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HiWASE: calibration of surface salinity measurements

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ABSTRACT

Between 1978 and 2009 the Norwegian weather ship *Polarfront* made continuous meteorological measurements at Station Mike (66ºN 2ºE). In September 2006, as part of the HiWASE project the ship's existing measurement systems were complemented by the AutoFlux system to measure the transfers of momentum, heat and CO_2 between the atmosphere and the ocean. Surface salinity was measured using a thermosalinograph (TSG) as part of the AutoFlux system.

The TSG data were calibrated by comparison to surface CTD measurements, Nansen surface bottles and underway bottle samples. The corrected TSG salinity data has a residual difference from the calibration data, which is generally less than ±0.1 psu except for the summer months when this increases ±0.2 psu. This is sufficient for this study since salinity was only used for the calculation of CO_2 solubility in the surface water.

The corrected salinity data show a sharp decrease in salinity of about 1 psu during July and August each year. The salinity measured during this time is highly variable and must be used with caution. The data are available from the British Oceanographic Data Centre, UK (http://www.bodc.ac.uk/).

KEYWORDS
OWS *Polarfront*, Station 'Mike', Thermosalinagraph, TSG, AutoFlux

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1. Introduction

Between 1978 and 2009 the Norwegian weather ship *Polarfront* made continuous meteorological measurements at Station Mike (66°N 2°E). In September 2006, as part of the HiWASE project (Brooks et al., 2009) the ship's existing measurement systems were complemented by the AutoFlux system (Yelland et al., 2009) to measure the transfers of momentum, heat and CO_2 between the atmosphere and the ocean. Surface salinity was measured using a thermosalinograph as part of the AutoFlux system. This report describes the calibration of the thermosalinograph salinity measurements by comparison to surface measurements made using a conductivity temperature and depth (CTD) sensor, Nansen bottle and underway bottle samples.

A Seabird SBE45 micro thermosalinograph (TSG) was used to measure the salinity of the surface waters from September 2006 to December 2009. Salinity was calculated in real time using the TSG measurements of temperature and conductivity. Water was taken from an inlet in the forward hold at a depth of 3 m and the TSG was located about 6 m from the water inlet. The pipe between the inlet and the TSG was insulated to reduce changes in temperature along its length. Measurements were recorded every 3 seconds. The TSG was installed on 4th September 2006 (Serial Number 4543156-0181). The instrument was swapped on 21st February 2008 (Serial Number 4540927-0159).

During most port calls the TSG was cleaned. This was either an ordinary clean (1 % soap solution) or, from September 2007 onwards, an extended clean. During the extended clean the instrument was flushed with diluted bleach before flushing with the 1% soap solution. Details of when the instrument was cleaned are contained in Table 1.

2. Calibration of underway salinity data

2.1 Introduction

The TSG salinity data were quality controlled by manually editing 4 day sections and removing all large outliers. Salinity measurements made when the ship was in port have been removed. An example showing the raw and cleaned up data is shown in Figure 1 (jday is day of year, with 1200 GMT on the 1st January being jday 1.5).

Three data sets are available to calibrate the TSG underway salinity measurements. These are 1) surface CTD measurements, 2) underway bottle samples taken from the water inlet in the forward hold and 3) Nansen bottles that were taken at the sea surface. CTD measurements were made 5 times per week for the Bjerknes Center for Climate Research, Bergen using a Seabird microCAT CTD. Surface CTD measurements between 0 and 4 m (0 to 4 dbar) were selected for this calibration study. Between February 2008 and September 2009 only 48 surface salinity measurements were available because of data storage problems with the microCAT CTD. Water samples from the Nansen bottles were used to calibrate the salinity measured by the CTD. Nansen bottle data from 2007 to

August 2008 are used in this study since the later Nansen data were not available to us. Underway bottle samples were taken from the water inlet once a week and usually coincided with the end of a CTD cast. There are significant periods when no bottle data are present, e.g. during 2006. In total 218 CTD surface salinity measurements were used to calibrate the TSG from September 2006 to November 2009. In addition, a total of 88 salinity measurements were made from underway bottle samples and 41 from Nansen bottles (Table 2). The data sets are compared in Section 2.2.

The TSG salinity measurements made every three seconds were averaged over 1 minute and compared with combined surface salinities measured using the three data sets described above. Corrections are derived for the two TSG sensors in Sections 2.3 and 2.4. The data were corrected in a piecewise fashion, to allow for changes in calibration corresponding to cleaning events. The accuracy of the corrections is discussed in Section 2.5.

2.2 Intercomparison of the calibration data sets

The difference in salinity between underway bottle samples, and the surface CTD and Nansen bottles is shown in Figure 2. In general the differences between the bottle data and the surface CTD and Nansen data are less than 0.05 psu. The two outliers between jday 90 and 100 during 2008 are discussed in Section 2.4. The difference between the Nansen and underway bottle data are generally positive, whilst the difference between the CTD and bottle data are negative. This results in a 0.05 psu offset in the difference between the surface CTD and Nansen bottles. This is unexpected as the Nansen bottles are used to calibrate the CTD salinities. The offset is assumed to be due to the different depths: the Nansen bottle samples were obtained near the surface whereas the CTD data used were at depths of up to 4 m. However, an offset of 0.05 psu or less is thought to be sufficient for this study as salinity was only used in the calculation of the mean solubility of the CO_2,. In addition, a possible error of 0.05 psu is small compared to the maximum TSG bias of about 1.0 psu. Therefore, the three data sets are combined in one calibration data set in order to calibrate the TSG.

