Recent changes in global sea surface layer salinity detected by Argo float array

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We investigated surface layer salinity distributions and characteristics of those spatial and temporal variations in the global ice-free ocean. Salinity at the ocean surface is a fundamental factor in the large-scale ocean climate. The surface water salinity is affected to a large extent by air-sea boundary processes such as evaporation and precipitation, and to a lesser extent by the horizontal and vertical advection of adjacent water. This means that the changes in surface layer salinity over a certain period allow us to estimate the corresponding changes in evaporation and precipitation, if appropriate suppositions are made about the effects of these horizontal and vertical advections. While, recent precipitation and evaporation data based on satellites have a potential to give us the information of freshwater exchange variability between atmosphere and ocean; however, the accuracy of the data is not enough yet, so the estimating changes in evaporation and precipitation can be difficult at sea. Thus, this indirect method for estimating changes in evaporation and precipitation on the global ocean offers a powerful alternative to direct observations [1].

Since the start of the Argo Project from 2000, the deployment of Argo floats in the global ocean has gradually increased year by year [2]. In late 2007, the number of Argo floats had been over 3000, with an average spacing of one float per 3° × 3° area. The floats observe basically temperature and salinity from the surface layer (5 dbar) down to 2000 dbar every 10 days. Using mainly data from these Argo floats, we have analyzed the distribution of, and long-term changes in, surface-layer salinity in the global ocean, and demonstrated the implication of changes in global evaporation and precipitation on the sea surface.

To investigate the surface layer salinity change, we applied a two-dimensional optimal interpolation method (OI) to the 2003–2007 Argo profile data from the surface to 100 dbar [3]. The statistical parameters such as decorrelation radius and error variances for the OI were given as a function of depth and latitude, producing 1°×1° gridded data of Argo seasonal mean salinity for each season, which was calculated based on the analysis of the monthly mean gridded data [4]. Using the same OI method, we calculated seasonal mean salinity climatology of historical conductivity-temperature-depth (CTD) data and bottle-sampling data for four seasons from the World Ocean Database 2005 for 1960–1989 (WOD05) [5]. We selected this period because we were able to filter out decadal signals and collect more data than for any other period To construct annual mean salinity data by filtering out the seasonal variability, we averaged the four seasonal salinity data of Argo seasonal mean and seasonal mean climatology (referred to here as the "Argo annual mean" and the "annual climatology"). An E-P flux dataset was calculated using the evaporation rates of the monthly mean latent heat reanalysis dataset of the National Centers for Environmental Prediction (NCEP) [6] and the precipitation rates of the Global Precipitation Climatology Project (GPCP) [7]. Using these datasets for the period 1979-1989, we calculated a 1°×1° gridded dataset of mean E-P flux (referred to here as the "E-P flux climatology").

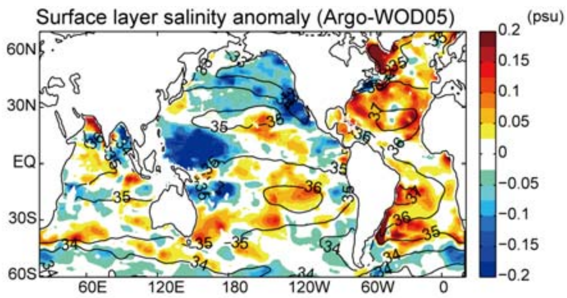

Figure 1. Surface-layer salinity anomaly (color) with the Argo annual mean salinity (contour). The color and contour intervals are 0.025 psu and 1.0 psu, respectively. The climatology was averaged on the basis of the seasonal salinity maps using WOD05 data in 1960–89. The Argo annual mean was calculated on the basis of the seasonal mean using Argo data in 2003–2007 [8].

Figure 1 shows the surface layer salinity difference between the Argo annual mean and the annual climatology based on WOD05 (referred to as the "salinity anomaly"). In the general characteristics of the global surface layer salinity climatology, salinity is lower in the subpolar and tropical regions and higher in the subtropical region, as many previous studies have shown [9]. In the salinity anomaly distribution of the Pacific Ocean, negative salinity anomalies occur in the northern and southern subpolar and tropical regions, while positive anomalies are found in the northern and southern subtropical regions. This shows that the contrast between the low and high salinity patterns is becoming enhanced. The Indian and Atlantic oceans show a similar anomaly pattern, except for the northern Atlantic subpolar region where the anomaly is positive [10]. Note that the difference between the Argo annual mean and the annual climatology is significant in almost all parts of the study area, from the test of Welch's unequal variance *t*-test [11].

