Constraining the southeastern tropical Pacific heat budget with observations

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Southeasterly winds round the subtropical High and blow on the surface of the Pacific Ocean along the South American coast of Chile and Peru. The alongshore wind drives offshore ocean Ekman transport and coastal upwelling of cold nutrient-rich water. Cool sea surface temperature (SST) extends westward into the southeastern tropical Pacific Ocean due to the ocean transport and atmosphere-SST feedbacks. SST also stays cool due to the shade of a canopy of stratocumulus clouds. A strong inversion between the cool marine air and warm potential-temperature air subsiding from above caps the clouds. Warmer SST and deeper convection are found north of the equator because north Pacific-American winds cross the Central American isthmus and blow offshore, unfavorable for upwelling.

The meridional asymmetry of eastern tropical Pacific SST and atmospheric heating is a basic element of the observed Hadley circulation and its seasonal cycle, yet it is poorly simulated in most general circulation models (GCMs). Simulated southeastern tropical Pacific SST is usually too high (+1.6°C median), and models simulate a variety of well-known “double intertropical convergence zone (ITCZ)” errors (Mechoso et al. 1995, de Szoeke and Xie 2008). Models have difficulty in resolving and parameterizing processes, especially wind flowing around the high and narrow Andes Mountains, offshore ocean eddy heat transport, and persistent shallow stratocumulus clouds and their interaction with aerosols and drizzle. Hypotheses tailored to improve our understanding of these key processes were tested in the VAMOS Ocean Cloud Atmosphere Land Study (VOCALS). To best effect model improvement, VOCALS brings together a hierarchy of models in the VOCALS Model Assessment along with field observations from the VOCALS Regional Experiment (REx) in October-December 2008 (Wood et al., this issue).

The NOAA research vessel Ronald H. Brown made the first of a series of Stratocumulus cruises to the southeast Pacific in 2001 during the East Pacific Investigation of Climate (EPIC, Bretherton 2002). The Stratocumulus research cruises culminated with two cruises for VOCALS REx in 2008. In all, 7 Stratocumulus research cruises were made in years 2001 and 2003-2008 to the Woods Hole Oceanographic Institution (WHOI) Stratus buoy at 20°S, 85°W. The track of the Stratocumulus cruise in each year is marked in Figure 1a-g. Each Stratocumulus cruise traversed the 20°S parallel between 85° and 75°W, collecting observations of surface meteorology, SST, surface radiative and turbulent fluxes, and cloud fraction, cloud base and top height, and liquid water path. Rawinsondes were also released around the clock providing winds and the thermodynamic profiles of the marine atmospheric boundary layer (MABL) and entire free troposphere. These seven years of observations provide seasonal climate data suitable for assessing GCMs and gridded analysis products in this remote climatically important region (de Szoeke et al. 2010, submitted).
Gridded global and basin-wide atmosphere-ocean surface flux data sets are another recent advance for atmosphere-ocean interaction studies (e.g. ISCCP FD, Zhang et al. 2004; UW Hybrid, Jiang et al. 2005; WHOI OAFlux, Yu and Weller 2007; NCAR CORE, Large and Yeager 2008). The gridded flux data are compared with the seven years of ship observations along 20°S. Figure 2 shows all the terms of the surface heat flux for the October climatology of three research-quality gridded flux products, NOAA Physical Sciences Division (PSD) ship observations, and WHOI buoy observations. Solar radiation (Figure 2c) is the only warming term in the budget. Latent heat flux (evaporation, Figure 2a) is the largest cooling, followed by longwave thermal radiation (Figure 2d). Sensible heat flux (Figure 2b) is small. The eastern tropical Pacific, with difficult-to-simulate climate feedbacks and relatively few historic observations, is a challenging test of the gridded surface flux products, yet the gridded products perform remarkably well. All three gridded products agree to within sampling variability of the ship data at almost every longitude. This suggests that studies can proceed to use these convenient gridded flux data sets for model evaluation. This article refers to observationally constrained gridded flux data sets as “observations” when they are compared to model simulations.

The net heat flux in Figure 2e is not zero. Part of the imbalance of the surface heat fluxes results in a 0.7°C per month warming tendency of the SST along 20°S in October. This SST tendency consumes 50 W m⁻² for a 50 m mixed layer, leaving a residual 30 W m⁻² surface heat flux. The cooling must be provided from within the ocean, either laterally or from below, for the SST to warm by only the observed amount. While previous studies have stressed the importance of clouds in maintaining the cool southeastern tropical marine climate, even under observed clouds the imbalance of surface fluxes requires the ocean to remove additional heat from the surface mixed layer.

Errors in the heat budget could explain the substantial simulated SST errors in the southeastern tropical Pacific Ocean. How well do models simulate the observed heat balance? Figure 2f shows observed and modeled heat budgets for October averaged along 20°S, 75-85°W, ranked by solar radiation. All but one model has too-strong latent and sensible turbulent heat fluxes, and some models have sensible heat flux errors several times the observed (10 W m⁻²). The lowest simulated solar flux is 30 W m⁻² stronger than the highest observed solar flux, consistent with a lack of cloud radiative forcing in the models.

