Modeling of diurnal variability in upper ocean processes using satellite and in-situ observations

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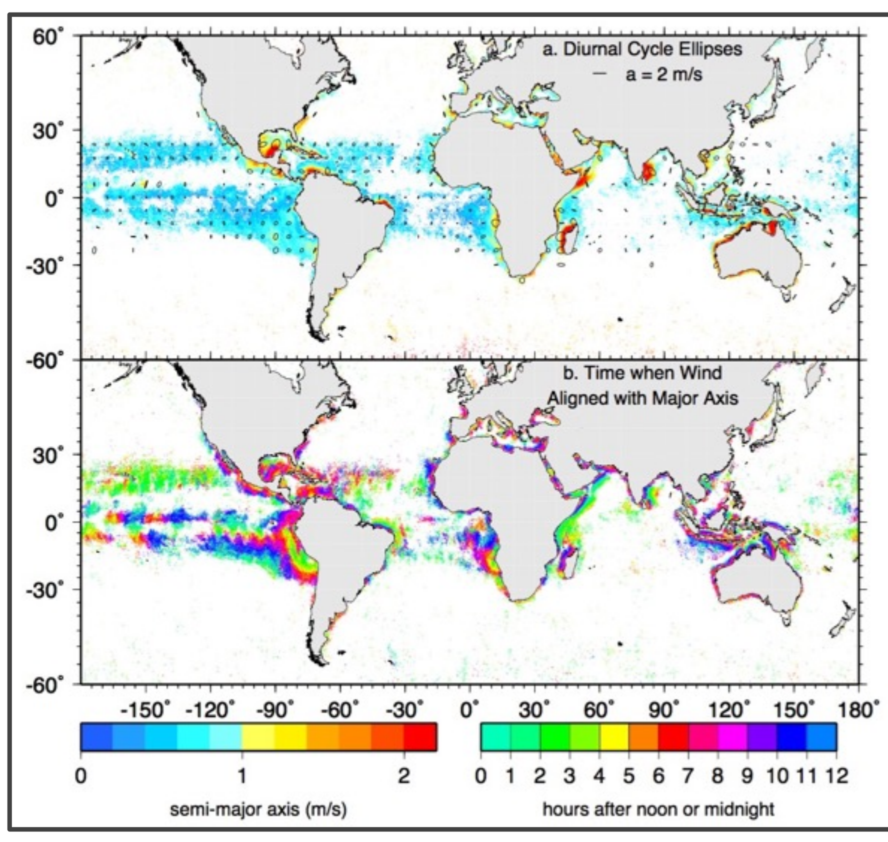
Motivation

- To improve parameterization of diurnal cycling of sea surface temperature, salinity and currents using in-situ and satellite observations and a process model.
- Hence saving on the computational expense of having to resolve the relevant ocean processes.
- To assess the net (rectified) role that diurnal winds play in the climate system.

