Accuracy in Mooring Motion Temperature Corrections

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ABSTRACT

Moored temperature sensors, whether fixed or profiling, routinely need to be corrected to remove the signals associated with the vertical motion of the sensors when the moorings "blow over" in strong flow events (for profiling sensors the problems occur only at the upper end of the profiling range). Hydrographic data are used to estimate the accuracy with which moored temperature sensors in the Gulf Stream can be corrected for mooring motion aliasing using standard correction techniques, and the implications for other ocean regions are discussed. Comparison with hydrographic data and coincident inverted echo sounder (IES) data from the Synoptic Ocean Prediction Experiment (SYNOP) shows that the errors inherent in mooring motion corrected temperatures during significant pressure deflections are potentially 2–3 times as large as previous estimates based on a smaller dataset of observations in the Kuroshio at approximately the same latitude in the Pacific. For sensors with a nominal level of 400 dbar and a typical root-mean-square pressure deflection of 150 dbar, accuracy limits of up to 0.7°C on the "corrected" temperatures are applicable. Deeper sensors typically have smaller accuracy bounds. There is a suggestion that the presence of a mode water layer near the nominal depth of the shallowest sensor can result in much higher errors in mooring motion corrected temperature data. The accuracy estimates derived herein should apply not only to moorings deployed in the Gulf Stream but also to all currents that exhibit similar velocity amplitudes and thermal gradients such as the Agulhas or Kuroshio.

1. Introduction

Tall taut-line subsurface moorings equipped with current meters, temperature sensors, and other instruments at several levels have been important tools in the oceanographers' toolbox for many years. For example, such moorings are presently or have recently been used in Minerals Management Service studies in the Gulf of Mexico, at the Woods Hole Oceanographic Institution Gulf Stream Transport Observations ("GUSTO") site, in an international U.S. and U.K. collaboration across the Atlantic Basin at 26°N in the Meridional Overturning Circulation Heat-flux Array (MOCHA)/RAPID program, and in a French project in the Drake Passage. A related new technology that is being utilized in some experiments (e.g., in the recently completed Kuroshio Extension System Study) is based on a profiling instrument package that climbs up and down a tall mooring making continuous measurements between fixed stoppers, often called a profiling mooring. While both styles of moorings provide very useful datasets, they also come with limitations. A well-known issue when using any tall subsurface moorings is that the top portion of the mooring tends to be pulled downward by the drag of water past the mooring when the mooring is exposed to strong oceanic currents, analogous to the bending over of a tree in a strong wind (e.g., Hogg 1986). This "mooring motion" affects both the standard moorings and the newer profiling moorings, although for the profiling moorings it is only an issue in the upper portion of the profiling range.

The precise drag-related motion for any particular mooring is a complex function of the distribution of buoyancy and equipment, the type of mooring line, and the vertical structure of the flow past the mooring. The vertical excursions of the instruments can exceed 300–600 m in strong currents (e.g., Cronin and Watts 1996; Hall 1989; Phillips and Rintoul 2000). Measurements in the Subantarctic Front from the Subantarctic Flux and Dynamics Experiment (Luther et al. 1997) show root-mean-squared (rms) deflections ranging from 75 to 105 dbar and maximum deflections of up to 300 dbar, while

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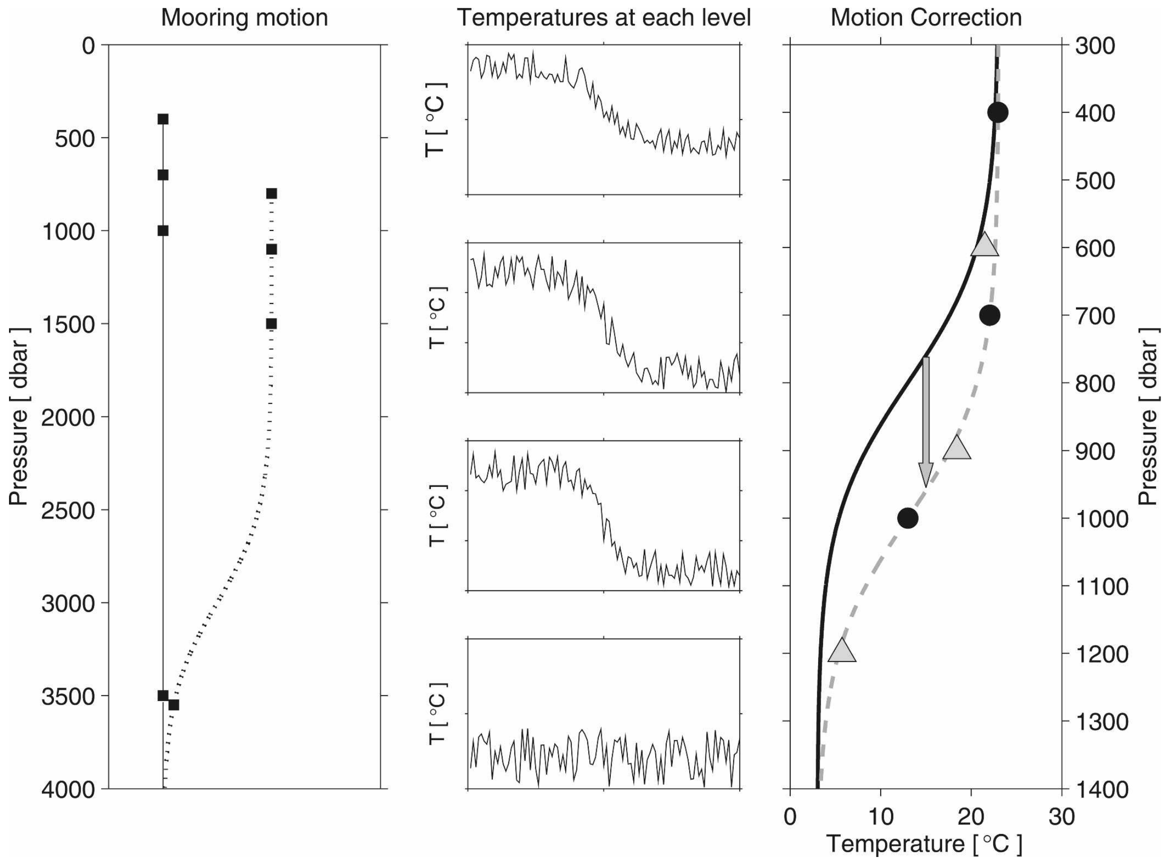

