FPInnovations
Wildfire Operations Research

PROJECT UPDATE

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Environmental lapse rate: description, detection, influence on wildfires, and relevant technologies

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INTRODUCTION

Wildland firefighter safety is influenced by sudden, unexpected changes in wildfire behaviour. Typically, these changes are brought about by sudden increases in wind speed and changes in wind direction. These changes can generally be predicted or anticipated. Cold fronts passing through can be predicted, sudden increases in wind speed or directional changes can also be anticipated from convective activity (e.g., thunderstorms). Cold fronts and convective activity tend to be visible to firefighters and because of this they are able to take precautions. Far less common, and generally not visible, are changes in wildfire behaviour caused by the extreme instability of the lower atmosphere. This instability can be caused by what is referred to as super adiabatic lapse rates, which are generally due to the extreme heating of the earth's surface in calm conditions.

Atmospheric stability is influenced by the environmental lapse rate. Extreme instability can influence wildfire behaviour and affect firefighter safety. Extreme instability is sometimes associated with super adiabatic conditions. A super adiabatic lapse rate occurs when the temperature change with height is greater than 10°C per km (the rate at which a parcel of dry air cools as it rises or warms as it falls) and is responsible for very unstable atmospheric conditions.

Historically, lapse rate data hasn't been used often in Canadian wildfire operations because there are few data collection points and an insufficient number of collection periods. Some agencies consult atmospheric profiles of temperature, but generally these are large-scale data and provide only general information on the stability of the atmosphere for a large area. For example, Environment Canada has only four collection points in British Columbia with twice-daily measurements.

In 2009, we worked with the British Columbia Forest Service to investigate whether we could collect the data necessary to calculate the local environmental lapse rate using a series of remote access weather stations (RAWS) spaced up a mountainside. After a summer of data collection, we determined that we did not have the tools to move the project forward.

In September 2013, we learned that Forest Protection Limited (FPL)—a private company owned by a group of New Brunswick stakeholders—had installed research-grade meteorology sensors on their fleet of AT-802s. These sensors may allow us to identify atmospheric stability that could be used by wildfire managers to identify potentially dangerous situations.

PROJECT ISSUE

Can real-time weather data collected using current technology (i.e., firefighting aircraft with the AIMMS-20) calculate local environmental lapse rates?

Can the data be used to provide warning to firefighting personnel in an area of concern?

PROJECT OBJECTIVES

1. Complete a literature review to understand environmental lapse rates, how they influence wildfires, and what is required to measure them.
2. Determine whether the AIMMS-20 can collect the necessary weather data, in a format that can be sent to those that will use the data for prediction purposes in real time or close to real time?
3. Determine the frequency (readings per minute) with which weather data needs to be collected.
4. Can the possible occurrences of super adiabatic lapse rate conditions be predicted in association with on-going forest fires and then identified with real-time data collection?

LITERATURE REVIEW

To address the project objectives, a review of the literature is required to understand the aspects of the project. We need to understand the atmosphere and specifically environmental lapse rates. This will allow us to understand how lapse rates and atmospheric stability influence wildfire behaviour. Other models exist and are used by the wildfire community to predict stability and impacts on wildfires, one of which is the Haines Index (Haines 1988). We will describe how it is used and what it provides in terms of predictive measures.

The term *super adiabatic* is not common in the literature in relation to wildfires. One of the few times super adiabatic conditions was mentioned in relation to wildfires was by Alexander *et al*. (1983):

> *High surface temperatures during the afternoon enhanced the atmospheric instability. The lapse rate during the afternoon was thus likely dry adiabatic or super adiabatic in the layer below 3000 m.*

Thus, it may have occurred, but it was not measured or documented. Anecdotally, it has led to wildfires exhibiting extreme behaviour but with little documented data. By understanding super adiabatic conditions, anticipating where it may occur, and then measuring it may increase overall safety of wildland firefighters. The scale of these phenomena tends to be valley size. Thus detecting them becomes difficult, but important if fires are burning in these valleys.

Part One: The Atmosphere

Definitions

ENVIRONMENTAL LAPSE RATE (ELR) – the rate air temperature decreases as altitude increases. It is compared to the dry adiabatic lapse rate or moist adiabatic lapse rate to determine the vertical motion of an air parcel. Generally assumed to be roughly 6.4°C per km.

