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Mooring Motion Correction of SYNOP Central Array Current Meter Data

Meghan Cronin,
Karen Tracey
and D. Randolph Watts

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Abstract

From May of 1988 to August 1990, as part of the SYNOP field program, twelve tall moorings measured the Gulf Stream's temperature and velocity fields at nominal depths of 400 m, 700 m, 1000 m, and 3500 m. Although stiff, high-performance moorings were used to maintain the top current meters at approximately 400 m below the surface ($\sim$ 4000 m above the sea floor), the jet's drag caused the moorings to make vertical excursions.

Therefore, the current meter data were corrected to constant horizons using a modified version of Hogg's (1991) mooring motion correction scheme. An important extension of Hogg's (1991) method is the inclusion of a weighted interpolation of the measured temperatures. This modification assures that as the current meter measurements approach the respective nominal depths, the corrected temperature and velocity outputs smoothly approach the measurements; i.e. the compensated u, v, T records are truer to the measured records.

This report documents the mooring motion correction of the SYNOP Central Array temperature and velocity data.

Contents

List of Tables

List of Figures

1 Introduction

In the region between Cape Hatteras and the Grand Banks, the Gulf Stream is a strong and coherent jet with instantaneous speeds of up to 2 m s^{-1} near the surface and up to 0.2 m s^{-1} near the bottom. As the Gulf Stream flows in deep water near 68°W, the jet experiences large amplitude meanders, often forming and interacting with rings. SYNOP (**SYN**optic **O**cean **P**rediction) is a multi-investigator research project, involving modelers, theoreticians, and observationalists, whose goals are to understand and model the dynamics governing the Gulf Stream meandering.

The SYNOP field program consisted of three arrays: an Inlet Array near Cape Hatteras, a Central Array near 68°W, and an Eastern Array just west of the Grand Banks near 55°W. The focus of this report is the Central Array, consisting of twelve tall, high-performance moorings which measured the Gulf Stream's temperature and velocity fields at nominal depths of 400 m, 700 m, 1000 m and 3500 m. In addition, Acoustic Doppler Current Profilers (ADCPs) were placed atop three of the moorings (I2, H3, and H4). Inverted echo sounders (IESs) with pressure sensors were placed near the base of each current meter mooring. The IES, ADCP and current meter sites in the Central Array are shown in Figure 1. Although most moorings had two deployment periods between May 1988 and August 1990, four of the tall moorings were in place for the full two-year period. During the second year, an additional thirteenth mooring, M13, was deployed. The current meter measurements are documented in Shay *et al.*, 1993.

Although fairing on the mooring wire and extra flotation were used to keep the moorings taut and maintain the top current meters at depths of approximately 400 m below the surface ($\sim$ 4000 m above the sea floor), the jet's drag caused the upper 1000 m of the moorings to make vertical excursions. Therefore, the current meter data was corrected to constant horizons using Hogg's (1991) mooring motion correction scheme. This report documents the mooring motion correction of the SYNOP Central Array's temperature and velocity data.

In the next section, Hogg's (1991) method will be briefly reviewed. In our application of Hogg's method, we made a slight modification to the temperature correction. This modification and the specific steps involved in correcting the SYNOP Central Array data set are discussed in Section 3. Extensive tests of the corrections are discussed in Section 4. Sections 5 and 6 show how we estimated the errors in the corrected temperature and velocity fields. Section 7

Figure 1: The SYNOP Central Array, centered near 38N/68W, is composed of twenty four IESs (boxes) and thirteen tall current meter moorings (x's). The IES at the base of each tall current meter mooring has a pressure sensor. Sites i2, h3, and h4 also have ADCPs (circles) atop the tall moorings.

discusses some useful byproducts of the mooring motion scheme, including the pseudo-IES and computation of the Brunt-Vaisala frequency.

2 Hogg (1991) Mooring Motion Correction Scheme

Hogg's (1991) mooring motion correction scheme assumes that all isotherms are parallel in a Gulf Stream cross-section. This is equivalent to assuming that the vertical profile of temperature has a 'canonical shape' at all times and locations; the profile is only shifted up and down as the Gulf Stream shifts back and forth across the mooring. The functional form used to describe the canonical temperature profile is a Nth order polynomial of the form:

$$\begin{aligned} T(x,p,t) &= F(p_{ref}(x,t)-p) && (1)\\ F(p_{ref}-p) &= 12^\circ\text{C} \;+\; \sum_{n=1}^{N} c_n\,(p_{ref}-p)^{N+1-n} && (2) \end{aligned}$$

The coefficients of the polynomial, c_n, are determined by performing a least-squares regression on the observed (T,p) data.

Once the coefficients have been determined, the canonical profile is shifted to fit the (T,p) measurements on a given mooring, yielding a time series of p_{ref} for that site. If the mooring consists of more than one current meter, the (T,p) pairs are regressed on the canonical profile to determine the optimal p_{ref}. Subsequently, the corrected temperatures at the desired pressure levels are obtained simply by

$$T_{cor}(p_{nom}) \;=\; F(p_{ref}(x,t)-p_{nom}). \qquad (3)$$

To correct the current meter velocity measurements for mooring motion, the velocity is interpolated using temperature. The first step is to use the rotation matrix, $\mathbf{R}$, to rotate the velocity components from east-north coordinates to stream-coordinates. After correcting for mooring motion, the velocities are rotated back.

$$\begin{aligned} [v_s\hat{s},\ v_n\hat{n}]' &= \mathbf{R}\left[u\hat{\imath},\ v\hat{\jmath}\right]' && (4)\\ \left[u\hat{\imath}, v\hat{\jmath}\right]' &= \mathbf{R}\left(\mathbf{R}\left[u\hat{\imath},\ v\hat{\jmath}\right]'\right) && (5)\\ &= \mathbf{R}\,[v_s\hat{s},\ v_n\hat{n}]' && (6) \end{aligned}$$

where

$$\mathbf{R} \quad = \quad \begin{bmatrix} cos\theta & sin\theta \\ sin\theta & -cos\theta \end{bmatrix} \tag{7}$$

and $\theta = atan((v_u - v_l)/(u_u - u_l))$. Note that $\mathbf{R}\,\mathbf{R}$ equals the identity matrix.

Assuming thermal wind and a well defined T-S relationship, the vertical change in the velocity can be related to the cross-stream temperature gradient. In stream coordinates, where the downstream (or shear) component of velocity is $\upsilon_s\ \hat{s}$, we obtain

$$\frac{\partial \upsilon_s}{\partial p} \quad = \quad -\frac{g\alpha}{f}\frac{\partial T}{\partial n} \tag{8}$$

$$\quad = \quad -\frac{g\alpha}{f}\frac{\partial p_{ref}}{\partial n}\frac{\partial F}{\partial p} \tag{9}$$

where α is the effective thermal coefficient of expansion, f is the Coriolis parameter and g is gravity. By integrating with respect to pressure, it can be shown that the change in velocity is proportional to the change in temperature:

$$\int_{p_u}^{p_l} \frac{\partial \upsilon_s}{\partial p}\partial p \quad = \quad \int_{p_u}^{p_l} -\frac{g\alpha}{f}\frac{\partial p_{ref}}{\partial n}\frac{\partial F}{\partial p}\partial p \tag{10}$$

$$\upsilon_s(p_l) - \upsilon_s(p_u) \quad = \quad -\frac{g\alpha}{f}\frac{\partial p_{ref}}{\partial n}[T(p_l) - T(p_u)]. \tag{11}$$

where the subscripts u and l refer to upper and lower depths. Thus,

$$\frac{\upsilon_s(p_{nom}) - \upsilon_s(p_l)}{T(p_{nom}) - T(p_l)} \quad = \quad \frac{\upsilon_s(p_l) - \upsilon_s(p_u)}{T(p_l) - T(p_u)} \tag{12}$$

$$\text{Or,} \qquad \upsilon_s(p_{nom}) \quad = \quad \frac{\upsilon_s(p_l) - \upsilon_s(p_u)}{T(p_l) - T(p_u)}\,[T(p_{nom}) - T(p_l)] \ + \ \upsilon_s(p_l) \tag{13}$$

$$\quad = \quad m\,[T(p_{nom}) - T(p_l)] \ + \ \upsilon_s(p_l) \tag{14}$$

The cross-stream component of the velocity υ_n must then be added to the corrected shear component $\upsilon_s(p_{nom})$ to obtain the corrected velocity vector, $\mathbf{U_{cor}}$:

$$\mathbf{U_{cor}} \quad = \quad \upsilon_s(p_{nom})\,\hat{s} + \upsilon_n\,\hat{n} \tag{15}$$

If the vertical shear is purely due to thermal wind, then m in Equation 4 is constant throughout the water column and the choice of levels u and l is arbitrary. However, it is advantageous to use the two current meters that are nearest in temperature to the corrected temperature: In the event that the measured temperature equals the corrected temperature, the corrected velocity will equal the measured velocity.

