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Density and Absolute Salinity of the Baltic Sea 2006–2009

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Density and Absolute Salinity of the Baltic Sea 2006–2009

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Abstract

The brackish water of the Baltic Sea is a mixture of ocean water from the Atlantic/North Sea with fresh water from various rivers draining a large area of lowlands and mountain ranges. The evaporation-precipitation balance results in an additional but minor excess of fresh water. The rivers carry different loads of salts washed out of the ground, in particular calcium carbonate, which cause a composition anomaly of the salt dissolved in the Baltic Sea in comparison to Standard Seawater. Directly measured seawater density shows a related anomaly when compared to the density computed from the equation of state as a function of Practical Salinity, temperature and pressure.

Samples collected from different regions of the Baltic Sea during 2006–2009 were analysed for their density anomaly. The results obtained for the river load deviate significantly from similar measurements carried out forty years ago; the reasons for this decadal variability are not yet fully understood. An empirical formula is derived which estimates Absolute from Practical Salinity of Baltic Sea water, to be used in conjunction with the new Thermodynamic Equation of Seawater 2010 (TEOS-10), endorsed by IOC/UNESCO in June 2009 as the substitute for the 1980 International Equation of State, EOS-80. Our routine measurements of the samples were accompanied by studies of additional selected properties which are reported here: conductivity, density, chloride, bromide and sulphate content, total CO₂ and alkalinity.

1 Introduction

In June 2009, the International Thermodynamic Equation of Seawater 2010 (TEOS-10, McDougall et al., 2009a) was endorsed by the IOC¹ on its 25th General Assembly in Paris; it will be adopted as a new world-wide standard for oceanography on 1 January 2010. TEOS-10 takes Absolute Salinity, S_A , (the mass fraction of sea salt in seawater) as its input variable to represent the concentration of dissolved sea salt in seawater.

¹IOC: Intergovernmental Oceanographic Commission, <http://ioc-unesco.org>

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This choice contrasts with its predecessor, the International Equation of State of Seawater 1980 (EOS-80) which is formulated in terms of Practical Salinity, S_p , measured on the Practical Salinity Scale of 1978 (PSS-78) and representing a measure of the conductivity of a seawater sample. For the first time in the history of oceanographic standards since 1902, this conceptual transition encourages an explicit consideration of composition anomalies in the world ocean (McDougall et al., 2009b) as well as in estuaries such as the Baltic Sea. In practice, this choice requires the development of conversion formulae from Practical Salinity, available for example from a CTD cast, to Absolute Salinity involving additional parameters such as estimates of the composition anomalies or the geographic position, the depth and, if the anomalies vary significantly on seasonal or climatological scales, the time.

For the Baltic Sea, such an algorithm was first published by Millero and Kremling (1976), derived from extensive measurements (Kremling, 1969, 1970, 1972). Since later studies revealed relevant systematic changes of the empirical coefficients (Kremling and Wilhelm, 1997), *the first and main aim* of this paper is to propose an updated empirical formula for the computation of Absolute Salinity of Baltic seawater, based on samples taken between 2006 and 2009, for use in conjunction with TEOS-10, as recommended by the IOC with its recent Resolution XXV-7 (IOC 2009).

The composition anomaly of the salt dissolved in the Baltic Sea compared to the composition of Standard Seawater (Millero et al., 2008) is mainly caused by dissolution of CaCO_3 in river water and the subsequent input of Ca^{2+} and alkalinity/total CO_2 into the Baltic Sea by river discharge (Rohde, 1966; Nehring and Rohde, 1967; Kremling, 1969, 1970, 1972; Millero and Kremling, 1976). The alkalinity excess controls the pH of the Baltic Sea surface water which at the present atmospheric CO_2 partial pressure ranges between 7.8 and 8.2 (Nehring, 1980) and is similar to the pH of ocean water (Millero, 2007; Marion et al., 2009). Below the permanent pycnocline, the pH may decrease to 7.0–7.3 (Fonselius, 1967) due the the accumulation of CO_2 by the mineralization of organic matter. *The second aim* of this paper is to estimate the salinity anomaly on the basis of the state of the Baltic Sea CO_2 system characterized by

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the alkalinity and total CO_2 concentrations. On climatological time scales the alkalinity in the Baltic Sea may increase because the rising atmospheric CO_2 may enhance the weathering of CaCO_3 in the catchment area. The increased alkalinity input may affect the salinity anomaly but also has consequences for the Baltic Sea acid/base system since it counteracts the pH decrease associated with increasing atmospheric CO_2 .

An estimate of the CaCO_3 excess of the Baltic Sea compared to Standard Seawater is required for chemical composition models of seawater such as FREZCHEM (Feistel and Marion, 2007) which can be used to evaluate the calcium carbonate supersaturation in relation to atmospheric CO_2 levels (Marion et al., 2009). Since the density anomaly of the Baltic Sea is varying on climatological time scales, *the third aim* of this paper is to provide a more recent anchor point for this model in relation to similar but more extensive investigations made forty years ago by Kremling (1969, 1970, 1972) and Millero and Kremling (1976).

The fourth aim of this paper is a conceptual one, related to the former ones. The different oceanographic salinity scales that are in use since 1902 are not metrologically traceable to SI units (Seitz et al., 2008). Both PSS-78 and the recent Reference-Composition Salinity Scale (Millero et al., 2008) are defined in terms of relative conductivity measurements with artefacts such as IAPSO Standard Seawater (SSW) or a potassium chloride solution used as a reference. Reliance on such artificial references introduces the risk of unnoticed property changes over time or between different samples. It would therefore be preferable to establish traceability to the highly reliable and independently realisable standards of the International System of Units (Jones, 2009). The SCOR²/IAPSO³ Working Group 127 (WG127) on the Thermodynamics and Equation of State of Seawater is currently developing a new concept for the measurement of Absolute Salinity based on SI-traceable density determinations (Wolf, 2008). The Baltic Sea with its strong density anomaly and pronounced trends in its properties is

²SCOR: Scientific Committee on Oceanic Research, <http://www.scor-int.org>

³IAPSO: International Association for the Physical Sciences of the Ocean, <http://iapso.sweweb.net>

a prominent example of the need for the development of this approach and a useful testing ground for the new but yet immature calibration technology. For this reason, we have carried out comparison measurements of conductivity and density in an SI-traceable way and we report the results in this paper. The presentation of results is accompanied by selected chemical composition data.

2 Salinity of Standard and Baltic Seawater based on previous measurements

Since the introduction of the Practical Salinity Scale, the electrolytic conductivity C of a seawater sample is practically measured by salinometers or conductivity sensors, calibrated with respect to a certified IAPSO Standard Seawater reference. The measured conductivity ratio is converted to conductivity using $C=4.2914 \text{ S m}^{-1}$ at $S_P=35$, $t=15^\circ\text{C}$ and $P=101\,325 \text{ Pa}$ (Culkin and Smith, 1980; SeaBird, 1989) and from C , the temperature T and the pressure P , Practical Salinity S_P is computed from the function (Perkin and Lewis, 1980)

$$S_P = s(C, T, P). \quad (1)$$

Over the range of concentrations where Practical Salinity is defined, it can be converted to Reference Salinity, S_R , by the factor $u_{PS}=(35.16504 \text{ g kg}^{-1})/35$ (Millero et al., 2008; Feistel, 2008):

$$S_R = S_P \times u_{PS}. \quad (2)$$

For Standard Seawater, S_R is the most accurate estimate currently available for the Absolute Salinity. Given S_R , the corresponding density estimate can be determined from the Gibbs function $g(S_R, T, P)$ of seawater (Feistel, 2008; IAPWS, 2008; McDougall et al., 2009a):

$$\rho = \frac{1}{g_P(S_R, T, P)} \quad (3)$$

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Here, the subscript P denotes the partial derivative with respect to the pressure, and T and P are the temperature and pressure at which the density is required, e.g. at laboratory conditions. T and P will be omitted from the equations below for simplicity. In the case of Standard Seawater, Eq. (3) provides our best estimate of the true density, ρ^{SSW} . In the case of Baltic Seawater, (3) yields an apparent density that is subject to significant error. The anomaly of the true Baltic seawater density relative to this rather uncertain estimate can be determined by measuring the true density, ρ^{BSW} , with a vibration densitometer (Kremling, 1971; Millero and Kremling, 1976). The Absolute Salinity, $S_A^{\text{BSW}} = S_R + \delta S_A$, of Baltic seawater can then be estimated by the “density salinity”, i.e., by computing the Absolute Salinity of Standard Seawater giving the measured density of Baltic seawater, from the formula (Millero et al., 2008),

$$\rho^{\text{BSW}} = \frac{1}{g_P(S_R + \delta S_A)} \approx \frac{1 + \beta \times \delta S_A}{g_P(S_R)}, \quad (4)$$

i.e., $\delta S_A = (\rho^{\text{BSW}} g_P - 1) / \beta$. Here, $\beta = -g_{SP} / g_P$ is the haline contraction coefficient.

In Fig. 1, the anomaly $S_A^{\text{BSW}} - S_R$ is shown as a function of S_R for 153 samples collected 40 years ago by Kremling (1969, 1970, 1972), computed by means of (2)–(4) from the published values of measured Practical Salinity, S_P , and the measured density, ρ^{BSW} .

The correlation relating “density salinity” to Practical Salinity is easily obtained since both Practical Salinity and density are easily measured on a regular basis. Based on Kremling’s data, the regression line is

$$\delta S_A = S_A - S_R = 0.00428 \times (S_{\text{SO}} - S_R) = 150 \text{ mg kg}^{-1} \times \left(1 - \frac{S_R}{S_{\text{SO}}}\right). \quad (5)$$

The fit was constrained to pass through ($S_R = S_{\text{SO}}$, $\delta S_A = 0$) because the Atlantic water part of the brackish mixture is free of the Baltic anomaly (Millero and Kremling, 1976). Here, the standard-ocean salinity is $S_{\text{SO}} = 35 \text{ u}_{\text{PS}} = 35.16504 \text{ g kg}^{-1}$ (Millero et al., 2008).

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The strong scatter visible in Fig. 1 at very low salinities is due to the inhomogeneous water properties caused by the very different loads of the many discharging rivers. The sampling is patchy, but adequate for the present purpose. The calcium carbonate that is primarily responsible for the Absolute Salinity anomalies is mainly carried by rivers draining the European lowlands, while the Scandinavian rivers flow over solid rocks and are subsaturated with respect to lime (Kwiecinski, 1965). Spatial distributions of the river water age (Meier, 2007) indicate weak lateral mixing of the properties between the various rivers which contributes to the spatial inhomogeneity of the Baltic surface water. The absence of a significant basin-wide mean surface circulation is evident from the climatological horizontal salinity gradient, Fig. 2 (Feistel et al., 2008).

Entrainment from below the pycnocline adds aged, mixed and possibly chemically transformed riverine solutes to the surface layer (Reissmann et al., 2009). In the deep water of the estuarine Baltic Sea environment, the dissolved species may be subjected to either reducing or oxidizing conditions that are sustained for extended periods of time (Nausch et al., 2008). The time scales associated with these processes are of the order of decades (Stigebrandt and Wulff, 1989; Meier et al., 2006; Feistel et al., 2008).

In the special case in which the stoichiometric deviation from the reference composition is caused by an excess of non-conducting solutes with low concentrations, the value of S_R represents the mass fraction of sea salt with reference composition in the sample, and δS_A represents the anomalous mass fraction of non-conducting species, at least to a practically reasonable accuracy. This can safely be assumed for the silicate anomaly in the North Pacific (McDougall et al., 2009b), but it is not generally the case in the Baltic Sea since the additional CaCO_3 dissociates and increases the conductivity by a non-zero amount, evidently less than what would result from adding the same mass of sea salt that has Reference Composition. Similarly, the algorithms used to estimate Practical Salinity at temperatures and pressures different from 15°C and $101\,325\text{ Pa}$ are not valid in the presence of the composition anomalies and Eq. (1) results in inconsistent estimates, which can result in the appearance that the salinity is not conservative when subjected to temperature or pressure changes. Consequently,

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the correlation shown in Fig. 1 may look different depending on the particular T or P at which the measurements were carried out in the lab. However, a study dedicated to this problem (Feistel and Weinreben, 2008) came to the conclusion that these apparent non-conservation effects for Baltic seawater do not exceed the measurement uncertainty over a reasonable temperature interval at atmospheric pressure. Consequently, the parameterisation of the Absolute Salinity of Baltic Sea water as a function of Reference Salinity is stable with respect to temperature variations at atmospheric pressure and is thus justified for application in the context of TEOS-10 (McDougall et al., 2009a).

The above approach to estimating Absolute Salinity relies on an empirical relation between Absolute and Practical Salinity in the Baltic Sea. It does not permit the separate estimation of the contributions from riverine input into the Baltic Sea and from the sea salt flowing in from the Atlantic. This separation is possible using measurements of the chlorinity, Cl , rather than conductivity since no relevant amounts of chlorine, bromine or iodine are discharged from the tributaries. Chlorinity can thus be used to estimate the Absolute Salinity contribution associated with input from the Atlantic and subtracting this value from the density salinity will provide an estimate of the contribution associated with local inputs. Millero and Kremling (1976) performed their correlation analysis based on chlorinity data. Two drawbacks of this method are that chlorinity is not a concentration measure to be used with TEOS-10, and silver titrations are not carried out regularly on modern research or monitoring cruises in the Baltic. Nevertheless, the approach can be used to separate the salt inputs from the Atlantic and from local runoff and to provide a comparison with the conditions found earlier by Knudsen (1901) and Sørensen (Forch et al., 1902).

