PACIFIC OCEAN EQUATORIAL CURRENTS

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Introduction

An essential characteristic of Pacific equatorial ocean currents is that they span the width of the Pacific basin (15 000 km at the Equator), linking to eastern and western boundary flows (**Figures 1** and **2**). While they have long zonal scales, the relatively strong near-equatorial flows have complex vertical and meridional structures. They exhibit energetic variability on timescales from days to years. In particular, the currents of the equatorial Pacific are considerably altered during El Niño/Southern Oscillation (ENSO) events.

These flows are subject to the distinctive physics associated with the equatorward decrease of the vertical component of the earth's rotation vector. The associated vanishing of the horizontal Coriolis force at the Equator results in relatively strong currents for a given wind stress or pressure gradient. Rapid adjustment of the currents to changing forcing is associated with a special class of internal wave motions termed linear equatorially trapped waves. There are several different types of waves with rich meridional and vertical structure, governed by dispersion relationships that tie zonal wavelength, meridional structure, and wave period together. The fastest waves cross the Pacific in only 2–3 months. With greater distance from the Equator, zonal propagation speeds become slower. The key feature is that these waves can transmit the signals of wind forcing to and from remote locations.

The Pacific equatorial surface currents are primarily wind-driven. Local forcing of the equatorial currents is dominated by surface wind stress (as opposed to heat and/or fresh water fluxes) and its variability. Variable wind forcing results in vertical pumping of the thermocline and subsequent dynamic adjustment, including radiation of equatorially trapped waves. The currents are not forced solely by local winds, however, because equatorially trapped waves carry wind-forcing signals across the entire basin, and similar boundary-trapped waves transmit information about forcing between the equator and higher latitudes. An important portion of the equatorial circulation is forced by winds and buoyancy forces (surface heat and fresh water fluxes) far from the equator.

The basic spatial structures and temporal variation of Pacific Ocean equatorial currents are presented here. Because systematic current measurements are available at only a few, widely separated locations, spatial variability is addressed primarily with the ocean assimilation/reanalysis from the US National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction, which combines a general circulation model of the ocean with atmospheric and ocean data to estimate the state of the tropical Pacific Ocean every week. Direct current measurements from several sites along the Equator maintained by the NOAA Pacific Marine Environmental Laboratory are used primarily to address temporal variability.

Mean Flow

Interior Flows

Zonal geostrophic flow, where meridional pressure gradients are balanced by Coriolis forces (due to flow on the rotating earth), dominates over meridional flow in the long-term annual-average Pacific equatorial circulation. In the surface layer (upper 50 m or so), currents directly driven by the generally westward Trade Winds typically flow poleward, superimposed on these strong zonal flows (**Figure 2**). The divergence of poleward-flowing surface currents is most pronounced along the Equator, leading to depth-dependent pressure gradients and strong vertical flow (called equatorial upwelling).

Surface currents The time-averaged surface flows (**Figure 2**) are dominated by the westward South Equatorial Current (SEC; between about 3°N and 20°S) and the North Equatorial Current (NEC; between about 10°N and 20°N). A persistent North Equatorial Countercurrent (NECC) flows eastward across the basin in the narrow band between about 5°N and 10°N. A weaker eastward-flowing South Equatorial Countercurrent (SECC) extends eastward from the region of the western boundary, but this flow only intermittently reaches the central and eastern Pacific.

North–south profiles of surface currents at three different longitudes across the Pacific basin

