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Abstract. The oceanic meridional heat transport (T_O) implied by an atmospheric General Circulation Model (GCM) can help evaluate a model's readiness for coupling with an ocean GCM. In this study we examine the T_O from benchmark experiments of the Atmoshperic Model Intercomparison Project, and evaluate the sensitivity of T_O to the dominant terms of the surface energy balance. The implied global ocean T_O in the Southern Hemisphere of many models is equatorward, contrary to most observationally-based estimates. By constructing a hybrid (model corrected by observations) T_O, an earlier study demonstrated that the implied heat transport is critically sensitive to the simulated shortwave cloud radiative effects, which have been argued to be prinipally responsible for the Southern Hemisphere problem. Systematic evaluation of one model in a later study suggested that the implied T_O could be equally as sensitive to a model's ocean surface latent heat flux. In this study we revisit the problem with more recent simulations, making use of estimates of ocean surface fluxes to contruct two additional hybrid calculations. The results of the present study demonstrate that indeed the implied T_O of an atmospheric model is very sensitive to problems in not only the surface net shortwave, but the latent heat flux as well. Many models underestimate the shortwave radiation reaching the surface in the low latitudes, and overestimate the latent heat flux in the same region. The additional hybrid tranpsort calculations introduced here could become useful model diagnostic tests as estimates of implied ocean surface fluxes are improved.

1. Introduction

The oceanic meridional heat transport (T_O) implied by an atmospheric General Circulation Model (GCM) can help evaluate a model's readiness for coupling with an ocean GCM. In this study we examine the (T_O) from AMIP2 simulations and evaluate its sensitivity to the dominant terms of the surface energy balance. Gleckler et al. (1995, hereafter referred to as G95) demonstrated that in AMIP1 the T_O implied by AGCMs was critically sensitive to the simulated cloud radiative effects. In many models excessive shortwave cloud-radiative cooling in the low latitudes led to insufficient surface heating, resulting in wildly different profiles of (T_O) in the Southern Hemisphere (SH). Many of the models in fact had a global ocean heat transport in the SH mid-latitudes that was northward. While heat transport in the South Atlantic is believed to be northward, estimates for the global ocean suggest a maximum transporsport in both hemispheres of greater than 1PW toward their respective poles (Trenberth, 1994).

G95 exploited ERBE measurements (Barkstrom et al, 1990) to construct a hybrid transport $\tilde{\mathrm{T}}_O$, which was a cross between the simulated net ocean surface heating with corrections in the observed top-of-atmosphere (TOA) energy balance. Specifically, deficiencies in the simulated TOA shortwave cloud radiative forcing (SWCRF, Cess et al., 1990) were corrected with estimates derived from ERBE radiances. The resulting T_O looked much more realistic, with most hybrid-adjusted models revealing the expected southward T_O in the SH. The results from this study led many to conclude that deficiencies in shortwave cloud radiative effects were the dominant problem in the implied (T_O) of AGCMs, and hence key to improving coupled model integrations (Climate Change, 1995, The Second Assessment of the IPCC).

Several years after the G95 study, Hack (1998) diagnosed (T_O) more closely to better understand the improvements in CCM3 over CCM2. Somewhat contrary to the findings of G95, Hack (1998, hereafter referred to as H98) demonstrated that the improvements in CCM3 were largely due to a reduction in the tropical latent heat flux that was primarily attributable to a deep formulation for parameterized moist convection. Considering the findings of G95 and H98 collectively, it is easy to imagine how a model's meridional distribution of net surface heating (and thus T_O) could be plausible but for the wrong reasons. For coupled ocean-atmosphere models, each term of the surface energy budget must be realistically simulated, not just their net effect.