FIG. 1. Cartoon illustrating mooring motion and the basic Hogg (1986, 1991) temperature correction method. (left) A typical mooring with temperature sensors at four levels: 400, 700, 1000, and 3500 dbar. The vertical solid line and distorted dotted line show, respectively, the distribution of the instruments when the mooring is and is not displaced vertically because of drag. (middle) An illustration of the temperatures that might be measured by each sensor as the mooring drags down. (right) How the temperature measurements for any particular day (gray triangles) are corrected using the Hogg (1986, 1991) technique by shifting the canonical profile (black line) so that it most closely matches the daily measurements. Once this has been done the temperatures on the fit line at the nominal depths (black dots) are extracted as the mooring motion corrected temperatures.

moorings in the North Atlantic Current experiment (e.g., Meinen and Watts 2000) show rms deflections ranging from 10 to 90 dbar and maximum deflections of up to 300 dbar.

Traditional moorings and profiling moorings both exhibit mooring deflections that bend down the mooring into a catenary or hyperbolic tangent shape such as that illustrated in Fig. 1 (left panel). While the impact of this motion on a traditional mooring is to move the sensors deeper in the water column, the impact of mooring motion on a profiling mooring is simply a downward deflection of the upper (and possibly the lower) stopper; assuming the lower stopper is well below the thermocline, the effect of mooring motion on a profiling mooring is limited to the depth range through which the upper stopper is deflected.

Vertical excursions of the sensors result in variations in the measurements that are unrelated to the ocean variability at the nominal depth of the sensors. Correction of mooring motion related variability has been shown to be critically important when calculating properties such as heat flux from mooring data because the temperature changes associated with the vertical motion of the moored temperature sensors can significantly exceed the temperature variations associated with the mesoscale variations being studied (e.g., Nowlin et al. 1985). The existence of this well-known problem has led to the development of techniques for correcting the temperature records from moored temperature sensors using data from collocated pressure sensors (Hogg 1986, 1991; Cronin and Watts 1996) and using both pressure sensor data and hydrography (Hall 1989; Fillenbaum et al. 1997; Johns et al. 2005). What is absent, however, with these correction techniques is a detailed test of the accuracy of the corrections.

While mooring motion correction techniques can be tested with hydrographic data (e.g., Hall 1989), the datasets collected in the Gulf Stream near 68°W as part of the Synoptic Ocean Prediction experiment (SYNOP) (e.g., Johns et al. 1995; Shay et al. 1995; Watts et al. 1995) provide an opportunity to compare mooring motion corrected temperatures to independent data and thereby to quantify explicitly how well the mooring motion correction is working. The purposes of this article are as follows: (i) to use hydrographic data collected in the SYNOP Central array region to estimate the magnitude of errors that can be expected to occur in correcting moored temperature sensors, and (ii) to compare several SYNOP Central array mooring motion corrected temperature time series to independent time series of temperature derived from inverted echo sounder (IES) data, and then compare the observed differences to the hydrography-derived accuracy estimates from (i). It is hoped that this work will provide researchers using mooring data with better estimates of the accuracy of their final mooring motion corrected temperature data.

2. Mooring motion techniques: Similarities and differences

To understand how the differences in techniques will interact with the accuracies evaluated herein, a discussion of how the techniques differ is required. Most mooring motion correction techniques fall into one of two "families." One family of correction techniques for moored temperature data originates with the method developed by Hogg (1986, 1991). The method is based upon the assumption that a single "canonical" temperature profile can describe the vertical structure of temperature at each point across a baroclinic current, with the profile simply being shifted vertically as it moves from the shallow thermocline on the cold side of the front to the deep thermocline on the warm side of the front (Fig. 1). Because the vertical structure of temperature is held to be constant across the current, with only the depth of the main thermocline allowed to change, this method assumes that all of the isotherms are parallel across the front. The canonical profile is derived in this technique by fitting a mathematical function, often a high-order polynomial, to the uncorrected temperature–pressure data from the mooring time series of collocated temperature and pressure sensors at several levels along the mooring(s). Once this function has been derived, the resulting functional profile is shifted vertically to least squares fit the data from the moored sensors at each time step (Fig. 1, right panel). When the profile has been fit to the directly measured values for a particular time step, the functional form is used to interpolate or extrapolate the measured temperatures to the nominal depths of the moored sensors. This process is then repeated for each time step of the record. One advantage of this technique is that it does not require any ancillary data beyond what is actually measured by the instruments on the mooring.

