J3.4 Use of ozone channel measurements for deep convective cloud height retrievals over the tropics

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Abstract

This study examines a possible use of ozone channel measurements around 9.7 micron from geostationary satellites for determining cloud top heights of convective clouds over the tropical latitudes. We determine the cloud top heights using Meteosat-8 measurements over the infrared window (IRW) and H_2O, CO_2, O_3 absorption bands with an aid of radiative transfer calculations. NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data were used as inputs to the radiative transfer calculations. Using cloud top heights from collocated CloudSat observation as a reference, cloud top heights determined from one-channel radiance, two-channel brightness temperature difference (BTD), and two-channel radiance ratio methods are compared for the clouds with thickness greater than 4 km. The comparison shows that retrievals from CO_2-IRW ratio and O_3-CO_2 ratio are in good agreement with CloudSat observations even when the cloud heights are low without significant bias. We also found that O_3-IRW BTD has very similar information of cloud height with IRW channel and O_3-IRW combination is not appropriate for the two-channel radiance ratio method.

1. Introduction

Tropical deep convection plays an important role in the Earth's radiation energy balance by transporting moisture to the upper troposphere and by redistributing clouds. Deep convective clouds sometimes overshoot the tropopause layer and thus influence the physical and chemical processes in the tropopause layer and lower stratosphere.

In line with the importance of tropical deep convection, it is important to quantify the heights and frequencies of deep convective clouds. Methods to identify the deep convective clouds and assign their heights are usually based on the infrared window (IRW) measurements. Some studies (Schmetz et al., 1997; Lattanzio, 2006) relate the convective activity to "warm water vapor pixels" where brightness temperature (TB) in the water vapor channel is higher than the TB in IRW channel. Figure 1 shows the simulated spectral signature of the convective systems with the cloud top from 6 to 20 km. TB of the water vapor channel (6.3 μm) is higher than the TB of window channel (10.8 μm) when cloud top is above 14 km. Ozone channel (9.7 μm) also shows the positive brightness temperature difference (BTD) signature for the cloud top above 11 km and the impact of ozone variation within the tropical standard deviation is not noticeable. The signal of BTD between ozone and window channels

(BTD9-11) is even much more significant than BTD6-11 near the tropopause suggesting that BTD9-11 can be a better indicator for the deep convective activity than BTD6-11.

Motivated by the simulated results, this study examines a possible use of ozone channel measurements from geostationary satellites for determining cloud top heights of deep convective clouds over the tropics. In general, cloud tops are determined from IRW channel alone for opaque clouds while CO_2-IRW ratioing and H_2O-IRW ratioing (or H_2O-IRW intercept) methods are applied for semi-transparent clouds (EUMETSAT, 2008). Cloud top heights determined from one-channel radiance, two-channel BTD, and two-channel ratio methods are compared using cloud top heights from collocated CloudSat observation as a reference. Based on the comparison results, we discuss if there is any improvement due to the inclusion of ozone channel and which method is most appropriate for the convective cloud height retrievals over the tropics.