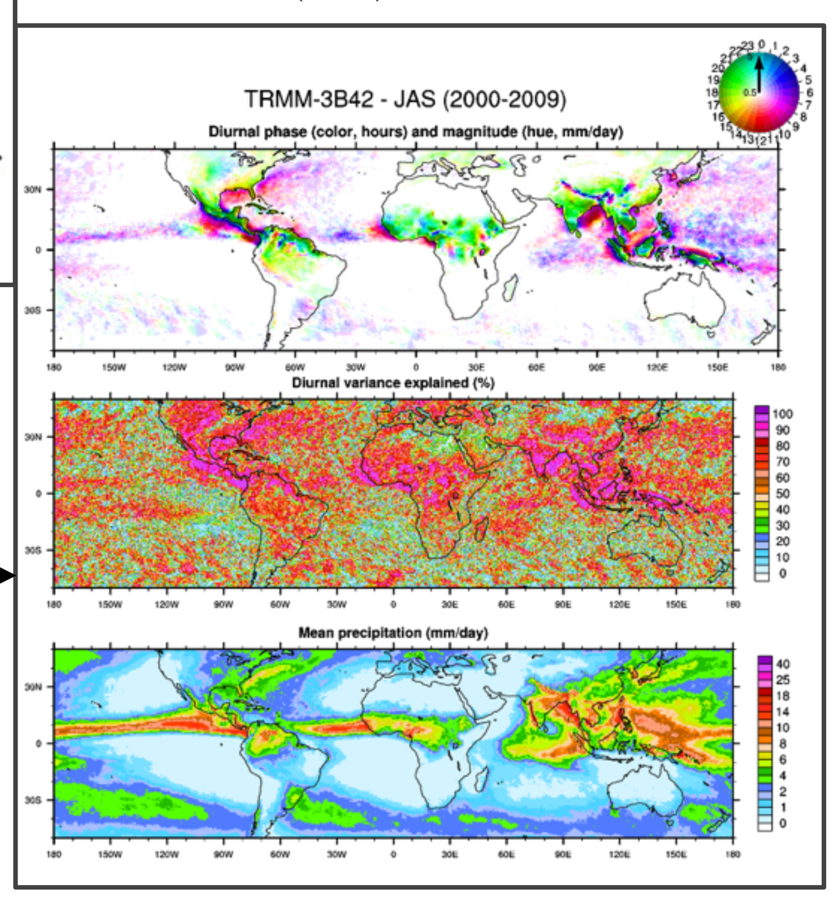
Observations

Introduction



- Locations with statistically significant diurnal wind variability are shown in color, with colors indicating the strength of the major axis. Wind ellipses are plotted once every 4 degrees.
- Phasing of diurnal cycle (indicated as time of day when wind is aligned along major axis).

From Gille et al. (2005).

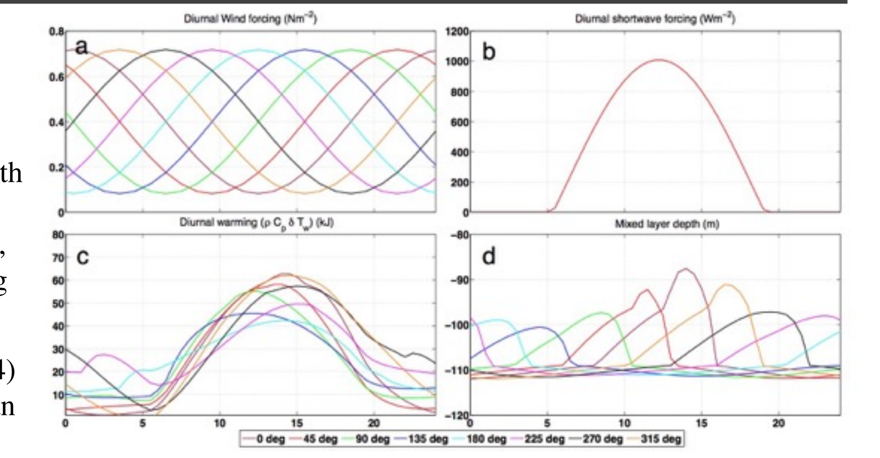


The diurnal cycle of precipitation using TRMM 3B42 3-houlry data for July/August/September. Amplitude and hourly phase of the first harmonic of precipitation (top) the variance explained (middle) and the JAS mean precipitation (bottom) in mm/day. (Neale, personal comm.)

