# Satellite Remote Sensing of Aerosols: Factors That Affect Smoke Plume Injection Heights

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ABSTRACT

Concerns among the scientific community are rapidly growing with the increased studies of aerosols and their effects on climate change. Wildland fires in North America contribute a great amount of carbon monoxide, nitrous oxides, and particulate matter (PM10 and PM 2.5) into the atmosphere. This study uses fire events previously observed by satellite remote sensing instruments aboard NASA's Terra and Aqua satellites to address the issue of predicting smoke plume injection heights and utilizes the results to improve modeled smoke plumes from wildfires. There are many factors that contribute to smoke plume injection height: fire radiative power, lower level atmospheric instability, elevation, and a vegetated area supplying a fuel source for the fire. Different regions in North America are affected by a unique combination of all of these factors. For example, in the western region of the United States the Haines instability index and the topographical elevation are the major contributors to determining smoke plume injection height. Once the effects of various factors on smoke plume injection heights can be accurately resolved the precision of smoke plume models will significantly increase.

## 1. Introduction

Smoke plumes contribute to today's overwhelming emission of aerosols into our atmosphere, emitting carbon monoxide, particulate matter (PM10 and PM2.5), and nitrous oxides. Aerosols have been shown to affect climate in many different ways. They act as reflectors of incoming solar radiation, and effectively cool the atmosphere. At the same time, aerosols have also been show to cause warming near the surface due to absorption of sunlight by particular particulates (Korean et al 2004). It is not only important to study the effects that aerosols have on the climate, but also where they are being injected into the atmosphere. Once the locations of these aerosols are determined we are able to predict which effect they have on global or local climate change.

Unlike aerosols contributed by human activity, smoke aerosols have been an important component of atmospheric particles for millions of years. For instance, fires in vegetated areas are definitely not a new occurrence. What has changed is the increased ability to monitor the resulting smoke plumes and their transport. In order to monitor, control, and prevent the spread of wildfires it is necessary to properly characterize fires and their smoke emissions.

Determining the strength, size and intensity of a fire from the surface of the earth is not a simple task. In the past, fire activity could only be estimated from the extent of the aftermath. Since the implementation of satellite imaging, it has become clear that the most feasible way to characterize large fires is remote sensing from space. However, this

science has not quite been perfected yet. It is important to understand the relationship of observations with reality before we can use them to forecast future events in models.

Fire and smoke plume modeling is a very useful tool that can be used to predict smoke plume injection heights and corresponding atmospheric transport. A critical observation needed to improve this modeling technique is the smoke plume injection height, the altitude at which the smoke particles are injected to the atmosphere before transport (Kahn et al 2008). The Multi-angle Imaging SpectroRadiometer (MISR) instrument aboard the Terra satellite is able to remotely sense the top of a smoke plume fairly accurately. Now, with the MISR smoke plume height, it is interesting to study the factors determining the smoke plume height. Some of the factors believed to affect smoke plume injection heights are fire intensity, smoke amount, fuel type, surface topography, and various environmental and meteorological factors. Since an important parameter for modeling wildfire smoke plumes is smoke plume injection height, it is important to understand the relative effects of these factors. This project is aimed to understand the relative effects of these factors on smoke injection height, with a final goal to improve smoke plume modeling.

## 2. Smoke Plume Characteristics

Combustion is the very rapid oxidation process occurring during a fire. As the vegetated area is burning, the combustion process produces heat and moisture. We will assume smoke plumes represent an adiabatic process meaning that there is no exchange of heat or moisture between the plume and the surrounding environment. Since it is a moist parcel, the smoke plume follows the moist adiabatic lapse rate, approximately -6.6° C/km. The combustion provides a lifting force for the plume known as buoyancy. If the moisture and temperature difference between the plume and the surrounding air is larger then the buoyancy force will be greater. Environmental factors that could affect plume height are fuel type, fuel moisture, relative humidity, atmospheric stability, and wind. The extent to which each parameter influences plume height is discussed in detail below.

### *Factors Believed to Affect Smoke Plume Heights*

In order to improve modeling techniques it is very important to understand the relationships between the various components of the system being modeled. We will analyze a few of the main factors affecting smoke plume injection heights, which are: elevation, fire radiative power, atmospheric stability, and vegetation type. It is suggested that for increased surface elevation or fire radiative power the smoke plume injection height will increase. With increased atmospheric stability the plume height has an inverse relationship; it will decrease. The main question that this paper will address is how much does each predominant factor affect smoke plume injection height for various fires and regions?

