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Key Points:
- Satellites synoptic global images of SSS provide new insight to the global water cycle
- Anomalies of SSS coupled to global water cycle
- Ocean processes governing sea surface salinity vary in space and time

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The marine hydrological cycle: The ocean's floods and droughts

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Abstract The sea surface salinity (SSS) displays fluctuations that are not solely in response to local air-sea flux of freshwater but also reflect ocean circulation and mixing processes. Ponte and Vinogradova (2016), using Estimating the Circulation and Climate of the Ocean output, estimate the relative roles of these forces for the global ocean. They find that the governing forces vary greatly across ocean regimes. Their research identifies features that will be addressed with enhanced SSS observations from orbiting satellites and in situ global arrays, which promise new insight into the marine water cycle and its place in the global hydrological system.

1. Introduction

There is justified concern about floods and droughts on land, as water impacts agricultural production and the welfare of populations. The ability to predict changes in terrestrial freshwater availability in response to natural and anthropogenic-induced climate change is of high priority, in that they enable preparedness and management of resources. It should come as no surprise that the ocean, amounting to 71% of the Earth's surface, also experiences floods and droughts, with periods of excess precipitation, or lack of it, reflected in changes of the sea surface salinity (SSS). Floods and droughts over land and ocean together mark a response, across a wide range of scales, of the global hydrological or water cycle [*Schmitt*, 2008; *Schanze et al*., 2010; *Durack et al*., 2012; *Durack*, 2015; *Lagerloef et al*., 2010, 2012]. The terrestrial and marine components are joined through atmospheric moisture transport and continental runoff.

There have been many studies of the relationship of climate to sea surface temperature (SST), often presented in terms of climate indices (of which there are many). Orbiting satellite have provided synoptic global coverage of SST for the last half century, defining the characteristics of SST anomalies and associated air-sea heat flux, which are dynamically linked as air-sea heat flux is governed by the difference between SST to air temperature. Specific SST anomalies have been related to terrestrial flood and drought, primary examples being the Pacific El Niño [*Dai et al*., 1998] and Atlantic SST anomalies linked to the Sahel drought [*Giannini et al*., 2003].

While there is satellite coverage of marine precipitation, with the Global Precipitation Mission, the direct detection of SSS anomalies, which reflects a broader range of air-sea and ocean factors, has been stymied by the lack of synoptic coverage. Blurry views of salinity, built upon many decades of ship-based data, depict a climatology that likely never exists at all points at the same time (Figure 1). We now have, at long last, near-synoptic global views of SSS from orbiting satellites [*Font et al*., 2010; *Lagerloef*, 2012] (Figure 1), as well as in situ coverage from the global array of Argo profilers and ocean drifters. These have finally "opened a window" to the marine component of the global hydrological cycle.

With the advent of near-synoptic mapping of SSS from space we are now aware that SSS anomalies are also related to terrestrial flood and droughts (*Li et al*. [2016a, 2016b], who link SSS to Sahel rainfall and to U.S. Midwest summer precipitation). *Zhu et al*. [2014] find that SSS variability plays an active role in El Niño–Southern Oscillation evolution, essential to correctly forecasting the 2007/2008 La Niña.

The global hydrological cycle in response to climate change is becoming more intense. *Durack and Wijffels* [2010] show that in the past five decades, the salty regions (e.g., the evaporation-dominant subtropical gyres) have become saltier and fresher regions (e.g., the tropical and high-latitude precipitation-dominant regions) have become fresher; the salinity contrast between the saltier Atlantic and fresher Pacific has also become larger, which has implication to the global thermohaline ocean circulation.

