

# Biomass Burning Plume Injection Height Estimates Using CALIOP, MODIS and the NASA Langley Back Trajectory Model

A.J. Soja<sup>ab,\*</sup>, T.D. Fairlie<sup>b</sup>, D.J. Westberg<sup>cb</sup>, G. Pouliot<sup>d</sup>, C.M. Ichoku<sup>e</sup>, L. Giglio<sup>f</sup>, and J.J. Szykman<sup>db</sup>

<sup>a</sup>National Institute of Aerospace/NASA Langley Research Center, Hampton, VA 23681, USA –  
(amber.j.soja, t.d.fairlie, david.j.westberg, james.j.szykman)@nasa.gov

<sup>b</sup>NASA Langley Research Center, Hampton, VA 23681, USA

<sup>c</sup>Science Systems and Applications Inc., Hampton, VA 23681, USA

<sup>d</sup>Environmental Protection Agency, Research Triangle Park NC, USA - Pouliot.George@epa.gov

<sup>e</sup>NASA Goddard Space Flight Center, Greenbelt, MD 20771- Charles.m.ichoku@nasa.gov

<sup>f</sup>University of Maryland, Greenbelt, MD 20771- giglio@hermes.geog.umd.edu

**Abstract** – CALIPSO data are analyzed in association with the HMS smoke product, Langley Back Trajectory Model, MODIS fire data, ecological and meteorological information to build an injection height database that links fire behavior and fire weather to plume rise. This presentation will show an example of an initial analysis of one CALIPSO segment that is attributed to 9 distinct fires burning on 3 different days. Each fire contributes to a unique horizontal and vertical portion of the aerosol plume identified in the CALIPSO data. We welcome suggestion for improvements from the larger fire, modeling, climate and atmospheric communities.

**Keywords:** fire, smoke plume injection height, satellite, GEOS-5, air quality, biomass burning emissions.

## 1. INTRODUCTION

### 1.1 Biomass Burning, Human Health and Climate

Biomass burning (BB) is largely a natural process that is integral to ecosystem maintenance and resolving the beginning and end of successional processes. However, BB can adversely affect human health and serves as an interface between the biosphere, atmosphere and climate systems by affecting carbon balances, altering hydrologic regimes, modifying patterns of clouds and precipitation, modifying permafrost structure, altering direct and indirect emissions, and altering radiative forcings by changing albedo, both directly (i.e. land cover change) and indirectly (i.e. black carbon deposition to the Arctic) (Radke *et al.* 1978; Konzelmann *et al.* 1996; Kaufman & Koren 2006; Randerson *et al.* 2006; Sokolik 2003). Additionally, changes in fire regimes have the potential to compel ecological change, moving ecosystems more quickly towards a new equilibrium with the climate (Dale *et al.*, 2001; Flannigan *et al.*, 2001; Turetsky *et al.*, 2002; Chapin *et al.*, 2006; Soja *et al.*, 2007).

With respect to human health and air quality, biomass burning is a primary source of PM<sub>2.5</sub> from direct emissions of PM<sub>2.5</sub> and formation PM<sub>2.5</sub>, precursors that form secondary organic aerosols (Kleindienst *et al.*, 2007). PM<sub>2.5</sub> describes particles found in the air, including dust, dirt, soot, smoke, and liquid droplets, with a mean diameter of 2.5 microns or less. PM<sub>2.5</sub> has been linked to a series of significant health problems, including aggravated asthma, increases in respiratory symptoms like coughing and difficult or painful breathing, chronic bronchitis, decreased lung function, and premature death. BB emissions are also a significant contributor to regional haze, which refers to air pollution that impairs visibility over widespread areas (Malm *et al.*, 2004).

Additionally, BB results in the emission of large amounts of ozone precursors, oxides of nitrogen (NO<sub>x</sub>) and volatile organic compounds (VOC), in roughly the same quantities as particulate matter. Ozone is created by a chemical reaction between NO<sub>x</sub> and VOCs in the presence of sunlight. Tropospheric ozone is a widely recognized air pollutant. Ozone can irritate lung airways and cause inflammation. Other symptoms include wheezing, coughing, aggravated asthma, reduced lung capacity, and increased susceptibility to respiratory illnesses like pneumonia and bronchitis.