2. Methodology

In this study we revisit the implied T_O in AMIP2 simulations and apply the diagnostic of G95. We then extend the hybrid $\tilde{\mathrm{T}}_O$ concept (model corrected by observations) to adjust the dominant terms of the surface energy balance instead of the TOA cloud radiative effects. This approach is less robust than the test of G95 because the observationally based TOA clear-sky shortwave measurements (from which cloud radiative forcing estimates follow) are more reliable than ocean surface flux estimates. However, by correcting for the dominant surface terms (incoming solar heating and latent heat cooling) we can revisit the results of G95 in the context of the findings of H98 for the suite of AMIP2 simulations. In what follows we use much of the terminology introduced in G95. The ocean heat transport

(T_O), implied by a model is calculated from the net ocean surface energy balance:

$$T_o(\phi) = 2\pi a^2 \int_{-\pi/2}^{\phi} [< N(\phi) > -\alpha] \cos(\phi\prime) d\phi\prime \tag{1}$$

where a is the radius of the earth, ϕ is the latitude (in radians), N is the net surface heat flux and the <> brackets denote a zonal average that is weighted by the fraction of ocean at each latitude. The area-weighted global ocean average N is represented by α , in which ensures a physically plausible result of no transport at the endpoint pole of integration. The choice of subtracting α uniformly in latitude is conventional but in fact rather arbitrary. The terms of the net surface heat balance are defined as:

$$N = SW + LW + LH + SH \tag{2}$$

with SW and LW respectively representing the net surface shortwave and longwave radiation at the ocean surface, LH the latent heat flux, and SH the surface sensible heat flux (all defined as + downward). In G95, the total atmospheric and ocean implied heat transport (T_{A+O} was partitioned into clear-sky and cloudy-sky TOA shortwave effects (T_{SWclr} and T_{SWCRF} respectively). T_O was then computed as a residual of T_{A+O} - T_A (the implied atmospheric transport) from which the following relation was derived:

$$\tilde{\mathrm{T}}_O \cong T_O + \delta T_{SWCRF} \tag{3}$$

yielding an adjustment to a model's implied ocean transport corresponding to the T_{A+O} differences between the model and observations ($\delta T_{SWCRF} = T_{SWCRF}^{Model}$ - T_{SWCRF}^{ERBE}). In G95 it was argued (and re-confirmed in this work) that the clear-sky model biases ($\delta T_{SWclr} = T_{SWClr}^{Model}$ - T_{SWClr}^{ERBE}) were of secondary importance to the implied heat transport sensitivity, hence the approximate relation of Eq.(3). We have also ruled out the possibility that LW or SH biases may have a comparable impact on the T_O in AMIP2 simulations.

3. Data: Models and Observations

The subset of models in the Atmospheric Model Intercomparison Project (AMIP, Gates et. al., 1999) II database used here (Table 1) include only those for which all terms surface and TOA energy budgets are available. All results in this study are defined as long term 'climatological' means, which for the case of the AMIP2 simulations is roughly 17 years in length. It is important to note that the simulations used here are not representative of current model versions. In any case, the features we are interested in here are quite sensitive to parameterization tuning, and therefore for our purposes it is the distribution of the collective that is of particular interest, not the individual simulations.

Observationally-based estimates of TOA (top of atmosphere) radiative fluxes are taken from ERBE (Barkstrom et al, 1990). For the surface fluxes, we focus on the dominant terms SW and LH. Estimates of SW are taken from the Southampton Oceanographic Centre (SOC) climatology (Josey, 1999) as well as two satellite derived estimates originating from the Global Energy Water Experiment Surface Radiation Budget (Darnell et al., 1992 and Pinker, 1992). The SOC climatology estimate of the latent heat flux is also be used along with the UWM/COADS estimate (daSilva, 1992). Finally, transport estimates global ocean T_O are taken from Trenberth (1994).

4. Results

The T_O from 17 AMIP2 models and observational estimates is shown in Figure 1, and the ERBE corrected calculation (Eq 3) is shown for this newer set of models in Figure 2.

