

Final Report NASA: NNX11AQ58G

Summary of Project Goals

The goals of this project was to both continue our investigation of the CALIOP cirrus optical depth bias relative to MODIS and the IR and investigate using CALIOP combined with passive radiometric measurements from MODIS and SEVIRI to estimate important ash cloud properties and compare the results to ash cloud properties derived from passive sensors alone (since passive visible/near-infrared/infrared observations from geostationary and low earth orbit satellites are most commonly used to operationally track volcanic ash clouds). A summary of our accomplishments is presented.

CALIOP Ash Cloud Heights

As shown in Pavolonis et al., (2013), and those referenced therein, passive infrared measurements in the 8 - 13 μm range are very useful for detecting volcanic ash and retrieving ash cloud height, mass loading, and effective particle radius. CALIOP is the perfect space-based instrument for characterizing the strengths and weaknesses of the infrared retrieved cloud heights. The infrared cloud heights were validated against the cloud top heights (of the highest cloud/aerosol layer) given in the 5 km cloud layers (CLAY) and 5 km aerosol layers (ALAY) L2 CALIOP product files. The output from the CLAY and ALAY products files were merged since volcanic ash may be classified as cloud or aerosol by the CALIOP feature classification algorithm. A data set comprised of 15 CALIPSO half-orbits from May 6, 2010 to May 16, 2010 were analyzed. Each half-orbit contained segments that overpassed airborne Eyjafjallajökull (Iceland) ash over the North Atlantic or Europe. The ash cloud overpasses were identified with very high confidence using a combination of CALIOP and SEVIRI. The combination of CALIOP and infrared measurements, particularly those with a large viewing angle (longer path length through the cloud), is very powerful for identifying optically thick or optically thin volcanic ash, and can be used to improve CALIOP feature classification. An example CALIPSO overpass of Eyjafjallajökull volcanic ash is shown in Figure 1 (the highest cloud layer in the cross-section is volcanic ash). Figure 1 indicates that the vertical location of the ash exhibits strong spatial variability. Many other CALIOP cross-sections from the Eyjafjallajökull event (and other events) also show significant spatial variability in the vertical location of the ash. This is a significant finding, as the height of dispersed ash has always been assumed to be spatially uniform. The bottom panel of Figure 1 shows that the SEVIRI infrared retrievals of ash cloud height are able to capture the spatial variability quite well (regardless of which mineral composition is assumed in the retrieval), even though the cloud is very much semi-transparent to infrared radiation. A more quantitative comparison between the SEVIRI cloud heights and the CALIOP cloud heights is shown in Figure 2. The comparison is performed as a function of mineral composition assumed in the SEVIRI retrieval, cloud emissivity, and cloud geometric thickness (from the CALIOP CLAY/ALAY products). The results indicate that the SEVIRI ash cloud heights are biased low (by 0.77 km when the mineral composition is taken to be andesite) relative to CALIOP,

which is expected given the different “vertical resolution” of the measurements. See Pavolonis et al. (2013) for more detailed information.

