TEN YEARS OF SHIPBOARD ADCP MEASUREMENTS ALONG THE NORTHWESTERN HAWAIIAN ISLANDS

BY

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ABSTRACT

Ten years of shipboard acoustic Doppler current profiler data, resulting in 105 transects along the Hawaiian Ridge, have been analyzed to describe the spatial and temporal variability of the mean currents and vertical shear structure in the vicinity of the Northwestern Hawaiian Islands. The analysis spans the period October 1990 through November 2000, with data being most sparse during the boreal winter months. The current field is dominated by mesoscale variability; only in a few locations is the mean statistically significant. The mean shows the North Hawaiian Ridge Current flowing westward south of Kauai and Nihoa. The average from March to July shows the eastward Subtropical Countercurrent, from Maro Reef to Necker Island. Information on ocean current structure is critical to better understand biological connectivity among the Northwestern Hawaiian Islands as well as between the Main Hawaiian Islands and the Northwestern Hawaiian Islands.

INTRODUCTION

The Hawaiian Archipelago is one of the most geographically and oceanographically isolated island groups in the world, extending northwest from the Island of Hawaii at 19° N latitude, 155° W longitude to Kure Atoll at 28° N latitude, 178° W longitude. The Archipelago includes the inhabited Main Hawaiian Islands (MHI) to the southeast comprised of high volcanic islands, and the uninhabited Northwestern Hawaiian Islands (NWHI) to the northwest, consisting of low coral islands and atolls, a few basaltic pinnacles, and submerged banks (Fig. 1). With the designation of the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (NWHI-CRER) by Executive Orders in 2000 and 2001, the Reserve is now the nation's largest marine protected area (MPA), and second globally only to Australia's Great Barrier Reef Marine Park. With this designation, there has been considerable attention to improving the management and conservation of the region using science-based ecosystem principles.

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Understanding the many complex biological and biophysical interactions of ecosystem science is challenging, and much of the recent focus for conservation ecologists and marine resource managers has been centered on the connectivity of the region. Managers are trying to identify ‘best places’ to locate no-take MPAs to effectively preserve the biodiversity and abundance of natural resources Archipelago-wide. The biological linkages of reef fish and other biota between and among islands and atolls of the NWHI and the MHI are poorly known. Recent surveys indicate that shallow-water reef fish populations in the NWHI are relatively pristine and those in the MHI, especially apex predators, are presently overexploited (Friedlander and DeMartini, 2002). Among many important factors influencing this connectivity, ocean circulation is among the least known.

The oceanographic isolation of the Hawaiian Archipelago has resulted in the highest percentages of endemic marine organisms in the insular tropical Pacific (Jurik et al., 1998; Randall, 1995, 1998; Randall and Earle, 2000; Allen, 2002; DeMartini and Friedlander, 2004). Researchers found a gradient of increasing endemism of reef fishes to the northwest along the Archipelago, with highest endemism by species, numbers, and biomass at the three northernmost atolls, Pearl and Hermes, Midway, and Kure, and reefs surrounding Lisianski Island-Neva Shoal (DeMartini and Friedlander, 2004). Other recent evidence suggests the central portion of the NWHI, from French Frigate Shoals to Lisianski Island, may be a ‘gateway’ of genetic diversity for the Archipelago (B. Bowen, pers. comm.). Rivera et al. (2004) found the highest nucleotide and gene diversity of the Hawaiian grouper, *Epinephelus querus*, within the Archipelago at Gardner Pinnacles. Ongoing genetic work on tube snails (A. Faucci, pers. comm.) and spinner dolphins (K. Andrews, pers. comm.) suggests diversity peaks in this same central portion of the NWHI. The highest species diversity of scleractinian corals in the Archipelago is found in this region (Maragos et al., 2004). Several species of the coral *Acropora*, a group absent in MHI and most of NWHI, are abundant in the mid-Archipelago (Maragos et al., 2004). The cone shell *Turbo articulatus* has only been reported within the Archipelago at French Frigate Shoals (S. Godwin, unpublished data). *E. querus*, *Acropora*, and *T. articulatus* are all common at Johnston Atoll, the closest shallow reef ecosystem to the Archipelago, situated several hundred km southwest (Heemstra & Randall, 1993). The relative proximity of these two atolls, along with the similarity in marine species composition, has led to hypotheses of an oceanographic connection between Johnston and the midsection of the NWHI (Grigg, 1981), which then serves as a stepping-stone for colonization of the rest of the Archipelago.

The ocean circulation in the vicinity of the NWHI has not been described in great detail, but the large-scale aspects are well known. Lying within the North Pacific Subtropical gyre, near a ridge of maximum dynamic height, is the transition between the eastward and westward upper ocean geostrophic flow (Kobashi and Kawamura, 2002). Lumpkin (1998) analyzed paths of World Ocean Circulation Experiment (WOCE) drifters moving through the region of the Hawaiian Archipelago, and found few passing north of 25° N. Lumpkin showed drifters moving toward the north around 160° W, with others moving to the lee side of the ridge, returning to the west in circular flows. Dynamic topography shows a highly variable eastward flowing Subtropical Counter

Current (STCC) roughly between 24° N and 27° N from 130° E to 160° W. The flow becomes more unstable in late fall to winter due to strong vertical velocity shear between the eastward flowing STCC and the underlying westward flow of the North Equatorial Current. To date, there have not been reports of direct observations of the STCC across the NWHI (Kobashi and Kawamura, 2002).

To better understand connectivity, biogeography, and endemism, we examine the spatial and temporal variability of mean currents and vertical shear structure in the vicinity of the NWHI using upper-ocean velocity measurements from10 years of shipboard acoustic Doppler current profiler (ADCP) transects along the Hawaiian Ridge. This general description of measurements collected by the Pacific Islands Fisheries Science Center on repeated cruises of the NOAA Ship *Townsend Cromwell* is used to examine the structure of long-term mean currents and shear to determine potential transport of larvae among the islands and atolls of the NWHI, and between the NWHI and MHI. We address the question of whether the NWHI are more likely to be a source or a sink of larvae for the MHI, and examine the mean currents for observational evidence of the eastward flowing STCC.

