9.2 THE EVALUATION AND APPLICATION OF CALIPSO PRODUCTS WITH FOCUS ON EXPEDITED DATA RETRIEVALS, TEMPERATURE DATASET COMPARISONS, AND TRAJECTORY MODELING

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1. ABSTRACT

A series of studies using lidar observations from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite were conducted to evaluate the performance and utility of several CALIPSO data products. Using Level 2 data from CALIPSO, an initial 15-day comparison revealed an 83 % agreement in cloud and aerosol feature detected between the nominal and expedited products. Also developed was a computational comparison between upper stratospheric temperature datasets used in CALIPSO Version 1.10 and 2.01 data releases, which revealed largest disagreements near the poles during the winter. Finally, it was demonstrated that aerosol layers detected from an expedited CALIPSO data product can be useful for identifying the Saharan Air Layer (SAL) over the Atlantic Ocean. Results from the first two projects will help characterize any biases in CALIPSO products for future product development, whereas results from the third project could help forecast and understand the formation and dissipation of tropical cyclones.

2. INTRODUCTION

With much time and effort currently being devoted to the topic of global climate change, climate models prove to be critically important tools in the assessment and prediction of the future climate system. Significant uncertainties in current models result from the presence of aerosols and optically thin clouds, which strongly impact the radiative properties of the atmosphere (Lorentz, 2008). Aerosols are inherently variable over time and space; moreover, thin clouds are difficult to detect by traditional remote sensing techniques such as radar. Aerosols and thin clouds are difficult to detect in the current climate system causing even greater complexity in producing reliable forecasts of these features using climate models.

Much can be learned about the small particles in Earth's atmosphere using data from NASA's CALIPSO satellite. The CALIPSO mission provides valuable information about the vertical profile of clouds and aerosols in the atmosphere. This mission is the first to employ on orbit a two-wavelength (532 and 1064 nm) polarization-sensitive lidar, named CALIOP, for remote sensing of the atmosphere (Winker, 2006). Lidar, which stands for Light Detection and Ranging, is a remote sensing instrument used to measure the properties of light scattered through a medium (Kovalev, 2004). Being that lidar operates at wavelengths much shorter than that of radar, lidar is more effective in detecting small objects in the atmosphere such as aerosols, small cloud droplets, and ice particles (Winker, 2006). For this reason, CALIPSO is advantageous for observing, analyzing, and interpreting the affects of clouds and aerosols on the climate system.

It is beneficial to collect both the temporal and spatial data of small particles in the atmosphere. The CALIPSO mission allows scientists to study the radiative effects of clouds and aerosols on a global scale. Level 2 CALIPSO data are available in two different forms: the nominal product and the expedited product. The nominal product is available approximately five days after measurements are collected and is the primary dataset for science analysis. The expedited product is designed to support real-time applications and uses a simple calibration scheme. Expedited processing does not wait for the arrival of more accurate ephemeris data and also uses climatology data instead of assimilated meteorological data. The expedited dataset is available ~12 hours after Level 0 data are down linked to a ground receiving station. Being that the nominal product goes through a more rigorous computational process and does not make calibration and climatology assumptions, we assume the nominal product to be the truth in comparison to the expedited product.

Calibration of the CALIOP lidar data at 532 nm is accomplished by comparing measurements to molecular scattering in a layer from 30-35 km (a region above possible backscatter from clouds and stratospheric aerosols). Being that molecular scattering can be determined directly from observations of temperature, temperature profiles obtained from the Global Modeling and Assimilation Office (GMAO) data products are used in CALIPSO Level 1 data processing. For the first CALIPSO data release (Version 1.10), the GMAO Version 4 dataset was used. For the second CALIPSO data release (Version 2.01), the GMAO Version 5 dataset was used. Determining the temperature differences between the two datasets helps to identify biases introduced by possible temperature uncertainties in the GMAO products.

One of the most important aspects of CALIPSO is its ability to measure the altitude of aerosol layers in the atmosphere. The altitude of aerosols strongly determines how long the particles remain suspended in the air. Aerosols in the troposphere are likely to be removed quickly through precipitation. Conversely, aerosols in the stratosphere have a greater likelihood of being suspended in the atmosphere for longer periods of time, often traveling extensive distances.

