A New Multi-Mission Sea Surface Salinity Optimum Interpolation (OISSS) Analysis for Ocean Research and Applications

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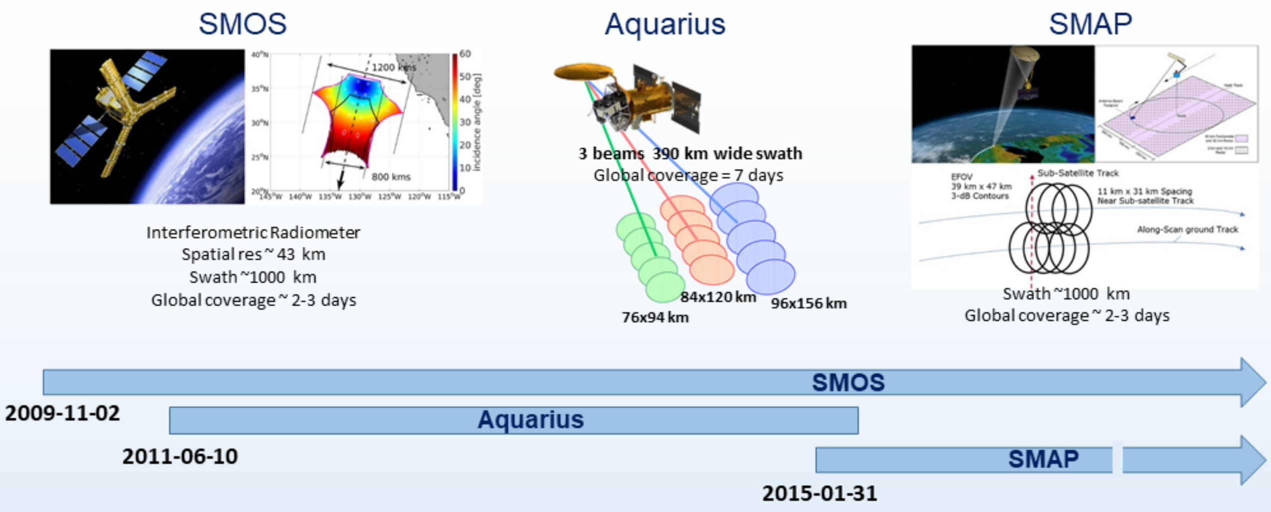


Adapted from Reul et al., 2020, Remote Sensing of Environment, 242 (2020)

The purpose of this presentation is twofold. First, we introduce a new multi-mission SSS dataset which combines observations from NASA's AQUARIUS/SAC-D and SMAP (Soil Moisture Active-Passive) missions into continuous and consistent SSS data record.

Second, we use the new dataset to characterize spatial patterns of SSS variability in the global ocean and on different time scales.

The figure from a review paper by Reul et al., 2020 is a reminder of what we have at hand initially. Three satellites, very different in design, sampling strategy, spatial resolution, and have different life span. The longest is ESA's SMOS (Soil Moisture and Ocean Salinity). The measuring instrument is MIRAS (Microwave Imaging Radiometer using Aperture Synthesis), a two-dimensional L-band interferometric radiometer, which consists of an array of 69 receivers arranged in a Y-shape structure. The instrument provides measurements of Brightness Temperature (Tb) in an approximately 1000-km wide swath with spatial resolution of ~45 km and revisit time of 3-5 days. The NASA's Aquarius/SAC-D provided observations of SSS from August 2011 to June 2015. The Aquarius instrument consisted of three microwave radiometers that generated three beams at different angles relative to the sea surface. The beams had elliptical footprints on the sea surface (76 x 94 km, 84 x 120 km, and 96 x 156 km) aligned across a ~390-km-wide swath with a 7-day repeat cycle. SMAP satellite has been providing SSS measurements since April 2015. The measuring instrument is a large rotating antenna which provides Tb observations within approximately 1000-km wide swath with nominal resolution of about 40-km and a near global coverage in 3-4 days.

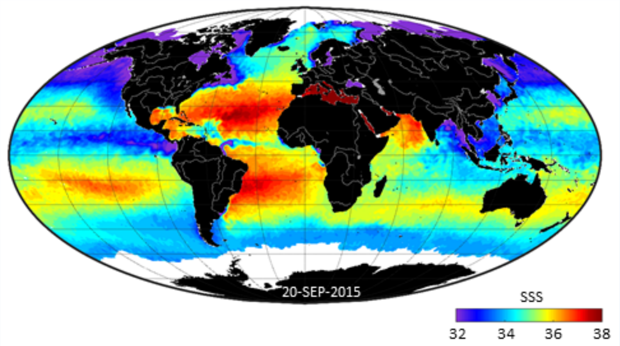
Ideally, by combining data from multiple satellites we should improve something. It could be coverage; it could be resolution; it could be accuracy it could be the record length, or all of the above.

