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SPURS: Salinity Processes in the Upper-ocean Regional Study

THE NORTH ATLANTIC EXPERIMENT

By Eric Lindstrom, Frank Bryan, and Ray Schmitt



BACKGROUND

In this special issue of *Oceanography*, we explore the results of SPURS-1, the first part of the ocean process study Salinity Processes in the Upper-ocean Regional Study (SPURS). The experiment was conducted between August 2012 and October 2013 in the subtropical North Atlantic and was the first of two experiments (SPURS come in pairs!). SPURS-2 is planned for 2016–2017 in the tropical eastern Pacific Ocean.

The scientific motivation behind SPURS arises from the desire to understand the patterns and variations of salinity at the ocean's surface. To first order, surface salinity patterns reflect the overlying patterns of evaporation and precipitation that force the freshwater balance in the upper ocean (Wüst, 1936). Maps of the net difference between evaporation and precipitation (E–P) appear to be quite similar in pattern to surface salinity. If

the surface salinity is determined only by (E–P), then the ocean itself might serve as crude “rain gauge.” In fact, it is already known that ocean circulation in the form of wind-driven surface currents must be accounted for in understanding surface salinity patterns (surface salinity maxima are offset poleward of subtropical E–P maxima due to Ekman currents induced by the trade winds). In addition, ocean mixing processes also affect the temporal evolution of surface salinity. SPURS was designed to examine the salinity balance in the upper ocean through observation of salinity and ocean circulation on a variety of scales.

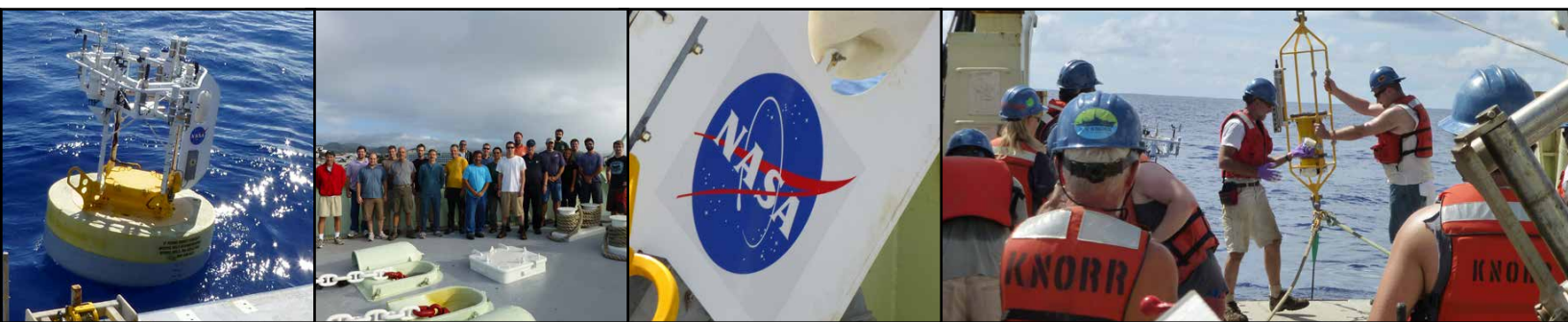
SPURS is primarily funded by the US National Aeronautics and Space Administration (NASA) to support the Aquarius/SAC-D satellite mission, which provides weekly estimates of surface salinity over the entire ice-free ocean. This unprecedented delivery of synoptic global

salinity maps prompted the push to quantitatively assess the processes responsible for the variations observed from space.

The combined analysis of the satellite and the SPURS in situ data is intended to improve models of the surface salinity variation. Because salinity is a state variable of the ocean, it is critical in the dynamics of many ocean phenomena. It is also an indicator of variability in the global water cycle, one of the most critical issues of climate change facing society. Better models are sought to improve, for example, predictions of water mass formation and El Niño. Analysis of Aquarius data has already led to a special section of the *Journal of Geophysical Research Oceans*, including several papers analyzing observations from the SPURS-1 field program (Asher et al., 2014; Bingham et al., 2014; Busecke et al., 2014; Hernandez et al., 2014).

