Met Office

Assimilating satellite SSS data from SMOS, Aquarius and SMAP into the FOAM global ocean forecasting system

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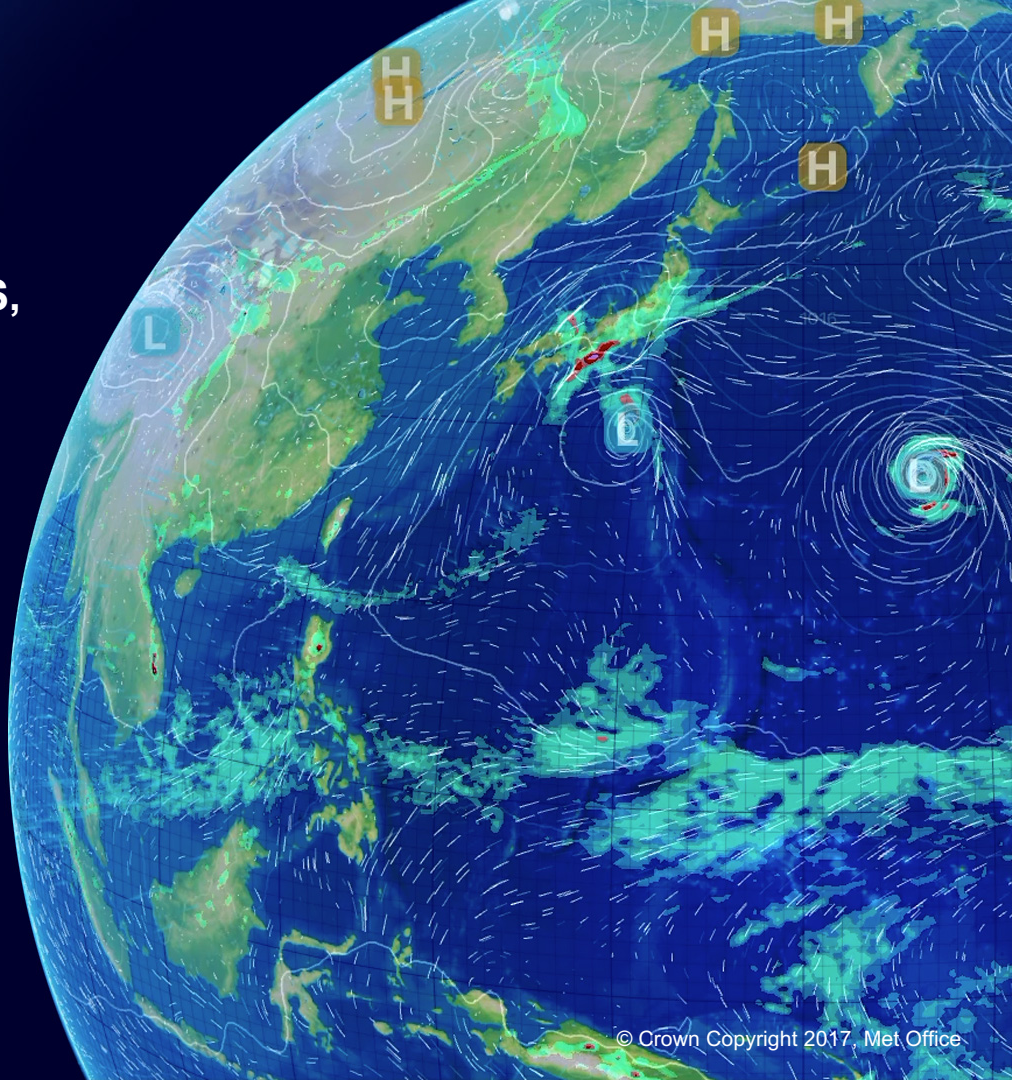
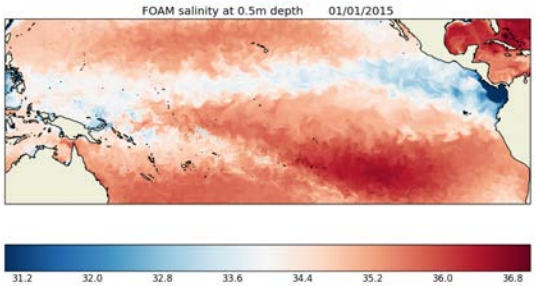


smos+ niño15
support to science element

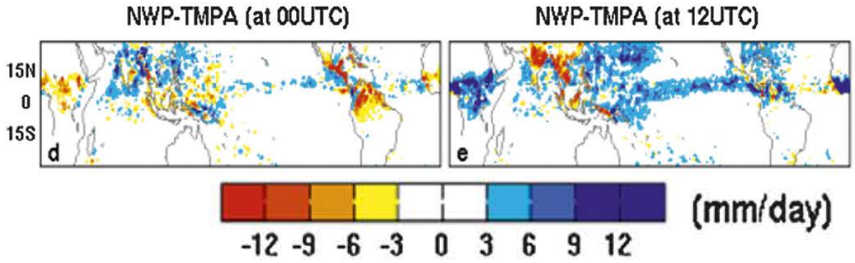
Contents

Ocean forecasting system overview

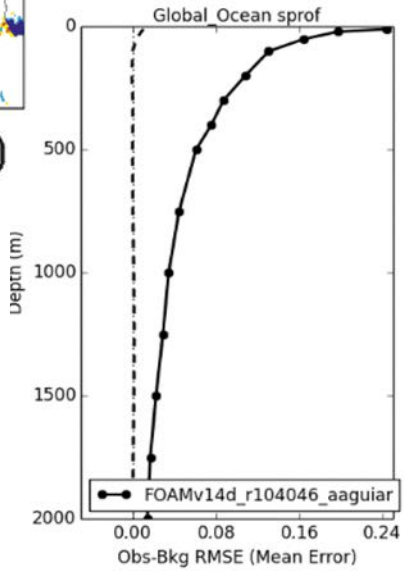
The UK Met Office ocean forecasting system is called FOAM (Forecasting Ocean Assimilation Model). It runs operationally once per day and produces analyses and 6-day forecasts of the 3D ocean and sea-ice. Outputs are distributed to various users including the UK Royal Navy, CMEMS, commercial customers. The global ocean/sea-ice analysis is also used to initialise coupled seasonal forecasts (GloSea), as well as a prototype coupled NWP system.



FOAM daily mean SSS during 01/2015



Liu et al. 2014. Biases comparing Met Office NWP precip. to satellite data.



Why assimilate satellite SSS data?

- Argo salinity data are sparse compared to the structures we're interested in.
- There are large errors in the precipitation and river inputs, e.g. too strong precip. in ITCZ.
- Large errors in near-surface salinity in FOAM. Large freshwater imbalances in the model can affect other variables, e.g. SSH drifts, density gradients affecting circulation.

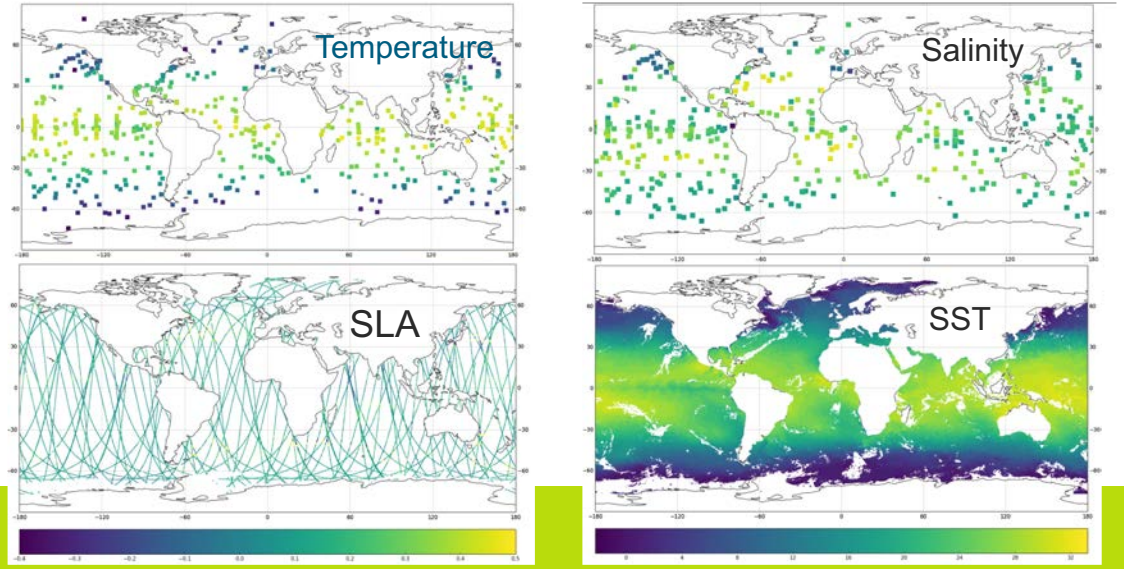
Model and data assimilation overview

- ***Model***:
  - **NEMO** 3.6 with **1/4° horizontal resolution** (Storkey et al., 2018), coupled to the CICE sea-ice model (Ridley et al., 2017).
  - 75 vertical levels with **~1m vertical resolution in the top 10m**.
  - Non-linear free surface, TKE vertical mixing.
  - Removed SSS surface climatological relaxation (which is used operationally).