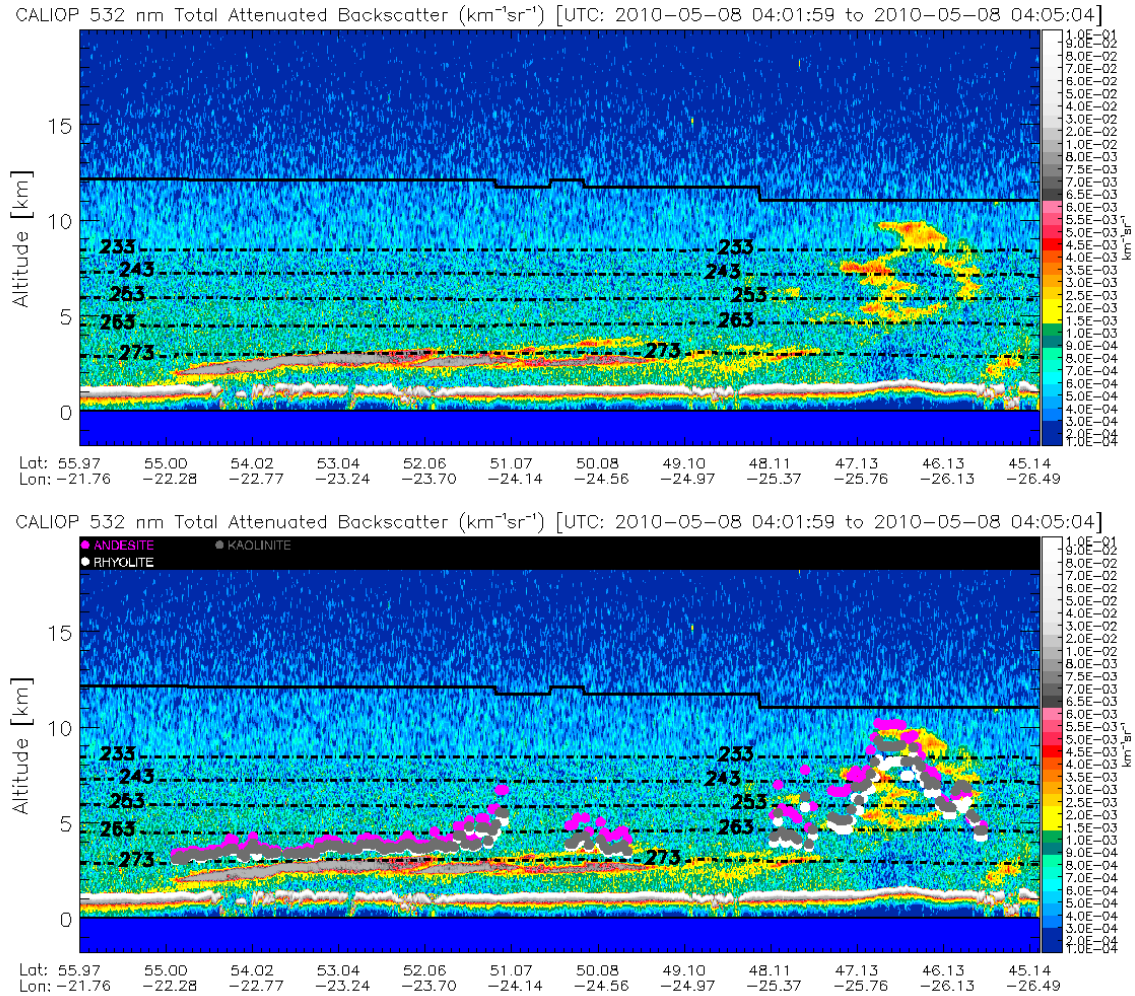


Figure 1: A CALIOP 532 nm total attenuated backscatter cross-section from 04:01:59 UTC – 04:05:04 UTC on May 8, 2012. The cross section is shown with (bottom) and without (top) the retrieved SEVIRI cloud heights (as a function of the assumed mineral composition) overlaid. Magenta circles represent andesite. White circles denote rhyolite. Gray circles represent kaolinite. In both panels, the solid black line denotes the tropopause and the dashed black lines represent select atmospheric isotherms (in Kelvin). [Taken from Pavolonis et al., 2013]

