Validation and Analysis of Ocean Model Simulations using Satellite Ocean Color Field

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1. INTRODUCTION

Solar shortwave heating of the ocean's upper layer, which depends on the incoming radiation and the optical properties of the water column, correlates with chlorophyll concentration through the modulation of heat absorption (Murtugudde, et al., 2002). Through changes in the near-surface vertical density profile, differential heating patterns cause changes in near-surface stability, air-sea heat flux, and baroclinic pressure gradients, which, in turn, impact the upper-ocean's three-dimensional circulation patterns. Thus, we examine changes in heat content and velocity in the top 300 m of the water column. Anomalous build-up of equatorial Pacific Ocean heat content is an important variable for the recharge-discharge oscillator theory for the evolution of El Niño events. Here, differences in the chlorophyll data used by the model are shown to cause significant changes in tropical Pacific Ocean heat-content anomalies. Thus, for seasonal predictions, it is important that the impact of the prescribed ocean color (chlorophyll-a concentration) data on the skill of ocean and coupled forecasts be studied. This study presents an analysis of ocean model simulations that employ different satellite ocean color fields, showing that the ocean model responds vigorously to differences in the prescribed ocean color (chlorophyll fields. The results are validated in comparison to ARGO temperature profiles and Argo-derived ocean heat content computed for the top 300m of the water column.

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2. SATELLITE OCEAN COLOR FIELDS

Sea-viewing Wide Field-of-View Sensor (SeaWiFS) satellite ocean color (chlorophyll) data sets were interpolated to the model grid. Four different ocean color datasets were prepared. These are (a) the current (**BASE**) operational data set: **1997-2001 monthly-mean climatology**; (b) **Extended monthly climatology** (**EXTD**) spanning 1998-2010; (c) **Sequential monthly-mean** (**SEQM**) SeaWiFS data for the period 1998-2010; and (d) **Sequential daily** (**SEQD**) composited SeaWiFS fields for the period 1998-2010. Gaps in the SeaWiFS coverage were filled by employing a technique that used climatological values. SeaWiFS data does not provide daily global coverage; therefore, a compositing technique provided a global daily product (SEQD). Long gaps in the SeaWiFS data record for 2008 posed a challenge. In figure 1a, the annual mean chlorophyll-a is plotted for the global oceans, while Figure 1b shows the difference between the annual mean for the extended period and the annual mean of the chlorophyll-a used operationally. Figure 1b shows that the base chlorophyll-a monthly-mean climatology (1997-2001) used operationally has a global bias, likely due to sample distortion from the very strong 1997-1998 El Niño. A Hovmöller plot of SeaWiFS monthly-mean chlorophyll concentration (Figure 1c) highlights the inter-annual variability provided by using sequential monthly-mean data, rather than a cyclical annual cycle of monthly-mean values. This interannual variability contributes to associated variability of near-surface ocean heat content, near-surface stability, and air-sea heat flux.