### *A. Fire Radiative Power*

Fire Radiative Power (FRP) is the rate of release of fire radiative energy per unit time, measured in Megawatts. It is observed at the 4-micrometer wavelength by the Moderate resolution Imaging Spectroradiometer (MODIS) sensor aboard the NASA Terra and Aqua satellites. Satellite measurement of FRP is presently the most accurate

way to measure the strength of a fire. While it is a good measure of a fire's intensity, there are many uncertainties in the estimation of FRP. Since the FRP is only being observed at the 4-micrometer wavelength, the sensor will not detect whether it is traveling through a very thick smoke plume. If this is the case, the FRP energy flux may seem less intense than it actually is. Also, the fire product retrieved from the MODIS sensor is derived from the radiance data of pixels that have size of 1 km x 1 km at nadir and can be 4-5 km x 4-5 km at edge of satellite viewing geometry. Since most fires cannot fill up one pixel there is a lot of averaging taking place. FRP measurements have been determined to categorize the strength of fires well (Mottram et al 2005).

*B. Atmospheric Stability*

Although the Convective Available Potential Energy (CAPE) index, the K index, the Severe Weather thrEAT (SWEAT) index, and the Lifted Index (LI) are all very good atmospheric stability indices, we cannot use these indices for this study since that they do not account for the fire itself. These indices base their values on the assumption that a moisture-rich lower atmosphere would induce an unstable environment. This is due to the fact that moist air is less dense than dry air, implying that the buoyant force on that lower, moist parcel is upward. In a fire, the parcel is given a buoyant force for a different reason. The combustion process leads to a very hot smoke plume. Since the warm plume is less dense than the surrounding cooler air, the plume is lifted. Another product of combustion is refore, the aforementioned indices are evaluating reversely, and they will not be much help, because they are based on the opposite assumption.

The Haines Stability Index is a more useful tool in determining lower level atmospheric stability. It is a system that measures temperature differences between two pressure levels and the moisture content of the atmosphere. If the elevation is low it measures the temperature difference at the 950 and 850 mb pressure levels. If the elevation is mid-level the temperature difference is measured between 850 and 700 mb, and if the elevation is high it calculates the difference between the 700 and 500 mb levels (Haines et. Al, 1988).The Haines index is valid because it takes into account the changes in dynamic parcel properties when observing a smoke plume.

*C. Elevation*

Topographic elevation can certainly play a key role in smoke plume height. At a higher elevation, for example a mountaintop, the atmosphere has a different profile than it does near sea level. When the Terra satellite passes overhead around 10:30 am, the temperature, moisture and pressure at a higher elevation is typically less than it would be at sea level. These two environments lead to different buoyant forces acting on the smoke plumes at their respective elevations. It is expected that a fire with a given intensity would produce a higher smoke plume if the fire were located at a higher elevation.

*D. Vegetation Type*

Once the vegetation is raised to its ignition temperature a fire starts. The chemical make-up of various vegetation types, also known as fuel, leads to differences in the way a fire burns. These differences in vegetation type should affect the smoke plume injection height. Vegetation with a lot of carbon should burn more effectively. Another factor to

consider is the moisture content of a particular vegetation. It is expected that dry fuel will burn hotter than a moist fuel producing a higher plume.

## 3. Instruments and Parameters

The Terra and Aqua satellites provide a new perspective for smoke plume analysis. Aboard both of these satellites is a Moderate- resolution Imaging Spectroradiometer (MODIS). This sensor obtains a variety of useful parameters for monitoring aerosols such as aerosol optical depth, and aerosol size. Another instrument aboard the Terra satellite is the Multi-Angle Imaging SpectroRadiometer (MISR). This device is equipped with nine cameras angled strategically to develop a three-dimensional image of the atmosphere. This provides additional unique aerosol parameters such as aerosol airmass, type, and height.

The first step in this project is determining which instruments and data will be the most beneficial. The study area is greater North America and ranges from -180˚ W to -60˚ W and 0˚ N to 90˚ N. The Terra and Aqua satellites pass through this region approximately 3-4 times per day, providing observations daily for every point in North America. This was determined to be the most efficient way to study this area.

Terra is a sun-synchronous, descending satellite, which means that as it crosses North America, during the daylight part of its orbit, it is traveling north to south and that it is always viewing a point on the earth immersed in sunlight. Terra passes the equator around 10:30 am. The Aqua satellite is an ascending satellite, and can be disregarded for this project because it passes at a different point in the day. On the Terra satellite are two very important instruments, the MODIS and MISR, which will be explained in the following section.

*The MODIS Instrument*

The Moderate Resolution Imaging SpectroRadiometer (MODIS) is an instrument aboard the Terra and Aqua polar-orbiting satellites. It is sun-synchronous which means that it is collecting data 24 hours a day on four wavelengths (red, green, blue, and NIR). One of the most important observations that this spectroradiometer collects is the aerosol optical depth, an optical measure of atmospheric mass loading, and is inversely proportional to visibility. Anything less than .1 implies a crystal clear day. This is a very useful measure of the amount of total aerosol in the atmosphere.

