The Structure and Interannual Variability of the Global Subtropical Underwater from 1950 to 2014 in the EN4 Data Product: Preliminary Results

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1. Introduction/motivation

In all five of the major oceans, i.e., the North and South Atlantic, North and South Pacific and the Indian Ocean, there are sea surface salinity (SSS) maximum regions corresponding to the subtropical maxima of E-P (evaporation minus precipitation) (Fig. 1a). These SSS maximum features extend to subsurface through subduction and are the origins of salty water masses, which are usually referred to as Subtropical Underwater (STUW, Talley et al., 2011) and are important expressions of the upper-ocean overturning and global water cycle. With the global hydrological cycle intensifying since 1950, these SSS maximum regions have become saltier (Durack et al., 2012). The interannual variabilities of the 3D STUW, however, haven't been well examined.

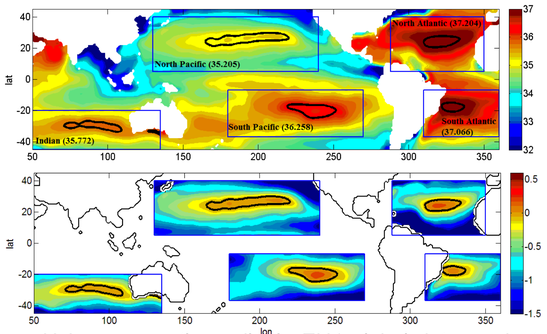


Fig. 1. (a) The global sea surface salinity (SSS) in the EN4 climatological mean fields from 1950 to 2014. The blue boxes are the defined regions of the SSS max regions in each ocean basin and the associated STUW. The reference salinity values S_0 for each SSS max and STUW are also labeled. **(b) the SSS anomaly** in each defined SSS max/STUW region. Note that the salinity anomaly in each ocean basin is calculated by subtracting its own salinity reference values.

Using a recently available EN4 global data product from produced from quality-controlled ocean temperature and salinity produced by the Met Office Hadley Centre (Good et al., 2013), this study investigates the climatological mean properties and year-to-year changes of the STUWs in all five major world oceans. The outcrop area, shape, volume, mean salinity, mean thickness and temperature are calculated, the 2D expressions of these SSS maximum regions and the 3D STUW features are compared. The interannual variability of the STUWs are also compared and discussed.

2. Data/Methodology

EN4 Data: the version 4 of the Met Office Hadley Centre "EN" series of data, whose data source includes WOD09, GTSPP, Argo, and ASBO collections (Good et al., 2013). The monthly objective analyses of the global T and S (from 1950 to 2014, 1˚x 1˚ horizontal and 42 levels from 5- 968 m) are analyzed here.

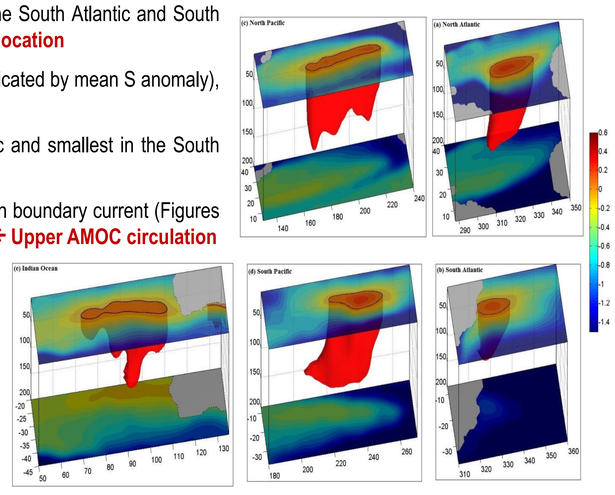
STUW Definition: Based on Gordon et al. (2014), we define that in the upper 300 m and in the defined subtropical regions as shown by blue rectangles in Fig. 1, **the water mass with salinity more than S_0 is the STUW**. The S_0 values are 37.204/37.066 in the North and South Atlantic, 35.205/36.258 in the North and South Pacific and 35.772 in the Indian Ocean (Table 1). The **outcrop** of the STUW at 5m is defined as the SSS max regions and the surface outcrops of the STUWs.