Cronin and Watts (1996) developed a modified version of the Hogg technique that relaxed the parallel-isotherms assumption to allow the corrected temperatures to approach the measured temperatures in the limit of zero mooring motion. This modification essentially introduces a linear weighting, with the weights of the actual measurement and the fit canonical profile given by the vertical distance of the observation site from the nominal sensor level. Regardless of whether the Cronin and Watts (1996) modification is used or not, when the shallowest moored sensor is below the shallowest nominal depth, which is often most of the record depending on the choice of the nominal depth, the canonical profile is used to extrapolate upward with no direct measurements constraining it above. The Cronin and Watts (1996) modification retains an important feature of the Hogg (1986, 1991) method in that the modified technique still does not require any independent data beyond those which are provided by the moored sensors, and it provides more accurate corrected temperatures than the original Hogg (1986, 1991) technique because it does not introduce errors during periods when the mooring is not deflected downward by the currents.

The second family of mooring motion correction techniques uses hydrography from the region of the mooring to develop a functional relationship between the vertical gradient of temperature ($\delta T/\delta z$) and temperature (T) itself (e.g., Hall 1989; Fillenbaum et al. 1997; Johns et al. 2005). The moored sensor data are combined with this hydrography-based relationship to interpolate or extrapolate the measured values to the nominal sensor depths. Because the $\delta T/\delta z$ versus T function utilizes a constant value of $\delta T/\delta z$ for a given value of T, regardless of the pressure at which T is observed, the vertical distance between neighboring isotherms is fixed in this technique, ergo it is the equivalent of the assumption of parallel isotherms. The techniques in this family generally involve integrating the derived gradients vertically both from the sensor below the nominal depth and from the sensor above when possible (e.g., Johns et al. 2005). The resulting temperature estimates from the above and below integrations are combined in a weighted average sense with the weighting dependent on the relative distances of the sensors from the nominal pressure. In essence this dual integration has two major impacts. First, it has the effect of relaxing the parallel isotherm assumption when the pressure deflections are small. Second, this dual integration, because the measured temperatures and pressures from vertically neighboring sensors do not need to fit the mean parallel structure imposed by the $\delta T/\delta z$ versus T function, provides some ability of the technique to adjust the mean vertical structure to account for instantaneous variability, which is something the Hogg (1986, 1991) family of corrections does not allow. On the downside this technique is more sensitive to small vertical scale (higher vertical mode) noise than the Hogg (1986, 1991) family of corrections because for any given nominal pressure the correction will be based solely on the two measurements above and below it (at most two) without utilizing the information the other sensors on the mooring provide about the low–vertical mode structure of the temperature profile.

Since both families of correction techniques assume that the isotherms are parallel as they cross the front, any interpolation in the vertical by the two techniques must provide similar results. It is possible, however, that the canonical profile derived via the Hogg (1986, 1991) technique using the mooring data alone may not have exactly the same vertical structure as the $\delta T/\delta z$ versus T function that is derived from ancillary CTD data under the Hall (1989)–Fillenbaum et al. (1997)–Johns et al. (2005) technique. It is also important to note that, for the top sensor on a subsurface mooring, both families of correction techniques require the extrapolation of the data from the shallowest sensor up to the nominal depth whenever the mooring has been deflected downward. As will be shown, this is where the largest errors are introduced in the "corrected" data. Before continuing, it must be stressed that these two families of techniques both require the correction to go to zero when the pressure deflection is zero, so the accuracy limits discussed herein relate only to periods when the mooring has been pulled downward by the current, not to quiescent periods.

3. Data

The primary phase of the SYNOP experiment began in June 1988 and ended in August 1990. The program involved many different institutions and included measurements from a wide variety of Eulerian and Lagrangian systems (e.g., Pickart and Watts 1990; Hogg 1992; Johns et al. 1995; Watts et al. 1995; Shay et al. 1995; Bower and Hogg 1996; Song and Rossby 1997). This paper will focus on observations made in the SYNOP Central array centered at 68°W (Fig. 2), and it will discuss measurements made by two types of moored instruments: temperature–pressure sensors attached to tall current meter moorings and inverted echo sounders. The study will also use hydrographic data collected in this region over the time period 1974–97; a total of 153 conductivity–temperature–depth profiles that reach at least 2000 dbar are available over the period. Moored temperature and pressure sensors and hydrographic CTD profiles are sufficiently well known as to need no further description. The IES is somewhat less well known; a detailed description of the instrument can be found elsewhere (e.g., Rossby 1969; Watts and Rossby 1977); however, a brief description is provided here.

An IES is a simple bottom-moored instrument that measures the round-trip travel time for a 10-kHz (or 12 kHz) sound pulse to travel up to the sea surface, reflect, and return to the instrument. This travel time measurement is not in and of itself particularly useful; however, numerous studies have shown that the combination of the IES travel time measurements with historical hydrography from a region can yield time series estimates of the full–water column profile of temperature, salinity, and density along with hydrography-based confidence limits (e.g., Meinen and Watts 2000; Watts et al. 2001). This IES analysis technique is called the gravest empirical mode (GEM) method (Meinen and Watts 2000). The GEM technique was developed some years after the completion of the SYNOP experiment, and it has not previously been applied to the IES data from the SYNOP study. Details of the GEM technique can be found in Meinen and Watts (2000); in brief, individual CTD temperature and salinity profiles from a particular region are used to simulate a round-trip travel time measurement at a particular level using the empirical equation of sound speed (Del Grosso 1974; Meinen and Watts 1997), and the individual CTD profile data are then sorted and smoothed on pressure levels as a function of travel time to produce lookup tables that can be combined with the IES travel time records to yield the full–water column profiles at each IES site.