2.3 TSG Sensor 1: jday 250 2006 to jday 326 2007

The difference between the TSG and the calibration data are shown against salinity and sea surface temperature (SST) in Figure 3. There is a linear trend with salinity, which has a 0.2 psu scatter in the salinity difference for salinities greater then 34.6. There was greater variability (0.5 psu) during the lower salinity summer months. From the installation date until jday 52 2007 there is a linear increase with increasing SST. During this time the TSG was in good agreement with the calibration data for the higher temperatures, but underestimated by up to 0.1 psu at the lower temperatures. During the rest of 2007 the trend in salinity difference with SST was reversed, i.e. the TSG underestimate became larger with increasing temperature. The TSG underestimated the calibration data by up to 0.6 psu at 12 °C. Figure 4 shows that the salinity difference plotted against jday for 2006 and 2007. In this case the scatter in the data is less than in Figure 3, suggesting that the drift in the TSG salinity data are dependent on time, rather than on SST or salinity. For this reason time-dependent corrections for the TSG data were developed.

The salinity corrections for the TSG is described by:

$$TSG - cal = 0.267 - 0.0009297 \times jday \quad 2006:254 \le jday < 2007:163 \qquad (1)$$

$$TSG - cal = 1.797 - 0.0038803 \times jday \quad 2007:166 \le jday < 2007:244 \qquad (2)$$

$$TSG - cal = 1.061 - 0.0019764 \times jday \quad 2007:253 \le jday < 2007:326 \qquad (3)$$

where *cal* is the combined surface CTD, underway bottle data and Nansen salinity data. When applying the corrections to the data, the jday variable has 365 added for 2007 and 730 added for 2008.

During the summer of 2007 (Eqn 2) the difference between the TSG and the calibration data had greater variability, and the bias was larger, than the rest of the year.

Unfortunately, no calibration data were available in the last month of 2007 and the first two months of 2008. Therefore, the regression (Eqn 3) was extended until jday 52 2008, the date when the TSG sensor was replaced with a new unit. Table 1 includes details of which Eqn was applied to which cleaning period. The final data set includes a variable to flag any period of extrapolation.

2.4 TSG sensor 2: jday 052 2008 to jday 335 2009

The difference between the TSG and the calibration data are shown against salinity and sea surface temperature SST in Figure 5. Outside the summer months of 2008 and 2009 there is a strong dependence on salinity. Again there is larger scatter during the summer months. There was no obvious trend with SST. Figure 6 shows that the scatter in the salinity difference with time is mostly much smaller than with salinity. With the exception of the period jday 247 to 333 during 2008, regressions varying in time were used to correct the TSG measurements. For jday 247 to 333 during 2008 it was thought a regression based on salinity was more appropriate (Figure 7). Two calibration points associated with the large outliers between jday 90 and 100 during 2008 (Figure 2) have been removed, because there is a large amount of good calibration data during this period.

The salinity correction for the TSG is described by:

$$TSG - cal = 0.127 - 0.0015588 \times jday \quad 2008:056 \le jday < 2008:187 \qquad (4)$$

$$TSG - cal = 1.196 - 0.006733 \times jday \quad 2008:199 \le jday < 2008:242 \qquad (5)$$

$$TSG - cal = -19.11 + 0.5402 \times TSGsalinity \quad 2008:283 \le jday < 2008:329 \qquad (6)$$

$$TSG - cal = 1.3809 - 0.0049985 \times jday \quad 2008:337 \le jday < 2008:355 \qquad (7)$$

During 2009 the difference in salinity between the CTD and TSG is described by:

$$TSG - cal = -0.822 + 0.0008714 \times jday \quad 2009:27 \le jday < 2009:55 \qquad (8)$$

$$TSG - cal = 0.157 - 0.0014552 \times jday \quad 2009:57 \le jday < 2009:135 \qquad (9)$$

$$TSG - cal = 2.483 - 0.0058062 \times jday \quad 2009:146 \le jday < 2009:192 \qquad (10)$$

$$TSG - cal = 8.823 - 0.016007 \times jday \quad 2009:205 \le jday < 2009:248 \qquad (11)$$

$$TSG - cal = -1.731 + 0.0023309 \times jday \quad 2009:261 \le jday < 2009:328 \qquad (12)$$

where jday for 2009 is plus 366 and *cal* is the combined surface CTD, underway bottle data and Nansen salinity data.

No calibration data were available during the first two months of 2009. Therefore Eqn. 7 was extrapolated until jday 27 when the system was cleaned. Initially the extrapolation was made to day 55 but this resulted in a step change in the corrected salinity data at day 55. Instead, "calibration" points were derived from the corrected TSG data prior to day 27 and after day 55, and a linear fit between these points was used to correct the data (Eqn. 8). This was sufficient as the corrected salinity did not vary a great deal during this time. Table 3 includes details of which equation was applied to which cleaning period. In the final data set a flag is set to 99 to identify any period of extrapolation. At all other times the flag is set to the equation number of the applied correction.

2.5 Accuracy of the corrected salinity data

Eq. 1-12 were applied to the raw salinity data (3 second sampling interval). The period the equations were applied over is detailed in Table 3. The corrected values were then averaged into 1 minute intervals. The 1 minute residual difference between the corrected TSG salinity and the calibration data is shown for each year in Figure 8. The residuals generally lie within ±0.1 psu, but this increases to ±0.2 psu in July and August of each year, when the salinity is very variable. There is one outlier associated with the high variability periods.

Figure 9 shows the calibration data and hourly-averaged (for clarity) raw and calibrated TSG data for the whole three year period. For periods where there were no calibration data available, the data were corrected by extrapolating the correction derived from an earlier period: these periods can be identified by a flag value of 99. At other times, the flag value is set to the relevant equation number.

Figure 10 shows calibrated TSG data from each calendar year, overlaid on each other. The salinity is typically about 35.2 psu from January to June. There is a sharp drop in salinity of about 1 psu during July and August each year. The salinity is lower between jday 200 to 250 (mid July to early September) during 2008 and 2009, than the previous year. This may be due to the difficultly in correcting the highly variable salinity data during the summer, or 2007 my have been a drier summer. In the autumn of each year the salinity increases from about 35 psu in September to a January value of about 35.2 psu.

3. Summary

Surface salinity measurements were made at station Mike (66N 2E) from September 2006 until the end of November 2009. The salinity measurements were obtained every 3

seconds using a Seabird SBE45 micro Thermosalinograph (TSG). Routine cleaning of the instrument was performed during port calls.

