GLAS long-range transport observation of the 2003 California forest fire plumes to the northeastern US

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[1] In October 2003, a series of forest and brush fires in southern California burned an area of over 2750 km^2 with plumes reaching up to 6 km in altitude over the Pacific Ocean. On October 27, 2003, the Santa Ana (foehn) conditions flowing westward out of the desert that fueled the combustion ceased and a portion of the smoke plumes turned and headed eastward. The Geoscience Laser Altimeter System (GLAS) on ICESat provided aerosol profiles of the smoke along numerous ICESat tracks acquired throughout the week following the reversal of the smoke plume. The GLAS observations place the height of the smoke aerosols at <7 km as the smoke moved eastward over North America. GLAS measurement cross-sections often preceded or trailed the main smoke pulses by a few hours and capturing the four-dimensional picture of this moving target was only possible by combining multiple sensor observations with back trajectory calculations. **Citation:** Hoff, R. M., S. P. Palm, J. A. Engel-Cox, and J. Spinhirne (2005), GLAS long-range transport observation of the 2003 California forest fire plumes to the northeastern US, *Geophys. Res. Lett.*, *32*, L22S08, doi:10.1029/2005GL023723.

1. Introduction

[2] NASA's Earth Observing System (EOS) has enabled observation of long-range transport of atmospheric pollutants from distant sources using satellite remote sensing (see *Engel-Cox et al.* [2004] for a review). Most of the instruments used are passive (e.g. the Total Ozone Mapping Spectrometer, TOMS, and the Moderate Resolution Imaging Spectrometer, MODIS), using either thermal radiation from the Earth or reflected solar radiation, and generally have little ability to discriminate altitudinal information [*King and Herring*, 2002]. While solar occultation instruments viewing the atmosphere through the Earth's limb (e.g. the Stratospheric Aerosol and Gas Experiment, SAGE II and III) can provide profile information, it is generally only down to the highest cloud layers integrated over an approximately 400 km horizontal path [*Chu et al.*, 1989]. Stereographic viewers, such as the Multiangle Imaging Spaceborne Radiometer (MISR) [*Kahn et al.*, 2005], show promise in retrieving aerosol altitude information but these altitude products are not fully validated.

[3] The use of active lidar instruments, such as the Geoscience Laser Altimeter System (GLAS), its predecessor (the Lidar In-Space Technology Experiment, LITE), and its successor CALIPSO (the Cloud and Aerosol Lidar for Pathfinder Spaceborne Observations), allow high resolution profiling of aerosols in the atmosphere. Here we describe an opportunity to observe long range transport of pollutants where the combination of a profiling lidar (i.e. GLAS) and an integrating imaging sensor (the MOderate Resolution Imaging Spectrometer, MODIS) improved our ability to detect the event and to demonstrate that the aerosol was from a long range source. Even with these two complementary instruments, independent trajectory modeling information was required to confirm our interpretation of this transport event. Long-range transport of such smoke plumes have been seen from ground based lidars [*Stohl and Trickl*, 1999; *Wandinger et al.*, 2002; *Hoff et al.*, 2004] and these important observations will in the future be augmented by spaceborne lidars. As such, this letter demonstrates the future of multi-instrument fusion in the new Global Earth Observing System of Systems (GEOSS) suite of instrumentation.

[4] In October 2003, a series of fires north and east of Los Angeles and east of San Diego, California, ravaged some 2750 km^2 of forest and dry vegetation. Observation of these fires from space has been reported for carbon monoxide by *McMillan et al.* [2004], using the Atmospheric Infrared Sounder on the Aqua satellite. The GLAS instrument was undergoing a validation test at the time of the fires. The measurements of *Hlavka et al.* [2005] provide a remarkable high resolution data set from the fires, which validates GLAS lidar performance against the NASA Cloud Physics Lidar (CPL). These measurements were made quite near the source region for the aerosols.

[5] At the same time as these studies, our group had been analyzing MODIS imagery acquired across the USA to understand the occurrence of long-range transport of pollutants. The MODIS imagery is obtained and analyzed in real time (see the US Air Quality Weblog http://alg.umbc.edu/usaq). We use these data to initiate special observations in the Regional East Aerosol Lidar Mesonet (REALM) [*Hoff et al.*, 2002, 2004].

