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Freshwater in the ocean is not a useful parameter in climate research

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ABSTRACT

Ocean water is freshwater with salt. The distribution of salt concentration in the ocean changes by addition and removal of freshwater in the form of precipitation, continental runoff, and evaporation, and by a flow of saline ocean water that gives rise to a salt flux divergence. Often, changes in salinity are described in terms of "freshwater content" changes and oceanic "freshwater transports", defined as fractions of freshwater. But these freshwater fractions are arbitrary, because they are defined by a non-unique reference salinity. Also all temporal and spatial comparisons and anomalies of such freshwater fractions in the ocean depend on the choice of reference salinity in a nonlinear way, because in the definition of the fraction it appears in the denominator. Consequently, any conclusion based on the comparison of freshwater fractions is ambiguous. Since there is no definite physical constraint for a unique reference salinity, freshwater fractions are declared not useful for the assessment of the state of ocean regions and the associated changes. In the light of ongoing changes in the water cycle and the global nature of climate science, scientific results need to be expressed in a way so that they can be easily compared and integrated in a global perspective. To this end, we recommend to avoid freshwater fraction as a parameter describing the ocean state. Instead, one should use the terms of the salt budget to obtain unique results for quantifying and comparing salinity.

1. Introduction

Physical oceanography, like any other field of science, is based on measurable and derived quantities that can be compared to each other and to the respective terms of physical laws. To derive any understanding of processes and gain, for example, insight into the ocean's role in the climate system, these comparisons need to be unambiguous. Here, by ambiguity we do not mean uncertainty due to instrumental errors, to non-synoptic observations, to interpolation, or to model resolution and parametrizations, but ambiguity due to an unavoidable arbitrary choice of reference. With ambiguous comparisons, also analyses and conclusions are ambiguous, and future scenarios can hardly be developed. As we will show, the concept of "freshwater in the ocean" inevitably leads to this type of ambiguity and thus is not useful in physical oceanography.

Calculation of quantities that depend on an arbitrary reference value yield arbitrary numbers by definition. Consequently, arbitrary parameters may cause considerable confusion if they come without clear specification through a name or a unit. For example, sound pressure level (loudness) is a parameter in acoustics, that needs a reference pressure. Since, for practical reasons, the reference pressure used in underwater acoustics is different from that used in air acoustics, and even though these references are internationally accepted standards, misunderstandings easily appear evoking even societal debates (Finfer et al. 2008; Slabbekoorn et al. 2010).

The notion of freshwater in the ocean is mostly invoked in recognition of salinity changes being caused by dilution or concentration due to adding or removing freshwater. This exchange of freshwater is an important part of the hydrological cycle. In the non-oceanic compartments of the earth, soil, land-ice and atmosphere, freshwater (which is simply termed "water" there) is an important quantity because the residence times, except for ice-sheets and glaciers, and the total amount of water are comparatively small and changes of the water exchange are crucial. In contrast, in the ocean the amount of water is large and changes are fairly small. But since these changes determine the distribution of salt concentration, the freshwater flux into and out of the ocean has a huge impact on ocean processes.

Salinity itself is a key feature of the ocean. Together with temperature, it determines the density of ocean water and thereby influences almost all dynamical processes, ranging from the large-scale overturning circulation to double diffusive mixing at the centimeter scale. Salinity varies greatly in the world ocean, but this variability is not a consequence of sinks and sources of salt, as indicated by the small ratio between salt input (O(10^{12} kg/year)) and salt content in the ocean (O(10^{19} kg)), but of freshwater

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(e.g. Talley et al. 2011). Precipitation, input from land by rivers, glaciers and groundwater, and loss by evaporation create large differences in salinity on various spatial and temporal scales. These salinity differences lead to ocean currents, but on the other hand, they are also subject to ocean currents as water masses with a surplus or a deficit of freshwater are transported to other regions.

In the first combined analysis of freshwater input and ocean salinities, Knudsen (1900) inferred the steady state ocean circulation between a partially enclosed basin and the adjacent ocean from salt and mass balances, including river runoff. This concept applies to any fixed volume of the ocean, also the global ocean (e.g. Talley 2008).

In the context of changes in the ocean, research also addresses changes of salinity. In the 1970s and 1980s, when large-scale salinity anomalies were first investigated they were still described as such, namely as "Great Salinity Anomalies" (Dickson et al. 1988; Belkin et al. 1998). Only a few recent publications continue to provide salt budgets (Mauritzen et al. 2012; Treguier et al. 2014).

Since the 1990s, research papers often presented terms of a freshwater budget instead (e.g. Rahmstorf 1996; Serreze et al. 2006; Yang et al. 2016; Holliday et al. 2016, to give only a few examples). These terms are then called "freshwater content" in the ocean as well as "freshwater transports", for example through individual sections and gateways. Such "freshwater content" V_{ff} and "freshwater transport" ϕ_{ff} in the ocean is then defined as

$$V_{\mathrm{ff}} = V\,\frac{S_{\mathrm{ref}} - S}{S_{\mathrm{ref}}} \qquad (1)$$

and

$$\phi_{\mathrm{ff}} = \iint_{\mathrm{sec}} u_{\perp} \left(\frac{S_{\mathrm{ref}} - S}{S_{\mathrm{ref}}} \right) dl\, dz, \qquad (2)$$

with an ocean volume V with salinity S, and an arbitrarily chosen reference salinity S_{ref}. The double integral is evaluated over a vertical cross section area sec to which the velocity component $u_{\perp}$ is perpendicular and dl and dz are the respective horizontal and the vertical line elements along the boundary.

The freshwater content of ocean water is, however, uniquely defined as

$$FW = 1 - 10^{-3} S_A \qquad (3)$$

with S_A the absolute salinity in $\mathrm{g\,kg^{-1}}$ (IOC, SCOR, and IAPSO 2010). This definition gives the mass relation, hence, the mass of freshwater in an ocean volume V. The freshwater mass $V\rho FW$ (ρ for density) is comprising almost the entire mass of ocean water.

