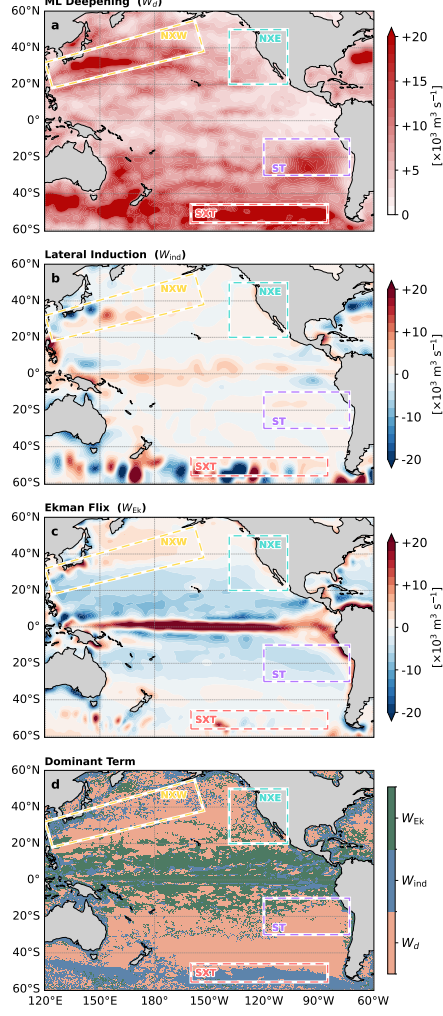


Fig. 3 Decomposition of the subduction flux (Eq. 1) into (a) winter mixed-layer deepening W_d , (b) lateral induction W_{ind} , (c) Ekman flux W_{Ek} at the base on the mixed-layer, and (d) dominant subduction term.

Decomposition of W into these three terms (Figure 3) reveals a coherent, latitudinal shift in the dominant subduction mechanism across the four source regions. Seasonal mixed-layer deepening (W_d , Figure 3a) contributes positively everywhere, reflecting late-winter re-stratification, strongest at the extra-tropical regions NXW and SXT where the seasonal cycle in surface heat flux and wind stress is most pronounced [34, 35].

Lateral induction (W_{ind} , Figure 3b) is generally weak across the basin, as it requires both a significant mixed-layer slope and a current traversing it, conditions met primarily in the extra-tropics, where the Kuroshio Extension [36, 37] and the Antarctic Circumpolar Current [38] traverse a steeply sloping mixed-layer base. At both regions

(NXW, SXT), the resulting mixed-sign pattern in W_{ind} reflects the highly variable structure of the mean current, a signature of the strong mesoscale eddy activity on these current systems [39].

Ekman flux (W_{Ek} , Figure 3c) is positive along the equator, where the easterly trade winds drive Ekman transport poleward on either side of the equator, producing surface divergence that draws subsurface water upward [e.g., 20, 40]. Poleward of this band and up to roughly 40° latitude, W_{Ek} turns negative, consistent with the negative wind stress curl between the easterly and westerly wind regimes, driving Ekman convergence and subduction across the subtropical source regions. The subtropical subduction regions are subtended by weak obduction in the northern extratropics, and generally weak subduction in the southern extratropics.

Assigning each grid point a dominant term from the rhs of Eq. (1), Figure 3d reveals a clear latitudinal regime shift in the mechanism driving subduction across the Pacific source regions. In the tropical region, W_{Ek} dominates, driving cross-isopycnal subduction through wind-forced downwelling at the mixed-layer base. The influence of W_d intensifies poleward from the subtropics (NXE, ST) into the extra-tropics (NXW, SXT), where it is reinforced by W_{ind} and drives progressively deeper entry onto steeply dipping isopycnals. The dominant subduction mechanism in each source region determines not only the rate of thermocline ventilation, but also the depth and the isopycnal layer at which each region’s water subducts. This, in turn, establishes its initial condition, fixing both the pathway along which it is advected and the thermohaline signal it may ultimately imprint on the equatorial thermocline.

In summary, a latitudinal regime shift in subduction mechanism sets distinct initial condition for each source region, which, as described below, shapes their differing contributions to the equatorial thermocline.

2.3 Thermohaline Conservation Along T-S Trajectories

The heterogeneity in subduction mechanism identified above is manifested in the resulting thermohaline trajectories, shown in Figure 4. The mean subduction-advection-upwelling trajectory for each source region follows the anticyclonic recirculation around the subtropical gyres (Figure 4a). Significant differences in initial subduction depth are seen across regions (as evident by the trajectory color gradients), as opposed to similar gradual shoaling rates as water parcels from all source regions approach the equator.

The T-S diagrams (calculated using Conservative Temperature Θ and Absolute Salinity S_A ; Figure 4b–e) provide a compact representation of the thermohaline evolution along each pathway, from subduction at the source region mixed-layer base (square markers) to obduction at the equatorial thermocline (circle markers, green boxes in panels b–e and in Figure 1). The three curves in each panel trace lower, middle, and upper pathway duration quartiles (Q_{25} , Q_{50} , Q_{75}). Black lines on the median trajectory (Q_{50}) mark the boundaries of the interior advection phase, identified independently of Θ and S_A from each particle’s speed record (Methods Section 4.5). Within each region the T-S structure is consistent across quartiles, indicating a well-defined pathway geometry.

For the NH extratropical source regions (NXW, NXE; Figure 4b–c), trajectories trace a common structure in T-S space that shifts toward denser, deeper conditions