*Figure 1: MODIS image of a fire 04-02-2002*

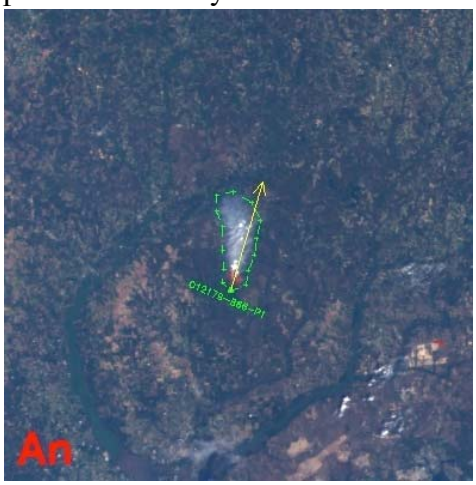
One major drawback to using MODIS data for aerosols distributed in smoke plumes is that the data gridded to a 10km x 10km pixel. A lot of averaging takes place since the total area of a fire does not usually comprise an entire pixel.

*The MISR Instrument*

The Multi-Angle Imaging SpectroRadiometer (MISR) is a unique sensing device aboard the Terra satellite. Unlike the MODIS instrument, MISR has a much narrower

swath width of only 360 km. Due to this narrow swath it only compiles global coverage about once every nine days. Conversely, a major benefit of MISR data is that it has very high resolution. For certain parameters MSIR can measure in .25 x .25 km. The plume height measurements are gridded to 1x1 km. Although this is not as precise as hoped for, it still provides a basis for an accurate assessment of smoke plumes.

MISR is unique because it uses nine cameras to simultaneously view the earth. One camera is aimed directly perpendicular to the earth's surface (nadir), four other cameras extend on either side at 26.1, 45.6, 60.0, and 70.5 degrees. These nine cameras pass successively over the same location enabling the instrument to view the same scene from nine different angles. Since the MODIS and MISR devices are aboard the same satellite, it is necessary to compare the MODIS and MISR AOD measurements. They should have a perfect correlation, because they are viewing the same area at the exact same time. MISR is very helpful in determining smoke plume height since the furthest cameras from nadir are able to view the vertical extent of a plume. Figure 2 is an example MISR image from the MISR Plume Height Climatology Project




*Digital Elevation Model (DEM)*

This elevation model, developed by the US Geological Survey (USGS), shows the terrain of North America in a 30-second arc resolution image. Each pixel is approximately 1 km x 1 km. The reason this map is used rather than the National Elevation Model produced and currently used by the USGS is that the DEM file was the map used during 2002. It is important that all the data are valid for the climatology's period of study. This map, like the MODIS and MISR, also ranges from -180º W to -60º W and from 0º N to 90º N.

*plume climatology*

*MODIS-IGBP Ecosystem Map*

The MODIS International Geosphere-Biosphere Programme Ecosystem Map portrayed the vegetation type for this project. This ecosystem map has a 1-minute arc resolution. Recall that 60 minutes make up one degree, so one minute equates to approximately a 2 km x 2km pixel size at the equator and less than 1km pixel size at the poles. Whichever vegetation is the most abundant in each pixel is the type displayed. There are sixteen different classifications for vegetation in this map.

*Haines Index Map*

The Haines index Map shows the atmospheric instability index for the United States and was used for this study. The Wildland Fire Assessment System provides a multitude of data evaluating the fire potential for each day. The Haines index is represented daily in a map. Haines looks at the radiosonde measurements for the 0000 Z time each day. The index is categorized into three elevation levels - low, medium, and high. The low elevation uses the temperature differences between the 950-850 mb and the 850 mb temperature-dew point spread. The medium elevation level makes the same calculations between the 850-700 mb levels. The high elevation level uses the 700-500 mb levels (Haines et al., 1988). Five categories are displayed ranging from very low to very high. Very low indicates that the lower level atmosphere has very low instability. If the atmosphere is very stable, the potential for a parcel with an initial lift to continue lifting is low. If a fire were to start in an area listed as very low, the smoke plume would not lift extravagantly.

## 4. Data Collection

The 2002 Multi-angle Imaging SpectroRadiometer (MISR) North America plume height climatology project is the basis of study for this research project. This climatology reported MISR information from 480 fires including these important parameters: the latitude, longitude, date, time, mean fire radiative power (FRP), aerosol optical depth (AOD), direction of the plume and median wind corrected plume height.

### *A. Downloading Data*

There were four main sources of data for this project: Level 2 Aerosol MODIS data from the Terra satellite, a collection of MISR observations in the smoke plume climatology project, the digital elevation model, and the ecosystem map. The most time consuming of the four sources was the collection and downloading of the MODIS data. The data was retrieved from the Ladsweb server. The observed (North American) area reached from -180º W to -60º W and from 0º N to 90º N. MODIS level 2-aerosol product was collected in the form of hierarchical data files (hdfs) for each day that a smoke plume existed in North America in 2002.

The MISR climatology data was already compiled into an Excel spreadsheet with 61 parameters for each fire, some of which were listed earlier. The DEM was already made into a hierarchical data file (hdf), and was simply evaluated at each latitude and longitude for each fire. The ecosystem map was also an hdf file, and data was extracted in the same way as the DEM file.

