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Preliminary Results from Assimilating SMOS Satellite Sea-Surface Salinity Fields in an NCEP Operational Ocean Forecast System

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Motivation

To understand the impact of satellite sea-surface salinity (SSS) data on the representativeness of ocean modling with the objective of quasi-near-real-time assimilation of SSS data.

Abstract

Recently available satellite sea-surface salinity (SSS) fields provide important global data for assimilating into ocean forecast systems. The use of daily satellite SSS fields is compared to the current operational use of the annual-mean climatological SSS field. We present results from assimilating the SSS data (from the European Space Agency's (ESA) Soil Moisture – Ocean Salinity (SMOS) mission) into NOAA's operational seasonal-interannual ocean model using a relaxation technique, running sensitivity experiments with different relaxation time periods to evaluate the importance of high-frequency (mesoscale) and low-frequency (seasonal) SSS variability on the ocean's overall state.

Satellite Sea-Surface Salinity (SSS) Fields

- NOAA World Ocean Atlas (WOA, 2009) annual mean SSS (1.0-degree resolution), interpolated to the model grid
- SMOS Barcelona Expert Centre (SMOS-BEC) gridded SSS fields for 2010-2012 (0.25-degree resolution) , averaged over a 3-day rolling window, updated every 3 days, interpolated to model grid

Model

NOAA's National Center for Environmental Prediction (NCEP) operational near-global Modular Ocean Model v.4 (MOM4), half-degree resolution, forced with daily NCEP Climate Forecast System Reanalysis (CFSR; Saha *et al*., 2010) and relaxed to daily satellite sea surface temperature (SST) fields. All runs were initiated from the same ocean initial condition and run for 2010-2012 only. The MOM4 provides the core for NOAA's Global Ocean Data Assimilation System (GODAS) (Behringer, 2007), the ocean component of NOAA's seasonal-interannual coupled Climate Forecast System (CFS).

CASES:

- CTRL30DY = Relaxed to WORLD OCEAN ATLAS *in situ* annual-mean SSS, relaxation period=30days (loosely constrained); current operational mode.
- SMOS30DY = Relaxed to SMOS-BEC Daily SSS (interpolated from 3-day SSS), relaxation period=30 days (loosely constrained).
- SMOS10DY= Relaxed to SMOS-BEC Daily SSS (interpolated from 3-day SSS), relaxation period=10 days (tightly constrained).

Satellite Sea-Surface Salinity (SSS) Fields

NOAA's current seasonal-interannual operational ocean model (MOM4) employs a SSS annual-mean climatology, neglecting temporal SSS variability. Figure 1.a depicts the WOA 2009 global annual-mean SSS field employed in NOAA's MOM4, with Figures 1.b and 1.c depicting the differences between SMOS winter/summer observations and WOA annual mean. Figure 1.d portrays SMOS SSS equatorial-mean (2°S – 2°N) temporal variability, highlighting the notable variability being introduced into the model for this state variable through the use of SMOS data.

Fig. 1. Sea-surface Salinity:

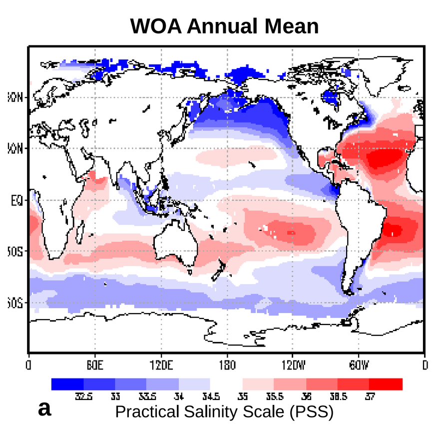
a) World Ocean Atlas (WOA) 2009 annual mean climatology;