The TSG data were calibrated by comparison to surface CTD measurements, Nansen surface bottles and underway bottle samples. The offset between the measured TSG salinity and the calibration data varied between 0 and 1 psu. A number of linear calibrations were applied to the measurements to remove trends in the data. All bar one of these were time-dependent corrections. The exception was the period between jday 247 and 333 2008 where a salinity-dependent correction was thought to be more appropriate. For periods where there were no calibration data available, the data were corrected by extrapolating the correction derived from an earlier period: these periods can be identified by a flag value of 99. At other times, the flag value is set to the relevant equation number.

The corrected TSG salinity data has a residual difference from the calibration data, which is generally less than ±0.1 psu except for the summer months when this increases ±0.2 psu. This is sufficient for this study since salinity was only used for the calculation of CO_2 solubility in the surface water.

The corrected salinity data show a sharp decrease in salinity of about 1 psu during July and August each year. The salinity measured during this time is highly variable and must be used with caution. The data is available from the British Oceanographic Data Centre, UK (http://www.bodc.ac.uk/).

Acknowledgements

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Yelland, M.J., Pascal, R.W., Taylor, P.K. and Moat, B.I. (2009): AutoFlux: an autonomous system for the direct measurement of the air-sea fluxes of CO2, heat and momentum. *Journal of Operational Oceanography*, **2**, (1), 15-23.

Figures

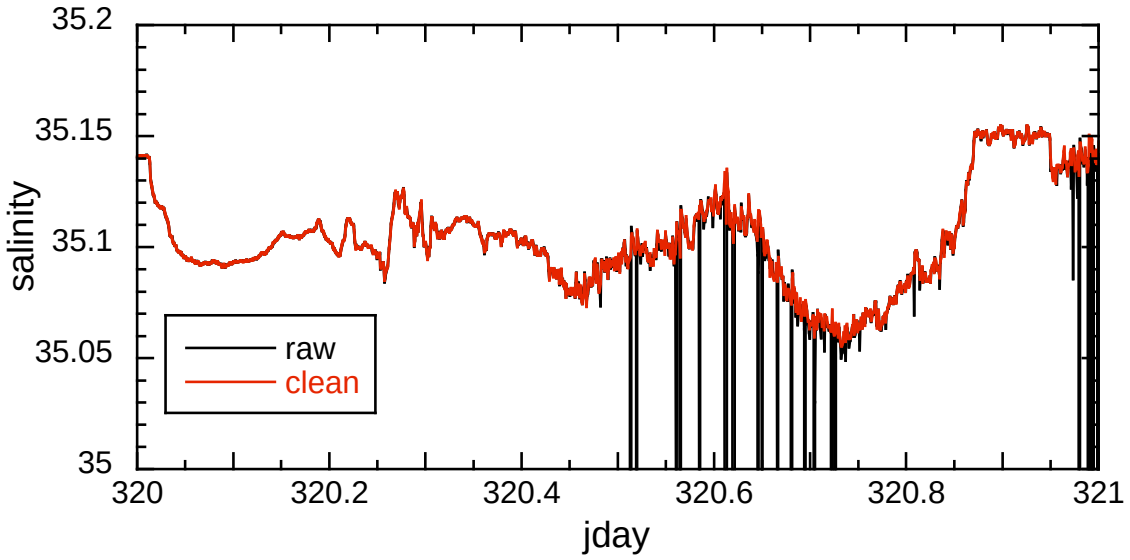

Figure 1 A section of the 2006 TSG salinity data showing the data before and after outliers were removed.