METHODS

Data Collection

From October 1990 to November 2000, shipboard ADCP data were collected on repeated cruises of the NOAA Ship *Townsend Cromwell*, resulting in 105 north or south sections along all or part of the NWHI from Honolulu to Kure Atoll. The hull-mounted RD Instruments narrow-band (150 kHz) ADCP transmitted sound pulses along four beams and measured the Doppler-shifted frequency of the backscattered sound to estimate the velocity of the scatters, such as plankton, small fish, and detritus, relative to the ship. Water velocity over ground is computed by removing the ship's velocity based on Transit satellite fixes for the early cruises and GPS positions after 1993 (Firing, 1991). To improve accuracy of velocity estimates, an Ashtech 3DF GPS provided ship's heading during the later years. Velocity profile data were ensemble-averaged over 5 minutes with an 8-m vertical resolution over the depth range of 20 to 300 m, with data often being inconsistent below 200 m due to limited scatterers in the water column or excessive air bubbles under the ship during heavy sea conditions. Figure 2 shows the temporal distribution of the 105 ADCP transects along the NWHI over the period from October 1990 to November 2000. The number of sections per year ranged from 1 in 1991 to 16 in 1997. From 1993 thru 2000, each year had at least eight sections along the NWHI. Seasonally, June through October had the highest density of observations, and the months of November and December had the lowest. All months, except December, had at least three sections along the NWHI.

Data Analysis

Data were processed using the Common Oceanographic Data Access System (CODAS) processing suite developed at the University of Hawaii (Firing, 1991). For statistical analysis, individual ADCP velocity sections were gridded using a coordinate system aligned with the ridge (Fig. 3); with 0.25° by 0.25° grid spacing (~25 km). From Honolulu to Kure Atoll, there are 88 along-ridge boxes by 10 across-ridge boxes. Only boxes with data from 15 or more sections are used for producing mean velocity vector maps, with the exception of the seasonal analysis of the Subtropical Counter Current. The mean, standard deviation, and standard error of the means were computed for current velocity and root mean square (rms) vertical shear of velocity. With one exception (noted in the caption), spatial maps are based on velocities depth-averaged from 28 to 148 m. Vertical sections of velocity and rms vertical shear of velocity along the ridge axis were computed by averaging in the across-ridge dimension.

RESULTS

Synoptic Sections

Before proceeding with the statistical analysis, it is useful to see the character of the individual sections. The northbound/southbound pair of sections from a single cruise in May and June 1997 illustrates the typical magnitude of the synoptic currents (0.2-0.5 ms^{-1}), and their spatial and temporal variability (Fig. 4). Although the southern ends of the sections were occupied less than two weeks apart, the measured currents look very different. This anticipates a major conclusion of the statistical analysis to follow: the long-term mean currents are weak relative to the variability, so there is generally little resemblance between any synoptic section and the long-term mean. Indeed, it is difficult to arrive at a statistically significant mean in much of the region.

Spatial Distribution of Depth-Averaged Velocity

Spatial distributions of depth-averaged mean horizontal velocity vectors along the entire Archipelago from Honolulu to Kure Atoll are shown in Figure. 5. In order to more closely examine mean currents, standard errors, and standard deviations, the NWHI is subdivided into three regions: a southern region from Oahu to Necker (157° W to 165° W; Fig. 6), a mid-region from Necker to Raita Bank (164° W to- 170° W; Fig. 7), and a northern region from Maro Reef to Kure Atoll (170° W to- 180° W; Fig. 8).

The mean currents in the southern region show moderately strong mean westward velocities (~0.15 ms^{-1}) south of Kauai and Niihau and in most of the region from Kauai to an area west of Nihoa Island (Fig. 6). This mean westward current most likely reflects the westward extension of the North Hawaiian Ridge Current (NHRC; Firing, 1996; Qiu et al., 1997), and suggests that the NHRC crosses the Hawaiian Ridge in the large region between Oahu and Nihoa. The westward extent of the NHRC in these observations appears to be near 164° W, just southwest of Necker Island. For most of this southern region, the mean velocities generally exceed the standard errors (Fig. 6a), but are much smaller than the standard deviations (Fig. 6b), indicating that the variability is greater than the mean for most locations. For this southern region, there was not an obvious seasonal cycle.

The mean currents in the mid-Archipelago region, between Necker Island and Raita Bank, showed a strong seasonal cycle with moderate eastward flow (~0.10 ms^{-1}) during March through July (Fig. 7a) and weaker northward flow during August through February (Fig. 7b). The eastward flow is consistent with the intermittent presence of the STCC in the late spring/early summer months described by Kobashi and Kawamura (2002); these observations provide the first direct evidence of the STCC impinging on the mid portion of the NWHI. During the fall/winter season, when the STCC is not recognizable, there is a moderately strong mean northward current between Gardner Pinnacles and Raita Bank (Fig. 7b).

The mean currents in the northern region of the NWHI, between Maro Reef and Kure Atoll, are based on fewer sections than are available in the central and southern region. Mean currents in this region are highly variable with eastward flow near Laysan Island and south of Maro Reef (Fig. 8). There appears to be coherent mean flow to the southwest between Pearl and Hermes and Kure Atolls and to the northeast between Pearl and Hermes and Pioneer Bank. Interestingly, there also appears to be an anti-cyclonic circulation around Lisianski Island/Neva Shoals, though this could be an artifact of spatial and temporal averaging of sparse data. Though the data here are too sparse to resolve a mean seasonal cycle, it is important to note that the transition zone chlorophyll front (TZCF) migrates south to intersect this region during some winters (Bograd et al., 2004).