Thus, we develop a multi-mission SSS dataset…

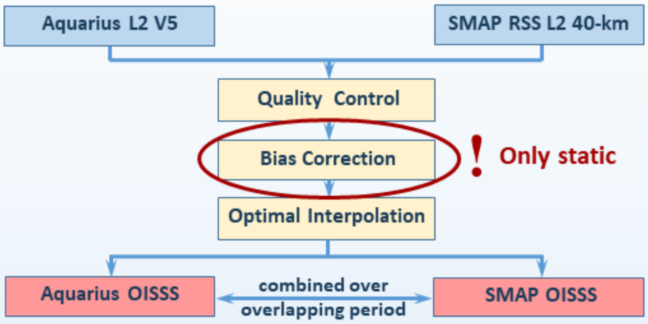
Multi-Mission Optimally Interpolated Sea Surface Salinity (OISSS) Global Dataset

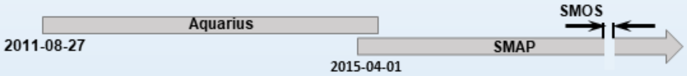
ESR: https://www.esr.org/data-products/oisss/

PO.DAAC: https://podaac.jpl.nasa.gov/dataset/OISSS_L4_multimission_7day_v1



Algorithm





The OISSS dataset combines observations from Aquarius and SMAP satellite missions into a continuous and consistent multi-satellite SSS data record. Measurements from SMOS satellite are used to fill gaps in SMAP observations during the periods when the SMAP satellite was in a safe mode and did not deliver scientific data.

The dataset covers the period from September 2011 to the present. The beginning segment, from September 2011 to June 2015, uses Level-2 data from the Aquarius satellite and is based on Optimum Interpolation (OI) analysis. The analysis (weekly SSS fields) is produced on a 0.25-degree grid at a 4-day interval and uses a dedicated bias-correction algorithm to correct the satellite retrievals for large-scale biases with respect to in-situ data. The time series is continued with the SMAP satellite-based SSS data provided by Remote Sensing Systems (RSS). SMAP SSS fields are produced from Level-2 (swath) data using the OI algorithm. To ensure consistency and continuity in the data record, SMAP SSS fields are subsequently adjusted using a set of spatial filters designed to reduce small-scale noise and, at the same time, to ensure that the dataset is consistent across the scales. For the overlap period (April-May 2015), the data from the two satellites are averaged together to ensure a smooth transition from one satellite to another. Measurements from the SMOS satellite, processed with the same OI algorithm, are used to fill gaps in SMAP observations during June-July 2019 and August-September 2022, when the SMAP instrument was in a safe mode and did not deliver scientific data.

The algorithm corrects the satellite retrievals for only persistent (time-mean) biases which are determined independently for Aquarius, SMAP and SMOS observations.

A Climate Data Record (CDR) is "a time series of measurements of sufficient length, consistency and continuity to determine climate variability and change" (US National Research Council, 2004).

Consistency and continuity should be across a full range of temporal/spatial scales resolved by satellite measurements

Challenges for developing a multi-mission SSS products from L2 SSS retrievals. There are many…

- Inter-mission differences introduce artifacts into combined data sets (e.g.., spurious trends, spurious seasonal cycle, spurious modulation of the seasonal cycle, etc.)
- Jumps in resolution and/or level of noise may result in spurious changes in SSS variance (e.g., Aquarius/SMOS vs SMOS/SMAP)
- Inter-calibration at SSS level may introduce biases rather than remove them (e.g., a multi-satellite product can be less accurate than a single satellite product)
- Because SSS is the final product, biases have to be removed manually. Empirical corrections are doable, in principle, but knowledge of the ground truth is limited, particularly in polar regions and coastal zones.
- Validation! How do we know that our product is indeed a continuous and consistent SSS data record?

Here we come to a definition of a continuous and consistent data record, particularly multi-instrument data record, or, in fact, a lack of precise definition. This is, for example, a definition of a climate data record given by the US National Research Council: A Climate Data Record (CDR) is "a time series of measurements of sufficient length, consistency and continuity to determine climate variability and change".

"Of sufficient length" is straightforward; "continuity" is straightforward, it means there is no data gaps, but what specifically "consistency" means is not that clear.

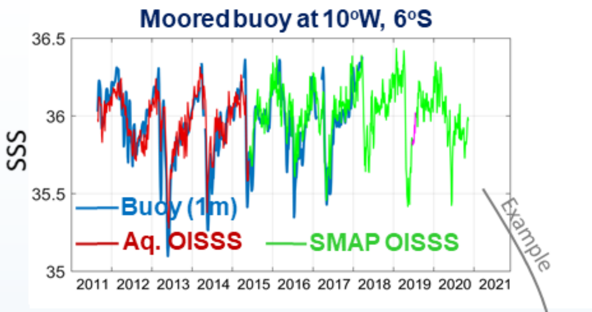
Certainly, we don't want biases to be there, particularly biases, which change along the data record, with transitions from one instrument to another. There should be no jumps and spurious trends.

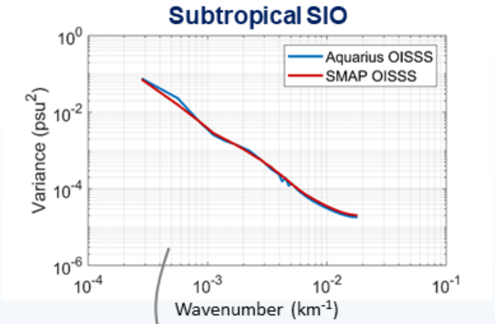
If we continue one dataset with another with different error characteristics, will it be continuous and consistent data record?

If we continue one dataset with another with different resolution, will it be continuous and consistent data record?

