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Empirical correction of XBT fall rate and its impact on heat content analysis

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Empirical correction of XBT fall rate and its impact on heat content analysis

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profile as the median of all CTD and OSD profiles selected in the region of collocation. The bias profile was then calculated by subtracting this reference profile from the XBT profile. Following Levitus et al. (2009) median rather than arithmetic average was used, as it reduces the influence of outliers. Moreover, we removed XBT profiles shallower than 200 m depth to exclude coastal regions. This method allows us to retain about 10^4 profiles a year between the year 1967 and 2007.

3 Test of the W08 correction

The W08 correction A is a linear correction computing the “true” estimated XBT depth Z_{true} from the depth Z calculated with the original fall rate.

$$Z_{\text{true}} = Z(1 - A) \quad (1)$$

W08 separated the deep XBT profiles (hereafter called XBTD) measuring temperature below 500 m (in standard levels) which are predominantly T7 or Deep Blue, and the others, shallow XBT profiles (hereafter called XBTS) which are predominantly T4 instruments. According to their study, W08 note a depth error near 400 m of 10 m for XBTS and half that for XBTD on average.

We first applied the W08 correction to our collocated profiles. Figure 2 shows the yearly raw and W08 corrected median bias on depth as a function of year. According to Gouretski and Koltermann (2007) and Wijffels et al. (2008) there is a positive bias between vertically averaged XBT temperature and high quality data like CTD and OSD. This median bias varies with the year of deployment of the XBT. It varies between 0.2°C and 0.1°C during the end of the 60’s until the beginning of the 80’s. Then the bias stabilizes around 0.05°C . Moreover this evolution agrees with the results of Levitus et al. (2009).

The vertical median bias is not uniformly reduced while applying the W08 correction. Obviously the linear correction does not correct the surface bias (Fig. 2). It can also be

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sometimes too large and induce a negative bias. Our comparison method thus suggests that a linear correction is not sufficient to properly reduce the observed biases.

4 Analysis of the XBT bias

We will try to refine the model of bias correction by examining in more detail the vertical and spatial structure of the XBT/CTD biases. The W08 correction does not properly reduce the global median bias of our XBT and CTD/OSD collocation. We begin to compare very close pairs with weak temperature gradients and we identify a thermal bias. This observation agrees well with the recent work of Gouretski and Reseghetti (2010). We then computed the median annual bias as a function of depth to adjust at a given temperature the depth indicated by the original fall rate. We can linearly interpolate to retrieve the temperature at standard levels. We compute the depth bias at each standard level with the first order approximation,

$$dZ = (T_{\text{CTD}} - T_{\text{XBT}}) \frac{\delta Z}{\delta T_{\text{CTD}}} \quad (2)$$

Our calculations of depth bias from collocated profiles points to several observations. As in Wijffels et al. (2008), the behavior of XBTS and XBTD was different. Moreover, the collocated profiles do not seem to be corrected by a linear function, but rather by a parabolic function.

This parabolic character is more or less pronounced according to year, geographical area and the type of XBT. We thus computed a second order correction with a least square fitting process for all years of deployment and all classes of XBT made in this study. The bias on depth also has a different behavior in the first meters of the probe fall. Between the surface and 30 m, the error deviates from its parabolic behavior, possibly due to the high variability of surface temperature added to low gradient of the surface mixed layer producing high variability in the calculated dZ quantities.

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On the other hand, there seems to be a correlation between depth bias and the temperature of the sea water where the probe had been deployed (Thadathil et al., 2002). Figure 3 shows the depth bias at 100 m as a function of average temperature between 0 and 200 m for XBTS (in red) and XBTD (in blue) averaged over the study period. We notice an increase of the bias toward low temperatures, without finding a different behavior between the two classes of XBT. Although, Fig. 3 still illustrates the need to process XBTs in categories of temperatures, nothing clearly distinguishes XBTS from XBTD at this depth.

Comparing the bias at a given depth is not a sufficient indicator as it is the behavior of the depth error that is essential. Figure 5 represents the linear part (Az) as a function of the parabolic part at 400 m depth (Bz^2) for a new correction for XBTS (circles) and XBTD (stars) at high temperature (left) and at low temperature (right). Each dial represents a different regime of the yearly median depth bias. Most profiles have to be corrected by a function having a negative parabolic part and a positive linear part. This indicates that the fall rate equation of most XBT probes badly estimates the actual speed of fall in the first meters and tends to approach it at greater depth. At lower temperatures, the behavior of XBTS and XBTD fall is totally different. Particularly in the end of the 70's and the 90's, we notice that the parabolic part of the XBTD becomes positive and several profiles have a negative linear part. Furthermore, we note that those probes need more different regimes of correction than the others.