For Standard Seawater, the Reference Salinity S_R can be computed from the chlorinity by multiplying by the factor $u_{Cl}=1.80655 \times u_{PS}$ (Millero et al., 2008; Feistel, 2008). For Baltic Sea water the result will differ from S_R , and is therefore referred to here as “chlorinity salinity”, S_{Cl} :

$$S_{Cl} = Cl \times u_{Cl} = 1.80655 \times Cl \times u_{PS}. \quad (6)$$

Using the chlorinity, Cl , and the density, ρ^{BSW} , data measured by Kremling (1969, 1970, 1972) and Millero and Kremling (1976) together with (4) in the form,

$$\rho^{\text{BSW}} = \frac{1}{g_P (S_{Cl} + \delta S^{\text{RI}})} \approx \frac{1 + \beta \times \delta S^{\text{RI}}}{g_P (S_{Cl})}, \quad (7)$$

the regression line for the river input, δS^{RI} , Fig. 3, is determined as

$$\delta S^{\text{RI}} = S_A - S_{Cl} = 0.00492 \times (S_{SO} - S_{Cl}) = 173 \text{ mg kg}^{-1} \times \left(1 - \frac{S_{Cl}}{S_{SO}}\right). \quad (8)$$

The difference between (5) and (8) is caused by the fact that the riverine input includes calcium carbonate and other solutes which alter the impact on the electrical conductivity compared to the effect of diluting with pure water whereas the riverine input includes no corresponding input of halides. Because of this latter fact, the intercept at $S_{Cl}=0$ corresponds to no contribution from North Atlantic water and provides a direct estimate of the contribution to Absolute Salinity due to the salt content of the local riverine inputs.

Millero and Kremling (1976) did an analogous fit to their data set with 153 samples but found an intercept at zero chlorinity of only $S_A^0=124 \text{ mg kg}^{-1}$. The reason for this difference is probably the older equation of state used at that time (F. J. Millero, personal communication, 2009).

It is also possible to estimate the relation corresponding to (8) based on data from the early 20th century. The Knudsen (1901) equation, $S_K=0.03 \text{ g kg}^{-1} + 1.805 Cl$, was calculated from Sørensen's analysis of 9 surface water samples, including 6 from the Baltic Sea, in particular, one from the Gulf of Finland, one from Gulf of Bothnia, two from the Great Belt and two from the Kattegat (Forch et al., 1902), which are reported for easy reference in Table 8.

The numerical value of S_K in g/kg or ‰ coincides with Practical Salinity (only) at $S_P=35$ which was used by PSS-78 to specify the coefficient relating S_P to Cl . Converting the chlorinity to a salinity estimate using (6), $S_{Cl}=C/u_{Cl}$, effectively gives the Absolute Salinity of Standard Seawater with this chlorinity. In addition, the absolute Knudsen

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salinity, S_K , can be corrected for the loss of volatile substances such as HCl using the factor relating Practical Salinity to Reference-Composition Salinity, thus providing an improved estimate of the true Absolute Salinity, $S_A = S_K / \left(\text{g kg}^{-1} \right) \times u_{PS}$. Using these two relations, the 1901 equation reads

$$S_A - S_{Cl} = 0.00086 \times (S_{SO} - S_{Cl}) = 30 \text{ mg kg}^{-1} \times \left(1 - \frac{S_{Cl}}{S_{SO}} \right). \quad (9)$$

The uncertainties associated with this formula are unknown, but probably quite large due to the small number of data inputs used to derive Knudsen's formula. Nevertheless, the slope and the intercept corresponding to the Knudsen equation are significantly lower than the more recent values, Fig. 3. Since the intercept at $S_{Cl}=0$ provides an estimate of the "density salinity" of local riverine inputs, this seems to indicate that the calcium carbonate content of these inputs increased significantly between the end of the 19th century and 1970. In a similar regression, Ohlson and Anderson (1990) calculated the riverine calcium concentration rising from $521 \mu\text{M}$ (1938) to $571 \mu\text{M}$ (1967) and $878 \mu\text{M}$ (1986), which correspond to approximately 52, 57 and 88 mg/kg in terms of CaCO_3 , respectively. M used to be the unit of amount-of-substance-concentration (molarity); its use is discouraged within the SI system. The results of Kremling and Wilhelm (1997) indicate that this increase continued between 1970 and 1995.

The relation between salinity, electrolytic conductivity and chlorinity in the Baltic Sea is not as well understood as for Standard Seawater (Millero et al., 2008). Kremling (1969, 1970, 1972) calculated separate correlation equations between measured pairs of chlorinity and Practical Salinity values for different subsets of his data; the salinity intercepts at zero chlorinity varied between 0.023 and 0.041. The difference between Reference Salinity (2) and chlorinity salinity (6) for Kremling's data is displayed in Fig. 4 as a scatter plot. The regression line is given by,

$$S_R - S_{Cl} = 0.00058 \times (S_{SO} - S_{Cl}) = 20 \text{ mg kg}^{-1} \times \left(1 - \frac{S_{Cl}}{S_{SO}} \right). \quad (10)$$

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In the absence of ocean water, $S_{Cl}=0$, (10) indicates a residual Reference Salinity of $S_R=20$ mg/kg. Dividing by ν_{PS} to convert to Practical Salinity and then using standard algorithms to invert (1) gives an average conductivity of about $C \approx 2.7$ mS m⁻¹ for the Baltic river waters at 20°C.

5 In a systematic study, Kwiecinski (1965) found that although the anomalous temporal or regional increase in the Practical Salinity usually follows that of calcium, there is no constant relation between them, and that additional factors such as the pH, the alkalinity or the dissolution of CO₂ may be important. Numerical composition models (Anderko and Lencka, 1997; Feistel and Marion, 2007; Pawlowicz, 2008) may provide
10 more detailed insight in the future. The composition of the Baltic Sea salt measured by different authors was summarized by Nehring (1980) as given in Table 1 in comparison to the Reference Composition (Millero et al., 2008).

3 Experimental methods used for recent measurements

15 In this section the experimental methods and uncertainties are described with regard to the samples collected from the Baltic Sea during the period 2006–2009. Results of the measurements are reported in the Digital Supplement of this paper (see <http://www.ocean-sci-discuss.net/6/1757/2009/osd-6-1757-2009-supplement.zip>).

3.1 Sample collection

20 The Baltic Sea water samples were collected from 2006 to 2009 at the positions shown in Fig. 5. The bottle depth ranged between the surface and 400 m. A total of 438 samples were analysed.

25 On the vessel, most of the samples were filled into Duran[®]-glass bottles (volume: 100 ml) by means of a CTD SBE-911 rosette equipped with IOW-freeflow samplers. Only the samples from the stations “FYxx” were collected from the cooling water inlet of the ferry and filled into PET plastic bottles.

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3.2 Routine salinometer and density measurements

For the determination of Practical Salinity, salinometers of the type AUTOSAL 8400B (Guildline Instruments, Canada) were used. Measurements of Practical Salinity were performed according to the rules of WOCE Operations and Methods (Stalcup, 1991).

5 Once a day the salinometer was first adjusted with IAPSO Standard Seawater (SSW) and the SSW density was then determined with the densitometer.

The results of the density measurements of Standard Seawater are shown in Fig. 6. The deviations from zero must be attributed to the stability of the SSW samples and the measuring technique. The calculations refer to the Practical Salinity value given
10 on the ampoule's label. Practical Salinity measurements could not be done because the SSW samples were used for the calibration of the salinometer. For SSW (only P-series) we found a mean value of the difference δS_A of -4.2 mg/kg with a standard deviation of 2.1 mg/kg. There is a slight dependence on the age of the sample. The related regression line is

$$15 \delta S_A / (\text{mg/kg}) = 0.0032 d - 6.1453, \quad (11)$$

where d is the age of the sample in days. For SSW (10L-series) the distribution and number of measurements was inadequate for reliable regression results to be obtained.

Measurements of the density were done by means of a densitometer DMA 5000 (Anton Paar, Austria). The device was calibrated daily with air and pure water. Measurements of the density and salinity were carried out at the same time as soon as
20 possible after collecting the samples on board, or after returning to IOW's laboratory. If the time that passed between collection and analysis of the samples was longer than one day, the samples were stored in a dark and cool place.

Because of the strong stratification in the Baltic Sea it must be assumed that the
25 content of a 5L-freeflow sampler is not necessarily homogeneous. For better results, 3 Duran[®] bottles were filled. The measurements of salinity and density were done with seawater from the same glass bottle. Before the measurements were made, the bottle

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temperatures were adjusted to the room temperature (circa 23°C). After uncapping the bottle a 20 ml disposable syringe was filled for the density measurements. Then the bottle was fitted with an adapter for a peristaltic pump. A peristaltic pump was connected to the salinometer for measuring the salinity of the sample.

5 High precision density measurements require very careful handling and elaborate procedures. To reduce the measurement uncertainty a procedure similar to that described by Wolf (2008) was used. Measurements were performed in the following order: with pure water (3 measurements), with the sample A (6 measurements), the sample B (6 measurements), and again with pure water (3 measurements). The formation of air bubbles inside the measuring cell was a severe problem that had to be
10 solved. Baltic Sea water has typical in-situ temperatures below the measuring temperature of the densitometer, 20°C. Because of the reduced gas solubility, the samples tend to form air bubbles in the oscillator which lead to significant errors in the readings. As a special procedure, the syringe to be filled was equipped with a hypodermic needle.
15 After insertion into the sample the plunger of the syringe was pulled back rapidly. The limited filling rate through the narrow needle forced a low pressure in the syringe and produced air bubbles in the syringe. These air bubbles were pushed outside. Then the syringe was attached to the inlet of the densitometer and one half of the content was pushed into the measuring cell. Three measurements were carried out and there-
20 after a further quarter of the syringe volume was pressed inside and three additional measurements were done.

To investigate the influence of suspended particles, a large fraction of the samples were measured with and without a polycarbonate syringe filter (0.2 μm). The comparison of the measurements of filtered and unfiltered samples is shown in Fig. 7.
25 The influence of the filtration is not easy to determine because the two samples were stored in different flasks. The flasks were collected from the same water bottle of the CTD rosette, but this does not automatically imply that the water of both flasks has the same properties because the water in the bottle is usually stratified. Thus the shown difference of δS_A between unfiltered and filtered samples depends not only on the influ-

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ence of filtration but also on the slightly different intrinsic properties of the two samples. We found a mean value of the difference of δS_A of 1.4 mg/kg with a standard deviation of 4.9 mg/kg. For comparison, the differences of S_R are additionally displayed in Fig. 7. The mean value of the differences of S_R is 1.7 mg/kg with a standard deviation of 20.4 mg/kg.

3.3 “Absolute” conductivity

Although the concept of an “absolute” measurement makes no sense from a strict metrological point of view, we will use this term for convenience to distinguish the measurements discussed here from those described in the previous section. Every quantity value that is indicated by a measuring device is inherently relative, since it is inevitably referred to something. Therefore metrological terminology prefers talking about *traceability* of a measurement result (VIM, 2008). This concept characterises the quantitative link between the indicated result and the quantity value that has been assigned to an agreed standard by a measurement or production procedure. The link is established by calibration measurements. In this sense the commonly measured conductivity ratio used to calculate practical salinity is traceable to the K_{15} ratio, which is indicated on Standard Seawater (SSW) ampoules used for device calibration. The production procedure for SSW according to PSS-78, which in particular links the electrolytic conductivity of SSW to that of the defined potassium chloride solution, must be seen as the corresponding primary procedure to realize K_{15} . In contrast, an “absolute” conductivity measurement result must be understood as traceable to the quantity value of a primary standard of the International System of Units (SI), which is realized by a primary measurement procedure. In the following we will use the expression “absolute” as a shorthand expression for this important concept of traceability.

A measuring system for absolute electrolytic conductivity C calculates it from a conductance measurement of a conductivity measuring cell that is filled with the solution

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under investigation:

$$C = K \times G. \quad (12)$$

K is the so called cell constant (not to be confused with the conductivity ratio K_{15} of SSW). Commercial conductivity meters typically measure the conductance G with respect to an (arbitrary) internal reference. In order to calculate absolute conductivity, therefore K is determined by a calibration using a reference solution of known absolute conductivity. In contrast, in a primary conductivity measurement method, under the condition of a specific cell design, K is determined by geometric measurements, while G is deduced from measured impedance spectra (Brinkmann et al., 2003). Since all quantities are measured traceable to the SI, this method allows for the realization of primary conductivity standards whose conductivity values are consequently traceable to the SI, too. Note that conductivity is usually indicated at a defined temperature T_0 . Thus the actual temperature T of the solution during the measurement is also measured and the measured conductivity value is corrected to T_0 .

