

**The Pennsylvania State University**  
**The Graduate School**  
**College of Earth and Mineral Sciences**

**QUANTIFYING FOREST FIRE ENHANCEMENT OF THE FREE  
TROPOSPHERIC OZONE COLUMN DURING THE IONS-04,  
IONS-06, AND ARC-IONS CAMPAIGNS**

A Thesis in  
Meteorology  
by  
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Submitted in Partial Fulfillment  
of the Requirements  
for the Degree of

Master of Science

May 2009

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## ABSTRACT

The Arctic is a beacon of climate change and a haven for pollution from the mid-latitudes and summer boreal fires. Ozonesonde profiles from the Arctic Intensive Ozonesonde Network Study (ARC-IONS) collected from June 26, 2008 to July 12, 2008 at Egbert, ON; Goose Bay, NF; Sable Island, NS; and Yarmouth, NS; were analyzed using a laminar identification (LID) method. The LID method classifies ozone into four different sources: boundary layer ozone, regional convection and lightning generated ozone, stratospherically injected ozone, and aged and advected ozone. The amount of fire-enhanced ozone was refined from the aged and advected ozone term by analyzing maps of MODIS fire hot spots, fire danger maps and approximate smoke plume heights to quantify the amount of forest fire enhanced ozone. In order to build a climatology of fire-generated ozone at these sites, the refined LID method was applied also to the IONS (INTEX (Intercontinental Transport Experiment) Ozonesonde Network Study) 2004 and IONS-06 data sets. The average amount of forest fire enhanced ozone at these four sites during all three campaigns was 5 DU or 12% of the total tropospheric ozone column. During the IONS-04 campaign, forest fires contributed 5 DU to the tropospheric ozone column at all three sites. The least amount of fire-enhanced ozone occurred during the IONS-06 campaign, because most of the fire enhancement was caused by smaller fires in the Midwestern U.S. ARC-IONS had the largest amount of fire influence, ranging from 2 DU at Goose Bay, NF to 7 DU at Sable Island, NS.

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## ACKNOWLEDGMENTS

The data used in this thesis were obtained during the IONS (INTEX (Intercontinental Transport Experiment) Ozonesonde Network Study)-04, IONS-06 and ARC-IONS (Arctic Intensive Ozonesonde Network Study) field campaigns supported by NASA's Tropospheric Chemistry Program through grants NNG06GB18G (IONS 06) and NNX08AJ15G (ARC-IONS). Thanks to program managers J.F. Gleason, B.G. Doddridge, and J.H. Crawford.

I would like to thank Anne Thompson for her thoughtful guidance and support throughout the thesis process. I would also like to thank my committee members Bill Brune and Mike Fromm for their helpful suggestions and input.

This amazing amount of research would not have been possible without support, suggestions and dedication of Stephan Gallagher and Elizabeth Baugher. Thanks also to Greg Garner and David Doughty for the never ending supply of candy, trivia and jokes.

Finally, I would like to extend a huge thank you to Patrick, my family and friends for their support throughout graduate school and the thesis process.



## **Chapter 1. INTRODUCTION**

Dozens of investigations of Arctic haze and forest fire emissions in the North American Arctic and sub-Arctic have taken place over the last two decades. Reports of Arctic haze by aircraft pilots prompted the formation of the Canadian Arctic Air Pollution Program in 1979 and the construction of an aerosol sampling network in 1980 (Barrie et al. 1981). In July 1990 and 1992, the National Aeronautics and Space Administration's (NASA) conducted the Arctic Boundary Layer Expeditions (ABLE, Special Issue: *JGR Atmos.* (1994) 99, D1), which were focused on Arctic haze in the lowest 6 km of the atmosphere across Alaska and Canada (Harriss et al. 1994). The National Science Foundation (NSF) conducted a similar mission in February-May 2000 (Jacob et al. 2007). Several papers (Pfister et al. 2005; Duck et al. 2007; Real et al. 2007) analyze the transport of forest fire emissions from Alaska to different parts of Canada.

The latest studies of North American Arctic haze and fire pollution were National Oceanic & Atmospheric Administration's (NOAA) Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC) mission in Fairbanks, Alaska in April 2008 and the National Aeronautics and Space Administration's (NASA) 2008 Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission during April, June and July of 2008. The goal of ARCTAS was to observe how pollutants from the mid and high-latitudes become trapped in the Arctic region and how boreal fires can influence aerosol and trace gas amounts (Jacob et al. 2007).

The Arctic Intensive Ozonesonde Network Study (ARC-IONS) yielded over 350 profiles in April, June and July of 2008. A complement of ARCTAS, the ARC-IONS

strategic ozonesonde network sites across Canada and the U.S. were selected for their expected proximity to forest fires based on historic Canadian and Alaskan fire climatology. The ARC-IONS campaign (<http://croc.gsfc.nasa.gov/arcions/>) used ozonesondes to identify and source layers of ozone in different regions, such as Asian pollution, regional convection and lightning, and forest fires. The analysis in this paper will quantify the amount of tropospheric ozone enhancement caused by forest fires.

Pfister et al. (2005) assimilated MOPITT CO data into the Model for Ozone and Related Chemical Tracers (MOZART) to conclude that ozone concentrations in the free troposphere can increase by 25% in the vicinity of a forest fire and by 10% if the forest fire pollution is advected into the measurement location. The free troposphere is made up of ozone that originates from regional convection and lightning, stratospheric influence, and recently advected and aged ozone. These three categories, along with boundary layer ozone, comprise the total tropospheric ozone column (TTOC). The tropospheric ozone budgets which quantify the contribution of each ozone source are described in Section 1.1

Section 1.2 discusses in detail the ozone source categories and classification.

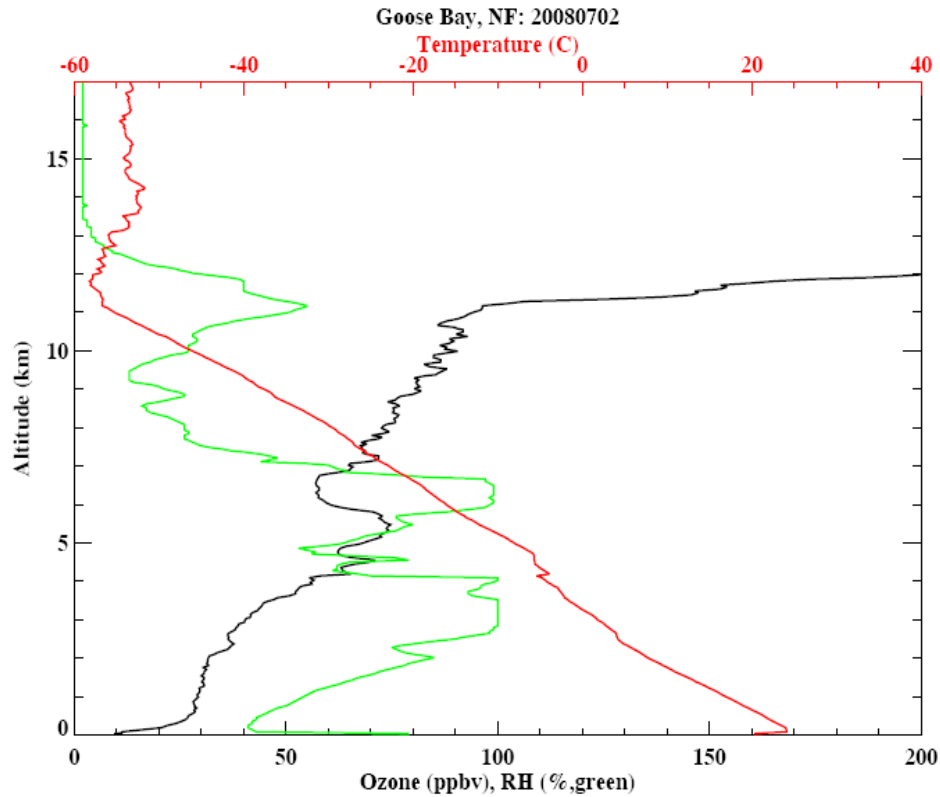
Background information about four ARC-IONS sites are discussed in Section 1.3.

Section 1.4 discusses how forest fires can influence the TTOC.

Chapter 2 describes the data and methods used in this thesis. The results of each objective are explored in Chapter 3. Chapter 4 summarizes the findings and suggests future directions for this research.

## **1.1 Lamina-labeling of Ozone Profiles**

The first step in calculating tropospheric ozone budgets is lamina-labeling, or the classification of ozone layers at different altitudes. A lamina is simply a layer of maximum or minimum ozone concentration that can last a few meters or several kilometers in height. The presence of laminae at high latitude sites in the spring between 15 and 23 km was analyzed by Dobson (1973). Teitelbaum et al. (1996) developed a lamina identification (LID) method to relate atmospheric waves to ozone laminae in the Arctic. Several other studies have confirmed the presence of laminae in the mid-latitudes (Reid and Vaughn (1991), Thompson et al. (2007a, b)) and in the subtropics and tropics (Grant et al. (1998), Loucks (2007), Thompson (2008)) during the summer. Figure 1 illustrates the laminar structure of ozone from a summertime ozonesonde launch over Yarmouth, Nova Scotia on June 30, 2008.



**Figure 1:** Laminar layering of the ozone mixing ratio (black) can be seen in this sample ozonesonde sounding from Goose Bay, NF on July 2, 2008. Most of the ozone profile contains smaller lamina layers, but a larger lamina layer is located between 5 and 6 km.

Pierce and Grant (1998) attributed one set of fluctuations in the ozone mixing ratio to regions of vertical transport by gravity waves and associated a second type of layer with horizontal transport induced by Rossby waves. Gravity waves in the troposphere are generated by frontal systems or topography. The vertical propagation of gravity waves can transport momentum from the lower atmosphere into the middle and upper atmosphere. Rossby waves are generated when a parcel is displaced north or south. The parcel's displacement creates a change in the Coriolis parameter, which generates vorticity and a velocity field. The velocity field farther displaces the parcel,

thus generating Rossby waves (Vallis 2006). Therefore, Rossby waves are associated with horizontal transport, while gravity waves are associated with vertical transport.

Pierce and Grant's (1998) representation of gravity waves and Rossby waves in the atmosphere followed on work by Danielsen et al. (1991) and Teitelbaum et al. (1996). Holton (1987) notes that Rossby wave transport occurs parallel to isentropic surfaces whereas gravity wave transport is often perpendicular to isentropic surfaces. Thus, there is a positive correlation between potential temperature and ozone laminae when a gravity wave is present, but there is no correlation between potential temperature and ozone laminae when a Rossby wave is present. Rossby wave induced laminae are associated with the injection of stratospheric ozone into the troposphere while gravity wave induced laminae are associated with convection that advects ozone from the boundary layer into the free troposphere (Teitelbaum et al. 1996, Stone 2006).

This thesis applies the formalism of using laminar classification to summer ozonesonde data from four Canadian ARC-IONS sites over three campaigns. Section 1.2 describes the categorization and origin of tropospheric ozone.

## **1. 2 Categorization of Tropospheric Ozone**

Thompson et al. (2007a,b) modified the techniques developed by Teitelbaum (1996) and Pierce and Grant (1998) to divide the TTOC into four categories: boundary layer ozone, ozone produced by a mixture of regional convection and lightning, stratospherically injected ozone, and advected or aged ozone. The latter term includes recently imported ozone as well as a typical background amount of ozone of mixed

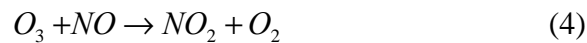
origins that cannot be distinguished without a chemical transport model (Pfister 2008).

These categories are depicted in Figure 2.



**Figure 2:** (Adapted from Yorks et al. 2009) A diagram summary of the four ozone categories that comprise the total tropospheric ozone column. The four categories are stratospheric ozone, regional convection and lightning, recently aged and advected ozone, and boundary layer ozone.

The first category of ozone is boundary layer (BL) ozone, which is ozone located in the lowest 1-2 km. The ozone mixing ratios in the boundary layer are often higher than in other parts of the troposphere because of anthropogenic emissions of  $\text{NO}_x$  ( $\text{NO} + \text{NO}_2$ ) and hydrocarbons (VOCs) (Baird and Cann 2005). Tropospheric ozone is produced by reactions 1-4.



When a photon with a wavelength less than 242 nm collides with a nitrogen dioxide molecule, one of the oxygen atoms breaks apart from the molecule. The lone oxygen atom rapidly bonds with a diatomic oxygen molecule to form ozone as shown in Reaction 2. This reaction is the main stratospheric process that produces ozone. Photons in the troposphere cannot split apart diatomic oxygen atoms because the stratosphere filters out any photons containing the high energy to break the bond (Baird and Cann 2005).

Higher ozone concentrations in the boundary layer result when Reaction 3 creates  $\text{NO}_2$  that increases the  $\text{O}_3$  concentration via the Reactions 1 and 2. Hydrocarbons in the boundary layer can react with the hydroxyl radical and form catalytic radicals that replace  $\text{HO}_2$  in Reaction 3. It is important to note that Reaction 4 is occurring simultaneously, but the amount of ozone destroyed by Reaction 4 is less than the amount of ozone produced in Reactions 1-3. Locations with higher boundary layer ozone concentrations include highly polluted areas with heavy traffic and industrialized areas (Morris et al. 2006). In this study, Sable Island, NS, and Yarmouth, NS, have the largest amounts of boundary layer ozone. These sites have an average boundary layer ozone amount of 5 DU, possibly caused by outflow from major Eastern U.S. cities including Washington, D.C., Philadelphia, PA, and Boston, MA.

