Evidence for the Existence of a North Hawaiian Ridge Current*

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ABSTRACT

Two different datasets are examined for information about the existence and characteristics of the North Hawaiian Ridge Current (NHRC). The pan-Pacific drifter dataset shows a mean NHRC to be confined to within about 100 km of the northern side of the Hawaiian Ridge. A close look at the distribution of the data shows that the current is mostly confined in time to a two-month period in the fall of 1991. MBT data from the Trade Wind Zone Oceanography Pilot Study conducted in the mid-1960s were also examined. Of the 14 cruises with sections north of the Hawaiian Ridge, 5 showed evidence of northwestward flow along the ridge. Of those 5, one was associated with northward meandering of the North Equatorial Current. It is thus suggested that the NHRC is highly intermittent. There are three related hypotheses for the formation of the NHRC, 1) propagation of Rossby waves westward into the ridge, 2) forking of the North Equatorial Current, and 3) as a western boundary current for the eastern Pacific north of 18°N. Evidence is presented pointing to hypothesis 2 as a plausible mechanism.

1. Introduction

There has been speculation about the existence of a northwestward North Hawaiian Ridge Current (NHRC) for a number of years. Discussion of the current can be found in White (1983), Mysak and Magaard (1983), Talley and de Szoeke (1986), and White and Walker (1985). Price et al. (1994) give an excellent review of the evidence for such a current, and the reader is referred to that paper for an extensive background. The reader is also referred to Roden (1991) for a comprehensive review of the understanding of the role of the Hawaiian Ridge in the large-scale circulation of the subtropical gyre.

There are several hypotheses normally invoked to explain such a current. One has been developed by Mysak and Magaard (1983), Magaard (1983), Oh and Magaard (1984), and more recently by Graef and Magaard (1994). This hypothesis sees the NHRC as a rectification of impinging Rossby waves producing a northwestward mean current along the ridge. There have been numerous reports of westward propagation of baroclinic eddies in the eastern North Pacific (e.g., Bernstein and White 1974). These eddies must impinge upon the Hawaiian Ridge where, the theory suggests, they interact with the ridge and form a series of alternating currents with an Eulerian mean flow to the northwest closest to the ridge. The Mysak and Maagard (1983) theory is formulated on the basis of a solid ridge extending from the bottom to the surface. The Hawaiian Ridge does not fit this description, being a comblike structure that is relatively continuous at its base, but punctuated by many gaps at the surface (Roden 1991).

A second hypothesis is that advanced by White and Walker (1985), which sees the NHRC as a western boundary current for the eastern half of the North Pacific subtropical gyre. Numerical models often show the NHRC in this form (H. Hurlburt 1993, personal communication; Qiu et al. 1997). Qiu et al. further concluded that the NHRC was a result of the time mean rather than the time variable wind forcing field in the North Pacific. They showed a good agreement between the transport computed from Godfrey's (1989) island rule and that seen in their model simulation.

A related hypothesis is that the northernmost extent of the North Equatorial Current (NEC) frequently reaches as far north as the Island of Hawaii, subsequently forking at the ridge and thereby generating a flow along its northern flank. Seckel (1968, 1975), Kessler and Taft (1987), and Taft and Kessler (1991) all found evidence of such a northward reach of the NEC.

Price et al. (1994) found no evidence of a contiguous, organized current along the northern flank of the ridge in four small surveys, equally spaced over one year. They speculated that the current was intermittent and possibly masked by the frequently occurring, energetic, mesoscale eddies and therefore required more frequent

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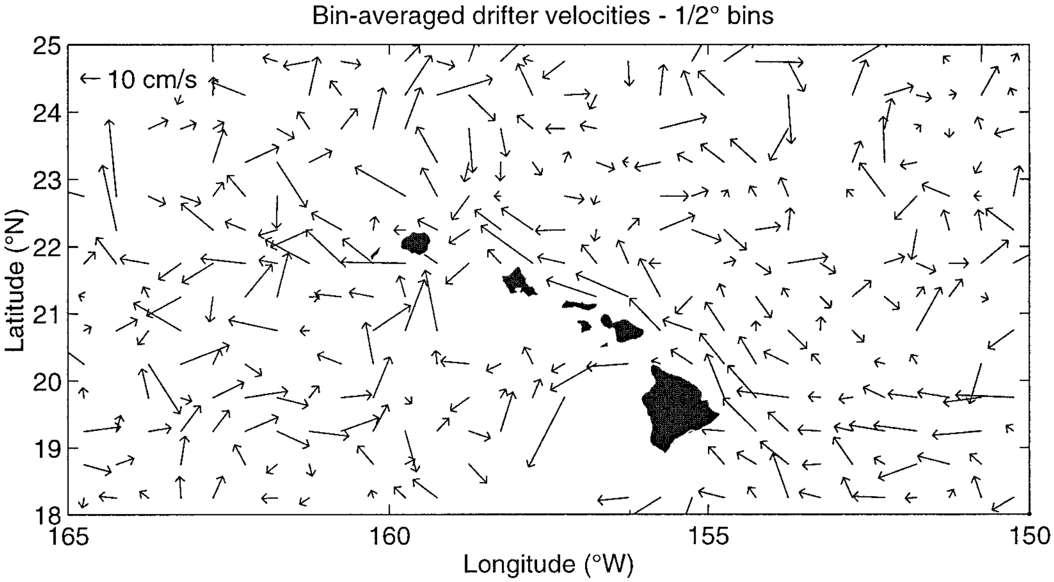

FIG. 1. Mean drifter velocities averaged in ½° bins. No estimate of velocity is made in areas where the flow is either undersampled or not significantly different from zero at the 90% confidence level.

observations to detect. The lack of coherent alongridge flow may also be related to the fact that the observations were surface only and did not reach a depth where the Hawaiian Ridge is continuous.