DRY ADIABATIC LAPSE RATE (DALR) – the rate air temperature decreases with height for a parcel of dry or unsaturated air rising under adiabatic conditions. Adiabatic refers to the parcel of air and that it does not exchange energy with the outside atmosphere. DALR is approximately 10°C per km.

MOIST ADIABATIC LAPSE RATE (MALR) – the air is saturated with water vapor (at its dew point). This lapse rate varies strongly with temperature. A typical value is around 5°C per km. It is sometimes called the saturated adiabatic lapse rate (SALR).

The reason for the difference between the dry and moist adiabatic lapse rate values is that latent heat is released when water condenses, decreasing the rate of temperature drop as altitude increases.

SUPER ADIABATIC LAPSE RATE – occurs when the temperature decreases with height at a rate of greater than 10°C per km. A super adiabatic lapse rate is usually caused by intense solar heating at the surface.

Figure 1 shows the various lapse rates and their associated stability. It is missing the environmental lapse rate line as that is what is measured and thus varies. Where it lies determines the atmospheric conditions.

Atmospheric Stability

Atmospheric stability is a measure of the atmosphere's tendency to encourage or deter vertical motion. Vertical motion is directly correlated to different types of weather systems and their severity. In unstable conditions, a lifted parcel of air will be warmer than the surrounding air at altitude. Because it is warmer, it is less dense and is prone to further ascent. Stability is determined by the environmental lapse rate compared to the dry and moist lapse rates.

Atmospheric stability is defined as the resistance of the atmosphere to vertical motion. This definition and its explanation are based on the parcel method of analysis appropriate to a vertical temperature and moisture sounding through the troposphere (Schroeder and Buck 1970).

STABLE – A temperature lapse rate less than the dry adiabatic rate of 10°C per km for an unsaturated parcel is considered stable, because vertical motion is damped.

UNSTABLE – A lapse rate greater than dry adiabatic favours vertical motion and is unstable.

NEUTRAL – In the absence of saturation, an atmospheric layer is neutrally stable if its lapse rate is the same as the dry adiabatic rate. Under this particular condition, any existing vertical motion is neither damped nor accelerated.

VERY UNSTABLE – Lapse rates greater than the dry adiabatic rate are called super adiabatic. But since they are unstable, the air tends to adjust itself through mixing and overturning to a more stable condition. Super adiabatic lapse rates are not ordinarily found in the atmosphere except near the surface of the earth on sunny days. When an unsaturated layer of air is mixed thoroughly, its lapse rate tends toward neutral stability. Strong heating may produce a pool of superheated air in poorly ventilated basins or mountain valleys. If cap is strong, and a sudden release occurs, a potentially explosive fire-weather situation may develop.