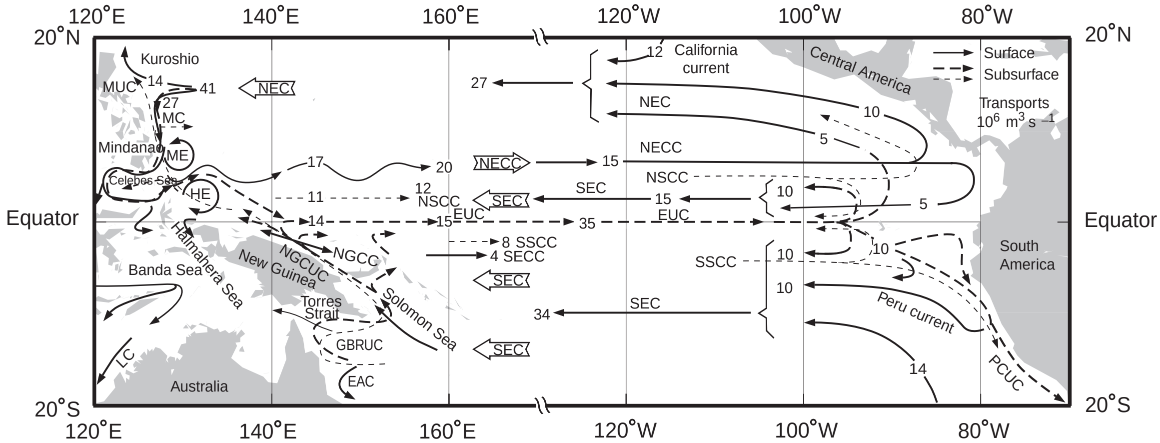

Figure 1 Schematic illustration of the major equatorial currents in the Pacific Ocean and their connections to eastern and western boundary currents. (Note the break in the longitude axis.) Surface currents are indicated by solid lines; subsurface currents are indicated by dashed lines, with deeper currents having lighter weight. Approximate average individual current transports ($10^6\,m^3\,s^{-1}$) are provided where known with some confidence. The equatorial surface currents are the North Equatorial Current (NEC), the South Equatorial Current (SEC), the North Equatorial Countercurrent (NECC), and the South Equatorial Countercurrent (SECC). The subsurface equatorial currents discussed here are the Equatorial Undercurrent (EUC), the Northern Subsurface Countercurrent (NSCC), and the Southern Subsurface Countercurrent (SSCC). Eastern boundary currents are the Peru Current and the Peru–Chile Undercurrent (PCUC). Western boundary surface currents are the Kuroshio, the Mindanao Current (MC), the New Guinea Coastal Current (NGCC) and the East Australia Current (EAC). Subsurface flows along the western boundary are the Mindanao Undercurrent (MUC), the New Guinea Coastal Undercurrent (NGCUC), and the Great Barrier Reef Undercurrent (GBRUC). The Mindanao Eddy (ME) and Halmahera Eddy (HE) are indicated.

clearly show the structure of these major zonal flows (**Figure 3**). The NEC, NECC, and SEC are strongest in the central Pacific where the Trade Winds are strongest. The SEC and NECC are considerably weaker in the west than in the east, reflecting the greater variability of the winds in the western Pacific. Very near the Equator in the central and eastern Pacific, there is a minimum in the speed of the SEC, and the relatively narrow filament of SEC north of the equator is stronger than the flow south of the Equator, except in the west. The SECC occurs between about 3°S and 10°S, but generally dissipates west of the dateline.

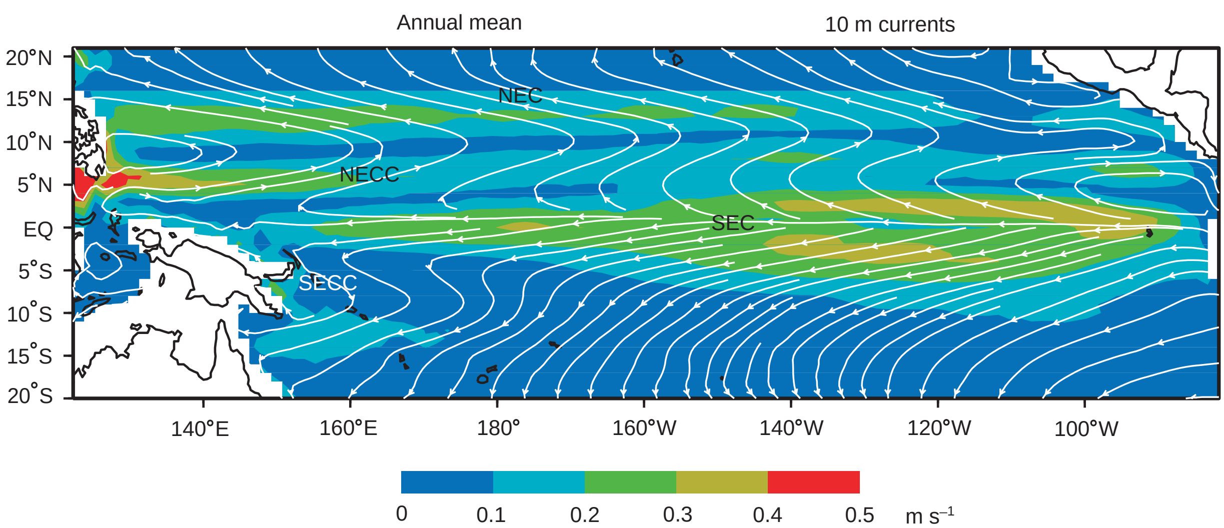

Figure 2 Map of long-term mean surface flow in the tropical Pacific. White lines and arrows indicate the direction of flow, while the colors indicate the speed of flow as given by the color bar. Current names are abbreviated as in **Figure 1**.

