Effect of rain-adjusted satellite sea surface salinity on ENSO Predictions from the GMAO S2S Forecast System

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ABSTRACT

The El Niño/Southern Oscillation (ENSO) phenomenon has a significant impact on climate variability throughout the world and so has been the key focus for improving coupled ocean-atmosphere forecasts. Assimilation of satellite altimetry and subsurface temperature and salinity from (mostly) Argo help to improve the initialization of the thermocline, while satellite SST aids in constraining surface heat-fluxes, leading to improved short-term forecasts of the coupled system. So far, few studies (e.g. Martin et al., 2019, Tranchant et al., 2018, Hackert et al., 2020) have focused on improving the near-surface density and mixing through assimilation of satellite sea surface salinity (SSS).

For expediency, most projects that do assimilate SSS do so as if these data were observed at the top model layer (typically centered at 5 m) instead of at the surface (i.e. top 1 cm). In rainy regions where buoyant water sits as a fresh lens at the surface, this assumption is likely invalid. Therefore, we adjust SSS so that it more accurately represents the "bulk" salinity (S_{bulk}, i.e. at 5 m). The Rain Impact Model (RIM – Santos-Garcia et. al., 2014) uses a simple diffusion model (Asher et al., 2014) to determine the near surface salinity gradient (i.e. 1 cm to 5 m). The Aquarius (V5) satellite SSS data are modified using this near-surface salinity gradient, so the salinity values are now valid at 5 m (we call this bulk Aquarius_RIM or S_{bulk}).

We assess the impact of satellite SSS observations for near-surface dynamics within ocean reanalyses and how these impacendt dynamical ENSO forecasts using the NASA GMAO Sub-seasonal to Seasonal coupled forecast system (S2S-v3, Molod et al. 2020). For all reanalysis experiments, all available along-track absolute dynamic topography and in situ observations are assimilated using the LETKF scheme (Penny et al., 2013). One reanalysis assimilates Aquarius SSS data as if it were bulk salinity at 5 m (as before) for Sep. 2011 to Jun. 2015. An additional reanalysis is performed assimilating the Aquarius_RIM data.

Validation statistics are compared for experiments that assimilate SSS (sub-optimally as before) versus the Aquarius_RIM. We also compare results of coupled forecasts that are initialized from these reanalyses for the big 2015 El Niño. We show that improved S_{bulk} estimates upgrades near-surface mixing leading to more accurate coupled air/sea interaction and better forecasts.

GEOS-S2S-3 System Characteristics

Model
- AGCM: Current GMAO NWP (including aerosol model) + two-moment cloud microphysics
- OGCM: **MOM5, ~0.25 deg, 50 levels**; **Improved Ice Sheet runoff**
- **New "atmosphere-ocean interface layer" - diurnal warm/cool layer**
- Sea Ice: CICE-4.0

Coupled Ocean Data Assimilation System
- atmosphere is "replayed" to **MERRA-2 and** "FPIT" (like MERRA-2); precipitation correction over land, **modified "replay" methodology = "Dual Ocean"**
- ODAS - LETKF (Penny et al, 2013), using **(updated)** static background error statistics
- Forecasts/Hindcasts: **initialized from "MERRA-2 Ocean" reanalysis, new perturbation/ensemble strategy**

Observations
- nudging of SST and sea ice fraction from MERRA-2 boundary conditions (i.e. OSTIA/Reynolds);
- assimilation of *in situ* T_z and S_z including Argo, XBT, CTD, tropical moorings;
- assimilation of satellite along-track ADT (Jason-3, Saral-Altika, CryoSat-2, Sentinel-3, etc.);
- **assimilation of Aquarius sea surface salinity (and now Aquarius_RIM)**

(S2S-3 improvements to Molod et al., 2020 are denoted in purple text)

Experiment Design

Ocean Reanalysis – Jan 1, 2014 – June 30, 2015
- All reanalyses assimilate all available in situ T_z, S_z
- All reanalyses assimilate all available satellite along-track ADT (Jason-2, Saral-Altika, HY-2A, and CryoSat-2)
- Assimilate Aquarius satellite information only (no SMOS nor SMAP)

AQUARIUS - Aquarius V5 SSS (~1cm)

AQUARIUS RIM - Aquarius V5 RIM-modified, i.e. SSS interpolated to salinity at 5 m using the RIM anomaly

