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Observed Ocean Bottom Temperature Variability at Four Sites in the Northwestern Argentine Basin: Evidence of Decadal Deep/Abyssal Warming Amidst Hourly to Interannual Variability During 2009–2019

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Key Points:
- Decade-long hourly records of ocean bottom temperature demonstrate a surprising amount of variability at a range of time scales
- Two deep/abyssal Argentine Basin sites (>4,500 m) exhibit significant warming trends of 0.02°C ± 0.01°C per decade over the period 2009–2019
- Sampling at least once a year is necessary to capture deep/abyssal temperature trends with at least ±50% accuracy (95% confidence limits)

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Abstract Consecutive multiyear records of hourly ocean bottom temperature measurements are merged to produce new decade-long time series at four depths ranging from 1,360 to 4,757 m within the northwest Argentine Basin at 34.5°S. Energetic temperature variations are found at a wide range of time scales. All sites exhibit fairly linear warming trends of approximately 0.02–0.04°C per decade over the period 2009–2019, although the trends are only statistically different from zero at the two deepest sites at depths of ~4,500–4,800 m. Near-bottom temperatures from independent conductivity-temperature-depth profiles collected at these same locations every 6–24 months over the same decade show roughly consistent trends. Based on the distribution of spectral energies at the deepest sites and a Monte Carlo-style analysis, sampling at least once per year is necessary to capture the significant warming trends over this decade to within 50% error bars at a 95% confidence limit.

Plain Language Summary Quantifying global temperature changes requires observations of the full atmosphere-ocean system; however, long-term, continuous observations of temperature deep within the ocean are exceedingly rare. This study presents several decade-long records of hourly temperature measurements from moored sensors 1 m above the seafloor in the northwestern Argentine Basin within the western South Atlantic Ocean. These sites, which range in depth from 1,360 to 4,757 m, show energetic temperature variations on daily to interannual time scales. The intensity of these variations is higher at the two shallower sites than is observed at the two deeper sites. In addition to the daily to interannual variations, long-term warming trends are also detected over the period 2009–2019 at all four sites. The study also uses the hourly records at the two deeper sites to estimate how frequently the temperature at these locations must be observed in order to estimate the long-term trends accurately.

1. Introduction

Temperatures on the Earth's surface vary on many different time scales, responding to changing forcing from solar insolation, atmospheric circulation, ocean dynamics, and Earth's orbital motions. In addition to natural temperature variations at periods of days to seasons to millennia, a global anthropogenic warming signal has been well documented over the past several decades based on robust observations across the planet (e.g., Intergovernmental Panel on Climate Change [IPCC], 2013). Temperature observations within the ocean show similar multidecadal warming trends in the upper ocean (e.g., Giglio & Johnson, 2017; Lyman et al., 2010; Wu et al., 2012) and in the deep ocean (e.g., Desbruyères et al., 2016; Johnson et al., 2014; Purkey & Johnson, 2010). However, the number of temperature observations in the ocean is quite small in comparison to the number of observations available on land. Measuring ocean temperature is important, as water has more mass and a higher heat capacity than has air, so the oceans are able to store vastly more heat than the atmosphere. Roughly 90% of the heat absorbed by the Earth goes into the oceans (e.g., Meyssignac et al., 2019; Rhein et al., 2014). The ocean surface has been measured in detail for the last few decades from both satellites and surface drifting buoys (e.g., Reynolds et al., 2002; Zhang et al., 2009), while most of the deeper ocean temperature measurements have historically been made from infrequent ship surveys. Common shipboard measurements include expendable bathythermograph (XBT) transects from cargo vessels, which collect temperature profiles within the upper ~700–800 m along a few repeated lines (e.g., Goni et al., 2010; Molinari, 2004; Rossby et al., 2005; Sprintall & Meyers, 1991), and repeated conductivity-temperature-depth (CTD) sections collected from dedicated research vessels, which generally capture temperature data throughout the full water column along even fewer lines (e.g., Mercier et al., 2015; Molinari et al., 1998; Purkey & Johnson, 2010). A significant newer addition to the ocean observing system has been the Argo float array, which captures CTD-equivalent observations above 2,000 m with 3,000–4,000 floats worldwide (e.g., Gould et al., 2004; Jayne et al., 2017; Roemmich & Owens, 2000).

