Deriving Marine-Boundary-Layer Lapse Rate from Collocated CALIPSO, MODIS, and AMSR-E Data to Study Global Low-Cloud Height Statistics

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***Abstract*—Global cloud-top height statistics of marine-boundary-layer clouds are derived from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Level 2 aerosol and cloud layer products. The boundary-layer lapse rate in the northeast region of the Pacific Ocean is investigated using sea surface temperature (SST) data from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E), cloud–top temperature data from the Moderate Resolution Imaging Spectroradiometer (MODIS), and cloud-top height data from CALIPSO. Based on the lapse rate derived from the combined CALIPSO/MODIS/AMSR-E measurements, cloud-top heights in regions within CALIPSO tracks are derived from AMSR SST and MODIS cloud temperature to test the validity of this approach. For homogeneous low-level clouds, the results agree with the cloud-top height from the collocated CALIPSO cloud-top height measurements. These results suggest that the database of derived lapse rates from the combined measurements can be applied to study cloud-top height climate statistics using the MODIS and AMSR data when CALIPSO observations are not available.**

***Index Terms*—Marine boundary layer (MBL), temperature lapse rate.**

I. Introduction

CLOUD-TOP height statistics of marine boundary layer (MBL) provide important information about ocean–atmosphere interaction and cloud-radiation-climate feedback [1]–[3]. The low-level cloud fraction, which measures the radiative impact of MBL clouds, is highly correlated with MBL cloud-top height [4]. It is a challenge to accurately measure the MBL cloud-top height from passive satellite remote sensing, due to temperature inversion and cloud heterogeneity.

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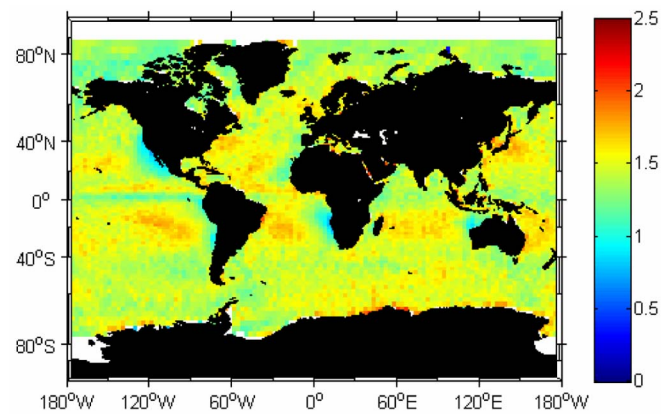

Fig. 1. Global map of the mean MBL cloud-top heights using CALIPSO observations from June 2006 to May 2007. The color scale covers a cloud-top height range of 0–2.5 km. The lands are in black.

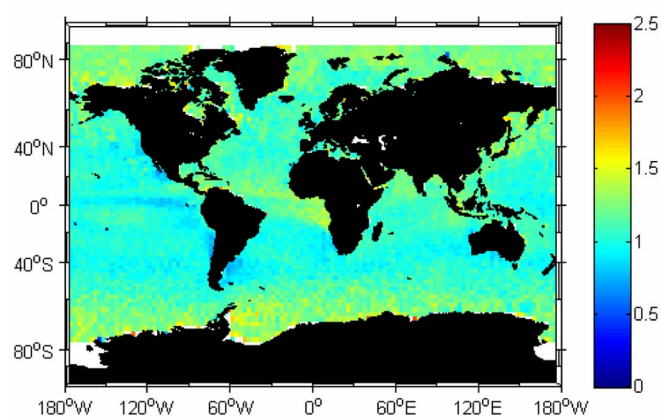

Fig. 2. As in Fig. 1 except for the mean mixed-layer aerosol top heights using CALIPSO observations from June 2006 to May 2007.