Collectively, the situation has improved somewhat from the earlier generation of AMIP1 models in that fewer models exhibit northward heat transport in the SH. The cause of the dramatic correction (Figure 2) for many models results from excessive SWCRF in the lower latitudes (Figure 3). A strong relationship (R = .74) between the SWCRF and the surface SW (Figure 4) is not surprising and reinforces our interest to investigate the relative importance of the surface SW on the implied T_O. The natural extension to revisit the findings of H98 will be to examine the effects of LH with a comparable measure.

The AMIP2 SW is shown in Figure 5. The observational dataset used for comparison is derived from ISCCP data with two algorithms (Pinker, 1992, and Staylor, 1992). While these observationally-based estimates are less reliable than their ERBE TOA counterparts, they suggest (Figure 5) that most models underestimate the low latitude SW, which is completely consistent with the SWCRF seen in Figure 3. The comparison of the simulated LH with the in-situ based estimates is also intriguing (Figure 6). Most all models have much more evaporation in the tropics than either of the COADS based climatologies. The uncertainty in theses observations is significant, but they are among the most reliable estimates available (Taylor et al, 2000). Reanalysis products are not shown, because the reanalysis implied (T_O suggests they suffer from deficiencies very similiar to the AMIP AGCM's. Surface fluxes are also widely recognized as among the lesser accurate reanalysis fields (Kalnay et. al.,1996).

To investigate the findings of H98 in the broader context of the suite of AMIP2 simulations, we construct a two new hybrid (model corrected by observations) implied $\tilde{\mathrm{T}}_O$'s, but this time making adjustments with the observationally-based SW and LH. We first construct hybrid surface net heat fluxes:

$$\tilde{\mathrm{N}}_\zeta = N + \delta_\zeta \qquad (4)$$

where ζ represents either SW or LH, with δ_ζ corresponding to the model corrections with observations (δ_{SW}=SW_{obs} - SW_{model}, δ_{LH}=LH_{obs} - LH_{model}).

From the $\tilde{N}_\zeta$ terms, adjusted global ocean averages (α's Eq. 1) can be can be computed followed by the hybrid transports $\tilde{T}_{O,SW}$ and $\tilde{T}_{O,LH}$ (Eq. 1). These observational corrections, not being true to the simulation, can be expected to result in relatively large α's compared to an internally consistent simulated surface energy balance (which in all the models used here is $< 5\mathrm{Wm}^{-2}$). Note however that the global average imbalances are uniformly removed in the T_O diagnostic calculation via α, and it is therefore only the meridional distributions that are being corrected by observations. Results of both calculations are shown in Figures 7 and 8.

5. Conclusions

Qualitative comparisons of the diverse collection models in Figures 7 and 8 confirm the findings of Hack (1998), which suggest that the implied meridional heat transport may have a sensitivity to latent heat biases that is comparable to that of cloud-radiative effects. These are of course intimately intertwined, and unraveling their interrelated processes may depend very much on the combination of parameterizations employed in a model, perhaps only to be resolved on a model-by-model bases. But routine use of a collection of hybrid implied T_O diagnostics may prove useful in the model development process. While the uncertainties in the observed surface flux terms are large, it is possible that further tests will help establish more faith in their meridional distributions (e.g., via bias cancellation) than we have in their absolute values. Moreover, the simple tests introduced here provide additional clues as to whether or not a realistic implied T_O is obtained for the right reasons at the air-sea interface.