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According to a study conducted at NASA's Jet Propulsion Laboratory, each year several hundred million tons of Saharan dust are picked up by the wind and dispersed into the atmosphere (Hansen, 2007). This wind-blown dust may be transported over the Atlantic Ocean to create hot, dry pockets of air which inhibit the growth of tropical waves. According to Beitler, it is theorized that a link exists between dust and tropical storm development. It is hypothesized that added dust particles in and near clouds can alter the distribution of cloud water droplets, effect cloud formation and inhibit further tropical cyclone development in the Atlantic basin (Beitler, 2008). Overall, improved detection of small particles in the atmosphere improves the output of global climate models. The results of these models are used to aid policymakers in making confident and informed decisions concerning global climate change.

3. METHODOLOGY

3.1 Expedited and Nominal Comparison

A comparison of the CALIPSO Level 2 nominal and expedited data products was made using the Version 2.01 Vertical Feature Mask (VFM) data product. This product identifies features in a scene that are cloud, aerosol, or in the stratosphere. As a convenience for users, the CALIPSO team produces 2-dimensional color-coded browse images of the VFM product that show the vertical and horizontal distribution of cloud and aerosol layers (Kusterer, 2008).

A qualitative and purely visual evaluation was performed first, detailing where nominal and expedited datasets agreed and disagreed. Images from various days in April 2008 were used for this part of the study. Later a quantitative analysis was conducted for the period June 13 through 27, 2008, which consists of approximately 218 evenly spaced polar orbits. A point for point comparison algorithm was developed that computes the percent agreement for the different elements below 8.2 km. These elements include cloud, aerosol, clear air, surface, subsurface, stratospheric feature, totally attenuated signal, and bad or missing data. Finally, a record of clear air agreement, feature agreement, false positives, and missed features was compiled.

3.2 Temperature Comparison

Using Level 1B data from CALIOP, a statistical comparison was made between two datasets from the Version 1.10 and 2.01 temperature algorithms. Version 1.10 is processed using the GMAO atmospheric model, the Goddard Earth Observing System Model, Version 4 (GEOS-4). Version 2.01 is processed using the GMAO atmospheric model, GEOS, Version 5 (GEOS-5) (Kusterer, 2008). The comparison was performed for a 2-day period representative of winter conditions in either hemisphere: Case 1, June 13 through 14, 2006, and Case 2, January 1 through 2, 2007. Data were compared at an altitude of 5 mb for points separated by 15 km along the satellite path.

The correlation coefficient and temperature differences were computed between the two datasets. Correlations were calculated after every CALIPSO orbit, while the differences were summed in a distribution over the entire time period. The differences are binned into three different latitude ranges: south of 30 °S, north of 30 °N, and between 30 °S and 30 °N. Correlations are found using,

$$R = \frac{\sum_m \sum_n (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{[\sum_m \sum_n (A_{mn} - \bar{A})^2][\sum_m \sum_n ((B_{mn} - \bar{B})^2)]} \quad (1)$$

where R is the correlation, A_{mn} is the data point for Version 1.10, B_{mn} is the data point for Version 2.01, $\bar{A}$ is the mean of Version 1.10, and $\bar{B}$ is the mean of Version 2.01. The indices m and n are incremented in time (horizontal position) and altitude. The correlations do not reveal how large the differences are, but rather where discrepancies exist in the two datasets. Therefore, it is important to look at the differences between the temperatures. The difference is found by,

$$D = A_{mn} - B_{mn}, \quad (2)$$

where D is the difference between the datasets.

3.3 Identifying Saharan Dust

To support investigations on the theorized link between African dust and tropical storm development, we used CALIPSO data to identify layers of airborne Saharan dust over the Atlantic Ocean using the CALIPSO VFM product. Once the dust layers were detected, we computed 4-day back-trajectories of the SAL using the Pierce and Fairlie Langley Trajectory Model. All back-trajectories were initialized on June 13, 2008 and ran over 96 hours. There are 3145 trajectories generated in the model output to provide an ensemble analysis of aerosol transport. The trajectory model does not account for diabatic heating of the layer by aerosols nor does it include particle sedimentation.

The back-trajectories were imported into the Google Earth browser to better visualize the data being presented. Each data point is assigned a value for latitude, longitude, and altitude, and therefore a 3-D representation of the data may be displayed in Google Earth. Moderate Resolution Imaging Spectroradiometer (MODIS) imagery and sea surface temperature overlays can be added to the display to provide supplementary information about the meteorological conditions during this time.