On average 2/3 of the solar excess is compensated by stronger longwave cooling, with the longwave and solar radiative errors correlated among models at \( r = -0.86 \). After canceling the compensating radiative errors, the net radiation error is smaller than the magnitude of the net turbulent flux error for most models. Figure 2g shows the heat budget term errors relative to the mean of the three gridded flux products and ship observations.

The total turbulent heat flux error combines sensible and latent heat flux errors. It is a cooling error for all simulations. The increased turbulent flux reflects increased wind speed and lower air-sea temperature differences. The simulated eastern Pacific heat
budgets in Figure 2g reveal that the ocean provides too little cooling of the surface mixed layer in all but 3 of the 16 models. Therefore, in addition to their inadequate cloud radiative forcing, coupled model ocean simulations need to transport and deposit more cooling into the offshore southeastern Pacific surface mixed layer.

The flux balance illustrates how simulations reach a new equilibrium with higher SST: Higher than observed solar flux due to a lack of clouds warms the ocean surface. In addition, the ocean too weakly cools the mixed layer. The SST reaches a warmer state, whereby turbulent flux (mostly evaporation) and thermal emission give off more heat to balance the solar excess and subsurface ocean cooling deficit.

VOCALS REx sought evidence of processes responsible for subsurface ocean cooling, which may be poorly represented in GCMs. Cooling could be achieved by vertical mixing in near-inertial oscillations, advection of temperature across differentially-inclined temperature and salinity gradients by geostrophic eddies (Toniazzo et al. 2009), or horizontal eddy heat flux divergence (Colbo and Weller 2007).

The ocean’s contribution to the annual average surface heat budget is calculated as the residual of the surface heat fluxes by assuming the long term tendency of SST is negligible. Gridded flux products (first row Figure 1a-c) show the spatial distribution of the ocean contribution to the surface heat budget. With low SST in the eastern Pacific, the strong tropical solar warming is not completely balanced by longwave radiation and turbulent surface flux. Thus the ocean gains heat through the surface. This is especially true of the cold-SST upwelling zones, with strongest cooling along the equator and South American coast. The three observational data sets have ocean heat budget contributions with cooling of $-40 \text{ W m}^{-2}$ to about $100^\circ \text{W, 20}^\circ \text{S}$. The ocean heat flux from nine coupled model simulations follows in Figure 1d-l. There is variety among the models in the overall strength of the ocean cooling contribution. Most models predict the cooling in the equatorial upwelling region well, but underpredict cooling along the coast of Peru.

The meridional north-south hemisphere difference in area-integrated ($90^\circ \text{W to the coast, equator to } \pm 20^\circ \text{ latitude}$) ocean cooling is a metric of its meridional asymmetry. This metric (in terawatts, TW) is printed on South America for each realization in Figure 1. The three observational data sets have asymmetry of $171\pm19 \text{ TW}$. Only models (d) and (i) have asymmetry in this range. Models (e,f,g,j) and (k) have north-south asymmetry less than 1/3 of observed, with equal or more ocean cooling in the northern hemisphere than the southern hemisphere South American coast.

The surface heat budget observed in the southeast tropical Pacific Ocean from the 7 years of Stratocumulus research cruises between EPIC 2001 and VOCALS REx 2008 (mostly in October) shows a $30 \text{ W m}^{-2}$ imbalance. The imbalance implies the ocean must be transporting cold water into, and removing heat from, the surface mixed layer in boreal autumn. Along with stratocumulus clouds, this ocean cooling contributes to lower SST in the southern-hemisphere tropical Pacific. Gridded flux data sets corroborate the ocean’s cooling contribution to the surface heat budget and show its spatial pattern. Most models simulate the strong ocean cooling contribution along the equator, but many have too
weak an ocean cooling contribution along the South American coast and too little cooling distributed offshore to the stratocumulus region. Diagnoses of ocean and coupled model experiments are required to understand how models succeed or fail to simulate ocean cooling through coastal upwelling, geostrophic eddies, offshore transport, and vertical mixing processes in the southeastern tropical Pacific. Subsurface ocean observations from VOCALS REx will help quantify these important processes.

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Figure 1. Plan view of ship tracks for EPIC 2001, Stratocumulus 2003-2007, and VOCALS REx 2008 research cruises (brown lines, panels a-g). Colored contours show the annual-average ocean contribution required to balance the surface heat budget. Negative values imply the ocean is cooling the surface mixed layer. Panels (a-c) are 3 observation-based gridded flux products, while (d-l) are 9 coupled model simulations. The number printed on South America is the north-south asymmetry of the area-integrated ocean contribution (terawatts) east of 90°W and equatorward of 20°S.
Figure 2. Left (a-e): October climatology along 20°S of three gridded air-sea flux products compared with NOAA PSD ship and WHOI buoy in situ observations. Radiative fluxes for the gridded products are based on the ISCCP Flux Data (FD). Latent (a) and sensible (b) turbulent flux, and thermal longwave (c) and solar (d) radiative flux, and the net sum of all terms (e). Right (f and g): October flux component climatology averaged along 75-85°W, 20°S for the three gridded flux products, ship observations, and 16 coupled model simulations. Data sets are ranked by solar radiation. Panel (g) shows anomalies relative to the mean of the four observational data sets.
Selected References