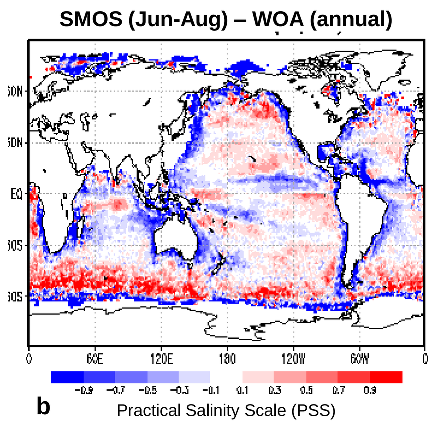
SSS Difference

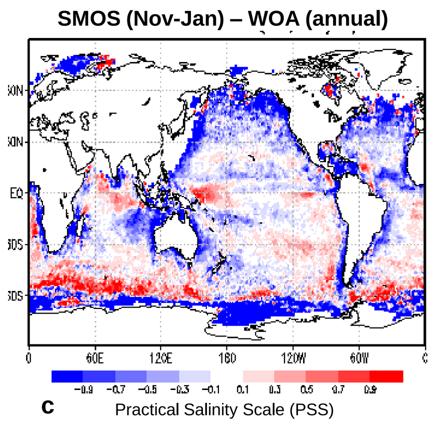
b) SMOS-daily SSS mean (Jun – Aug 2010) minus WOA annual-mean SSS,

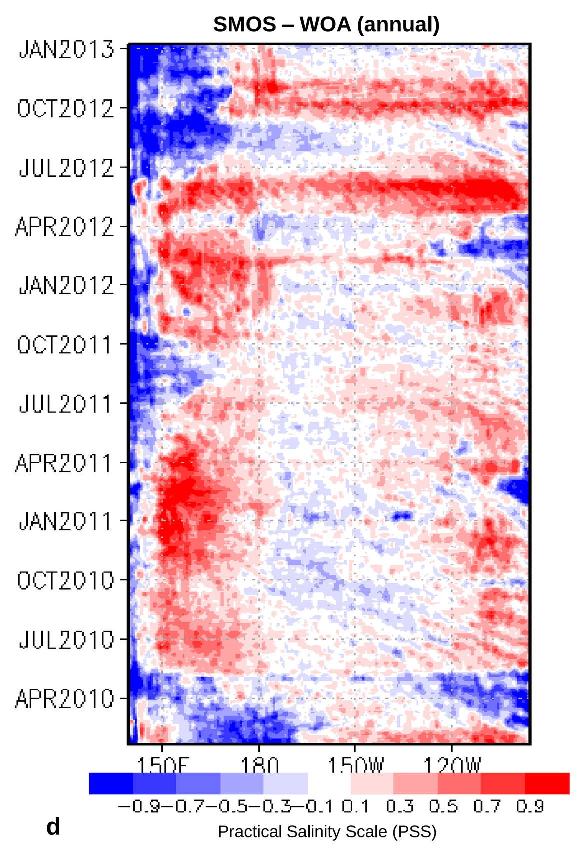
c) SMOS-daily SSS mean (Nov 2010 – Jan 2011) minus WOA annual-mean SSS.

d) SMOS-daily Equatorial-mean SSS (2°S – 2°N) minus WOA annual-mean SSS









Model Sensitivity to SSS

Examining the broader equatorial Pacific Ocean response at the end of the model runs, representative of 2010 through 2012 (Figures 2 and 3), the greatest temperature differences due to the sea-surface salinity differences were typically found in the near-surface at or above the average depth of the 20°C isotherm. Salinity differences were much shallower, typically about 50 m depth. When using the SMOS data, tightening the relaxation period to 10 days produces an additional impact of about the same magnitude as using daily SSS values in place of annual-mean values. With respect to the equatorial Pacific Ocean, the most significant salinity-induced temperature differences were clustered along the 20°C isotherm in the eastern half of the Pacific Ocean. The most significant salinity differences occurred in the Western Pacific Ocean warm pool, produced by freshening consistent with elevated precipitation in that region. Figure 4 is the reflection of the impact of the SSS differences on modeled sea-surface height (SSH), both in terms of height difference (cm) and percentage of CNTRL30DY SSH variability. SSH differences appear to manifest as sets of equatorial waves, notably intensifying with the tightening of the relaxation period.