While these ocean-observing systems have been providing valuable temperature data for a decade or more, they all have one limitation—irregular spatiotemporal coverage. Standard Argo floats provide observations every 10 days, but the floats move where the ocean currents carry them, so at any given fixed location, the Argo observations can be far less frequent (e.g., Roemmich et al., 2009, 2019). Furthermore, at present, Argo only captures the upper 2,000 m of the ocean, leaving the deeper waters unobserved (developing enhancements to the Argo array will ultimately sample from the surface down to 4,000–6,000 m; Roemmich et al., 2019). CTD sections collected by research vessels generally capture the full water column, but these sections are quite expensive, so they are infrequently repeated—with short sections sampled quarterly, semiannually, or annually (e.g., Szuts & Meinen, 2017; Valla et al., 2018; van Sebille et al., 2011) and trans-basin sections typically observed only once per decade (e.g., Purkey & Johnson, 2013; Sloyan et al., 2019; Talley et al., 2016). A strength of the XBT data sets is that some of these observations extend back an impressive 40–50 years (e.g., Molinari, 2011); however, the XBTs measure temperature only above 800 m depth, and they are typically repeated quarterly or less frequently (e.g., Goni et al., 2019). Due to their irregular sampling, the changes that these data sets capture are subject to aliasing of variability at time scales shorter than the sampling period.

In order to quantify the errors associated with aliasing of higher frequency signals into crucial temperature records in the ocean, continuous, high frequency observations are needed. However, the challenge is that lengthy highly temporally resolved temperature records in the deep ocean are rare. This study presents, for the first time, unique decade-long records of hourly temperature measurements from four sites just above the ocean bottom in the Argentine Basin at 34.5°S (Figure 1 and Table 1), at depths ranging from 1,360 to 4,757 m. These hourly temperature records, collected as part of a long-term project to observe the western boundary current variations associated with the meridional overturning circulation in the South Atlantic (e.g., Meinen et al., 2012, 2013, 2017, 2018), represent an ideal new data set for determining the range of time scales at which near-bottom temperature varies over a full decade-long period from 2009 through 2019. This observational data set can also be used to quantify the errors in trends (e.g., Garry et al., 2019) that one might estimate over this 10 year period based on infrequent “snapshot” observations rather than hourly data.

2. Data and Methods

The Southwest Atlantic Meridional Overturning Circulation (SAM) project first deployed four pressure-equipped inverted echo sounder (PIES) moorings along 34.5°S in March 2009 (e.g., Meinen et al., 2017). The inverted echo sounder has been around for about 50 years (e.g., Rossby, 1969; Watts & Rossby, 1977) and measures vertical acoustic travel times. The addition of a bottom-pressure sensor greatly expanded its capabilities (e.g., Watts et al., 1995), as did the development of the gravest empirical mode method for analysis and interpretation of PIES travel time data (e.g., Meinen & Watts, 2000). When deployed, the PIES is anchored approximately 1 m above the seafloor. The addition of the pressure sensor provided an unexpected further advantage—as an integrated temperature sensor is necessary to convert the engineering units in the pressure sensor into physically meaningful units (e.g., Watts & Kontoyiannis, 1990). Tracey et al. (2017) recently demonstrated that the temperature data collected by the PIES was precise (to within 0.0002°C), that the PIES temperature sensor lags the ambient ocean temperatures by only 1 hr (because the sensor is physically located inside a glass sphere), and that any record-length mean bias (absolute accuracy) can be corrected using simultaneous CTD measurements at the site. The instruments used by Tracey et al. (2017) were all PIES that were additionally equipped with a single-point acoustic current meter located 50 m above the PIES (called a CPIES). Because those current

