EVALUATION OF PASSIVE SATELLITE REMOTE SENSING OF CLOUD LIQUID WATER

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1. INTRODUCTION

Cloud liquid water is an important geophysical quantity forming a crucial link between the hydrological and radiative properties of the climate system. Shallow oceanic clouds, whose longwave and shortwave radiative fluxes are mostly determined by their liquid water content, play a particularly important role due to their ubiquitous nature. These boundary layer clouds, such as marine stratocumulus and trade wind cumulus, represent the major source of uncertainty in simulated tropical cloud feedbacks because the interannual variability of their albedo is underestimated in current climate models. Consequently, future climate projections would significantly benefit from accurate observations of marine cloud liquid water content. Unfortunately, existing satellite observations show considerable discrepancies in the global distribution of this quantity. Our research aims at better constraining passive space-borne cloud liquid water estimates by systematically investigating inconsistencies between microwave and optical remote sensing methods with the ultimate goal of creating a consensus cloud liquid water climatology which would combine the strengths of the individual retrieval techniques.

2. DATA AND METHODOLOGY

In this study, we analyzed one year of spatially and temporally matched microwave and optical cloud liquid water path (CLWP) estimates from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the Aqua satellite. Specifically, microwave CLWPs were produced by the Wentz algorithm from a combination of the various AMSR-E brightness temperatures, while optical CLWPs were parameterized from MODIS cloud optical thickness and droplet effective radius. We considered both the operational MODIS estimates assuming vertically homogeneous clouds and an adiabatic cloud model which reduces operational values by ~17%. The comparison was performed at the 0.25° scale of the gridded microwave dataset by gridding and averaging the 1-km resolution optical retrievals. Because microwave CLWPs represent gridbox averages while optical CLWPs are in-cloud averages, the latter were scaled by the gridbox-mean liquid cloud fraction estimated from the MODIS cloud mask. The AMSR-E rain rate classified data as either 'non-precipitating' (rain = 0) or 'precipitating' (rain > 0), while the MODIS cloud phase product characterized ice contamination. We then systematically investigated differences between AMSR-E and MODIS cloud liquid water retrievals as a function of a variety of factors such as cloud fraction, geographic location, effective radius profile, cloud heterogeneity, solar/view geometry, cloud temperature, and rain rate.

3. RESULTS

The presence of rain and/or ice poses difficulties to both retrieval techniques. Microwave methods cannot separate cloud and rain signals and, hence, have to make a priori assumptions on cloud-rain partitioning in precipitating clouds. Similarly, the interpretation of the optical signal is rather ambiguous in mixed-phase clouds and optical methods employ the questionable practice of setting the phase of the entire atmospheric column to that of cloud top. In order to avoid these difficulties, we mainly focused on non-precipitating and ice-free gridboxes, which, in any case, constituted the vast majority of our data. However, we will briefly discuss cloud-rain partitioning issues at the end of this section.

3.1. Overall comparison

When all cloud fractions were considered, AMSR-E CLWPs tended to overestimate operational MODIS CLWPs with corresponding global annual means of 58 g/m^2 and 40 g/m^2, respectively, the rms difference was 42 g/m^2, and the datasets were only moderately correlated with a coefficient of 0.71. Global monthly means showed similar AMSR-E overestimations of 15-25 g/m^2. These results were due to a high bias in microwave retrievals, which rapidly increased with decreasing cloud fraction but also depended on water vapor amount. Obviously, the adiabatic correction to optical estimates, which further reduces MODIS values, would have made the comparison worse. This positive AMSR-E bias in broken cloud fields is not yet fully understood but preliminary analysis suggests it is related to the use of outdated gaseous absorption models and lack of beamfilling corrections in rain-free cases by the Wentz algorithm, and to 3D effects in MODIS retrievals.

In strictly overcast cases, the datasets were significantly better correlated with a coefficient of 0.83, but now operational MODIS retrievals were on average 16% larger than AMSR-E values. The global annual means were 91 g/m^2 and 108 g/m^2 for AMSR-E and MODIS, respectively, with an rms difference of 35 g/m^2. Consequently, adiabatically corrected optical retrievals resulted in excellent agreement with microwave mean values with an annual bias of only 0.3 g/m^2. The adiabatic correction worked equally well for global monthly means yielding microwave-optical biases within ±5 g/m^2.