Coupled Forecasts
- Initial states are taken from April 2015 (4/11, 4/16, 4/21, 4/26)
- 9-month forecasts are executed

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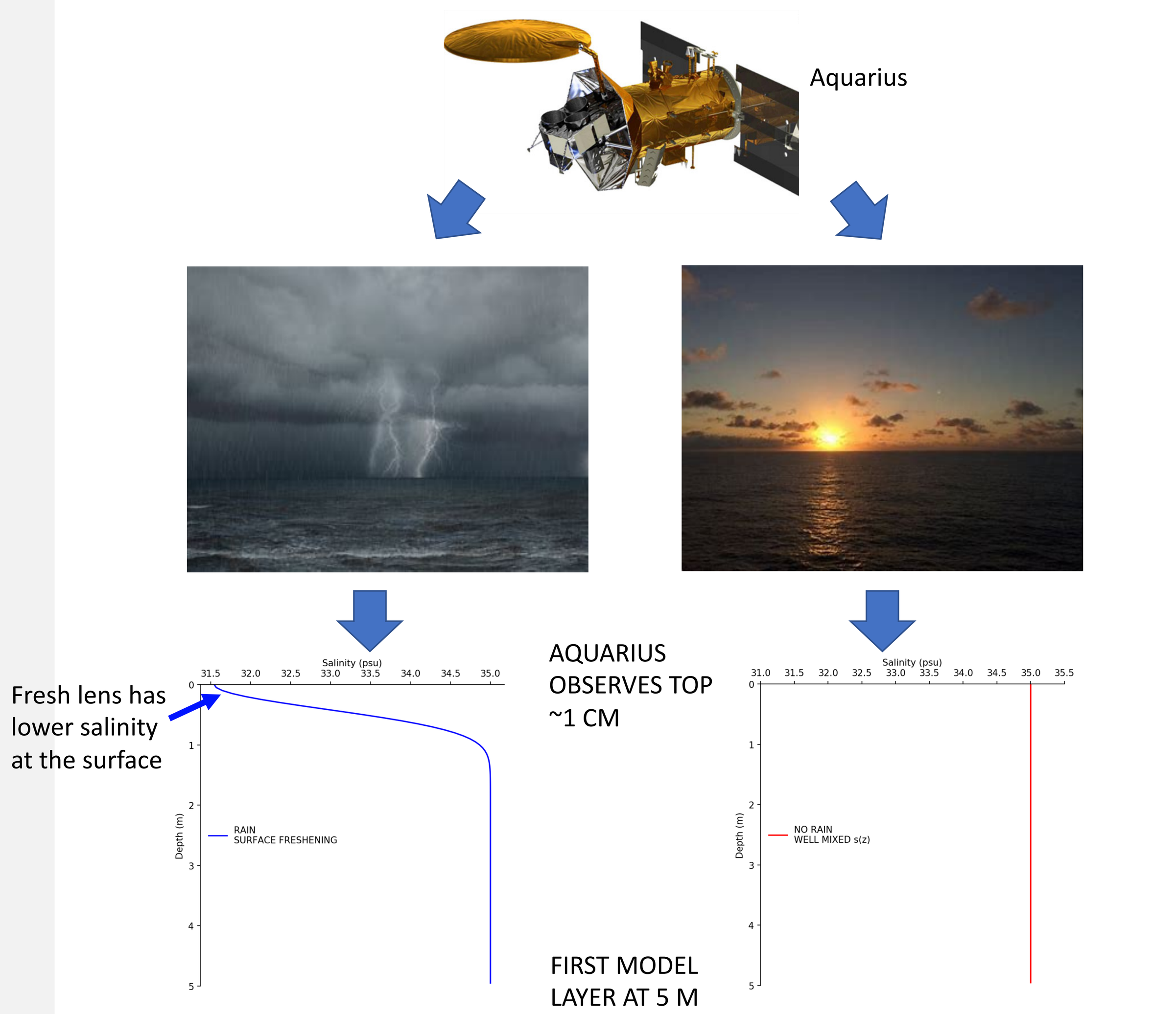
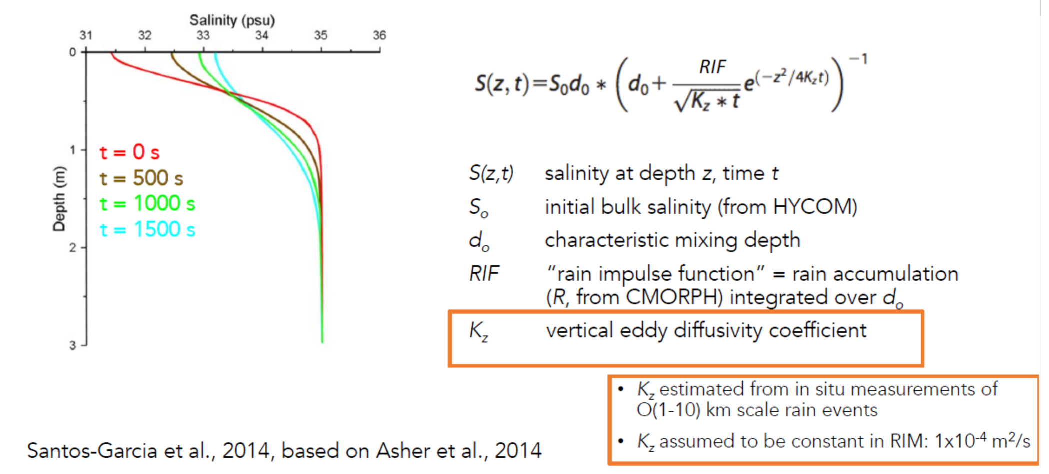
Rain Impact Model (RIM) Background