Equatorial Pacific Ocean (5°S – 5°N)

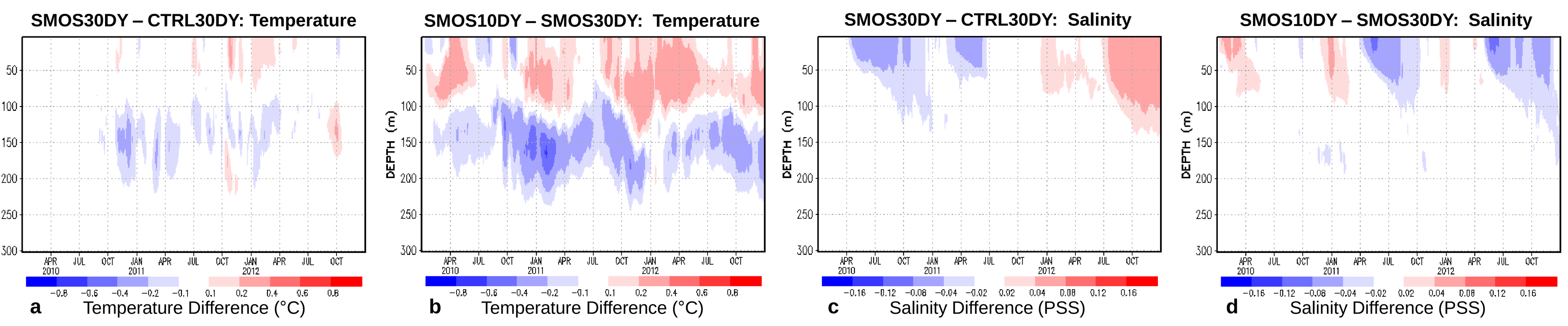


Fig. 2: Temporal model vertical response to SSS assimilation and different relaxation periods (NINO3.4 region (5°S-5°N; 170°W-120°W): Temperature difference a) SMOS30DY minus CTRL30DY, b) SMOS10DY minus SMOS30DY; Salinity difference c) SMOS30DY minus CTRL30DY, d) SMOS10DY minus SMOS30DY.

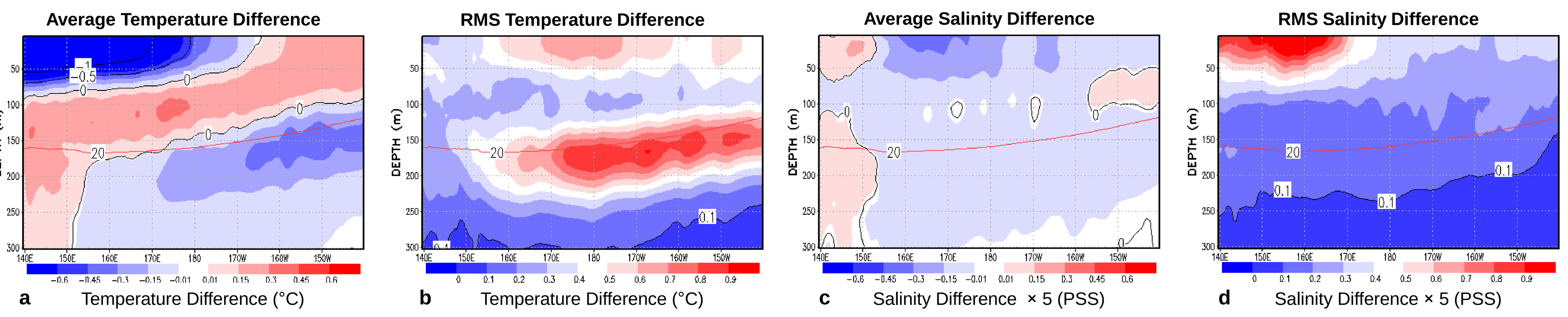


Fig. 3. Net vertical difference (SMOS10DY minus CTRL30DY) along an equatorial slice (5°S – 5°N): a) average temperature difference, b) RMS temperature difference, c) average salinity difference, and d) RMS salinity difference. Salinity differences (right panels) are multiplied by a factor of 5. The seasonal thermocline is indicated in each plot by the mean depth of the 20°C isotherm (shown in a red line).