Variation of Velocity with Depth

The previous section showed results of depth-averaged velocity vectors. In this section, we focus on the mean vertical structure of velocity along the Archipelago, where velocities are averaged in the across-ridge dimension (Figs. 9, 10). Beginning with the mean over all seasons (Fig. 9), the moderate westward flow of the NHRC is observed in the Kauai Channel between Oahu (158° W) and Kauai (160° W) and between Kauai and Nihoa (162° W) and south of the bank to the west of Nihoa at 163° W. For most of this region between 159° W and 163° W, the westward NHRC extends over the depths of the measurements from 20 m to 250 m, with maximum velocities observed south of Nihoa Island at depths between 100 and 200 m. From French Frigate Shoals westward, there are several regions of moderate eastward mean velocity in the upper 50 – 80 m that probably indicate the presence of the STCC. The strongest eastward mean velocities (~0.10 ms^{-1}) are observed in the regions between Southeast Brooks Bank (167° W) and the area west of Gardner Pinnacles (169° W) and between Lisianski Island (174° W) and Pearl and Hermes Atoll (176° W). Weaker mean eastward surface velocities are noted between Maro Reef (171° W) and 173° W. The meridional component of the mean flow tends to alternate from north to south through various channels in the Hawaiian Ridge.

Flow is moderately strong to the south just east of Maro Reef (possibly between Maro Reef and Raita Bank) and moderate to the north in the deep channel between West St. Rogatien Bank and Gardner Pinnacles; in both cases these meridional currents extend throughout the measurement depths.

Dividing the year into summer (March through July) and winter (August through February) seasons, we find that the summertime mean zonal velocity (Fig. 10a) is similar to the overall mean (Fig. 9), except for the greater strength and extent of eastward flow (STCC) across the broad region between Necker Island (164° W) and Pearl and Hermes Atoll (172° W). A stronger and broader eastward flow in the summer season is also seen from Laysan (172° W) to Pearl and Hermes Reef across the channel at 176° W. The winter mean zonal velocity (Fig. 10b) shows intensified westward flows in the Kauai Channel and between 173° W and 174° W (just east of Lisianski Island). A surprising feature of the depth structure, the subsurface maximum of the westward flow from 161° W to 163° W, is evident in both seasons (Fig 10).

Variation of RMS Shear with Depth

Root mean square (rms) vertical shear of velocity is maximal at the base of the presumed mixed layer (Fig. 11). The depth of maximum shear gradually shoals from ~50-60 m in the southern region (Oahu to Necker) to ~20-30 m in the northern region (Maro Reef to Kure Atoll). More notable, however, is that rms shear is relatively small for the entire region from the Kauai Channel (159° W) to Necker Island (164° W) and relatively large from French Frigate Shoals (166° W) to Kure Atoll (178° W). The most noteworthy seasonal differences of rms shear are that summertime maxima are stronger and shallower than during the winter season.

DISCUSSION

Although the currents along the NWHI are dominated by mesoscale variability, there are many features in the mean or seasonal components of the flow described here which have important influences on larval dispersion and recruitment in the Hawaiian Archipelago. These ADCP observations provide the first observational evidence describing the spatial and vertical extent and magnitude of both the NHRC and the STCC within the NWHI. Concerning the NHRC, the mean flow is westward from the MHI toward the NWHI, crossing the Hawaiian Ridge between Oahu and Nihoa. Observations here also show that the NHRC in this region extends from near the surface to at least 200 m with relatively little rms shear. While the high variability of the NHRC certainly allows for the possibility of direct larval transport toward the MHI, the mean currents indicate that direct recruitment is more likely from the MHI to the NWHI. That said, it is recognized that indirect paths of larval transport are clearly possible. In fact, recent Surface Velocity Program (SVP) drifter observations have confirmed some transport from the NWHI to the MHI (Firing et al., 2004). Nevertheless, these long-term mean observations suggest that the NWHI alone are not likely a suitable refuge to replenish resources in the MHI.

Concerning the STCC, the ADCP observations reported here provide evidence for mean eastward flow to the mid-Archipelago region roughly between Lisianski Island and Necker Island during March to July. These findings are consistent with oceanographic observations based on dynamic topography that indicate the likely presence of a seasonal STCC impinging on the NWHI in this same region (Kobashi and Kawamura, 2002). Furthermore, these observations of the STCC are consistent with biological and genetic observations showing higher diversity in this part of the NWHI (Maragos et al., 2004; Rivera et al., 2004). The observed eastward velocities during the summer months have maxima near the surface layer (20-60 m) with significant rms shear across this layer and decreasing eastward velocity with depth. Generally, these eastward surface currents oppose the presumed northward Ekman drift driven by the prevailing northeast trade winds. While eastward currents appear to increase northwestward of Brooks Bank (167° W), northeast trade winds decrease northwestward along the Archipelago (Brainard et al., 2004).

These observations show predominantly southwestward mean currents in the vicinity of the three northern atolls of the NWHI, Kure, Midway, and Pearl and Hermes, and eastward surface currents to the southeast of Pearl and Hermes Atoll. This pattern of the mean currents suggests that these northern atolls might be more oceanographically isolated than the other islands and atolls to the southeast, which is consistent with increased endemism in this northwestern portion of the Archipelago (DeMartini and Friedlander, 2004).

While there is an obvious need for more detailed information on the circulation in the NWHI to better understand larval dynamics, these observations of the mean currents provide useful insights for resource managers to more effectively manage and conserve the resources of the region. Measurements on finer space and time scales are needed to increase our understanding of larval retention, dispersion, and recruitment in the Hawaiian Archipelago.

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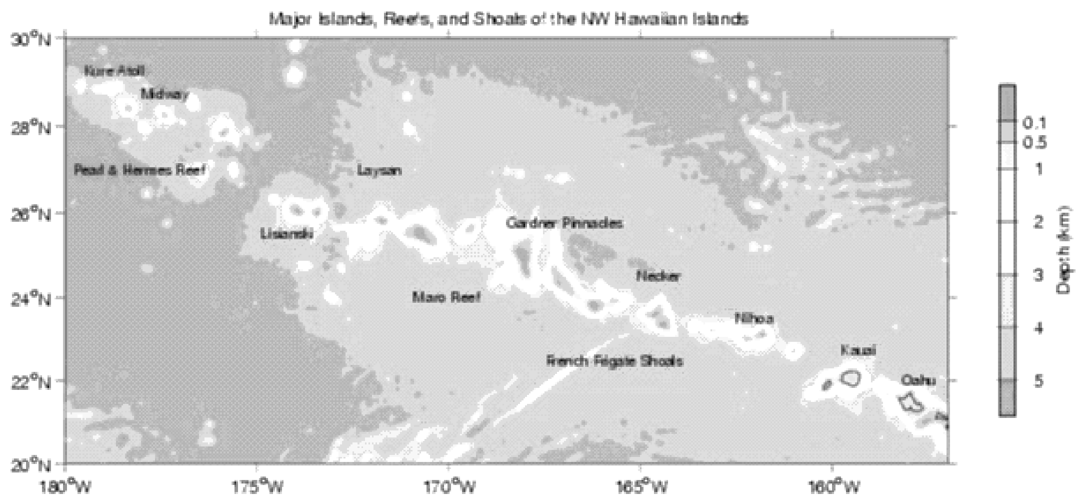

Figure 1. Map of NWHI. Shaded bathymetry from Smith and Sandwell (1997).

