GLOBAL SURFACE ALKALINITY FROM AQUARIUS SATELLITE

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AQUARIUS/SAC-D

Introduction

The unprecedented salinity coverage from the Aquarius satellite provides the opportunity to calculate surface alkalinity globally. In the ocean, total alkalinity (TA) is a gauge of the ability of seawater to neutralize acids. TA can be measured in seawater samples, and is defined as

$$\mathbf{TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + \text{other minor bases}}$$

There is a strong correlation between surface ocean TA and salinity (Broecker and Peng, 1982; Millero et al., 1998 a, b; Lee et al., 2006) (Figs. 1a and b). Processes affecting TA include addition of freshwater by precipitation and sea ice melting, mixing, and removal during evaporation and sea ice formation. Non-conservative behavior has been shown to affect TA, specifically production of $CaCO_3$ that reduces TA and dissolution of $CaCO_3$ that increases TA (Bates et al., 1996; Winn et al., 1998).

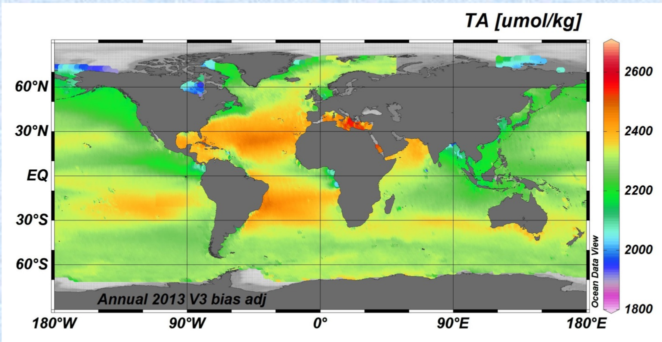

Figure 1a. TA (umol/kg) annual averaged 2013 using Aquarius SSS and Reynolds SST.

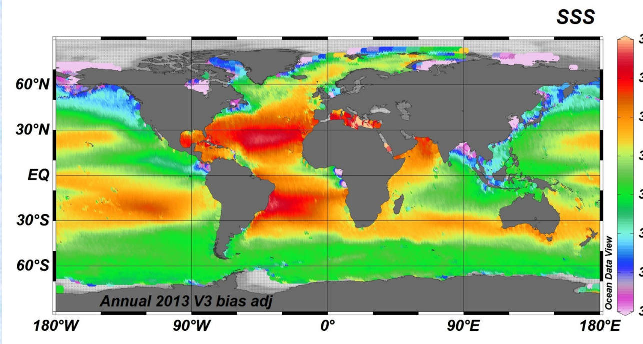

Figure 1b. SSS annual averaged 2013 from Aquarius SSS.

In the subtropics, the salinity maximum zones correspond to regions of maximum TA. Toward the equator and higher latitudes, TA generally decreases with decreasing salinity. TA shows a positive correlation with SSS over the ocean except perhaps for the Arctic low salinity waters and Southern Ocean where there is upwelling of TA enriched waters (Key et al., 2004).

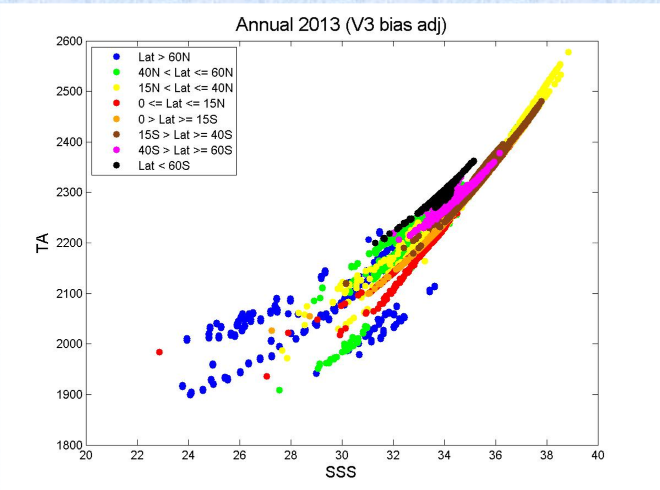

Figure 2. Annual averaged 2013 satellite derived TA (µmol/kg) plotted versus Aquarius SSS.