Consequently, the parameters defined by eqs. (1) and (2) describe only fractions of the freshwater defined by eq. (3). Accordingly, we will call these terms "freshwater fraction" and "freshwater fraction transport" throughout this paper. This also differentiates the latter from "true" freshwater inflow or removal through precipitation, evaporation, and continental runoff. Note that Treguier et al. (2014) suggested to use the terminology of "freshwater anomaly", but we find "anomaly" misleading and also inconsistent with definition (3), because "anomaly" usually refers to a deviation from a mean.

Freshwater fractions first appeared in the context of regional analyses, but ultimately the nature of ocean and climate science is global. This global nature requires that all analyses and results are formulated in a way that they can be integrated in a global perspective easily and seamlessly. Results that depend on a locally determined reference cannot satisfy this requirement.

In one of the first publications on freshwater fraction transports, Aagaard and Carmack (1989) provided estimates of freshwater budgets of the Arctic Ocean and of the Nordic Seas. These budgets included the exchange between the two basins and with the North Pacific and the North Atlantic. Based on the same volume transports through the connecting passages Fram Strait and Barents Sea Opening and the same salinities in the passages, Aagaard and Carmack (1989) estimated different freshwater fraction transports depending on whether they calculated them for the Nordic Seas or for the Arctic Ocean because they based these transports on different reference salinities S_{ref}. For example, they calculated the freshwater transport by southward flow in Fram Strait to be $820\,\mathrm{km^3\,yr^{-1}}$ and at the same time to be also $1160\,\mathrm{km^3\,yr^{-1}}$. From a physical point of view, such an ambiguity of results is not acceptable because it does not allow closing an overall budget. The root of the problem is the requirement of a reference salinity for computing the freshwater fraction terms.

Treguier et al. (2014) strongly recommended to use salinity in global analyses and to avoid analysing "freshwater in the ocean" as defined by eqs. (1) and (2) as the results are ambiguous. To our knowledge, their study is the only one that avoids assessing freshwater fraction explicitly for this reason. In this paper, we emphasize particularly that freshwater fraction terms are not only ambiguous by themselves but, even more important, comparing them is ambiguous as well, because the reference value in the denominator determines also their differences. Since temporal or spatial comparisons or anomalies are the rationale for any study, freshwater fraction cannot be a useful variable, neither on regional nor on global scales.

In this paper, we revisit the salt and volume budget (section 3) and stress that the relative change in ocean volume through addition or removal of pure fresh water is so small that in almost all cases this change can be neglected. Note that we will use the term "pure" freshwater for water that is supplied to the ocean from outside or leaving it. If the ocean volume remains constant and only the salt amount varies locally, all salinity changes can only be a consequence of a salt transport divergence. None of this is new.

For the stationary case, the salt and volume conservation reduces to the concept of Knudsen (section 4). In section 5 we lay out the corresponding concept of freshwater fraction in the ocean and in section 6 we address how the spatial and temporal comparison of the different terms depends on the arbitrary choice of the reference salinity.

We discuss the question of a physical constraint for a particular reference salinity (section 7) that should be used, and, since there is no such constraint, whether it would be useful to seek an international binding agreement for such a reference (section 8). We strongly suggest in section 9 to use salt content, salt transport and changes thereof and to avoid all freshwater fraction terms because they are ambiguous and not physically convincing.

2. Data

We demonstrate the implications of the concept of freshwater fraction and the impact of the choice of reference salinities in the context of the Arctic Ocean. The Arctic Ocean has a large input of pure (riverine and meteoric) fresh water and at the same time various oceanic connections to the Pacific and the Atlantic. We use data of a very simple toy model of the Arctic Ocean that are inspired by data of the real Arctic Ocean. In addition, temporal changes of transports through passages between the Arctic Ocean and the Nordic Seas are addressed with simulations of a global configuration with an Arctic focus of the finite element sea-ice ocean model FESOM (Wekerle et al. 2017). The advantage of using a toy ocean is that a closed salt and volume budget can be prescribed. Also, basic insights are accessible more easily with a simple model. In contrast, FESOM is sufficiently complex to mimic observational data with the additional advantage of no data gaps. Using observational data is not an alternative since the uncertainties due to a lack of representativeness of point measurements also lead to residuals in the salt and mass budget (e.g. Tsubouchi et al. 2018).

3. Conservation of salt and volume

As derived in numerous textbooks (e.g. Olbers et al. 2012) and publications (e.g. Wijffels et al. 1992), the salt budget of the ocean is controlled by the conservation laws of salt and mass of ocean water. Since sources of salt are negligible on the relatively short time scales of decades that are typical for physical oceanography, any change of salinity S in a fixed finite ocean volume V can only be caused by a lateral diffusive and advective salt flux divergence through the enclosing fixed lateral boundary A. Neglecting the variability of density and the diffusive salt fluxes through the boundary, the conservation for the mass of salt s in the volume V can be written as

$$\frac{\partial s}{\partial t} = \rho \oint_{\partial A} \int_{bot}^{top} S u_\perp \, dz \, dl \tag{4}$$

with t for time, and $u_\perp$ for the velocity normal to the vertical boundary A. dz and dl are vertical and horizontal line elements. The sign convention makes inward fluxes positive. The integration over the lateral boundary is written as an explicit vertical integration from bottom to top and a horizontal integration along the surface boundary ∂A of the enclosing vertical boundary A. The salt transport divergence appears as a closed integral over the oceanic flow through the lateral boundaries, because there is no surface flux of salt.

A finite volume V of sea water can change by lateral transport through the boundaries and the flux of pure freshwater $[P-E+R]$ through the surface:

$$\frac{\partial V}{\partial t} = \oint_{\partial A} \int_{bot}^{top} u_\perp \, dz \, dl + [P-E+R]. \tag{5}$$

For convenience we have lumped all contributions to $[P-E+R]$, the input from land through rivers, glaciers and groundwater R, the precipitation P, and the loss of freshwater through evaporation E, into a flux that can be thought of as a surface flux.