In the present study we used the primary measurement method of the Physikalisch-Technische Bundesanstalt (PTB) (Brinkmann et al., 2003) to measure the absolute conductivity C_S of three samples from stations 361, ABB and 213, Fig. 5. After arrival, the samples were stored under cold and dark conditions. Prior to measurement the samples and the conductivity measuring cell were brought to a set temperature of 15°C (ITS-90) over night in a temperature bath. We additionally measured the absolute conductivities C_{SSW} of IAPSO SSW/P-series (batch P149) and 10L10-series (Practical Salinity 9.926, dated 14 June 2006) and calculated the conductivity ratio

$$R_{15} = \frac{C_S}{C_{SSW}} K_{15} \quad (13)$$

of the samples under investigation in order to scale the absolute conductivity measurement results to PSS-78. K_{15} ratios were taken from the SSW ampoules (0.99984 for P-series and 0.31712 for L10-series). Conductivity values have been linearly corrected to

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15°C (IPTS-68) using a temperature coefficient of 1.97%/K. Finally we calculated Practical Salinity from the PSS-78 formula (Perkin and Lewis, 1980). The uncertainty of the absolute conductivity results includes contributions from the determination of temperature, conductance and the cell constant, and accounts for the statistical spread of the indicated values. Uncertainty propagation was calculated according to GUM (2008).

3.4 High-accuracy density measurements

Highly accurate density measurements at the PTB Braunschweig were performed for comparison with an oscillation-type density meter (Anton Paar DMA 5000) using a substitution method (Wolf, 2008). In a substitution method the sample to be measured and a reference sample are measured alternately several times. This method decreases the measurement uncertainty considerably as contributions to the uncertainty are mostly correlated and thus vanish when looking for the difference between sample and reference.

The reference liquid was ultra pure degassed water. The deviation of its density from seawater is below 3%; thus, a very good correlation of the measurements performed on seawater and on ultra pure water is obtained provided that the handling of the samples is the same. The water we used was de-ionised reverse osmosis water (Milli-Q water; Millipore, USA) with a resistance of 18.2 M Ω cm and total organic carbon of less than 10×10^{-9} immediately after purification. It was made from Braunschweig tap water. The reference density value was taken from the IAPWS-95 formulation (Wagner and Pruß, 2002). A correction was made for the isotopic composition. This was measured to be $-8.5 \delta\text{‰}$ for ^{18}O and $-59 \delta\text{‰}$ for D compared to Vienna Standard Mean Ocean Water. Thus, the density reference value for this Braunschweig tap water is 999.0996 kg/m 3 at 15°C.

An uncorrelated uncertainty contribution is given by the reproducibility of the device measurement temperature $\Delta t_{\text{reproducibility}}$; it was measured to be below 3 mK. Another uncertainty contribution arises from the deviation of the device measurement temperature Δt_{device} from the absolute temperature. This can be expressed as a calibration

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uncertainty of the measurement temperature. With our device Δt_{device} was measured to be 0 mK at 15°C and –5 mK at 25°C. The uncertainty of individual temperature measurements is ± 5 mK. Typical temperature deviations for other devices of the same type are 20 mK. The two temperature deviations act in a different way for seawater and for ultra pure water, as their effect on density is given by multiplying with the thermal expansion coefficient which is different for seawater and for ultra pure water:

$$\rho_{\text{pure water measured}} = \rho_{\text{pure water}}(1 + \gamma_{\text{pure water measured}}(\Delta t_{\text{device}} + \Delta t_{\text{reproducibility}}))$$

$$\rho_{\text{seawater measured}} = \rho_{\text{seawater}}(1 + \gamma_{\text{seawater measured}}(\Delta t_{\text{device}} + \Delta t_{\text{reproducibility}})).$$

A third uncorrelated uncertainty contribution is caused by the different handling of the samples concerning its gas content. The ultra pure water is degassed and will remain degassed during the measurement, whereas the seawater is saturated with air. The gas content is determined by the storage temperature of the seawater; during the short time the sample is cooled or heated to the measuring temperature (about 15 min) no new equilibration will occur. Thus, the storage temperature affects the density by the gas content. This effect can be reduced by storing the samples at well controlled reproducible conditions. In our measurements we stored the samples at refrigerator temperatures and warmed them up to room temperature over night before measuring. The contribution of this handling to the combined uncertainty (GUM, 2008) is not investigated up to now and, thus, estimated to be rectangular with a halfwidth of 0.5 ppm.

3.5 Ion chromatography

The mass fractions of chloride, bromide and sulphate of the samples 361, ABB and 213 were determined by means of ion chromatography. For validation purposes the mass fractions of the same anions were measured in a P149 SSW sample. The P149 results for chloride and sulphate were compared to earlier results on sample P149 determined also by ion chromatography but using a different instrumental configuration.

The ion chromatography system used here consisted of a Metrohm 881 Compact IC pro (Metrohm, Switzerland) with a Metrosep A Supp 5 column. The eluent was 3.2 mmol/L sodium carbonate plus 1 mmol/L sodium hydrogen carbonate.

All solutions were prepared gravimetrically using Milli-Q water (Millipore, USA). All seawater samples were diluted prior to injection. The calibration solutions were prepared from certified standard solutions delivered by Fluka (Fluka, Switzerland). The mass fractions as specified by the manufacturer are for

chloride : $w_{\text{Cl}}=1003 \pm 3 \text{ mg/kg}$

sulphate : $w_{\text{SO}_4}=1006 \pm 8 \text{ mg/kg}$

bromide : $w_{\text{Br}}=1003 \pm 4 \text{ mg/kg}$.

Calibration solutions containing similar mass fractions of anions as the seawater samples were prepared from the standards. Three series of measurements, each using freshly prepared sample dilutions were generated for chloride, sulphate and bromide, respectively. Mean values of the mass fractions are reported from these measurements in Table 5. The relative expanded uncertainties (coverage factor $k=2$) are 0.5% for chloride, 0.8% for sulphate and 1% for bromide. The main contributions to the measurement uncertainty are from the mass fractions of the certified standard solutions and from the preparation of the sample and calibration solution, respectively, by dilution.

4 Results

4.1 Parameterisation of Absolute Salinity

The 438 samples collected in the period 2006–2009 in the Baltic Sea between the Kattegat and the Gulf of Bothnia (Fig. 5) were analysed for Practical Salinity, Sect. 3.2, and

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density, Sect. 3.4. The related regression line computed from (4) using 436 samples with salinity $S_R > 2 \text{ g kg}^{-1}$ is

$$S_A - S_R = 0.00247 \times (S_{SO} - S_R) = 86.9 \text{ mg kg}^{-1} \times \left(1 - \frac{S_R}{S_{SO}}\right), \quad (14)$$

as shown in Fig. 5. Here, the standard-ocean salinity is $S_{SO} = 35 \text{ u}_{PS} = 35.16504 \text{ g kg}^{-1}$ (Millero et al., 2008). Comparison of (14) with (5) suggests that the density anomaly has decreased by about 40% during the last 40 years. This result is in contrast to the findings of Dyrssen (1993), and of Kremling and Wilhelm (1997) that the mean calcium concentrations increased significantly by about 4% between 1966/1969 and 1994/1995.

The causes of the strong decadal variability are not known; it may be related to technical, agricultural or climatological changes in the drainage region of the Baltic Sea, and/or to the dramatic transition in the inflow regime from the North Sea that occurred in the 1980s (Matthäus et al., 2008), and the related consequences for the marine chemistry in the deep water (Nausch et al., 2008).

For three selected Baltic Sea water samples taken in November 2008 from the surface water at the stations 361 (Kiel Bight), ABB (Arkona Basin) and 213 (Bornholm Deep), Fig. 5, the analysis was repeated with state-of-the-art measurements of the absolute conductivity, Sect. 3.3, and of density, Sect. 3.5.

The results, Table 2, of the comparison between measurements of density and conductivity at PTB and IOW can be pairwise combined to compute the salinity anomaly as a function of the Reference Salinity, Fig. 9. The four combinations are very close to each other and confirm the regression (14) based on the full set of IOW measurements.

In Fig. 10, the results from the density measurements of PTB and IOW, Table 2, are combined with chlorinity values of the samples computed from the ion chromatography, Table 5, for comparison with Fig. 3. Figure 10 shows a riverine salt input of 130 mg/kg, which is a reduced value compared to the data from 1966–1969 but enhanced compared to the value of 30 mg/kg from 1901, and to 79 mg/kg reported by Ohlson and

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Anderson (1990). Our recent value has high uncertainty due to the small number of samples used for its computation.

For Standard Seawater, Reference Salinity (2) equals chlorinity salinity (6), while for the Baltic Sea their difference indicates the electrolytic conductivity of the riverine water, Fig. 4 and the discussion following Eq. (10). The similar graph to Fig. 4, computed from the samples 361, ABB and 213 collected in 2008, is shown in Fig. 11. The strong scatter of the few available data points prevents any definite conclusions on a possible change of the river water composition since 1969.

4.2 Density comparison measurements

The density measurements carried out at the PTB, Sect. 3.4, on Baltic seawater samples collected in November 2008 at the station 213, ABB and 361, Fig. 5, served two different purposes, i) an independent confirmation of the density results obtained at the IOW, Sect. 3.2, and ii) a study of the uncertainty of seawater density measurements intended to be used as an SI-traceable substitute for salinity measurements that are traceable only to the IAPSO Standard Seawater artefact which is not a part of the SI system.

The results of the PTB density measurements are reported in detail in Tables 3, 4 and Figs. 12–15. Expanded uncertainties for seawater densities are estimated to be in the range of $1\text{--}2\text{ mg/m}^3$, the standard deviation of pure-water measurements is even below 1 mg/m^3 .

The agreement of the PTB results with IOW data is excellent, as seen from the Absolute Salinity results shown in Table 2 and Figs. 9–10. The lowering of the Baltic salinity anomaly in 2006–2009 compared to 1966–1969 derived from IOW data is confirmed by the PTB determinations.

The typical uncertainties displayed in Figs. 12–14 for Baltic Seawater apply similarly to Standard Seawater, Fig. 15; the measurement method is not modified for brackish salinities. The uncertainties of salinities S_A computed from the PTB density measurements, Table 2, are comparable to those of the Practical Salinity measured at IOW with

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conventional conductivity methods. Thus, the results presented here support the idea of measuring salinity by means of SI-traceable density.

Another important aspect of the substitution method used here is the automatic consistency with IAPWS-95 densities of pure water. This permits the computation of the saline part of the specific volume of seawater (IAPWS, 2008) from measured seawater densities without additional loss of accuracy.

4.3 Conductivity comparison measurements

Figure 16 shows the differences between Practical Salinity measured at the IOW with a salinometer (S_p^{sal}), Sect. 3.2, and Practical Salinity calculated from absolute conductivity measurements (S_p^{abs}), Sect. 3.3. Zero in Fig. 16 can be taken as a representative for S_p^{abs} , the dots then mark the deviation of S_p^{sal} with respect to S_p^{abs} . The error bars indicate the expanded (coverage factor 2) uncertainties. Bars with a cross bar are those of S_p^{sal} and without cross bars those of S_p^{abs} . They indicate a 95% degree of confidence for the results. Only the statistical fluctuation of the internally measured conductance enters into the uncertainty of S_p^{sal} , since systematic uncertainties are assumed to cancel out by the SSW calibration procedure. In an absolute conductivity measurement the absolute conductance value of seawater in the measuring cell must be determined. Its uncertainty therefore enters into the uncertainties of C_S and C_{SSW} in Eq. (13). This results in a larger uncertainty of S_p^{abs} as can be seen in Fig. 16.

Figure 16a compares results where R_{15} of the absolute measurement is scaled with the measured conductivity value of SSW/P-series, having a nominal Practical Salinity around 35. Here all salinometer and absolute measurements fit very well within the uncertainty limits. Figure 16b compares results where R_{15} of the absolute measurement is scaled with the measured conductivity value of SSW/L10-series, which is SSW diluted to a nominal Practical Salinity around 10. Although the uncertainty ranges of the salinometer and the absolute measurement results do barely touch this must be assessed as a significant deviation. This is a surprising observation. Since PSS-78

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is based on Practical Salinity measurements of SSW at different salt concentrations, scaling with SSW/P-series or L10-series should lead to the same result. The deviation may be an indicator that today's internal scaling of the measuring device is different to the devices taken to establish PSS-78. Alternatively the physical chemical properties of SSW could have slightly changed such that PSS-78 cannot be reproduced anymore over the complete scale. Of course, such a far-reaching conclusion can certainly not be drawn from a single measurement. Consequently, further investigation is currently ongoing. But based on the present results in the Baltic Sea measurement range one has to expect an additional uncertainty contribution to Practical Salinity in the order of the deviation of about 0.06% to 0.07%. At least the results demonstrate the necessity of an independent and stable reference for Practical Salinity measurements like the SI.