Empirical relationship between TA, SSS and SST

In earlier work (Lee et al., 2006), the ocean was divided into five regions where an empirical relationship was used to represent surface TA as a function of SST and SSS.

$$\mathbf{TA = a + b\,(SSS - 35) + c\,(SSS - 35)^2 + d\,(SST - 20) + e\,(SST - 20)^2},$$

where the coefficients a-e are defined for five ocean regions: the subtropics (30°N-30°S), Pacific equatorial upwelling, North Atlantic (30°-80°N), North Pacific (≥30°N, and including a term for longitude), and Southern Ocean (30°-70°S).

Satellite Data and Errors

A motivation for using satellite data is that there are special challenges for understanding the carbon system in high latitudes. One such challenge is scarcity of carbon data. Since August 2011, Aquarius has been continuously collecting and distributing SSS data. We are using Aquarius Version 3.0, bias-adjusted (Lagerloef et al., 2014), L3 mapped product, with a spatial resolution of 1°, smoothed monthly. For SST, we are using NOAA OI.v2 SST monthly fields 1x1° grid (Reynolds, et al., 2002). These data are providing, for the first time, an opportunity to document spatial and temporal variability in surface TA. The following errors are contributing to satellite TA: satellite SSS bias ±11 µmol/kg, Lee et al. (2006) empirical relationship ± 8.1 µmol/kg, and averaging errors due to eddies ~±10 µmol/kg. Taking the square root of the sum of the squares of these errors gives ~±17 µmol/kg error in satellite derived TA. This greatly exceeds the uncertainty of analytical measurements of ± 1.2 µmol/kg.

Spatial variability

The difference between the 2013 annual average TA and SSS at each grid point from the global annual average of TA = 2299 and SSS = 34.645 are shown in Figs. 3a, and b. Differences can exceed ±200 µmol/kg for TA, or about ±8.7%, and ±5 for SSS, or ±14.4%. With over 34,000 ocean grid points, 1.3% fall outside the range for TA ±200 µmol/kg, and 0.8% fall outside the range for SSS ±5. It is clear from these maps that spatial variations in TA are highly correlated with spatial variations in SSS. The TA and SSS differences from a global annual average are considerably larger in the high latitude northern than southern hemisphere. In addition, these spatial variations greatly exceed temporal variations.

Acknowledgement

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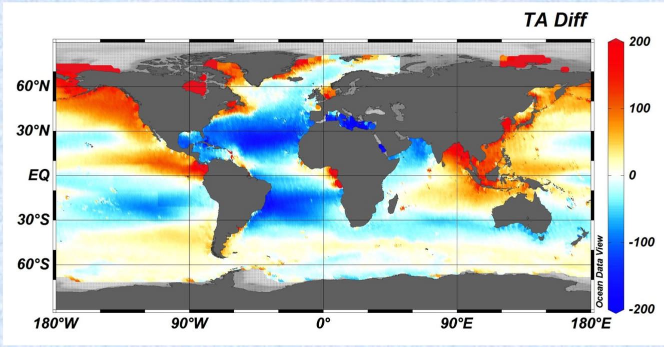

Figure 3a. Map of difference between annual average at each grid point from global 2013 annual average TA of 2299 µmol/kg using satellite SSS and SST.

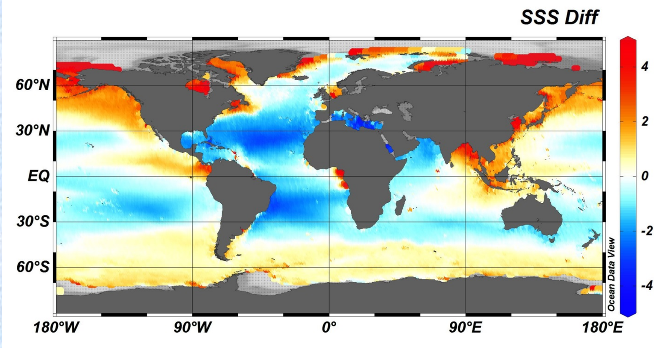

Figure 3b. Map of difference between annual average at each grid point from global 2013 annual average SSS of 34.645 using Aquarius SSS.