4. RESULTS

4.1 Expedited and Nominal Comparison

The visual comparison between CALIPSO nominal and expedited VFM data products reveals strong agreement. The browse products are visually similar, excluding minor differences on a small scale. The differences that did appear can be grouped into five categories. First, most disagreements occur in areas beneath thick or multiple cloud decks. Assuming that the nominal product is truth, clouds are often labeled as aerosols when the returned lidar signal is nearly fully attenuated and uncertainties are high. Second, the expedited product shows an overestimation of aerosols, except near mountains. Conversely, during night hours near mountains, the expedited product shows overestimation of aerosols. Third, the expedited product recognizes fewer areas of bad or missing data during the day, but recognizes more areas of bad or missing data at night. Fourth, the expedited product does not consistently recognize stratospheric features, and occasionally incorrectly places these features at tropopause level. Finally, we found no obvious disagreements related to latitude. Fig. 1 is an example of how the two products are visually similar, but how some of the above disagreements are obvious on the small scale.

Table 1 details the results of the quantitative comparison between the CALIPSO nominal and expedited VFM data products performed for June 13 through 27, 2008. The white boxes of Table 1 display the total percent match when considering all seven VFM features (61.6%) as well as considering only cloud and aerosol features (83.2%). The gray boxes represent an assessment of whether the nominal and expedited products agree on the detection of clear air as opposed to the detection of any other feature. The false reading category illustrates the percentage of times when the expedited product detected a feature while the nominal product detected clear air for the same point in space. Conversely, the missed feature category illustrates the percentage of times when the expedited product overlooked a feature that the nominal product identified.

Total Match	61.6%
Cloud/Aerosol Match	83.2%
Clear Agreement	51.7%
Feature Agreement	28.7%
False Reading	10.0%
Missed Feature	9.6%

Table 1: White boxes detail low total agreement but high agreement for cloud and aerosol features. Gray boxes detail detection of any feature vs. detection of clear air

4.2 Temperature Comparison

Correlations in each hemisphere during the winter months were found to be much lower than the summer months (Fig. 2). The winter correlations reach as low as -0.70 in the northern hemisphere and -0.20 in the southern hemisphere. Summer correlations, in both hemispheres, remain consistent with a mean correlation of 0.95. These finding are generally consistent with the fact that much larger variances in temperature are