In this paper, I examine observations of the currents in this area that offer larger spatial and temporal coverage than those made by Price et al. (1994) and find evidence that appears to show the NHRC as a meander or forking of the NEC.

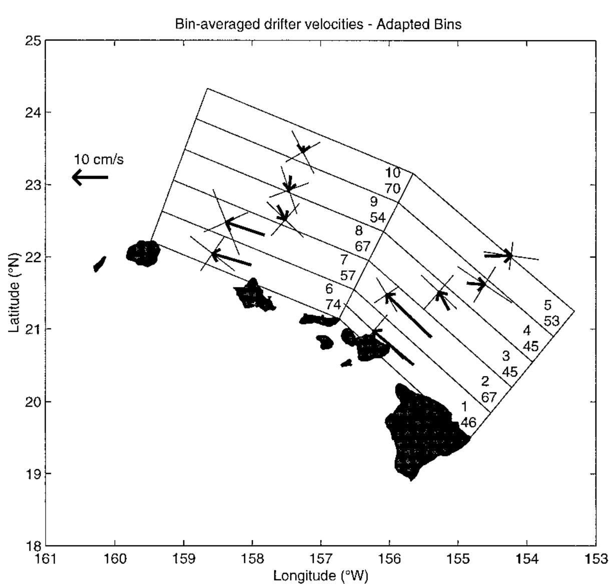

FIG. 2. Bin-averaged drifter velocities for the set of bins indicated. Perpendicular lines at the tip of each vector show principal axes of variance. The lengths of these lines are 90% confidence limits on the mean velocities in the directions indicated. The numbers at the bottom right of each bin are the (top) bin number and (bottom) the number of drifter-days of observations used in forming the average. A 10 cm s^{-1} scale is shown on the left-hand side.

2. Drifters

A set of pan-Pacific drifter data drogued at 15 m was examined for indications of the existence of a NHRC. The raw drifter positions were objectively analyzed to ¼-day intervals and smoothed before analysis. Details of the objective analysis scheme can be found in Hansen and Herman (1989). Drifter observations were collected over a five year period January 1988–December 1992. They include 227 separate drifters that circulated inside the box 10°–30°N, 140°–180°W during this period.

Average drifter velocities in ½° bins are displayed in Fig. 1. They show the existence of a mean NHRC along the north side of the Hawaiian Ridge. The speed of this current is approximately 20–30 cm s^{-1} to the northwest. The current decays within two bin lengths of the ridge, giving a current width of less than 100 km. Their picture also suggests that the NHRC is a continuation of the North Equatorial Current (NEC), which appears to split at the eastern tip of the Island of Hawaii. The current flows along the northeast side of the Hawaiian Ridge until it reaches the westernmost major Hawaiian Island of Kauai, at which point it mostly disappears. Qiu et al. (1997), using a similar dataset, show that the continuation of the NHRC crosses the ridge west of Kauai.

Using these data I concentrate my attention on the flows observed in the near vicinity of the ridge. In order to do this I have made the assumption that it is appropriate to average the observations in a coordinate system elongated parallel to the ridge. With this in mind, a set of bins have been constructed for averaging the drifter

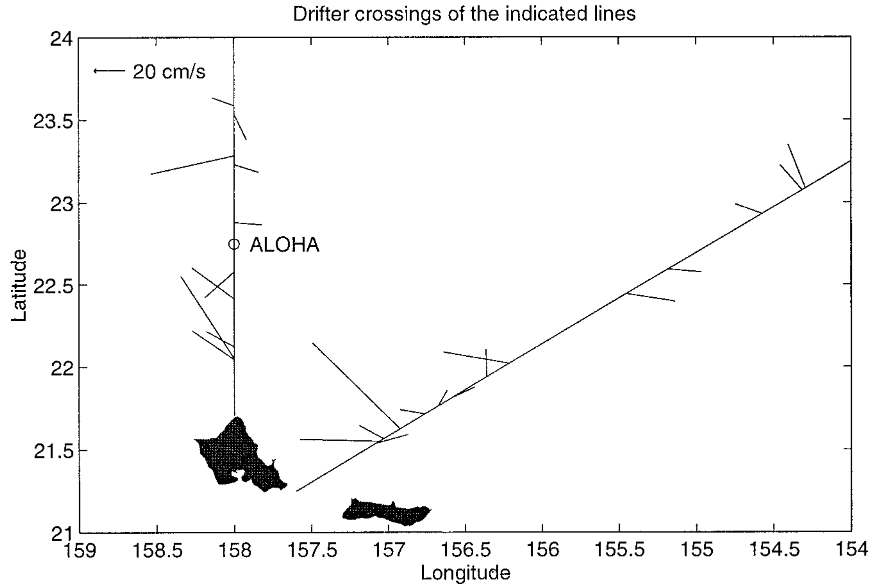

FIG. 3. Individual drifter crossings of the indicated lines. Velocity vectors are shown here with their tail on the line. A 20 cm s^{-1} scale is shown in the upper left-hand corner. For reference the site of the Hawaii ocean time series repeat hydrographic site (station ALOHA) is shown as well.