### 1.2 Plume Height Background and Motivation

To address concerns of human health and welfare effects such as regional haze and to explore feedbacks to climate change, it is essential to accurately quantify BB emissions and characterize the transport of emissions within regional- and global-scale chemical transport models (CTM). Biomass plume injection heights are a critical input to CTM to accurately predict and assess transport and associated impacts. Plume injection height directly influences the distance a smoke plume will travel, which then impacts where and when a community might experience health risks and reduced visibility due to remote BB events. Moreover, significant quantities of BB emissions were recently and unexpectedly found in the Arctic spring, which has implications for ice, snow and cloud albedo feedbacks in the sensitive early-season Arctic (Soja *et al.*, 2008) (websites - ARCTAS; CATF).

Historically, plume rise height was based on the pioneering work of G.A. Briggs (1969; 1971) and verified with limited field campaign data (Clements *et al.*, 2007), which has made the verification of plume rise within models difficult to impossible. We have relied on anecdotal on-ground visual estimates, coincident aircraft pilot information and isolated lidar measurements. An example of a plume height underestimate and our potential to improve model estimates is provided in Figure 1.

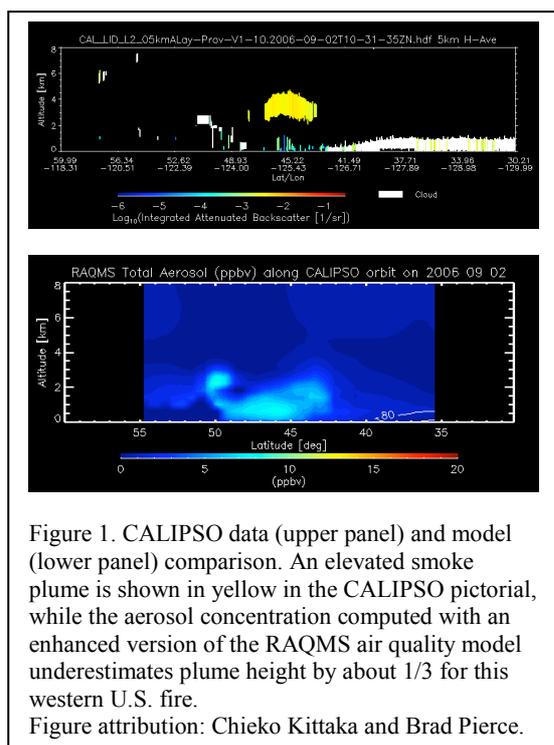
Presently, we have an increasing number of ground-based lidar instruments, aircraft field campaign observations, and two satellites that can provide the statistics necessary to understand and verify BB plume height. Both the Multi-angle Imaging SpectroRadiometer (MISR) and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data are capable of distinguishing BB injected height in the atmosphere (Vaughan *et al.*, 2004; Kahn *et al.*, 2007; Mazzoni *et al.*, 2007; Kahn *et al.*, 2008). MISR has a substantially larger swath width (360 km; pixel - 1.1 km horizontal x 500 m vertical) than CALIPSO (100 m diameter x 30 m vertical), which results in a greater opportunity to capture

smoke plumes and plumes more closely to their source. However because MISR relies on multi-view angles to estimate the stereo height of distinct features, it requires abrupt well-defined columns, which would limit views of large fires that generate extensive cumulous-like plumes. Also, MISR is a morning overpasses, so it does not capture the natural temporal variation of wildfires or the likely maximum injection height, which peaks at about solar noon. On the other hand, CALIPSO is able to identify plume heights from extensive smoke fields and is able to capture the natural temporal variation of smoke plumes. A low bias in injection height would overestimate local surface concentrations and underestimates long range transport and remote surface concentrations.