A study of salinity variations in the

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ocean from all the accumulated ship-board measurements of surface salinity over the last 50 years reveals very interesting trends (**Durack**, in this issue). These trends provide the context for the relationship between ocean salinity and the global water cycle. It turns out that the high-salinity regions of the subtropics have been getting saltier and the low-salinity regions of the rain belts have been getting fresher. This observation can be interpreted as a “fingerprint” of an accelerating water cycle—something we expect in a warmer world where the atmosphere holds more water vapor. Models show that this state, roughly speaking, leads to drier dry places and wetter wet places—just what the salinity trends of the ocean seem to suggest. Unless there is an alternative explanation—that’s where oceanography comes in—the conclusion about the water cycle is only true if other oceanographic explanations for the trends in surface

salinity are ruled out. In other words, is there some combination of oceanographic processes that could explain why salty places appear to be getting saltier and fresher places fresher? SPURS is ultimately about answering such questions, so we can use global salinity data and ongoing monitoring of salinity as a powerful tool for diagnosing global environmental changes. As **Durack** shows, changing salinity fields can affect the patterns of future sea level rise, so they are of vital importance to society.

The concept behind SPURS is not new. Attempting to close balances in the ocean (“caging a piece of ocean”) through observing arrays has decades of heritage—consider, for example, MODE (Mid-Ocean Dynamics Experiment) and POLYMODE (Joint US-USSR Mid-Ocean Dynamics Experiment) in the 1970s and TOGA COARE (Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere

Response Experiment) in the 1990s, to name just a few. Given the challenge of capturing salinity variability in both space (millimeters to thousands of kilometers) and time (seconds to years), with open boundaries in the ocean, and a corrosive, hostile environment for instruments, perfection in achieving closed budgets is not a realistic goal. The goals, rather, are to assess the magnitude and importance of key processes at the relevant scales and use that insight to guide the development and testing of parameterizations in ocean models. The improved models can then be used to bridge the scales from mixing to climate.

SPURS focuses on three primary spatial scales (basin, mesoscale, and microstructure) and three time scales (annual, daily, and minutes). The program uses the large-scale global array of Argo floats and drifters, ships of opportunity, and satellites to provide the basin-scale context over the

annual cycle. SPURS adds moorings, gliders, additional Argo floats, and drifters to observe mesoscale variability and place it in basin-scale context. Microstructure profiling and surveys, wave gliders, and moorings provide observations of small-scale variability at high frequency to embed mixing estimates into the mesoscale array. So, SPURS is more about put-

SPURS-1 PLANNING

In June 2011, NASA launched a new Earth-observing instrument to measure the surface salinity of the ocean from space. The instrument, called Aquarius, is flying on the Argentine satellite SAC-D and delivers a global map of ocean surface salinity weekly (<http://aquarius.nasa.gov>). These data give unprecedented

“ A central theme of the SPURS approach is that the ship’s primary mission is to deploy and service the web of sensors and to serve as home base for temporary enhancements to the sensor web while on site. ”

ting a balance of assets across the formidable range of scales of salinity variability than about attempting to cage a piece of ocean at any one scale.

The sites for SPURS were chosen with some deliberation. The range of processes to be covered suggested two separate experiments. One would be in a high-salinity subtropical gyre where evaporation dominates ([Gordon et al.](#)), and a second would be in a low-salinity regime where precipitation dominates (planned for 2016–2017 and described by the [SPURS-2 Planning Team](#)). The two experiments are consistent in addressing salinity processes across the range of scales with global, mesoscale, and microstructure measurements. However, differences in stratification and advection regimes demand modifications to experimental design to account for local conditions. It is hoped that the two detailed experiments at the extremes of the ocean water cycle will assist in formulating and optimizing the representation of salinity processes in ocean models across the full range of global ocean surface conditions.

insight into the variations of the surface salinity of the ocean. While sea surface temperature has been regularly measured from space for over 30 years, salinity is a much more difficult measurement to make from space.

SPURS came about as result of planning for full utilization of the Aquarius data. Discussions of a salinity-focused process study began, and a prospectus was developed, within the US CLIVAR Salinity Working Group in 2005–2007 (see the *Oceanography* special issue on Salinity, volume 21, number 1, <http://tos.org/oceanography/archive/21-1.html>). Prior to the launch of Aquarius, in February 2010, NASA called for researchers to participate in an Ocean Salinity Field Campaign whose primary research questions would be:

- What are the physical processes responsible for the location, magnitude, and maintenance of the subtropical Atlantic sea surface and subsurface salinity maximum?
- How will the ocean respond to changes in thermal and freshwater forcing

associated with a changing climate?