velocities (Fig. 2). These bins are 50 km wide. The first set of bins, numbers 1–5, are tilted at an angle of 41° to lines of constant latitude and have an average length of 291 km. The second set of bins (6–10) are at an angle of 21° and have an average length of 318 km.

The mean velocities plotted in Fig. 2 show the NHRC in the two bins closest to the Hawaiian Ridge. That is, the NHRC is confined to within 100 km of the ridge. This is consistent with Firing (1996) who found the NHRC to be generally south of the Hawaii ocean time series station ALOHA (22°45′N, 158°W; Fig. 3) with occasional excursions to the north. Where the NHRC is present it has a speed of 15–20 cm s^{-1} to the northwest. Away from the NHRC, mean velocities are zero to within 90% confidence limits. There is a strong indication that the NHRC both slows down and changes direction to remain parallel to the ridge as it moves along the island chain from southeast to northwest.

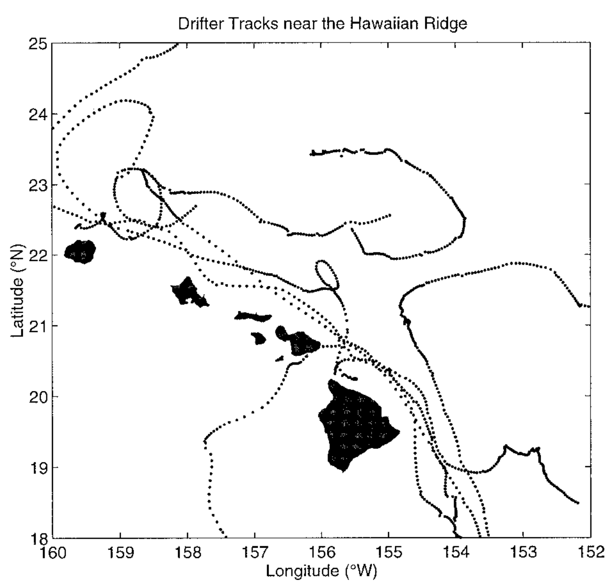

FIG. 4. Drifter tracks near the Hawaiian Ridge from the period 15 Sep–1 Dec 1991. Each dot is a 1/4 day objectively smoothed drifter position. All drifters near the ridge are moving northwest along the ridge.

Drifter crossings of specific lines are also examined to see the motion of individual drifters near the ridge (Fig. 3). For the line going directly north from Oahu, there is a cluster of drifters crossing toward the west south of station ALOHA. Most of these are going in a northwestward direction in agreement with the assumed picture of the NHRC. The speeds observed are 20–30 cm s^{-1}. For the other line depicted in the figure, the velocities are more scattered. One drifter is moving extremely rapidly (77 cm s^{-1}) to the northwest, while the motion of the others is slower and more variable. Most, however, are moving to the upper left side of the line drawn.

While the drifter dataset presented so far shows a well-defined picture of a NHRC, further examination of this data begins to show the current as more elusive and difficult to quantify. In fact, the average NHRC seen in Fig. 1 is based on only a few months of data. Figure 4 shows observed drifters on the northeast side of the Hawaiian Ridge for the period 15 September–1 December 1991. This picture indicates that during this 2.5-month period, several drifters passed rapidly in the NHRC to the northwest (direction of travel is not in-