- Forced with Met Office NWP fluxes (3 hourly heat/freshwater, 1 hourly momentum), with monthly climatological river inputs.

- ***Data assimilation*** (Waters et al., 2015) :
  - 3DVar-FGAT (first-guess-at-appropriate-time) method with a **1-day time window** using NEMOVAR.
  - Assimilates T/S profiles, along-track altimeter, L2/L3 satellite and in situ SST data, sea-ice concentration data.
  - Bias correction schemes to deal with satellite SST biases, and biases in the mean dynamic topography.

1-day of observations (6/1/2018)



Satellite SSS observations

We want to assimilate observations with at least **daily frequency**. Assimilating lower level observations in principle should reduce some of the complications in their error characteristics (even if the errors themselves are larger).

SMOS:

- Daily, 25km L3 Debias v2 from LOCEAN (www.catds.fr) with separate ascending/descending data (Boutin et al. 2018).
- Large differences with the model towards the edges of the swath so we **remove any obs >300km from the swath centre**.

Aquarius:

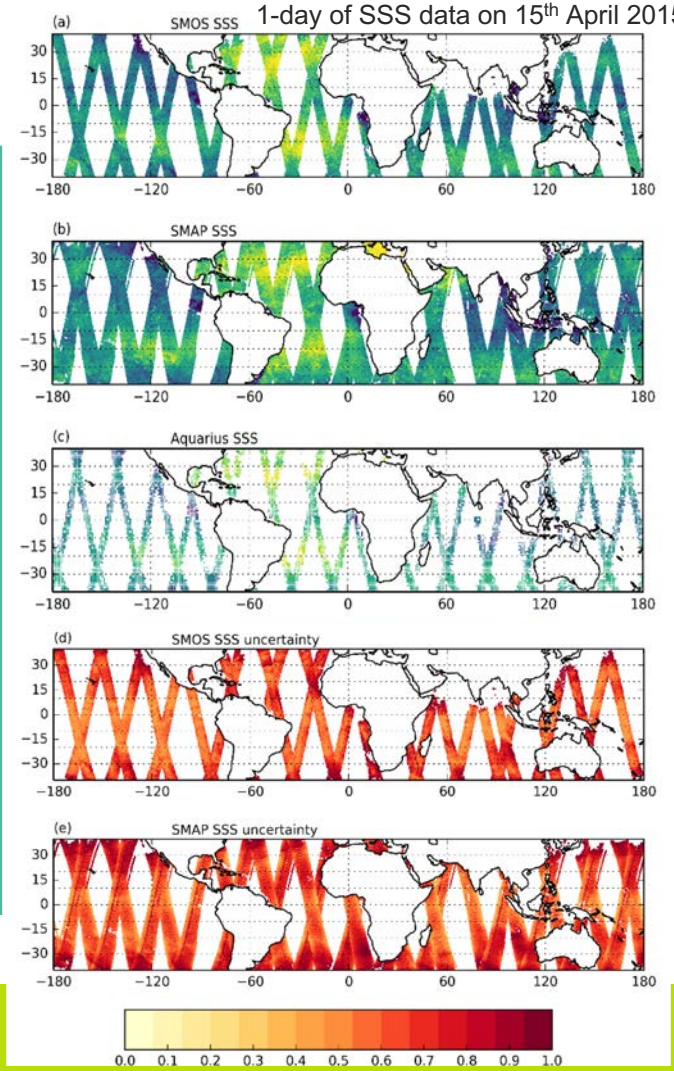
- Daily, 1° L3 from JPL (www.podaac.jpl.nasa.gov) with separate ascending/descending data. V4.0.
- No uncertainty information in the daily files.

SMAP:

- Daily, 25km L2B V4.0 from JPL (www.podaac.jpl.nasa.gov).

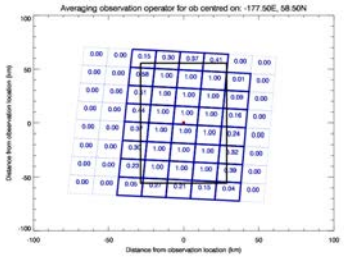
- Only assimilate the satellite SSS data ***equatorward of 40° N/S.***
- For SMOS and SMAP, any obs with **uncertainty > 1pss were discarded**
- All data underwent an **additional QC** against the 1-day model forecast.

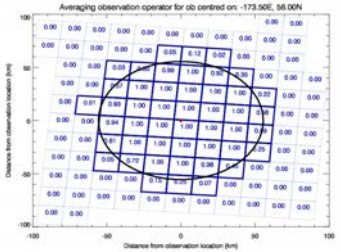
1-day of SSS data on 15th April 2015



SSS data assimilation

Observation operator: SMOS, Aquarius and SMAP represent the SSS over a large area compared to the model grid so we average the model values over the footprint of the observation.





Background (forecast) error covariances for SSS:

- The background errors for near-surface salinity vary spatially and seasonally and are **about 0.25 pss in the trop. Pacific**.
- Horizontal error correlations have length-scales with two components (Rossby radius + 400km).
- **Vertical length-scales** at the surface **vary based on the mixed layer depth** in the background field.

Observation error covariances for satellite SSS data are assumed spatially uncorrelated.

- We use the error variances that come with the input files and add extra 1.0 pss to account for:
  - Vertical representation: satellites measure the skin SSS, model is at 0.5m depth, Argo is at ~5m depth.
  - Errors unaccounted for in the estimates provided by the data producers.
  - To avoid over-fitting the observations which have unaccounted-for spatial error correlations.
- We **artificially increase the errors towards the coast** to avoid issues with land contamination and RFI which have complicated error characteristics.

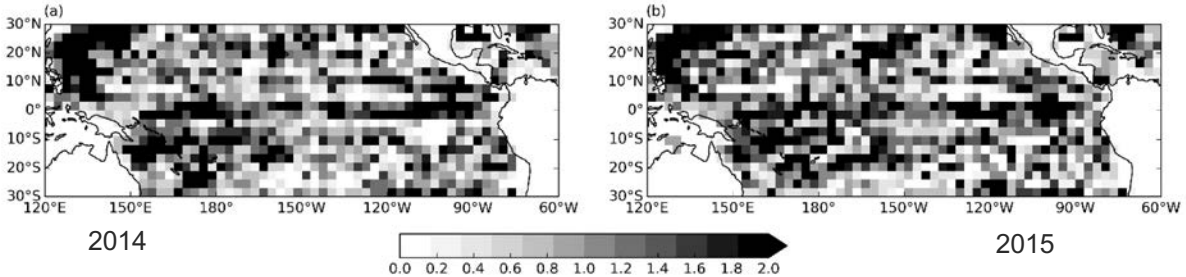
Observation bias correction

Two new terms have been added to the standard 3DVar cost function to estimate a **per-satellite bias** correction:

1. The satellite observation-minus-forecast (innovation) values contribute to an estimate of the bias.
2. “observations-of-bias” are used to constrain the bias estimates. These are differences between reference data (near-surface Argo salinity < 10m depth) and the satellite SSS data, collocated spatially (50km) and temporally (24 hours). Obs used in these match-ups are not assimilated directly.

The observation bias estimates are **updated each day as part of the data assimilation**, but are designed to vary smoothly in time and space.