5 A new correction

Based on the previous analysis, we propose the following new correction for XBTs:

- Correction of thermal bias:

$$T_{\text{XBT}} = T_{\text{XBT}} - T_{\text{off}} \quad (3)$$

– Correction of the depth bias:

$$Z_{\text{true}} = Z_{\text{obs}}(1 - A - BZ_{\text{obs}}) - Z_{\text{off}} \quad (4)$$

5.1 Thermal correction

Errors on the calibration of the temperature probes can also be a source of bias. In addition, as the XBTs are passive sensors, the possibility of parasites resistances or other circuit-dependent parameters can induce errors in the temperature data reported by the instrument. Comparing neighboring XBT and CTD/OSD profiles in the upper mixed layer, we observed a positive thermal bias between 10 m and 30 m. Following Gouretski and Reseghetti (2010), we selected close profiles with a weak temperature gradient in the upper layer (less than $0.0025^\circ\text{C m}^{-1}$). This criterium guarantees that the observed bias is not related to the estimation of the depth of the XBT probe but to a error of calibration.

As we did not find significant differences between profiles measured in high or low water temperature, we decided to separate them only in two categories. We compute an offset T_{off} related to XBTS and another for XBTD (Eq. 5, Table 1). The thermal offset associated with XBTS is largely positive between 1968 and 1980 (0.069°C in average) and tends to zero afterward. The thermal bias of XBTD is more constant. A maximum is reached before 1980 (0.040°C in average) which decreases during the 80's and becomes again maximum at the end of the 90's (0.047°C in average between 1995 and 2005).

5.2 Second order correction

The parabolic character of the correction is certainly due to a too simple approximation of the XBT fall rate. Indeed, it is possible that the first XBT fall rates calculated by observation of the fall of a probe in a water tank were not adapted to forecast their behavior

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the coefficients for the XBTD in this region are very different from the others. The coefficient A is largely positive in the first years and decreases until 1985 and B is strongly negative and increases with time. The depth offset is also strong. This behavior is specific to those regional XBTD. The other difference is referred to the temperature offset (Table 2). During the first years, the regional temperature offset is positive but not as strong as for the other XBTs (Table 1). From 1975 it becomes slightly negative.

6 Calculation of the corrected heat content

Following Wijffels et al. (2008) and Levitus et al. (2009), we also estimated a median depth bias on Mechanical BathyTermograph (MBT). The following figures result from the correction of both XBTs and MBTs. Using the same methodology, we performed a second order correction added to an offset. We also separated MBT deployed at high and low temperatures. For those probes, the selected threshold was 12°C for the median temperatures calculated between the surface and 100 m depth.

With the globally corrected database, we can easily map the observations on a latitude and longitude grid ($4^{\circ} \times 8^{\circ}$). The annual mean anomalies of temperature are obtained by subtracting the WOA05 climatology. We attributed to empty boxes the value of the annual mean anomaly of all full boxes. Figure 9 shows the 0–700 m integrated heat content calculated from the corrected XBT database (green), the raw XBT database (red), the entire WOD05 database (red) and the entire database where XBT and MBT have been corrected (blue).

The calculation of the corrected heat content suggests that the local warming observed during the 70's was the result of the positive bias of XBT probes. On the other hand, we note that the global heat content calculated from corrected XBTs is very close to that calculated with the entire corrected database (such agreement is also found when considering specific layers like 0–400 m or 400–700 m). This suggest that XBT data are now globally closer to CTD data. This new correction allow us to find a linear trend of global heat content of $0.32 \cdot 10^{22} \text{ J/year}$ between 1970 and 2008. Of

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course, this is strongly dependent on the assumption to fill missing boxes with the annual anomaly for that year, as much southern hemisphere boxes were not sampled in the early periods.

7 Conclusions

5 We had to consider 6 different XBT classes to compute a globally second order correction on depth. We chose to separate XBTS and XBTs mostly related to T4 and T7 during the study period. We also separate XBTs deployed in cold or warm water (colder or warmer than 10° on average between the surface and 200 m) due to the dependence of temperature on the behavior of the XBT probes. A parabolic correction was not sufficient, and it was necessary to apply offsets: One thermal offset only
10 depending on the XBT type to apply to the temperature profiles and a second one, a depth offset. Although we adopt a global perspective, we separated XBTs launched in the western Pacific basin between 1968 and 1985 because of their particular behavior. Our empirical approach does not attempt to find the reasons why those probes have
15 a particular behavior but doing this exception allows to increase the robustness of our global correction. This specific case has also been discussed in W08. They found that the depth error at 400 m was almost similar between the different basins except for the western Pacific region. As we also show here, they identify a regional negative error.

Furthermore, the thermal offset can be compared to the results obtained by Gouretski and Reseghetti (2010). Our analysis detects an offset almost two times smaller
20 than theirs. This distinction is probably due to our selection criteria which is more stringent. We selected fewer profiles but only those with a thermal gradient lower than $0.0025^{\circ} \text{ m}^{-1}$, whereas their upper limit is $0.005^{\circ} \text{ m}^{-1}$. Despite the lower total number of profiles selected, the calculation of the offset remains statistically accurate.