It should be noted however, that in Hogg's correction scheme this same principle does not apply to the temperature correction. In the event that the current meter is at the nominal pressure, the corrected temperature, obtained from the canonical profile, is not necessarily the measured temperature. As described in the next section, in our application of Hogg's correction scheme to the SYNOP Central Array data, we modified the temperature correction procedure to require that $T_{cor}(p_{nom}) = T_p$ when $p = p_{nom}$.

3 Application to the SYNOP data

3.1 The SYNOP Central Array measurements

Typically, the vertical excursions of the SYNOP current meter moorings were on the order of 50 meters. Occasionally though, the excursions were larger. For example, one large excursion taken by mooring H6 exceeded 550 m.

The moorings were designed to have their upper 1000 meters remain essentially vertical at all times. Additionally, fairing was installed on the wire between the three top current meters to improve the performance. Table 1 summarizes the conditions of the fairing upon recovery. As noted in that table, fish nets were tangled on some moorings. However, the nets were always near the bottom current meter and therefore did not significantly affect the mooring motion.

For most moorings, the typical pressure differences between the level 1 and level 2 current meters were 3060 kPa (303 m[1]). Between level 1 and level 3 the typical delta pressures were 2.02×3060 kPa (612 m). However, due to differences in flow conditions (e.g. strong, moderate, or weak currents) and differences in the buoyancy and drag (fairing) of each mooring, the actual delta pressures vary from mooring to mooring. Table 2 lists the differences between the measured pressures by the current meters at levels 1 and 2 (and between levels 1 and 3 where available). First order statistics on the vertical excursion of each mooring are also given in Table 2.

Each of the three moorings prepared by the University of Miami (H3, H4, and I2) had an ADCP, with pressure and temperature sensors, mounted 12 m above the top current meter (Figure 2). The ADCPs measured the velocities throughout the upper 400 m of the water column. To reduce noise, the velocities are averaged within 9 m bins. As shown in Figure 2,

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[1] Note that 1 m = 1.01 db = 10.1 kPa.

Figure 2: Schematic diagram of a tall current meter mooring.

Table 1: Comments on Condition of Moorings from Recovery Logbooks. The upper three current meters on each mooring were separated by 300 m pieces of wire. These two sections are designated as L1 and L2. Fairing, in 1–5 ft lengths, was installed on both the L1 and L2 wire lengths.

YEAR 1	
G2	Two 2–3 ft pieces of fairing were stuck on L1.
G3	OK
H3	Eight 5 ft pieces of fairing jammed on L1.
H4	Three or four 1–5 ft pieces of fairing jammed on L1.
H5	Some pieces of fairing were jammed on both L1 and L2.
I2	Two 5 ft pieces of fairing jammed on L1.
I3	OK
I4	OK
YEAR 2	
G2	One piece fairing not spinning freely. One piece of fairing is jammed.
G3	Damaged fairing: about 10 pieces were broken, cut, or jammed.
H2	Two pieces of fairing on L1 and two pieces on L2 were cocked.
H3	The pieces of fairing on L1 was jammed together, but were spinning freely. 8 glass balls (above bottom VACM) tangled in 1m by 6m fishnet. 1 glass ball imploded at bottom.
H4	2 m of jammed fairing in L1. Snagged net at the connection between the two 500m sections above bottom VACM (2000m below the level 3 current meter).
H5	One piece of jammed firing.
H6	6m of fish net somewhere between 200-700m above bottom VACM. 1 glass ball imploded (3rd from bottom).
I1	Three pieces of fairing were jammed and cocked on L1. About 20% of fairing was cocked, but this probably happened on recovery.
I2	10m of fairing jammed together, but these were spinning freely.
I3	OK
I4	OK
I5	OK
M13	Two pieces of jammed fairing. Two of 16 glass balls imploded near bottom.

Table 2: Current Meter Pressure Statistics. First order statistics of the level 1 current meter pressures in the SYNOP Central Array are listed. Also tabulated are the means and the standard deviations of the pressure differences between the level 1 and levels 2 and 3 sensors. The pressure sensors, at nominal depths of 400m, 700m, and 1000m are respectively denoted as P1meas, P2meas, and P3meas. Pressures are expressed in units of 1000 kPa (or 100 db). The symbol NA indicates no data. NOTE: For site I4 during Year 2, the standard deviation between levels 1 and 2 is greater than that between levels 1 and 3 due to a drift in the level 2 sensor. However this drift is on no consequence because the observed level 2 pressures are not used in the mooring motion correction.

YEAR 1								
	P2meas-P1meas		P3meas-P1meas		P1meas			
Site	Mean	Std	Mean	Std	Mean	Min	Max	Std
G2	3.043	0.039	NA	NA	3.572	3.200	4.663	0.371
G3	NA	NA	NA	NA	4.052	3.470	5.116	0.448
H3	3.131	0.008	6.401	0.014	3.259	3.226	3.695	0.068
H4	3.044	0.035	6.221	0.085	3.989	3.483	5.464	0.363
H5	NA	NA	NA	NA	3.846	3.336	6.414	0.609
I2	3.207	0.014	NA	NA	3.389	3.363	3.654	0.042
I3	NA	NA	NA	NA	3.755	3.176	5.956	0.481
I4	3.085	0.028	NA	NA	3.743	3.188	5.409	0.507
YEAR 2								
	P2meas-P1meas		P3meas-P1meas		P1meas			
Site	Mean	Std	Mean	Std	Mean	Min	Max	Std
G2	3.043	0.039	NA	NA	3.572	3.200	4.663	0.371
G2	NA	NA	NA	NA	3.845	3.396	5.318	0.408
G3	NA	NA	NA	NA	3.957	3.547	6.023	0.460
H2	3.077	0.003	NA	NA	3.720	3.664	4.602	0.112
H3	3.122	0.050	NA	NA	3.360	3.127	4.656	0.291
H4	3.009	0.018	NA	NA	3.890	3.547	5.669	0.351
H6	NA	NA	NA	NA	4.470	3.665	9.676	1.246
I1	3.093	0.004	NA	NA	3.775	3.723	4.584	0.107
I2	NA	NA	NA	NA	NA	NA	NA	NA
I3	3.046	0.038	6.250	0.079	3.599	3.136	5.804	0.567
I4	3.025	0.120	6.257	0.082	3.737	3.171	6.847	0.668
I5	3.101	0.012	NA	NA	4.301	3.627	8.373	0.936
M13	3.081	0.049	NA	NA	3.654	3.157	6.167	0.496

the Bin 1 velocities are located 9 m above the ADCP itself and 21 db above the top current meter. Thus the ADCPs provided redundancy in the top level measurements.