### *B. Extracting Essential Parameters and Programming*

The MISR smoke plume climatology project provided a set of 480 confirmed fire cases throughout 2002. The first step was to extract the essential parameters from all of the collected MODIS data. To do this, it was necessary to build an IDL program. This program began by finding the correct hdf containing the correct date, time, and location of each fire. Once these 480 files were found, the program extracted the latitude, longitude, and aerosol optical depth measurements from the scientific data sets (SDSs). With these data, the program pinpointed the exact pixel corresponding to the latitude and longitude of each MISR fire case. It saved the AOD value of that pixel and also made a

5x5 pixel box surrounding it. I extracted the latitude, longitude, and AOD values from all 25 pixels to find the maximum and minimum AOD in the vicinity of the fire. Once the maximum and minimum values are determined the program saves the corresponding AOD value, latitude and longitude for those pixels.

## 5. Methods

### *A. Compare MODIS and MISR*

The MODIS and MISR instruments simultaneously take measurements of aerosol optical thickness. To improve the accuracy of our research it is important to validate the similarity of these measurements. First, the correlation of all MODIS and MISR AOD measurements at each fire location was calculated. Ideally, the correlation should be 1, since both sensors are observing the same location at the same time. They proved to have a very high correlation of .7956.

The largest difference in AOD observed between sensors is 1.2. MISR observes AOD 1.2 greater MODIS AOD. This is very significant when analyzing about aerosol optical depth, because AOD is a ratio of light that is absorbed by the sensors. A variation like this can be the difference between a perfectly clear day, and a haze filled sky with a filtered sunlight. One thing that I noticed is that the MISR is over estimating when the AOD is a low value, and the MODIS is overestimating when the AOD value is higher. It is in our best interest to use the MODIS aerosol optical depth as truth for this study. This is due to the fact that we are extracting MODIS AOD directly over the fire pixel that the climatology lists. The MISR climatology project observes the maximum AOD value and records that for each plume. The downfall to this method is that the AOD measurement may not be the highest directly above the fire pixels.

### *B. Compare DEM to MISR elevation*

Again the correlation between the DEM elevation and the MISR elevation for each fire should approach 1. Fortunately, the correlation is .8678. For this project, the digital elevation model is taken as truth. The main weakness with the MISR elevation is that the when it passes there may be clouds or aerosols interfering with the measurement. The DEM goes through a very rigorous process to calculate the elevation. For this project the DEM elevation is taken as truth.

### *C. General observations*

An overall picture of the fire cases is helpful. I plotted all 480 measurements of fire radiative power, elevation, and smoke plume injection height. They are all shown on a color scale with blue as the lowest value, and red as the highest.

The figures below represent all 480 measurements of each parameter. Figure 3 shows the smoke plume injection height. This value was calculated by subtracting the DEM topographical elevation in meters above sea level from the mean wind corrected smoke plume injection height observed by the MISR instrument, also in meters above sea level. This value is the specific height from the top of the earth's surface to the top of the plume located directly over the fire pixel. Figure 4 is the fire radiative power measurement at each fire location. This is calculated by the MODIS instrument and is

measured in Megawatts. Figure 5 shows the topographical elevation extracted from the DEM file. It is observed in meters above sea level. Figure 6 is the vegetation classification. There are 16 categories listed. This image is derived from retrievals of the MODIS instrument.

Some of the results that can be determined by these maps are that there is a region of high smoke plume injection height in the central plains, western United States and central Canada. This is highly correlated with the elevation and the fire radiative power. It is shown that the highest smoke plumes exist where the elevation and the fire radiative power are the greatest. Also, the vegetation types that have the highest smoke plume injection height are the: grasslands, and open shrubs of the plains and western United States, and the mixed forest and evergreen in central Canada. The weakness in these images is that what is shown is not supported by simple calculations of correlation. In fact, the elevation only forms a correlation of 0.0785 with the smoke plume injection height, and the FRP gives a 0.3939 correlation. These values are not large enough to determine the effect that each parameter has on smoke plume injection height, and whether it is positively correlated.