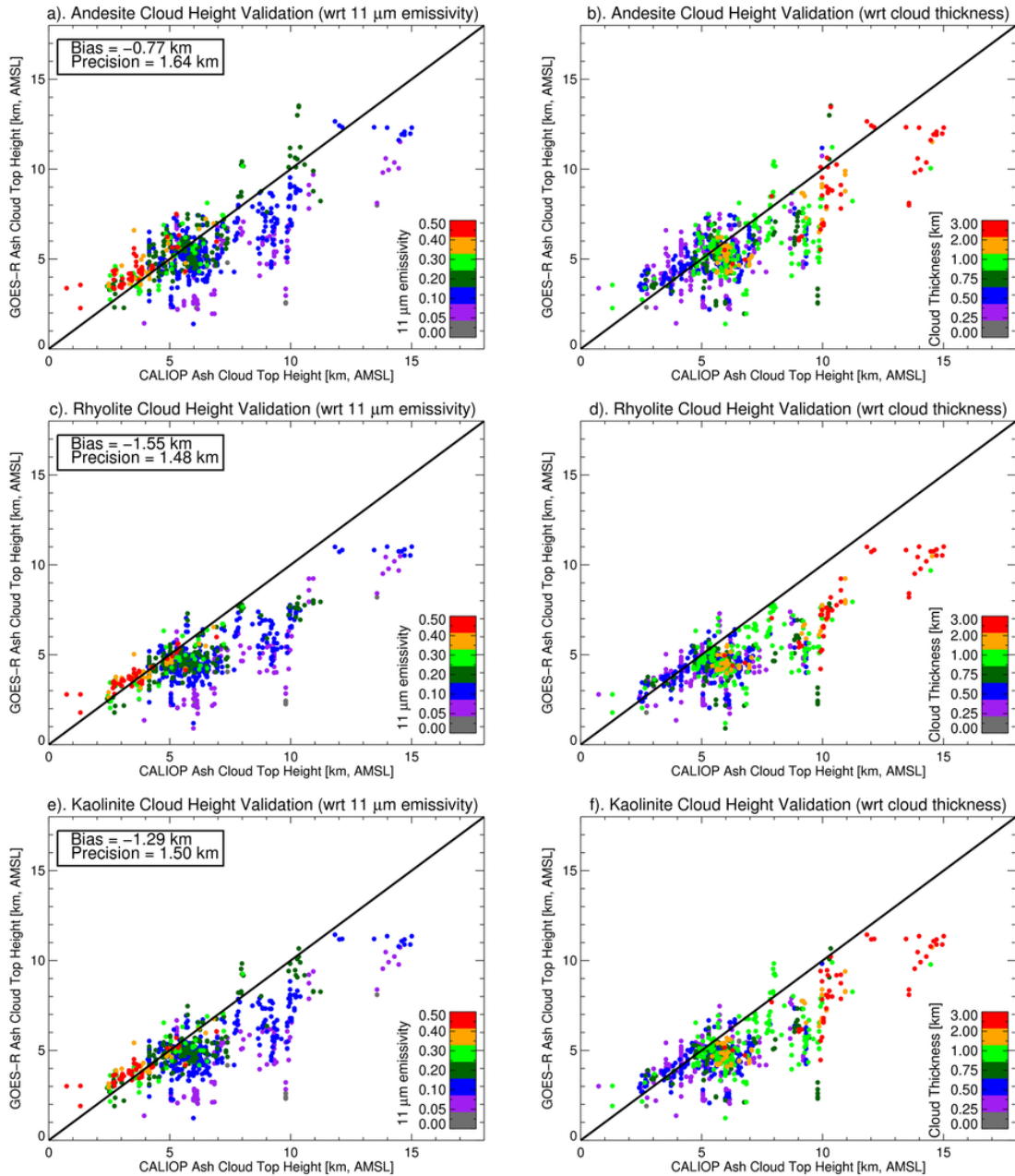


Figure 2: A comparison of SEVIRI ash cloud heights retrieved using the GOES-R approach and CALIOP measured cloud top heights is shown as a function of the nadir 11 μm cloud emissivity derived from a combination of CALIOP and SEVIRI (first column) and the cloud geometric thickness given by CALIOP (second column). Each color represents a different 11-μm cloud emissivity or cloud thickness bin. The results are also shown as a function of the mineral composition assumed by the retrieval (top=andesite, middle=rhyolite, bottom=kaolinite). The 1:1 line is shown in black. A total of 796 data points were used in this analysis. [Taken from Pavlonis et al., 2013]

