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Observations of the Flow of Abyssal Water through the Samoa Passage

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ABSTRACT

During the fall of 1994 a conductivity–temperature–depth/hydrographic survey was carried out as part of the World Ocean Circulation Experiment one-time survey, Line P15N. The survey included standard water properties required by WOCE. Line P15N extended southward from the Aleutian Islands along 165°W into the vicinity of the Samoa Passage. The line was adjusted to follow the axis of the passage, and time was found to complete a cross-section survey across the passage. This paper will present geostrophic computations of flow velocities through the gap, including transport estimates, and will present longitudinal plots of properties. The longitudinal plots show evidence of hydraulic control at the sill in the Samoa Passage. A best estimate of northward transport of water colder than 1.2°C (potential temperature) is determined to be 8.4 Sv.

1. Introduction

It is well known that the dense water masses in the ocean are formed in relatively few places. Lately the northern North Atlantic has captured attention. It is interesting that the densest water mass formed anywhere in the North Pacific is the Pacific Intermediate Water mass, with a mean potential density anomaly of about 26.8 kg m^{-3} (Freeland et al. 1998) and this penetrates downward from the surface only to pressures less than 1000 dbar. Nevertheless, there is dense bottom water in the North Pacific basin, but it has formed elsewhere. Dense water can be formed in the North Atlantic or in the Southern Ocean, and, irrespective of the source, this dense water must enter the Pacific Ocean from the south. However, the South Pacific basin is separated from the North Pacific basin by a system of ridges with relatively few gaps. Dense water must enter the North Pacific basin through the Samoa Passage (near 10°S, 169°W) or two other smaller passages (in the Robbie Ridge and Manihiki Plateau) that we believe allow the transport of significantly less water. This dense water is usually called Antarctic Bottom Water, but is referred to by Johnson and Toole (1993) as Lower Circumpolar Water (LCW). As will be seen later, this water is cold ($\theta_{\min} \approx 0.8°C$), salty ($S_{\max} = 34.708$ psu), more oxygen rich ($O_{2\max} \approx 205$ μmol kg^{-1}), and silicate poor ($Si_{\min} \approx 122$ μmol kg^{-1}), in accordance with the properties listed for LCW by Johnson and Toole. Since the LCW is, in fact, a mixture of water deriving from North Atlantic Deep Water and Antarctic Intermediate Water, we find the designation LCW appealing and will use this throughout the remainder of this paper.

There have been several previous surveys of the flows through the Samoa Passage. In 1968 the Styx expedition completed a detailed survey in the immediate vicinity of the passage (Reid and Lonsdale 1974). It is surprising that although direct current observations were carried out on the Styx expedition, no estimate was made of the transport through the passage. Observed speeds were typically 4–5 cm s^{-1} within Samoa Passage. An east–west (E/W) survey was completed in 1987 as part of the TEW (Transport of Equatorial Waters) expedition (Taft et al. 1991), which confirmed that strong flows, up to about 10 cm s^{-1}, did occur in the Samoa Passage with transport through the passage estimated at $6.0 \pm 1.1 \times 10^6$ m^3 s^{-1}. In 1992 a CTD section was occupied across the passage in support of an expedition to deploy a current meter array specifically to monitor deep flows through the Samoa Passage. A geostrophic estimate of the volume transport of water colder than 1.2°C was made and reported by Johnson et al. (1994) to be $4.8 \pm 0.6 \times 10^6$ m^3 s^{-1}. The direct current observations were reported by Rudnick (1997), who determined that transports were highly variable and ranged between 1.1 and 10.7 ($\times 10^6$ m^3 s^{-1}) with a mean of 6.0 and a standard deviation of 1.5×10^6 m^3 s^{-1}. More recently, a hydrographic survey was completed in 1994 (Roemmich et al. 1996) as a contribution to the World Ocean Circulation Experiment. The stations constituting this survey followed the axis of the ridge system extending from Fiji, along the Robbie Ridge, through the Samoan Passage, and thence to the Manihiki Plateau, finishing in Fiji. During the survey current meters were recovered that had been deployed in September 1992. This survey