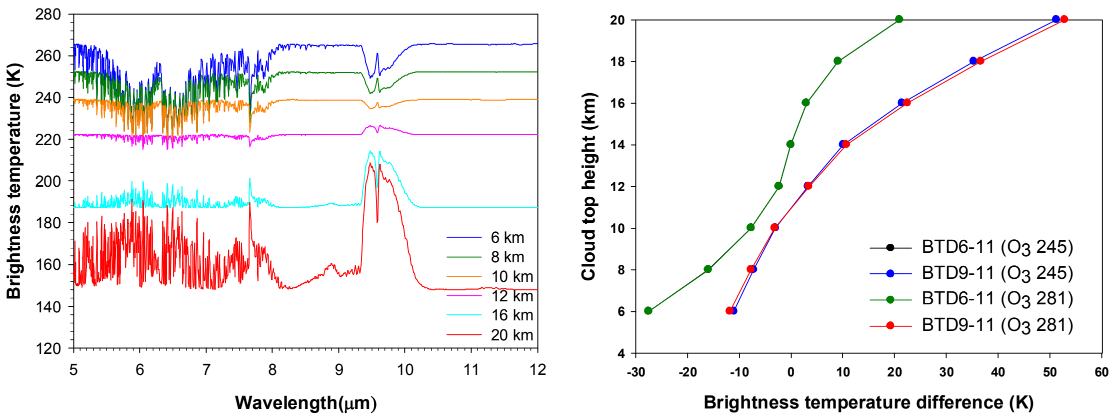

Figure 1. MODTRAN simulations of the convective system with the bottom fixed at 4 km and top growing up from 6 to 20 km. **Left**: Spectrum changes over the wavelength between 5 and 12 μm. **Right**: Meteosat-8 BTD changes and the impact of ozone variation within the standard deviation at Mauna Loa site (19.54°N, 155.58°W).

2. Methodology and dataset

2.1 Meteosat-8 and CloudSat collocation

Meteosat-8 measurements over the infrared window channel (10.8μm, IRW), and water vapor (6.3 μm, H_2O), ozone (9.7 μm, O_3), carbon dioxide (13.4 μm, CO_2) channels are used for cloud height retrievals. Cloud top heights from collocated CloudSat observation are used as a reference. For the cloud identification, we use cloud mask values of 30 to 40, which are high-confidence detections (CloudSat Data Processing Center, 2007). Only single-layer clouds are considered in this study.

We construct the collocated Meteosat-8 and CloudSat dataset by finding closest Meteosat-8 nine pixels for each CloudSat footprint. The time and spatial differences between two satellites are within 350 seconds and 0.01 degrees. We reduce the effect of potential mismatching by averaging nine Meteosat-8 pixels and by applying the homogeneity criterion which requires normalized standard deviation less than 0.03 between the nine pixels. The dataset is collected over the area of 30˚N–30˚S, 40˚W–40˚E and over the period of 15 October – 15 November 2006 (except for 19 October – 21 October when data file are damaged).

2.2 cloud height retrieval methods

The cloud top heights are retrieved from Meteosat-8 measurements with an aid of radiative transfer calculations. NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data were used as inputs to the radiative transfer model, RTTOV-9, to get the clear sky top radiance and overcast black cloud radiance on each level. Cloud top height is assigned with the best agreement of measured and calculated values as follows:

– One-channel radiance method:

Measured radiance is compared to the calculated overcast black opaque radiances between the surface and the tropopause to find the level of smallest difference. The measurements of the four channels (IRW, H_2O, O_3, CO_2) are individually used for the cloud height determination.

– Two-channel BTD method:

Brightness temperature differences between two channels are used in the cloud height retrievals instead of one-channel radiances. We applied the four combinations of H_2O–IRW, O_3-IRW, CO_2-IRW, and O_3-CO_2.

–Two-channel radiance ratio method:

The ratio method, which is so-called slicing method (Menzel et al., 1983; Nieman et al, 1993), uses the ratio of the deviations in observed radiances R_{obs} and clear sky radiances R_{clr} for two spectral channels of frequency ν_1 and ν_2. The ratio can be equated as

$$\frac{R_{obs}(\nu_1)-R_{clr}(\nu_1)}{R_{obs}(\nu_2)-R_{clr}(\nu_2)}=\frac{N\varepsilon(\nu_1)\int_{P_c}^{P_S}\tau(\nu_1,p)\frac{dB[\nu_1,T(p)]}{dp}dp}{N\varepsilon(\nu_2)\int_{P_c}^{P_S}\tau(\nu_2,p)\frac{dB[\nu_2,T(p)]}{dp}dp} \qquad (1)$$

where *N* is the cloud fraction, ε is the cloud emissivity, P_S is the surface pressure, P_C is the cloud top pressure, τ is the fractional transmittance from the pressure level *p* to the top of the atmosphere, and *B* is the Plank radiance for the temperature *T(p).* Since the emissivities at the 4 channels for deep convective clouds are roughly the same as a unit emissivity, we can assume $\varepsilon(\nu_1)=\varepsilon(\nu_2)$. The left side of Eq. (1) is obtained from the Meteosat-8 observed radiances and clear radiances calculated from an atmospheric profile. The right side comes from a series of radiative calculations at various cloud top pressures P_C. Cloud top pressure (or height) is assigned when the calculated ratio (right side) best satisfies the observed one (left side). We applied the six combinations of H_2O–IRW, O_3-IRW, CO_2-IRW, O_3-H_2O, O3-CO_2, and H_2O-CO_2.

