The assessment of salinity impact on surface water mass transformation in the North Atlantic.

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Abstract. In this study, we investigate sensitivity of total surface water transformation to salinity from different data sources. Here we use surface salinity from NCEP CFSv2 reanalysis, GLORYS ocean reanalysis, Aquarius satellite data and ISAS-15 (product of optimal interpolation of ARGO buoys) as well as heat and freshwater fluxes from NCEP CFSv2 reanalysis. The largest spread in estimates of salinity is observed for Aquarius satellite in subpolar regions. The best correspondence between transformation computed using salinity from different datasets is observed for subtropical waters. Model-based products (CFSv2 and GLORYS) are the most consistent in estimates of surface water transformation and the largest discrepancies between these datasets are observed in the regions with high freshwater fluxes.

1. Introduction

Buoyancy flux in the upper ocean is important for the mixed layer formation. It is determined by the intensity of air-sea heat and freshwater exchange. Among the components of buoyancy flux, the largest uncertainties in terms of measurements are associated with salinity and precipitation. In particular, inconsistencies between different sources of information about salinity are reported in different studies [1, 2]. Our aim here is to investigate how using salinity from different data sources affects the values of total surface water transformation in the North Atlantic. In particular, we focus on one year (2014) which was characterized by the high intensity of air-sea heat exchange [3].

2. Data and Methods

In this study, we used four different datasets with the information about surface salinity. The main analysis is based on the NCEP CFSv2 reanalysis provided by the US National Center for Environmental Prediction (NCEP) [4]. It is the new generation of the NCEP CFSR reanalysis (1979-2011) and covers the period from 2011 to the present time with the 6-hourly output data. NCEP CFSv2 is based on the coupled configuration of atmospheric model NCEP GFS (with the spatial resolution of 0.205°), ocean circulation model GFDL MOM4 with the spatial resolution 0.5°. Direct observations of salinity in the upper ocean from TAO [5], PIRATA [6] and TRITON buoys [7] as well as from World Ocean Database [8] which contains CTD measurements on 1 m are assimilated in NCEP CFSv2. The upper vertical level of the ocean model is 5 meters.

The second alternative source of information about surface salinity used in this study is the ocean reanalysis GLORYS2V4 [10]. It is based on the version 3.1 of NEMO model with ORCA025 configuration (with average spatial resolution being 0.25°) driven by momentum, heat and freshwater fluxes from ERA-Interim atmospheric reanalysis. The assimilation of observational data in reanalysis includes information from satellite data as well as sea ice concentration, ocean surface temperature and in-situ profiles from the CORA4 base including high frequency profilers (e.g. ARGO and CTD) surface and sub-surface timeseries (e.g. thermosalinographs and surface drifters) [11].

One of the most reliable sources of information about salinity is considered to be the contact measurements from ARGO drifting buoys [12]. In ARGO, salinity is calculated from conductivity measured by a buoy sensor [13] at the depth of 5 meters [1]. Since buoy data provides point measurements which limits their applications, there are products, such as AMIGO [14] and ISAS-15.
[15] which contains the ARGO buoy data interpolated onto a regular grid for monthly averaged data. Here we use ISAS-15 dataset which is the product of the optimal interpolation of ARGO drifting data and provides monthly mean salinity for the period from 2002 to 2015 with a spatial resolution of 0.5°.

Apart from ocean reanalyses and ARGO-based product, we also used the information about surface salinity from Aquarius satellite [16] measurements, covering the period from 2011 to 2015 with a spatial resolution of 1° and a stated accuracy of up to 2 PSU. Satellite data provide measurements of salinity within the first centimeters from the ocean surface. In this way, the depth where information about salinity is provided vary across these products: 0.5 m for NCEP CFSv2, GLORYS and Argo buoys, up to 0.01 m for satellites. To analyze the differences between datasets, ISAS-15 and Aquarius and GLORYS data were interpolated to 0.205° grid corresponding to the spatial resolution of atmospheric part of NCEP CFSv2 reanalysis.

