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1. Introduction

The atmospheric downwelling longwave radiation at surface (LWd_{sfc}) is one of the most important energy components. To calculate the LWd_{sfc} fluxes using satellite measurements, currently either broadband radiative transfer model or its parameterization is needed (Zhang et al. 1995; Charlock and Alberta 1996; Gupta et al. 1999). The inputs for the calculations are atmospheric temperature, column water vapor, cloud amount, cloud top and base heights, and cloud optical thickness (τ). All these parameters except the cloud base height can be obtained from satellite visible and infrared observations. The estimations of cloud base height are mainly based on empirical relationship of cloud top temperature, cloud top height and cloud optical thickness, e.g., Minnis et al. (1995). The bias errors for these estimates are about 5~10 W/m² in clear conditions, and ~15W/m² under cloudy skies. Some of the errors are caused by the uncertainties of cloud height of low-level clouds or cloud base (Charlock and Alberta 1996).

There are almost no reliable satellite remote sensing techniques for multi-layer clouds, except thin cirrus over water clouds. Lin et al. (1998 a & b) have combined passive microwave, visible, and infrared (MVI) satellite data to estimate both ice and water cloud properties. Since microwave (MW) remote sensing is generally only sensitive to water clouds as long as particle size within ice clouds is less than 150 μ m, the combination of MVI can detect both upper layer ice clouds and lower layer water clouds, even the ice clouds are thick. Besides the strong temperature dependence of microwave water absorption coefficients (Lin et al. 2001), water absorption at high frequencies (\geq 85GHz) is much stronger than those at lower frequencies. Thus, the physical properties of the multi-layer cloud systems, such as optical depth, liquid water path, cloud top temperature and cloud water temperature, can be estimated using MVI technique. The errors of water cloud heights estimated from the microwave method are about 1 ~ 2km (Lin et al., 1998 a & b).

Current study uses MVI cloud properties retrieved from Tropical Rainfall Measuring Mission (TRMM) satellite data to improve LWd_{sfc} estimations. The LW flux calculations are based upon Fu-Liou code, following Charlock et al. (1997). The TRMM satellite data are collocated with three island ground measurements, and the estimated LWd_{sfc} fluxes are compared with the in situ observations.

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2. Data sets and Algorithms

The satellite data are from TRMM Microwave Imager (TMI) and Visible and Infrared Scanner (VIRS) measurements during the first 5 months of 1998. For each VIRS pixel, the VIRS cloud properties including clear/cloud and water/ice phase detections, cloud top temperature, cloud particle size and optical depth are estimated using the Visible Infrared Solar-Infrared Technique (Minnis et al. 1995). TMI is a nine-channel, passive MW radiometer measuring radiance at 10.65, 19.35, 21.3, 37.0 and 85.5 GHz (hereafter 10, 19, 21, 37 and 85 GHz for short). All wavelengths have both the vertical (V) and horizontal (H) polarizations except 21 GHz that only has a vertical polarization channel. The 85 and 37 GHz channels that are used in cloud water amount and water temperature retrievals have effective field of view (EFOV) about 4.6 km \times 7.2 km and 9.1 km \times 16 km, respectively. The cloud properties derived from normal 2km-spatial-resolution VIRS pixels are convoluted to the footprints of each TMI wavelength. The convolution of VIRS products to TMI footprints minimizes spatial collocation errors. Because TMI and VIRS are on the same platform, the temporal mismatches (~0.04 sec) of VIRS cloud products and TMI measurements are also much smaller than those between SSM/I and other satellites. The uncertainties of TMI estimated LWP and T_w values are similar to those from SSM/I (about 0.04mm and 10K, respectively (Lin et al. 1998a)) due to similar wavelengths and viewing geometries used in the two instruments. For low level clouds, study (Ho et al., 2001) found that the averaged LWP value estimated from TMI using Lin et al. (1998 a & b) method is only 0.005mm different from that of the VIRS cloud products.