4.4 Chemical composition

Table 5 summarizes the results of the ion chromatography measurements, Sect. 3.6, together with the expanded uncertainties⁴ (coverage factor 2, GUM, 2008). The mass fractions of the anions chloride, bromide and sulphate were determined in the samples 361, ABB and 213 and in a sample of P149 SSW. In columns 2 and 3 of Table 7 the mass fractions of sulphate to chloride and bromide to chloride are given. Figures 18 and 19 show the results graphically. In Fig. 17 the mass fractions of sulphate determined in two samples of P149 SSW are compared. One sample P149 was measured at the same time as the Baltic Sea samples the other was measured one year before using a different instrumental configuration (Metrohm 850 professional IC, Metrosep A Supp 4/5 Guard column, Metrohm, Switzerland) and done by a different operator. The results shown in Table 6 agree well within the stated uncertainty. For sulphate both values are slightly below the reference composition (Millero et al., 2008) as can be seen

⁴The expanded uncertainty U defines an interval about the result of the measurement. U is calculated from a combined standard uncertainty u_c and a coverage factor k : $U = k u_c$. A coverage factor $k=2$, as applied in the publication, corresponds for a normal distribution to a coverage probability of approximately 95%.

from Fig. 17.

The mass fractions of bromide to chloride and sulphate to chloride of the Baltic Sea samples were compared to the ratio of anions as obtained for P149 and as given for the reference composition. The results are summarized in Table 7 and shown in Figs. 18 and 19.

Results for calcium could not be obtained.

In addition to CaCO_3 , the Baltic Sea exhibits a weaker anomaly in MgSO_4 (Rohde, 1966; Kremling, 1969; Nehring, 1980; Nessim and Schlunbaum, 1980), Table 1. Apparently the ratios $w(\text{SO}_4^{2-})/w(\text{Cl}^-)$ given in Table 7 show a related systematic trend proportional to the chlorinity. The sulphate fraction of Standard Seawater can be computed from the reference composition (Millero et al., 2008), Table 1, and subtracted from the measured sulphate concentration, $\text{SO}_4^{\text{meas}}$, to provide an estimate of the mean riverine sulphate input, $\text{SO}_4^{\text{river}}$, as

$$\text{SO}_4^{\text{river}} = \text{SO}_4^{\text{meas}} - 0.14 C / . \quad (15)$$

The result for the data given in Table 5 computed from Eq. (15) is displayed in Fig. 20. The regression results in an intercept at $C_l=0$ of about 16 mg/kg of SO_4 discharged from the rivers; due to the small number of samples a high uncertainty of this value must be assumed.

4.5 Contribution of CaCO_3 dissolution to the salinity anomaly

The dissolution of CaCO_3 in river water adds Ca and total CO_2 ($C_T = \text{CO}_2 + \text{H}_2\text{CO}_3 + \text{HCO}_3^- + \text{CO}_3^{2-}$) to the Baltic Sea and constitutes the major contribution to the salinity anomaly in the Baltic Sea. To quantify this effect, a subset of the samples from stations 2, 113, 213, 256, 271, and 284 (Fig. 5) collected between 2006 and 2008 were analyzed for both C_T ($n=64$) and total alkalinity, A_T ($n=29$).

The chemical analyses for C_T and A_T were performed by coulometry and closed-cell titration, respectively, according to the standard operation procedures described

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by Dickson et al. (2007). The A_T were plotted as a function of Practical Salinity S_p and a regression line was calculated which was fixed to $A_T=2350 \mu\text{mol kg}^{-1}$ at $S_p=35$ (Fig. 21). This value corresponds to the ocean end-member of the A_T/S_p mixing diagram and was estimated by extrapolation of A_T measurements in the Belt Sea/Kattegat area (B. Schneider, unpublished data) to $S_p=35$. The scatter of the data around the regression line is considerable and can be explained by the extreme differences in A_T in river water entering the Baltic Sea. The A_T in Scandinavian rivers amounts to a few hundred $\mu\text{mol kg}^{-1}$, whereas river water originating from continental Europe have alkalinities larger than $3000 \mu\text{mol kg}^{-1}$ (Hjalmarsson et al., 2008). Hence, extrapolation of the A_T /salinity regression line to $S_p=0$ yields a mean river water value, $^{\circ}A_T$, that is weighted with the contribution of river water from different source areas. As a consequence, the A_T at a given salinity depends on the horizontal mixing pattern that may vary in space and time, and a well-defined A_T /salinity relationship for the Baltic Sea does not exist. The mean $^{\circ}A_T$ obtained from our limited set of samples was $1470 \mu\text{mol kg}^{-1}$. Attributing $^{\circ}A_T$ entirely to the dissolution of CaCO_3 yields a Ca concentration in river water of $735 \mu\text{mol kg}^{-1}$ corresponding to 29mg kg^{-1} . Maximum and minimum $^{\circ}A_T$ were estimated by calculating upper and lower limit mixing lines which enclosed all A_T data. The $^{\circ}A_T$ ranged from $1339 \mu\text{mol kg}^{-1}$ to $1585 \mu\text{mol kg}^{-1}$ and is equivalent to Ca concentrations between 27mg kg^{-1} and 32mg kg^{-1} . This range is consistent with the river water Ca concentration (28mg kg^{-1}) obtained by extrapolation of Ca measurements at chlorinities higher than 4.5 (Kremling and Wilhelm, 1997).

CO_3^{2-} ions released during the dissolution of CaCO_3 react with CO_2 and form HCO_3^- ions according to the thermodynamic equilibrium conditions of the marine CO_2 system. Therefore, the total CO_2 concentrations in river water are controlled by both the alkalinity and the CO_2 partial pressure, $p\text{CO}_2$. To estimate $^{\circ}C_T$, we first calculated the ocean endmember ($S_p=35$) C_T on the basis of the endmember A_T ($2350 \mu\text{mol kg}^{-1}$) and assuming equilibrium with the present day atmospheric $p\text{CO}_2$ (about $380 \mu\text{atm}$). The calculations were performed for the mean temperature during sampling (5.7°C) using

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the CO_2 solubility and the CO_2 dissociation constants suggested by Weiss (1974) and Millero et al. (2006), respectively. The obtained value ($2182 \mu\text{mol kg}^{-1}$) was then fixed for the calculation of a regression line for the C_T /salinity relationship (Fig. 21). Extrapolation of the regression line to $S_p=0$ yielded a mean river water ${}^\circ C_T$ of $1462 \mu\text{mol kg}^{-1}$.

5 To convert ${}^\circ C_T$ into mass units, the contributions of CO_2 (H_2CO_3), HCO_3^- and CO_3^{2-} to ${}^\circ C_T$ were calculated from ${}^\circ C_T$, ${}^\circ A_T$ and temperature using again the dissociation constants by Millero et al. (2006). Multiplying the concentrations of the different C_T species with the corresponding molecular weight resulted in a mean river water total CO_2 of 89 mg kg^{-1} . The minimum and maximum values were $79 \mu\text{mol kg}^{-1}$ and

10 $101 \mu\text{mol kg}^{-1}$, respectively. Hence, the mean total Absolute Salinity anomaly that refers to the selected sampling stations amounted to 118 mg kg^{-1} (29 mg kg^{-1} from CaCO_3 and 89 mg kg^{-1} from CO_2) and varied between 106 mg kg^{-1} and 133 mg kg^{-1} . This range is consistent with the estimate available from Fig. 10.

5 Discussion

15 In preparation for the analysis of recently collected data we have reconsidered the measurements of Kremling 1966–1969 using the new equation of state (TEOS-10, McDougall et al., 2009). The parameterisation of the salinity anomaly as a function of the Reference Salinity, (5), Fig. 1, and of the chlorinity, Eq. (8), Fig. 3, resulted in new equations valid for that observation period, in particular, in an extrapolated Absolute Salinity of 150 mg kg^{-1} at zero Reference Salinity, and of 173 mg kg^{-1} at zero chlorinity

20 for the Kremling data. For our recent measurements from 2006 to 2009, these values have changed to 87 mg kg^{-1} at zero Reference Salinity, Fig. 8, and 130 mg kg^{-1} at zero chlorinity, Fig. 9. This is a reduction of the anomaly by 42% and 25%, respectively, over the last 40 years. Of these two, the new chlorinity intercept is derived from only six data

25 points (three chlorinity values) and must be considered as relatively uncertain since values observed at different times or positions may scatter significantly. Our finding of

a reduced anomaly is in contrast to the results of Kremling and Wilhelm (1993) who described an increase of the anomaly after 1970.

The new Eq. (14) that estimates Absolute Salinity S_A from Reference Salinity S_R of Baltic seawater is based on 436 measured samples, Fig. 8, and is confirmed by independent determinations of density and conductivity, Fig. 9:

$$S_A = S_R + 87 \text{ mg kg}^{-1} \times \left(1 - \frac{S_R}{S_{SO}}\right) \quad (16)$$

Here, $S_{SO}=35.16504 \text{ g kg}^{-1}$ is the standard-ocean Reference Salinity that corresponds to the Practical Salinity of 35. Reference Salinity, S_R , is computed from Practical Salinity, S_P , by means of Eq. (2).

In this paper we have consequently used a regression method that was, to our knowledge, first introduced by Millero and Kremling (1976) to study the Baltic Sea anomalies. In this method, Baltic Sea water is considered as a mixture of Standard Seawater that has standard-ocean salinity, with riverine water which contains unknown amounts of unknown solutes. Properties of diluted Standard Seawater can be computed from the equation of state and compared with Baltic seawater properties of the same salinity, conductivity or chlorinity. In using this method, the Baltic anomalies are assumed to disappear at related standard-ocean conditions such as $S_R=S_{SO}$, Eq. (16). This end member datum permits a robust regression with respect to the scattered readings obtained from the Baltic Sea at different positions, times and salinities, and a correspondingly rigorous extrapolation to the opposite end-member, the average riverine water. Since a Reference Composition model was defined recently as a part of the new international seawater standard (Millero et al., 2008; IAPWS, 2008; McDougall et al., 2009; IOC, 2009), the oceanic component can be computed on this basis, resulting in well-defined anomalies that can be compared between different studies. This is a significant advantage over the earlier situation when every author used his particular preferred seawater composition model, thus giving incompatible quantitative results for the anomalies between different studies. Such a lack of comparability is especially

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inconvenient and possibly misleading for trend analyses of e.g. the density anomaly on decadal or century time scales. We have applied this regression method based on the Reference Composition to the anomalies of density, as described in the previous paragraph, to historical and to our recent data, as well as to the conductivity, Fig. 4, and the sulphate anomaly, Fig. 20.

The measurements analysed in this paper are intended to support future model studies, first, of the effect of CaCO_3 excess on thermodynamic properties of seawater derived from Pitzer equations (Feistel and Marion, 2007), and second, of the anomalous effects on the electrical conductivity of mixed aqueous electrolytes (Pawlowicz, 2008). In order to support independent investigations and future comparisons, observational data of this study are available from the digital supplement of this paper.

Since 1902, oceanographers routinely measure the salinity of seawater relative to certified samples of Standard Seawater. These salinity measurements are not traceable to SI standards (Seitz, 2008) which implies reduced comparability and increasing uncertainty of the results on climatological timescales. For selected Baltic Sea samples, SI-traceable state-of-the-art measurements of electrolytic conductivity and density were carried out at the PTB Braunschweig. The results reported in Sects. 4.2 and 4.3 indicate that the density of seawater can be measured with significantly smaller uncertainty than the conductivity. These findings support the intended proposal of the SCOR/IAPSO WG127 to calibrate instruments for salinity measurements in the future with respect to density rather than or in addition to conductivity. Further studies are required to develop this technology in more detail.

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Table 1. Ratios $r_X = w(X)/Cl$ of mass fractions $w(X)$ to chlorinity Cl of the main sea salt constituents X compiled by Millero et al. (2008) for Standard Seawater and by Nehring (1980) for Baltic seawater from different sources. Molar masses A_X are those compiled by Millero et al. (2008). The oceanic value of $r_{Cl} = [1/(0.3285234 A_{Ag}) - r_{Br}/A_{Br}] \times A_{Cl}$ is inferred from the definition of chlorinity, using the molar mass $A_{Ag} = 107.8682(2)$ g/mol of silver. The Baltic r_{Cl} is calculated from the same formula using Kremling's value for r_{Br} .