The global cloud-top height statistics of MBL clouds can be derived from the observations of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). Fig. 1 shows the global map of mean MBL cloud-top heights for the lowest cloud layers lower than 3 km, obtained from the CALIPSO Level 2 cloud layer product [5]. The 5-km horizontal-resolution cloud layer product is used for June 2006–May 2007. Fig. 2 shows the global map of mean mixed-layer aerosol top heights for the same period. This is the mean lowermost aerosol-layer top height for aerosol layers lower than 3 km obtained from the CALIPSO Level 2 aerosol-layer

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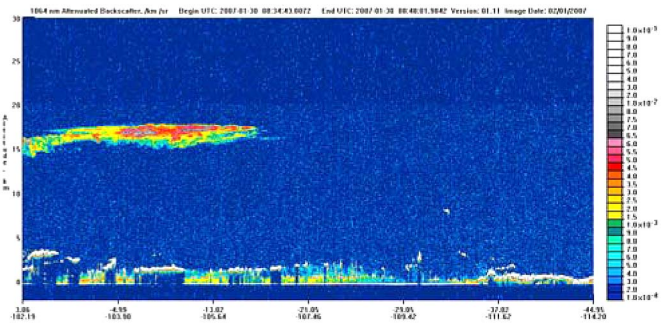

Fig. 3. Nighttime orbit of CALIPSO's 1064-nm lidar backscatter. The horizontal axes are annotated with latitude (deg) and longitude (deg). Color scale is for attenuated backscatter. White colors refer to clouds, whereas yellow colors near the ground refer to aerosols. Further details can be found at http://www.calipso.larc.nasa.gov/products/lidar.

product [5]. Both the cloud- and aerosol-layer top heights are averaged over $2^\circ \times 3^\circ$ grids. The mean MBL cloud-top height in the open oceans is between 1.0 and 1.5 km, which is higher than the mean mixed-layer aerosol-layer top height, because the cloud and surface mixed layers are well separated there. They are, however, close to each other near the west coasts of the continents, where clouds are formed near the tops of the mixed layer. Fig. 3 shows an example of the sampling curtain of CALIPSO's 1064-nm lidar backscatter. Color scale is for attenuated backscatter. White colors refer to clouds, whereas yellow colors near the ground refer to aerosols. In many cases, there is a cloud layer above the aerosol layer, and the MBL is well separated from the surface mixed layer where aerosols reside. This indicates that CALIPSO is capable of discriminating aerosols and clouds and provides accurate MBL cloud-top height information.

While CALIPSO can provide height information about MBL clouds, the nadir-viewing-only observations limit its application in climate studies, which require both the spatial and temporal distribution statistics. The goal of this study is to derive MBL lapse rates from the collocated CALIPSO, the Advanced Microwave Scanning Radiometer-EOS (AMSR-E), and the Moderate Resolution Imaging Spectroradiometer (MODIS) data and use them to determine the cloud-top height statistics in areas where CALIPSO observations are not available. The key question to be addressed is whether the MBL lapse rates from the combined data can be extrapolated to the surrounding areas beyond the CALIPSO tracks in order to determine global low-cloud height statistics.

Boundary-layer lapse rate has been used for estimating MBL cloud-top height in previous studies. By using a fixed lapse rate (7.1 K km^{-1}), sea surface temperature (SST), and cloud-top temperature, Minnis estimated the boundary-layer heights in the northeast (NE) Pacific [6]. This method has been very effective in air quality modeling studies. Betts *et al.* [7] found lapse rates to be in the range of 7–8.5 K km^{-1} over the NE Pacific. Wood and Bretherton [8] found that the lapse rate can be parameterized as a function of the boundary-layer height. A global database of MBL lapse rate derived from the combined CALIPSO with passive-sensor measurements can be useful to study the physical processes within MBL and may lead to improved parameterizations of boundary-layer processes.

Section II introduces a method for deriving MBL lapse rates using the collocated AMSR-E, MODIS, and CALIPSO data. The lapse rate statistics in the region off the west coast of South America are analyzed and discussed in Section III. In Section IV, a fixed lapse rate value is used to derive cloud-top heights from AMSR-E SST and MODIS cloud temperature data for different times and locations. The results are then compared with the cloud-top heights from the collocated CALIPSO data.

II. Data and Method

To derive the MBL lapse rate, the temperature difference is computed from the collocated AMSR-E SST and MODIS cloud-top temperature (T_{top}) for the selected cases, where CALIPSO lidar backscatter indicates that the MODIS 1 km $\times$ 1 km pixel is covered by single-layer low-level clouds. The corresponding cloud-top height (H) is computed from the averaged cloud-top heights from CALIPSO lidar profiles within the MODIS pixel. The lapse rate (Γ) is then computed as

$$\Gamma = \frac{\mathrm{SST} - T_{\mathrm{top}}}{H}. \tag{1}$$

The daily observations of SST are obtained from the AMSR-E Version-5 Daily AMSR-E Ocean Product. Cloud-top temperatures are calculated by using 11-μm channel (band) brightness temperature data from the CloudSat MODIS-AUX data product [9], which provides the MODIS data along CloudSat tracks. MBL cloud-top height data are obtained from the collocated CALIPSO Level-2 1-km horizontal-resolution lidar cloud layer product. For each MODIS pixel, SST is the mean AMSR-E value of the closest $0.25^\circ \times 0.25^\circ$ grid. To ensure that the clouds are uniform and optically thick, the standard deviation of the MODIS brightness temperature within a 10 km $\times$ 10 km area is required to be less than 0.2 K.

