REAL-TIME COLLECTION OF TEMPERATURE LAPSE RATE DATA FROM AIRCRAFT FOR USE IN FIRE OPERATIONS

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ABSTRACT:

FPInnovations investigated the possibility of collecting real time temperature-altitude data that could be used to determine the stability of the atmosphere. Unstable atmospheric conditions have been associated with erratic and extreme fire behaviour. An increased awareness of atmospheric stability conditions would provide fire managers an additional tool to plan firefighting activities. A firefighting aircraft with a specific sensor was sourced and two years of data was collected and analysed to determine if temperature profiles could be built using the data. Results show the data was sufficiently accurate and was collected at a frequency where temperature lapse rates can be calculated, and the stability of the atmosphere in the area of a fire could be determined.
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1 BACKGROUND - LITERATURE REVIEW

The dynamic and volatile nature of wildfire can result in rapid, unpredicted increases in fire behaviour. On some fires, post-fire reviews of the events have suggested that unrecognized, ‘super-adiabatic’ temperature lapse rates may have contributed to this spread by creating very unstable atmospheric conditions conducive to convection. FPInnovations was asked to study these conditions when they may occur, and to investigate techniques to identify (measure) these conditions where active fires are ongoing. The purpose of this is to provide a ‘heads-up’ to fire behaviour specialists to warn firefighters and fire managers of potential blow-up fire situations.

FPInnovations produced a literature review investigating the use of the environmental lapse rate as a mechanism to identify unstable atmospheric conditions in close proximity to active forest fires. Our objective was to determine if super-adiabatic conditions could be measured and identified in near-real time, and this information subsequently being sent to fire behaviour specialists to provide warnings to operational personnel. Unstable conditions can accelerate convective activity through increased atmospheric mixing and create dangerous fire behaviour conditions for those fighting fires. These conditions can sometimes occur unexpectedly with little atmospheric warnings such as cloud development or dust devils.

The term super adiabatic is not commonly found in the literature in relation to wildfires, but one example 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, accelerated mixing may have occurred, but it was not measured nor documented. Anecdotally, these conditions have led to wildfires exhibiting extreme behaviour but there has been little documentation. Understanding super adiabatic conditions, anticipating where they may occur, and then measuring them may increase the overall safety of wildland firefighters. The scale of these phenomena tends to be local in nature, thus rendering detection difficult, but important if fires are burning in these locations.

1.1 The Atmosphere

1.1.1 Definitions

Adiabatic – Refers to a parcel of air that does not exchange energy with the surrounding atmosphere.

ENVIRONMENTAL LAPSE RATE (ELR) – the rate at which 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, it is assumed to be roughly 6.4°C/1000 m.

DRY ADIABATIC LAPSE RATE (DALR) – the rate at which air temperature decreases with height for a parcel of dry or unsaturated air rising under adiabatic conditions. DALR is approximately 10°C/1000 m.

MOIST ADIABATIC LAPSE RATE (MALR) – air saturated with water vapor (at its dew point). This lapse rate varies strongly with temperature. A typical value is around 5°C/1000 m. 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 for the moist air.
SUPER ADIABATIC LAPSE RATE — occurs when the temperature decreases with altitude at a rate of greater than 10°C/1000 m. 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. This figure is missing the measured environmental lapse rate line.

![Diagram of Lapse Rates and Stability](image)

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

1.1.2 Atmospheric Stability

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).

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.

**STABLE** — a temperature lapse rate less than the dry adiabatic rate of 10°C per 1000 m for an unsaturated parcel is considered stable, because vertical motion is damped.

**UNSTABLE** — a lapse rate greater than the 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 a stable, overlying air mass, or cap, is punctured by an unstable, rising air mass, a potentially explosive fire-weather situation may develop.

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

- Temperature (°C): Preferably from the surface to at least 3000 m in altitude, so a lapse rate profile covering a portion of the lower atmosphere can be built and to observe if there is a cap in place.
- Relative humidity (%): Used to calculate dew point temperature.
- Altitude (m): From surface to an altitude high enough to show the environmental lapse rate.

A radiosonde (Figure 2) measures pressure, temperature, and relative humidity profiles. 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 preparation, courtesy of the Digital Image Library, UCAR](image)

![Figure 3 Sounding locations across North America](image)

An example of the product using the collected data from the radiosonde is presented below (Figure 4) from Environment Canada’s Fort Smith observatory. The data is collected and sent to the University of Wyoming for processing and diagram production. This example is taken from the day the Ft. McMurray fire ‘blew-up’.