Temporal Variability

To visualize temporal variability in TA and SSS, the distribution of the 2013 seasonal amplitude from satellite data is calculated by differencing maximum minus minimum applied to monthly mean TA and SSS at each grid point (Figs. 4a and b). The seasonal amplitude in TA is as large as 100 µmol/kg or less than 4%, and in SSS it is 4. The total number of TA grid points is > 34,000. The percentage exceeding 100 µmol/kg for TA is 4.6%, and exceeding 4 for SSS is 0.9%. Largest seasonal amplitudes in TA are observed in the high latitudes, tropical Pacific and Atlantic and coastal regions where largest seasonal amplitudes are also observed in salinity.

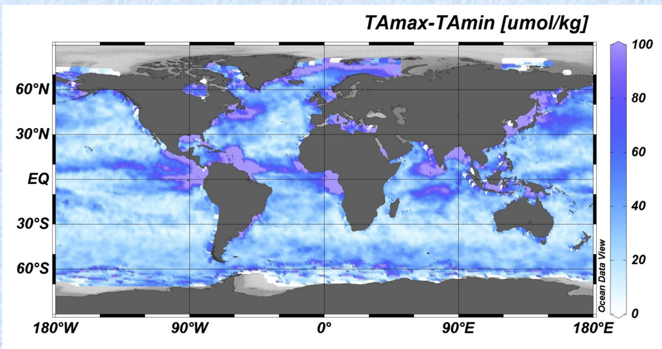

Figure 4a. Seasonal amplitude of TA(µmol/kg) from 2013 satellite data, difference between the maximum and minimum applied to monthly mean TA at each grid point.

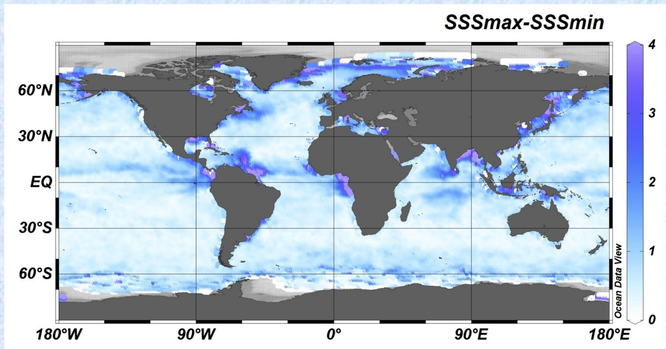

Figure 4b. Seasonal amplitude of SSS from 2013 satellite data, difference between the maximum and minimum applied to monthly mean SSS at each grid point.

SSS variations at northern hemisphere high latitudes are particularly large in summer and fall months (Fig. 5b), they are several times as large as in southern hemisphere (Fig. 5d). Large SSS variations are reflected in the northern high latitude and subtropical TA variations (Fig. 5a) as compared with southern (Fig. 5c). In southern hemisphere, there is less salinity variability.

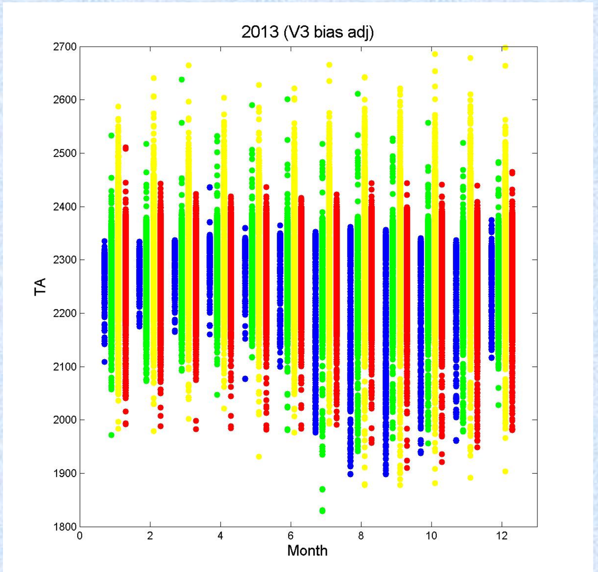

Figure 5a. Satellite monthly TA (µmol/kg) for 2013 **northern hemisphere** regions: blue latitudes >60, green 40 < lat <=60, yellow 15 < lat <=40, and red 0<= lat <=15.