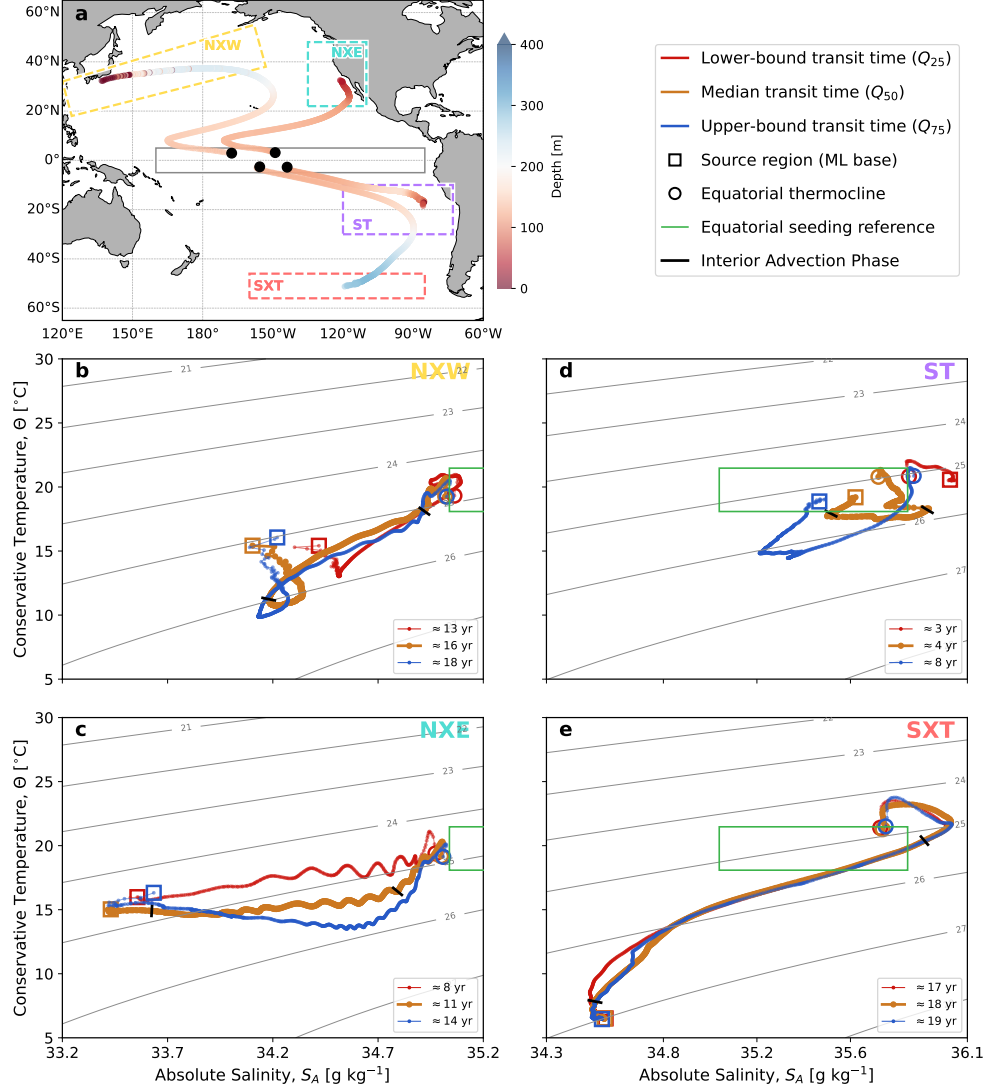


Fig. 4 Thermohaline evolution along the mean subduction-advection-upwelling pathway for each non-tropical source region. **a**, Mean trajectory from source region to the equatorial thermocline, colored by depth [m]. **b–e**, Conservative Temperature–Absolute Salinity (Θ – S_A) diagrams for **b**, NXW; **c**, NXE; **d**, ST; and **e**, SXT, showing the lower-bound (Q_{25}), median (Q_{50}), and upper-bound (Q_{75}) transit times. Square markers denote subduction at the source region mixed-layer base; circle markers denote obduction at the equatorial thermocline. Black ticks mark the boundaries of the dynamic interior advection phase along the median (Q_{50}) trajectory, and the box indicates the equatorial seeding reference. Data taken from SODA3 for 1997–2018.

with increasing duration, consistent with the stratified Pacific interior, where density increases with depth [41]. The difference in the initial salinity for NXW (Figure 4b) is consistent with the strong horizontal gradients across the Kuroshio Extension [36, 37].

The southern subtropical (ST) region (Figure 4d) also exhibits strong differences in salinity at subduction between the quartiles, but this signature arises from double-diffusive convection, in which relatively warm, salty water on the western part of ST intrudes adjacent to cooler, fresher water of similar density on its eastern side [12, 42].

Among all regions, SXT (Figure 4e) exhibits the narrowest quartile spread, reflecting a remarkably consistent transit time and a nearly invariant direct interior pathway to the equator.

It is commonly assumed that, because interior advection occurs without exchanging heat with the atmosphere, large-scale ocean advection is approximately both adiabatic and isopycnal [e.g., 11, 41, 43]. However, the T-S trajectories reveal varying degrees of departure from this assumption across regions. Specifically, the western-northern and southern extratropical regions (NXW, SXT; Figures 4b,d) converge onto the same potential density $\sigma \in [25, 26] \text{ kg m}^{-3}$ layer with Θ and S_A evolving gradually within the layer as parcels are advected equatorward. The eastern northern extratropical region (NXE) follows a different character, generally conserving Θ while σ drifts gradually due to uncompensated changes in S_A , making its transport more isothermal than isopycnal despite relatively small overall density changes. The oscillations visible in the NXE trajectory as parcels approach the equatorial thermocline reflect the strong seasonal cycle of the mixed-layer in tropical latitudes [7, 44]. The southern subtropical region (ST), with its short transit time and proximity to the seeding region, shows the least thermohaline modification en route, positioning it closest to the canonical adiabatic paradigm.

To quantify the degree of thermohaline conservation following subduction, we examine the particle-level distributions of Conservative Temperature change $\Delta\Theta$ (Figure 5a) and potential density change $\Delta\sigma$ (Figure 5d) sustained during the interior advection phase – the less energetic segment of each particle’s trajectory, identified from its speed record independently of temperature and salinity (Methods Section 4.5). The southern subtropical region (ST) and the eastern northern extratropical region (NXE) peak closer to zero in both quantities, indicating that the dominant population arrives with its subduction properties largely preserved. The western northern extratropical region (NXW) exhibits broader and more heterogeneous distributions, consistent with the diverse thermohaline conditions across the Kuroshio Extension, which nevertheless yield small $\Delta\Theta$ and $\Delta\sigma$ on average, comparable to those seen in ST and NXE. In contrast, the southern extratropical region (SXT) shows a sharp coherent shift ($\Delta\Theta \approx +15^\circ\text{C}$, $\Delta\sigma \approx -2 \text{ kg m}^{-3}$), reflecting systematic cross-isopycnal warming and lightening during the equatorward transit. This variability ultimately determines each region’s net contribution to OHC_{EPac} , as explored in the following section.