2. Following a Moving Target From Space: The Transport of the California Fire Plumes Across the Continent

[6] As the fires developed in late October 2003, we observed the transition from the unusual Santa Ana west-

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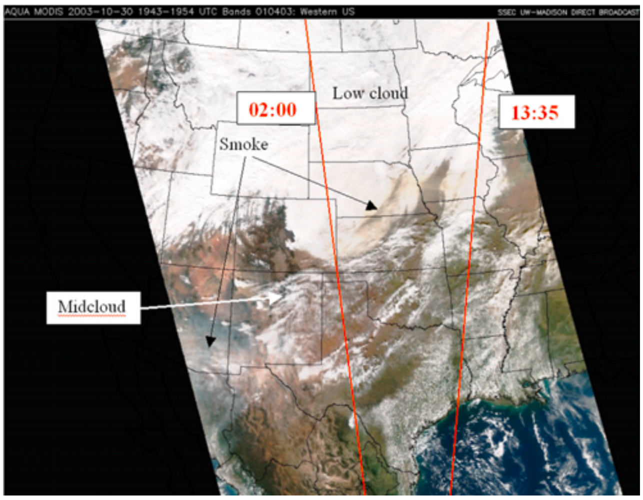

Figure 1. MODIS RGB image from 19:43–19:53 UTC October 30, 2003, showing the smoke above clouds in Nebraska. The 02:00 UTC and 13:35 UTC ICESat Tracks (numbers 124 and 131, respectively) are shown in the image.

ward smoke flows to an eastward zonal motion in the MODIS imagery. Some material was observed heading east-southeast over Arizona and towards Texas. Unfortunately, the transition in the flow was caused by a weather system that encompassed the aerosol plume and obscured its observation from space. On October 30, 2003, a noticeable brownish haze was seen in the Aqua MODIS Red-Green-Blue (RGB) product at 19:43–19:53 UTC in the US Midwest, and at an altitude higher than the prevailing clouds (Figure 1). This was interpreted as smoke in our analysis and prompted the examination of ICESat data.

[7] In January 2003 the Geoscience Laser Altimeter System (GLAS) was launched into a near-polar orbit aboard the Ice Cloud and land Elevation Satellite (ICESat) [*Zwally et al.*, 2002]. GLAS utilizes 3 diode-pumped, ND:YAG lasers operating at the fundamental wavelength of 1064 nm for surface altimetry and clouds, and the frequency doubled 532 nm wavelength that provides high sensitivity (photon counting detectors) for atmospheric measurements of thin clouds and aerosols [*Spinhirne et al.*, 2005]. The analysis presented here utilizes GLAS GLA07 data (level 1b, tracks 124,131,145,152,153) from the laser 2a observation period (September 25–November 18 2003). During this time, both atmospheric channels (532 and 1064 nm) were functioning optimally with particulate backscatter detection sensitivity approaching 2.0×10^{-7} and 2.0×10^{-6} m^{-1} sr^{-1} (1 second average) for 532 and 1064 nm, respectively.

[8] Two ICESat tracks crossed the same region on October 30: Track 124 at 02:00 UTC and Track 131 at 13:35 UTC (Figures 2a and 2b, respectively, with the ICESat overpasses of Figure 1 shown as red ground tracks). Neither profile shows significant smoke plumes, since the first GLAS lidar data cross-section was still to the east of the plume.

[9] This same plume was reported to be in the Maine/Gulf of Maine region on October 31 (http://alg.umbc.edu/usaq/archives/2003_10.html). ICESat profiles from Tracks 145 and 152 acquired on October 31 confirm the presence of smoke off the east coast of the US. Figure 3a shows several layers of thin smoke over the Massachusetts region. Later in the day, GLAS observed an intense 5.5–7.5 km altitude plume from 42°–46°N, with a vertical areal extent of the plume in the plane of the cross-section of about 900 km^2 (Figure 3b). At a mean backscatter ratio of approximately 4×10^{-6} m^{-1} sr^{-1}, we estimate the aerosol optical depth (AOD) of this plume (given a lidar ratio of 60 ± 20 sr at 532 nm [*Cattrall et al.*, 2005]) to be 0.48 ± 0.16. The inset in Figure 3b shows the color ratio between the 1064 nm and 532 nm channels on GLAS. The color ratio of 0.4 gives an Angstrom coefficient of 1.8, indicating submicron aerosols in this plume, consistent with recent results by *Cattrall et al.* [2005]. Assuming the aerosol-specific scattering coefficient of the plume was a uniform 5.0 m^2 g^{-1} (a global value given by *Charlson et al.* [2002]), the mean particulate concentration in the plume would be 48 ± 15 μg m^{-3} at STP. The observed wind speed in the trajectory was 22 ± 5 m s^{-1} and would give a flux of 950 ± 300 t/s of aerosol across the ICESat plane. We believe that such estimates of mass fluxes of aerosol plumes are only possible using vertically profiling lidar remote sensors.