The second category of tropospheric ozone is regional convection and lightning (RCL) generated ozone. This middle and upper tropospheric ozone category is attributed to gravity waves as detected by the LID method explained in Section 1.1. Regional convection lifts boundary layer ozone and ozone precursors into the free troposphere. Multiple studies show that NO reaches the free troposphere through convection

(Dickerson 1987) and is also produced by lightning in the middle and upper troposphere (Bond et al. 2001; Zhang et al. 2003; Choi et al. 2005). As shown in Reaction 3, NO must react with HO<sub>2</sub> to form NO<sub>2</sub>, which then forms O<sub>3</sub>. Without lightning, the free troposphere is too NO<sub>x</sub>-poor for ozone production.

Stratospheric (ST) ozone that is injected into the troposphere through the breaking of Rossby waves comprises the third category of tropospheric ozone (Merrill et al. 1996). According to Thompson et al. (2007b), stratospheric ozone made up 20-25% of the TTOC over northeastern North America during the INTEX (Intercontinental Transport Experiment) Ozonesonde Network Study 2004 (IONS-04) campaign.

The final category of tropospheric ozone is recently aged or advected (ADV) ozone. This two-part category is comprised of background ozone and ozone transported into the area by weather systems. ADV ozone is the ozone that remains in the TTOC when the other three categories have been subtracted. This category of unidentified ozone often accounts for 50% of the TTOC value.

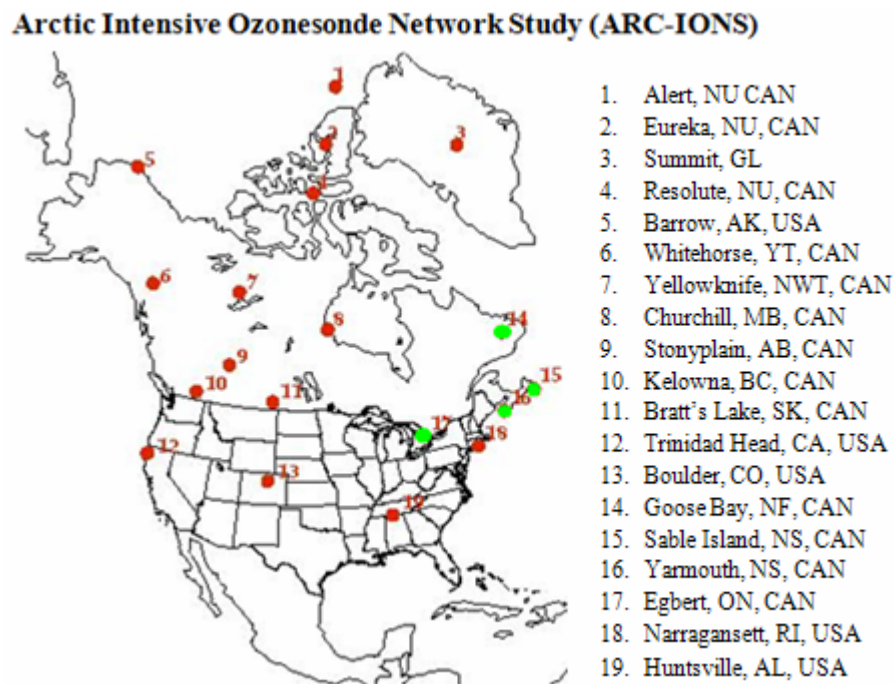
### **1.3 Introduction to Selected ARC-IONS Launch Sites**

The ARC-IONS field campaign in the summer of 2008 launched ozonesondes at 19 sites in North America, Canada and Greenland (Figure 3). Four of these sites will be analyzed in this paper: (17) Egbert, Ontario; (14) Goose Bay, Newfoundland; (15) Sable Island, Nova Scotia; (16) Yarmouth, Nova Scotia. These sites were chosen because of their close geographical locations and similar meteorological conditions (Table 1). All of these sites are operated by Environmental Canada. Egbert, Sable Island and Yarmouth



were also used in the IONS-04 and IONS-06 campaigns (Tarasick and Slater 2007).

Sites closer to the fires were not chosen because they did not participate in IONS-04 and IONS-06 (Thompson et al. 2008). Mean summer (June/July/August) meteorology data for each site is listed in Table 1. The ozone pollution at each of these sites during the 3 campaigns will be explored in Section 3.



**Figure 3:** (Adapted from <http://croc.gsfc.nasa.gov/ARC-IONS/>) Map showing the location of the ARC-IONS launching sites. The four sites featured in this paper are highlighted in green: Egbert, Ontario; Goose Bay, Newfoundland; Sable Island, Nova Scotia, and Yarmouth, Nova Scotia. Map courtesy of Jaquie Witte.

**Table 1:** Station name, location, mean summer (JJA) precipitation, mean summer high temperature, and mean summer low temperature for four ARC-IONS sites. Climatological data provided by Environment Canada (2006).

<b>Station</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Mean JJA Precip.</b>	<b>Mean High Temp. JJA (°C)</b>	<b>Mean Low Temp. JJA (°C)</b>
Egbert, ON	44.2 °N,	-79.8 °W	3.2''	25	12.7
Goose Bay, NF	53.3°N	-60.3 °W	4''	19.2	8.0
Sable Island, Nova Scotia	45 °N	-59.98 °W	4.2''	17.6	12.1
Yarmouth, Nova Scotia	43.9 °N	-66.1 °W	3.3''	19.8	11.5

While the locations of these sites may appear pristine on a map, they are actually downwind of large pollution centers. Egbert and Yarmouth both experience pollution from the Great Lakes and southern Canada. Goose Bay is downwind from the Hudson Bay, the Great Lakes and the Ohio Valley in the United States. On the contrary, Sable Island is located several hundred kilometers from other landmasses, but it receives outflow from the Eastern Seaboard of the United States. The ozone pollution at each of these sites during these three campaigns will be explored in depth in Section 3.

#### **1.4 Forest Fire Influence**

The influence of forest fire emissions on tropospheric ozone column amounts was the focus of the ARC-IONS campaign because of their widespread impact on air quality. In addition to producing their own weather systems and changing aerosol optical depths, forest fires and smoke typically increase the amount of ozone production (Duck et al. 2007, Real et al. 2007; Trentmann et al. 2003). Forest fire plumes can have hemispheric pollution and radiation impacts. Damoah et al. (2004) analyzed a 17-day hemispheric

transport of a Siberian smoke plume in May 2003. The smoke plume traveled eastward across Alaska and Canada before making its way to Europe and Asia.

During the ARC-IONS campaign, there were several fires burning in Canada, most of which were in Manitoba and Saskatchewan. Days with forest fire influence should have a larger ADV term in the ozone budget as well as an overall increase in the TTOC amount. Analyzing back trajectories and maps showing fire locations for each site can indicate whether or not the fires may have influenced the profile.

Quantifying the amount of forest fire influence on the TTOC with a laminar approach is the motivation for this thesis. The investigation focuses on determining forest fire influence for multiple atmospheric heights each day and then recalculating the ozone budgets for each site in order to account for ozone due to forest fires. This analysis was also completed for IONS-04 and IONS-06 data to allow for comparison between the three campaigns. The objective in this section will be explored in depth in Chapter 2.

## **Chapter 2. METHODOLOGY**

The tropospheric ozone profiles collected during ARC-IONS were obtained with electrochemical concentration cell (ECC) ozonesondes and pressure-temperature-humidity (P-T-U) radiosondes. The ozonesondes and radiosondes are attached to a weather balloon and launched into the atmosphere, sometimes reaching as high as 35 km above the surface. Each site was responsible for launching one ozonesonde and radiosonde package daily from June 27 to July 11, 2008, with a launch time corresponding to either 18 UTC or a satellite overpass.

The TTOC budgets, calculated using the LID method introduced in Section 1.1, were analyzed using back trajectories from the NOAA Air Resource Laboratory Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model and Ertel's potential vorticity (EPV). The HYSPLIT model was run using the Global Data Assimilation System version 1 (GDAS-1) dataset for the 2008 data and the FNL meteorological data for the 2004 and 2006 data. EPV was calculated using the Goddard Earth Observing Model version 4 (GOES-4).

This chapter is divided into two sections. The first section is an in-depth discussion of tropospheric ozone budgets, while Section 2.2 describes the analysis of forest fire influence on the ozonesonde profiles.

### **2.1 Tropospheric Ozone Budgets**

Tropospheric ozone budgets were calculated using the LID method described in Section 1.1. As previously stated, the ozone laminae in the vertical profile are

normalized to identify correlations between ozone and potential temperature as either Rossby wave influence (RW) or gravity wave influence (GW), as per the method described in Pierce and Grant (1998). First, linear interpolation is used to calculate a high resolution profile for each sounding. Next, a mean vertical ozone profile for each launch is created by using a 2.5 km moving average to smooth the profile. Then, the mean vertical profile is subtracted from the high-resolution profile. Finally, the normalized perturbation mixing ratio is determined by dividing this difference by the mean profile (Loucks 2007). This procedure is repeated to construct a normalized potential temperature profile for each sounding. The normalized potential temperature profile is then multiplied by a scale factor,  $R(z)$ , to yield the mean perturbation potential temperature profile.

$$R(z) = \left( \frac{1}{O_3} \frac{\partial O_3}{\partial z} \right) \cdot \left( \frac{1}{\theta} \frac{\partial \theta}{\partial z} \right)^{-1} \quad (1)$$

where  $O_3$  is the mean ozone concentration, and  $\theta$  is the mean potential temperature at some altitude  $z$ .

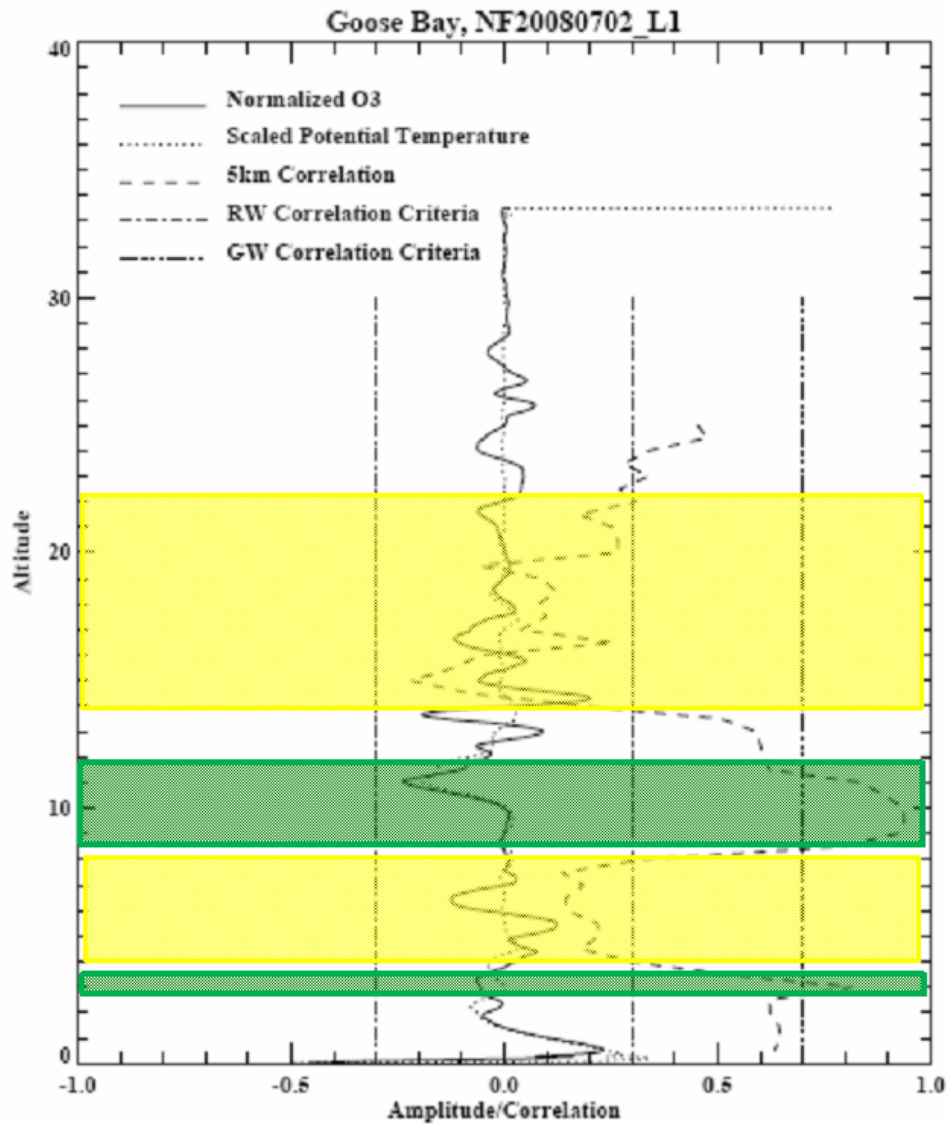
The scaled normal potential temperature profile is found using

$$\Theta_z(z) = R(z) * \Theta_n(z) \quad (2)$$

where  $\theta_n$  is the normalized potential temperature profile.

