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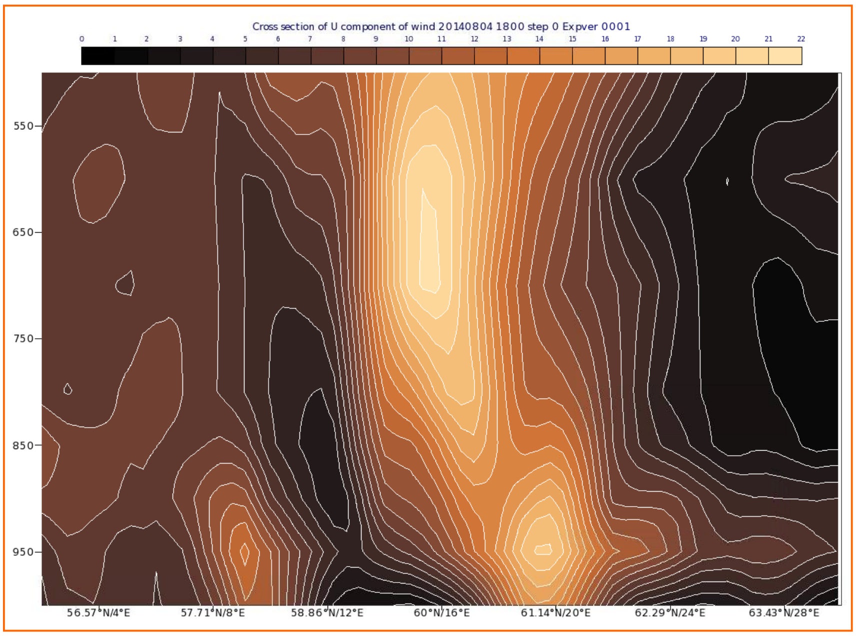

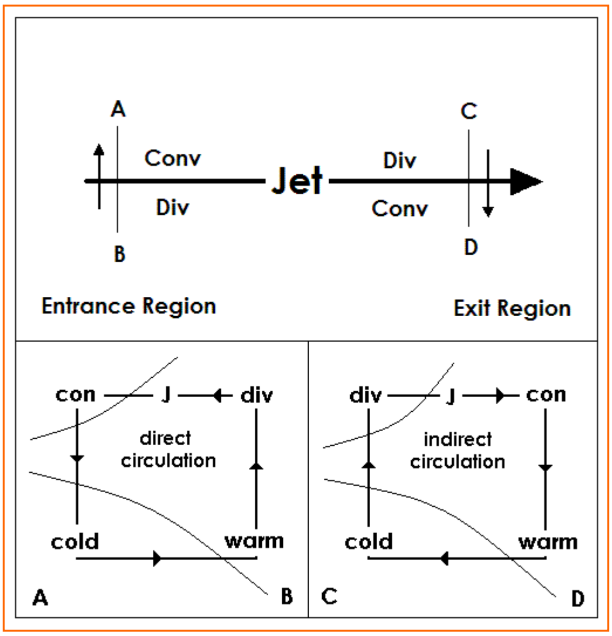

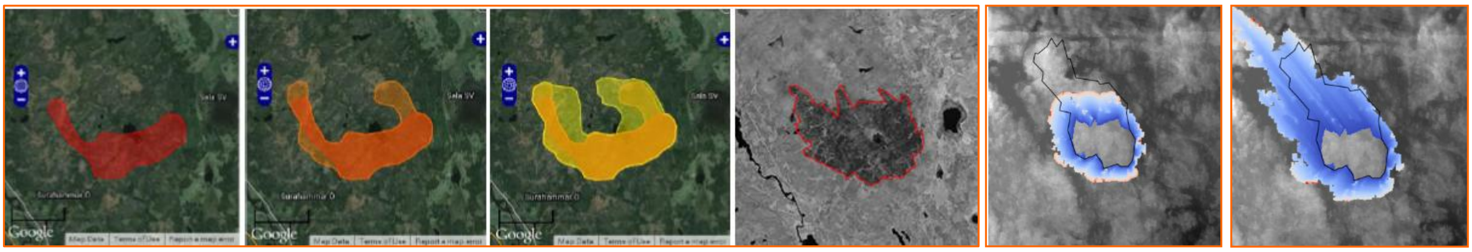

Stability of Atmospheric Flow and Low-Level Jets Influencing Forest Fire Behavior – An EFFIS Report

