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ОРИГИНАЛЬНАЯ СТАТЬЯ ORIGINAL ARTICLE

THE EFFECT OF USING LOCAL MEAN VERSUS CONSTANT REFERENCE SALINITY TO ESTIMATE ARCTIC OCEAN FRESHWATER CONTENT CHANGES

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Summary

Changes of high-latitude freshwater content (*FWC*) play an important role in shaping the variability of polar oceans. *FWC* is defined as depth-integrated departure of salinity from a reference salinity S_{ref} divided by this S_{ref} . A constant S_{ref} is often used for high-latitude *FWC* estimates. Here it is argued that for analyzing *FWC* spatiotemporal changes the use of *local* mean S_{ref} is a better choice. Analysis of 2007 *FWC* anomalies in the 25–75 m layer demonstrated, for example, that the choice of S_{ref} = 34.8 (which is often used in climate studies) leads to *FWC* spatial anomalies exaggerated, on average, by ~0.6 m, which is a substantial fraction of total spatial *FWC* changes. The problem is aggravated in areas where the difference between the local S_{ref} and S_{ref} = 34.8 is greater. Thus, it is concluded that using climatological mean salinities as S_{ref} provides superior estimates of spatiotemporal Arctic Ocean *FWC* changes.

Keywords: Arctic Ocean, freshwater content, reference salinity.

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INTRODUCTION

High-latitude regions play a special role in shaping variability in sub-polar oceans through regulating convection in the Labrador and Greenland seas via freshwater exchanges [e. g. 1, 2]. Hence, Arctic Ocean freshwater content (FWC) variations are of primary importance for detection and attribution of regional and global climate change. Several studies have addressed questions related to changes in the FWC of the Polar Basin [e. g. 3–12].

The total FWC stored in a water column is usually computed as

$$FWC = \int_{z_1}^{z_2} \frac{S - S_{ref}}{S_{ref}} dz , \tag{1}$$

where S is salinity, S_{ref} is reference salinity, and z_1 and z_2 are the upper and lower boundaries of the water layer for which *FWC* is calculated. With this formulation, *FWC* is equivalent to the freshwater column (m) required to adjust water salinity to S_{ref}; and negative *FWC* anomalies are associated with fresher ocean. *FWC* is often computed relative to a constant S_{ref}. For example, for the Arctic Ocean Aagaard and Carmack [3] used S_{ref} = 34.8, which may be found at ~200–250 m in the Eurasian Basin and down to 350m and deeper in the Canada Basin. S_{ref} = 35.2 was used by Dickson et al. [13] as the salinity of inflowing intermediate Atlantic water of the Arctic Ocean. For discussion in depth of the choice of various definitions for S_{ref} see Carmack et al. [9]. Aagaard and Carmack [3] were arguably the first who used different reference salinities to calculate *FWC* budgets for different high-latitude regions. This approach has been adopted in recent studies in which local climatological mean salinities were used in analyses of long-term *FWC* changes of the North Atlantic Ocean [14] and Arctic Ocean [10].

The goal of this note is to demonstrate potential problems which may arise from using a constant S_{ref} to analyze changes of the Arctic Ocean *FWC*.

DATA AND METHODS

The analysis area comprises the Arctic Ocean together with its Siberian marginal seas (Kara, Laptev, East Siberian, and Chukchi). We employed extensive observational data collected during the International Polar Year in 2007. This data set consists of 3452 temperature and salinity profiles measured using Conductivity-Temperature-Depth (CTD) instruments. Typical measurement errors are 0.003–0.005 °C for temperature and 0.003–0.005 psu salinity and vertical resolution of observations is ~1–2 m or even better. This data set includes summer ship-based observations and annual drifting buoy observations; for consistency, only summer observations were used in this analysis.