Process Modeling

Probing physical processes with a one-dimensional upper-ocean model

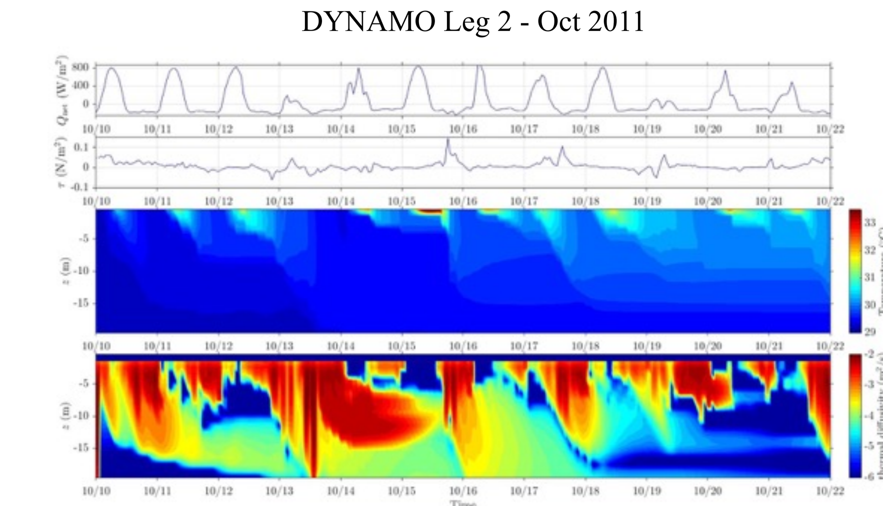
- The relative phasing of diurnal winds varies spatially (Gille et al., 2005), while diurnal radiative forcing is governed by the sun and therefore largely phase locked, with maximum surface heat flux Q_{net} near local noon.
- The diurnal forcing drives a diurnal cycle in "deep cycle" mixing below the depth range that directly responds to surface forcing, and the mechanisms responsible for this deep mixing have been the subject of considerable modeling and debate, though studies have tended to focus on buoyancy forcing effects while assuming no diurnal wind component (e.g. Smyth et al., 2013; Pham et al., 2013).
- We use a one-dimensional K-Profile Parameterizatio (KPP) of Large et al. (1994) run at 1 m (or finer) vertical resolution, allowing detailed analysis of upper ocean penetration of heat and momentum.
- The mixed-layer warming and mixed-layer depth are both strongly sensitive to the phasing of the diurnal wind forcing relative to the phasing of the surface heat forcing, Q_{net}.
- The results suggest a 50% difference in upper ocean diurnal warming, depending on the representation of the diurnal winds.



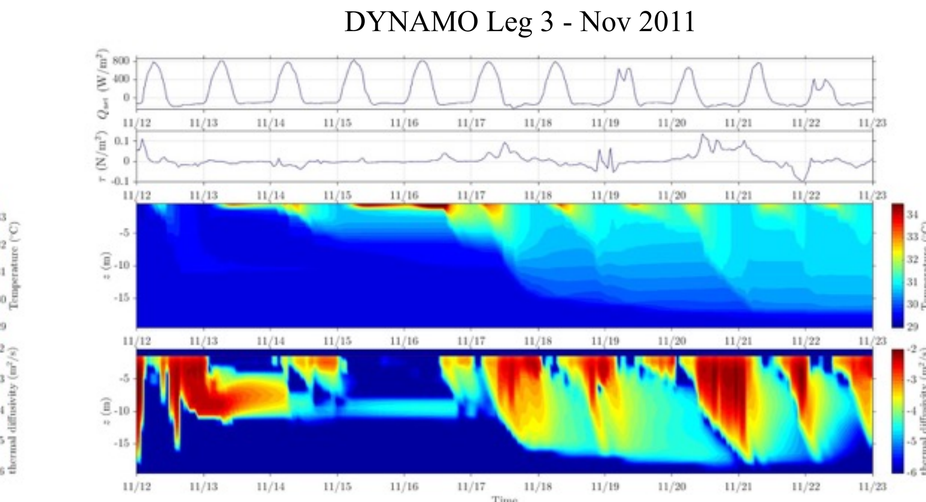
(a) Strength of diurnal wind as a function of time, for the 1D KPP model run (b) Surface forcing Q_{net} (c) Diurnal heat content gain for the mixed layer (computed as $\varrho C_p T_w$, where $T_w = T_{0m} - T_{25m}$. (d) Mixed-layer depth from model, computed as bottom of top boundary layer. Phase of 0˚ -> max. wind at midnight. 180˚ phase -> indicates a max. wind aligned with the max. surface heat flux Q_{net} .