Combined CALIOP/Infrared Estimates of Ash Mass Loading

The combination of the CALIOP merged CLAY/ALAY product and infrared measurements from SEVIRI were used to estimate ash mass loading. The mass loading retrieved from a combination of CALIOP and SEVIRI is far more constrained

than the mass loading that can be retrieved using either instrument alone. Effective cloud optical depth (τ) for a given SEVIRI spectral band or bands can be computed using a combination of CALIOP vertical cloud boundaries and co-located SEVIRI infrared measurements [e.g. Heidinger and Pavolonis, 2009; Garnier et al., 2012]. We utilize the method of Heidinger and Pavolonis (2009) to compute $\tau(11\mu\text{m})$ and $\tau(12\mu\text{m})$ of the highest cloud layer. The ratio, $\tau(12\mu\text{m})/\tau(11\mu\text{m})$, is directly related to cloud microphysics (Pavolonis, 2010). The effective infrared optical depths computed from a combination of CALIOP and SEVIRI will be consistently more accurate than those retrieved using SEVIRI alone because the CALIOP vertical cloud boundaries provide a very tight constraint on the effective cloud temperature and no cloud microphysical assumptions are needed. The ash mass loading can then be computed from $\tau(11\mu\text{m})$ and $\tau(12\mu\text{m})$ using the methods described in Pavolonis et al., (2013). Figure 3 shows the comparison between the ash mass loading derived from a combination of CALIOP and SEVIRI and SEVIRI alone (the same CALIOP/SEVIRI co-locations shown in Figure 2 were used). Figure 3 shows that the andesite mineral composition results in the lowest bias (no large systematic bias) and spread. Relative to the combined CALIOP/SEVIRI retrievals, the SEVIRI alone retrievals tend to underestimate the ash loading of lower level ash clouds and overestimate the loading of higher-level clouds. A closer inspection of the cases used in this analysis indicates that multiple cloud layers (usually ash with underlying meteorological cloud layers) are often present when the differences are larger. We are able to account for multiple distinct cloud layers in the combined CALIOP/SEVIRI retrieval with much greater skill compared to the SEVIRI alone retrieval. Further analysis of CALIOP data may allow us to better account for multiple cloud layers in the SEVIRI alone retrieval.