Unlike MISR data, which has been interrogated (Val Martin et al., 2010), CALIPSO plume height potential is in its infancy (V. Amiridis et al., 2010), which is the motivation behind this work. In concert, CALIOP and MISR data have the potential to add the statistical knowledge necessary to improve our knowledge of the dynamics of fire plume injection height.

### 1.3 Biomass Burning Plume Rise

BB plume rise is dependent on characteristics of the fire, precedent fire weather and atmospheric stability (Freitas et al., 2007; Liu et al., 2010; Val Martin et al., 2010). Val Martin et al. (2010) produced a classic MISR manuscript based on the analysis of 5 years of satellite observations of smoke injection heights from North America fires (2002 and 2004–2007). They found plumes range from a few hundred meters to over 5000m. The largest plumes were found over boreal regions (median values of 850m), and the smallest plumes were found over cropland and grassland fires in the contiguous US (median values of 530m). A significant fraction (4–12%) of fire plumes were injected above the boundary layer (BL), and most of the plumes located above the BL (>83%) were trapped within stable atmospheric layers.



The intensity of a fire and fire behavior are dependent on the amount of fuel held within an ecosystem, the relative amount of moisture contained in the vegetation, duff and soil organic layer, wind and topography. These variables are largely under the control of weather and climate (Stocks and Street, 1982; Stocks et al., 1998; Goodrick, 2002; Westerling et al., 2006; Soja et al., 2007). For this reason, it is essential to capture fire plume data from various ecosystems and under numerous weather conditions to fully assess and improve BB plume injection heights.

### 1.4 Objectives

The ultimate goal of this work is to build a BB plume injection height database using the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, onboard CALIPSO (first light on June 07, 2006). CALIOP is an active lidar that can discriminate clouds and atmospheric aerosols, similar to those found in smoke plumes.

Specifically in this presentation, we intend to demonstrate the methodology, show an example of the process, provide initial results and solicit input for improvement from the larger fire, smoke, modeling, atmospheric, and climate communities.

## 2. METHODS, RESULTS AND DISCUSSION

### 2.1 Methodology

First, a spatial and temporal coincidence in CALIPSO data and the Hazard Mapping System (website - HMS) Smoke product is identified (Figure 2). Next, time and location of air parcels are extracted from the CALIPSO aerosol feature mask, and the Langley Trajectory Model (LaTM) is run backwards in 3-dimensional space and time until coincidences are identified with MODIS fire detection locations (Pierce et al., 2000; Giglio et al., 2003). An air parcel and a fire detection coincide when the following criteria are met: temporal and spatial coincidence; MODIS fire detection confidence must exceed 35%; horizontal range of the air parcel trajectory to fire must be under 20 km; and if the injection height is above the BL, coincidence must be with 10 or more active fire detections.

The height at which the air parcels and fire detections coincide is recorded. These data are associated with the following parameters that will be used to improve our knowledge of the factors that influence plume height: location; time; ecosystem type; MODIS Fire Radiative Power, brightness temperature, percent confidence and satellite; number of air parcels; mean range and altitude; minimum and maximum altitude; surface and Mean Sea Level pressure; height of the planetary boundary layer and the top of the atmosphere; temperature and dewpoint at 2 and 10 m; wind speed at 2 and 10m; wind direction at 2 and 10m; relative humidity at 2 and 10m; and bottom, peak and top of the stable layer.

### 2.2 Trajectory Initialization and Coincidence

The trajectories are initialized at ~1 second intervals along the CALIPSO smoke segment track and at 500m vertical intervals within the smoke plume, as shown in Figure 3. There is a 15 minute trajectory time step. As the air parcel trajectories are traced back in time, each day there are unique coincidences with fires on the ground (Figure 4). In our example, back trajectories first pass over “fires of interest” in North-Central Washington in the mid-troposphere (~500mb, ~17000ft, ~5.2km) at

initialization minus 20 hours. At initialization minus 36 hours, back trajectories pass over “fires of interest” in North-West Montana, in the lower troposphere (~800mb, ~6500ft, ~2km).