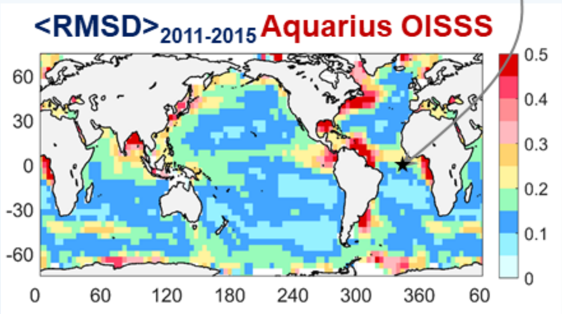
We believe that continuity and consistency shall be across a full range of temporal and spatial scales resolved by the data record. That is what we are trying to build.

OISSS: error characteristics



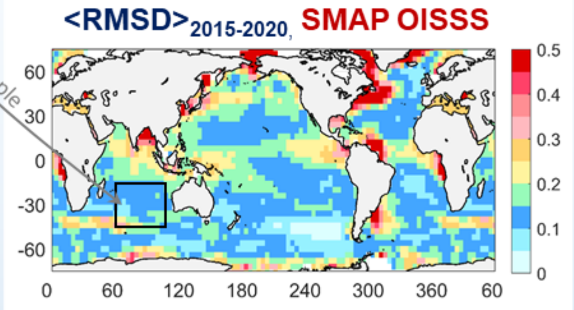


OISSS
<RMSD> = 0.22 psu
<bias> = 0



stitched

OISSS
2011-2023



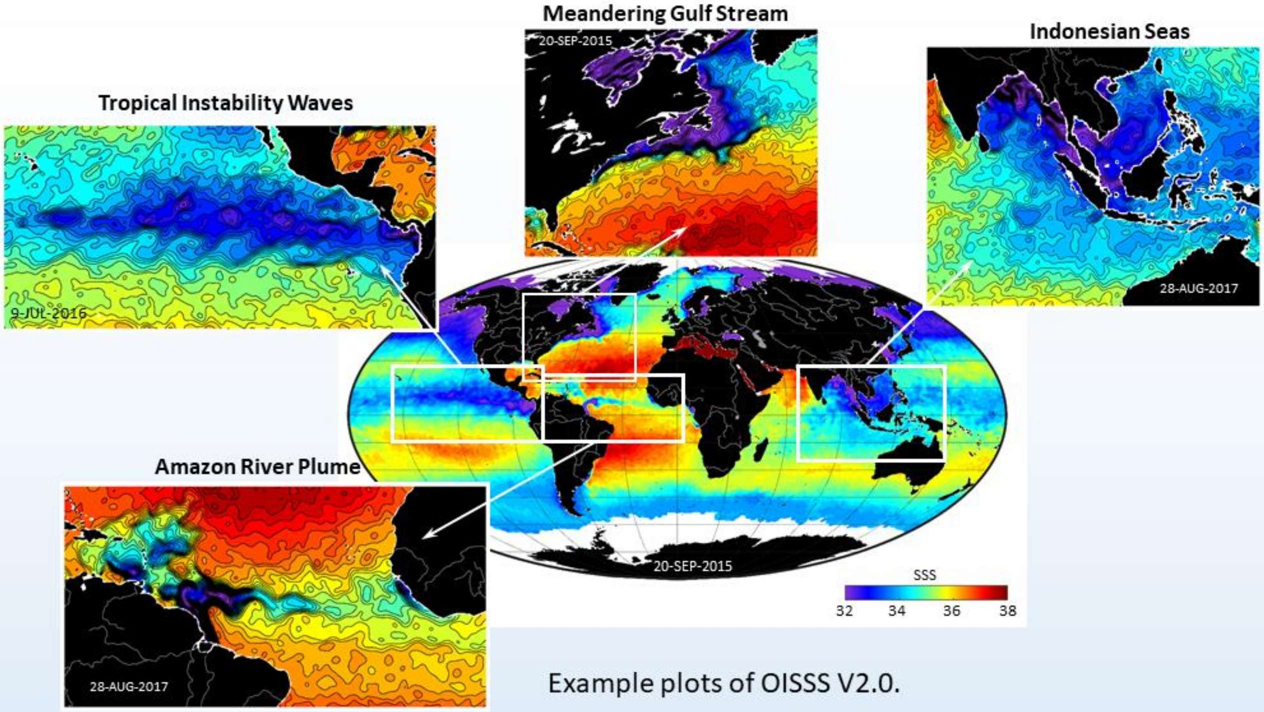
The error statistics are calculated by comparing Argo buoy measurements (z<10m) for a given week with SSS values at the same locations obtained by interpolating the corresponding L3/L4 SSS maps.

The OISSS data record is designed to be as accurate as possible.

Bottom panels show maps of RMSD between the Aquarius (on the left) and SMAP (on the right) OISSS fields and concurrent Argo buoy data. First, the error characteristics of the Aquarius-derived and SMAP-derived OISSS fields are nearly identical. They do not change when transiting from one instrument to another. Second, over most of the ocean the RMSDs are smaller than 0.2 psu, even in polar latitudes, Third, these RMSDs include the so-called sampling error, which is due to unresolved small-scale variability, and these patterns are consistent with what we should expect (e.g., Vinogradova and Ponte, 2013).