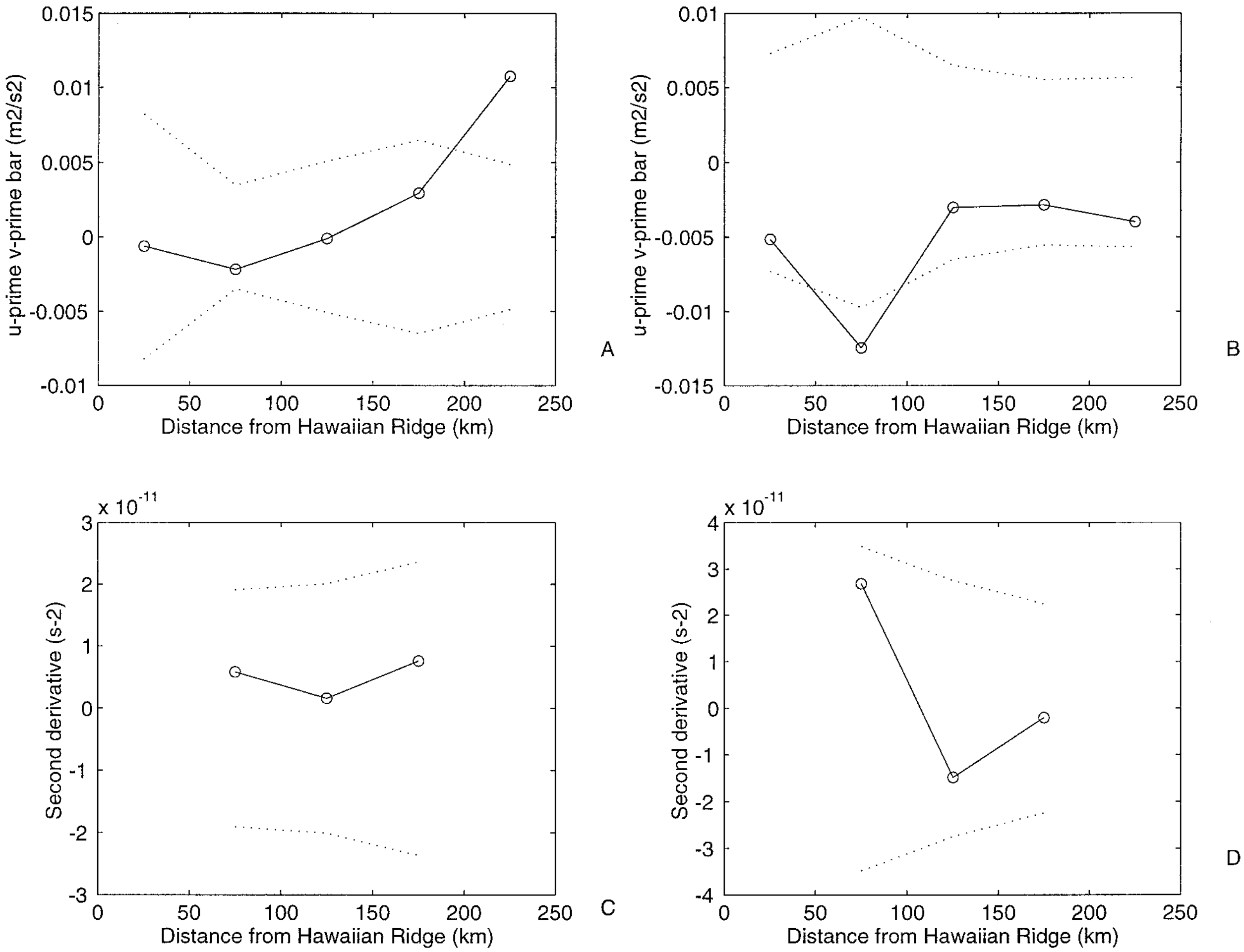

FIG. 5. In (a) and (b) $\overline{u'v'}$ is calculated from drifter observations. Velocities are rotated into a coordinate system aligned with the Hawaiian Ridge. Dashed lines are 90% confidence intervals on covariance. Here (a) is from bins 1–5, (b) is from bins 6–10; $\partial^2\overline{u'v'}/\partial y^2$ from (c) bins 1–5 and (d) bins 6–10. Dashed lines are 90% confidence intervals on the calculated value.

dicated in the figure, but all drifters shown near the ridge are traveling to the northwest) along the island chain from the island of Hawaii to Kauai. Several of the drifters that do get entrained into the NHRC come from the south and east. Also, most of the drifters in the NHRC are detrained to the northeast, with only one passing through the island chain. The actual passing of the drifters on the north side of the Hawaiian Island chain is associated with a shorter period of about 30 days.

It is not clear from examination of this dataset why this particular time period showed such a strong NHRC. During other time periods, drifters approached the Hawaiian Island chain, but many either passed directly through, looped and meandered without regard to any possible NHRC, or drifted to the southeast along the ridge, in a direction opposite to the NHRC. Perhaps the time period of late in 1991 had drifters placed in such a way that they happened to get easily entrained in the current.

In the theory of Mysak and Magaard (1983) Reynolds stresses play an important role. Firing (1996) calculated these stresses using ADCP data. Firing's Eq. (4) states that

$$\beta u \sin\alpha + R\frac{\partial u}{\partial y} = \frac{\partial^2 \overline{u'v'}}{\partial y^2}, \tag{1}$$

where β is the rate of change of Coriolis parameter with latitude, α is the clockwise rotation of the Hawaiian Ridge with respect to lines of constant latitude, u is the time mean along-ridge component of velocity, x is the along-ridge coordinate (positive southeastward), y is the across-ridge coordinate (positive northeastward), R is a damping parameter, and u' and v' are fluctuating components of the along- and across-ridge velocities. Equation (1) expresses the vorticity balance in the Mysak and Maagard theory, with the first term being northwestward advection of planetary vorticity, the second term being friction, and the right-hand side representing the divergence of the Reynolds stresses resulting from Rossby waves propagating toward and away from the ridge. It is straightforward to estimate the right-hand