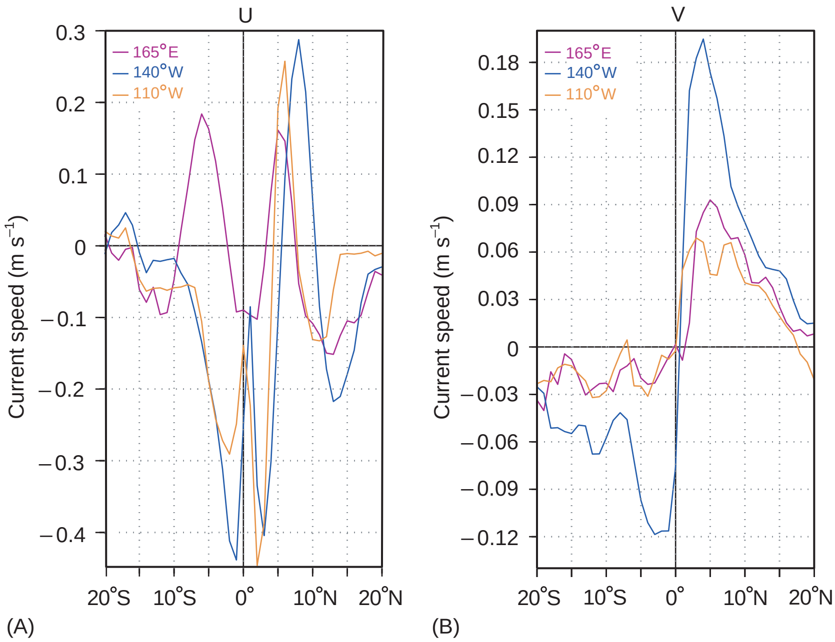

Figure 3 North–south profiles of zonal (A) and meridional (B) current in the western (165°E), central (140°W) and eastern (110°W) Pacific. Positive current is eastward and northward. Note the difference in the velocity scales between the two panels.

The meridional flows are considerably weaker than the zonal flow (**Figure 3**). The average currents have a northward component north of the Equator, and southward to the south of the Equator. The transition occurs rapidly very close to the Equator at all three longitudes, due to east-to-west trade winds and the change in sign of the Coriolis force at the Equator. This divergence causes equatorial upwelling, which is responsible for colder surface temperatures along the Equator than just to the north or south.

Subsurface structure The zonal flow of the NECC is unusual among the surface currents in that it has a subsurface maximum near 50 m (**Figure 4**). This is due to its flowing eastward against the prevailing Trade winds. The directly wind-driven flow vanishes below the mixed layer (usually shallower than 100 m), and currents below are zonally-oriented except near the eastern and western boundaries.

The time-averaged subsurface flows are dominated by the eastward Equatorial Undercurrent (EUC; **Figures 4–6**), which is the strongest equatorial Pacific current, reaching speeds of about 1 m s^{-1} between 120°W and 140°W (**Figures 5** and **6**). The EUC is found within the very strong equatorial thermocline just below the westward SEC (**Figures 4** and **5**). The strong mean shear above the core of the EUC gives rise to strong vertical mixing. Note also the strong meridional shear of the zonal flow on either side of the EUC, and between the SEC and NECC.

Much weaker Northern and Southern Subsurface Countercurrents (NSCC and SSCC) flow eastward below the poleward flanks of the EUC (**Figure 4**). The westward Equatorial Intermediate Current (EIC) is found directly below the EUC across the Pacific. Both the EUC and EIC slope upward toward the east (**Figure 5**), tending to follow shoaling isopycnal surfaces. On the Equator, alternating deep equatorial jets (not shown) are found below the EIC.

The poleward wind-driven meridional flows are mostly confined to the upper 50 m (**Figure 4**). The central Pacific section (**Figure 4E**) shows meridional flow nearly symmetric with respect to the equator, with divergent poleward flow in the near-surface, and convergent equatorward flow near the core of the EUC. This classical picture is not seen in the eastern and western sections, due to a cross-equatorial component of the surface winds, especially in the east.

Boundary Flows

Surface The westward flow of the NEC impinges on the Philippines where it splits near 14°N into a northward-flowing Kuroshio Current and southward Mindanao Current (MC) along the western boundary (**Figures 1** and **2**). The MC has surface speeds exceeding 1 m s^{-1}, and the flow reaches to depths of 300–600 m. The upper 100 m flow splits