- Where **Argo data are sparse**, the bias estimate will be **dominated by satellite-model differences**.
- Where we have **Argo data** we will be able to **adjust model biases**, and that information will be spread to nearby satellite observations through horizontal correlations (of 3 degrees) in the bias estimates.
- Average differences between the surface and Argo depth will be included in the bias and removed from the satellite observations.



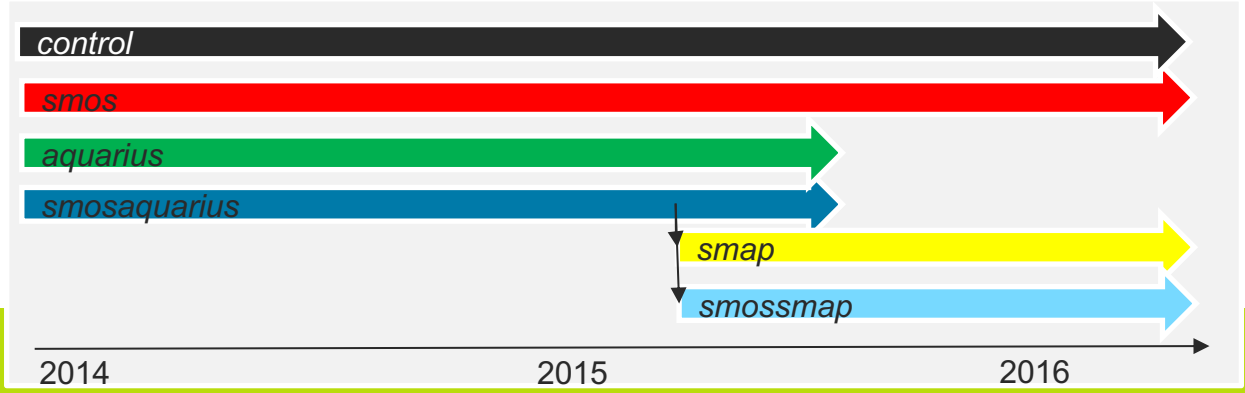
Average number of Argo salinity profiles per 10 days with a value shallower than 10 m depth in 3°x3° bins in the tropical Pacific

Experiment set-up

- These experiments were coordinated with CLS/Mercator as part of the ESA SMOS-NINO15 project.
- See presentation by Tranchant, and poster by Remy.

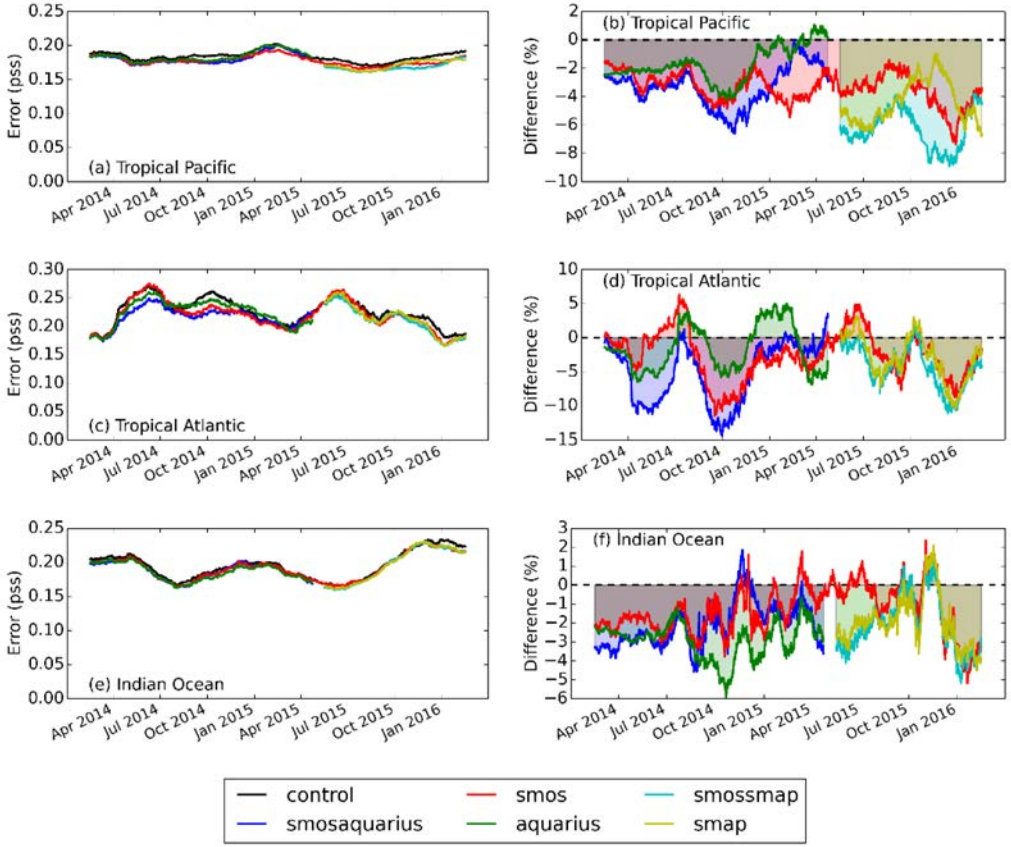
- Aim: assess impact of SSS data in tropics during 2015/16 El Niño in the context of the standard observing systems (i.e. what extra does satellite SSS data bring).
- Initial conditions on 1st January 2014 from a long assimilative run (with no satellite SSS assimilation).
- Control: assimilate standard set of observations, e.g. standard FOAMv14 (except for SSS relaxation and no TAO salinity data).
- Then a series of experiments which are the same as the control except they also assimilate the satellite SSS data.

Experiment name	Data assimilated	Time period
control	Standard data (SST,SLA,SIC,T/S profiles)	1st January 2014 – 31st March 2016
smos	Standard data and SMOS	1st January 2014 – 31st March 2016
aquarius	Standard data and Aquarius	1st January 2014 – 7th June 2015
smap	Standard data and SMAP	2nd April 2015 – 31st March 2016
smosaquarius	Standard data, SMOS and Aquarius	1st January 2014 – 7th June 2015
smossmap	Standard data, SMOS and SMAP	2nd April 2015 – 31st March 2016

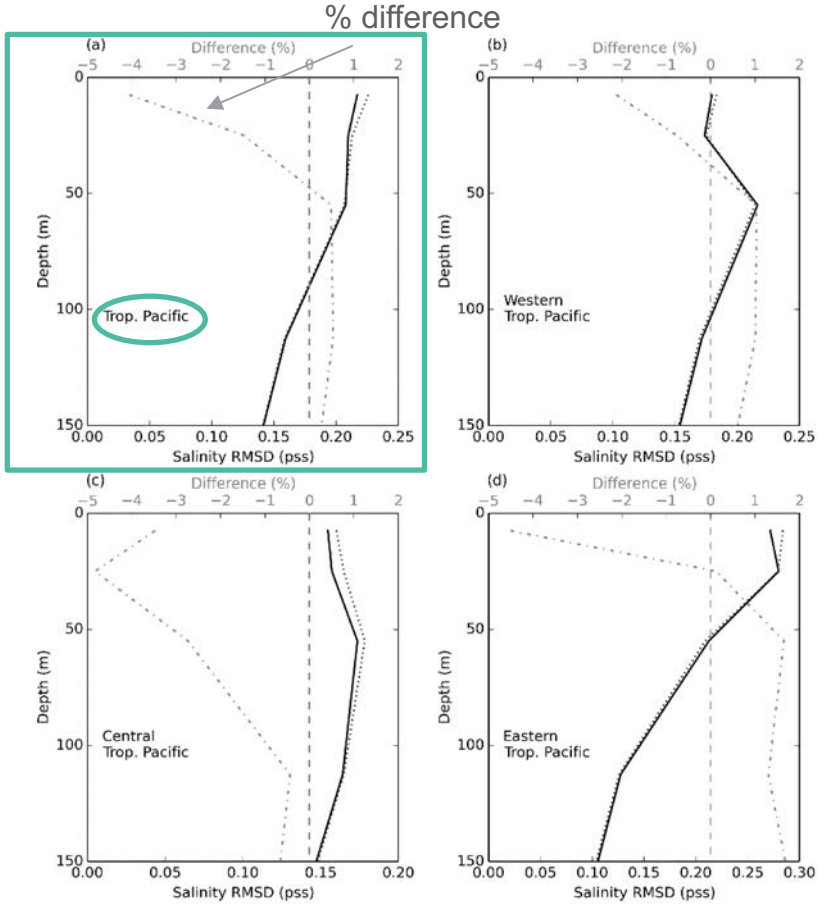


Results – RMS errors compared to near-surface Argo

- Comparing the model's **1-day forecast salinity** compared to near-surface (<10m depth) Argo data (before they are assimilated). RMSD with 90-day smoothing applied.
- Consistent **small positive impact** (reduced RMS errors) on near-surface salinity from all satellites in most tropical regions.
- In **tropical Pacific, combination of satellites** (blue and cyan) are **better than individual ones** (red, green, yellow)
- Improvements in tropical Atlantic are variable – due to seasonality of Amazon river?
- Smaller impact in Indian Ocean.