Appendix A compares the temperatures measured by the ADCPs and the upper level current meters at four sites. For two of the sites, H3_YR2 and I2_YR2, there is good consistency between the measurements. This was not the case for two other sites, H3_YR1 and H4_YR1. However, the differences are not surprising because the accuracy of the ADCP temperature measurements is not as good as that of the current meters. Thus, the ADCP temperatures were not used in the mooring motion correction procedures except for when the sensors on the level 1 current meters failed.

On the other hand, the ADCP pressure measurements could be validated by acoustic tracking (B. Johns, pers. comm.) and were deemed to be more trustworthy than the current meter pressures. Thus the ADCP pressures were used whenever possible. First order statistics of the ADCP pressures are reported in Table 3 together with the mean pressure differences between the ADCP and the upper two current meters.

Taking into account the wire lengths and mooring design, it was shown that there was a 6 db discrepancy between pressures measured by the ADCP and those of the top level current meters on all three Miami moorings. Comparisons with the acoustic tracking depths revealed that the current meter pressures were too large (most likely caused by calibration errors). Therefore, the ADCP pressures were used for the mooring motion correction with data gaps filled by the current meter pressures after subtracting the 6 db bias.

In order to correct the velocities and temperatures for mooring motion, the pressure of each current meter at the time the measurements were made must be known. However not all of the level 2 and level 3 current meters had pressure sensors, and furthermore, some of the measurements were questionable. For example, several of the level 2 current meters on the Miami moorings exhibited pressure biases similar to those found with the level 1 instruments. Based on the mooring design, the differences in pressure between the top three current meters were expected to be nearly constant despite the mooring motion. Thus, the top current meter pressures were used together with constant offsets to simulate the daily pressures at the level 2 and 3 instruments as

$$p2(t) = p1(t) + \mathrm{delp12} \tag{16}$$

$$p3(t) = p1(t) + \mathrm{delp13} \tag{17}$$

Table 3: ADCP Pressure Statistics. First order statistics of the ADCP pressures in the SYNOP Central Array are listed. Also tabulated are the means and the standard deviations of the pressure differences between the ADCP and current meters at levels 1, 2, and 3. The ADCP pressures, designated as Pbin1, correspond to the depth of the Bin 1 velocities (9 m above the ADCP or 21 m above the level 1 current meter). The current meter sensors, at nominal depths of 400 m, 700 m and 1000 m, are respectively denoted as P1mean, P2meas, and P3 meas. Pressures are expressed in units of 1000 kPa (or 100 db). The symbol NA indicates no data.

YEAR 1										
	P1meas-Pbin1		P2meas-Pbin1		P3meas-Pbin1		Pbin1			
Site	Mean	Std	Mean	Std	Mean	Std	Mean	Min	Max	Std
H3	0.258	0.007	3.384	0.008	6.658	0.016	2.994	2.979	3.081	0.019
H4	0.280	0.014	3.309	0.037	6.442	0.089	3.831	3.239	4.448	0.336
YEAR 2										
	P1meas-Pbin1		P2meas-Pbin1		P3meas-Pbin1		Pbin1			
Site	Mean	Std	Mean	Std	Mean	Std	Mean	Min	Max	Std
H3	0.272	0.025	3.394	0.060	NA	NA	3.088	2.862	4.431	0.296
I2	NA	NA	3.216	0.035	NA	NA	3.251	3.034	5.065	0.314

The offsets delp12 and delp13 were determined for each mooring based on both the mooring design (wire lengths and stretching) and the observations.

Comparisons of the simulated and observed pressures were made by looking at the mean and extreme differences between the records. The results are summarized in Table 4. In general, the differences are under 10 db (0.10 kPa) as anticipated by the mooring design. The large mean differences on Miami moorings H3 and I2 are assumed to be related to calibration errors of the current meters since $p2$ and $p3$ are simulated from the acoustically-verified ADCP pressures. Table 4 also indicates long term drifts in the observed pressures. Several instruments had drift rates of about 4 db per year. While these drifts are too high to use the observed pressures for dynamical analyses, they are small enough that that do not significantly affect the mooring motion correction.

In the above equations, $p1$ is defined as the pressure at the upper most temperature measurement ($T1$). For the most part, $T1$ and $p1$ refer to the measurements made by the level 1 current meter (Table 5). However this is not true for M13 and the three Miami moorings. For site M13, the level 1 pressure sensor didn't function properly during a 50 d period. So instead, we used the level 2 current meter data as $p1$ and chose the appropriate values for delp12 and delp13 to simulate the level 1 and level 3 pressures. For Miami moorings H3_YR1, H3_YR2, and H4_YR1, ADCP pressures were used instead of the current meter pressures. However, the level 1 current meter temperatures were still used as $T1$ for those moorings. Consequently, the ADCP pressures (Pbin1) needed to be adjusted by 21 m from the depth of the Bin 1 velocities to the depth of the level 1 current meter (Figure 2). Thus $p1 = P\text{bin}1 + 21$ db for those moorings. For Miami moorings H3_YR2 and I2_YR2, the ADCP temperatures were used as $T1$; thus the Pbin1 pressures were offset by 9 m depth to be the depth of the ADCP (Figure 2). Since the ADCPs failed on moorings I2_YR1 and H4_YR2, the current meter pressures were used for the mooring motion correction. However, as noted above, these needed to have a 6 db bias removed. Table 5 summarizes how $p1$ and $T1$ were determined for each mooring. The offset constants, delp12 and delp13, are also listed in Table 5.

The mooring motion scheme also requires that the upper most velocity ($U1$) and its pressure (PU) be specified. As indicated in Table 5, the level 1 current meter velocities were used in all but two cases. Thus, typically $PU = p1$. However when the ADCP velocities were used, $PU = P\text{bin}1 = p1 - 9$ db.

Table 4: Comparison of the Simulated and Measured Pressures

Table 5: Data Sources of the Top Level Temperatures, Pressures, and Velocities used in the Mooring Motion Correction. Pressures are expressed in units of decibars. The constant offsets, delp12 and delp13, were used to simulate P2 and P3 respectively from P1 according to Equations 16 and 17. The university technical group that prepared each mooring is indicated. See the text and Appendix E for further explanations for each site. T1 = Measured temperature at top level U1 = Measured velocity at top level P1 = Measured pressure at top temperature PU = Pressure at top velocity CM1 = Top level is level 1 current meter CM2 = Top level is level 2 current meter ADCP = Top level temperature is ADCP (12 m above CM1) Bin1 = Top level is Bin 1 (9 m above ADCP; 21 m above CM1)

YEAR 1							
Mooring	Group	T1	U1	P1	delp12	delp13	PU-P1
G2	URI	CM1	CM1	PCM1	304	2.03*304	0
G3	URI	CM1	CM1	PCM1	306	2.03*306	0
H3	MIAMI	CM1	CM1	Pbin1+21	306	2.04*306	0
				PCM1-6			
H4	MIAMI	CM1	CM1	Pbin1+21+10	306	2.03*306	0
H5	URI	CM1	CM1	PCM1	306	2.03*306	0
I2	MIAMI	CM1	CM1	PCM1-6	305	2.04*305	0
I3	URI	CM1	CM1	PCM1	306	2.03*306	0
I4	URI	CM1	CM1	PCM1	308	2.03*308	0
YEAR 2							
G2	URI	CM1	CM1	PCM1	306	2.03*306	0
G3	URI	CM1	CM1	PCM1	306	2.03*306	0
H2	WHOI	CM1	CM1	PCM1	308	2.04*308	0
H3	MIAMI	CM1	CM1	Pbin1+21	306	2.03*306	0
		ADCP	Pbin1	Pbin1+9			-9
H4	MIAMI	CM1	CM1	PCM1-6	304	2.03*304	0
H6	WHOI	CM1	CM1	PCM1	309	2.02*309	0
I1	WHOI	CM1	CM1	PCM1	309	2.04*309	0
I2	MIAMI	ADCP	Pbin1	Pbin1+9	306+12	(2.04*306)+12	-9
I3	URI	CM1	CM1	PCM1	305	2.02*305	0
I4	URI	CM1	CM1	PCM1	306	2.04*306	0
I5	WHOI	CM1	CM1	PCM1	310	2.02*310	0
M13	URI	CM2	CM2	PCM2	-308	2.03*308	0