The IES–GEM density profiles can be vertically integrated to produce dynamic height anomaly (ΔD) profiles, and differencing the ΔD profiles between neighboring IESs can yield geostrophic relative velocity profiles. The IES–GEM velocities could be used to test the mooring motion correction of the moored current meter velocities; however, as geostrophic estimates the IES–GEM velocities represent averages across the horizontal span between the observations sites (~40 km in SYNOP) while moored or profiling current meters make point measurements in the horizontal sense. As such, a velocity comparison is inappropriate

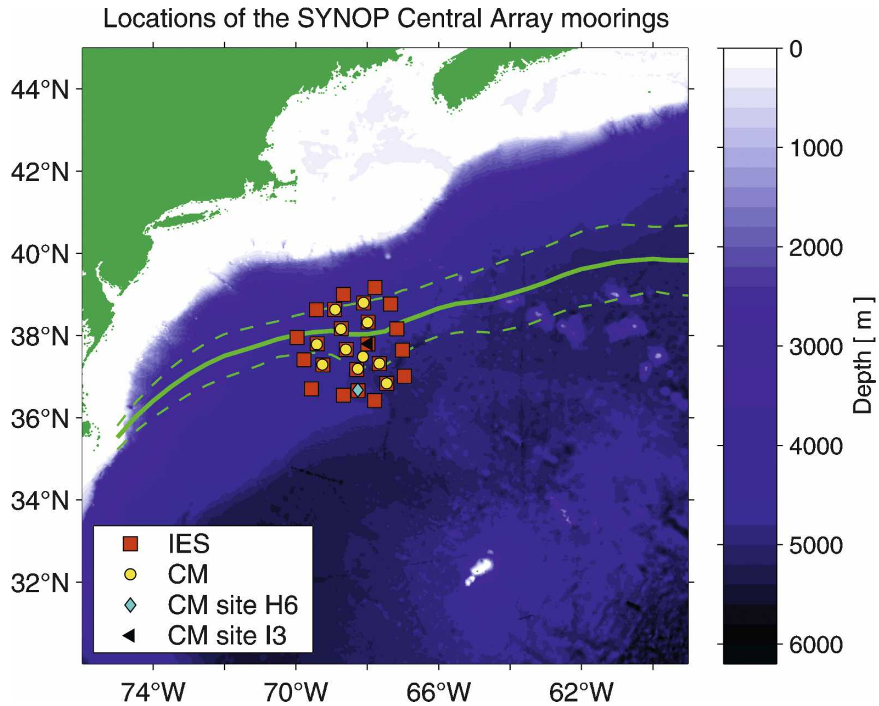

FIG. 2. Map illustrating the location of the moored instrumentation in the SYNOP Central array. Specific current meter moorings discussed in the paper are highlighted in the legend. Bathymetry is from the Smith and Sandwell (1997) dataset. Green lines are the mean (solid) and standard deviation (dashed) of the Gulf Stream position from 1982 to 1989 estimated using SST data (Lee and Cornillon 1996).

for this mooring motion accuracy study and it is beyond the scope of this paper.

4. Hydrographic simulation of mooring motion accuracy

Hall (1989) simulated mooring motion correction using 20 CTD profiles to estimate that temperature sensors moored in the Kuroshio at nominal depths of 250 and 500 m would be accurate to within 0.18°C when corrected for mooring motion that had a standard deviation of around 50 dbar (maximum deflections were near 340 dbar). A similar approach, using a far larger number of CTD profiles, is used herein to estimate the confidence limits at a wide range of depths for mooring motion corrected temperature data in the SYNOP region. Each CTD is used to simulate an individual temperature profile that could be observed on a particular day/time step at the mooring site. For brevity, only the Hogg (1986, 1991) technique will be explicitly simulated herein; however, the differences with other methods will be discussed throughout the text where appropriate.

For illustration of the errors inherent in mooring motion correction, 153 CTD profiles from the area of the SYNOP Central array will be used to simulate the profiles of temperature that might be observed by a large number of temperature sensors on a mooring (Fig. 3, left panel). The complete set of CTD profiles is appropriate for simulating the observations made at point location instruments like those on a mooring because the meandering of the Gulf Stream will expose the mooring to a wide range of different temperature profiles. We focus here on the depth range in which mooring motion typically results in the largest temperature changes—the main thermocline depth range from 300 to 1500 dbar. Also shown is the canonical profile of temperature (seventh-order polynomial) that was derived by Cronin et al. (1992) from the moored temperature and pressure data at the central and southern moorings from the SYNOP Central array (Fig. 3, left panel, thick black line). The Cronin et al. canonical profile will be used "as is" herein; all "fitting" of the canonical profile discussed hereafter refers only to vertical shifting of the Cronin et al. canonical profile to best fit the data points.