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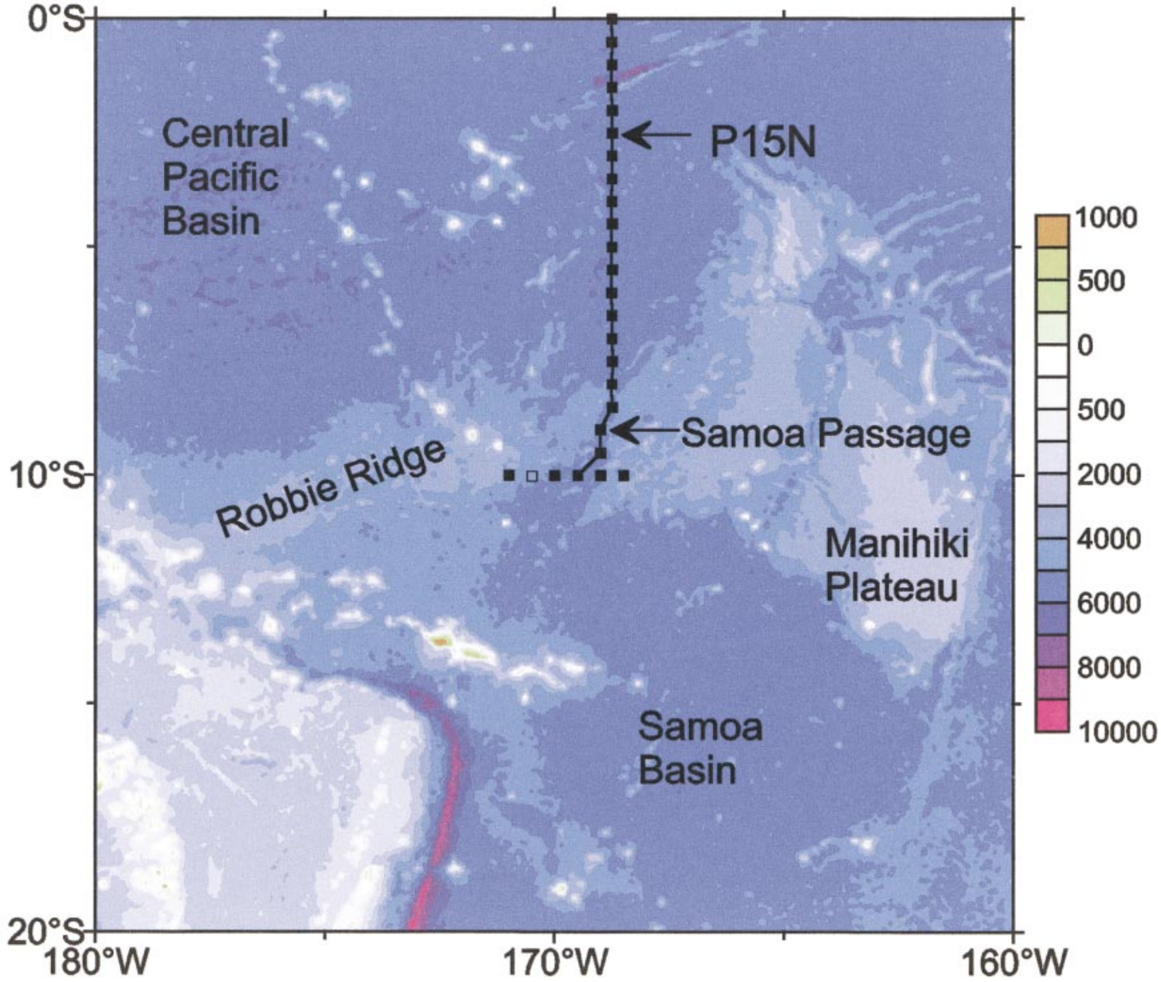

FIG. 1. Locations of the hydrographic stations used in the paper in relation to the principal topographic features.

estimated the volume flux to be 7.1 × 10^6 m^3 s^{-1}, slightly higher than the previous estimate in Taft et al. (1991).

