A Comparison of Techniques for Referencing Geostrophic Velocities*

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ABSTRACT

A geostrophic velocity section across the Gulf Stream and deep western boundary current near 35°N is referenced four different ways: using a POGO float (acoustically tracked transport float), shipboard acoustic Doppler current profiler (ADCP), and bottom current meters, and by assuming an isotherm level of no motion. The comparison between the first two techniques is emphasized because they are most easily applied. In general, reference velocities calculated using the float data agree well with those obtained from the ADCP data. However, there is disagreement at locations where the ADCP velocity is not in thermal wind balance, in which case the POGO value is deemed more accurate because the float samples deeper into the subsurface geostrophic flow. Disagreement is also caused by insufficient cross-stream POGO spacing (although this could be avoided). The isotherm- and current meter-referenced sections, while similar to each other, both show unrealistic features. It is argued that the POGO method is preferable to the shipboard ADCP for a deep-water hydrographic experiment.

1. Introduction

The task of objectively determining a reference level for geostrophically calculated velocities has always been problematic. Through the years many techniques have been employed, some of which rely on various assumptions about the flow, others requiring additional in situ data. One of the earliest methods was used by Defant (1941), who assumed that the level at which the vertical shear of velocity vanished coincided with a level of no motion. However, this is now known to be generally untrue. Another early approach, still employed today, is to use water mass boundaries as a guide for determining the level of no motion. An example of this is in Worthington's (1976) North Atlantic study where the core temperature of the Labrador Sea water was used as a reference level for the abyssal flow.

The above techniques are easy to apply (although the justification may be difficult). More sophisticated objective methods have been developed, such as the use of inverse calculations where the flow is quantitatively constrained by a prescribed set of conservation laws. Wunsch and Grant (1982) formulated the appropriate methodology and applied it to the western North Atlantic circulation. Unfortunately this approach is generally impractical: not only can the calculation itself be quite complex, but the in situ sampling pattern must form closed regions.

The most straightforward and objective way to estimate the reference velocity is by directly measuring the flow. Various instrumentation has been used for this, ranging from Lagrangian drifters to Eulerian arrays. Some techniques are easier to implement than others, but perhaps the most serious issue is the ageostrophic nature of the instantaneous flow. The basic question is, Can one discern anything quantitative about the low-frequency geostrophic current from direct measurements? Furthermore, how practical is the given approach? The desire is to make the velocity measurements quickly with minimal impact to the overall experiment. With these questions in mind we present a careful comparison of two direct referencing methods: use of acoustic transport floats (POGO floats), and use of a shipboard acoustic Doppler current profiler. We explore the advantages and disadvantages of each approach, and outline what we consider to be an effective plan for obtaining reference velocities in a deep-water hydrographic experiment.

Although the use of moored arrays is less practical than these two approaches, current-meter data have often been used for referencing geostrophic velocities. The hydrographic section used in this study coincided with a line of bottom current meters; thus, we include the current-meter approach in our analysis. We also

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compare these three direct methods to the more traditional technique of using an isotherm as a level of no motion.

2. Experiment setting

In summer of 1990 R/V *Endeavor* (EN214) occupied a set of hydrographic sections across the continental slope off Cape Hatteras, North Carolina, to study the interaction of the Gulf Stream and deep western boundary current (DWBC) (Pickart et al. 1992). In this region, the Gulf Stream separates from the continental margin and crosses the equatorward-flowing DWBC. One of the hydrographic sections (Fig. 1) was chosen specifically to coincide with a line of bottom current meters maintained as part of the Synoptic Ocean Prediction Experiment (SYNOP, see Pickart and Watts 1990a). To obtain absolute geostrophic velocities, we deployed POGO floats throughout the hydrographic cruise that measure the vertically integrated current. Because R/V *Endeavor* is equipped with an acoustic Doppler current profiler (ADCP) and because of the presence of the SYNOP array, this was an ideal opportunity to compare the different direct referencing techniques quantitatively.

The hydrographic section consisted of eight stations to the bottom and took approximately one and a half days to occupy. Each CTD (conductivity–temperature–depth) station also included a POGO drop. The station spacing was 25–30 km, which sufficiently resolved the cross-stream structure of both the Gulf Stream and DWBC. The total length of the section was 200 km, completely crossing both currents (the Gulf Stream is located above the DWBC at this location). The CTD stations bracketed the deep mooring sites (Fig. 1) to make the current-meter referencing calculation as accurate as possible.

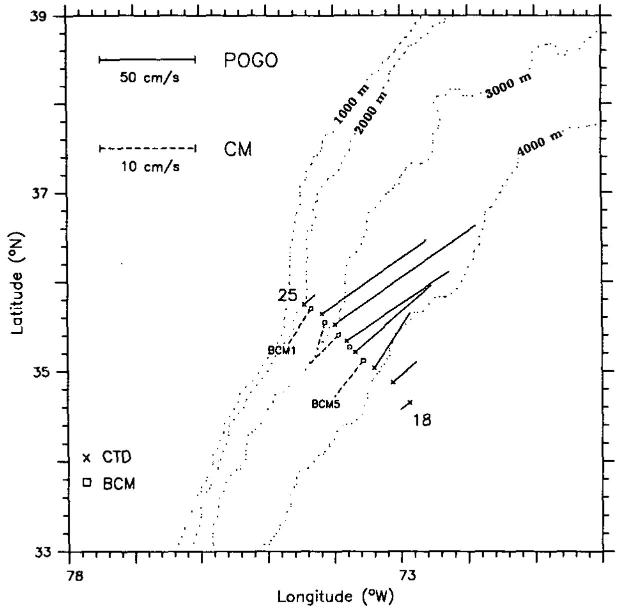

FIG. 1. Location of the hydrographic section and coincident mooring line. Each mooring contained a single current meter 95 m above the bottom. The moorings are labeled BCM1 (onshore) to BCM5 (offshore). The solid sticks are the POGO vectors (to 1000 m) obtained at the station sites, which reveal the Gulf Stream. The dashed sticks are 1-yr mean current-meter vectors revealing the DWBC. Current meter BCM4 was not recovered due to failure of the acoustic release.