Solute X	Molar Mass g/mol A_X	Reference Composition r_X	Baltic Sea r_X	Baltic Sea Source
Na	22.989 769 28(2)	0.556 4924	0.5549–0.5562 0.5554 0.5547(21)	Zarins and Ozolins (1935) Culkin and Cox (1966) Kremling (1969)
K	39.0983(1)	0.020 6000	0.0200 0.0205 0.0206(6)	Zarins and Ozolins (1935) Culkin and Cox (1966) Kremling (1969)
Mg	24.3050(6)	0.066 2600	0.06692 0.0674(4) 0.0672(3)	Voipio (1957) Nehring and Rohde (1967) Kremling (1969, 1970, 1972)
Ca	40.078(4)	0.021 2700		
Sr	87.62(1)	0.000 4100		
Ca+Sr		0.021 6800	0.0225–0.0268 0.0218–0.0273	Rohde (1966) Nehring and Rohde (1967) Kremling (1969, 1970, 1972)
Cl	35.453(2)	0.998 9041	0.998 9409	
SO ₄	96.0626(50)	0.140 0000	0.1410 0.1413(19) 0.1436(42) 0.1406(10)	Zarins and Ozolins (1935) Kwiecinsky (1965) Trzosinska (1967) Kremling (1969, 1970, 1972)
CO ₂	44.0095(9)	0.000 0220		
Br	79.904(1)	0.003 4730	0.00329–0.00349 0.00339(6)	Morris and Riley (1966) Kremling (1969, 1970, 1972)
B	10.811(7)		0.00025(2)	Kremling (1969, 1970, 1972)
B(OH) ₃	61.8330(70)	0.001 0030		
B(OH) ₄	78.8404(70)	0.000 4100		
F	18.998 4032(5)	0.000 0670	0.000078(4)	Kremling (1969, 1970, 1972)

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Table 2. Independent PTB measurements of conductivity and density of Baltic surface water at the selected stations 361, ABB and 213, Fig. 5, compared with the IOW data for density, Practical Salinity. All values are given at 15°C and atmospheric pressure, except IOW density which was measured at 20°C. Values for S_A were computed from the related density by means of (3). Note that the effect of temperature on density is automatically removed when calculating the “density salinity”, which is reported as S_A . Related expanded uncertainties (coverage factor 2) are given below the values.

Sample	PTB $C\ S\ m^{-1}$	PTB S_p	IOW S_p	PTB $\rho\ kg\ m^{-3}$	PTB $S_A\ g\ kg^{-1}$	IOW $\rho\ kg\ m^{-3}$	IOW $S_A\ g\ kg^{-1}$
361	2.29564 0.00136	17.5487 0.0116	17.5438 0.0020	1012.5989 0.0014	17.6746 0.0018	1011.5384 0.0130	17.6732 0.0192
ABB	1.24454 0.00050	9.0190 0.0046	9.0166 0.0010	1006.0781 0.0014	9.1205 0.0019	1005.0975 0.0130	9.1223 0.0182
213	1.06730 0.00030	7.6403 0.0034	7.6409 0.0009	1005.0259 0.0021	7.7402 0.0028	1004.0577 0.0130	7.7415 0.0181

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Table 3. Results of the high-accuracy measurements of seawater density carried out at the PTB. Absolute Salinity is computed from the density by means of the Gibbs function (3). Given is the expanded uncertainty of the density at 15°C (coverage factor 2).

sample	date of filling	date of measurement	storage	density at 15°C kg/m ³	total uncertainty kg/m ³	Absolute Salinity S_A g/kg
213-1	2008-12-18	2009-02-04	refrigerator	1005.0261	1.5E-03	7.7405
213-3	2008-12-18	2009-03-11	refrigerator	1005.0268	2.8E-03	7.7414
213-9	2008-12-18	2009-03-27	refrigerator	1005.0248	2.0E-03	7.7388
213-2	2008-12-18	2009-02-03	room temp.	1005.0263	1.5E-03	7.7408
ABB-1	2008-12-17	2009-02-05	refrigerator	1006.0784	1.3E-03	9.1209
ABB-3	2008-12-17	2009-03-10	refrigerator	1006.0780	1.3E-03	9.1204
ABB-8	2008-12-17	2009-03-26	refrigerator	1006.0778	1.7E-03	9.1201
ABB-2	2008-12-17	2009-01-29	room temp.	1006.0802	1.5E-03	9.1233
361-1	2008-12-16	2009-03-09	refrigerator	1012.5983	1.4E-03	17.6738
361-9	2008-12-16	2009-03-25	refrigerator	1012.5995	1.4E-03	17.6753
361-2	2008-12-16	2009-02-02	room temp.	1012.5971	1.9E-03	17.6722
P151-1		2009-04-06	room temp.	1025.96745	2.2E-03	35.1538
P151-2		2009-04-07	room temp.	1025.96641	1.3E-03	35.1525
P151-3		2009-04-08	room temp.	1025.96722	1.9E-03	35.1535
P151-4		2009-04-09	room temp.	1025.97145	1.5E-03	35.1590

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Table 4. Experimental standard deviations of the mean (st. dev.) and numbers of measurements of the high-accuracy measurements of density carried out at the PTB with seawater and with pure water.

	seawater	seawater	seawater	pure water	pure water
sample	st. dev. $u(\rho)$ ($k=2$) kg/m^3	number of measurements	therm. expansion coefficient at 15°C K^{-1}	st. dev. $U(\rho)$ ($k=2$) kg/m^3	number of measurements
213-1	7.5E-04	16	0.00016628	7.7E-04	20
213-3	2.5E-03	20	0.00016628	6.1E-04	24
213-9	1.4E-03	20	0.00016628	9.5E-04	26
213-2	8.9E-04	12	0.00016628	6.4E-04	16
ABB-1	4.9E-04	16	0.00016893	7.6E-04	18
ABB-3	6.8E-04	18	0.00016893	4.7E-04	22
ABB-8	9.9E-04	14	0.00016893	9.0E-04	18
ABB-2	6.2E-04	20	0.00016893	9.1E-04	22
361-1	8.6E-04	18	0.0001847	4.3E-04	22
361-9	6.2E-04	18	0.0001847	6.0E-04	22
361-2	1.5E-03	20	0.0001847	5.8E-04	20
P151-1	1.5E-03	18	0.00016628	0.00094558	22
P151-2	9.5E-04	18	0.00016628	0.00033488	22
P151-3	1.1E-03	18	0.00016893	0.00075593	22
P151-4	5.2E-04	18	0.00016893	0.000599095	22

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Table 5. Mass fraction of chloride, sulphate and bromide for Baltic Sea samples 213, ABB and 361 together with the expanded measurement uncertainty (coverage factor 2). Chlorinity Cl is computed from the formula (Millero et al., 2008), $Cl = 0.3285234 A_{Ag} [w(Cl)/A_{Cl} + w(Br)/A_{Br}]$, and the chlorinity salinity S_{Cl} is computed from Eq. (6).

Sample component i	213		ABB		361	
	$w(i)$ g kg ⁻¹	$U(w(i))$ g kg ⁻¹	$w(i)$ g kg ⁻¹	$U(w(i))$ g kg ⁻¹	$w(i)$ g kg ⁻¹	$U(w(i))$ g kg ⁻¹
Cl ⁻	4.199	0.020	4.964	0.025	9.704	0.050
SO ₄ ²⁻	0.607	0.0050	0.710	0.0057	1.354	0.011
Br ⁻	0.015	0.0002	0.017	0.0002	0.033	0.0003
Cl	4.204		4.969		9.714	
S_{Cl}	7.630		9.020		17.632	

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Table 6. Mass fractions of chloride and sulphate measured in SSW P149 in parallel with Baltic Sea samples and in 2008 at PTB, compared to the reference composition (Millero et al., 2008).

Sample component <i>i</i>	P149 this paper		P149 PTB in 2008		reference composition Millero et al. (2008)	
	$w(i)$ g kg ⁻¹	$U(w(i))$ g kg ⁻¹	$w(i)$ g kg ⁻¹	$U(w(i))$ g kg ⁻¹	$w(i)$ g kg ⁻¹	$U(w(i))$ g kg ⁻¹
Cl ⁻	19.39	0.04	19.34	0.03	19.35271	exact
SO ₄ ²⁻	2.694	0.006	2.702	0.004	2.71235	exact

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Table 7. Mass fraction of sulphate to chloride and bromide to chloride for the Baltic Sea samples, the Standard Seawater sample compared to SSW P149 and to the reference composition (Millero et al., 2008).

Sample	$w(\text{SO}_4^{2-})/w(\text{Cl}^-)$	$w(\text{Br}^-)/w(\text{Cl}^-)$
213	0.1445	0.003566
ABB	0.1429	0.003425
361	0.1395	0.003351
P149	0.1389	0.003448
Ref. Comp.	0.1390	0.003480

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Table 8. Samples collected from the Baltic Sea in 1900 and analysed by Sørensen (Forch et al., 1902). It may be the extreme effort of salinity determination by drying at 150–480°C over 120 h that prevented Sørensen from the analysis of all available samples. Additional samples taken from outside the Baltic Sea are omitted from this table.

Sample	Cl ‰	S_K ‰	N. Lat.	E. Lon.	Depth m	Date, Time	Sea
#32	1.4736	2.688	60°07′	28°33.5′	0	19 Jul 1900, 20:50	G. Finland
#33	2.9274	5.321	62°07′	20°02′	0	24 Jul 1900, 15:00	G. Bothnia
#29	4.6075		54°39.5′	12°17.3′	0	7 May 1900, 08:00	Belt Sea
#30	8.0888	14.634	55°42.2′	10°43.7′	0	8 May 1900, 14:10	Gr. Belt
#9	10.4102	18.818	55°52′	10°52′	0	23 Apr 1900, 18:00	Gr. Belt
#10	12.8422	23.204	56°53′	11°07′	0	26 Apr 1900, 18:15	Kattegat
#25	16.0200	28.956	57°38′	10°46′	0	27 Apr 1900, 09:00	Kattegat
#28	5.837		54°40′	11°58′	0	7 May 1900, 14:00	Belt Sea
#7	10.117		56°15′	12°26′	0	19 Apr 1900, 12:00	Kattegat
#8	10.873		56°30.5′	12°09′	0	19 Apr 1900, 14:00	Kattegat
#12	14.295		57°04′	10°49′	0	26 Apr 1900, 20:00	Kattegat
#11	17.895		56°08′9	11°11′2	27.3	23 Apr 1900, 20:30	Gr. Belt
Swedish	18.780		57°44′	11°22′	72	21 Mar 1900	Kattegat

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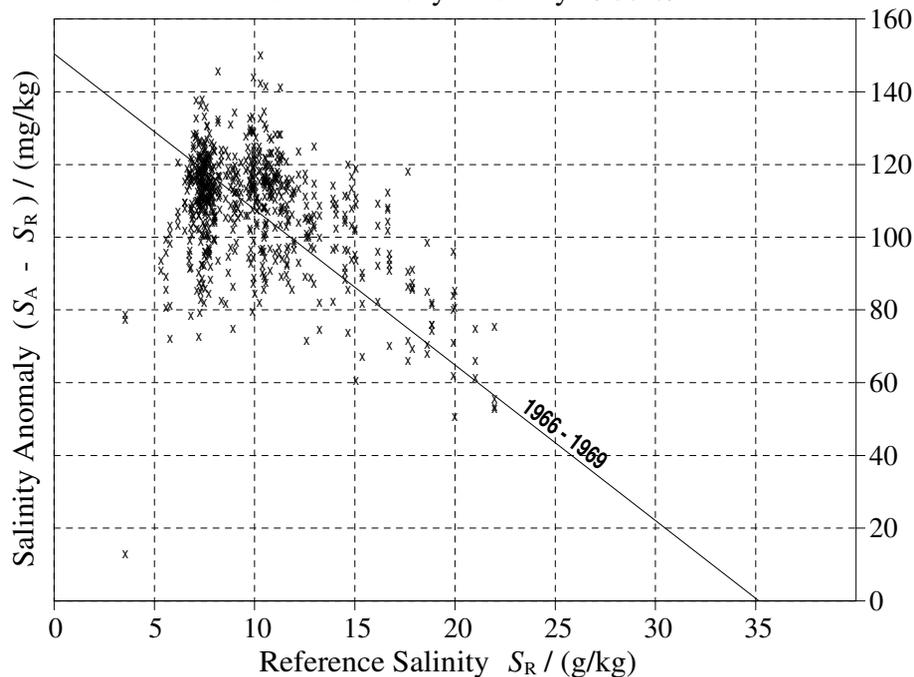


Fig. 1. Salinity anomaly $\delta S_A = S_A - S_R$ computed by means of Eqs. (2)–(4) from Practical Salinity and density data measured by Kremling (1969, 1970, 1972) and Millero and Kremling (1976) in the period 1966–1969. The sample near $S_R = 4$ g/kg with exceptionally low anomaly was excluded from the fit (5); it was collected in the Vistula Estuary.

