

# DOWNWARD MIXING IN THE CONTINENTAL ARCTIC BOUNDARY LAYER DURING A SMOKE EPISODE

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## ABSTRACT

Downward mixing in the Continental Arctic Boundary Layer (ABL) is investigated during a period of regional haze due to forest fires in the boreal sub-arctic region during summer 2005. A description of the vertical dilution leading exchange processes taken place during the buildup of the diurnal cycle of the continental ABL is given when a polluted smoky air mass was advected from the North Eastern part of Alaska. The ABL structure in urban environment was documented during three days June 28-30, 2005 by daytime vertical profiling with the Compact Eye-Safe Backscatter Lidar Instrument working at 1.574  $\mu\text{m}$  at the Geophysical Institute in Fairbanks, Alaska. Starting on June 29, overnight advected plumes of particulate matter and contaminants gases are shown overlaying the ABL in the morning hours. Thereafter, during the ABL diurnal development, convective rising thermal plumes entrain and incorporate the smoky air mass into the boundary layer volume as revealed by the backscattering structure of the vertical profiles and the evolution of surface PM<sub>2.5</sub> fine particulate signature. Surface fine particulate peaks  $\sim 130 \mu\text{g}/\text{m}^3$  during afternoon hours as results of the upper level downward mixing interaction between the convective ABL and the overlying polluted air mass. In this article a discussion of the aerosol concentration exchange leading a severe unhealthy Air Quality episode is given based on the time-height backscatter Lidar signature, surface PM<sub>2.5</sub> particulate matter and additional meteorological and satellite information.

## 1. INTRODUCTION

Population exposure to high level concentration of contaminants and particulate matter during forest fire events leading unhealthy Air Quality conditions is a subject of important concern for environmental organizations (i.e: Environmental Protection Agency) and for local state institutions (i.e: Fairbanks North Star Borough). Gases and particulate matter released into the atmosphere during forest fires episodes have different time scale impact depending upon dynamic conditions: in the local area ( $\sim 1\text{km}$ ) where the fire is produced, the time scale is dominated by local scale process (i.e. turbulent transport and dispersion); in the

nearby region ( $\sim 2\text{-}10 \text{ km}$ ), it is dominated by mesoscale transport and, moreover, at the continental scale by long range transport ( $> 10 \text{ km}$ ). In particular, the combination of mesoscale transport overnight driven by specific synoptic situation and mesoscale patterns can lead episodic pollution events in nearby regions. Forest fire in high latitudes have major impact in Air Quality (AQ) degradation including direct consequences in the boreal ecosystem, sub-soil anomalies (i.e: permafrost reduction), impacts in the short and long term population health effects and visibility reduction. In addition, forest fire represents a particular scenario for studying atmospheric feedbacks by the activation of the dynamical-chemical-radiative interaction chains at regional and local scale during the period of time of the atmospheric perturbation. During forest fire episodes local AQ can be largely affected by increasing volume concentration of gas contaminants from combustion products and particulate released into the atmosphere. Chemical composition of particulate matter released includes acids (nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (fragments or pollens or mold spores). Aerodynamic sizes of the released materials ranges from small particles (2.5  $\mu\text{m}$  in diameter or less), that can be identified as smoke and/or haze in the atmosphere; to coarse particles (found in wind-blown dust), having diameters ranging from 2.5 to 10  $\mu\text{m}$ . Total suspended particles can be described mainly by the coarse particle evolution whereas the population health danger is related mostly with fine mode particles. Regional AQ is also degraded when local production of particulates and gases are injected in the atmospheric flow after being dispersed locally in the boundary Layer. This mechanism becomes dangerous when urban emissions are combined with stagnation condition, prevalent at mesoscale level, due to the resident time enlargement of contaminant and particles and suppression of vertical mixing. Final concentration in the near surface is regulated by dispersion in the BL which plays a central role in the estimation of space-time concentration of major tracers. The BL can be seen as an atmospheric reservoir where the air is mixing with pollutants (primary or secondary) from local and regional origin [4, 5, 6]. In this atmospheric