3. Referencing techniques

a. Isotherm referencing

Offshore of Cape Hatteras the Gulf Stream flows northeastward in the upper layer, transporting water of southerly origin; in the deep layer the DWBC flows equatorward transporting North Atlantic deep water (Fig. 1). Thus it is an appropriate setting to use the water mass boundary technique to reference the geostrophic velocities. We consider this method first since it is the most traditional and least objective of the techniques considered. Worthington (1976) chose the 3.5°C (potential temperature) isotherm as the reference level for the DWBC, which is the core temperature of the Labrador Sea water located near the western boundary (Fig. 2a). The rationale was that since so little pure Labrador Sea water was found west of the Grand Banks, its equatorward transport must be negligible. The deep tracer distributions offer some support to this claim (Pickart et al. 1992): for example, there is a relative minimum in chlorofluorocarbons (CFCs) in the Labrador Sea water (Fig. 2b), indicative of a longer transit time from its area of formation than for the deeper Norwegian–Greenland overflow water. Furthermore, the 3.5°C isotherm seems appropriate for the Gulf Stream since it is a middepth reference level (~2000 m, Fig. 2a) consistent with previous direct observations in this region (Pickart and Watts 1990b).

For each station pair we computed the geostrophic velocity profile relative to 500 db using the dynamic method and then referenced the profiles using the 3.5°C isotherm as a level of no motion. The resulting absolute geostrophic velocity section is shown in Fig. 3a. While it contains a realistic looking Gulf Stream and a bottom-intensified DWBC as would be expected (Fig. 3a), there are aspects of the flow that are unrealistic and in disagreement with the results of the direct methods, as discussed in section 4.

b. Referencing by POGO floats

A POGO float is a Lagrangian drifter launched off the stern of the ship and tracked acoustically. It sinks at a constant rate to a predetermined depth (1000 m in this case) and then releases a weight and rises to the surface, at which time it is recovered. It is the modern-day version of the acoustic transport float (Richardson

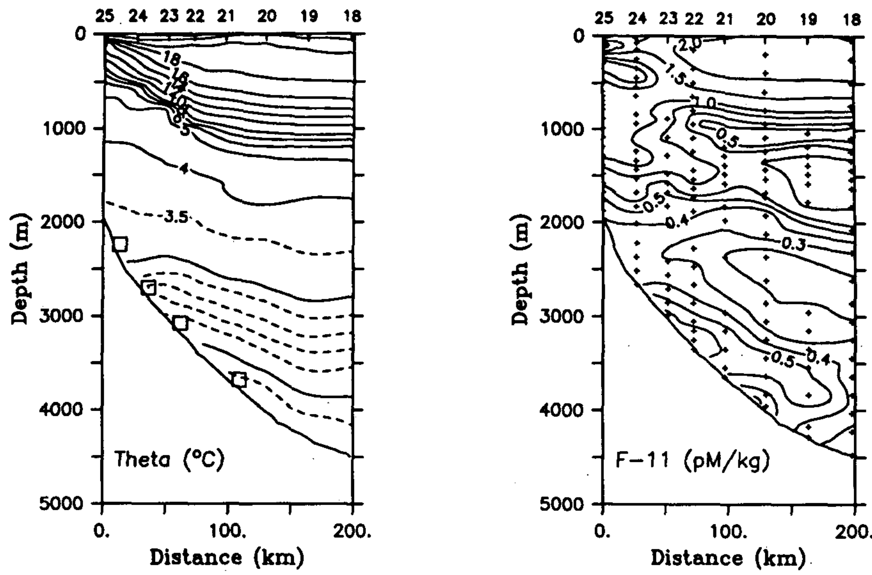

FIG. 2. (a) Section of potential temperature. The locations of the bottom current meters are indicated by the boxes. (b) Section of F-11.

and Schmitz 1965). By measuring the displacement vector (launch position to surface position) and by knowing the depth of penetration, one obtains a measure of the vertically integrated horizontal current over that depth. For a detailed description of the POGO float and the tracking process, see Rossby et al. (1991). The error in the POGO measurement is primarily due to loran navigation uncertainties and sighting error after the POGO surfaces, which Rossby et al. (1991) estimate to be ± 2 cm s^{-1}.

POGO float data were collected throughout EN214 in order to reference the geostrophic velocities. It was most efficient to deploy the floats at the CTD station sites rather than at the midpoints, which are more appropriate for the referencing calculation. This is mainly because a float can be launched while the CTD is still in the water and timed so that shortly after the CTD is secured on deck the float surfaces. This overlapping of tasks can save a significant amount of time over the length of a cruise. The referencing was done by computing the average POGO velocity for each pair of stations and then matching the vertically averaged CTD velocity (over the top 1000 m) to the POGO component normal to the station line.

The POGO-referenced absolute velocity section is markedly different from the velocity section obtained using the isotherm level of no motion (cf. Figs. 3b and 3a). In fact, at first glance one might be inclined to discount the POGO-referenced section as unrealistic: the Gulf Stream appears to extend to the bottom in two narrow regions, bracketed by jets of equatorward flow. However, as explained in Pickart and Smethie (1993), not only are these alternating poleward–equatorward deep jets characteristic of other directly referenced velocity sections in this region (e.g., Richardson and Knauss 1971; Joyce et al. 1986), but they are consistent with the deep current meter velocity time series from the SYNOP moored array. The continental slope off of Cape Hatteras often contains energetic topographic Rossby waves that have been generated downstream (and offshore) by the deep Gulf Stream and have subsequently refracted onto the slope (see Pickart and Watts 1990a; Schultz 1987). These waves are quasigeostrophic with the flow oriented approximately alongslope. Figure 3b thus reveals a combination of the upper-layer Gulf Stream and bottom-intensified DWBC, with topographic Rossby waves superposed.