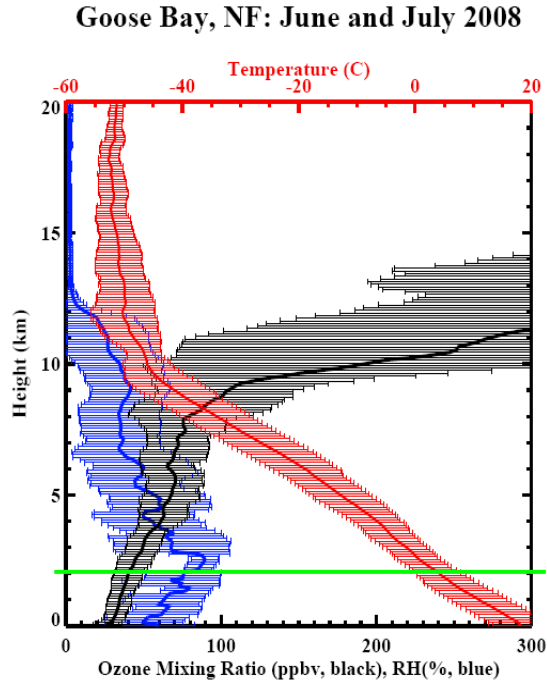
Once the normalized ozone profile and the scaled perturbation potential temperature profile are calculated, the correlation between the two profiles is determined every 0.1 km for 5 km intervals. As mentioned in Section 1.1, this correlation is used to determine RW and GW influence. Correlations between -0.3 to 0.3 are classified as RW influence, while correlations greater than 0.7 are classified as GW influence (Pierce and

Grant 1998, Thompson 2007a,b). Any ozone that is not due to GW influence or RW influence is classified as “other” ozone. The cutoffs for GW influenced ozone and RW influenced ozone are depicted in Figure 4.



**Figure 4:** An example of a perturbation sounding from Yarmouth, Nova Scotia on July 2, 2008. The ozone laminae correlation (dashed line) between normalized ozone mixing ratio (solid) and scaled potential temperature (dotted) shows Rossby wave influence (yellow) between 4 and 8 km, and again between 14 and 22 km and gravity wave influence (green) between 2.5 and 3 km and again between 9 and 12 km.

The variability of tropospheric ozone budgets can then be calculated using the Pierce-Teitelbaum (PT) method as described in Thompson et al. (2007a,b). As described in Section 1.2, the ozone profile can be divided into two regions: the boundary layer (BL) and the free troposphere (FT). BL ozone is the ozone that exists between the surface and the planetary boundary layer (PBL). The PBL height for each of the four sites was determined using the mean profile for each summer. The PBL was placed at the location of a temperature inversion and where the ozone profile at the surface conformed to the ozone profile of the free troposphere as shown in Figure 5. The tropopause is placed where the largest ozone gradient in each profile occurred between 5 km and 20 km and where the ozone is less than 170 ppbv (Dougherty 2008). These conditions ensure that the tropopause placement is reasonable for the profile, even if a sharp ozone gradient does not exist in the profile.



**Figure 5:** The mean profile for Goose Bay, NF during ARC-IONS. The solid line represents the mean profile, while the error bars represent one standard deviation from the mean profile. The green line marks the temperature inversion and signifies the PBL height (2.2 km) that was used for this study.

As described in Section 1.2, the RW and GW classifications are used to divide the troposphere into four categories: (1) boundary layer (BL) ozone, (2) regional convection and lightning generated (RCL) ozone, (3) stratospherically injected (ST) ozone, and (4) recently aged or advected (ADV) ozone. Boundary layer ozone is any ozone that is below a certain height. For this study, the top of the boundary layer was estimated from the temperature inversion on a mean profile plot for a particular site during a specific campaign. As reported by Thompson et al (2007a), the high correlation between gravity wave layers and RCL ozone leads to the classification of all GW laminae as RCL. RW laminae can be classified as either ST ozone or ADV ozone. To determine the ozone's origin, each layer of RW laminae is analyzed using relative humidity profiles, EPV plots and HYSPLIT back trajectories. If low relative humidity exists in a layer of high ozone



concentrations where the back trajectories pass through a region of high EPV, the laminae is classified as ST ozone. This term, along with the BL and RCL terms are subtracted from the TTOC to produce ADV ozone.

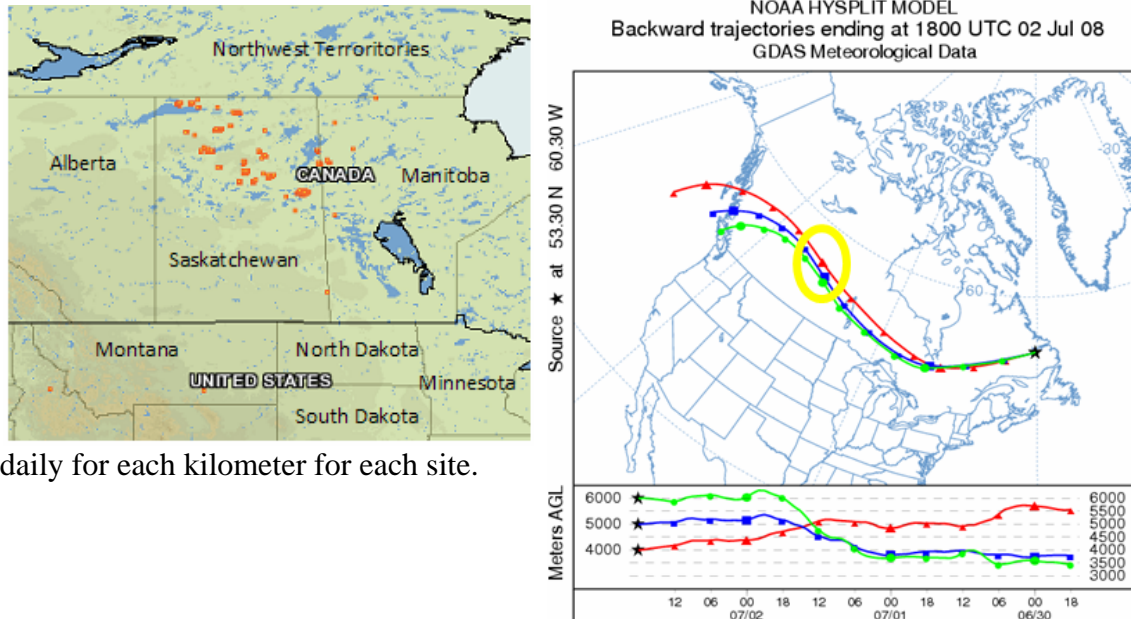
Ozone budgets were calculated for each ozonesonde launch during the IONS-04, IONS-06 and ARC-IONS campaigns for each of the four sites to show daily trends and averaged to show seasonal trends. An in-depth analysis of seasonal TTOC trends will be explored in Chapter 3.

## **2.2 Determining Forest Fire Influence on the Ozonesonde Profile**

The goal of the summer ARC-IONS campaign was to investigate forest fire influence on the TTOC, as stated in Section 1.4. This analysis was completed by using HYSPLIT back trajectories and the University of Maryland's Fire Information for Resource Management System (FIRMS) Web Fire Mapper. It is important to note that changes in BL ozone were not analyzed because previous studies have shown that forest fire plumes are more likely to be transported longer distances in the free troposphere (Real et al. 2007, Tang et al. 2003).

HYSPLIT back trajectories, dating back 72 hours, were calculated for 1 km levels from the surface up to the tropopause for each ozonesonde launch. Seventy-two hour back trajectories were used because this time period was used in the original TTOC budgets to calculate ST ozone. The tropopause height was calculated in the LID budgets described in Section 2.1. The back trajectories were then compared to FIRMS fire maps. FIRMS uses a web-based Geographical Information Systems (GIS) program to plot the

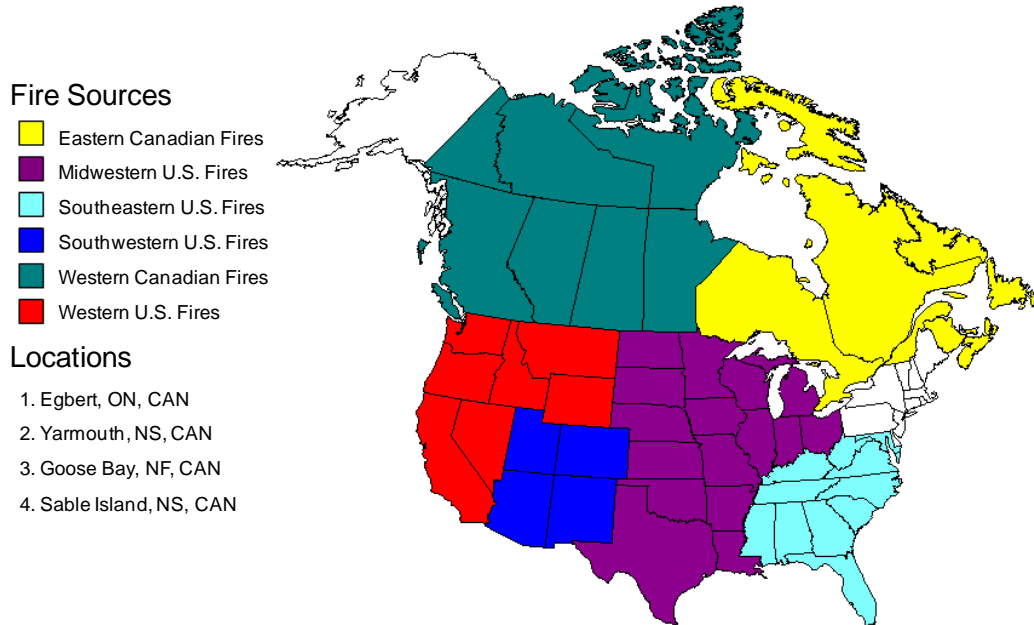
MODIS rapid response detected forest fire hot spots. An example of this method is shown in Figure 6. The number of trajectories passing over MODIS hot spots and the location of these hotspots were recorded



daily for each kilometer for each site.

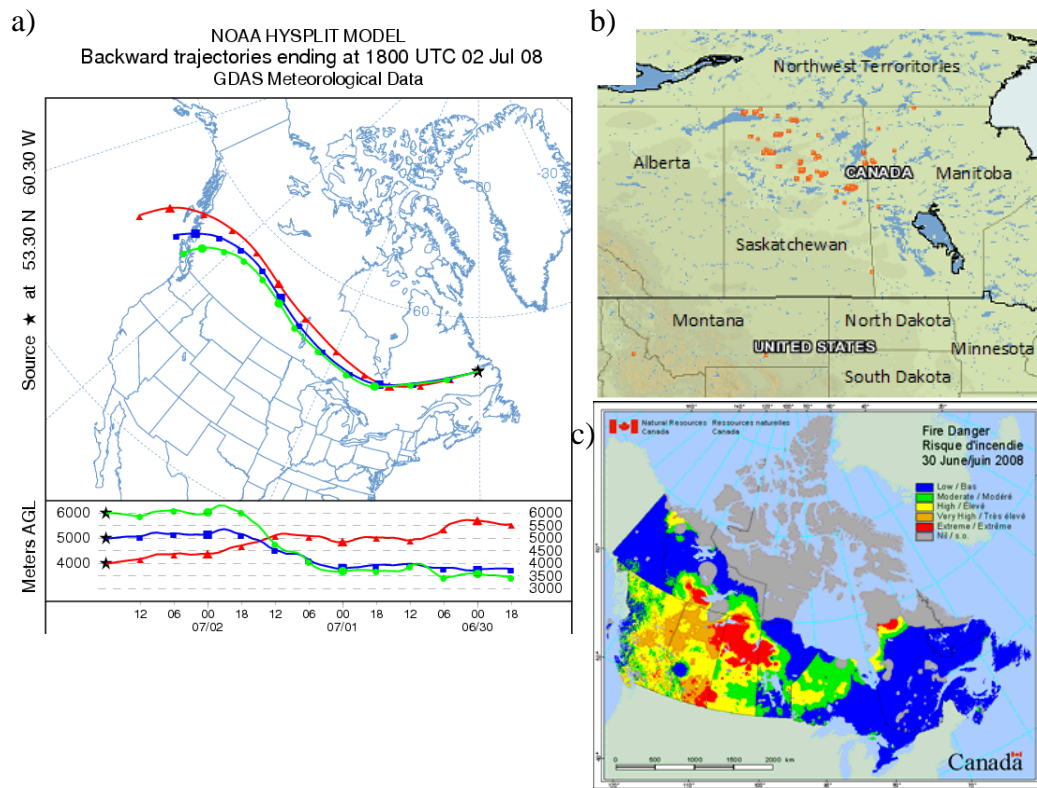
**Figure 6:** An example of how forest fire influence on the TTOC is detected using FIRMS maps (left) and HYSPLIT back trajectories (right). On July 2, 2008 at Goose Bay, NF, the 4, 5, and 6 km back trajectories all pass over fires in Saskatchewan. The fire identification method deduces that there is forest fire influence in the 4, 5, and 6 km levels for this day.