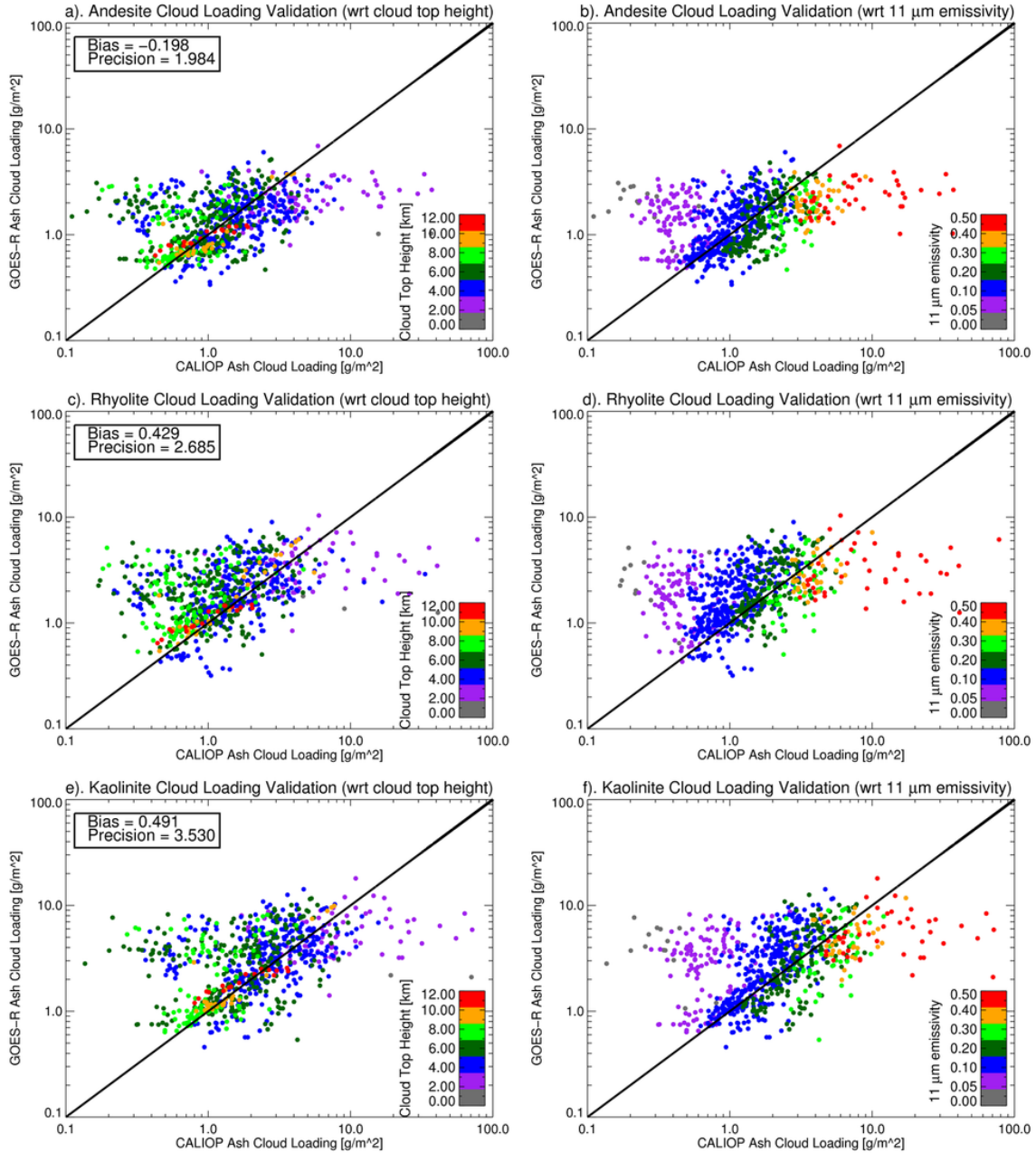
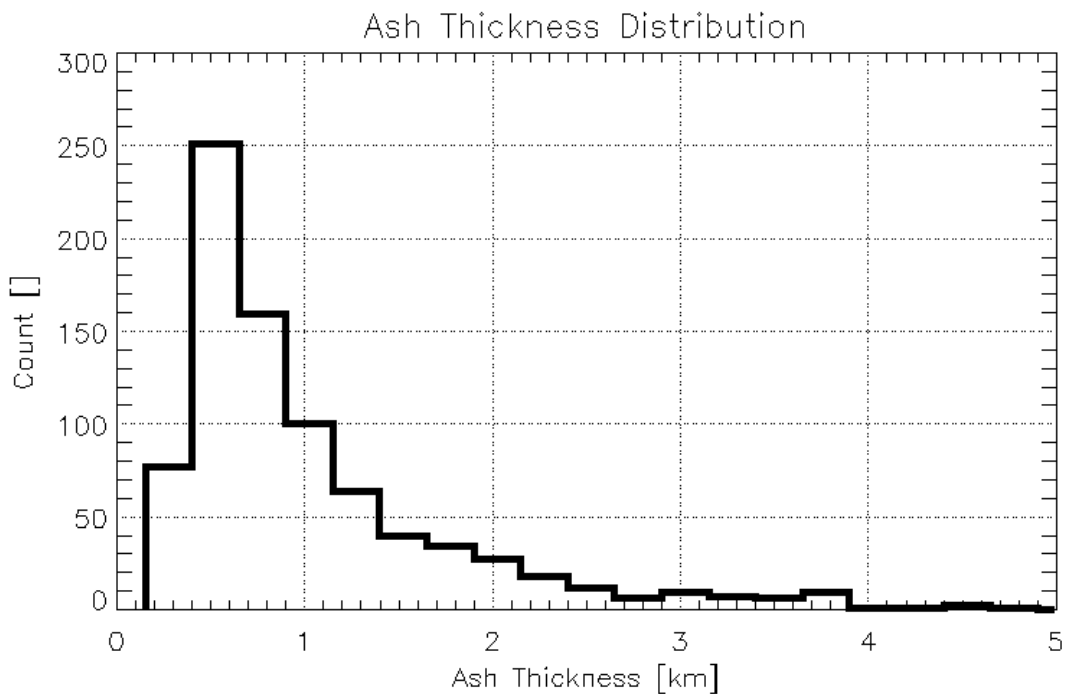