By employing a spatial low-pass filter, Pickart and Smethie (1993) successfully removed the high-wavenumber topographic wave signal in this velocity section. Briefly, the velocity was smoothed along density surfaces using a filter that removed the dominant topographic signal and passed the broader DWBC signal. The result is shown in Fig. 4a, which clearly reveals the Gulf Stream and DWBC. Interestingly, after removing the waves this section shows more resemblance to the isotherm-referenced section (Fig. 3a); however, there are significant differences (discussed in section 4).

c. *Referencing by ADCP*

1) DATA REDUCTION AND ERRORS

During EN214, 3-min-averaged ADCP velocities were obtained with an RDI 150-kHz instrument. The profiles extended to roughly 300 m in 8-m bins. As described in Joyce (1989) and Pollard and Read

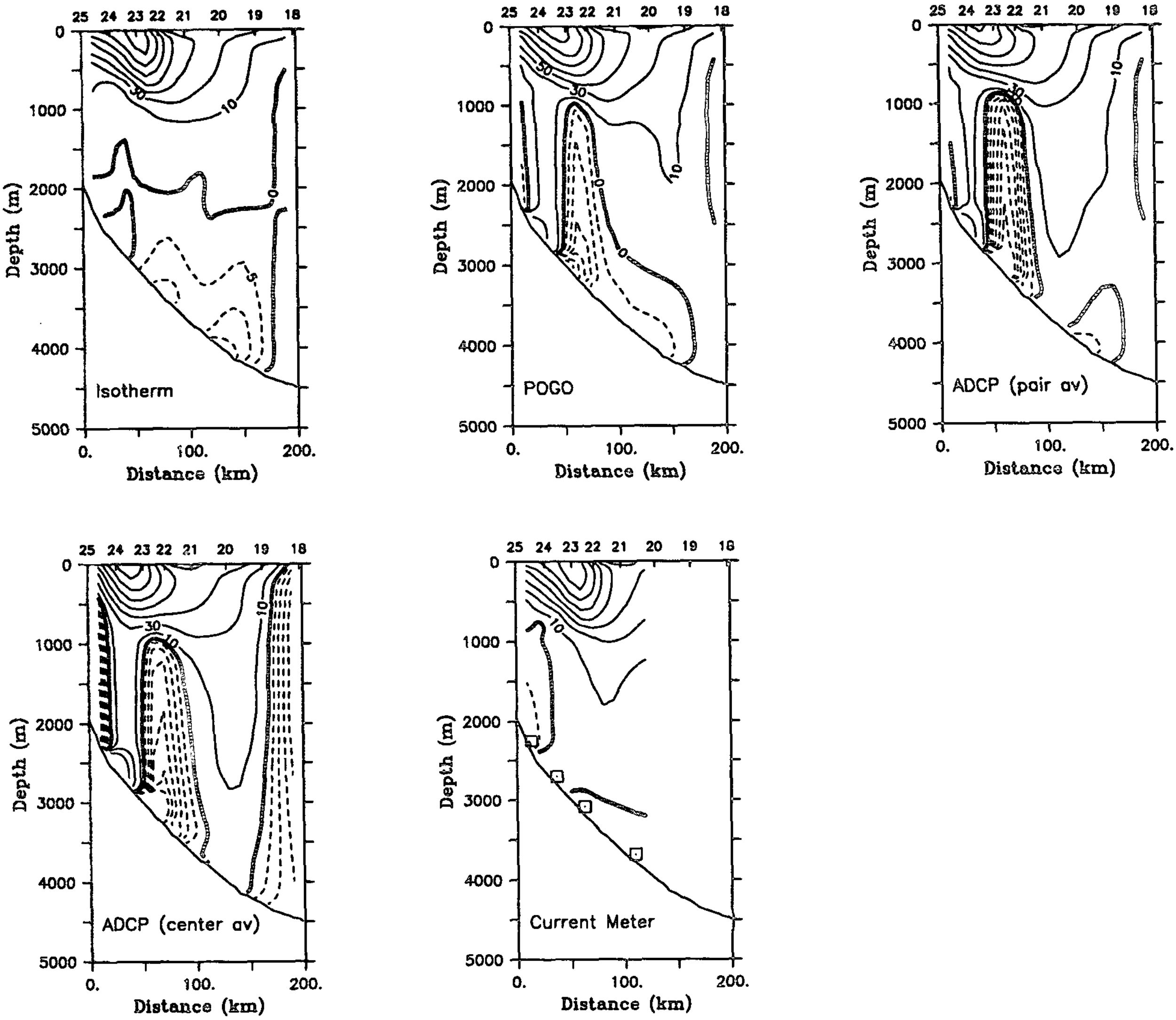

FIG. 3. Sections of absolute geostrophic velocity referenced using the different techniques. The contour levels are 10–150 cm s^{-1} by 20 cm s^{-1} increments, and −30–0 cm s^{-1} by 5 cm s^{-1} increments. (a) By isotherm level of no motion of 3.5°C (note: the zero velocity line does not perfectly coincide with the 3.5°C isotherm due to slight inaccuracy of the contouring routine). (b) By POGO floats. (c) By ADCP (pair averaged). (d) By ADCP (center averaged). (e) By bottom current meters.

(1989), the shipboard ADCP data need to be adjusted because of possible misalignment of the ADCP transducer and nonzero trim of the transducer and ship. The former is represented by an angle α and introduces error in the velocity component perpendicular to the ship's heading. The latter is represented by a scaling factor $1 + \beta$ and influences the velocity in the direction of the ship's heading.

Midway through the cruise, the ship steamed back and forth (a single time) over the same portion of cruise track. We split this portion into three equal segments and computed an α and β as in Joyce (1989) for each segment at six different depths. To perform the calculation it is necessary to know the ship speed, which was computed using the Loran C navigational fixes. To reduce the noise in the derived ship speed we required that changes in speed not exceed 1.5 m s^{-1} during any one segment. The three values of α and β agreed well, and the average values ($\bar{\alpha} = 3.0478$, $1 + \bar{\beta} = 1.0213$) were used to correct the Doppler velocities as in Joyce (1989).