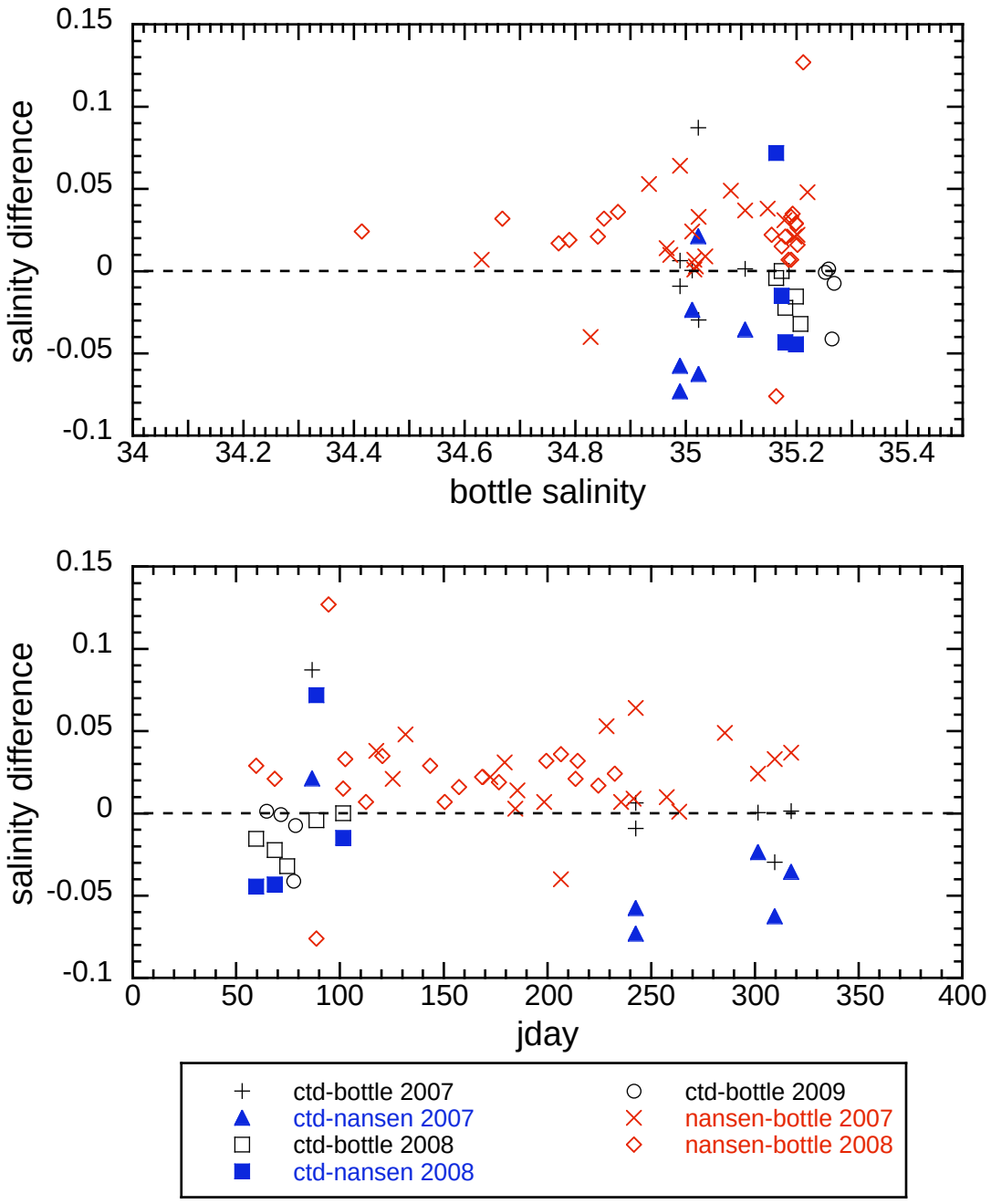

Figure 2 An intercomparison of the calibration data sets as shown in the key. Salinity differences against (top) salinity and (bottom) jday.

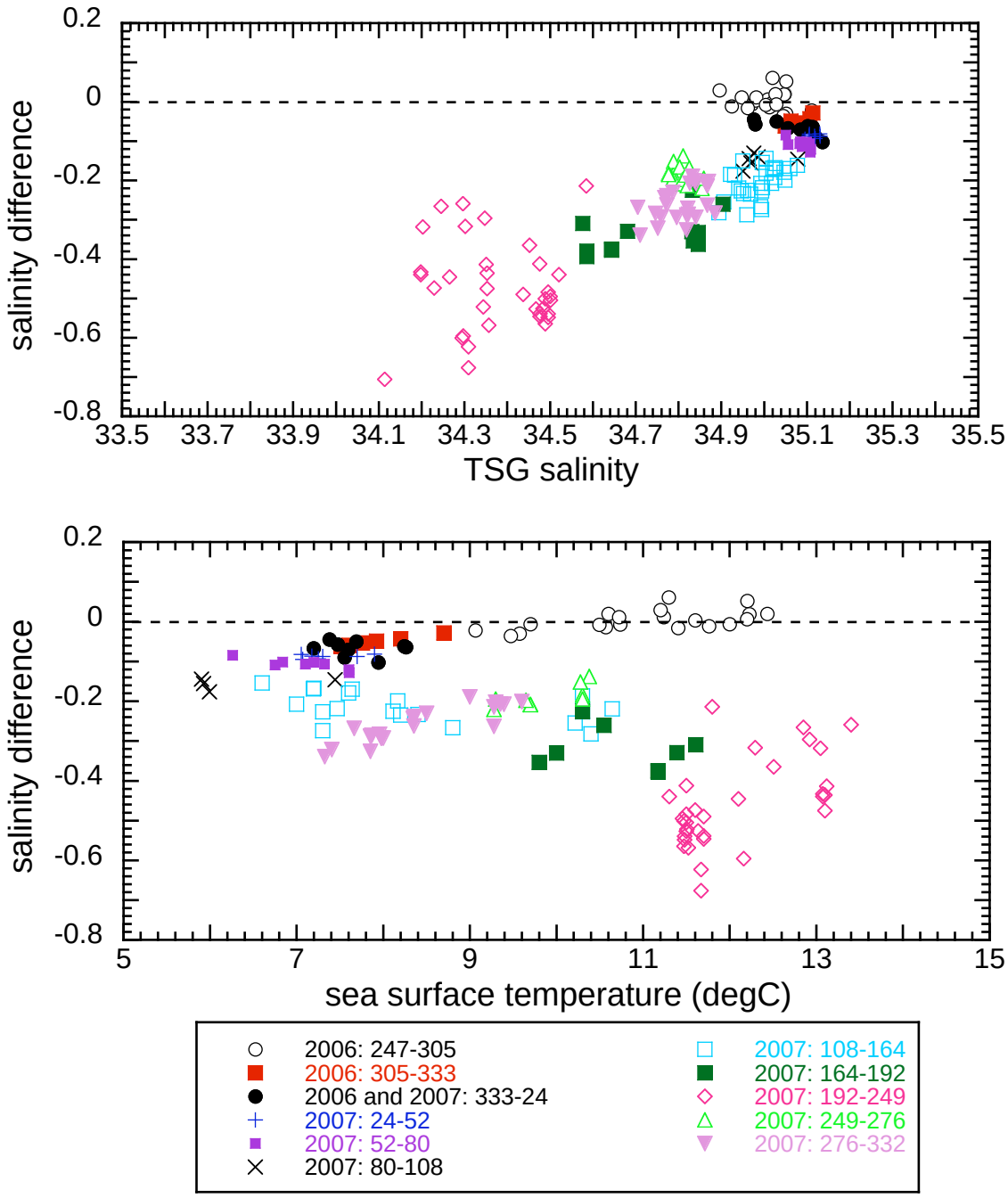

Figure 3 Salinity difference (TSG data - calibration data). The different symbols indicate different cleaning periods. The numbers in the legend indicate the year and jday.

