FINAL REPORT TO THE JOINT FIRE SCIENCE PROGRAM
PROJECT # 10-S-02-1

Identification of Necessary Conditions for Arctic Transport of Smoke from United States Fires

http://airfire.org/projects/arctic-transport

Authors
Narasimhan K. Larkin[1], Jennifer L. DeWinter[2], Tara M. Strand[3], Steven G. Brown[2], Sean M. Raffuse[2], Jonathan Callahan[4], Kenneth J. Craig[2], Robert C. Solomon[1], Hilary R. Hafner[2]

Affiliations
1) U.S. Forest Service AirFire Team, Seattle, Washington
2) Sonoma Technology, Inc., Petaluma, California
3) Scion Research, New Zealand
4) Mazama Science, Seattle, Washington

Principal Investigator and Corresponding Author:
Narasimhan K. Larkin. U.S. Forest Service AirFire Team
400 N. 34th St Suite 201, Seattle, Washington USA 98103
206.732.7849 (W) 206-732.7801 (F) larkin@fs.fed.us (E)

September 29, 2011

Abstract

The deposition of black carbon (BC), a dark absorbing aerosol, is a significant contributor to observed warming trends in the Arctic (Hansen and Nazarenko, 2004; Jacobson et al., 2007). Biomass burning outside of the Arctic, including wildland prescribed fires, is a major potential source of Arctic BC. Therefore, limiting or eliminating spring prescribed burning has been suggested to Congress as a BC reduction technique (e.g., Zender, 2007). However, there are large uncertainties in the current estimates of the sources, source regions, and transport and transformation pathways of BC transported to the Arctic region (Shindell et al., 2008; Hegg et al., 2009, Quinn et al., 2008).

This study is the first comprehensive examination of the meteorological conditions required for emissions from the contiguous United States (CONUS) to be transported to Arctic. Using a simple trajectory modeling technique, we characterize the potential for transport of emissions from fires in CONUS to reach the Arctic and Greenland. The potential for Arctic transport is examined as

- A 30-year climatology (1980-2009) of transport potential based on trajectory modeling using historical meteorology and split out by season, month, starting plume injection height, and time to reach the Arctic.
- A real-time (daily) forecast system of transport potential to the Arctic that shows which layers of the atmosphere can reach the Arctic today, tomorrow, and the next day.

The methods used here do not include wet or dry deposition and other factors that can further limit the ability of actual emissions to reach and deposit in the Arctic. Instead, by focusing on only one *necessary* aspect (a *necessary but not sufficient* condition) – the ability of the atmosphere to transport emissions – this study examines

- Under what meteorological transport conditions can CONUS emissions potentially impact the Arctic?

However, this allows for the ability to answer the corollary question:

- Under what meteorological transport conditions will CONUS emissions *not* impact the Arctic?

This inverse question allows for identification of times, locations, and plume injection heights where emissions sources (such as a prescribed burn) will not have an impact on the Arctic. This knowledge allows for both more targeted future studies and more precise mitigation strategies that do not focus on areas and times where Arctic impact is unlikely.

1. Background and Purpose

The deposition of BC, a dark absorbing aerosol, is a significant contributor to observed warming trends in the Arctic (Hansen and Nazarenko, 2004; Jacobson et al., 2007). BC has been identified as second only to carbon dioxide (CO_2) in global warming potential (Jacobson et al., 2007). BC is of particular concern when it deposits on snow and enhances melting, such as in the springtime in the Arctic. Recent studies suggest that anthropogenic BC may have caused 25% of last century's observed warming in the Arctic (Hansen and Nazarenko, 2004), and that this effect may increase in the future. The susceptibility of the Greenland ice-sheet to melting is also likely exacerbated by BC-induced snow aging (Overpeck et al., 2006). Contributions of BC in the Arctic region are associated with biomass-burning emissions from regions as far away as southeast Asia (Koch and Hansen, 2005). High-latitude boreal forest fires also contribute large amounts of BC to the Arctic (Stohl et al., 2006).

The U.S. Congress, the U. S. Environmental Protection Agency (EPA), and the White House are all looking at near-term controls to reduce BC emissions. Specifically:

- The White House, in a press release on 12/17/2009, announced U.S. involvement in an international effort to reduce BC emissions affecting the Arctic.
- Bill HR2996 required the EPA to complete a report on BC (U.S. EPA, 2012). The report includes an inventory of BC emissions and identifies approaches to reduce those emissions.
- In early 2012, several nations formed the Climate and Clean Air Coalition to reduce short-lived climate pollutants by developing mitigation strategies and legislative action to collectively reduce BC, methane, and hydrofluorocarbons. The G8 nations have subsequently joined this coalition.

In the above efforts (and others), BC emissions from fire have been identified as a major contributor to Arctic warming and questions are being posed about limiting or eliminating springtime prescribed burning to reduce the warming effect of BC (Zender, 2007). There are large uncertainties in the current estimates of the sources, source regions, and transport and transformation pathways of BC transported to the Arctic region (Shindell et al., 2008; Hegg et al., 2009, Quinn et al., 2008). Despite these significant uncertainties and many unanswered questions in the current scientific understanding of the Arctic BC problem, regulation to prevent BC transport may occur in the near future.

There are two mechanisms for the transport of BC from the mid-latitudes, including the CONUS, into the Arctic regions.

A. If BC aerosol has a small diameter and is lofted high, near or into the stratosphere (approximately 14 km above ground level [AGL] in mid-latitudes), it will remain for a long time (months to years) and can be transported via general upper-atmospheric circulation patterns from the United States to the Arctic.
B. If the BC aerosol is only lofted into the troposphere and/or it is of larger diameter, the presence of synoptic and global meteorological patterns that allow for transport in a few days are required for it to reach the Arctic.

Very few (< 1%, e.g., ValMartin et al., 2009) fire plumes reach the stratosphere. Indeed few satellite-detected fire plumes (10-30%) even reach the free troposphere (ValMartin et al., 2009). For the bulk of fire emissions that are lofted into the troposphere, the general circulation patterns of the mid-latitude cell and the polar cell generally inhibit transport from CONUS to the Arctic. Only under certain conditions, meteorological synoptic patterns or ideal temperatures, will the boundary between the mid-latitude cell and the polar cell be pushed north far enough or be porous enough to allow BC particles emitted in CONUS latitudinal zones to be transported to the Arctic. For example, Warneke et al. (2009) found that the low snow amount in Siberia allowed the 2008 fire season to start early when Siberian temperatures were still low and near equal to those across the Arctic dome, which provided a pathway for biomass smoke in the lower troposphere to transport into the Arctic region. These types of conditions can occur anywhere in the northern hemisphere and are thought to occur primarily during the winter and spring months (Koch and Hansen, 2005; Flanner et al., 2007), when Arctic BC is observed to increase, both on the snow and as haze.

To date, apportionment studies have located sources of Arctic BC in a global scope, focusing on continental or latitudinal zones. Latitudes identified as responsible for the majority of Arctic BC deposits and haze range from 28˚ S to 60˚N (Shindell and Faluvegi, 2009). In addition, Shindell et al. (2008) estimated that BC emissions from all BC sources in North America are responsible for 40% of the BC deposited in Greenland. Through a limited backward trajectory analysis, wildland burning in eastern North America was cited as a likely source of Arctic BC during the months of June-November with transport time from source to Arctic in three days or less (McConnell et al., 2007).

This work represents the first comprehensive study of the meteorological conditions required for fire emissions to travel from CONUS to the Arctic. Using a simple trajectory modeling technique, we characterize the potential for transport of emissions from fires in CONUS to reach the Arctic and Greenland (Figure 1). We note that while the motivation behind this research was to understand BC transport from fire sources, this research is applicable to all CONUS sources of BC. The potential for Arctic transport is examined as:

- A 30-year climatology (1980-2009) of transport potential based on trajectory modeling using historical meteorology and split out by season, month, starting plume injection height, and time to reach the Arctic.
- A real-time (daily) forecast system of transport potential to the Arctic that shows which layers of the atmosphere can reach the Arctic today, tomorrow, and the next day.

The methods used here do not include wet or dry deposition and other factors that can further limit the ability of actual emissions to be deposited in the Arctic. Instead, by focusing on only one *necessary* but *not sufficient* aspect – the ability of the atmosphere to transport emissions – this study examines:

- Under what meteorological transport conditions can CONUS emissions potentially impact the Arctic?

However, this allows for the ability to answer the corollary question:

- Under what meteorological transport conditions will CONUS emissions *not* impact the Arctic?

Posed this way, this research identifies the times, locations, and plume injection heights where emissions sources (such as a prescribed burn) will *not* have an impact on the Arctic. This formulation allows for both more targeted future studies and more precise mitigation strategies that do not focus on areas and times where Arctic impact is unlikely, but focus instead on emissions that do have the potential for Arctic transport.

Figure 1. Map showing receptor locations used in this study - Arctic Circle (gray line), Greenland (green), sea ice (blue) and snow cover (white). Snow and ice coverages are shown for their climatological April extent. The North American Regional Reanalysis (NARR) modeling domain is also shown (red outline). Areas outside the NARR used the NCEP-NCAR global renanalysis (see Section 2).

