Aquarius Version 5 Salinity Product Tutorial

Aquarius Sea Surface Density and Spiciness

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Welcome to the NASA web tutorial on Aquarius Sea Surface Density and Spiciness. My name is Julian Schanze and I work at Earth and Space Research in Seattle. Here's a little bit about me. I did my undergraduate and masters in oceanography at the University of Southampton. This was in physical oceanography and remote sensing. So my passion is always been to combine those two things - physical oceanography meaning of observational physical oceanography (actually going out there measuring things) as well as remote sensing. And this I continued at the MIT Woods Hole Oceanographic Institution joint program with my advisor there Ray Schmidt. That was really mostly physical oceanography driven but I was using a lot of satellite datasets analyzing satellite datasets so I never got away from remote sensing. And I did a postdoc at Woods Hole for about a half a year and became a Research Associate at Earth and Space Research and Seattle and became promoted about a year ago to Research Scientist instead of Research Associate.

Today I'm going to be talking about the following: density and spice, why are we doing this, and a little bit of a preview to get you interested before we get into some of the nitty-gritty. Namely the sum of dynamic "Equation of State 2010," why we use it, how we use it, and why it's useful as opposed to other equations of state that used to be used. Then the new product of density and spiciness from Aquarius so this will be decomposed into the thermal components and into the haline components. We will then talk about some of the applications of this research, and going forward and some of the conclusions of the work that I've been doing.

This is a field of Aquarius density. You can see it is very dynamic, you can also see some of the regions: such as the outflow regions from major rivers, you can see the Amazon plume here very well, you can see the Congo, you can see the freshwater input into the Bay of Panama here, and you can even see outputs from the Mississippi River into the Gulf of Mexico. There are seasonal cycles of the monsoon visible here in the Indian Ocean, as well as the Intertropical Convergence Zone. So it's a very dynamical system of course and with density there's also a huge shift up and down or north and south as the seasons progress. So you can see a tremendous wealth of information that you can see eddies you can see westward propagating features. These are some of the things that we really are unable to capture using system such as Argo, even though those of course have what you need to match this too all this satellite data.

This here is the map of spiciness. Spiciness is a variable that I'll be describing a little bit and it's very interesting because traces some of the contrast between that you cannot see in density. Quite frequently density can be compensated in temperature and salinity - that means if the temperature goes up the density goes down but if salinity goes up the density goes up as well. So you can have a warmer saltier water that has the same density as a colder fresher water mass. And that is something that you can trace uniquely in spiciness. Because a high spiciness level means that it is warm and salty so it's one plus the other instead of one minus the other, if that makes sense.

Alright, so here you can see some of the fronts that you couldn't see before. Here in parts of the Indian Ocean you can see some fronts occur in here, and the North Atlantic you can see quite a bit and in high latitudes and you can see some features here, current around these regions here in the South Atlantic for instance. So there are a number of regions that are very interesting in terms of density compensated for fronts that are very visible in spiciness. So it's a very useful product and also useful as a diagnostic for the interior ocean, that's something I'll get to later.

So let's get to part one which is the Thermodynamic Equation of State 2010, density and spiciness and how they relate.

This here is a plot of conservative temperature on this axis absolute salinity on this axis. And those are both variables that, if you're familiar with the previous equation of state, the UNESCO 1980 Equation of State, conservative temperature is akin to potential temperature, and absolute salinity is akin to salinity, even though this is something that includes the mass fraction of the chemical constituents in seawater. So it's actually quite a bit higher, and that's something that all oceanographers should be using. Now if you do anything that's got something to do with water masses, tracing water masses, or deep water formation or any water mass transformation studies, it is highly recommended that you use absolute salinity and conservative temperature.

This here, in the contours, you can see the density and you can see already that it’s highly nonlinear. See these curvatures here occurring. Density is defined as cold and salty is positive so it's the haline minus the thermal component. If you look here at the equation it's Density: $\rho = \rho_0 \cdot (1 + b \cdot \mathbf{SSS} - a \cdot \mathbf{SST})$. So there is a minus here.