To obtain absolute (i.e., not ship relative) velocities, the Doppler velocities and ship velocities were then combined. The largest source of error is in the ship speed due to the uncertainty in Loran C position. The rms error of the Northstar-7000 Loran C receiver on R/V *Endeavor* is ±20 m (Liu and Rossby 1992), which translates to an uncertainty of approximately 15 cm s^{-1} for the 3-min averaging period. This was improved to approximately 6 cm s^{-1} by cross-stream averaging the velocity profiles

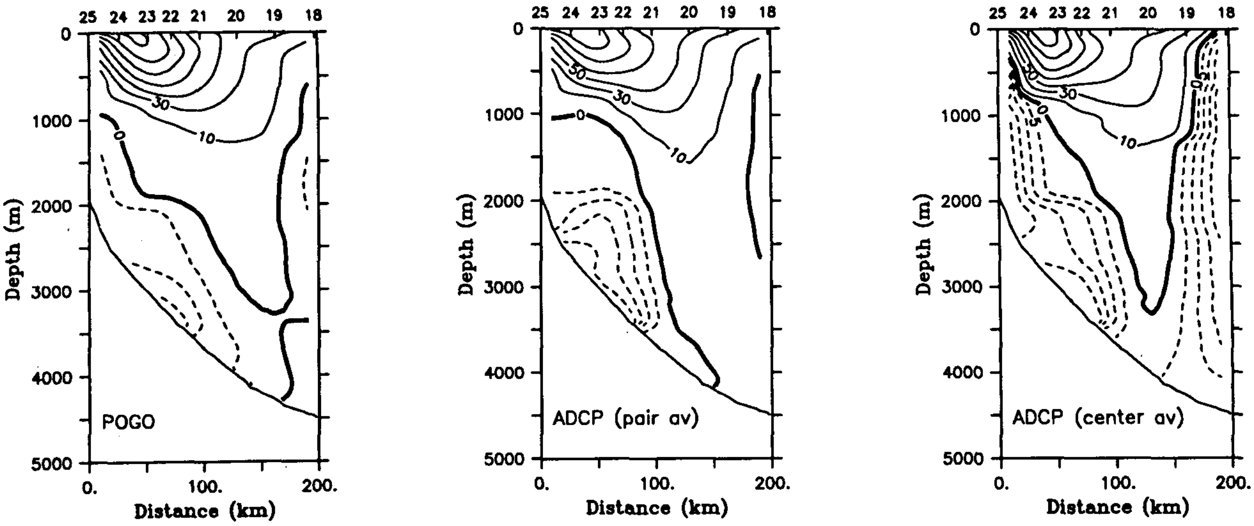

FIG. 4. Low-pass-filtered absolute geostrophic velocity sections (same contour levels as Fig. 3). (a) POGO-referenced section. (b) ADCP-referenced section (pair averaged). (c) ADCP-referenced section (center averaged).

(see next section). The Gulf Stream signal is clearly evident in the Doppler data, with peak speeds in excess of 150 cm s^{-1} at the 100-m depth (Fig. 5).

2) Pair-averaged referencing

Since the ADCP measurements are continuous along the section line, two different approaches were used to reference the geostrophic velocities. To make the comparison between the POGO and ADCP most meaningful, we first used a comparable approach to that used for the POGO. Specifically, an ADCP velocity profile was obtained at each station site using a 13-km centered average (one-sided average for end stations). This filter width was used because it resulted in the best agreement between the POGO and ADCP. The ADCP profiles were then pair averaged in analogous fashion to the POGO velocities. Finally, the downstream component of the resulting ADCP velocity profile was matched in a least-squares sense to the geostrophic velocity profile. The match did not include the near-surface portion of the ADCP profile that was clearly ageostrophic. To determine the first usable depth we computed the difference in vertical shear between the ADCP and CTD velocities; in each case it was obvious where to apply the cutoff (always between 50 and 100 m). Figure 3c shows the absolute geostrophic velocity section referenced using the ADCP data in this manner.

The comparison between the POGO- and ADCP-derived reference velocities (i.e., the absolute velocity at 500 db) is favorable (Fig. 6a). Of the seven locations only two (CTD pairs 23–22 and 21–20) show disagreement larger than the measurement error. Interestingly, it is precisely at these two locations where the largest disagreement in vertical shear exists between the ADCP and CTD profiles (Fig. 7). The discrepancy for CTD pair 21–20 can be explained straightforwardly. At this location in the Gulf Stream there is a transition in the character of the near-surface vertical shear, from a region of increasing velocity with depth (station 21, still in the warm surface core of the Gulf Stream, Fig. 2) to a region of decreasing velocity with depth (station 20, offshore of the warm core). When the ADCP profiles of stations 21 and 20 are averaged together, the resulting mixture is in disagreement with the CTD profile. This can be corrected for by using a "center" ADCP profile constructed from data between stations 21 and 20 (see next section). This improves the agreement in vertical shear between the ADCP and CTD, as well as the agreement between the ADCP- and POGO-derived reference velocities (Fig. 6b).

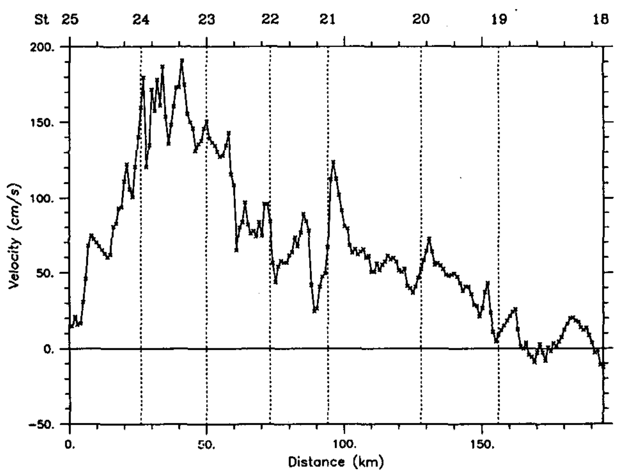

FIG. 5. ADCP Gulf Stream profile at 100 m (rotated to 40°T). The locations of the CTD stations are indicated.