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Abstract

During the past years, there have been a considerable number of occasions that a forest fire burns with such strong intensity that seems far out of proportion to apparent burning conditions. This proved to be the case for the Sweden fire "blow-up" that took place during 4 August 2014 between Sala and Surahammar municipalities. The fire broke out after an unusual spell of hot, dry summer weather in northern Europe and proved to be the Sweden's largest wildfire in 40 years encompassing an area of ~15,000 hectares. The fire was declared a national emergency.

Close investigation of fire weather parameters revealed the existence of an upper-air trough linked to a dissolving warm front on the previous day (3 August) providing low stability values over the fire centroid and the approach of a cold front from southwest further lowering the stability of the atmosphere. But above all, the air dryness and the prevailing of strong surface wind gusts due to a Secondary Low-Level Jet (SLLJ) at 950 hPa accompanied by a short-wave trough most pronounced at 700 hPa made ideal conditions for such an extreme event. In such a case, the left entrance area of SLLJ would have allowed an ageostrophic circulation to feed dry air by a direct downward current the fire during the critical hours of 4 August.

The time that the SLLJ was crossing and intensifying over and to the east of the fire centroid found to be in agreement with the position and movement of the area of maximum instability as defined by the very high (and at times "saturated") values of Haines index (HI). Both Haines Index (HI) and Continuous HI (CHI) give an indication about the potential for a fire "blow¬ up" due to low stability values of the atmosphere. A fire blow¬up would lead to erratic/extreme fire behavior. These very high values of HI were also combined by an almost "saturated" daily Fire Weather Index (FWI).

Most of the initial simulations utilising ECMWF instantaneous wind speed values, as driving terms for EFFIS (European Forest Fires Information System) fire evolution models, namely FireSim and FARSITE, were inaccurate due to errors in the intensity and gustiness of true prevailing winds. By introducing model gust factor values (GFs) instead of instantaneous speeds (WSs) significant improvement in accuracy was accomplished in all fire evolution simulations. In such distinct unstable environment and under the influence of LLJs/SLLJs the utilization of model gust factors instead of instantaneous winds seems more appropriate.

Overall, it seems quite important to consider the concept of atmospheric stability, dryness and the presence of LLJs/SLLJs as key elements in the forest fire management system particularly in circumstances conducive to interactions within the PBL (Planetary Boundary Layer).

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The time that the SLLJ was crossing and intensifying over and to the east of fire centroid found to be in agreement with the position and movement of the area of maximum instability as defined by the very high (and at times "saturated") values of Haines Index (HI) being combined with almost "saturated" Fire Weather Index (FWI) values. The HI gives an indication about the potential for a fire "blow-up" due to low stability values of the atmosphere whereas FWI provides a description of the fire suppression difficulty. It should be noted that a fire blow-up would lead to erratic/extreme fire behavior.

Most of the initial simulations utilising ECMWF instantaneous wind speed values, as driving terms for EFFIS (European Forest Fires Information System) fire evolution models, namely FireSim and FARSITE, were inaccurate due to errors in the intensity and gustiness of true prevailing winds. By introducing model gust factor values (GFs) instead of instantaneous wind speeds (WSs) significant improvement in accuracy was accomplished in all fire evolution simulations. In such distinct unstable environment and under the presence and influence of both LLJ and SLLJ the utilization of model gust factors instead of instantaneous winds found to be more appropriate for simulating fire evolution behavior.

Overall, it seems quite important to consider the concept of atmospheric stability, dryness and the presence of LLJs/SLLJs as key elements in the forest fire management system particularly in circumstances conducive to interactions within the PBL (Planetary Boundary Layer).

