Closing the Seasonal Ocean Surface Temperature Balance in the Eastern Tropical Oceans from Remote Sensing and Model Reanalyses

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Research Supported by NASA Energy and Water Cycle Study (NEWS)

Research Objectives

The Eastern tropical ocean basins are regions of significant atmosphere-ocean interaction and are important to variability across subseasonal to decadal time scales. Limitations in the observing system of important terms of the mixed layer temperature balance (MLTB) introduce uncertainty into the analyses of processes controlling sea surface temperature variability. Through estimation and examination of the terms of the MLTB, the primary objectives of this study are:

1. **Assess the ability of current observation-based analyses to close the upper ocean MLTB on seasonal time scales;**
2. **Investigate seasonal mixed layer depth variability and its contribution to the MLTB;**
3. **Quantify impacts of surface heat flux uncertainty on the prediction of sea surface temperature**

Summary Points

1. Residual forcing necessary to close the MLTB on seasonal time scales are largest in regions of strongest surface heat flux forcing. Identifying the dominant source of error — surface heat flux error, mixed layer depth estimation, ocean dynamical forcing — remains a challenge in the eastern tropical oceans where ocean processes are very active. Improved sub-surface observations are necessary to better constrain errors.

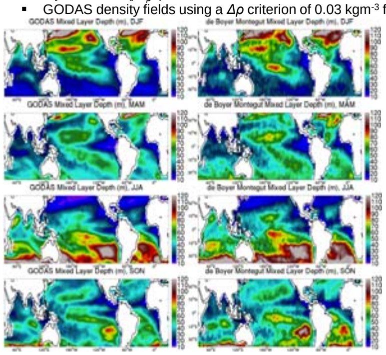
1. Mixed layer depth evolution is critical to the seasonal evolution of mixed layer temperatures. It determines the inertia of the mixed layer, and scales the sensitivity of the MLTB to errors in surface heat flux and ocean dynamical forcing. This role produces timing impacts for errors in SST prediction.

2. Errors in the MLTB are larger than the historical 10Wm^{-2} target accuracy. In some regions, a larger accuracy can be tolerated if the goal is to resolve the seasonal SST cycle.

Mixed Layer Temperature Balance Estimation

$$\underbrace{\frac{\partial \theta_m}{\partial t}}_{(1)} = \underbrace{-\vec{v}_m \cdot \nabla \theta_m}_{(2)} \underbrace{- \frac{w_e \Delta T}{h}}_{(3)} + \underbrace{K_h \nabla^2 T}_{(4)} + \underbrace{\frac{1}{\rho c_p h}}_{(5)} \underbrace{\left[F_{swr} + F_{lwr} + F_{lhf} + F_{shf} + F_{vdiff} \right]}_{(6)}$$

1. Mixed layer temperature (θ_m) tendency
   - Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) sea surface temperature (SST)
2. Advection by average mixed layer velocity ($\boldsymbol{v_m}$)
   - Ocean Surface Current Analysis (OSCAR) and TMI SST
3. Entrainment flux from entrainment velocity (w_e) and temperature gradient (ΔT) at base of mixed layer (*depth h*)
   - Upper ocean divergence from OSCAR
   - Mixed layer depth variability from Global Ocean Data Assimilation System (GODAS)
   - Subsurface temperature gradient from GODAS
4. Horizontal diffusion with horizontal eddy diffusivity K_h
   - Parameterized following Okubo (1971); TMI SST
5. Mixed layer "inertia" ($\rho c_p h$)
   - GODAS density fields using a $\Delta\rho$ criterion of 0.03 kgm^{-3} from a reference level of 10m to compute *h*

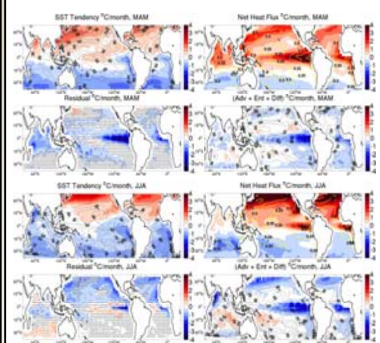


Seasonal mixed layer depth evolution computed from GODAS and from de Boyer Montégut (2004) seasonal climatology.

- The density criterion is applied to pentad-resolution GODAS estimates
- The seasonal evolution of mixed layer depths based on these estimates follows closely the climatology of de Boyer Montégut (2004)
- There is a deepening of the mixed layer in the extratropics of the winter hemisphere and shoaling in the summer hemisphere
- Deeper mixed layers are found under the atmospheric subtropical ridges
- The eastern tropical oceans typically have the shallowest mixed layer depths with little seasonal variation.

1. Net heat flux into ocean mixed layer
   - Shortwave and Longwave — ISCCP-SRF,GEWEX-SRB,NOCS2, MERRA, CFSR, ERAINT
     - Penetrative shortwave radiation following Sweeney et al. (2005)
   - Latent and Sensible — OAFlux, SeaFlux, GSSTF2b, JOFURO2, NOCS2, MERRA, CFSR, ERAINT
   - Vertical diffusion following Pacanowski and Philander (1981)
2. All terms are estimated on a 2.5°x2.5° spatial grid at pentad temporal resolution covering the period 1998-2007.