The fire information was used to classify the fire sources into six geographically-based groups: Western U.S., Southwestern U.S., Midwestern U.S., Southeastern U.S., Western Canada, and Eastern Canada. The boundaries for each region are arbitrarily defined. Figure 7 shows the exact locations of these regions as they are defined for this analysis. The fire region analysis was used to determine which region was most likely to influence each location.



**Figure 7:** A map showing the six regional classifications for forest fires. This map was created by Stephan Gallagher.

A vertical altitude maximum of forest fire influence for each day was also determined in an effort to refine the ozone enhancement amounts. Smoke plume height was estimated by comparing fire danger maps and FIRMS maps. Fire danger maps use a relative index to depict the ease of igniting a fire, difficulty of the fire to control, and the amount of damage it can cause. Figure 8 shows an example of this analysis.



**Figure 8:** An example of a (c) fire danger map (c) for Canada on June 30, 2008. The comparison between (b) the HYSPLIT back trajectories, (b) the FIRMS fire map and this image shows that the forest fires in Saskatchewan are located within the extreme (red) region. Using the plume height values in Table 2, it would be assumed that any back trajectory passing over these fires on this day would have ozone enhancement.

The link between the scales used by both the Canadian Wildland Fire Information System and the United State Forest Service and the expected smoke plume height was used to estimate the maximum forest fire plume height. This relationship is shown in Table 2.

**Table 2:** A list of expected smoke plume heights for a fire danger rating. The upper limits of the plume height values were used for both U.S. and Canadian fire maximum influence levels (Amber Soja, personal communication).

<b>Fire Danger Level</b>	<b>Expected Fire Type</b>	<b>Expected Plume Height</b>
Low	Surface Fire	1 – 2 km
Moderate	Surface Fire	0.3 – 6 km
High	Intermittent Crown Involvement	5 – 7 km
Very High	Full Crown Involvement	7 – 9 km
Extreme	High-Intensity Crown Fire	> 9 km

The LID budgets were then recalculated for each 1 km layer for each of the 4 sites. Unlike the prior LID budgets, the ADV ozone in any layer in which the back trajectory passed over a fire at a plausible height was assumed to be fire-generated ozone. Plausible heights were determined using the fire danger maps to calculate the top of the smoke plume (Table 2). The new fire term allows for further refinement of the ADV term.

Because the LID budgets were recalculated for each 1 km layer, the ST ozone column amounts may have changed. In previous LID budget calculations, the ST ozone amounts in the column were calculated by multiplying the RW-induced ozone by a fraction. This fraction was computed by analyzing RW ozone with concentrations greater than 75 ppb, low relative humidity values, and back trajectories that passed through regions of high EPV. The fractions for each layer of RW influence were then averaged to compute a daily fraction. The daily fraction was then used to evaluate ST ozone. The LID budgets that calculate a forest fire ozone term do not use an average fraction to calculate ST ozone. Instead, they use a fraction for each layer to determine the ST ozone within that layer.

After the budgets have been calculated for each layer, the ozone values for each layer are added together to create daily ozone amounts. LID budgets that are refined for fire-enhanced ozone are referred to as “Tropospheric Ozone with Fires” budgets. The final LID budgets that account for the height of the fire plume are referred to as “Height-Adjusted” budgets. The results from this analysis are discussed in Section 3.1.

## **Chapter 3. RESULTS AND DISCUSSION**

This chapter is divided into two sections. Section 3.1 explores the impact of forest fire location on the resultant ozone enhancement at each site. Section 3.2 discusses the fire ozone term in the TTOC budgets. Unless otherwise stated, only the height-adjusted ozone budgets will be discussed.

### **3.1 Impact of Forest Fire Location**

As stated in Section 2.2, the fires were divided into 6 regions based on their geographical location. The smoke plume height analysis revealed that each region's fires reached different heights. For example, it was rare for a smoke plume in the Midwestern U.S. to reach a height above 6 km, while smoke plumes from Western U.S. fires often reached 7- 9 km above the surface.

The amounts of ozone enhancement due to the fires in each region are listed in Tables 3 and 4. The positive values represent the original ozone amount in that category as higher than the refined values. The negative values indicate that the refined budgets have a larger ozone amount in that category than the original budget had for the same category.

Changes in ST ozone from the original budgets to the height-adjusted budgets were caused by the fraction recalculation explained in Section 2.2. The ST ozone amounts in the original budgets were an upper limit, while the height-adjusted budgets calculate a lower limit of ST ozone. Any ST ozone in the original budget that is not categorized as ST ozone in the height-adjusted budgets became ADV ozone. Thus,

changes in the ST ozone amount led to an increase in the ADV ozone amount prior to refinement of the ADV ozone for fire ozone. As a result, changes in the ST and ADV ozone are discussed.

**Table 3:** The amount of ADV ozone change (DU) for each forest fire location. The values are averaged for all 3 campaigns, with the exception of Goose Bay, which participated in only the 2008 ARC-IONS campaign. The average values have been rounded to the nearest whole number.

Location	Western Canada	Western U.S.	Southwestern U.S.	Midwestern U.S.	Southeastern U.S.	Eastern Canada
Egbert	2	4	0	5	0	5
Goose Bay	6	9	0	5	0	0
Sable Island	-2	6	18	4	4	1
Yarmouth	0	-3	-2	-3	2	9
<b>AVERAGE</b>	<b>1</b>	<b>4</b>	<b>4</b>	<b>3</b>	<b>1</b>	<b>6</b>

**Table 4:** The amount of ST ozone change (DU) for each forest fire location. The values are averaged for all 3 campaigns, with the exception of Goose Bay, which participated in only the 2008 ARC-IONS campaign. The average values have been rounded to the nearest whole number.

Location	Western Canada	Western U.S.	Southwestern U.S.	Midwestern U.S.	Southeastern U.S.	Eastern Canada
Egbert	4	4	0	11	0	5
Goose Bay	2	0	0	0	0	8
Sable Island	12	7	0	7	4	8
Yarmouth	5	5	3	7	1	-1
<b>AVERAGE</b>	<b>6</b>	<b>4</b>	<b>0</b>	<b>6</b>	<b>1</b>	<b>5</b>

Overall, the ST ozone change is larger than the ADV ozone change. This was unexpected because only the ADV ozone was recategorized as fire ozone. The ST ozone was only modified because this analysis assigned fractions by layer, not as a continuous value for each day. This method suggests that using one fraction to represent ST influence for an entire day may over-predict the amount of ST ozone.



Adding the values from Tables 3 and 4, the amount of fire induced ozone change in the TTOC can be calculated. The amount of ozone change varies by fire location and ozonesonde launching site. The largest average amount of ozone change occurred when the ozonesonde launching sites were influenced by Eastern Canadian fires. This large ozone increase was mainly due to the proximity of the fire relative to the ozonesonde launching site.

The largest overall site enhancement occurred at Sable Island in 2008 from fires in the Southeastern U.S. Sable Island had the largest number of back trajectories that passed over this region. Yarmouth in 2008 also had a large amount of fire influence from fires in the Southeastern U.S. Most of the fire-influenced back trajectories in the Southeastern U.S. occurred on days when the smoke plumes reached heights of 5 – 7 km. The Southeastern U.S. had the smallest overall average amount of ozone enhancement.

The large values of ozone enhancement from Western Canadian and Western U.S. fires occurred primarily because of the heights of the fire plumes. Fires in the Western U.S. and Western Canada often reached 9 km, thus causing forest fire influence at many different altitudes. As a result, the fire influence in these regions led to a combined ST and ADV average change of  $8 \pm 3$  DU in the Western U.S. and  $7 \pm 2$  DU in Western Canada.

The smallest amount of ozone enhancement due to forest fires occurred when back trajectories passed over forest fires in the Southwestern U.S. Very few back trajectories passed over this region and very few fires occurred in this region. The fires in this region generated smoke plumes that reached heights of at least 9 km, with several

smoke plumes reaching the tropopause. Unfortunately, the small number of occurrences may be responsible for the relatively small fire enhancement in this region. As will be discussed in Section 3.2, only Sable Island and Yarmouth had fire influence from this region.

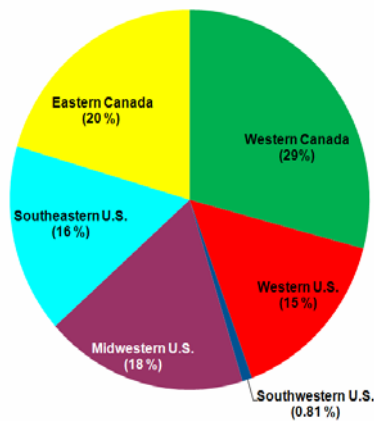
The summertime flow patterns on the Eastern Seaboard of the U.S. may be partly responsible for the amount of Southeastern U.S. fire influence at Sable Island and Yarmouth in 2008. The back trajectories for this period start over the Southeast U.S., move to the Atlantic coast, and then curve up towards Nova Scotia. The flow pattern most commonly observed is that associated with the Bermuda high. This pressure system brings air from the southeastern U.S. into the Northeastern U.S. during the summertime. The dominant flow pattern may explain why the Southeastern U.S. fire influence is almost absent from the Egbert and Goose Bay analysis, but dominates at Sable Island and Yarmouth during 2008.

In the Midwestern U.S., fire plumes only reached heights of 5 – 7 km, but led to a combined ST and ADV ozone increase of  $9 \pm 2$  DU. This is a peculiar result because small fires caused a large amount of ozone enhancement. Unlike the other fire regions, this region influenced all 4 launching sites during the 3 campaigns. Some of these fires, such as those in Michigan and Ohio, occurred close to Egbert, which may account for the large ozone increase at that site.

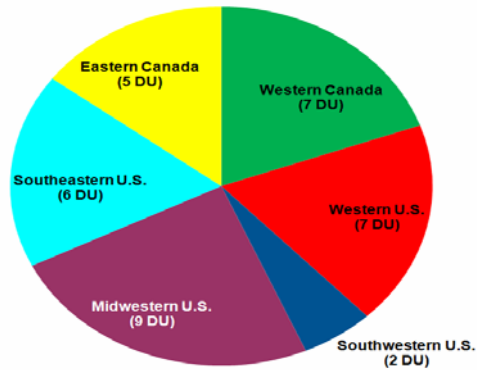
In order to put the numbers in Tables 3 and 4 into perspective, the number of back trajectories that passed over each of these fire regions needs to be considered. Figure 9 illustrates the percentage of back trajectories that passed over each region as well as the

average amount of ozone enhancement in each region. The percentages were calculated by dividing the number of occurrences in which a back trajectory passed over a fire by the number of possible combinations. The number of possible combinations was calculated by multiplying the total number of trajectories for a particular site during a campaign by the six classification regions. The percentages in Figure 9 are relative to the number of back trajectories that passed over a fire, not the total number of back trajectories.

Back Trajectory Analysis for Heights with Fire Influence



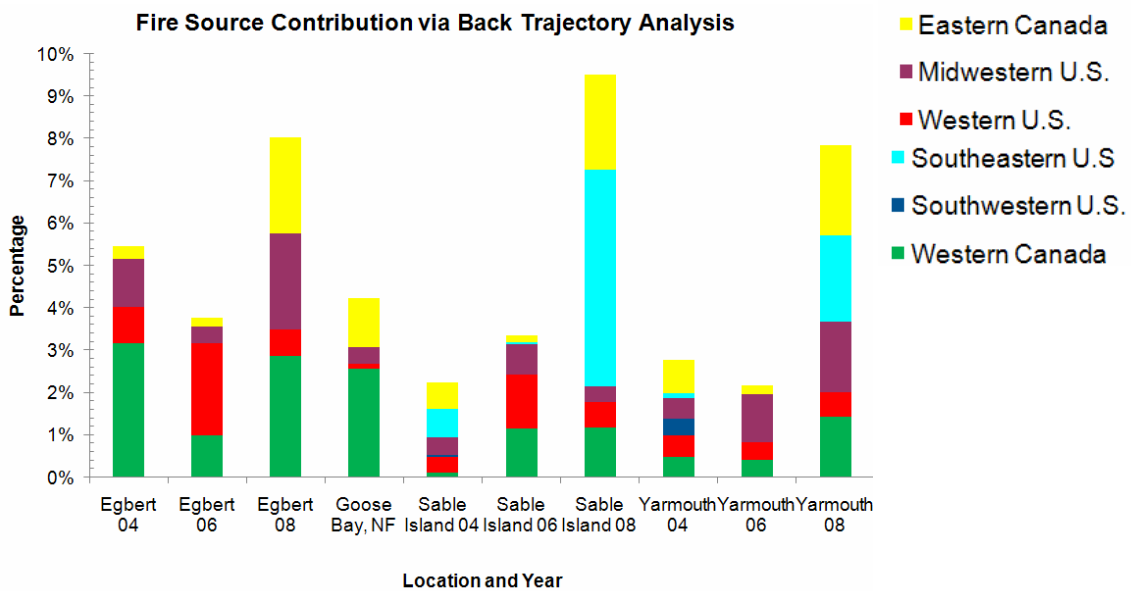
Average Amount of Ozone Contributed by Fire Source



**Figure 9:** Source apportionment based on back trajectory analysis for heights that were influenced by forest fires (left) and the amount of ozone that forest fires contributed to the TTOC (right).