III. Lapse Rate Result

For demonstration purposes, this letter reports on the lapse rate results of the southeast Pacific Ocean, which covers from 5° to 30 °S in latitude and from 100 °W to the west coast of South America in longitude. One month (January 2007) of data is used for the analysis. The top panel of Fig. 4 shows the histogram of the calculated lapse rates using the method outlined earlier. The full width at half maximum is about 1 K km^{-1}, and the peak lapse rate is approximately 8.0 K km^{-1}. Green and red lines are the nighttime and daytime portions of the statistics, respectively. The result of the statistics is mainly contributed by the nighttime data due to the CALIPSO data selection. The lower panel of Fig. 4 shows the 3-D histogram of the calculated lapse rate versus the cloud-top height. The peak of the lapse rate, near 8.0 K km^{-1}, occurs mainly in the region where the cloud-top height is about 1.4 km.

The lapse rates derived from the combined AMSR-E SST, MODIS cloud brightness temperature, and CALIPSO cloud-top height data are slightly smaller than the values derived from Wood and Bretherton's parameterization [8] plotted in the lower panel of Fig. 4 as the red curve. Assuming that the MBL

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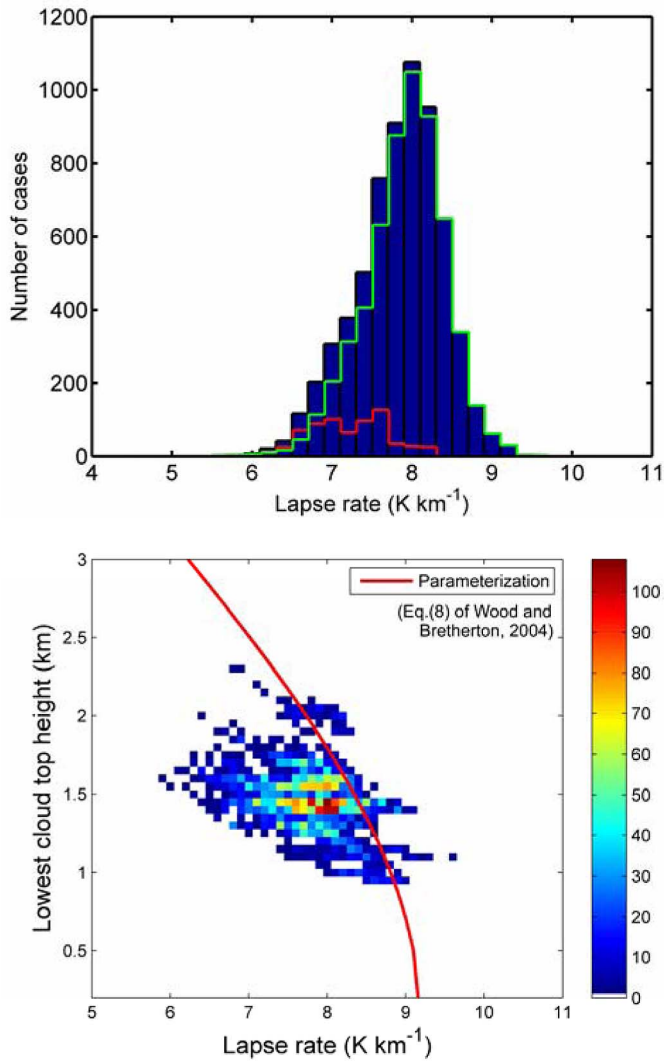

Fig. 4. (Top) Histogram of the calculated lapse rates. Green and red lines are the nighttime and daytime portions of the statistics, respectively. (Bottom) Locations of retrieved lapse rate values versus the lowest cloud-top heights. Colors indicate the frequency of occurrence. The x-axis is the lapse rate calculated from the AMSR-E SST, MODIS cloud temperature, and the collocated CALIPSO cloud-top height. The red curve represents the parameterization presented in [8].

cloud-top height is 1.4 km, the lapse rate derived from Wood and Bretherton's parameterization is 8.4 K km^{-1}. The relative difference between 8.4 K km^{-1} and our 8.0 K km^{-1} is about 5%. Average atmospheric water vapor absorption of 1 K was introduced in the calculation. Thus, the difference is mainly due to the overcorrection of the absorption of atmospheric water vapor above clouds. The fact that CALIPSO's cloud-top height can be slightly higher than the actual effective cloud thermal emission level associated with MODIS observations can also contribute to this small difference.