3. OCEAN MODEL SIMULATIONS

NOAA's operational seasonal-interannual global half-degree latitude/longitude

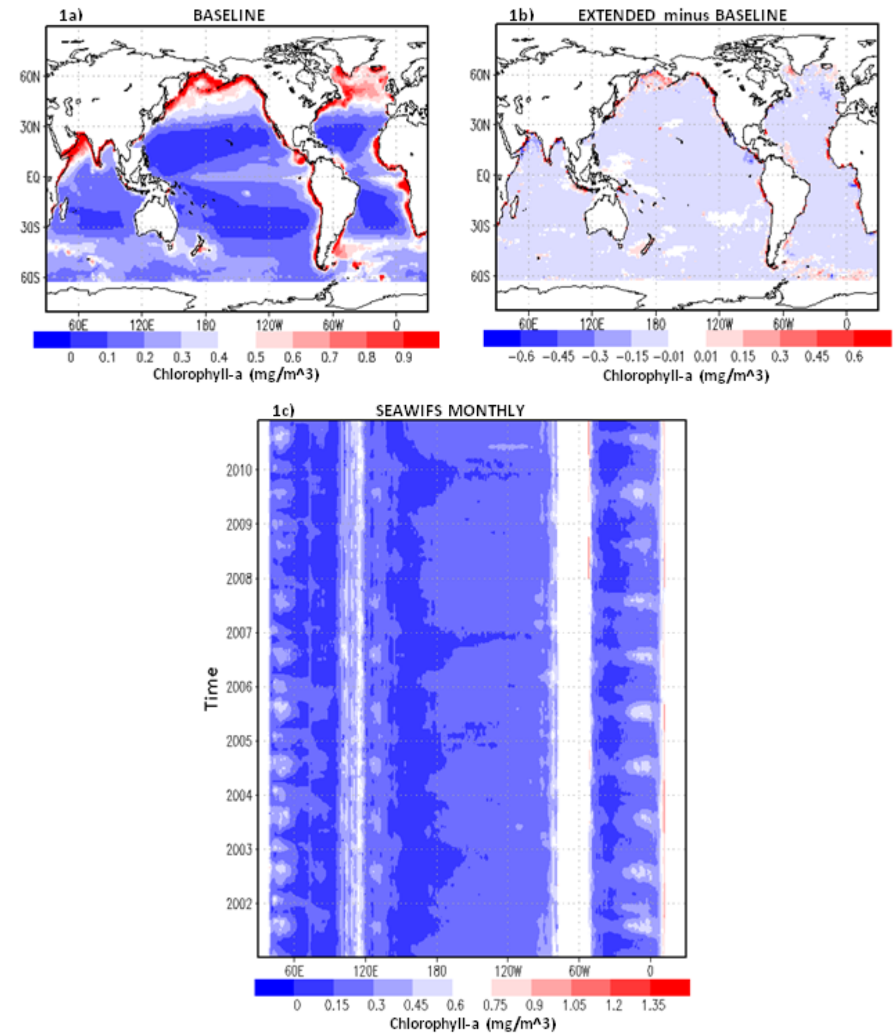

Figure 2. The time-evolution of upper-ocean vertical temperature profile differences (°C) for NiñO3.4 (170^0W-120^0W, 5^0S-5^0N): a) EXTD minus Base, b) SEQM minus EXTD, c) SEQD minus SEQM.

resolution model, the Modular Ocean Model Version 4 (MOM4), with a tripolar grid and 40 vertical levels, is used for this study. The model is forced with NCEP Climate Forecast System Reanalysis (CFSR) daily fluxes (Saha, *et al*., 2010). Relaxation to daily satellite sea-surface temperature (SST) and monthly climatological sea-surface salinity fields is used to constrain model state evolution. All simulations are started from the same initial state and span the years 2001-2010. Results are validated against NOAA's Global Ocean Data Assimilation System (GODAS) (Behringer, 2007), which employs the same MOM4 computational core, for the entire simulation period and ARGO gridded (1-degree resolution) monthly profiles of temperature and salinity (Lebedev, *et al*., 2010) for 2005-2010. The GODAS profiles are saved as pentads, and are linearly interpolated to daily values for comparisons with the daily temperature and salinity profiles from the model simulations. When comparing model to Argo data, the daily temperature and salinity profiles for each simulation case are averaged to monthly-mean values.

4. SENSITIVITY TO OCEAN COLOR FIELDS

Two different aspects of the ocean color data (chlorophyll-a) significantly influence, with comparable impacts, the modeled equatorial ocean temperature: 1) the use of more representative climatological data from extending the satellite data record period