In total, this smoke plume can be attributed to 9 separate fires, burning on different days (12 event days): in Washington (Tripod fire), coincidence is noted on August 6<sup>th</sup>, and the plume is injected to ~3400m and on August 7<sup>th</sup>, to a mean of 3300m, range 1900–6300m; also in Washington (WA), a medium-sized fire is identified on August 7<sup>th</sup> (range 2200–4400m); a plume is identified in British Columbia (BC) on August 7<sup>th</sup> at about 3400m; two fires are coincident in Montana (MT) burning on August 6<sup>th</sup> (mean 1980m); three fires are identified in Saskatchewan (SK) on August 6<sup>th</sup> and 7<sup>th</sup> (~1000m); and three fires are also identified in North Dakota (ND) burning on August 7<sup>th</sup> (~2000m).

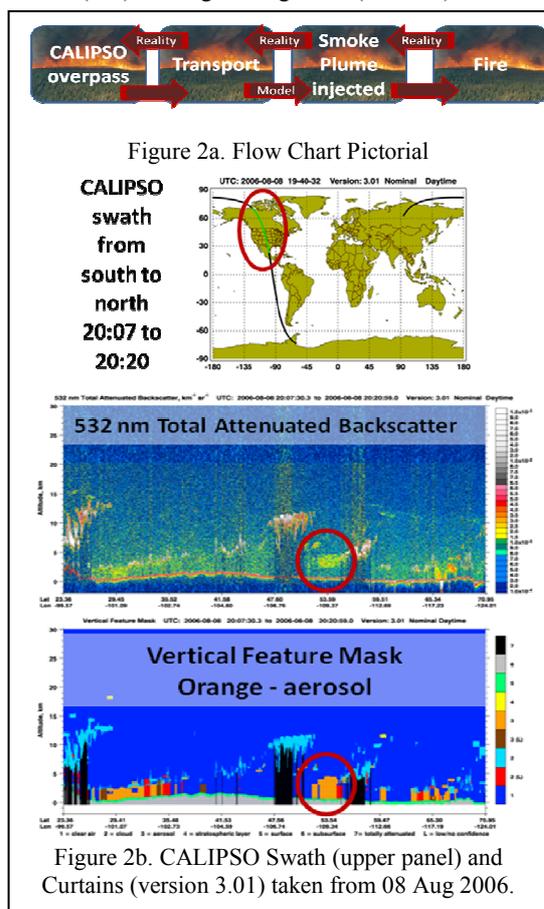
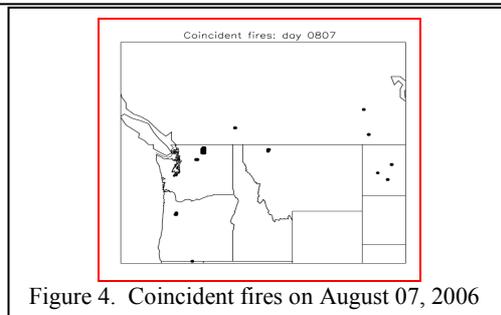
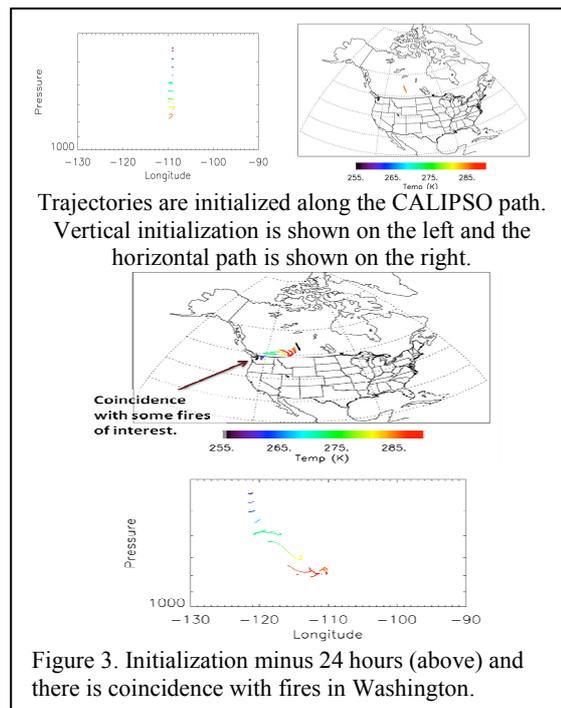


Figure 2b. CALIPSO Swath (upper panel) and Curtains (version 3.01) taken from 08 Aug 2006.