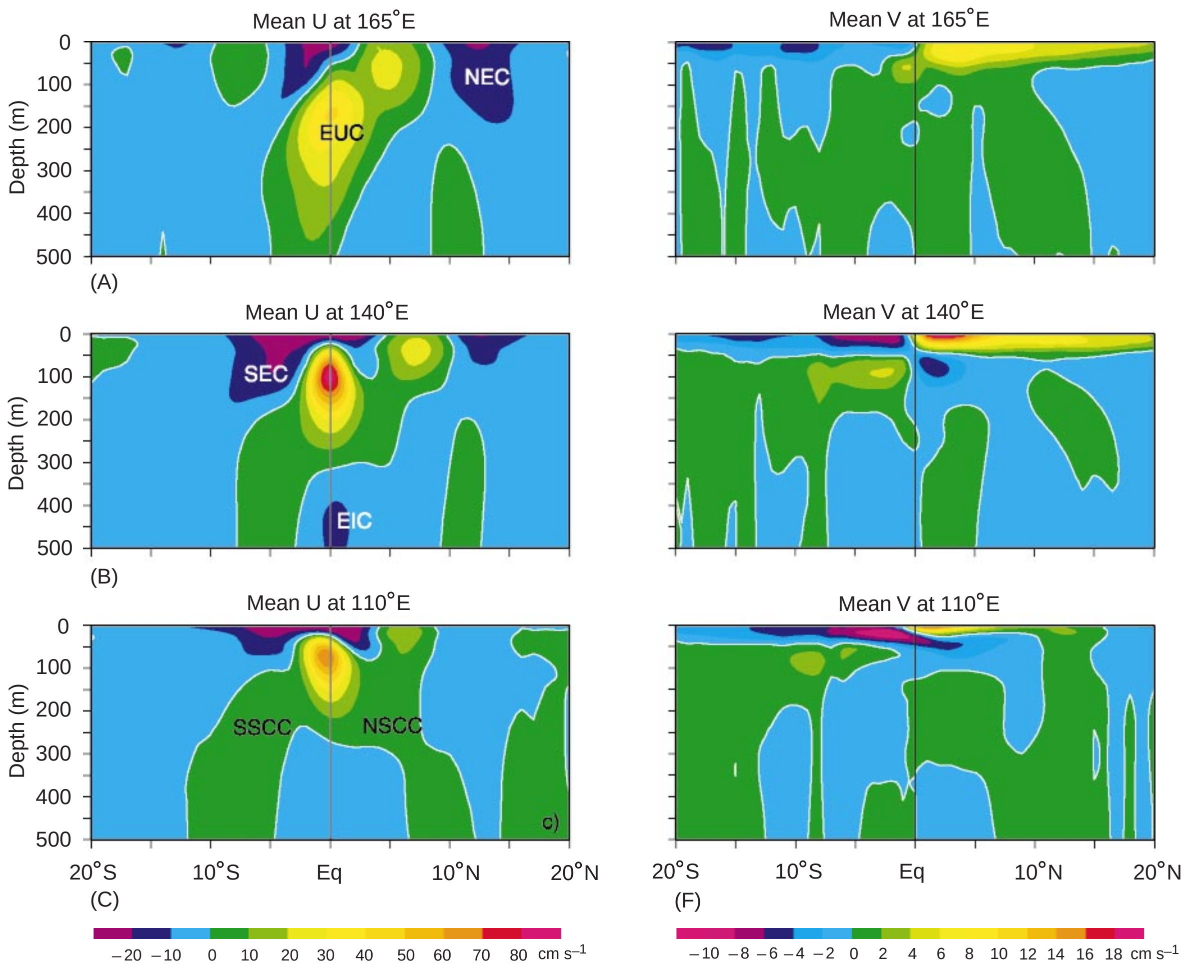

Figure 4 Vertical section showing the zonal (A–C) and meridional (D–F) components of mean flow in the upper 500 m of the western (A, D), central (B, E) and eastern (C, F) Pacific Ocean. Color bars give magnitude of flow (note that zonal and meridional scales are not the same); positive values are eastward and northward. Zero values are indicated by white contours.

at the south end of Mindanao Island, with a significant portion entering the Sulawesi Sea, and most of the rest retroflecting into the NECC. A small portion recirculates around the persistent Mindanao Eddy. A portion of the flow in the Sulawesi Sea transits through the Makassar Strait and ultimately through the Indonesian Seas and into the Indian Ocean, while the rest returns to the Pacific to join the NECC (**Figure 6**). Deeper portions of the MC are also split between the Indonesian Throughflow and the Pacific equatorial circulation, with the latter flowing into the EUC and NSCC.

The SEC impinges on the north-eastern coast of Australia and the complex of islands including New Guinea. Similarly to the NEC, it splits into poleward and equatorward boundary flows near 14°S (**Figure 1**). The poleward branch is the East Australia Current, and the northward branch flows under a shallow southward surface flow as the Great Barrier Reef Undercurrent, eventually becoming the New Guinea Coastal Current (NGCC) and New Guinea Coastal Undercurrent (NGCUC), which follow a convoluted path around topographic features ending up with westward flow along the north coast of New Guinea. In this region, the surface flow of the NGCC reverses seasonally with the Asian winter monsoon westerly winds.

