

# Adapting CALIPSO Climate Measurements for Near Real Time Analyses and Forecasting

M. Vaughan<sup>a</sup>, C. Trepte<sup>a</sup>, D. Winker<sup>a</sup>, M. Avery<sup>a</sup>,  
J. Campbell<sup>b</sup>, R. Hoff<sup>c</sup>, S. Young<sup>d</sup>, B. Getzewich<sup>e</sup>, J. Tackett<sup>e</sup>, J. Kar<sup>e</sup>

<sup>a</sup>NASA Langley Research Center, Hampton, VA, USA – (mark.a.vaughan, charles.r.trepte, david.m.winker, melody.a.avery)@nasa.gov

<sup>b</sup>U. S. Naval Research Laboratory, Monterey, CA, USA – james.campbell@nrlmry.navy.mil

<sup>c</sup>University of Maryland Baltimore County, Baltimore, MD, USA – hoff@umbc.edu

<sup>d</sup>CSIRO Marine & Atmospheric Research, Aspendale, VIC, Australia – stuart.young@csiro.au

<sup>e</sup>SSAI, Hampton, VA, USA – (brian.j.getzewich, jason.l.tackett, jayanta.kar)@nasa.gov

**Abstract** – The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission was originally conceived and designed as a climate measurements mission, with considerable latency between data acquisition and the release of the level 1 and level 2 data products. However, the unique nature of the CALIPSO lidar backscatter profiles quickly led to the qualitative use of CALIPSO's near-real-time (i.e., "expedited") lidar data imagery in several different forecasting applications. To enable quantitative use of their near-real-time analyses, the CALIPSO project recently expanded their expedited data catalog to include all of the standard level 1 and level 2 lidar data products. Also included is a new cloud-cleared level 1.5 profile product developed for use by operational forecast centers for verification of aerosol predictions. This paper describes the architecture and content of the CALIPSO expedited data products. The fidelity and accuracy of the expedited products are assessed via comparisons to the standard CALIPSO data products.

**Keywords:** CALIPSO, expedited, cloud, aerosol, lidar, profile

## 1. INTRODUCTION

On April 28, 2006, years of research and development undertaken as a joint partnership between the national space agencies of the United States (NASA) and France (CNES) culminated with the successful launch of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission (Winker et al., 2010). CALIPSO carries three Earth observing remote sensing instruments: a three-channel imaging infrared radiometer, a single-channel wide field camera, and the Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) (Winker et al., 2009). The primary payload is CALIOP, a dual-wavelength elastic backscatter lidar that transmits linearly polarized laser light at 532 nm and 1064 nm. Its three channel receiver measures the total backscatter at 1064 nm, and, at 532 nm, the components of the backscatter polarized parallel and perpendicular to the polarization plane of the transmitted beam.

The CALIPSO mission was originally conceived as a climate measurements mission, designed to improve human knowledge and understanding of direct and indirect aerosol forcing, the uncertainties associated with estimates of these forcings, and to help better assess cloud-climate feedbacks. However, because CALIOP is uniquely able to provide continuous, global measurements of the vertical structure of the atmosphere, the CALIOP images distributed via the CALIPSO web site (e.g., as in Figure 1) were quickly adopted for near-real-time uses by agencies tasked with aerosol modeling, air quality forecasting and in-situ measurements. For example, CALIOP near-real-time data imagery has been used in flight planning for NASA field campaigns such as the Arctic Research of the

Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission (Jacob et al., 2010). One of the earliest full-time adopters of the CALIOP images is the U. S. Air Quality Web Log provided by the University of Maryland, Baltimore County (see <http://alg.umbc.edu/usaq/>), where researchers use CALIOP and other satellite data, along with ground-based measurements, and model forecasts to develop daily evaluations of air quality throughout the United States.

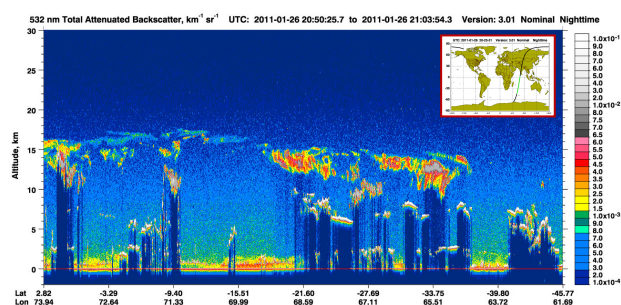


Figure 1. CALIOP measurements of 532 nm attenuated backscatter coefficients acquired over the Indian Ocean on January 27, 2011. Images for the entire mission are available at <http://www-calipso.larc.nasa.gov/products/>.