The minimum errors that are possible under the Hogg (1986, 1991) style of mooring motion correction can be determined by assuming zero vertical motion

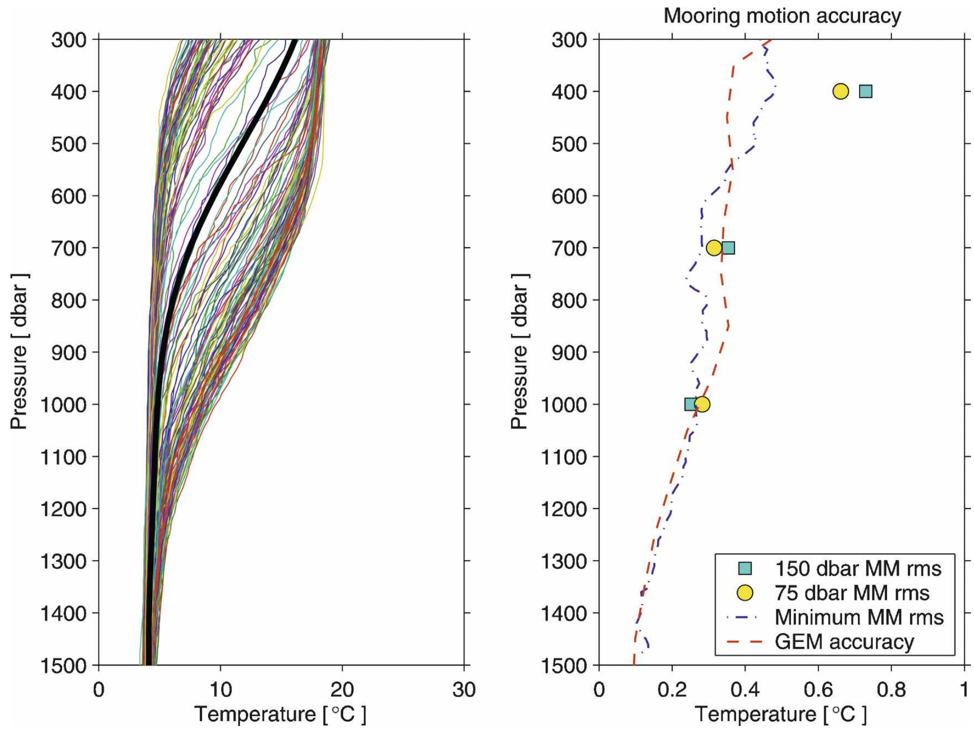

FIG. 3. Mooring motion accuracy based on the Monte Carlo–style testing described in the text. (left) 153 CTD profiles from the domain near the SYNOP array over the period 1974–97, illustrating the range of temperature profiles that might be observed at a location near the center of the SYNOP array. Also shown is the canonical mooring motion temperature profile derived by Cronin et al. (1992) for the central and southern mooring locations (thick black line). (right) Root-mean-squared (rms) errors resulting from the application of the canonical profile under either mooring motion with an rms value of 150 dbar (blue squares) or 75 dbar (yellow circles). Note that only those samples where the pressure deflection exceeded 50 dbar were used in the rms calculations for the 75- and 150-dbar mooring motion simulations. Also shown (blue dash–dot line) is the minimum accuracy that would be observed when no mooring motion is observed but the canonical profile is still forced onto the data. For comparison, the rms accuracy of IES–GEM temperature profiles is shown (red dashed line); however, note that the mooring motion correction profile is applied directly to the CTD data, not to the IES–GEM profiles.

and fitting the canonical profile directly to the observed temperature profile on each day. The high-wavenumber "noise" on the individual CTD profiles makes fitting the canonical profile difficult. The technique used herein was to first identify the pressure levels of the 10°, 12°, and 14°C isotherms on the canonical profile (seventh-order polynomial). These three pressure–temperature pairs were then least squares fit to the pressure–temperature profile from each CTD profile, yielding the "best" vertical offset required to fit the canonical profile through the pressures of the 10°, 12°, and 14°C isotherms on each particular CTD profile (which is itself simulating the observations that might be made by moored sensors on a particular day/time step).[1] By calculating the root-mean-square difference between the fit canonical profile temperatures and the actual temperature values at the same depths/pressures, the "error," or "confidence limit," associated with the canonical profile is quantified. For the purposes of the present study this calculation provides a minimum bound for the errors associated with using a canonical profile in the Hogg (1986, 1991) technique. When this no-flow (i.e., no mooring motion) error calculation is made for each of the 153 CTD temperature profiles, the rms temperature difference is about 0.10°C near 1500 dbar and it increases slowly up to about 0.30°C around 1000 dbar. The value is fairly constant between 600 and 1000 dbar, and then it increases to about 0.45°C above 500 dbar (Fig. 3, right panel, blue dash–dot line). The increase in error at shallower levels than 500 dbar is likely due to the influence of 18°C mode water on the south side of the Gulf Stream (e.g., Worthington 1959). While the

[1] Least squares fitting of the canonical profile at each 10-dbar level between 300 and 1500 dbar to the CTD profile was also tested, and the results were not significantly different.

Cronin and Watts (1996) modification to the Hogg (1986, 1991) technique was designed to eliminate precisely the type of error quantified in Fig. 3, it will be shown that the improvement is smaller than might be hoped when the deflections are larger than 50 dbar.