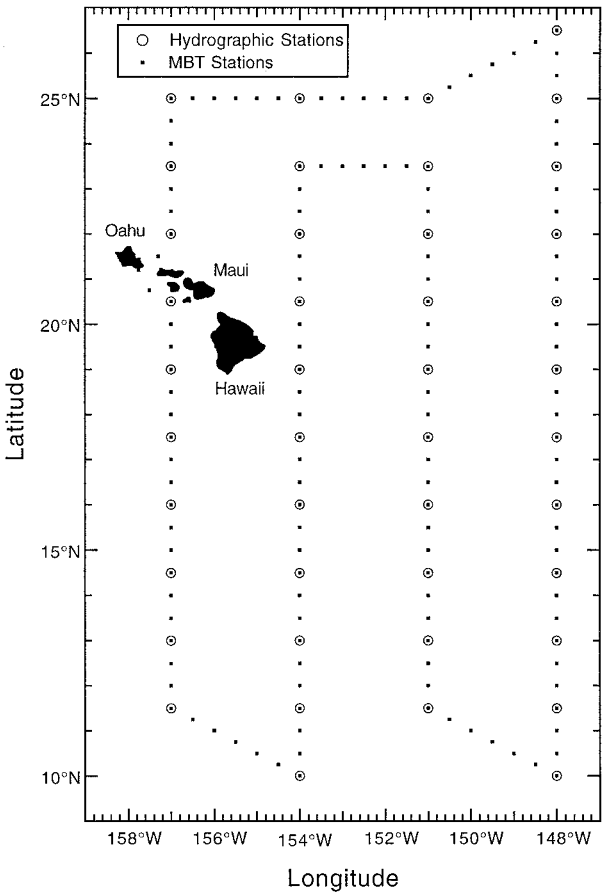

FIG. 6. Cruise track of the R/V *Townsend Cromwell* during the Trade Wind Zone Oceanography Pilot Study. Small dots are locations of BT casts and open circles are locations of hydrographic casts. See Table 1 for a list of cruise dates.

side of (1) using the bin-averaged drifter data. The results of this calculation (Fig. 5) show that the correlation between fluctuating velocity components is weak and that the right-hand side of (1) is zero to within the confidence limits measurable by this dataset. Thus, the NHRC is not in a region of net dissipation of vorticity or momentum. As Firing concludes, it is quite possible that Eq. (1) is inadequate to describe the NHRC.

In order to obtain a true picture of the surface currents near the Hawaiian Ridge, a long-term effort would be necessary. Drifter data have an inherent sampling bias that is difficult to eliminate. We know that there is a strong mesoscale eddy field with timescales of about 1 month. In addition, Chiswell (1994) found significant dynamic height variability at tidal frequencies. However, from the limited dataset we have we can make the following tentative conclusions. The NHRC is highly intermittent as speculated by Price et al. (1994). The NHRC as observed in the drifter data appears to be a part of the NEC that gets split off by the end of the Hawaiian Ridge and continues in an eastward direction. As a result of this interpretation, it would be most helpful to examine meridional fluctuations of the position of the NEC, in hopes of relating northward movement of the NEC with the existence of the NHRC.

TABLE 1. Dates of the cruises of the R/V *Townsend Cromwell* in the Trade Wind Zone and Oceanography Pilot Study.

Cruise number	Beginning date (mo/d/yr)	End date (mo/d/yr)
1	2/15/64	3/6/64
2	3/17/64	4/5/64
3	4/13/64	5/4/64
4	5/17/64	6/5/64
5	6/16/64	7/5/64
6	7/14/64	8/1/64
7	9/2/64	9/20/64
8	10/2/64	10/20/64
9	11/5/64	11/24/64
10	12/2/64	12/20/64
11	1/6/65	1/24/65
12	2/9/65	2/27/65
13	3/9/65	3/28/65
14	4/12/65	4/30/65
15	5/13/65	5/31/65
16	6/11/65	7/2/65

3. Cromwell data

With the drifter data in mind, we take a more historical perspective by examining data from the Trade Wind Zone Oceanography Pilot Study (TWZOPS). The TWZOPS was originally undertaken to try to learn about the seasonal variability of water mass properties in the region east of Hawaii. The TWZOPS was a series of 16 cruises on the R/V *Townsend Cromwell*, one each month, done between February 1964 and July 1965. The same ship track (Fig. 6) was repeated for each cruise, with the data concentrated along four meridians: 157°, 154°, 151°, and 148°W. The dates for each cruise are presented in Table 1. At each of the stations indicated by numbers and open circles, hydrographic casts measuring temperature and salinity were made to about 1500 m. Additionally, at the locations indicated by the dark dots, MBT temperature profiles were made to about 250 m. The original data were reported by Charnell et al. (1967).

Using the MBT data from the TWZOPS we can view the downward tilt of the thermocline associated with the NHRC and begin to understand its time evolution. Because the MBTs are so shallow however, dynamic height cannot be calculated relative to a deep level. One is thus required to use a proxy for the tilt of the thermocline. Here a quantity is used that is readily calculated from the MBT observations, the temperature at 200 m; 200 m is in the middle of the thermocline, and thus a slope in the thermocline would show up as a change in temperature at that depth. Price et al. (1994) found a linear correlation of 0.93 between 0/500 dbar dynamic height and 200-m temperature for the region north of the Hawaiian Ridge.