3.2 STEP 1: Determine the canonical profile

Hogg's mooring motion correction method relies upon the assumption that the isotherms are parallel and therefore a canonical temperature profile exists. Although this assumption is generally valid below 16°C, it is not necessarily true for warmer waters, especially near 18°C. Because the 16°C isotherm is typically found at depths above the uppermost current meter (400 m) across most of the Gulf Stream, this assumption is nearly valid for all SYNOP current meter moorings. Despite this, we found that it was best to apply different profiles to the northern and southern moorings. To create these profiles, the moorings were separated into two groups. For each region, the data were then strung together to create a single long $p1$ time series and corresponding time series of temperature for all three levels. Additionally, long time series of $p2$ and $p3$ were determined according to Equations 16–17 using representative values for delp12 and delp13. Separate profiles for the northern and southern regions were subsequently determined by least squares regression. (The MATLAB codes are given in Appendix B.)

Temperature data from the first year of moorings H3 and I3, and the second year of moorings H2, I1, I2, and H3 were used to determine the northern profile. The criteria used to select those sites were as follows: (1) The mooring must have at least two working current meters (Figure 3 shows the data recovery for each current meter). (2) The separation between the level 1 and level 2 current meters on the mooring must be 3070 kPa ± 30 kPa, and it must be 6250 kPa ± 50 kPa between the level 1 and level 3 instruments. (3) For most of the time, the mooring should be located north of the north wall but not in the recirculation region.[2] (4) Changes in the canonical profile caused by the inclusion of the data from that site improves the motion corrected data, as indicated by tests such as those described below in Section 4. The northern profile, shown in Figure 4, is a 7th order polynomial whose coefficients are listed in Table 6.

The data on moorings H2, H3, I1, I2 for both years, and the first year of data on moorings G2 and I3, and the second year of data on mooring H4 were corrected using the northern profile.

Similarly, the temperature data from year 1 of moorings H3, I4, and I5, and data from year 2 of moorings H3, I4, M13, and I5 were used to determine the southern profile. Again, the criteria for choosing these sites were: (1) The moorings must have at least two working current meters. (2) The separation between levels 1 and 2 must be 3075 kPa ± 50 kPa, and

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[2] During the first year, the H2 and I1 moorings were in the recirculation region and their data has been exluded from the determination of the northern profile.

Figure 3: Current Meter Temperature and Velocity Data Recovery

Figure 4: Northern and Mid-stream/Southern Canonical Profiles

Table 6: Coefficients for the Northern and Southern Canonical Profiles. The southern profile is a 9th order polynomial in z where z = $p_{ref} - p$ (in Pa). The northern profile is a 7th order polynomial. The coeficients were found by least squares regression. The zeroth order coeficient was set to be 12. Thus when $p = p_{ref}$, T = 12°C.

n	Southern Profile Coefficients	Northern Profile Coefficients
9	-2.2649178e-08	0.0000000e+00
8	-9.3254665e-07	0.0000000e+00
7	-8.4516302e-06	6.9965043e-06
6	7.9955372e-05	1.8593337e-04
5	1.2677613e-03	1.1301407e-03
4	-1.8511301e-03	-7.5093500e-03
3	-6.7733505e-02	-8.5146575e-02
2	-1.0571906e-03	6.1521248e-02
1	2.4092789e+00	2.6986492e+00
0	12	12

between levels 1 and 3 it must be 6240 ± 30 kPa. (3) The mooring must generally be positioned either mid-stream or on the southern side of the north wall. (4) The inclusion of the data from that site to define the profile enhances the overall motion correction as indicated by the tests described in Section 4. For example, although mooring H3 was corrected using the northern canonical profile, it was found that the inclusion of H3 in determining the southern canonical profile helped improve the correction of moorings I3 and M13. The southern profile, shown in Figure 4, was used to correct both years of data from moorings G3, H6, I4, I5, and the first year of data from H4 and H5, and the second year of data from moorings G2, M13, and I3. The coefficients for the southern profile, a 9th order polynomial, are listed in Table 6.

3.3 STEP 2: Correct the temperature data on a given mooring

3.3.1 STEP 2a: Determine reference pressure

The first step in correcting the temperature is to determine the reference pressure, p_{ref}. The reference pressure is defined as the pressure of the 12°C isotherm, as specified by the zeroth order coefficients of the northern and southern profiles (Table 6). We solve for p_{ref} by minimizing $\sum_{k=1}^{N}[T_k - F(p_{ref} - p_k)]$ for the temperature and pressure (T, p) measurements at the two or three (N) current meters on each mooring. The polynomial $T = F(p_{ref} - p)$ is specified to be either the northern or southern profile, depending on the criteria listed previously. The minimization is performed for each sample period, producing a time series of p_{ref} for each mooring. How well this minimization procedure works for each mooring can be ascertained by the plots of measured temperatures versus $p_{ref} - p$ shown in Appendix C.

There were a few moorings which required special treatment. The top current meter on mooring I2_YR2 failed; this is a critical instrument for determining p_{ref} because it was located in the high gradient portion of the canonical profile. Fortuitously, there was a working ADCP located 12 m above the current meter. Thus we were able to use the ADCP temperatures and pressures for the regression to determine p_{ref}. At two other sites, H4_YR1 and G2_YR2, the moorings had only one working temperature sensor, making it impossible to determine p_{ref} by regression. However we were able to obtain p_{ref} at those sites from a different data source. As part of the Central Array, IESs were located near the base of each mooring. The IESs measure the depth of the thermocline as indicated by the 12°C isotherm. Thus, the Z_{12} measured by the IESs is equivalent to the reference pressure (after taking into account the unit conversions from depth to pressure, $p_{ref} = 1.01 * Z_{12}$) because by definition, $T = 12$ when $p = p_{ref}$. However, there was a 2-5 km distance separating the current moorings and the IESs. This separation was considered too far to use the IES Z_{12} measurements directly in the mooring motion correction. Instead, we interpolated objectively-analyzed maps of Z_{12} (Tracey and Watts, 1991) to obtain time series of p_{ref} right at the two mooring sites. At mooring H4_YR1, a second current meter worked for half of the deployment year. Thus we were able to obtain a partial record of p_{ref} by regressing the current meter data. A comparison of the regressed p_{ref} to that of the IES revealed a bias of 10 db between the records. Thus in order to make the records consistent, the 10 db offset was added to the Pbin1 pressures record of site H4_YR1 before correcting the temperatures.

Not only did we interpolate the IES maps to sites H4_YR1 and G2_YR2, we also interpolated them to obtain Z_{12} records at all the moorings. Plots of p_{ref}, determined from the current meters and scaled into depth in meters, are shown together with the Z_{12} records from the IESs in Appendix D for all the moorings. The agreement between the two types of records is quite good, with rms differences between the two records generally less than 25 m.