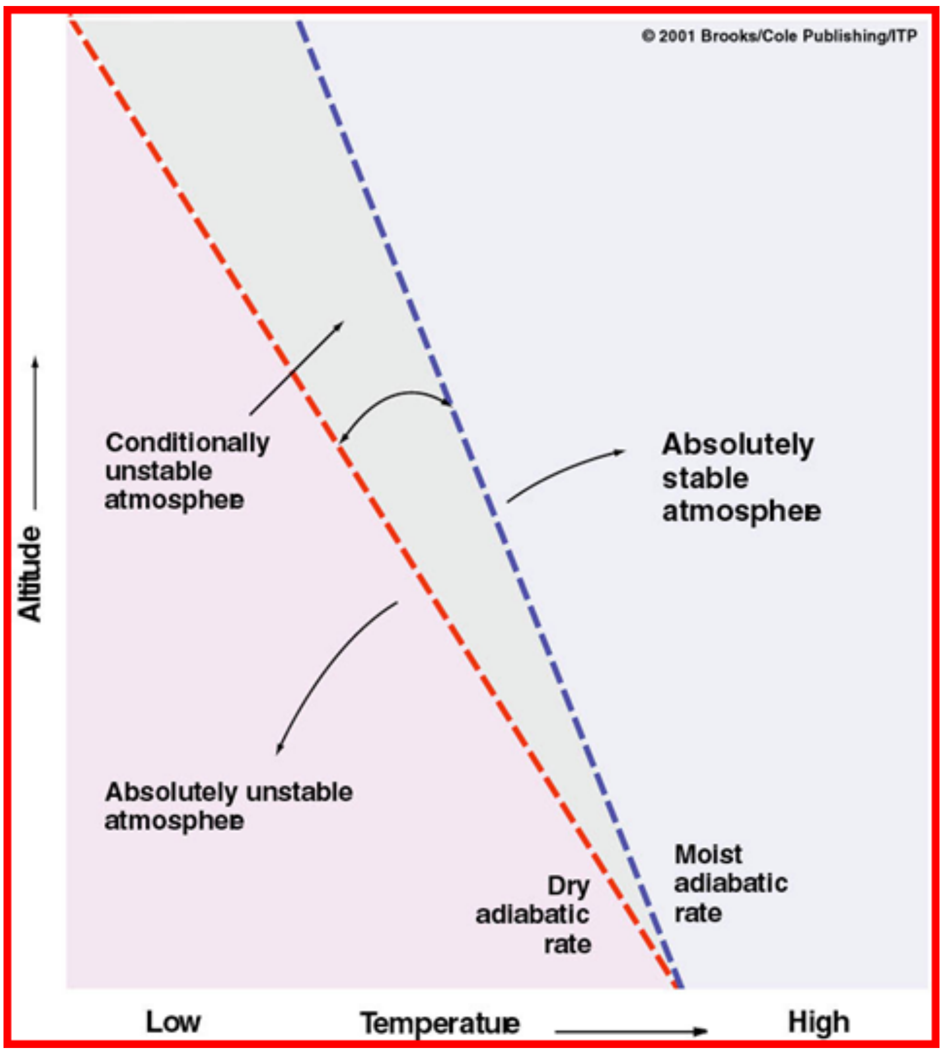

Figure 1. General diagram of lapse rates and stability. Where the slope of the atmospheric lapse rate lies (not shown) determines the stability.

Part Two: Measurement

The following needs to be collected to calculate the stability of the atmosphere:

- temperature (^{o}C). Preferably from the surface to at least 3000 m so a lapse rate profile covering a portion of the lower atmosphere can be built to observe if there is a cap in place.
- relative humidity (%). Used to calculate dew point temperature (see Appendix).
- altitude (m). From surface to an altitude high enough to show the environmental lapse rate.
- atmospheric pressure (kPa)

Sensors on a radiosonde (Figure 2) measure profiles of pressure, temperature, and relative humidity. Wind speed and direction aloft are also obtained by tracking the position of the radiosonde in flight using GPS, or a radio direction finding antenna. Environment Canada releases balloons twice daily from a number of locations across the country (Figure 3) to construct lapse rate profiles for weather prediction. These are sparsely spread across the country and mountainous terrain (Minder *et al*. 2010).

Figure 2. Radiosonde being prepared for release. Courtesy of the Digital Image Library, UCAR.

Figure 3. Sounding locations across North America. The density of sites decreases considerably in Western Canada. Source: http://weather.uwyo.edu/upperair/sounding.html.

An example of the product using the collected data from the radiosonde is presented below (Figure 4). It is from Environment Canada's Stony Plain observatory. The data is collected and sent to the University of Wyoming for processing and diagram production. Figure 5 shows a diagram where it is very unstable near the surface.