3. Results

3.1 The relationship of Meteosat-8 measurements with the cloud top height

In order to analyze the spectral signature of tropical deep convective clouds in Metoesat-8 measurements, Meteosat-8 TBs and BTDs are paired with CloudSat cloud top height (Figure 2). Color indicates cloud thickness and only clouds with thickness greater than 4 km are plotted. In the case of window channel, the relation between cloud height and a TB is subject to variability in temperature profile while the relation is subject to both temperature and absorber profiles for absorption channels.

H_2O channel shows much smaller scatter than other channels for heights lower than 14 km and this is caused by the compensation effect of moisture. Moisture of the warm atmosphere cools TB6 leading to lower values and smaller scatter compared to TB11. Near the tropopause above 14 km, there is no compensation effect due to the very low water vapor concentration and thus TB6 shows similar scatter plots with TB11.

Low cloud tops show colder TBs at absorption channels than TB11 due to the gas absorptions. With higher cloud tops, the absorption effects by H_2O and CO_2 get smaller and thus the differences between TB6 and TB11 (BTD6-11), and between TB13 and TB11 (BTD13-11) approaches zero. Some positive values of BTD6-11 and BTD13-11 are found where very deep convective clouds are present. These positive BTDs are explained by the adiabatic cooling in the convective system and the presence of absorbers in the stratosphere because the cloud top and TB11 are colder than the environmental air and absorbing gas. For high clouds above 12 km, TB9 shows significantly higher values than other channels due to the warming by stratospheric ozone. The warming effect results in the sharply increasing values of BTD9-11 and BTD9-13 with high cloud tops above 12 km. These relationships suggest the possibility that BTD9-11 and BTD9-13 will be better indicator for deep convective activity than TB11 and BTD6-11, consistently with the result of Figure 1.

3.2 Comparison of cloud height retrieval methods

Using cloud top heights from collocated CloudSat observation as a reference, Meteosat-8 cloud height retrievals from 14 different methods are compared. We applied one-channel method for 4 channels individually, two-channel BTD method for 4 combinations, and two-channel radiance ratio method for 6 combinations. Figure 3 and Table 1 show scatter diagrams and statistics for the comparison. Plots and calculations were done only for the clouds with thickness ≥ 4 km. When the measured value does not appropriately match calculated values between the tropopause and the surface, the retrieval is classified as failure and is not accounted in the statistics. The numbers of failure for 14 methods are also presented in Table 1.

Among one-channel radiance methods, H_2O channel is most close to the line of one-to-one correspondence. Retrievals from other channels (O_3, IRW and CO_2) are noticeably above the line of one-to-one correspondence indicating the underestimation of cloud height. Among two-channel BTD methods, only O_3-CO_2 BTD shows one-to-one correspondence while other BTD methods underestimate the cloud height. Although the bias and RMSE of H_2O radiance and O_3-CO_2 BTD methods are small, considerable parts of cloud height assignments are failed below 11 km. Those failures are apparently due to the small variation of TB6 and BTD9-13 with cloud top heights below 11 km as shown in Figure 2. Cloud top heights determined from H_2O-IRW and CO_2-IRW BTD methods show worse agreement with CloudSat compared to one-channel radiance methods. Retrievals from O_3-IRW BTD method is similar with the results from IRW channel alone method, implying that there is no significant improvement of cloud height retrieval in O_3-IRW BTD method, due to the inclusion of ozone channel, compared to IRW channel method.

The two-channel radiance ratio methods are in one-to-one correspondence except O_3-IRW combination. O_3-IRW ratio method underestimates cloud heights and about 11 % of the retrievals are failed. It also shows lowest correlation coefficient and highest RMSE, suggesting that O_3 and IRW combination is not appropriate for the radiance ratio method. O_3-H_2O ratio method seems to have problem in assigning cloud heights below 11 km. H_2O-IRW ratio and H_2O-CO_2 ratio methods also show significant failure of the cloud height assignments below 11 km. Retrievals from CO_2-IRW ratio and O_3-CO_2 ratio methods are in good agreement with CloudSat observations for almost all the samples even when the cloud heights are below 10 km.