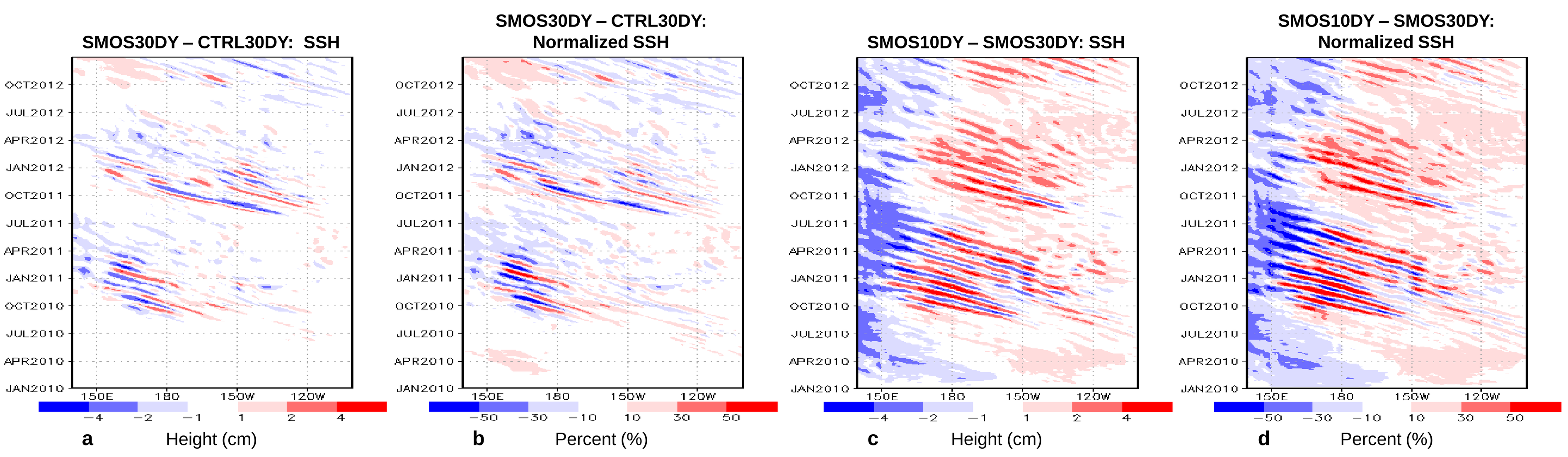


Fig. 4. Sea-surface height differences in equatorial Pacific SSH (5°S-5°N): a) SMOS30DY minus CTRL30DY, b) normalized SMOS30DY minus CTRL30DY, c) SMOS10DY minus SMOS30DY, d) normalized SMOS10DY minus SMOS30DY. Figures 4.b and 4.d are normalized as a percentage of the variance in CTRL30DY.

References:

- Behringer, D.W., 2007, "*The global ocean data assimlation system at NCEP,*" in 11th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, American Meteorological Society 87th Annual Meeting, San Antonio, TX.
- Saha, et al., 2010, "The NCEP Climate Forecast System Reanalysis," *Bull. Amer. Meteor. Soc. (19) 1015-1057.*
- Leuliette, E., and R. Scharroo, 2010, "Integrating Jason-2 into a Multiple-Altimeter Climate Data Record," *Marine Geodesy* 33(S1): 504-517.
- SMOS-BEC Team, Technical Note BEC-SMOS-0001-PD version 1.1 "*SMOS-BEC Ocean and land Products Description*", 24 July 2013.

Verification

Sea-surface Salinity (SSS)

For verification, the modeled sea-surface salinity (SSS) for the CTRL30DY case is first compared to SMOS satellite SSS data. Figure 5 depicts RMS differences between case results and corresponding salinity data. Figure 5.a (CNTRL30DY) highlights a broad expanse of large errors, order 1 PSS, resulting from simply using annual-mean SSS values. Figure 5.b (RMS differences from satellite SSS observations) and 5.c (difference plot for 5.b minus 5.a) show that using daily satellite SSS observations broadly reduce model errors by 70%, or more, to 0.2-0.35 PSS. Figure 5.d depicts additional error reduction due to tightening the relaxation period from 30 days to 10 days. Figure 5.e shows the net improvement from using satellite SSS data and decreasing the relaxation period to 10 days versus using the existing operational method (CNTRL30DY). Figures 5.f and 5.g provide the global perspective of Figures 5.c and 5.d.