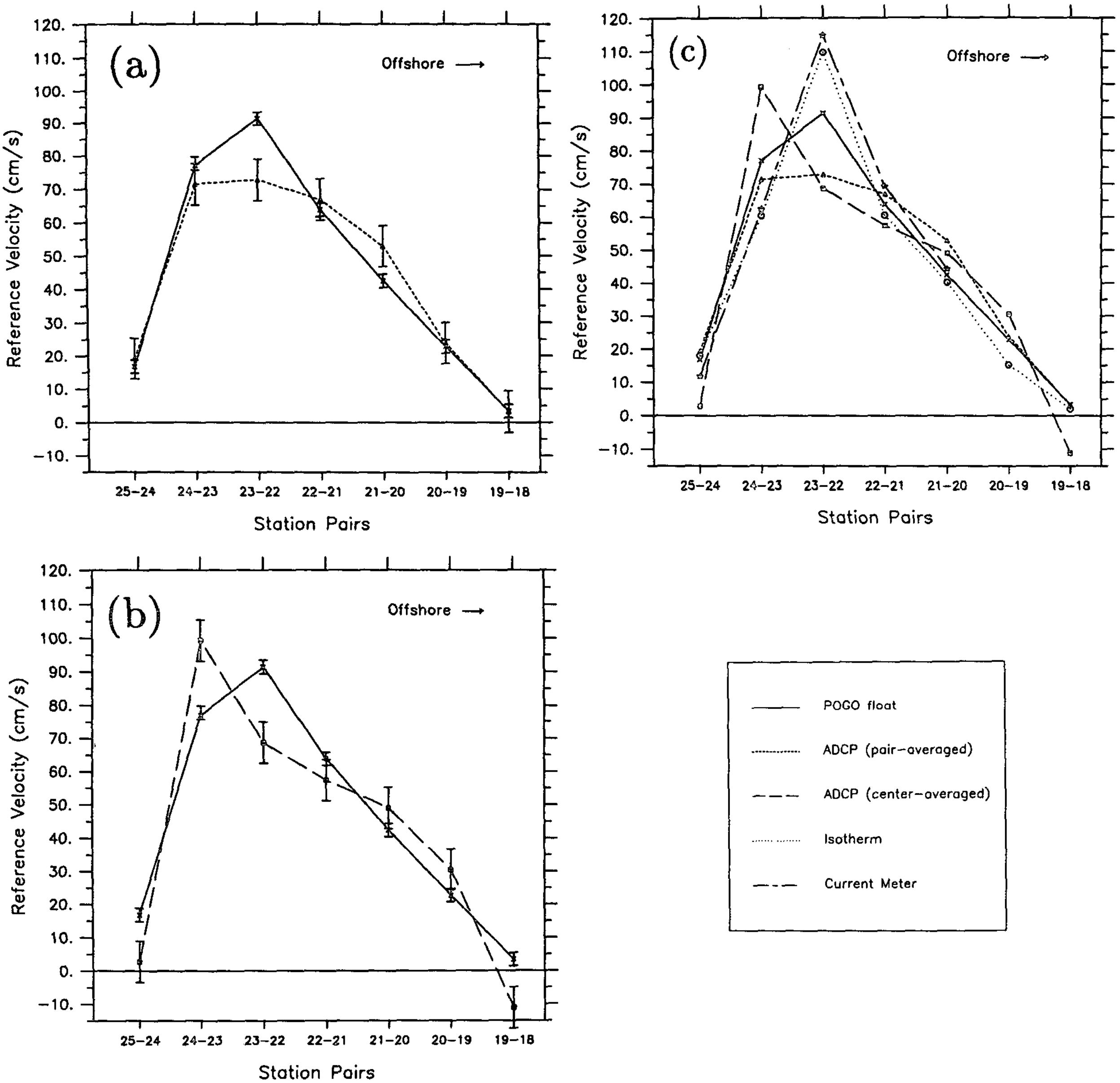

FIG. 6. (a) Reference velocities (absolute geostrophic velocity at 500 db) determined by the POGO floats (solid line) and by the ADCP pair-averaged technique (short-dashed line). The measurement uncertainty of each technique is indicated. (b) Same as (a) but comparing the POGO-derived (solid) and ADCP center-averaged (long dash) reference velocities. (c) Comparison of all referencing techniques (see the key).

The discrepancy in shear (and reference velocities) for CTD pair 23–22 (Fig. 7) cannot be accounted for. This is also a location in the Gulf Stream marked by a transition in vertical shear (from the core of the Gulf Stream into the 18° water, Fig. 2), but using a center ADCP profile only heightens the disagreement. Since this is the edge of the Gulf Stream core, one might suspect a significant near-surface ageostrophic contribution (measured by the ADCP) due to the swift current. Johns et al. (1989) found substantial disagreement between geostrophic and directly measured velocities in the upper core of the Gulf Stream 100 km downstream of this location. However, they attributed most of the disagreement to nonlinear effects associated with the strong curvature of the Gulf Stream (radius of curvature of order 200 km). That is clearly not the case here. In addition to the bottom current meters at this location, the SYNOP array contained three lines of inverted echo sounders from which a time series of Gulf Stream curvature can be obtained. During the