To assess the intensity of the surface water transformation, we used the value of density flux, first proposed by [17]. It describes change in the density of the surface water due to heat and fresh water fluxes at the ocean-atmosphere interface. This value is particularly important for the certain areas such as the North Atlantic which is one of the key regions for the global conveyor belt. Due to the active energy exchange between the ocean and the atmosphere in this region both surface and intermediate and deep waters are being formed there. Density flux is an inverse of buoyancy flux and derived using the following expression:

\[ f = \frac{-\alpha}{c_p} Q_{\text{net}} + \rho_0 \beta \frac{(E-P)S}{(1-s)}, \]  
\[ (1) \]

where \( f \) is density flux \([\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}]\), \( Q_{\text{net}} \) is net heat flux into the ocean, \( c_p \) is specific heat of seawater at constant pressure, \( \rho_0 \) is a reference density of seawater, \( E \) is evaporation, \( P \) is precipitation, \( s \) is salinity in portions of unity, \( S \) is salinity in PSU, and \( \alpha \) and \( \beta \) are the thermal expansion and haline contraction coefficients:

\[ \alpha = \frac{\partial \rho}{\rho \partial T}, \beta = \frac{\partial \rho}{\rho \partial S} \]  
\[ (2) \]

Thus, the total density flux equation consists of two parts: the first term on the right-hand side of the equation (2) represents thermal density flux, and the second term represents haline density flux.

The impact of salinity on the total density flux is nonlinear since it is used both in the equation of state (thus implicitly impacting both thermal expansion and saline contraction) and also directly impact the haline part of density flux.

The rate of surface water transformation characterizes how much water of a certain density was transformed in a given area per unit time and is determined by the following equation [18]:

\[ F(\rho) = \frac{1}{T} \int dt \int f \cdot \delta(\rho - \rho') \, d\Sigma, \]  
\[ (3) \]

where \( T \) – time period, \( f \) – density flux, \( \Sigma \) – square of waters of certain density.

To calculate the density flux, we used heat and fresh water fluxes (eq.1) from NCEP CFSv2 reanalysis and four sources of information about salinity described above.

3. Discrepancies in surface salinity data

Differences between the monthly mean salinity according to CFSv2 reanalysis, satellite data Aquarius, buoy data ISAS and GLORYS reanalysis reveal certain regional patterns shown in Figure 1. In January, surface salinity from CFSv2 exceeds other data sources at subequatorial latitudes in regions with high precipitation. At the Amazon estuary, salinity from CFSv2 is lower than other datasets. The largest difference is observed for [CFSv2 – GLORYS] being up to 2 PSU. In July salinity from CFSv2 exceeds satellite and buoy measurements at Amazon estuary where differences between CFSv2 and Aquarius reach 5.6 PSU. Large differences between datasets are observed in the Gulfstream region. Differences between CFSv2 reanalysis and ISAS do not exceed 0.5 PSU and are the most smoothed due to CFSv2.
assimilation system, where information from buoys are used for calculation of surface salinity. The differences between reanalysis and satellite are larger compared to [CFSv2 – ISAS]. This may be due to different depths attributed to surface salinity in these datasets. The difference between two reanalyses (CFSv2-GLORYS, Figure 1c, 1f) reflects that GLORYS has the highest resolution (0.25°) which allows to resolve ocean dynamics of smaller scales than CFSv2.

![Figure 1](image-url) Differences between surface salinity according to different data sources: (a, d) [CFSv2 – Aquarius], (b, e) [CFSv2 – ISAS], (c, f) [CFSv2 – GLORYS]; top row (a-c) corresponds to January, bottom row (d-f) corresponds to July in 2014.

4. Density fluxes and transformation

4.1. Density fluxes

The highest values of density fluxes in the North Atlantic are observed in January (Figure 2a). Their magnitudes mainly depend on heat flux. In this study, positive values of density flux refer to increasing density due cooling or evaporation while negative values refer to decreasing density as a result of warming or freshening of the surface waters. The highest values of 4.5·10⁻⁵ kg·m⁻²·s⁻¹ are observed in the Gulf Stream region. These are characteristic high values for the warm western boundary currents in the cold season. In January, almost the entire North Atlantic is characterized by positive density fluxes, which is due to winter cooling and, as a result, an increase in the density of the surface waters. Negative values of density fluxes amount up to -1.3 · 10⁻⁵ kg·m⁻²·s⁻¹ and are observed in low latitudes. Such values of density flux are a consequence of the predominance of precipitation over evaporation in this region.

In July, almost the entire water area of the North Atlantic is characterized by negative values of the density flux (Figure 2b), including areas of the western boundary currents. The largest negative values of the density flux are observed in the area of the Newfoundland Bank and amounts up to -1.3·10⁻⁵ kg·m⁻²·s⁻¹ while in equatorial waters it amounts up to -1.2·10⁻⁵ kg·m⁻²·s⁻¹. Small positive values amounting up to 8·10⁻⁶ kg·m⁻²·s⁻¹ are observed only in equatorial waters west of Africa. This is a result of low heat fluxes to the ocean due to cloudiness in the intertropical convergence zone (ITCZ).
4.2. Transformation

Next, we analyzed total water transformation which characterizes the values of density fluxes within the certain ranges of density, integrated over time and the area occupied by waters of this density (an example is shown in lining in Figure 2). Surface water transformation is defined by equation (3).