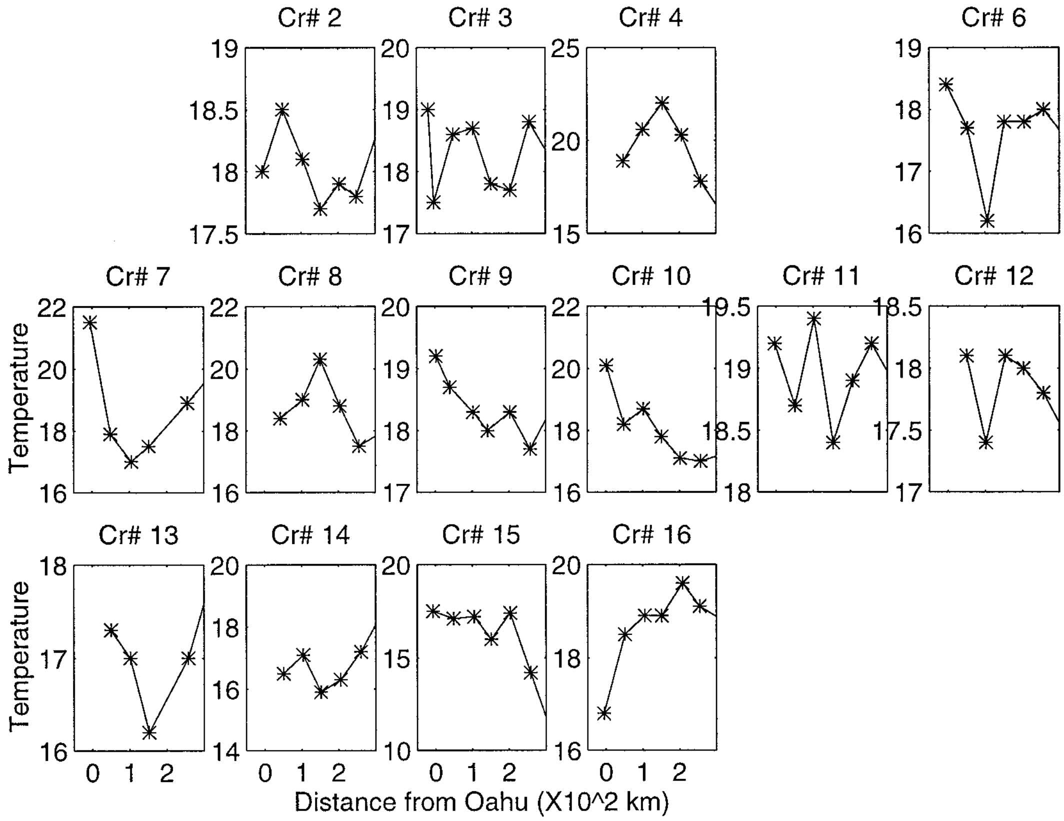

FIG. 7. Temperature at 200 m north of Oahu for the Cromwell cruises. Note the ordinate and vertical scale is different for each subplot, but the abcissas are the same. Distance presented is in kilometers from the southeastern tip of Oahu (see Fig. 6).

The 157°W line is the only one from the TWZOPS that crosses the Hawaiian Ridge, so we use the section that goes diagonally northeastward from the eastern end of Oahu to (22°N, 157°W) and directly northward from there. The temperature at 200 m along that line is displayed in Fig. 7 for the 14 of 16 Cromwell cruises for which the MBT data are available. Several features stand out from these plots. Of the 14 available sections, only 5 display a significant tilt of the thermocline in the direction that might possibly indicate the presence of the NHRC, downward, or increasing temperature with distance. These sections are from cruises 2, 4, 8, 14, and 16. There are several other sections that display a significant tilt in the opposite direction, decreasing temperature with distance. There are also other sections that display little or no change in temperature. Also apparent from these observations is that there is no coherence from one month to the next. The picture is not one of a slowly evolving pattern, but of a rapidly changing field that has been sampled at too low a frequency to determine the nature of the change. One is thus led to believe that the NHRC appears and disappears on timescales of less than one month. Tidal aliasing could also account for some of this variability. The intermittency of the NHRC is consistent with the drifter observations reported above.

I examine the large-scale circulation patterns to see if they indicate any correspondence with the presence of the NHRC as indicated in Fig. 7. Again I use the proxy measurement of thermocline distribution, 200-m temperature, plotted for the each cruise (Fig. 8).

Cruise 4 appears to be associated with an elongated anticyclonic circulation on the north side of the ridge. The NEC is divided up into two parts: one which goes westward around 20°N and the other at about 15°N. The branch at 20°N splits when it reaches the Island of Hawaii and some of it flows along the north side of the ridge, forming the thermocline tilt shown in Fig. 7.

For cruise 8, the presence of the NHRC is associated with an eddy circulation on the north side of the ridge, which is manifested at 154° and 157°W. However, this time, the NEC does not appear in the 200-m temperature field anywhere near the Hawaiian Ridge, being concentrated to the south at 15°–17°N.