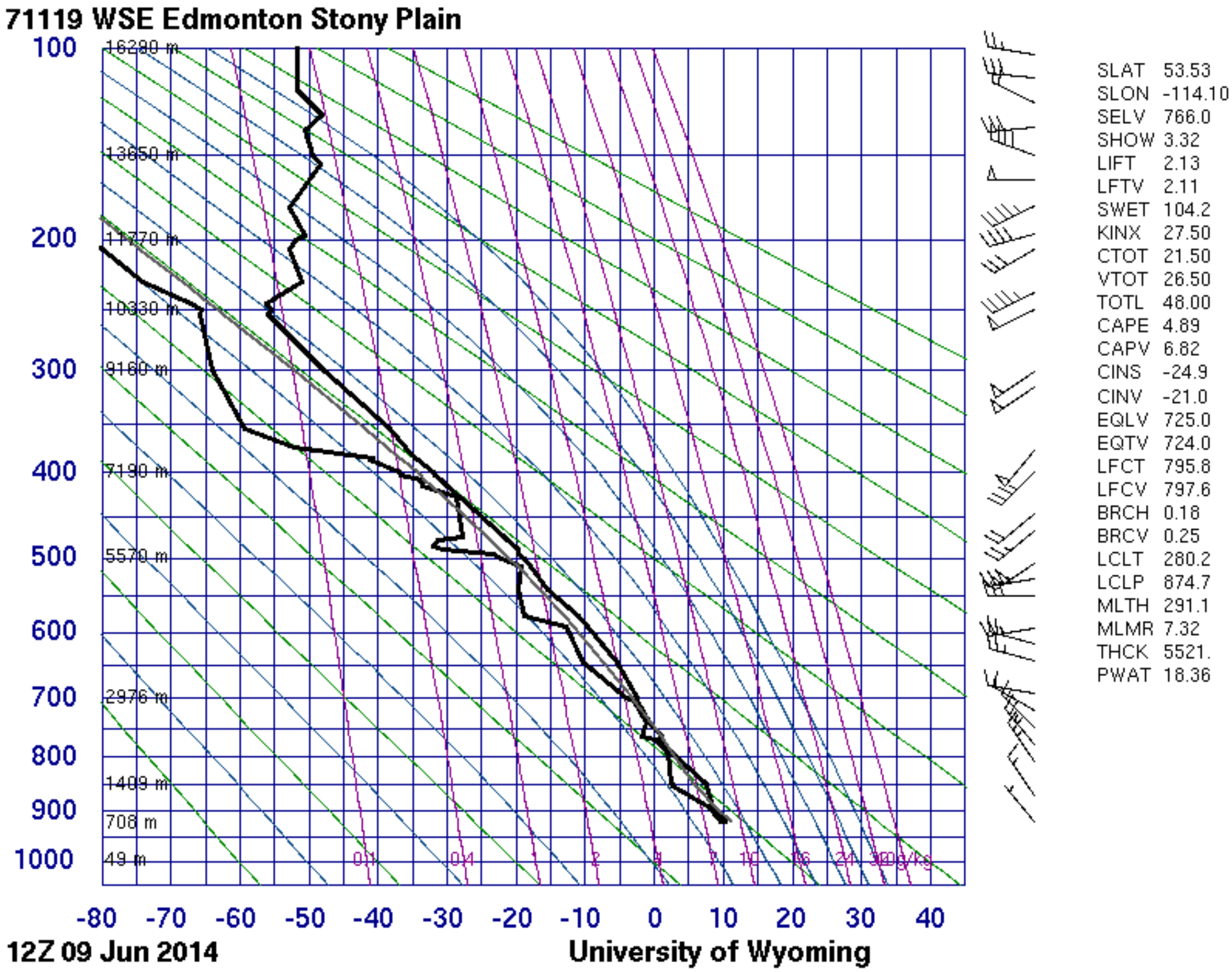

Figure 4. A sounding from Stony Plain, Alberta for June 9, 2014. The left line is the dew point and the right line is the temperature. The dew point is calculated from the temperature and the relative humidity. The stability of the atmosphere can be determined from this diagram.