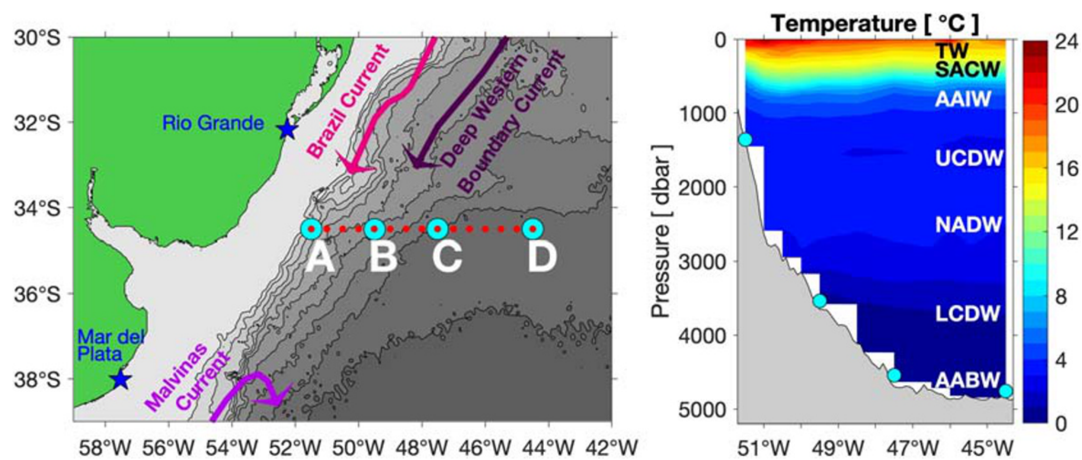

Figure 1. (left) Map indicating the locations of the four PIES moorings (large cyan circles) and the nominal locations of the CTD profiles collected on routine research cruises (red dots). PIES site names are denoted by large white letters. Bottom topography from the Smith and Sandwell (1997) data set is shown as gray-filled contours with a 500 m contour interval. Simple schematic arrows indicating the locations of the nearby major ocean currents are included to illustrate the array position relative to the large-scale flow features; schematic modified from Valla et al. (2018). (right) Vertical section of temperature (averaged from four CTD sections during 2009–2012) along the PIES mooring line. PIES locations are shown as cyan circles. Nominal central depths of key water mass layers denoted by acronyms following Valla et al. (2018). TW = Tropical Water; SACW = South Atlantic Central Water; AAIW = Antarctic Intermediate Water; UCDW = Upper Circumpolar Deep Water; NADW = North Atlantic Deep Water; LCDW = Lower Circumpolar Deep Water; AABW = Antarctic Bottom Water.

meters had an independent temperature sensor within them, those investigators could make direct comparisons between the two temperature sensors, which further quantified the accuracies of the PIES temperature sensor.

The PIES sites maintained as part of the SAM project (Figure 1 and Table 1) do not have the additional current meter; however, they are otherwise identical to those used by Tracey et al. (2017), so the accuracies derived in that study are equally relevant to the temperature sensors in the SAM instruments. PIES deployments are generally for a period of 36–54 months on a single set of batteries, and at the end of that period, the PIES are recovered, refurbished, and redeployed. Over the approximately 10 year period of the SAM study to date (2009–2019), each of the four sites has had three successive deployments and recoveries. The original instruments were all deployed over the course of about a week on the same deployment cruise in March 2009; however, they were not all recovered and redeployed during the same cruises, so the records at some sites are shorter than others by about 6–12 months. At Site B only one near-bottom temperature record is available, because the first instrument was damaged during recovery and the third PIES failed to surface at the end of the deployment. The SAM experiment is ongoing, so additional data are presently being collected at all of these sites.

The absolute accuracy of the temperature sensors inside the PIES has traditionally not been carefully calibrated at the factory, as absolute accuracy is not essential to the pressure unit conversion. As noted earlier, Tracey et al. (2017) demonstrated that the absolute accuracy of the sensor can be calibrated using concurrent

Table 1
Locations of the PIES Moorings, Along With Basic Statistics of the Observed Temperatures (Maximum, Minimum, Record-Length Mean, Temporal Standard Deviation, and Integral Time Scale) and the Trend (Linear Slope Fit) of Each Record Along With the 95% Confidence Limit Accuracy for the Trend