3.3.2 STEP 2b: Correct the temperature data

Once p_{ref} is obtained for a given mooring, the temperatures at the desired pressure levels can be determined by using Hogg's method (Equation 3) and specifying the appropriate canonical profile. However we modified Hogg's method slightly by using a weighted average of the temperature correction from the two nearest temperature-pressure pairs, (T_u, p_u) and (T_l, p_l). That is,

$$\begin{aligned} T_{cor} &= w_u \mathcal{T}_u + w_l \mathcal{T}_l && (18) \\ \text{where,} \quad \mathcal{T}_u &= F(p_{ref} - p_{nom}) + [T(p_u) - F(p_{ref} - p_u)] && (19) \\ \text{and,} \quad \mathcal{T}_l &= F(p_{ref} - p_{nom}) + [T(p_l) - F(p_{ref} - p_l)] && (20) \\ \text{while,} \quad w_u &= \frac{|p_l - p_{nom}|}{|p_{nom} - p_u| + |p_{nom} - p_l|} && (21) \\ \text{and,} \quad w_l &= \frac{|p_{nom} - p_u|}{|p_{nom} - p_u| + |p_{nom} - p_l|} && (22) \end{aligned}$$

The weights sum to 1 and are linearly proportional to the pressure differences of the measurements away from p_{nom}; the $\mathcal{T}_u$ and $\mathcal{T}_l$ differ from $T_{nom} = F(p_{ref} - p_{nom})$ by the measured temperature differences at the respective levels. This modification forces the corrected temperature to smoothly approach and agree with the measured temperature when the current meter pressure approaches and equals the nominal pressure; i.e. when $p_j = p_{nom}$, $T_{cor} = T_j$.

On the moorings not used to determine the canonical profiles (Appendix E), it is possible for the current meters to be deeper or shallower than the canonical profile, i.e. either $p_{ref} - p_u$ or $p_{ref} - p_l$ lies beyond the range for which the polynomial $T = F(p_{ref} - p)$ has been defined. Under those conditions, the temperatures are not corrected using Equation 18, but instead are corrected using Equation 3, where $T_{cor} = F(p_{ref} - p_{nom})$. If $p_{ref} - p_{nom}$ is also beyond the range of the canonical profile, then the temperature cannot be corrected. The pressure ranges for the northern and southern profiles can be found in the first column of Table 8.

3.4 STEP 3: Correct the velocity data

To correct the velocity data of a given current meter, the data from two *nearest* current meters are used. These current meters are selected based on their *temperatures*; the ones closest in temperature to the corrected temperature are chosen. First, the velocities are decomposed into cross-stream and downstream components as in Equation 4. Next, the downstream component is linearly interpolated to the corrected temperature according to Equation 13. Subsequently, the cross-stream component is added back to the corrected downstream component to obtain the corrected velocity (Equations 6 and 15). Note that with our modification to Hogg's temperature correction, if one of the current meters is at the nominal pressure, the corrected temperature is the measured temperature and the corrected velocity is the measured velocity. If the current meter is not at the nominal pressure, the corrected velocity is a smoothly varying function between the two measurements.

If the temperature sensor on a given current meter did not work, the mooring motion temperature correction scheme was used to simulate temperature data at the current meter's *observed* pressure. Subsequently, the simulated temperature was used as either $T(p_l)$ or $T(p_u)$ in Equation 13 to correct the measured velocities. If there was only one velocity measurement among the upper three levels, the deep (3500 m level) velocity and temperature measurements were used as $(T(p_l), u(p_l), v(p_l))$ in Equation 13.

On moorings I2_YR2 and H3_YR2, no velocity data were obtained by the level 1 current meters. However, we were able to use the ADCP Bin 1 velocities to fill those gaps. To correct the ADCP velocities to the nominal pressure level according to Equation 13, the ADCP temperatures first had to be corrected to the Bin 1 level, located 9 m above the ADCP instrument itself.

The corrected temperature and velocity data are shown in Appendix F.

4 Tests of the Corrections

We now present the results of extensive testing that show that this correction scheme is very robust. In particular, two tests will be discussed. The first test examines the ability of the correction scheme to simulate data by interpolating between two current meters, and the second test evaluates extrapolation. Each test was applied to both a northern mooring (I1) and a southern mooring (I4_YR2); these moorings were selected because all three current meters worked properly.

For 'Test 1', level 1 and level 3 current meters are used to interpolate to level 2, which is approximately 300 m away from either input. The simulated level 2 current meter temperature and velocity data, as well as covariances and heat fluxes, are then compared to the directly measured level 2 data. The comparisons are shown in Figure 5 and the rms errors are listed in Table 7.

The simulated and observed velocities exhibit rms differences of under 6 cm s^{-1}, which is quite small considering the large 600 m distance between the level 1 and level 3 current meters.

An even more rigorous test involves an extrapolation. For 'Test 2', level 2 and level 3 current meters are used to extrapolate up to level 1. Again, the simulated level 1 temperature and velocity data, as well as covariances and heat fluxes, are then compared to the measured level 1 current meter data. The simulated and the observed time series are shown in Figure 6 and the rms errors are listed in Table 7. The velocities for the northern mooring have rms differences of under 8 cm, while those for the southern mooring are twice as large. The larger errors for the southern mooring can be attributed to the deeper and more frequent vertical excursions taken by the mooring because it was located in a higher-velocity region of the current. Considering the large extrapolation distances (the level 1 current meter is 300 m and 600 m away from the level 2 and level 3 instruments, respectively) the observed errors are small and indicate that the correction scheme is robust.

Figure 5: Test 1: Simulating Level 2 Data by Interpolation

Table 7: Root-mean-square Error Between Measured and Simulated Data for Tests 1 and 2. Each test was run for both a northern mooring, I1, and a mid-stream/southern mooring, I4_YR2. Test 1 uses current meters at level 1 and 3 to interpolate to level 2. Test 2 uses current meters at level 2 and level 3 to extrapolate to level 1. Units of velocity are ms^{-1}. Temperature units are $^{\circ}C$. Figure 4 shows the observed and simulated time series of each test.

	Northern Mooring Site I1		Mid/Southern Mooring Site I4_YR2	
	Test 1	Test 2	Test 1	Test 2
:w err(T):	0.2	0.6	0.7	0.9
err(u):	0.01	0.08	0.06	0.16
err(v):	0.02	0.07	0.05	0.14
err(u'u'):	0.007	0.068	0.050	0.231
err(u'v'):	0.003	0.034	0.024	0.117
err(v'v'):	0.004	0.040	0.028	0.181
err(T'T'):	1.0	3.7	4.7	6.9
err(u'T'):	0.057	0.340	0.265	0.699
err(v'T'):	0.040	0.286	0.168	0.477

Figure 6: Test 2: Simulating Level 1 Data by Extrapolation

These tests are very strenuous compared to the typical vertical distances used for correcting the temperature and velocity data for mooring motion. Most observed vertical excursions of the current meters required interpolations or extrapolations of less than 50 m to put the data onto the desired pressure horizons.

Our tests show that the method works sufficiently well that data can be simulated at any of the three levels when one of the current meters failed. Figure 3 shows that most of the instrument failures in the Central Array were at level 2. Therefore using the mooring motion correction scheme to interpolate to level 2, the associated errors for those moorings will be similar to the errors presented for Test 1. In addition, several of the level 1 current meters had gappy or short velocity records; they include sites G3_YR1, H4_YR2, I3_YR2, and I5_YR2. Thus for those moorings, the velocity and covariance errors at 400 m during the gappy periods will be on the order of those described in Test 2. Because the Hogg (1991) mooring motion correction method works so well, these data gaps, although unfortunate, are not as troublesome as might have been feared.

5 Error Estimations of the Motion Corrected Data

5.1 Estimating the error in T_{cor}

Errors associated with the corrected temperatures arise from both errors in the temperature measurements and errors in the reference pressure. The error in T_{cor} also depends on how the correction was determined, either by using either Equation 3 for one working instrument or Equation 18 for two instruments.