As a contribution to the WOCE Hydrographic Program (WHP) of the World Ocean Circulation Experiment (WOCE) a series of observations was carried out along a nominal longitude of 165°W from the Aleutian Islands to Samoa. As the line of stations approached the Samoa Passage, the track was allowed to deviate from the nominal longitude to follow the talweg of the passage. The subsequent path to Samoa was thence along 169°W. This line of stations is designated P15N by the WHP. Furthermore, a series of five extra stations was completed along 10°S, as shown in Fig. 1. The objective was to define the properties and geostrophic velocities in the water entering Samoa Passage. Unfortunately, after completing one of the E–W stations we experienced a major failure in our main winch system. We were able to continue using a backup winch, but this had insufficient wire on its drum to allow sampling below 4400-m. In fact, this failure affected only one station, shown by the open box in Fig. 1, the next station being slightly shallower than 4400 m. Thus, in the charts to be shown there will be a small amount of data loss indicated. This failure also compromised sampling between 10°S and 15°S, but these stations are not used in this paper.

Full water property sampling was carried out to WOCE standards along the primary line of stations that constitutes P15N. The CTD profiles were taken using a Guildline model 8737 digital CTD sampling at 40 Hz and a nominal lowering rate of around 1 m s^{-1}. A rosette sampler with 23 conventional 10-L PVC Niskin bottles was also employed to collect water samples that were analyzed for salinity, dissolved oxygen, nutrients (nitrate, silicate, and phosphate), chlorofluorocarbons (CFC-11 and CFC-12), and carbonate system parameters (total inorganic carbon, alkalinity, and pH). Observations were acquired, as far as possible, according to normal WOCE protocol as described in the WOCE Operations Manual (WHPO 1991) and so were at stations separated, nominally, by 30 n mi. However, at the extra stations along 10°S only the CTD was used.