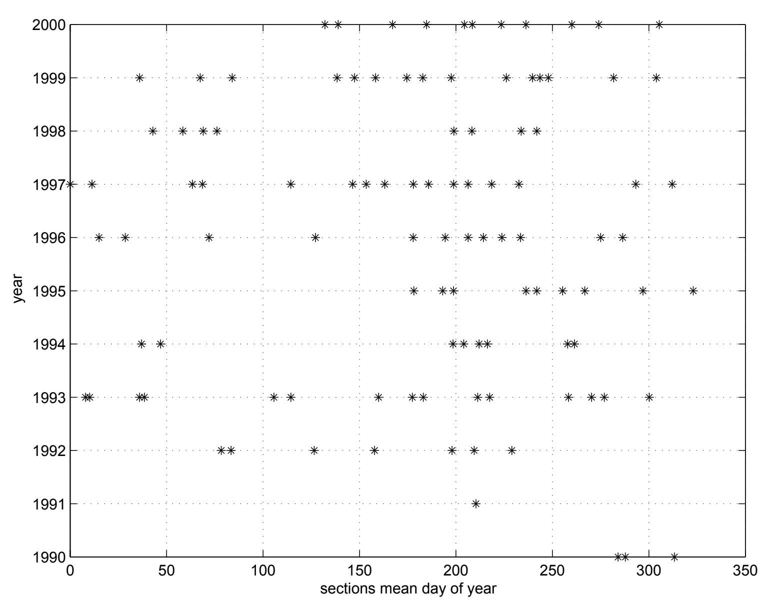

Figure 2. Temporal distributions of research cruises of the NOAA ship *Townsend Cromwell* along the NWHI from October 1990 to November 2000 showing mean day of year of each cruise for the 105 ADCP transects used for this analysis.

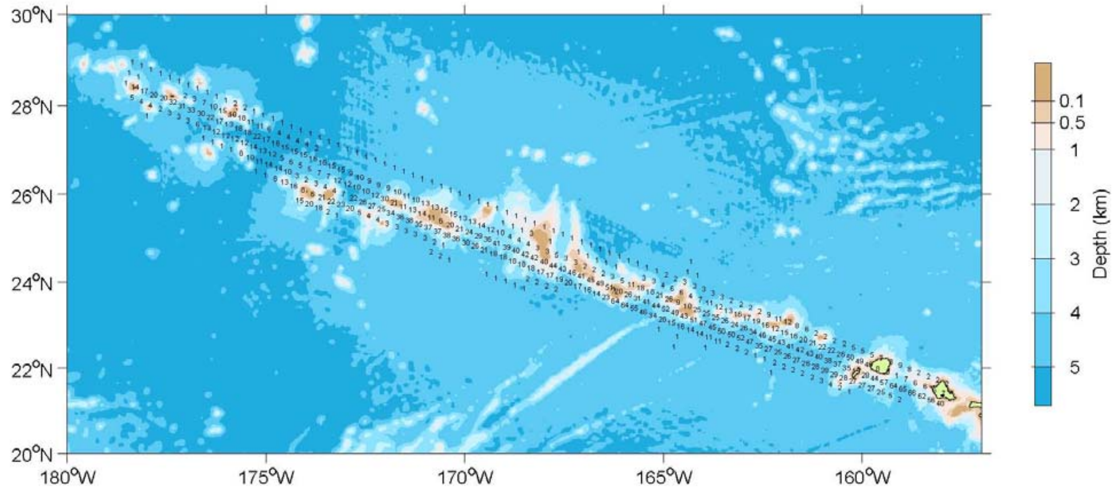

Figure 3. Spatial distribution of gridded 0.25° by 0.25° rotated boxes showing number of cruise sections within each grid box over the period from October 1990 to November 2000.

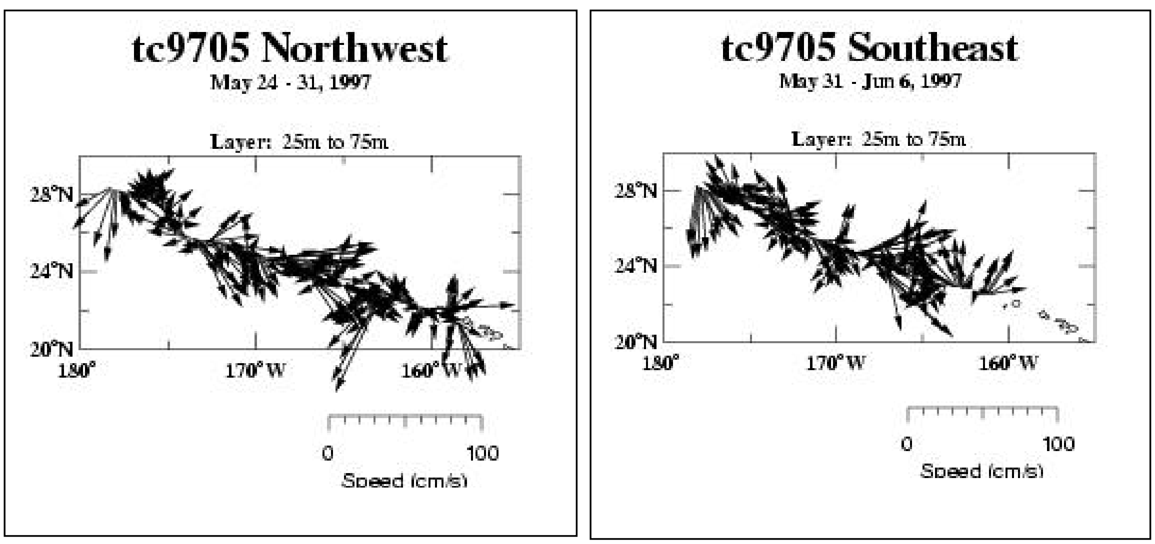

Figure 4. Depth-averaged (25-75 m) velocity vectors from the northwestward leg of cruise TC-9705, May 24-31, 1997 (left panel), and from the southeastward leg, May 31- – June 6 (right).