Table of contents

Acronym	*Label*
CEMS	*Copernicus Emergency Management Service*
CHI	*Continuous Haines Index*
COMET	*UCAR's & NOAA's Training Program for Mesoscale Meteorology*
DP	*Dew-Point Depression*
ECMWF	*European Centre for Medium-Range Weather Forecasts*
EFD	*European Fire Database*
EFFIS	*European Forest Fires Information System*
ERCC	*Emergency Response Coordination Center of European Commission*
FFDI	*Australian McArthur Forest / Grassland Fire Danger Indices*
FWI	*Fire Weather Index*
GF	*Gust Factor*
GOLF-GOLD	*Global Observation of Forest and Land Cover Dynamics*
HI	*Haines Index*
LASI	*Lower Atmosphere Severity Index*
LLHI	*Low-Level Haines Index*
LLJ	*Low-Level Jet*
MENA	*Middle East North African (region)*
MLHI	*Middle-Level Haines Index*
MTerm	*Moisture Term (of Haines Index)*
NOAA	*National Oceanographic and Atmospheric Administration*
NWP	*Numerical Weather Prediction*
ROS	*Rate Of Spread (of a fire)*
SLLJ	*Secondary Low-Level Jet*
STerm	*Stability Term (of Haines Index)*
TLR	*Temperature Lapse Rate*
UCAR	*University Corporation for Atmospheric Research*
WS	*Wind Speed*

1. Introduction

1.1 Stability of Atmospheric Flow

Meteorological data (observations) and numerical weather prediction model products (fields) are considered essential to forecast the potential for fires to begin and their behavior once started (GOFC-GOLD-36 Report, 2008). Wind speed, slope, fuel characteristics and fuel moisture are the main factors influencing the fire ROS (Rate Of Spread). ROS, fuel height and fuel load primarily determine fire intensity. The relative importance of wind speed, fuel characteristics and fuel moisture on fire behavior varies at different wind speeds (Scott, 2012). As wind speed increases, it begins to dominate as an influence on fire behavior. On the other hand, temperature, as a single factor, has not a significant impact on fuel moisture and fire behavior, while the direction of fire travel is determined by wind speed and terrain (Tasmanian Bushfires Report, 2013).

The Wind and direction of slope have a similar effect of reducing the distance between the fire and un-burnt fuel. The wildfire industry has long focused primarily on surface weather forecasts, a minor element of the output of weather prediction systems, along with fuel loads and simple terrain metrics (McRae and Sharples, 2013). Besides the weather conditions at ground level, the stability of atmospheric flow should be also considered as it influences the fire behavior (Haines, 1988). In highly unstable atmospheric conditions, fires are more likely to form large convection columns, increasing the fire ventilation rate and, in turn, increasing wind speed and decreasing humidity. Fires burning in unstable atmospheric conditions are much more likely to have enhanced levels of fire behavior.

The effect of stability on fire behavior was firstly studied by Crosby (1949). He concluded that stable air dampened convection currents over a fire, whereas unstable air increased the speed and depth of convection currents. Furthermore, Brown (1950) stated that the stability of air over a fire is as important to fire behavior as temperature and humidity. The desire to provide some quantitative indication of the effects of atmospheric stability on fire behavior led Haines (1988) to develop a lower atmosphere severity index, the so-called Haines Index (HI), based on the stability and moisture content of the lower atmosphere. Since HI is dependent on elevation there exist three combinations of atmospheric layers being used to construct the Haines Index (Low, Middle and High). The HI is the sum of a stability term and a moisture term. The sum provides an indication for the potential of ROS on a given day. In its original formulation it gets integer values from two to six, with six representing the most severe conditions.

In simple words, the drier and less stable the air mass becomes, the higher the HI and the greater the threat of large forest fire and extreme fire behavior since HI values provide a direct indication about the potential for a fire "blow- up" (Potter 2002, Potter *et al,* 2002). A fire blow-up would lead to extreme and erratic fire behavior.