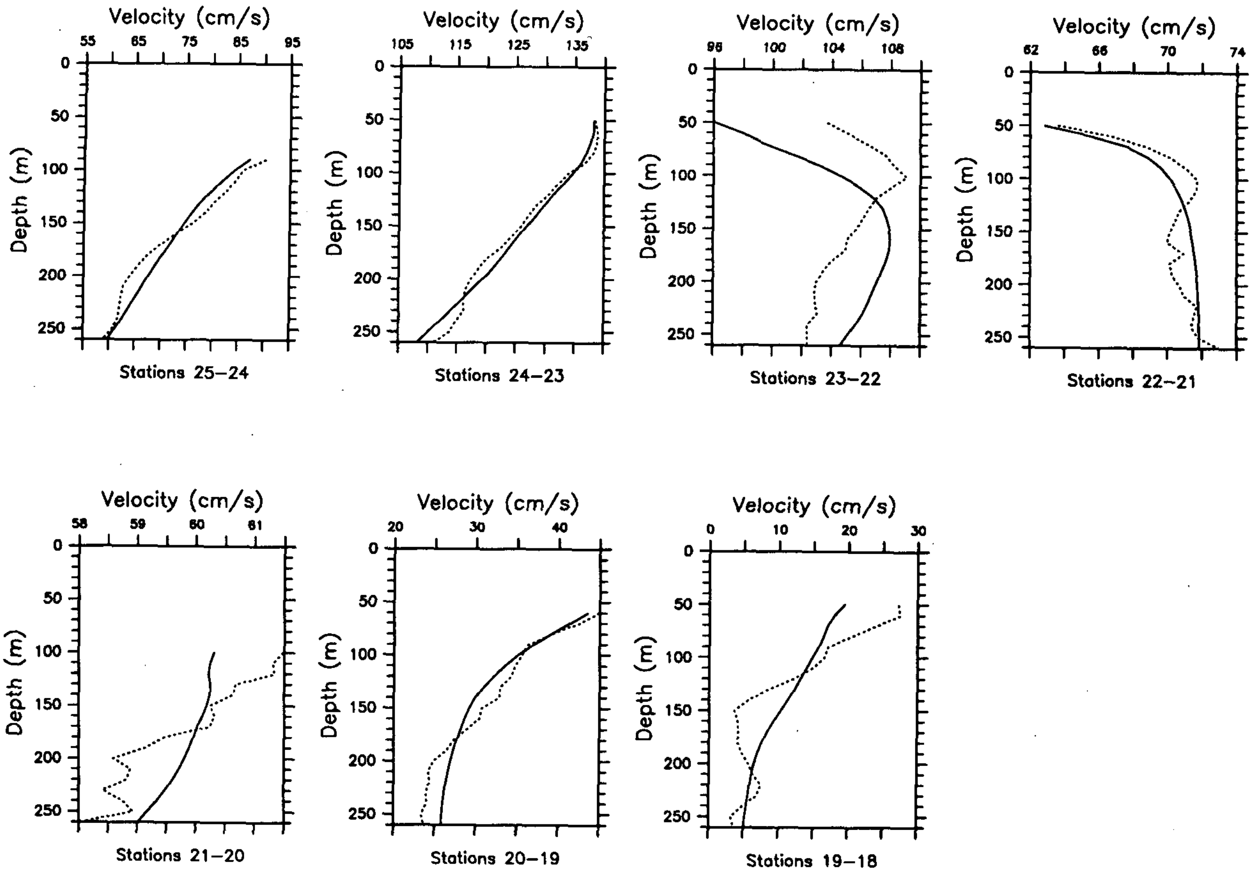

FIG. 7. Vertical profiles of geostrophic velocity for each station pair (solid line), compared to the pair-averaged ADCP profiles (dashed line). The geostrophic profiles have been referenced using the ADCP data over the depth range shown. Each ADCP profile is the local normal component to the station line.

occupation of the EN214 section (30 June–1 July 1990), the curvature of the Gulf Stream off of Cape Hatteras was essentially zero.

Nonetheless, the observed disagreement in vertical shear between the ADCP and CTD profiles for CTD pair 23–22 implies that this portion of the current (during the time of occupation of the section) was not in thermal wind balance; hence, it is not appropriate to use the ADCP for referencing the geostrophic velocity here. Since this is also the only place where there is unaccountable disagreement between the POGO- and ADCP-derived reference velocities, the inference is that the POGO value is more accurate in this regard. This is because the POGO measurement extends four times deeper and is influenced more by the subsurface geostrophic flow and less by near-surface ageostrophic contributions. Note, however, that this assertion cannot be directly verified since the POGO does not provide a vertical profile (an inherent disadvantage of the POGO).

If we assume that in this instance the POGO does provide a more realistic reference velocity, then the ageostrophic contribution at CTD pair 23–22 can be obtained by subtracting the POGO-referenced geostrophic profile from the ADCP profile. The difference reveals a Gaussian-like profile with its peak near 200 m and a vertical scale of roughly 400 m (obtained through extrapolation). Its amplitude is approximately 20 cm s^{-1}, though based on the above error bars it may be as small as 12 cm s^{-1} (with a 300-m vertical scale). Sources of ageostrophy include internal waves, submesoscale eddies, and Ekman currents. The latter can be immediately dismissed because of scale discrepancies; observed Ekman spirals are on the order of the mixed-layer depth (about 25 m across our section), with amplitudes less than or equal to 5 cm s^{-1} (Price et al. 1987; Chereskin and Roemmich 1991). The observed scales do, however, fall into the realm of the other two ageostrophic phenomena. A more detailed analysis of this ageostrophic feature is not pursued in the present study.

3) CENTER-AVERAGED REFERENCING

Had the shipboard ADCP been the only available means to reference the geostrophic velocities, we would not have used the above pair-averaging approach (appropriate for comparison to the POGO). Instead, we would have used an average profile between station pairs. The results of such a calculation are presented here (using a 13-km average centered at the midpoint). The center-averaged absolute geostrophic velocity section is shown in Fig. 3d. The agreement between the reference velocities calculated in this manner and the POGO-derived values is generally worse (Fig. 6b): four of the seven locations disagree significantly. As before, a discrepancy exists for CTD pair 23–22 likely due to ageostrophic effects. Ageostrophy also causes disagreement at pair 19–18 (the offshoremost profile). Between stations 19 and 18 the ADCP reveals a near-surface flow reversal that is a part of an oscillation (Fig. 5) indicative of a smaller-scale ageostrophic eddy (with an anomalous vertical shear, not shown). Johns et al. (1989) noted similar near-surface ageostrophic features. This eddy did not affect the above pair-averaged reference velocity because the Gulf Stream signal just inshore of it dominated the pair average.

In contrast to these two locations influenced by ageostrophic effects, the disagreement at the remaining two locations (CTD pairs 25–24 and 24–23) is seemingly due to insufficient cross-stream spacing of the POGOs. Here the vertical shear of the ADCP profiles agrees well with the respective geostrophic profiles, and the pair-averaged POGO- and ADCP-derived reference velocities agree nicely as well. The problem is one of cross-stream resolution. CTD pair 24–23 brackets the peak of the Gulf Stream (Fig. 5), so the center-averaged ADCP value results in a larger reference velocity than the average of the two POGOs (located on the shoulders of the core). Similarly, the large POGO value from station 24 (close to the core) in the pair average of 25–24 causes a bigger reference velocity than the ADCP center-averaged profile. These discrepancies arise because of the nonlinearity of the cross-stream velocity profile, and both are instances where a midpoint POGO would have made a significant difference.

d. Bottom current meter referencing

The CTD stations were occupied between the deep mooring sites (Figs. 1 and 2) to facilitate referencing using the current-meter data. Recall that each mooring contained a single current meter approximately 100 m above the bottom. The value of vertical shear was assumed constant from the bottom of each geostrophic profile to the depth of the current meter, at which point the extrapolated geostrophic velocity was matched to the current-meter component normal to the section. The coincident 40-h low-passed current-meter velocities were used, since these are more indicative of the low-frequency geostrophic flow (although the instantaneous values did not differ significantly). The missing value at BCM4 (Fig. 2a) was obtained by interpolating BCM3 and BCM5. The current meter–referenced section of absolute geostrophic velocity is shown in Fig. 3e.