The spatial distribution of the MBL lapse rate averaged over $1^\circ \times 1^\circ$ grid of the study region is shown in Fig. 5. Green and yellow grid points, corresponding to the lapse rates approximately from 7.5 to 8.5 K km^{-1}, represent most of the observations in this study region. This result suggests that the variability of MBL lapse rate is restricted to a narrow range, which is in agreement with the previous studies [7], [8].

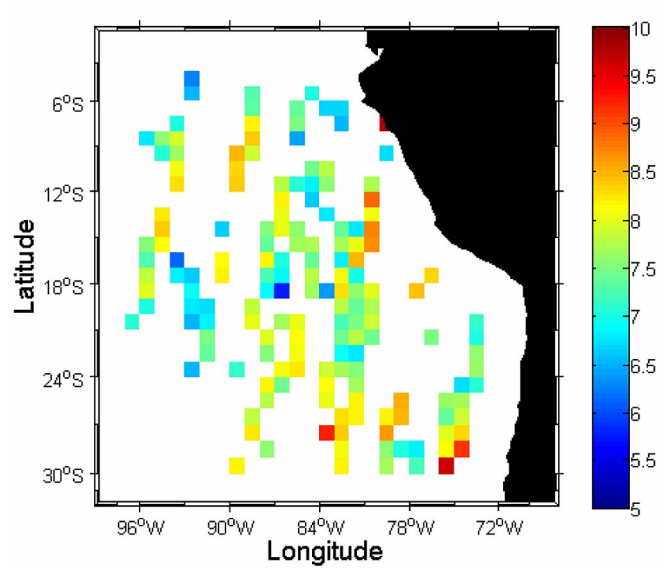

Fig. 5. Distribution of the calculated marine-boundary-layer lapse rates. Colors indicate lapse rates from 5 to 10 K km^{-1}. The ocean is shown in white and the South America continent in black.

IV. Deriving Cloud-Top Heights From Lapse Rates

A lapse rate distribution database is compiled using this method with the available combined AMSR-E, MODIS, and CALIPSO data. Based on the derived lapse rate database, MBL cloud-top height statistics can be estimated from the historical AMSR-E and MODIS data. To test the validity of this approach, for simplicity, a fixed lapse rate value (8.0 K km^{-1}) from the database is selected and used to estimate the cloud-top height from the AMSR-E SST and MODIS cloud temperature data in a region near the CALIPSO tracks at a different period. That is, the MBL cloud-top height (H) is computed from the AMSR-E SST and MODIS MBL cloud temperature (T_{top}) with the following formula:

$$H = \frac{\mathrm{SST} - T_{\mathrm{top}}}{8.0}. \tag{2}$$

The cloud-top heights computed from the AMSR-E SST and MODIS cloud temperature data are compared with the CALIPSO's cloud-top heights. Fig. 6 shows that the derived cloud-top heights agree with the CALIPSO cloud-top heights. On the top panel, the red dots are the CALIPSO cloud-top heights, and the blue dots are the cloud-top heights computed from the AMSR-E SST and MODIS cloud temperature data while applying a fixed lapse rate chosen from the database. The green dots are the cloud-top heights derived using the Wood and Bretherton's parameterization [8]. The CALIPSO track in this plot is a part of the January 7, 2007, nighttime orbit that started at 06:21:29 UTC. At the bottom panel of Fig. 6, the histogram shows that the root-mean-square difference of the cloud-top heights is less than 100 m. Similar agreements are also found for other cases (not shown). The small differences between the derived and CALIPSO-measured cloud-top heights are an encouraging result because the lapse rate database can be confidently used to derive cloud-top heights for periods (regions) when (where) only AMSR-E and MODIS data are