The consistency across the scales can be verified with the spectral analysis as shown in an example in the Southern Indian Ocean (upper right), or using continuous time series from moored buoys (upper left). There are not many, however, and the problem of validation remains.

OISSS: coverage and resolution



Tropical Instability Waves

9-JUL-2016

Meandering Gulf Stream

20-SEP-2015

Indonesian Seas

28-AUG-2017

Amazon River Plume

28-AUG-2017

20-SEP-2015

Example plots of OISSS V2.0.

In order to stitch Aquarius and SMAP observations into a continuous and consistent data record we had to sacrifice SMAP resolution (yet improving mapping errors). The final resolution of the product is not that bad, however.

The plot in the center is global and shows the product spatial coverage. The OISSS dataset covers the full global ocean including the Arctic and Antarctic in the areas free from ice. The coverage includes coastal areas and marginal seas, such as the South China Sea and the Gulf of Mexico, and internal seas, such as the Mediterranean and the Baltic Sea, when and where high quality Level-2 observations are available.

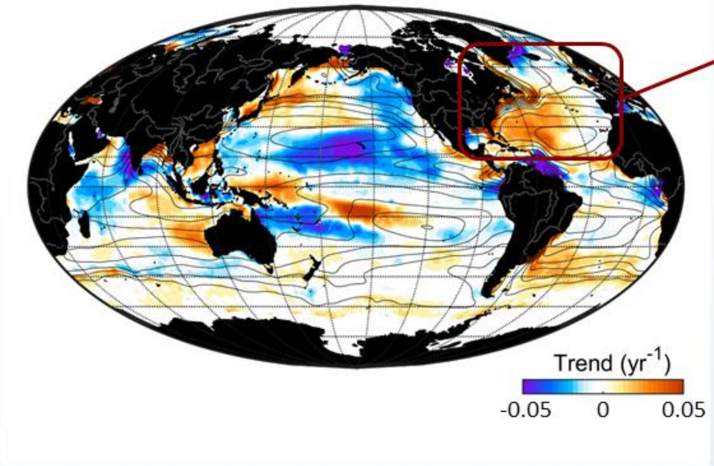
The resolution capabilities of the OISSS analysis can be inferred from the regional maps. In particular, the upper panel in the center shows a zoom on a large area in the North Atlantic. Among the many features represented in the map is a frontal structure associated with the Gulf Stream and Gulf Stream Extension, which separates low-salinity slope water from the salty Sargasso Sea. The front extends further north into the Labrador with local salinity gradients as large as 1 psu/100 km.

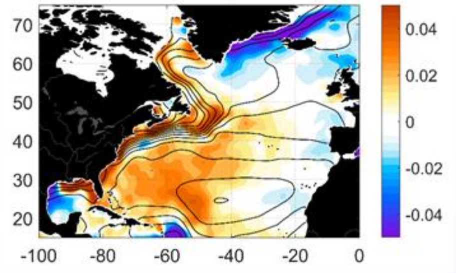
Another prominent example is in the eastern tropical Pacific (upper left). The figure shows the SSS signature of Tropical Instability Waves (TIWs) clearly seen as cusp-like features between ~0° and 5°N with wavelength of ~1,000 km (~10° of longitude). The waves have a dominant period of about 30 days and propagate westward at a speed of about ~0.5 m s^{-1} (not shown in figure).

These examples (and the spectral analysis) show that the spatial resolution of the OISSS analysis allows observing large mesoscale features and fronts. The estimated effective resolution of the product is about 500-600 km in terms of a wavelength (length scale larger than about 120 km).

Global Patterns of SSS variability

Trend 2011-2022

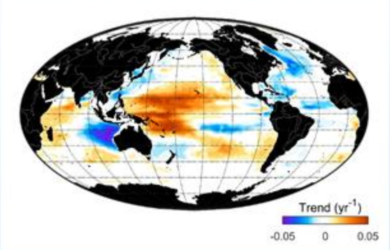




Significant changes in the subtropical and sub-polar North Atlantic

The trends are reversed compared to the preceding decade (2005-2015, estimated from Argo) and are seemingly a part of a longer term oscillation