Site	Latitude (°S)	Longitude (°W)	Depth (m)	Maximum temperature (°C)	Minimum temperature (°C)	Mean temperature (°C)	Standard deviation (°C)	Integral time scale (day)	Trend (°C per decade)	Trend 95% confidence limits (°C per decade)
A	34.5	51.5	1,360	3.586	2.899	3.200	0.071	38	+0.041	0.066
B	34.5	49.5	3,535	1.136	0.112	0.542	0.181	27	+0.018	0.097
C	34.5	47.5	4,540	0.277	0.185	0.219	0.008	349	+0.022	0.013
D	34.5	44.5	4,757	0.271	0.209	0.241	0.007	343	+0.020	0.012

CTD profiles. As part of the SAM project, CTD observations are collected at each of the PIES sites nominally every 6 months from the surface down to 10–20 m above the seafloor (e.g., Valla et al., 2018). Weather and/or equipment difficulties have in practice led to gaps of longer periods between CTD observations at some sites, particularly at the deeper sites in the mid-2010s. Despite these issues, all deployments have several CTD profiles that can be used for this absolute calibration with the exception of the second deployment at Site C. For that particular record, the absolute calibration of the temperature sensor was done by comparison to the data immediately before and after the record from the bounding deployments. Because the calibrations here are of only the absolute accuracy for the sensors, the calibration corrections are constant in time for each PIES deployment (i.e., only a constant offset is added to the hourly temperature record to best least squares fit the concurrent nearest-bottom CTD temperature values). As such, the temporal variability of the CTD data is still independent of the temporal variability of the PIES temperature records.

Once the individual hourly PIES temperature records were calibrated, the subsequent deployments at each site were merged to create a single hourly temperature record at each site over the full time period. Two other minor notes are as follows: (1) the first ~12 hr of the temperature record for each PIES deployment are removed as the instruments are equilibrating after being at the surface; and (2) during communication with a research vessel the instrument can warm up if the internal vacuum is poor, so removal of short ~5–10 hr temperature spikes from individual records can be necessary during the well-documented times when the instrument was visited by a ship. All temperature values presented herein from the PIES moorings are "in situ temperature," rather than potential temperature. Since the PIES do not simultaneously measure salinity, conversion from in situ to potential temperature cannot be done. Tests calculating potential temperature assuming a constant salinity were completed, and all results for temperature variability/trends presented herein are not sensitive to having used in situ temperature versus potential temperature.

3. Results and Discussion

The PIES temperature records all show energetic variations at many time scales, particularly at the shallower sites, with much smaller temporal standard deviations at the two deeper sites (Figure 2 and see also Table 1). The independent CTD data exhibit variability that spans nearly the same range as the PIES records (Figure 2). The estimated dominant time scales of variability (integral time scale; Emery & Thomson, 1997) at the two shallower PIES locations, Sites A and B, are 27–38 days. This illustrates the impacts of mesoscale variability on the near-bottom temperatures at these sites, particularly at Site B, which is located roughly in the core of the weakly sheared southward flowing Deep Western Boundary Current at this latitude (e.g., Meinen et al., 2017; Valla et al., 2018). At the deeper locations, Sites C and D, the dominant time scale is approximately 1 year, suggesting that even 4,500+ m below the sea surface the seasonal progression of the Earth around the Sun has a significant impact on the ocean temperatures.

Variance-preserving spectra (e.g., Emery & Thomson, 1997) of the temperature records (Figure 2) display energetic variations at a broad range of periods around 10–365 days, with both Sites A and D also showing a small but significant energy peak at a 12 hr period (i.e., semidiurnal). Tracey et al. (2017) also found a semidiurnal signal in some of their ocean bottom temperature records in the Drake Passage, so this is not entirely surprising. They attributed these signals to internal tides interacting with the rough topography, while they argued that sites not exhibiting this semidiurnal variability were in regions of relatively flat topography. For the sites in the SAM array described herein, none of the locations are known to be near particularly rough topography; however, the bathymetric data available in the Argentine Basin may not be as detailed as data available within Drake Passage. Beyond the semidiurnal peak, there are no clear or consistent "peaks" in the four variance-preserving spectra of these temperature records (Figure 2), suggesting that the observed deep/abyssal temperature variability likely results from many different sources (e.g., topographic Rossby waves and tides). With only four locations, and with longitudinal spacing of 200–300 km between moorings, it is difficult to infer the physical characteristics of the flow features associated with any given temperature event. The records are not significantly correlated with one another, with correlation coefficients $r < 0.25$ for all pairs except between Sites C and D, which have $r = 0.58$ (which is still not significantly different from zero, given the long integral time scale at those two sites—see Table 1). Coherence spectra between the various sites (not shown) also suggest a lack of coherence, with values generally below 0.5 aside from the overall