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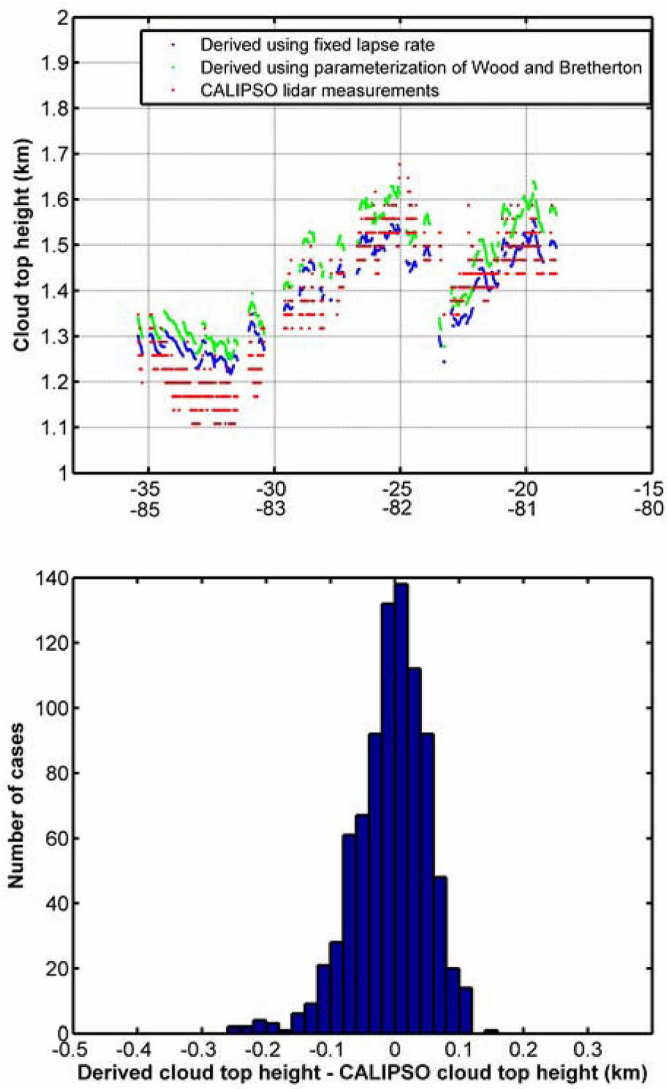

Fig. 6. (Top panel) A comparison of the derived cloud-top heights (blue dots for using fixed lapse rate and green dots for using the parameterization of Wood and Bretherton) and (red dots) CALIPSO cloud-top heights. The horizontal axes are annotated with (top values) latitude and (bottom values) longitude. (Bottom panel) Histogram of the differences between the derived and CALIPSO cloud-top heights shown in top panel.

available. Further analyses of the derived global low-cloud height statistics will be presented elsewhere.

Holz and Ackerman gave the global distribution results of the comparison of the MODIS and CALIPSO lidar cloud-top height measurements. They used a model pressure profile to convert the MODIS cloud pressure retrievals to cloud-top heights [10]. For low clouds (cloud-top height of < 5 km), the global cloud-top height difference has a mean of -0.19 km. The negative difference means that the cloud-top height retrieved from the MODIS measurement is beneath that from CALIPSO lidar.

V. Conclusion

With the combined measurements of CALIPSO MBL cloud-top height, AMSR-E SST, and MODIS cloud temperature, the global and seasonal distributions of MBL lapse rates have been estimated. This letter reports on the preliminary results of an MBL lapse rate study using the combined CALIPSO/MODIS/AMSR-E observations with a goal of deriving global low-cloud height statistics using the lapse rate database.

The lapse rates derived from the combined observations and the MBL heights obtained from CALIPSO data show a good agreement with the Wood and Bretherton parameterization. Similar parameterization evaluation studies may help in understanding the boundary-layer processes once the MBL lapse rate database is populated globally with longer-term measurements.

Preliminary results indicate that it is possible to compute MBL cloud-top heights from SST and cloud-top temperature data from passive-sensor measurements by applying the MBL lapse rate database derived from this study. The errors are only about 100 m, compared to direct measurements from CALIPSO.

Although CALIPSO observations provide unprecedented details of the vertical structure of atmosphere, the satellite's limited spatial and temporal coverage limits their impact in climate studies. This study is an attempt to maximize the usage of the CALIPSO observations to estimate global low-cloud heights from passive remote sensing data, using the physical properties derived from the combined CALIPSO and passive remote sensing observations.

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