DYNAMO Case Study

DYNAMO Leg 2 - Oct 2011



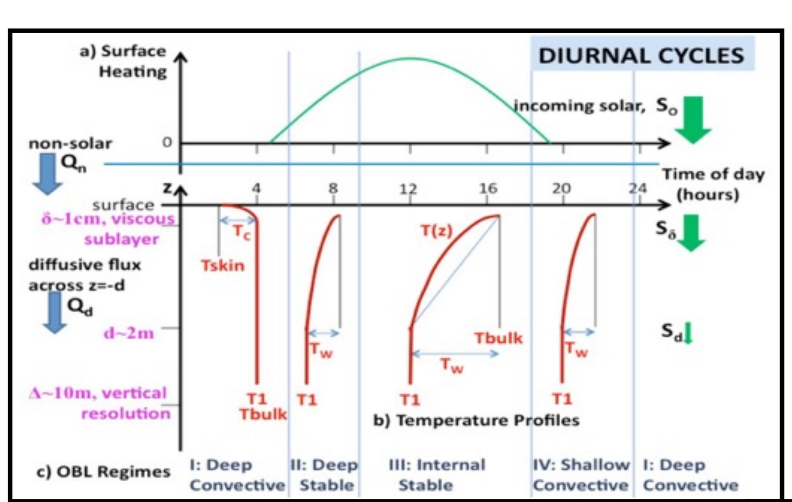
DYNAMO Leg 3 - Nov 2011



- The top two panels in both figures show the surface net heat and wind stress forcing during DYNAMO leg 2 and 3.
- The temperature profile evolution in time for the top 20m of 250m deep 1D KPP model forced with the observed windstress and heat flux is shown in the third panels from the top. The corresponding heat diffusivity in the top 20m of the water column is also shown in the bottom two panels.
- The diurnal cycle in upper ocean temperature and the penetration of heat to the lower levels during days of increased wind amplitudes shows that the wind and heat flux together lead to heat input to the ocean interior. This could then lead to a non-linear rectification of longer term variability in ocean heat uptake and related processes.
- Period of strong diurnal net heat flux into the ocean with weak winds leads to strong warming at the surface with very little mixing down below. This would then lead to high amplitude diurnal warming events which can also impact atmospheric boundary layer stability and convection, leading to nonlinear rectification of longer term variability in atmospheric dynamics (such as synoptic and MJO timescales)
- Some of these effects are not captured by the Large and Caron (2015) parameterization and we plan to work on translating some of these process understanding into improving the diurnal cycle model that can be used in global models.

Parameterization

Diurnal cycling at the sub-grid scale



Prognostic equations for the trapping of heat, T_w, freshwater (salt), S_w, and momentum, U_w above the bulk ocean column

- Four Ocean Boundary Layer (OBL) regimes for the diffusivity, K_d, are represented

I - Nighttime surface cooling; Very well mixed deep convective OBL of depth

II - Early morning surface heating; OBL depth scales with Monin-Obukhov depth,

III - Peak and afternoon surface heating; Internal diurnal boundary layer,

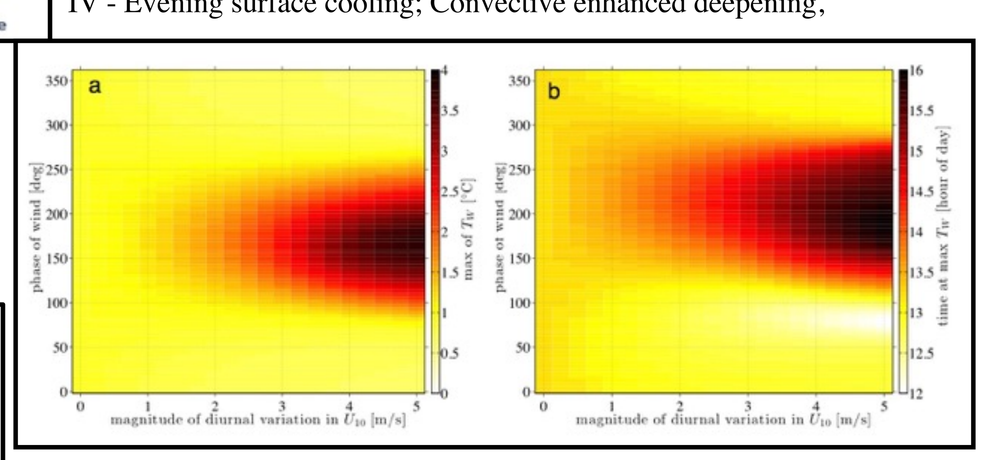
IV - Evening surface cooling; Convective enhanced deepening,