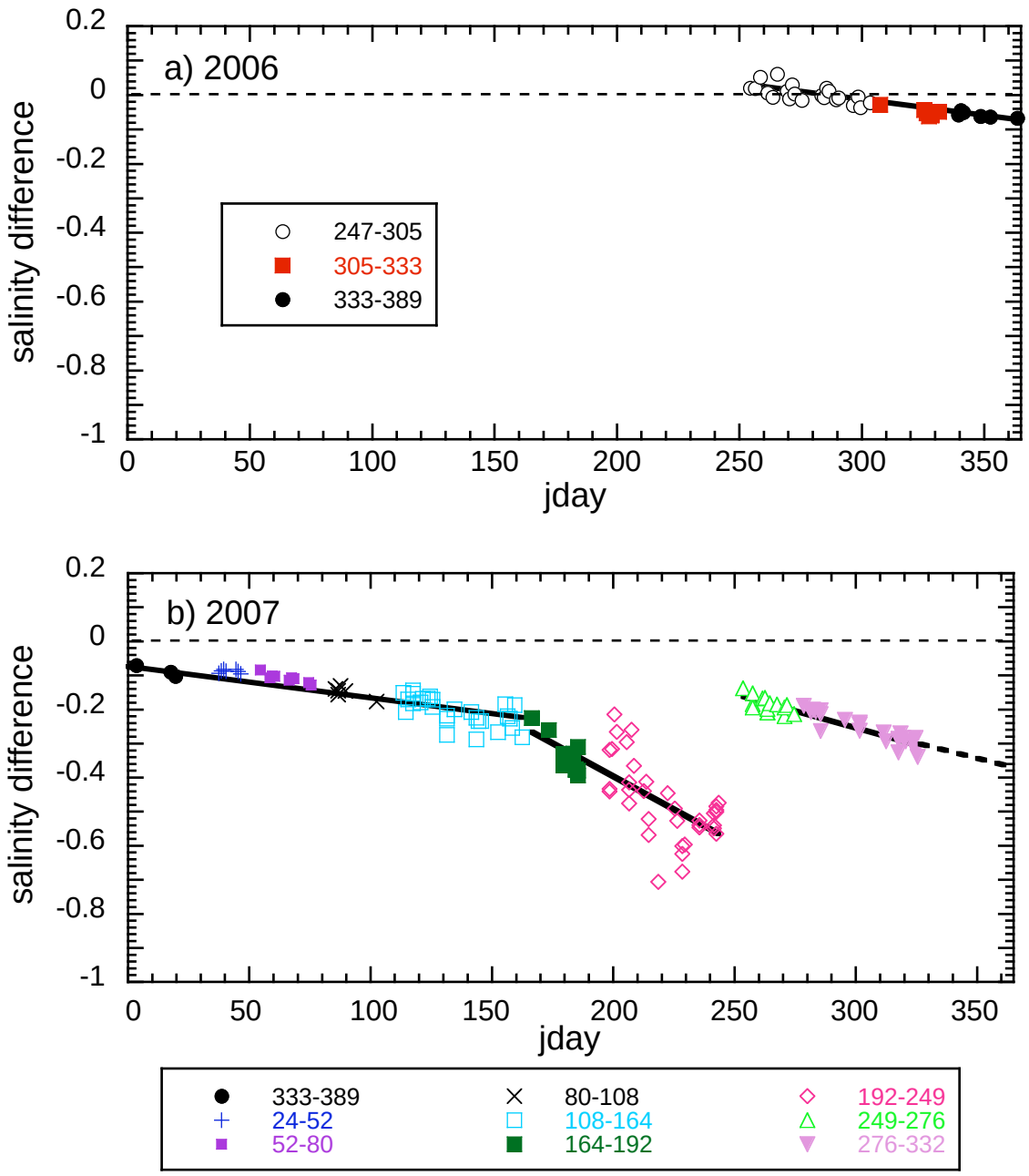

Figure 4. Three liner corrections fitted to the salinity difference (TSG data - calibration data). The thick dashed line indicates the regions where the correction has been extrapolated. The different symbols indicate the different cleaning periods of the TSG. The numbers in the legend indicate the jday.