3. Results

3.1 Climatological mean features of the global STUWs

- Wind sock shapes with east-west main axes at surface, toes tilting toward equator, most pronounced in the Atlantic and South Pacific Oceans ⟵ **Upper ocean subduction**
- Latitude range: the North Atlantic and North Pacific, 20-30˚N. the South Atlantic and South Pacific, 15-25˚S. the Indian Ocean, 25-35˚S ⟵ **ITCZ location**
- North Atlantic and North Pacific STUW have more variability (indicated by mean S anomaly), the Indian Ocean SSS has the least variability
- largest outcrop area and volume in the North and South Pacific and smallest in the South Atlantic. Indian Ocean STUW has the largest depth
- The South Atlantic STUW is the only one attached to the western boundary current (Figures 1 and 2b)and whose mean 3D salinity is larger mean 2D salinity ⟵ **Upper AMOC circulation**

STUW properties	N. Atlantic	S. Atlantic	N. Pacific	S. Pacific	Indian
Shape /Orientation	Wind Sock Southwestward toe (Fig. 2a)	Wind Sock Northwestward toe (Fig. 2b)	Flat wind sock 3 downward toes (Fig. 2c)	Wind Sock Northwestward toe (Fig. 2d)	Flat wind sock 3 Northwestward toes (Fig. 2e)
Volume V $(\times 10^{14} m^3)$	1.7	0.8	2.6	3.3	1.3
Outcrop area A $(\times 10^{12} m^2)$	1.5	0.8	3.0	2.2	1.6
Max depth (m)	135.6	114.7	139.0	165.6	190.1
Reference S0 Value	37.204	37.066	35.205	36.258	35.772
Mean SSS anomaly over A	0.120	0.070	0.056	0.107	0.045
Mean S anomaly over V	0.096	0.069	0.049	0.096	0.035

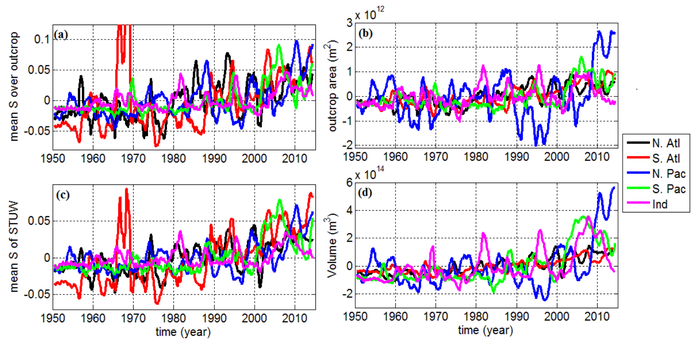


Top: Fig. 2. The climatological mean 3D shapes of the global STUW in the (a) North Atlantic (b) South Atlantic (c) North Pacific (d) South Pacific and (e) Indian Ocean.

Right: Table 1. The comparison of climatological mean basic features of the STUW in each of the five ocean basins. The values in **red**/**blue** are the **maximum**/**minimum** values among five STUWs.

4.2 Interannual variability

4.2.1 The intensification of the global STUW



- **The increasing trend in all the variables and for all five STUWs, i.e., the global STUW is intensifying.**
- STUW in Atlantic Oceans has the largest intensification rates for salinity (Fig. 3 and Table 2)
- STUW in Pacific Oceans has the largest intensification rates for the outcrop area and volume(Fig. 3 and Table 2)
- Indian ocean has the least intensification rates for salinity and outcrop area(Fig. 3 and Table 2)

Top: Fig. 3 The interannual variality of the **(a) mean salinity over the outcrop area (b) the outcrop area (m^2) (c) the mean salinity over the 3D volume and (d) the 3D volume (m^3) of the STUW** in each ocean basin. The values shown in the figure are the anomalies of the 13 month running mean of the monthly values.