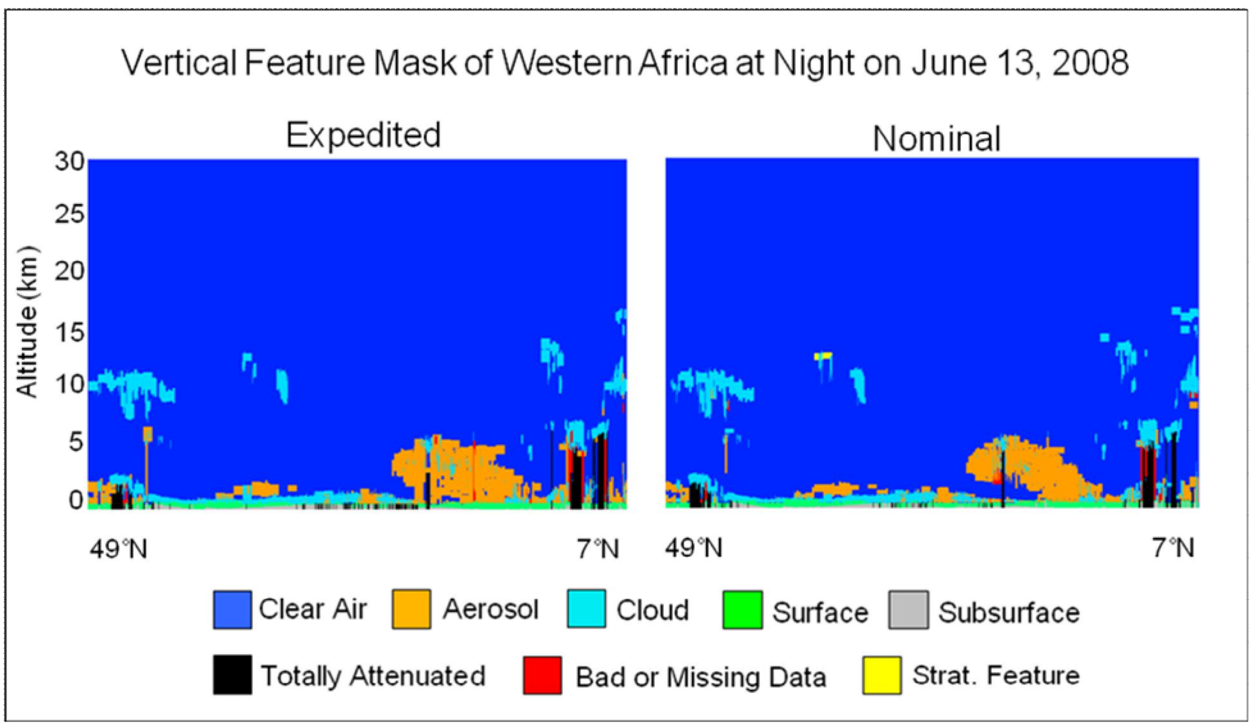

Fig. 1: Visual comparison between the CALIPSO Level 2 expedited and nominal data products. A qualitative assessment was performed by visually comparing images such as these. Notice the similarities between the products, yet small scale differences are apparent.

present in the winter hemisphere, where latitudinal temperature gradient is largest.

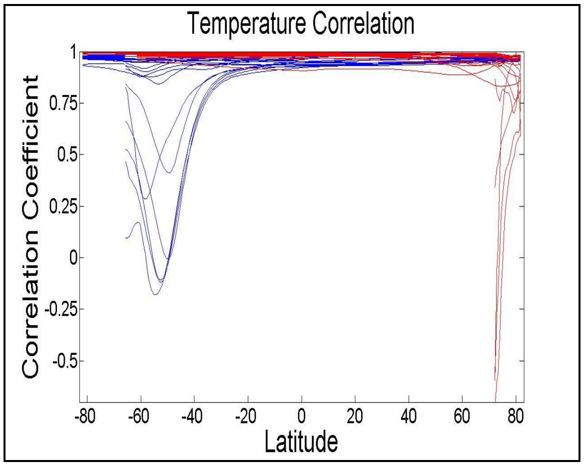

Fig. 2: Correlations between the Version 1.10 and 2.01 temperature algorithms. Lines in red represent measurements from June 14th 2006, while the lines in blue represent measurements from January 1st 2007

Differences between the summer and winter days in each hemisphere are also observed with larger temperature differences between the datasets found during the winter (Fig. 3). Comparing only the summer and winter dates north of 30 °N and south of 30 °S, the winter has a distribution nearly three times larger than the northern hemisphere. Differences in the winter range from -6.7 °C to +12.0 °C, while in the summer, differences range from -2.6 °C to +3.6 °C. This pattern is confirmed by looking at the standard deviation of the differences. Summer days have a standard deviation of ±0.78 °C, while the winter days have a standard deviation of ±2.1 °C.

4.3 Identifying Saharan Dust

Upon completion of the back trajectory model run, all data points are scattered across western and northern Africa (Fig. 4). As the back trajectory model is run forward in time for 96 hours, the air parcels migrate to the central location where all of the back trajectories were initialized using a CALIPSO browse image (Fig. 5). This migration to the initialization point illustrates the movement of air parcels.