When there is only one working current meter on the mooring, the corrected temperature is $T_{cor} = F(p_{ref} - p_{nom})$. In this case, the correction error is predominantly due to the scatter of the observed temperature-pressure pairs on the canonical profiles, $\sigma_F(p_{ref} - p_{nom})$. However, the measurement errors also cause a small error in the daily reference pressure which in turn affects the corrected temperatures. Thus, the total temperature error is:

$$
\begin{aligned}
err(T_{cor}) &= err(F) && (23)\\
&= \sqrt{\sigma_F(p_{ref} - p_{nom})^2 \;+\; \left(\left.\frac{\partial F}{\partial p_{ref}}\right|_{p_{ref} - p_{nom}} err(p_{ref}) \right)^2} && (24)
\end{aligned}
$$

The term $\sigma_F(p_{ref} - p)$ is the standard deviation envelope of observed temperatures around canonical profile. Table 8 lists the observed scatter as a function of pressure for both the northern and southern profiles. The derivative $\frac{\partial F}{\partial p_{ref}}$, can be computed analytically in a straightforward manner because the canonical profiles are modeled as polynomials. However, estimating the error in the reference pressure, $err(p_{ref})$ is not straightforward and is discussed in Section 5.2.

When there are at least two current meters working on the mooring, then the temperature correction can be computed according to Equations 18–22. Accordingly, the error in the corrected temperature is:

$$
\begin{aligned}
err(T_{cor}) \;=\; & \Bigg[(w_u^2 + w_l^2) err(T)^2 \;+\; w_u^2 \left(\sigma_F(p_{ref} - p_{nom}) - \sigma_F(p_{ref} - p_u)\right)^2 \;+ \\
& w_l^2 \left(\sigma_F(p_{ref} - p_{nom}) - \sigma_F(p_{ref} - p_l)\right)^2 \;+ \\
& \left(\left.\frac{\partial F}{\partial p_{ref}}\right|_{(p_{ref} - p_{nom})} - w_u \left.\frac{\partial F}{\partial p_{ref}}\right|_{(p_{ref} - p_u)} - w_l \left.\frac{\partial F}{\partial p_{ref}}\right|_{(p_{ref} - p_l)} \right)^2 err(p_{ref})^2 \;+ \\
& \left(\left(\frac{\partial w_u}{\partial p_u} \mathcal{T}_u + \frac{\partial w_l}{\partial p_u} \mathcal{T}_l \right)^2 \;+\; \left(\frac{\partial w_u}{\partial p_l} \mathcal{T}_l + \frac{\partial w_l}{\partial p_l} \mathcal{T}_l \right)^2 \right) err(p)^2 \Bigg]^{1/2}
\end{aligned}
\tag{25}
$$

The errors of the temperature and pressure observations are $err(T_u) = err(T_l) = err(T) \sim 0.03°C$ and $err(p_u) = err(p_l) = err(p) \sim 5$ db, respectively. The derivative terms can be computed analytically from Equations 2 and 21–22.

Typical values of $err(T_{cor})$ for all three levels are 0.14–0.17°C. The highest errors of 0.27°C were estimated for the 700 m level at site G2_YR2.

5.2 Estimating $err(p_{ref})$

The daily p_{ref} is found by fitting the (T, p) measurements from the working current meters on a mooring to the canonical profile $T = F(p_{ref} - p)$,

$$
0 \;=\; \frac{\partial}{\partial p_{ref}} \left[\sum_{i=1}^{M} (p_{ref} - p_i - F^{-1}(T_i))^2 \right] \tag{26}
$$

Table 8: Error between the Observed Temperatures and the Canonical Profiles

$$p_{ref} = \sum_{i=1}^{M} \frac{p_i + F^{-1}(T_i)}{M} \tag{27}$$

where M is the number of current meters on the mooring. Thus, assuming each of the M instruments have random temperature and pressure measurement errors, the error in the reference pressure is:

$$\begin{aligned} err(p_{ref}) &= \sqrt{M(\frac{err(p)}{M})^2 + \sum_{i=1}^{M}\left(\frac{\partial}{\partial T}F^{-1}(T_i)\frac{err(T)}{M}\right)^2} && (28) \\ &= \sqrt{\frac{err(p)^2}{M} + \left(\frac{err(T)}{M}\right)^2 \sum_{i=1}^{M}\left(\frac{\partial}{\partial T}F^{-1}(T_i)\right)^2} && (29) \end{aligned}$$

Rather than inverting the polynomial, $F(p_{ref} - p)$, we found it simpler to fit the northern data and southern data to an arctanh function, $G(T)$:

$$\begin{aligned} p_{ref} - p &= G(T) && (30) \\ &= C_u \operatorname{atanh}\left(\frac{T - C_l}{C_3}\right) + C_4 && (31) \end{aligned}$$

such that $G(T) \sim F^{-1}(T)$. Thus,

$$\begin{aligned} \frac{\partial F^{-1}(T)}{\partial T} \sim \frac{\partial G(T)}{\partial T} &= \frac{C_u}{C_3}\left(\frac{1}{1 - arg^2}\right) && (32) \\ \text{where,} \qquad arg &= \frac{T - C_l}{C_3} && (33) \end{aligned}$$

Note that this derivative is defined only for $-1 < arg < 1$. Because the observed temperatures were sometimes different than the canonical profile, values of arg that were less than or equal to -1, were replaced by -0.99. Likewise, values of arg greater than or equal to 1 were replaced by $+0.99$.

Values of $err(p_{ref})$ for all three levels ranged between 0.042 kPa and 0.10 kPa. The mean value for all sites was 0.061 kPa.

5.3 Estimating the error in U_{cor}

The error in the corrected velocity (U_{cor}) depends on (i) the measurement error err(U) ~ 2 cm s^{-1}, (ii) the error in the corrected temperature, err(T_{cor}), which was discussed above, (iii) the error in the angle of the shear, err(θ) $\sim 5°$, and (iv) the error in the assumption that the change in the velocity shear is proportional to the change in the temperature, $err(m)$. The error in m depends upon whether the velocity correction is an interpolation or an extrapolation. For interpolation where $T_u \geq T_{cor} \geq T_l$, we found $err(m) \sim 0.01$. Otherwise, $err(m) \sim 0.02$.

Assuming these errors are independent,

$$err(\mathbf{U_{cor}}) = \sqrt{\left(\frac{\partial U_{cor}}{\partial \theta} err(\theta)\right)^2 + \left(\frac{\partial U_{cor}}{\partial T_{cor}} err(T_{cor})\right)^2 + \left(\frac{\partial U_{cor}}{\partial m} err(m)\right)^2 + err(V)^2} \tag{34}$$

The partial derivatives can be determined by examining Equation 14.

Mean $err(\mathbf{U_{cor}})$ values of 0.02 m s^{-1} were obtained for all moorings except three (sites G3_YR1, I3_YR1, and G3_YR2) where the mean errors were 0.15–0.17 m s^{-1}.

6 Useful By-products of the Correction Scheme

The canonical profile can be exploited in a variety of ways to obtain additional data products.

6.1 The Pseudo-IES

Because the canonical profile is represented by a Nth order polynomial whose zeroth order coefficient is set to be 12°C, the reference pressure is the pressure of the 12°C isotherm, $T(p = p_{ref}) = F(0) = 12°C$. Furthermore, the reference pressure can be divided by a factor of 1.01 to convert pressure into depth in meters. Thus we can obtain a time series of the depth of the 12°C isotherm at the current meter site.

This is the same measurement obtained by the IESs which were also deployed in the Central Array. As discussed in Section 2.3, we used the IES Z_{12} records as p_{ref} for two sites when several current meters on those moorings failed. Likewise, the moorings can be used as "pseudo-IES"s to help map the thermocline topography where the IESs failed. Appendix D show comparisons of the Z_{12} measurements from IESs and pseudo-IESs at all the mooring sites. Typically, the rms differences between the two time series are under 25 m, which is less than the error of the objectively mapped IES Z12.