There are some discrepancies between the current meter–derived reference velocities and those obtained from the POGO and ADCP (Fig. 6c). Curiously, the bottom flow measured by current meters BCM2 and BCM3 is relatively weak, precisely where the POGO- and ADCP-derived sections reveal a strong topographic wave signal (cf. Fig. 3e to 3b). This is also near the core of the DWBC (Fig. 4a). Recall that the topographic wave signal at Cape Hatteras was first revealed by the current meters, and indeed the deep flow reversals seen in the POGO-referenced section are present in the current meter–referenced section, only they are weaker beneath the core of the Gulf Stream. This discrepancy is well beyond the range of measurement uncertainty. Pickart and Watts (1990a) noted the surprisingly weak mean equatorward velocities (from these same current-meter records) that are two to three times weaker than DWBC core speeds measured by moored arrays elsewhere on the continental slope (e.g., Luyten 1977; Watts 1991). Using the CTD data we computed the thickness of the bottom boundary layer and found that it averaged 80 m (the current meters were located 95 m above the bottom), so this apparently is not a bottom boundary layer effect.

4. Section comparisons

How different are the absolute geostrophic velocity sections obtained from the different referencing techniques (Figs. 3a–e)? The sections referenced by the POGO and ADCP are qualitatively similar: the upper-layer Gulf Stream gives way to the deep jets of the topographic waves superposed on the DWBC. By contrast, the current meter– and isotherm-referenced sections have relatively weak flow beneath the Gulf Stream core, although farther offshore the isotherm-referenced section has a stronger equatorward flow (the current meter section does not extend this far downslope). Perhaps the best way to answer this question quantitatively is to compare the transports of the Gulf Stream and DWBC. To do this the POGO and ADCP sections were first cross-stream filtered using the technique of Pickart and Smethie (1993) to remove the topographic waves (Figs. 4a–c).

In terms of total Gulf Stream transport, all the methods show good agreement with transports in the 85–95-Sv (1 Sv = 1×10^6 m^3 s^{-1}) range (Table 1). However, the cross-stream distribution of transport reveals that the isotherm- and current meter–referenced transports are anomalous in that both have larger onshore contributions and weaker offshore contributions (Fig. 8a). To compute the DWBC transport we first needed to determine the limits of the current. We define the DWBC as the (equatorward flowing) Norwegian–Greenland overflow water deeper than 2000 m; this water mass is characterized by high CFC concentra-

TABLE 1. Total transport (Sv) of the Gulf Stream and DWBC for the different velocity sections. The current meter–referenced section did not extend far enough offshore to compute a total DWBC transport.

	POGO	ADCP (pair averaged)	ADCP (center averaged)	Current meter	Isotherm
Gulf Stream	93	97	86	85	84
DWBC	−9.9	−12.7	−15.8	—	−10.2

tions. From the CFC distribution (Fig. 2b) it is clear that the equatorward flow at the offshore edge of the section (extending up to shallow depths, Fig. 4) is not part of the DWBC. Excluding this flow, the total DWBC transports from the different sections also agree fairly well (10–15 Sv, Table 1). However, the isotherm-referenced section is again anomalous in that there is larger transport farther downslope (Fig. 8b). This is contrary to the CFC distribution: the highest deep CFC concentrations suggest the core of the current is more onshore as in the ADCP and POGO sections. The current meter–referenced section also has weak flow upslope (the section does not extend far enough offshore to fully resolve the flow).

Of the five vertical sections of absolute geostrophic velocity, the POGO-derived section and ADCP pair-averaged section clearly show the best agreement in Gulf Stream and DWBC signatures (cf. Figs. 3a, 3e, 4a, 4b, and 4c). The most conspicuous difference in the center-averaged ADCP section (Fig. 4c) is the large equatorward flow at shallow depths on both ends of the section. The strong flow offshore is unrealistic because it arises from the presence of the ageostrophic eddy measured by the ADCP (as discussed in section 3); the resulting error in reference velocity together with the weak vertical shear at the offshore edge of the section causes the large barotropic flow. Contrary to this, the strong equatorward flow at the onshore edge of the section is probably more indicative of the actual flow than the POGO-referenced velocities because of insufficient POGO spacing.

5. Advantages of POGO

The POGO float has an inherent advantage over the shipboard ADCP for referencing geostrophic velocities in deep water because it is a vertical integral extending over a much greater depth range (up to 3000 m) than the ADCP measurement (typically 300 m). For a swift current such as the Gulf Stream, the ADCP measurement may sometimes contain a large ageostrophic