Today, a volume change from freshwater input on timescales of years to decades can only stem from the net mass loss of glaciers and ice sheets. Assuming an eustatic sea level rise of about 50 cm until the year 2100 (Stocker et al. 2013) this would be equivalent to an 0.15 permille increase of the ocean volume. The corresponding global mean salinity decrease would be 0.004 PSU which is at the limit of today's measurement accuracy. Even a short local volume input such as the seasonal peak of river runoff into the Arctic Ocean (Haine et al. 2015) does not raise the sea surface over a substantial time because any surface pressure gradient resulting from the input immediately excites barotropic waves that remove the height difference within days to weeks (Treguier et al. 2014). Therefore, we can state that, for our purposes, the volume of an ocean region can be considered constant, and the left hand side of eq. (5) can be neglected.

4. A steady state ocean with freshwater input - the Knudsen theorem

More than one hundred years ago, Knudsen (1900) used the conservation of mass and salt in steady state to derive estimates of the ocean circulation. Since then, the so-called Knudsen theorem (see the English translation in Burchard et al. 2018) has been widely used in estuarine research, for example, when river runoff and the salinities of inflow and outflow at the connecting ocean passages were used to infer the circulation and thus the flushing times of the estuary (Burchard et al. 2018). The Knudsen theorem can, however, also be applied to any ocean region when the inflow or evaporation of pure freshwater and the salinity along sections enclosing that region are known.

In a simple case, a river provides input of pure freshwater to an estuary at a known rate R. This water mixes with saline water in the estuary and in steady state, saline water with a salinity S_{out} leaves the estuary to the open ocean (Fig. 1a). To compensate the loss of salt and water, inflow of water with $S_{in} > S_{out}$ is required. The subscripts *in* and *out* indicate inflowing and outflowing water. From conservation of salt ($\phi_{in}S_{in} - \phi_{out}S_{out} = 0$) and volume ($R + \phi_{in} - \phi_{out} = 0$), it follows that

$$R = \phi_{out}\frac{S_{in} - S_{out}}{S_{in}} \quad (6)$$

in volume flux units, for example, Sv (1 Sv $= 10^6$ m^3 s^{-1}). Note that in the convention used here the transport ϕ is always positive, so that ϕ_{in} increases the volume and $-\phi_{out}$ reduces the volume. From eq. (6) and with S_{in} and S_{out} known (e.g. measured), ϕ_{out} can be calculated and ϕ_{in} can be computed from the difference between ϕ_{out} and R (Fig. 1a).

Note that Knudsen did not seek to trace "freshwater" in the ocean, but the great step forward of his theorem was that it provided a simple method to make use of the information of pure freshwater input and relatively easy-to-obtain salinity values to quantify not-so-easy-to-obtain ocean transports. The theorem allows to derive these numbers in an unambiguous way. It was applied many times, for example to estimate the exchange in the Strait of Gibraltar (Nielsen 1912, and many others thereafter). In a very elaborated way, Talley (2008) used the Knudsen principle to assess which parts of the global circulation match the pure freshwater flux divergences.

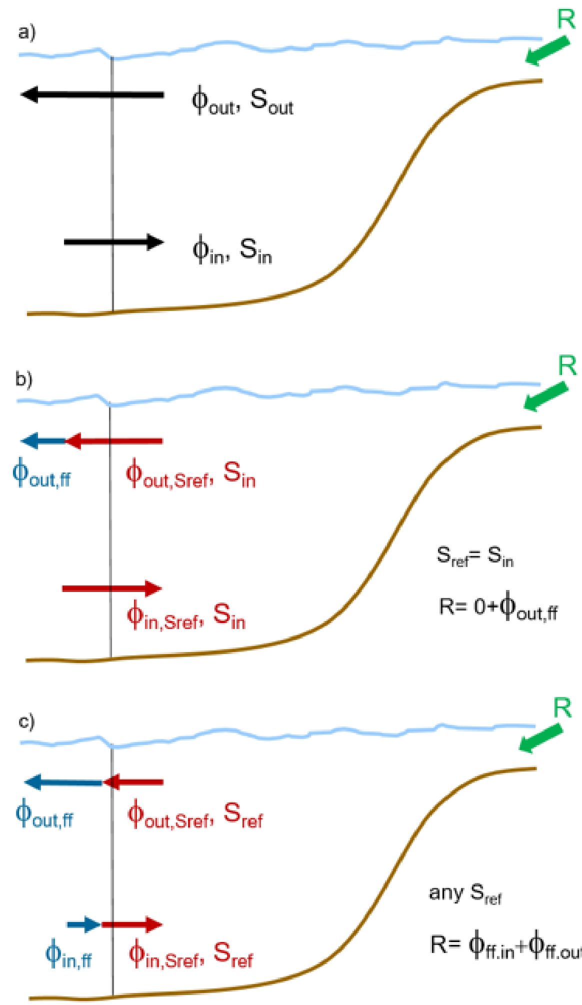

FIG. 1. Sketch of an estuary with inflow of freshwater R (green), outflow with salinity S_{out} and respective inflow with salinity S_{in} across a section denoted by the vertical line. a) shows the sketch in the sense of the Knudsen theorem where only the absolute flows are of interest; in b) the outflow is split into a transport fraction with the salinity S_{in} (red), and a fraction of freshwater transport $\phi_{out.\text{ff}}$ (blue); in c) the case is generalized to arbitrary reference salinities: both in- and outflow are split into a transport fraction with an arbitrary salinity S_{ref} and a fraction of freshwater transport. Both flow fractions carrying salt ($\phi_{in.S_{\text{ref}}}$ and $\phi_{out.S_{\text{ref}}}$) are of equal size and the combination of the freshwater flow fractions $\phi_{in.\text{ff}} - \phi_{out.\text{ff}}$ is always R.