25 We corrected the MBT database with the same methodology to obtain a entire corrected database. We were able to compute a revised 0–700 m heat content and a corresponding estimate of a new linear trend. These calculations agree with other

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recent papers, thus supporting that the anomalous increase of heat content during the 70's originated from uncorrected XBT biases. It is now necessary to perform a more detailed analysis to highlight the potential gain of such a new correction on an entire database.

- 5 *Acknowledgements.* We thank Karina Von schuckmann, Clement de Boyer Montegut and Cecile Cabanes for the useful comments and discussions during the preparation of this manuscript. Mathieu Hamon work is funded by IFREMER and Meteo France as part of a Coriolis Phd Grant.

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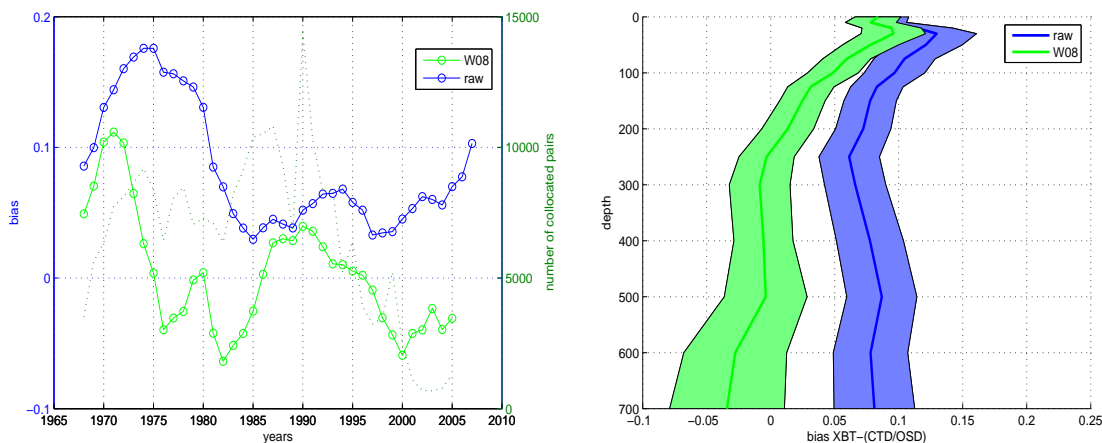


Fig. 1. Evolution of XBT-CTD 0/700 m median raw bias (blue) and corrected by W08 (green) integrated between 0 and 700 m. The number of yearly collocated pairs is indicated with the green dotted line (left). Median raw bias (blue) and corrected by W08 (green) as a function of depth averaged over the study period (right). The width represents the standard deviation of the annual median bias.

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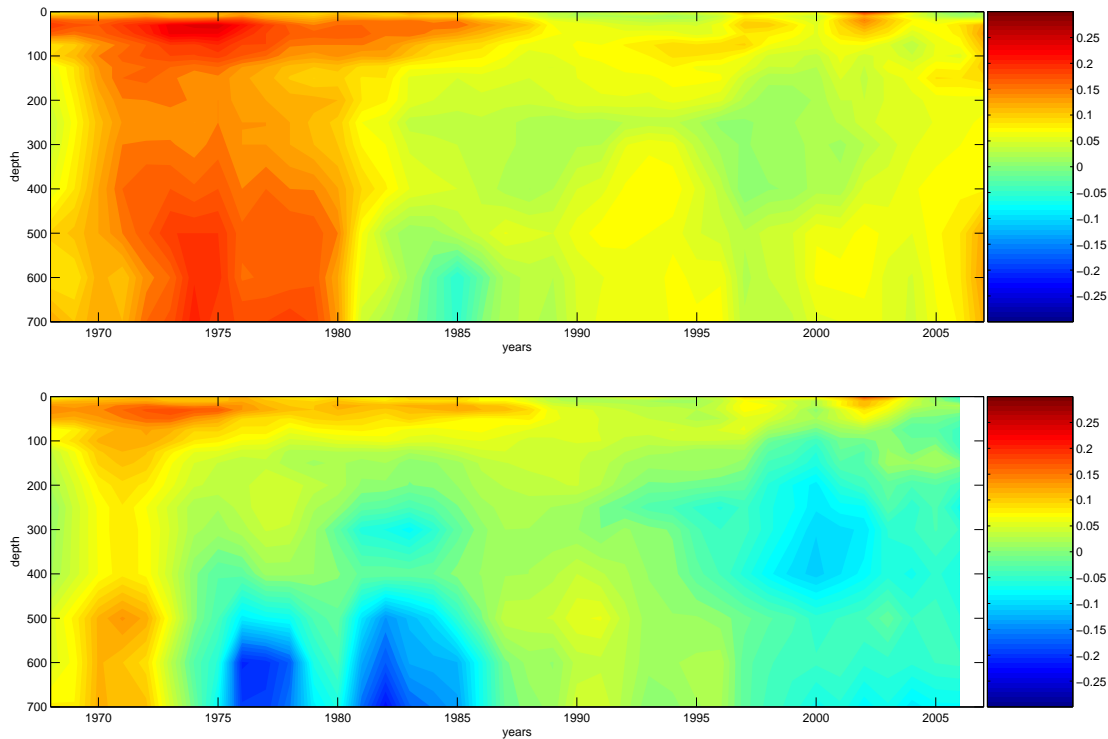


Fig. 2. Evolution of XBT-CTD median raw bias (above) and corrected by W08 (under) as a function of depth and time.