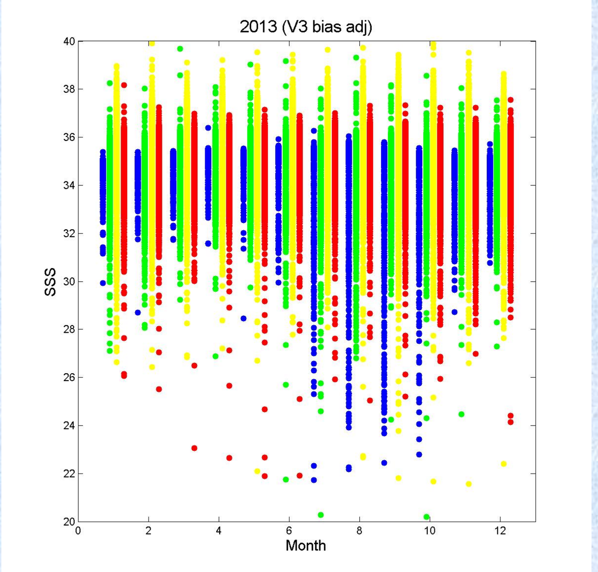

Figure 5b. Satellite monthly SSS for 2013 **northern hemisphere**. Regions and color patterns are same as Fig. 5a.

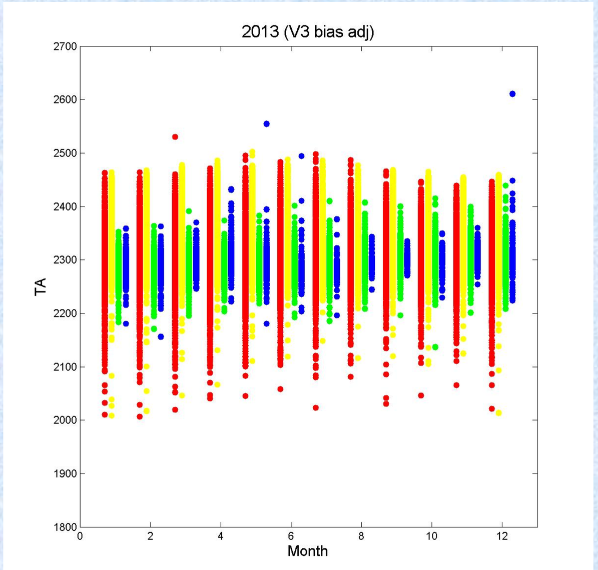

Figure 5c. Satellite monthly TA (µmol/kg) for 2013 **southern hemisphere** regions: blue latitudes >60, green 40 < lat <=60, yellow 15 < lat <=40, and red 0< lat <=15.

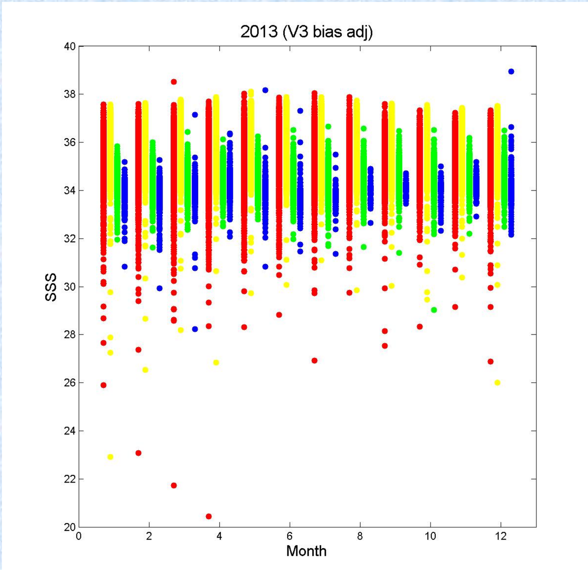

Figure 5d. Satellite monthly SSS for 2013 **southern hemisphere** .Regions and color patterns are same as Fig. 5c.