5. The concept of freshwater fraction in the ocean

Despite the unique freshwater definition (IOC, SCOR, and IAPSO 2010, and eq. (3)), a plethora of publications (see section 1) use freshwater fraction terms and their changes with space and time to describe salinity changes. Fig. 2 illustrates the general concept. Any volume of ocean water V with a salinity S may be considered as a composition of a fraction of freshwater V_{ff} (subscript ff containing no salt and a fraction $V_{S_{\text{ref}}}$ with salinity S_{ref}, hence $V = V_{\text{ff}} + V_{S_{\text{ref}}}$. The total amount of salt is then given by $V_{S_{\text{ref}}}S_{\text{ref}} = VS$. These two equalities can be combined into eq. (1)

$$V_{\text{ff}} = V\frac{S_{\text{ref}} - S}{S_{\text{ref}}}.$$

This equation already illustrates the problem of the concept. S_{ref} appears in the denominator so that the volume of freshwater V_{ff} depends non-linearly on the reference salinity. This makes the definition fundamentally different from other physical quantities, including the TEOS10 freshwater definition of eq. (3).

Within the concept of freshwater fraction transports in the ocean (eq. 2), the outflow ϕ_{out} in eq. 6 and Fig. 1a can be seen as the combination of a flow $\phi_{out.S_{\text{in}}}$ exporting the salt that is imported by ϕ_{in} and that has the same salinity S_{in} (and thus equals ϕ_{in}) and a flow of freshwater $\phi_{out.\text{ff}}$ compensating the inflow R (Fig. 1b). Consequently,

$$\phi_{out.\text{ff}} = \phi_{out}\frac{S_{in} - S_{out}}{S_{in}}. \quad (7)$$

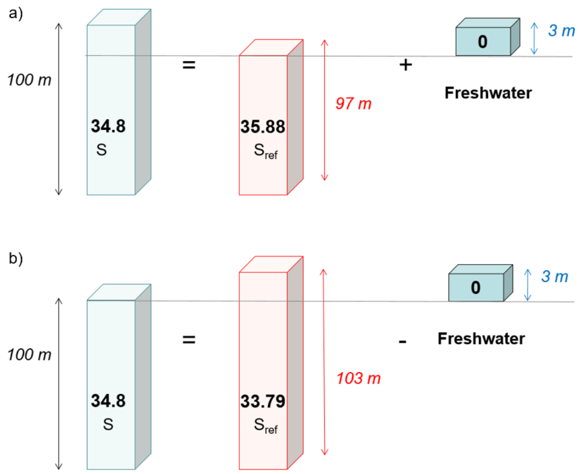

FIG. 2. Illustration of a water column with a salinity $S = 34.8$ that is interpreted as a combination of a column of salinity S_{ref} and a column of freshwater, (a) for dilution, (b) for concentration.

In contrast to eq. (6), eq. (7) is equivalent to percieving S_{in} as a reference salinity for the flow of an oceanic freshwater fraction.

Eq. (7) can, however, also be formulated with any other arbitrary reference salinity S_{ref} (eq. 1). It then implies that ϕ_{out} is composed of a respective saline $\phi_{out.S_{\text{ref}}}$ and freshwater flow fraction $\phi_{out.\text{ff}}$. In this general case, also the inflow ϕ_{in} consists of respective fractions $\phi_{in.S_{\text{ref}}}$ and $\phi_{in.\text{ff}}$ (Fig. 1c). Salt conservation requires again that $\phi_{in.S_{\text{ref}}} = -\phi_{out.S_{\text{ref}}}$, and volume conservation requires that $\phi_{out.\text{ff}} - \phi_{in.\text{ff}} = R$. In other words, in a steady state both the divergence of ocean currents and the divergence of flows of arbitrary freshwater fractions are equal to the pure freshwater input or output, no matter which S_{ref} was used to define $\phi_{in.\text{ff}}$ and $\phi_{out.\text{ff}}$ in terms of eq. (7) or, generally, eq. (2).

Volume V in Fig. 2 can also be interpreted as water with salinity S that originates from a volume $V_{S_{\text{ref}}}$ with salinity S_{ref}, of which a certain amount of freshwater has been removed but the salt has been retained. The removed water has then been replaced by water with S_{ref} (Fig. 2b). Note that this description is equivalent to a salt transport divergence.

It is evident from eq. (1) that in any ocean volume the content of freshwater defined in this way depends as much on the observed salinity as on the reference salinity. Accordingly, from a physical point of view, any volume of ocean water can be described containing a freshwater fraction ranging from large negative values to values approaching 100%. In principle, anyone can arbitrarily decide how much freshwater is to be contained in a given sample of ocean water. Often, authors use mean values of a basin (Aagaard and Carmack 1989) or along (set of) sections (Bacon et al. 2015).

6. The freshwater fraction budget

In section 5, we introduced the concept of artificially dividing a fixed ocean volume into a freshwater fraction and a fraction with the salinity S_{ref}. For such an ocean volume, the budget can also be divided into one for the freshwater fraction and a second one for the water with salinity S_{ref}. Obviously, global conservation requires that the two budgets match.

The freshwater fraction budget is given through a balance between the change of freshwater fraction content with time, the freshwater fraction transport divergence (a closed integral over the flow of freshwater fraction perpendicular to the lateral boundary), and finally external sources and sinks:

$$\frac{\partial V_{\text{ff}}}{\partial t} = \oint_{\partial A} \int_{bot}^{top} u_{\perp,\text{ff}}\, dz\, dl + [P - E + R]. \tag{8}$$

To keep the total ocean volume V constant,

$$\frac{\partial V_{\text{ff}}}{\partial t} + \frac{\partial V_{S_{\text{ref}}}}{\partial t} = 0,$$

there has to be a compensating exchange of water with the reference salinity. Thus, we get the second budget

$$\frac{\partial V_{S_{\text{ref}}}}{\partial t} = \oint_{\partial V} u_{\perp,S_{\text{ref}}}\, da, \tag{9}$$

where now the closed integral means integration over the entire surface ∂V of volume V. Eq. (9) makes clear that the concept of freshwater fraction repeats nothing else but that the salt content change is invoked by a salt flux divergence.

The flux divergence on the right hand side of eq. (8) may be composed of several individual branches through the lateral boundary and pure freshwater input. We show that comparing freshwater fraction transports across individual sections that do not form a closed boundary of a defined volume yields ambiguous results, not only for absolute values, but also for anomalies. Unfortunately, such comparisons are made often (Tsubouchi et al. 2018; Schmidt and Send 2007, to name a few).