Whereas in spiciness, it is the haline plus the thermal component. So let me show you spiciness up next. So this is spiciness and it maximizes the differences between water masses in the new definition by McDougall and Krzysik.

If you plot both together here you can see this notion of them being orthogonal is not really accurate and for more details I shall refer you to that paper off McDougall and Krzysik 2015. But the key is that spiciness is used where density compensation occurs as a tracer for the interior, and also for the surface, so it's a very useful indicator of water masses.

Here we have the haline component minus the thermal component but for spiciness we have the healing component plus the thermal components.

So why are we using the Thermodynamic Equation of State 2010? The functions to compute derived variables were computed be consistent and that is in contrast to other functions, such as the Equation of State 1980. If you went from one thing to another thing and you convert it back you may end up with a different result than what you started out with - which is not a good thing.

So this is something that was addressed in the Thermodynamic Equation of State 2010, and the Gibbs seawater toolbox. So it's using a Gibbs function to go between one thing and another thing. Conservative temperature is actually pretty much conservative, whereas for potential temperature, you can show that it's really not all that conservative, in certain conditions. This is mostly something that is related to some deep ocean processes, so at the surface it doesn't matter, in situ temperature, conservative temperature, potential temperature are all essentially the same.

However, absolute salinity now has the units it is grams per kilogram it is a true mass fraction, so that makes it uniquely different than practical salinity. All the salinities that are provided in a dataset such as Aquarius are given in practical salinity. The reason for that is it's better for archival so for anything where you have to store these information in a dataset, you would store them as practical salinity, then compute absolute salinity from that.

The Thermodynamic Equation of State has now been adopted by all major standardization bodies in the oceanographic community. It really should be used for any study that deals with temperature, salt, density, spiciness, any thermodynamic variable related to seawater. Really everything to do with sea water should be computed using Thermodynamic Equation of State 2010.

Does it matter for Aquarius? Well actually, the changes are non-trivial as I mentioned all the archival salinity data will remain in the PSS-78 standard, so practical salinity, the salinity, that most of you may be used to. However, all publications should be using the new absolute salinity. It uses something that is called pre-formed salinity, this is standard seawater that is scaled by the chlorinity of the sea water and has a correction factor that's based on silicic acid. It's not only silicic acid but essentially it is how old the water is, how much biology has happened in the water column that has modified this water to make it potentially denser, which is something you do see. So there is a global map that you use to compute absolute salinity, so you have to input latitude longitude now as an extra variable now when you go from practical salinity to absolute salinity.

That's one of the reasons why we're providing you with these days it's at so you don't have to we're providing you with density and spiciness already so that you don't have to compute it yourself and possibly make a mistake - we're not saying that you would - but still it's always good to have something that we know and checked is the correct value for it.

So for the first time we have this influence of spatially varied composition of seawater. It can be taken into account through the use of absolute salinity. In the open ocean this has a non-trivial effect. There are things that oceanographers measure relatively frequently, there are these transects that you do across the ocean and then you compute the total velocities that occur. To compute the meridional overturning circulation, it actually makes a pretty big difference. So using this thing called the "thermal wind" relation, which is something that atmospheric scientists really started but it is also applicable to the ocean, you can relate the total changes in the temperature or in this case also the salinity gradient to the velocity in the ocean and that allows you compute these velocities, which is a unique function. So it actually makes a pretty significant difference, almost 10% for some of these computations in extreme cases.

Some of the resources here there is the whole manual, which is over 200 pages and is a bit unwieldy. But there are actually much more user-friendly resources out there if you just wanted to get a quick overview of what's happening. So there is the TEOS-10 primer, by Rich Pawlowicz, which is something that is really quite accessible, well-written and easy. Also there's this thing that I'm actually the Gibbs seawater toolbox and this is what you would use for a number of programming languages such as MatLab, Fortran, C, Java… It's really easy enough to use it's really not that hard to use and there are number of cheat sheets (if you will) where you go from the previous seawater toolbox (which I'm sure many of you use or have used) to the new Thermodynamic Equation of State 2010 and the Gibbs seawater toolbox.