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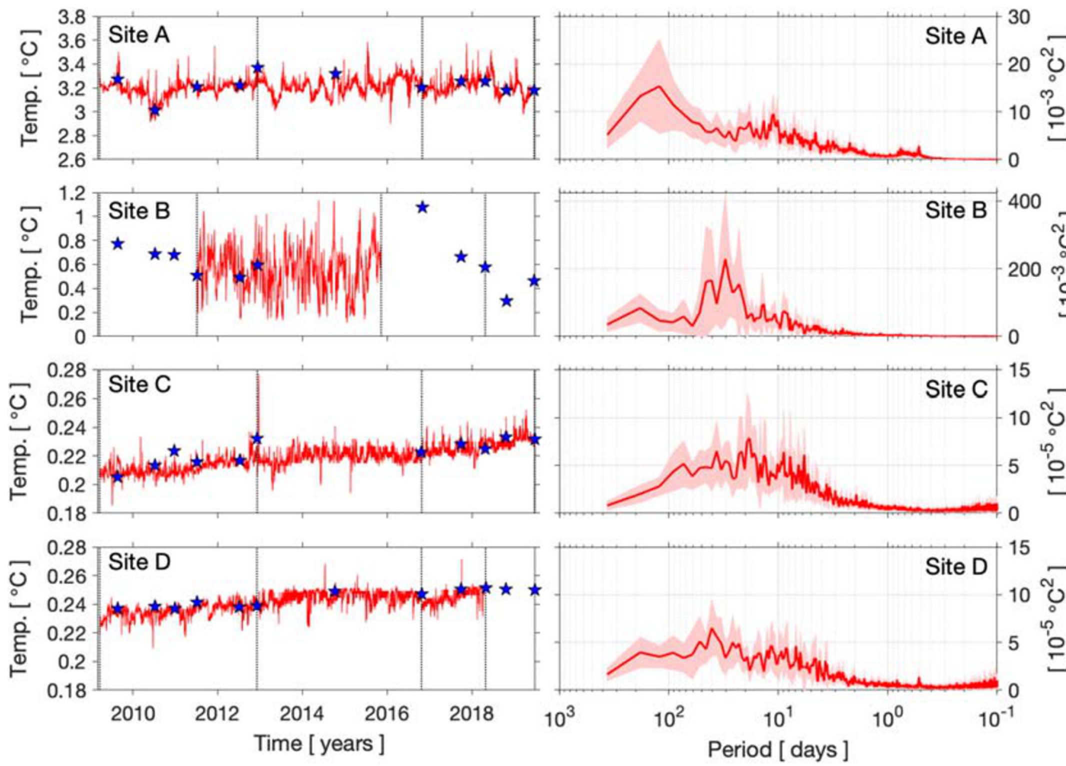

Figure 2. (left column) Merged temperature records at each of the four PIES sites (red lines), along with the CTD measured temperatures (blue stars). Vertical dotted lines indicate the starts of the individual 3–4 year-long PIES records at each site. Note that different vertical scales are used for the top two panels (1.2°C total range) and the bottom two panels (0.1°C total range). (right column) Variance-preserving temperature spectra (solid lines) with 95% confidence limits (shading). Note the different *y*-axis ranges and orders of magnitudes on the spectra panels. Spectra were calculated using Welch's averaged periodogram method (e.g., Emery & Thomson, 1997) using a 1 year window, allowing a half-year of overlap.

record-length trends. This lack of correlation and coherence demonstrates that most or all of the energetic near-bottom ocean temperature variability in the region has spatial scales smaller than 200–300 km.