As shown above, the transports of freshwater fractions ϕ_{ff} can be derived as an expression analogous to that for the content; hence repeating eq. (2)

$$\phi_{\text{ff}} = \iint_{\text{sec}} u_{\perp} \left(\frac{S_{\text{ref}} - S}{S_{\text{ref}}} \right) dl\, dz.$$

Both $u_{\perp}$ and S vary with l and z and may also vary with time. Here, the section sec need not enclose a volume.

We will use the Arctic Ocean to illustrate the ambiguity of such freshwater fraction transports. The Arctic Ocean receives a huge amount of pure freshwater through the rivers draining the North American and Eurasian catchments and therefore it is often regarded as a large estuary. It is however, connected to both the Pacific and the Atlantic Oceans through various passages. Pacific water with relatively low salinity (as compared to the Arctic Ocean mean salinity) and sea ice is imported through the Bering Strait; North Atlantic water with relatively high salinity is imported through the Fram Strait and the Barents Sea Opening. Low salinity water and sea ice is exported from the Arctic Ocean in the East Greenland Current and through the straits in the Canadian Archipelago. The salinities of the outflows are determined by mixing and dynamics within the Arctic Ocean. The Bering Strait inflow is also considered a freshwater inflow because its salinity is low.

Often the freshwater fraction transports through the different passages are calculated for the purpose of comparing them to each other and to the pure freshwater in- and outflow (Serreze et al. 2006). Some authors investigate, how the transports vary with time (Wekerle et al. 2013; Rabe et al. 2013; Haine et al. 2015; Tsubouchi et al. 2018), and how much of a freshwater fraction is gained or lost by the Arctic Ocean (Rabe et al. 2014). In the following, we demonstrate that all results depend on the choice of reference salinity.

a. Steady-state freshwater transports

In section 5, we mentioned in the context of the Knudsen theorem that in steady state the sum of freshwater fraction transports equals the pure freshwater input. The individual transports, however, and, most importantly, their relation to each other depend on the choice of S_{ref}. To illustrate this, we use a simple toy model of the Arctic Ocean. The values for the volume transports through the different passages and their bulk salinities are given at the bottom of Fig. 3. For simplicity, we combine here the Atlantic Water inflow through Fram Strait and Barents Sea Opening. Since we simulate an equilibrium case, the values of the in- and outflow transports and salinities are chosen in a way that the net input and output of volume and of salt are zero. Fig. 3 shows the freshwater fraction transports that enter or leave the Arctic Ocean based on different reference salinities and that no clear judgement about neither their absolute nor their relative size can be made:

- For S_{ref}=36 (a salinity typical for brine-enriched shelf water in winter) the freshwater fraction inputs through the Bering Strait inflow (rather low salinity) and the combined Fram Strait/Barents Sea Opening (WSCBSO) inflow (highest salinity of all inflows) are almost equal. Both are larger than the pure freshwater input ϕ_{ff} from runoff etc. The freshwater fraction outflow is largest through the East Greenland Current (EGC) and the outflow through the passages of the Canadian Arctic Archipelago (CAA) is about two thirds of the EGC outflow.

- For S_{ref}=35 (a typical Atlantic Water inflow salinity), the difference between the Bering Strait and the WSCBSO inflows is huge since the WSCBSO freshwater fraction flow is now zero. While the Bering Strait inflow is again slightly larger than the pure freshwater input, the WSCBSO flow, being zero, is now much smaller than the runoff. The Canadian Archipelago outflow is now only about one third of the EGC outflow.

- For S_{ref}=34 (a salinity typical for the lower halocline (Rabe et al. 2011)) the freshwater fraction flow through WSCBSO is negative, and in fact considerably so, namely more negative than the outflow through both outflow passages. The Bering Strait inflow is now slightly smaller than the pure freshwater input, and the freshwater fraction transport through the Canadian Archipelago is even positive, that is, directed into the Arctic Ocean.

- For the boundary averaged salinity of 33.38, the "only correct reference salinity" (Bacon et al. 2015),

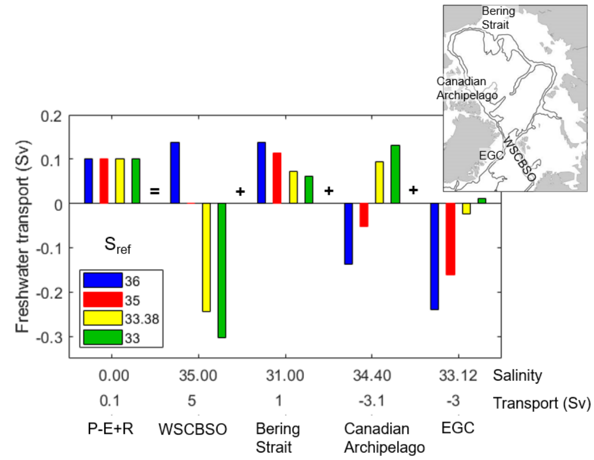

FIG. 3. Freshwater transports by net pure freshwater inflow, $[P-E+R]$, and freshwater fraction fluxes through four oceanic gateways of a toy model of the Arctic Ocean based on different S_{ref}s (legend). The x-axis shows the salinity (upper labels) and the volume flow (middle labels) of the gateways (lower labels). The gateway acronyms mean WSCBSO for the combined West Spitsbergen Current/Barents Sea Opening inflow, and EGC for the outflow through the East Greenland Current. The salinities and transports are chosen in a way so that they are in equilibrium. The reference salinities are chosen as a fairly large (36) and a medium (34) value (see text), as salinity of the West Spitsbergen Current (WSC) (35), and the average salinity of all in and outflows in this configuration (33.38), following Bacon et al. (2015). Note that the sum of all oceanic freshwater transports for each S_{ref} (each color) is equal and identical to P-E+R.

the WSCBSO inflow provides now the largest negative freshwater fraction contribution. Again, the Bering Strait inflow is positive but smaller than the runoff, however the second largest positive input is now provided through the Canadian Archipelago outflow while the EGC outflow remains a freshwater fraction sink.