In five short years, CALIOP datasets have provided unmatched context for a host of cloud and aerosol climate research initiatives. During this time, the science community has embraced these data and grown more familiar with the potential of lidar monitoring. The CALIPSO project is now poised to release a full catalog of expedited lidar products for near real-time processing and applications. These expedited products contain all of the information reported in the standard products, with the primary difference between expedited and standard processing being the accuracy of the meteorological data used in the analyses. The standard processing uses data provided by NASA's Global Modeling and Assimilation Office (GMAO) that is temporally and spatially matched to the CALIOP measurement locations. However, the latency between acquisition of the CALIOP data and the production and distribution of the corresponding GMAO data is on the order of two or three days. The expedited processing therefore uses the most recently available GMAO data, which is typically from one to two days earlier. While this lag time is held to a minimum, it nevertheless introduces differences in all aspects the CALIOP data processing scheme, including calibration, layer detection, layer classification, and the retrieval of layer optical properties. The remainder of this paper is devoted to describing how these differences arise, and quantifying their expected magnitudes.

## 2. CALIOP LEVEL 1 EXPEDITED DATA

The standard CALIOP data products are classified by processing level according to the definitions given by NASA's Earth Observing System (EOS) project. Level 1 data products

report calibrated and geolocated instrument measurements. Level 2 data products report the geophysical parameters derived from the level 1 data. The CALIOP level 1 data consist of profiles of attenuated backscatter coefficients at 1064 nm and 532 nm (e.g., as shown in Figure 1), while the level 2 data report such quantities as layer location (i.e., base, top, latitude, and longitude), layer type (e.g., cloud or aerosol), and a number of derived optical parameters, including optical depths. Two main issues affect the quality of the CALIOP level 1 expedited data relative to the nominal processing: calibration and geolocation. CALIOP's primary calibration is obtained by normalizing the high altitude (30–34 km) 532 nm backscatter signal acquired during the nighttime portions of each orbit to a molecular backscatter model derived from GMAO meteorological data (Powell et al., 2009). The accuracy of this calibration therefore depends on the accuracy of the molecular model used. Since the same calibration procedure is used for both standard and expedited processing, any changes in the molecular density in the calibration region that occur as a result of the two day GMAO data latency will manifest themselves as differences between the standard and expedited nighttime 532 nm calibration coefficients. Fortunately, the time rate of change of stratospheric molecular number density is generally small, and the nighttime 532 nm calibration error introduced by using 2-day old GMAO data is typically less than 1%.

All other CALIOP backscatter measurements are calibrated relative to the 532 nm nighttime calibration. The 532 nm daytime calibration is derived by scaling the daytime mean attenuated scattering ratios in clear sky regions between 8 km and 12 km to match the nighttime values in the same altitude region. Operationally this is accomplished using the mean calibration coefficient from the previous nighttime orbit and a latitudinally dependent table of scaling factors (Powell et al., 2010). Values in this table are updated once every 24 hours using nighttime and daytime clear air measurements acquired over the previous seven days. Like the nighttime procedures, the daytime 532 nm calibration procedures are also identical for both standard and expedited processing, with the daytime expedited calibration using the most recent table of night-to-day calibration scale factors. Therefore, changes in the daytime 532 nm calibration between expedited and standard processing will reflect both changes in the high-altitude molecular density profile and any changes that may occur in the night-to-day calibration scale factors. The 1064 nm measurements are calibrated using the backscatter signal from dense cirrus clouds (Vaughan et al., 2010). For each daytime and nighttime granule in the standard processing, a mean 532-to-1064 calibration scale factor is computed using all dense cirrus measurements encountered during the course of the orbit segment. A slightly different procedure is used for the expedited processing. Instead of computing granule mean 532-to-1064 scale factors, the expedited processing uses previously calculated daily means derived for the same temporal offset used in the 532 nm expedited processing. This use of different 532-to-1064 scale factors will, of course, introduce additional differences into the expedited 1064 nm calibrations when compared with the standard processing.