The number of back trajectories that passed over each area and the average ozone enhancement for each region had an integral part in determining the fire budgets. This analysis revealed that 29% of the back trajectories with fire influence passed over fires in Western Canada. Each day a fire passed over this region, the TTOC had an average increase of  $7 \pm 2$  DU. On the contrary, fires in Eastern Canada contributed  $5 \pm 2$  DU of fire ozone, yet 20% of the back trajectories with fire influence passed over this region.

The fire influence not only varied by the amount of enhancement over all three campaigns, but it also varied by fire location. Figure 10 displays the percentage of back trajectories that passed over each fire region during all three campaigns for each site. The percentages were calculated using the same method as Figure 9, except Figure 10 shows the percentages at the amount relative to the total number of back trajectories, not relative to number of fire-influenced back trajectories.



**Figure 10:** Source apportionment based on a back trajectory analysis illustrating which fire regions had the most influence on each site.

Figure 10 illustrates the small amount of back trajectories that were influenced by fires at each location. Less than 10% of the back trajectories passed over each fire region, and most sites had less than 6% of the back trajectories with fire influence.

Forest fires in the Western U.S., Midwestern U.S. and Eastern Canada influenced all four sites each year, while the influence from the other three regions varied greatly.

Fires in the Southwestern U.S only influenced Sable Island and Yarmouth in 2004.

Sable Island and Yarmouth were also the only sites that had fire influence from the Southeastern U.S.

The fires in Western Canada were the largest in size and number during the IONS-04 campaign. During this time, the fires were responsible for 6 fire enhancement events at each site. Each fire event contributed an average of  $6 \pm 1$  DU to the TTOC. While this amount may seem insignificant, these fires were responsible for 58% of the fire enhancement events at Egbert, 5% of the fire enhancement events at Sable Island and 18% of the fire enhancement events at Yarmouth. The fire influence from Western Canadian fires was greatly reduced during the IONS-06 and ARC-IONS campaigns. IONS-06 was not focused on forest fire influences. Reasons for the reduced amount of impact will be discussed in Section 3.2. While the largest fires during the ARC-IONS campaign were burning in Saskatchewan and Manitoba, there were also a few fires burning in Alaska, the Yukon and Northwest Territories. Fire fighting resources are not used to control fires in remote regions of Canada, allowing them to grow unrestricted and generate more ozone enhancement than controlled fires.

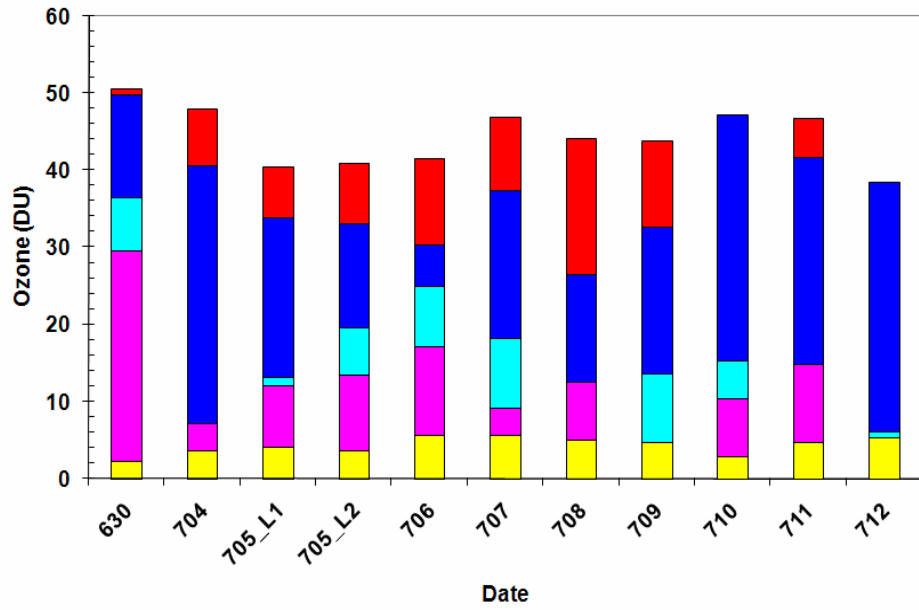
### **3.2 Quantifying Forest Fire Influence**

The methodology used to calculate the forest fire influence at a particular ozonesonde launching site was discussed in Section 2.2. The analysis was completed twice: once to get an upper limit of forest fire influence and a second time to refine the ozone enhancement to the maximum height of the fire plumes.

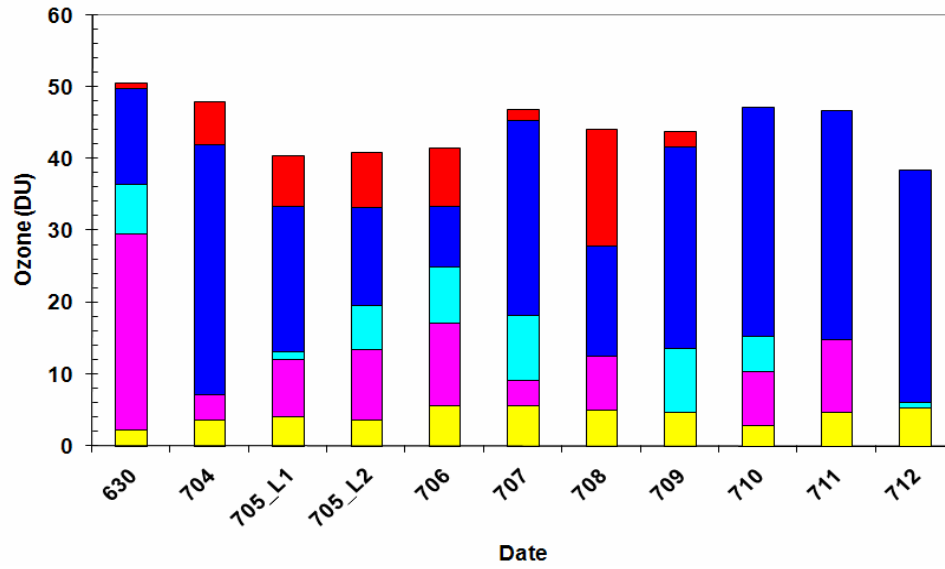
The upper limit of forest fire influence was calculated to be an average of 10 DU or 23% of the TTOC at all four sites for the three campaigns. The smoke plume height-adjusted budgets lowered the average amount of fire ozone in the TTOC to  $5 \pm 1$  DU or 12% of the TTOC during the same period. Any fire ozone in the upper limit budget which occurred at an altitude higher than the top of the smoke plume was reclassified as ADV ozone. Thus, the BL, RCL and ST ozone amounts are constant between the two budgets.

Figure 11 displays both the upper limit and the height-adjusted ozone budgets for Egbert, Goose Bay, Sable Island and Yarmouth during the 2008 ARC-IONS campaign. The same images from the IONS-04 and IONS-06 data can be viewed in the Appendix.

a) Tropospheric Ozone with Fires: Egbert, ON 2008

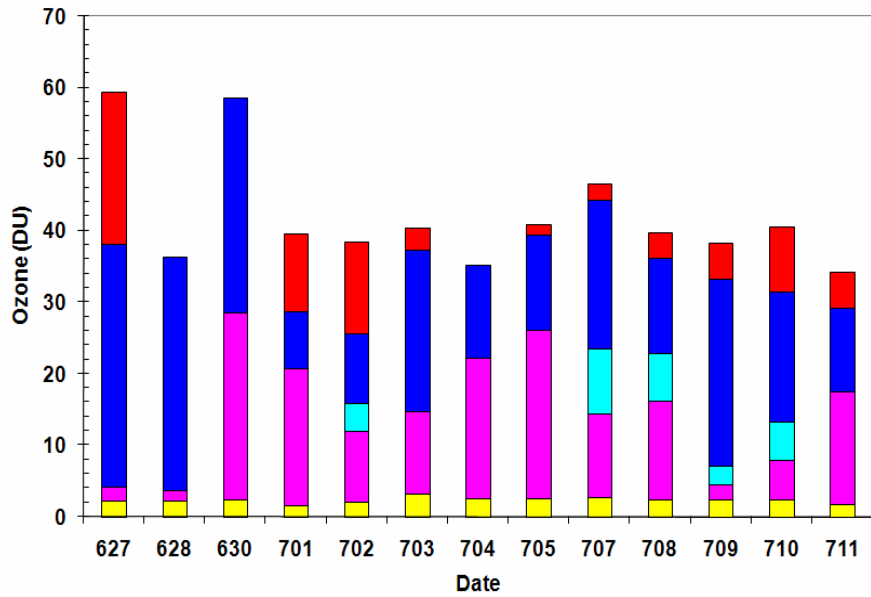


b) Tropospheric Ozone with Height-Adjusted Fires: Egbert, ON 2008

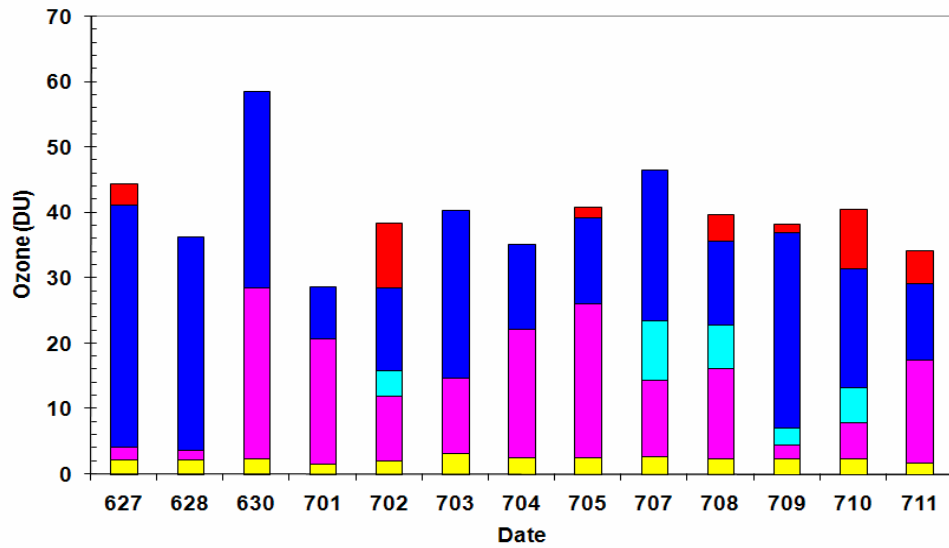


■ BL ■ RCL ■ ST ■ ADV ■ Fire

c) Tropospheric Ozone with Fires: Goose Bay, NF 2008



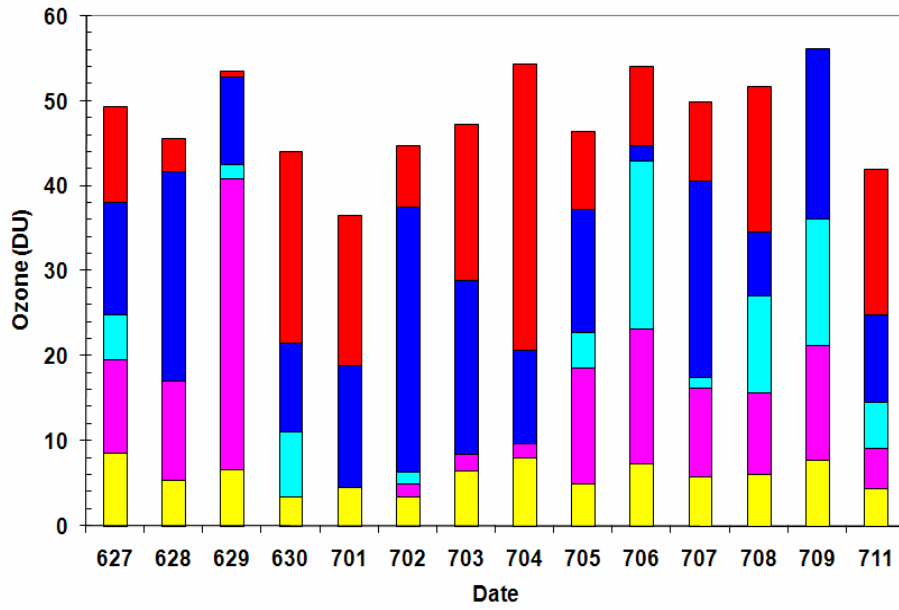
d) Tropospheric Ozone with Height-Adjusted Fires: Goose Bay, NF 2008