So now, some of the background on spiciness. It's now newly defined in this paper below here, it is now part of the Thermodynamics Equation of State 2010, and it is thermodynamically consistent with it. So that's excellent news because previous definitions of spiciness (or spicy or spice or whatever the office called it) generally didn't have that property and had some rather arbitrary decisions as to how they were defined. There are still a few decisions to be made here but the main message is that it's no longer defined as an orthogonal property, which I sort of put here, but it's instead, a water mass change-maximizing variable. In any case, it's part of the toolbox we will be providing it in Aquarius Version 5.

Let's talk about constituents of density and spiciness and how we can take those apart. So I mentioned earlier that both density and spiciness are based on Alpha x SST plus or minus Beta SSS. So here is a global map of Alpha that I derived from the mission duration of Aquarius. So this is taking all available data, to take the mean of it and then plotting it out to compute the thermal coefficient Alpha. And you can see this color scale here ranges from almost zero to 3.5 x 10-4. The point is that it goes over more than order of magnitude and that means that these changes are huge. It changes from having almost no influence at high latitudes, or really at cold temperatures I should say, to having a large effect at low latitudes or high temperatures.

However, for Beta that isn't true at all. So here is the haline coefficient and this only changes from about 7 to 7 .8 x 10-4 and it has the opposite sign in the sense that it has its highest changes at high latitudes, which means at low temperatures. And it has the lowest value here in low latitudes or relatively warm temperatures. And that means is that salinity is incredibly important in high latitudes where Beta is really the dominant effect so the haline affect. The haline component of either density or spiciness is the dominant effect that drives water mass transformations or anything else in the ocean to a large degree. Of course temperature still plays the role but less so than in most other parts of the ocean.

Here is a global mean map of sea surface density from Aquarius. This is still using version 4.0 which is the current latest production version and it shows you some of the features. You can see some of the lowest densities occur here in the bay of Panama and you have the

Intertropical Convergence Zone visible, you have the mean outflow from the Amazon, the Congo River, you have the monsoon regions here. So you have signatures of the freshwater inputs into the ocean, both from riverine and from precipitative sources. You can also see that at high latitudes you generally have high density which is of course sensible because this is where some of the deepest water formation regions in the world are, so you have the Labrador and Irmiger Sea up here and you can see that these are some of the densest water masses that we have. This is a combined effect of both the haline and thermal components.

So here we see spiciness, and warm and salty water as I mentioned earlier is spicier than cold in freshwater. You can see the usual features here you can see the contrast between the Atlantic and Pacific. So of course the Atlantic is saltier than the Pacific, as I'm sure all of you know, and you can see these effects that you have some of the highest spiciness here in the subtropical gyres especially in the North Atlantic you have very high spiciness. Here also in the South Atlantic you can see some of the usual features that you would expect. You can see the Gulf Stream pretty well as a very sharp gradient, you can see the upwelling zone you can see the west coast of the United States with its upwelling and you can see the Peruvian upwelling zones. You can see some of the monsoon affect here and so this is an interesting contrast to density.

Alright next we are going to have a look at decomposing these into its constituents. So for that I'm going to be doing an evaluation of Aquarius density and spiciness. So for this I'm going to be decomposing density into thermal and haline components. This is relative to standard seawater which is defined as having a practical salinity of 35 and a temperature of 15 degrees so in the reference salinity that would be 35.165 grams/kilogram and a conservative temperature of theta equals 14.99 degrees. This is going to highlight some of the contributions from Aquarius so really the advancement of the field of sea surface density through the introduction of remotely sensed sea surface salinity data. Of course this has implications for water mass formation and transformation studies. And it's also constrained for interior processes. This is an idea of power integrals that was proposed by Malcolm Stern in the 70s and then has been applied the people like Terry Joyce at Woods Hole, Schneider/Bhatt in 2002. Something I did my thesis on, and it has been done by Frank Bryan for a salinity budget. And then and we have an upcoming paper that compares density and spiciness variance in the ocean that hopefully will be released very soon.

