Ship observations in the southeast Pacific confront coupled model heat budgets

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Introduction

Coupled models in the southeastern tropical Pacific often have +1°C SST errors below the stratocumulus cloud deck. Warmer SST is empirically related to lower cloud fraction; models simulating this interaction have a positive feedback toward higher SST and lower cloud fraction. To understand model SST errors, model surface heat budgets are compared to three optimized turbulent flux analyses and ship observations from 8 research cruises along 20°S, 75-85°W.

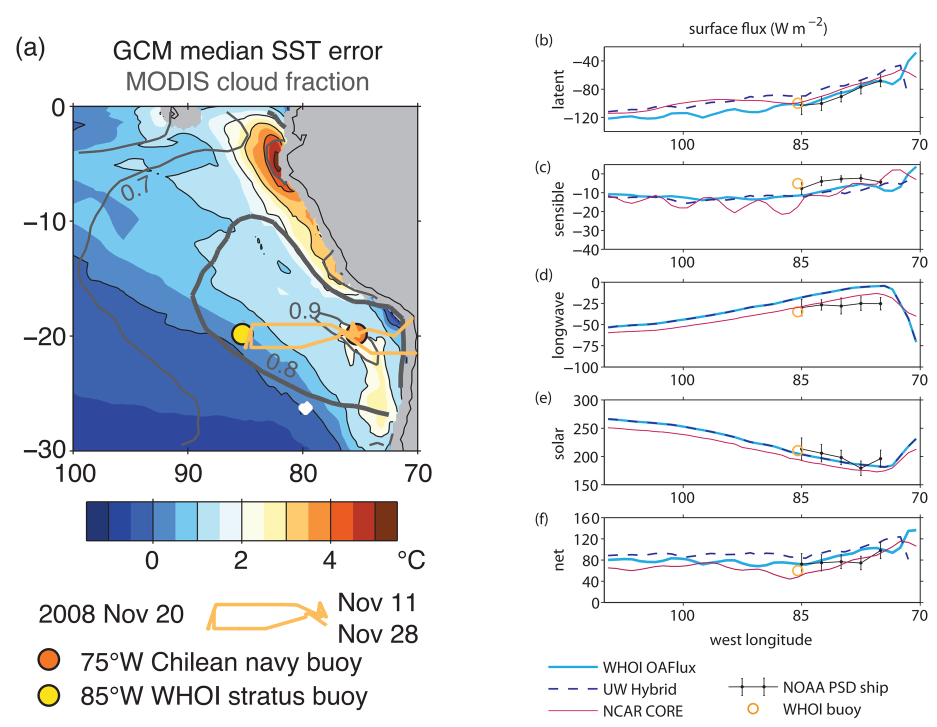

Fig. 1. (a) Median GCM SST error (shaded, °C) and MODIS satellite cloud fraction (gray contour). Half of the CMIP3 models have errors greater than the median SST error. The yellow line shows the track of VOCALS leg 2. (b-f) Three surface flux analysis products (WHOI OAFlux, UW Hybrid, and NCAR CORE) compare favorably to ship observations along 20°S.

Observed clouds and radiation

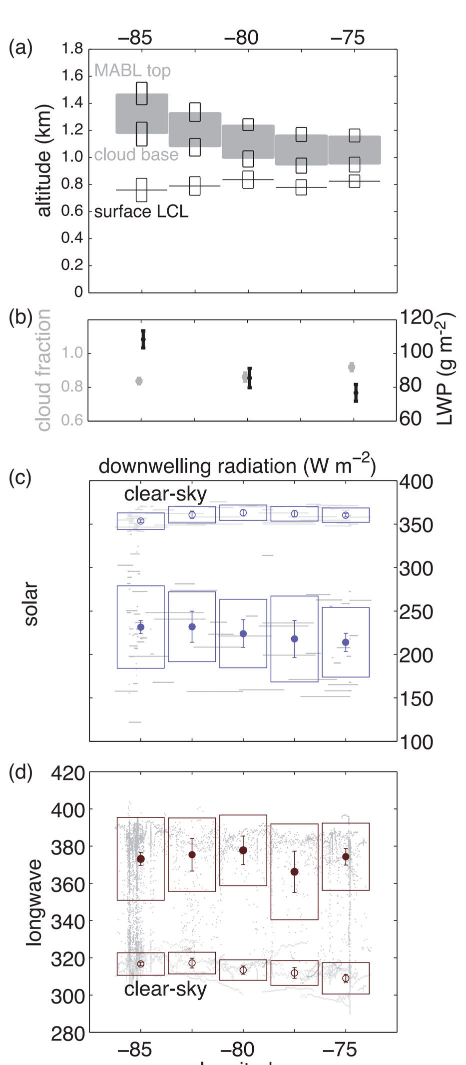

Fig. 2. Average cloud properties varying with longitude along 20°S.
(a) Cloud top height, base height, and lifting condensation level (LCL) for a parcel lifted adiabatically from above the surface layer. Cloud top and base height rise westward, LCL and cloud thickness are relatively constant.
(b) Cloud fraction decreases slightly westward, as liquid water path (LWP) increases. (LWP courtesy P. Zuidema)
(c) Solar downwelling surface radiation, and modeled clear-sky radiation.
(d) Longwave downwelling surface radiation, and modeled clear-sky radiation.