2. Study Description and Location

2.1 Arctic Transport Potential Climatology

An objective of this work is to characterize a climatology of the potential of emissions from CONUS sources (such as prescribed fires) to be transported to the Arctic (defined here as crossing the Arctic Circle) and Greenland. Our approach used a forward trajectory modeling system that simulated a grid of potential source locations across CONUS for 30 years (1980 to 2009). The frequency that these source locations' trajectories reach the Arctic Circle and/or Greenland was quantified and analyzed. The ability for transport to reach typical seasonal snow and ice cover locations was also analyzed. The results were segregated by season, by climatological month, by individual month and year, by decade, by El Nino/La Nina climate phase, by plume injection (trajectory starting) height, and by the time to reach the destination of interest (the Arctic and/or Greenland and/or seasonal snow and ice extent). Over 600 million trajectories were modeled to create the climatology.

Modeling Setup

The National Oceanic and Atmospheric Administration's (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model v4.9 January 2010 release (Draxler, 1996; Draxler and Hess, 1997) was used for the trajectory modeling. HYSPLIT is a widely used model that calculates the path of a single air parcel from a specific location and height above the ground over a period of time; this path is the modeled trajectory. Ten-day forward trajectories were used to cover the time period of interest (McConnell et al., 2007), consistent with other studies of this type (e.g. Brock 1990, Hegg et al., 2009); analyses were done for the full ten-day period and for shorter transport times as well. The model options used for this study are listed in Table 1.

Table 1. Model configuration

	Climatological Runs	**Daily Forecasts**
Trajectory model	HYSPLIT v 4.9 (Jan 2010)	
Meteorological data	NARR: 32-km regional where available; NCEP / NCAR Global Reanalysis 2.5-degree elsewhere	National Weather Service Global Forecast System 00Z forecast model runs (northern hemisphere)
Time period	1979-2009	Daily since April 2012
Starting locations	Centroid of every other NARR land grid cell in CONUS (see Figure 2)	Every 1-degree x 1-degree land grid cell in CONUS, Alaska, and Canada (see Figure 3)
Trajectory time length	240 hours (10 days forward)	96 hours (4 days forward)
Starting heights	500, 1000, 1500, 2000, 2500, 3000, 5000 m AGL (see Figure 4)	
Starting times	Every 6 hours starting at 00Z	Every 3 hours starting at 00Z

Table 1. Model configuration (*continued*).

HYSPLIT Model Settings		
Vertical motion method	Isobaric (constant pressure)	
Top of model	20,000 m (agl)	
Integration time step	Dynamic (DELT=0)	
Time step to grid cell ratio	0.75 (TRATIO=0.75)	
Minimum size for meteorological sub-grids	10 grid cells (MGMIN=10)	
Mixed layer depth calculation method	From meteorological data (KMIXD=0)	From temperature profile (KMIXD=1)
Input height specification	Relative to terrain height from meteorological model (KMSL=0)	
Trajectory output interval	Hourly (TOUT=60)	

The use of forward trajectory modeling is a departure from the proposed backward trajectory modeling; the reasons for this change are discussed in *Section 2.3 Departure From Proposed Methodology*.

HYSPLIT uses meteorological data as input in order to calculate the trajectories. Here we used the high-resolution regional North American Regional Reanalysis (NARR; Mesinger et al., 2005) nested within the coarser National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) Global Reanalysis (NNRP; Kalnay et al., 1996). The NARR data are available at three-hr intervals for 23 vertical levels on a 32-km Lambert Conformal Conic grid that covers North America and most of the western half of the Arctic Region (see Figure 1). For areas outside the NARR, the NCEP-NCAR reanalysis is available every six hours for 28 vertical levels at 2.5-degree x 2.5-degree resolution with global coverage. Only the northern hemisphere was modeled here.

Source locations were defined as the centroids of every other NARR grid location. Overall, 1,926 source points within CONUS on an approximate 64-km grid were used for this study. Trajectories were released every 6 hours (000, 0600, 1200, and 1800 Coordinated Universal Time (UTC)) from seven starting heights (0, 500, 1000, 1500, 2000, 2500, 3000, and 5000 meters above ground level (AGL)), for the full 30-year period (Figure 2). These source heights were chosen to adequately capture transport from the typical range of smoke injection heights from the vast majority of fires (ValMartin et al., 2009), satellite measurements of which ranged between a few hundred meters to 5000 m for fires in the range of biomes in the cited study. It should be noted that some wildfires have been observed to reach the stratosphere (>10 km) but these events are not common (Fromm et al., 2000, 2005; Damoah et al., 2006). Overall 53,928 trajectories were released every day, and over 600 million trajectories were released over the 30-year period modeled.

We analyzed the trajectories to determine if and when each trajectory reached the sensitive receptors identified here (Arctic Circle, Greenland, or seasonal snow and ice extent). Snow and ice cover was only considered for spring months (March-May) using the National Snow and Ice Data Center climatological seasonal snow cover with glaciers and the climatological seasonal sea ice extent. Maps were created displaying source locations and source heights that reached the sensitive receptor. An emissions source location / source height combination was flagged as

reaching the sensitive receptor even if only one trajectory out of many reached that receptor. More than 200,000 aggregate maps showing the percentage of days with transport to the sensitive receptors were created and are available on the climatology web page[1] (see Section 7).

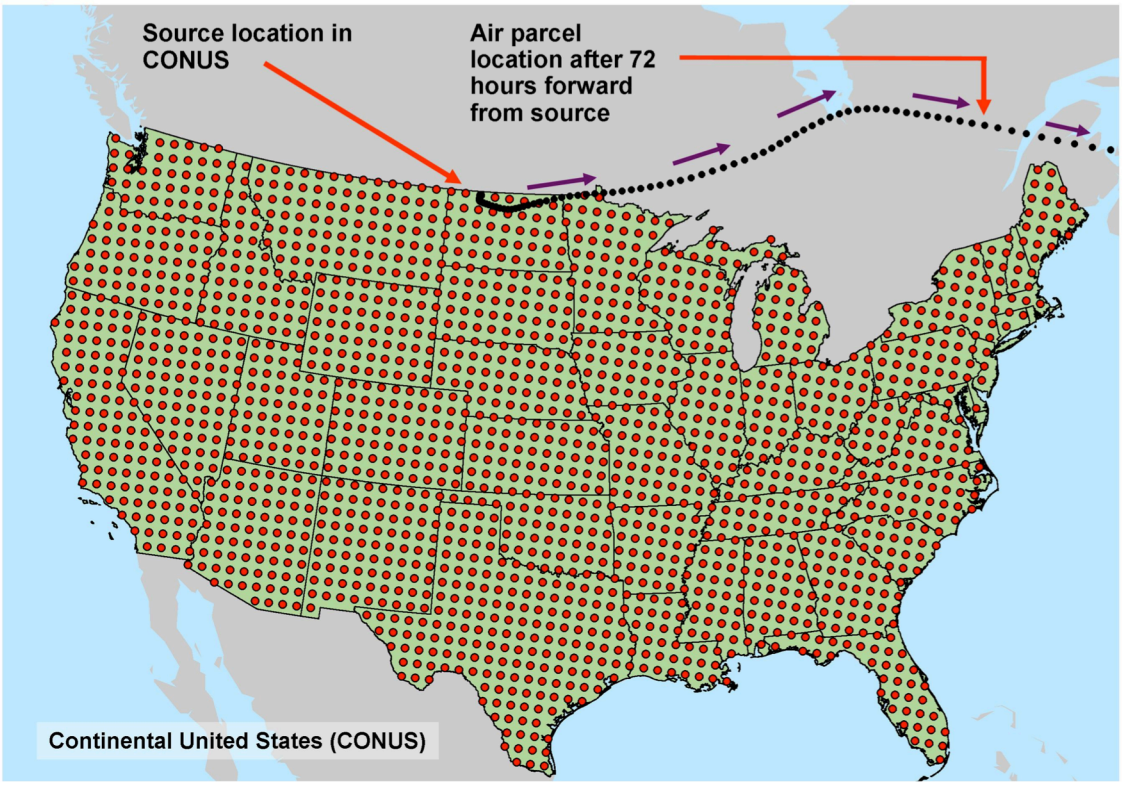

Figure 2. CONUS source locations for the climatology modeling. Each source location was run for all starting heights: 500, 1000, 1500, 2000, 2500, 3000, and 5000 m every six hours. Example trajectory (purple arrow path) modeled forward from sources (red dots) in the CONUS. Each trajectory is defined by location and attributes at each hour of transport (black dots).

Analyses were conducted to investigate the effect of using the nested NARR reanalysis data within the global NCEP-NCAR reanalysis data. There is some discontinuity in trajectory paths at the interface between meteorological datasets because of differences in the wind and temperature values. Vertical wind discontinuities can also cause horizontal trajectory path discontinuity when vertical wind shear is present. Trajectory transitions between these grids in the Arctic region were tested, and were found to be smooth, varying by less than 0.5%. HYSPLIT trajectory paths generally remain well-behaved at the NARR/NCEP-NCAR reanalysis data boundary in the Arctic region, with modest horizontal (within 45 degrees) and vertical (within 50 mb) discontinuities observed during testing. Most of the northern NARR domain boundary resides well within the Arctic region. Therefore, much of the modeled transport from

[1] The Arctic Transport Potential Climatology webpage is available online at http://www.airfire.org/data/arctic-transport-clim/

CONUS to the Arctic region takes place entirely within the NARR domain, and artificial discontinuities induced by dataset transitions on the trajectory path should not significantly impact modeled transport from CONUS to the Arctic region. Overall, the advantages gained by using the higher resolution NARR dataset when possible appear to outweigh any dataset transition issues.