Figure 3: A comparison of SEVIRI ash mass loading retrieved using the GOES-R approach and the ash mass loading derived from a combination of CALIOP and SEVIRI are shown as a function of the CALIOP measured cloud top height (first column) and the nadir 11 μm cloud emissivity derived from a combination of CALIOP and SEVIRI (second column). Each color represents a different cloud top height or cloud emissivity bin. The results are also shown as a function of the mineral composition assumed by the retrieval (top=andesite, middle=rhyolite, bottom=kaolinite). The 1:1 line is shown in black. A total of 796 data points were used in this analysis.

Ash Cloud Geometric Thickness from CALIOP

Prior to the availability of CALIOP measurements, information on the vertical extent (e.g. geometric thickness) of dispersed ash clouds was simply not available. Thus,

CALIOP has provided the first opportunity to study ash cloud geometric thickness in any detail. Figure 4 shows the CALIOP-derived distribution of geometric ash cloud thickness for Eyjafjallajökull ash overpasses and overpasses of additional ash clouds produced by a variety of eruptions including Cordon Caulle (2011), Grimsvotn (2011), Kasatochi (2008), Okmok (2008), Soufriere Hills (2010), and Redoubt (2009). The Eyjafjallajökull distribution indicates that 75% of the ash layers sampled by CALIOP are less than 1 km thick. Similarly, the distribution from the other volcanic events indicates that 73% of ash layers sampled are less than 1 km thick. The majority of the ash layers sampled were well dispersed from the volcano. These results show that the majority of dispersed ash clouds have a geometric thickness that is too small to be resolved with current forecast and dispersion models. Thus, current dispersion model forecasts will be exceptionally prone to over-estimating the vertical extent of dispersed ash clouds. This has very important implications for aviation.