- What is the nature of the cascade of salinity variance from the largest (climate) scales down to dissipation scales of a few millimeters?
- What new information must be supplied to ocean models in order for these questions to be adequately examined?

To address these questions, an observational and modeling program was planned to last throughout an annual cycle. NASA received 18 proposals and funded seven of them to conduct an experiment beginning in 2012. Recently, in its Research Opportunities in Space and Earth Science (ROSES) 2014 program, NASA again called for salinity field campaign proposals and, after reviewing 21 proposals, selected 12 scientists to lead implementation of SPURS-2 in 2016–2017.

The SPURS experiment involves not only seagoing oceanographers but also modelers, and of course, remote-sensing scientists using satellite data. An objective of SPURS is to provide a high-resolution, near-real-time data stream that can be assimilated into ocean models. Because the ocean is so large and complex, and our at-sea capacity to measure it so puny, we rely on ocean modeling and data assimilation to help us interpret the environment. The model results can be used in planning work at sea and to diagnose the balance of salinity in the upper ocean. The observations are essential to locking model results into the real oceanographic environment. The model is essential to estimating things we cannot measure directly and expanding upon the interpretations provided by the observations.

The first SPURS experiment involved a number of expeditions and nations working cooperatively at a single location in the North Atlantic centered around 25°N, 38°W. The French R/V *Thalassa* arrived in the SPURS region first in August 2012 with a US team aboard from the University of Washington Applied Physics Laboratory. [Reverdin et al.](#) describe their findings from this cruise in this issue.

The French team launched a glider that was later retrieved by the US R/V *Knorr*, which joined SPURS-1 in September 2012 with NASA Program Scientist Eric Lindstrom aboard as blogger and photographer. Most of the photos illustrating this special issue are from his work aboard *Knorr*, and all 32 of his blog posts from *Knorr* are available at <http://earthobservatory.nasa.gov/blogs/fromthefield/category/spurs>, including an account of our phone call with the International Space Station (Schmitt). Along with three moorings, many floats, drifters, and gliders were deployed from *Knorr*, and the shipboard party also surveyed the upper-ocean salinity fields with traditional and novel sampling gear, including autonomous underwater vehicles (AUVs).

Further US expeditions used R/V *Endeavor* to follow up the measurements made from R/V *Knorr*. The first of these two expeditions, in spring 2013, serviced SPURS-1 equipment that required maintenance after six months. A final expedition in fall 2013 recovered all the moored equipment and the SPURS-1 gliders. Both cruises entailed underway sampling and surveys, though they were not as extensive as those conducted on R/V *Knorr*.

A Spanish cruise on R/V *Sarmiento* also occurred in spring 2013. It involved towing a “SeaSoar” device to examine the mesoscale salinity fields and an upper-ocean microstructure profiler from Ireland that was especially designed to sample the ocean surface. A high-seas salinity summit was held when *Sarmiento* and *Endeavor* rendezvoused in the SPURS-1 salinity maximum.

Bingham et al. describe the coherent data management plan they developed for SPURS. The entire SPURS data set will be archived at the Jet Propulsion Laboratory Physical Oceanography Distributed Active Archive Center (PODAAC; <http://podaac.jpl.nasa.gov>). SPURS also has a significant outreach and communication component (deCharon et al.). Together, SPURS and Aquarius

offer the opportunity to make the public aware of ocean salinity and the roles of the ocean and the water cycle in our land-locked lives.

NASA’S APPROACH TO IN SITU PHYSICAL OCEANOGRAPHY

Historically, the NASA Physical Oceanography Program has supported the in situ observing needs of its satellite missions by taking advantage of observations already in place for other purposes (e.g., tide gauges for altimetry missions, long-term buoys for scatterometer [wind] missions, surface drifter array for sea surface temperature missions). For Aquarius, NASA utilizes the Argo array of >3,000 profiling floats to provide near-surface (5 m depth) salinity. Standard Argo floats do not provide information closer to the surface than 5 m in order to protect the salinity sensor from contamination and bubbles at the surface. In the case of Aquarius, which senses salinity in the upper 1 cm of the ocean, an additional more comprehensive approach is being taken in order to more fully understand salinity variability in the upper few meters of the ocean (Riser et al.).