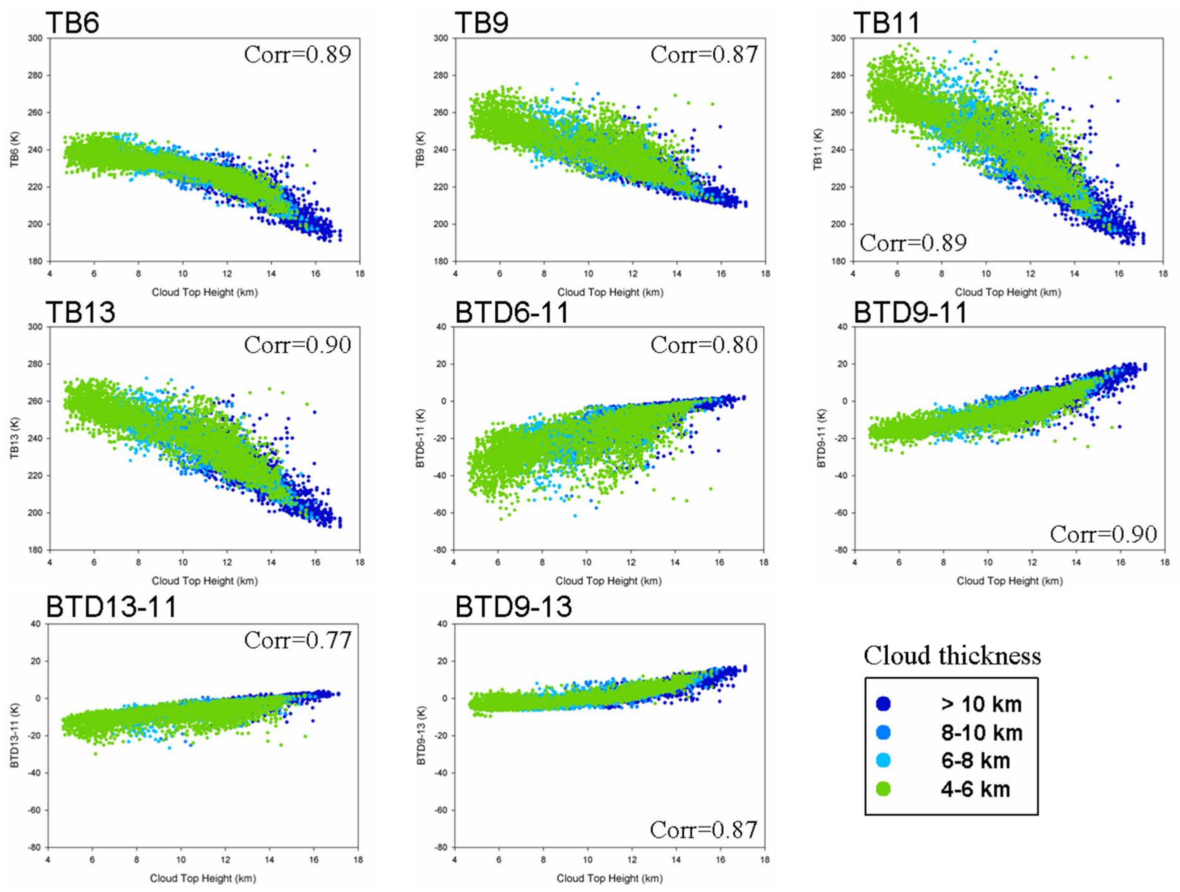

Figure 2. Scatter plots between CloudSat cloud top height, and Meteosat-8 TBs and BTDs. Color indicates cloud thickness