Data storage and processing presented a major challenge to this work. Over 4 TB of compressed, binary data were created from the over 600 million trajectories modeled. New dataset formats were created to enable efficient data storage and extraction of results; a custom data analysis/data extraction system was developed using Python to allow analysis of the data. The extraction system produces mapped data in both NetCDF and ERDAS Imagine formats. Maps were made in ArcGIS using the ERDAS Imagine output.

2.2 Daily Forecast of Arctic Transport Potential

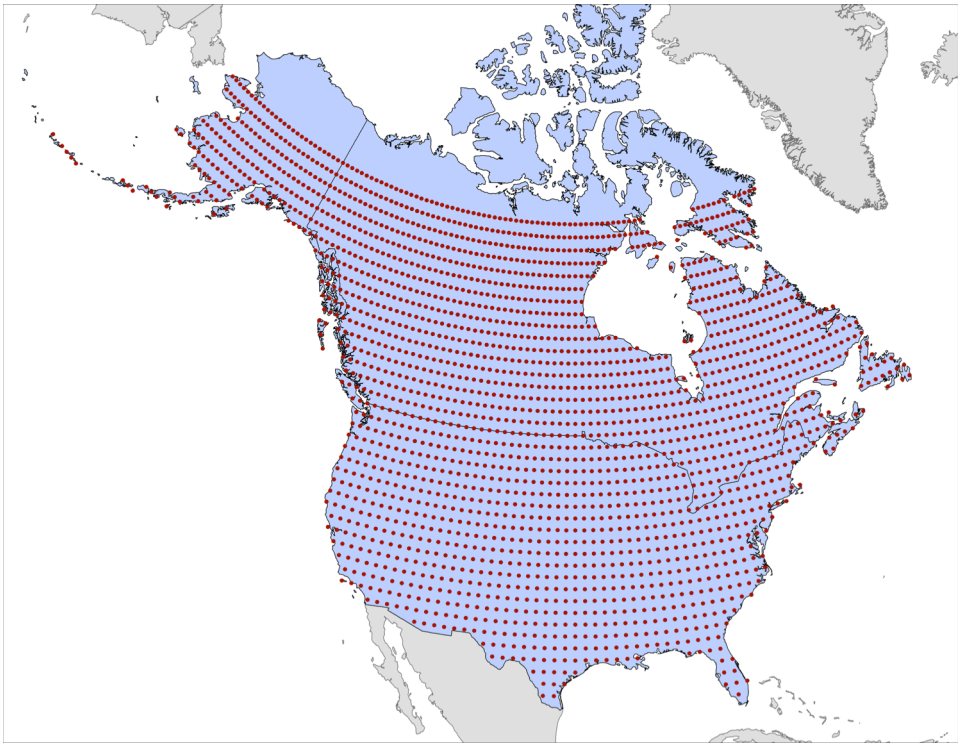

Figure 3. Source locations for the daily predictions - 2297 locations based on the National Weather Service Global Forecast System model grid.

Daily forecasts of arctic transport potential were created using methods similar to those used to create the climatological maps. While the original proposal envisioned a two-step process of identifying map-types that could be used to help forecast Arctic transport potential, the switch to forward trajectory modeling (see Section 2.3), allows for an improved direct approach. Daily trajectory runs were made with HYSPLIT using the U.S. National Weather Service's Global Forecast System (GFS) daily meteorological model forecast output. Trajectories were started

every three hours from each GFS grid cell in CONUS, Canada, and Alaska (Figure 3) for the same starting heights as in the climatological system (Figure 4). Trajectory paths are forecasted for the next four days. A full list of model parameters used is shown in Table 1.

The output of the daily HYSPLIT runs are analyzed through a sequence of custom Python scripts to produce a NetCDF output map. Graphics are then created using R statistical software. The results are displayed in a custom web interface (see Section 7 for links).

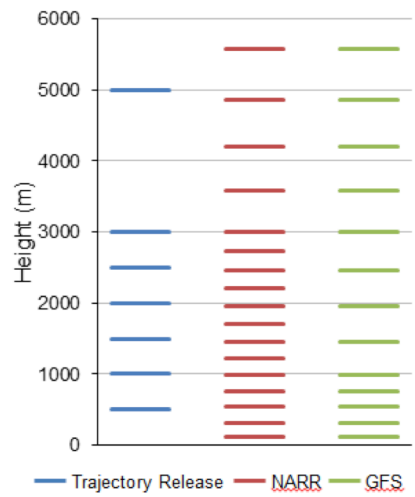

Figure 4. Modeled trajectory release heights and locations of NARR and GFS vertical levels.

2.3 Differences with Original Proposed Methodology

The modeling systems used above differ significantly from those proposed. In the proposal, a smaller modeling effort was envisioned that utilized *backward* trajectories. The advantage of backward trajectories is that they need only be run for the receptor areas, rather than for all potential source areas of interest. A full backward trajectory dataset for the climatological portion of this work was created and stored, but was not used in these analyses.

Significant differences were discovered between backward and forward trajectories near mountain ranges. Specifically, the treatment of the trajectories in the layer near the ground differed between the two trajectory methodologies (due to the handling of the windfield). Further examination in consultation with the model developer revealed that this finding is likely an inherent issue in backward trajectory modeling. A more complete analysis and journal paper are underway discussing the results of this investigation.

Based on the backward/forward trajectory comparison analysis results, we switched to a forward trajectory modeling approach to avoid the complications found with backward trajectories. This methodology change resulted in the need to process an order of magnitude more trajectories and caused some project delays, but the forward trajectories do not suffer from the same problems as the backward trajectories.

The switch to forward trajectory modeling required a change in the development of the daily forecast tool. The original trajectory tool envisioned was a two-step process of first map-typing the backward trajectory results and then using the map types to produce maps of which regions were likely to have high Arctic transport potential over the next few days. The switch to forward trajectory modeling allowed for a more direct approach where the meteorological forecasts could be directly examined to determine the source locations likely to reach the Arctic. Because this is a single-step, more direct approach, it also is likely to be more accurate than the proposed approach.

3. Key findings

The following points summarize the key findings from the Arctic Transport Potential project.

- **All regions and seasons (CONUS, 1980-2009) exhibited the potential to transport emissions to the Arctic, but there are strong regional gradients and differences.**

  We find substantial transport potential between CONUS and the Arctic overall for all regions and seasons studied over the years 1980-2009. Figure 5 shows the overall percent of days exhibiting transport during this period for injection heights ≤ 2000 m and transport times ≤ 7 days. Similar results were found for individual seasons and other transport times.

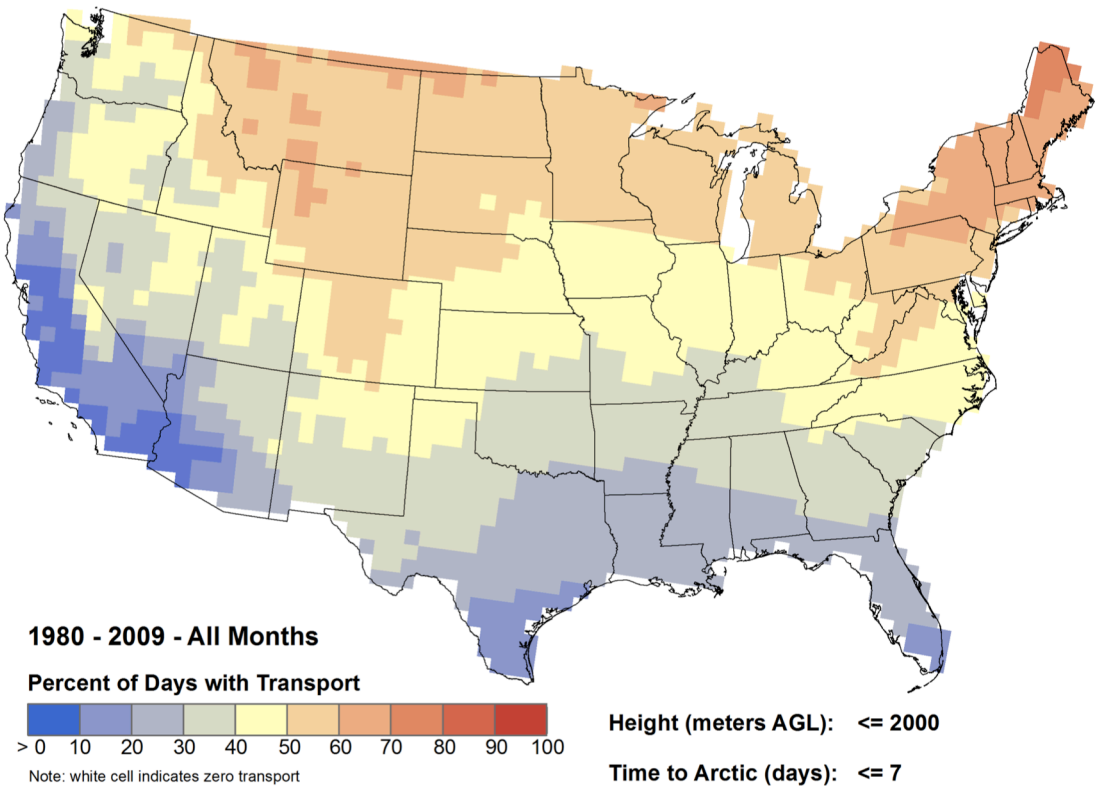

Figure 5. The percent of days with transport potential from CONUS to the Arctic Circle for January 1980 through December 2009. Only trajectories reaching the Arctic in ≤ 7 days and originating at heights of ≤ 2000 meters AGL were included.