***Figure 3: Smoke Plume Injection Heights***

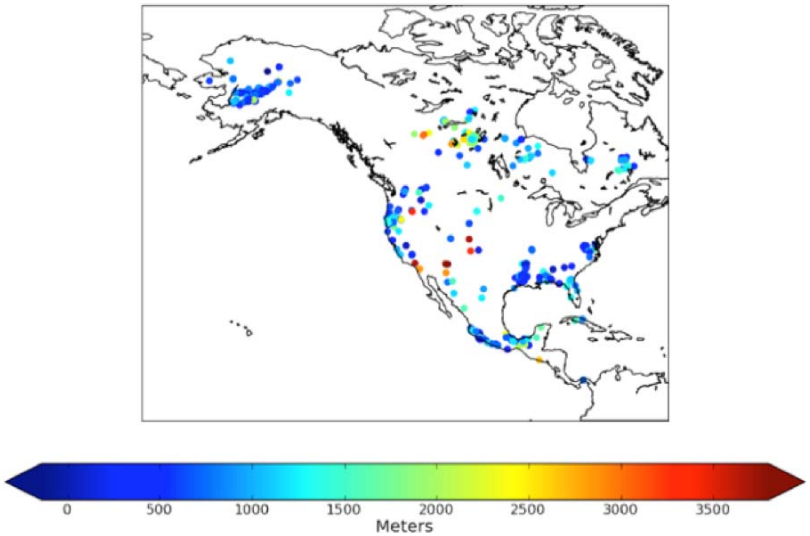



***Figure 4: Fire Radiative Power***

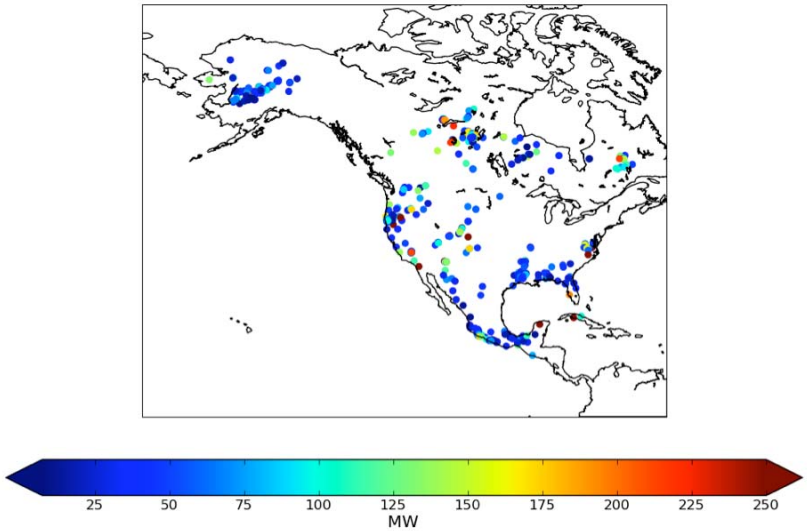



***Figure 5: DEM Elevation***

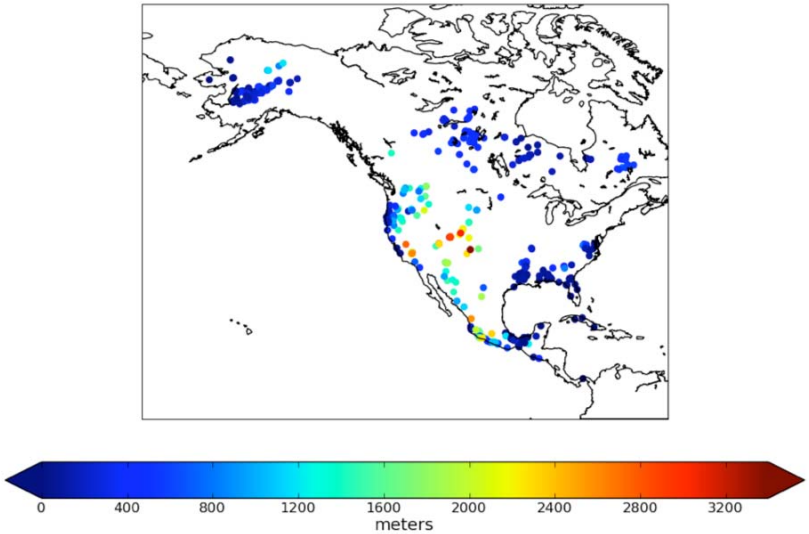
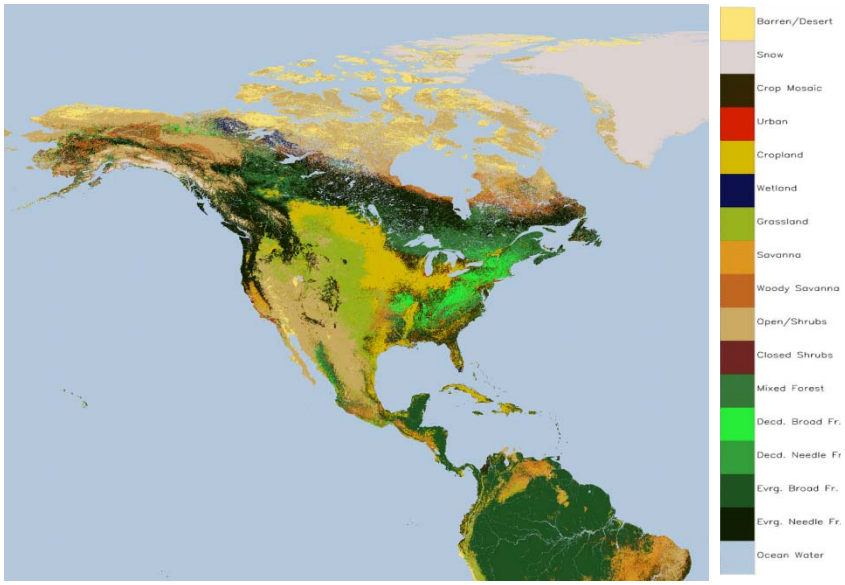