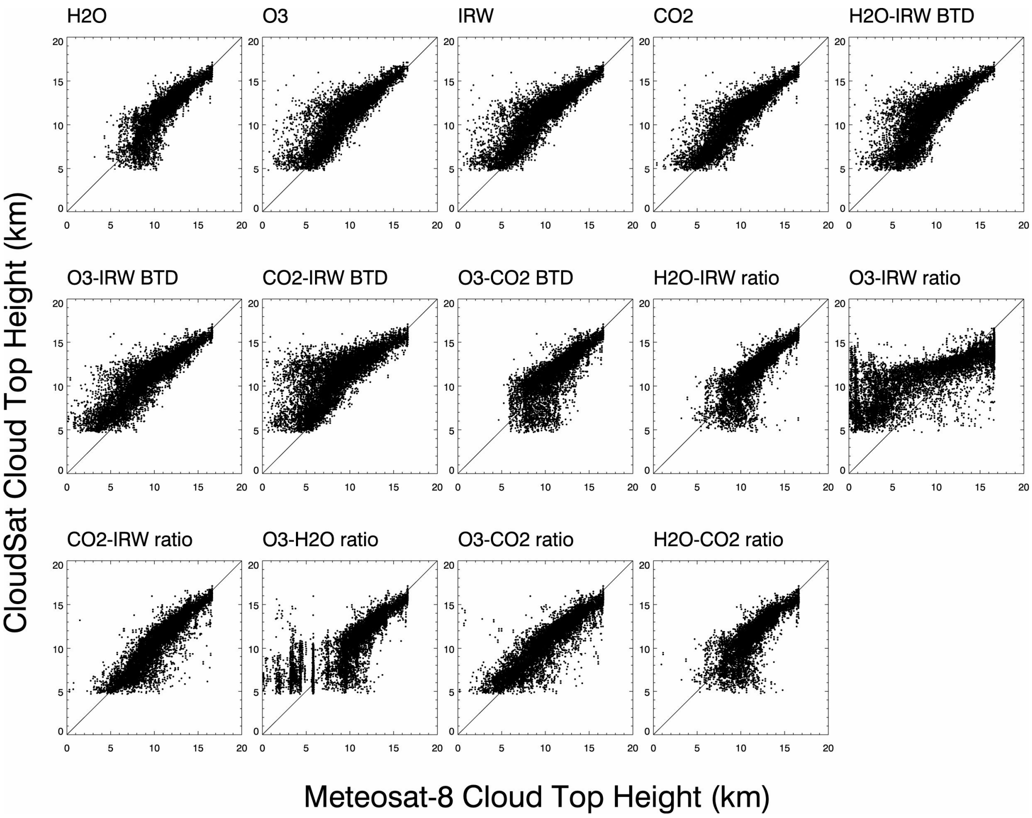

Figure 3. Scatter plots of cloud top heights for Meteosat-8 retrieval versus CloudSat observation. Plots were done only for the clouds with thickness ≥ 4 km.

Table 1. Statistics of Meteosat-8 cloud height retrievals for 14 methods. Calculations were done only for the clouds with thickness ≥ 4 km. The number of total sample is 11444.

Method		Corr.	Bias (km)	RMSE (km)	No. of fail
One-channel radiance	H_2O	0.87	0.01	1.23	2012
	O_3	0.87	-0.86	1.71	0
	IRW	0.88	-0.90	1.71	2
	CO_2	0.90	-0.58	1.41	1
Two-channel BTD	H_2O-IRW	0.82	-1.22	2.08	6
	O_3-IRW	0.90	-1.03	1.82	48
	CO_2-IRW	0.78	-1.67	2.68	18
	O_3-CO_2	0.80	0.15	1.54	1947
Two-channel radiance ratio	H_2O-IRW	0.83	0.34	1.43	2045
	O_3-IRW	0.76	-1.69	4.28	1305
	CO_2-IRW	0.90	0.26	1.26	67
	O_3-H_2O	0.83	-0.05	1.99	29
	O_3-CO_2	0.90	0.05	1.42	66
	H_2O-CO_2	0.82	0.39	1.49	2106

3.3 Analysis of convective growth case

A convective overshooting cell is analyzed using a series of Meteosat-8 image through its growth process (1912 UTC, 22 Oct. 2006 – 02:57 UTC, 23 Oct. 2006). We analyze the cell within the red box (10×10 pixels, centered at 9.90˚S, 26.24˚E) shown in the left panel of Figure 4.