As one verification of our process, forward trajectories are initialized from unique fire sources, like those identified in Figure 5, and these distinguish the contribution to the observed CALIPSO smoke plume transect. Each fire contributes to distinct horizontal and vertical portions of the CALIPSO segment. The larger WA fire (Tripod) contributes smoke up to 7 km altitude, while the BC fire contributes smoke up to 4 km, and the smaller fires in MN, SK and ND contribute to BL altitudes.

### 3. CONCLUSIONS

CALIPSO data are interrogated and paired with the NOAA HMS smoke product, the Langley Back Trajectory Model, MODIS fire products, ecosystem and meteorological parameters to link fire behavior and fire

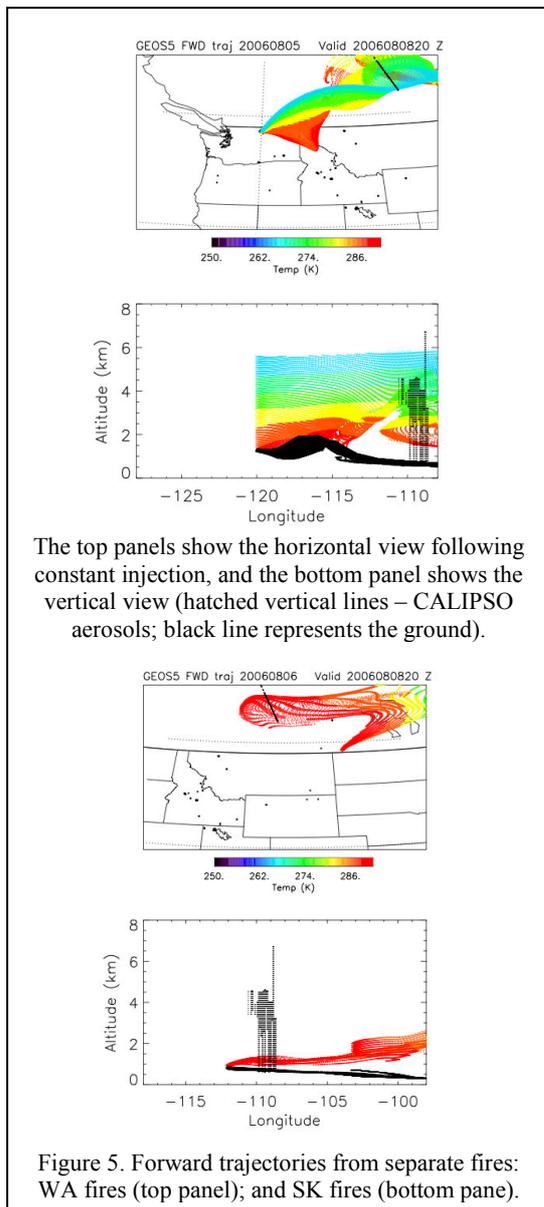


weather to plume rise so that these data will be useful for verifying and improving regional- and global-scale plume rise modeling for air quality and climate communities.

Next, we intend to verify and validate plume heights by taking advantage of existing MISR plume height data, coincident field campaigns, aircraft instrument and in-situ data. Additionally, interacting with and soliciting requirements from regional- and global-scale modelers during the development of this database is essential to its application.