The addition of mooring motion to this simulation can only lead to error estimates larger than that of the minimum. To quantify the accuracy of mooring motion corrected temperatures a Monte Carlo–style approach was taken. The sampling proceeded as follows: one of the 153 CTD temperature profiles was selected at random, and a specific estimate of pressure deflection was selected, also at random.[2] The pressure variations were modeled as Gaussian-distributed values with rms values similar to the observed pressure deflections. The shallowest temperature–pressure sensor on the I3 mooring (see Fig. 2) had a nominal depth of about 400 dbar, and an rms pressure variation of about 75 dbar. The shallowest instrument on the H6 mooring (see Fig. 2) also had a nominal depth of 400 dbar; however the rms pressure variation was about 150 dbar. Gaussian distributions with each of these two rms values were modeled to provide the random mooring motion for the Monte Carlo–style evaluation. Once the random pressure deflection δp had been found for a particular realization, the actual temperatures were extracted from the CTD temperature profile at pressures equal to δp plus the nominal pressures of 400, 700, and 1000 dbar. The canonical seventh-order polynomial profile of Cronin et al. (1992) was then fit to the three temperature–pressure pairs in a least squares sense to find the optimum vertical shift of the canonical profile, and the predicted temperature at each of the nominal pressures was determined by interpolating or extrapolating with the canonical profile. This was repeated for 10 000 random combinations of CTD temperature profiles and mooring motion, and the rms differences between the mooring motion corrected temperatures and the true temperatures at the nominal pressures were calculated (Fig. 3, right panel). In what follows, only those samples where the pressure deflection is greater than or equal to 50 dbar are used, as the various mooring motion correction families all have no errors when the pressure deflection approaches zero (assuming the Cronin and Watts modifications are used for the Hogg technique). At the nominal pressure of 1000 dbar the rms differences for the Monte Carlos simulations with either 75- or 150-dbar Gaussian mooring motion are essentially equal to the minimal temperature error associated with the canonical profile (0.282°, 0.252°, and 0.264°C, respectively). At the nominal pressure of 700 dbar the rms differences for the mooring motion corrected data exceed the minimum error by ~20% (0.315°, 0.354°, and 0.283°C, respectively). At the nominal pressure of 400 dbar the rms differences are the largest, with the rms differences for the mooring motion corrected data exceeding the minimum error by ~40% (0.662°, 0.730°, and 0.483°C, respectively). The values at the 400-dbar level exceeded by more than a factor of 3 the 0.18°C accuracy limits determined by Hall (1989) for the sensors at the 250- and 500-m levels in the Kuroshio. The Hall (1989) measurements in the Kuroshio were from 35°N, only slightly south of the latitude of the SYNOP array, and the vertical gradient of temperature across the thermocline is fairly similar at that latitude in the Kuroshio to the gradient in the Gulf Stream in the SYNOP region. As such the values found by Hall (1989) should be comparable to the values derived herein when the pressure deflections are roughly equal. The fact that the values are significantly larger here may reflect the larger database of CTD profiles (153 versus 20) that was used in the present study.

For comparison to the corrected mooring confidence limits, the estimated error bars on IES–GEM predicted temperatures are significantly smaller at the 400-dbar level, while they are roughly equal at the 700- and 1000-dbar levels (Fig. 3, right panel, red dashed line). This suggests that, based on this simulation, moored temperature sensors at 400 dbar in the Gulf Stream corrected for mooring motion will be less accurate than temperatures estimated by an IES whenever the mooring exhibits vertical motion of at least 75 dbar (rms value), while sensors at 700 and 1000 dbar will have roughly similar accuracy limits to what an IES would provide. It is important to note, however, that the mooring motion correction errors illustrated in Fig. 3 apply only for events where the moored sensor has deflected a significant amount (greater than 50 dbar) away from the nominal level. Nevertheless, since the larger pressure deflections are generally associated with large temperature or velocity changes, it is reasonable to assume that the variability in a quantity like horizontal temperature flux will be influenced by accuracy limits similar to those shown in Fig. 3.

5. An example illustrating mooring motion correction accuracy

In SYNOP, typical mooring motion amplitudes ranged from rms values of 75–150 dbar, with maximum

[2] It could be argued that choosing a temperature profile at random and a pressure deflection at random is unwise since variations in one might be correlated to the other. While this is certainly true at times, any pressure deflection events that are due to barotropic velocities, which can be quite strong in the Gulf Stream, can indeed be uncorrelated to the baroclinic temperature changes.