6.2 Computing the Mean Stratification

Because the SYNOP moorings were arranged along lines approximately perpendicular to the mean Gulf Stream path, the mean temperature profiles at each mooring along a line can be contoured into a Eulerian mean temperature cross-section. Figure 7 shows both the year 1 and year 2 mean temperature cross-sections along the I line (near 68°W).

Furthermore, because the canonical profile has an analytical form, the Brunt-Vaisalla frequency, $\overline{\mathcal{N}^2} = \overline{g\alpha \frac{\partial T}{\partial p}}$ (where $\alpha = -\frac{1}{\rho_0}\frac{d\rho}{dT}$ and the overline indicates a time average) can be computed simply as:

$$\overline{\mathcal{N}^2} \;=\; \overline{g\alpha \sum_{n=1}^{N-1} (N+1-n)\, c_n\, (p_{ref}-p)^{(N-n)}}. \tag{35}$$

The year 1 and year 2 mean stratification cross-sections along the I line are shown in Figure 8.

7 Summary

Hogg (1991) provides a robust mooring motion correction method. We made a slight modification to his method however, by using a weighted average of the corrections of the two nearest temperature measurements. This revision allows the corrected temperature to equal the measured temperature when current meter is at the nominal pressure.

The tests discussed in Section 4 show that even when there were only two working current meters on a mooring, the temperature and velocity measurements could be 'corrected' to all three nominal levels.

A feature of this method is that it uses the uncorrected data to create the canonical profiles and reference pressure. Thus, this scheme provides a method of correcting temperature and velocity data for mooring motion, even in the absence of historical data sets.

Because of the wealth of data in the SYNOP Central Array, other types of measurements could be incorporated into the correction scheme to improve the velocity and temperature corrections. Specifically, ADCP pressure measurements were used whenever possible, because they could be verified by independent acoustic calculations of the depth. Additionally, the ADCP temperatures and Bin 1 velocities were used whenever possible to fill data gaps left by the current meters. Furthermore, IES Z_{12} data were used as the reference pressures for

Figure 7: Mean Temperature Cross-sections at Line I

Figure 8: Mean Stratification Cross-section at Line I

moorings that had only one of the upper level current meters functioning properly.

Finally, we have also noted that the moorings can be used as pseudo-IESs. We have already done this by incorporating their p_{ref} records into our objective maps of the thermocline field. The inclusion of these current meter data into the IES maps sharpened the thermocline gradients and improved the maps in regions where there were no IES measurements.

Altogther, Hogg's (1991) mooring motion correction scheme allows the IES and current meter data to be mutually beneficial.

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Appendix A: ADCP Temperature Evaluations

Due to differences in the calibration procedures, we believe the absolute temperatures of the level 1 current meter ($T1$) but not those of the ADCP (T_{ADCP}). However, we know that in general T_{ADCP} should be approximately $0.2 - 0.25$°C warmer than $T1$ since the ADCP was located 12 m above the current meter. This is based on a typical thermocline gradient of 1°C for $48 - 60$ m. Since these sites were located in the northern portion of the array where the thermocline is frequently shallow, the ADCPs (at roughly 400 m depth) were sometimes below the thermocline in colder water. In those cases, we might expect a smaller thermal gradient, e.g. 0.15°C/12 m = 1°C/80 m, corresponding to temperature differences of 0.15°C. Likewise in 18°C water, we might expect a *very* small gradient. However, except for rare intrusion events, the gradients should always be positive since the ADCPs are positioned above the current meters on the moorings.

Comparisons of the $T1$ and T_{ADCP} records were made for all four of ADCPs. These included the full records for sites H3_YR1, H3_YR2 and H4_YR1, as well as a short record for site I2_YR2, when the current meter failed after a 4-month period. No ADCP data were obtained for sites I2_YR1 and H4_YR2. The results of these comparisons are summarized here. The error in these temperature offsets is $\pm - 0.05$°C. "Good" means that the difference $\Delta_T = T_{ADCP} - T1$ corresponds to a realistic temperature gradient. Plots of the temperature difference Δ_T versus $T1$ are shown in Figure 9.

H3_YR1:

T_{ADCP} appears to have an offset of approximately -0.5°C. It's too cold.

- The ADCP temperature is *always colder* than the current meter $T1$. Thus T_{ADCP} is *bad.*
- For $T1 = 6 - 10$°C, $\Delta_T = -0.4$ to -0.25°C. It should be $+0.15$ to $+0.2$°C.
- For $T1 = 10 - 14$°C, $\Delta_T = -0.3$ to -0.1°C. It should be $+0.25$°C.
- $T_{ADCP} - T1$ is less than -0.5°C during one *cold* event ($T1 = 6$°C). This is probably an intrusion.

H4_YR1:

- T_{ADCP} looks like it has an offset of -0.25 to -0.3°C. It is *too cold.*

- For $T1 = 5 - 10°\text{C}$, $\Delta_T = -0.15$ to $-0.10°\text{C}$. It should be $+0.15$ to $+0.2°\text{C}$.
- For $T1 = 10 - 17°\text{C}$, $\Delta_T = -0.05$ to $+0.25°\text{C}$. It should be around $0.25°\text{C}$.
- For $T1 = 18°\text{C}$, $\Delta_T = -0.20$ to $-0.25°\text{C}$. It should be $0.0 - 0.1°\text{C}$.

H3_YR2:

- T_{ADCP} looks good. If anything, there might be an offset of $-0.05°\text{C}$, which is too cold.
- For $T1 = 7 - 10°\text{C}$, $\Delta_T = 0.05$ to $0.2°\text{C}$.
- For $T1 = 10 - 16°\text{C}$, $\Delta_T = 0.2$ to $0.4°\text{C}$.
- For $T1 = 18°\text{C}$, $\Delta_T = +0.0$ to $0.05°\text{C}$
- There are 2–3 spikes when T_{ADCP} was about $0.02°\text{C}$ or so colder than $T1$. Overall however, this is a very reasonable record.

I2_YR2:

- T_{ADCP} looks good. If anything, the T_{ADCP} might be $0.1°$ C too warm.
- For $T1 = 6 - 10°$ C, $= 0.2°\text{C}$.
- For $T1 = 10 - 16°\text{C}$, $\Delta_T = 0.25 - 0.5°\text{C}$. and occasionally $\Delta_T = 0.5 - 0.7$ C warmer.
- The T_{ADCP} is never colder than $T1$ over the 500-point record (4 months).

In summary, these comparisons show that it is reasonable to use the ADCP temperatures in the mooring motion correction of sites H3_YR2 and I2_YR2. However, extra precautions should be taken when using the ADCP temperatures of sites H3_YR1 and H4_YR1. We did not use either of these two records for the mooring motion corrections describe in this report.

Figure 9: T_{ADCP} versus $T1$

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Appendix B: Mooring Motion Correction Matlab Codes

There are two basic driver programs associated with the mooring motion correction scheme. The first computes the canonical profile from a subset of the temperature and pressure data, and the second uses the canonical profile to correct the temperature and velocity data of a current meter to the nominal depth. However because we classified the moorings as either northern and southern sites, we needed two distinct canonical profiles. Thus we created two versions of each of the driver programs, one version for the northern sites and the other for the southern sites. For the northern sites, the program **synopbznorth.m** computes the canonical profile and **mmcorn.m** uses that profile to correct the temperature and velocity data of a single current meter on a given mooring. The programs **synopbzmid.m** and **mmcors.m** are the respective codes for the southern moorings.

The driver programs for determining the canonical profiles, **synopbznorth.m** and **synopbzmid.m**, each call three subroutines: (1) **mcor.m** performs the iteration to determine the coefficients of the polynomial. (2) **nlreg.m** iterates to determine the reference pressure. (3) **errbzp.m** calculates the polynomial and its derivative for each day.

The other two driver programs, **mmcorn.m** and **mmcors.m**, each call four subroutines: (1) **zest.m** computes the daily reference pressure. (2) **tempcor.m** computes the corrected temperature and estimates the associated error. (3) **tprefer.m** computes the error in the reference pressure, and (4) **velc.m** computes the corrected velocity and estimates its error.