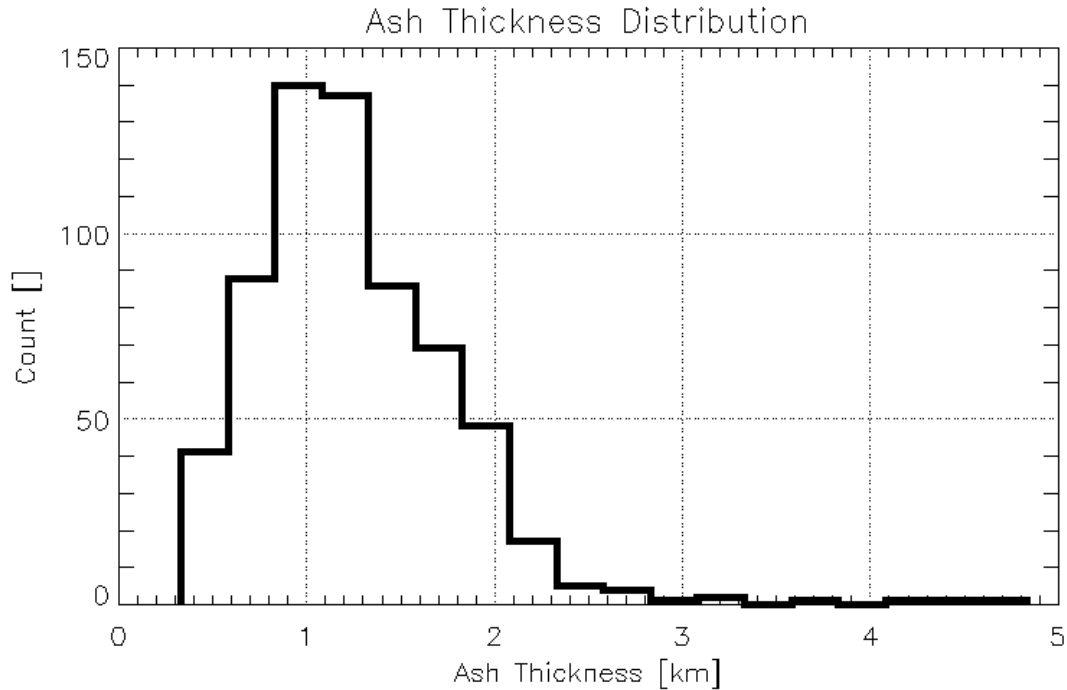


Figure 4: The CALIOP-derived distribution of geometric ash cloud thickness is shown for Eyjafjallajökull ash overpasses (top) and overpasses of additional ash clouds produced by a variety of eruptions including Cordon Caulle (2011), Grimsvotn (2011), Kasatochi (2008), Okmok (2008), Soufriere Hills (2010), and Redoubt (2009) (bottom). The distribution shown in the top panel indicates that 75% of the ash layers sampled by CALIOP are less than 1 km thick. Similarly, the bottom panel distribution indicates that 73% of ash layers sampled are less than 1 km thick. The majority of the ash layers sampled were well dispersed from the volcano.

MODIS and CALIOP Optical depth investigation

The signal to noise requirement limits the CALIOP constrained retrieval primarily to nighttime FOV due to the increased solar background during the day. This precludes direct comparison with the MODIS optical property retrieval, a daytime only retrieval. The MODIS IR COT retrievals can be applied day and night with the sensitivity independent of the time of day. These characteristics allow the CALIOP constrained and un-constrained COT to be compared to the IR providing a means to evaluate the two retrieval methods.

Figure 5 presents the joint histogram between the unconstrained CALIOP and MODIS IR COT for January 2012 day/night observations for single layer. The layer optical thickness was filtered using the extinction quality control (QC) flags provided as part of the L2 products. Only QC values of 0 or between 2-8 were selected. There is a significant low bias between the IR and CALIOP unconstrained COT with a non linear dependence as a function of the COT. The comparison reveals a distinct difference between the CALIOP constrained and unconstrained retrievals with the constrained results demonstrating a significantly smaller bias relative to the IR COT. As discussed in the methodology section the CALIOP COT retrieval requires estimates of the multiple scattered contributions for both the constrained and unconstrained methods with the un-constrained retrieval also requiring

knowledge of the lidar ratio. Because both retrievals use the same fixed multiple scattering coefficient difference in the biases between the constrained and unconstrained retrievals likely results from the selection of the fixed lidar ratio used in the unconstrained retrieval. The Version 3 CALIOP products use a lidar ratio of 25 which was derived using a combination of ground based lidar observations and inter-comparisons with the NASA Cloud Physics lidar (CPL) which fly's on the NASA ER. Although these datasets provide valuable constraints on the cirrus lidar ratio there remains considerable uncertainty in the global mean value and variability of the lidar ratio.

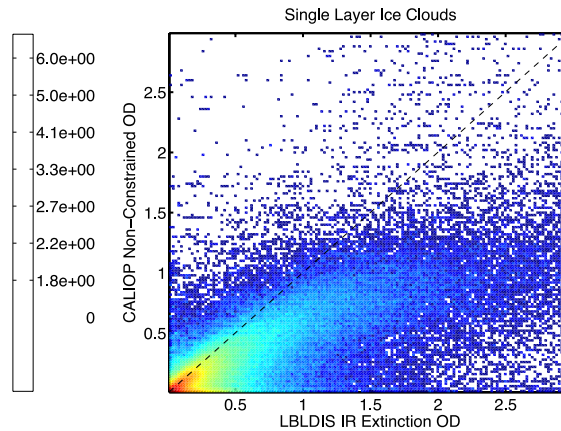


Figure 5 The 2-D histogram comparing the MODIS C5 (a) and CALIOP V3 (b) retrievals to the reference IR retrieval run on the MODIS 11um channel.