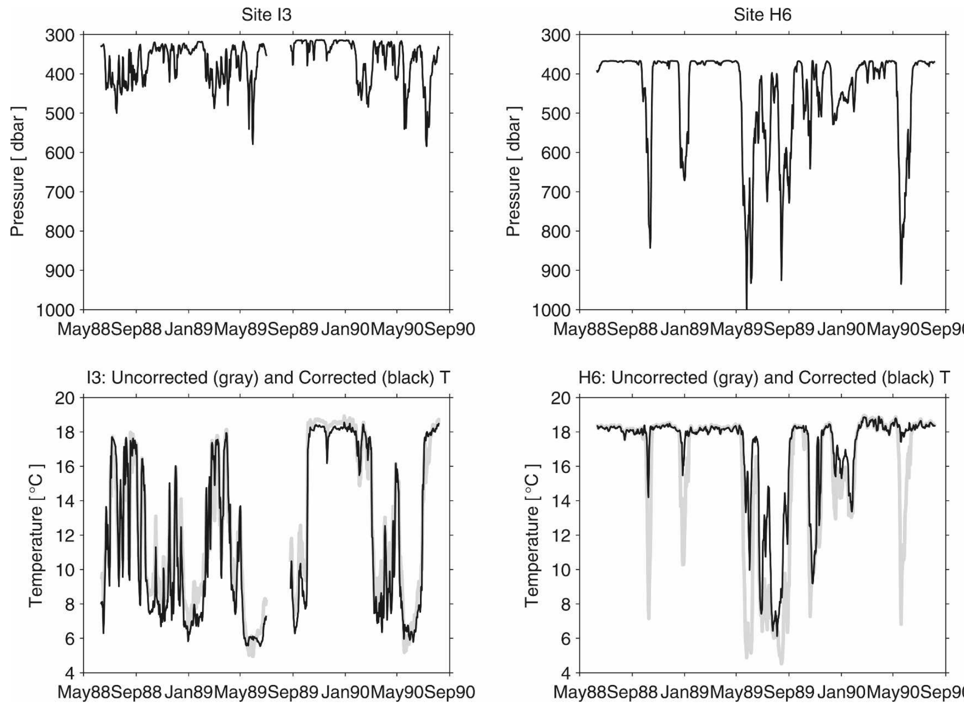

FIG. 4. Examples of mooring motion and the temperature signals associated with it. (top) The observed pressure records for instruments moored at a nominal 400-dbar level at sites (left) I3 and (right) H6. See Fig. 1 for locations of these two moorings. (bottom) The uncorrected temperature records (gray) and the mooring motion corrected temperature records (black) produced by Cronin and Watts (1996).

deviations of up to 600 dbar. The temperature fluctuations associated with these large deflections can be quite large. Figure 4 illustrates actual pressure records from the top instruments on two of the SYNOP moorings that are typical for the region. Note that the pressure deflections are often event-driven, not random. This is most evident in the record from site H6 (Fig. 4, top right), where the instrument moved little if at all from February to April 1989, and then moved rapidly deeper by about 600 dbar and persisted at significantly higher pressures until it returned to the nominal pressure for a short period in September 1989. The record from site I3 (Fig. 4, top left), which was close to the center of the SYNOP array and was near to the mean position of the Gulf Stream core during these 2 yr, shows deflections that are smaller in magnitude but more frequent, with the pressure sensor indicating the nominal pressure only for short periods throughout the record. Note that these moorings had essentially the same design.

The temperature variations observed by these two sensors often exceed 5°C and at times exceed even 10°C (Fig. 4, lower panels). Much of this signal is due to the strong temperature front of the Gulf Stream meandering back and forth past the mooring. Some of it, however, is due to the mooring motion indicated by the pressure records (Fig. 4, upper panels). Comparing the mooring motion corrected records produced by Cronin and Watts (1996) to the uncorrected records (black and gray lines, respectively, in the lower panels of Fig. 4), one can see that while the majority of the temperature variability is associated with the motion of the temperature front, there are strong temperature variations exceeding 5°C that are attributable to the pull down of the mooring by the strong current. In May 1990, for example, there is a mooring motion event that results in a spurious 12°C temperature change in the 400-dbar temperature sensor at site H6 that is completely removed by correcting for mooring motion (Fig. 4, lower right panel). The question this leads to is, how accurately can these temperature records be corrected?

It is possible to directly compare the mooring motion corrected temperature records from the moorings that were produced by Cronin and colleagues (Cronin et al. 1992; Cronin and Watts 1996) to the IES–GEM data; however, more germane to the understanding of the accuracy of mooring motion correction is to compare the *correction* itself (i.e., the difference in temperature applied to the measured values to correct for mooring motion) to the temperature difference between the observed and nominal pressures from the IES–GEM data. This allows for the isolation of the correction itself, and

TABLE 1. Rms and standard deviation (std) of the differences between the mooring motion *correction* from Cronin and Watts (1996) and the correction that would be applied based on the coincident IES–GEM data. Values are shown for the full records at each site as well as for only those periods when the sensors had moved deeper than their nominal level by greater than 75 or 150 dbar.

	Rms difference	Std difference
Site I3, nominal 400 dbar		
Complete record	0.109°C	0.109°C
P deflections > 75 dbar	0.114°C	0.114°C
P deflections > 150 dbar	0.186°C	0.188°C
Site H6, nominal 400 dbar		
Complete record	0.272°C	0.266°C
P deflections > 75 dbar	0.477°C	0.434°C
P deflections > 150 dbar	0.564°C	0.515°C

provides an estimate of the differences introduced because of the departure of the canonical profile used in mooring motion versus the profile from the IES–GEM data. Table 1 documents the observed differences for the top sensors on the moorings (see also Fig. 5).

The differences in mooring motion corrections are similar in magnitude to the estimated mooring motion accuracies derived via the hydrographic testing (Fig. 3), and they are clearly a loose function of the magnitude of the pressure deflection (see Fig. 5, upper and lower panels). However, there are counterexamples where largish pressure deflections do not yield large correction differences (e.g., see early January 1990 at site I3; Fig. 5, left panels). In general the correction differences at site I3, near the core of the Gulf Stream, are smaller than those at the south flank, even for pressure deflections of comparable size. In fact, this leads to one of the more important results in this paper. As noted in the hydrographic tests earlier, from above 500 dbar to the south of the core of the Gulf Stream there are temporally varying amounts of 18°C mode water (e.g., Worthington 1959). The sporadic appearance and disappearance of thick mode water layers above 500 dbar leads to large discrepancies between the canonical profile, which by the nature of its derivation must be a quasi-mean estimate of the vertical structure through this depth range, and the true temperature profile at any time. Extrapolation upward from a top instrument into a mode water layer using either family of correction techniques (canonical profile or $\delta T/\delta z$ versus T) will likely lead to significant errors and should be avoided at the mooring design and planning stage.