To calculate LW fluxes at sea surface, the reanalysis data of the European Center for Medium Range Weather Forecast (ECMWF) are used to construct the atmospheric temperature and pressure profiles. The humidity profiles are also obtained from the ECMWF data with constraint on TMI observed CWV values. Due to limited cloud top temperature (from VIRS) and cloud water temperature (from TMI) retrievals within each TMI EFOV, this study assumes all cloud systems in a TMI pixel have maximum two-layer clouds. Cloud vertical structures including multi-layer systems are built upon VIRS and TMI estimated cloud properties as follows:

- 1). The 1st step to construct cloud vertical structure is to check if it is daytime or nighttime, and if the cloud systems are multi-layered by using the differences of VIRS cloud water path (WP) and TMI LWP values. If it is daytime, and the differences are larger than 0, multi-layer clouds are assumed, otherwise single layer clouds

are constructed. If it is nighttime, only cloud liquid water path values from TMI are used (and, of course, single layered systems are assumed) since no WP retrievals for VIRS nighttime observations.

2). For the assumed multiple (actually 2) layer clouds, the cloud top of upper level clouds is set to be at the level consistent with VIRS observed cloud top temperature. The cloud liquid or ice water amount for the upper level clouds is the difference of VIRS WP and TMI LWP values. The cloud thickness is then calculated from the empirical relationship of cloud optical depth, temperature and water/ice phase (Minnis et al. 1995).

3). For the lower level clouds, a cloud layer with water amount equal to TMI observed LWP is inserted into atmospheric profile according to TMI estimated cloud water temperature (T_w). Similar to upper layer clouds, the thickness of this lower layer clouds is also estimated from the empirical relationship of Minnis et al.

4) When clouds are assumed to be single layered, the cloud vertical position and water amount are decided in the same way as lower level clouds in multiple layer systems by using the TMI LWP and T_w estimates.

For cloud effective particle size (r_e) of each constructed cloud layer, VIRS cloud particle size estimates are used whenever they are available. For lower layers of multiple layer cloud systems or nighttime water clouds $10\mu\text{m}$ cloud particle size is assumed. For nighttime ice clouds, the effective ice diameter (D_e) $60\mu\text{m}$ is used.

LWd_{sfc} values using only VIRS cloud properties are also estimated for comparisons. In this case, the cloud vertical profiles are constructed according to the single layer assumption as the cases using the cloud products of both VIRS and TMI, except the cloud water path, effective temperature and thickness are all from VIRS. This approach is similar to the standard surface radiative energy products of CERES (Wielicki et al. 1996 and reference therein).

Ground in situ measurements are obtained from three small islands: Kwajalein Island (8.72°N , 167.72°E), Manus (2.06°S , 147.43°E), and Bermuda (32.27°N , 295.67°E). The satellite data around the islands are collocated with ground LWd observations within 30minutes and 100km. In this study, only clear sky and overcast cases are investigated.

3. Results

Figure 1 plots calculated and in situ observed LWd_{sfc} values over Kwajalein Island. Left panel is for both day and night, and right one is for nighttime only. The estimated LWd_{sfc} values using both VIRS-only (\times symbols) and MVI (+ symbols) methods generally agree with ground observations well. The bias errors are small ($<4\text{ W/m}^2$). The rms (root-mean-square) errors are about $14\sim 17\text{ W/m}^2$. Many sources contribute to the rms errors observed: e.g., the uncertainties in temporal and spatial collocations, water vapor retrievals, and cloud optical thickness estimates, and even small island effects. Compared with VIRS-only LWd_{sfc} estimates,

MVI results reduce both bias and rms errors slightly. Because of no reliable cloud WP, τ and r_e retrievals, and the calculated LWd_{sfc} is basically determined by LWP, lower level cloud temperature and atmospheric temperature and humidity profiles, nighttime VIRS-only LW estimation for this island is less accurate than those of daytime. The accuracy of LW values calculated from MVI retrievals during nighttime is about the same as that of daytime because the algorithm to estimate TMI LWP and T_w values are the same for day and night times. These characteristics can be also seen in the results of other two islands (c.f., Figs. 2 and 3 later).

Compared to those at midlatitudes, tropical cloud water amount and base temperature have less effects on LWd_{sfc} since atmospheric water vapor amount is high over the Tropics, especially within boundary, which results that MVI estimates only slightly improve the accuracy over VIRS-only values for both day and nighttimes. The comparison of calculated LWd_{sfc} fluxes with in situ measurements in the center of tropical western Pacific warm pool (Manus site; Fig. 2) clearly shows this feature. Statistically, there are almost no differences between two versions of satellite estimates for the most humidity region. Most of the calculated values from the two techniques are clustered together. Based on sensitivity studies of clouds on LW radiation, Zhang et al. (1995) concluded that clouds play small role in downwelling LW fluxes at surface, especially in moisturized environments.