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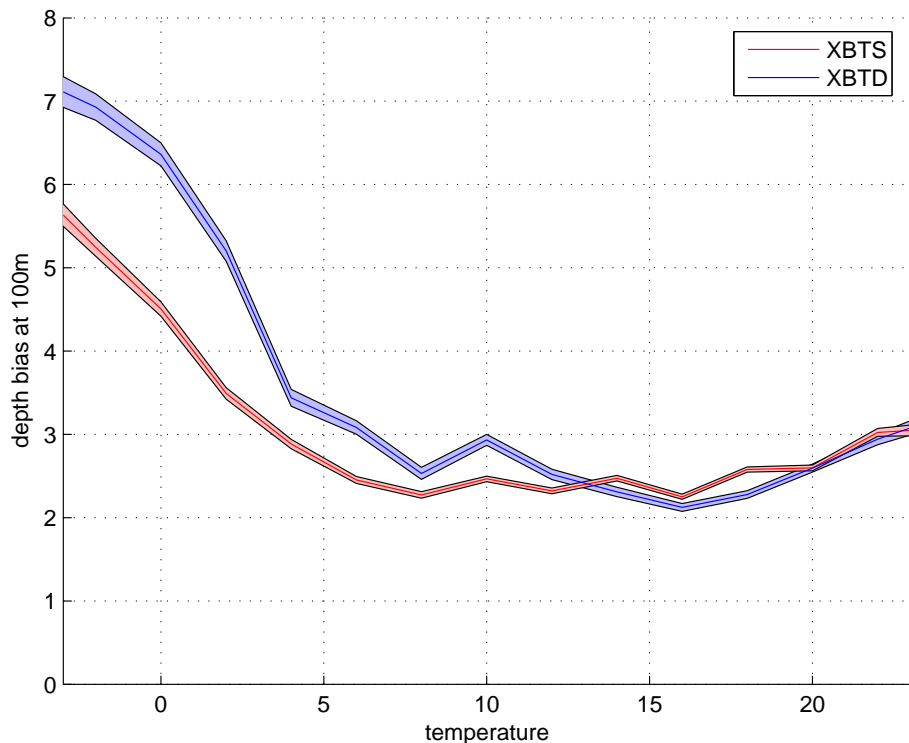


Fig. 3. Median XBT-CTD depth bias at 100 m depth as a function of the integrated temperature between 0 and 200 m depth for XBTS (red) and XBTD (blue). The standard deviation divided by the square root of the number of selected pairs in each class is represented with the colored area.

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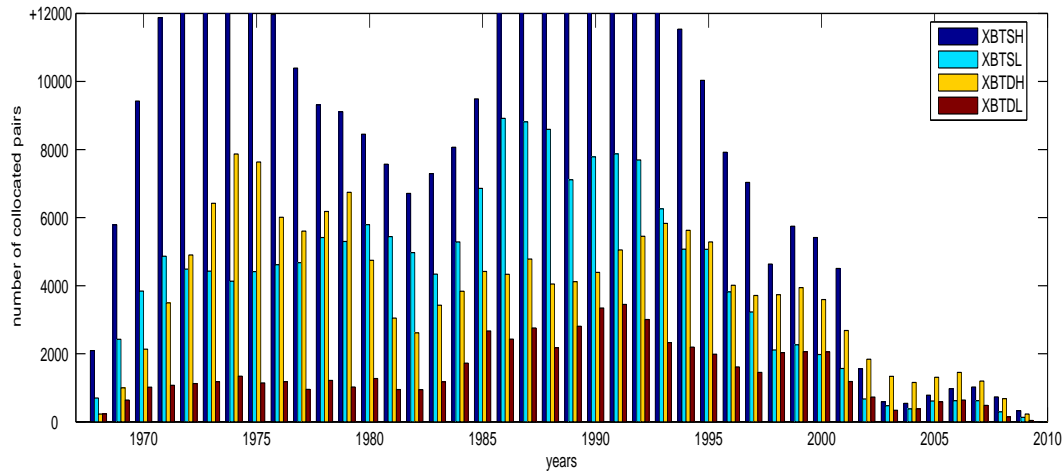


Fig. 4. Number of collocated pairs for the four classes of XBT function of time. XBTS(D)H/XBTS(D)L correspond to shallow (deep) XBTs deployed in high and low temperatures.