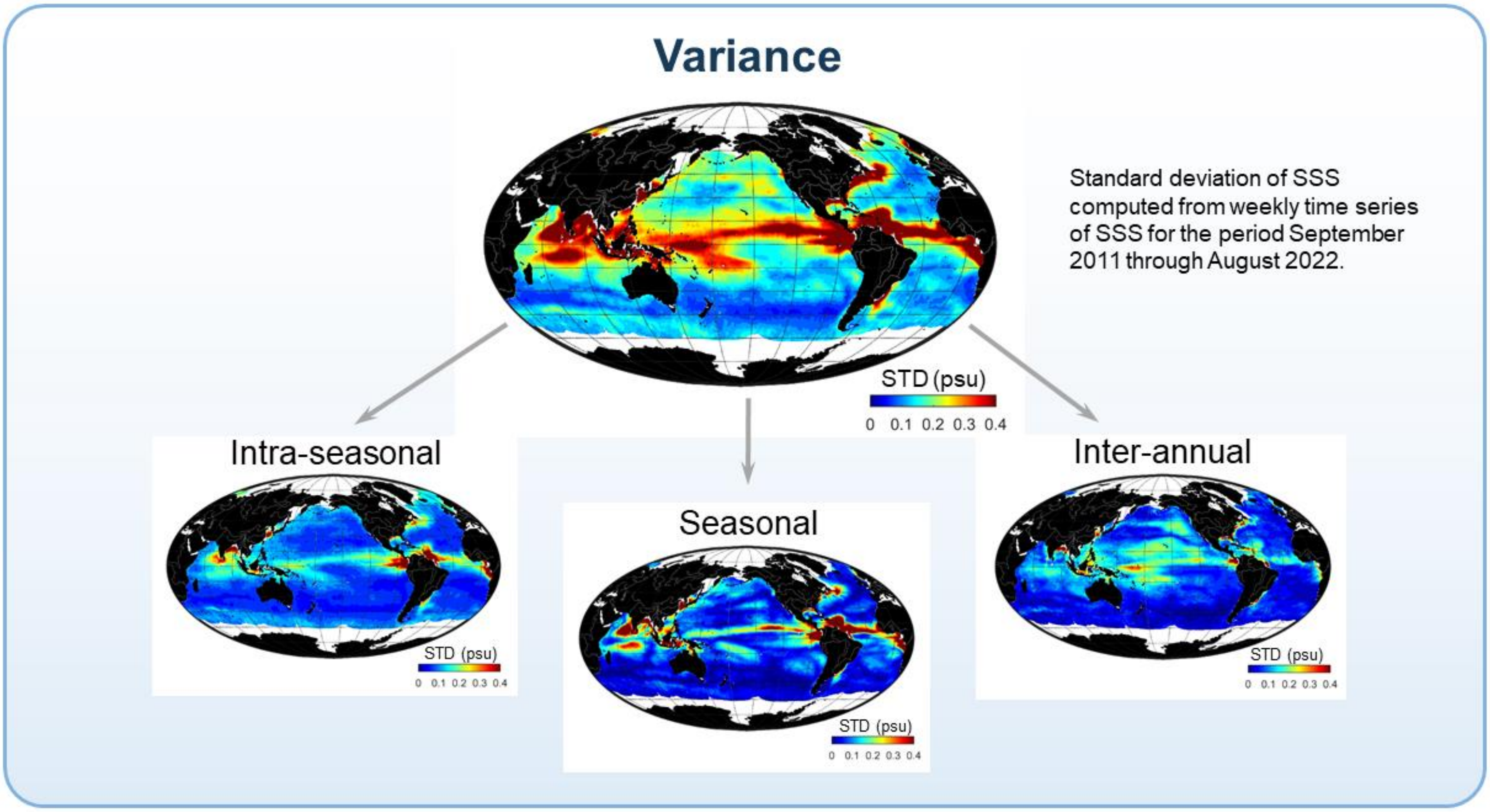
Trend 2005-2015



Salinity trend from Argo (RG) over 2005-2015

The new dataset is used to characterize spatial patterns of SSS variability in the global ocean and on different time scales.

First is a linear trend, which is not necessarily a trend, in a classical definition, as the data record is still too short, but is likely a part of a longer-term variability, particularly decadal variability. Indeed, as you can see, the trends are reversed, nearly everywhere, compared to the preceding decade (estimated from Argo data). Yet, we can see dramatic shifts in the tropical Pacific, it is becoming fresher, while the subtropical Atlantic and Indian Oceans are becoming saltier. A zoom on the North Atlantic (upper right) shows that the slope water and Sargasso Sea are becoming saltier, while the core of the Gulf Stream, in its mean position, is becoming slightly fresher or remains neutral. This kind of detail is not available from traditional in-situ observing systems such as Argo. The eastern part of the sub-polar North Atlantic is becoming fresher, and we know how important this may be for the regional climate and potentially the AMOC.

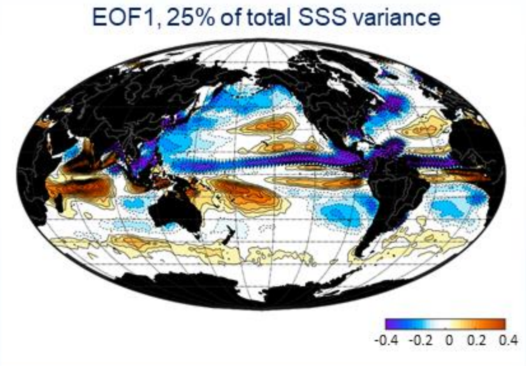


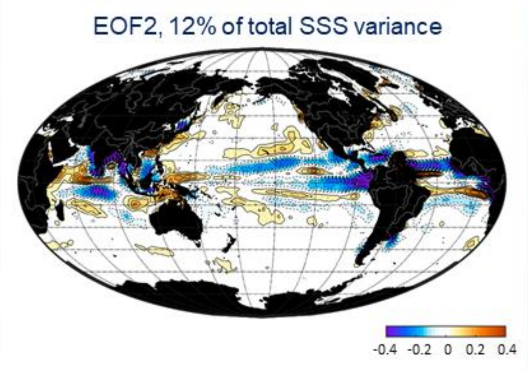
Standard deviation of SSS computed from weekly time series of SSS for the period September 2011 through August 2022.