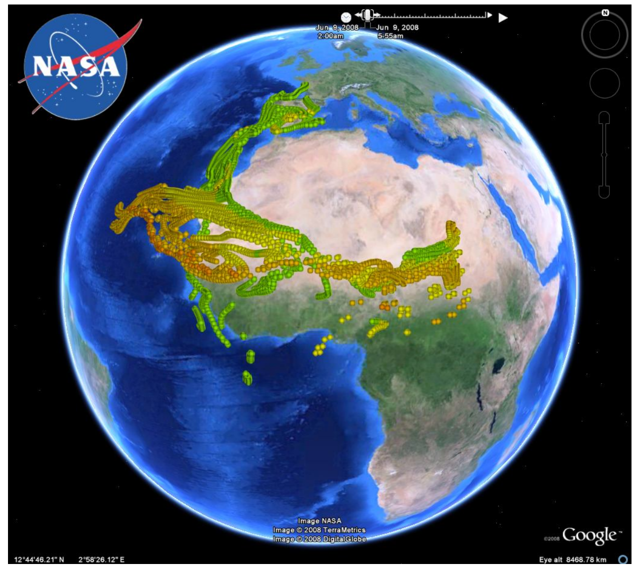

Fig. 4: Google Earth visualization of 96-hour back trajectories over West Africa

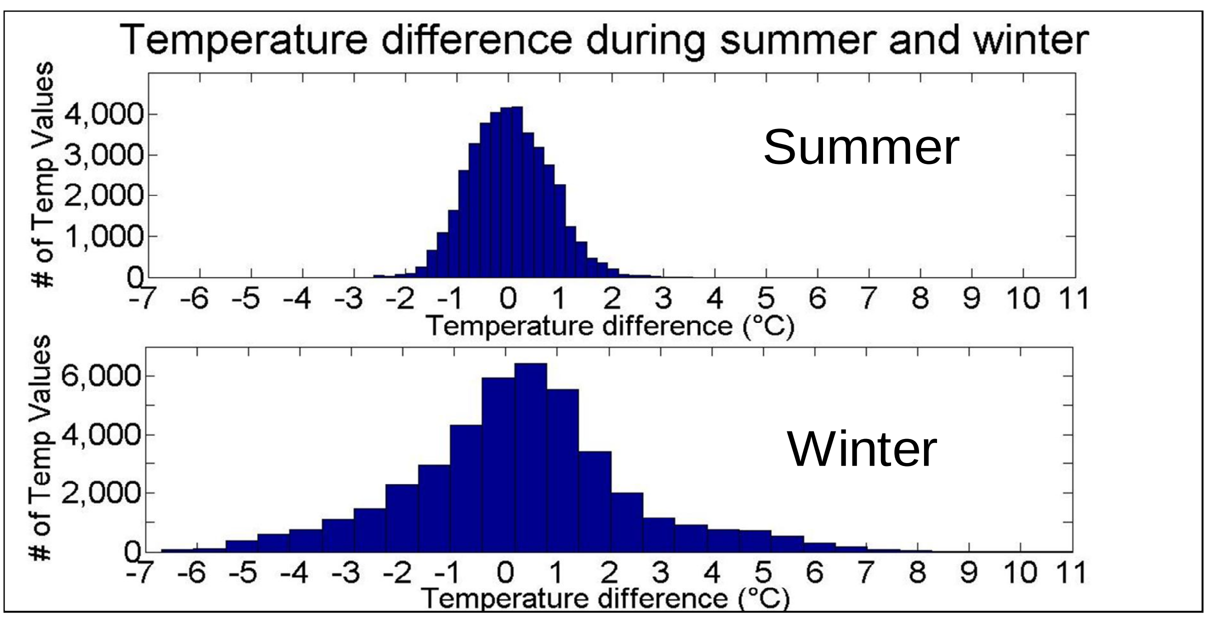

Fig. 3: Temperature difference distribution sorted by summer and winter. The top graph is a summation of the temperature differences during the summer in both hemispheres, and the bottom graph is a summation of the temperature differences in the winter in both hemispheres.

All trajectories are initialized on June 13, 2008 along a location where Saharan dust was detected by CALIPSO. Fig. 5 shows the initialization of the back trajectories near the coast of West Africa. Each of the 3145 data points are categorized into four color-coded divisions of 2000-meter intervals with respect to mean sea level.

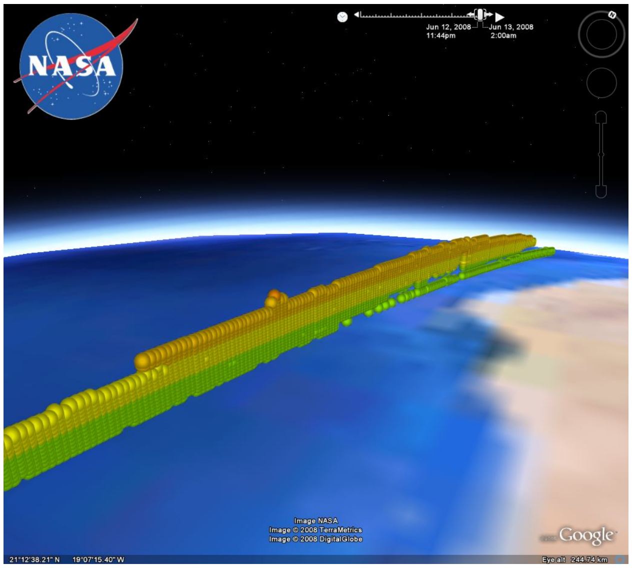

Fig. 5: The initialization points of back trajectories displayed in Google Earth.

5. DISCUSSION

5.1 Expedited and Nominal Comparison

The 15-day comparison revealed that cloud/aerosol features are generally in agreement between datasets. The expedited product can be used reliably for analysis of cloud or aerosol features for real-time application, such as when identifying and tracking Saharan dust. Confirmation of the CALIPSO Science Team's expected results have enhanced their confidence in the quality of the expedited retrievals. Low product agreement occurs beneath thick or multiple cloud decks where the lidar signal is fully, or nearly fully, attenuated.