Bally (1995) showed that a large proportion of fire activity in Tasmania occurs on days with HI values falling in the two top categories, and HI could provide information independent of and complementary to the FFDI (Australian McArthur Forest / Grassland Fire Danger Indices, Luke and McArthur, 1978). It should be noted that in practical terms the HI is used in combination with the FFDI in determining the need to issue a fire weather warning (Mills and McCaw, 2010). In recent years there has been a growing awareness of the importance of the vertical structure of the lower atmosphere in the formation of extreme wildfires since it has become evident that upper-air conditions influence wild land characteristics as well (Zimet *et al,* 2007).

1.2 Upper-air parameters influencing fire evolution behavior

Besides the stability of air, other critical weather parameters appear to play a significant role in the evolution behavior of a fire. For instance, over 35 years ago, Brotak and Reifsnyder (1977) identified the presence of an upper level trough in northwesterly flow as a critical factor contributing to the development of large fires. Upper level troughs are regularly associated with upper level frontogenetic processes particularly in the presence of an upper-tropospheric jet feature. These upper processes are associated with intense descent that forces air of upper levels downward along isentropes, which have been tilted into the vertical.

Brotak and Reifsnyder (1977) also examined the location of specific fires relative to frontal structures and associated them with specific, quantitative measures of the atmosphere in order to determine surface and upper-air synoptic weather conditions necessary for large wildland fires resulting that nearly 75% of the investigated fires occurred immediately prior to, or just after, the passage of a notably dry cold front. Based on this, it seems that detailed meteorological data are needed for resolving the exact fire weather conditions prevailing over the greater area of fire (Werth *et al,* 2011).

Critical fire weather patterns also should be carefully examined for the presence of strong low-level jets (i.e., reverse vertical wind profile). Research conducted by Byram (1954) showed a strong connection between low-level jets and extremefire behavior. Schroeder *et al* (1964) performed an extensive study on fire weather patterns, which resulted in the classification of several synoptic patterns associated with high fire danger in 14 regions of the United States. Such synoptic-scale flow is often associated with the development of upper-level frontal zones, also known as upper-level jet-front systems and may be indicted as contributing factors in some wildfire episodes, as suggested by Charney *et al.* (2003).

1.3 Fire suppression difficulty

Fire danger indices on the other hand provide a description of the fire suppression difficulty. The primary index used in Europe is the Fire Weather Index (FWI) adapted by EFFIS (European Forest Fires Information System) that provides a numerical rating for a particular location using air temperature, relative humidity, wind speed and a drought factor (San-Miguel-Ayanz *et al,* 2012). The FWI forecast module of EFFIS generates daily maps of 1- to 10-day projected fire danger level in EU using (surface) weather forecast data.

Common terminology (COMET module, Unit 11) used to describe extreme fire behavior includes the terms "wind-driven" and "plume-dominated" fires. These two terms refer to distinct forcing mechanisms on the fire. However, most fires exhibiting extreme fire behavior are influenced by both mechanisms to some extent. The distinction should be used to describe which force is strongest. In a wind-driven event, the power of the wind is greater than the power of the fire. When the power of the fire is greater than the power of the wind, a plume-dominated pattern is exhibited. Fires that are initially wind-driven, can transition into a more plume-dominated event as the convective column associated with the fire grows and begins to affect the surrounding environment. In the current Sweden case (blow-up event of 4 August 2014) though, it seems that things followed an opposite transition: from plume to wind-driven type of fire.

This work examines the driving weather forcing factors behind the Sweden's fire blow-up by examining the importance of atmospheric flow's characteristics not only in the surface but also at upper levels. The work is structured as follows. The main characteristics of Sweden fire are presented in Section 2, followed by the data and methodology (Section 3) used in investigating the physical forcing factors behind the fire blow-up. Results are contained in Section 4, followed by discussion and conclusions (Section 5).