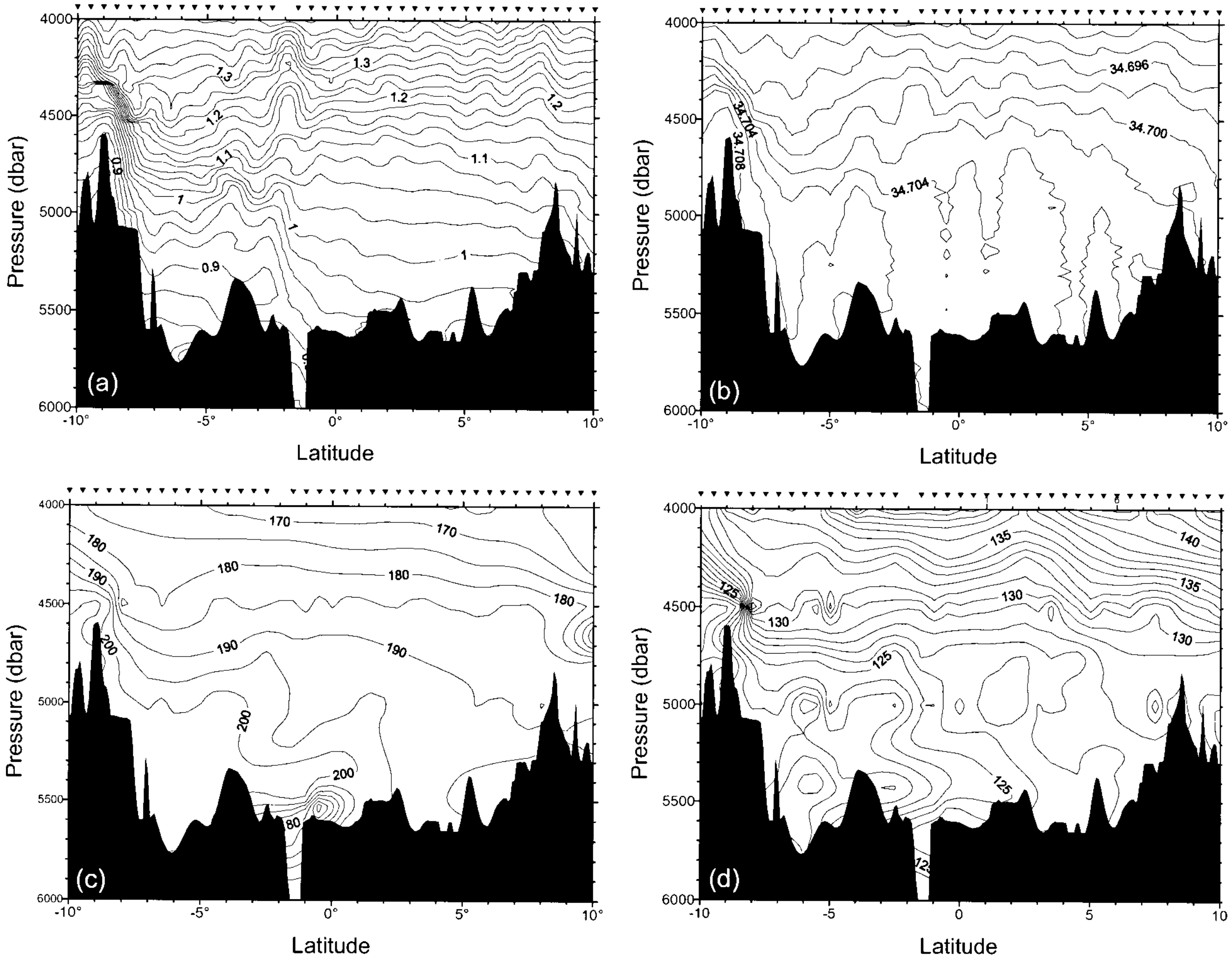

FIG. 2. Contour plots of (a) potential temperature relative to 4000 dbar, (b) salinity, (c) dissolved oxygen, and (d) silicate between 10°S and 10°N. The solid triangles indicate the station locations.

This paper will describe the properties of water passing through the Samoa Passage into the Central Pacific Basin. Geostrophic calculations of velocities near the bottom in the approaches to the passage will be presented from an analysis of the section along 10°S, and an estimate of the total transport through the passage will emerge. The velocities estimated by the geostrophic method will then be compared with velocities and transports estimated from the N–S section through an analysis of the hydraulic control at the sill.

2. Water properties

Figure 2 shows the distribution of some properties in the north–south direction. All properties show the descent of contours by up to 1000 dbar through Samoa Passage. Also striking is the apparent contraction of surfaces and increase in the steepness of property gradients directly over the sill. This is strongly suggestive of hydraulic control of the flow. This abrupt deepening of isopycnals was noted by Reid and Lonsdale (1974), though they did not have as detailed a picture as is shown in Fig. 2 and did not comment on the significance. Farmer and Armi (1999) indicate that the asymmetry of the isopycnals alone indicates that the flow is controlled at the sill. If this is the case, then assuming that the internal Froude number Fr = 1 at the position of steepest gradients should allow an estimate of the average velocity over the sill. Though the same pattern is evident in all of the four property plots constituting Fig. 2, temperature, and especially salinity, gradients are weak. The gradients in dissolved oxygen and silicate are not weak and clearly indicate a flow of a very distinctive water mass over the sill of the Samoa Passage into the central Pacific basin.