### REFERENCES

- Briggs, G. A., 1969, Optimum formulas for buoyant plume rise. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical sciences*, 265: 197.
- Briggs, G. A., 1971, Plume rise - recent critical review. *Nuclear Safety*, 12: 15.
- Chapin, F. S., III, Oswood, M., Cleve, K. V., Viereck, L. A. and Verbyla, D., 2006, *Alaska's Changing Boreal Forest*, Oxford, Oxford University Press, 354.
- Clements, C. B., Zhong, S., Goodrick, S., Li, J., Potter, B. E., Bian, X., Heilman, W. E., Charney, J. J., Perna, R., Jang, M., Lee, D., Patel, M., Street, S. and Aumann, G., 2007, Observing the dynamics of wildland grass fires - FireFlux - A field validation experiment. *Bulletin of the American Meteorological Society*, 88: 1369.
- Dale, V. H., Joyce, L. A., McNulty, S., Neilson, R. P., Ayres, M. P., Flannigan, M. D., Hanson, P. J., Irland, L. C., Lugo, A. E., Peterson, C. J., Simberloff, D., Swanson, F. J., Stocks, B. J. and Wotton, B. M., 2001, Climate change and forest disturbances. *Bioscience*, 51: 723-734.



The top panels show the horizontal view following constant injection, and the bottom panel shows the vertical view (hatched vertical lines – CALIPSO aerosols; black line represents the ground).

Figure 5. Forward trajectories from separate fires: WA fires (top panel); and SK fires (bottom pane).

Flannigan, M. D., Cambell, I., Wotton, B. M., Carcaillet, C., Richard, P. and Bergeron, Y., 2001, Future fire in Canada's boreal forest: Paleocology results and General Circulation Model-Regional Climate Model simulations. *Canadian Journal of Forest Research*, 31: 854-864.

Freitas, S. R., Longo, K. M., Chatfield, R., Latham, D., Dias, M. A. F. S., Andreae, M. O., Prins, E., Santos, J. C., Gielow, R. and Carvalho, J. A., 2007, Including the sub-grid scale plume rise of vegetation fires in low resolution atmospheric transport models. *Atmos. Chem. Phys. Discuss.*, 7: 3385-3398.

Giglio, L., Descloitres, J., Justice, C. O. and Kaufman, Y. J., 2003, An Enhanced Contextual Fire Detection Algorithm for MODIS. *Remote sensing of environment*, 87: doi:10.1016/S0034-4257(03)00184-6.

Goodrick, S., 2002, Modification of the Fosberg fire weather index to include drought. *International Journal of Wildland fire*, 11: 205-211.

Kahn, R. A., Li, W.-H., Moroney, C., Diner, D. J., Martonchik, J. V. and Fishbein, E., 2007, Aerosol source plume physical characteristics from space-based multiangle imaging. *J. Geophys. Res.*, 112: doi:10.1029/2006JD007647.

Kahn, R. A., Chen, Y., Nelson, D. L., Leung, F.-Y., Li, Q., Diner, D. J. and Logan, J. A., 2008, Wildfire smoke injection heights: Two perspectives from space. *Geophysical Research Letters*, 35.

Kleindienst, T. E., Jaoui, M., Lewandowski, M., Offenber, J. H., Lewis, C. W., Bhawe, P. V. and Edney, E. O., 2007, Estimates of the contributions of biogenic and anthropogenic

hydrocarbons to secondary organic aerosol at a southeastern US location. *Atmos. Environ.*, 41: 8288-8300.

Liu, Y., Achtemeier, G. L., Goodrick, S. L. and Jackson, W. A., 2010, Important parameters for smoke plume rise simulation with Daysmoke. *Atmospheric Pollution Research*, 1: 250-259.

Malm, W. C., Schichtel, B. A., Pitchford, M. L., Ashbaugh, L. L. and Eldred, R. A., 2004, Spatial and monthly trends in speciated fine particle concentration in the United States. *Journal of Geophysical Research*, 109: D03306, doi:10.1029/2003JD003739.

Mazzoni, D., Logan, J. A., Diner, D., Kahn, R., Tong, L. L. and Li, Q. B., 2007, A data-mining approach to associating MISR smoke plume heights with MODIS fire measurements. *Remote Sensing of Environment*, 107: 138-148.