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Table 1. Simulation Origins

Acronymn	Center	Location
CCCMA	Canadian Centre for Climate Modleing and Analysis	Victoria,Canada
CCSR	Center for Climate System Research	Tokyo, Japan
CNRM	Centre National de Recherches Meteorologiques	Toulouse,France
COLA	Center for Ocean Land and Atmosphere	Maryland
DNM	Department of Numerical Mathmatics	Moscow, Russia
ECMWF	European Centre for Medium-Range Weather Forecasts	Reading, UK
GFDL	Geophysical Fluid Dynamics Laboratory	Princeton, New Jersey
GLA	Goddard Laboratory for Atmospheres	Greenbelt, Maryland
JMA	Japan Meteorological Agency	Tokyo, Japan
MGO	Main Geophysical Observatory	St. Petersburg, Russia
MRI	Meteorological Research Institute	Ibaraki-ken, Japan
NCAR	National Center for Atmospheric Research	Boulder, Colorado
NCEP	National Centers for Environmental Prediction	Suitland,Maryland
SUNYA	State University of New York at Albany	Albany, New York
UKMO	United Kingdom Meteorological Office	Exeter, UK
YONU	Yonsei University	Seuol, S.Korea

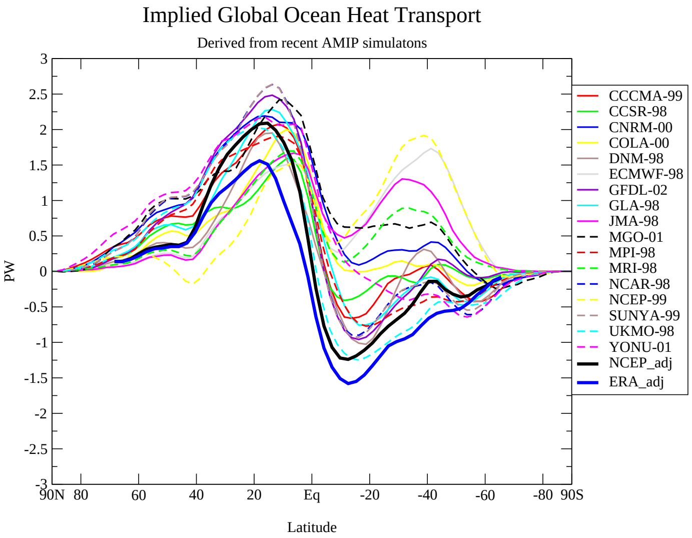

Figure 1. Implied Ocean Heat Transport: AMIP Models and Observational Estimates

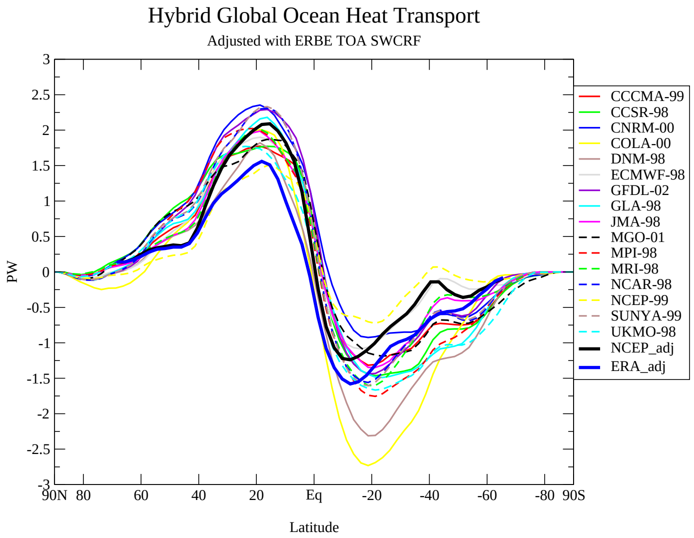

Figure 2. Implied Ocean Heat Transport Corrected with ERBE: AMIP Models and Observational Estimates