In Fig. 3 we show two plots of the distribution of potential density, relative to a 4000-dbar pressure surface (σ_4). Panel (a) shows the rapid contraction of density surfaces close to the sill in Samoa Passage and the drop in surfaces, suggesting a cascade of water flowing over a sill from the Samoa Basin into the Central Pacific Basin. Panel (b) shows the same property in the E–W

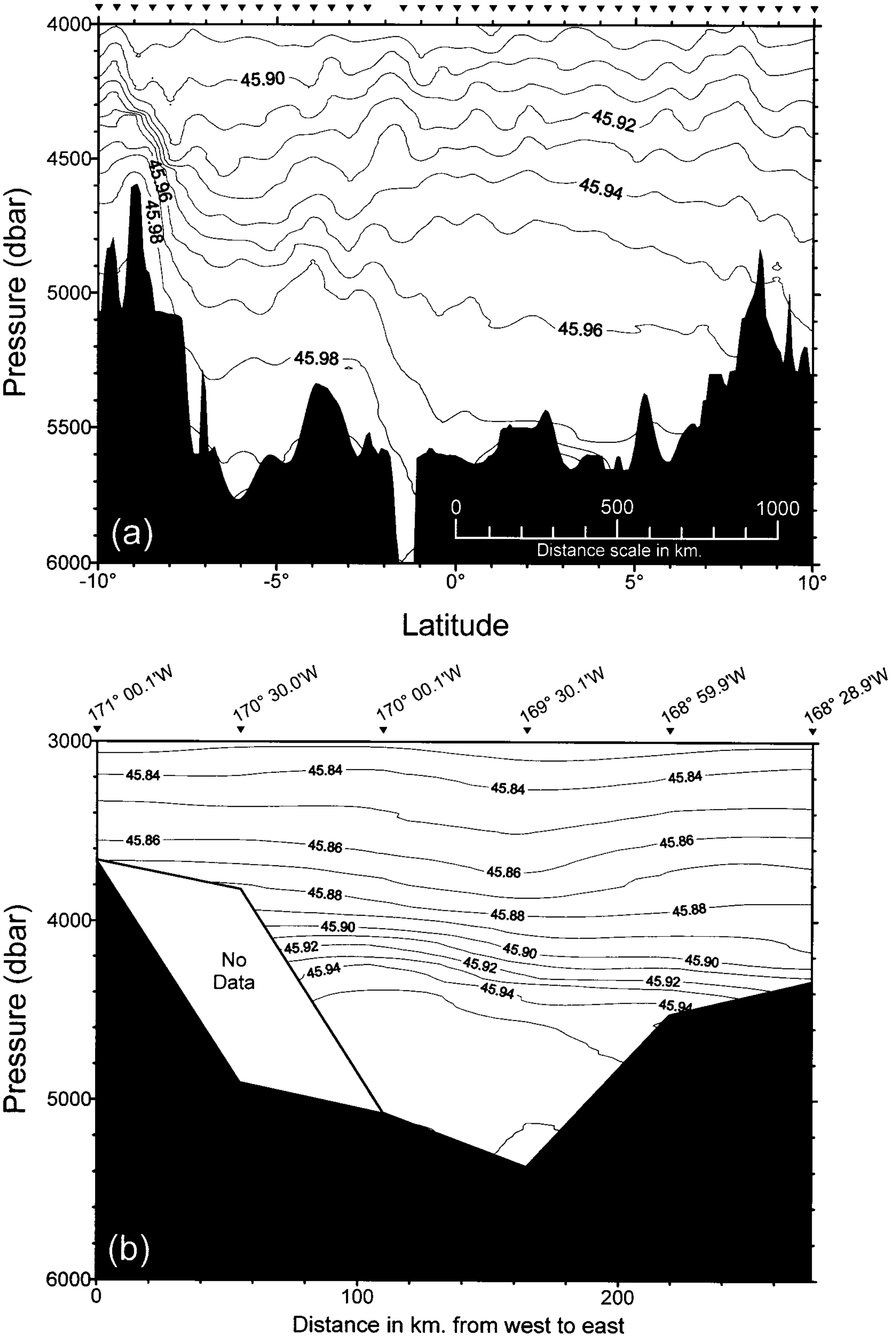

FIG. 3. Potential density (σ_4) relative to a pressure of 4000 dbar (a) in a N–S section from 10°S to 10°N and (b) an E–W section at 10°S. The solid triangles indicate the station locations.