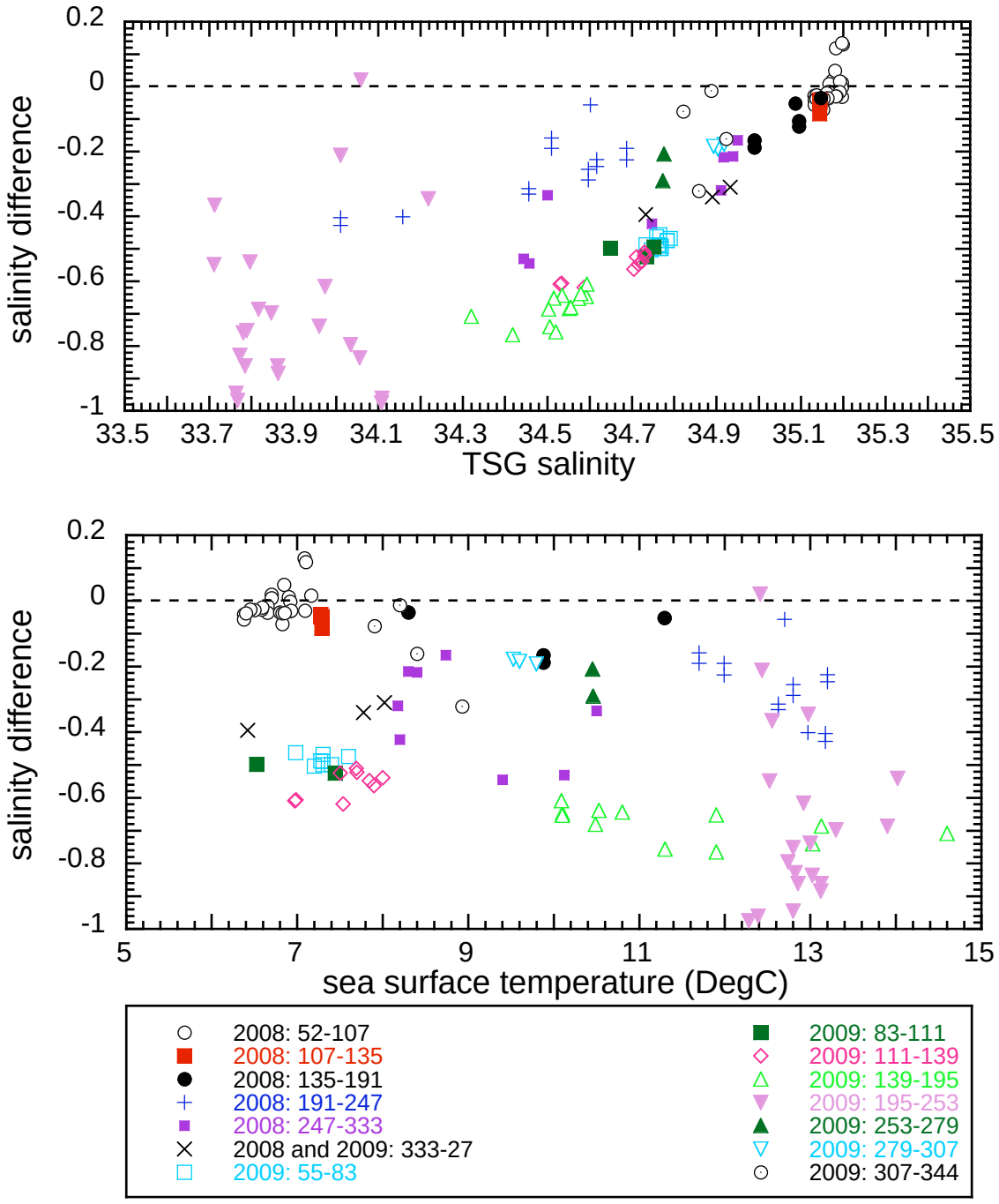

Figure 5 Salinity difference (TSG data - calibration data). The different symbols indicate different cleaning periods.

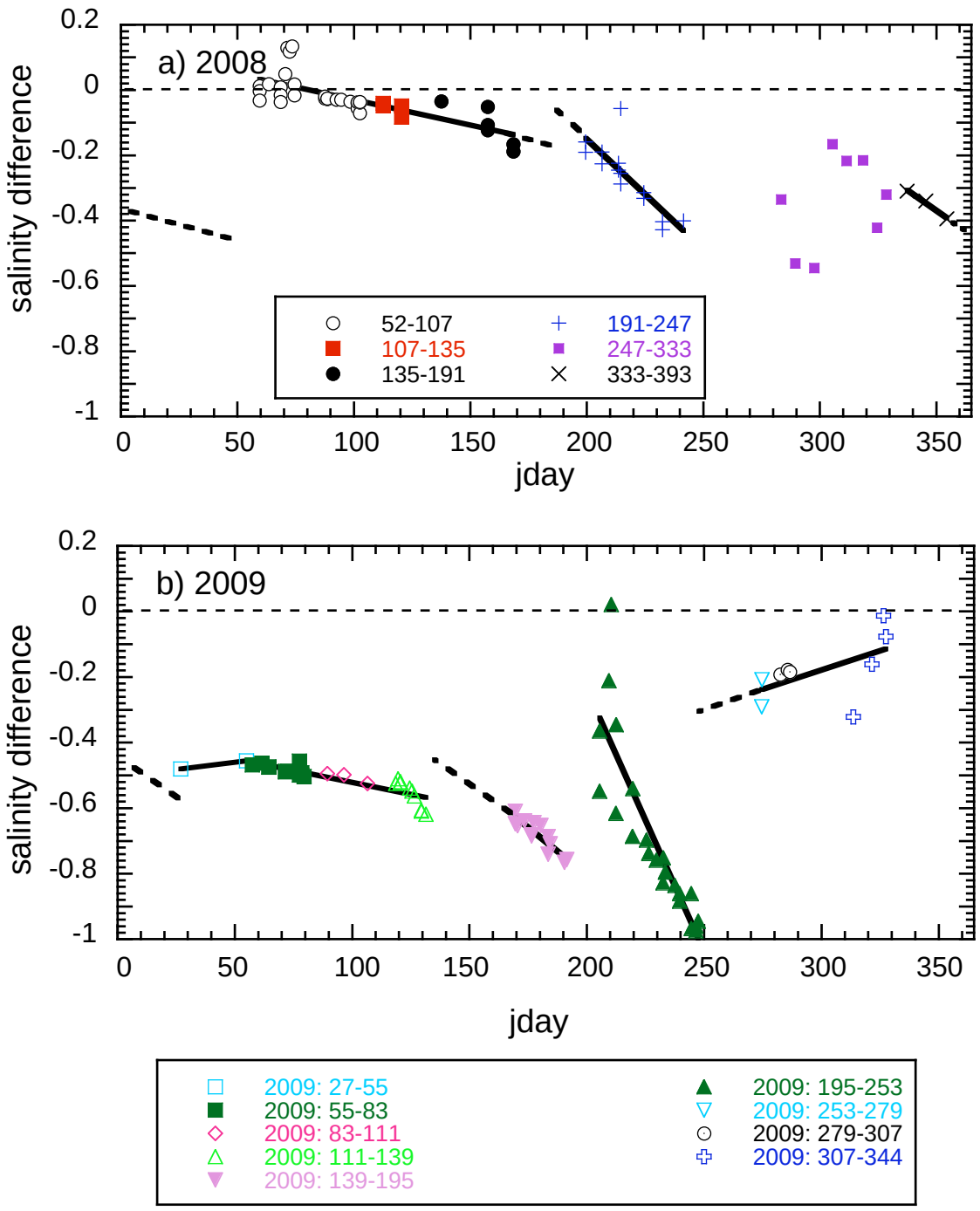

Figure 6 Linear corrections fitted to the salinity difference (TSG data - calibration data). The thick dashed lines indicate the regions where the correction has been extrapolated. The different symbols indicate the different cleaning periods of the TSG. The numbers in the legend indicate the jday. The large step in the correction on jday 52 2008 is when the TSG instrument was changed. NOTE that the "calibration" points used for the period 27-55 2009 were derived from the corrected TSG data either side of this period.