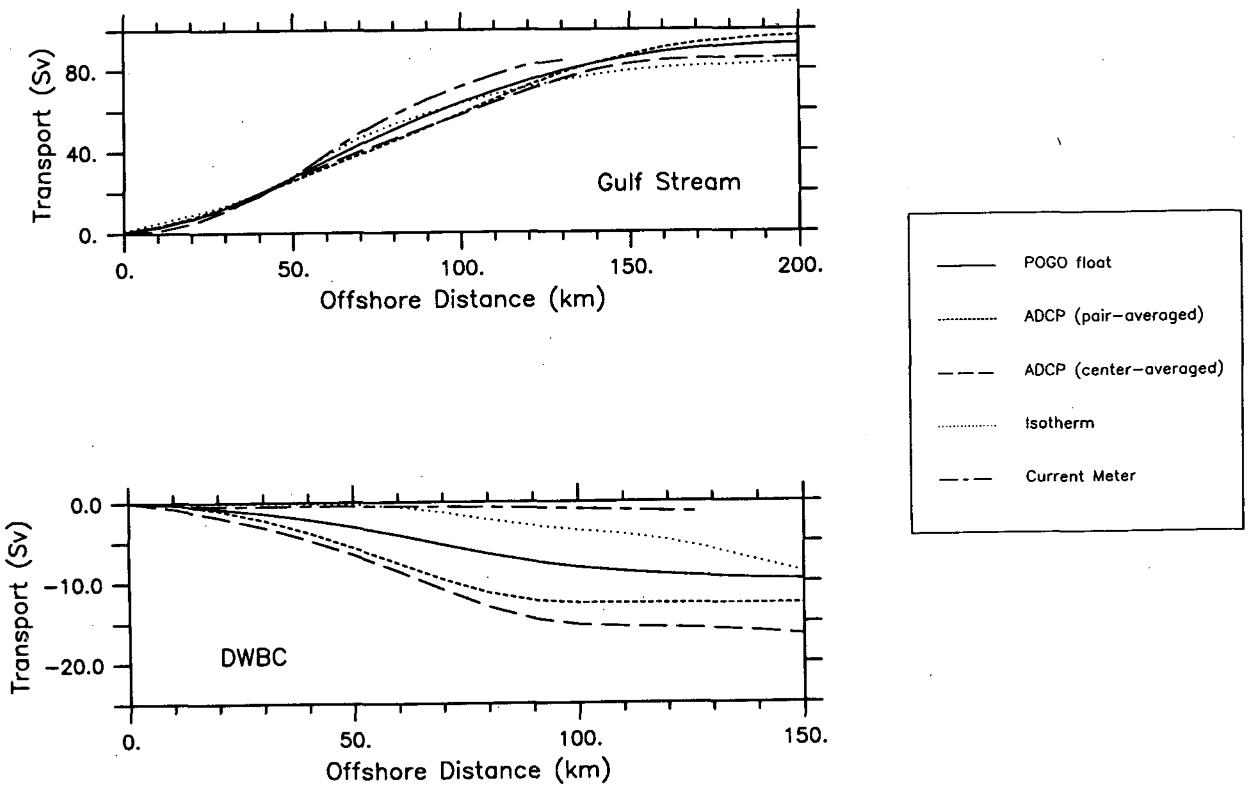

FIG. 8. (a) Cross-stream distribution Gulf Stream transport for the five different sections (Figs. 3a, 3e, 4a, 4b, and 4c). All the sections were objectively interpolated resulting in the smooth trends. (b) Same as (a) only for DWBC transport.

component (e.g., due to strong curvature, rings, or eddies). Typically these phenomena are surface intensified (top 250–500 m, Johns et al. 1989). A deep POGO float spends most of the time in the slower, deeper geostrophic flow and hence is less "contaminated" by the swift shallow currents.

Other ageostrophic effects that influence direct velocity measurements are internal waves and inertial oscillations. These can be easily filtered out of current-meter records with a temporal low pass; however, such direct velocity measurements of extended duration are generally very difficult to obtain in combination with hydrography. The POGO effectively reduces these high-wavenumber signals by performing a vertical average. We simulated a POGO drop on two instantaneous velocity profiles obtained one-half inertial period apart in the Mid-Atlantic Bight (Sanford 1975). The two profiles contain many small-scale oscillations that are mirror images of each other (vertical wavelengths on the order of 300–500 m); the average of the two profiles is representative of the low-frequency geostrophic flow (Sanford 1975). We found that the simulated POGO velocity computed from the two individual profiles converged to that of the average profile for POGO drops deeper than about 1200 m (note of course that the amplitudes of such waves are often much smaller than the geostrophic signal).

A shortcoming of the POGO measurement is that it is influenced by the barotropic tide, though this is likely a small source of error in deep water. We calculated the amplitude of the semidiurnal (i.e., most energetic) tidal signal in the bottom current meter records and found it to be only about 1 cm s^{-1}, with little variation over the length of the array. Since the instruments are so deep, this is a measure of the barotropic tide, which is in fact minimal.

6. Conclusions

Four different methods for determining geostrophic reference velocities were applied to the same hydrographic section across the Gulf Stream and DWBC. Three of the methods used direct estimates of the flow (POGO floats, shipboard ADCP, and bottom current meters); the fourth method assumed that a deep isotherm is the level of no motion based on water mass considerations. Special focus was placed on the comparison between the POGO and ADCP techniques since they are most readily implemented in a hydrographic experiment.

Overall, the POGO- and ADCP-derived reference velocities agreed well. However, there were cases when the ADCP velocity profile included a significant ageostrophic contribution, rendering the measurement inappropriate for geostrophic referencing. The conclusion is that the POGO-derived value is more accurate at these locations since the float extended to 1000 m—well below typical near-surface ageostrophic effects and deep enough to reduce high vertical wavenumber oscillations. On the other hand, it was found that the cross-stream POGO spacing was insufficient on the cyclonic side of the Gulf Stream where velocity changes are drastic over short cross-stream distances.

The isotherm and current-meter methods produced suspect velocity sections. The isotherm-referenced section did not contain any topographic Rossby waves, and its cross-stream distribution of Gulf Stream and DWBC transports was less realistic. While the current meter–referenced section did reveal the deep topographic waves, a portion of the deep flow was weak; like the isotherm-referenced section, the distribution of transport was not realistic. Thus, for this particular section across the Gulf Stream and DWBC (at this time of occupation), the POGO floats and shipboard ADCP were the best methods for referencing the geostrophic velocities. That is not to say that the isotherm method is not applicable in other situations; it may in fact be more suitable for certain midbasin sections where geostrophic interior velocities are weaker than the error associated with POGO. However, the direct methods are obviously most general.

Because of strong near-surface ageostrophic effects and the short vertical extent of the measurement, we conclude that shipboard ADCP data are less desirable than POGO float measurements for referencing geostrophic velocities in deep water. Of course ADCP sampling has less impact on a hydrographic experiment, but POGO floats are easy to deploy and add only a small amount to the time of a CTD cast. POGOs are relatively inexpensive and the data processing is trivial in comparison with the ADCP (and done in near real time). The POGO measurement error is small, and contamination due to the barotropic tide is negligible in deep water. The biggest concern regarding POGOs is the finite cross-stream resolution. However, potential errors might be lessened by applying a higher-order along-section fit to the POGO data and deploying additional floats between stations, particularly near the ends of sections.

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