reservoir chemical reactions and radiative processes take place in conjunction with transport and mixing during the diurnal cycle driven by different atmospheric processes from small to large scales. In particular, over continental arctic environment, these above mentioned features are amplified during the two major seasonal periods: diurnal warming  $\sim 23$  hr daylight,  $18$  C on annual average during summer time and radiative cooling with surface temperature  $\sim -50$  C are verified. Consequently the dynamic engine for in-place aerosols and pollutants cycling and processing will behave differently than other latitude regions. Forest fire events occur frequently during summer time whereas ventilation conditions are supposed to be optimum for vertical dispersion of local pollution; because it is widely recognized that the diurnal BL cycle “cycles” the pollutants reducing near surface concentration by vertical dilution by increasing the internal BL volume along the diurnal incorporating free atmosphere air. Nevertheless, following this classical concept, when vertical dilution is expected during daily hours to effectively reduce the local concentration of contaminants near surface, downward mixing of a non-local smoke plume overlying the BL can severely damage this natural cleaning process by incorporating “smoky air mass” to the local air mass composition instead of the expected “clean free atmospheric air”.

In this work we concentrate our attention in the downward mixing process introducing new particulates in the BL air increasing surface concentration by vertical dilution exchange process during the buildup of the diurnal cycle. The framework for this case study is described in section 2. The instrumental deployment and the specific lidar signals analysis are exposed in section 3. A discussion of the vertical exchange process is given based on the backscattering Lidar signals and the surface particulate measurements in section 4. The summary address in specific the importance of dynamics processes during summer time as a negative factor for AQ degradation that could lead severe unhealthy situations.

## 2. FOREST FIRE CYCLOGENESIS

Interior Alaska has sub-arctic continental climate characterized by cold winters and warm summers. The interior region is limited to the north by the Brooks Ranges and to the south by the Alaska Ranges. During summer time the Arctic and sub-Arctic region becomes dry and warm whereas the synoptic meteorology in most of the cases is driven by the presence of semi-permanent anticyclone over eastern interior Alaska/Western Yukon Territories. The high pressure system suppresses widespread cloud cover and precipitation carrying surface heating increase with a mean surface temperature  $\sim 18$  °C during summer. As results of this prevailing meteorological situation,

increase in the amount of convection is verified. This meteorological variable setup closes the loop for forest fires cyclogenesis by triggering thunderstorm occurrence more than normal consequently increasing of the number of lightning strikes. Statistically forest fires genesis has been verified to be 97% originated by this process [3]. In addition dry surface conditions facilitates the uncontrolled spreading of fires which in most of the cases the atmospheric dispersion efficiency is compromised with an important regional stagnation for a certain number of days until a new synoptic situation breaks down the stagnation period. During the last week of June 2005 the anticyclone presence on the north eastern part of the state of the Alaska govern the air flow in interior of Alaska in the lower troposphere. The forest fires episode outbreaks in the interior region of Alaska where fires sources had been located between the Alaska Range and the Brooks Range. Approximately 35% of the area was impacted by smoke. Fires spots in the Sheenjek River and Northeast of Fort Yukon have experienced periods of visibility down  $\frac{1}{2}$  mi. Fires spots were also identified in Chapman Creek and south central Brooks Range in continuous during the lidar observation period (June 28 to 30)[7]. North-easterly winds drive the smoke plume (south-eastward) toward interior of Alaska. Fig. 1 shows the smoke signature pathways from MODIS visible channel fumigating interior Alaska region. Red points indicate the location of hot spots after processing IR-MODIS channels identifying the source position of smoke production.