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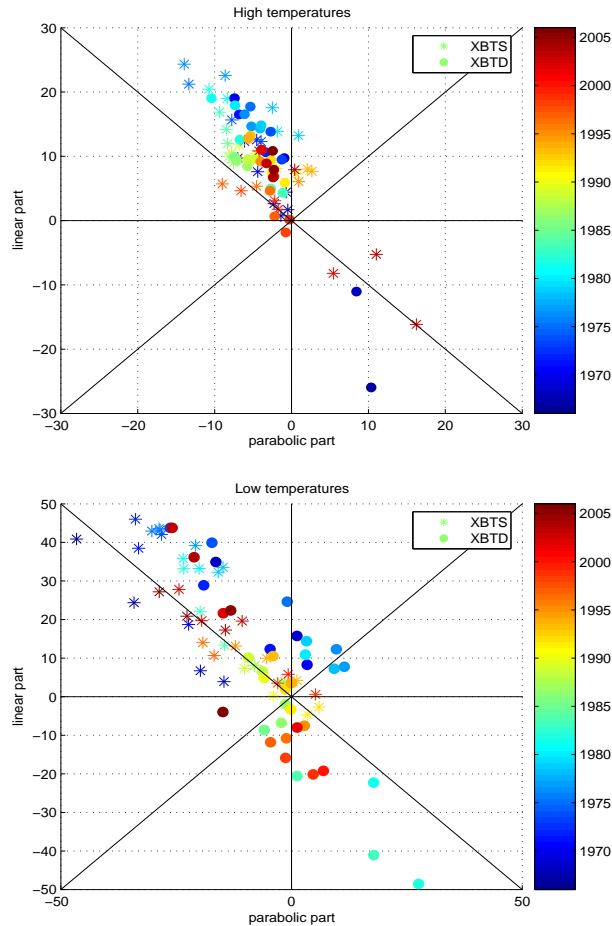


Fig. 5. Linear part (coefficient $B(t)$) as a function of parabolic part ($A(t) \times 400$) at 400 m depth for XBTS (large dots) and XBTD (stars). The upper figure represents XBTs deployed at high temperatures and at the bottom, XBTs deployed at low temperatures. Years are indicated with the colorbar.

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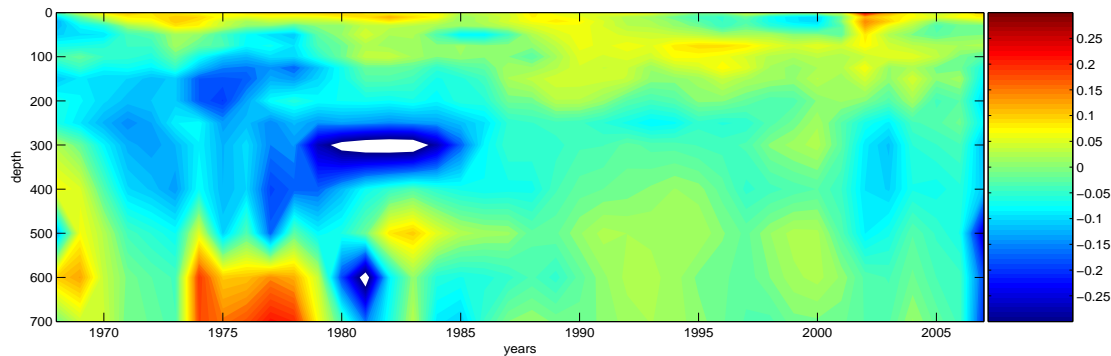


Fig. 6. Evolution of XBT-CTD median bias deployed in the western Pacific basin (the region is bounded by 180° E and 20° S) between 1968 and 1985, corrected by a global parabolic correction, as a function of depth and time.