The correction comparisons at site I3, which is near the mean location of the core of the Gulf Stream and which does not generally have thick mode water layers,

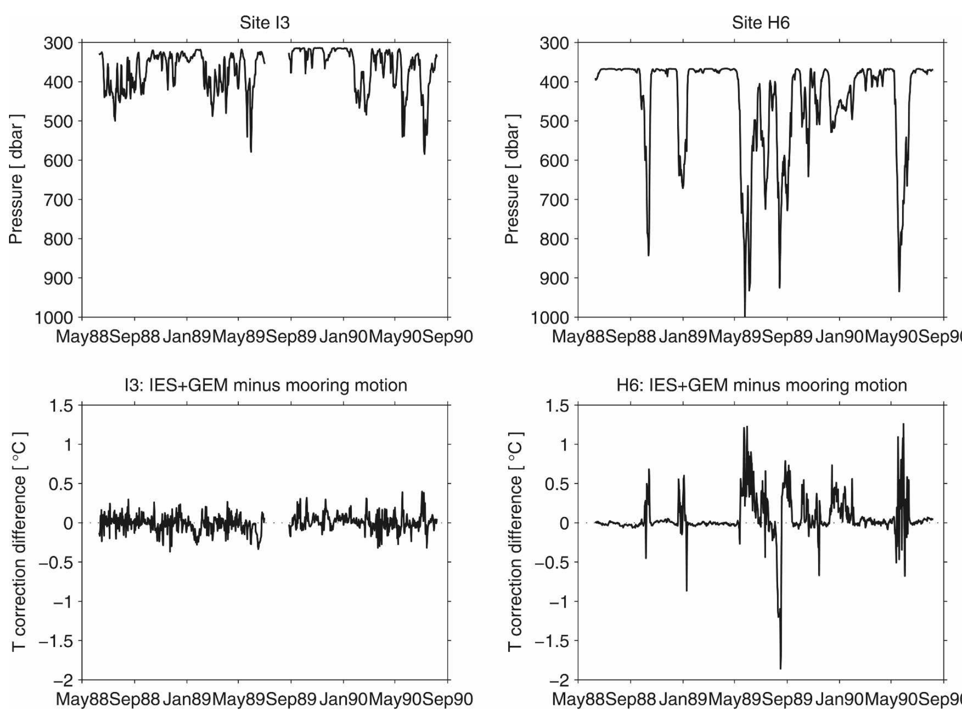

FIG. 5. (top) Pressure records from the nominal 400-dbar instruments on the moorings at sites I3 and H6. (bottom) The difference between the temperature correction that would be suggested by the IES–GEM technique vs the temperature correction suggested by the canonical profile used by Cronin and Watts (1996).

still indicate that the differences in the corrections are a function of the magnitude of the pressure deflection although the relationship is less clear than for site H6. For example, the large pressure spikes in May and July 1990 at I3 correspond to the largest positive temperature correction differences (Fig. 5, left panels). This suggests the perhaps unsurprising result that the use of a canonical profile to extrapolate upward from the top instrument yields progressively worse results when the pressure deflections increase in size. The change in magnitude of the correction differences (Table 1) for deflections greater than 75 dbar and greater than 150 dbar is nothing like a factor of 2, and the offsets are clearly going to be event-specific (see Fig. 5); however, it is clear that a "stiffer" mooring design will yield smaller uncertainties for the mooring motion corrected temperatures, regardless of whether the mooring is located in a mode water region or not.

6. Conclusions

The results of these analyses indicate that mooring motion corrections using the Hogg (1986, 1991) canonical profile technique yield accuracy levels that are highly sensitive to the presence of mode water layers and suffer particularly at the upper level from extrapolation upward from the shallowest sensor. For all of the other techniques discussed herein (Hall 1989; Cronin and Watts 1996; Fillenbaum et al. 1997; Johns et al. 2005), the extrapolation upward problem, and hence the herein described confidence levels, persist regardless of technique. Furthermore, these results will also apply to the more modern profiling mooring sensors, where the upper stopper on the profiling wire will deflect downward, altering the profiling range, as well as the more traditional fixed sensors. For sensors below the uppermost instrument, the methodological improvements developed by Cronin and Watts (1996) and the dual-integration technique inherent in the methods of vertical temperature gradient techniques (Hall 1989; Fillenbaum et al. 1997; Johns et al. 2005) should yield significant improvement over the numbers shown herein, although the direct comparison of the corrections derived from the IES–GEM versus the mooring motion corrections (Fig. 5, Table 1) suggests that under strong mooring motion the improvements implemented by Cronin and Watts (1996) resulted in less reduction in error than might have been hoped.

Based on the results shown herein, for rms deflections around 75–150 dbar, the accuracy of the corrected temperature values during strong pressure deflections ranges from just over 0.2°C for a sensor with a nominal level of 1000 dbar to 0.6°–0.7°C for a sensor with a nominal level of 400 dbar. For nominal levels shallower than 500 dbar, the IES–GEM temperature estimates are likely to be more accurate than the corrected moored sensor when the mooring is deflecting, while for deeper levels the accuracy is comparable. Variations in other current regimes with similar thermal gradients, such as the Agulhas or Kuroshio, are expected to see similar accuracies for equal pressure deflections. Accuracy of corrected temperatures from moored temperature–pressure sensors where the moorings are in mode water regions can probably be improved by adjusting the mooring design to ensure that the top sensor will not dip below the base of the mode water layer.

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