From this simple example we can easily see that almost every combination of "main input contribution" versus "smaller input" or of "strongest/weakest output" and inverse relations between inputs and outputs of freshwater fractions can be obtained simply by the choice of reference salinity in a fairly moderate range of possible ocean salinities. On the other hand, the associated salt transports are uniquely 0, 175, 31, −107, and −99 $\mathrm{kt\,s^{-1}}$ for $[P-E+R]$, WSCBSO, Bering Strait, Canadian Archipelago, and EGC. Here, a constant density of $1000\,\mathrm{kg\,m^{-3}}$ was assumed for simplicity.

Note also, that no information about the average salinity of the toy ocean is required neither for the freshwater fraction nor for the salt budget. The fact that each ocean is inhomogeneous with respect to salinity is the ultimate reason for having different outflow salinities (Dickson et al. 2007; Aagaard and Carmack 1989).

b. *Time variability of freshwater fraction content and transports*

One of the main goals in climate research is to consider non-stationary systems and to determine anomalies and the magnitude and direction of changes. Thus a considerable observational effort is directed to quantifying the variable content and transport of quantities in the ocean. From eq. (1), we can see immediately how the choice of the reference salinity S_{ref} influences not only the freshwater fraction volumes themselves but also their difference ΔV_{ff} when the salinity is changing from S_1 to S_2:

$$\Delta V_{\mathrm{ff}} = V\left(\frac{S_{\mathrm{ref}}-S_2}{S_{\mathrm{ref}}} - \frac{S_{\mathrm{ref}}-S_1}{S_{\mathrm{ref}}}\right) = V\,\frac{S_1-S_2}{S_{\mathrm{ref}}}$$

For the example values in Table 1, the magnitude of the resulting ambiguities are of the order of 10% and more. Note that the range of S_{ref} in Table 1 is approximately that of ocean salinities. From a physical point of view also much smaller or much larger S_{ref} can be chosen, which would result in a larger ambiguity of a change in freshwater fraction content.

The arbitrariness of comparisons of freshwater fraction contents or transports can also be seen in time series of the transport through a single passage (Fig. 4). Here we use results derived from FESOM simulations of velocities and salinities (Wekerle et al. 2017). From a 30 year time series in the East Greenland Current the liquid freshwater fraction export from the Arctic Ocean into the Nordic Seas is

TABLE 1. Numerical example for the ambiguity in freshwater fraction content differences as a consequence of the choice of a reference salinity.

reference salinity S_{ref}	**30**		**38**	
salinity S	34	35	34	35
freshwater content V_{ff} (%)	-13.33	-16.67	10.53	7.89
difference in freshwater fraction content ΔV_{ff} (%)	**-3.33**		**-2.63**	

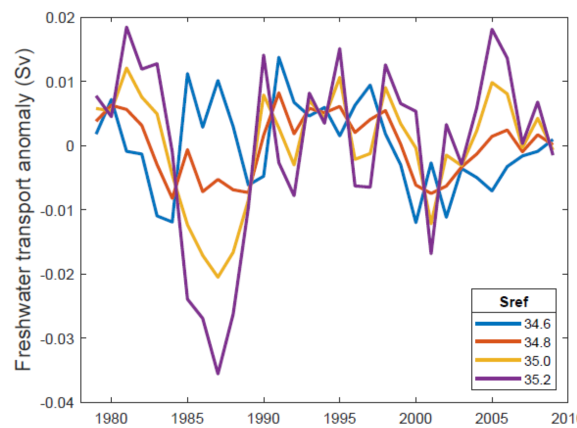

FIG. 4. Anomaly of southward liquid freshwater fraction transports through the Fram Strait for different reference salinities. Salinity and volume transport data (see Fig. 5) from FESOM simulation (Wekerle et al. 2017; Horn 2019).

computed. Again, different reference salinities give very different absolute values (not shown). More relevant in the context of climate change research, the rates of change in the transport anomalies (Fig. 4) are different at almost any instance, and over many periods they do not even agree in the direction of change: during several phases, the freshwater fraction export from the Arctic Ocean in the East Greenland Current has been both increasing and decreasing in the same time interval. It is entirely unclear how to use such information in the context of climate change research.

7. Are there physical constraints for a particular reference salinity?

The ambiguity in the concept of freshwater fraction in the ocean, apparent in eq. (1), may be resolved if a universal reference salinity could be derived from physical principles. We argue that there is no such universal reference salinity.

Common choices for reference include the mean salinity of an ocean volume (e.g. Aagaard and Carmack 1989; de Steur et al. 2018), the "maximum salinity of inflowing water" (e.g. Dickson et al. 2007; Rabe et al. 2014), or the average salinity along the entire lateral boundary of a given volume (Bacon et al. 2015; Tsubouchi et al. 2018). Although all authors argue for their reference value, the different choices have in common that they change with time and also with the (adjacent) ocean basin. The fact that a basin or boundary average or transport maximum salinity changes with time makes these constant reference salinities incompatible with studying salinity change. In section 1, we discussed how different reference salinities for adjacent ocean basins immediately lead to conflicting values of "freshwater" flux through the connecting passage.

The average salinity along the entire lateral boundary of a given volume was even claimed to be the only correct reference salinity (Bacon et al. 2015). Indeed, this choice does close the total budget of the freshwater fraction in the given volume – just as any other choice does. The proof of uniqueness in Bacon et al. (2015), however, is not convincing because it is based on an inconsistent analogy. Further, in following the rule of Bacon et al. (2015) a neighbor ocean with a different boundary average salinity is again assigned a different reference salinity. Any passage connecting the two adjacent oceans would then have two "correct" reference salinities and thus two "unique" freshwater fluxes. If the different boundary mean S_{ref}s were unique to specific ocean basins and regions, a combination of them to obtain global budgets would be impossible. This may serve as an independent indication that there cannot be a "unique" or "correct" S_{ref}.

8. Is it useful to seek an international agreement on a universal reference salinity?

In the absence of a plausible physical constraint for a reference salinity, it may be useful for the community to (1) agree on an internationally binding reference salinity and to (2) assign a special name and unit to the respective freshwater terms. In reflecting a few very general principles of physical parameters, we discuss in the following, why such an effort is not worth consideration.