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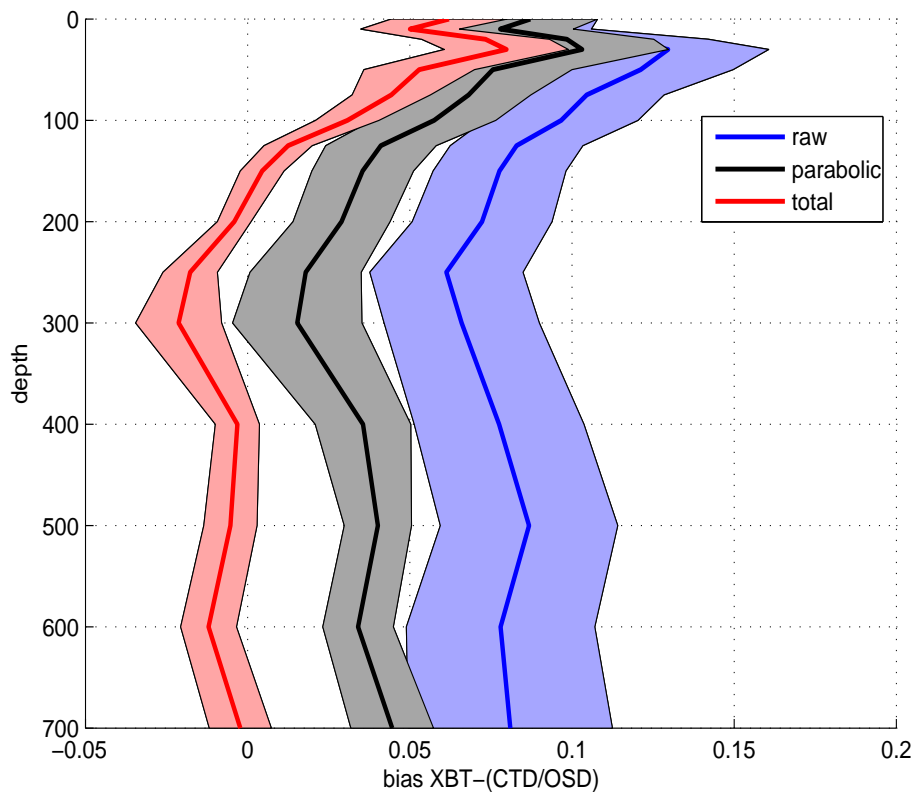


Fig. 7. Median raw bias (green), corrected by the parabolic correction (blue) and corrected by a parabolic correction added an offset (red) as a function of depth averaged over the study period 1968/2007.

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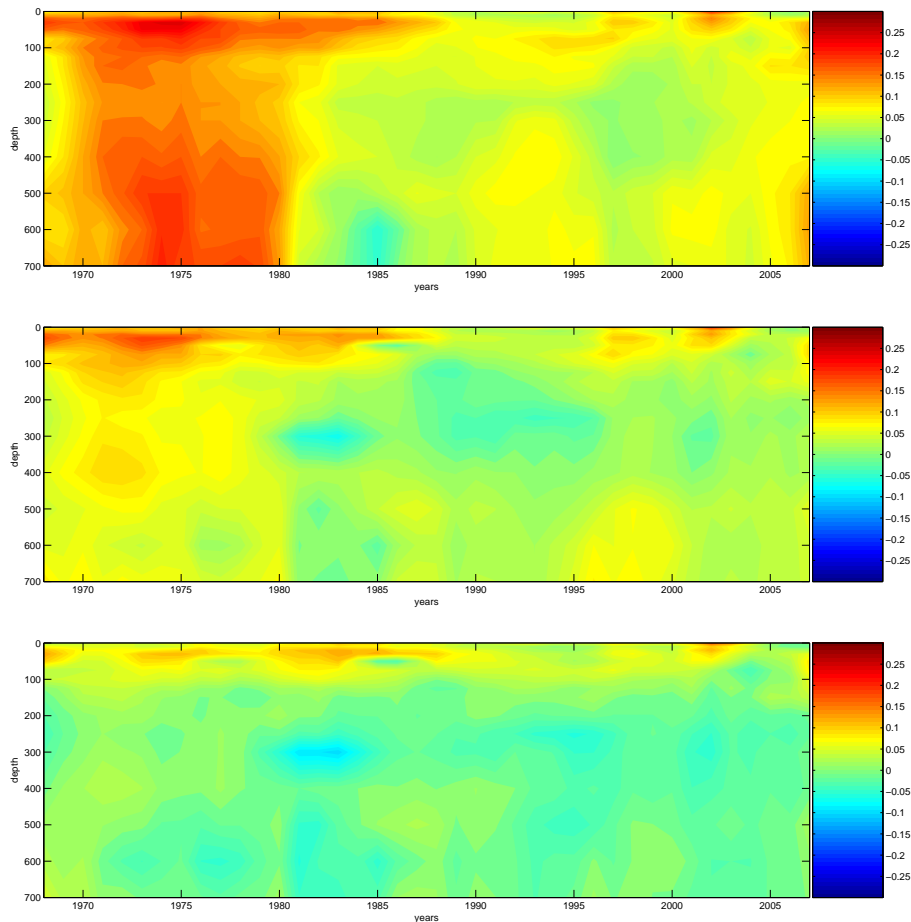


Fig. 8. Evolution of XBT-CTD median raw bias (above) and corrected by a parabolic correction (middle) and corrected by a parabolic correction added an offset (under) as a function of depth and time.