Transport potential follows a strong latitudinal gradient, with the greatest transport originating from northern areas. In addition, there are features corresponding with longitude; in general, there is more transport at a given latitude in the eastern United

States than at the same latitude in the western United States, and transport is generally much less from points west of the Rocky Mountains. For example, along the California/Oregon border (approximately 42 degrees north latitude) 10%-20% of the days have transport to the Arctic, whereas on the western Pennsylvania-New York border, also at approximately 42 degrees north, 50%-60% of the days have transport. The area with the highest transport potential is in the northeastern United States. This overall pattern is one of the most consistent features found in the climatology.

- **Transport potential varies considerably by season.**

There is substantial variation in the likelihood for transport by season. Table 2 summarizes results across CONUS. The seasonal climatology is shown in Figure 6 (left side). While some areas during each season have very high transport potential, with over half of the days having transport to the Arctic, there is seasonal variability in the national average percent of days with transport. Summer transport potential is lowest, with an average of 23% of days of transport nationwide, while winter transport potential is highest at 57% of days; spring and fall have similar transport potential. Monthly variability is higher than seasonal variability.

Table 2. Nationwide statistics for the percent of days with transport potential by season and for all months, for the 30-year time period 1980-2009. Only trajectories with starting heights ≤ 2000 m and transport to the Arctic in ≤ 7 days were included.

Seasons (Months)	Minimum	Maximum	Mean	Standard Deviation
Winter (DJF)	8.2	84.6	57.1	14.5
Spring (MAM)	3.7	70.7	41.2	13.0
Summer (JJA)	0.6	61.6	22.8	13.7
Fall (SON)	4.8	74.7	44.7	15.1

The climatological transport potential is similar during the spring (March-May), and fall (September-November) seasons. However, because of Arctic snowpack extent during the spring, springtime transport of BC emissions is radiatively more important than fall transport.

- **Transport potential affects all types of emissions sources.**

The modeling used here is independent of source type (i.e., smoke or other emissions source). Thus, the results are not dependent on assumptions related to how fires produce emissions, and can be used to identify other emissions sector sources (i.e., fossil fuel combustion) with the potential to be transported to the Arctic.

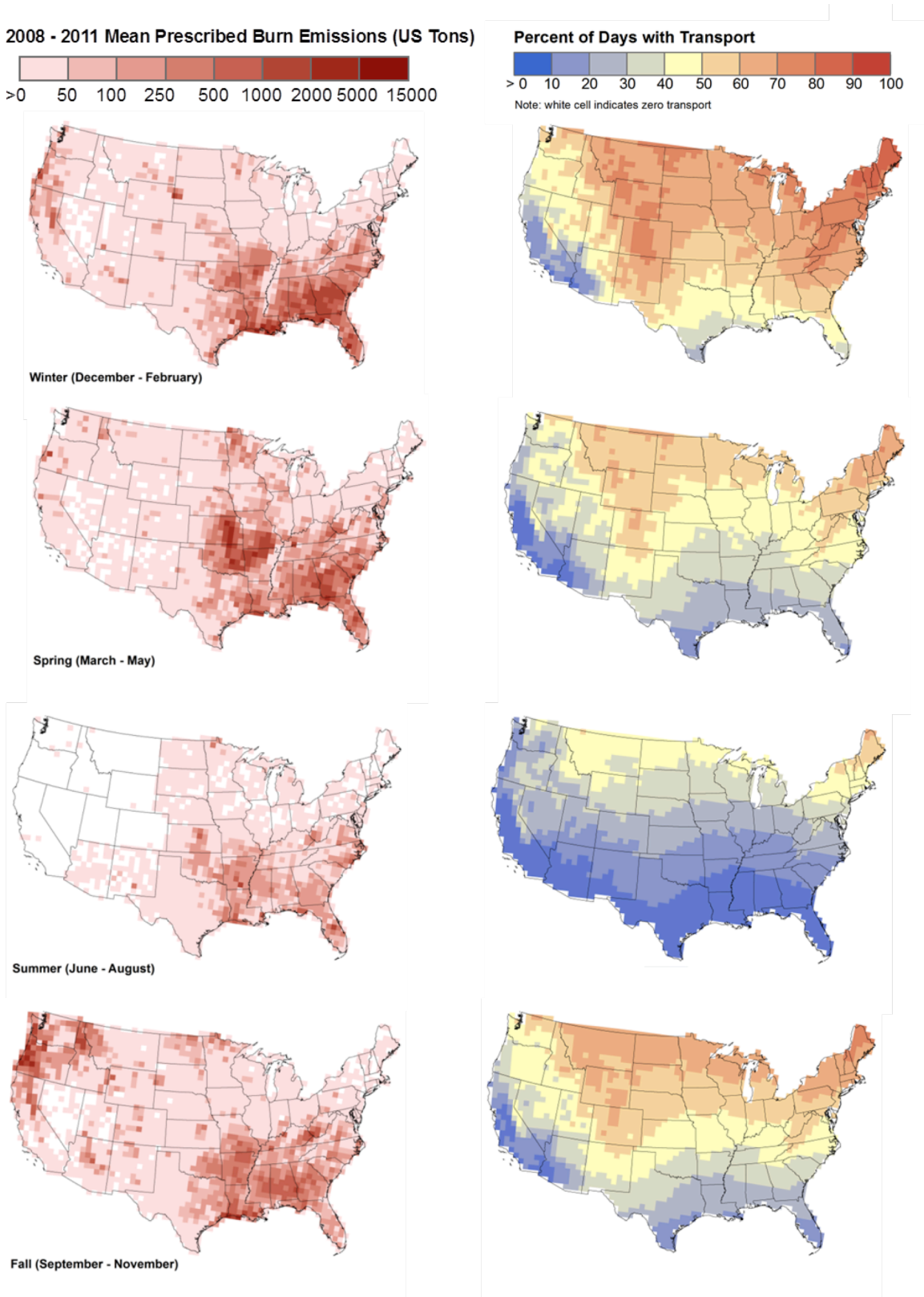

Figure 6. Seasonal prescribed burn emissions (left) compared to seasonal transport potential (right) for 2008-2011, by season. Seasonal transport is for injection heights ≤ 2000 m and transport times ≤ 7 days. Emissions include satellite-detected prescribed fires using methods found in Raffuse et al. (2012).

- **Emissions from fires occur in areas with high transport potential.**

  As shown in Figure 6, emissions from prescribed fires, on a climatological basis, occur in places where there is high Arctic transport potential. Of particular focused concern (see Section 1) has been the springtime prescribed burn season in the southeast. Figure 6 shows the southeast had the most prescribed fire emissions of any region in the CONUS during the 2008-2011 period but has relatively low transport potential during the spring. By comparison, northern states such as North Dakota and Minnesota have higher transport potential.

- **Even in regions and seasons with high transport potential, a significant number of periods exist when meteorological conditions do not allow for transport.**

  The modeling technique used here is conservative in that it likely *overpredicts* the ability of emissions to reach the Arctic – because other factors such as removal of BC by rainfall are not considered. Therefore, the percent of days with no transport should be lower than these results indicate. Despite our conservative approach, even in regions of the highest transport potential, a large number of periods with no transport potential can be found. Figure 7 compares two consecutive four-day periods and shows the influence of synoptic patterns on Arctic transport.

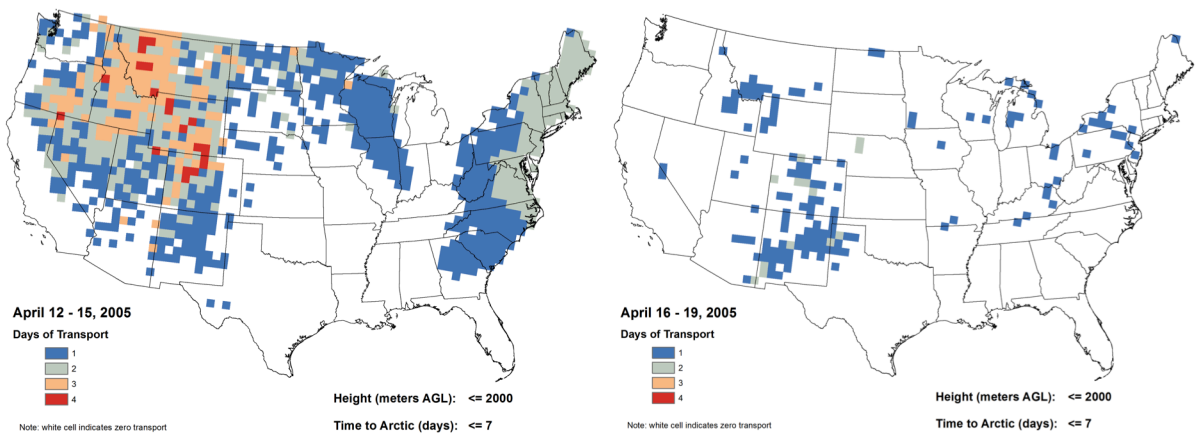

Figure 7. Comparison of transport potential found on consecutive four-day periods (April 12-15 and 16-19, 2005). Colors indicate the number of days within each four-day period showing transport, with white indicating none of the days showed transport and red indicating all of the days showed transport. The left panel shows transport from the northern Rocky Mountains throughout the time period and 1-2 days with transport in the eastern seaboard. The right panel shows that there is very little transport to the Arctic from across CONUS on the subsequent four days.