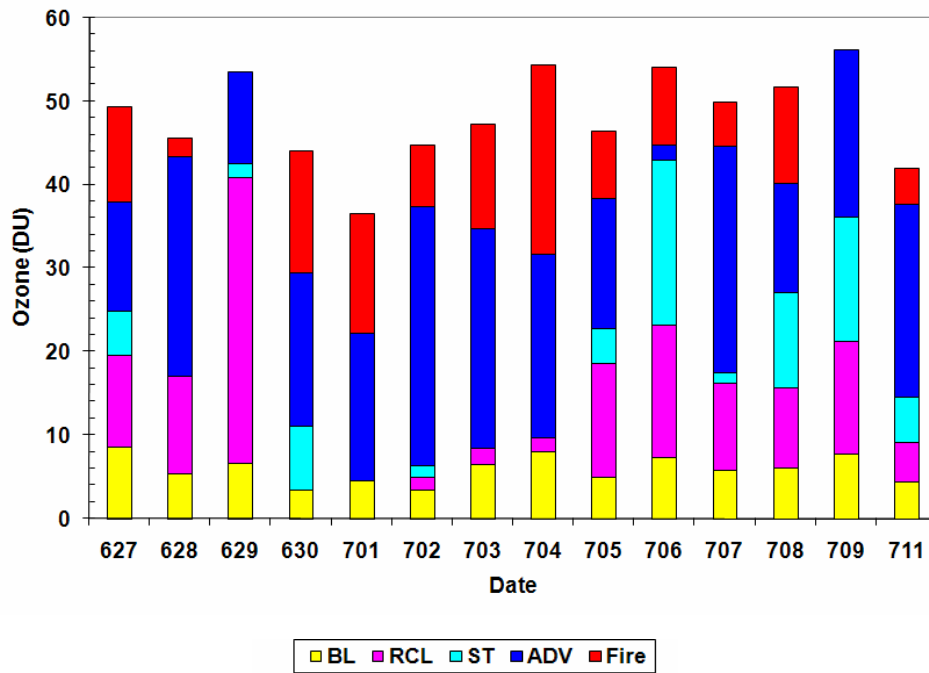
BL RCL ST ADV Fire

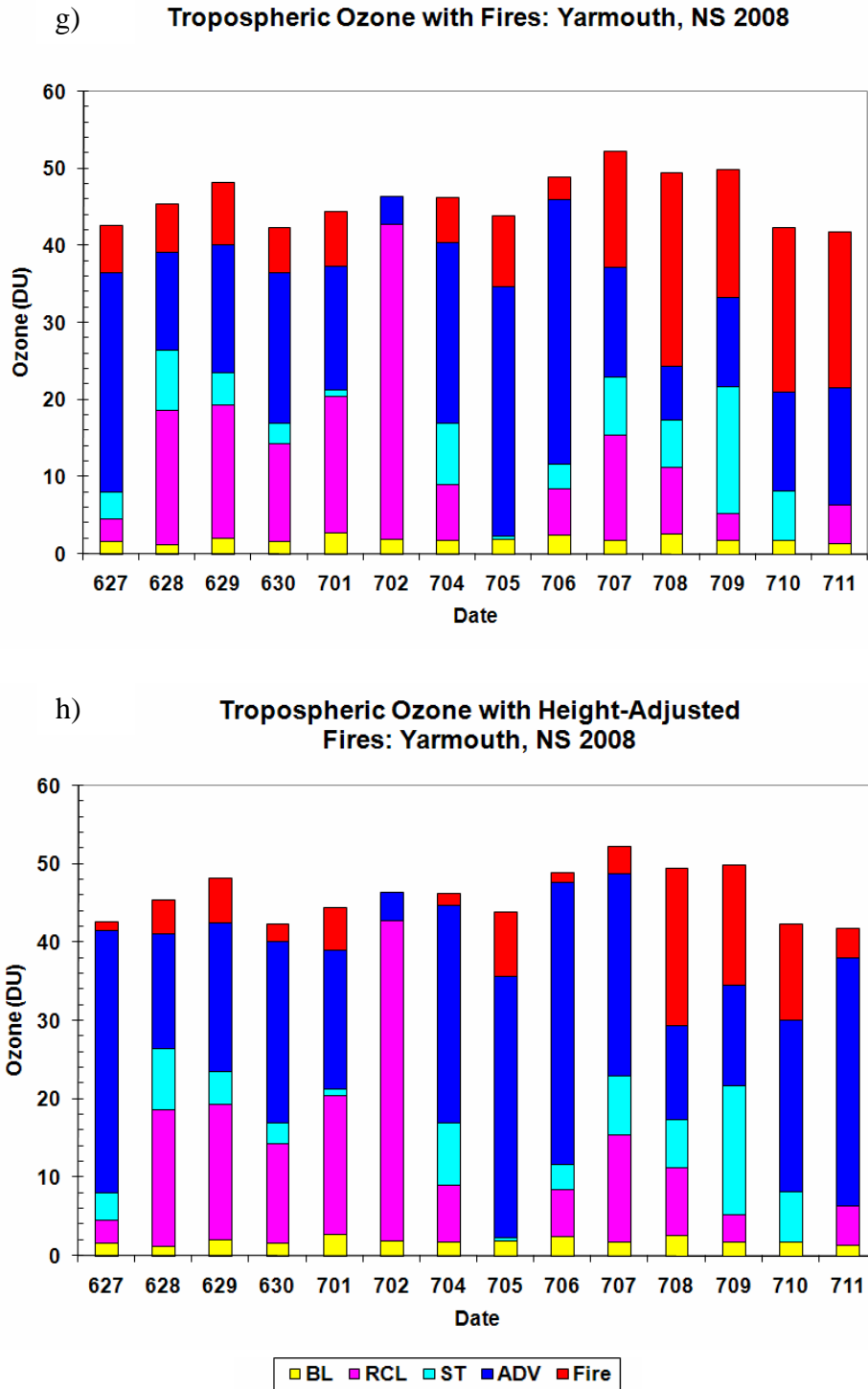


e) Tropospheric Ozone with Fires: Sable Island, NS 2008



f) Tropospheric Ozone with Height-Adjusted Fires: Sable Island, NS 2008





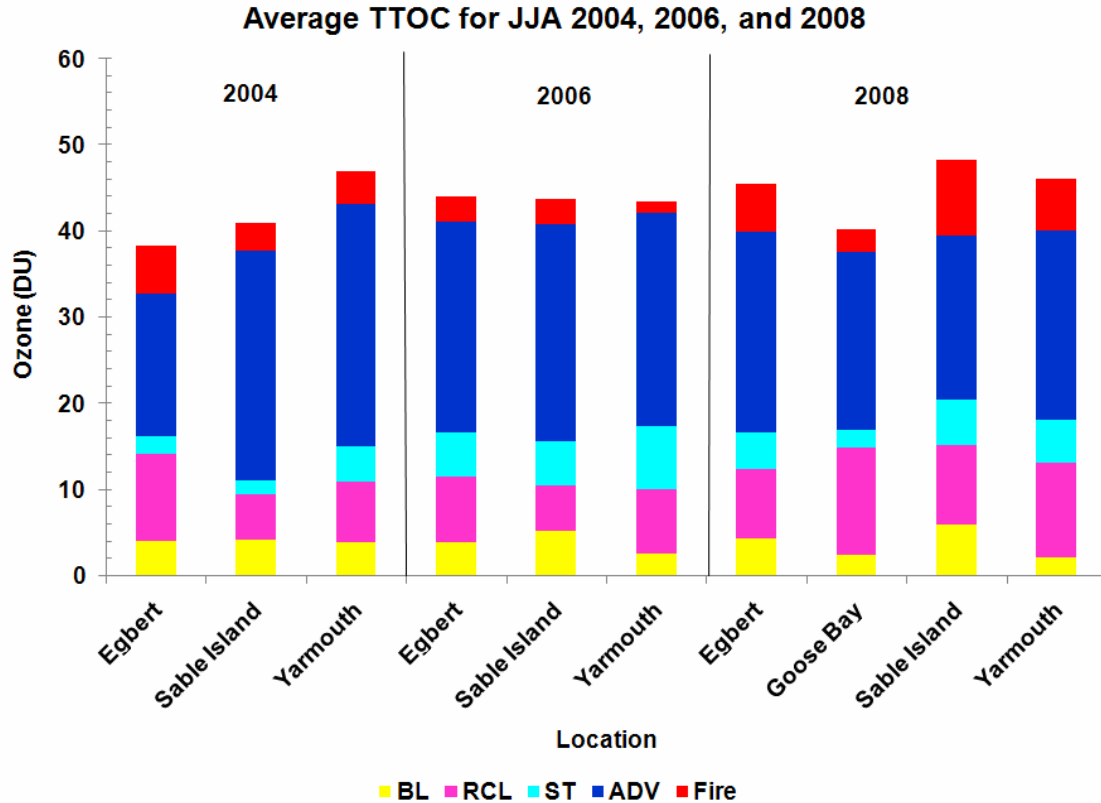
**Figure 11:** Tropospheric ozone budgets for (a,b) Egbert, (c,d) Goose Bay, (e, f) Sable Island and (g,h) Yarmouth 2008 ARC-IONS campaign are shown for both the upper limit of ozone enhancement (top) and the height-adjusted enhancement (bottom). The amount of forest fire influence is shown in red.

To better compare the fire terms, Table 5 lists the fire ozone contribution at each site during each campaign, for both the upper limit budgets and the height-adjusted budgets. After Table 5, only height-adjusted budgets will be discussed.

**Table 5:** A table showing the original and refined fire ozone amounts at each location. The amount of fire ozone decreased by more than 20% at each location when the fire influence was adjusted to the height of the smoke plume.

Location	Year	Original Fire Ozone (DU)	Adjusted Fire Ozone (DU)	Original –Adjusted (DU)
Egbert	2004	8	6	2
Egbert	2006	4	3	1
Egbert	2008	8	5	3
Goose Bay	2008	6	3	3
Sable Island	2004	6	5	1
Sable Island	2006	6	3	3
Sable Island	2008	13	7	6
Yarmouth	2004	10	4	6
Yarmouth	2006	6	1	5
Yarmouth	2008	11	6	5

Fire ozone was not the only term to change in the average ozone budgets between the campaigns. Yarmouth’s 2004 TTOC budgets contain several ST events, while the Yarmouth 2008 budgets have a larger RCL term. Egbert’s 2006 ozone budget has less RCL ozone than the 2004 and 2008 ozone budgets. Sable Island’s TTOC amount increased from 2004 to 2006, but the ADV ozone did not change. In order to observe these yearly trends in more detail, average ozone budgets were generated. Figure 12 displays the average height-adjusted fire budgets for each of the sites during 2004, 2006, and 2008.



**Figure 12:** Average height-adjusted TTOC values for Egbert, Goose Bay, Sable Island and Yarmouth during the IONS-04, IONS-06, and ARC-IONS Campaigns.

Even though forest fire influence on the TTOC was not the primary focus of the IONS-04 campaign, the fires in Alaska and Northwestern Canada caused an average ozone enhancement of 5 DU. The size and prolonged burning period of these fires proved to have a wide-spread influence on North American air quality. Sable Island and Yarmouth had minimal influence from the Western Canadian fires.

Egbert experienced an average fire influence of 6 DU during the IONS-04 campaign, mostly caused by fires in Western Canada. As previously stated, most of the fires during this campaign period were located in the Yukon and Northwest Territories in Western Canada. These fires reached heights of 9 km almost daily, causing ozone enhancement at most altitudes every day.

In 2004, Sable Island's 5 DU of fire ozone was not caused by Western Canadian fires. Few of the back trajectories during this period passed over the Western Canadian fires. Instead, the fire influence is almost evenly distributed between Eastern Canadian fires, Southeastern U.S. fires, Midwestern U.S. fires, and Western U.S. fires.

Yarmouth also had very little fire influence from Western Canadian fires during the IONS-04 campaign, yet the average fire ozone for this period was 4 DU. Similar to Sable Island, the fire influence was almost evenly distributed between Eastern Canadian fires, Midwestern U.S. fires, Southwestern U.S. fires and Western U.S. fires. 2004 was the only year in which Yarmouth had fire influence from Southwestern U.S. fires.

The amount of fire-enhanced ozone decreased by 50% during the IONS-06 campaign from its average value during the IONS-04 campaign. The number of back trajectories with forest fire influence at Goose Bay and Yarmouth was halved during this period, as compared to the IONS-06 and ARC-IONS campaigns. Sable Island, however, had an increase in the number of back trajectories that passed over a fire. Fire ozone was detected almost daily at Egbert and Yarmouth, while it was only detected in half of Sable Island's ozonesonde profiles.

During the IONS-06 campaign, the TTOC value at Egbert increased, while the fire ozone decreased to 3 DU. Most of the fire ozone was attributed to Western U.S. fires, which often reached 9 km above the surface. Because the majority of the fire encounters were in plumes that reached at least 7 km, the location of the fires does not appear to be a factor in the low fire ozone. Therefore, the decreased fire ozone amount was most likely a product of the reduced fire encounters.

Sable Island's decrease in average fire ozone from 2004 to 2006 was balanced by an increase in ADV and ST ozone. As a result, the average TTOC value did not change. Fire ozone decreased to 3 DU, despite an increase in the number of back trajectories with forest fire influence. Most of forest fire ozone was due to fires in Western Canada, the Western U.S., the Midwestern U.S., and Eastern Canada. In 2006, the smoke plumes in Western Canada and the Western U.S. reached an average height of 7 and 9 km, respectively. Smoke plumes from fires in the Midwestern U.S. only reached heights of 6 km. As a result, the fire ozone during the Midwest influence events was less than the fire ozone transported from the West. Despite the fires in the West generating the majority of fire ozone, most of the fire-influenced back trajectories at Sable Island encountered Eastern Canadian and Midwestern U.S. fires.