The diurnal cycles of (a) surface heating, (b) temperature profiles, and (c) ocean boundary layer regimes (OBL). (Caron and Large, 2011)

$$\partial_t T_W = H_d \frac{(p+1)}{p\,d} - K_d\, T_W \frac{(p+1)}{d^2}$$

$$\partial_t S_W = F_d \frac{(p+1)}{p\,d} - K_d\, S_W \frac{(p+1)}{d^2}$$

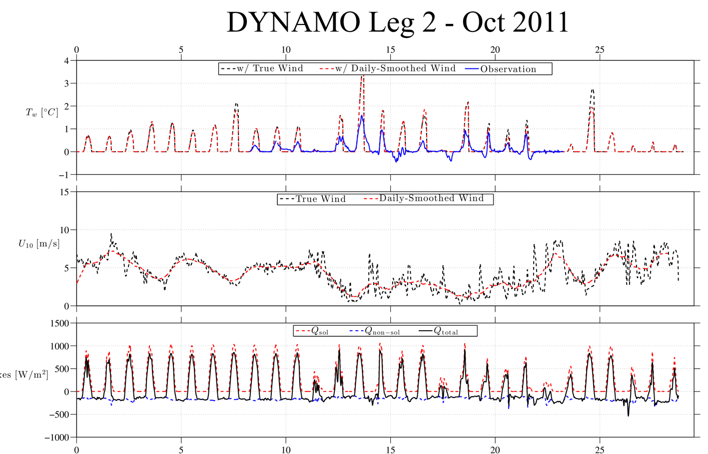
$$\partial_t V_W = u^{*2} \frac{(p+1)}{p\,d} - \nu_d\, V_W \frac{(p+1)}{d^2}$$



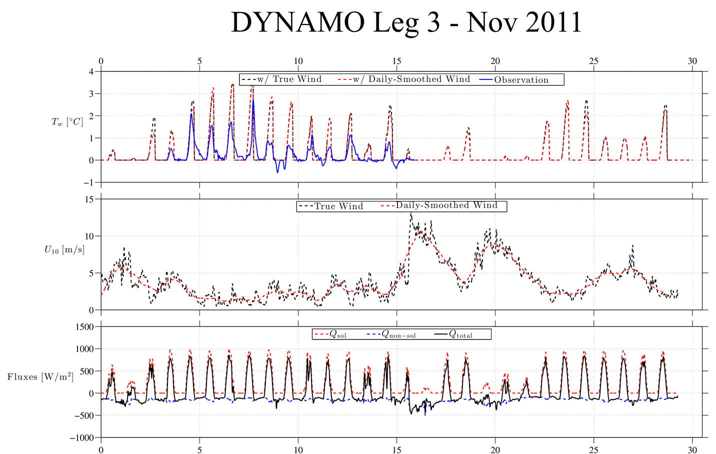
(a) Amplitude of maximum day–night surface temperature warming T_w , as a function of the amplitude of the diurnal wind (x-axis) and the phasing of the maximum wind (y-axis) from the Large and Caron (2011) model simulation. The wind phase 0˚ corresponds to maximum wind at noon, coinciding with maximum solar radiation. (b) Time of day when maximum surface warming T_w is observed.