The record-length trends over 2009–2019 at all four sites are positive, consistent with the sign of the well-documented planetary-scale global warming trend (e.g., IPCC, 2013; Lyman et al., 2010). The rates of increase, determined via least squares linear fits to the hourly data, are approximately equal at the three deepest locations (Sites B, C, and D), with the trend at the shallower Site A being about 100% larger (Table 1). The PIES temperature trend at Site A of +0.041°C per decade is quite close to the large-scale Argentine Basin value estimated using Argo for roughly this depth range (+0.044°C per decade) as found by Giglio and Johnson (2017). It must be noted, however, that even with a decade of nearly continuous hourly data, the trend estimated using the PIES Site A data is not significantly different from zero in a statistical sense, with the estimated 95% confidence limits (e.g., Emery & Thomson, 1997) on the trend being 0.066°C per decade. This leads to two immediate questions. First, why is the trend from the hourly PIES record nearly equal to the basin-wide trend previously estimated from Argo data? Second, if a decade of hourly observations at Site A cannot establish a statistically significant trend, how could a meaningful ocean temperature trend be observed using irregular snapshot observations every quarter/year/decade as are commonly collected from ship sections? In theory, if a trend persisted for multiple decades, and the energy at the higher frequencies remained approximately constant, the trend would become easier and easier to identify the longer the record became. However, the Argo data set analyzed by Giglio and Johnson (2017) was also about a decade in length (2006–2015), so that does not explain how the irregular in space/time Argo data could successfully quantify the same trend as an hourly continuous record. The explanation mostly likely relates to the spatial averaging of the Argo data used by Giglio and Johnson (2017). These had been objectively mapped and averaged onto a monthly 1° × 1° grid. The spatial/temporal averaging and smoothing associated with the

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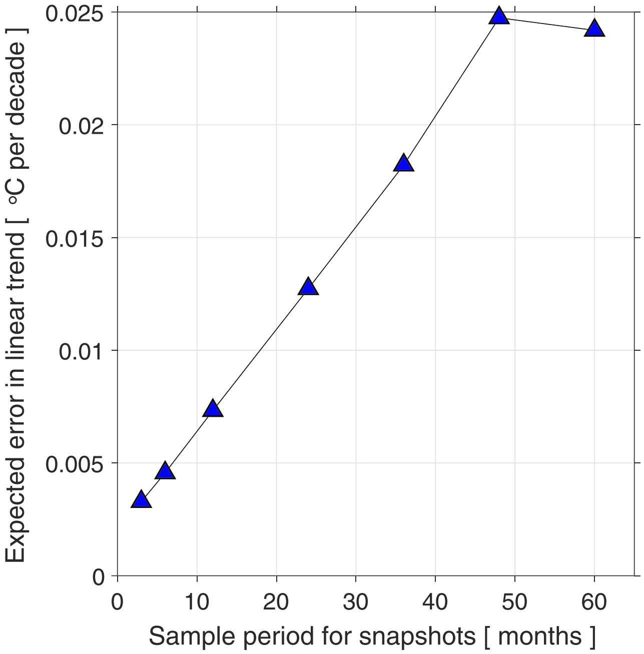

Figure 3. Estimated accuracy (error bar) that can be expected for a calculated decadal trend at Site C if calculated using snapshot observations at the indicated sample period. The downturn at 60 months is an artifact that results from insufficient realizations at that sample period, given the temperature record used for the testing is only 10 years (120 months) long.

objective mapping must be removing some of the highest frequency variability, yielding a robust estimate of the trend despite the temporal irregularity of the original observations. The results presented herein, however, do suggest that the trend error bar determined as a basin-averaged spatial standard deviation by Giglio and Johnson (2017), ± 0.001°C per decade, may underestimate the true temporal trend error bar.