2. Sea Surface Salinity Governing Processes

SSS responds to the amount of water exchange between the atmosphere and ocean: evaporation (E) and precipitation (P), as well as the formation and melting of sea ice (sea ice having a salt content of ~20% of

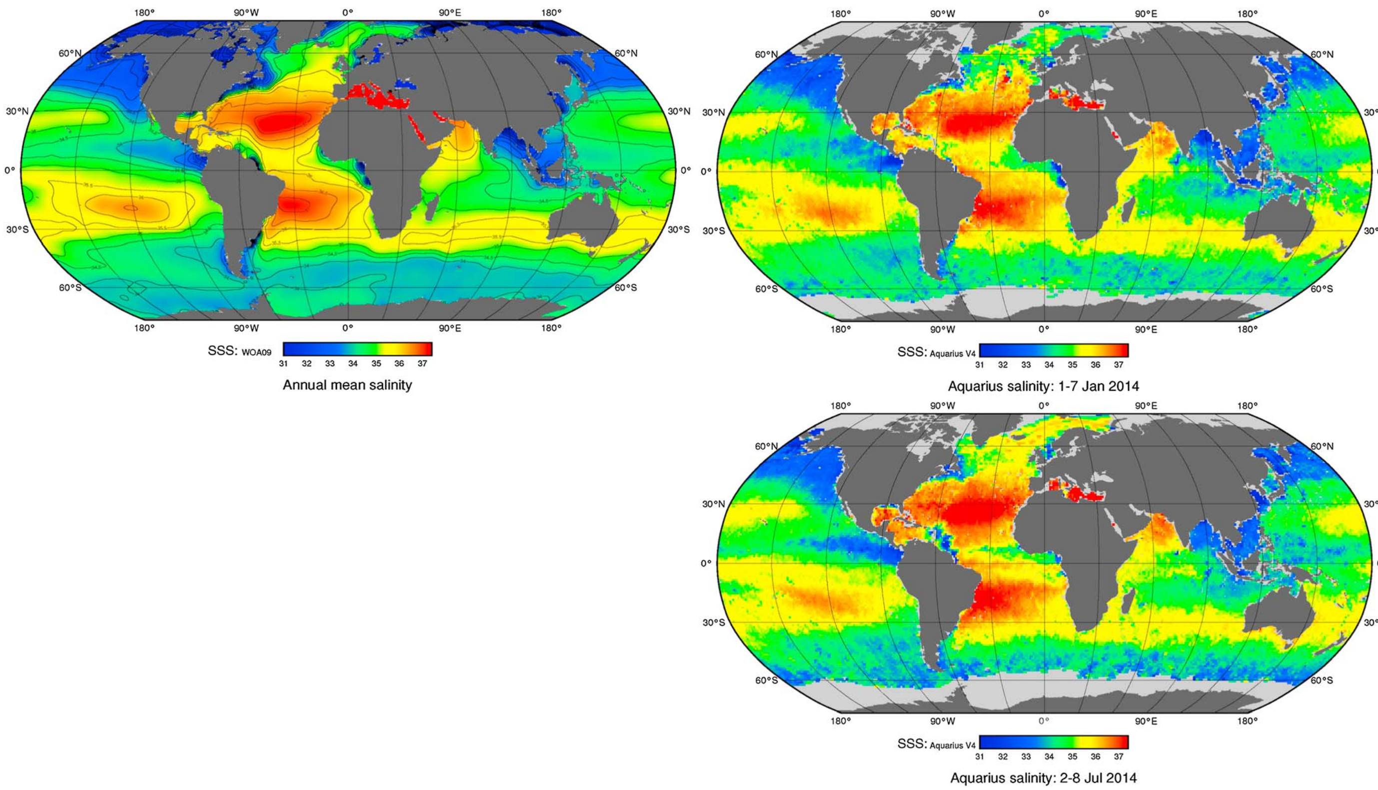

Figure 1. (left) Sea surface salinity (SSS) [*Antonov et al*., 2010] constructed from ship data obtained over many decades depict SSS climatology that likely never exists at all points at the same time. (right) With the advent of orbiting satellite views of SSS (NASA/CONAE Aquarius/SAC-D satellite mission; ESA's Soil Moisture and Ocean Salinity, SMOS; and Soil Moisture Active Passive, SMAP) we now have, at long last, near-synoptic, global views of the SSS. The Aquarius satellite data, http://podaac.jpl.nasa.gov/aquarius, enable construction of global SSS maps at 7 day resolution. (top right) The first week of January 2014; (bottom right) the first week of July 2014. The ever changing SSS field provides insight to the complex realm of the global water cycle and terrestrial and ocean flood and droughts.

sea water). In this way SSS might be thought of as a rain gauge, but this is an oversimplification. Under the influence of E-P SSS would steadily increase or decrease were it not for compensating power of ocean processes. Ocean processes involve horizontal and vertical advection, including wind-induced Ekman transport, the spreading of river runoff (R), and mixing by ocean eddies and vertical diffusion, which result in net divergence or convergence of freshwater to offset E-P. Air-sea exchange and the array of ocean processes achieve a quasi steady state condition. However, the balance is not perfect, resulting in SSS variability across a wide range of spatial and temporal scales.