Differences in geolocation and altitude registration will also increase the disparity between standard and expedited calibration coefficients for both wavelengths. Geolocation and altitude registration for the expedited processing rely on GPS coordinates and calculations by onboard orbit propagation software. The standard processing uses more accurate post-processed ephemeris that only becomes available ~24 hours after the initial downlink of the data from the CALIPSO

spacecraft. The magnitudes of the altitude registration differences are generally small. For example, for January 01–09, 2011, the altitude registration difference for any one profile was no greater than 60 m, and in 97% of the cases the change was 30 m or less.

Table 1 presents a complete set of expedited-to-standard calibration comparisons for daytime and nighttime measurements at both wavelengths computed over the time period from 01–09 January 2011. While the extreme values in all cases are relatively large – in excess of 10% – the means, medians, and standard deviations are acceptably small. For both daytime and nighttime, the mean difference between the 532 nm expedited and standard calibration is less than 1%. While the 1064 nm calibration coefficients show a somewhat greater variability, the mean magnitude of these differences is also small, at just under 2%.

Table 1: Relative difference between expedited and nominal calibrations for 15,624,885 valid profiles acquired between 2011-01-01 and 2011-01-09. Relative difference is a signed quantity computed as (expedited – nominal) / nominal.

	532 night	532 day	1064 night	1064 day
min	-0.1020	-0.1459	-0.1428	-0.1783
max	0.1390	0.1124	0.2138	0.1474
median	0.0041	0.0054	0.0137	0.0107
mean	0.0062	0.0059	0.0189	0.0104
st. dev.	0.0225	0.0165	0.0493	0.0393

### 3. CALIOP LEVEL 2 EXPEDITED DATA

The primary CALIOP level 2 data products are layer base and top heights, layer classification (e.g., cloud vs. aerosol) and optical depths, and profiles of extinction coefficients. For the level 2 products, the three primary sources of differences between the standard and the expedited products are the calibration coefficients computed for the level 1 data, the GMAO molecular model, which is used in the layer detection and classification algorithms and in the extinction retrievals, and geolocation and altitude registration.

#### 3.1 Layer Detection and Classification Comparisons

The CALIOP layer detection algorithm is a thresholding scheme that iterates through multiple spatial resolutions, detecting successively weaker layers at increasingly coarse spatial resolutions. At each iteration, layers are identified as “any extended, vertically contiguous region of enhanced backscatter that rises significantly above the signal magnitude expected from a purely molecular atmosphere” (Vaughan et al., 2009). The data being searched are the 532 nm attenuated scattering ratios, which are computed by dividing the 532 nm total attenuated backscatter coefficients by a molecular backscatter model derived from GMAO meteorological data. The level 2 expedited processing uses the same ~2-day old GMAO data that are used in level 1. Differences in the molecular density profiles in the calibration region will thus introduce a bias error throughout an entire attenuated scattering ratio profile, via the calibration coefficient. This bias can have significant effects in the detection of faint layers (e.g., diffuse aerosol and subvisible cirrus), but has little if any effect on more robust layers. Additional localized differences will also be present wherever the 2-day old density profile differs from the true molecular density when the measurement was made, and whenever there are changes in altitude registration from expedited to nominal. To distinguish between clouds and aerosol layers, the CALIOP cloud aerosol discrimination

algorithm utilizes 5-dimensional probability distribution functions (Liu et al., 2009). Separate probability distributions characterize clouds and aerosols as functions of layer-mean attenuated backscatter coefficient ( $\langle\beta'_{532}\rangle$ ), integrated attenuated backscatter color ratio ( $\chi'$ ), integrated volume depolarization ratio ( $\delta_v$ ), mid-layer altitude ( $Z_{mid}$ ), and laser footprint latitude. Two of these five attributes ( $\langle\beta'_{532}\rangle$  and  $\chi'$ ) are influenced by differences in calibration and molecular models, while two others ( $Z_{mid}$  and latitude) can be slightly affected by changes in geolocation and/or altitude registration.