Aquarius satellite observes only the top ~1 cm of the ocean surface. Rain generates near-surface freshening leading to a strong vertical salinity gradient in the upper few meters of the ocean (schematic at bottom left). Therefore, the Rain Impact Model (RIM) was developed at the Central Florida Remote Sensing Laboratory (CFRSL) to quantify the vertical salinity gradients generated by rain.

RIM predicts near-surface freshening from satellite rain measurements using a diffusion model



$$S(z,t)=S_0 d_0 * \left(d_0+\frac{RIF}{\sqrt{K_z * t}}e^{(-z^2/4K_z t)}\right)^{-1}$$

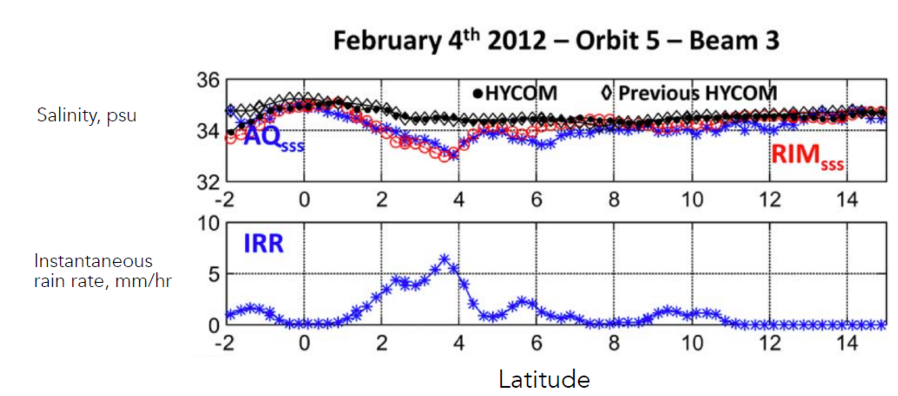
$S(z,t)$	salinity at depth z, time t
S_o	initial bulk salinity (from HYCOM)
d_o	characteristic mixing depth
RIF	"rain impulse function" = rain accumulation (R, from CMORPH) integrated over d_o
K_z	vertical eddy diffusivity coefficient

- K_z estimated from in situ measurements of O(1-10) km scale rain events
- K_z assumed to be constant in RIM: 1×10^{-4} m^2/s

Santos-Garcia et al., 2014, based on Asher et al., 2014

Given the local rain perturbation (from CMORPH – Joyce et. al., 2004) and an initial bulk salinity from first layer of HYCOM ocean model, the near surface salinity gradient can be estimated using a diffusivity model. **NOTE that RIM estimates are likely too fresh since wind mixing is ignored in this formulation.**

RIM works well in many cases
RIM predictions of SSS are included in the Aquarius V5 product