Fig. 5. Verification for the equatorial Pacific Ocean, using RMS differences with respect to SMOS sea-surface salinity observations (Practical Salinity Scale (PSS)):

a) CNTRL30DY, operational configuration using *in situ* annual mean SSS

b) SMOS30DY, daily satellite SSS

Equatorial Pacific Ocean improvement (**blue** represents reduction of RMS error):

c) SMOS30DY RMSE minus CTRL30DY RMSE (Fig 5.b – Fig 5.a)

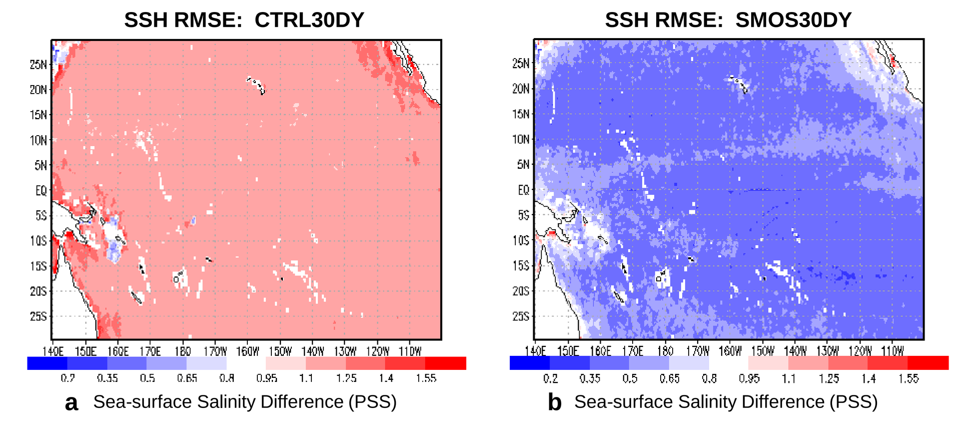
d) SMOS10DY RMSE minus SMOS30DY RMSE depicts error reduction due to tightening the relaxation period to 10 days

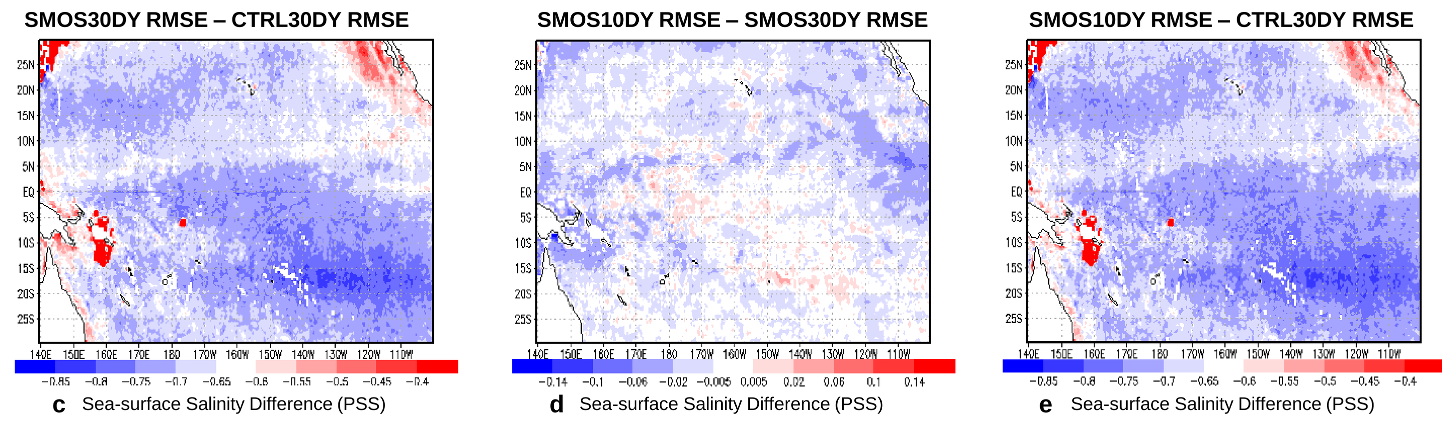
e) Net improvement (SMOS10DY RMSE minus CTRL30DY RMSE)