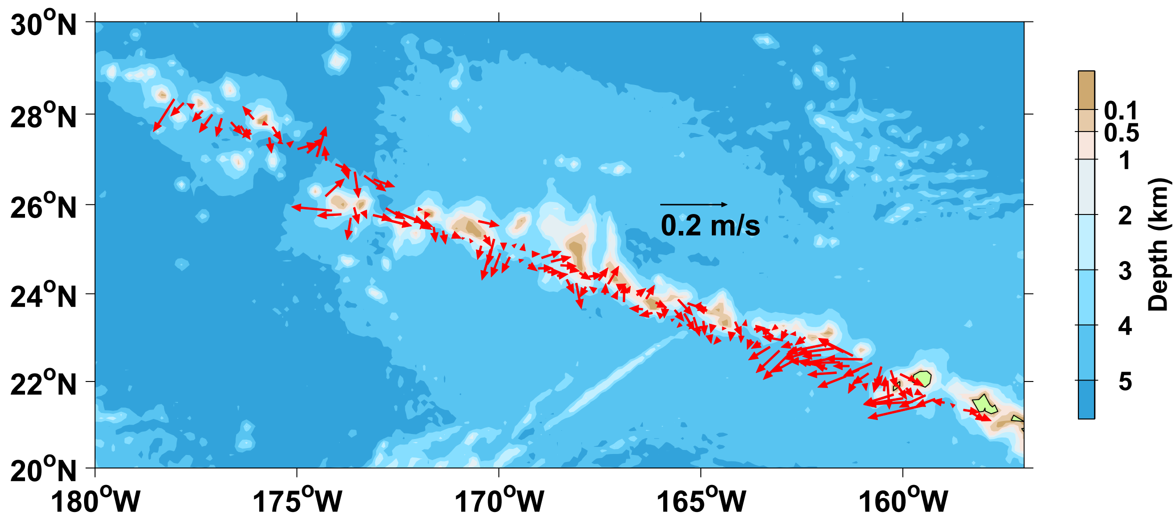

Figure 5. Mean velocity vectors, depth-averaged from 28-148 m, for all grid boxes with 15 or more sections along the Hawaiian Archipelago from Honolulu to Kure Atoll.

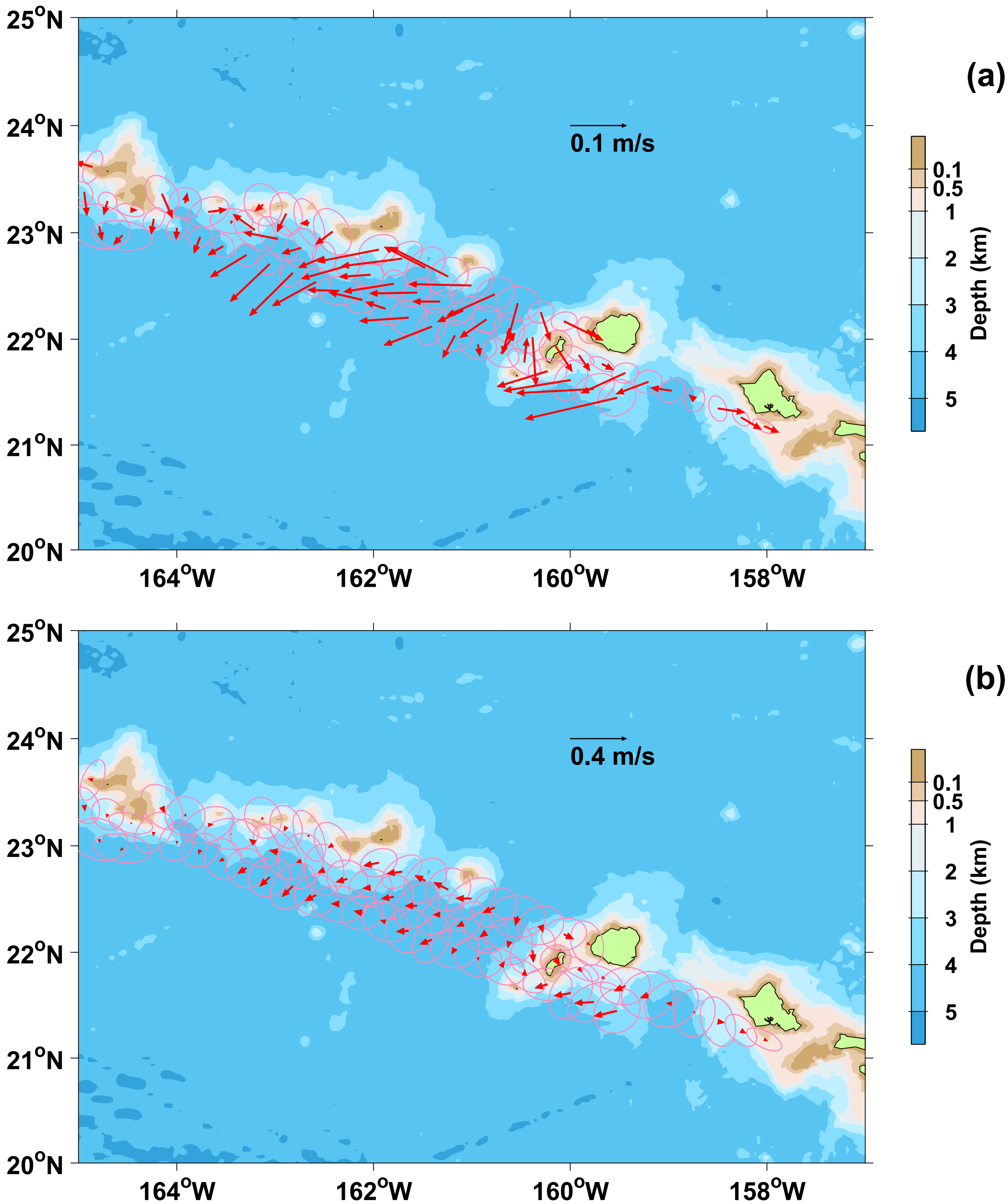

Figure 6. Long-term mean current vectors in the southern region from Oahu (158° W) to Necker Island (164.5° W). The dominant westward current south of Kauai and Nihoa may come from the North Hawaiian Ridge Current. In the top panel, the ellipses show standard errors of the mean; vectors which extend beyond the ellipses are considered significant. In the lower panel, the ellipses show the standard deviations; the variability everywhere exceeds the long-term mean.