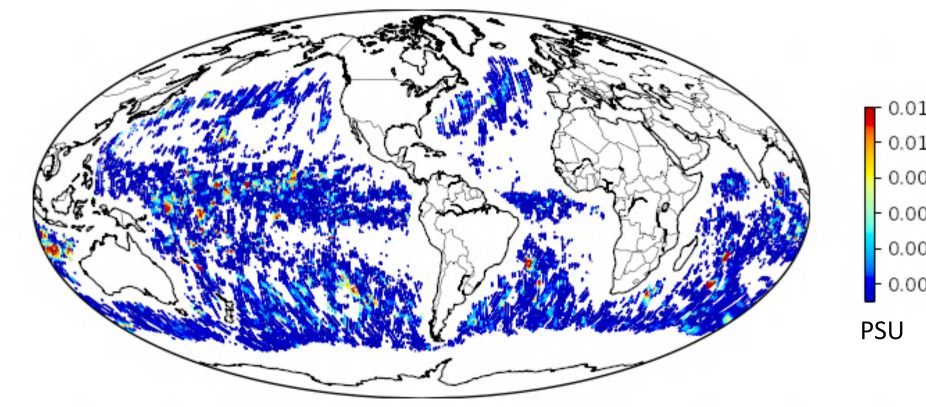


Santos-Garcia et al., 2014

Example of the RIM Model – Top panel shows sea surface salinity (SSS) from Aquarius satellite observations (blue), from the RIM-adjusted HYCOM layer 1 salinity (red), and the original HYCOM salinity from first model layer at 10 m (black). Bottom panel shows the CMORPH instantaneous rain rate (IRR). Note that the freshening due to the rain can be accurately reproduced using the RIM model (i.e. red line matches blue). *All figures from this column are reproduced from Santos-Garcia et. al., 2014.*

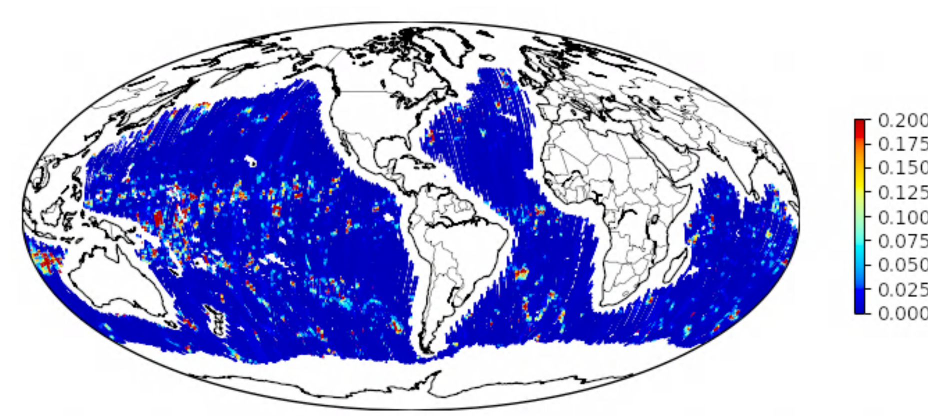
RIM Anomalies of Aquarius V5 data April 15-20, 2015