2.4 Non-tropical Contribution to Equatorial Thermocline Heat Content

The effective thermal contribution of each source region to the equatorial thermocline is captured by the thermal anomaly Θ' : the difference between Θ at the equatorial

window (the point at which each parcel crosses 10° latitude, Θ_{10} ; Figure 5b) and the equatorial thermocline mean (black line in Figure 5b). The equatorial-window distributions of conservative temperature and potential density (Figure 5b,e) reveal a fundamental hemispheric asymmetry in the net thermal contribution to the equatorial thermocline. The NH regions arrive consistently below the equatorial mean, exerting a net cooling influence, regardless of the degree of modification sustained during transit. Their thermohaline structure at the equatorial window (Figure 5b,e) mirrors that at

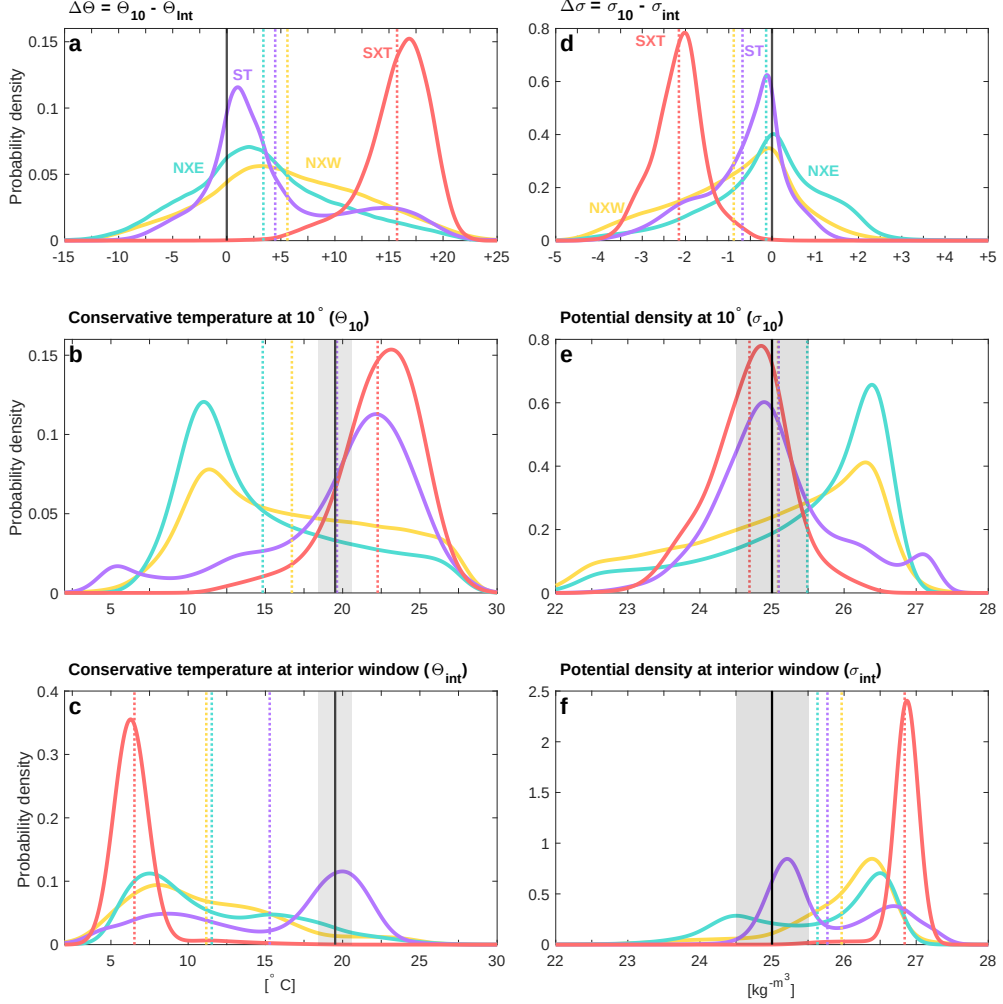


Fig. 5 Conservative Temperature (Θ , left column) and potential density (σ , right column) distributions. (a,d) Change in Θ and σ between (c,f) the interior subduction stage and (b,e) the equatorial thermocline entry window. Dotted vertical lines indicate the ensemble mean for each region. The vertical black line and gray shading indicate the mean and ± 1 standard deviation of the equatorial thermocline Θ and σ evaluated at the seeding region.

the interior window (Figure 5c,f), which marks the start of the interior advection phase (Figure 5c,f), right after subduction, indicating that the distribution heterogeneity is inherited from the source region and preserved throughout the interior pathway.

In contrast, the SH regions arrive at or above the equatorial thermocline mean, despite subducting at temperatures far below it. For the southern subtropical region (ST), the bimodal structure present at the interior window (Figure 5c,f) is inherited directly from double-diffusive convection within the source region [12, 42]. The larger, warmer sub-population pulls the mean of the combined distribution close to the equatorial mean. This, and its dominant share of the remote subduction flux ($\sim 35\%$ of the SSM), suggest that it has an important role in regulating the equatorial thermocline's background thermal state.

The southern extratropical region (SXT) subducts at the coldest temperatures of all source regions (Figure 5c), yet arrives at the equatorial thermocline the warmest (Figure 5b). As SXT parcels travel equatorward through the stratified Southern Ocean, they undergo systematic cross-isopycnal lightening and warming before entering the ST corridor, where double-diffusive mixing delivers the final transformation of this cold subduction signal into a warm contribution to the equatorial thermocline [42, 45–47]. Thus, surprisingly, the Southern Ocean, long regarded as a potential source of cold thermocline water, is found to be a net supplier of warm anomalies to the equatorial Pacific.

The sign and magnitude of each region's thermal contribution depends not only on Θ' , but also on the mass flux it delivers. We therefore quantify each region's effective contribution to OHC_{EPac} as Θ' weighted by the effective subduction flux, $f_{\text{SSM}} =$

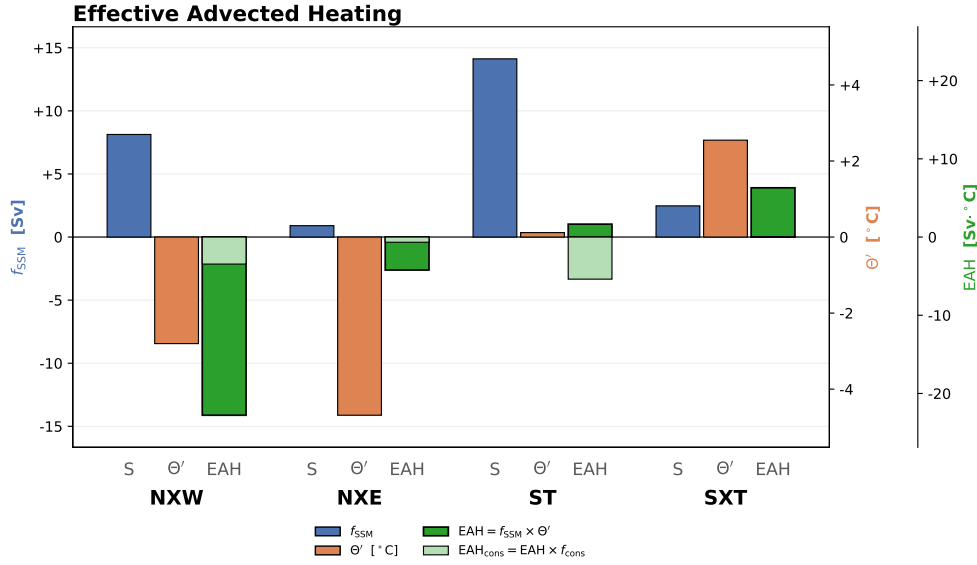


Fig. 6 Effective Advected Heating (EAH) by non-tropical source region. Positive (negative) EAH values indicate net warming (cooling) of the equatorial thermocline. All quantities are summarized in Table 1.