***Figure 6: MODIS-IGBP Ecosystem Map***



*C. Split into Regions*

The data set in its entirety did not provide very beneficial results. They gave a general idea of which parameters are the most important, but it covered too broad of an area. It was necessary to split the North American data set into 10 regions: Alaska, Quebec, Canada Central, Canada West, Ontario, US West, US Central, US East, Mexico, and Venezuela. The regions were divided in this way:

| | **Min_lon** | **Max_lon** | **Min_Lat** | **Max_Lat** |
|---|---|---|---|---|
| **Alaska** | -170 | -140 | 50 | 75 |
| **Quebec** | -80 | -55 | 45 | 65 |
| **Canada West** | -140 | -120 | 50 | 70 |
| **Canada Central** | -120 | -100 | 50 | 70 |
| **Ontario** | -100 | -80 | 50 | 70 |
| **US West** | -125 | -110 | 25 | 50 |
| **US Central** | -110 | -85 | 25 | 50 |
| **US East** | -85 | -70 | 25 | 50 |
| **Mexico** | -120 | -85 | 15 | 30 |
| **Venezuela** | -80 | -45 | 0 | 15 |

*Table 1: Latitude and Longitude of the ten regions of North America*

A broad study was done of each region, but it is much more manageable to work with smaller regions to assess which factors affect each area the most. The focus was on the regions with the most cases, this is to improve the statistical validity of correlations.

*D. Reduce Study to Alaska, US Central, and US West*

The regions with the most observations of wildfires were Alaska, Canada Central, US West and US Central. Therefore, these three regions were focused on in the study. The US West and US central regions have the Haines index available, which is a major indication of atmospheric stability. Also, as seen in the elevation, FRP, and smoke plume injection height maps, these regions contain a wide range of measurements across the area. These regions include very low and very high measurements for each parameter. This will be helpful in showing how accurately each parameter predicts a change in smoke plume injection height. Future studies would include an index similar to the Haines index for the rest of the North American regions.

## 6. Results and Discussion

*Alaska*

Unfortunately, for the Alaska region the Haines index does not exist. Disregarding this measure of atmospheric instability, the most important factor affecting smoke plume injection height in the Alaska region is FRP. The two are sufficiently correlated at 0.5353. Based on a study by Mottram et al, I grouped the fires into three fire radiative power categories. The first category of fires with FRP less than 50 MW showed a slight negative correlation of elevation with smoke plume injection height. The second category where FRP ranged from 50-100 MW gave a very small negative correlation

again between elevation and plume height. It wasn't until I measured the correlation between those two parameters for FRP values greater than 100 MW that it was largely positively correlated at 0.4686. It was determined that for many of the regions elevation was slightly negatively correlated with smoke plume height. The reason that this categorization of FRP is important is that it proves with a more intense fire In this study,

Also, in Alaska the various ecosystems were analyzed. The three main vegetation types, with corresponding classification numbers, are: evergreen needleleaf forests (1), open shrublands (7), and woody savannas (8). As expected, the correlations between smoke plume injection height and various environmental and meteorological parameters varied between vegetation types. The ecosystem that produced the highest correlation between plume height and FRP was the woody savannas with 0.5353. This means that if a fire was burning in a woody savannah we would be able to predict with some accuracy the height of the plume. The remaining ecosystems did not portray a good correlation among any of the parameters. For the Alaskan region, knowing the vegetation type does not aid in predicting smoke plume injection heights.

Overall, the FRP is the best parameter to predict plume heights in the Alaskan region. Hopefully, in the near future the Haines index will be made available to the rest of North America, because, as I will address in the following paragraphs, it is a very accurate way to categorize atmospheric instability and predict smoke plume injection heights.