Observations from the 1970s were used to calculate local decadal-mean salinities, applied as the local climatological mean S_{ref} for estimates of *FWC*. These historical observations were obtained from Nansen bottle water samples and discrete temperature measurements. Although the accuracy of these data is at least an order of magnitude worse than that of the CTD measurements and the data have rather coarse vertical resolution, they span a reasonable horizontal extent; seven repeated 1973–1979 surveys totaling 775 oceanographic stations make these data an invaluable resource of information about the decadal-mean water-mass structure within the Arctic Ocean. These data were interpolated onto a spherical spatial grid with 0.2° step along both latitude and longitude following the method of Polyakov and Timokhov [15] (Fig. 1*a*).

For each Arctic Ocean location with available 2007 CTD profiles, *FWC* was estimated by integrating S and (in case of spatially variable) S_{ref} over a constant-depth (z) layer of 25–75 m (thus avoiding the generally noisy data from the upper 25 m ocean and reducing the effects of the seasonal signal). S_{ref} was found by searching for the nearest grid node with a mean climatological S, which was not further than ~11km. Displacement of isopycnal surfaces strongly impacts estimates of *FWC* anomalies [10]; however, for simplicity we used z-based estimates in this study.

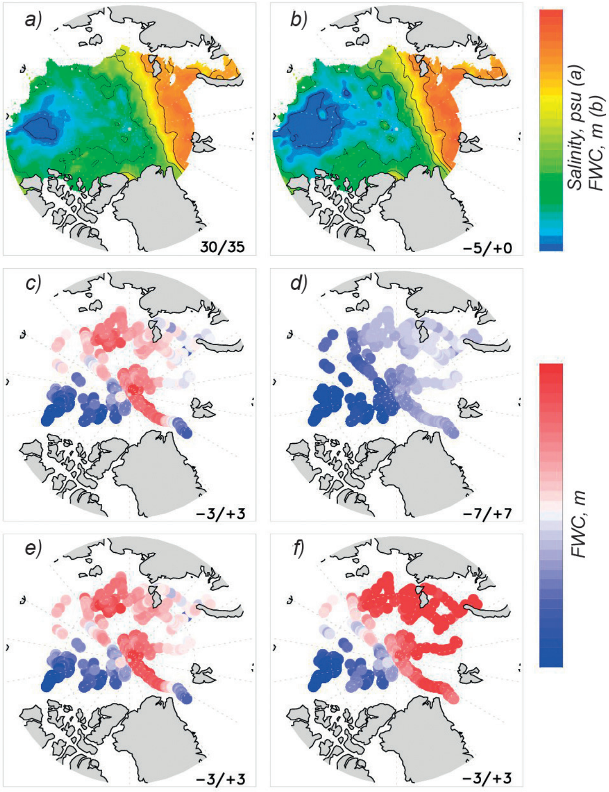

Fig. 1. Freshwater content (*FWC*, m) and its anomalies in the subsurface 25–75 m layer of the Arctic Ocean.

a — decadal mean (1970s) salinity (psu) used as local reference salinity S_{ref} in calculations of *FWC*; *b* — *FWC* in the 1970s calculated using constant S_{ref} = 34.8; *c* — 2007 *FWC* calculated using local mean S_{ref}; *d* — 2007 *FWC* calculated using constant S_{ref} = 34.8; *e* — 2007 (local mean S_{ref}) *FWC* anomalies relative to *FWC* spatial mean; *f* — 2007 (constant S_{ref} = 34.8) *FWC* anomalies relative to *FWC* spatial mean. Color maps indicate linear change of corresponding parameters between their maximum and minimum values, which are shown in the right bottom corner of each panel

Рис. 1. Пресноводный баланс (ПБ, м) и его аномалии в подповерхностном 25–75 м слое Северного Ледовитого океана.