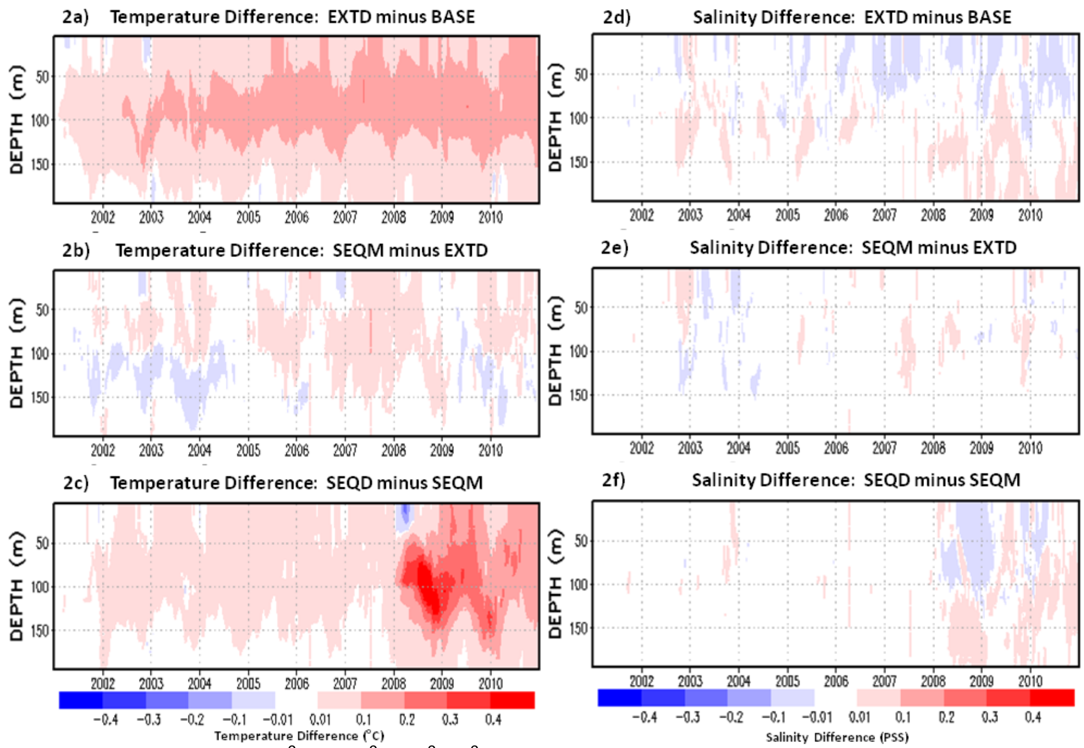

Figure 2. For NiñO3.4 (170^{0}W-120^{0}W, 5^{0}S-5^{0}N): Time-evolution of upper-ocean vertical temperature profile differences (°C) a) EXTD minus Base, b) SEQM minus EXTD, c) SEQD minus SEQM; Time-evolution of upper-ocean vertical salinity profile differences (PSS): d) EXTD minus Base, e) SEQM minus EXTD, f) SEQD minus SEQM.

(Figure 2a) and 2) the inclusion of temporal variability (Figures 2b and 2c). Similar impacts are seen in the modeled equatorial salinity. Temperature and salinity impacts are confined to the near-surface, approximately 300m and less depth. A point to note is that large differences between SEQD and SEQM in 2008 may be due to the methodology used to fill large gaps in the SeaWiFS data record. This issue will be examined as a part of future efforts. Circulation patterns (not shown) are not very sensitive to prescribed chlorophyll fields. In most parts of the equatorial oceans, differences in mean zonal velocity are less than 10 percent between cases. The most obvious differences in temperature are between the EXTD and BASE cases, while the differences between SEQM and EXTD are always small, suggesting that interannual variability does not cause large changes in the model state. However, the differences between SEQD and SEQM are frequently as large as or larger in magnitude than between any of the other cases, highlighting the importance of high-frequency variability. Figure 3 depicts the differences between the mean equatorial upper-ocean temperature and salinity profiles for the four cases, highlighting the component contributions to the net change that would be experienced by using near-real-time chlorophyll data instead of climatology in NOAA's operational seasonal-interannual model.