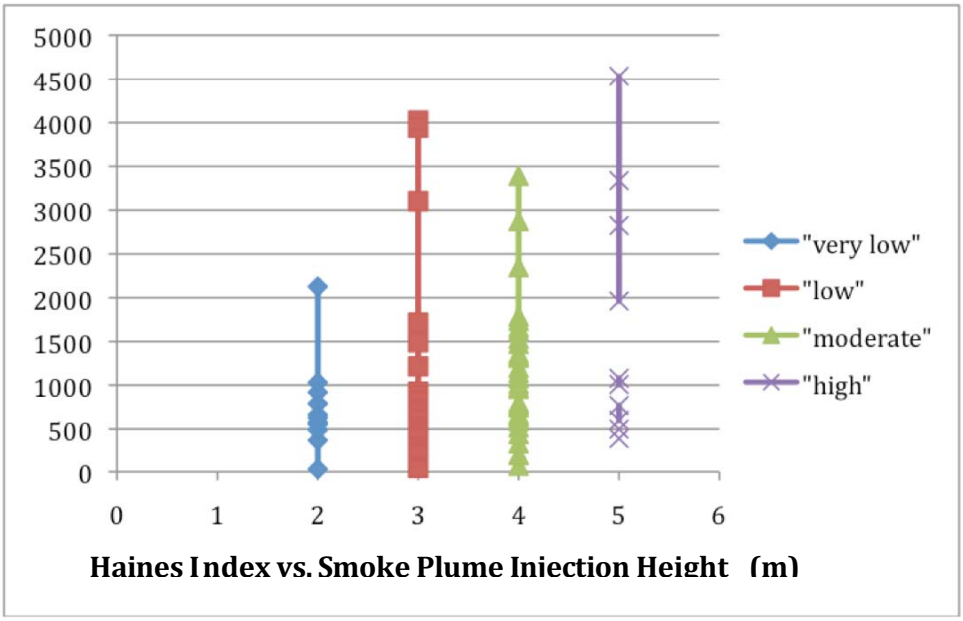
*US West*

For this region the ultimate deciding factor was the Haines index. The correlation between the Haines index and smoke plume injection height was highly significant 0.9618. The chart below shows that the Haines index effect on smoke plume injection height. The Haines index shows categories 2-6 ranging from very low to very high instability. Although the highest category (6) agreed with the rest of the data, it was omitted on the chart because there was only one fire that exhibited that environment. The smoke plume for that very high instability index was 2200 m. Next to the chart is the mean and median smoke plume injection heights for categories 2-6. Since the Haines index shows the highest correlation with smoke plume injection height, it can be said that in this region atmospheric instability is the greatest determining factor for plume height.

The next highest factor was the fire radiative power which was also positively correlated at .5010. As the fire radiative power increased, the smoke plume injection height increased. Since FRP is a measure of brightness temperature, the method of measurement can have a huge margin of error. Sometimes this error is caused by the large amount of smoke directly over the fire. In that case the FRP measurement would be drastically reduced. Another interesting result is that there is a sweet spot for FRP correlation with smoke plume injection height based on the amount of MISR AOD in the column above the fire pixel. The correlation between FRP and injection height when the AOD is < 0.05 is a miniscule 0.0249. When AOD is between 0.05 and 0.1 the relationship jumps to 0.7364. When the AOD is greater than 0.1 the correlation is 0.6196. This shows that when the AOD is minimal, FRP and injection height correlation is so small that the two cannot be classified as correlated.

Also, the topographic elevation is slightly positively correlated with a value of 0.1131. This implies that if the fire exists at a higher elevation that it will have a higher

smoke injection plume height. This is not a strong enough correlation to conclude that elevation affects smoke plume injection height in this region. I expected this value to be slightly higher. Overall, one can conclude that the Haines index had the greatest affect on smoke plume injection height in the US West region.



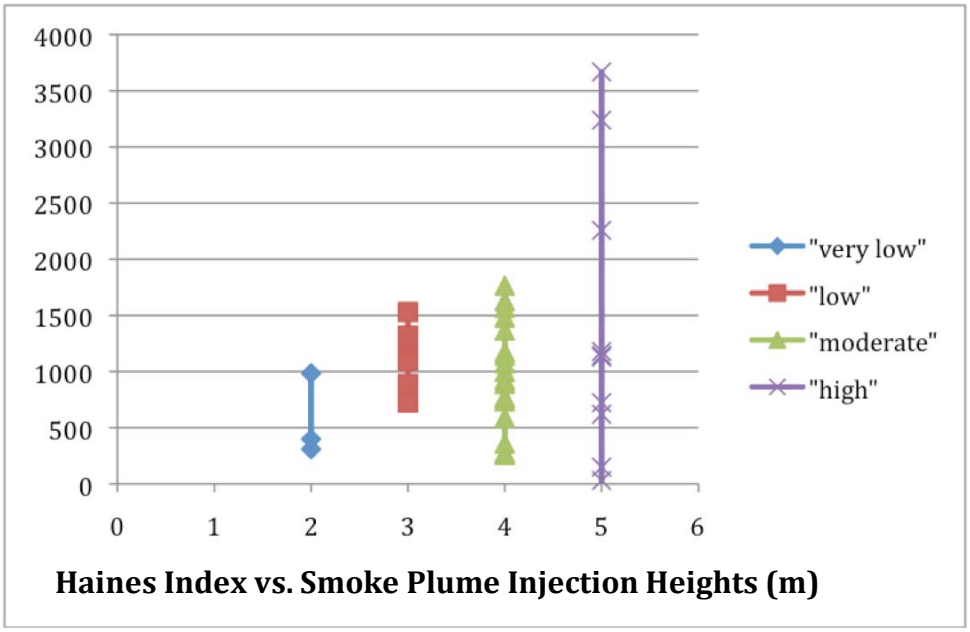

| Mean |
|---|
| 747.416667 |
| 1118.45455 |
| 1113.45714 |
| 1700.7 |
| 2200 |
| |
| Median |
| 645 |
| 714 |
| 1015 |
| 1043.5 |
| 2200 |

*Chart 1: Haines index distribution in US West region*

*US Central*

US Central was chosen as a third region of interest to test whether the Haines index was accurate in more than the US West region. Although the evidence is not as convincing, the correlation remains high at 0.8436. To prove that the Haines index is an accurate measure of atmospheric instability, this data is very reassuring. It can be deduced that atmospheric instability is the dominant factor in predicting smoke plume injection height for wildland fires in the US West and US Central regions.

