Estimation of Sea Surface Heating Anomalies During the Last Two Decades

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In-situ global net heat uptake: $0.77 \pm 0.06$ Wm$^{-2}$
Ocean: $0.62 \pm 0.05$; Deeper ocean: $0.062 \pm 0.038$
Land: $0.037 \pm 0.004$; Melting ice: $0.031 \pm 0.006$
Air T/q: $0.014 \pm 0.009$

The trends of 0–2,000 m ocean and CERES TOA heat flux anomalies are is $0.43 \pm 0.40$ W m$^{-2}$ decade$^{-1}$ and $0.50 \pm 0.47$ W m$^{-2}$ decade$^{-1}$, respectively. (Loeb et al., GRL 2021)
Other energy cycle components of the climate system could have related variations due to the fundamental linkage among these components within the energy cycle, especially over oceans such as turbulent heat (TH) flux.
Large TH and LH trends of ~ 0.35 Wm$^{-2}$/year were found. Explained as the changes of meteorological variables affecting these fluxes, especially SST, $\Delta q$ and wind.

Yu and Weller, BAMS 2007
Global climate change: warmer temperature, melting ice and sea level rise. Loeb et al. (2021) found accelerated heating, mainly for the ocean, from both TOA net radiation and in-situ observations.

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This study tries to analyze ocean heating changes from surface turbulence and radiation observations during the 21st century.

Data used: OAFlux data V3 monthly; CERES: EBAF Ed4.1 (monthly)
Oceanic Heat Flux and Energy Balance

- Ocean heating from surface to deep ocean:
  \[ R_{\text{net}_sfc} - TH - \nabla \cdot F - OH = 0; \quad (LH + SH = TH; \ SW + LW = R_{\text{net}_sfc}) \]
  Or, global ocean heating: \[ OH = R_{\text{net}_sfc} - TH \approx R_{\text{net}_{TOA}} \]

- Ocean heat balance anomaly:
  climatological heating removed; bias potentially reduced
  \[ \Delta OHB = \Delta TH - \Delta R_{\text{net}_sfc} + \Delta OH = 0 \] (focusing on TH fluxes here)

- Climatology: 2001 – 2005

- Observationally-based estimates of these anomalies may reveal systematic errors and/or uncertainties.

SW & LW: downward short-/long-wave radiative fluxes, respectively; LH & SH: upward latent/sensible heat fluxes, respectively \( \nabla \cdot F \): horizontal heat transport. \( \nabla \cdot F = 0 \) when averaged over globe; OH: ocean heating, ocean warming, \( \approx \) TOA Net; note: no surface turbulent heat flux observations over sea ice
Generally, local TH changes are within 30 Wm\(^{-2}\). Higher latitudes may have an increased TH release. However, TH release may be decreased at lower latitudes >>> decreased TH globally. TH and LH over Gulf Stream increased considerably, but no clear sign over Kuroshio, could be reduced.
Global monthly mean sea sfc TH & LH anomalies

Both estimated global sea sfc TH and LH fluxes showed a sign of decreases. Reduced heat release to atmosphere would keep more heat within the ocean.
Sea surface turbulent flux estimation

Bulk formula:

\[ \begin{align*}
LH &= \rho \, L_v \, c_e \, (U - U_s)(q_s - q_a) \\
SH &= \rho \, c_p \, c_h \, (U - U_s)(T_s - T_a) \\
E &= \frac{LH}{(\rho_w \, L_v)}
\end{align*} \]

LH, SH, E: the latent heat, sensible heat and moisture fluxes
\( \rho, \rho_w \): the air density, and sea-water density,
\( L_v \): the latent heat of vaporization
\( c_p \): the isobaric specific heat
\( c_e, c_h \): turbulent exchange/transfer coefficients, stability dependent
\( U, U_s \): wind speed & ocean-surface current velocity
\( T_s, T_a \): sea-surface temperature (SST), and potential air temperature
\( q_a, q_s \): specific humidity and saturation specific humidity

Annual mean systematic error could be about 7 W/m\(^2\) or 8% (Cronin et al. FMS, 2019; Yu et al., JC, 2017)
Global monthly mean SST, wind & humidity

Decreased surface wind and increased SST and sea surface humidity (but unclear in change of humidity gradient).

Long-term trends in windspeed, humidity and temperature could cause estimated turbulent trends.
Various changes in sea surface meteorological state variables: water/air temperature, humidity, and wind. Bulk formula and parameterized Ta vs Ts could generate spurious variations.
The estimated decreases in TH and LH fluxes are likely associated with the decreased sea surface wind and increased sea surface humidity (or decreased humidity gradient) estimates.
Ta, along with Ts, is directly related to flux estimates. However, Ta CANNOT be observed remotely.
Could be large variations related to major climate events, especially for surface radiative fluxes?
Ocean Heat Balance and Anomaly
(exremely large heating? or significant systematic errors or uncertainties)
(Note: if TOA net removed, these suppose to be ocean heating)

Seem increases though not strong. Which are major error sources contributing to these estimates: turbulent and/or radiative fluxes?
Strong relations among ocean heat balance errors and sea surface turbulent heat fluxes. Bulk formula, parameterized Ta vs Ts, and other variables could generate spurious variations.
Summary

- Sea surface turbulent heat flux and its anomaly estimated have decreasing trends during the 21st century, a same sign as TOA net radiation and in-situ observations.

- The ocean ‘heating’ estimated from a combination of surface net radiation and turbulent heat is much bigger than those from TOA net radiation and in-situ estimates.

- The ocean heat balance and its anomaly estimated should be close to zero, however, they generally increase. Large systematic errors and uncertainties could exist based on the 20 years of data.

- All bulk formula, meteorological state variables and surface radiative fluxes estimated could contribute to the systematic errors.
Sea surface turbulent flux data were obtained from OAFlux (http://oaflux.whoi.edu). Radiation data were obtained from the CERES ordering site (http://ceres.larc.nasa.gov/order_data.php).

Thank you!