5. VALIDATION OF SIMULATIONS

5.1 Subsurface Temperature Profiles

Relaxation of the ocean model simulations to SST and SSS fields constrains surface values; thus, it is not very meaningful to analyze simulated SST response due to changes in the prescribed ocean color fields. Therefore, changes in the vertical profiles of temperature are analyzed and compared with the observation profiles. Figure 4a depicts the root-mean-square-error in the near-surface equatorial (5°S–5°N) vertical temperature profile for the BASE case over 2005-2010, referenced to ARGO monthly profiles. Examining root-mean-square errors (RMSE), the effects of

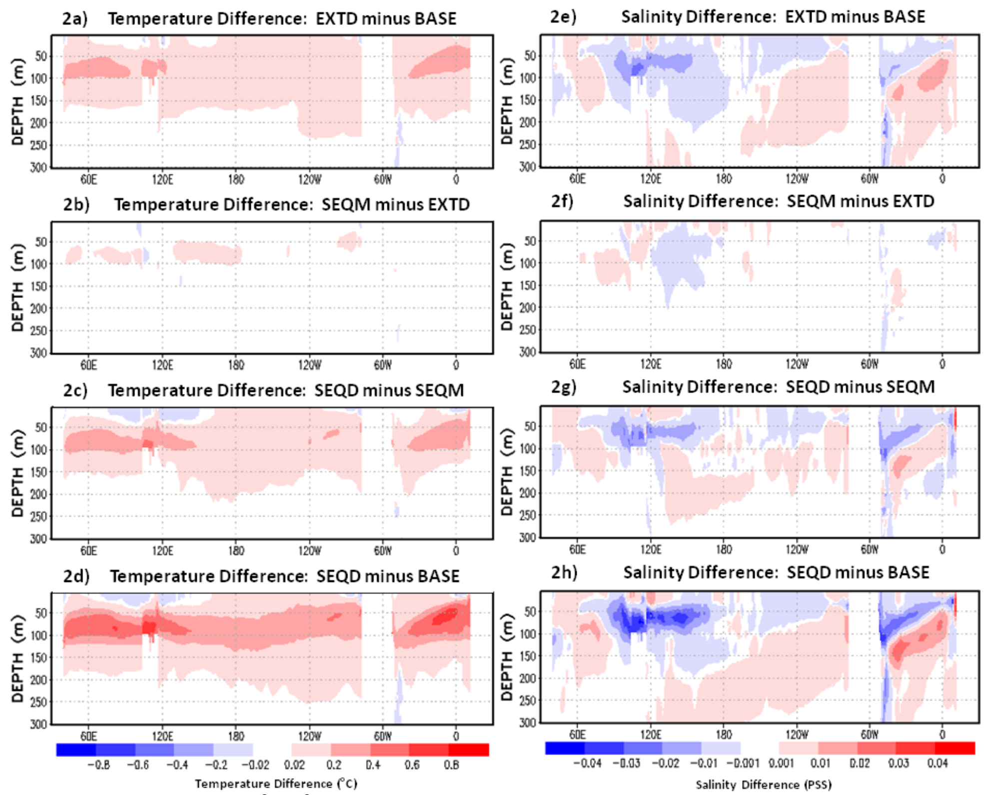

Figure 3. Mean equatorial (5^{0}S-5^{0}N) upper-ocean vertical: temperature profile differences (°C) a) EXTD minus Base, b) SEQM minus EXTD, c) SEQD minus SEQM, and d) SEQD minus BASE; salinity profile differences (PSS) e) EXTD minus Base, f) SEQM minus EXTD, g) SEQD minus SEQM, and h) SEQD minus BASE.

chlorophyll-a on the simulations are compared, separately referenced to Argo observations and GODAS model results. The impact of high-frequency variability (daily to mesoscale) on the RMSE of temperature profiles is of interest as a reflection of potential impacts from near-real-time ocean color data (chlorophyll-a) assimilation. A comparison of Figures 4a and 4b reveals that the RMSE referenced to GODAS is 10-20% higher than when referenced to ARGO for the same period (2005-2010), which may be due to errors in simulating mesoscale variability. In Figure 5, the RMSE of the equatorial temperature profiles for the different simulations are depicted, referenced to Argo and GODAS. The largest intensification of RMSE differences result from the introduction of higher-frequency variability in the SEQD case.