Yarmouth's average TTOC value decreased from its IONS-04 value, but the fire ozone term was the only term to noticeably decrease. Average fire ozone of 1 DU was concurrent with fewer back trajectories that passed over forest fires. Also, the majority of the forest fire influence shifted from Western Canada, the Western U.S. and the Southwestern U.S. to the Midwestern U.S. As discussed in Section 3.1, fires in the Midwestern U.S. were noticeably smaller, with the top of the smoke plume rarely reaching heights above 6 km. The smaller fires, combined with fewer back trajectories encountering fire plumes likely led to a smaller fire ozone term.

Forest fires during the 2008 ARC-IONS campaign produced ozone enhancement values similar to those produced during the IONS-04 campaign. Fire ozone values

ranged from 2 DU at Goose Bay, to 7 DU at Sable Island. There are several reasons for this variation, each of which will be discussed by the ozonesonde launching site.

The largest average TTOC amount at Egbert occurred during the 2008 ARC-IONS campaign, a time when the fire ozone term averaged 5 DU. Most of the fire ozone enhancement was caused by forest fires in Canada and the Midwestern U.S., which are the same two regions that had the most fire impact on the TTOC during the IONS-04 campaign. The 2008 average fire ozone was not drastically different from the 2004 value, despite an increase in the number of fire-influenced back trajectories.

Because Goose Bay was only used as an ozonesonde launching site during the ARC-IONS campaign, its average fire ozone amount of 2 DU cannot be compared to past results. Compared to the other 2008 sites, Goose Bay had less fire events, with only 4% of the back trajectories encountering a smoke plume. The few fire enhancement opportunities may have been caused by Goose Bay's remote location, or by its distance from the forest fires. The fire influence at this site was mostly due to fires in the Southeastern U.S. and Eastern Canada. Fires in these regions tended to be surface fires, thus limiting the number of back trajectories as well as the amount of possible fire ozone.

Sable Island had an average fire ozone term of 7 DU during the ARC-IONS campaign. The number of fire-influenced back trajectories during this campaign was 2.5 times larger than the number of fire-influenced back trajectories during the IONS-04 and IONS-06 campaign at this location. Most of the fire enhancement was due to small fires in the Southeastern U.S. and Eastern Canada, which rarely reached heights above 6 or 7 km.

Unlike the previous campaigns, the majority of Yarmouth's fire ozone was transported from fires in the Southeastern U.S. and Eastern Canada. During the 2008 ARC-IONS campaign, Yarmouth averaged 6 DU of fire ozone. The number of back trajectories with forest fire influence during this period is almost triple the number of fire-influenced back trajectories in 2004 and 2006, while the total number of ozonesondes launched was almost constant between the 3 campaigns. It is possible that the ozone in the fire-impacted levels was lower than it was at the same levels in the past, or despite the number of fire encounters, very little of the ozone was influenced by the fire.



#### **Chapter 4. SUMMARY AND CONCLUSIONS**

The fire influence on the TTOC not only varied by the amount of enhancement over all three campaigns, but it also varied by fire locations. Fire locations were evaluated in order to parameterize the typical height of the fire smoke plumes. For example, fires in the Midwestern U.S. rarely reached heights above 6km, while fire plumes in Western Canada and the Western U.S. often reached 9 km. The number of back trajectories that passed over each fire region was an integral part in understanding the amount of fire influence during all three of the campaigns. As explained in Section 3.1, fires in Eastern Canada only contributed 5 DU of fire ozone, yet 20% of the fire-influenced back trajectories passed over this region.

Fires in Alaska and Northwestern Canada caused an average ozone enhancement of 5 DU during the IONS-04 campaign. Egbert's 2004 budgets had an average fire ozone term of 6 DU, mostly caused by fires in Western Canada. Sable Island's 5 DU of fire ozone and Yarmouth's 4 DU of fire ozone were caused by fires in the Midwestern U.S. and Eastern Canada.

There was a reduced amount of fire influence during the IONS-06 campaign, which was most likely caused by a reduced amount of fire-influenced back trajectories. Fewer back trajectories passed over fires, which led to a decrease in the amount of fire ozone. Egbert's fire ozone decreased to 3 DU, even though most of its fire ozone was caused by fires in the Western U.S. Fires in Western Canada, the Western U.S., the Midwestern U.S., and Eastern Canada were responsible for Sable Island's 3 DU of fire ozone. The majority of Sable Island's fire ozone was caused by surface fires in the

Midwestern U.S. and Eastern Canada. Yarmouth's average fire ozone during the IONS-06 campaign was 1 DU. This decrease in ozone was caused by a shift in forest fire influence from fires in the Western U.S. and Western Canada to fires in the Midwestern U.S.

Forest fires during the 2008 ARC-IONS campaign produced ozone enhancement values similar to those produced during the IONS-04 campaign. Forest fires in Canada and the Midwestern U.S. were responsible for Egbert's 5 DU fire ozone term. Goose Bay, which was not an ozonesonde launching site during either the IONS-04 or IONS-06 campaigns, had an average fire ozone term of 2 DU. Most of the fire ozone at Goose Bay was due to fires in the Southeastern U.S. and Eastern Canada. Fires from these regions also contributed to Sable Island's average fire ozone term of 7 DU. Yarmouth had an average of 6 DU of fire ozone.

There are several sources of error associated with refining the ADV term of the ozone budget for fire-enhanced ozone. First, the LID method is very complicated and there are significant differences in the ST ozone term as it calculated in the new fire LID budgets. It is believed that the original budgets were calculating an upper limit of ST ozone, while the new budgets are calculating a lower limit of ST ozone. Second, HYSPLIT back trajectories show only an approximate path of the air parcels. The FLEXPART model would have provided a much better estimate of the trajectories, but time did not permit for this model to be used. Third, the fire plume height approximations contributed to the uncertainty. No precise method has been developed for estimating the

top of a fire smoke plume, but there is other remote sensing data that could be analyzed to better parameterize the maximum altitude of the smoke plume.

Future work for this project includes incorporating the use of Atmospheric Infrared Sounder (AIRS) CO data, cloud mass flux data from NASA and Geostationary Operational Environmental Satellites (GOES) cloud top imagery. The AIRS CO data will help to further illustrate the location and transport of the smoke plume. The cloud mass flux data will be helpful in differentiating between clouds and smoke in the satellite imagery. The GOES cloud top imagery can be analyzed to estimate the plume height. Refining the plume height to within a kilometer will lead to more precise values of fire enhancement of the TTOC.

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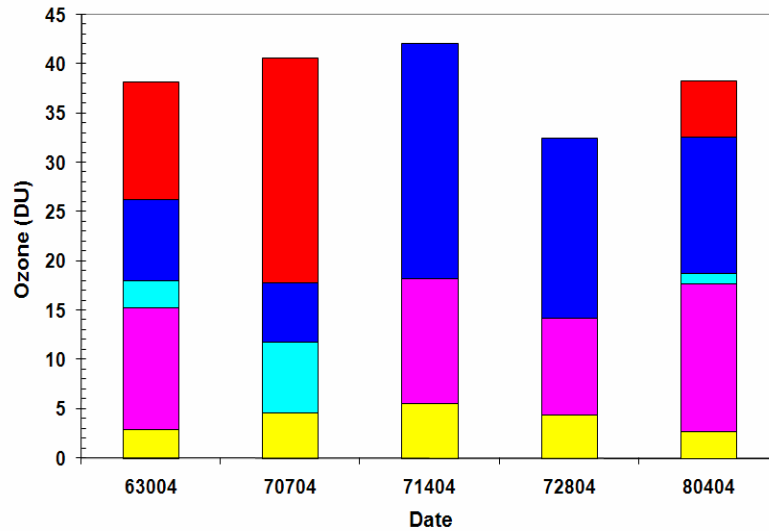
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### APPENDIX: IONS-04 and IONS-06 Fire Budgets

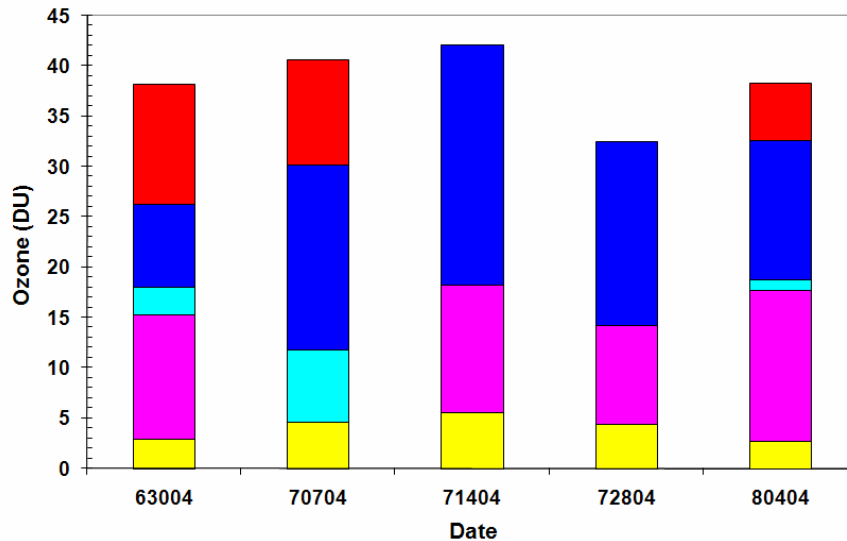
Ozone budgets for Egbert, Sable Island Yarmouth 2004 and 2006 are listed

below. The top budget on each page represents the maximum amount of fire influence on the TTOC. The bottom budget on each page is the height-adjusted fire budget.

Tropospheric Ozone with Fires: Egbert, ON 2004



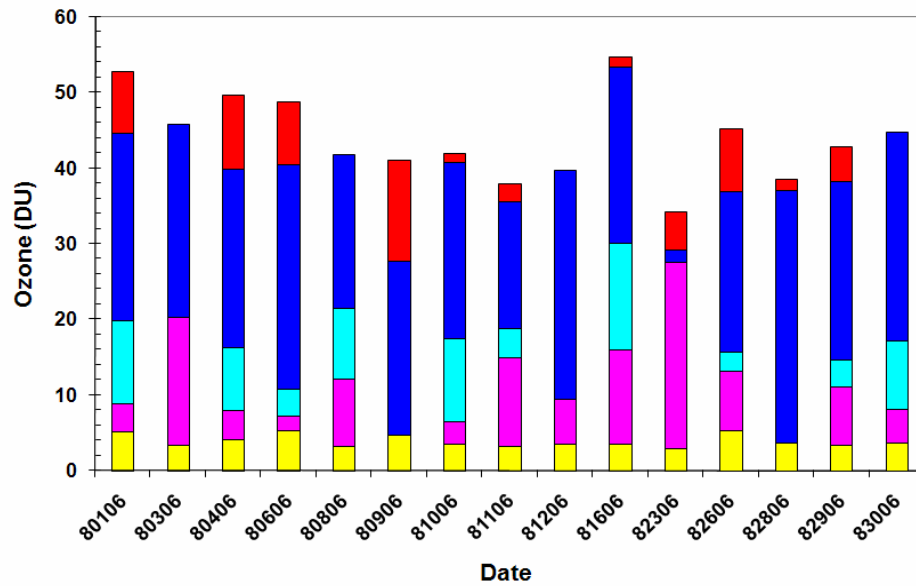
Tropospheric Ozone with Height-Adjusted Fires: Egbert, ON 2004