а — среднедекадная (1970-е гг.) соленость (ЕПС), использованная в качестве локальной относительной солености S_{ref} в расчетах ПБ; *b* — ПБ в 1970-е гг., рассчитанный с использованием постоянной S_{ref} = 34,8 ЕПС; *c* — 2007 г. ПБ, рассчитанный с использованием локальной средней S_{ref}; *d* — 2007 г. ПБ, рассчитанный с использованием постоянной S_{ref} = 34,8 ЕПС; *e* — 2007 г. (локальная средняя S_{ref}) аномалии ПБ относительно среднего по области ПБ; *f* — 2007 г. (постоянная S_{ref} = 34,8 ЕПС) аномалии ПБ относительно среднего по области ПБ. Цветовые карты используют линейное изменение параметра между максимальными и минимальным его значениями, которые приводятся в правом нижнем углу каждого рисунка

PATTERNS OF 2007 ARCTIC OCEAN FRESHWATER CONTENT

Spatial distribution of decadal-mean (1970s) salinity in the 25–75m layer of the Arctic Ocean is shown in Fig. 1*a*. It exhibits such well-known features as the Canada Basin salinity minimum of ~30 psu and increased salinities in the Eurasian Basin due to intensive communication between the polar basins and the North Atlantic Ocean. Data from the

1970s were used to compute *FWC* based on constant S_{ref} = 34.8 (Fig. 1*b*). Expectedly, *FWC* faithfully copies the salinity pattern with the minimum *FWC* in the Canada Basin and an increase towards the Eurasian Basin. The *FWC* values suggest, for example, that in order to reach a salinity of 34.8 psu the 25–75 m layer in the Canada Basin must lose up to 5 m of fresh water. An analogous map based on local mean S_{ref} is not shown because the entire domain in this case is filled with zeros. However, this is useful information attesting that the Arctic Ocean salinity (or *FWC*) is at its most probable state (assuming normal distribution of *FWC* changes) and no additional fresh or salty water is required for the layer to move its *FWC* closer to this state. We will henceforth refer to this state as "normal state".

We now direct our attention to the analysis of *FWC* observed in 2007. Fig. 1*d* shows that *FWC* values based on S_{ref} = 34.8 are universally negative owing to the fact that the S_{ref} = 34.8 is much higher than any of the observed salinities in this layer of the Arctic Ocean; indeed, this S_{ref} is so high that, arguably, it has never been observed at this depth range in the Polar Basin (i.e. this is a highly unlikely state of the layer). *FWC* based on the local mean S_{ref} shows that in 2007 the western Arctic Ocean was actually saltier than normal, whereas the eastern Arctic Ocean was fresher; a comparable magnitude (up to several meters) of positive and negative *FWC* spatial differences was observed in the eastern and western Arctic Ocean (Fig. 1*c*).

A closer look at the *FWC* spatial patterns shown in Figs. 1*c* and 1*d* suggests a certain similarity between these two distributions with lower *FWC* values in the eastern Arctic Ocean and higher values in the western Arctic Ocean. This similarity is clouded in Figs. 1*c* and 1*d* by very different spatial means defined by different S_{ref}. Indeed, when these means are subtracted, the spatial patterns of *FWC* anomalies look quite similar (Figs. 1*e* and 1*f*), which is confirmed by the high pattern correlation (R = 0.88). However, there are still some noticeable differences between these distributions. Most notably, *FWC* anomalies based on S_{ref} = 34.8 are greater than those based on the local mean S_{ref}. This is confirmed by differences between these two anomalous freshwater distributions (Fig. 2). This difference

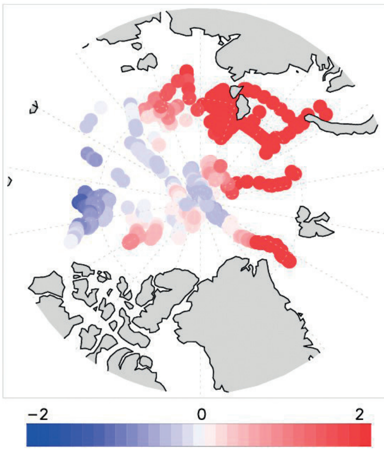

Fig. 2. Difference between *FWC* anomalies (m) in the subsurface 25–75 m layer of the Arctic Ocean calculated using local mean S_{ref} or constant S_{ref} = 34.8.