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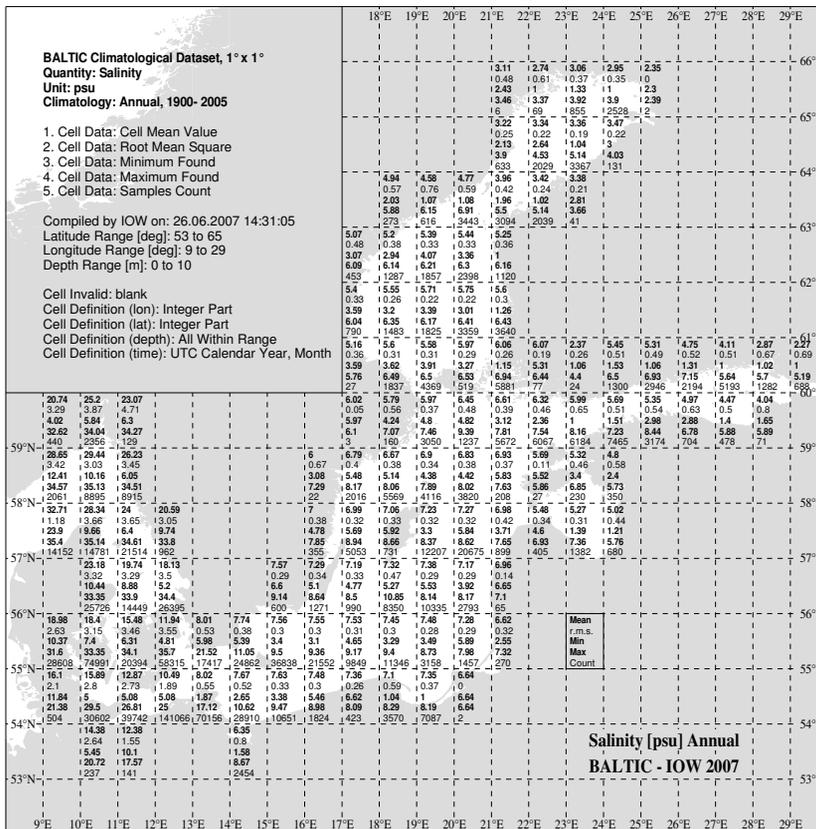
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Fig. 2. Climatological surface distribution of Practical Salinity from the Baltic Atlas of Long-Term Inventory and Climatology (BALTIC, Feistel et al., 2008). For each grid cell of $1^\circ \times 1^\circ \times 10$ m size, Practical Salinity values measured during 1900–2005 are represented by the mean value, the root-mean square (r.m.s.) deviation, the minimum and maximum values observed, as well as the total number of samples available (count).

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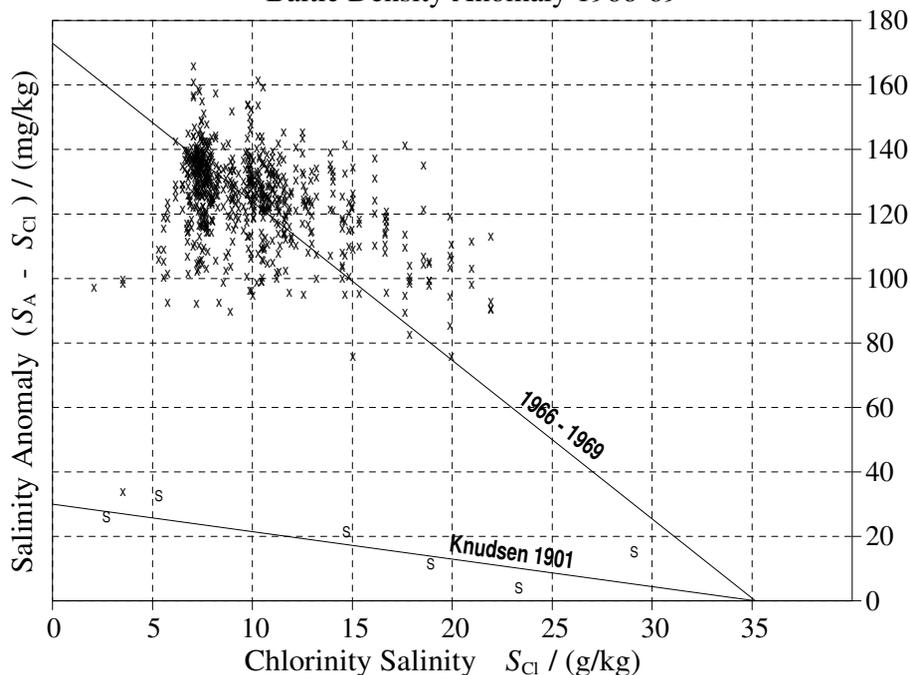


Fig. 3. Salinity anomaly associated with local runoff $\delta S_{Cl} = S_A - S_{Cl}$ computed by means of Eqs. (4)–(6) from chlorinity and density data, symbol “x”, measured by Kremling (1969, 1970, 1972) and Millero and Kremling (1976) in the period 1966–1969. The sample with exceptionally low anomaly collected in the Vistula Estuary was excluded from the fit (7) giving the line indicated by “1966–1969”. The “Knudsen 1901” equation (9) was derived by Knudsen (1901) from the measurements of Sørensen (Forch et al., 1902), symbol “S”, Table 8.

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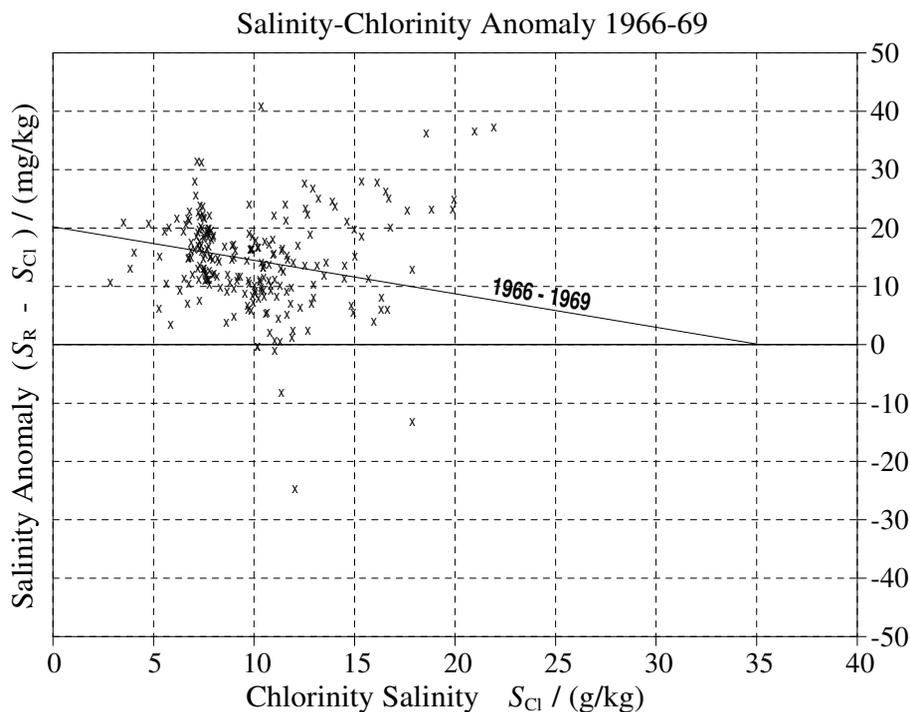


Fig. 4. Deviation between the Reference Salinity (2), S_R , and the chlorinity salinity (6), S_{Cl} , computed from Kremling's data collected between 1966 and 1969. Note that this relation does not account for the additional contribution to Absolute Salinity given by Eq. (5) and illustrated in Fig. 1. The regression line (10) quantifies the average conductivity of the riverine water.

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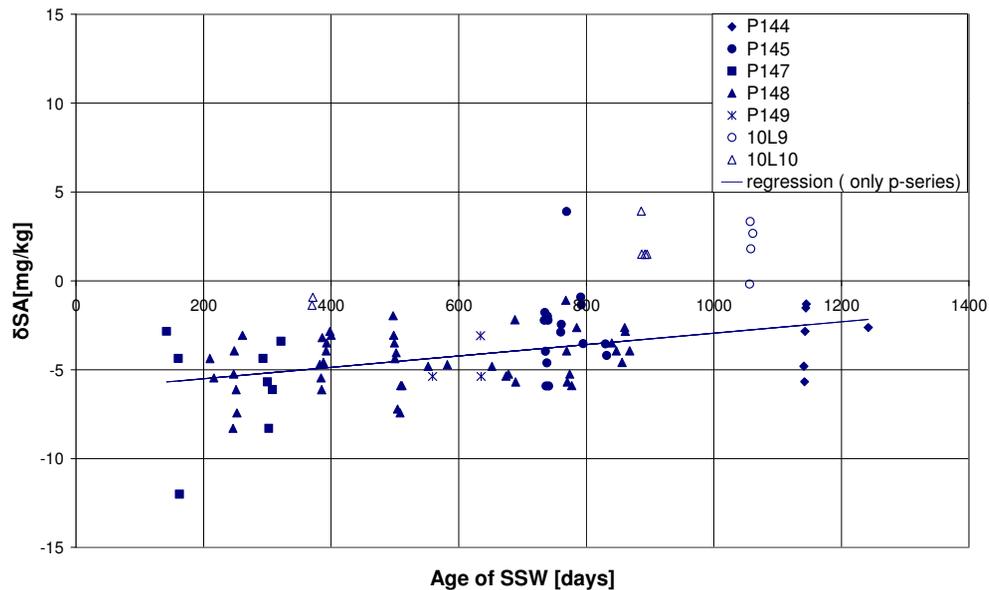


Fig. 6. Results of density measurements on Standard Seawater. Each data point represents a measurement of one bottle of SSW. P144 to P149 are batches of SSW with $S_p=35$ and 10L9 and 10L10 are batches with $S_p=10$. On the ordinate, the apparent salinity anomaly is shown, computed from (4), as a function of the sample age, in days.

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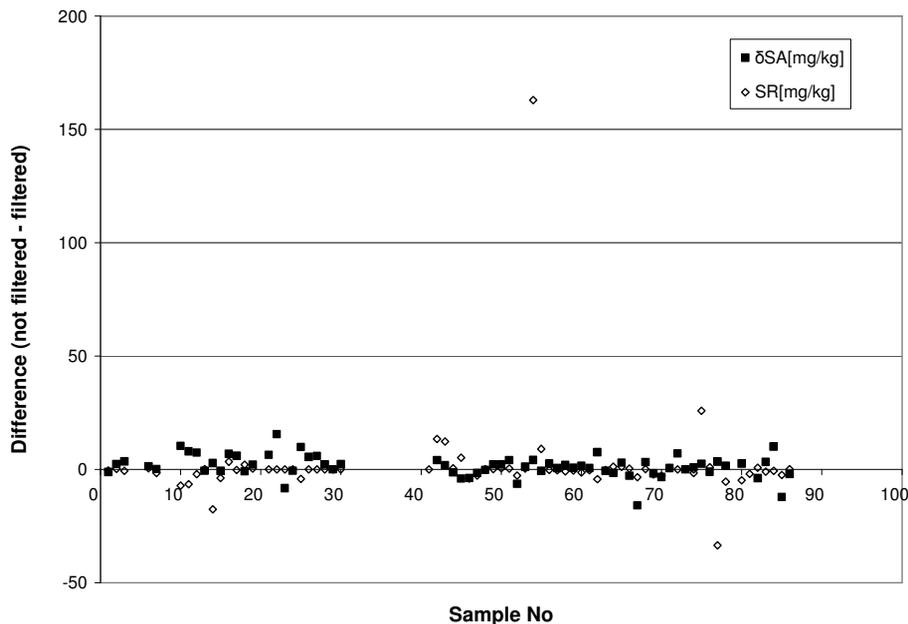


Fig. 7. Results of the comparison between filtered and unfiltered samples from the Baltic Sea. The particular pairs of samples were collected from the same CTD bottle but filled into separate flasks, subsequently.

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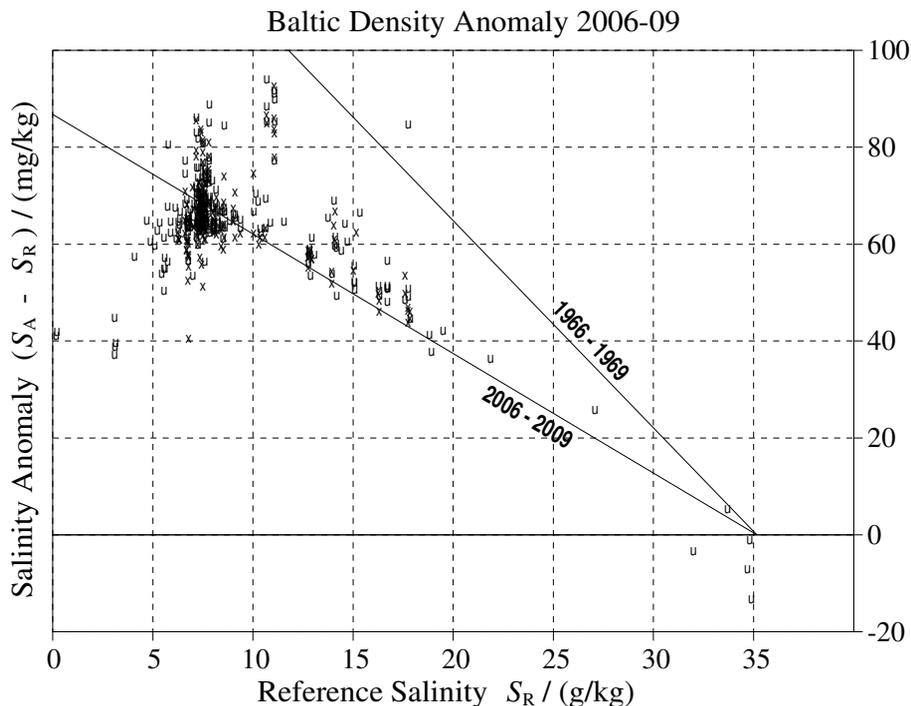


Fig. 8. The results of densitometer measurements in the Baltic Sea during 2006–2009, Fig. 5, converted to Absolute Salinity anomalies using Eq. (4). Symbol “x”: filtered samples, “u”: unfiltered samples. 436 samples with salinity $>2 \text{ g kg}^{-1}$ were used for the fit (14). At vanishing Reference Salinity S_R , the limiting anomaly is $S_A^0 = 86.8 \text{ mg kg}^{-1}$. The line marked 1966–1969 is the regression line (5) with regard to the data from 1966–1969 of Millero and Kremling (1976), Fig. 1.