RIM SALINITY ANOM @ 10 m

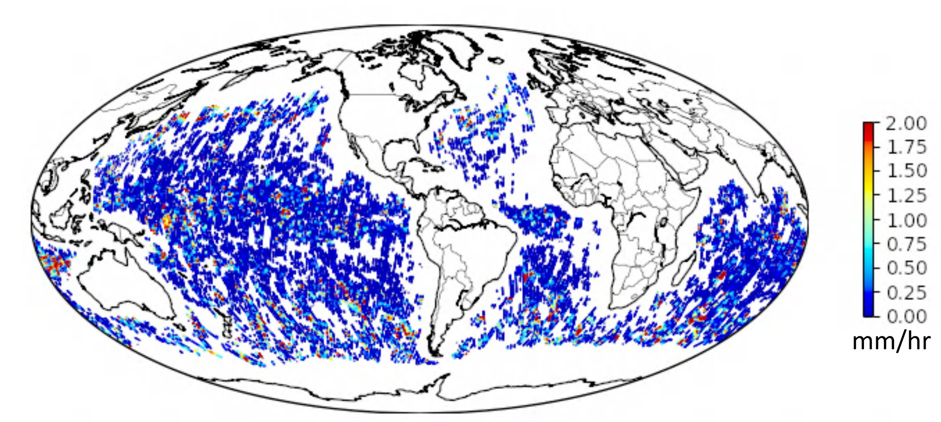


This plot shows the calculated RIM salinity anomaly for April 15-20, 2015. Positive anomalies correspond to regions where Aquarius SSS data are fresher than the 10 m model salinity (i.e. model 1st layer salinity). In other words, positive regions correlate with rainy areas. Note that although the amplitudes of the anomalies are very small, the anomalies cover much of the globe and are particularly intense in the western Pacific and the Pacific ITCZ. Rather than subtracting these values from the model first layer (as was demonstrated in the bottom panels of the column to the left), we subtract these values from the Aquarius SSS to give Aquarius_RIM bulk salinity (S_{bulk}) at 5 m.