Mixed Layer Temperature Balance Closure



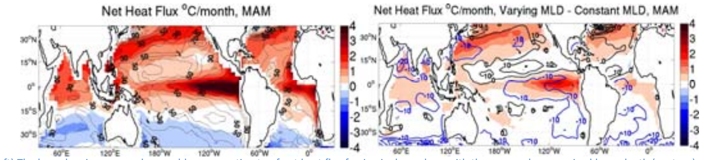
Eastern tropical oceans

- Heating by the net heat flux in all seasons and cooling via dynamical ocean processes during all seasons
- Net heating (heat fluxes dominate) during boreal fall (weak) and winter (strong); net cooling (ocean dynamics dominate) during boreal spring (weak) and summer (strong)
- Residual imbalances are largest in the eastern tropical ocean and represent a need for additional cooling during all seasons (not shown).
- Residual imbalances are largest in regions of shallowest mixed layer depths and the magnitudes follow the peaks of net heat flux forcing and net heat flux spread.
- The spread in heat flux forcing estimates is typically smaller than the unaccounted for cooling. This suggests:
  - *i) the net heat flux warming estimates are all systematically too strong;*
  - *ii) the mixed layer depth over which the forcing is applied is systematically too shallow;*
  - *iii) the ocean dynamical cooling is too weak; or*
  - *iv) a combination of all of the above.*

Seasonal mean mixed layer temperature balances are shown for boreal spring (MAM) and summer (JJA). The panels depict the seasonal mean temperature tendency, ensemble mean net heat flux tendency, ocean dynamical forcing tendency (Advection+Entrainment+Diffusion), and the residual forcing necessary to close the budget. Seasonal mixed layer depths are contoured in the temperature and ocean forcing tendency panels; ensemble heat flux spread is contoured in the net heat flux tendency panel. Hatched regions in the residual panel denote areas where the magnitude of the residual is smaller than the spread of the net heat flux estimates.

Role of Mixed Layer Depth Variability

- As the mixed layer depth evolves seasonally, it governs the inertia of the mixed layer temperature. That is, for a deeper mixed layer (more inertia) a larger amount of forcing is needed to change the average temperature of the layer by a given amount.
- Mixed layer depth evolution itself can therefore generate temperature variability. For example, boreal spring net heat flux warming of the eastern tropical oceans is significantly larger than if the same forcing were applied to a constant mean mixed layer depth. This is due to a seasonal shoaling of the mixed layer during this period.



(Left) The boreal spring seasonal ensemble mean estimate of net heat flux forcing is show along with the seasonal mean mixed layer depth (contour). (Right) Difference in the ensemble mean estimate between using a varying mixed layer depth and one fixed to the long-term mean. Black (blue) contours indicate seasonal mean deeper (shallower) mixed layers.

Mixed Layer Temperature Sensitivity to Surface Forcing

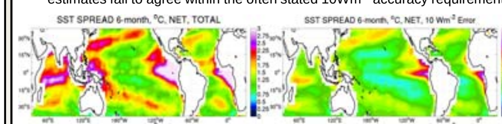
- The mixed layer temperature (MLT) evolution generated only by a specified surface net heat flux forcing can be estimated as:

$$MLT(t) = MLT(t=0) + \int_0^t \frac{F_{net}}{\rho c_p h} dt$$

- For a systematic error in the net heat flux estimate, F_{net}*, the error in the mixed layer temperature contribution from the net heat flux, *MLT**, becomes:

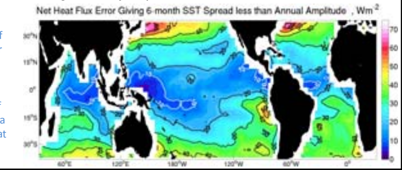
$$MLT^*(t) = F_{net}^* \int_0^t \frac{1}{\rho c_p h} dt$$

- Because the error is systematic, the error contribution pattern is controlled by the mixed layer inertia and is scaled by the net heat flux error.
- Integrating the mixed layer temperature evolution using available net flux products and assessing the spread after 6-months, shows that current estimates fail to agree within the often stated 10Wm^{-2} accuracy requirement.



(Left) The mean absolute deviation of sea surface temperature evolutions are shown for 6 month time horizons using 12 net heat flux estimates. (Right) The prediction error produced after a 6 month integration given by a systematic 10Wm^{-2} error in the net heat flux.

- A desired accuracy of the net heat flux can be constructed by specifying a target MLT for a given time horizon of integration.
- Designating a MLT evolution with error less than the annual MLT amplitude after 6-months produces an accuracy requirement that gives the 10Wm^{-2} error over the tropical warm pools, but shows much larger systematic errors can be tolerated in other regions.
- Under this approach, both the mixed layer inertia and annual MLT cycle are accounted for in setting accuracy requirements.



The target accuracy of the net heat flux error for a 6 month mixed layer temperature projection that is less than the amplitude of the annual cycle of sea surface temperature at each location.