Shown here is the field of Aquarius density, and you can see the evolution here and you can see it how much it changes. You can see the riverine outflows, again you can see the Amazon beautifully here changing throughout the seasonal cycle but also between years. You can see the Congo outflow, you can see the Bay of Panama here, and you can see the strong freshwater inflows the intertropical Convergence Zone you can see the migration of the Intertropical Convergence Zone, you can even see the propagation of subtropical instability waves. You can see westward propagating features and western boundary currents. You can see the [agolis] here, you can see the Gulf Stream up here changing rather dramatically. Of course that's still all including both temperature and salinity but that will be shown decomposed in the next few slides. And that'll highlight the temperature and haline components of this.

First of all let's compare this to the Argo density field. So this is using the EN4 MET office Argo gridded fields comparing it to Aquarius. You can see there are a lot of changes, a lot of high frequency changes. Some of them are systemic problems that we're still addressing for version 5 in Aquarius so that's something you should be aware of (especially that there is a seasonal effect that is happening that may not be representative of what's actually going on). But they're also a lot of features especially in these river outflow regions. Here again in the Amazon and you have other freshwater regions in the Intertropical Convergence Zone, you have the monsoon regions that are just spatially undersampled by Argo.

Argo has very good accuracy but the problem is the spacing is so wide, that really between each buoy that pops up in this location or that, we do not have a whole lot of idea of what's happening in between those individual measurements. So really you have to consider that.

Shown here is the difference between Aquarius and Argo density so this is a field that shows you both the strengths and weaknesses of Aquarius and some of the weaknesses of Argo, but also some of the strengths of Argo. Of course Argo has very good accuracy where it pops up so you have floats that make profiles every 10 days or so. But generally the spacing is pretty wide and they tend to be undersampled in certain regions of the ocean and especially in boundary currents. It is very hard to keep any float in a boundary current or in highly dynamical regions. This is where Aquarius shines because you get a lot of spatial information from Aquarius that you do not get from Argo. So you know the absolute accuracy of the individual Argo measurements is good, the representation error is a problem. That means that Aquarius has this unique capability of really capturing some of the spatial details - some of the fronts, some of the structures. That’s something you can see here in the difference field too. You can again see the outflow regions, you can see The Intertropical Convergence Zone, you can see some of the monsoon effects that are happening and you can definitely see all the western boundary currents that are highly variable in both temperature and salinity.

However, there's also this problem with Aquarius that we still have at the moment. There is a slight seasonal bias especially in the Northern Hemisphere. That you can see here it becomes an anomalously red occasionally, and then becomes a little bit blue... but mostly there is a positive bias. That's something that we are actively working on to remove that in version 5.0.

Shown here is the thermal component of Aquarius density. So this shows you the migration up and down it also shows you some of the propagation so this is only based on the Aquarius auxiliary sea surface temperature which is a [Grist?] product that is resampled to the footprint sizes of Aquarius for each of the three beams. It is one of the better SST datasets out there - Sea Surface Temperature datasets out there - and it shows you also very nice structure. Of course this is not something that Aquarius brings to the table so this is something that we already had from all the satellites, this is the information of sea surface temperature that we have from other satellites.

The message here is that it's mostly the seasonal cycle goes up and down it's mostly meridional effects rather than zonal effects. So it’s really a north-south movement as the seasons progress. So here is the change between Argo and Aquarius which means really the ancillary sea surface temperature field. You can see that there are some effects especially western boundary current regions where Argo is undersampling you can also see there are a couple of temperature affect in the intertropical Convergence Zone that are not picked up by Argo. So this is just an overview of what is missed by *in situ* measurements relative to high quality satellite measurements.

Now let's look at the same thing for the healing component, so really this is the unique contribution of Aquarius. This is a map of the haline components. Again this is relative to standard seawater as before, and you can see a lot of these regions - here you can see the changes due to the freshwater fluxes into the ocean both from riverine outputs and precipitation. Precipitation here in the Intertropical Convergence Zone, you have outflows here to Amazon of course being the biggest driver but the Congo also has a massive influence. You have the monsoon cycle and the monsoon continues here over Indonesia and the number of other places. You have western boundary currents visible in this, you can see the Gulf Stream you can see the [Kurischio] to an extent you can see the [Angola] an extent even though it has a much stronger signature and temperature in that case.