$W \times \text{SSM}_{\%}$, where W is the climatological subduction flux (Figure 3) and $\text{SSM}_{\%}$ is each region’s fractional contribution to the SSM (Figure 2a). The product of f_{SSM} and Θ' provides a measure of the Effective Advected Heating

$$\text{EAH} = f_{\text{SSM}} \times \Theta' \quad (2)$$

of the equatorial Pacific by the remote sources [26]. Figure 6 shows the effective subduction flux (blue bars), temperature anomalies (orange bars), and EAH (saturated green bars) by the four source regions.

The EAH ranges from -21.5 to $+5.6 \text{ Sv} \cdot ^\circ\text{C}$ across the four regions (Table 1). This range is consistent with estimates by McPhaden and Zhang [40] and Zhang and McPhaden [48], who linked $\sim 7\text{--}13 \text{ Sv}$ anomalies in pycnocline transport into the equatorial Pacific belt to a 0.8°C shift in equatorial SST – equivalent to $5.6\text{--}10.4 \text{ Sv} \cdot ^\circ\text{C}$. A comparable transport magnitude for this same region ($5^\circ\text{S}\text{--}5^\circ\text{N}$, $120^\circ\text{E}\text{--}80^\circ\text{W}$) is reported by Meinen and McPhaden [49], who estimate net warm water volume inflow of $5\text{--}15 \text{ Sv}$ during the recharge phase of the ENSO cycle. This is corroborated by Bosc and Delcroix [50], who derive comparable-magnitude net meridional transport anomalies entering the same equatorial band from satellite altimetry, reaching approximately 60 Sv during the 1997–98 El Niño, in close agreement ($R=0.91$) with the *in situ* transport estimates of Meinen and McPhaden [49]. The EAH values identified here are therefore within the range of independently estimated ENSO-related transport magnitudes.

The thermally conservative fraction adds a further, independent layer of information. Specifically, light green bars in Figure 6 show the portion of EAH attributable to thermally conservative trajectories (EAH_{cons}), defined here as EAH by particles satisfying $|\Delta\Theta| < 1.0^\circ\text{C}$ (i.e., smaller than the equatorial thermocline natural variability of $\sim 1.1^\circ\text{C}$). The sensitivity of this classification to the choice of threshold is reported in Supplementary Table 1; all quantities are summarized in Table 1. Since the SSM itself differs somewhat between ocean reanalyses and initial seeding depth (Supplementary Figures 2 and 3), the exact f_{SSM} values may shift accordingly, though the general pattern is robust across reanalysis products.

Consistent with theory, despite the ST region’s net warming contribution, the conservative fraction of ST carries a cooling anomaly ($\Theta'_{\text{cons}} = -2.5^\circ\text{C}$), reflecting the bimodal structure of ST’s arrival temperature distribution in which the conservative sub-population corresponds to the cooler of the two modes. The survival of a coherent

Region	W [Sv]	Θ' [$^\circ\text{C}$]	f_{SSM} [Sv]	EAH [$\text{Sv} \cdot ^\circ\text{C}$]	f_{cons} [%]	Θ'_{cons} [$^\circ\text{C}$]	EAH_{cons} [$\text{Sv} \cdot ^\circ\text{C}$]
NXW	66.1	−2.8	7.7	−21.5	6.3	−6.8	−3.3
NXE	12.5	−4.7	0.8	−3.6	9.6	−7.7	−0.6
ST	50.3	+0.1	17.5	+2.1	15.3	−2.5	−6.7
SXT	31.3	+2.5	2.2	+5.6	0.0	—	0.0

Table 1 Effective Advected Heating (EAH) and conservative fraction for each source region. W : climatological subduction flux; f_{SSM} : SSM-weighted flux; Θ' : mean arrival temperature anomaly relative to equatorial thermocline mean; f_{cons} : thermally conservative fraction ($|\Delta\Theta| < 1.0^\circ\text{C}$); Θ'_{cons} : arrival temperature anomaly of the conservative subset.

thermal anomaly over multi-year-to-decadal advection, largely unmodified by mixing, is itself remarkable. While the thermally conservative fraction is small in most regions, ST delivers a substantial conservative flux, and even the more modest contributions from NXW and NXE represent traceable, subduction-imprinted signals that persist from source to equator largely intact. Anomalies reaching the equator today therefore partly reflect conditions set at non-tropical source regions years to decades earlier, a signal that could in principle be monitored at its source well before it reaches the equatorial thermocline, pointing to a potential predictive handle on equatorial heat content variability.

3 Discussion

Equatorial Pacific thermocline heat content is shaped by both local air-sea interaction and by water subducted years to decades earlier at non-tropical latitudes and carried equatorward through the three-dimensional interior ocean circulation. Using twenty years of Lagrangian back-trajectories seeded at the equatorial thermocline, we have traced these remote contributions to their source regions, quantified the mechanisms governing subduction, and assessed each region’s net thermal contribution to the equatorial thermocline.

The dominant subduction mechanism shifts systematically with latitude, from Ekman pumping in the tropics through seasonal mixed-layer deepening in the subtropics to lateral induction at extra-tropical latitudes, where the steeply sloping mixed-layer base and energetic mesoscale activity associated with the Kuroshio Extension and the Antarctic Circumpolar Current amplify the induction term (Figure 3). This organization sets the isopycnal depth at which each parcel enters the thermocline and therefore the three-dimensional pathway along which it subsequently travels to the equator, with direct consequences for transit time, thermohaline modification, and the thermal anomaly ultimately delivered to the equatorial thermocline.

Once subducted, canonical theory assumes that interior advection conserves each parcel’s thermohaline properties, carrying it toward the equator approximately adiabatically and along isopycnals. The T-S trajectories (Figure 4) show this assumption holds only partially, and to different degrees across regions. The southern subtropical region (ST), with its short transit time and proximity to the seeding region, sustains the least modification and sits closest to the canonical adiabatic paradigm; the northeastern extratropical region (NXE) conserves its temperature while its density drifts, making its transport more isothermal than isopycnal; and the northwestern extratropical region (NXW), despite a more heterogeneous pathway, undergoes modification comparable in magnitude to ST and NXE. The southern extratropical region (SXT) undergoes the clearest departure from the canonical paradigm of extra-tropical ventilation identified in this study.