In general, as synoptic systems move through an area, that area will go through periods of having- and not having- transport potential, although the ratio of the timing of these periods varies geographically, seasonally, and by injection height.

- **Transport potential is critically dependent on plume injection height.**

  Injection height is key to whether or not emissions reach the Arctic. There is substantial variation in the likelihood for transport by injection height (Table 3). Even in areas and times of known concern, only a limited number of days connect to the Arctic from lower plume injection heights. High (i.e., > 3000 m) injection heights are conducive to transport to the Arctic virtually all the time from everywhere.

Table 3. Nationwide statistics for the percent of days with transport potential by season and for all months, for the 30-year time period 1980-2009. Only trajectories with transport to the Arctic in ≤ 7 days were included.

Season (Months)	Height (meters AGL)	Minimum	Maximum	Mean	Std. Deviation
Spring (MAM)	≤ 1000	1.4	48.0	20.5	9.8
Spring (MAM)	≤ 2000	3.7	70.7	41.2	13.0
Fall (SON)	≤ 1000	1.1	54.1	25.3	12.1
Fall (SON)	≤ 2000	4.8	74.7	44.7	15.1

- **Even small and medium-sized CONUS fires have the potential (via transport) to impact the Arctic.**

  We find large amounts of transport between CONUS and the Arctic during the spring season, when deposition of BC on Arctic snow has the greatest ability to affect the Arctic radiative balance. Based on our 30-year climatology, we see transport occurring during all spring months from all regions of CONUS at plume injection heights available to even small and medium sized fires (e.g., ≤ 1000 m AGL or ≤ 2000 m AGL). Transport capability changes with synoptic patterns.

- **The overall transport potential patterns from CONUS to Greenland resemble the overall transport potential patterns from CONUS to the Arctic, just with less frequency.**

  The potential for transport to Greenland closely follows the Arctic transport potential patterns both climatologically and also even for individual months. Figure 8 shows the springtime Greenland transport potential in a manner analogous to the Arctic transport potential shown in Figure 5. In general, the areas of larger transport potential are similar, but the percent of days showing transport is 10-20% less than for the Arctic.

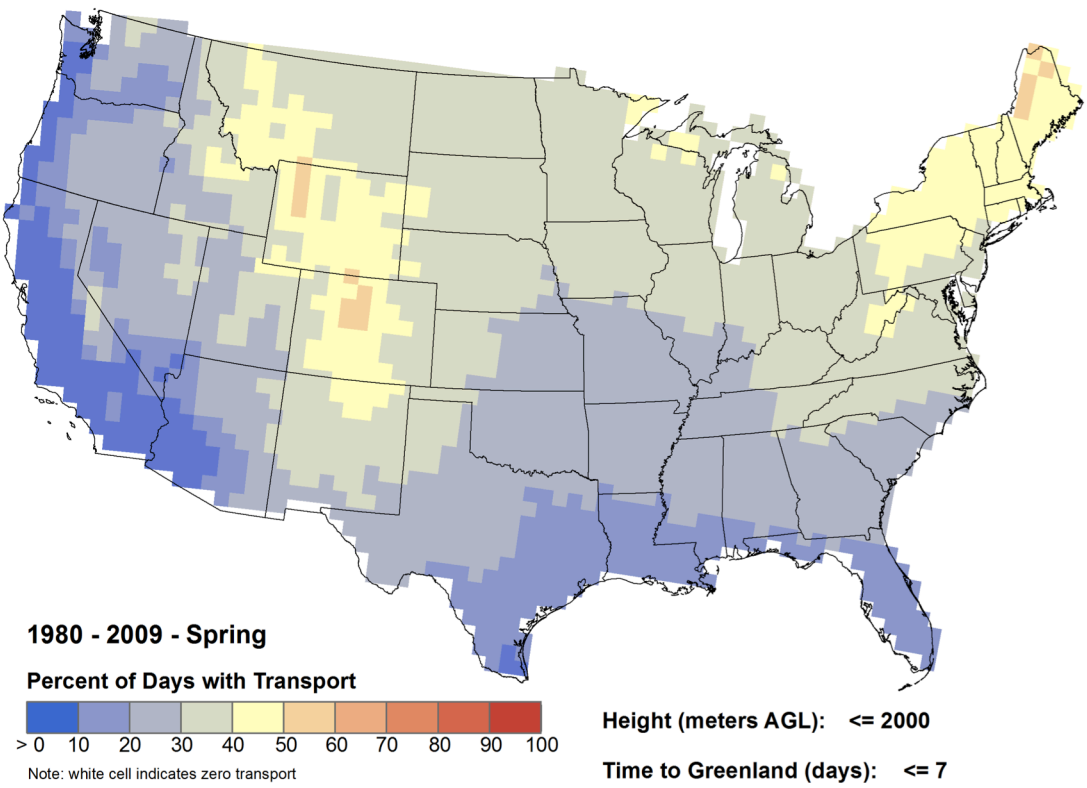

Figure 8. Spring 1980-2009 Greenland transport potential climatology for injection heights ≤ 2000 m and transport times ≤ 7 days.

- **The overall transport potential to seasonal snow and ice cover is substantially greater and shows different patterns than transport to the Arctic.**

  The focus for this project is on transport to the Arctic, and also, to a lesser extent on transport to Greenland, due to the scientific and policy relevance of these regions in particular. However, we also examined the potential for transport to snow and ice cover based on snow and ice extents obtained from the National Snow and Ice Data Center. Because the snow and ice cover extend far below the Arctic Circle in the winter and spring, even into North America (Figure 9 left panel), the transport to these regions (Figure 9 right panel) is substantially greater and shows substantially different patterns than the transport to either the Arctic or Greenland. Should mitigation of BC deposition on seasonal snow and ice become a management focus, this will substantially reduce the number of days that our study finds are available for burning without impact to snow and ice in any given season.

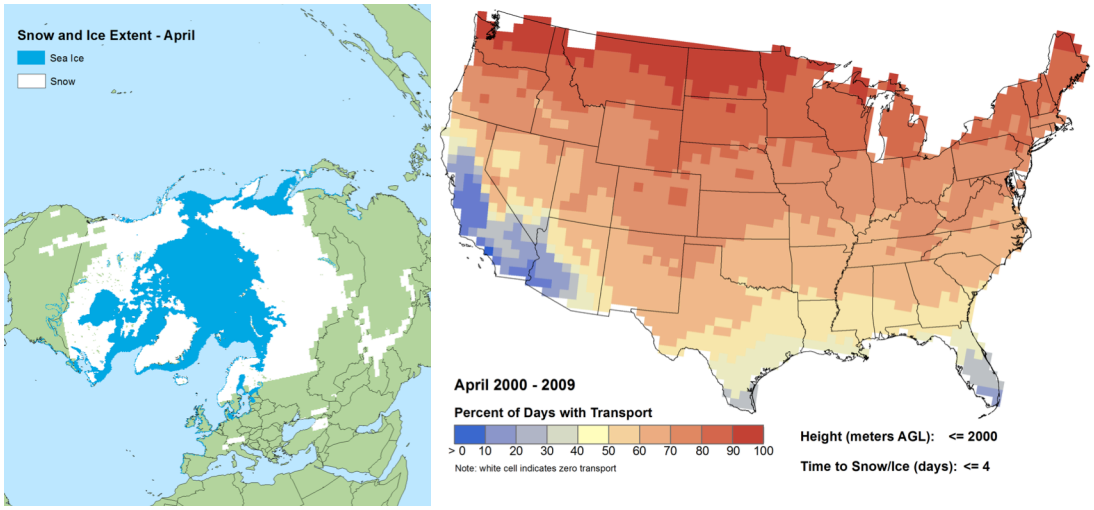

Figure 9. April snow and ice extent (left) and the corresponding April 2000-2009 transport potential for injection heights ≤ 2000 m and transport times ≤ 4 days (right).

- **While there is substantial year-to-year variability in all the transport potential studies here (Arctic, Greenland, seasonal snow and ice cover), El Nino years and La Nina years show the same overall pattern shape, with more transport potential in La Nina years.**

  Figure 10 shows the spring Arctic transport potential for both El Nino and La Nina years. The same general patterns found in the all-years analysis also pertains here. Only modest differences are seen, although La Nina years show more transport potential than El Nino years in aggregate.