Right: Table 2. The comparison of the trends/slopes of the STUW properties as shown in Figure 3 over the study time period of 1950 to 2014. The values in **red**/**blue** are the **maximum**/**minimum** values among five STUWs.

STUW properties' trend	N. Atlantic	S. Alantic	N. Pacific	S. Pacific	Indian
Mean S over A $(10^{-2}/yr)$	0.10	0.11	0.09	0.08	0.04
Mean S over V $(10^{-2}/yr)$	0.08	0.14	0.06	0.08	0.03
Outcrop area $(10^{10}\, m^2/yr)$	1.43	1.62	1.72	1.58	0.80
Volume $(10^{12}\, m^2/yr))$	2.89	2.09	4.08	5.06	3.58

4.2.2 2D vs 3D: the manifestation of the global STUW at the surface

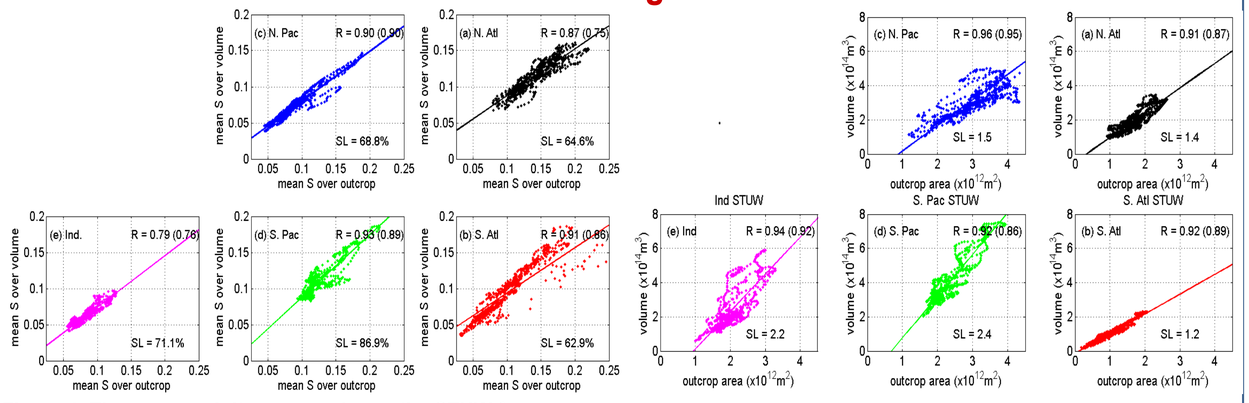


Figure 4. The mean salinity averaged over the STUW full volume versus the mean salinity averaged over the STUW outcrop area in the (a) North Atlantic (b) South Atlantic (c) North Pacific (d) South Pacific and (e) Indian Ocean. The correlations (R) between the mean salinity over the STUW full volume and the outcrop area are labeled in the upper right corner of each panel, the R values in the parenthesis are the correlations after the trends of the data are removed. **The slopes (SL)** indicate the **changing rate ratios** between the mean S over the volume and over the outcrop in each ocean and are labeled in the lover right corner of each panel.

Figure 5. The same as that in Figure 4 except it is the **STUW volume versus the STUW outcrop area**.

For STUW in all five oceans:

- the mean salinity over volume and over surface outcrop area are highly correlated with/without the trends (Fig. 4),
- The volume and outcrop area are highly correlated with/without the trends (Fig. 5)
- The changing rate ratios between the 3D salinity and surface salinity, between the volume and outcrop area, are both the largest in the South Pacific and smallest in Atlantic Oceans (Fig. 4, 5)

5. Summary

- Global STUWs' shapes and latitude locations are linked to upper ocean subduction, ITCZ location and AMOC.
- Global STUWs are intensifying from 1950 to 2014
- Global STUWs' surface 2D features are highly correlated with their 3D features
- SSS over the outcrop area is the manifestation of the global STUW at the surface

Future work: Data bias, especially from sampling errors, should be considered and evaluated!

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References:
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