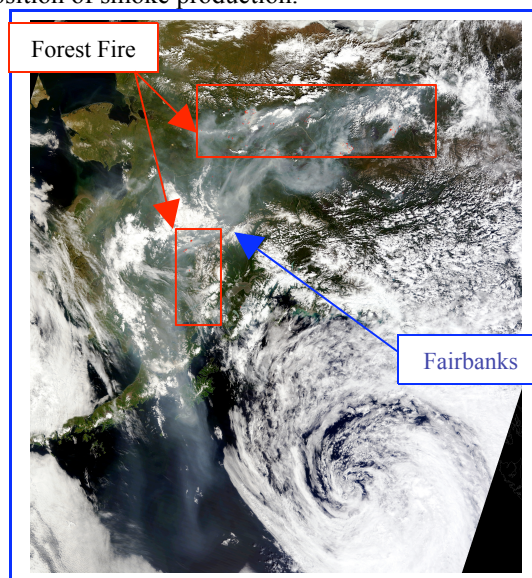


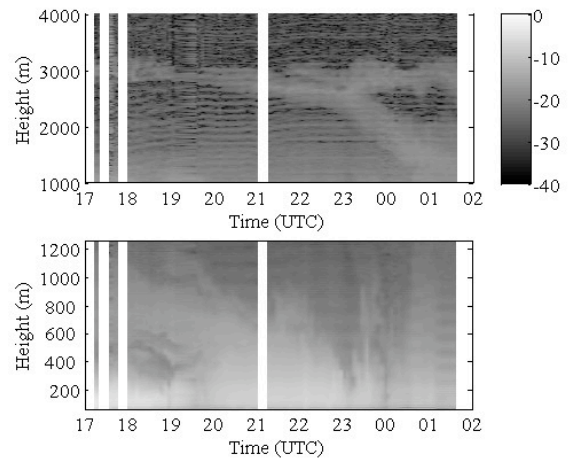
Fig. 1. MODIS satellite image on June 29, 2005 at 18.25 UTC (13:15 AKT). Red labels indicate the geospatial location of the forest fire and in light-white the smoke plume pathways from the North eastern part of Alaska to the interior. Courtesy of GINA –

Geographic Information Network of Alaska, Geophysical Institute, AK.

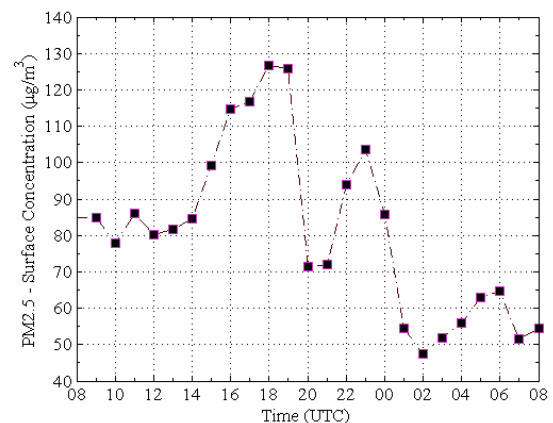
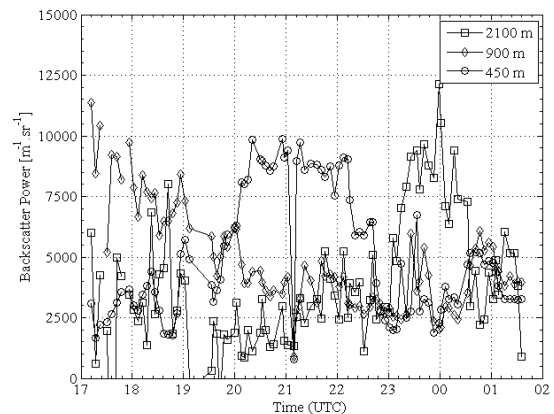
High pressure stagnant the scenario lowering in altitude the smoke plume dispersion. Northeasterly (from the observation site in Fairbanks) winds oriented the plume trajectory toward interior of the state whereas weak intensity wind increase the residence lifetime of aerosols. Moreover the arriving plumes to the observation site, spreads in three main layers as seen in the Lidar backscatter power signature Fig. 2 during June 29, 2005. A low altitude plume, which remain trapped in the Residual Layer, lower than 450 m; a second plume which overlies the ABL during early morning hours located between ~700-1050 m which is mixed-down during the buildup of the diurnal cycle and a third layer propagating in upper levels at ~3 km layer which is observed to subside along the day as results of the high pressure dominant (low shear flow) and is mixed and entrained down in the evening hours complicated by the extended diurnal cycle heating on the Arctic summer. The pressure trends evidence the changes of the synoptic condition at the end of the week whereas a cyclone system becomes dominating the interior region of the Alaska by (July 1 and 2, 2005).