Despite gradients in cloud geometry and LWP between 75° and 85°W, surface radiation and cloud radiative properties have little gradient.

Simulations have too few clouds

Models have too strong net surface radiation because they have too few clouds (0.45 compared to 0.9, Fig. 3). On the whole, simulated clouds have approximately the right cloud radiative forcing when present. Longwave cloud forcing offsets half of the 120 W m^{-2} solar cloud forcing in observations, and its error offsets about half of solar cloud forcing error in models.

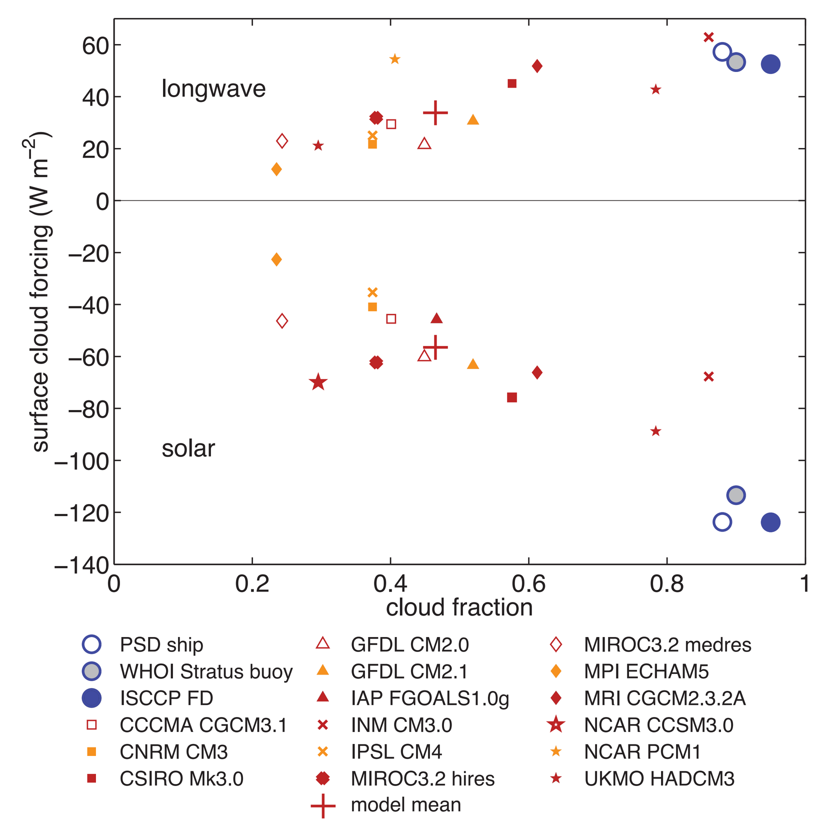

Fig. 3. Solar and longwave cloud forcing as a function of cloud fraction simulated CMIP3 models (red/orange), compared to stronger cloud fraction and cloud forcing from ISCCP satellite retrieval, the WHOI Stratus buoy, and NOAA ship observations (blue/gray).