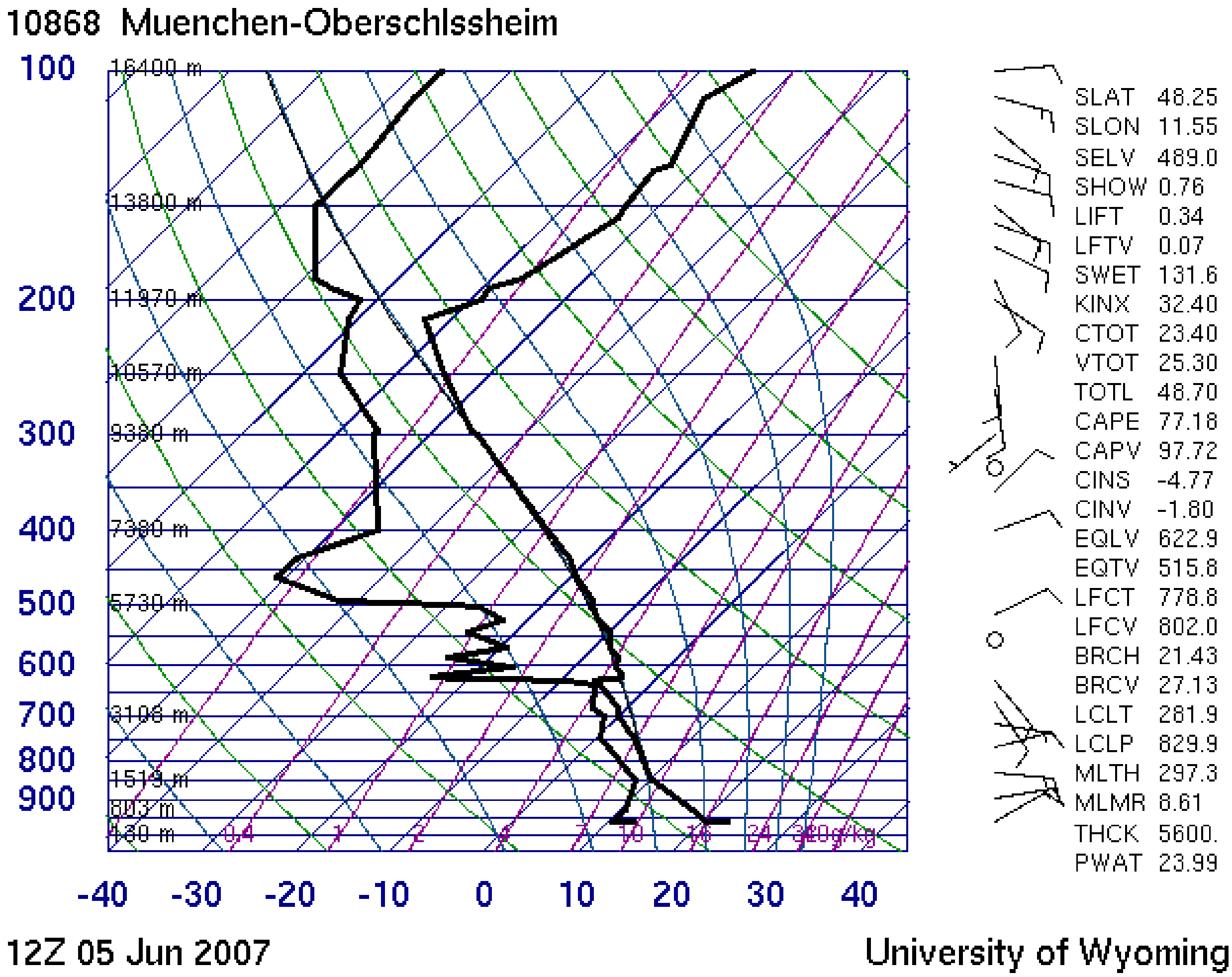

Figure 5. An example of absolute instability. Steep lapse rates near surface.

Part Three: Atmospheric Influence on Wildfire Behaviour

Wildfires are greatly affected by atmospheric motion and the properties of the atmosphere that affect its motion. Most important in evaluating wildfire danger are surface winds, temperature, and humidity. Also important are vertical motions that influence wildfire in many ways. Atmospheric stability encourages or suppresses vertical air motion. The heat of fire itself generates vertical motion, at least near the surface, but the convective circulation thus established is affected directly by the stability of the air. In turn, the indraft into the fire at low levels is affected, and this has a marked effect on wildfire intensity. Also, in many indirect ways, atmospheric stability will affect wildfire behavior. For example, winds tend to be turbulent and gusty when the atmosphere is unstable, causing wildfires to behave erratically. Thunderstorms with strong updrafts and downdrafts develop when the atmosphere is unstable and contains sufficient moisture. Their distinctive winds can influence wildfire behavior as well (Schroeder and Buck 1970).

Problematic Stability for Wildfires

Gusty winds can lead to problematic wildfire behaviour. This can be caused by steep lapse rates leading to mixing, or by the breakdown of a capping layer. The steeper the environmental lapse rate the gustier the winds may become. There are visual signs and measurable data that can be used to confirm these conditions (Countryman 1971). At times, it may be possible to take upper-air observations with portable instruments in fixed-wing aircraft, or helicopters. In mountainous country, temperature and humidity measurements taken at mountaintop and valley-bottom stations provide reasonable estimates of the lapse rate and moisture conditions between the two levels. This was tried by FPInnovations, but the site chosen to collect the data may not have been a site conducive to the development of steep lapse rates. In areas where inversions form at night, similar measurements indicate the strength of the inversion and thus the stability.

Visual indicators are often helpful in understanding current atmospheric stability. Stability in the lower layers can be indicated by the steadiness of the surface wind. A steady wind is indicative of stable air. Gusty winds, is typical of unstable air. Dust devils are always indicators of instability near the surface. Haze and smoke tend to hang near the ground in stable air and to disperse upward in unstable air.