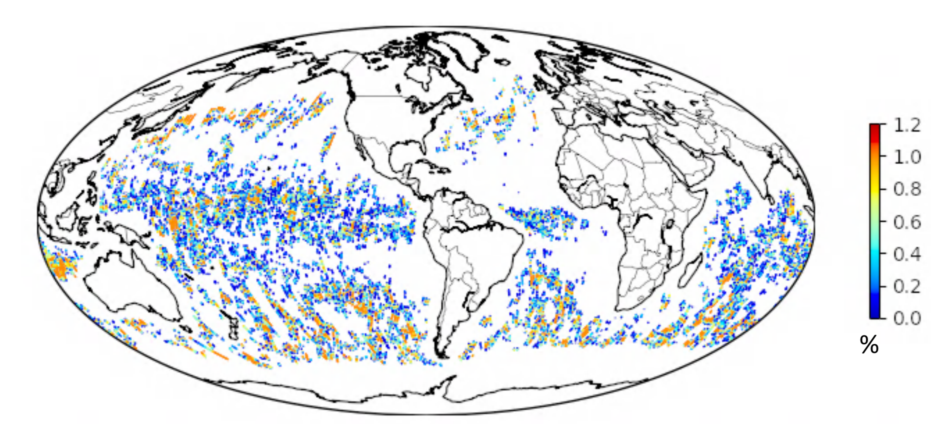
RAIN BEAM FILL FRACTION



CMORPH Instantaneous Rain Rate

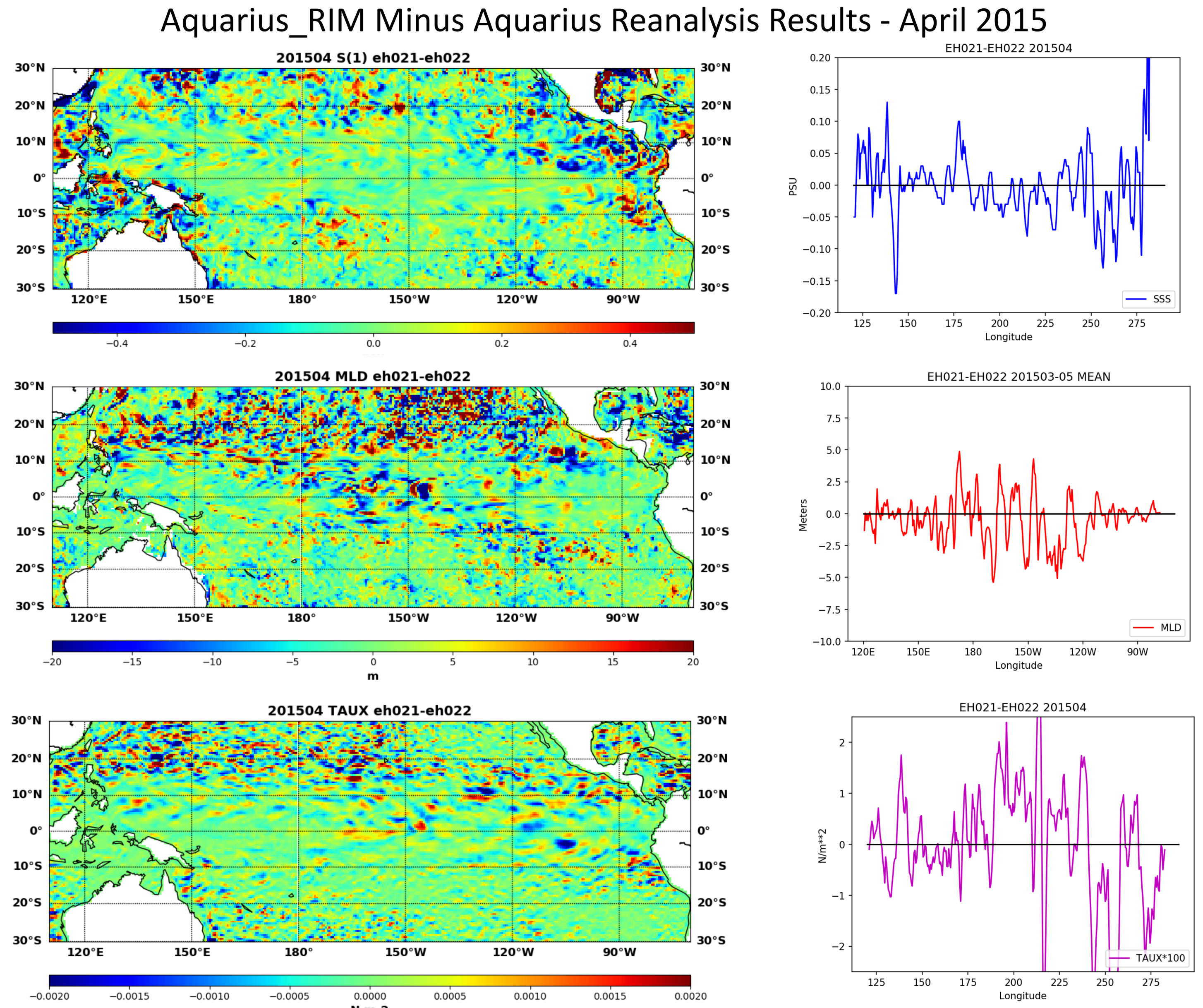


RIM PROBABILITY OF SALINITY STRATIFICATION



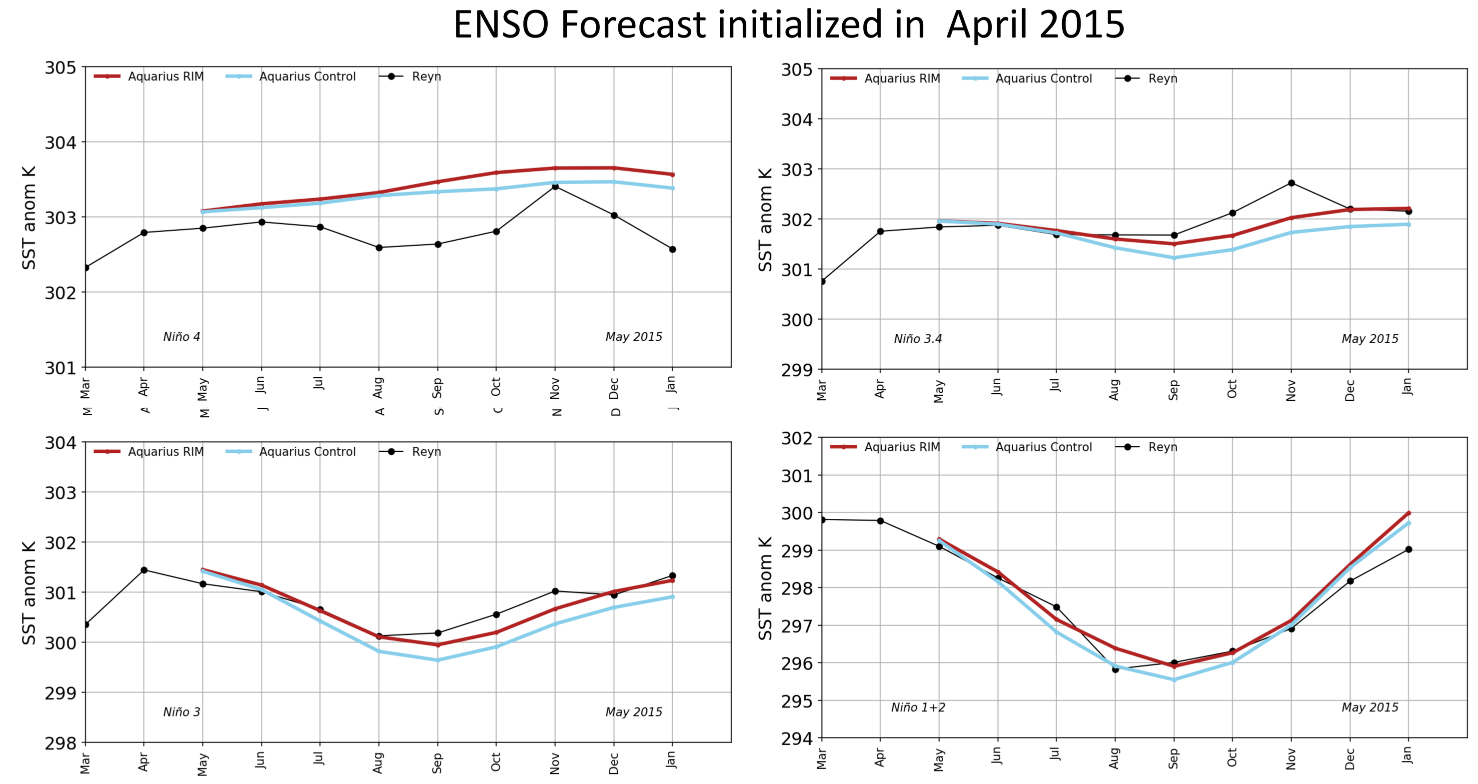
The bottom three plots above (all for April 15-20, 2015) are presented to validate the RIM salinity anomalies shown in the very top panel. Rain beam fill fraction (top) comes from the Aquarius satellite and measures the attenuation due to rain. The 2nd panel comes from the CMORPH instantaneous rain rate derived from independent satellite information (i.e. passive microwaves aboard the SSM/I, AMSU-B, AMSR-E and TMI). The bottom panel shows the RIM-estimated likelihood that there is salinity stratification due to rain and accompanying fresh lenses at the surface. Note that all three agree well particularly in the western Pacific and Pacific ITCZ. *All these variables are available as part of the Aquarius V5 release* (https://podaac.jpl.nasa.gov/aquarius/DOCUM-AQR02).)

Aquarius_RIM Minus Aquarius Reanalysis Results - April 2015



Left figures shows the equatorial Pacific results for April 2015 for the reanalysis differences between the assimilation using RIM adjusted Aquarius SSS (eh021) minus conventional Aquarius assimilation (eh022). Right figures show +/- 5° zonal means of the corresponding equatorial Pacific plot. Increasing bulk salinity (S_{bulk} – top) leads to increased MLD (middle). Shallower mixed layer depth leads to more efficient air-sea coupling and westerly TAUX anomaly (bottom) especially over the central Pacific. Shallowed MLD and increased westerly anomaly TAUX should lead to amplification of the downwelling associated with the 2015 El Niño.