Cloud radiative forcing

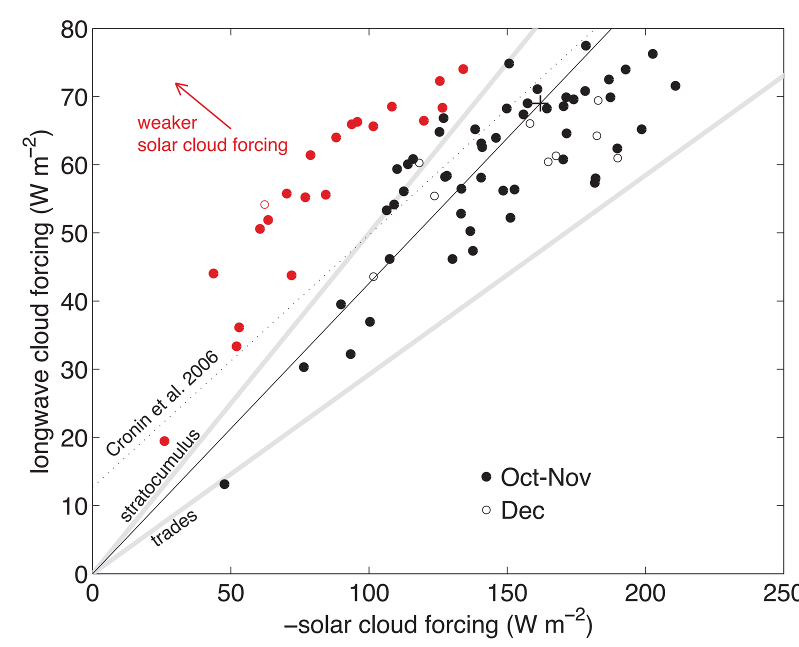

Fig. 4. Observed daily average longwave vs. solar cloud forcing for clouds along 20°S in the eastern Pacific. Red points have relatively weak solar cloud forcing, $|S-S_0| < 2(R-R_0)-10$ W m^{-2}.

Daily solar cloud forcing along 20°S falls within a wide range, from the stratocumulus regime $|S-S_0|=2(R-R_0)$ to the warmer trade cumulus regime $|S-S_0|=3(R-R_0)$. Red points approach a cooler climate regime. Fig. 5 shows the red points have weaker solar cloud forcing, because of 3% lower cloud fraction. *When* the clouds are present matters: clearing is in the afternoon, having a strong effect on the radiation. Cloud fraction weighted by the clear-sky solar flux (crosses) is effectively lower than daily average cloud fraction.

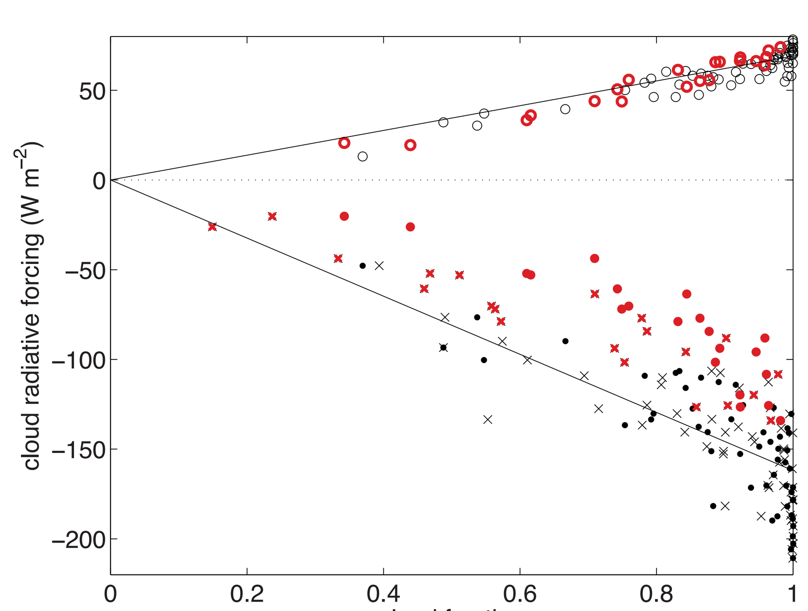

Fig. 5. Observed longwave (circles) and solar (dots) surface cloud radiative forcing. Red points as in Fig. 4. Crosses show solar cloud forcing for the clear-sky weighted cloud fraction, which is less than the daily cloud fraction because of clearing in the afternoon.

Surface fluxes imply subsurface cooling

In Fig. 6 observed and model heat budgets are ranked in order of the solar radiation absorbed at the surface for October along 20°S, 75-85°W. Because of the lack of clouds, the least solar forcing is 30 W m^{-2} higher than the observations, but clouds are not the only model error. The upper ocean gains a net heat flux of 30 W m^{-2} beyond its change in SST, implying that ocean subsurface heat transport cools the mixed layer and SST (shown by the residual).

Coupled general circulation models mostly do not simulate enough cooling by ocean transport, compounding warm SST errors. Fig. 6b shows each model's anomaly from the mean observed heat budget. Most models have too little cooling in the ocean transport residual. With excess radiative warming and insufficient subsurface cooling, model oceans reach a warmer SST at which turbulent fluxes (mostly evaporation) provide the cooling necessary to balance the heat budget.