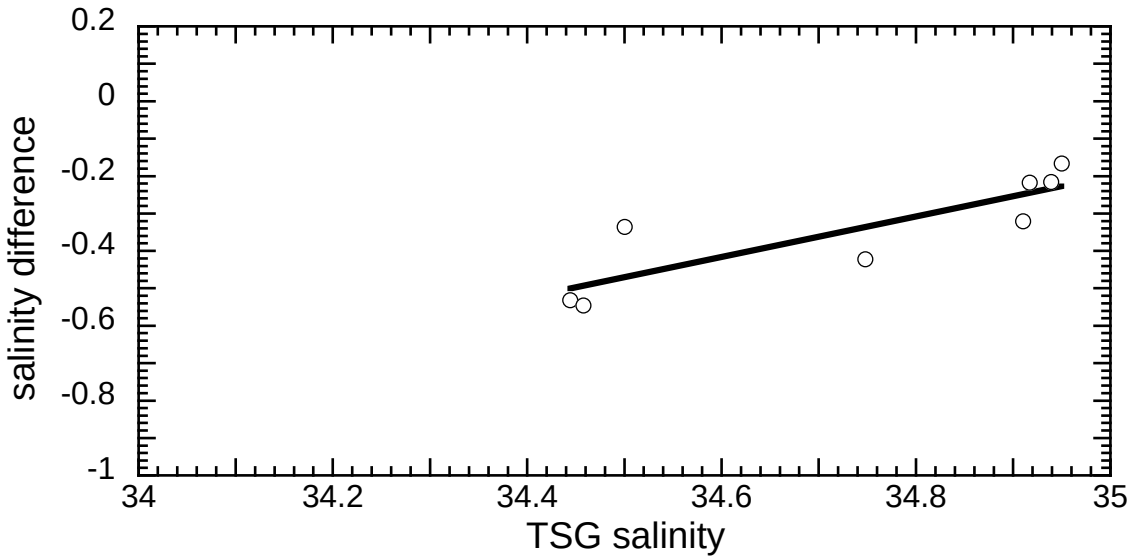

Figure 7 Linear corrections fitted to the salinity difference (TSG data - calibration data) for the period jday 247 to 333 during 2008.

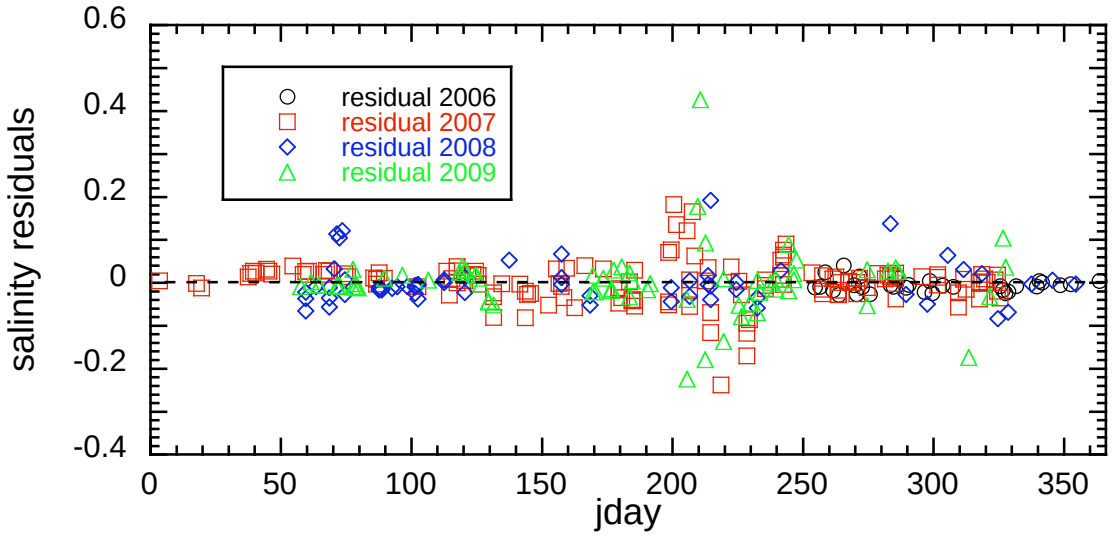

Figure 8 TSG salinity residuals (corrected TSG - calibration data).