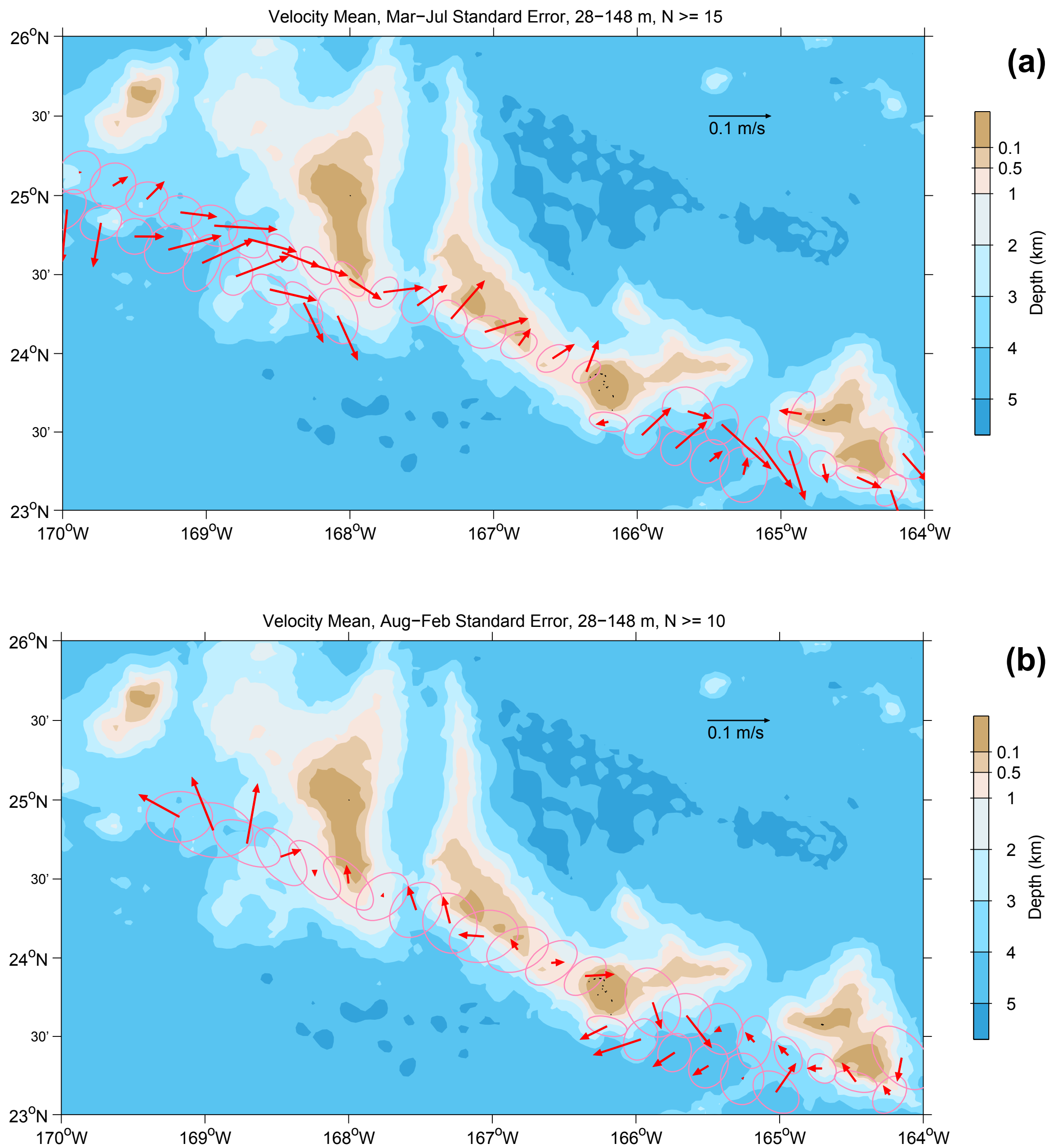

Figure 7. Long-term mean current vectors and standard error ellipses in the middle region of the NWHI from Necker Island (164.5° W) to Raita Bank (169° W) during the period March through July (top panel), and August through February (bottom panel). The dominant eastward current during March through July is the Subtropical Counter Current; it is not observed in the August-February average.