Low-latitude boundary currents in the eastern Pacific are not nearly as strong as along the western boundary, but they play a significant role in closing the circulation of the Pacific Ocean (**Figure 1**). The Peru Current flows northward along the west coast of South America, ultimately turning offshore into the SEC. North of the Equator, the NECC flows into the Gulf of Panama and retroflects around the Costa Rica Dome into the NEC, joining southward flow from the California Current.

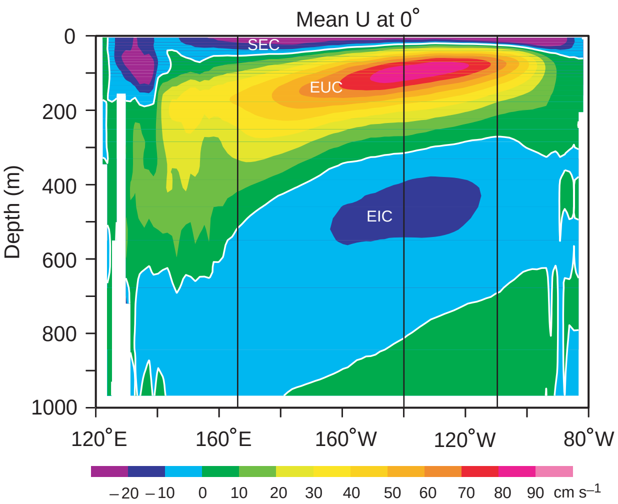

Figure 5 Zonal flow speed in the upper 1000 m in a vertical section along the Equator. Speeds are given in the color bar, with positive values eastward. The vertical lines indicate the longitudes of long-term current meter measurements (see **Figure 7**).

Subsurface Along the western Pacific boundary (**Figure 1**), the NGCUC flows westward along the north coast of New Guinea with a maximum near 200 m, but extending to at least 800 m. The upper thermocline waters contribute a small fraction to the Indonesian Throughflow, with the rest retroflecting around the persistent Halmahera Eddy to form (with contributions from the MC) the eastward-flowing EUC (**Figure 6**). The deeper portions of the NGCUC flow across the Equator and are traced into the weak Mindanao Undercurrent (MUC) which flows northward below the MC, carrying Antarctic Intermediate Water into the North Pacific.

In the east, the Peru–Chile Undercurrent flows poleward along the west coast of Ecuador, Peru and Chile, basically an extension of the EUC past the Galapagos Islands that then turns southward after converging at the coast of Ecuador. Some of these waters join the westward flows of the Peru Current and SEC through upwelling. The fate of waters flowing eastward in the NSCC and SSCC is not well known.

Variability

The variability of equatorial currents is complex, spanning a broad range of time and space scales. This variability is largely forced by changing winds; an important fraction of these wind changes are due to sea surface temperature changes in the equatorial zone, these being associated with changes in the currents and winds. These coupled variations include the well-known El Niño phenomenon, but also include the annual cycle.

Annual cycle

Although the annual cycle of wind forcing near the equator is not as extreme as in mid latitudes, the Pacific Trade Winds vary enough to force significant changes to the currents discussed above. Because of equatorial wave dynamics and coupling with the atmosphere, the relationship of the current variability to the winds is quite complex.

Figure 7 shows the long-term mean plus annual cycle of zonal and meridional current in the near-surface layer and at depth within the EUC for