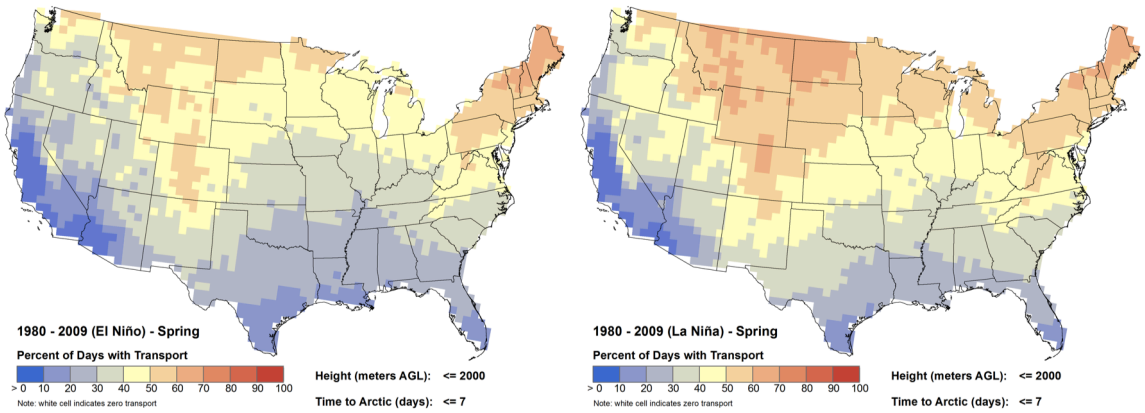

Figure 10. El Nino (left) and La Nina (right) April Arctic transport potential for injection heights ≤ 2000 m and transport times ≤ 7 days.

- **Backward trajectory modeling behaves differently near mountains than it does in flat areas.**

  Our original project plan was to use backward trajectory modeling, as this method is commonly employed in source apportionment studies. After significant test work, this approach was abandoned in favor of forward trajectory modeling (which required significantly more trajectories and computer time; over 600 million trajectories were modeled). This switch was made after working with the model developer and determining that the backward modeling introduces error when trajectories get close to the ground near high topographic elements (as happens when a trajectory passes over mountain ranges). The backward trajectories tended not to come back down to the surface after passing over the mountain range, obscuring any areas (such as California) that are in the backward "lee" of the mountain range. Forward trajectories eliminate this problem. A manuscript is under preparation in collaboration with the model developer that discusses this problem.

- **Meteorological forecast models provide more specific, and conceptually cleaner, predictions of Arctic transport potential than map-typing.**

  Because of the switch from backward trajectories to forward trajectories, we were able to move beyond the two-step process discussed in the proposal: map-typing the backward trajectory results and using these map-types to identify future transport periods. Instead, we developed a forecast tool that directly uses the National Weather Service GFS forecasts and performs forward trajectory model runs to provide three-day predictions of Arctic transport (Figure 11).

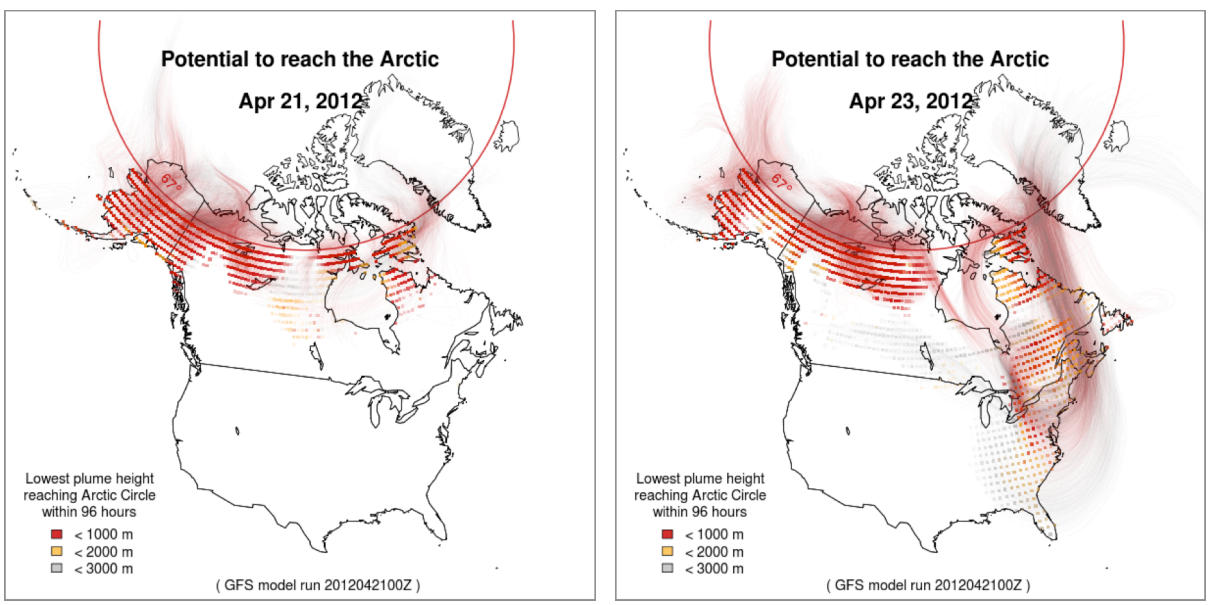

Figure 11. Prediction of Arctic transport potential using the U.S. National Weather Service GFS forecast output. Day 1 (4/21/12, left) and day 3 (4/23/12, right) predictions are shown for the April 21, 2012 00Z model run. Results are color-coded by the lowest plume injection height level where trajectories reached the Arctic. Grey = 2000-3000 m; Orange = 1000-2000 m; Red = 0-1000 m. The synoptic variability for this period can be seen in the presence of CONUS locations with transport potential in day 3 but not day 1 results.

- **Meteorological forecast models show significantly more Arctic transport from Alaska and Canada than CONUS.**

  While only CONUS was studied for this climatology, the forecast modeling is also performed for Alaska and Canada. As expected, forecast modeling shows that Alaska and Canada have significantly more transport potential than CONUS. The focus on CONUS for this project is not because CONUS is the primary contributor, but because of the need to inform management and policy decisions for CONUS-based fires.

- **Meteorological forecasts provide information that may be able to help mitigate Arctic impact concerns from controllable emissions.**

  Because of the overall transport potential found for CONUS (e.g., Figure 5) and the fact that Arctic transport is critically dependent on both synoptic meteorological patterns and plume injection height (e.g., Figure 11), in most locations and time periods, keeping the plume height low and/or shifting the date of burning one to three days can lead to a no-transport or low-transport-probability window. Thus, managers wishing to mitigate Arctic transport can use the predictions generated here to inform their decision processes.

4. Management Implications

While this project produced information relevant to managers, its primary purpose was to inform conversations happening at the overall policy level. As discussed in the Introduction, springtime biomass burning has been identified as a potential source of Arctic BC, and questions have been raised over methods to mitigate the effects on the Arctic of BC emissions from CONUS, especially from southeast springtime biomass burning sources (e.g. Zender, 2007). Proposed mitigation strategies include potentially significant changes to current forest prescribed burning practices, such as requirements to move all prescribed burning to the fall.

This work shows that, even within seasons and regions with high levels of Arctic transport potential, there are a substantial number of days when no Arctic transport is possible. Specifically, springtime prescribed burning in the southeast may be able to be mitigated by shifting burn timing or changing the plume injection height (e.g., by changing the ignition sequence to create a less coherent plume).

The EPA was tasked with producing the *Report to Congress on Black Carbon* (U.S. EPA, 2012). One of the major foci for this project was providing data on transport timing and injection heights to the EPA for their consideration. This was done, and a figure and accompanying text were supplied which were subsequently included in the report. The Report also contained mitigation possibilities, which included the moving of burns based on "meteorological scheduling" (p. 230).

At a large scale, managers and policy makers interested in mitigating Arctic BC effects can use the transport patterns identified here to focus on emissions sources, regions, and seasons with the most potential for transport. Or conversely, managers can identify the emissions sources, regions, and seasons *without* the potential for transport and de-prioritize mitigation activities in these areas. This use of transport patterns to inform decisions can help focus activities and reduce cost of mitigation efforts. The climatological and forecast tools developed through this project are useful for all BC emission sources.

For land managers interested in mitigating Arctic BC effects and working on a specific prescribed burn, the atlas produced here can provide information on preferable months (in terms of lack of Arctic transport potential) for burn activities. Differences in the climatology between different plume injection height levels can help with decisions on ignition procedures, which are often related to the ability of the fire to organize into hot convective cores. The heat cores of the fire are associated with plume injection heights and hotter cores can reach higher plume injection heights. Additionally, the daily forecasts can provide information to allow land managers to choose to shift the ignition day of prescribed burns or move to a lower-intensity fire to minimize the likelihood for emissions to be transported to the Arctic.

5. Relationship to Other Recent Findings and Ongoing Work

This project is primarily related to:

- The 2012 U.S. EPA *Report to Congress on Black Carbon* (U.S. EPA, 2012)
- The U.S. State Department Initiative on Black Carbon[2]

The connections to the 2012 EPA report have been discussed in Section 4. One of the major goals of this work was to provide information to be used in that report. This was completed and preliminary results from this project were used within the Report.