To investigate the sensitivity of the CALIOP COT retrievals to the lidar ratio selection a month of CALIOP L2 products was processed (January 2010) with the default lidar ratio increased to 32. Increasing the lidar ratio will result in an increase of the CALIOP COT. The modified products were then collocated and inter-compared with both the MODIS C5 and C6 products and the MODIS IR retrievals with the modified CALIOP unconstrained COT inter-compared with the MODIS reference IR COT in Figure 6a.. Compared to the standard V3 the change in the lidar ratio significantly reduced the bias compared to the IR COT with the non-linear behavior of the bias with respect to COT almost completely removed. This result suggests that the current V3 unconstrained lidar ratio of 25 is not representative of the actual global mean cirrus scattering properties and should be increased in future versions of the CALIOP retrieval.

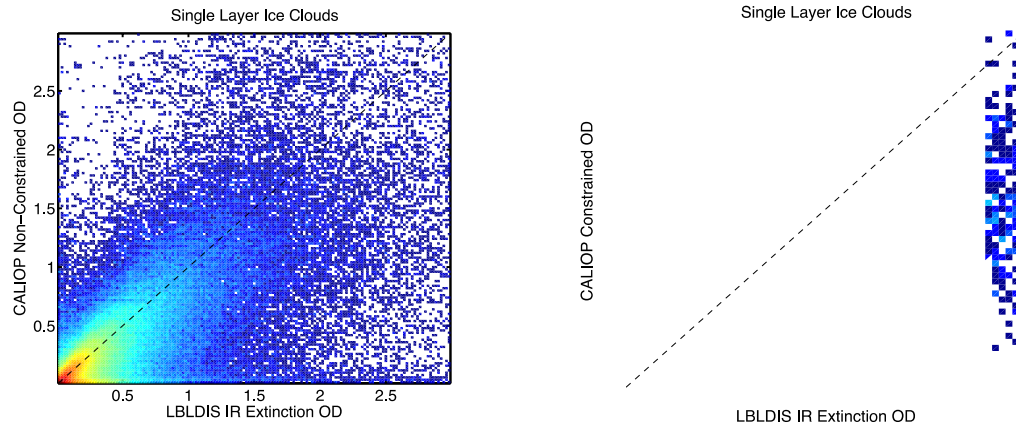


Figure 6 The joint histogram the CALIPSO non-constrained COT using a the modified lidar ratio of 32 is compared to collocated IR MODIS retrieved COT in the left figure with the CALIPSO constrained COT compared to the IR in right figure. A logarithmic color scale is used for both figures.

References

Garnier, A., J. Pelon, P. Dubuisson, M. Faivre, O. Chomette, N. Pascal, and D. P. Kratz, 2012: Retrieval of Cloud Properties Using CALIPSO Imaging Infrared Radiometer. Part I: Effective Emissivity and Optical Depth. *Journal of Applied Meteorology and Climatology*, **51**, 1407-1425, doi:10.1175/JAMC-D-11-0220.1.

Heidinger, A. K., M. J. Pavolonis, 2009: Gazing at Cirrus Clouds for 25 Years through a Split Window. Part I: Methodology. *Journal of Applied Meteorology and Climatology*, **48**, 1100-1116, doi:10.1175/2008JAMC1882.1 ER.

Pavolonis, M. J., 2010: Advances in Extracting Cloud Composition Information from Spaceborne Infrared Radiances-A Robust Alternative to Brightness Temperatures. Part I: Theory. *Journal of Applied Meteorology and Climatology*, **49**, 1992-2012, doi:10.1175/2010JAMC2433.1 ER.

Pavolonis, M., A. Heidinger, and J. Sieglaff, 2013: Automated retrievals of volcanic ash and dust cloud properties from upwelling infrared measurements, *J. Geophysical Research*, **118(3)**, 1436-1458.