Evidence of Systematic Biases in Ocean Surface Heat Fluxes Simulated by AGCMs

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Evidence of systematic biases in ocean surface heat fluxes simulated by AGCMs

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1. INTRODUCTION

The Atmospheric Model Intercomparison Project (AMIP, Gates 1992) has provided a unique opportunity to evaluate atmospheric general circulation model (AGCM) simulations made with realistic boundary forcing. Here we report on some results from AMIP Subproject No. 5, making use of a suite of observationally-based estimates of ocean surface heat fluxes to evaluate the seasonal cycle of surface heating as simulated by AGCMs.

To emphasize the points to be made here, we make use of the AGCM simulations collectively (as opposed to focusing on an individual simulation). The observational products will be examined in a manner which illustrates the discrepancies between them. The model results from the 28 AGCMs used here (described by Phillips, 1994) are all ten year averages. 30 modeling groups have participated in AMIP, but two of them did not save the surface fluxes.

Here we focus on the dominant heating and cooling terms of the ocean surface energy balance: the surface net shortwave radiation, SW (heating), and the latent heat flux, LH (cooling). The objectives of this study are similar to those of Randall and Gleckler (1995), but our approach is different. Randall and Gleckler utilized the uncertainty analysis of Gleckler and Weare (1995). Here we evaluate the model simulations with respect to a range of observational estimates rather than relying on the uncertainty estimates that were based on a single product. We will find that the conclusions drawn from the two studies are fully consistent, namely that despite the very large unknowns in the observed surface fluxes, they do suggest systematic biases in fluxes simulated by AGCMs.

2. OBSERVATIONAL PRODUCTS

Three classes of observationally-based estimates will be used here. The first may be described as ‘surface-based’ climatologies. To construct these atlases, researchers have made use of data products (most notably COADS) that consist of measurements which are routinely made by the voluntary observational fleet of merchant vessels. The quantities which are measured or estimated are not fluxes (which are inherently difficult to measure), but rather fields which are more relevant to surface weather such as surface air temperature, wind speed, etc. Parameterizations have been developed which enable estimation of surface fluxes with the commonly observed quanti-
ties. Because the observations are scant in the open ocean, especially in the low latitudes and Southern Hemisphere, for most purposes only climatological monthly mean flux estimates are utilized. The products used here (see Table 1) are based on 30 or more years of data. Estimates of both SW and LH will be examined.

The second class of observationally-based estimates used here are those which have been derived from satellite observations. In recent years a variety of SW estimates have been published, all using somewhat different algorithms to model attenuation of radiation in the clear and cloud-sky atmosphere. Such products offer promise in improved precision over the surface-based climatologies because of their superior sampling, but currently the accuracy of these products is a subject of active debate (e.g., Cess et al., 1994). We have averaged multiple year products together yielding 'climatologies,' and tests have demonstrated that whether we use a single year or average them together makes little difference to our findings regarding AGCM simulations.

Finally, we consider some recent results from the reanalysis efforts underway at four centers. Multiple year integrations have been averaged to produce monthly climatologies for each reanalysis: ECMWF (79-85), NMC (85-91), NASA-GSFC (86-93), and NRL (85-88). Once again, the averaging process has little impact on our conclusions. We only make use of the LH, because the SW is expected to be mostly dependent upon the model.

Table 1: Observational Products

<table>
<thead>
<tr>
<th>Source</th>
<th>Product type</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>da Silva and Levitus (1994)</td>
<td>Surface-based</td>
<td>SW, LH</td>
</tr>
<tr>
<td>Oberhuber (1988)</td>
<td>Surface-based</td>
<td>SW*, LH</td>
</tr>
<tr>
<td>Hsiung (1986)</td>
<td>Surface-based</td>
<td>SW, LH</td>
</tr>
<tr>
<td>Taylor (1993)</td>
<td>Satellite-based</td>
<td>SW</td>
</tr>
<tr>
<td>Pinker (1993)</td>
<td>Satellite-based</td>
<td>SW</td>
</tr>
<tr>
<td>Li (1993)</td>
<td>Satellite-based</td>
<td>SW</td>
</tr>
<tr>
<td>Chertock (1992)</td>
<td>Satellite-based</td>
<td>SW</td>
</tr>
<tr>
<td>ECMWF</td>
<td>Reanalysis</td>
<td>LH</td>
</tr>
<tr>
<td>NMC</td>
<td>Reanalysis</td>
<td>LH</td>
</tr>
<tr>
<td>NASA-GSFC</td>
<td>Reanalysis</td>
<td>LH</td>
</tr>
<tr>
<td>NRL</td>
<td>Reanalysis</td>
<td>LH</td>
</tr>
</tbody>
</table>

* adjusted following Gleckler and Weare (1995)
3. RESULTS

Our objective is to reveal the differences between the observational products and to determine if, despite their discrepancies, they shed any light on ocean surface heat fluxes simulated by AGCMs.

In Fig. 1a the spread of the zonal and annual average global ocean SW simulated by the 28 AGCMs is represented by the inter-model average ± one standard deviation. Also shown are the spread of the SW observational products, depicted by error bars that illustrate the maximum and minimum values of each type of product as a function of latitude. This figure clarifies that there are substantial differences between the estimates of a given class of observations, and that furthermore the two (surface and satellite based) are not in agreement at all latitudes. In the low latitudes the spread of the satellite based SW estimates are systematically larger than the surface based products. There is more consistency between the two classes of observations at higher latitudes.