Examination of the record-length trends at the three deeper locations (Sites B, C, and D) reveals warming trends of approximately +0.02°C per decade at all three sites, although the trend at Site B is not statistically significant (Table 1), likely due to both a much higher amplitude of high frequency variability (see Figure 2) and a shorter record at that location. These trends of +0.02°C per decade are essentially the same as those that have been found using repeat hydrography sections to the north on the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) A10 line along 30°S and to the east on the GO-SHIP A16 line along roughly 25°W (e.g., Johnson et al., 2014; Purkey & Johnson, 2013). The trend is also similar to that observed from infrequent CTD sections through the Antarctic Bottom Water layer in the Vema Channel just to the north at about 31°S (Morozov et al., 2018) and farther north within the Brazil Basin (Herrford et al., 2017). The trend estimate of +0.02°C per decade from the GO-SHIP data spans a much longer time period (1989–2014; Johnson et al., 2014), as does the estimate of +0.009°C per decade from the sections in the Vema Channel (2002–2017; Morozov et al., 2018) and the estimate of +0.025°C per decade from the sections in the western Brazil Basin (1989–2014; Herrford et al., 2017). While the trend observed in the SAM PIES temperature records is essentially the same as what has been observed from irregular ship sections in the region in the past, the hourly nature of the observations collected by the PIES results in a much more robust statistical estimate for the accuracy of the estimated trend (Table 1). Both the Sites C and D PIES have an estimated accuracy of ±0.012–0.013°C per decade over the time period 2009–2019. The concurrent CTDs at Sites C and D show similar trends, 0.018°C ± 0.019°C and 0.016°C ± 0.006°C per decade, respectively.

Beyond providing more robust statistical accuracy estimates for the deep ocean trends, the long hourly records from the PIES are also useful for examining the accuracy with which one might estimate a trend using infrequent snapshot observations (e.g., quarterly, or annual, ship sections). A Monte Carlo-style analysis (e.g., Emery & Thomson, 1997) of the longest temperature record, Site C, was performed using 2,000 repeated subsamplings of the record at each of 3, 6, 12, 24, 36, 48, and 60 month subsample periods. For example, a random hour in the first 3 months of the record was selected, and then the record was subsampled every 3 months from that hour until the end of the record, with the resulting snapshot points used to produce one estimate of the trend over the 10 years from 2009 to 2019. This procedure was then repeated, selecting a new random hour within the first 3 months as a starting point, until 2,000 trend estimates had been made based on a sampling period of 3 months. The same procedure was followed for the other sampling periods. The true trend from the record was defined as the linear fit to the full-length hourly time series. The expected error for each sampling period was determined as the standard deviation between the 2,000 estimates of the trend and the true trend; in order to have 2-sigma (95% confidence limit) error bars, the standard deviation was then doubled (Figure 3). The true trend of the record from Site C is +0.02°C per decade; the Monte Carlo-style analysis suggests that in order to estimate a trend for this 10 year period that is accurate to within ±0.01°C per decade at a 95% confidence level, one must collect observations approximately once per year or more frequently. The Monte Carlo-style estimates from the Site D record are very similar (not shown). Sampling any less frequently than every 36 months yields error bars equal to or larger than the true trend. It should be stressed that these results represent the error bars in estimating a trend over a single decade. This is the longest period that can be tested with the temperature records from the SAM PIES to date. For multidecade trends typically estimated via GO-SHIP sampling (e.g., Johnson et al., 2014) and/or other repeated hydrography sampling (e.g., Herrford et al., 2017), one would expect the errors would be smaller as long as the trend remained consistent over the longer time window and the levels of energy at higher frequencies remained about the same over the full time period.

4. Conclusions

Four unique records of hourly ocean bottom temperature in the northwestern Argentine Basin at depths ranging between 1,360 and 4,757 m over the period 2009–2019 demonstrate a surprising amount of variability at time scales ranging from a few hours to a few months superimposed on a 10 year warming trend. At middepths (1,360 m), the warming trend is approximately +0.04°C per decade, consistent with what has been previously observed with Argo data averaged over the full Argentine Basin (e.g., Giglio & Johnson, 2017); however, even with hourly observations, this estimated trend is not statistically different from zero, given the energetic variability at higher frequencies (Table 1). At greater depths (3,535 to 4,757 m), the observed warming trend is smaller, roughly +0.02°C per decade; the trend is statistically different from zero at the two deeper sites at 4,540 and 4,757 m, where the 95% confidence limits on the trends are about ±0.01°C per decade. The energetic variability near the seafloor at all four locations demonstrates the importance of routine, high frequency observations in order to accurately quantify deep and abyssal ocean temperature variations and longer-term trends.

Data Availability Statement

The PIES data used herein are freely available to the public from the NOAA National Centers for Environmental Information (NCEI) via accession numbers 0125596, 0175745, and 0205725; the PIES and CTD data are also available on request from the authors and at the project web page: www.aoml.noaa.gov/phod/research/moc/samoc/sam/.

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