In response to the international Copenhagen climate conference in 2009, the U.S. State Department initiated a call for work with Russia on BC. An extension of this Arctic BC transport potential project to Eurasia, with particular focus on Russia, was included as part of the USDA project funded by the State Department initiative. This work is still underway, with output products similar to those for this project. Also, as part of the State Department work, Dr. WeiMin Hao is leading an effort to do advanced photochemical modeling of BC transport to the Arctic; the Russia extension of this project is helping to focus this computationally expensive modeling effort toward regions of concern. As part of the State Department-funded work, this project was presented at a recent USDA-Russia workshop organized in part by the USDA Foreign Agricultural Service.

Several other agencies (the EPA, DOE, and DOI) working on various projects as part of the State Department Initiative have also expressed interest in the results of this project. Specifically, these agencies are interested in whether the results can help focus areas of interest for mitigation efforts in Russia.

This work has also been presented to the recent U.S. Forest Service Greenhouse Gas – Black Carbon Synthesis Report effort. A special volume of *Forest Ecology and Management* is being produced for this effort. Part of this special edition will be a journal paper examining U.S. fire emissions inventories, including BC and the importance of these emissions for the Arctic.

Findings from this project can also inform the BC modeling funded by JFSP in 2010. The trajectory analyses do not include wet or dry deposition or chemical transformation and therefore represent the "worst-case scenario." This study, combined with a one-atmosphere model, will help to further understand the likelihood of transport and further narrow the regions of transport origin.

[2] Information on the U.S. State Department initiative can be found at http://www.state.gov/p/eur/rls/fs/193106.htm

6. Future Work Needed

This work can lead in a number of different directions; this is because the work can be foundational for modeling and mitigation work for any type of emissions source.

Currently, the continuation of this project, through funding from the U.S. State Department, is focused on conducting the same type of analyses for the rest of the northern hemisphere, with particular emphasis on Russia. Arctic transport potential climatologies and forecasts are being generated from Russia in a manner similar to CONUS as reported here.

Climatological runs should be done for Alaska and Canada to complement the CONUS runs done here and the Eurasian runs done for the State Department Initiative.

Additional plume heights should be added to complement the plume heights modeled here. Plans are underway to model every 250 m in height which will double the 4TB dataset produced here.

Follow-on work to this project can include examination of the areas of greatest concern using more sophisticated full-photochemical transport models like WRF-Chem; some work of this nature is being led by Dr. WeiMin Hao for the State Department Initiative. Such studies would allow for examination of whether the Arctic transport potential identified here can be correlated to *actual Arctic transport and deposition*, or if other factors such as rainout confound simple correlations. Additional work on the expected residence times of BC in the atmosphere would also help identify the best maps to use from the modeling done here.

A complete write-up of the backward trajectory issue identified here is ongoing with the model author. Backward trajectories are much more conducive than forward trajectories to source apportionment, but the topographic issue found in our study needs to be clarified and the impact of this issue discussed.

Other areas for future work are to examine specific areas of interest such as wintertime transport from the Black Hills, northern Great Plains transport in the spring, and other areas.

Additional work is needed to examine the transport and deposition of BC to snowfields and glaciers within CONUS, such as in the Rocky Mountains, where BC can still have large radiative effects. Recent studies found BC on local snowfields and glaciers to have a large effect on global warming and the amount of melting taking place (Bond et al., 2010). Future work to identify the potential for wildfire and prescribed fire sources to reach these small snowfields (within CONUS and North America, including Alaska) is necessary. The trajectory work done for this project can help identify the source region areas to investigate further. Field work and other modeling efforts (such as those done in #11-1-5-13) can also be used to determine the relative impact wildland burning has on local snowfields compared to other BC sources (i.e., fossil fuel combustion) and to compare it with results from follow-on modeling studies of the type done here.

7. Deliverables

The deliverables for this project differ from the proposed deliverables primarily in that the map-typing was not needed after the methodology switch from backward to forward trajectory modeling. Not included in the following list is the full 30-year backward trajectory database which was produced but is not used here because of the issue identified (see Key Findings).

Table 2: Deliverables

Deliverable Type	Description	Completion Status
Dataset + Refereed publication	An atlas of maps that show the probability of fire emissions from any point in CONUS reaching the Arctic, separated: · by climatological month · by impact area · by plume injection height. Published as a refereed GTR by USFS PNW Research Station	Complete. On web; GTR in press.
Analysis Report (Non-refereed publication)	A summary document discussing the implications of the work with respect to the potential for prescribed fire versus wildfire to reach the Arctic.	Complete. Done as presentations, discussions, and draft text edits for the EPA Report to Congress.
Invited presentation	Presentation of results at EPA; it is also expected that multiple non-invited presentations at conferences will be given.	Complete. Preliminary results presented to EPA and then included in EPA Report; see below for other invited presentations.
~~Journal Article (Refereed publication)~~	~~Peer-reviewed journal article detailing the regions, timing, and synoptic maps necessary for continental U.S. fire emissions to reach the Arctic.~~	Not done; Project adjusted to use real-time forecasts

Table 2: Deliverables (*continued*)

Deliverable Type	**Description**	**Completion Status**
~~Dataset + Refereed publication~~	~~An atlas of synoptic map-type progressions that allow for transport to the Arctic, separated:~~ ~~· by source region~~ ~~· by impact area, and~~ ~~· by plume injection height.~~ ~~Published as a refereed GTR by USFS PNW Research Station.~~	Not done; Project adjusted to use real-time forecasts instead; Real-time forecasts included in GTR publication
Decision Support Tool (Computer software + website)	A tool that examines the current National Weather Service forecasts for those conditions identified for probable Arctic transport and highlights regions where transport to the Arctic is expected to be likely over the course of the next 7-days.	Complete. Real-time tool available via the web.
Journal Article (Refereed publication)	Peer-reviewed journal article detailing the results of the work.	In draft review. To be submitted to journal Nov 2012.
Final Report	Final report detailing the back-trajectory, ~~map-typing~~, and forecast tool work peer JFSP standards.	Complete. Submitted Sept 2012 (this document)
Additional: Journal Article (Refereed publication)	Comparison of forward and backward trajectory results and issue near topography	In process. Expect submission in Winter 2012.

List of presentations:

Larkin, N.K., DeWinter, J.L., Brown, S.G., Raffuse, S.M., Strand, T.M., Craig, K.J., Solomon, R.C., and Roberts, P.T. (2012) Identification of necessary conditions for transport to the Arctic. USDA-RIAMA Workshop, Puskino, Russia, March.

DeWinter, J. L., Larkin, N. K., Strand, T.M., Raffuse, S.M., Brown, S.G., Craig, K.J., and Roberts, P.T. (2011) Synoptic scale patterns and variability in long-range transport from the CONUS to the Arctic Circle: informing controlled burn strategy and regulation. AGU Fall Meeting, San Francisco, CA, December.

Kinder, B., Hao, W.M., Larkin, N.K., McCarty, G., O'Neal, K.J., Gonzalez, O., Luxenberg, J., Rosenblum, M., and Petkov, A. (2011) Black carbon in the Arctic: assessment of and efforts to reduce black carbon emissions from wildfires and agricultural burning in Russia. AGU Fall Meeting, San Francisco, CA, December.

Larkin, N.K., DeWinter, J.L., Brown, S.G., Raffuse, S.M., Strand, T.M., Craig, K.J., Solomon, R.C., and Roberts, P.T. (2011) Identification of necessary conditions for transport to the Arctic. USDA/State Department presentation, Washington, D.C., December.

DeWinter, J. L., Raffuse, S.M., Brown, S.G., Craig, K.J., Roberts, P.T., Larkin, N. K., and Strand, T.M. (2011) Mitigating the impact of prescribed burning in the continental United States using trends in synoptic scale transport to the Arctic region. Air & Waste Management Association, Greenhouse Gas Strategies in a Changing Climate, San Francisco, CA, November.

Larkin, N.K., Brown, S.G., Craig, K.J., DeWinter, J.L., Raffuse, S.M., Strand, T.M., Roberts, P. T., and Solomon, R.C. (2011) Identifying the potential for Arctic transport of smoke. Ninth Symposium on Fire and Forest Meteorology, Palm Springs, CA, October.

Larkin, N.K. (2011) AirFire science applications: beyond BlueSky. USFS PNW Station Management Team, Webinar, July.

Larkin, N.K., DeWinter, J.L., Brown, S.G., Raffuse, S.M., Strand, T.M., Craig, K.J., Solomon, R.C., and Roberts, P.T. (2011) Identification of necessary conditions for transport to the Arctic. USDA State Department Black Carbon Initiative, Washington, D.C., February.

Larkin, N.K. (2011) Air quality modeling and decision support tools for wildland fire. USFS Conversations with the Chief series, Webinar, January.

DeWinter, J.L., Larkin, N.K., Strand, T.M., Raffuse, S.M., Brown, S.G., Craig, K.J., Roberts, P.T., and Draxler, R.R. (2010) Climatology of air mass transport to the Arctic from locations of prescribed burning in the United States. AGU Fall Meeting, San Francisco, CA, December.

DeWinter, J.L., Raffuse, S.M., Brown, S.G., Craig, K.J., Roberts, P.T., Larkin, N.K., and Strand, T.M. (2010) Climatology of air mass transport to the Arctic from locations of prescribed burning in the United States. 29th Annual AAAR Conference, Portland, OR, October.