A fundamental hemispheric asymmetry emerges in the net thermal contribution to the equatorial thermocline (Figure 5b). NH source regions deliver water cooler than the equatorial mean, exerting a net cooling influence established at subduction (EAH of -21.5 and -3.6 Sv $\cdot^{\circ}\text{C}$ for NXW and NXE, respectively), while SH sources deliver water above the equatorial mean ($+2.1$ and $+5.6$ Sv $\cdot^{\circ}\text{C}$ for ST and SXT). The most striking

expression of this asymmetry is SXT, which subducts at the coldest temperatures of any source region yet arrives at the equatorial thermocline as the warmest contributor, driven by systematic cross-isopycnal lightening during equatorward transit through the Southern Ocean and the final transformation within the double-diffusive ST corridor. The Southern Ocean therefore functions not as a cold water supplier to the equatorial thermocline but as a net source of warm anomalies, contradicting the expectation that high-latitude subduction pathways cool the equatorial Pacific.

The thermally conservative fraction of the subducted flux carries a further and independent significance. Only 6–15% of the flux from NXW, NXE, and ST retains its ventilation-imprinted thermal signature intact over the multi-year-to-decadal transit to the equator, yet this fraction is traceable. More broadly, even the non-conservative majority follows well-defined pathways with characteristic transit times and predictable degrees of thermohaline modification, including SXT, such that the arrival temperature distribution of each region is structurally stable and in principle foreseeable. Its origin, transit time, and thermal anomaly are all established at the moment of subduction, years to decades before the corresponding anomaly reaches the equatorial thermocline. Given transit times of a decade or more for NXW or SXT, thermal anomalies subducted in the late 2000s to early 2010s are currently arriving at the equatorial thermocline, actively shaping equatorial heat content. This traceable component constitutes a physically grounded source of predictability on interannual-to-decadal timescales, pointing toward a means of extending the predictability barrier beyond what locally forced equatorial variability alone can provide. For example, this may offer a route around the boreal-spring predictability barrier, the well-documented drop in ENSO forecast skill for predictions [51, 52], when tropical precursors are only weakly expressed. Indeed, recent works have shown that inclusion of extratropical predictors can significantly extend the temporal range and enhance the prediction skills of statistical ENSO prediction models [53–56]

The framework developed here provides a new perspective on non-tropical drivers of equatorial Pacific heat content, with implications for climate variability (i.e., ENSO), model biases [e.g., the Pacific cold-tongue bias; 11, 26, 57], and discrepancies between modeled and observed equatorial warming trends under global warming [58, 59]. The identification of a traceable, subduction-imprinted signal that arrives coherently at the equatorial thermocline years to decades after leaving the surface, suggests that non-tropical subduction pathways are a structurally important component of the equatorial Pacific heat budget. Natural next steps include extending the trajectory integration beyond 20 years to capture the full transit time distribution of the slowest pathways, applying the framework to additional datasets, and moving from the climatological analysis presented here to a time-varying framework. The latter would allow direct quantification of how past surface anomalies, including those associated with natural modes of variability such as the Pacific Decadal Oscillation (PDO) or extreme subduction events, are imprinted on equatorial Pacific heat content today. This would be particularly timely given the projected increase in frequency and intensity of extreme El Niño events under continued global warming [60, 61].

4 Methods

4.1 Ocean Reanalysis Data

We base our analysis on monthly mean data by the Simple Ocean Data Assimilation (SODA) reanalysis, version 3.3.2, during 1980–2018 [$0.5^\circ \times 0.5^\circ$ horizontal resolution, 50 vertical levels; 62]. The main datasets used by SODA3 are the World Ocean Database of historical hydrographic profiles [63] and both *in situ* and remotely sensed SST data [62]. SODA3 reanalyses are based on the Modular Ocean Model, version 5 (MOM5), which is the ocean component of the Geophysical Fluid Dynamics Laboratory CM2.5 coupled model [64]. The specific ensemble member utilized in this study is driven by the atmospheric reanalysis Modern-Era Retrospective analysis for Research and Applications, Version 2 [65].

To assess the sensitivity of our results to the choice of ocean reanalysis, we repeat the analysis using the Copernicus Global Ocean Reanalysis and Simulation (GLORYS12), a global eddy-resolving reanalysis at $1/12^\circ$ horizontal resolution produced by Mercator Ocean International within the Copernicus Marine Environment Monitoring Service [66]. GLORYS12 spans the satellite-altimetry era, 1993–present, which constrains our sensitivity comparison to 1993–2018. We adopt SODA3 as our primary reanalysis due to its longer available record, allowing 20-year back-trajectory integrations vs. five years for GLORYS. The two reanalyses yield qualitatively similar results, suggesting that our results are not sensitive to the choice of reference dataset (Supplementary Figures 2 and 4).

4.2 Lagrangian Back Trajectories

To identify the source regions of ocean water parcels that resurface at the equatorial Pacific, we calculate Lagrangian back trajectories of virtual particles seeded at the equatorial Pacific. The Lagrangian trajectories are integrated backward using the Parcels Lagrangian ocean analysis framework [67] – an open-source tool for tracking oceanic tracers, capable of solving differential equations of motion on any curvilinear grid. Specifically, it integrates an ensemble of virtual passive particles with zero spatial extent within a three-dimensional, time-evolving velocity field. The velocity fields are linearly interpolated to daily resolution, while particle positions and properties are archived at 10-day intervals.

We seed 300,000 particles every month between 1997 and 2018, randomly placed within the equatorial Pacific thermocline layer (5°S – 5°N , 160°E – 275°E , and potential density $\sigma = 24.5$ – 25.5 ; Figure 1, green rectangle). This region captures the core of equatorial thermocline variability across timescales ranging from interannual ENSO cycles [4, 8] to lower-frequency modes such as the PDO [68], and corresponds closely to the equatorial warm water volume that has been established as a key predictor of El Niño onset [49].

Our analysis is thus based on nearly 80 million trajectories, run backward for 20 years. Back integrations are stopped once a particle re-enters the mixed-layer. Particles that are advected to locations with no velocity data (i.e., land), remain fixed at their last valid location and are therefore removed from the analysis.

For consistency with previous works [e.g., 11, 12, 26], we additionally seeded particles at the base of the mixed-layer, defined as the depth where temperature differs from the surface value by more than 0.2K [11]. A density-based criterion of 0.03kg m^{-3} relative to the surface yields qualitatively similar results. The two seeding approaches yield a nearly identical source-region attribution (Supplementary Figure 3). One key difference, however, is that seeding directly within the maximum variability layer bypasses the near-surface potential vorticity barrier described by Harper [10], which otherwise partially inhibits the NH contribution when seeding at the mixed-layer base.