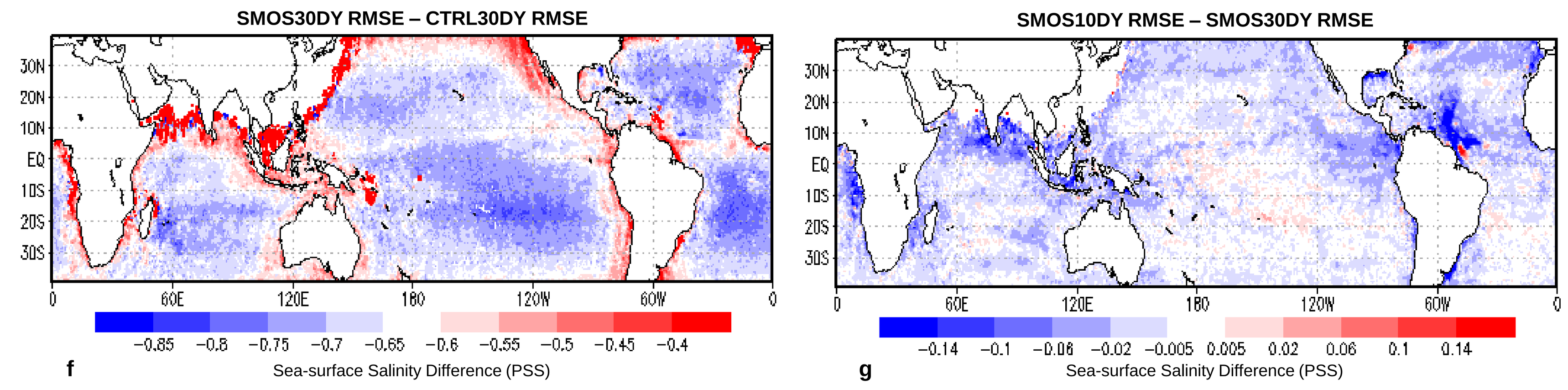
Global verification (**blue** represents reduction of RMS error):

f) SMOS30DY RMSE minus CTRL30DY RMSE

g) SMOS10DY RMSE minus SMOS30DY RMSE



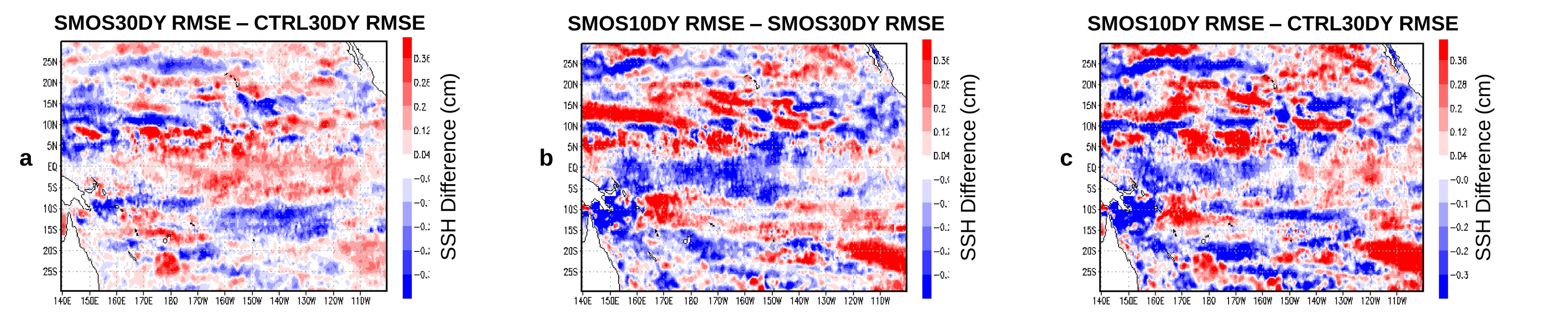




Sea-surface Height (SSH)

Satellite altimetry observations of sea-surface height (SSH) are used to verify model case performance. Assimilating satellite SSS observations reduces SSH RMS errors in the near-tropical regions, which are further improved by tightening the relaxation period from 30 days to 10 days (Figure 6). SSH improvements are of order 0.2 – 0.3 cm, which equates to improvements of 10 – 15 percent. Figure 7 depicts the cross-correlation of model results with satellite SSH observations. Figure 7.a clearly shows strong cross-correlation (red) of the SMOS30DY case with SSH observations, with Figure 7.b indicating near-equatorial improvements from using daily SSS values in place of annual-mean SSS values. Tightening the relaxation period to 10 days produces improvements along the equatorial Pacific Ocean, but mixed performance poleward of 10° N/S.