To assess differences between expedited and standard processing for layer detection and classification, we examine the CALIOP level 2 vertical feature mask (VFM) product. The VFM provides a concise classification of the atmospheric state of each range bin in the downlinked lidar backscatter data. As shown in Figure 2, plotting the data reported in the VFM files reveals the locations and classifications for all layers detected. A complete description of the vertical feature mask product can be found at [http://www-calipso.larc.nasa.gov/resources/calipso\\_users\\_guide/data\\_summaries/vfm/](http://www-calipso.larc.nasa.gov/resources/calipso_users_guide/data_summaries/vfm/).

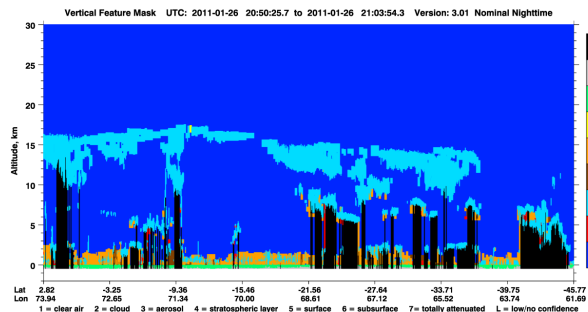


Figure 2. Vertical feature mask image showing layer locations and layer types for the scene shown in Figure 1.

Comparisons of the vertical feature masks from expedited and standard processing show differences in layer detection (i.e., layers detected in one file that are not detected in the other) for ~3% of all range bins. These differences are slightly higher for the nighttime data; however, this is to be expected, as the expedited and standard layer detection configurations are identical for daytime data, but slightly different for nighttime. For layer locations that are identical in both expedited and standard processing, there are changes in layer classification for ~1% of the samples detected during daytime, and ~6% of the samples detected at night.

### 3.2 Optical Properties Comparisons

The ultimate goal of the CALIOP calibration, layer detection, and layer classification analyses is to enable the accurate estimation of cloud and aerosol extinction profiles and layer optical depths. However, because the extinction calculation requires the solution of a nonlinear equation (Young and Vaughan, 2009), small changes in the inputs can spawn very large changes in the outputs. This situation is illustrated in Figure 3, which shows two different comparisons of the standard and expedited cloud column optical depths calculated for all data acquired on 27 January 2011. The left panel shows a scatter plot of cloud column optical depths retrieved by the standard (x-axis) and expedited processing (y-axis). The color coding indicates the number of samples at each plot location. While the data show a very large spread, the majority of the points lie along the one-to-one line. The unusual behavior seen above optical depths of 2.5 is an artifact of the retrieval scheme that occurs due to numerical instabilities in the retrieval of extinction profiles in very dense, often opaque layers. The right panel of Figure 3 shows a histogram of the relative

differences ( $(\text{expedited} - \text{standard}) / \text{standard}$ ) in cloud column optical depths. Again, the spread is seen to be very large; however, for ~50% of cases, the differences are less than 10%, and for ~75% of cases differences are less than 25%.

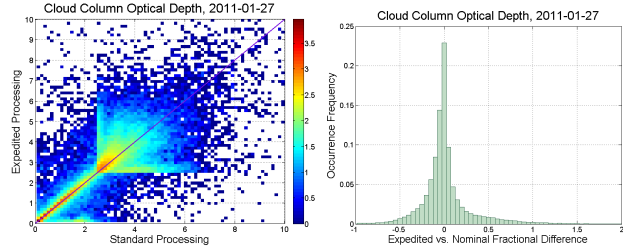


Figure 3. left panel: scatter plot of cloud column optical depths for standard and expedited processing; right panel: distribution of relative differences

## 4. CALIOP LEVEL 1.5 EXPEDITED DATA

Unlike the level 1 and level 2 expedited products, the CALIOP level 1.5 expedited product does not have an exact analog in the nominal processing. Instead, as indicated by its processing level, the level 1.5 product is a fusion of the information contained in the level 1 and level 2 products. Like the level 1 product, the level 1.5 product reports profiles of attenuated backscatter. However, the profiles reported in level 1.5 are cloud-cleared at single shot resolution, using a cloud mask derived from the level 2 vertical feature mask, and then averaged to a uniform resolution of 20 km horizontally and 60 m vertically. A comparison of the level 1.5 product to its level 1 source data is shown in Figure 4. The upper panel shows level 1 532 nm attenuated backscatter coefficients measured during daytime over northeast Africa, averaged to a uniform horizontal resolution of 1 km. The discontinuity seen at ~8.2 km occurs due to a change in vertical resolution, from 60 m above to 30 m below (Hunt et al., 2009). The lower panel of Figure 4 shows the level 1.5 cloud-cleared 532 nm backscatter coefficients. Aerosol layers that are completely obscured by noise in the level 1 data (e.g., between 2°N and 4°N, and again from 14°N to 20°N) appear prominently in the level 1.5 image.