There are small differences between satellite 2013 and 2012 annual (and monthly, not shown) averages (TA, ±50 µmol/kg) (Fig. 7a) , which are highly correlated with salinity differences (Fig. 7b). Differences reflect variability from year to year in heating, cooling, eddies, currents, fronts, etc. Differences between 2013 and 2012 satellite TA and salinity appear to be largest in high latitudes and coastal regions (Figs. 7a and b), where there is a lot of variability in salinity. Striking similarities are seen in patterns of the differences between satellite TA 2012 and WOD 2011 and WOA 2001, and these maybe related to biases in version 3.0 Aquarius data. Reported biases for the Aquarius SSS are mostly in the high latitudes, southern hemisphere, Asia-Pacific, under ITCZ, and eastern and western North Atlantic (Lagerloef et al., 2014). Most of the differences between satellite 2012 TA and WOD 2011 and WOA 2001 are within ~ ±50 µmol/kg (Figs. 6a and b), which is about three times the global RMS for the version 3.0 Aquarius derived TA data.

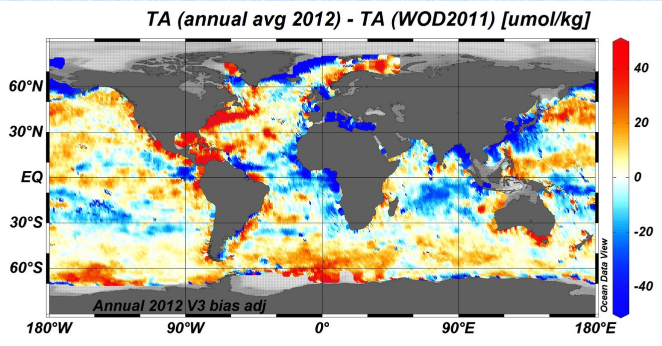

Figure 6a. Difference between annual averaged satellite derived TA (µmol/kg) in 2012 and WOD 2011 (2011 data).

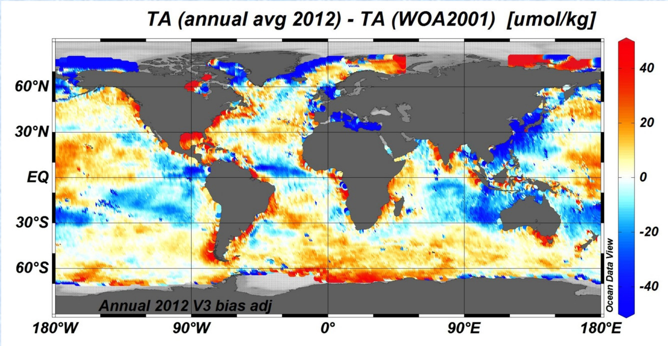

Figure 6b. Difference between annual averaged satellite derived TA (µmol/kg) in 2012 and WOD 2001 (climatology including data up to 2001).

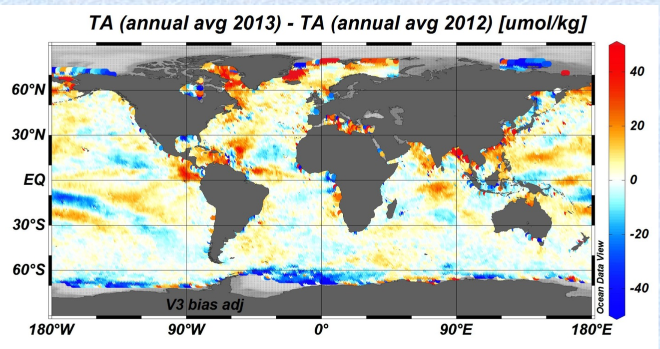

Figure 7a. Difference between annual averaged satellite derived TA (µmol/kg) in 2013 and 2012.