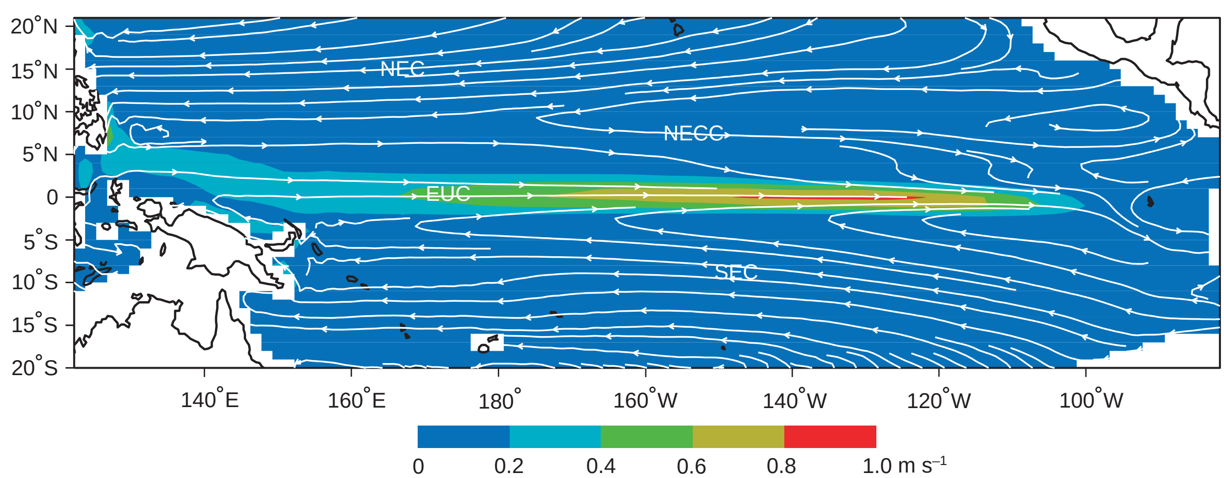

Figure 6 Map of long-term mean flow in the tropical Pacific on the isopycnal surface $\sigma_\theta = 24.5\,\mathrm{kg\,m^{-3}}$, which lies within the high-speed core of the Equatorial Undercurrent. White lines and arrows indicate the direction of flow, while the colors indicate the speed of flow as given by the color bar. Current names are abbreviated as in **Figure 1**.

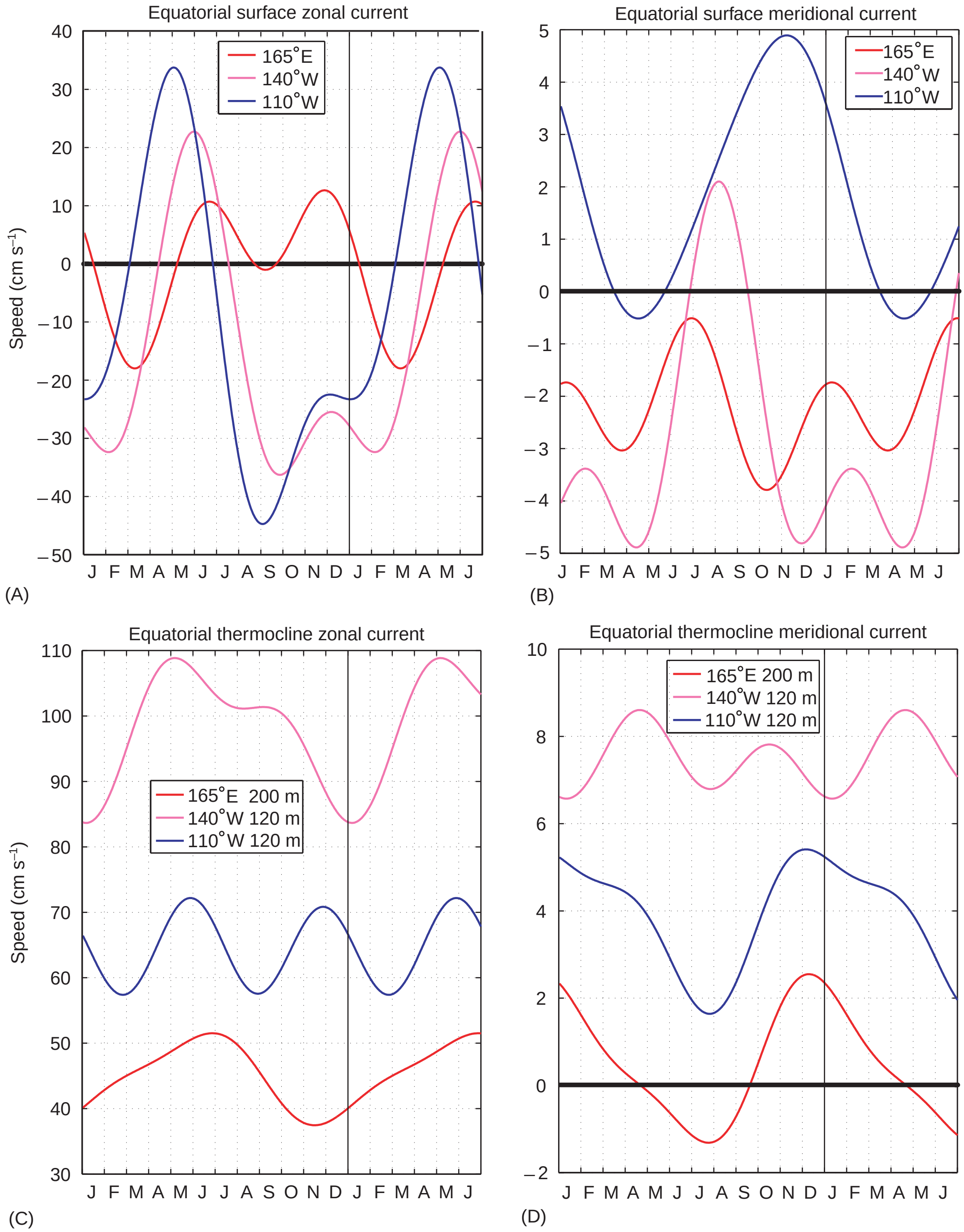

Figure 7 Mean annual variation of zonal (A, C) and meridional (B, D) currents at 10 m depth (A, B) and in the thermocline (C, D) on the Equator at three locations across the Pacific Ocean indicated in **Figure 5**. Because the thermocline is deeper in the western Pacific, currents are presented for a corresponding depth there. Note the different speed scales for each panel.

locations in the western, central and eastern Pacific. (Here, the annual cycle is the sum of annual and semiannual harmonics analyzed from direct current measurements.) The range of zonal current variation is about one order of magnitude larger than the meridional variations. The annual harmonic dominates the annual cycle of surface flow, except in the western Pacific where monsoon winds cross the equator twice each year. Also, zonal current in the eastern equatorial thermocline and meridional current in the central equatorial thermocline show strong semiannual signals.