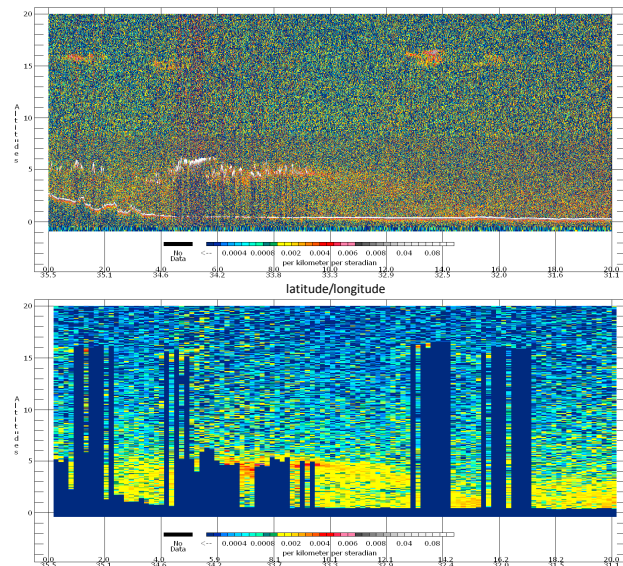


Figure 4. upper panel: CALIOP level 1 532 nm attenuated backscatter coefficients from 2011-01-30 averaged horizontally to a 1-km resolution; lower panel: 20-km averaged attenuated backscatter coefficients reported in the level 1.5 product.

The level 1.5 product was specifically designed to meet the needs of operational forecast centers to assess the performance of aerosol transport models and air quality forecasts. During the development process, members of the CALIPSO team consulted frequently with researchers from the United States Naval Research Laboratory (NRL), the European Center for Medium-Range Weather Forecasts (ECMWF), the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP), and the Japan Meteorological Agency. By request, the level 1.5 data files also contain 20 km averages of the aerosol extinction profiles derived by the CALIOP level 2 processing. Additional information provided includes layer type information, molecular backscatter profiles derived from GMAO meteorological data for computing attenuated scattering ratios, and uncertainty estimates for all optical profile parameters.

## 5. APPLICATIONS OF CALIOP EXPEDITED DATA

The authors fully expect that the expedited CALIOP data products will be used by a growing segment of the community performing data assimilations to regulate aerosol mass in global transport models. More specifically, aerosol optical depths retrieved from passive radiometric satellite datasets (i.e., MODIS) are already assimilated operationally by multiple agencies to improve the two-dimensional (horizontal) aerosol distribution. The expense, however, of an inaccurate vertical profile is error downstream in the forecast field from diverging trajectories with height. CALIOP is the only present sensor capable of providing this critical context. To fully enable this capability, researchers at the NRL are currently designing tools to ingest CALIOP data into the Navy Aerosol Analysis and Prediction System (NAAPS) model so that the vertical profile for aerosol structure can be processed and assimilated in near real-time to improve model response and forecast accuracy (Campbell et al., 2010).

A small subset of the expedited data products have already been made available to some members of the forecasting community on a limited basis. For example, the CALIOP expedited VFM product is being used to assess the performance of components of the Australian Community Climate and Earth System Simulator (ACCESS) (Protat et al., 2010), a global, coupled atmosphere-ocean climate model based on the Unified Model of the U.K. Meteorological Office. A high-resolution atmosphere-only version combined with a 4DVAR assimilation system is being used for numerical weather prediction. Forecast cloud and precipitation fields along CALIPSO orbit tracks in the Australian region are being compared with a composite cloud and precipitation mask created from CALIOP expedited VFM and CloudSat data (Young et al., 2011).

As of this writing, the CALIOP level 1 and level 2 expedited data products are currently available to CALIPSO science team members via the Atmospheric Science Data Center (ASDC) at NASA-Langley (see <http://eosweb.larc.nasa.gov/>). Full public release of these products is expected to occur sometime in the spring of 2011. The level 1.5 product will also be released in the same time frame. However, this data will initially be available by subscription only. Users desiring access are asked to contact the ASDC for more information.