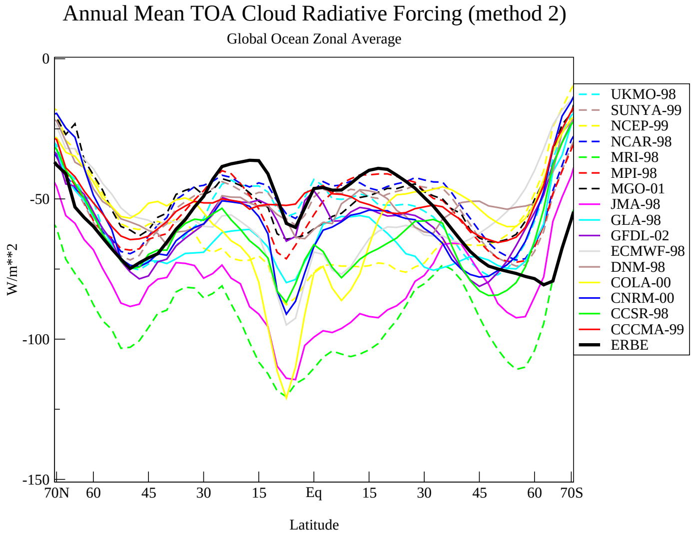

Figure 3. Global Ocean Zonal and Annual Average Top-of-Atmopshere Shorwave Cloud Radiative Forcing (Wm^{-2}): AMIP Models and Observational Estimates

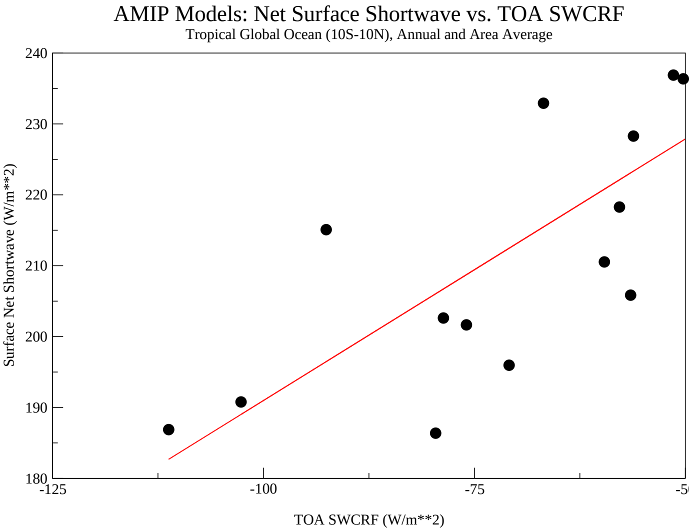

Figure 4. Tropical (10N-10S) Global Ocean Net Surface SW versus Top-of-Atmosphere Shortwave Cloud Radiative Forcing (both(Wm^{-2})

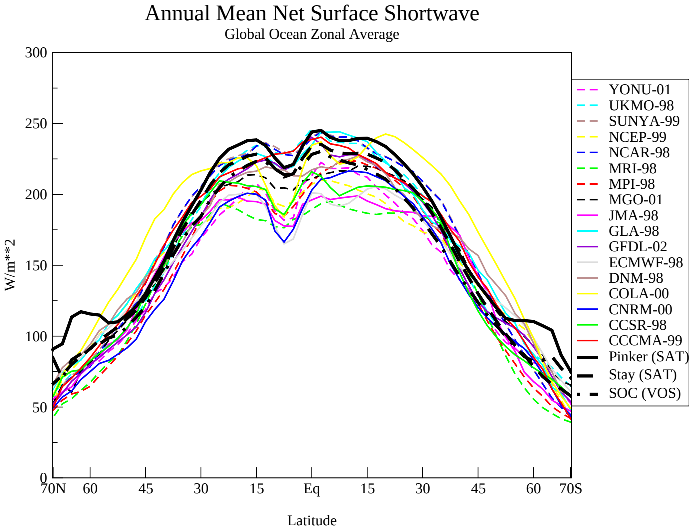

Figure 5. Global Ocean Zonal and Annual Net Surface Shorwave (Wm^{-2}): AMIP Models and Observational Estimates