Both random and uniform particle placement within the seeding region yield similar pathways. The relative importance of source regions, however, varies with the zonal position of the seeding region within the equatorial Pacific. Specifically, particles seeded in the western part of the domain reproduce the full source-region distribution reported here, whereas particles seeded in the eastern part receive contributions almost exclusively from subtropical source regions, with extra-tropical pathways largely absent.

To assess the sensitivity of the results to temporal resolution (i.e., our choice of monthly mean fields), we repeated the analysis using pentad velocity fields and daily interpolations. Consistent with previous works, the resulting trajectory statistics and transport pathways are qualitatively similar across the monthly, pentad, and daily analyses, indicating that the identified pathways reflect robust large-scale circulation features that are statistically not sensitive to the influence of ocean eddies on the trajectories [11, 26]. To test our results for tool-dependency, we also reproduced the trajectories using the PaTATO Lagrangian trajectory framework [69] and found negligible differences (not shown).

4.3 Source Subduction Map

We identify each particle’s origin by its re-entry into the mixed-layer along the back trajectory, representing its original subduction point. These subduction points are then used to create probability density functions (PDFs) of particle origins. Consistent with previous works, since we are interested in the non-tropical contribution to the equatorial thermocline, we only consider particles that ventilated beyond 10° latitude [12, 28, 70]. We nevertheless tested boundaries of 8° , 9° , and 10° and found the resulting PDFs to be insensitive to the specific latitude chosen within this range.

This latitudinal criterion excludes most local processes such as re-circulation by the equatorial Pacific meridional overturning cells [13, 14] and the sweeping of particles into the mixed-layer by seasonal variations of the equatorial thermocline [44], thus allowing us to focus on remote contributions. Approximately 30% of particles crossing the 10° latitude criterion do not re-ventilate: 35% subduct to greater depths, while the remainder persist below the thermocline.

The PDFs are generated for each month of seeded particles, calculated by normalizing the number of particles at a subduction point by the total number of particles that ventilated beyond 10° latitude, ensuring that the spatial integration of each PDF equals 1. To represent the spatial distribution of source regions on a linear scale, a two-dimensional cumulative distribution is derived from the aggregate of these monthly PDFs, hereafter referred to as source subduction map (SSM), following Ariel et al. [26].

The SSM at each point (x, y) is defined as:

$$\text{SSM}(x, y) = \int_0^{\text{PDF}(x, y)} \text{PDF}(n) \, dn, \quad (3)$$

where $\text{PDF}(n)$ is the area-weighted PDF expressed as a one-dimensional function sorted by increasing values n . The resulting SSM retain the spatial structure of the PDF while converging to a fixed maximum of 100%, facilitating a clear visualization of key subduction regions using a linear scale [26].

4.4 Conservative Temperature as a Metric of Heat Content

We use Conservative Temperature (Θ) as our primary measure of heat content throughout this study. Under the TEOS-10 framework [71], Θ is defined to be proportional to potential enthalpy, h^0 , such that $\Theta \equiv h^0/c_p^0$, where c_p^0 is a constant reference specific heat capacity. Θ is therefore a direct measure of heat content per unit mass expressed in $^\circ\text{C}$ rather than J kg^{-1} for convenience. We pair Θ with Absolute Salinity (S_A), which quantifies the mass fraction of dissolved material in seawater and, unlike Practical Salinity, accounts for spatial variations in seawater composition, providing a more accurate measure of density-relevant salt content [71].

Water parcels subducted from the mixed-layer into the thermocline are assumed to follow isopycnal surfaces as they are advected toward the equatorial thermocline. Under the additional assumption that diapycnal mixing is negligible along these pathways, parcels conserve their potential enthalpy [43], so that thermohaline anomalies imprinted at subduction are preserved and communicated to the equatorial thermocline. Conservation of Θ and S_A along isopycnal pathways therefore implies that thermohaline anomalies imprinted at subduction persist upon reaching the equatorial thermocline [e.g., 9–11].

Non-conservation results from isopycnal stirring by mesoscale eddies and diapycnal mixing driven by internal wave breaking or double diffusion, both of which can progressively modify a parcel’s thermohaline properties along its pathway [37, 72, 73]. The degree of modification may therefore depend on travel time, as longer pathways accumulate greater exposure to these processes. Similarly, the degree of modification may vary with thermohaline structure encountered en route, with sharp gradients and elevated mesoscale activity amplifying both isopycnal stirring and diapycnal mixing [74]. When these modifications are density-compensated, the original thermal signal is not preserved; instead, it is the spiciness anomaly [75] – the density-compensated thermohaline combination set at ventilation – that propagates as a passive tracer toward the equatorial thermocline [12].

4.5 Interior Advection Phase

Assessing thermohaline conservation during equatorward advection requires that the segment boundaries be defined independently of temperature and salinity. The equatorward boundary is set at $\pm 10^\circ$ latitude, coinciding with the boundary of the equatorial Pacific meridional overturning cells [13, 20], equatorward of which parcels

are subject to equatorial recirculation and mixing. Results are insensitive to the exact choice within the 8° – 10° range.

The poleward boundary is identified dynamically for each particle from its three-dimensional speed $|\mathbf{u}| = \sqrt{u^2 + v^2 + w^2}$, using Otsu’s method [76], an automatic thresholding technique that identifies the cut point separating a one-dimensional distribution into two populations by maximizing the variance between them. Applied to the speed record of single particle trajectory, this cut point separates a comparatively energetic phase, associated with source region subduction, from a calmer phase corresponding to interior advection. The interior segment is then the longest contiguous interval below this threshold, with a 10% tolerance to prevent brief transient excursions from spuriously terminating the segment.

References

- [1] Philander, S. G. El niño, la niña, and the southern oscillation. *International geophysics series* **46**, X–289 (1989).
- [2] McPhaden, M. J., Zebiak, S. E. & Glantz, M. H. Enso as an integrating concept in earth science. *science* **314**, 1740–1745 (2006).
- [3] Santoso, A., Mcphaden, M. J. & Cai, W. The defining characteristics of enso extremes and the strong 2015/2016 el niño. *Reviews of Geophysics* **55**, 1079–1129 (2017).
- [4] Lian, T., Wang, J., Chen, D., Liu, T. & Wang, D. A strong 2023/24 el niño is staged by tropical pacific ocean heat content buildup. *ocean-land-atmo res* 2 (0011) (2023).
- [5] Peng, Q. *et al.* Strong 2023–2024 el niño generated by ocean dynamics. *Nature Geoscience* 1–8 (2025).
- [6] Wyrtki, K. El niño—the dynamic response of the equatorial pacific ocean to atmospheric forcing. *Journal of Physical Oceanography* **5**, 572–584 (1975).
- [7] Kessler, W. S., McPhaden, M. J. & Weickmann, K. M. Forcing of intraseasonal Kelvin waves in the equatorial Pacific. *Journal of Geophysical Research: Oceans* **100**, 10613–10631 (1995).
- [8] Jin, F.-F. An equatorial ocean recharge paradigm for enso. part i: Conceptual model. *Journal of the atmospheric sciences* **54**, 811–829 (1997).
- [9] Gu, D. & Philander, S. G. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science* **275**, 805–807 (1997).
- [10] Harper, S. Thermocline ventilation and pathways of tropical–subtropical water mass exchange. *Tellus A: Dynamic Meteorology and Oceanography* **52**, 330–345 (2000).