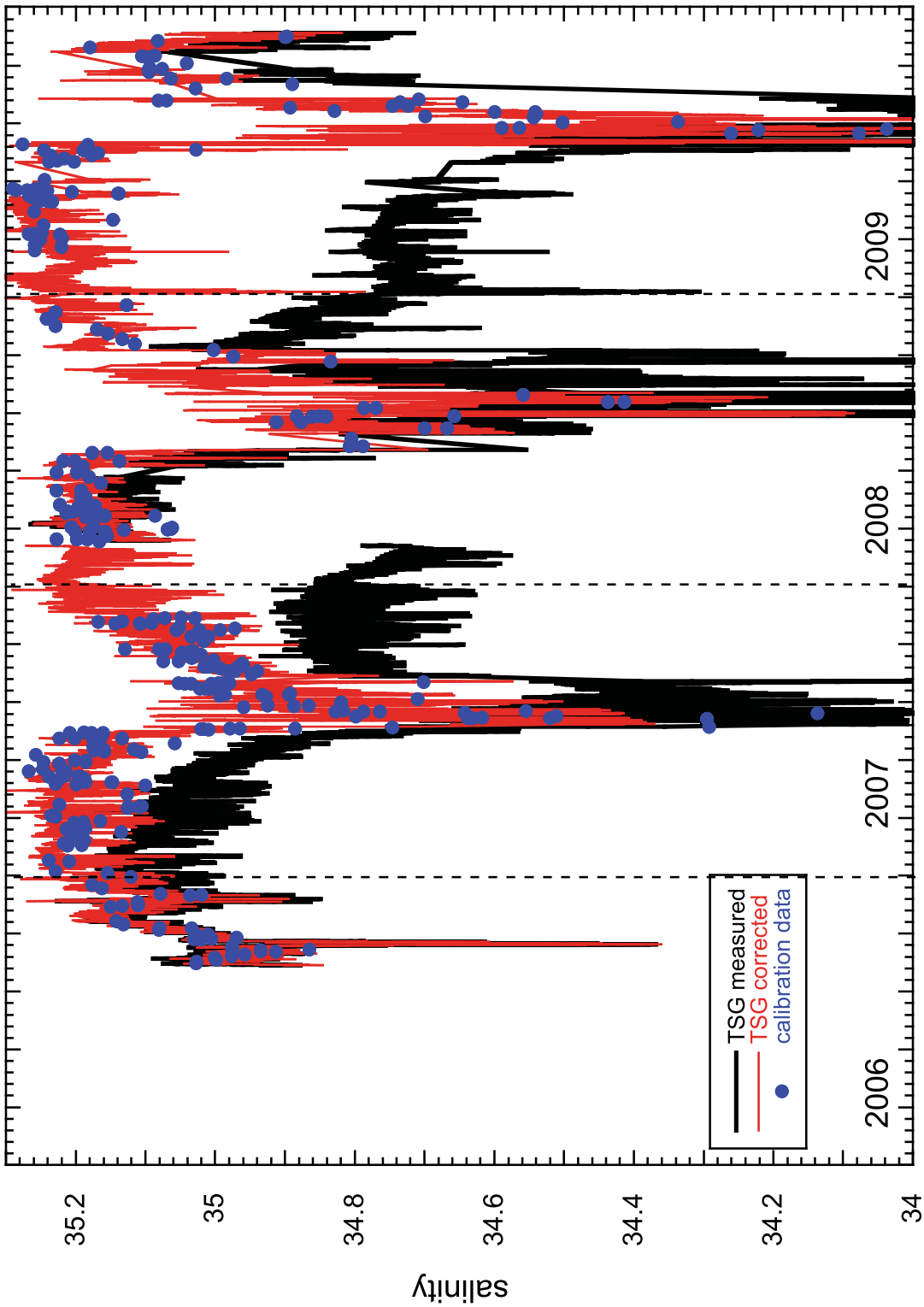

Figure 9. Hourly averaged raw and calibrated TSG data, along with individual calibration values, as shown in the key.

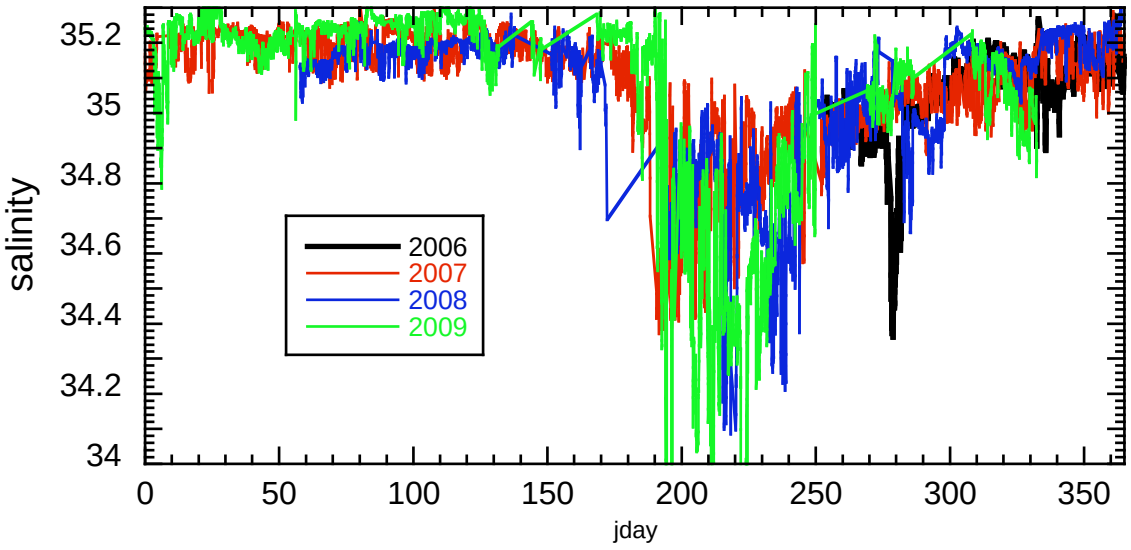

Figure 10. Calibrated TSG salinity data for each year overlaid.

Tables

Year	Day of year	Month	Day	Type of clean
2006	247	September	4	TSG S/N 4543156-0181
	305	November	1	Ordinary
	333	November	29	Ordinary
2007	024	January	24	Ordinary
	052	February	21	Ordinary
	080	March	21	Ordinary
	108	April	18	Ordinary
	164	June	13	Ordinary
	192	July	11	Ordinary
	249	September	6	Extended
	276	October	3	Extended
	332	November	28	Extended
2008	052	February	21	TSG S/N 4540927-0159
	107	April	16	Extended
	135	May	14	Extended
	191	July	9	Extended
	247	September	3	Extended
	274	September	30	Extended
	333	November	28	Extended
2009	027	January	27	Extended
	055	February	24	Extended
	083	March	24	Extended
	111	April	21	Extended
	139	May	19	Extended
	195	July	14	Extended
	253	September	10	Extended
	279	October	6	Extended
	307	November	3	Extended
	334	November	30	System removed

Table 1 The TSG cleaning dates.

	Surface CTD	Underway bottle	Nansen Bottle
2006	34	none	None
2007	106	22	22
2008	21	33	19
2009	57	33	None

Table 2 The number of calibration samples available.

Period (year: jday)	Equation number
2006: 247 to 2007: 164	1
2007: 164 to 2007: 249	2
2007: 249 to 2008: 052	3
2008: 052 to 2008: 191	4
2008: 191 to 2008: 247	5
2008: 247 to 2008: 333	6
2008: 333 to 2009: 027	7
2009: 027 to 2009: 055	8
2009: 055 to 2009: 139	9
2009: 139 to 2009: 195	10
2009: 195 to 2009: 253	11
2009: 253 to 2009: 344	12

Table 3 The equation numbers used to correct the TSG salinity data.