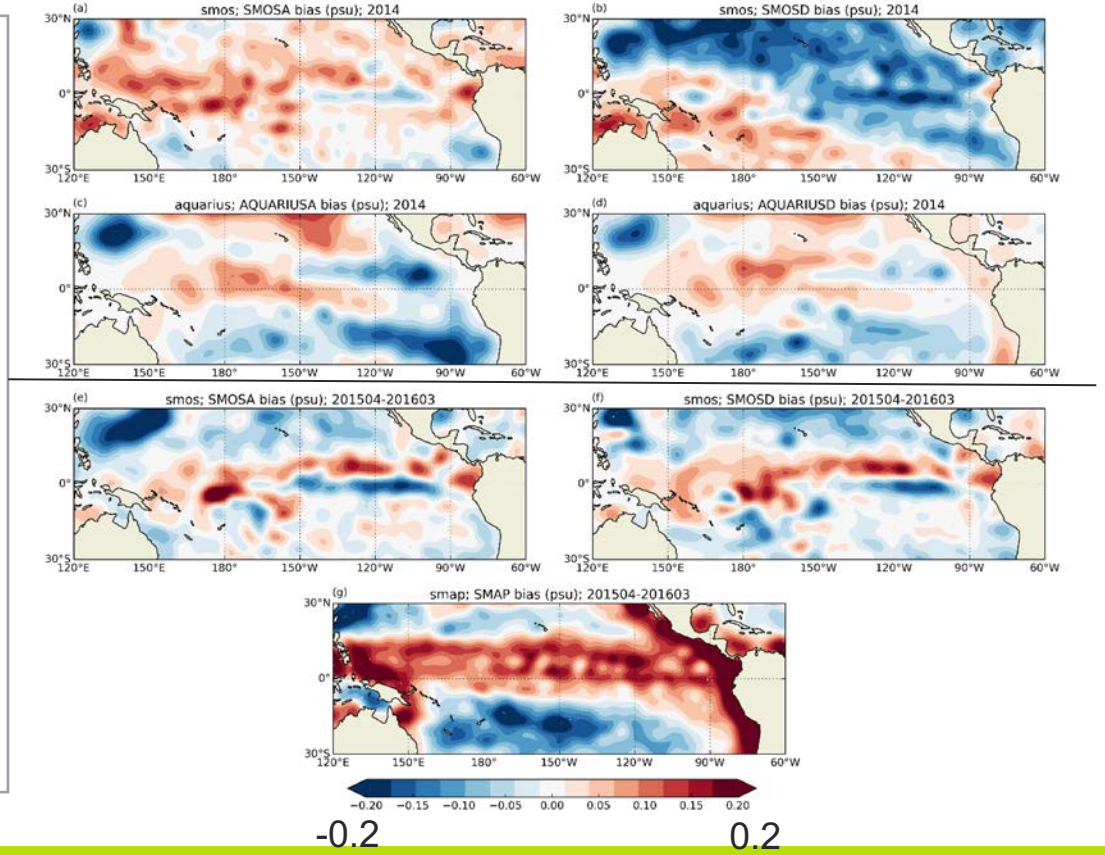
Comparisons to Argo S as a function of depth



- Focus on the ***smos* experiment** since it was run for the entire period (Jan 2014 -> March 2016).
- Impact on RMSD compared to Argo salinity in *smos* experiment as a function of depth in tropical Pacific. Averaged over the entire experiment.
- In Tropical Pacific as a whole, the reduction in RMSD at the surface **propagates down to about 50 m depth**. Below that there is a small increase in RMSD from assimilating SMOS.
- In the **central region**, there is a **reduction** in error **at all depths**.
- **Degradation at depth** occurs in the **Western** and **Eastern** parts of the Trop. Pacific. Could be due to changes in the **vertical correlation of the salinity errors** due to barrier layers and/or upwelling.

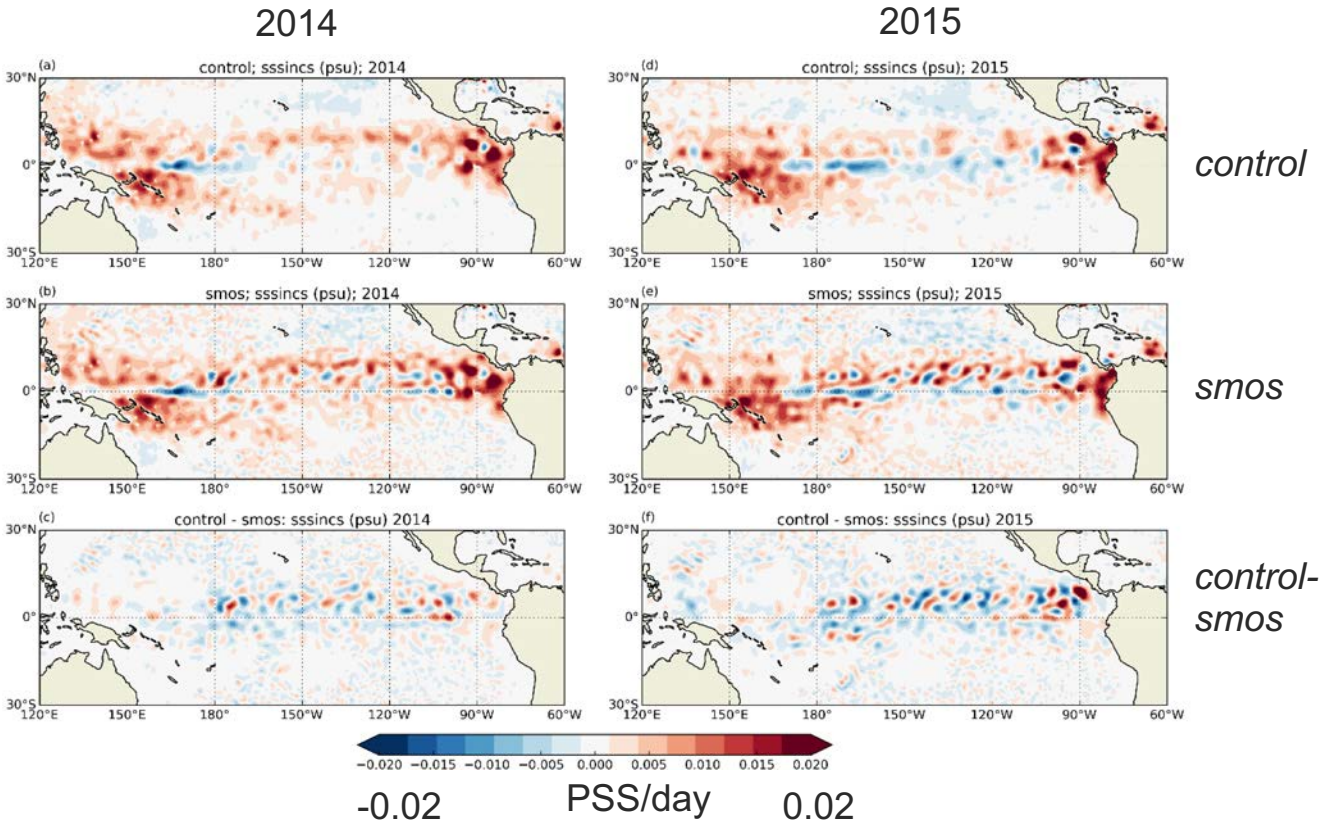
Results – observation bias estimates

- **Annual mean bias estimates** for the different satellites.
- **RFI** signal in **north-west of domain** in all products.
- Solar activity affecting the SMOS descending data in 2014 (top right).
- Aquarius has similar ascending/descending biases.
- **SMOS biases in Apr 2015- Mar 16 show large positive bias in ITCZ** and maritime continent which might be reflecting precip biases (positive bias implies that the SMOS data are more saline compared with the reference data and the model). Perhaps some **real signal is being lost to the bias correction**.
- **SMAP is L2 data-set** so no pre-processing to correct for the largest biases. On-line bias correction seems to allow us to **still extract useful information from SMAP** (see Argo RMSD impact).