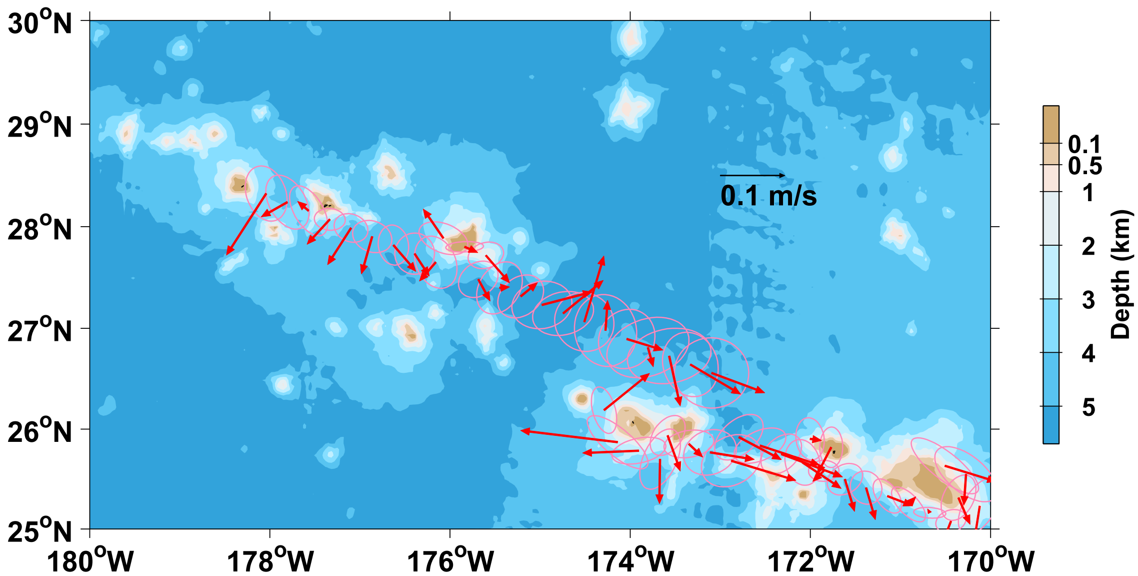

Figure 8. Long-term mean current vectors and standard error ellipses in the northern region of the NWHI, from Maro Reef (170.5° W) to Kure Atoll (178° W) for grid boxes having at least 15 cruise sections. Unlike all previous figures, the vertical averaging interval for this region is 28-100 m.

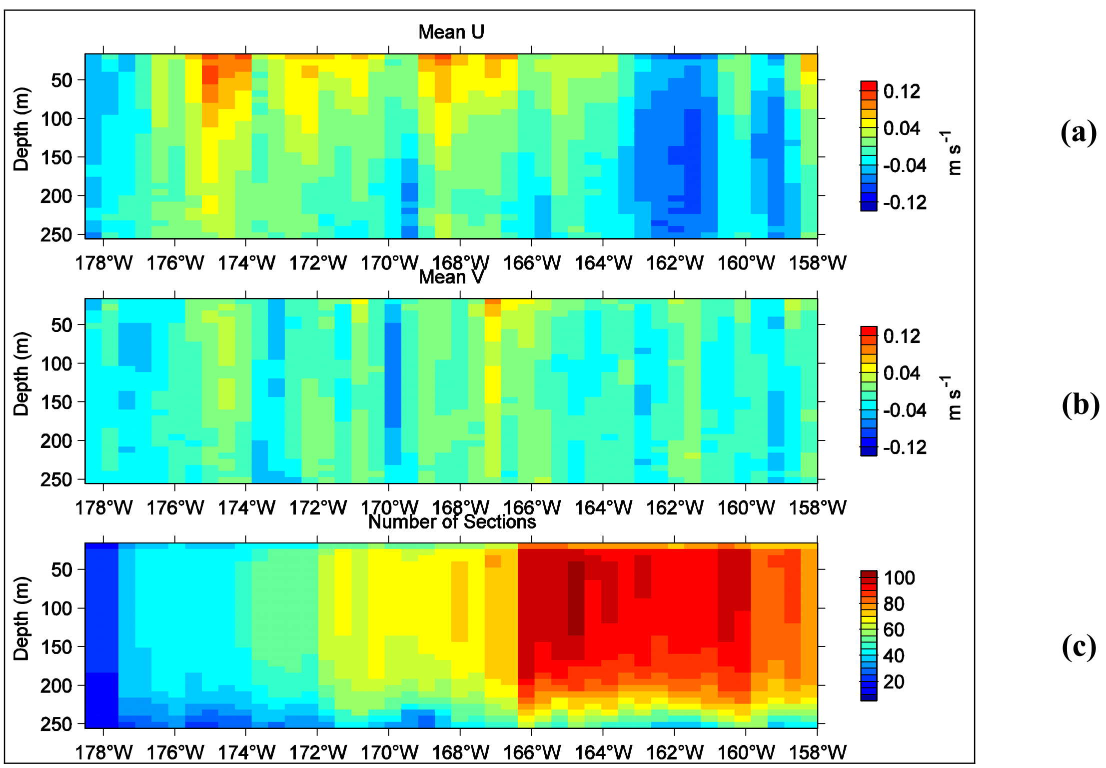

Figure 9. Long-term mean a) zonal and b) meridional velocity along the rotated-longitude on the axis of the NWHI between Honolulu and Kure Atoll during all seasons. Velocities are averaged across rotated-latitude sections. c) Number of cruise sections used for each velocity calculation.