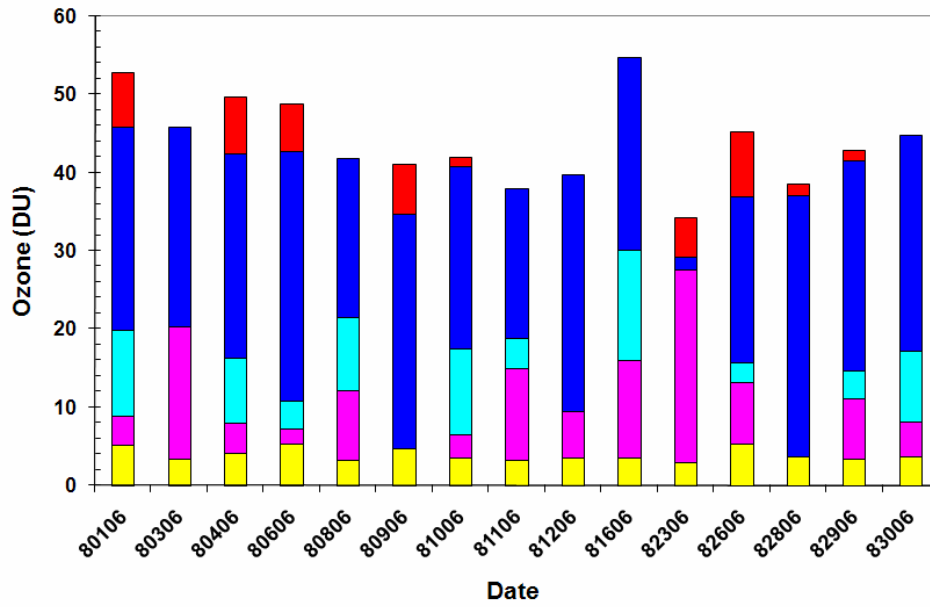
BL RCL ST ADV Fire



Tropospheric Ozone with Fires: Egbert, ON 2006

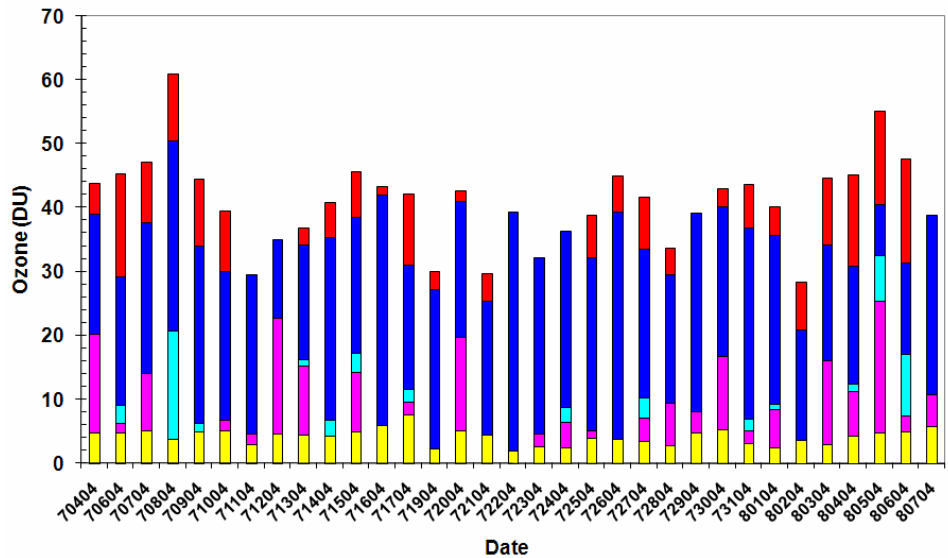


Tropospheric Ozone with Height-Adjusted Fires: Egbert, ON 2006

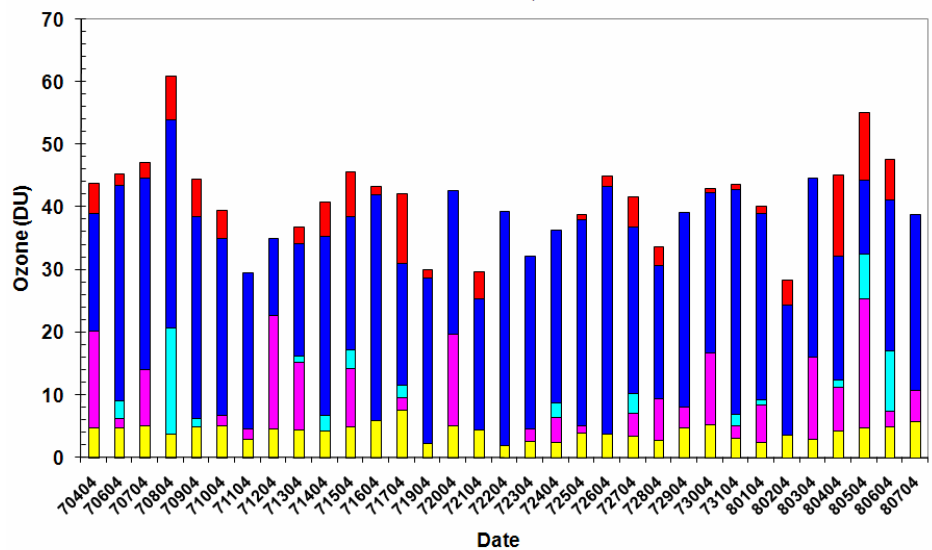


BL RCL ST ADV Fire

Tropospheric Ozone with Fires: Sable Island, NS 2004

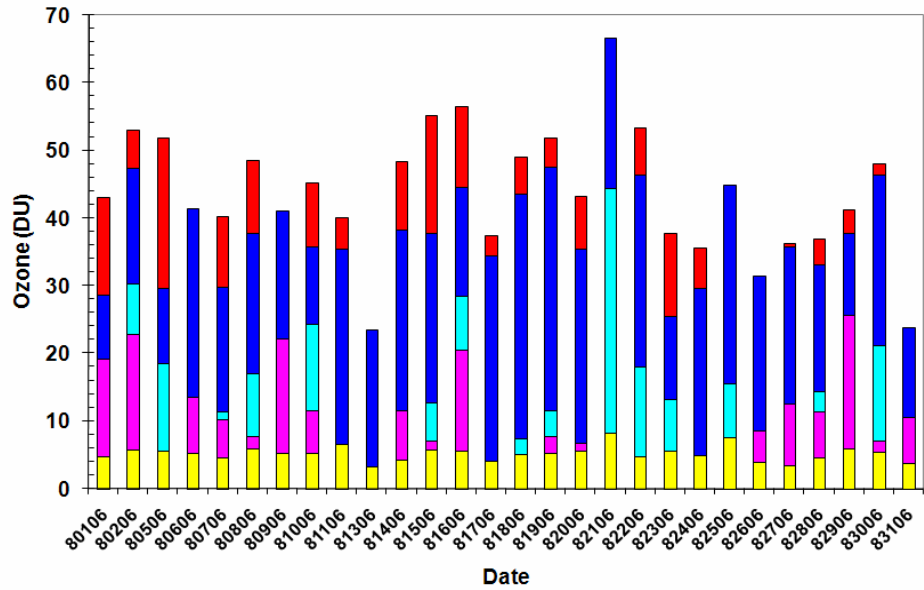


Tropospheric Ozone with Height-Adjusted Fires: Sable Island, NS 2004

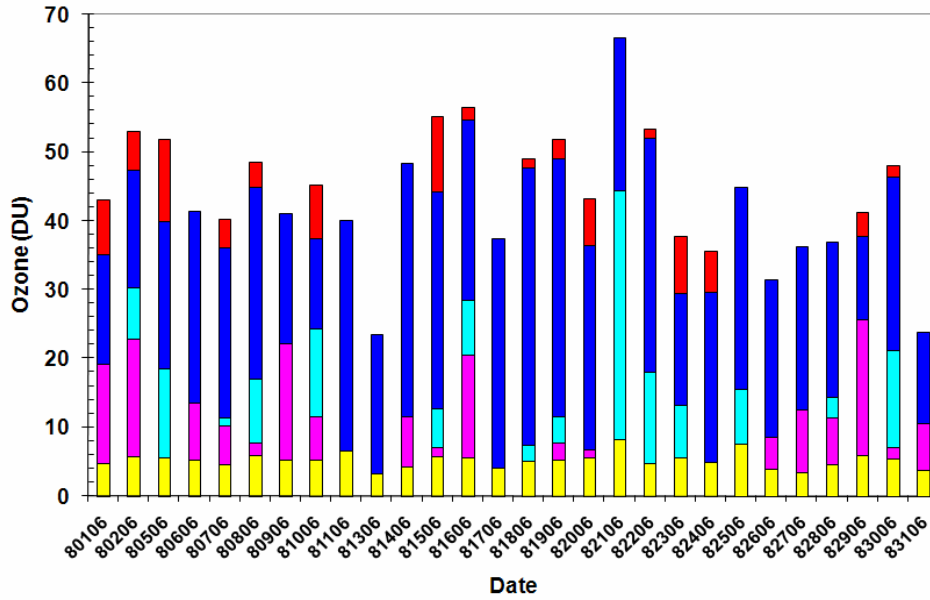


BL RCL ST ADV Fire

### Tropospheric Ozone with Fires: Sable Island, NS 2006

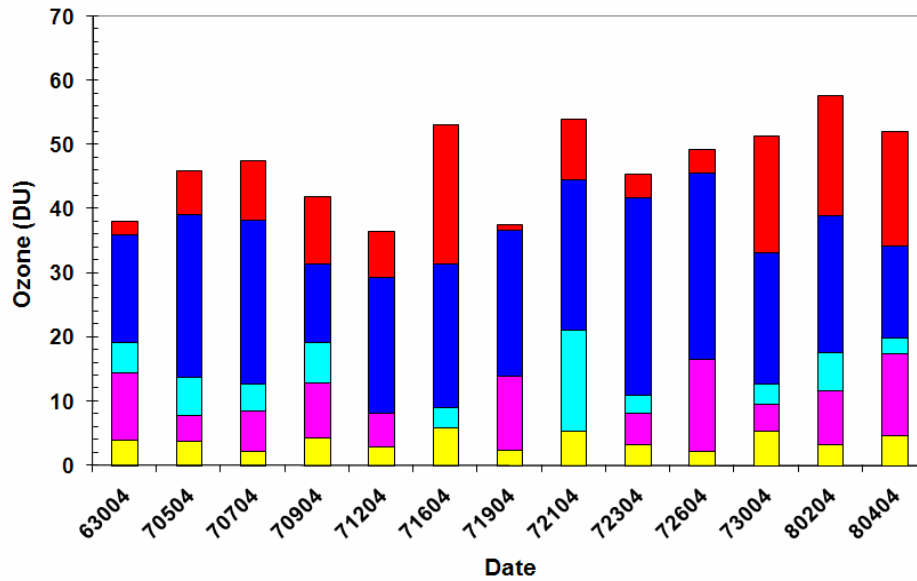


### Tropospheric Ozone with Height-Adjusted Fires: Sable Island, NS 2006

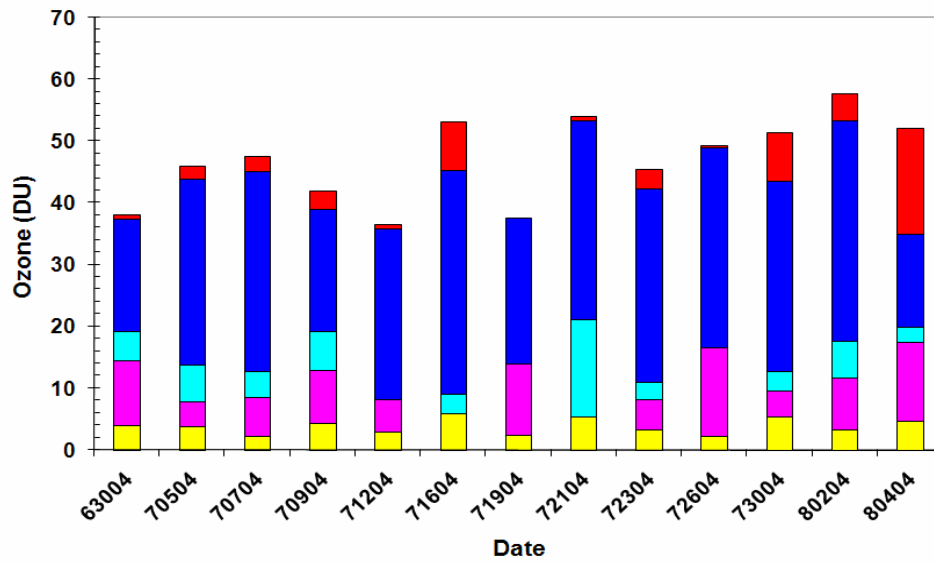


Legend: BL (yellow), RCL (magenta), ST (cyan), ADV (blue), Fire (red)

### Tropospheric Ozone with Fires: Yarmouth, NS 2004

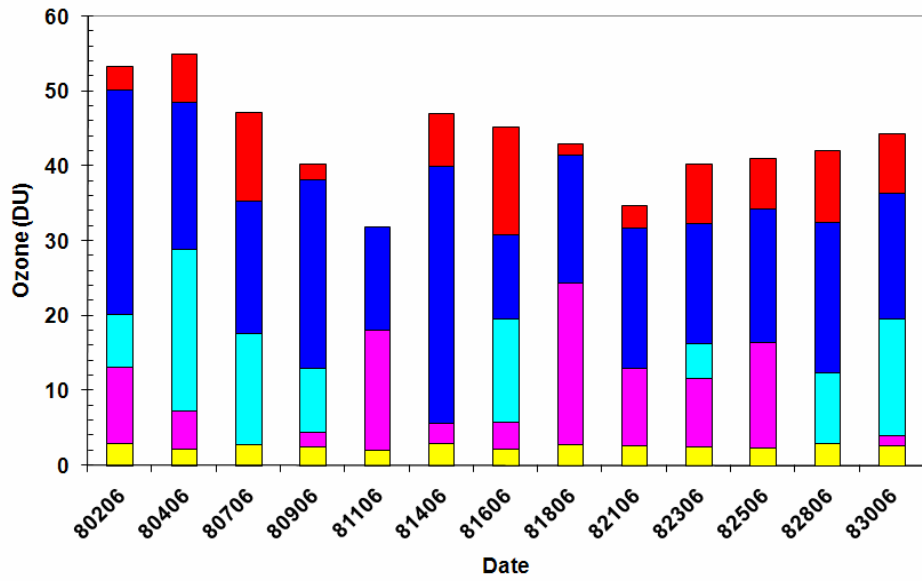


### Tropospheric Ozone with Height-Adjusted Fires: Yarmouth, NS 2004



Legend: BL (yellow), RCL (magenta), ST (cyan), ADV (blue), Fire (red)

**Tropospheric Ozone with Fires: Yarmouth, NS 2006**



**Tropospheric Ozone with Height-Adjusted Fires: Yarmouth, NS 2006**