Other Environmental Influences

One of the key factors that will have a large influence on the formation and detection of super adiabatic lapse rates will be the local topography. For these conditions to develop, a valley protected from upper winds and exposed to the sun can produce very steep lapse rates due to intense surface heating and little or no wind movement.

Surface conditions (dark or light coloured) can also act to influence the surface heating. A dark surface (a ploughed field, or recently burnt area) can heat up more than surfaces of other colours and help to produce steep lapse rates.

Smoke insulating the surface can reduce surface heating and is also an indicator of stable conditions.

Other Uses of Atmospheric Data

The data collected by a balloon, or an aircraft flight, can be used for other purposes in wildfire management.

WIND: If winds are strong at altitude, the chances are they will be strong if mixing down to surface occurs. Strong surface winds influence wildfire behaviour (Flannigan and Wotton 2001).

CAPPING STRENGTH: Identifying how thick, or deep the capping layer is can have an influence on wildfire behaviour. A capping inversion is an elevated inversion layer that caps a convective boundary layer. Some caps may be as thin as a few hundred metres. A thin cap can breakdown quickly causing a sudden mixing of the air and an increase in fire intensity. To determine the thickness of the cap frequent readings from the sensor would be required (i.e., every second) to identify temperature changes with altitude if the aircraft is climbing or descending. If the cap is thick it will take strong influences to break it down. It may be thick enough to create stable conditions.

BOUNDARY LAYER: The boundary layer is the part of the atmosphere that is closest to the ground. Normally, the sun heats the ground, which in turn heats the air just above it. Thermals form when this warm air rises into the cold air (warm air is less dense than cold air). This is convection. A convective layer such as this has the potential for cloud formation, since condensation occurs as the warm air rises and then cools.

INVERSION LAYER: An inversion layer is when the normal temperature (warm air below, cold air above) profile is reversed, creating a stable configuration of dense, cold air sitting below lighter, warm air. An elevated inversion layer is thus a region of warm air above a region of cold air, but higher in the atmosphere (generally not touching the surface).

CAPPING INVERSION: A capping inversion occurs when there is a boundary layer with a normal temperature profile (warm air rising into cooler air) and the layer above that is an inversion layer (cooler air below warm air). Cloud formation from the lower layer is capped by the inversion layer. If the capping inversion layer, or cap, is too strong (too close to the surface), it will prevent thunderstorms from developing. A strong cap can result in foggy conditions. However, if the air at the surface is unstable enough, strong updrafts can be forced through the capping inversion. This selective process of only allowing the strongest updrafts to form thunderstorms often results in outbreaks of severe weather.[1]

Stability Models

The Haines Index measures the potential for dry, unstable air to contribute to the development of large or erratic wildfires. The index is derived from the stability (temperature difference between different levels of the atmosphere) and moisture content (dew point depression or dew point spread) of the lower atmosphere (Mills and McCaw 2010). This data may be acquired with a radiosonde, or simulated by a numerical weather prediction model. The index is calculated at low elevation (950–850 mb), mid-elevation (850–700 mb), and high elevation (700–500 mb) (Winkler *et al*. 2007; Goodrick, 2003; Jenkins *et al*. 2003).

A Haines Index of 6 means a high potential for an existing wildfire to become large, or exhibit erratic behaviour. An index of 5 means medium potential, 4 means low potential, and anything less than 4 means very low potential. These are large-scale calculations and may not be accurate at a local scale as the data is collected from the closest national weather station.

[1] Source: http://en.wikipedia.org/wiki/Capping_inversion

Part Four: The Technology

The AIMMS-20 sensor may be useful for identifying environmental lapse rates and was brought to our attention by Forest Protection Limited (FPL) of New Brunswick. FPL has equipped some of its aircraft with these sensors to collect temperature, pressure, altitude, relative humidity, wind speed, and wind direction (Figure 6). FPL uses the data to monitor how spray will deposit and drift during spraying operations.