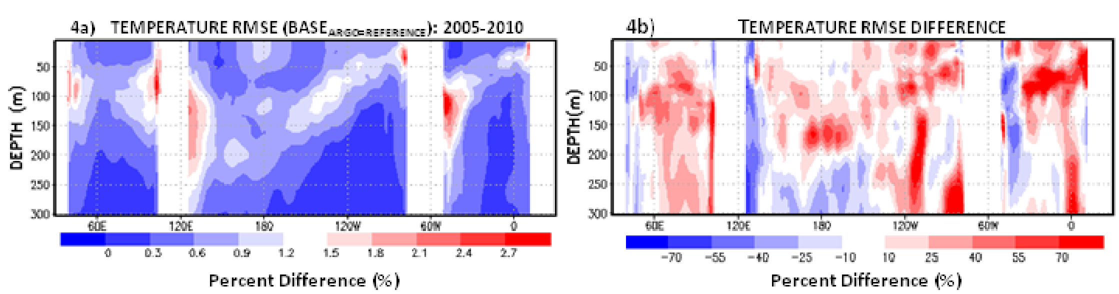

Figure 4. a) RMSE in ^{0}C for the equatorial (5^{0}S-5^{0}N) temperature for BASE, referenced to ARGO gridded monthly for 2005-2010; b) the normalized RMSE(BASE) percentage difference for 2005-2010 with GODAS pentad data as reference.