Pierce, R. B., Al-Saadi, J. A., Eckman, R. S., Fairlie, T. D., Grose, W. L., Kleb, M. M., Natarajan, M. and Olson, J. R., 2000, Dynamical climatology of the NASA Langley Research Center Interactive Modeling Project for Atmospheric Chemistry and Transport (IMPACT) model (Paper 2000JD900248). *Journal of geophysical research*, 105: 29,109-29,134.

Soja, A. J., Tchepakova, N. M., French, N. H. F., Flannigan, M. D., Shugart, H. H., Stocks, B. J., Sukhinin, A. I., Parfenova, E. I., Chapin III, F. S. and Stackhouse Jr., P. W., 2007, Climate-induced boreal forest change: Predictions versus current observations. *Global and Planetary Change, Special NEESPI Issue*, 56: 274-296, doi:10.1016/j.gloplacha.2006.07.028.

Soja, A. J., Stocks, B. J., Maczek, P., Fromm, M., Servranckx, R., Merritt, T. and Brian, B., 2008, ARCTAS: The Perfect Smoke. *Canadian Smoke Newsletter*, Fall: 2-7.

Stocks, B. J. and Street, R. B., 1982, Forest fire weather and wildfire occurrence in the boreal forest of northwestern Ontario. *Resources and Dynamics of the Boreal Zone*, Ottawa, Canada, (Association of Universities of Canadian Universities for Northern Studies), 249-265.

Stocks, B. J., Fosberg, M. A., Lynham, T. J., Mearns, L., Wotton, B. M., Yang, Q., Jin, J. Z., Lawrence, K., Hartley, G. R., Mason, J. A. and McKenney, D. W., 1998, Climate change and forest fire potential in Russian and Canadian boreal forests. *Climatic Change*, 38: 1-13.

Turetsky, M., Wieder, K., Halsey, L. and Vitt, D., 2002, Current disturbance and the diminishing peatland carbon sink. *Geophysical Research Letters*, 29: 21: 1-4.

V. Amiridis, E., Giannakaki, D. S., Balis, E., Gerasopoulos, I., Pytharoulis, P., Zanis, S., Kazadzis, D. Melas and Zerefos, C., 2010, Smoke injection heights from agricultural burning in Eastern Europe as seen by CALIPSO. *Atmos. Chem. Phys. Discuss.*, 10: 11567-11576, doi:10.5194/acp-10-11567-2010.

Val Martin, M., Logan, J. A., Kahn, R. A., Leung, F.-Y., Nelson, D. L. and Diner, D. J., 2010, Smoke injection heights from fires in North America: Analysis of 5 years of satellite observations. *Atmos. Chem. Phys.*, 10: 1491-1510.

Vaughan, M., Young, S., Winker, D., Powell, K., Omar, A., Liu, Z., Hu, Y. and Hostetler, C., 2004, Fully automated analysis of space-based lidar data: an overview of the CALIPSO retrieval algorithms and data products. *Proc. SPIE, Laser Radar Techniques for Atmospheric Sensing*, 5575: 16-30.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R. and Swetnam, T. W., 2006, Warming and earlier spring increase western US forest wildfire activity. *Science*, 313: 940-943.

#### References from Websites

ARCTAS, Arctic Research of the Composition of the Troposphere from Aircraft and Satellites, 2008, <http://www.espo.nasa.gov/arctas/>

CALIPSO <http://www-calipso.larc.nasa.gov/>

CATF (Clean Air Task Force) International Meeting on Open Burning and the Arctic: Causes, Impacts, and Mitigation Approaches, 2010, Saint Petersburg, Russia, <http://www.bellona.org/fires-and-the-arctic>

HMS <http://www.osdpd.noaa.gov/ml/land/hms.html>

MODIS Fire Data <http://maps.geog.umd.edu/firms/>

#### ACKNOWLEDGEMENTS

We are greatly appreciative of the support provided by NASA Research Opportunities in Space and Earth Sciences (ROSES) solicitation: NNN08ZDA001N-DECISIONS: Decision Support through Earth Science Research Results.