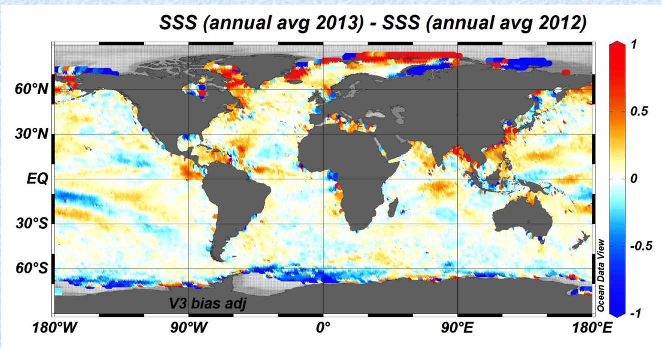

Figure 7b. Difference between annual Aquarius SSS in 2013 and 2012.

Ground Truthing Satellite TA data

Satellite derived TA and salinity are compared to recent ocean observations at BATS and HOTS (Figs. 8a and b) (Bates et al., 1996; Winn et al., 1998). Differences are well within the errors of the satellite TA of ± 17 µmol/kg, except for late winter 2012 at HOTS. Differences are related to salinity differences, which may be due to distances between *insitu* stations and satellite points.

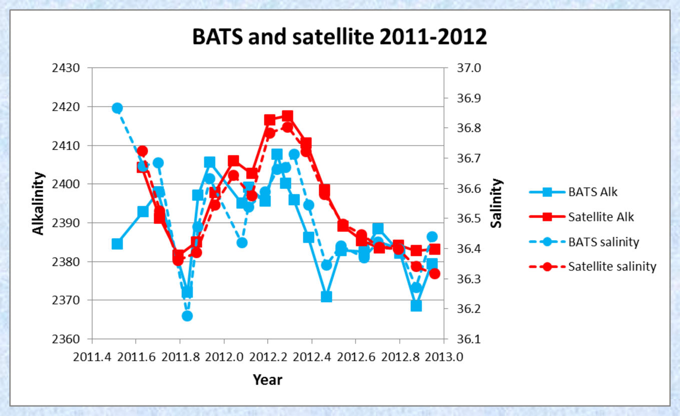

Figure 8a. TA and salinity for BATS station (32.0°N, 64.0°W) and satellite (Aquarius location 31.5°N, 64.5°W). Analytical error in measurement of TA (± 1.2 µmol/kg).

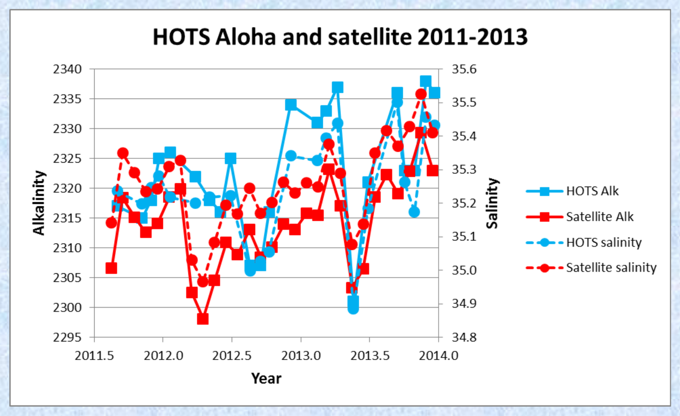

Figure 8b. TA and salinity for HOTS station (22.75°N, 158.0°W) and satellite (Aquarius location 22.5°N, 158.5°W).

Conclusions

Aquarius satellite data allow global mapping of TA. Spatial and temporal variability in TA are mostly due to variability in salinity. Spatial variability in TA and salinity exceed temporal variability including seasonal and within the 2000s decade and climatology. The northern hemisphere has the most spatial and monthly variability in TA and salinity, while less variability in Southern Ocean TA is due to less salinity variability and upwelling of waters enriched in TA. This work is a step toward providing a global baseline for TA that can be used to compare future data, and for evaluating spatial and temporal variability and past trends.

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