### 3. LIDAR AND SURFACE ANALYSIS

The CESBL is a compact, rugged, solid state laser technology, working at 1.574  $\mu\text{m}$  with an EHF (Eye-Hazard Factor) higher than 200 whereas the operational wavelength is having the lowest attainable molecular backscatter when compares with current Lidars in use [8]. During the haze event the instrument was deployed in the Geophysical Institute, University of Alaska Fairbanks from 28 to 30 June 2005. Collocated surface meteorological instruments and radiation parameters were continuously operating as part of the Alaska Climate Research Center. Fine particulate matter PM<sub>2.5</sub> and carbon monoxide was measured at surface in downtown Fairbanks by the Air Quality Division of the Fairbanks North Star Borough. Lidar profiling was performed with 10 Hz pulse repetition frequency at 1.5 m vertical resolution recording the complete BL diurnal cycle. Raw lidar signal has been de-noised by digital filtering giving a final vertical resolution of 15 m with 5 minutes interval per profile. In Fig.2 overnight, stacked aerosols in the BL settled in the Residual Layer at lower levels (red color below 500 m between 10 - 12 Local Time), elevated aerosol layers outflow BL represented by yellow colored layers between 500 m and 1200 m display low density aerosols. Elevated aerosols layer at 3000 m subsides during the day and are mixed down during uplift convection activity late in the evening.



**Fig. 2.** CESBL backscattering power profiles. Color displays total backscatter power in logarithmic scale. Aerosol layers from forest fires originating in northeastern Alaska are transported in filamentary form at different levels. The time is indicated in UTC (AKT+8).



**Fig. 3.** Backscatter power at 1.574  $\mu\text{m}$  temporal evolution at different height levels (2100, 900 and 450 m) following the evolution of the downward mixing process (upper panel). Surface PM in the 2.5  $\mu\text{m}$  diameter fraction (PM<sub>2.5</sub>) sampler located in downtown Fairbanks during June 29, 2005.

#### 4. DISCUSSION AND SUMMARY

During transition from June 28 to 29 surface fine particulate matter increases from  $\sim 45$  to  $\sim 85 \mu\text{g}/\text{m}^3$  as shown in Fig. 3 lower panel whereas the background level was  $20 \mu\text{g}/\text{cm}^3$  for the period (June 24 to July 4, 2005) not shown here. The dynamic mechanism driving this process is associated with mesoscale overnight transport. Some contribution might be expected from nocturnal settlement (just few hours in the middle of summer). The first peak in the surface particulate matter  $\sim 130 \mu\text{g}/\text{m}^3$  is verified at  $\sim 11$  hrs originated in the morning transition by local flow overturning and downward mixing during the (nocturnal to diurnal transition) [2]. During this case study local flows increase the aerosol concentration while the convective boundary layer drives downward mixing at low entrainment rate below the residual layer generating a slow overloading gradient in lower layers. The second peak at 15 hrs correspond to a “fumigation” process [1,4,5] clearly indicated by more than 2 hrs of high backscattering return values on the 450 m backscatter slice whereas the BL height is above that level for this indicated period of time Fig. 2. Non-local smoke layers propagating filamentary in the outflow-BL intercepts the top of the convective BL and mixed-down after 12 hrs. Vertical dilution, where the top of the CBL entrain free atmosphere air (in this case smoky air), is driving the downward mixing process during this period of time. After more than 2 hrs aerosols from upper layers appears to settle down in the near surface as shown in Fig. 3 (lower panel). These results are in agreement with laboratory tank simulations [1]. Horizontal slices in the backscatter power Fig.3 (upper panel) shows higher backscatter levels at 900 m upper layers than in lower layers (as for example in the 450 m slice) between 9 – 11 hrs LT. When the BL intercepts the smoke layers and start to entrain them, the mixing down process occurs doubling the backscatter power level on the 450 m slice.

Boundary Layer exchange process can lead unhealthy pollution episodes at surface level. The combination of overnight transport and subsidence in lower levels lead severe unhealthy conditions. New conceptual schemes of the ABL dynamics in summer time need to be considered to diagnose with more accuracy the consequences of downward mixing processes under forest fire scenarios.

Despite of the representativity of the BL measurements, limited in theory to the length of the mixed layer in this case 1 km maximum, further studies in urban atmospheres using scanning lidar system will be conducted to assess the tri-dimensional structure of this downward mixing process. The combination of these studies with satellite information for geospatial location of hot spots and their proximity to urban locations as well as aerosols transport information will enable us to improve the AQ forecast.

#### 5. ACKNOWLEDGMENTS

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