Strong annual variation of zonal surface current is sufficient to reverse the direction of the flow on the equator, especially during the Northern Hemisphere spring (**Figure 7A**). In the east, this feature occurs nearly every year, and has been erroneously described as a 'surfacing' of the EUC. In the central Pacific, such reversals are mainly observed during strong El Niño events, and its appearance in the annual cycle here may be due to the occurrence of several El Niño events during the record that was analyzed (1984–1998). It is noteworthy that the maximum eastward deviation of the annual cycle appears progressively later toward the west, thought to be coupled with westward propagation of the annual cycle of zonal wind and sea surface temperature.

The annual cycle in the strong eastward flow of the EUC within the thermocline (**Figure 7C**) is not large enough to reverse the current direction. (On interannual timescales, however, the flow may reverse—see below.)

El Niño/Southern Oscillation (ENSO)

The strongest variability of the zonal equatorial currents is associated with El Niño episodes that occurred in 1986–87, 1990–91, 1993, and 1997–98, and with La Niña episodes of 1984, 1988, and 1996. Current meter records that have had their mean and annual cycles removed are presented in **Figure 8**, showing that El Niño variations are large enough to reverse the westward flow of the SEC, especially in the western equatorial Pacific. Strong eastward surface flow in the warm water pool of the western equatorial Pacific (e.g., 1997) has been implicated in the warming of the sea surface in the central and eastern equatorial Pacific. Also, the eastward flow of the EUC is reversed during some of these events (e.g., in **Figure 8B** at 140°W during 1997). This disappearance of the EUC was first observed during the strong 1982–83 El Niño event.