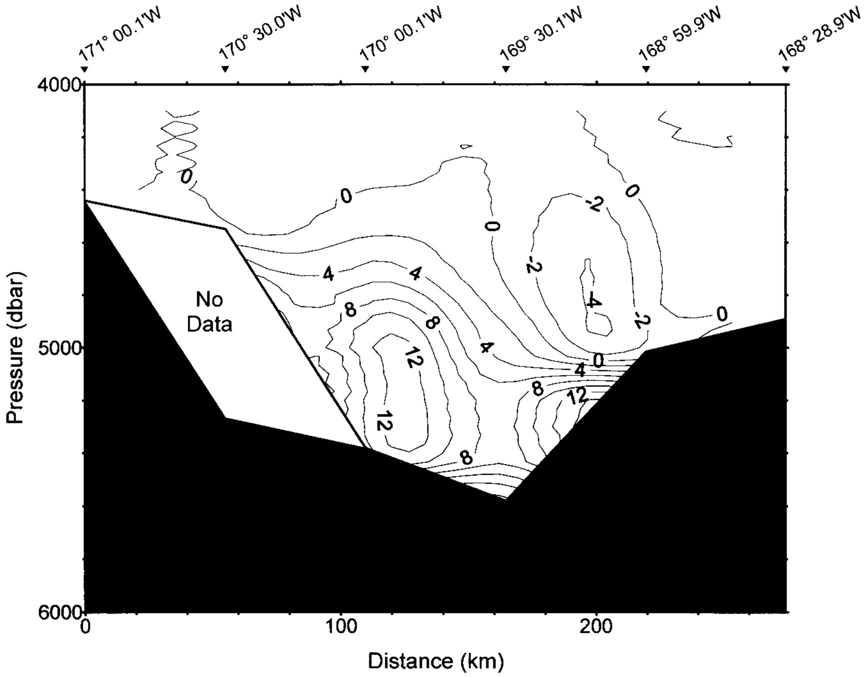

FIG. 4. Geostrophic velocity relative to 1.2°C potential temperature surface. Negative values connote northward flow.

section across the Samoan Passage. It was on recovery of the CTD at the station shown at a distance of 105 km that the main winch suffered irreparable damage, so only at the next station, at about the 50 km mark, were we unable to sample to the bottom, resulting in the data loss shown. At 10°S the Coriolis parameter is fairly small, so we do not expect to see a large tilt in the isopycnals across the passage. Indeed, the tilt showing in Fig. 3b is small, but clearly present and indicative of a flow of bottom water northward through the passage, as expected.

Geostrophic calculations can be completed as usual, but inevitably the question of a reference level occurs. In this particular case we are fortunate that we are looking at the flow of a distinct water mass, and this leaves few reasonable alternatives. Any surface chosen within the region of relatively steep gradients will supply essentially the same result. In this case we follow the lead of Roemmich et al. (1996) and estimate transports relative to the 1.2°C potential temperature surface. The flow is strong, showing near-bottom speeds of up to 12 cm s^{-1}. The transport can be estimated by integrating under the velocity contours and then multiplying by a factor to account for the fraction of the Samoa gap missed because of a broken winch. Scaling purely by the area lost suggests a factor of 1.4. However, we do have physical reasons for believing that the flow through the passage should be more intensified on the left-hand side, suggesting that a larger increment would be appropriate. The effect of losing this area was examined in relation to the mean flow through Samoa Passage as computed by Rudnick (1997, his Fig. 2). Eliminating this area and recomputing the implied transports would suggest a factor of 1.51. Using the smaller value yields a transport estimate of 8.4×10^6 $\mathrm{m}^3\,\mathrm{s}^{-1}$ and an average speed through the section of about 6.7 cm s^{-1}, and using the larger value yields a transport estimate of 9.1×10^6 $\mathrm{m}^3\,\mathrm{s}^{-1}$ and an average speed through the section of about 7.2 cm s^{-1}. These are both somewhat higher than the estimate of 7.1×10^6 $\mathrm{m}^3\,\mathrm{s}^{-1}$ estimated by Roemmich et al., and significantly higher than the estimate of 6.0×10^6 $\mathrm{m}^3\,\mathrm{s}^{-1}$ found by Taft et al., and the speeds seen in Fig. 4 are much larger than the 3–4 cm s^{-1} speeds reported by Reid and Lonsdale (1974).