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http://weather.uwyo.edu/upperair/sounding.html.
1.3 Atmospheric Influence on Wildfire Behaviour

Wildfires are greatly affected by atmospheric motion and the factors that influence instability, specifically surface winds, temperature, and humidity; 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 surrounding 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 behaviour. 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 behaviour, as well (Schroeder and Buck 1970).

1.3.1 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 the mountaintop and valley-bottom stations provide reasonable estimates of the lapse rate and moisture conditions between the two levels. This was attempted by FPInnovations, but the site chosen to collect the data was not 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 stability.

Visual indicators are often helpful in identifying 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 are 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 disperse upward in unstable air.

1.3.2 Other Environmental Influences
One of the key factors that have a large influence on the formation and detection of super adiabatic lapse rates is 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. Albedo (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.

1.3.3 Other Uses of Atmospheric Data
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, chances are they will be strong if mixing down to surface occurs. Strong surface winds influence wildfire behaviour (Flannigan and Wotton, 2001).

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 cooler 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 an area of warm air above 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), thunderstorm development is prevented. 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.\(^b\)

CAPPING STRENGTH: Identifying how thick or deep a 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 break down quickly causing a sudden mixing of the air and an increase in fire intensity. To determine the thickness of the cap frequent readings from a sensor would be required (i.e., every second) to identify temperature changes with altitude. If the cap is thick, it will take strong influences to break it down. It may be thick enough to create stable conditions.

1.3.4 Stability Models
The Haines Index measures the potential for unstable, dry air to contribute to the development of large or erratic wildfires. It 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 over three ranges of atmospheric pressure: low elevation (950–850 mbar), mid-elevation (850–700 mbar), and high elevation (700–500 mbar) (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.

1.4 Data Collection Technology
If aircraft can collect real-time atmospheric data en-route to and over a fire, the information may be useful in identifying when the atmosphere is unstable. We located a sensor used on an aircraft to collect atmospheric data in crop spraying operations. The sensor used, the AIMMS-20, collects research quality temperature, relative humidity, pressure, altitude, and aircraft speed.

Forest Protection Limited (FPL) of New Brunswick has equipped some aircraft with sensors to collect temperature, pressure, altitude, relative humidity, wind speed, and wind direction data (Figure 5). FPL then uses the data to monitor how spray will deposit and drift during 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 on board 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 then be sent via a satellite network to a ground station. The ground station then forwards the data via email to where it is required.

Six reports documenting the use of the AIMMS-20 sensor were found. 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 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 identifying super adiabatic lapse rates, the precision of the collected data is adequate. Figure 6 shows a temperature profile from data collected using the AIMMS-20 from a flight. Following the discovery of the AIMMS-20 and the associated reports, Conair approached FPInnovations to let us know that they also collect atmospheric data.
1.4.1 Conair

Conair is an experienced specialty aircraft operations provider, delivering a comprehensive range of aerial fire control products and services to a variety of national and international customers and partners. They have a fleet of 65 aircraft from which some form of atmospheric data is collected on all of their flights. FPInnovations was provided files to see if the data could be used to build atmospheric temperature profiles. Conair provided a list of the variables collected during their flights and FPInnovations found the data could be further analyzed for potential use. Initially, we analyzed the following data from 20 flights in western North America:

- Time (local and UTC)
- GPS location
- GPS altitude
- Outside relative humidity (RH%)
- Outside air temperature (°C)
- Pressure Altitude (feet)
- GPS Altitude AGL (feet)

We decided to investigate the use of their flight data, as it could potentially provide lapse rate data for a large area in western North America (and Australia). We looked at the sensors used to collect data and where they sit on the aircraft. Two temperature readings are recorded by Conair aircraft; these are ‘Outside Temp’ and ‘OAT’ (outside air temperature). The sensors are located on different parts of the aircraft and thus provide two different temperature patterns as illustrated in Figure 7.
Figure 7 Temperature profiles from two sensors on a Conair aircraft from the same flight.

The ‘Outside Temp’ (blue line) is not as sensitive to changes in temperature as the OAT sensor as seen in the figure. FPInnovations determined that the ‘Outside Temp’ sensor does not respond quickly enough and this could affect the accuracy of lapse rate profiles. Unfortunately, the OAT sensor is only available on a few aircraft – specifically the RJ85 tanker. This limits the number of aircraft available for data analysis.

FPInnovations chose an RJ85 and analyzed flight data from 2015. The aircraft was based in Alaska during the summer of 2015 which was a busy fire season. We collected data for the month of June 2015, and produced case studies. To produce these case studies, we required other data including:

- Satellite images to identify busy fire days.
- Fire weather data from Alaska Fire Service.
- Atmospheric soundings (lapse rate profiles) for the month of June for 00Z from Fairbanks and McGrath.
- Weather data to calculate daily Haines Index values.