SSH RMSE Differences: Referenced to Satellite Altimetry SSH Observations



Normalized SSH RMSE Differences: (Normalized RMSE differences = 100 × (RMSE$_1$ – RMSE$_2$)/RMSE$_{Ref}$)

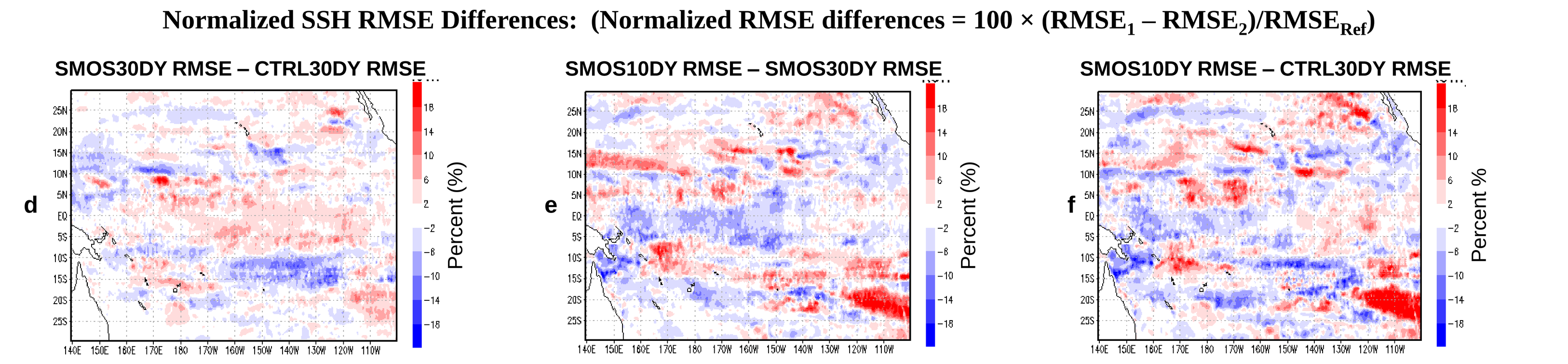


Fig. 6. Differences between model case SSH RMSE (cm), referenced to altimetry observations: a) SMOS30DY, referenced to altimetry data, minus CTRL30DY RMSE, referenced to altimetry data; b) SMOS10DY, referenced to altimetry data, minus SMOS30DY RMSE, referenced to altimetry data; c) SMOS10DY, referenced to altimetry data, minus CTRL30DY RMSE, referenced to altimetry data. Normalized differences (percent (%)), referenced to altimetry observations: d) normalized Fig. 6.a, e) normalized Fig. 6.b, f) normalized Fig. 6.c. **Blue** represents reduction of RMS error.

SSH Cross-correlation: Referenced to Satellite Altimetry SSH Observations

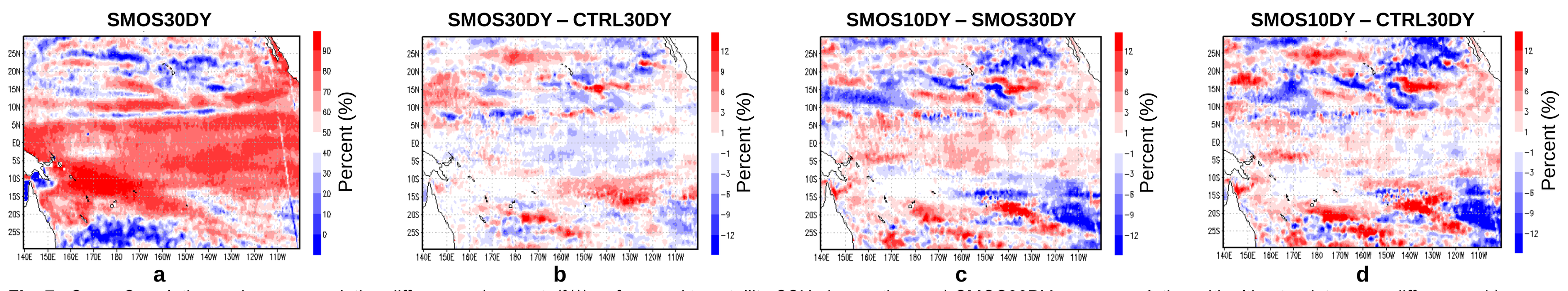


Fig. 7. Cross-Correlation and cross-correlation differences (percent (%)), referenced to satellite SSH observations: a) SMOS30DY cross-correlation with altimetry data; case differences b) SMOS30DY minus CTRL30DY, c) SMOS10DY minus SMOS30DY, d) SMOS10DY minus CTRL30DY. **Red** represents improved model cross-correlation with respect to satellite altimetry data.