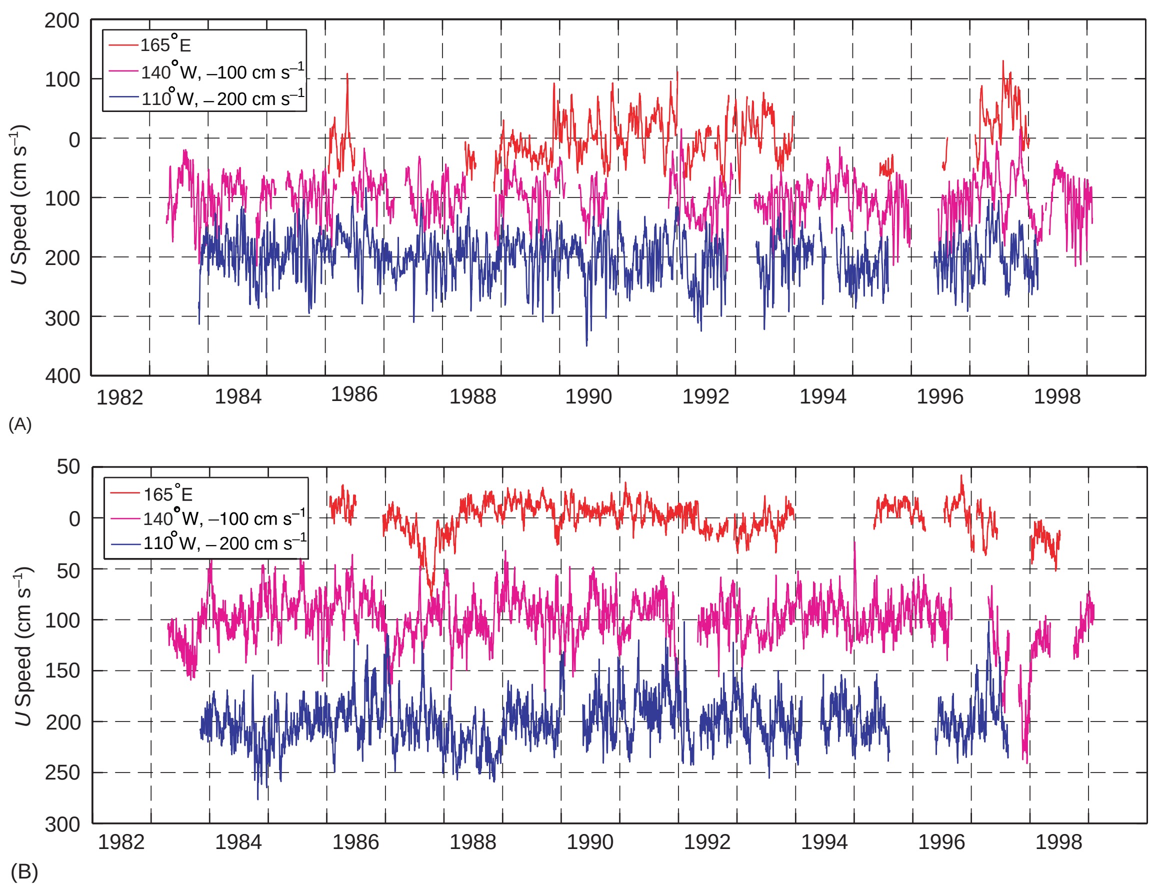

Figure 8 Time series of observed zonal currents, with mean and annual cycle removed, at three locations (indicated in **Figure 5**) along the Equator in the surface layer (A) and in the thermocline (B). Warm El Niño events are indicated by red shading along the time axis; blue shading indicates cold La Niña events. Missing observations are indicated by gaps. Note that time series have been offset from each other for clarity.

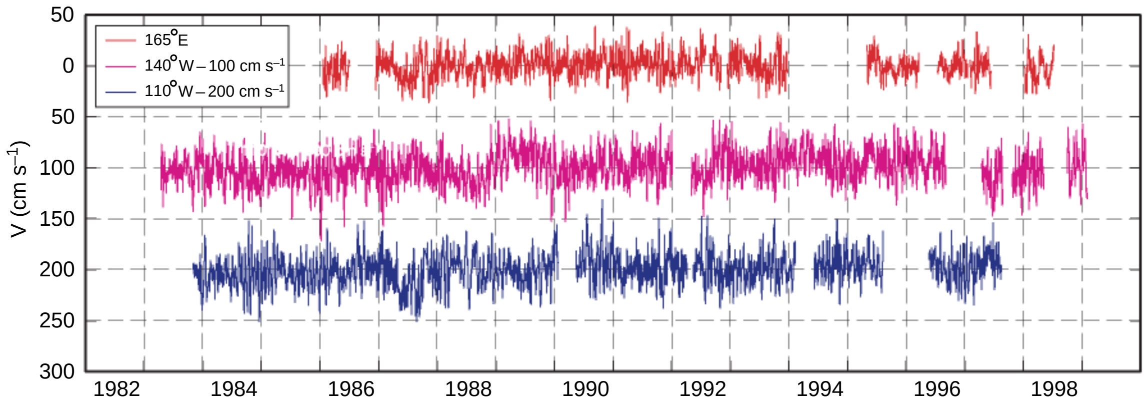

Figure 9 Time series of observed surface layer meridional currents, with mean and annual cycle removed, at three locations along the Equator. Missing observations are indicated by gaps. Note that time series have been offset from each other for clarity.

The current systems off the Equator are also affected by ENSO, again through a combination of local wind forcing and remotely-forced baroclinic waves. The NECC strengthens in the early phases of El Niño. The off-equatorial portion of the SEC weakens during El Niño, and strengthens during La Niña. The interannual variations of the NEC show a correlation with the NECC, but there are also strong variations with longer timescales than ENSO.

High-frequency current variability

Equatorially trapped waves with periods of a few days to a couple of months are quite energetic and ubiquitous (**Figures** 8 and 9). Zonal current fluctuations are dominated by intraseasonal fluctuations associated with the atmospheric intraseasonal (30–60 days) oscillation; eastward-propagating equatorially trapped Kelvin waves play an important role in transmitting this variability from the western Pacific to the eastern Pacific (e.g., **Figure 8A** during 1997). Meridional current fluctuations tend to have more energy at higher frequencies than the zonal current variations (compare **Figures** 8 and 9). Here, dominant periods are in the range 20–30 days. The amplitude of meridional current variability is largest at the surface in the east, and becomes somewhat smaller in the central Pacific, and much smaller in the west. The dominant mechanism is the tropical instability wave, which arises from the strong shears of the zonal flows discussed earlier. Modulation of the amplitudes of these waves occurs seasonally (largest amplitude in the northern fall) and interannually (small amplitude during El Niño) as the shears are affected by the annual cycle and ENSO.

See also

Data Assimilation in Models. East Australian Current. Ekman Transport and Pumping. Elemental Distribution: Overview. El Niño Southern Oscillation (ENSO). El Niño Southern Oscillation (ENSO) Models. Kuroshio and Oyashio Currents. Single Point Current Meters. Upper Ocean Time and Space Variability. Wind Driven Circulation.

Further Reading

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