These velocities are high by the normal standards of abyssal currents, and it is worth looking at the hypothesis that flow is controlled by hydraulic processes at the sill; this should serve as a plausibility check on the current speeds estimated by geostrophy. The flow suggested by Fig. 3a is of a dense water mass flowing over a shallow sill with control at the shallow point by the usual Froude number relation Fr = 1. The number Fr is the ratio of a typical flow speed to the local wave speed, but what is the local wave speed?

Let us try a simple model of the stratification and estimate the relevant wave speed. Represent the density structure directly above the sill as having a vertical gradient defined by Brunt–Väisälä frequency $N = N_0$ between $z = 0$ (the top of the sill) and $z = h$. Above the level $z = h$ we have an infinite quiescent fluid with no density gradients, thus $N = 0$ above the level $z = h$:

$$\frac{d^2W}{dz^2} = \left(\frac{N^2 - \omega^2}{\omega^2 - f^2}\right)k^2W(z) = 0$$

with $W = 0$ at $z = 0$. It is a simple matter to extract a dispersion relation, namely,

$$\omega \tan(\kappa_0 h) + \sqrt{N_0^2 - \omega^2} = 0,$$

where

$$\kappa_0 = k\sqrt{\frac{N_0^2 - \omega^2}{\omega^2 - f^2}},$$

and $c = \omega/k$ is the phase speed. As usual there is an infinite set of modes, each defined by discrete values of the phase speed c_n. For frequencies approaching f we find an asymptotic limit defined by $\kappa_0 h = (2n - 1)\pi/2$, which yields a simple dispersion relation $c_n = 2hN_0/[(2n - 1)\pi] = 18$ cm s^{-1}. This wave speed is rather faster than the typical flow speeds observed in Samoa Passage and is, in fact, closer to the peak speeds shown in Fig. 4 rather than the average. However, the section at 10°S is rather to the south of the control point. In Fig. 3a we see that the thickness of the northbound water decreases in thickness by at least 50%. Thus the average speed across the section estimated previously at 6.7 cm s^{-1} could easily have been accelerated in the vicinity of the control point. Thus, the observations of geostrophic flow at 10°S are consistent with the hypothesis of hydraulic control at the sill of the Samoa Passage.

A careful analysis of the dynamics of such control sections is presented by Whitehead (1998). Whitehead analyzes a selection of passages wider than or narrower than the local Rossby radius of deformation. In particular, Whitehead shows how density profiles upstream of a control section are modified by passage through a control point. In summary, the volume flux through a control section is given by

$$Q = \frac{\frac{\Delta\rho}{\rho}gh_u^2}{2f},$$

where the critical parameters h_u and $\Delta\rho$ are defined knowing the sill height and having two CTD profiles, one upstream and the other downstream of the control point, both of which have been completed to depths greater than the sill depth. The density difference $\Delta\rho$ is the largest difference at or above the sill depth, and the height h_u is the difference between the sill depth and the depth of the bifurcation in the CTD profiles. Whitehead (1998) estimates a volume flux of 7×10^6 m^3 s^{-1}, based on the observations of Rudnick (1997). We find a rather larger density difference ($\Delta\sigma_4 = 0.0497$, compared with the Whitehead/Rudnick estimate of 0.03) but a smaller height ($h_u = 730$ m compared with 1050 m) and using Whitehead's formula we estimate a volume flux $Q = 5.7 \times 10^6$ m^3 s^{-1}. This estimate is rather smaller than the volume flux estimated geostrophically and also smaller than Whitehead's own estimate. In fact, this method is rather sensitive to the definition of the height h_u, so internal wave activity could lead to variations in the estimate of the height sufficient to cause significant variations in the flux estimates. In Fig. 5, two downstream profiles are included to show the apparent insensitivity to the choice of the specific station.