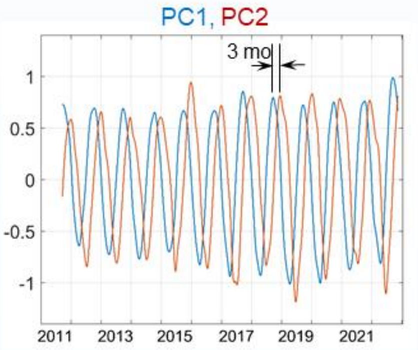
To organize and simplify the analysis of SSS variability, we split it into 3 frequency bands: intra-seasonal, seasonal and inter-annual. Total SSS variance is the largest in the tropics and in some sense repeat the pattern of precipitation. However, the patterns for different spectral components are generally different from each other.

Variance of intra-seasonal SSS even more resembles the pattern of precipitation, emphasizing the role of external forcing and synoptic nature of precipitation, yet, with few exceptions. All river outflows, including the Amazon, Congo, Mississippi, Plata, Ganges and Brahmaputra, have strong intra-seasonal variability, emphasizing the role of rapid coastal processes. Fronts (e.g., the Gulf Stream and Gulf Stream Extension) typically have strong intra-seasonal variability, presumably associated with frontal instabilities.

Seasonal cycle

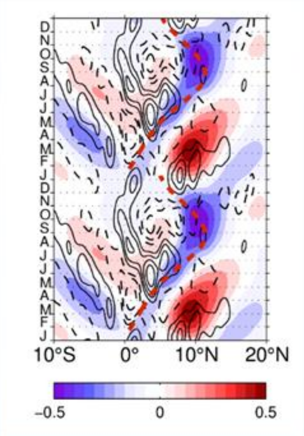

EOF1, 25% of total SSS variance


EOF2, 12% of total SSS variance



A 3 month phase shift between PC1 and PC2 indicates propagation

The signal propagates poleward in both Hemispheres

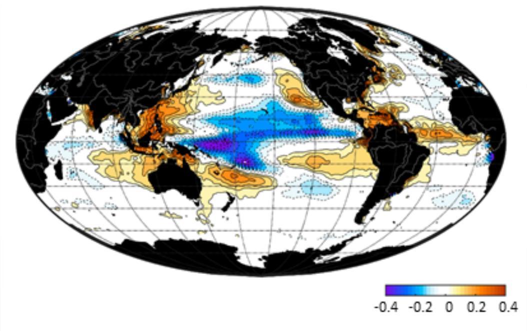


Seasonal SSS anomaly (color) zonally averaged between 135° and 115°W. Contours show rate of change in SSS due to meridional advection (C.I.=0.05 psu/month). The thick red dashed line shows seasonal migration of ITCZ. (From Melnichenko et al., 2019)

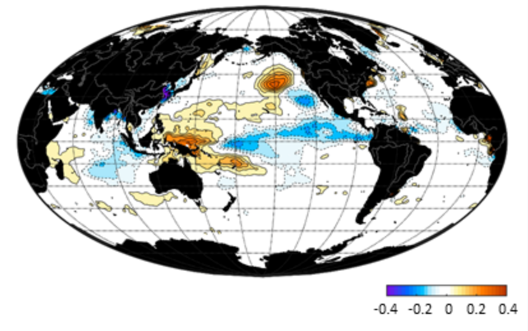
The largest signal is the seasonal cycle which can be described, remarkably, by two leading Empirical Orthogonal Functions (EOFs). The two EOFs account for nearly 37% of the total! SSS variance and describe both standing oscillations in the subtropics and polar latitudes and propagating anomalies in the tropics. The anomalies propagate poleward in both hemispheres. The propagation is seemingly due to Ekman advection and the near-equatorial signal can reach subtropical latitudes as far as 25N in the North Pacific, for example, potentially affecting the formation sites of the North Pacific Tropical Water.