We compared the above data to that collected from the RJ85 aircraft (Figure 11). We looked at days with flights that occurred near 00Z time so we could compare flight data to the release of weather balloons. A months’ worth of data was processed and, from this, three days were chosen for case studies. One day had very high hazard, but few fires. Another day had large fire growth from many fires, and the third was a cool, damp day.
Figure 8 The RJ85 dropping a load of retardant in California in 2016.

2 CASE STUDIES

June 16, 2015

June 16th was selected for a case study even though there were not many fires on the landscape (Figure 9). June 16th was a hot, dry day that was drying the fuels for fires that occurred a few days later. The atmosphere did produce a tephigram that can be considered as ‘super-adiabatic’ (temperature lapse rate greater than 9.8°C/1000 m).

Figure 9 A satellite image of Alaska for June 16, 2015. Only a few fires are visible (red dots).

The satellite image above shows clear skies over the majority of Alaska and especially in the interior where the majority of fires occur. Surface temperatures in Fairbanks were almost 29°C at 1600 local time. FPInnovations
downloaded the flight data for T160 (tanker 160) for June 16 and plotted the data collected from flights that occurred close to 00Z. The comparative data we are interested in comes from balloons released from Fairbanks and McGrath.

On June 16th, T160 flew a mission very close to 00Z (1620 local time). We extracted temperature, altitude and GPS location from the dataset and compared to the temperature lapse rate from the weather balloon.

The circed area on the tephigram (Figure 10) is the height and temperature of the atmosphere that we compared to the flight data. This range represents the lower atmosphere which has the greatest influence on fire behaviour. This is the layer of air that heats up, mixes and has direct contact with the fire. Sudden strong mixing of this layer caused by an unstable atmosphere can cause a fire to increase in intensity. The lapse rate calculated from the tephigram is 12.35°C for the first 1000 m above ground level. There is potential for this to mix as the atmosphere tries to achieve greater stability. The data above is plotted against flight data in Figure 11.

Figure 10 The tephigram from Fairbanks for 00Z on June 16, 2015. This equates to June 15th at 1600 local time.

Figure 11 Aircraft data (RJ85) compared to the Tephigram for June 16th.
Figure 11 shows that the temperatures are slightly different between the balloon data and that collected by T160, but the pattern is similar. The initial difference in temperature may be the result of a number of things such as the aircraft instrument not being calibrated to the balloon instrument, the small time difference when temperature collection began, the different direction the balloon rose compared to the flight path, or even the influence of a warm tarmac on the aircraft. The slopes of each line are similar suggesting that the lapse rates produced by both methods of data collection are accurate.

June 30th 2015

The second case study was a day with many fires on the landscape (Figure 12) that grew in size considerably (the fires added 250,000 acres to the overall burned area of Alaska that day). With a bit of cloud cover, the day was not as hot as June 16th, but even with slightly cooler temperatures, the temperature lapse rates were high, indicating unstable conditions which could influence fire growth. Temperature lapse rates for both the weather balloon (tephigram) and the RJ85 T160 (Altitude) are roughly 11.25°C for the lower 1000 m of the atmosphere. Again, the rate of temperature change is very close between these two methods of data collection. Differences assumed to be caused by tarmac temperatures, the placement of the sensor on the aircraft and changes in altitude all appear to be consistent. The flight took off 20m47s following 00Z.

Figure 12 Satellite image for Alaska on June 30th showing extent of fire activity across the State, as indicated by red dots on the map.
June 27, 2015

The lapse rates developed from the aircraft temperature sensors on the hot days have shown to closely mimic the results from the 00Z tephigram from the Fairbanks airport. June 27 was a cooler and damper day than the other case studies. Clouds covered the State and humidities increased providing a break for the fire crews. We are interested in seeing if flight data on cooler days provides similar lapse rates as the balloon data (Fig 15). The flight we collected data from took off 5 minutes after the weather balloon was released.
A different shape to the temperature line is visible in the tephigram above when compared to the other two days used as case studies. The line is more vertical meaning temperature change with altitude is not as great as in tephigram shown for June 16th or 30th. Surface temperatures were well below 20°C. Even with this, the two lines are similar and the slopes are close. It is interesting to note that the aircraft temperatures are always slightly warmer than those recorded by the weather balloon (but do produce same lapse rates).

Figure 15 Comparison of aircraft and balloon (Tep) data.

2.1 Case Study Summary

The three case studies provided three different ‘types’ of weather and fire days Alaska experienced in June of 2015. One day was a clear, hot day with few fires on the landscape; another day was selected that experienced fire growth of a quarter million acres and the third day was a cool, damp day. Flights were selected as close to the release of the weather balloons to try and collect data as close to the same time as possible.