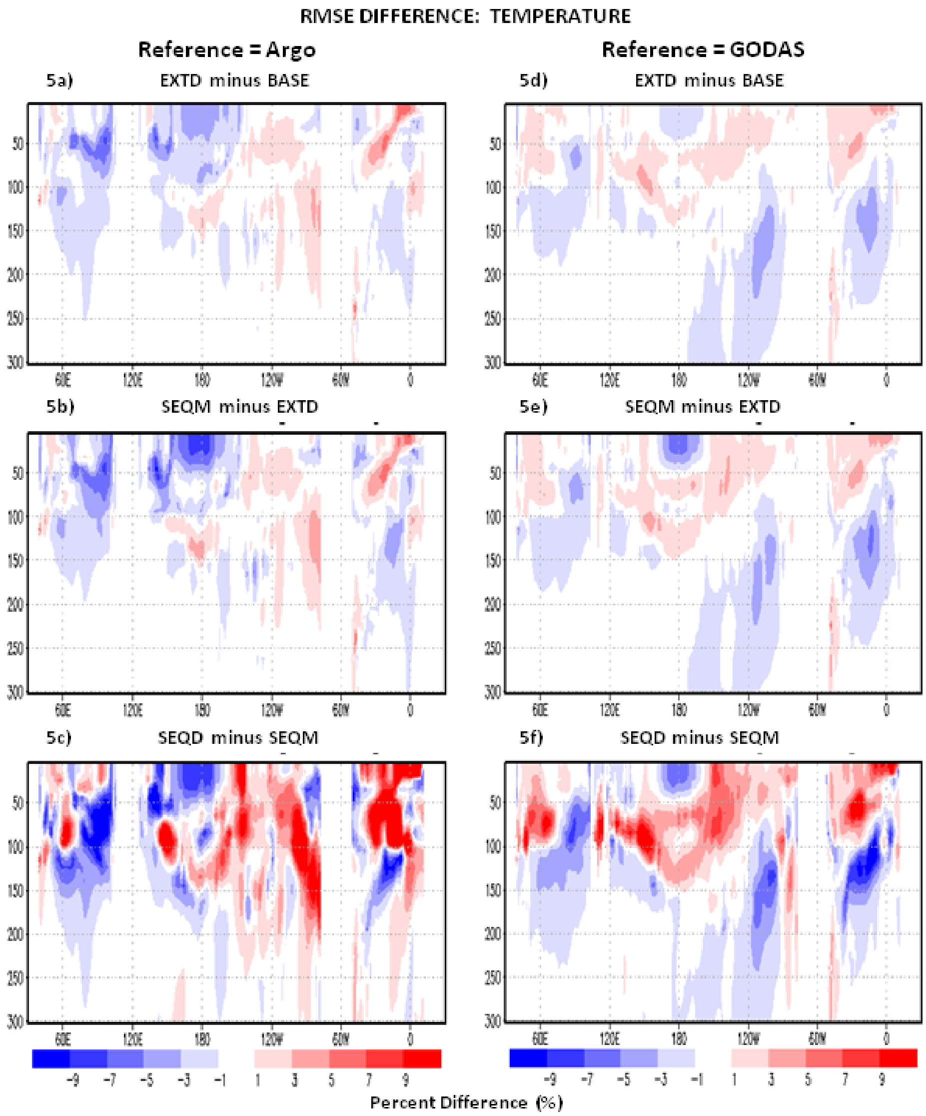

Figure 5. RMSE percentage change in equatorial (5^0S-5^0N) temperature due to ocean color forcing differences: Left column referenced to gridded ARGO temperature profiles (2005-2010) a) EXTD minus BASE, b) SEQM minus BASE, and c) SEQD minus BASE; Right column referenced to GODAS pentad observations (2001-2010) d) EXTD minus BASE, e) SEQM minus BASE, and f) SEQD minus BASE.

5.2 Ocean Heat Content

Ocean heat content is an important variable for seasonal prediction; consequently, to analyze model response to differences in prescribed chlorophyll-a fields, the simulated ocean heat content of the top 300m of the water column is compared to values computed from Argo gridded monthly profiles. Figure 6 shows that the EXTD case outperforms the BASE case in most parts of the equatorial oceans and mixed results elsewhere, with improvements and weakened performance intensifying with the use of sequential data and the introduction of higher-frequency variability. The SEQM case introduces notable improvement in the equatorial Indian and Atlantic Oceans. In the equatorial oceans, the SEQD case outperforms all of the other cases, but the SEQD case also intensifies weakened performance elsewhere, notably in the Inter-Tropical Convergence Zone (ITCZ) and northwestern Atlantic and Pacific Oceans. Clearly, the information added by using sequential monthly or daily data, versus climatological chlorophyll-a fields (EXTD and BASE), improves the ocean model's performance.