Nonseasonal SSS variability

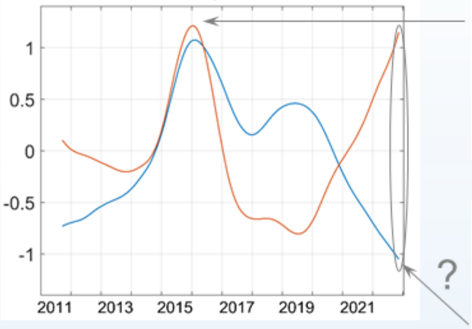
EOF1, 42% of nonseasonal SSS variance



EOF2, 15% of nonseasonal SSS variance

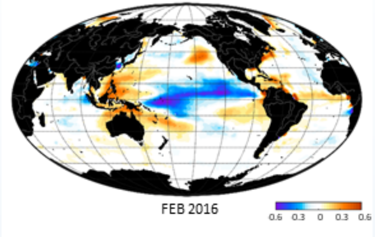


PC1, PC2

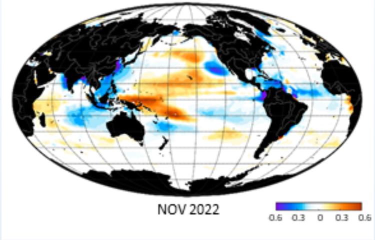


Two leading EOFs of linearly detrended monthly SSS anomalies

Super El Nino 2015-2016



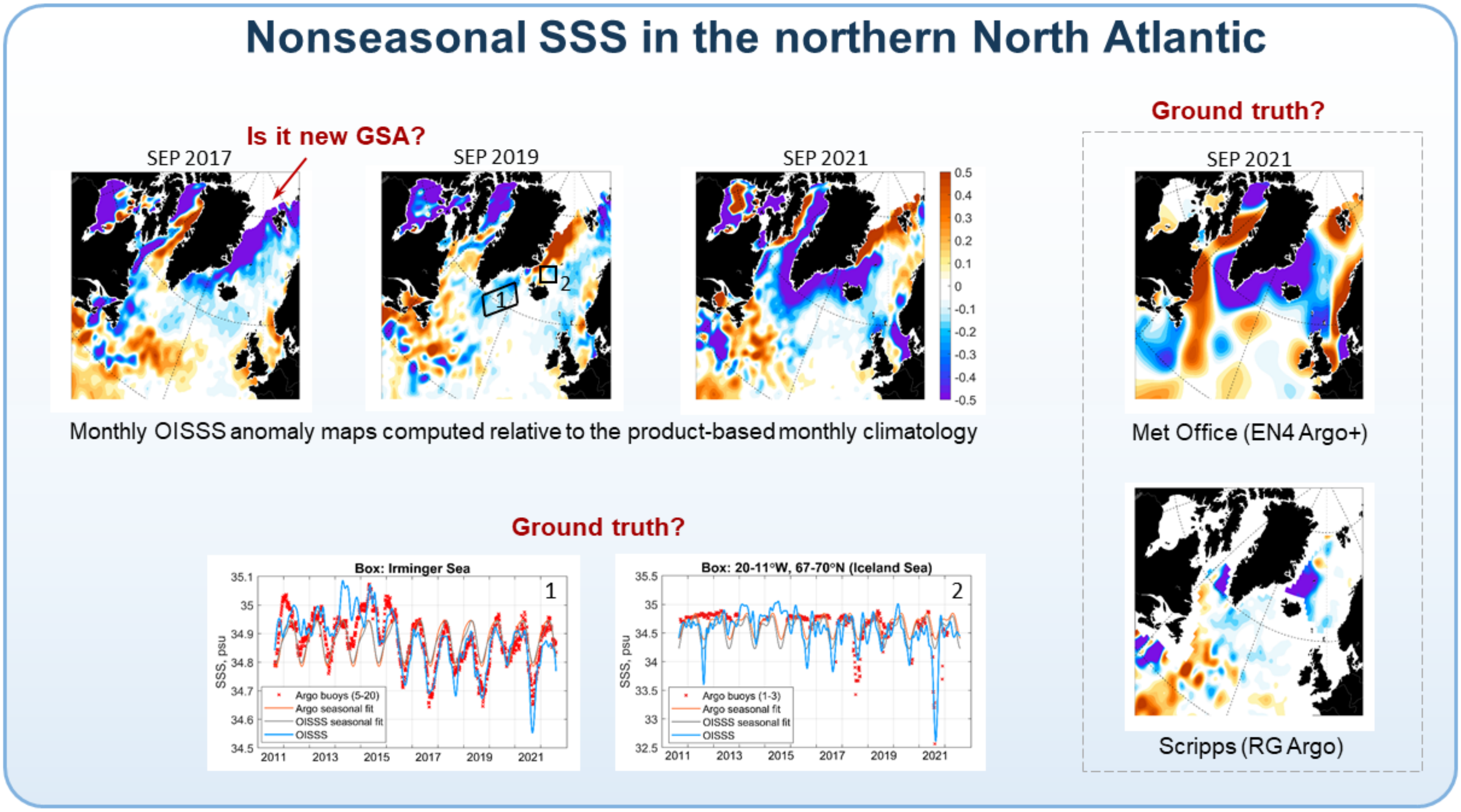
Developing now



Considering inter-annual SSS signal, shown on the left are two leading EOFs based on linearly detrended monthly anomalies during the period 2011-2022. They describe more then 55% of non-seasonal SSS variance globally. The modes are computed over the global ocean, but they are essentially the ENSO modes with the largest contribution from the Pacific. Here, in the tropical Pacific we can easily recognize the leading EOF from the paper by Delcroix et al., 1998, which was based on historical in-situ observations. But with the satellite SSS we can expand the analysis to include regions not available by conventional in-situ measurements, such as the Indonesian Seas, and to obtain more accurate patterns.

The EOF modes can be used to describe a coherent SSS response to the super El Nino of 2015 (upper right). We can see substantial freshening in the western and central equatorial Pacific, and the North Pacific ITCZ, but saltier western Pacific warm pool and the Indonesian Seas, as well as the South Pacific Convergence Zone.

We can also see what is happening now due to prolonged La Nina (lower right)– quite the opposite.



Nonseasonal SSS in the northern North Atlantic

Is it new GSA?

SEP 2017

SEP 2019

SEP 2021

Monthly OISSS anomaly maps computed relative to the product-based monthly climatology

Ground truth?

SEP 2021

Met Office (EN4 Argo+)

Scripps (RG Argo)

Ground truth?

Finally, we show patterns of non-seasonal SSS in the northern North Atlantic. The northern North Atlantic is an important region of deep water formation, which is an essential component of the AMOC and thus the Earth's climate system. Salinity here controls stratification and, therefore, deep water formation.