2. Main characteristics of Sweden Fire

2.1 Details of Sweden’s largest wildfire in the last 40 years

On the afternoon of Thursday 31 July 2014 a wildfire broke out on the border between Sala and Surahammar Municipalities in Vastmanland County in Sweden. This fire proved to be the Sweden's largest wildfire in the last 40 years. The fire broke out after an unusual spell of hot, dry summer weather in northern Europe. The fire was declared a national emergency. It finally encompassed ~15,000 hectares in an area northwest of Sala. One person was reported to have died and thousands evacuated when Sweden's biggest forest fire in modern history spread across eastern and central areas of the country in the first week of August.

By Sunday 3 August, the blaze spread to encroach upon homes as an all-time high of 33°C was recorded in Visby, Gotland, with dry storm clouds producing more than 47,000 lightning strikes. Sunday's hot weather broke the heat record for August since 1992 while more tropical temperatures, rain and thunderstorms, were forecast for the coming days. The position of the fire at noon hours of 4 August is shown in Figure 2.1.1 (a).

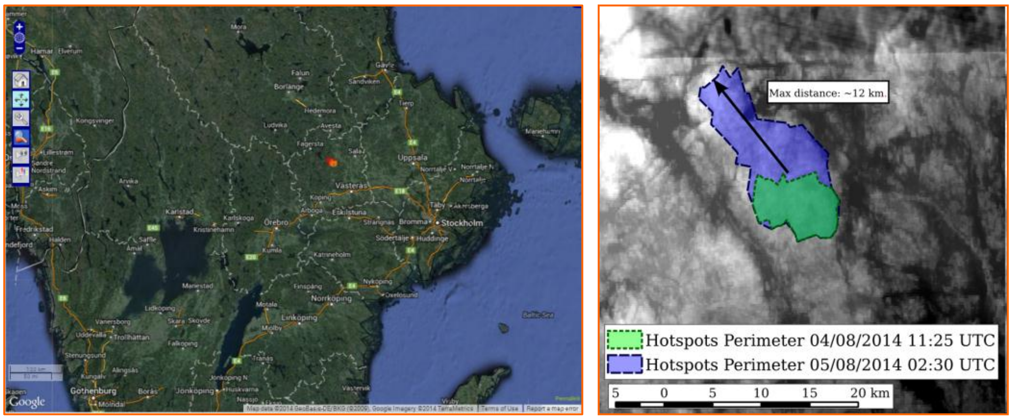

Figure 2.1.1. (a) Position of Sweden fire (indicated by red color) during noon hours of 4 August 2014. (b) Perimeters as defined by hotspots valid for 11:25 (4/8) and 02:30 (5/8).

In Norberg, fires threatened to enter city neighborhoods as residents were obliged to stop seeking help from over 100 volunteers to defend their homes due to risk of loss of life. The decision to halt volunteer efforts came after the event that encroaching flames trapped nine of the workers. They were volunteering to drive water out with tanker vehicles. Firefighters were trying to put out the fire along the road with helicopters so that they can go in with fire trucks and rescue the volunteers. At that time, the main focus of fire suppression efforts had been to stop the fire from spreading towards the northwest and northeast since fires were extraordinarily energetic and appear to have engaged the basement layer. As with other recent Arctic fires in permafrost or near permafrost zones, areas well below the surface soil zone are involved, resulting in risk of a very intense, long time-scale event.

The dramatic change of the fire perimeter and its astonishing expansion of about ~12 km towards northwest taken place during the afternoon and late hours of Monday can be seen in Figure 2.1.1 (b) valid for Tuesday early morning hours (02:30 UTC). The perimeters have been obtained applying an algorithm that utilises fire anomalies from MODIS. This algorithm refers to the selection of a fire and filtering of its hotspots at two stages. Firstly, only the hotspots from MODIS fire anomalies with a confidence higher than 80% are selected. Secondly, hotspots that do not have a certain number of points inside a radius are discarded. Finally, all the edges are discarded except the external edges of the polygon. By utilising this algorithm fire perimeters are obtained using hotspots as inputs. The time stamp assigned for the final perimeter is the time of the last hotspot.