SPURS can be viewed as an attempt to deploy a “sensor web” in the ocean to examine the salinity in one locale over a year. Ships can provide intensive observing capability over about one month using, for example, thermosalinographs, underway conductivity-temperature-depth (CTD) systems, and acoustic Doppler current profilers. Moorings can provide detailed time series at one site over a year, floats and drifters can provide a regional Lagrangian view, and gliders provide the capability to bridge the “gap” between Eulerian and Lagrangian perspectives. All together, these many platforms amount to a web of sensors.

A central theme of the SPURS approach is that the ship’s primary mission is to deploy and service the web of sensors and to serve as home base for temporary enhancements to the sensor web while on site. The various sensors report data in near-real time for assimilation into a

high-resolution ocean model in order to define the state of the ocean in the locale under study. In fact, during SPURS-1, such state estimates were very useful in guiding the use of the ship to map transient salinity features.

SPURS-1 used Argo floats as a centerpiece of the sensor web (Riser et al.). Not only did the dense array of Argo floats provide temperature and salinity maps of the overall thermohaline structure of the upper 2,000 m during the year, they were also specially equipped to provide salinity profiles between the surface and 5 m depth, and rainfall estimates via acoustics (Yang et al.). The sensor web was “anchored” by the central mooring (Farrar et al.) and used an array of Seagliders (Shcherbina et al.) to monitor upper-ocean conditions over the full annual cycle. It is expected that, due to stronger surface currents, the SPURS-2 sensor web in the eastern tropical Pacific will require even more emphasis on observations in the upper 5 m and a different approach to Lagrangian observations.

ALTERNATIVE APPROACHES TO ADDRESSING THE BUDGET QUESTION

The framework for evaluating the importance of various processes that determine the upper-ocean salinity distribution across the SPURS domain is expressed mathematically as

$$\frac{DS}{Dt} = \frac{\partial S}{\partial t} + \vec{u} \cdot \vec{\nabla} S = \quad (1)$$

Forcing + Mixing

where the leftmost derivative $\frac{DS}{Dt}$ represents the rate of change of salinity following a parcel of fluid, the center equality represents the time rate of change of salinity at a fixed location $\frac{\partial S}{\partial t}$ and advection of salinity by the currents $\vec{u} \cdot \vec{\nabla} S$, and the right-hand side represents the non-conservative effects of forcing (E–P) and small scale turbulent mixing processes. SPURS investigators have taken a range of approaches for estimating components

of this balance equation by using different observational assets, by integrating this balance over different control volumes, and by averaging over different time scales. Each provides insights into the dominant processes acting on different spatial and temporal scales, and they collectively aid in establishing the robustness of the measurements and methods.

Centurioni et al. use an array of surface drifters equipped with salinity sensors to evaluate the Lagrangian rate of change of salinity following the flow, and gridded mixed-layer current estimates and Aquarius salinity retrievals to evaluate the advection by both time mean and time varying currents. That is, they assess the left equality in Equation 1. They find advection by the time mean flow within the salinity maximum to be small, as expected because the time mean gradients are at a minimum near the salinity maximum, while advection by transient currents matches the Lagrangian estimate of the derivative to within the observational uncertainties. At the other extreme of approaches to evaluating terms in the

of processes, including entrainment of fresher water from below and advection that changes sign on month-to-month time scales associated with the passage of mesoscale eddies. **Dong et al.** and **Dohan et al.** follow similar approaches to evaluating the salinity balance integrated over the surface mixed layer across the SPURS-1 region, but they utilize different combinations of gridded observational products and focus on different time scales and regional averages. Both show advection by the wind-driven Ekman currents acting to decrease salinities to the south of the salinity maximum, and rather weak mean advection over the northern half. However, **Dong et al.** focus on the mean seasonal cycle, averaged over a decade, while **Dohan et al.** examine the balance over the shorter period of the SPURS-1 field deployment and observational products with higher frequency and spatial resolution. As a consequence, the **Dohan et al.** analysis estimates larger magnitudes of the balance terms and a greater degree of variability in both space and time. An inter-

outcomes by systematically examining the sensitivity of the budget results to choice of observational products, spatial resolution, control volume size and position, and temporal averaging period.