[10] Figure 4 shows the high resolution (250 m) RGB MODIS image of the same plume. ICESat Track 152 at 23:01 UTC sampled the dense plume, which, from the trajectory analysis below, was determined to have been over the Bay of Fundy six hours before. MODIS-derived AOD in this plume ranged from 0.4–0.6 and the Angstrom coefficient was 1.6–2.0 (http://alg.umbc.edu/usaq/archives/2003_10.html), which is in good agreement with the GLAS-estimated values above. In order to confirm that this smoke plume was the same one as was observed 36 hours

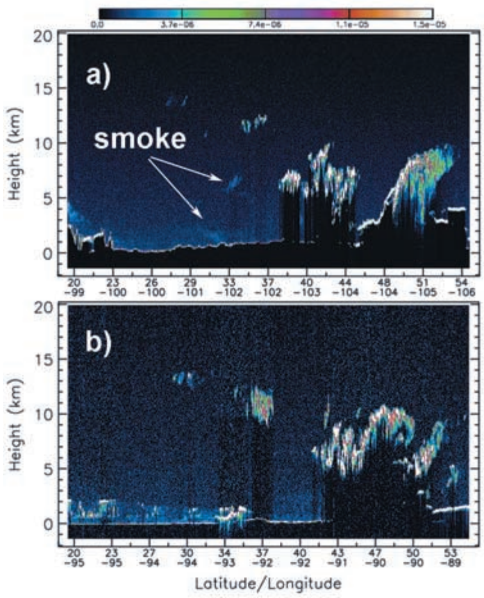

Figure 2. GLAS backscatter cross-sections from the GLA07 product from (a) the 02:00 UTC October 30, 2003 GLAS ascending Track 124 and (b) the 13:34 UTC descending Track 131. In the 02:00 UTC image, the leading wisps of the smoke were reaching the ICESat plane. In the 13:35 image, the smoke had not yet reached the ICESat Track 131 plane.

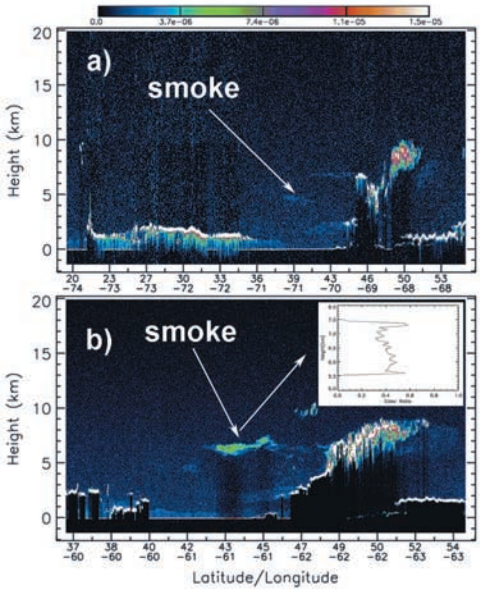

Figure 3. (a) GLAS cross-section from October 31 at 12:08 UTC (Track 145) with the leading edge of the smoke over Massachusetts. (b) GLAS cross-section from October 31 at 23:01 UTC (Track 152) with the smoke over Nova Scotia. Figure 3a (inset): 1064 nm/532 nm backscatter color ratio of a vertical slice through the smoke plume in Figure 3b. A color ratio of 0.4 ($\beta_{1064\ nm}/\beta_{532\ nm}$) corresponds to an aerosol Ångstrom coefficient of 1.8 which is indicative of small submicron particles.

previously in Kansas/Nebraska, we ran NOAA HYSPLIT air trajectories at 5.5, 6.5, and 7.5 km, corresponding to the top, middle and bottom of the smoke plume (Figure 5). This confirmed that the timing of the 6.5 km back trajectory corresponds with the observation in Figure 1. We traced the