- [11] Thomas, M. D. & Fedorov, A. V. The eastern subtropical Pacific origin of the equatorial cold bias in climate models: A Lagrangian perspective. *Journal of Climate* **30**, 5885–5900 (2017).
- [12] Zeller, M., McGregor, S., van Sebille, E., Capotondi, A. & Spence, P. Subtropical-tropical pathways of spiciness anomalies and their impact on equatorial pacific temperature. *Climate Dynamics* **56**, 1131–1144 (2021).
- [13] Lu, P., McCreary, J. P. & Klinger, B. A. Meridional circulation cells and the source waters of the pacific equatorial undercurrent. *Journal of Physical Oceanography* **28**, 62–84 (1998).
- [14] Song, L. *et al.* Tropical meridional overturning circulation observed by subsurface moorings in the western pacific. *Scientific Reports* **8**, 7632 (2018).
- [15] Ballester, J., Bordoni, S., Petrova, D. & Rodó, X. On the dynamical mechanisms explaining the western pacific subsurface temperature buildup leading to enso events. *Geophysical Research Letters* **42**, 2961–2967 (2015).
- [16] Wang, W. & McPhaden, M. J. The surface-layer heat balance in the equatorial Pacific Ocean. Part I: Mean seasonal cycle. *Journal of physical oceanography* **29**, 1812–1831 (1999).
- [17] Wang, W. & McPhaden, M. J. The surface-layer heat balance in the equatorial pacific ocean. part ii: Interannual variability. *Journal of Physical Oceanography* **30**, 2989–3008 (2000).
- [18] Luyten, J., Pedlosky, J. & Stommel, H. The ventilated thermocline. *Journal of Physical Oceanography* **13**, 292–309 (1983).
- [19] Tsuchiya, M., Lukas, R., Fine, R. A., Firing, E. & Lindstrom, E. Source waters of the pacific equatorial undercurrent. *Progress in Oceanography* **23**, 101–147 (1989).
- [20] McCreary, J. P. & Lu, P. Interaction between the subtropical and equatorial ocean circulations: The subtropical cell. *Journal of Physical Oceanography* **24**, 466–497 (1994).
- [21] Liu, Z., Philander, S. & Pacanowski, R. A gcm study of tropical–subtropical upper-ocean water exchange. *Journal of Physical Oceanography* **24**, 2606–2623 (1994).
- [22] Marshall, J. C., Williams, R. G. & Nurser, A. G. Inferring the subduction rate and period over the north atlantic. *Journal of Physical Oceanography* **23**, 1315–1329 (1993).
- [23] Ekman, V. W. On the influence of the earth’s rotation on ocean-currents. (1905).

- [24] Stommel, H. Determination of water mass properties of water pumped down from the ekman layer to the geostrophic flow below. *Proceedings of the National Academy of Sciences* **76**, 3051–3055 (1979).
- [25] Guo, Y. & Wei, M. Interannual variability of isopycnal ocean heat content in the subtropical northeast pacific. *Journal of Geophysical Research: Oceans* **129**, e2024JC020994 (2024).
- [26] Ariel, O., Adam, O., Wolff, M. S. & Gildor, H. Pacific cold tongue bias in cmip5/cmip6 linked to shifts in extratropical subduction zones. *Journal of Climate* **38**, 4463–4473 (2025).
- [27] Schneider, N. A decadal spiciness mode in the tropics. *Geophysical Research Letters* **27**, 257–260 (2000).
- [28] Johnson, G. C. & McPhaden, M. J. Interior pycnocline flow from the subtropical to the equatorial Pacific Ocean. *Journal of Physical Oceanography* **29**, 3073–3089 (1999).
- [29] Schott, F. A., McCreary, J. P. & Johnson, G. C. Shallow overturning circulations of the tropical-subtropical oceans. *Earth Climate: The Ocean–Atmosphere Interaction, Geophys. Monogr* **147**, 261–304 (2004).
- [30] Rodgers, K. B. *et al.* Extratropical sources of equatorial pacific upwelling in an ogcm. *Geophysical research letters* **30** (2003).
- [31] Kim, S.-B., Lee, T. & Fukumori, I. Mechanisms controlling the interannual variation of mixed layer temperature averaged over the niño-3 region. *Journal of Climate* **20**, 3822–3843 (2007).
- [32] Vijith, V. *et al.* Closing the sea surface mixed layer temperature budget from in situ observations alone: Operation advection during bobble. *Scientific reports* **10**, 7062 (2020).
- [33] Williams, R. G., Marshall, J. C. & Spall, M. A. Does stommel’s mixed layer “demon” work? *Journal of Physical Oceanography* **25**, 3089–3102 (1995).
- [34] Vallis, G. K. *Atmospheric and oceanic fluid dynamics* (Cambridge University Press, 2017).
- [35] de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A. & Iudicone, D. Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology. *Journal of Geophysical Research: Oceans* **109** (2004).
- [36] Dong, S. & Kelly, K. A. Heat budget in the Gulf Stream and Kuroshio Extension regions. *Journal of Physical Oceanography* **34**, 1191–1208 (2004).