DYNAMO Case Study

DYNAMO Leg 2 - Oct 2011



DYNAMO Leg 3 - Nov 2011

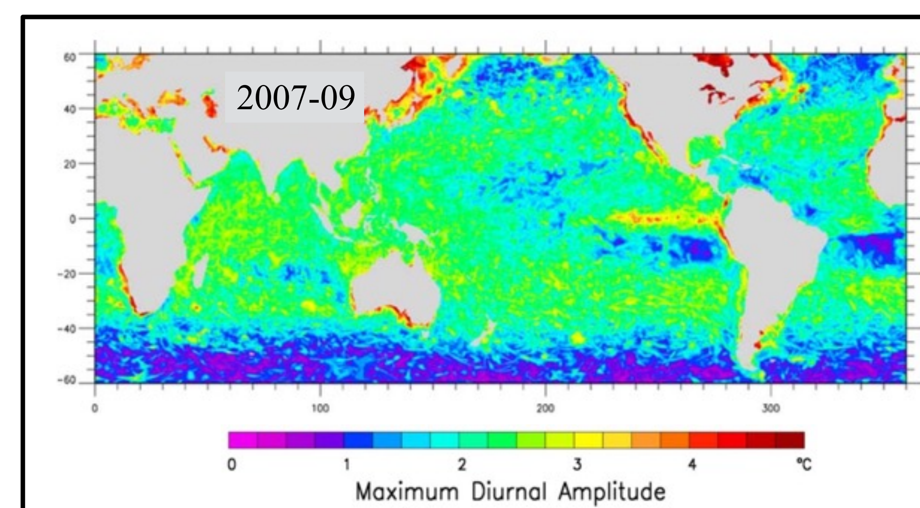


- The blue line shows observations collected by Jim Moum's group during DYNAMO leg 2 and 3, in comparison with model simulations in the top panel of both figures.
- Observed skin–bulk temperature differences (blue solid line) are well represented when the model is forced by diurnally varying winds (black dashed line in middle panels) or by daily average winds (red dashed line in middle panels), along with diurnally-varying buoyancy forcing (in bottom panels).
- However, the parameterization seems to cool off faster than the observations, suggesting that it still has limitations that we are working to improve. One possible source of error may stem from the dependence of mixed-layer heat storage on the phasing of wind relative to radiative forcing

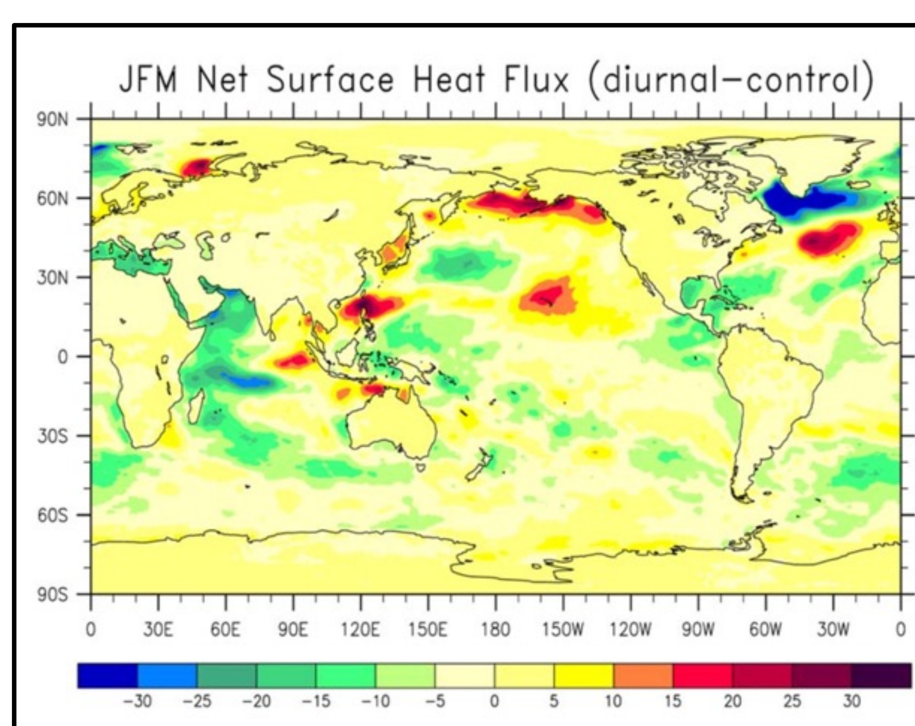
Climate Models and Future Work

Translating process understanding to improve climate models

- Characterize diurnal wind variability from multi-satellite data that are currently available, focusing on limits of detection from ASCAT and OSCAT.
- Incorporate RapidScat data into diurnal wind analysis. Compare scatterometer- derived diurnal wind cycles with tropical and extra-tropical mooring wind measurements and ship observations, as appropriate.
- Evaluate seasonal variability of diurnal winds.
- Using a 1D KPP model, assess how seasonal to interannual modulations to diurnal wind modify upper ocean structure.
- Using scatterometer data, assess sensitivity of diurnal winds to MJO, ENSO phase, and tropical instability waves. Assess interannual variability in diurnal winds.
- Modify climate model parameterization for diurnal mixed-layer processes, accounting for sensitivity to wind and buoyancy forcing.