It is the first time we can see these remote areas such as the Baffin Bay and Nordic Seas in full display, thanks to satellite observations. The upper three panels show monthly OISSS anomaly maps computed relative to the product monthly climatology. The maps are for September 2017, 2019, and 2021, respectively. Large SSS anomalies are observed, particularly in the Greenland Sea, Iceland Sea, and the Baffin Bay, up to 0.5 psu and larger. This may appear suspicious because the anomalies are large and particularly because SSS is difficult to observe in polar latitudes, due to cold water, so the errors are large, too.

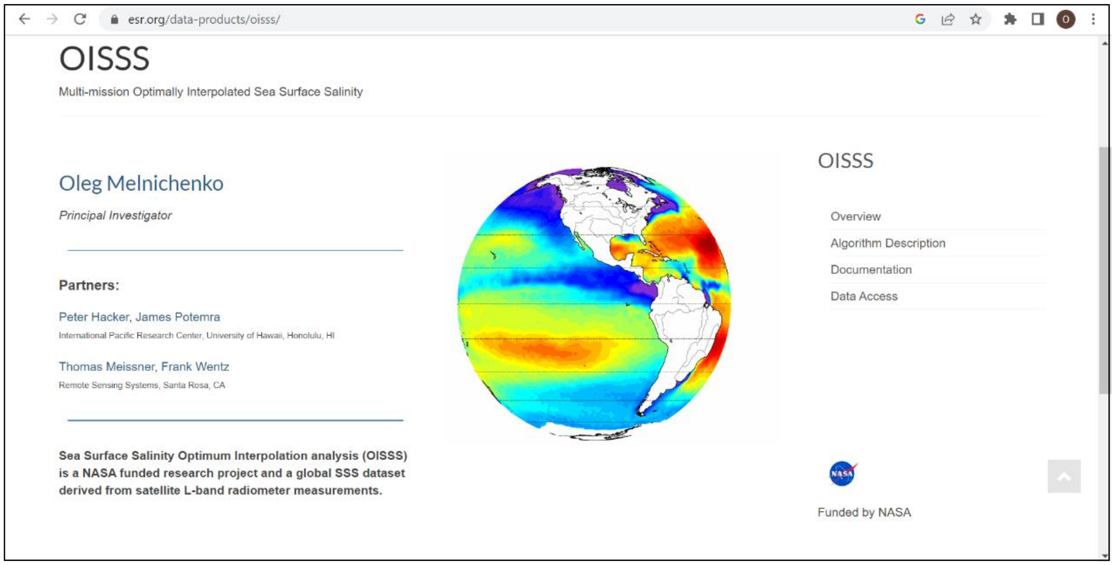
The two panels on the left show the comparison with the ground truth for September 2021, which may encourage you or discourage you to use the satellite data depending on which ground truth you are willing to pick for comparison. The upper panel is the Met Office EN4 product, which uses all types of in-situ data including Argo, and the lower is Scripps Argo, which uses only Argo data. Certainly, there is lack of in-situ data coverage as the corresponding products are very sensitive to it.

This example also emphasizes the advantage of satellite SSS data as the satellites provide unprecedented coverage and resolution. Digging a little dipper with available in-situ data we find that the truth is out there, and we can use the satellite data as a guide.

Summary

Multi-mission OISSS V2 is available for ocean research; 11+ years and counting; estimated RMS error=0.22 (psu) for weekly SSS fields; mean bias=0.

https://www.esr.org/data-products/oisss/



esr.org/data-products/oisss/

OISSS

Multi-mission Optimally Interpolated Sea Surface Salinity

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Sea Surface Salinity Optimum Interpolation analysis (OISSS) is a NASA funded research project and a global SSS dataset derived from satellite L-band radiometer measurements.

OISSS

- Overview
- Algorithm Description
- Documentation
- Data Access

Funded by NASA

PO.DAAC:

Weekly: https://podaac.jpl.nasa.gov/dataset/OISSS_L4_multimission_7day_v1 (V2 is coming soon)

Monthly: https://podaac.jpl.nasa.gov/dataset/OISSS_L4_multimission_monthly_v1 (V2 is coming soon)

From 11 years of continuous satellite SSS data:

- ✓ SSS variability is comprised of different time scales, from intra-seasonal (thanks to satellites we can observe it globally) to inter-annual. The spatial patterns are quite different for different frequency band.
- ✓ The intra-seasonal signal is the strongest in the tropics and repeat the pattern of precipitation (ITCZ and SPCZ). The intra-seasonal signal is strong in outflows of all major rivers, including the Amazon, Congo, Mississippi, Plata, Ganges and Brahmaputra, and in the areas of strong SSS fronts (e.g., the Gulf Stream).
- ✓ The annual cycle is a dominant signal globally and can nicely be described by two leading EOFs (> 35% of the total! SSS variance). The signal propagates away from the Equator in both hemispheres (presumably due to Ekman advection) affecting subtropical latitudes.
- ✓ The strongest non-seasonal signal over the 11-year period of the satellite SSS time series is associated with the 2015-2016 El Niño event. The response is mainly in the tropical Pacific and represents substantial freshening in the central and eastern equatorial Pacific (particularly in the convergence zone) and salinification in the western equatorial Pacific, SPCZ, and Indonesian Seas.
- ✓ Thanks to satellite SSS, we can now observe areas not routinely available by traditional in-situ observing systems such as Argo. One such area is the northern north Atlantic where interesting things are happening. The example in the northern North Atlantic emphasizes the need for even higher resolution SSS data.