In cruise 16, the NEC is well to the south of the Island chain. However, in cruise 15, the NEC is observed to have split at 154°W into a northern and southern branch. Perhaps the temperature rise observed in cruise 16 (Fig.

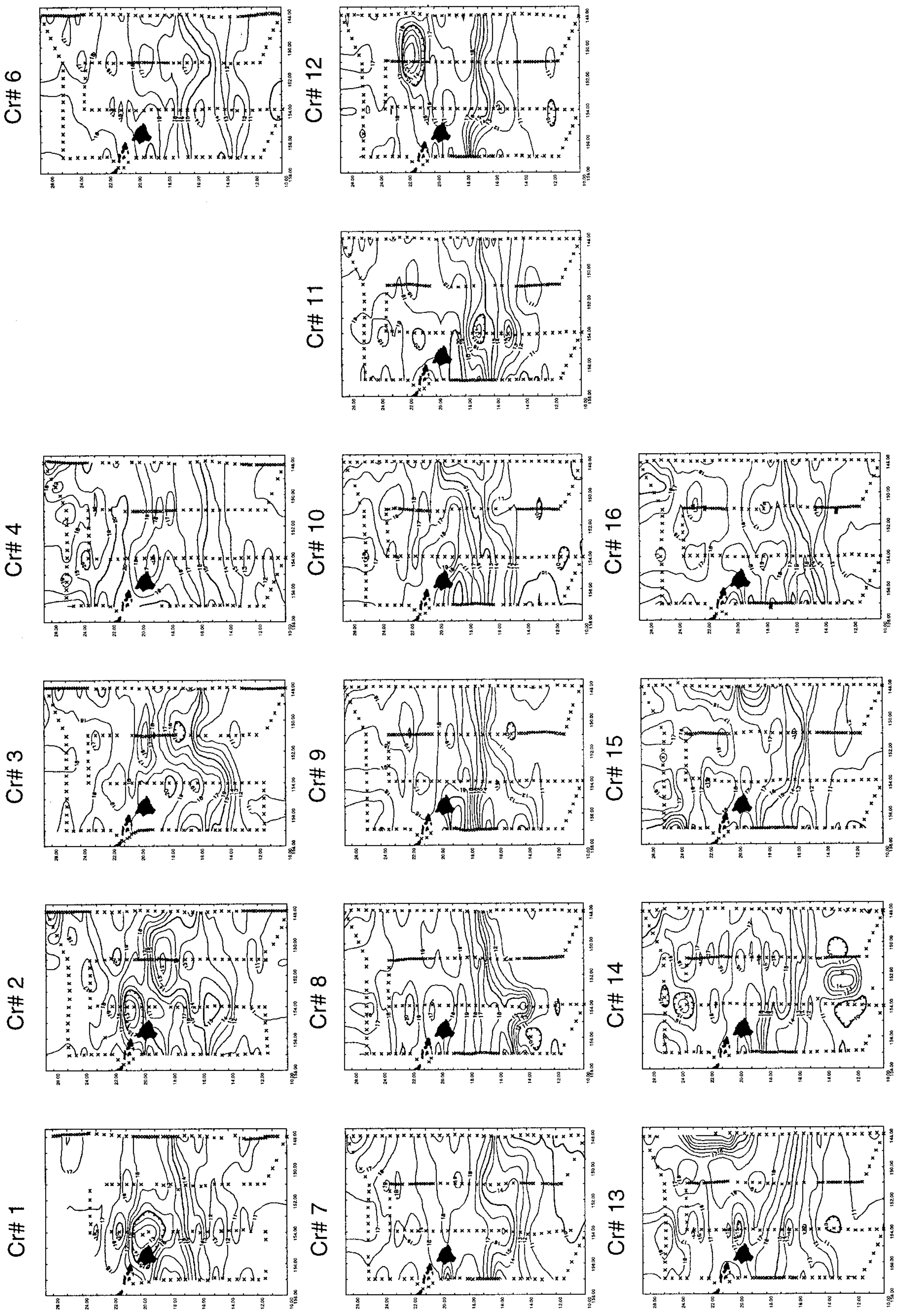

FIG. 8. The 200-m temperature over the study region for each of the Cromwell cruises where the data were available.

7) is a propagating signal from this split that has reached the north of Oahu.

4. Discussion

I have explored two different datasets for insight into the structure and variability of the NHRC. The drifter data showed that the current is not there most of the time. There were other times when anticyclonic eddies existed on the north side of the Hawaiian Ridge, leading to an along-ridge flow to the northwest that was not particularly coherent or connected. There was one short interval seen in the drifters where there was a connected, along-ridge current flowing from the Island of Hawaii to Kauai. The drifters caught up in this burst of current were carried along the ridge at 20–80 cm s^{-1} and ejected on the north side of the ridge. They came from south and east of Hawaii, suggesting a northwestward transport of tropical surface water.

The Cromwell data show the NHRC to be present intermittently over a period of 1½ years, probably having timescales of less than one month.