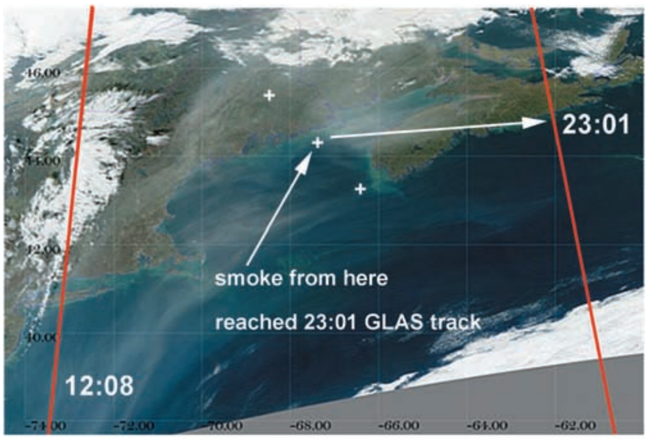

Figure 4. MODIS AQUA 17:20 UTC 250 m RGB image of the smoke in Figure 3b over Nova Scotia. The ICESat tracks at 12:08 UTC and 23:01 UTC are shown in red. The smoke moved approximately 4–6 degrees of longitude between the MODIS overpass and the ICESat overpass. Estimated edges of the smoke in Figure 3 are shown by + symbols. (Image processed by N. Jordan, UMBC.)

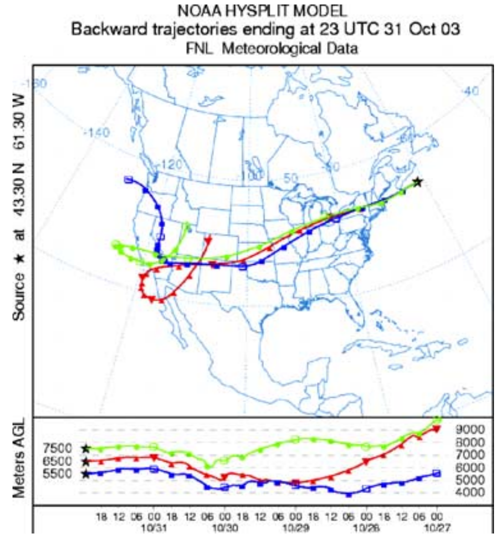

Figure 5. Air back trajectories showing the position of the smoke at 6.5 km altitude at 23:01 UTC coming from California. The position of the 1800 UTC waypoint for the 6500 m trajectory is in Northern Kansas which agrees with the smoke seen in Figure 1. HYSPLIT trajectory courtesy of http://ready.noaa.gov (Air Resources Laboratory, NOAA).

trajectory back to southern California confirming that it was indeed from the California fires. Variations in data sources can affect trajectory positions [*Harris et al.*, 2005]. We followed the recommendation in that work and ran two different trajectory models with four (AVN, FSL, NCEP reanalysis, and ETA) winds. This allowed us to interpret the area (extending across three symbols in Figure 4) where the smoke was six hours previously in the MODIS image. Midplume trajectories all were very similar passing through southern California on October 26–27.

[11] Over the next two days, smoke continued to pass through the east coast states. On November 1, a broad lower tropospheric smoke layer was seen over low cloud in ICESat Track 153. This plume was impossible to observe in MODIS due to the highly reflective underlying clouds. On the afternoon November 2, 2003, we observed a well-isolated plume of material in the MODIS images over the US mid-Atlantic states [*Hoff et al.*, 2004]. This led to a spectacular visual display of smoke plumes at sundown in Maryland. On the morning of November 3, we observed these smoke plumes using ground-based lidar at UMBC.

3. Implications for Future Observations

[12] The strong case for identification of the October 30–November 2, 2003, west coast to east coast smoke observations was aided by the synergy of these multiple sensor systems. The pulses of smoke were sporadic in nature and the ICESat orbits, while providing up to three observations per day over a wide region of the continent, often missed the peak scattering from the smoke aerosols. MODIS observations of the brownish haze above the clouds in the US Midwest could have been attributed to shadows or other interpretation. This points out the importance of having multiple tools available to observe aerosols. Each of these sensors has limitations. MODIS optical depths have been

put under some question over regions that have high surface albedo [*Chu et al.*, 2003] and the conservative nature of the MODIS cloud masking eliminates a great deal of high optical depth aerosols as "clouds". For these types of events, the combination of multiple data tools can be effectively used to discriminate between cloud and aerosol. A number of these tools are being integrated into the CALIPSO algorithm development process. This paper shows, however, that inclusion of visual imagery and optical depths from the MODIS sensor, along with dynamic models to visualize aerosol movement, can broaden our interpretive ability of vertical profiling lidar data, as well. The results from ICESat point to a future where vertical profiling lidars will give exponentially greater ability to detect aerosol plumes, both natural and anthropogenic.

[13] There are a limited number of such instruments proposed for future missions (CALIPSO, and an Atmospheric Lidar, ATLID, slated to fly on ESA's Earth Radiation Mission) and these will have a 2–4 year lifetime. It will be appropriate to plan for continuity in the lidar observations for future routine systems (e.g. NPOESS), as has been done for the MODIS follow-on instruments (e.g. VIIRS).

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