Рис. 2. Разница между аномалиями ПБ (м) в подповерхностном слое 25–75 м Северного Ледовитого океана, рассчитанными по локальным S_{ref} или постоянной S_{ref} = 34,8 ЕПС was quantified by estimating the spatial standard error, which was found to be 0.62 m and thus constitutes a substantial fraction of anomalous *FWC* (Figs. 1*e*,*f*). This quantity suggests that the use of different S_{ref} leads not only to different means (Figs. 1*c* and 1*d*) but also substantially exaggerates spatial *FWC* anomalies.

CONCLUDING REMARKS

Using 2007 observational data as an example, this paper demonstrates substantial differences between 25–75 m Arctic Ocean mean and anomalous *FWC* calculated using local mean S_{ref} and the constant $S_{ref} = 34.8$, which is often used in climate studies. Estimates based on the latter S_{ref} may be useful in illustrating very different *FWC* in the upper and lower layers of the Arctic Ocean or the fresher state of the Polar Basin compared with sub-polar oceans. However, we argue that for analyzing *FWC* spatiotemporal changes the use of the local mean S_{ref} is a better choice since the local S_{ref} represents the most probable local state defined by the climatological mean local salinity.

Estimates of 2007 *FWC* anomalies demonstrated that the choice of $S_{ref} = 34.8$ leads to *FWC* spatial anomalies exaggerated, on average, by ~0.6 m; this is a substantial fraction of spatial *FWC* changes. It is evident (but not shown here) that temporal *FWC* anomalies will suffer the same problem when $S_{ref} = 34.8$ is used. The problem is aggravated in areas where the difference between the local S_{ref} and arbitrary S_{ref} is bigger. We note that defining climatological mean *S* is not a trivial task, either. For illustrative purposes, in our analysis we used “climatology” defined by data averaged over the 1970s. A better choice would be to use means defined over a longer time interval. However, a rapidly changing Arctic Ocean and the lack of historical data challenges our ability to provide a well-constrained estimate of the most probable state of the Arctic Ocean. Despite this problem, we argue that even existing climatologies would be a better choice for analyzing spatiotemporal changes of the Arctic Ocean *FWC*.

Competing interests. The author has no competing interests.

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ЭФФЕКТ ИСПОЛЬЗОВАНИЯ ЛОКАЛЬНОЙ ОТНОСИТЕЛЬНОЙ ПОСТОЯННОЙ СОЛЕНОСТИ В ОЦЕНКЕ ИЗМЕНЕНИЙ ПРЕСНОВОДНОГО БАЛАНСА СЕВЕРНОГО ЛЕДОВИТОГО ОКЕАНА

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Изменения высокоширотного пресноводного баланса (ПБ) играют важную роль в формировании изменчивости полярных бассейнов. ПБ определяется как интегрированное по глубине отклонение солености от относительной солености S_{ref}, деленное на S_{ref}. Для оценок высокоширотного ПБ часто используется постоянная S_{ref}. В данной работе показывается, что использование локальной средней S_{ref} предпочтительнее. Анализ аномалий ПБ 2007 г. в слое 25–75 м демонстрирует, например, что выбор S_{ref} = 34,8 ЕПС (который часто используется в климатических исследованиях) приводит к искаженным аномалиям ПБ порядка 0,6 м, что составляет значительную долю от общего пространственного изменения ПБ. Проблема усугубляется в областях со значительными отклонениями локальной S_{ref} от S_{ref} = 34,8 ЕПС. Таким образом, использование климатической средней солености в качестве S_{ref} является предпочтительным для оценок пространственно-временных изменений ПБ Северного Ледовитого океана.

Ключевые слова: относительная соленость, пресноводный баланс, Северный Ледовитый океан.

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