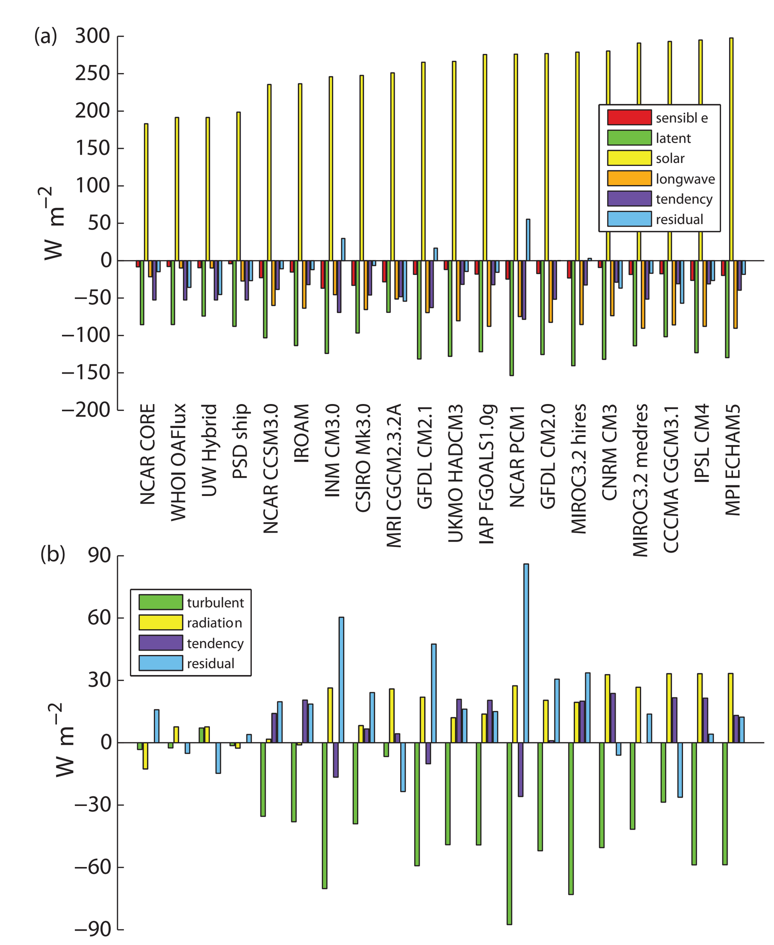

Fig. 6.
(a) October 20°S, 75-85°W surface heat budget for 4 observational products and 16 models. All terms including the residual sum to zero.
(b) Anomalous heat budget (observational average subtracted) with solar and longwave radiation combined and turbulent fluxes combined. The residual is due to transport in the subsurface ocean.

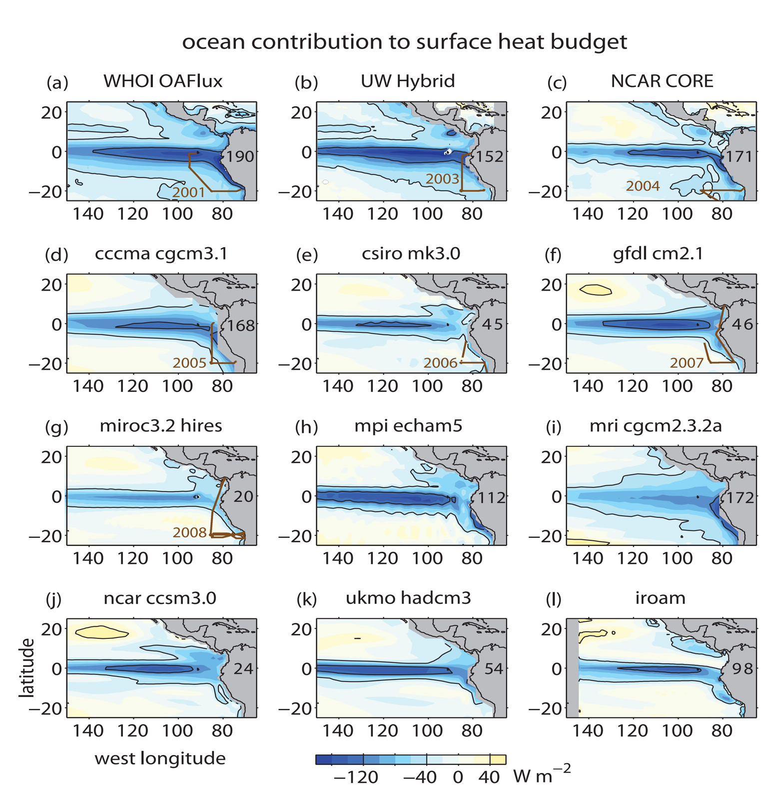

Fig. 7. (a) Long-term surface heat budget residual for 3 observational products and 9 models. Ocean heat transport must provide heat flux equivalent to the residual to maintain the SST.

Figure 7 shows tropical east Pacific long term residual cooling due to the subsurface ocean heat transport for the 3 optimal analyses and 9 coupled models. Most of the models have too-weak off-equatorial cooling. The mechanisms by which the ocean cools its surface remain unknown, and may involve salt fingering, vertical mixing through the thermocline by near-inertial oscillations or geostrophic eddies where the halocline crosses the thermocline.

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