In winter, two maxima of transformation are observed (Figure 3a). The first one corresponds to subtropical waters in areas of warm currents (density from 1025.6 to 1026 kg·m⁻³) and amounts up to 200 Sv. The second maximum corresponds to the subpolar waters in the Labrador Sea (density from 1027.3 to 1027 kg·m⁻³) and amounts up to 110 Sv. The positions of both peaks for all data sources are similar, while their absolute values differ across datasets. GLORYS-based transformation is larger than others for subtropical waters (density from 25 to 25.5 kg/m³) while Aquarius-based transformation is the largest for waters with density from 26.2 to 26.8 kg/m³ which could be a consequence of high uncertainties in information about salinity over the Gulf Stream region (Figure 1).

In summer, overall negative transformation is observed which reflects the decreasing density of the surface waters due to ocean heating (Figure 3b). The largest magnitude of this negative transformation corresponds to tropical waters (with density of approximately 24.3 kg/m³) with values amounting up to 125 Sv. This is true for all data sources except ISAS where this maximum is shifted towards lower density. In general, the discrepancies between transformations obtained using different sources of information about salinity are larger in summer than they are in winter. This is due to larger sensitivity of density flux to precipitation and evaporation which directly effect the salinity, and the distribution of this characteristic over the upper meters become more significant. For subequatorial waters with densities 22.3–23.3 kg/m³ and 24.5–25.5 kg/m³, the largest differences among data sources are observed. This is the Gulf Stream region, and though the magnitudes of density flux are low compared to winter, the differences between salinity from various datasets are high in this region.

Figure 2. Density flux (shown in color shading) and surface density (shown in contours) in January (a) and July (b) of 2014 computed from CFSv2 reanalysis. Lining shows an example of areas occupied by waters of certain density, further used in computation of transformation.
4.3. Transformation on TS-plane

In order to identify the water masses corresponding to the largest uncertainties between different datasets in Figure 4 we show the values of transformation on the TS-plane. This type of analysis is widely used in the studies of water masses in physical oceanography.

The largest scatter among all T-S classes along the salinity axis is observed for satellite data (Figure 4b) which indicates inaccuracies in the salinity measurement from the satellite. This is particularly true for subpolar mode waters. GLORYS reanalysis and the ISAS dataset show lower spread of values along
the salinity axis. The values of transformation in the cores of subtropical and subpolar mode waters are larger in CFSv2 compared to Aquarius. The highest transformation values are observed with salinity from GLORYS.

Transformations based on different datasets are closest for subtropical mode waters (STMW) with temperature of 20°C and salinity of 36 PSU, since these waters are also characterized by the large values of heat flux in the Gulf Stream region. The location of this maximum heat flux in all sources is the same. The satellite (Figure 4b) poorly represents transformation of subpolar waters (SPMW) with salinity of 35.2 PSU and temperature of 12°C, while all other datasets represent these waters reasonably well.

5. Conclusion
In this study, we analyzed surface water mass transformation using four different datasets with information about upper ocean salinity: reanalysis NCEP CFSv2, NEMO-based GLORYS ocean reanalysis, satellite Aquarius and the product of optimal interpolation of ARGO buoys - ISAS. The largest differences between surface salinity from these datasets are observed in the estuary of the Amazon river and in the Gulf Stream region. The best correspondence between transformation computed using different datasets is observed for subtropical mode waters while subpolar mode waters are poorly represented in case of using salinity from Aquarius satellite. In winter, in all datasets the largest transformation is attributed to the same values of density, however, their absolute values vary depending on the dataset. The same is true for summer, with the exception of ISAS. On TS-plane, the largest spread of salinity is observed for subpolar waters, especially in Aquarius-based transformation, while the lowest spread is observed for model-based products (CFSv2 and GLORYS).

The results obtained in this study suggest that estimates of surface density fluxes are sensitive to the source of information about salinity. It effects both magnitude of total water mass transformation and water density corresponding to its local maxima. Among all datasets reanalyses are found to be the most consistent, however, the largest difference between them in regions with high precipitation requires further investigation. The obtained results provide a background for understanding the sensitivity of surface density fluxes and water mass transformation to fresh water fluxes as well as for further analysis of their seasonal and interannual variability.

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