Also, in the US Central region elevation plays a major part in smoke plume injection height with a correlation of 0.7427 when the FRP is greater than 100. If the FRP is less than 100 a fairly large correlation is still observed 0.4157. The US Central, more so than other regions, is also affected a great deal by the FRP value, the atmospheric instability, and the elevation. FRP also shows a strong correlation of 0.6609. This information indicates that even though the Haines index has the strongest correlation it is important to take all three of these factors into account in order to accurately predict smoke plume injection height in the great plains of the central United States.




| | |
|---|---|
| Mean | |
| | 564 |
| | 1152.42857 |
| | 946.75 |
| | 1413.7 |
| Median | |
| | 399 |
| | 1237 |
| | 910 |
| | 1136.5 |

*Chart 2: Haines index in US Central region*

*A. Most Important Factors*

Fire radiative power and atmospheric stability are accurate ways to predict smoke plume injection heights. The fire radiative power is a measure of brightness temperature, which is dependent on fuel type, fuel moisture, and available fuel. Previously, a relationship was determined between the amount of biomass consumed and a fire's radiative energy (Wooster et al 2005). A relationship also exists between FRP and vegetation type (Ichoku et al 2008), this explains why FRP may have a strong correlation with smoke plume injection height in some regions and not in others. This research was divided into regions specifically for that reason; smoke plume injection heights must be determined region by region because the vegetation type and elevation vary by region. Also, in some regions atmospheric instability has proven to have the greatest affect on plume height. If an environment is conducive to very buoyant smoke plumes, the injection height will be much greater than a stable environment. This study reinforces the conclusion that smoke plume heights are affected by a combination of environmental and meteorological factors.

*B. Haines Stability Index*

The Haines index proved to be a very useful tool in predicting lower level atmospheric instability for wildfires. We know from Newton's first law of motion that an object in motion will remain in motion until an external force acts upon it. In the case of a smoke plume, the object is the plume and the external force is gravity. The smoke plume injection height is determined the plume's buoyancy; it will continue lifting until the vertical pressure gradient force and gravity are in balance. The pressure gradient force on the plume is determined by a number of factors, two of which are the temperature

gradient and relative humidity of the surrounding atmosphere. This lower level atmospheric instability is precisely what the Haines index measures which explains why this index should be accurate in predicting smoke plume injection height. Unlike other atmospheric instability indices, the Haines index is specifically designed to account for the added element of the fire combustion process. The accuracy of this index has not been completely analyzed because Haines index data was only collected for two regions, the US West and US Central regions. In order to fully assess this index it is imperative that further research in numerous regions be conducted.

## 7. Conclusions

As years progress, weather prediction and climate modeling are rapidly becoming more accurate. There are still many unknowns, some of which are the effects that various environmental and meteorological factors have on smoke plume injection heights. This is very important to understand because wildland fires emit an enormous amount of aerosols into the atmosphere. Some of these are extremely harmful to the environment and human health.

Fire radiative power and atmospheric instability proved to be the factors having the greatest effect on smoke plume injection height. This information is valuable in smoke plume modeling. If the injection height can be accurately modeled, the transport direction and distance can be predicted. This will aid not only in modeling wildland fire events, but also will increase the reliability of air quality forecasts in populated areas. Climate models also use this data to determine the effects that a particular amount of PM has on the environment.

This research was limited to data from 2002 in North America. In order to fully understand the factors that determine plume height it is necessary to analyze multiple years to see if the trend persists. A more in-depth look at the Haines index would be very valuable since it seems to have a strong impact on plume height in the US West region. In future research, a principal component analysis should be done on all of the parameters to generate an equation for calculating the smoke plume height given a certain set of measurements.

## Special Thanks

Thank you very much to everyone who made this internship possible. I thoroughly enjoyed working at NASA Goddard Space Flight Center in the Earth Sciences Division. I had a wonderful experience, and learned an incredible amount in these ten weeks. I would specifically like to thank my mentors Dr. Charles Ichoku, Dr. Jun Wang and Dr. Ralph Kahn for all their guidance and support. Also, thank you to the Summer Institute for Earth Sciences, the University of Maryland Baltimore County, Dr. Franco Einaudi, and Dr. Aly Tokay for the funding and opportunities. Finally, thank you to Ms. Valerie Casasanto and Ms. Valerie Buxton for the time and hard work that they put into this amazing program.

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