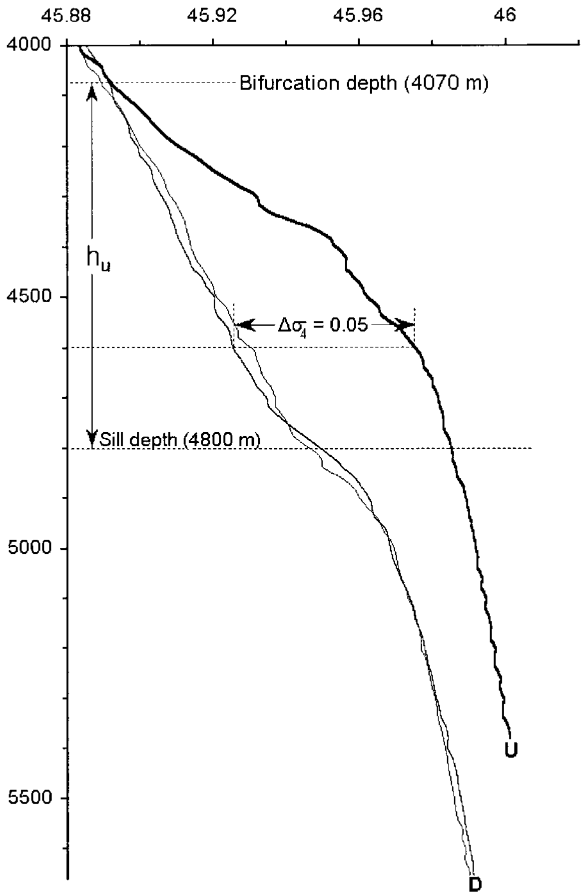

FIG. 5. Potential density (σ_4) below 4000 dbars for stations at 5°S, 6°S, and 10°S representing conditions upstream (U) and downstream (D) of the control point in Samoa Passage. Calculations are based on the 6°S profile, the one at 5°S being shown for comparison.

Before leaving this topic we should take note of an intriguing comment made by one of the referees. Though Fig. 5 is very similar to the diagram presented by Whitehead (1998), based on Geosecs observations, the values of σ_4 at the bifurcation depth are very different—45.98 in the Geosecs data compared with 45.89 in the present dataset. We have no explanation for this difference, but note that it might hint at large long-term changes taking place in deep water properties.

3. Conclusions

This paper presents some new observations of the flow of Lower Circumpolar Water through Samoa Passage. We find abyssal velocities up to 12 cm s^{-1} and estimate the transport of bottom water at 8.4–9.1 Sv (Sv $\equiv 10^6$ m^3 s^{-1}), depending on how missing data are handled. The Samoa Passage contains the coldest water that is observed flowing out of the system of basins within the South Pacific and flowing into the North Pacific. The contraction of property surfaces and the asymmetry of properties over the sill in the Samoa Passage indicates hydraulic control. An estimate of the controlling wave speed, assuming that the flow is controlled by Froude number, $Fr = 1$, suggests that speeds even higher than those computed geostrophically must occur; this is plausible given the likely vertical contraction of the dense water layer. The observed speeds and the calculated wave speed are sufficiently similar that the hypothesis that the flow is controlled hydraulically is probably correct, though the flow through the pass is rather larger than that estimated from a formula suggested by Whitehead (1998) based on the hypothesis of hydraulic control.

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