2.2 Synoptic analysis

Based on synoptic surface analysis maps two main weather elements appeared to play an important role in the evolution of the Sweden fire. The first is the upper-air trough (depicted as a solid line) over the area of interest in 00 UTC map of 4 August as shown in Figure 2.2.1 (a) since such troughs contribute considerably to the instability of atmospheric flow.

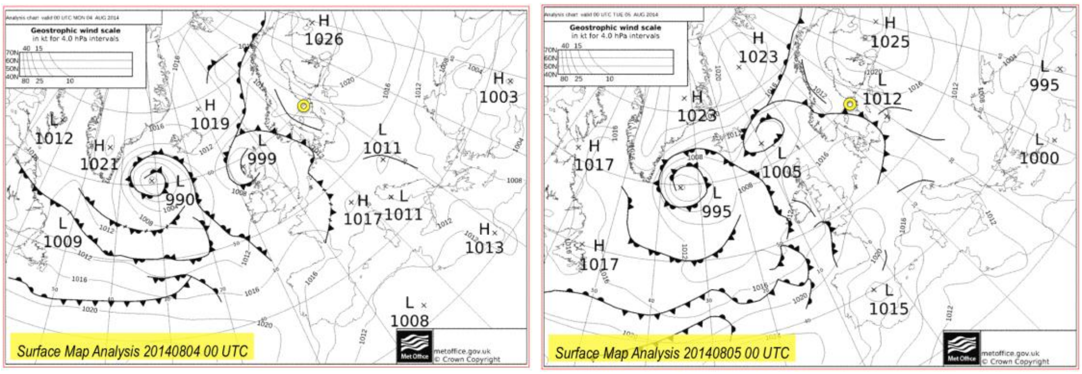

Figure 2.2.1. (a) Synoptic conditions for 4 August 2014 (00 UTC). The position of the greater area of interest (Sala) is denoted by a yellow ring. A cold front is depicted over Denmark while an upper-air instability trough is affecting the western areas of Sala. (b) As in (a) but for 5 August 2014 (00UTC). The surface cold front is depicted as it is approaching over Sala area.

This trough appeared to be linked to a dissolving warm front affecting Sala area the day before (3 August 2014). Besides the instability related to the upper-air trough, the second element had been a weak cold front being depicted on the same map centred over Denmark moving slowly following a north-eastern direction and contributing to the establishment of even more unstable conditions. The same front was depicted at the map of 00 UTC of 5 August as it was approaching over Sala area.

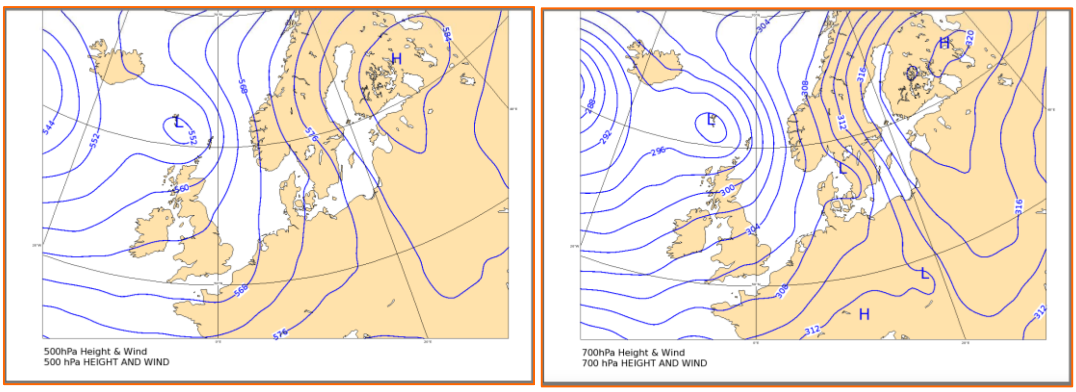

Figure 2.2.2. (a) Upper-air omega blocked circulation based on ECMWF 500 hPa Analysis (T+00) of 4 August 2014 12 UTC. (b) As in (a) but for the pressure level of 700 hPa.