3.2. Geographical variations

Overall comparisons can mask systematic regional discrepancies; therefore, we also analyzed the geographical distribution of AMSR-E – MODIS CLWP bias, correlation, and rms difference. Because the overwhelming feature of broken cloud fields is an AMSR-E overestimation, in the following we focus exclusively on overcast scenes in order to minimize this, as yet, not fully understood effect. In general, differences were not random but showed significant coherent spatial patterns. Zonal means were in relatively good agreement in the summer hemisphere; however, in the winter hemisphere, MODIS CLWP sharply increased toward the poles in contrast to AMSR-E. At latitudes above 30° and also in subtropical marine stratocumulus regions, where most of our data occurred, MODIS overestimated AMSR-E while in the relatively sparsely sampled tropics/subtropics the reverse was generally true. All in all, the adiabatic correction resulted in reduced differences between the datasets in 75% of the cases. We found the tightest agreement between microwave and optical retrievals in marine stratocumulus regions with correlations as high as 0.95 and rms differences as low as 15-20 g/m^2. Our findings strongly suggest a cloud type dependence in AMSR-E – MODIS differences with MODIS overestimating in stratiform clouds and the reverse being true in cumuliform clouds, producing interesting bias patterns in regions where marine stratocumulus transitions into trade wind cumulus.

3.3. Error sources

We identified several potential error sources in both techniques, which might explain the observed global bias pattern. First, our analysis pointed to significant 3D effects in 1D plane parallel MODIS retrievals at large solar zenith angles. In contrast to AMSR-E, MODIS CLWP sharply increased with solar zenith angle above 60º driven by an increase in cloud optical thickness. Classifying scenes according to Cahalan's homogeneity parameter revealed that this behavior was due to heterogeneous scenes; in homogeneous scenes the solar zenith angle dependence of MODIS CLWP was similar to that of AMSR-E CLWP. In addition, the view angle dependence of MODIS retrievals was generally more pronounced for heterogeneous scenes, further indicating that 3D effects could be important under certain solar/view geometries and cloud types. Second, the fact that MODIS tends to observe the cloud-top droplet effective radius and its CLWP parameterization assumes vertically homogeneous clouds can lead to both negative and positive biases depending on the actual droplet profile. Indeed, we found significant correlations between AMSR-E – MODIS CLWP bias and MODIS 1.6-3.7 micron effective radius difference, which can be used as proxy for the droplet profile. The adiabatic correction to optical CLWPs largely compensates for MODIS overestimations in clouds where droplet effective radius tends to increase with height such as marine stratocumulus, but exacerbates the MODIS low bias when the slope of the droplet effective radius profile is opposite, a case which might be more prevalent in cumuliform clouds. Our results suggest one might derive statistical corrections to optical retrievals in such cumuliform clouds as well based on MODIS-observed effective radius difference values.

We also found the temperature parameterization in the Wentz algorithm having a negative bias compared to MODIS cloud-top temperatures, especially in marine stratocumulus clouds where the temperature underestimation can be as high as 10-15K. Because microwave absorption strongly increases with decreasing temperature this leads to significant underestimations in microwave CLWPs explaining some of the observed AMSR-E – MODIS bias. Finally, uncertainties in cloud-rain partitioning also introduced non-negligible errors. We found that when rain-free and precipitating gridboxes were combined mean AMSR-E CLWPs increasingly underestimated mean MODIS CLWPs above 180 g/m^2, while in strictly precipitating cases AMSR-E CLWPs showed increasing overestimations as rain rate increased. We could quantitatively explain this behavior by considering the particular cloud-rain partitioning formula and the fixed 180 g/m^2 precipitation threshold used in the Wentz algorithm: a portion of the liquid water content of non-precipitating clouds with CLWP above 180 g/m^2 was erroneously assigned to precipitation.

In the next phase of our research, we will perform sensitivity analyses with the Wentz algorithm and combine cloud-resolving model simulations with a hierarchy of radiative transfer models to better quantify the observed microwave-optical retrieval differences and possibly derive statistical corrections.