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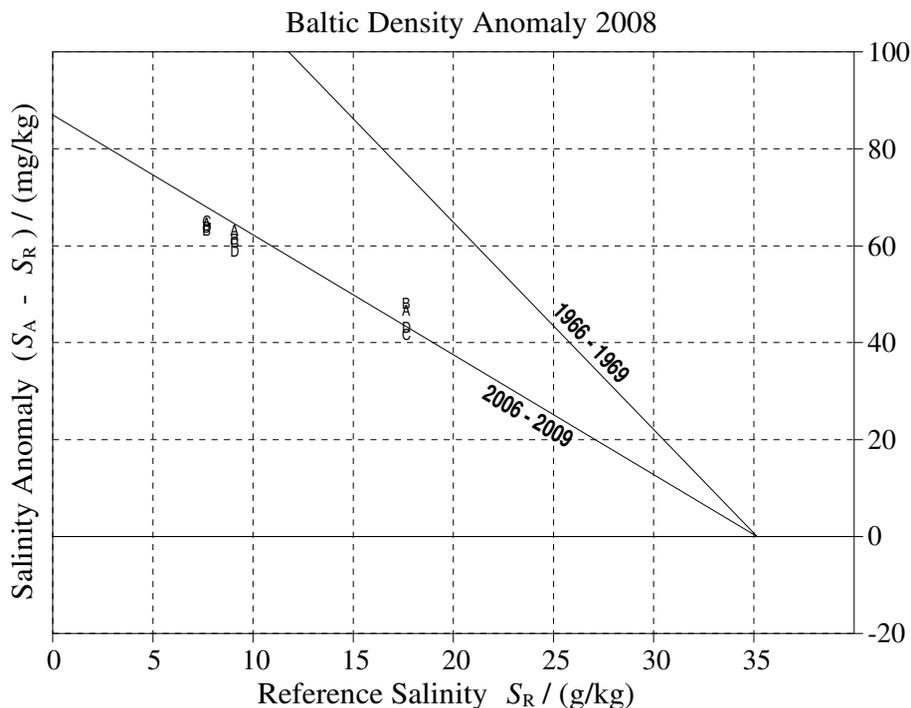


Fig. 9. Results of PTB-IOW comparison measurements of the salinity anomaly as a function of the Reference Salinity of the Baltic Sea samples 361, ABB and 213, Table 2. Symbols “A”, “B”: S_R from IOW, “A”, “C”: S_A from IOW, “C”, “D”: S_R from PTB, and “B”, “D”: S_A from PTB. The line marked 2006–2009 is the regression line (14) with regard to the data 2006–2009 of this paper, Fig. 8. The line marked 1966–1969 is the regression line (5) with regard to the data 1966–1969 of Millero and Kremling (1976), Fig. 1.

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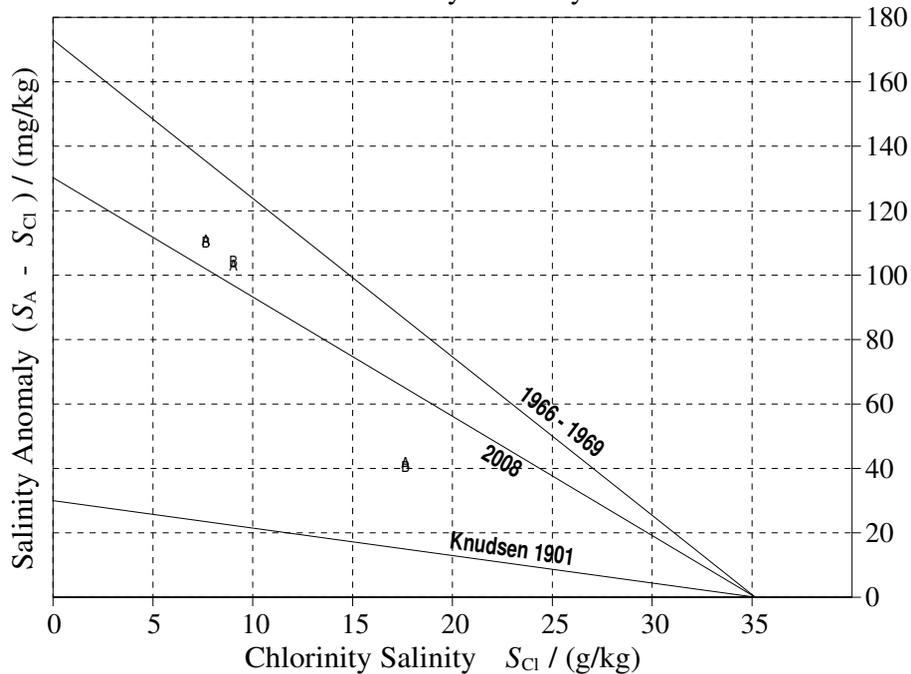


Fig. 10. Results of PTB-IOW comparison measurements of the salinity anomaly, Table 2, as a function of the chlorinity of the Baltic Sea samples 361, ABB and 213, Table 5. Symbols “A”: S_A from IOW, “B”: S_A from PTB. The regression line “2008” with respect to these data has an intercept of 130 mg/kg at $S_{Cl}=0$. The line marked “1966–1969” is the regression line (8) associated with the data from 1966–1969 of Millero and Kremling (1976), Fig. 3. The “Knudsen 1901” equation (9) was derived by Knudsen (1901) from the measurements of Sørensen (Forch et al., 1902), Table 8, Fig. 3.

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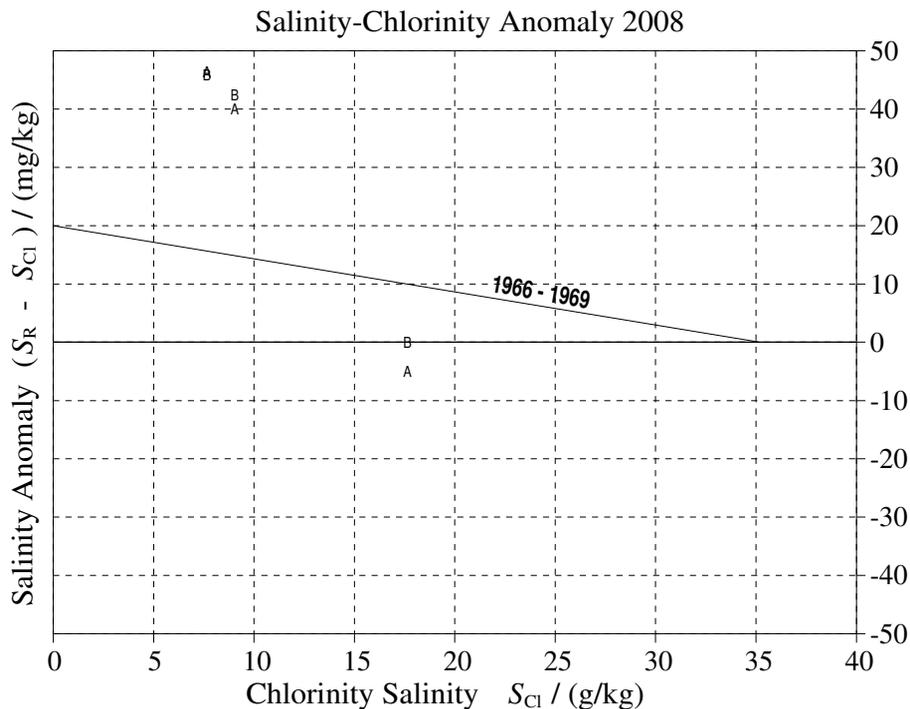


Fig. 11. Deviation between Reference Salinity (2), S_R , from Table 2, and chlorinity salinity (6), S_{Cl} , from Table 5, of the Baltic Sea samples 361, ABB and 213, compared with the regression line “1966–1969” with respect to Kremling’s data collected between 1966 and 1969, Fig. 4. The deviation from the abscissa quantifies the conductivity of the riverine water. Symbols “A” with Practical Salinity from the IOW, “B” from the PTB.

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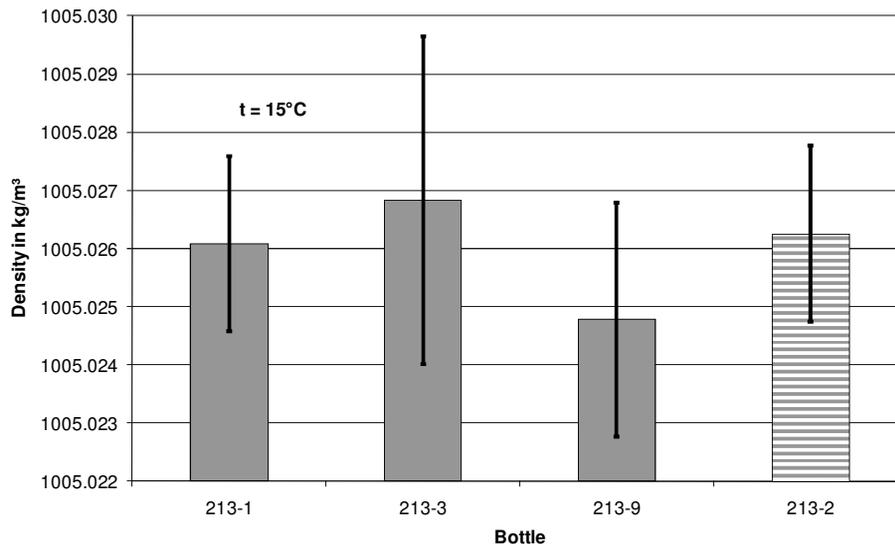


Fig. 12. Densities and uncertainties of the different batches, Table 3, of surface water from the Baltic Sea station 213, Fig. 5, measured at the PTB.

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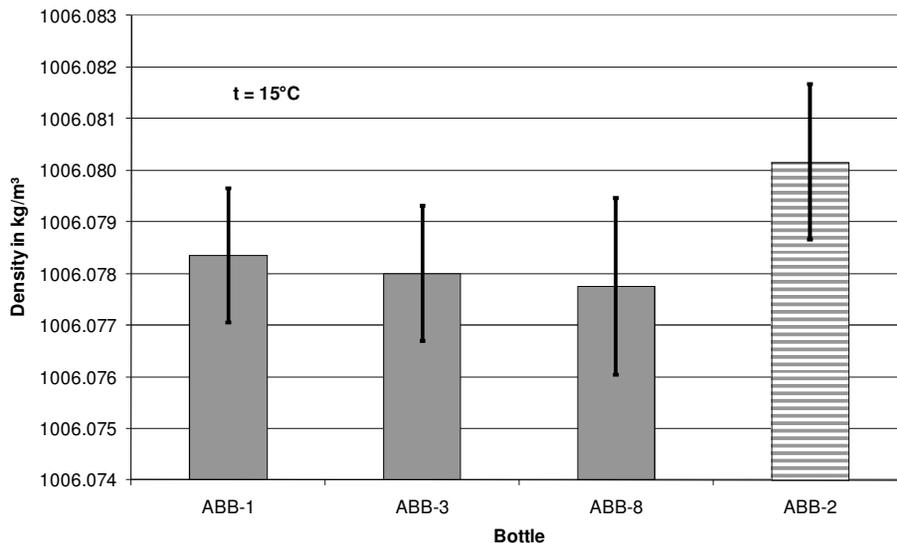


Fig. 13. Densities and uncertainties of the different batches, Table 3, of surface water from the Baltic Sea station ABB, Fig. 5, measured at the PTB.

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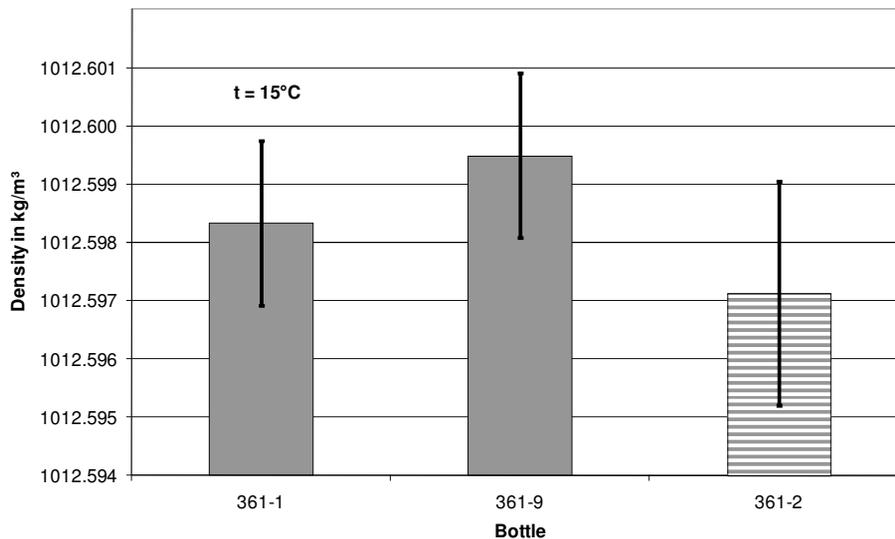


Fig. 14. Densities and uncertainties of the different batches, Table 3, of surface water from the Baltic Sea station 361, Fig. 5, measured at the PTB.