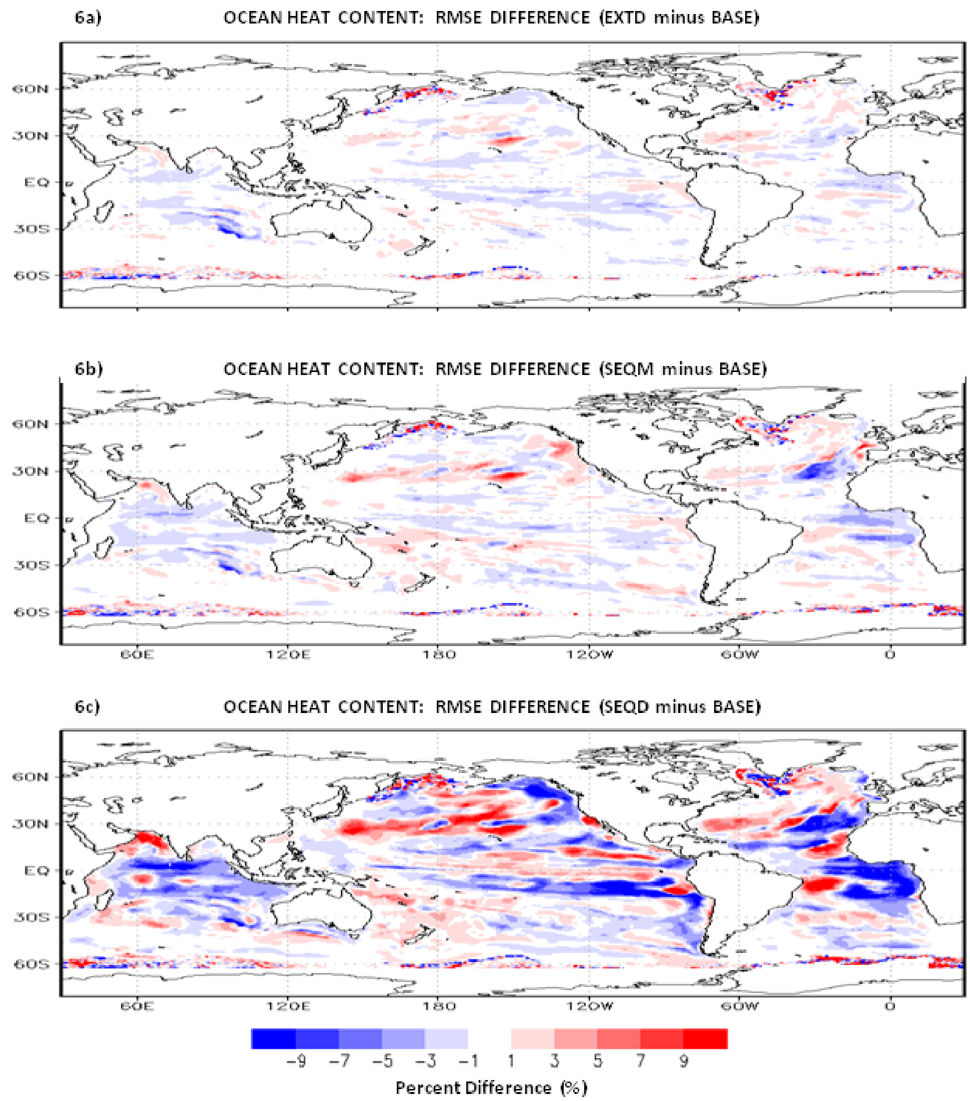

Figure 6. Upper-ocean heat content RMSE percent change due ocean color forcing differences, referenced to gridded monthly ARGO temperature and salinity profiles (2005-2010): a) EXTD minus BASE, b) SEQM minus BASE, and c) SEQD minus BASE.

6. DISCUSSION

The base chlorophyll-a monthly-mean climatology (1997-2001) used operationally by NOAA is not representative over extrapolated periods, likely due to distortion from the very strong 1997-1998 El Niño. The extended monthly climatology has lower values of chlorophyll-a everywhere, and the inter-annual variability provided by using sequential monthly-mean data, rather than a cyclical annual cycle of monthly-mean values improves the simulated ocean state only modestly as validated by observations (Figures 5 and 6). While Figures 5 and 6 show that using sequential, rather than cyclical, monthly forcing mildly improves modeled results, using more frequent (daily) sequential updates notably and globally improves the accuracy of modeled near-surface ocean heat content by up to ± 10%. These results indicate that the assimilation of sequential daily satellite ocean color (chlorophyll-a) data is important for adequately modeling upper-ocean stability and heat content, particularly in support of better air-sea heat flux for coupled ocean-atmosphere models.

7. SUMMARY

The model simulations are sensitive to the representativeness of the chlorophyll-a fields used, as well as the update frequency, with significant improvements achieved from extending the climatology to 13 years versus using the operational 4-year SeaWiFS climatology. While the mean differences in temperature and salinity profiles are not large, significant improvements in the simulation of variability are found when using the sequential monthly or daily chlorophyll-a datasets. Upper-ocean heat content (0-300m) throughout the equatorial oceans (especially, in the Indian and Atlantic oceans) is best simulated by the SEQD case.

8. REFERENCES

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