The results from these case studies are positive and suggest we continue to pursue the use of Conair aircraft to collect data to build temperature lapse rate profiles. The advantage of this method is that the Conair aircraft can travel to areas of active fires and provide data to produce stability profiles to anticipate blow-up fire behaviour. Figure 16 shows the data collected for the month of June from the RJ85. This identifies several days where a superadiabatic condition was measured (7) and the days where fires increased dramatically in size. It is anticipated that possible warnings could be issued when lapse rates surpass the 9.8°C/1000 m threshold. Days with temperature lapse rates over the threshold were June 15, 17, 18, 21, 22, 25, and 30th. Days with extreme fire behaviour were June 17, 25, and 26th.
A month’s worth of lapse rate data from the RJ85 from Alaska in June 2015. The line identifies a lapse rate of 9.8°C/1000 m; the threshold to super-adiabatic conditions.

2.2 Summer 2016

Conair based two of their RJ85’s in BC during July and August (2016). FPInnovations collected data from 32 flights between June 5th and August 21st. As in Alaska, tephigrams were collected to compare to each flight. The one difference with this data is that all flights were used instead of just those that took place close to the time the weather balloons were released. If they occurred close to balloon release it was a bonus, but since we have already established that the data collected from the aircraft was accurate, lapse rates from all times of the day could be observed. The data collected over the summer is shown in Figure 17. Lapse rates are shown for the flight to the fire and on the return flight back to the airport. The ‘red’ squares show the mean lapse rate for the flight. Only 11 flights had temperature lapse rates above the threshold of 9.8°C/1000 m. 2016 was relatively quiet in BC with fewer prolonged hot periods than normal.

In addition to the lapse rate data collected on flights to and from fires, photographs from the bird dog aircraft were collected as well. These images showed the smoke column from the fire and thus also provided information on atmospheric stability. Data was collected from the aircraft at take-off; 1000 m AGL; 3000 m ASL; at the drop site; then from the return flight at the same altitudes. This created an atmospheric temperature profile from the airport to the fire and back.
The data shown above (figure 8) is the mean lapse rates for the flights in BC. The red line is the ‘super-adiabatic lapse rate’ (greater than 9.8°C/1000 m). The green arrow is pointing at a flight where the mean lapse rate was 9.29°C/1000 m. This value shows the atmosphere is unstable but has not reached a super-adiabatic state. Photographs of the fire were collected from the Air Attack Officer on this fire. The two photos were taken only 38 minutes apart and show an increase in fire behaviour. The flight data was studied in more detail and we found that the lapse rate when the first photo was taken was 8.86°C/1000 m (Figure 19(A)) and when the second photo was taken was 10.69°C/1000 m (Figure 19(B)). This is a big change in lapse rate and occurred only 38 minutes apart. Fire behaviour increased over this time, perhaps partly due to this increase.
3 DISCUSSION

Two years of data collection has shown that the RJ85, when equipped with an outside temperature sensor, collects data that is both accurate and capable of building temperature lapse rate profiles. During this project, it took two days for data to be downloaded for us to access. This was a research project and therefore this time lag was not a concern. If agencies would like to use this data, then a process is required to gather the data as close to real time as possible.

Conair sends back ‘packets’ of data every time an aircraft makes a drop. This packet of data is small and it should be possible to add a few columns to the data to include temperature and altitude. This data would not affect the efficiency or cost of transmitting the data. This process can be investigated with Conair. Receiving and then rapidly processing the data are the next steps that would be required. The data would need to be sent to a server and into a database with a program to turn the data into a useable format that perhaps includes a ‘warning’ option that produces a ‘red flag’ when lapse rates are above 9.8°C/1000 m. The data would then need to be sent to a fire behaviour expert for use on their particular fire. It would be one more ‘tool’ in their kit to anticipate possible fire behaviour. The associated increase in situational awareness for agencies could support effective fire management decision making and heighten the safety of responders and the public.

4 FUTURE

FPInnovations has shown that atmospheric data collection is possible and the data collected can be used to build atmospheric temperature profiles from the ground to the maximum altitude the aircraft reaches while en-route to a forest fire. It is hoped now that an agency will take these results and implement a process for the use of this data. Data is currently collected on all flights in Canada, the US and Australia where the RJ85 is flown by Conair and potentially on other aircraft if there is a demand. Working together with Conair and their data management company could allow agencies to build near real-time atmospheric profiles to be used for planning purposes and firefighter safety.
5 REFERENCES


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