Figure 2 shows the zonally averaged distribution of the salinity anomaly (a), salinity climatology (b), and E-P flux climatology (c) in the global ocean. In Fig. 2(a), the anomaly pattern generally shows the negative extrema are in the subpolar and tropical regions, whereas the positive ones are in the subtropical region. Meridional patterns of annual averaged salinity anomalies displayed a similar tendency from 2003 to 2007 (not shown), indicating that the averaged anomaly pattern in 2003–2007 is typical. The pattern of the zonally averaged salinity climatology (Fig. 2b) is similar to that of the salinity anomaly (Fig. 2a). The zonally averaged E-P flux climatology also has a similar tendency, although the pattern of the E-P flux climatology is sharper and shifted equatorward compared with that of the salinity climatology (Fig. 2c).

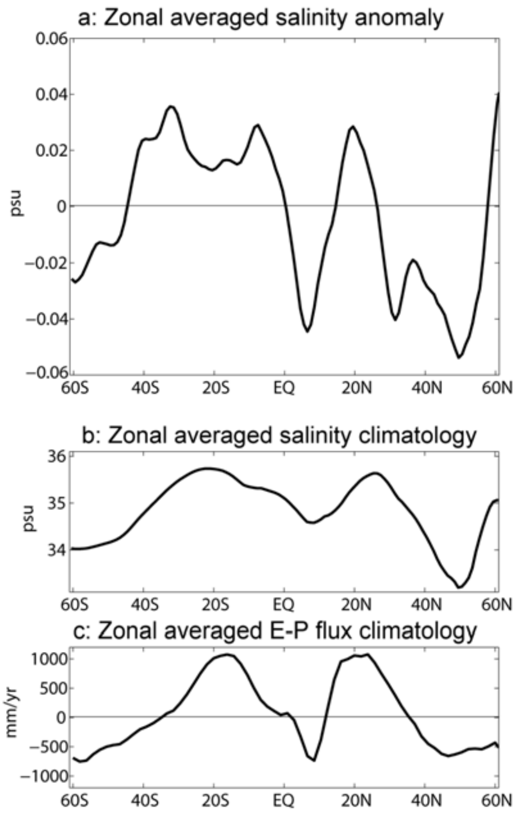

Figure 2. (a) Zonally averaged surface-layer salinity anomaly in the global ocean. (b) Zonally averaged annual surface-layer salinity climatology. (c) Zonally averaged annual mean E-P flux climatology. The E-P flux climatology is averaged except for land area [8].

From the results indicating enhancement of the contrast between low and high salinity patterns over 30 years, we attempted to make an estimation of the change in E-P flux over the corresponding period. We treated any area of the surface layer as a black box in which the salinity is maintained by the salinity flux resulting from evaporation and precipitation through the air-sea boundary, lateral exchange between adjacent areas, and vertical exchanges through the bottom boundary. We divided the entire ocean into 12 areas with the boundaries selected as the lines connecting the midpoints of adjacent low and high regions in the climatology of the surface-layer salinity distribution. In an arbitrary area, the surface-layer salinity budget was climatologically balanced by E-P flux through the air-sea boundary and salinity fluxes in adjacent areas. The exchange coefficient between the adjacent areas depends on lateral advection and diffusion and is assumed to be independent of time. By calculating from the northernmost area to the southernmost end, we obtained 11 exchange coefficients. Using these coefficients, we calculated the E-P flux anomaly, which is defined as the difference between the E-P flux in 2003–2007 and the E-P flux climatology in an arbitrary area.

After estimating the E-P flux anomalies, we calculated the ratio of the E-P flux anomaly to the E-P flux climatology for each area. We then obtained the globally averaged ratio and connected it to the change in the global hydrological cycle. The E-P flux anomalies are generally smaller than the climatology by order 1 or 2. The positive (negative) E-P flux anomaly corresponds to the positive (negative) salinity anomaly in nine areas, suggesting that the negative/positive E-P flux pattern in the global ocean is enhanced. The global averaged E-P flux enhancement is 3.7±4.6%, suggesting that there is a high probability that the global hydrological cycle has been enhanced in the past 30 years. The global averaged E-P flux calculated by the same method using the Argo float data in 2005 and 2006 showed an enhancement of 2.4±5.1% and 3.1±4.2%, which are very close to the average value found for 2003– 2007. The calculation of E-P flux anomaly is just a trial estimate to demonstrate the implication of surface layer salinity change. The estimate is thus not especially accurate due to the many assumptions made. If detailed parameters are clarified, the error may be small.

Our study shows a negative salinity anomaly in the North Pacific subpolar region. This result is consistent with those of previous studies reporting a long-term negative trend in oceanic salinity based on CTD data from limited regions [12]. Reference [9] described a positive salinity anomaly in the North Atlantic subpolar region. Reference [8] displayed that the pattern of zonal mean salinity trend for 50 years had been similar tendency of our research in the surface layer except for the North Atlantic subpolar region. These observational results are consistent of our analysis of E-P flux change and enhancement of the global hydrological cycle.

Reference [13] has presented clear evidence of increasing atmospheric temperatures, and studies using numerical simulations have linked atmospheric temperature increases to enhancement of the global hydrological cycle [14][15]. Although our estimate is somewhat rough, our result is also consistent with the previous studies of enhancement of the global hydrological cycle.

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