Regional SSS differences (Figure 1) reflect their place in the global climate system and ocean circulation. Even regions in the same climate belt, such as the salty subtropical regimes display differences from each other [*Gordon et al*., 2015], as they respond to local conditions. To understand the factors that affect SSS, we must develop a quantitative grasp of the governing physics, which involves air-sea exchange and ocean processes: which are dominant? Which are minor players?

Yu [2011], using an array of observationally based data compilations, present a global view of the dominant process governing seasonal surface mixed layer salinity (effectively SSS), finding that freshwater fluxes across the air-sea interface, on a global basis, account for nearly 14% of the seasonal SSS changes, with the seasonal changes in Ekman advection accounting for 13%. The mean annual Ekman transport and entrainment at the base of the mixed layer are each about 7%. These four terms account for about 40% of the total SSS seasonal variance, with the remainder being a consequence of uncertainty, mainly in the form of mixed layer dynamics. The processes driving seasonal SSS variability, as expected, display large spatial variability. For example, E-P is the first dominant term, accounting for 40 to 70% of SSS seasonal variability, in the rainy intertropical convergence zones, and sections of evaporative subtropical regions, whereas closer to the equator and at higher latitudes Ekman advection and vertical entrainment take on larger roles.

Ponte and Vinogradova [2016, PV16], noting the uncertainty of observational data, use "a model-data synthesis efforts that are both close to the observations and that allow for calculation of full, closed property budgets." They use ECCO (Estimating the Circulation and Climate of the Ocean) [*Wunsch et al*., 2009] version 4, release 1, which is optimized to fit an array of observations, taking into account their uncertainties, to determine the contributions to SSS (upper 10 m) variability of horizontal and vertical advection (ocean currents, including Ekman transport), diffusion, and the air-sea flux of freshwater (E-P, runoff, and sea ice formation/ melting). PV16 find that the sum of advection and diffusion and air-sea flux are close to zero for the 18 year (1993–2010) averaged ECCO output, as would be expected if they properly incorporate the essentials of the freshwater fluxes.

PV16 maps clearly show that the relative contributions of each component change significantly across the ocean regimes. Diffusion and air-sea flux generally compensate each other, while advection can boost or decrease SSS. Diffusion and air-sea flux are the dominant factors in the subtropics and subpolar regimes, while the tropics and polar region advection becomes a more dominant component. Advection is particularly significant in the Atlantic Ocean. At low latitudes advection acts to decrease SSS, both in regions of excess P and in excess E. As PV16 say: "Given the variable nature of horizontal gradients in [SSS] and also surface currents, the large scale, single sign behavior of [advection] in the tropics is not a trivial result"; PV16 suggest that this issue "merits future scrutiny". Within the Bay of Bengal, advection and diffusion balance each other, with air-sea fluxes playing a reduced role. In the polar areas of net sea ice production and ocean diffusion boost SSS, which are then compensated by advection.

3. Summary and Way Forward

The *Yu* [2011] and PV16 results clearly show that variability in air-sea freshwater fluxes alone do not properly track changes in SSS: the full range of ocean processes are needed, to resolve the spatial and temporal changes of the marine hydrological cycle and its place in the global system. The near-synoptic global view of the SSS from space, as well as the enhanced in situ observational array, has opened the door to a more quantitative understanding and appreciation of the marine hydrological cycle and of its governing physics.

The Salinity Processes in the Upper-ocean Regional Study 1 and 2 field programs [*Lindstrom et al*., 2015; *SPURS-2 Planning Group*, 2015] are delving into these issues, made possible by our new views of SSS, which will no doubt sharpen as the observational data sets grow and model simulations incorporate the essential elements to finer resolution. We will finally acquire an understanding of the full, global hydrological cycle and its coupling to the natural and anthropogenic-forced climate change. As often happens, we can expect new observations to open the door to discovery.

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