The measurement of a quantity Q, which is the first step in any metrological consideration, is just the comparison of the measured value with a standard, or reference. The used reference is expressed as the unit. The combination of a value x and a unit b, for example distance relative to the unit meter, is unambiguously expressed as

$$Q = x \cdot b. \tag{10}$$

From the measured quantities, other quantities can be derived that are unambiguous as well. This quantity is absolute in the sense, that a value of zero implies that there is nothing of this quantity.

For example, length is an absolute parameter. It can be given in meters, inches, miles and other units. An identical length will then have different combinations of values and units. The key point is that also the difference between two different lengths will be unambiguous through the unit:

$$\Delta Q = Q_2 - Q_1 = (x_2 - x_1) \cdot b, \tag{11}$$

while the ratio between two different lengths is even independent of units and thus of the reference system:

$$r_Q = \frac{Q_2}{Q_1} = \frac{x_2}{x_1}. \tag{12}$$

Also salinity is an absolute parameter, that is, there is either no salt in the water, hence the salinity is zero, or there is some salt the concentration of which can be given in various units or no units, depending on which salinity is given (IOC, SCOR, and IAPSO 2010). These comparison principles hold for almost all parameters that are used to describe physics in a quantified way.

The other type of quantification is made relative to a reference value that is chosen arbitrarily either since there is no absolute value (for example for potentials) or because of practical reasons. The most prominent example for a practical scale is temperature, for which the Celsius scale is used in daily life in most of the world and in Earth system science. The Celsius scale is based on an international agreement (Comité International des Poi Mesures 1969; Preston-Thomas 1990) and it has its own unit, °C. The Celsius scale and the Fahrenheit scale, the other practical scale that is in use, are no longer absolute, because the linear relation between unit and parameter value includes now an offset a,

$$T = a + b \cdot x. \tag{13}$$

A ratio between two temperatures, T_1 and T_2, would therefore have the form:

$$\frac{T_1}{T_2} = \frac{a + b \cdot x_1}{a + b \cdot x_2} \tag{14}$$

and a statement like "temperature 1 is twice as large as temperature 2" cannot be made in the practical scales. It can be made for temperatures given in the Kelvin scale, for which $a = 0$.

Yet, any temperature difference is again well defined by the respective unit. Furthermore, the amount of heat (energy) necessary to raise the temperature of a sample is independent of the temperature scale because it is expressed by the temperature *difference* and two temperature differences, ΔT_n and ΔT_m, can again be related unambiguously. Consequently, the introduction of a practical scale for temperature with a reference offset is very meaningful and for all scales (Kelvin/Celsius or even Fahrenheit) the unit reveals the value of the absolute values immediately.

For oceanic freshwater fraction terms, none of these principles hold. They have different values for different S_{ref} but the units (typically m^3 for contents and mSv for transports) remain the same. Moreover, all comparisons depend on the choice of S_{ref}, as is obvious from eq. (b)

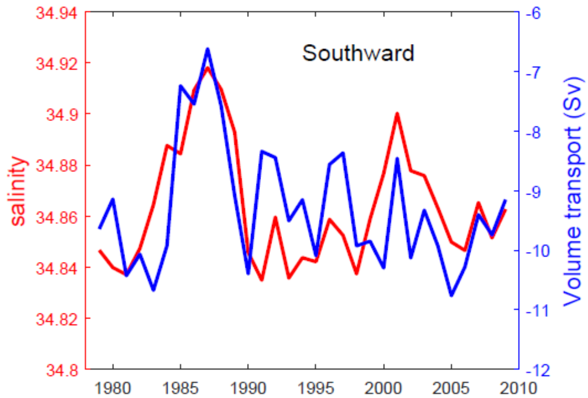

FIG. 5. Time series of velocity weighted salinity (red) and volume transport (blue, positive northward) of the southward flow in Fram Strait. Data based on the FESOM simulation (Wekerle et al. 2017; Horn 2019).

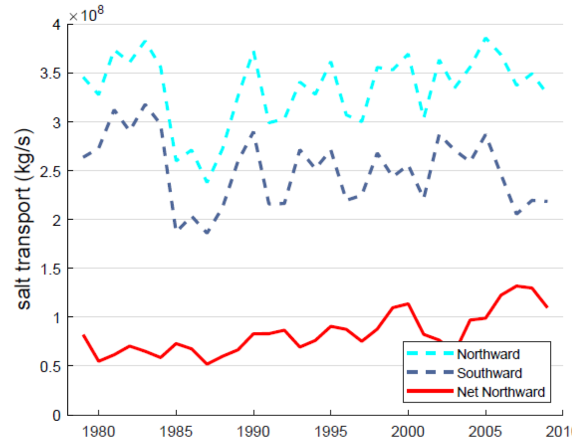

FIG. 6. Salt transports in kt s^{-1} through Fram Strait by the northward and southward flows (dashed lines, both drawn as positive flows) and the difference between the two (red solid line) resulting in a net salt transport that is directed northward.

and Figures 3 and 4. Neither the difference nor the relation between freshwater fractions (content or transport) are independent of the reference salinity. Therefore, the oceanographic community should not strive to obtain an agreement on a universal reference salinity.

9. Return to salt and volume budget

We reviewed that the freshwater terminology does not help to explain ocean salt content, its changes, and oceanic transport variability, because, with the exception of pure freshwater, it is inherently ambiguous. To explain ocean salinity changes, we strongly recommend instead to return to the analysis of salinity and volume transports, and ultimately salt transports, considering that changes of the salt content in an ocean volume (i.e., changes of the volume average salinity) are a consequence of salt transport divergences (sections 3 and many oceanographic text books). In contrast to freshwater fraction transports, salt transports are robust and unique absolute numbers.

As an incentive, consider the simulated freshwater transports in Fig. 4. They are based on time series of the southward volume transport through the Fram Strait and the respective transport-average salinity (Fig. 5). These time series immediately reveal two important features that cannot be seen from the freshwater plots: (i) there seems to be a correlation between volume transport and salinity with a weaker southward flow having a larger salinity and vice versa, and (ii) the range of variation is much larger for the volume flow (ca. 40% of the absolute value) than for salinity (0.3% of the absolute value).