The 15-day comparison results reveal that false positives and missed feature scenarios occur infrequently at approximately 10% of the time for each. Aside from the clear air detections, it is unknown how often individual features match because the category for feature agreement considers all seven atmospheric attributes. For example, the decision process as it stands would consider detection of a stratospheric feature in the nominal product and detection of a cloud in the expedited product as an agreement. Therefore, it would be more helpful to scrutinize the feature agreement category and understand how features are being incorrectly labeled.

It is hypothesized that the differences could be due to several factors – the simplified calibration approach used for the expedited products being the most likely candidate. For example, in regions where the lidar beam is highly attenuated (below clouds), the cloud-aerosol feature finder algorithm could be susceptible to regions of noise. A slightly different calibration constant could cause different characterization of the scene. The use of a climatological data base for tropopause altitudes would also allow some misclassification of stratospheric features near the tropopause in the expedited dataset. Nevertheless, the preliminary findings suggest that the bulk of features identified in the expedited dataset are consistent with those observed in the nominal dataset.

Additionally, this study used global data and has not been specifically applied to any particular region or time period. For example, qualitatively it is known that the expedited product is influenced by the diurnal cycle because the use of a simplified calibration approach does not account for day/night differences. It would be useful to have a more detailed analysis that uses an ensemble of small regions where time of day and elevation are the main focus of comparison.

5.2 Temperature Comparison

The low correlations, observed during the winter months in each hemisphere, correspond to the large temperature differences found near 60 °S and 70 °N. These differences can be attributed to the change to GEOS-5 in Version 2.01 and, presumably, to improvements to the assimilation model. The lower correlations are found during the daytime hours. This is an unexpected result and deserves further study.

The change from GEOS-4 to GEOS-5 models in the temperature algorithms could also have a large impact on temperature differences. If a change in the physics package was made in Version 2.01, the ability to pick up certain features, such as planetary waves, would be affected. In the winter months for each hemisphere, the planetary waves are larger due to a greater temperature gradient, thus causing a stronger Brewer-Dobson circulation. If Version 1.10 was not able to incorporate the stronger circulation in the upper altitudes, a greater temperature difference in the winter hemispheres would result.

It is important to take these results and apply them to future work. This work includes an analysis to test further seasonal variations during the fall and spring months, and to test temperature differences at different altitudes. If the pattern found during the summer and winter months are consistent, the spring and fall months should show similar differences in both hemispheres. This analysis will be used to aid in comparisons of future algorithms and atmospheric models.

5.3 Identifying Saharan Dust

Plumes of Saharan dust over the Atlantic Ocean need to be monitored regularly during the summer an autumn because of the possible impact on tropical cyclone development. Profile dust observations by CALIPSO offer a unique opportunity to enhance information of the SAL.

The application of CALIPSO in future research is ideal because of its unique detection capabilities.

CALIPSO data can be used with back-trajectory models to track the path of Saharan dust over time. Given that the trajectories are generated in three dimensions, CALIPSO data provides high accuracy in tracking Saharan dust.

6. CONCLUSIONS

The results of this work are significant to the CALIPSO Science Team and have broad implications for the entire mission. Work from Projects 1 and 2 may be used to help improve techniques for calibrating CALIPSO data. By comparing data from different versions, we may characterize biases in the data such that these biases may be resolved in later versions. By evaluating the techniques for calibrating data, we provide the groundwork for making comparisons of other parameters in the future. Concerning Project 3, the approach highlights how vertical information from CALIPSO can be coupled with other diagnostic tools to aid our understanding of aerosol transport. Detecting Saharan dust using CALIPSO provided an example of this approach and the versatility of applying results with the Google Earth browser.

Extensions of this work may be applied in future research. It would be beneficial to develop a quantitative comparison between the nominal and expedited products while ignoring situations where the CALIPSO satellite detects high signal attenuation. Also, a case study could be performed using CALIPSO to identify and track the motion of effluents in the atmosphere, such as pollen, volcanic ash, and forest fire smoke. Finally, as an extension of Project 3, forward trajectories of Saharan dust over the Atlantic Ocean could be generated to identify patterns of aerosol distribution that relate to the development of tropical cyclones. Future research using CALIPSO data is fundamentally important for the utility of the mission.

7. ACKNOWLEGMENTS

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