So let’s look at the difference between the two and you can already see a lot of these features that are missed by Argo. Some of these actually are saturating this -1 to 1 kilograms per cubic meter color bar that we are showing here. You can see the Intertropical Convergence Zone you can see all the river and outflows that I've mentioned before.

As I was saying earlier there is still this seasonal bias so you have to be aware off and that is currently still present but it is something that will be removed in the final Version 5.

Shown here, then, is the total field of spiciness which I showed you in the beginning. So again let's decompose this into the thermal and haline components so this is the difference between Aquarius and Argo spiciness. It looks somewhat similar even though some of these effects only seasonal effects are somewhat compensated for, a little bit more muted. But it's still something that you should use with a little bit of caution until the final version 5.0 is released. You can see the same features that I described earlier you can see riverine outflows, so you can see the Intertropical Convergence Zone, you can see some of the Western Boundary Currents and upwelling regions and the changes that occur over time.

Now let's talk about some of the applications of surface density and spiciness. Really water mass formation and transformation could be one of the main applications of this and so far they've been very few studies. [Roberto?] Sabia has done some work, but really mostly with SMOS so far. As I mentioned earlier there is a very low thermal effect on density at high latitudes. So Aquarius (even though it has of course less sensitivity at cold temperatures than it does at warm temperatures to the salinity), it is still somewhat suitable or maybe more than somewhat suitable to do some of these studies because they are systematically undersampled using Argo. You don't really want to have Argo in a partially ice-covered ocean. It’s very tricky you can't really have it on shelves and in a lot of these regions Aquarius actually has decent data quality. So it's something that I think more people should look into.

It's clearly suited to study some mode water formation processes, such the subpolar mode water, but also probably 18 degree water or number of other intermediate water mass formation processes. So I mentioned earlier that you can also use these surface variables to constrain the ocean interior through surface processes through power integrals, relating the surface forcing to the interior dissipation. So what goes in at the surface must be dissipated in the interior of the ocean.

So in conclusion, we now have operational sea surface density and we will soon have spice in its final form of Version 5, even though it's already in the test bed if you want to try it in version 4.2.

From Aquarius there is a significant temporal and spatial improvement over the Argo measurements even though I would like to caution you that you need to take care and some of the areas that I previously mentioned namely the high latitudes off the North Pacific and the North Atlantic. Then some coastal areas where there may be some coastal contaminations, land contamination and areas that have known radio frequency interference problems. So those are some areas that you have to be a little bit cautious and applying these Aquarius data.

But other than that, there are a number of regions where these products are incredibly well-suited and they provide a whole new outlook a whole new spatial awareness of density and spiciness in the ocean. This has implications for water mass formation and transformation studies so this could be ideally suited to that if you combine it with ocean flux datasets, you can use it as a diagnostic of interior processes that was mentioning earlier.

So in the future we're currently providing the Thermodynamics Equation of State 2010 density from Aquarius. In Version 5 we will still provide that and hopefully an even cleaner version than we are providing right now, that has some of the problems that I just mentioned, addressed.

But we will also provide operational spiciness and this is currently being tested in the test bed, as I mentioned. If you're interested you should download this and have a look. Spiciness is now a part of the Thermodynamic Equation of State 2010, which is great so we can do everything consistently and have everything using the same Gibbs formula that computes these variables.

So there’s a continuity of measurements even though of course the Aquarius mission has now ended. Using SMAP and SMOS, and SMAP is already providing excellent day to right now and it will be applied to have the same density and spiciness product coming from the SMAP processing that we are currently providing you an Aquarius. I mentioned that these data are uniquely suited to these water mass transformation studies, due to the fact that alpha is very low and beta is very high in high latitudes, so really salinity is a key player here. It is also very suitable for mode border formation studies especially waters that may be a little bit warmer, 18 degree water for instance, some of these studies are very interesting.

Can we assimilate this into Ocean State estimates? I hope so. I think it would be a valuable product for that. You can do local isohaline, isothermal, isopycnal and “isospiciness” budgets, such as in Walin (1982) which used some of these processes. That's something that I'm actually working right now that's in preparation.

With that I would like to conclude and thank you very much for watching. It's been my pleasure thank you and enjoy the data!