The important budget term, however, is the salt transport. For the timeseries in Fig. 5, the salt transport variation follows largely the volume transport variation and such a relation is probably true for most ocean transports. This immediately suggests oceanographic interpretations of the flow that are otherwise obscured by the ambiguity of the relation between volume flow and freshwater flow.

No matter how small its salinity, the southward flow in Fram Strait exports salt from the Arctic Ocean and imports salt to the subarctic North Atlantic. While this salt transport is a robust number, it still does not say much about the contribution of this flow to salt content changes in either ocean since these changes are a consequence of the local salt transport divergence. To conserve volume, the large volume flow variation (Fig. 5) must be compensated and only in case of a salinity difference between the in- and the compensating outflows, the Arctic Ocean and North Atlantic will gain or lose salt. In the case of Fram Strait, a considerable part of the southward volume flow, including its variations, is balanced by the northward West Spitsbergen Current. Comparing the respective salt transports shows that an excess of 100 kt s^{-1} salt is carried northwards (Fig. 6). The variations in the individual salt transports, which are mostly induced by variations of the volume transport, are largely compensated and do not show up in the net transport. What remains from the two opposite flows is that the net salt import to the Arctic Ocean through Fram Strait has been smoothly increasing over the last 30 years (in this model simulation). Again, all salt transport time series, northward, southward and net salt transport through Fram Strait, yield themselves to immediate oceanographic interpretation.

There are a number of recent publications where the ambiguities of the freshwater terminology are avoided by quantifying the variation of salt content in a given ocean volume instead (e.g., Mauritzen et al. 2012) or by specifically quantifying salt transports instead of freshwater transports across latitudes (e.g., Treguier et al. 2014). Jackson and Straneo (2016) computed salt transports to analyze ocean variability in a glacier fjord with pure freshwater input through melting.

10. Conclusion

"Freshwater transport in the ocean can be a puzzling subject, with much confusion arising simply out of differences in what is meant by the term freshwater transport." (Wijffels et al. 1992). After elucidating the meaning of the parameter "freshwater" in the ocean as an arbitrary fraction we conclude that not only "can" freshwater transports within the ocean be puzzling, but rather they "are puzzling" by definition. We claim that, because of their arbitrariness, they are not useful for quantifying and understanding ocean change.

The parameter "freshwater in the ocean" formulated as an arbitrary freshwater fraction cannot be used in any meaningful way because the results of comparisons and anomalies (both relations and differences) depend fundamentally on the reference salinity. Comparisons, however, are the ultimate reason for any quantification.

Further, in the context of global changes, results from regional analyses, where for a short time a small community of researchers may reach a local consensus on a particular reference value, need to be comparable between each other. This type of comparison is not possible with regionally defined freshwater fractions, either.

There are cases where certain types of freshwater in the ocean are of interest. For example, it is interesting to discriminate between glacial melt and meteoric water in the ocean and to trace the pathways of these waters. Such tracing can be uniquely achieved with source-specific tracers, such as oxygen isotopes (Bauch et al. 2016) or Helium (Huhn et al. 2018).

There is an increasing degree of arbitrariness in the use of ocean freshwater fraction:

- i – In a stationary case or in climatological considerations, freshwater sources and sinks can be quantified without any arbitrariness. They can be computed unambiguously as divergences of freshwater fraction transports (e.g. Talley 2008). The results are unique and independent of S_{ref} as pointed out by both Talley (2008) and Treguier et al. (2014).
- ii – For all reference salinities, a freshwater fraction, often called "freshwater content", in a given volume will be larger for a lower salinity than for a higher salinity. However, the size of the difference depends on the reference salinity.
- iii – For a freshwater fraction transport that is not mass balanced not even the sign is unique.

We emphasize that specifying freshwater fraction terms is not wrong in a physical sense. Fractions of freshwater contents or transports with respect to a specifically chosen reference salinity are well defined, but this choice is only as valid as any other choice. Both mean values as well as anomalies of freshwater fraction transports are entirely ambiguous, including the sign of comparisons.

A fundamental misunderstanding already appears in the interpretation of "adding" or "removing" freshwater. Adding pure freshwater to a region in the ocean does not result in a local volume change because of fast adjustment processes. Instead, the amount of salt changes because the added freshwater volume is compensated by an outflow of saline ocean water. Replacing saline water with pure freshwater is just a statement of salt flux divergence.

There is no physical constraint for a particular reference salinity and thus in the oceanographic literature, reference salinities are chosen in a suggestive and therefore subjective way. Supposedly "correct" reference salinities (Bacon et al. 2015) turn out to be based on an inconsistent analogy. It can be — and sometimes it is — argued that the dependence of the freshwater fraction terms on the different reference salinities in the oceanographic literature is not large, because the published S_{ref} values do not differ very much. This reasoning resembles the joke about the drunkard seeking his lost key in the light cone of the street lantern, because in the darkness outside of the light cone he would not see it anyway. It is certainly not incorrect that similar S_{ref} lead to similar freshwater terms, but this insight is hardly a justification for dealing with arbitrary numbers. And it evokes immediately the question why there are different reference salinities in the first place.

The arbitrariness of freshwater budgets can easily be avoided (Treguier et al. 2014). Mass and salt conservation are unambiguous in both stationary and non-stationary cases. Salt transports through individual sections can unambiguously be compared since the mass of salt is an absolute quantity. Furthermore, salt budget terms have the profound advantage over freshwater fractions in that they lead more directly to oceanographical interpretation.

Salinity itself is a sophisticated quantity, which has been difficult to define (IOC, SCOR, and IAPSO 2010), and measuring it with high accuracy is difficult even today (Budéus 2011). Despite remaining caveats (Schmidt et al. 2018; Budéus 2018), practical salinity can be determined as a unique parameter, and salinity changes can be analyzed by assessing salinity and ocean transports in a unique way, including the input of pure freshwater. It is entirely counter-productive to dilute the parameter salinity by watering it down with the artificial and ambiguous construction of "oceanic freshwater fraction".

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