ENSO Forecast initialized in April 2015



Coupled forecasts are initialized from different April 2015 start dates using the Aquarius_RIM (red) and Aquarius (blue) reanalyses (differences of these reanalyses are shown above). Accounting for the surface rain freshening using RIM adjusted SSS assimilation improved the ENSO forecasts for all but the far western Pacific forecasts (i.e. NINO4 region) . Forecasts initialized from March 2015 and May 2015 show qualitatively similar results. Click on Figure to see all ensembles.

Results

1) **The diffusive Rain Impact Model (RIM of Santos-Garcia et. al., 2014) can be used to accurately estimate the salinity gradient between ~1cm SSS (where Aquarius observations are valid) to bulk salinity at 5 m (where the model first layer assimilates the salinity).**
2) **Separate reanalyses were performed assimilating Aquarius RIM (S_{bulk} at 5m) and the original Aquarius (SSS). Increased salinity anomalies in the top model layer leads to shallower MLD and increased TAUX in the central Pacific.**
3) **More efficient air-sea coupling of the shallower MLD and westerly TAUX anomalies lead to an amplification of the downwelling Kelvin wave associated with the 2015 El Niño and more accurate forecasts of the NINO 3.4, NINO3 and NINO1+2 regions.**

National Aeronautics and Space Administration