The dynamics of the NHRC are not easy to assess using these datasets. It appears however that, when the NHRC is present as it is in Fig. 4, it is an extension of a northward meandering NEC being entrained by the tip of the Hawaiian Ridge and the island of Hawaii. An of example of this process was presented in Fig. 8. The NEC is baroclinically unstable by the criterion of Gill et al. (1974) and meanders far enough northward to interact with the Hawaiian Ridge. Mitchum (1995) has observed 90-day oscillations of sea level at Wake Island. These oscillations were shown to be consistent with westward currents that occasionally impinge on the island of Hawaii, the same mechanism suggested here for the generation of the NHRC.

Anticyclonic eddies may also cause northwestward flow along the ridge, but this flow is not connected or organized on a large scale. Drifting cyclonic eddies are just as likely to push the flow in the other direction.

The evidence presented here suggests the possibility that the ridge current is an extension of a meandering and unstable NEC. The Hawaiian Ridge is geographically placed to catch a small percentage of those northward meanders. This placement of the Hawaiian Ridge may mean that enough NEC water gets pulled to the north to have a significant effect on the water properties found north of the ridge. Whether or not this is true is a question left for future studies.

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REFERENCES

Bernstein, R., and W. White, 1974: Time and length scales of baroclinic eddies in the central North Pacific. *J. Phys. Oceanogr.,* **4,** 613–624.

Charnell, R., D. Au, and G. Seckel, 1967: The trade wind zone oceanography pilot study. U.S. Fish and Wildlife Service Special Rep. 552. 78 pp. [Available from National Marine Fisheries Service, 2570 Dole St., Honolulu, HI 96822.]

Chiswell, S., 1994: Vertical structure of the baroclinic tides in the central North Pacific subtropical gyre. *J. Phys. Oceanogr.,* **24,** 2032–2039.

Firing E., 1996: Currents observed north of Oahu during the first five years of HOT. *Deep-Sea Res. II,* **43,** 281–303.

Gill, A., J. Green, and A. Simmons, 1974: Energy partition in the large-scale ocean circulation and the production of mid-ocean eddies. *Deep-Sea Res.,* **21,** 499–528.

Godfrey, J. S., 1989: A Sverdrup model of the depth-integrated flow for the World Ocean allowing for island circulations. *Geophys. Astrophys. Fluid Dyn.,* **45,** 89–112.

Graef, F., and L. Magaard, 1994: Reflection of nonlinear baroclinic Rossby waves and the driving of secondary mean flows. *J. Phys. Oceanogr.,* **24,** 1867–1894.

Hansen, D., and A. Herman, 1989: Temporal sampling requirements for surface drifting buoys in the tropical Pacific. *J. Atmos. Oceanic Technol.,* **6,** 599–607.

Kessler, W., and B. Taft, 1987: Dynamic heights and zonal geostrophic transports in the central tropical Pacific during 1979–1984. *J. Phys. Oceanogr.,* **17,** 97–122.

Magaard, L., 1983: On the potential energy of baroclinic Rossby waves in the North Pacific. *J. Phys. Oceanogr.,* **13,** 38–42.

Mitchum, G., 1995: The source of 90-day oscillations at Wake Island. *J. Geophys. Res.,* **100,** 2459–2475.

Mysak, L., and L. Magaard, 1983: Rossby wave driven Eulerian mean flows along non-zonal barriers, with application to the Hawaiian Ridge. *J. Phys. Oceanogr.,* **13,** 1716–1725.

Oh, I., and L. Magaard, 1984: Rossby wave induced secondary flows near barriers, with application to the Hawaiian Ridge. *J. Phys. Oceanogr.,* **14,** 1510–1513.

Price, J., M. Van Woert, and M. Vitousek, 1994: On the possibility of a ridge current along the Hawaiian Islands. *J. Geophys. Res.,* **99,** 14 101–14 111.

Qiu, B., D. Koh, C. Lumpkin, and P. Flament, 1997: On the existence and formation mechanism of the North Hawaiian Ridge Current. *J. Phys. Oceanogr.,* **27,** 431–444.

Roden, G., 1991: Effects of the Hawaiian Ridge upon oceanic flow and thermohaline structure. *Deep-Sea Res.,* **38**(Suppl. 1), S623–S654.

Seckel, G., 1968: A time-sequence oceanographic investigation in the North Pacific trade-wind zone. *Trans. Amer. Geophys. Union,* **49,** 377–387.

——, 1975: Seasonal variability and parameterization of the Pacific North Equatorial Current. *Deep-Sea Res.,* **22,** 279–401.

Taft, B., and W. Kessler, 1991: Variations of zonal currents in the central tropical Pacific during 1970 to 1987: Sea level and dynamic height measurements. *J. Geophys. Res.,* **96,** 12 599–12 618.

Talley, L., and R. deSzoeke, 1986: Spatial fluctuation north of the Hawaiian Ridge. *J. Phys. Oceanogr.,* **16,** 981–984.

White, W., 1983: A narrow boundary current along the eastern side of the Hawaiian Ridge; The North Hawaiian Ridge Current. *J. Phys. Oceanogr.,* **13,** 1726–1731.

——, and A. Walker, 1985: The influence of the Hawaiian Archipelago upon the wind-driven subtropical gyre in the western North Pacific. *J. Geophys. Res.,* **90,** 7061–7074.