Over midlatitude site (Bermuda; Fig. 3), although rms errors ($\sim 22\text{ W/m}^2$) are about the same for MVI and VIRS-only techniques, the LWd_{sfc} bias errors obtained by MVI method are much smaller than those from VIRS-only method (the errors shrink from $\sim 10\text{ W/m}^2$ to $\sim 3\text{ W/m}^2$). The rms errors in midlatitudes are higher than those in the Tropics because the uncertainties in water vapor, cloud total water path, cloud liquid water amount, and cloud top and base temperatures have much bigger influences on LWd_{sfc} estimates than those in the Tropics. Furthermore, detailed vertical structures of atmospheric temperature and humidity profiles in midlatitudes play relatively bigger roles in calculation than those in the Tropics due to weaker boundary layer gas absorption. ECMWF model simulated temperature and humidity have large uncertainties above boundary layer, especially for upper tropospheric humidity. Thus, the rms errors in midlatitudes are larger. For gridded and monthly mean values used for climate studies, rms errors should be significantly reduced from current instantaneous error values. The bias errors obtained by VIRS-only method are about the same as other studies (Charlock and Alberta 1996; Zhang et al. 1995). With extra information from satellite microwave measurements, the bias errors are generally smaller, especially in midlatitudes.

4. Summary

Based on cloud properties retrieved from combined microwave, visible and infrared satellite data, this study has calculated downward longwave radiation at sea surface under clear and overcast conditions. The

advantage using the combined data sets is that microwave measurements have certain information about cloud liquid water path and cloud water temperature. With additional cloud properties retrieved from visible and infrared technique, layering characteristics (water amount and temperature) of cloud systems with ice on the top and water below can be obtained. These more complete cloud properties provide us better opportunity in longwave calculations than that using visible and infrared measurements. Compared with in situ measurements, the bias errors are less than 8 W/m^2 , mostly within 3 W/m^2 . The rms errors vary from ~ 14 to $\sim 22 \text{ W/m}^2$. There are no significant differences between daytime and nighttime longwave estimates. These results, especially over midlatitudes and during nighttime conditions, are improved the values estimated using only visible and infrared satellite data. One limitation of this method is the microwave remote sensing for clouds only validates over oceans. Over land much higher variable surface emissivity is the major concern. More studies of clouds over land are needed.

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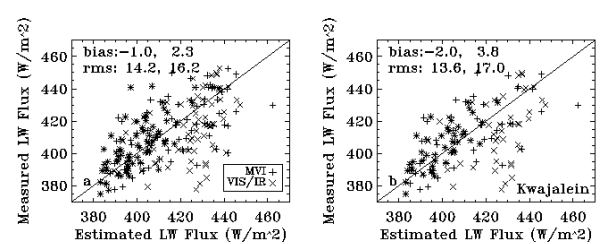


Fig. 1 LW fluxes of Kwajalein for day and night times (a) and nighttime only (b).

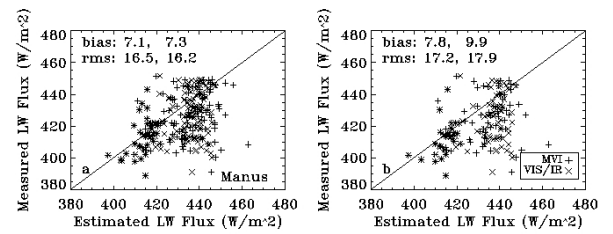


Fig. 2 same as Fig. 1, except for Manus.

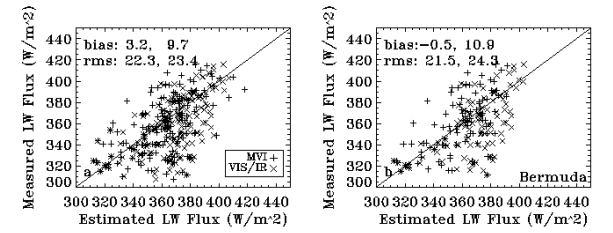


Fig. 3 same as Fig. 1, except for Bermuda.