Raffuse, S. M., Larkin, N.K. ,Strand, T.M., DeWinter, J.L., Brown, S.G., Craig, K.J., and Roberts, P.T. (2010) Identifying conditions necessary for CONUS fires to impact the Arctic. 3rd Fire Behavior and Fuels Conference, Spokane, WA, October.

List of publications:

DeWinter, J. L., Raffuse, S.M., Strand, T.M., Larkin, N.K., Brown, S.G., Craig, K.J., and Roberts P.T. (2011) Mitigating the impact of prescribed burning in the continental United States using trends in synoptic scale transport to the Arctic region. Air & Waste Management Association Greenhouse Gas Strategies in a Changing Climate, San Francisco, CA, November. (5 pages)

Larkin, N.K., DeWinter, J. L., Hafner, H.R., Brown, S.G., Raffuse, S.M., Strand, T.M., Callahan, J., Craig, K.J., and Solomon, R.C. (2012) An Atlas and Daily Forecasts For Assessing the Potential for Emissions Transport to the Arctic. General Technical Report, U.S. Forest Service Pacific Northwest Research Station, Portland, Oregon. (in review)

Larkin, N.K., DeWinter, J.L., Hafner, H.R., Strand, T.M., Brown, S.G., Raffuse, S.M., Callahan, J., Craig, K.J., and Solomon, R.C. (2012) Arctic transport potential patterns: 1980-2009. J. Applied Met. Clim. (in preparation)

References

Bond, T.C., Zarzyck, C., Flanner, M.G., and Koch, D.M. (2010) Quantifying immediate radiative forcing by black carbon and organic matter with the specific forcing pulse. *Atmos. Chem. Discuss*. 10, 15713-15753.

Brock, C.A. (1990) Microphysical, chemical, and meteorological aspects of aerosol hazes in the arctic. PhD dissertation, University of Washington, Seattle, WA.

Damoah, R., Spichtinger, N., Servranckx, R., Fromm, M., Eloranta, E. W., Razenkov, I. A., James, P., Shulski, M., Forster, C., and Stohl, A. (2006) A case study of pyro-convection using 20 transport model and remote sensing data, Atmos. Chem. Phys., 6, 173–185, http://www.atmos-chem-phys.net/6/173/2006/acp-6-173-2006.pdf.

Draxler, R.R. (1996) Boundary layer isentropic and kinematic trajectories during the August 1993 North Atlantic Regional Experiment Intensive. *J. Geophys. Res.*, **101**, 29555-29268.

Draxler, R.R. and Hess, G.D. (1997) *Description of the HYSPLIT 4 Modeling System*; ERL ARL-224; Technical Memorandum by National Oceanic and Atmospheric Administration: Silver Spring, MD.

Flanner, M.G., Zender, C.S., Randerson, J.T., and Rasch, P.J. (2007) Present-day climate forcing and response from black carbon in snow. *J. Geophys. Res.* 112, D11202, doi:10.1029/2006JD008003.

Fromm, M., Alfred, J., Hoppel, K., Hornstein, J., Bevilacqua, R., Shettle, E., Servranckx, R., Li, Z., and Stocks, B. (2000) Observations of Boreal Forest Fire Smoke in the Stratosphere by POAM III, SAGE II, and Lidar in 1998, Geophys. Res. Lett., 27, 1407–1410.

Fromm, M., Bevilacqua, R., Servranckx, R., Rosen, J., Thayer, J. P., Herman, J., and Larko, D. (2005) Pyro-cumulonimbus injection of smoke to the stratosphere: Observations and impact of a super blowup in northwestern Canada on 3–4 August 1998, J. Geophys. Res., 110, 1–16, doi:10.1029/2004JD005350.

Hansen, J., and Nazarenko, L. (2004) Soot climate forcing via snow and ice albedos, *Proc. Natl. Acad. Sci., 101,* 423-428, doi:10.1073/pnas.2237157100.

Hegg, D.A., Warren, S.G., Grenfell, T.C., Doherty, S.J., Larson, T.V., and Clarke, A.D. (2009) Source attribution of black carbon in Arctic snow, *Environ. Sci. & Technol., 43*(11), 10.1021/es803623f, 4016-4021.

Jacobson, M.Z., Bond, T.C., Ramanathan, V., Zender, C., and Schwartz, J. (2007) Hearing examines Black Carbon and Global Warming, House Committee on Oversight and Government Reform Testimony, http://tinyurl.com/yz2jesv.

Kalnay. E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetma, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Jenne, R., and Josepgh, D. (1996) The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.,* 77, 437-470.

Koch, D., and Hansen, J. (2005) Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment, *J. Geophys. Res., 110*, D04204, doi:10.1029/2004JD005296.

McConnell, J.R., Edwards, R., Kok, G.L., Flanner, M.G., Zender, C.S., Saltzman, E.S., Ryan Banta, J., Pasteris, D.R., Carter, M.M., and Kahl, J.D.W. (2007) 20th-Century industrial black carbon emissions altered Arctic climate forcing, *Science* 317, 1381-1384.

Mesinger, F., DiMego, G., Kalnay, E., Mitchell, K., Shafran, P.C., Ebisuzaki, W., Jovic, D., Woollen, J., Rogers, E., Berbery, E.H., Ek, M.B., Fan, Y., Grumbine, R., Higgins, W., Li, H., Lin, Y., Manikin, G., Parrish, D. and Shi, W. (2005) North American Regional Reanalysis, *Bull. Am. Met. Soc.*, 87, 3, 343-360.

Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B., and Kiehl, J.T. (2006) Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise, *Science, 311,* 1747-1750, doi:10.1126/science.1115159.

Quinn, P.K., Bates, T.S, Baum, E., Doubleday, N., Fiore, A.M., Flanner, M., Fridlind, A., Garrett, T.J., Koch, D., Menon, S., Shindell, D., Stohl, A., and Warren, S.G. (2008) Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies, *Atmos. Chem. Phys*. 8, 1723-1735.

Raffuse S., Du, Y., Larkin, N., and Lahm, P. (2012) Development of the 2008 wildland fire national emissions inventory. *20th International Emission Inventory Conference*, August, Tampa, Florida.

Shindell, D.T., Chin, M., Dentener, F., Doherty, R.M., Faluvegi, G., Fiore, A.M., Hess, P., Koch, D.M., MacKenzie, I.A., Sanderson, M.G., Shulz, M.G., Stevenson, D.S., Teich, H., Textor, C., Wild, O., Bergmann, D.J., Bey, I., Bian, H., Cuvelier, C., Duncan, B.N., Folberth, G., Horowitz, L.W., Jonson, J., Kaminski, J.W., Marmer, E., Park, R., Pringle, K.J., Schroeder, S., Szopa, S., Takemure, T., Zeng, G., Keeting, T.J., and Zuber, A. (2008) A multi-model assessment of pollution transport to the Arctic, *Atmos. Chem. Phys., 8,* 5353-5372.

Shindell, D.T. and Faluvegi, G. (2009) Climate response to regional radiative forcing during the twentieth century, *Nat. Geosci*., 2, 294-300.

Stohl, A., Andrews, E, Burkhart, J.F., Forster, C., Herber, A., Hoch, S.W., Kowal, D., Lunder, C., Mefford, T., Ogren, J.A., Sharma, S., Spichtinger, N., Stebel, K., Stone, R., Strom, J., Torseth, K., Wehrli, C., and Yttri, K.E. (2006) Pan-Arctic enhancements of light absorbing

aerosol concentrations due to North American boreal forest fires during summer 2004, *J. Geophys. Res., 111,* D22214, doi:10.1029/2006JD007216

U.S. Environmental Protection Agency (2012) Report to Congress on black carbon. Report prepared by the Office of Air Quality Planning and Standards, Office of Atmospheric Programs, Office of Radiation and Indoor Air, Office of Research and Development, and Office of Transportation and Air Quality, Research Triangle Park, NC, EPA-450/R-12-001, March. Available on the Internet at http://www.epa.gov/blackcarbon/.

ValMartin, M., Logan, J.A., Kahn, D., Leung, F.Y., Nelson, D., and Diner, D. (2009) Smoke injection heights from fires in North America: analysis of 5 years of satellite observations. *Atmos. Chem. Phys. Dis.*, 9, 20515-20567.

Warneke C., Bahreini, R, Brioude, J., Brock, C.A., deGouw, J.A., Fahey, D.W., Froyd, K.D., Holloway, J.S., Middlebrook, A., Miller, L., Montzka, S., Murphy, D.M., Peishl, J., Ryerson, T.B., Schwartz, J.P., Spackman, J.R., and Veres, P. (2009) Biomass burning in Siberia and Kazakhstan as an important source for haze over the Alaska Arctic in April 2008. *GRL*, 36, L02813, doi:10.1029/2008GL035194, 6pp.

Zender, C.S. (2007) Arctic climate effects of black carbon. Written testimony to the Oversight and Government Reform Committee, U.S. House of Representatives, October 18.

More Information

For more information, please see

Project home page:	http://airfire.org/projects/arctic-transport
Climatology/atlas:	http://airfire.org/data/arctic-transport-clim
Daily forecasts:	http://airfire.org/data/arctic-transport-forecast

or contact

Dr. Narasimhan K. ("Sim") Larkin
U.S. Forest Service AirFire Team
400 N. 34th St #201, Seattle, WA 98103
206-732-7849
larkin@fs.fed.us