Fig. 1a illustrates that there is a large spread among the simulated SW of the models. In the low latitudes, most of the observations lie within this range of the models. If for the moment we assume that there is no reason to believe any one observation more than another, then the observations are not adequate to identify model biases in the tropics. In the mid latitudes however, all 8 of the observational products suggest that most of the models are in fact allowing too much shortwave radiation to reach the ocean surface.

Fig. 1b depicts the number of models whose annual mean simulated SW is greater than all 8 observational products. Here we see that most models overestimate the SW in areas where marine stratus is common (Hahn et al., 1982), presumably because of inadequate modeling of these clouds. Interestingly, in Fig. 1c we find that in the western tropical and subtropical oceans the SW for most models is less than all 8 observations.

Figure 1: Annual mean global ocean net surface shortwave radiation a) zonal average - the white line represents the 28 model average and the shading the average ± the inter-model S.D.. The maximum-to-minimum spread of satellite-based and surface-based estimates are shown as the vertical thick and thin bars respectively; b) at each grid point the number of models whose simulated SW is greater than all 8 observationally-based products used here; c) at each grid point the number of models whose simulated SW is less than all 8 observationally-based products used here.
Figs. 2a-b are analogous to Fig. 1a for the extreme seasons, and confirm that the excessive annual mean midlatitude SW simulated by the models (Fig. 1a-b) is mostly due to summertime biases. Not surprisingly, there is better agreement in the winter hemispheres between the models and the observations. This is consistent with a SW model bias that is proportional to the insolation and at least partially attributable to cloudy-sky deficiencies (Fig. 1b).

Figs. 3a-b are analogous to Figs. 1a-b, but are for LH rather than SW and depict the spread of reanalyses instead of satellite based estimates used in Fig 1. Fig. 3a shows that the simulated tropical evaporation in most of the models is greater (our convention is a downward flux being positive) than all 8 observational products. To a lesser extent, the figure is also suggestive of model biases at higher latitudes. Fig. 3b depicts the number of models whose simulated evaporation is in excess of all 8 observational products, a feature which is especially apparent in the warm pool area, but other tropical regions as well. Extending the analysis of Fig. 3 to examine the simulated seasonal cycle of the latent heat flux (not shown) suggests that LH biases are evident during all seasons.
It is not yet possible to retrieve reasonable estimates of the surface net heating (N) from satellite observations. N is of course available from reanalysis, but it is our feeling that this represents much more a model simulation than it does an observationally-based product. Thus for the moment, the only available estimates of N which are strongly influenced by observations in all terms of the surface energy balance are the surface based climatologies. We have thus chosen to make use of the uncertainty analysis of Gleckler and Weare (1995) to examine the AGCM simulations.

Figure 4 depicts the simulated N, along with the error bar estimates of Gleckler and Weare (1995). As with the surface flux climatologies used in the previous figures, estimates are not used south of 40°S because of the paucity of observations. The annual mean case is shown in Fig. 4a. The simulated N for most models is within the observational error bars, but the situation is not an encouraging one because the estimated errors are so large ( > 35 W m⁻² at many latitudes). The large error bars are the result of the propagation of uncertainties from each term of the surface energy balance, the SW and LH being the largest. The lower bounds of the error bars imply a net surface heating only equatorward of 5°, a situation which hardly seems likely, but rather is indicative of the very large uncertainties in the surface-based climatologies. Only in the tropics does Fig. 4a demonstrate that some of the models lie outside the error bounds, strongly suggesting model deficiencies given the very large error bounds. Inadequate N in the tropics may be attributed to deficient SW resulting from poor treatment of cloud-radiative effects (see Gleckler et al., 1995), excessive evaporation, or both. At this time it is not clear how strong the relationship between a bias in the SW and LH might be. The smaller error bars with respect to Fig. 4a are indicative of the different scaling of the figures. Fig. 4b is perhaps more encouraging than Fig 4a., because it demonstrates that despite the biases described in this study, that the simulated N is in qualitative agreement with the observationally-based estimates of the seasonal cycle of surface net heating.

![Figure 4](https://example.com/figure4.png)

**Figure 4**: Global ocean net surface heat flux for a) annual mean and b) DJF. The white line represents the 28 model average and the shading the inter-model average ± 1 S.D. The error bars are taken from Gleckler and Weare (1995).
4. DISCUSSION

The results presented here provide another perspective to the findings of Randall and Gleckler (1995), who compared the surface-based ocean surface heat flux uncertainty estimates of Gleckler and Weare (1995) to AGCM simulations. The results of these studies were that: 1) the simulated SW for most models is in excess to the observational error bounds in the midlatitudes and to a lesser extent in the tropics; 2) the simulated LH for most models is in excess to the observational error bounds in the tropics and to a lesser extent in the midlatitudes. In the present study, we have taken a different approach. We have compared a suite of observationally-based estimates of surface heat fluxes with those simulated by AGCMs. Our findings are fully consistent to those of Randall and Gleckler (1995).

To varying degrees, all of the observational product used here rely on some sort of model to infer surface fluxes from other more directly observed quantities. For the moment however, they represent our best global scale perspective of the ocean surface energy balance. Further tests are clearly necessary, but the consistency of this study with the results of Gleckler and Weare (1995) is suggestive that there are detectable biases in the simulated heat fluxes, despite the very large uncertainties in the observational products.

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