The AIMMS-20 air data probe (ADP) integrates pressure, temperature, and humidity sensors in a single probe assembly. It is a fully integrated system that can be installed on a wide variety of aircraft. Raw sensor data is processed onboard the aircraft, resulting in datasets comprised of temperature and humidity, each tagged in three-dimensional space and time. The AIMMS-20 combines air data from an externally mounted probe with GPS and inertial signals to compute high-accuracy wind speed and direction data in real time (Witsaman *et al*. 2005). Data can be sent via a satellite network, with the AIMMS-20 operation being completely transparent to the pilot. Data can be transmitted from the aircraft to a satellite, then to a ground station. The ground station then forwards the data via Internet email to where ever it is required.

The AIMMS-20 is essentially an up-to-date five-hole probe, with all elements of the sensor, data processing and analysis in a stand-alone package. The system consists of four modules:

- ADP air data probe; comprising of a five-hole pressure port head and built-in temperature and humidity sensors
- GPS global positioning system; linked to antennae on each wing
- IMU inertial measurement unit
- CPM central processing module

The modules are linked by a high-speed digital serial link known as the Controller Area Network (CAN), which also carries power between the modules (Beswick *et al*. 2008).

Six reports have been collected that document the AIMMS-20 sensor. It has been shown to be accurate and has been used to determine stability over a controlled burn and in conditions conducive to the build-up of the atmosphere to convective storms (Beswick *et al*. 2008). The literature shows this instrument works, and thus the purpose of this work is not to find an instrument that can be used, as it exists. The accuracy of the unit can be tested (Holder *et al*. 2011; Beswick *et al*. 2008; Foster and Chan 2012; McLeod 2011; McLeod *et al*. 2012), but for the identifying of super adiabatic lapse rates, the precision of the collected data is adequate. Figure 7 shows a temperature profile from data collected using the AIMMS-20.

Figure 6. Front view of the AIMMS-20. Source: Witsaman *et al*. 2005.

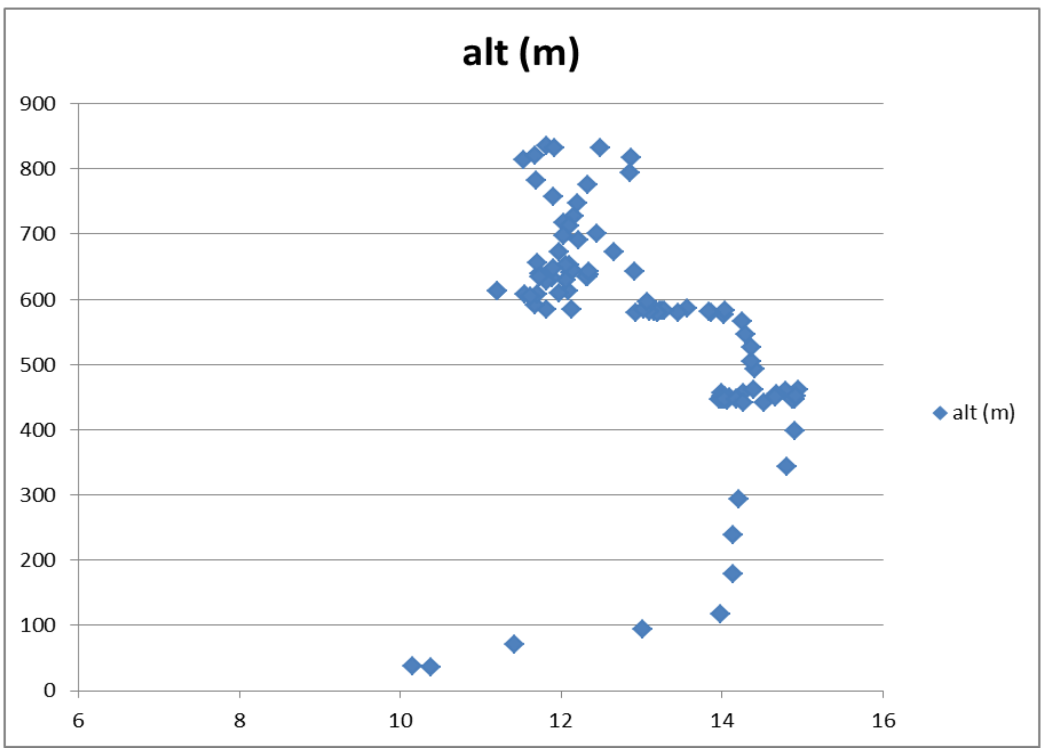

Figure 7. Temperature and altitude data collected by the AIMMS-20 on June 12, 2013, for one 40-minute flight. This flight originated at 36 m elevation and flew to over 900 m. This temperature profile is sufficient to identify lapse rates.