A long list of meteorological parameters and weather elements were investigated in an effort to define possible/potential causes contributing to this fire blow-up. Besides the basic surface maps a vast number of weather parameters of the upper atmosphere were investigated as well. The most dominant feature had been the omega circulation system at 500 hPa causing a south/southeastern blocked upper-air flow as shown in Figure 2.2.2 (a).

In such an environment short-wave upper-air troughs at the western area of the upper anticyclone ridge of the omega circulation system could be contributing to the instability of the flow as they are accompanied by positive advection of relative vorticity maxima. Such a short-wave trough is visible and most pronounced at the levels of 700 hPa affecting the greater area of interest at 12 UTC as shown in Figure 2.2.2 (b).

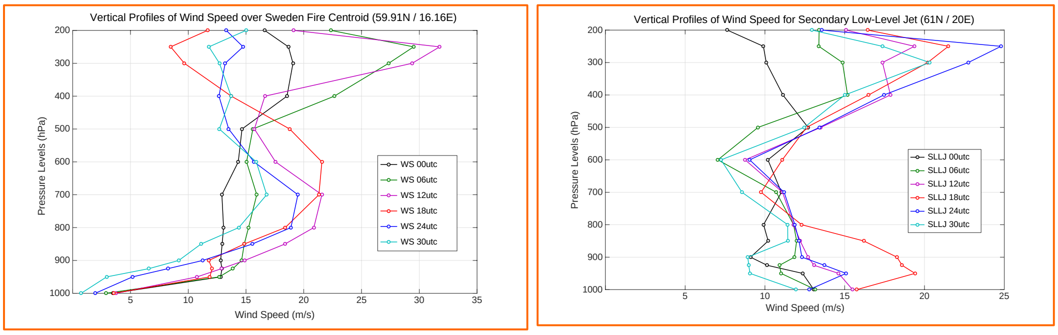

Figure 2.2.3. (a) Vertical profile of wind speeds over fire centroid during the critical time interval (20140804 00 UTC to 20140805 06 UTC). (b) As in (a) but over the position of the SLLJ.

Investigating over the existence of low-level jets various vertical profiles of wind speed were constructed utilizing ECMWF Operational High-Resolution (HIRES) analyses of 4 and 5 August 2014. In Figure 2.2.3 (a) the possible position of a jet reaching 22 m/s (~80 km/h) was depicted at the level of 700 hPa (~3,000 meters above the ground) over the fire centroid. Besides this Low-Level Jet (LLJ) most pronounced at 12 UTC another significant jet, a Secondary LLJ (SLLJ) was depicted to the northeast affecting the fire between 12 and 18 UTC. It became clear that during these critical hours, the area of fire was under the influence of the left entrance region of the SLLJ. This is an area of strong convergence and direct downward circulation. In Section 4, the significance of this SLLJ is being presented in full details.

2.3 Activation of EU protection mechanism

By Sunday 3 August, Sweden had activated the EU Civil Protection Mechanism to fight the forest fires, based on which Italy and France have sent fire-fighting aircraft to reinforce efforts to contain the fire. In addition, the Copernicus Emergency Management Service (CEMS), coordinated by the JRC, was activated on Monday 4 August. The request triggered a rapid reaction from the European Commission's Emergency Response Coordination Center (ERCC) that immediately alerted the civil protection authorities of all the countries participating in the Mechanism.

A large-scale response to the blaze included a small army of fire fighters from three Swedish regions, the Swedish military and aid from the European Union nations France and Italy. From EFFIS maps, the burned area was estimated 3,300 ha at midday 4 August. According to a preliminary EFFIS estimation made for the morning of Tuesday 5 August, the burned area had increased quite significantly and it had been well above this value (due to its distinct blow-up during the previous hours). Furthermore, the latest hotspots detected from the satellite imagery on Tuesday morning were indicating that the fire had been quickly progressing towards northwest due to a combination of strong gusty winds and maximum values of atmospheric instability.