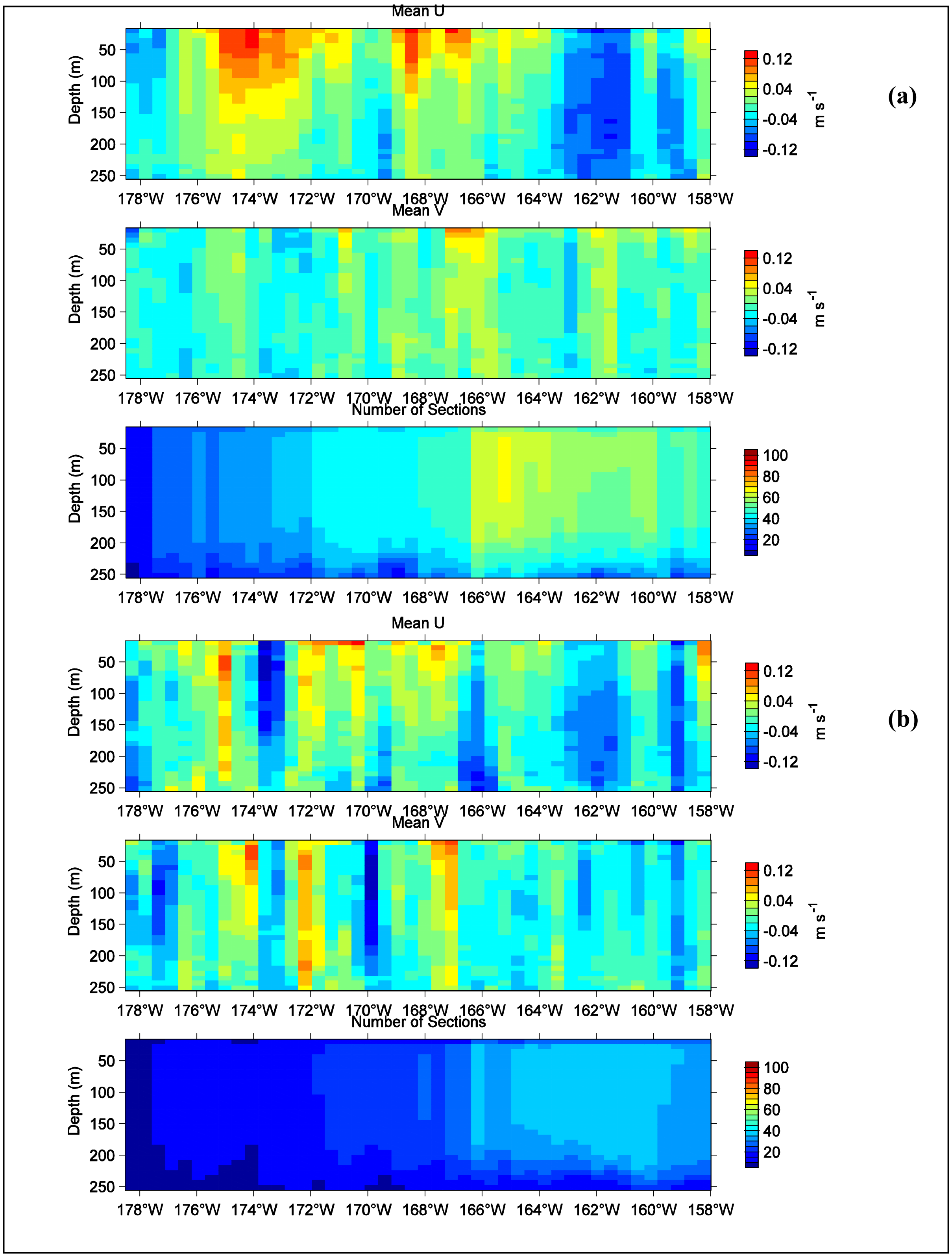

Figure 10. Long-term mean zonal and meridional velocities and number of sections for a) summer months (March – July) and b) winter months (August – February).

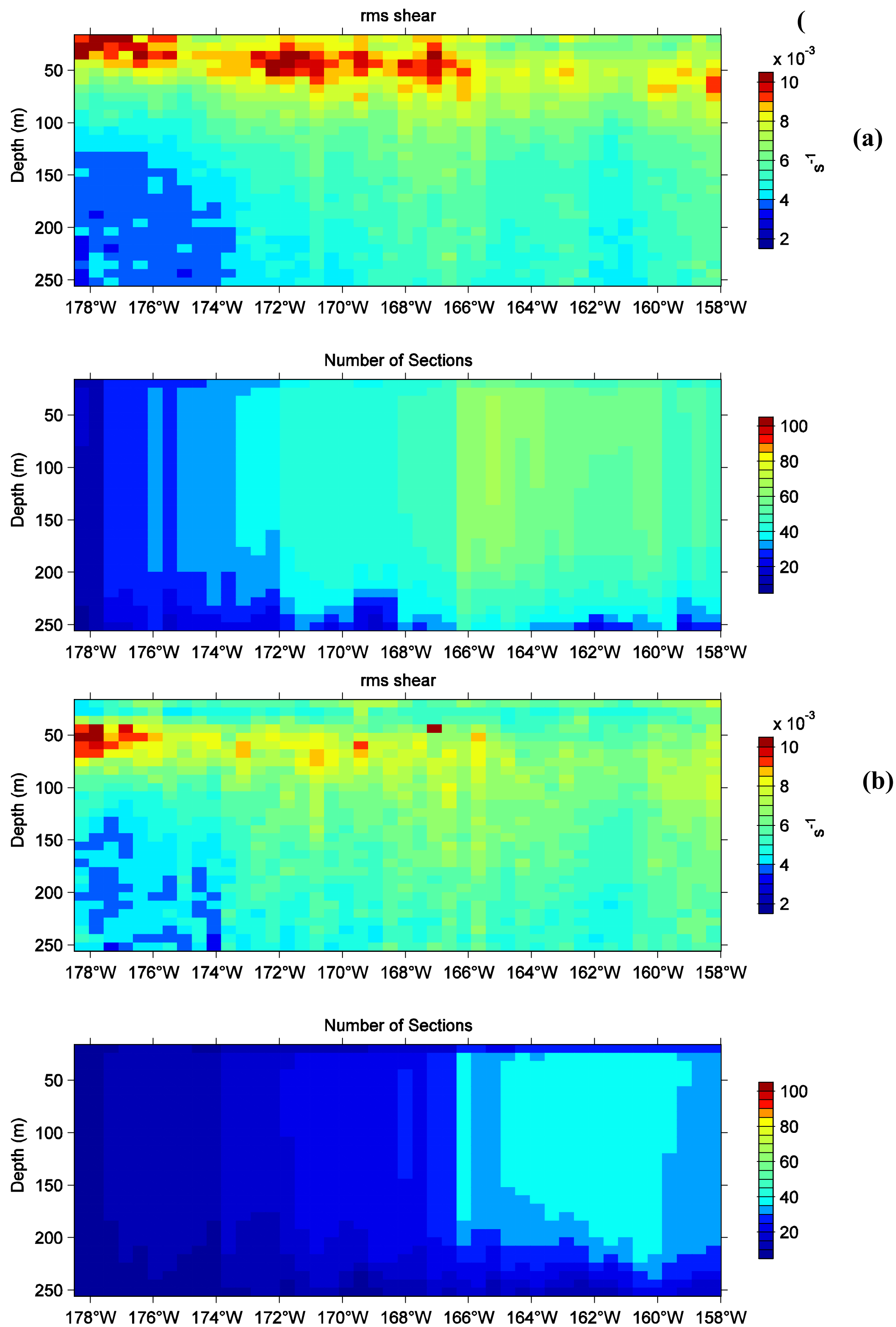

Figure 11. Long-term mean rms vertical shear of velocity and number of sections for a) summer months (March – July) and b) winter months (August – February).

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