In the right panel of Figure 4, TB6−TB11 (BTD6-11) and TB9−TB11 (BTD9-11) are plotted as a function of TB11 for the red box area with the color indicating the observation time. BTD6-11 approaches zero as TB11 gets cold (i.e. cloud top grows) and sometimes shows even positive values. Although it is very hard to notice the variation of BTD6-11 when TB11 is below 200 K, the sign change (negative to positive) can be easily used in representing convective activity (i.e. warm water vapor pixels). BTD9-11 and TB11 are in very good linear relationship, indicating that BTD9-11 has almost the same information with TB11 through the convective growth. This linear relationship between BTD9-11 and TB11 explains why the O_3-IRW BTD method does not show noticeable improvement compared to IRW channel method.

To understand the results of two-channel radiance ratio methods, the change of observed radiance ratios ($R_{obs} - R_{clr}$) between two channels are analyzed following the convective growth stages. H_2O-IRW, O_3-IRW, and CO_2-IRW radiance ratios are shown in Figure 5 as a function of TB11 with the atmospheric transmittance profile for the Meteosat-8 channels of H_2O, O_3, IRW, and CO_2. O_3-IRW ratio has much smaller variation range compared to other ratios. This small variation can be related to the poor cloud height retrievals from O_3-IRW ratio method. Two-channel radiance ratio method (i.e. slicing-method) is appropriate for two spectral channels with significantly different molecular absorption characteristics. As shown in right of Figure 5, the transmittance change of O_3 channel is very similar to that of window channel although the value is much different. This transmittance comparison helps us to understand why O_3-IRW combination is not appropriate for the radiance ratio method.

4. Conclusions

This study presents the comparison results from several cloud height retrieval methods and the test results of a possible use of ozone channel measurements for convective clouds (thickness ≥ 4 km) over the tropics. Meteosat-8 retrievals from one-channel radiance, two-channel BTD, and two-channel ratio methods have been examined against with CloudSat observations.

One-channel methods for O_3, IRW and CO_2 channels and two-channel BTD methods for H_2O–IRW, O_3-IRW, and CO_2-IRW combinations tend to underestimate cloud top heights. H_2O alone, O_3-CO_2 BTD, H_2O-IRW ratio, O_3-H_2O ratio, and H_2O-CO_2 ratio methods show lots of failure of poor results for cloud height assignment when clouds are below 11 km, indicating that those method are applicable only for high clouds above 11 km. The comparison results show that CO_2-IRW ratio and O_3-CO_2 ratio methods provide good retrievals with high correlation, low bias and low RMSE even when the cloud heights are below 10 km. O_3-IRW BTD dose not show noticeable improvement compared to IRW channel method and O_3-IRW combination is not appropriate for the two-channel radiance ratio method. From the analysis of convective growth case, we found that O_3-IRW BTD has very similar information with IRW and O_3-IRW ratio has much smaller variation range with the increase of cloud height, compared to other ratios. The analysis results explain why there is no improvement by the inclusion of ozone channel for convective cloud height retrievals over the tropics.