- [37] Yeager, S. G. & Large, W. G. Observational evidence of winter spice injection. *Journal of Physical Oceanography* **37**, 2895–2919 (2007).
- [38] Orsi, A. H., Whitworth, T. & Nowlin, W. D. On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep-Sea Research Part I: Oceanographic Research Papers* **42**, 641–673 (1995).
- [39] Chelton, D. B., Schlax, M. G. & Samelson, R. M. Global observations of nonlinear mesoscale eddies. *Progress in oceanography* **91**, 167–216 (2011).
- [40] McPhaden, M. J. & Zhang, D. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature* **415**, 603–608 (2002).
- [41] Talley, L. D., Pickard, G. L., Emery, W. J. & Swift, J. H. *Descriptive Physical Oceanography: An Introduction* 6th edn (Elsevier, Boston, 2011).
- [42] Wong, A. P. S. & Johnson, G. C. South pacific eastern subtropical mode water. *Journal of Physical Oceanography* **33**, 1493–1509 (2003).
- [43] McDougall, T. J. Potential enthalpy: A conservative oceanic variable for evaluating heat content and heat fluxes. *Journal of Physical Oceanography* **33**, 945–963 (2003).
- [44] Huang, B., Xue, Y., Wang, H., Wang, W. & Kumar, A. Mixed layer heat budget of the el niño in ncep climate forecast system. *Climate Dynamics* **39**, 365–381 (2012).
- [45] Sun, G., Qi, J., Qu, T. & Yin, B. Variability of the south pacific eastern subtropical mode water and associated causal mechanism during the argo period. *Journal of Geophysical Research: Oceans* (2025).
- [46] Schneider, W., Fuenzalida, R., Rodríguez-Rubio, E., Garcés-Vargas, J. & Bravo, L. Characteristics and formation of eastern south pacific intermediate water. *Geophysical Research Letters* **30**, 1581 (2003).
- [47] Reyes-Macaya, D. *et al.* Isotopic characterization of water masses in the southeast pacific region: Paleooceanographic implications. *Journal of Geophysical Research: Oceans* **127**, e2021JC017525 (2022).
- [48] Zhang, D. & McPhaden, M. J. Decadal variability of the shallow Pacific meridional overturning circulation: Relation to tropical sea surface temperatures in observations and climate change models. *Journal of Climate* **19**, 4097–4114 (2006).
- [49] Meinen, C. S. & McPhaden, M. J. Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña. *Journal of Climate* **13**, 3551–3559 (2000).

- [50] Bosc, C. & Delcroix, T. Observed equatorial Rossby waves and ENSO-related warm water volume changes in the equatorial Pacific Ocean. *Journal of Geophysical Research* **113**, C06003 (2008).
- [51] McPhaden, M. J. Tropical Pacific Ocean heat content variations and ENSO persistence barriers. *Geophysical Research Letters* **30**, 1480 (2003).
- [52] Duan, W. & Wei, C. The ‘spring predictability barrier’ for ENSO predictions and its possible mechanism: results from a fully coupled model. *International Journal of Climatology* **33**, 1280–1292 (2013).
- [53] Shi, L. & Ding, R. Contributions of tropical-extratropical oceans to the prediction skill of enso after 2000. *Atmospheric and Oceanic Science Letters* **13**, 338–345 (2020).
- [54] Chen, H.-C., Tseng, Y.-H., Hu, Z.-Z. & Ding, R. Enhancing the enso predictability beyond the spring barrier. *Scientific Reports* **10**, 984 (2020).
- [55] Tseng, Y.-h., Huang, J.-H. & Chen, H.-C. Improving the predictability of two types of enso by the characteristics of extratropical precursors. *Geophysical Research Letters* **49**, e2021GL097190 (2022).
- [56] Tan, J., Feng, L., Jiang, H., Zhou, Q. & Huang, Y. A new enso statistical prediction model considering extratropical effects and its application to the prediction of the 2015/16 el niño event. *Weather and Forecasting* **39**, 1635–1649 (2024).
- [57] Burls, N. J., Muir, L., Vincent, E. M. & Fedorov, A. Extra-tropical origin of equatorial Pacific cold bias in climate models with links to cloud albedo. *Climate Dynamics* **49**, 2093–2113 (2017).
- [58] Seager, R. *et al.* Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases. *Nature Climate Change* **9**, 517–522 (2019).
- [59] Wills, R. C., Dong, Y., Proistosescu, C., Armour, K. C. & Battisti, D. S. Systematic climate model biases in the large-scale patterns of recent sea-surface temperature and sea-level pressure change. *Geophysical Research Letters* **49**, e2022GL100011 (2022).
- [60] Timmermann, A. *et al.* El niño–southern oscillation complexity. *Nature* **559**, 535–545 (2018).
- [61] Collins, M. *et al.* The impact of global warming on the tropical pacific ocean and el niño. *Nature Geoscience* **3**, 391–397 (2010).
- [62] Carton, J. A., Chepurin, G. A. & Chen, L. SODA3: A new ocean climate reanalysis. *Journal of Climate* **31**, 6967–6983 (2018).

- [63] Boyer, T. P. *et al.* World ocean database 2013 (2013).
- [64] Delworth, T. L. *et al.* Simulated climate and climate change in the gfdl cm2. 5 high-resolution coupled climate model. *Journal of Climate* **25**, 2755–2781 (2012).
- [65] Gelaro, R. *et al.* The modern-era retrospective analysis for research and applications, version 2 (merra-2). *Journal of climate* **30**, 5419–5454 (2017).
- [66] Jean-Michel, L. *et al.* The copernicus global 1/12 oceanic and sea ice glorys12 reanalysis. *Frontiers in Earth Science* **9**, 698876 (2021).
- [67] Delandmeter, P. & Van Sebille, E. The parcels v2. 0 lagrangian framework: new field interpolation schemes. *Geoscientific Model Development* **12**, 3571–3584 (2019).
- [68] Mantua, N. J. & Hare, S. R. The pacific decadal oscillation. *Journal of oceanography* **58**, 35–44 (2002).
- [69] Fredj, E., Carlson, D. F., Amitai, Y., Gozolchiani, A. & Gildor, H. The particle tracking and analysis toolbox (patato) for matlab. *Limnology and Oceanography: Methods* **14**, 586–599 (2016).
- [70] Lee, T. & Fukumori, I. Interannual-to-decadal variations of tropical-subtropical exchange in the Pacific Ocean: Boundary versus interior pycnocline transports. *Journal of Climate* **16**, 4022–4042 (2003).
- [71] McDougall, T. J. & Barker, P. M. Getting started with TEOS-10 and the Gibbs Seawater (GSW) oceanographic toolbox. Tech. Rep., SCOR/IAPSO WG127 (2011).
- [72] Sasaki, Y. N., Schneider, N., Maximenko, N. & Lebedev, K. Observational evidence for propagation of decadal spiciness anomalies in the north pacific. *Geophysical Research Letters* **37** (2010).
- [73] Ledwell, J. R., Watson, A. J. & Law, C. S. Evidence for slow mixing across the pycnocline from an open-ocean tracer-release experiment. *Nature* **364**, 701–703 (1993).
- [74] Thorpe, S. A. *The Turbulent Ocean* (Cambridge University Press, Cambridge, 2005).
- [75] Munk, W. Internal waves and small-scale processes. *Evolution of physical oceanography* (1981).
- [76] Otsu, N. A threshold selection method from gray-level histograms. *IEEE transactions on systems, man, and cybernetics* **9**, 62–66 (1979).

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