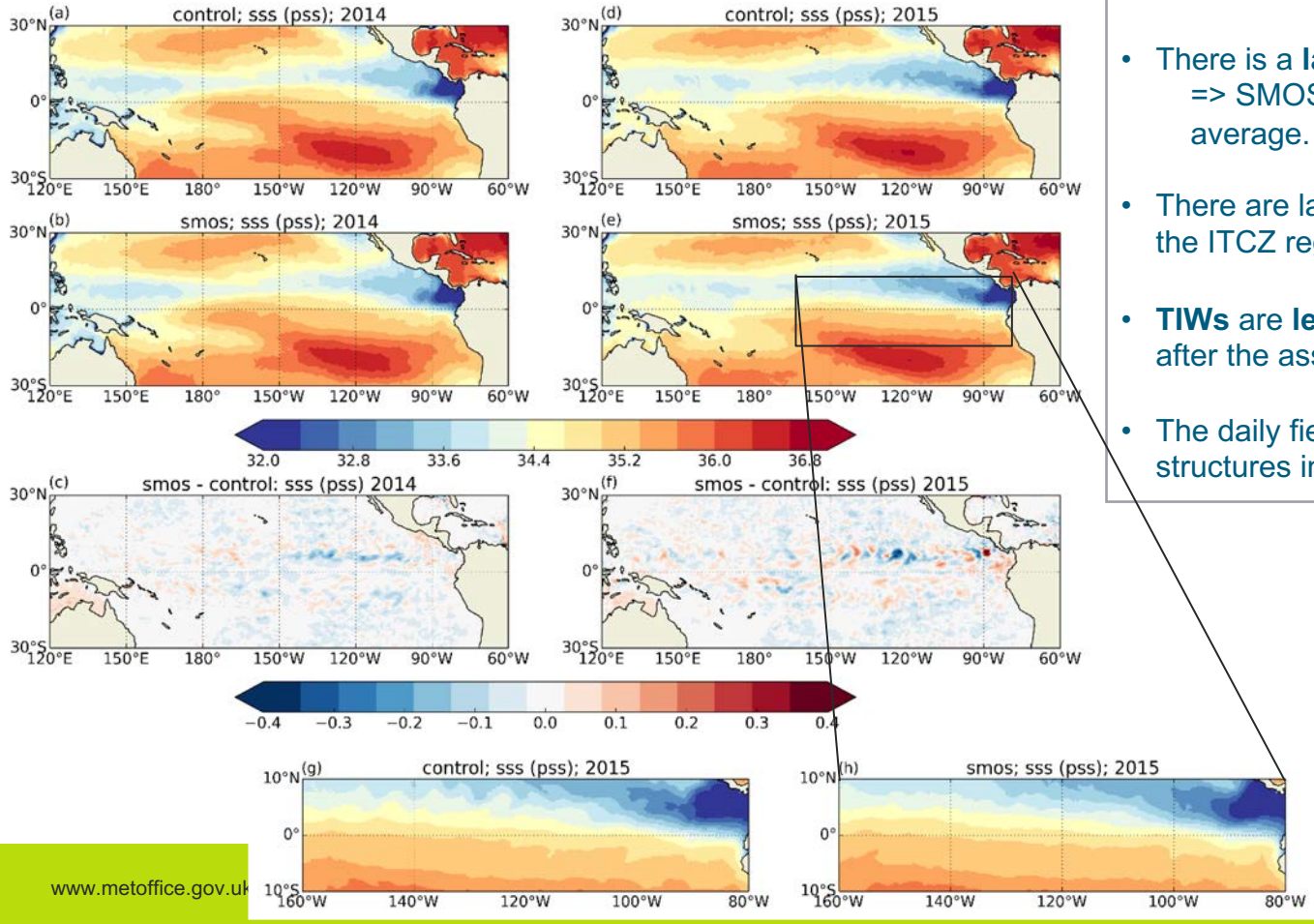


Results – data assimilation increments

- Annual mean SSS increments (changes that the data assimilation makes to bring the model into line with the observations, after removal of observation biases).
- **Similar patterns** with and without SMOS data in most regions.
- **Additional structures** put in by SMOS assimilation particularly in the region between **0-10°N, east of the date-line**.