## REFERENCES

Campbell, J. R., J. S. Reid, D. L. Westphal, J. Zhang, E. J. Hyer, and E. J. Welton, "CALIOP aerosol subset processing for

global aerosol transport model data assimilation", *IEEE J. Sel. Top. Appl.*, vol 3, pp. 203–214, 2010.

Hunt, W. H, D. M. Winker, M. A. Vaughan, K. A. Powell, P. L. Lucker, and C. Weimer, 2009: "CALIPSO Lidar Description and Performance Assessment", *J. Atmos. Oceanic Technol.*, vol 26, pp. 1214–1228, 2009.

Jacob, D. J. and 14 coauthors, "The Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission: design, execution, and first results", *Atmos. Chem. Phys.*, vol 10, pp. 5191–5212, 2010.

Liu, Z., M. A. Vaughan, D. M. Winker, C. Kittaka, B. J. Getzewich, R. E. Kuehn, A. Omar, K. Powell, C. R. Trepte, and C. A. Hostetler, "The CALIPSO Lidar Cloud and Aerosol Discrimination: Version 2 Algorithm and Initial Assessment of Performance", *J. Atmos. Oceanic Technol.*, vol 26, pp. 1198–1213, 2009.

Powell, K. A., C. A. Hostetler, Z. Liu, M. A. Vaughan, R. E. Kuehn, W. H. Hunt, K. Lee, C. R. Trepte, R. R. Rogers, S. A. Young, and D. M. Winker, "CALIPSO Lidar Calibration Algorithms: Part I – Nighttime 532 nm Parallel Channel and 532 nm Perpendicular Channel", *J. Atmos. Oceanic Technol.*, vol 26, pp. 2015–2033, 2009.

Powell, K. A., M. A. Vaughan, R. R. Rogers, R. E. Kuehn, W. H. Hunt, K-P. Lee, and T. D. Murray, "The CALIOP 532-nm Channel Daytime Calibration: Version 3 Algorithm", *Proceedings of the 25th International Laser Radar Conference*, pp. 1367–1370, ISBN 978-5-94458-109-9, 2010.

Protat, A., L. Rikus, S. Young, J. Le Marshall, P. May, and M. Whimpey, "Evaluation of ACCESS-A Clouds and Convection using Near Real-Time CloudSat-CALIPSO Observations", *CAWCR Research Letters*, vol 4, pp. 27–33, 2010.

Vaughan, M., K. Powell, R. Kuehn, S. Young, D. Winker, C. Hostetler, W. Hunt, Z. Liu, M. McGill, and B. Getzewich, "Fully Automated Detection of Cloud and Aerosol Layers in the CALIPSO Lidar Measurements", *J. Atmos. Oceanic Technol.*, vol 26, pp. 2034–2050, 2009.

Vaughan, M. A., Z. Liu, M. J. McGill, Y. Hu, and M. D. Obland, "On the Spectral Dependence of Backscatter from Cirrus Clouds: Assessing CALIOP's 1064 nm Calibration Assumptions Using Cloud Physics Lidar Measurements", *J. Geophys. Res.*, vol 115, D14206, 2010.

Winker, D. M., M. A. Vaughan, A. H. Omar, Y. Hu, K. A. Powell, Z. Liu, W. H. Hunt, and S. A. Young, "Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms", *J. Atmos. Oceanic Technol.*, vol 26, pp. 2310–2323, 2009.

Winker, D. M. and 18 coauthors, "The CALIPSO Mission: A Global 3D View Of Aerosols And Clouds", *Bull. Am. Meteorol. Soc.*, vol 91, pp. 1211–1229, 2010.

Young, S. A. and M. A. Vaughan, "The retrieval of profiles of particulate extinction from Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) data: Algorithm description", *J. Atmos. Oceanic Technol.*, **26**, 1105–1119, 2009.

Young, S. A., A. Protat, M. Whimpey, L. Rickus, and M. Borgas, "Use of Near Real-Time CALIPSO and CloudSat Observations to Assess the Performance of a Numerical Weather Prediction Model", *These Proceedings*, April 2011.