The studies discussed above focused on the salinity distribution and variations within the surface mixed layer. **Schmitt and Blair** take a rather different approach by considering a control volume bounding the three-dimensional salinity maximum—including its subsurface expression, rather than just the two-dimensional surface salinity maximum. By integrating Equation 1 over a control volume bounded by a surface of constant salinity, it can be shown that the advection term vanishes, leaving a balance between the volume-integrated salt content tendency and the forcing and mixing terms on the right-hand side. By considering the balance for a long-term climatological average distribution of salinity, the tendency term vanishes, allowing them to estimate the average magnitude of mixing from surface forcing data alone. A similar approach was used in Bryan and Bachman (2015) using high-resolution general circulation model output. Both the observational and modeling analyses of the isohaline bounded budget again point to a combination of vertical mixing and eddy-mediated lateral mixing processes balancing net evaporation over the salinity maximum region.

TOWARD SPURS-2

SPURS-1 is providing us with new insights into the mixing processes in an evaporation-dominated high-salinity region, but of equal interest are the processes that operate in precipitation dominated low-salinity regions. When examining the distribution of evaporation and precipitation over the globe (Schanze et al., 2010), we find that the average areas of net evaporation and net precipitation are about equal, even though evaporation occurs nearly all of the time and rainfall is very intermittent and locally patchy. That is, nearly every part of the ocean gets some rainfall over the course of a year. In

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balance equation, **Farrar et al.** use measurements of current, salinity, and meteorological conditions from sensors at and surrounding the central mooring to estimate terms on either side of the rightmost equality in Equation 1, integrated over the depth of the surface mixed layer. They find the systematically positive (saltening) surface forcing from net evaporation is balanced by a complex combination

esting dichotomy between these studies and those discussed above is the role of advection by transient motions—neither of these studies attribute a large role in the salinity budget to eddy advection, while **Centurioni et al.** and **Farrar et al.**, along with investigations of SPURS-1 observations in Busecke et al. (2014) and Gordon et al. (2014) do. Future work should address how to reconcile these

contrast to the subtropical mid-gyre location of the high-salinity regions of net evaporation, the fresh regions tend to be near the coasts under the influence of river flows, and in both high and low latitudes. The low-latitude fresh regions are beneath the Intertropical Convergence Zones (ITCZs), where moisture evaporated by the trade winds falls as rain onto the ocean. This precipitation completes a large-scale overturning in the atmosphere, where dry subsiding air under the subtropical high-pressure systems sinks and blows across the ocean, picking up moisture that it drops when it rises in the tropics.

So, while the fresh regions of the ocean do not have the same mid-gyre concentration extrema as salty regions, a location for SPURS-2 was sought that would again focus on open-ocean processes and, obviously, would not be influenced by river flows. One of the regions with the greatest rainfall is the eastern tropical Pacific, and it represents ITCZ conditions that are found more widely through the tropics. In many ways, it is the perfect complement to SPURS-1—one reason for the area's low salinity is that the trade winds transport moisture from the Atlantic across the narrow Central American landmass. In a sense, we plan to study how the water evaporated from the North Atlantic salinity maximum returns to freshen the tropical Pacific and thereby study both extremes of the global water cycle.

Of course, adding freshwater from rain to the surface ocean leads to very different physics than taking it away by evaporation. Freshwater is strongly stabilizing and can inhibit vertical mixing, whereas evaporation is inherently destabilizing and enhances mixing. We expect “rain puddles” to form on the ocean surface that can have their own peculiar behavior (Soloviev et al.). These areas of fresher water at the ocean's surface can lead to strong differences between the salinity detected by Aquarius and that detected by an Argo float just a few meters deeper. The many scientific issues of concern

for SPURS-2 are discussed at length in the final paper of this special issue (SPURS-2 Planning Group).

SUMMARY

SPURS is an ongoing endeavor, and this special issue provides insight into our work midway through the enterprise. Weekly global maps of surface salinity from remote sensing have stimulated a resurgence of work on salinity processes in the upper ocean and the role of the ocean in the global water cycle. It is amazing to see the emerging analyses of salinity variability over the full range of temporal and spatial scales, from microstructure to basin-scale. We can expect more exciting insights about the vitally important global water cycle as SPURS-1 analysis progresses and SPURS-2 begins. 🌐

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