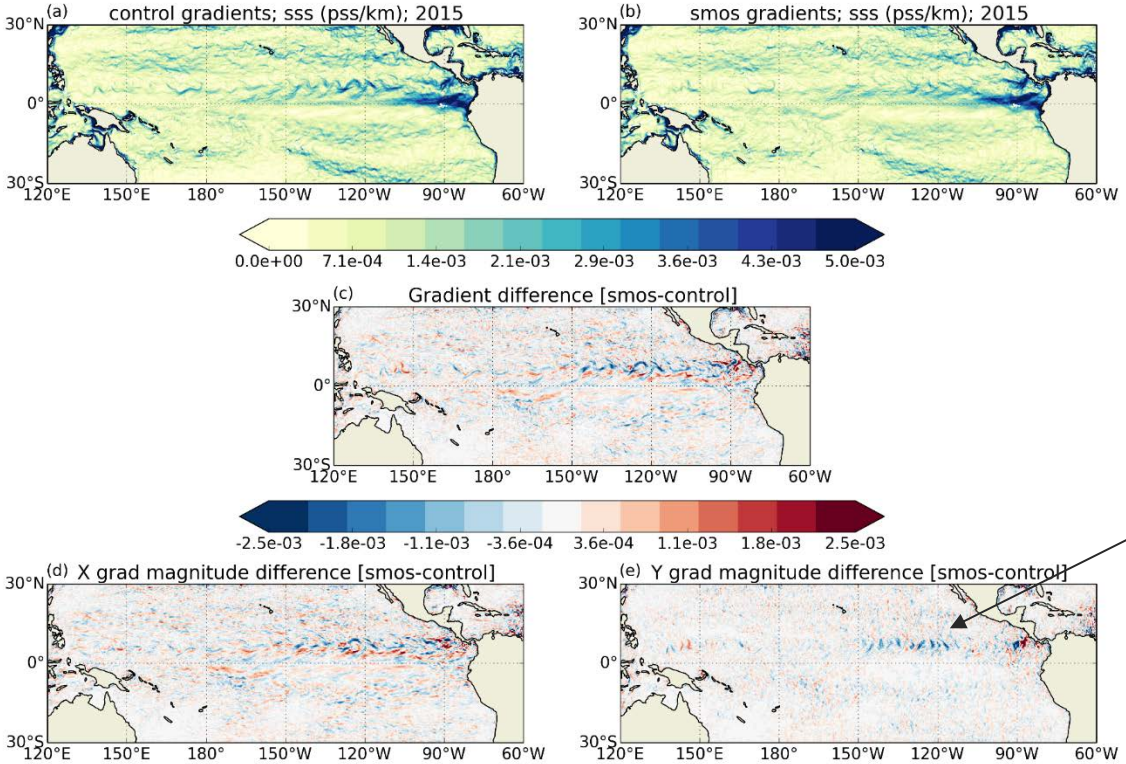


Results – SSS fields



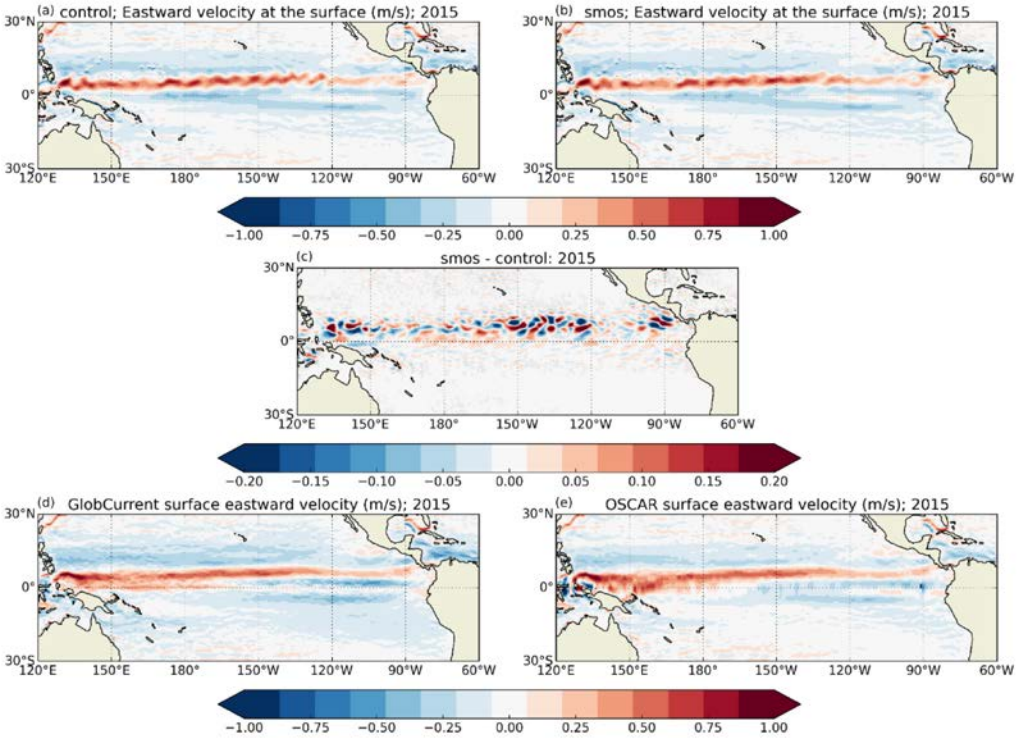
- Annual mean SSS fields are quite similar overall in the *control* and *smos* experiments.
- There is a **large-scale small -ve difference**.
  => SMOS data are reducing the SSS on average.
- There are larger local changes, particularly in the ITCZ region east of 150°W.
- **TIWs** are **less prominent** in the **annual mean** after the assimilation of SMOS.
- The daily fields do still show small-scale structures including the TIWs.

Results – horizontal SSS gradients



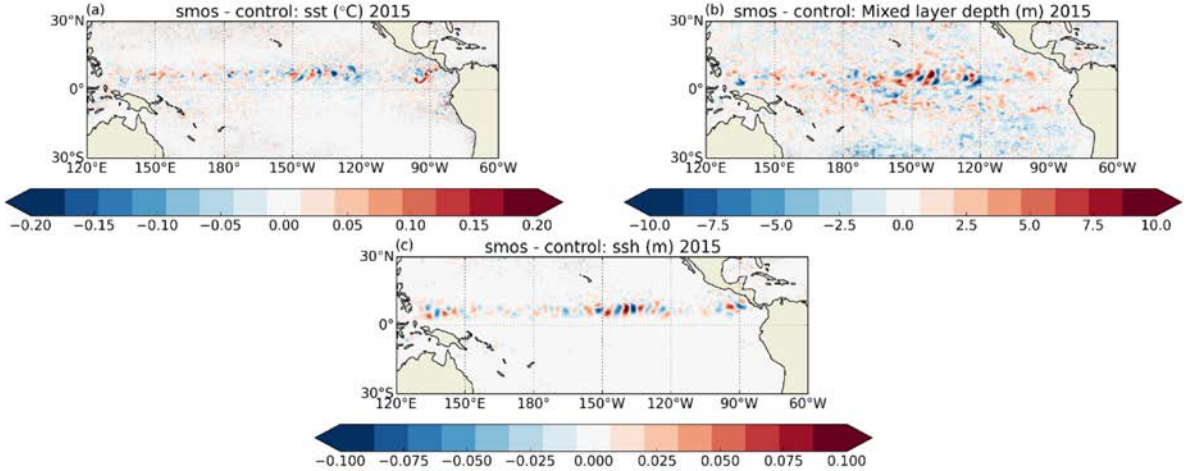
- Annual mean (2015) horizontal SSS gradients.
- **SMOS data is reducing these gradients** in the TIW region and smoothing out the features in the annual mean.
- **Particularly** obvious in the **N/S gradients** (blue means the SMOS data are reducing the gradient magnitude).

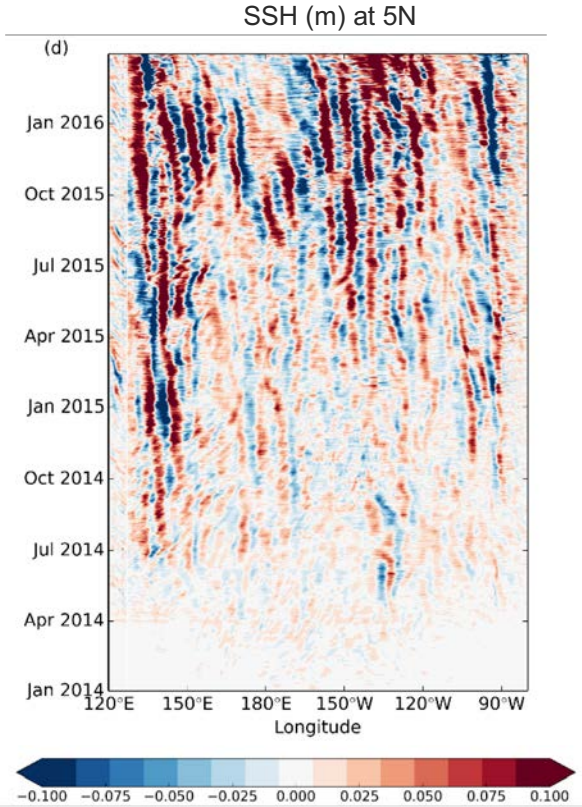
Results – impact on zonal currents



- Annual mean (2015) zonal currents.
- Compared to the GlobCurrent and OSCAR surface current products, the *smos* experiment has more realistic surface currents in the annual mean.