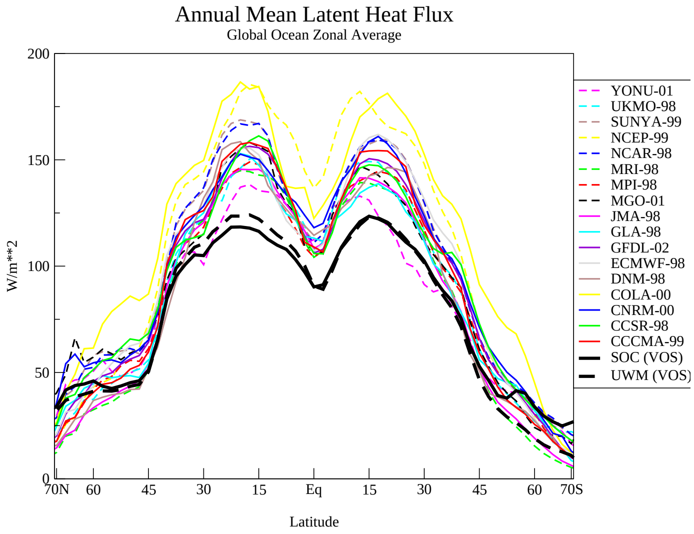

Figure 6. Global Ocean Zonal and Annual Latent Heat Flux (Wm^{-2}): AMIP Models and Observational Estimates

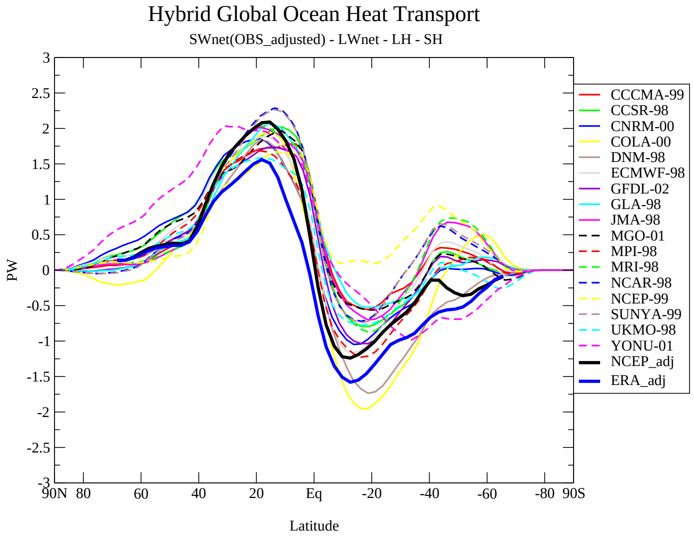

Figure 7. Implied Ocean Heat Transport Corrected Surface Shortwave Observational Estimates: AMIP Models and Observational Estimates

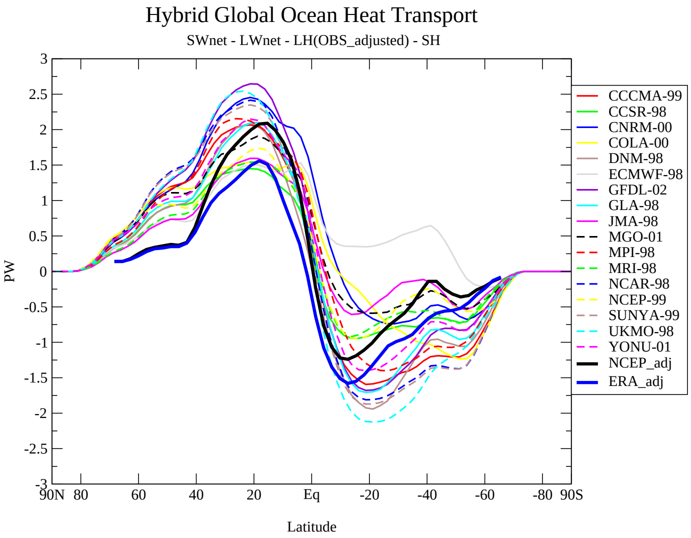

Figure 8. Implied Ocean Heat Transport Corrected with Latent Heat Flux Observational Estimates: AMIP Models and Observational Estimates