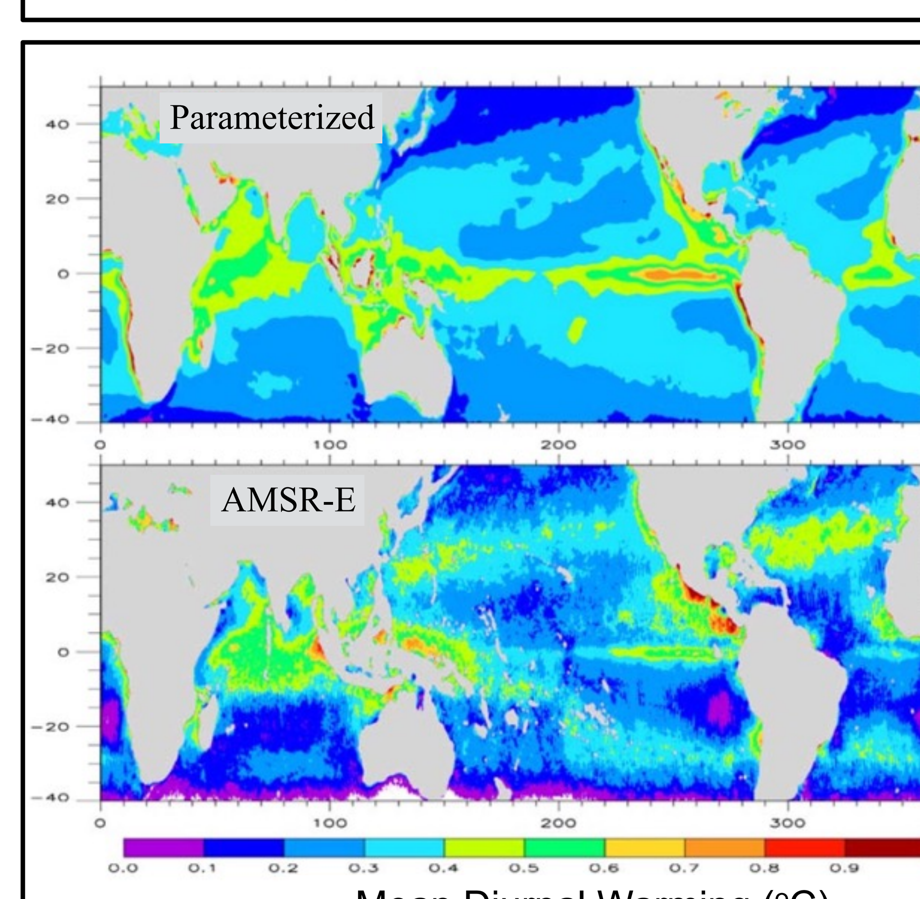


Maximum diurnal amplitude (T_w at 14:00 h) from diurnal cycle model constrained by observations during the 3 years, 2007–2009



Difference (diurnal - control) in 15 year (1990–2004) mean seasonal net surface heat flux, Q_{net} (W/m^2) due to the diurnal cycle parameterization for January-February-March (JFM) season.

Large and Caron (GRL, 2015)



Three year (2007–2009) mean diurnal amplitudes (bottom) from the AMSR-E satellite SST product and (top) from diurnal cycle parameterized model. Large and Caron (GRL, 2015)

Summary

- A newly developed diurnal cycle parameterization for sea surface temperature, salinity and momentum forced with observed forcing fields is able to represent the diurnal cycle in upper ocean temperature fields well. However, it shows a faster rate of cooling compared to observed temperature fields.
- Tests with a 1D KPP process model validate the behavior of the parameterized scheme, but also informs on the profile of mixing in the vertical in the diurnal warm layer. This will then be used to test if the assumed profile of mixing in the parameterization represents the processes well or if it has to be modified.
- We also use satellite and in-situ observations to inform on the variability of diurnal winds globally. The nonlinear rectification of the diurnal wind variability onto longer term climate variability will be explored in the future.