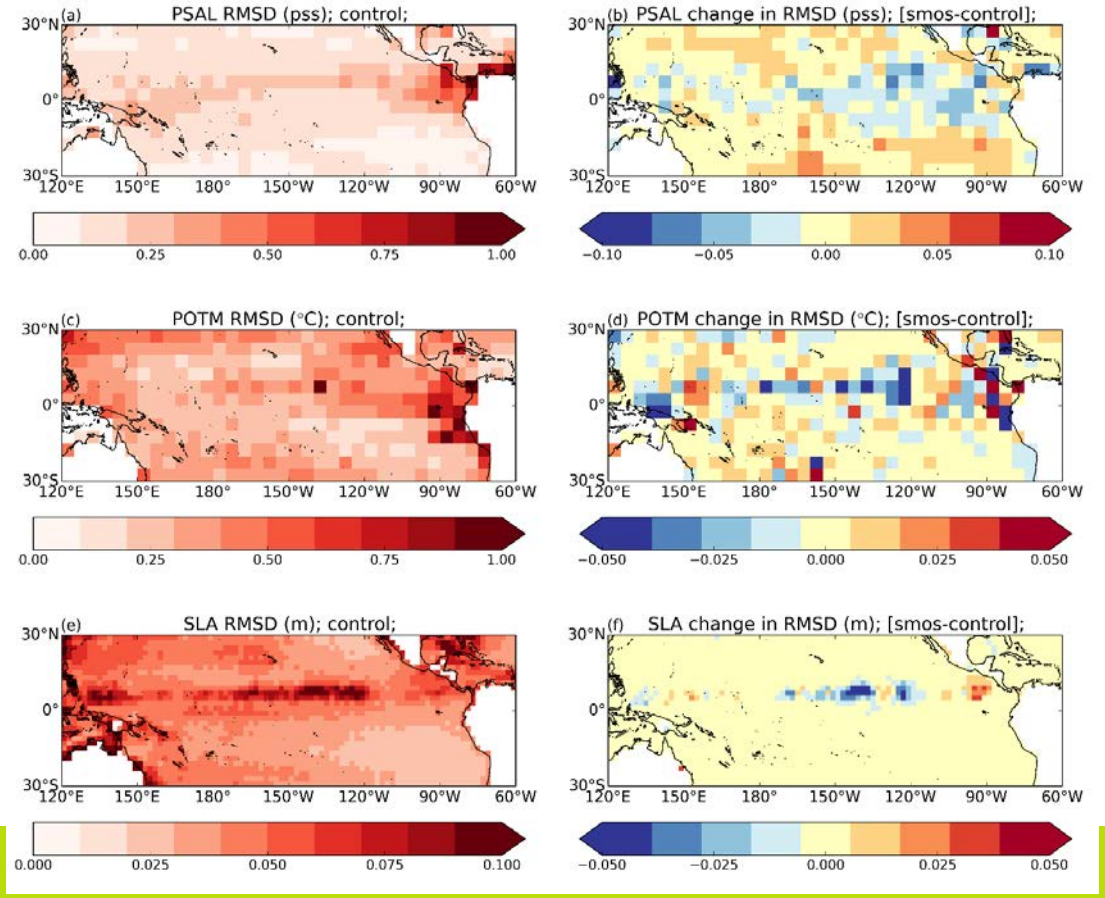
Results – impact on SST, MLD, SSH





- Annual mean (2015) differences [smos-control] in SST, MLD and SSH.
- Largest **changes in SST in the ITCZ region** where there are likely to be many fewer infra-red SST obs.
- **MLD** is **reduced a small amount** over large areas: ties in with the reduced SSS implying **increased surface stratification**.
- **SSH** changed mainly **at 5-10N with large local differences of up to 10cm** in the annual mean.
- Hovmuller at 5N shows that these SSH differences grow throughout the experiment.

Results – spatial pattern of RMSD for SSS, SST, SLA



- For entire experiment: Jan 2014 – Mar 2016.
- Plots show the RMS differences of the model forecast to Argo near-surface salinity and temperature, and to altimeter SLA.
- The difference between *smos* and *control* experiments RMSD are also shown (-ve implies that the errors are smaller in the *smos* experiment).
- The SMOS assimilation is improving the SSS, SST and SSH in the central Pacific region.
- There is a degradation in SLA in the eastern Pacific.

Summary and conclusions

- Assimilation of daily L2/L3 satellite SSS from SMOS, Aquarius and SMAP implemented and assessed during the 2015/16 El Niño.

- There were small reductions in SSS RMSE compared to near-surface Argo by assimilating satellite SSS data.
  - The largest reductions of 8% RMSE were from the SMOS-SMAP combined assimilation.
  - The SSS data assimilation also led to improvements in SST and SSH in the central equatorial Pacific.

- Issues for operational implementation:
  - Understand issues with the vertical propagation of information.
  - Further investigations into results in the Atlantic and Indian Ocean.
  - Further tuning of the various error covariance parameters.
  - Understand if there is likely to be significant impact on seasonal forecasting calibration. Long time-series needed for ocean reanalysis.

- Continuity of satellite SSS would help the case for operational implementation (e.g. CIMR mission).

- In situ reference data for SSS are sparse – more in situ data would greatly improve the bias correction and impact of the satellite data.

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Thank you for listening

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Extra slides

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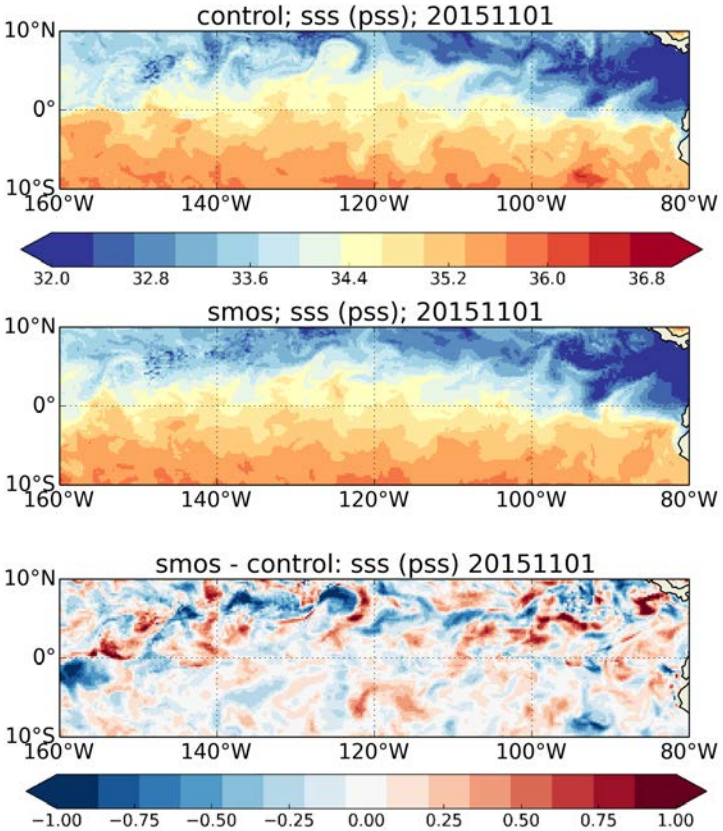
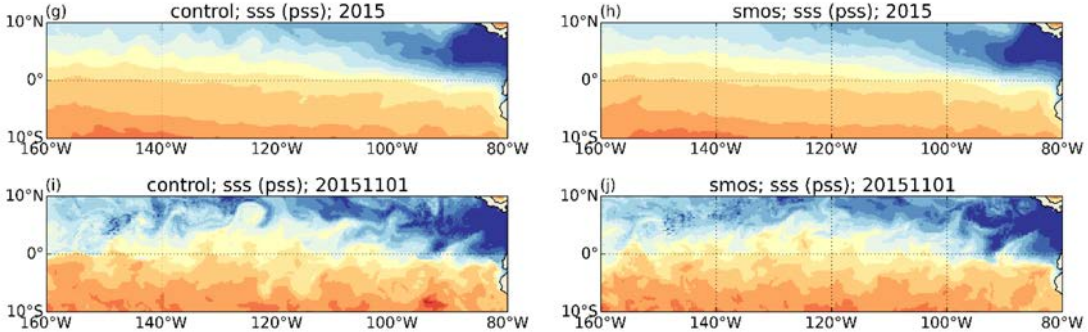




- Zoom in the TIW region in 2015.
- Annual mean SSS fields don't show up the TIWs after the assimilation of SMOS.
- The daily fields do still show small-scale structures including the TIWs.
- The removal of the meandering features of the TIWs in the annual mean – is this more realistic or less?

Data assimilation of SSS data
Observation bias correction

- Two new terms have been added to the standard 3DVar cost function (initially developed for SST bias correction).

$$J(\delta \boldsymbol{x}, \delta \boldsymbol{b}) = \frac{1}{2}\delta \boldsymbol{x}^T \boldsymbol{B}_x^{-1}\delta \boldsymbol{x} + \frac{1}{2}(\boldsymbol{H}_x(\delta \boldsymbol{x} + \delta \boldsymbol{b}) - \boldsymbol{d})^T \boldsymbol{R}_x^{-1}(\boldsymbol{H}_x(\delta \boldsymbol{x} + \delta \boldsymbol{b}) - \boldsymbol{d}) + \frac{1}{2}\delta \boldsymbol{b}^T \boldsymbol{B}_b^{-1}\delta \boldsymbol{b} + \frac{1}{2}(\boldsymbol{H}_b \delta \boldsymbol{b} - \boldsymbol{l})^T \boldsymbol{R}_b^{-1}(\boldsymbol{H}_b \delta \boldsymbol{b} - \boldsymbol{l})$$

- NEMOVAR minimised this cost function with respect to:
  - δx - the increments to the ocean state (T, S, SSH, u, v, SIC).
  - δb - the increments to the observation bias (SST, SSS, SSH). Separate estimates for each satellite.