The error estimates depend on knowing the standard deviation envelope of the temperature measurements about the canonical profile. For completeness, the code, **tenv.m**, which computes the lookup table for the standard deviation envelope, is included in this appendix.

Appendix C: Temperature versus Pressure Profiles

Measured temperatures are plotted against the pressure, $p_{ref} - p$, for each mooring. Level 1 data are indicated by crosses, level 2 data by squares, and level 3 data by triangles. The canonical profile is also shown for each site. The reference pressure, p_{ref}, was determined by least-squares regression for all sites except two. For sites G2_YR2 and H4_YR1, p_{ref} was obtained from the IES data.

Appendix D: Pseudo-IES and IES Z_{12} Records

Time series of the depth 12°C isotherm as determined by the current meter moorings and the IESs are presented.

The current meter reference pressure records, p_{ref}, have been scaled by a factor of 1.01 to convert the units from decibars into meters. We refer to these scaled data as 'pseudo-IES' records.

The actual IES observations are not shown in the following figures because the IES and current meter sites were separated by as much as 5 km. Instead, we interpolated objective maps of the IES Z_{12} fields to obtain time series of Z_{12} right at the current meter mooring locations. These interpolated records are the ones presented here.

In the following figures, the IES data are shown by the dashed lines and the pseudo-IES records by the solid lines. Due to IES instrument failures, either partial data or no data are shown for the IESs at sites H2_YR1, I1_YR1, I3_YR1, and I1_YR2. We did not deploy an IES at the base of the mooring at site M13_YR2; thus no IES data is shown for that site. Additionally, no pseudo-IES data are shown for sites H4_YR1 and G2_YR2 because there was insufficient current meter data to determine p_{ref}.

For convenience, the Year 1 data are plotted from May 1988 to August 1989 and the Year 2 data for May 1989 to August 1990. Consequently there is an overlap of approximately three months in these figures. Thus some of the current meter data (specifically, the four two-year moorings at sites H2, H6, I1, and I5) are repeated during that time period. Except for the IES sites noted above, the IES records are continuous throughout the two year period.

Table 9: Statistics on the Pseudo-IES Data

Appendix E: Comments on Mooring Motion Corrections

G2_YR1

- Not used to determine either profile.
- Corrected using northern profile.
- Level 4 velocities were never used due to highly-energetic events.

G3_YR1

- Not used to determine either profile.
- Corrected with southern profile.
- Special handling required to make sure all levels began at same time.
- Data gaps in level 1 velocities. Filled by extrapolation from levels 2 and 3.

H3_YR1

- Used to determine northern and southern profiles.
- Corrected using northern profile.
- Level 4 velocities were never used due to highly-energetic events.
- ADCP pressures used. However, level 1 current meter pressures were used to fill a data gap at end of record. A bias of 6 db was subtracted from the current meter pressures before using them.

H4_YR1

- Not used to determine either profile.
- Corrected with southern profile.
- ADCP pressures used instead of level 1 current meter pressures..
- Only one working temperature sensor.
- Used IES Z_{12} as p_{ref} after scaling from meters to decibars.
- A comparison of the p_{ref} (determined from the current meter data for a short time period) and the IES Z_{12} showed a 10 db bias between the two records. Since we used the IES Z_{12} data for the mooring motion correction, we added 10 db to the ADCP pressures to make the two data sets consistent.
- Biases in the current meter pressures are the sources for the discrepancies between delp12 of Table 5 and the observed delta pressures in Tables 2 and 3.

H5_YR1

- Not used to determine either profile.
- Corrected with southern profile.

I2_YR1

- Not used to determine either profile.
- Corrected using northern profile.
- Level 4 velocities were never used due to highly-energetic events.

- ADCP failed. Used level 1 current meter pressures after removing the 6 db bias.
- Special handling required to make sure all levels began at same time.

I3_YR1

- Used to determine northern profile.
- Corrected using northern profile.
- Special handling to truncate level 1 to same length as levels 2 and 3.

I4_YR1

- Used to determine southern profile.
- Corrected with southern profile.
- Special handling to truncate level 3 to same length as levels 1 and 2.

G2_YR2

- Not used to determine either profile.
- Corrected with southern profile.
- Level 4 velocities were never used due to highly-energetic events.
- Only one working temperature sensor.
- Used IES Z_{12} as p_{ref} after scaling from meters to decibars.

G3_YR2

- Not used to determine either profile.
- Corrected with southern profile.

H2_YR2

- Two-year long record
- Used to determine northern profile.
- Corrected with southern profile.
- Level 4 velocities were never used due to highly-energetic events.
- Data gaps in level 1 velocities. Filled by extrapolation from levels 2 and 3.

H3_YR2

- Used to determine northern and southern profiles.
- Corrected using northern profile.
- ADCP pressure used.
- Level 1 current meter failed after a short period. ADCP temperatures and Bin 1 velocities were used for the remaining time period.
- Level 4 velocities were never used due to highly-energetic events.

H4_YR2

- Not used to determine either profile.

- Corrected using northern profile.
- ADCP failed. Used the level 1 current meter pressures after subtracting a 6 db bias.

H6_YR2

- Two-year long record.
- Not used to determine either profile.
- Corrected with southern profile.
- Very large excursion of 550 m used taken by mooring.

I1_YR2

- Two-year long record.
- Used to determine northern profile.
- Corrected using northern profile.
- Special handling to truncate last data point of all levels except level 1.
- Level 4 velocities were never used due to highly-energetic events.

I2_YR2

- Used to determine northern profile.
- Corrected using northern profile.
- ADCP pressures used.
- Level 1 current meter failed. Used ADCP temperatures and velocities instead.
- Level 4 velocities were never used due to highly-energetic events.

I3_YR2

- Not used to determine either profile.
- Corrected with southern profile.
- Level 2 temperatures get bad near the end of record. Use only the first 1230 data points of this record.
- Level 1 velocities failed after a short period. Thus corrected velocities at this level were obtained by extrapolation from levels 2 and 3. The largest velocities were obtained for this site (Table D1).

I4_YR2

- Used to determine southern profile.
- Corrected with southern profile.

I5_YR2

- Two-year long record.
- Used to determine southern profile.
- Corrected with southern profile.
- Data gaps in level 1 velocities. Many gaps filled by extrapolation from levels 2 and 3. Some periods were not filled because the mooring took large excursions.

M13_YR2

- Used to determine southern profile.
- Corrected with southern profile.
- Level 1 pressures were bad. Used level 2 pressures as P1 and adjusted delp12 and delp13 accordingly (see Table 5).

Appendix F: Mooring Motion Corrected Data

Plots of the mooring motion corrected temperature and velocities are shown for each mooring. All data have been corrected to constant depths of 400 m, 700 m, and 1000 m. These data have also been lowpassed using a 40-hr Butterworth filter.

The plots on each page are organized in the same manner. In the uppermost panel, corrected temperatures at all three depth levels are shown. The corrected velocities are shown in the bottom three panels, one for each of the pressure horizons. The solid line in each panel shows the u-component of velocity and the dashed line indicates the v-component. Some data gaps are still evident in these figures.

The temperature and velocity records for each mooring are presented on two pages. The first page shows the data for the Year 1 deployment period, May 1988 to August 1989. The Year 2 data, May 1989 to August 1990, are shown on the second page. There is a three-month overlap in these two figures; thus the corrected data at several sites are repeated in the two figures.

The reference pressure, p_{ref}, at each mooring are not shown in this appendix. They are shown in Appendix D together with the corresponding IES Z_{12} records.

Table 10: Time Bases of the Mooring Motion Corrected Records

Table 11: Corrected Temperature and Velocity Statistics