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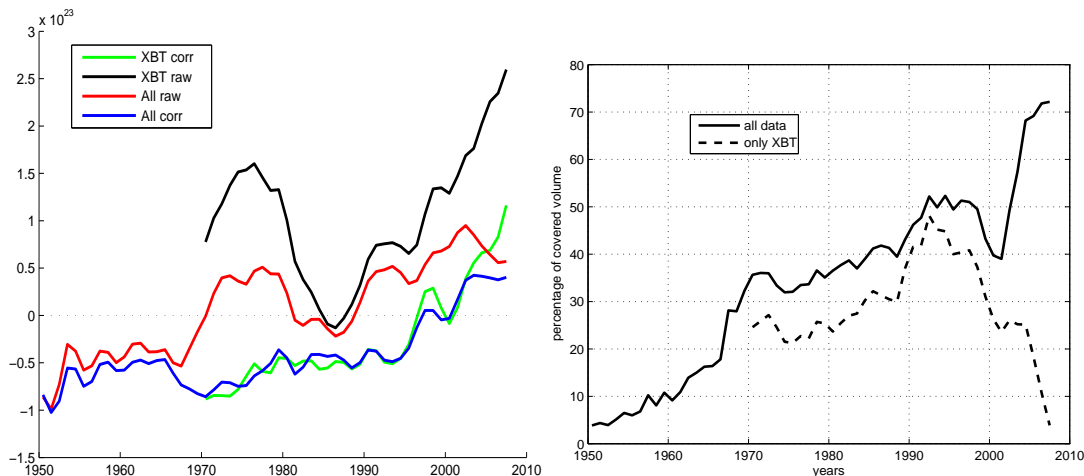


Fig. 9. Integrated heat content between the surface and 700 m depth calculated using the entire raw dataset (red), the entire corrected dataset (blue), and only using raw XBTs (black) and corrected XBTs (green) function of years (left). Percentage of the oceanic volume covered by $4^\circ \times 8^\circ$ boxes including all data (full line) and only XBT data (dotted line) (right).

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Table 2. Thermal offset as a function of time for XBTs deployed in the west Pacific basin between 1968 and 1985.

Year	T_{offset}
1968	0.048
1969	0.041
1970	0.039
1971	0.029
1972	0.031
1973	0.022
1974	0.010
1975	-0.004
1976	-0.013
1977	-0.020
1978	-0.019
1979	-0.011
1980	-0.004
1981	-0.002
1982	-0.003
1983	0.002
1984	0.008
1985	0.017

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Table 3. Coefficients of the parabolic correction and the depth offset for XBTD deployed in high temperatures.

Year	A_{DH}	B_{DH}	Offset _{DH}
1968	0.000065	-0.065	1.2
1969	0.000053	-0.028	0.6
1970	-0.000006	0.024	0.1
1971	-0.000046	0.048	0.3
1972	-0.000043	0.041	0.7
1973	-0.000021	0.027	0.6
1974	-0.000008	0.024	0.2
1975	-0.000017	0.035	0.0
1976	-0.000033	0.044	-0.1
1977	-0.000038	0.041	-0.5
1978	-0.000033	0.037	-0.8
1979	-0.000026	0.036	-0.8
1980	-0.000025	0.037	-0.5
1981	-0.000046	0.045	-0.2
1982	-0.000065	0.048	0.0
1983	-0.000042	0.032	0.0
1984	-0.000007	0.011	0.0
1985	-0.000017	0.013	0.2
1986	-0.000046	0.025	0.8
1987	-0.000045	0.023	1.5
1988	-0.000036	0.021	1.7
1989	-0.000036	0.024	1.1
1990	-0.000030	0.024	0.4
1991	-0.000016	0.019	0.0
1992	-0.000005	0.015	-0.3
1993	-0.000017	0.024	-1.0
1994	-0.000033	0.033	-1.4
1995	-0.000035	0.032	-1.2
1996	-0.000025	0.023	-0.6
1997	-0.000018	0.012	-0.1
1998	-0.000014	0.002	0.6
1999	-0.000005	-0.005	1.1
2000	-0.000002	0.001	0.8
2001	-0.000014	0.017	0.1
2002	-0.000024	0.028	-0.2
2003	-0.000024	0.028	-0.3
2004	-0.000020	0.022	-0.5
2005	-0.000015	0.017	-0.7
2006	-0.000014	0.020	-0.4
2007	-0.000015	0.027	0.0

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Table 4. Coefficients of the parabolic correction and the depth offset for XBTD deployed in low temperatures.