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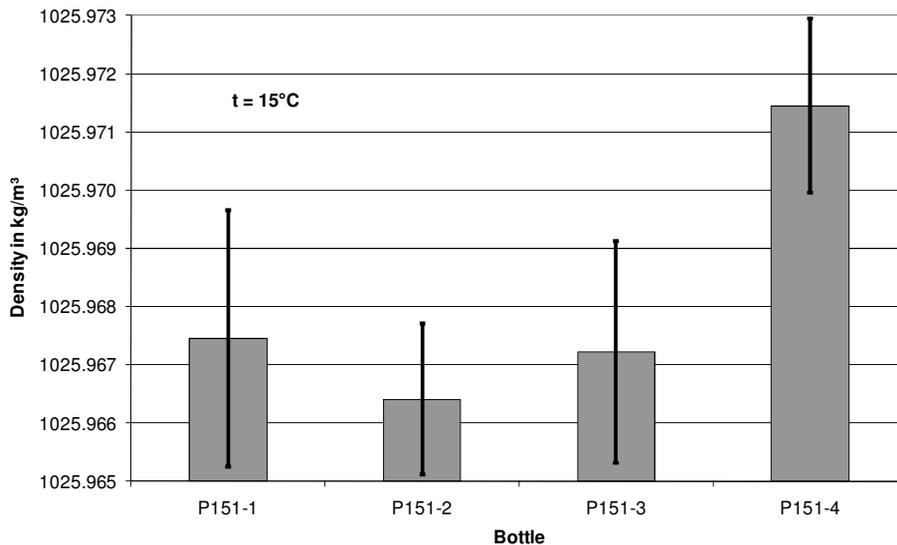


Fig. 15. Densities and uncertainties of the different batches of IAPSO Standard Seawater, measured at the PTB.

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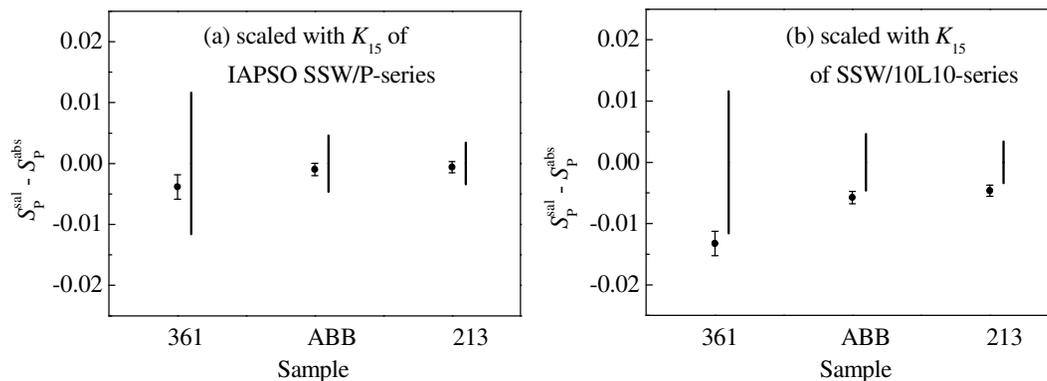


Fig. 16. Deviation of Practical Salinity results S_P^{sal} measured with a salinometer from those calculated from absolute conductivity measurements S_P^{abs} . Error bars without cross bars are related to zero (deviation) and indicate the expanded uncertainty of S_P^{abs} , while the error bars with cross bars indicate the expanded uncertainty of S_P^{sal} . **(a)** Absolute conductivity results scaled according to Eq. (13) using SSW/P-series, **(b)** using SSW/10L10 series.

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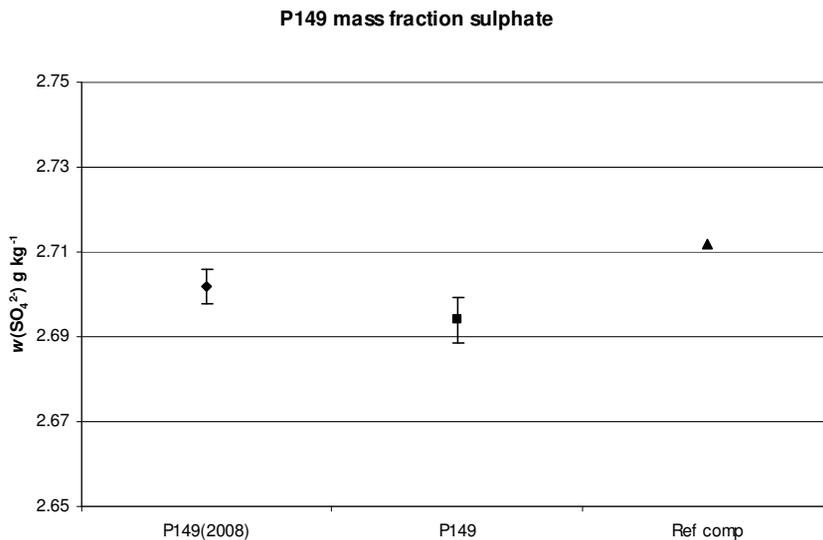


Fig. 17. Mass fraction of sulphate measured in SSW P149 in parallel with Baltic Sea samples and in 2008 at PTB compared to the reference composition (Millero et al., 2008).

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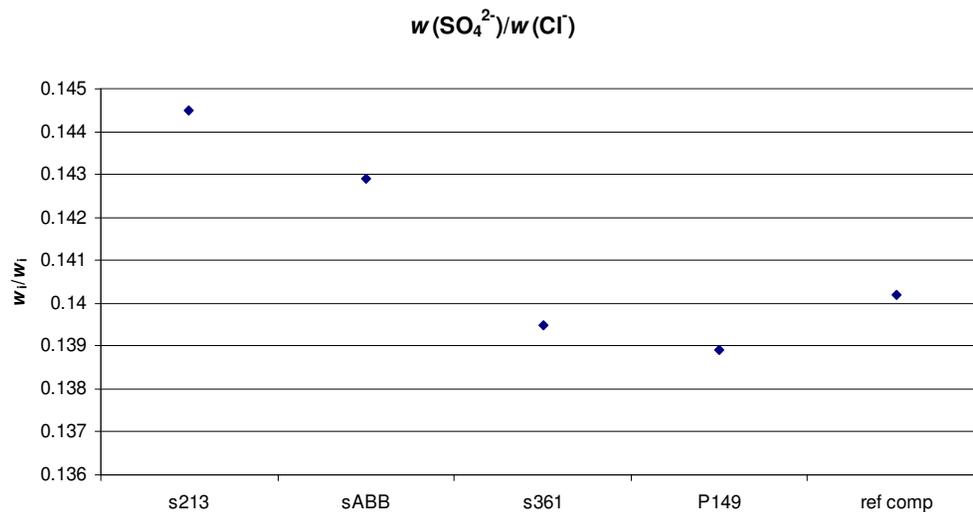


Fig. 18. Mass fraction of sulphate to chloride for the Baltic Sea samples. SSW P149 and to the reference composition (Millero et al., 2008).

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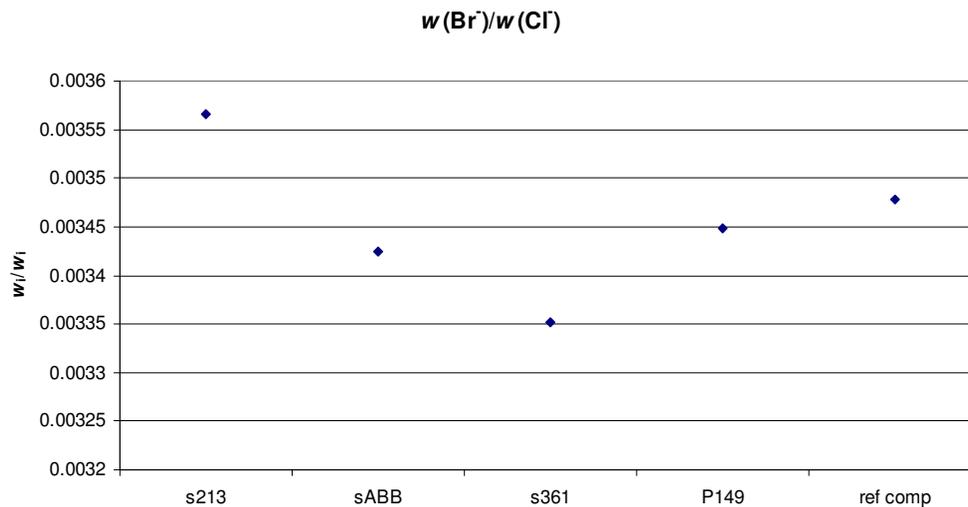


Fig. 19. Mass fraction of bromide to chloride for the Baltic Sea samples, SSW P149 and the reference composition (Millero et al., 2008).

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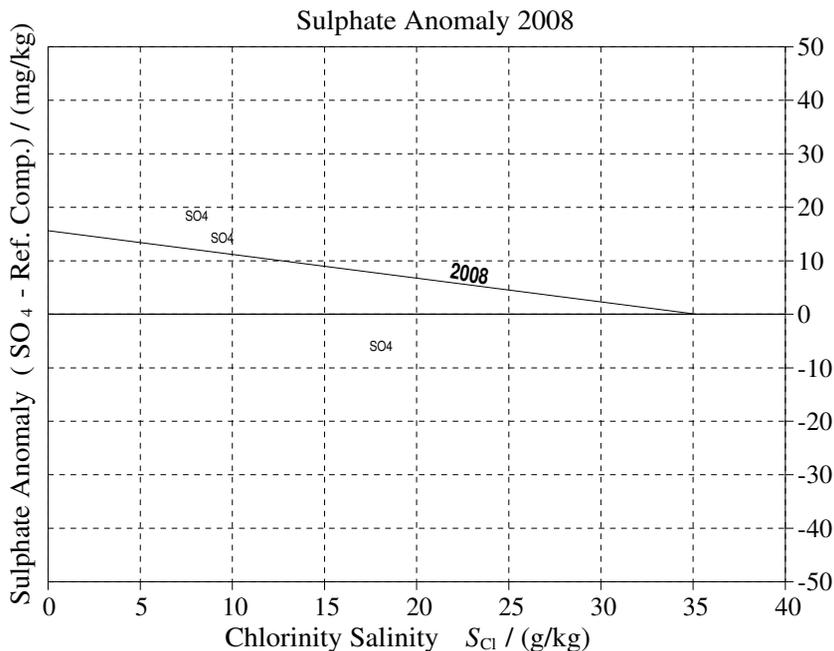


Fig. 20. Sulphate anomaly with respect to the reference composition computed from Eq. (15) with measured values, Table 5, at the Baltic Sea stations 213, ABB and 361 in November 2008, symbols “SO₄”. The regression line “2008” with respect to these data suggests a riverine discharge of order 16 mg/kg of SO₄. The uncertainty in this estimate is large due to the few available samples.

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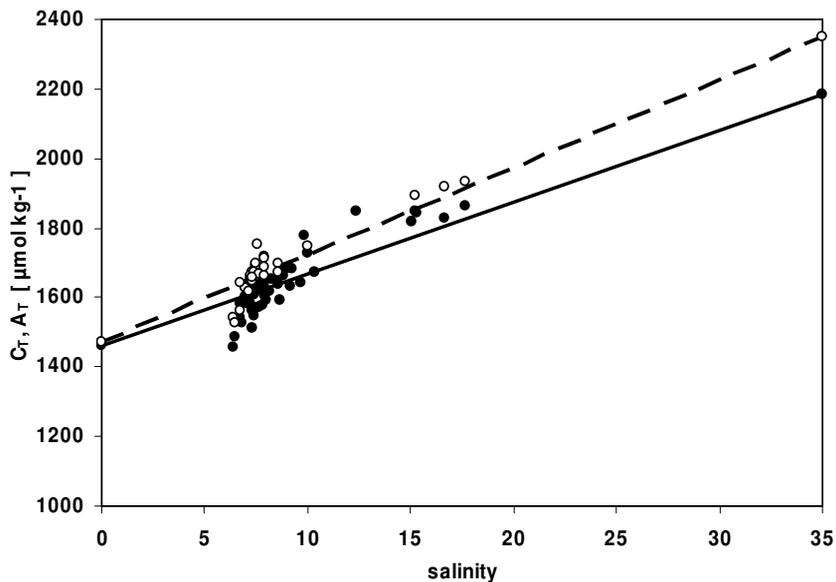


Fig. 21. Regression lines for total CO₂ (full circles, solid line) and alkalinity (open circles, dashed line) as a function of salinity. The calculation of the regression lines are based on fixed C_T (2182 μmol kg⁻¹) and A_T (2350 μmol kg⁻¹) at S_p=35.

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