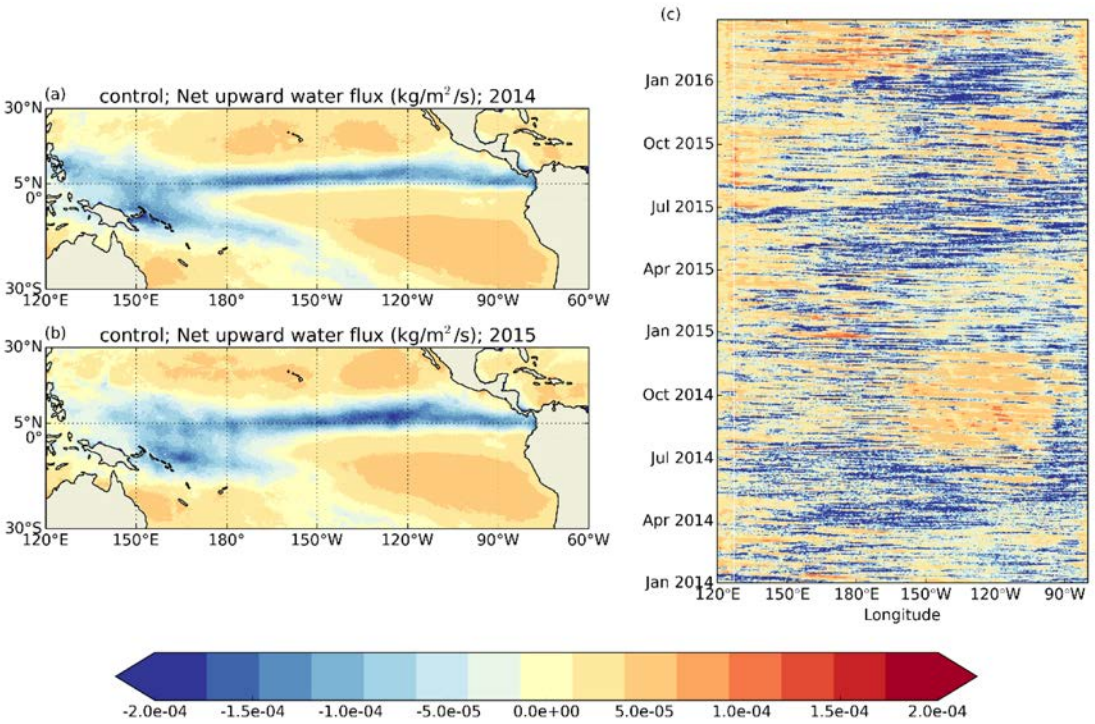
1. The standard obs-minus-forecast (innovation) values $\boldsymbol{d} = \boldsymbol{y} - \boldsymbol{h}(\boldsymbol{x}^f)$ contribute to an estimate of the bias, and changes to the background bias value are limited by the bias background error covariance $\boldsymbol{B_b}$.

2. "observations-of-bias", $\boldsymbol{l}$, are used to constrain the bias estimates. These are differences between reference data (near-surface Argo salinity < 10m depth) and the satellite SSS data, collocated spatially (50km) and temporally (24 hours). Obs used in these match-ups are not assimilated directly.

- The obs bias estimates are updated each day as part of the data assimilation, but are designed to vary smoothly in time and space.

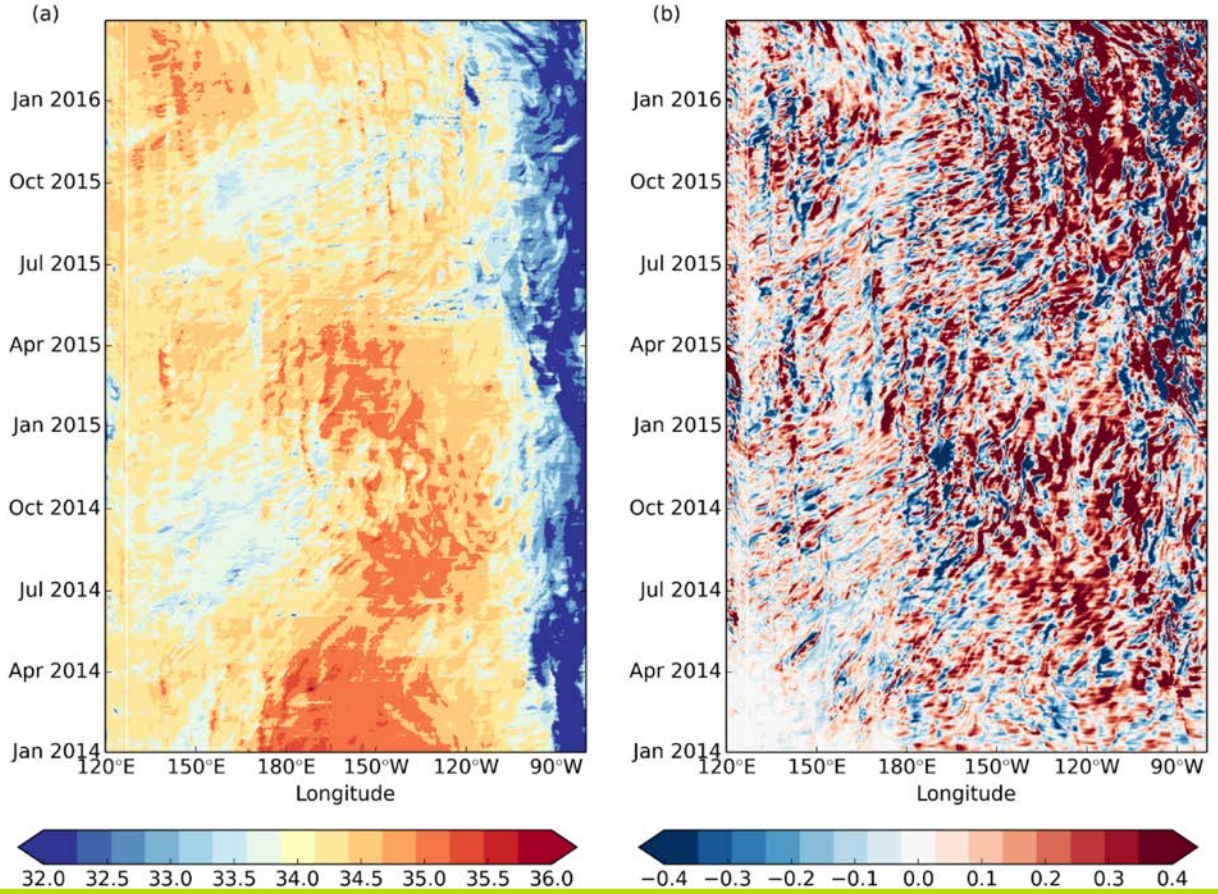
Evaporation-minus-precipitation

- Annual mean evaporation-minus-precipitation and a Hovmuller plot at 5°N.
- A period of evaporation dominates in August – Dec 2014.
- Periods of very strong precipitation from April 2015 onwards.
- Overall much larger precipitation in 2015 in the ITCZ in the central Pacific.

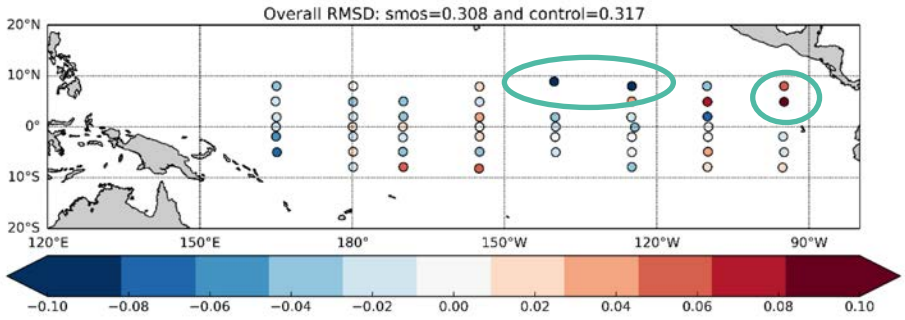


Results – SSS fields

- Hovmuller plots at 5°N.
- Eastern fresh pool extends further westwards in 2015
- SMOS data act to reduce the SSS under the ITCZ on average and there are large changes.
- Small scale structures associated with Tropical Instability Waves.



Comparisons to independent TAO surface salinities



PSS

- Impact on RMSD compared to TAO mooring SSS in *smos* experiment averaged over the entire experiment (-ve difference implies a reduction in RMSD by the SMOS assimilation).
- Overall, there is a small reduction in RMSD.
- Difficult comparison due to issues with the TAO moorings: large data gaps, drifts in the observed salinities, …. not really a very good assessment data-set for this work.
- Mixed results depending on location.
- Largest reduction in errors at 5-10N east of 150W.
- Largest increase in errors at 100W.