Year	A_{DL}	B_{DL}	Offset _{DL}
1968	-0.000231	0.129	0.7
1969	-0.000102	0.087	1.7
1970	0.000007	0.039	2.4
1971	0.000021	0.021	1.9
1972	-0.000029	0.031	1.2
1973	-0.000119	0.072	1.7
1974	-0.000164	0.110	2.4
1975	-0.000108	0.100	2.6
1976	-0.000006	0.062	2.9
1977	0.000061	0.031	2.5
1978	0.000072	0.019	1.2
1979	0.000058	0.018	0.1
1980	0.000020	0.036	0.4
1981	0.000019	0.027	0.9
1982	0.000111	-0.056	-1.0
1983	0.000172	-0.121	-3.3
1984	0.000111	-0.103	-2.8
1985	0.000007	-0.051	-0.7
1986	-0.000037	-0.021	1.0
1987	-0.000014	-0.017	2.1
1988	-0.000008	-0.005	2.5
1989	-0.000039	0.017	1.4
1990	-0.000058	0.025	-0.2
1991	-0.000037	0.012	-0.7
1992	-0.000001	-0.008	-0.2
1993	-0.000008	0.005	0.0
1994	-0.000025	0.026	0.0
1995	-0.000000	0.009	0.0
1996	0.000017	-0.019	0.2
1997	-0.000007	-0.027	0.9
1998	-0.000028	-0.029	1.7
1999	-0.000008	-0.040	2.2
2000	0.000029	-0.050	1.6
2001	0.000043	-0.048	0.1
2002	0.000008	-0.020	-1.4
2003	-0.000093	0.054	-1.9
2004	-0.000162	0.110	-1.6
2005	-0.000132	0.090	-1.1
2006	-0.000082	0.056	-0.4
2007	-0.000093	-0.010	1.7

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Table 5. Coefficients of the parabolic correction and the depth offset for XBTS deployed in high temperatures.

Year	A_{SH}	B_{SH}	Offset $_{SH}$
1968	-0.000003	0.004	-1.5
1969	-0.000009	0.002	-0.8
1970	-0.000014	0.007	0.0
1971	-0.000027	0.019	0.6
1972	-0.000038	0.031	1.0
1973	-0.000028	0.031	1.0
1974	-0.000025	0.031	0.3
1975	-0.000048	0.039	-0.3
1976	-0.000083	0.053	-0.5
1977	-0.000087	0.061	-0.6
1978	-0.000054	0.057	-1.1
1979	-0.000016	0.044	-1.5
1980	0.000006	0.033	-1.5
1981	-0.000012	0.035	-1.2
1982	-0.000052	0.048	-1.0
1983	-0.000067	0.051	-0.9
1984	-0.000058	0.042	-0.8
1985	-0.000053	0.035	-0.6
1986	-0.000052	0.030	-0.5
1987	-0.000051	0.025	-1.0
1988	-0.000047	0.022	-2.1
1989	-0.000049	0.026	-2.5
1990	-0.000043	0.029	-2.0
1991	-0.000028	0.026	-1.4
1992	-0.000012	0.020	-1.2
1993	0.000003	0.018	-1.2
1994	0.000013	0.020	-0.8
1995	0.000016	0.019	-0.3
1996	0.000006	0.015	0.0
1997	-0.000028	0.013	-0.2
1998	-0.000056	0.014	-0.6
1999	-0.000041	0.012	-1.0
2000	-0.000014	0.008	-1.0
2001	-0.000011	0.004	-0.6
2002	0.000034	-0.021	-0.1
2003	0.000102	-0.040	0.2
2004	0.000069	-0.013	-0.1
2005	0.000003	0.020	-0.9
2006	-0.000026	0.027	-1.2
2007	-0.000044	0.024	-0.8

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Table 7. Coefficients of the parabolic correction and the depth offset for XBT deployed in west Pacific basin between 1968 and 1985.

Year	<i>A</i>	<i>B</i>	Offset
1968	0.000000	0.000	0.0
1969	0.000000	0.000	0.0
1970	0.000000	0.000	0.0
1971	0.000000	0.000	0.0
1972	0.000124	−0.096	4.6
1973	0.000059	−0.019	3.2
1974	0.000148	−0.088	4.6
1975	0.000200	−0.029	5.0
1976	0.000041	−0.015	2.4
1977	0.000012	0.023	0.4
1978	−0.000054	0.050	0.3
1979	0.000035	0.020	0.3
1980	0.000012	0.015	0.2
1981	0.000054	−0.003	−0.2
1982	0.000072	−0.021	−1.7
1983	−0.000089	0.057	−3.4
1984	−0.000065	0.067	−4.0
1985	−0.000044	0.033	−4.0

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Table 8. Coefficients of the parabolic correction and the depth offset for XBTS deployed in west Pacific basin between 1968 and 1985.

Year	<i>A</i>	<i>B</i>	Offset
1968	0.000099	-0.034	-2.5
1969	0.000044	-0.013	-2.1
1970	-0.000018	0.010	-1.7
1971	-0.000036	0.019	-1.3
1972	-0.000008	0.017	-1.1
1973	0.000015	0.017	-1.1
1974	0.000007	0.021	-1.1
1975	-0.000030	0.034	-0.9
1976	-0.000052	0.047	-0.8
1977	-0.000048	0.046	-0.5
1978	-0.000049	0.042	-0.1
1979	-0.000043	0.035	0.0
1980	-0.000027	0.031	0.0
1981	-0.000012	0.025	0.0
1982	0.000011	0.013	0.1
1983	0.000039	0.001	0.2
1984	0.000058	-0.004	0.2
1985	0.000055	-0.004	0.1