The literature shows the AIMMS-20 can collect the required data to build an environmental lapse rate figure. The challenge now is to identify the conditions that may lead to lapse rates that may have an influence on forest fires while on an active fire and then to employ the AIMMS-20 to verify the conditions may be super adiabatic. This can be a multiple approach. First, look at flight data and see if we can identify situations where the atmosphere was unstable. Second, compare the occasions where lapse rate is indicated to be unstable with a nearby (nearest) ground station. Is there a correlation? Pull fire flight data and examine the lapse rates.

More work may need to take place on transmitting the collected data from the sensor and then inputting it into a program that builds and shows the lapse rate, which then identifies potential issues with stability changes and forest fires. A true lapse rate figure includes pressure, altitude and dew point temperature.

SUMMARY

The technology exists to collect the required data on an aircraft. The AIMMS-20 sensor has been shown to be effective in a number of studies. The precision of the sensor is sufficient that the data collected would identify the trends in a lapse rate. This does not appear to be the challenge in this project, but does need to be verified for ease of use.

The challenge in this project will be identifying when environmental conditions are conducive to the development to super adiabatic lapse rates. This will take a thorough study of lapse rates and the conditions that promote the development of extreme instability. This knowledge will assist in the next step, which is to determine where and when they may develop and in what proximity to active wildfires. Data on winds aloft and the thickness of the cap are also valuable pieces of data to the fire behaviour specialists that can be collected and used.

Elements required to increase the possibility of super adiabatic lapse rates and to test the sensor:

- a busy fire season, to increase data collection possibilities
- high Fire Weather Index (FWI) values
- very dry conditions
- a valley situation so a cap can develop
- light winds into the afternoon
- intense heating of surface
- aircraft with sensors in area

Stability regimes can be quite different from valley to valley. To determine the local stability for wildfire behaviour and weather predictions requires a sounding at the time of interest. Inversions in valleys may, or may not be horizontally continuous in extent, but rather developing in isolated pockets along the valley's axis. Locations along the valley floor may have areas of weaker surface inversions that could result in a faster inversion breakup and could potentially lead to different wildfire behaviour only hundreds of meters away (Werth *et al*. 2011).

Experiments during inversion breakup on valley floors to investigate fire behaviour during transition periods would be ideal.

Next Steps

1. Circulate this report to gather interest from possible collaborators and those interested in sitting on an advisory group to direct the project.
2. Put together an Advisory Group to provide advice on the project.
3. Investigate methods and technology to measure wind speeds outside an aircraft. http://aventech.com/
4. Acquire data from the AIMMS-20 collected on flights for fire suppression purposes if possible. Data will be studied for presentation and ease of use.
5. Obtain or have a program written to create lapse rate profiles from the data provided by the AIMMS-20.
6. Use this website to observe days of known steep lapse rates, extreme instability: http://weather.uwyo.edu/upperair/sounding.html
7. Work with meteorologists to identify the conditions leading to the potential development of super adiabatic lapse rates.

APPENDIX

Calculating dew point from temperature and the relative humidity (Lawrence 2005).

Relative humidity gives the ratio of how much moisture the air is holding to how much moisture it could hold at a given temperature. This can be expressed in terms of vapour pressure and saturation vapour pressure:

$$RH = 100\% \times (E/Es)$$

where, according to an approximation of the Clausius-Clapeyron equation:

$$E = E0 \times \exp[(L/Rv) \times \{(1/T0) - (1/Td)\}] \text{ and}$$

$$Es = E0 \times \exp[(L/Rv) \times \{(1/T0) - (1/T)\}]$$

where E0 = 0.611 kPa, (L/Rv) = 5423 K (in Kelvin, over a flat surface of water), T0 = 273 K (Kelvin), and T is temperature (in Kelvin), and Td is dew point temperature (also in Kelvin).

So, if you know the temperature, you can solve for Es, and substitute the equation for E into the expression for relative humidity and solve for Td (dew point).

A simpler calculation (Lawrence 2005):

$$Td = T - ((100 - RH)/5.)$$

where Td is dew point temperature (in degrees Celsius), T is observed temperature (in degrees Celsius), and RH is relative humidity (in percent). Apparently this relationship is fairly accurate for relative humidity values above 50%.

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