Ocean Heat Content (OHC): 0 – 300m

Normalized RMSE Differences Referenced to GODAS OHC

Sea-surface height changes are the surface manifestation of changes in both dynamics and heat content (density); consequently, examining upper-ocean heat content further examines the impact of salinity differences and provides insight on changes in the interior of the ocean. The ocean heat content resulting from full assimilation of *in situ* and remotely-sensed observations provided NOAA's operational GODAS served as the reference state. Figure 8 depicts the percent heat content differences, referenced to CNTRL30DY case RMS differences with respect to the GODAS. The value of using daily SSS values is largely negated when employing the 30-day relaxation period; however, notable improvements are seen in the equatorial region when employing the 10-day relaxation period. Results elsewhere are mixed.

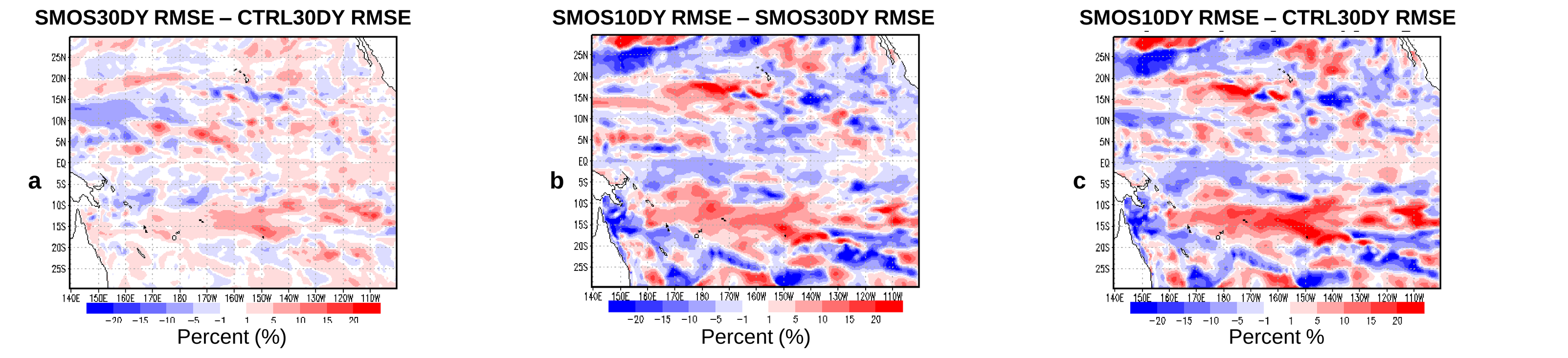


Fig. 8. Normalized RMSE ocean heat content (OHC) model case differences, referenced to NOAA's GODAS OHC: a) SMOS30DY, referenced to GODAS OHC, minus CTRL30DY RMSE, referenced to GODAS OHC; b) SMOS10DY, referenced to GODAS OHC, minus SMOS30DY RMSE, referenced to GODAS OHC; c) SMOS10DY, referenced to GODAS OHC, minus CTRL30DY RMSE, referenced to GODAS OHC. **Blue** represents reduction of RMS error.

Summary and Conclusions

- These results show that assimilating SMOS SSS fields improve the simulated ocean state, thus providing better initialization of coupled seasonal and tropical cyclone forecast systems.
- For the equatorial Pacific region, the SMOS10DY outperforms the SMOS30DY with respect to the RMSE metric; however, the SMOS10DY case underperforms SMOS30DY poleward of about 10° N/S.
- Smoothing the SMOS SSS fields before they are assimilated may improve the cross-correlation by removing SMOS high-frequency signal contamination of the cross-correlation metric. The SMOS high-frequency signal may not influence the altimetric SSH fields and/or be resolved by the model.