Acknowledgments

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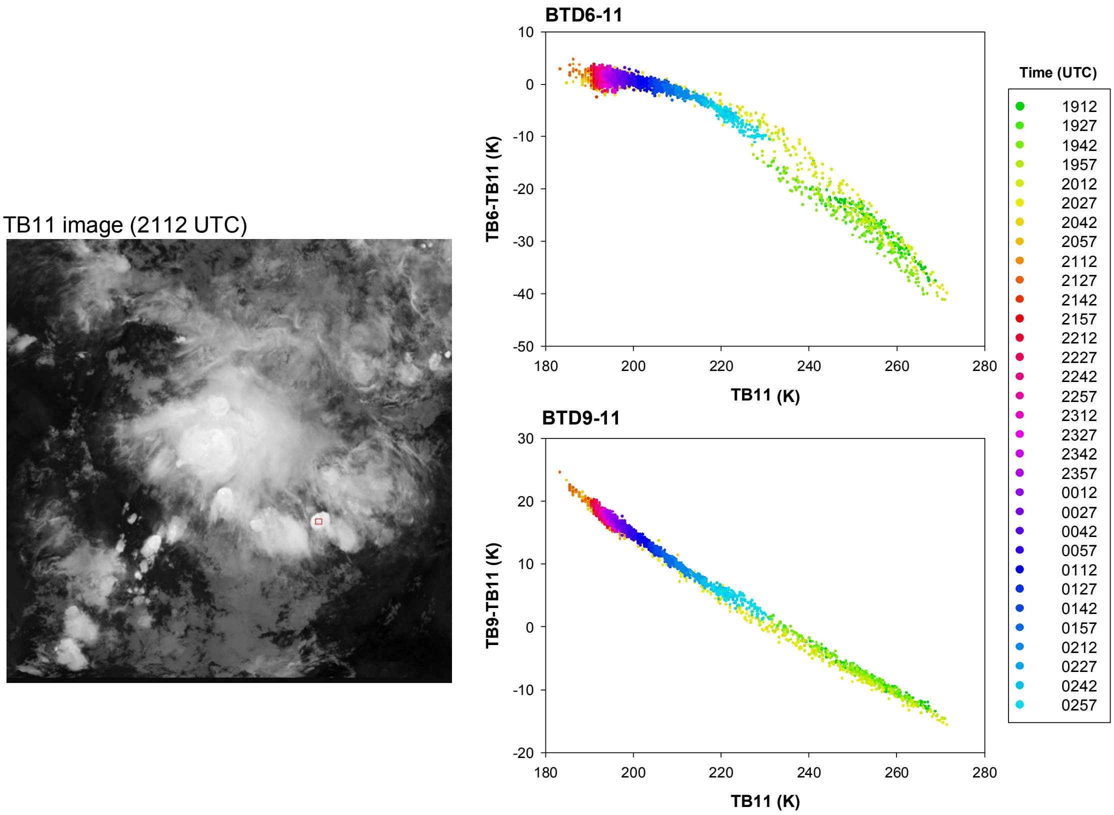

Figure 4. **Left**: Box (red color) superimposed on TB11 image of Meteosat-8 at 2112 UTC, 22 Oct. 2006. **Right**: Scatter plots of observed BTD6-11 and BTD9-11 as a function of TB11. Color indicates Meteosat-8 observation time in UTC.

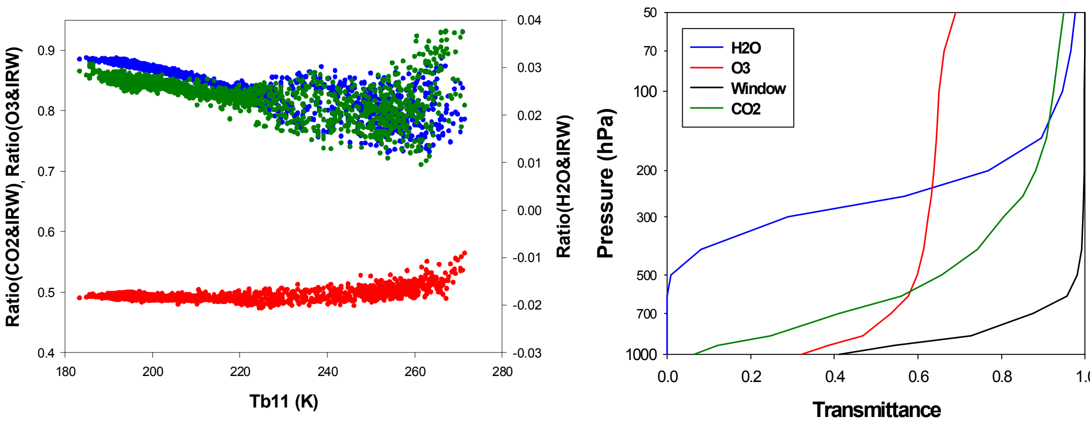

Figure 5. **Left**: Scatter plot of observed radiance ratios (R_{obs}-R_{clr}) between two channels (H_2O-IRW, O_3-IRW, and CO_2-IRW) as a function of TB11. Clear sky radiances R_{clr} are from radiative transfer calculations. **Right**: Atmospheric transmittances of Meteosat-8 channels of H_2O, O_3, IRW, and CO_2. Radiative transfer calculations are done for the tropical mean atmospheric profile.