3. Data and methodology

As a first step in assessing the possible link of atmospheric stability to extreme fire behavior, the European Fire Database (EFD) of the European Forest Fires Information System (EFFIS) was utilised focusing on the past large fires having a burned area greater than 500 ha. A collection of 1,135 large fires was possible for a period of six years (2009-2014) referring to both European and MENA (Middle East / North African) countries.

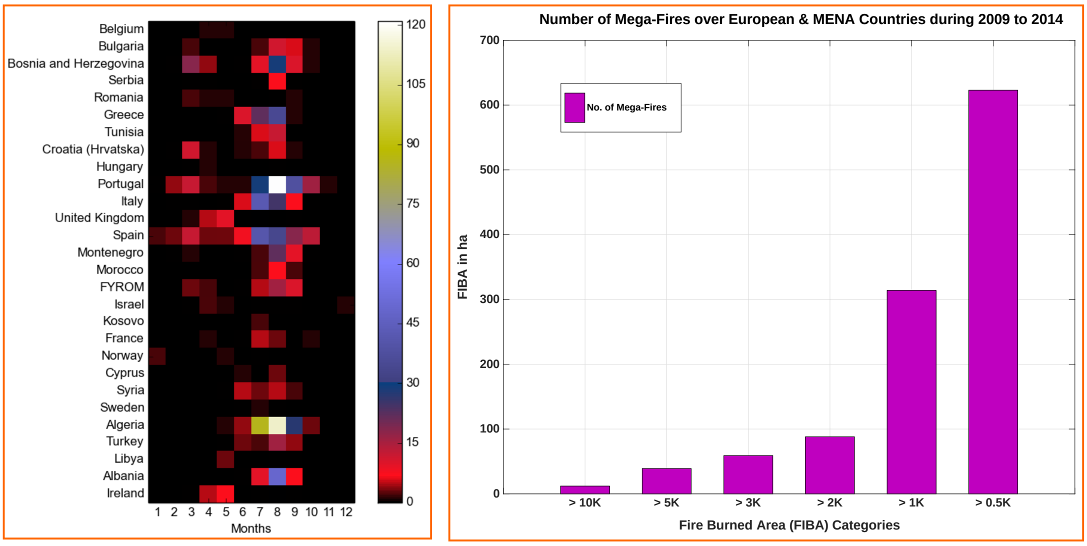

Figure 3.1. (a) Number of large fires per country (Europe & MENA). (b) Number of fires falling into different categories of FIBA (FIre Burned Area).

The EFD is the largest repository of information on individual fire events in Europe as clearly described in San-Miguel-Ayanz *et al,* 2012. It is the end product of a long collaboration between European countries and the European Commission on forest fires. Since 2000, the forest fire data provided each year by individual EU Member States and other European countries have been checked, stored and managed by JRC within EFFIS. During the years, both the EFD and the number of Member States and other participating European countries that contribute to EFD has been gradually increasing.

Figure 3.1 (a) contains the number of large fires per country (belonging to Europe or MENA) and it is obvious that the most affected Mediterranean countries (overshooting the blue category) are Portugal, Spain, Italy and Greece with emphasis during summer months. In Figure 3.1 (b) different categories of fires were considered based on FIBA (FIre Burned Area) and it becomes clear that the top FIBA category (FIBA > 10,000 ha) has 12 members. Concerning the Sweden fire it was found to belong in this top-12 very large fire category.

3.1 Stability and fire weather indices

Concerning the use of stability indices in meteorology these are generally applied for the discrimination of low stability (high unstable) environments that might lead to the formation of thunderstorms. Almost all of these indices are based on parcel theory (Seinfeld and Pandis, 1998). Stability indices generally incorporate low-level moisture and temperature, together with some mid-tropospheric temperature component, and assume that at some point a lifted parcel will cool to condensation, and subsequently ascend along a saturated adiabat (Emanuel, 1994). For fire weather applications the atmosphere is usually dry, so moist convection is less of an issue, at least until after a pyro-cumulus cloud is formed (Mills and McCaw, 2010).

Table 3.1.1. Components of Low-Level (LLHI) and Mid-Level (MLHI) Haines Index formulation following Haines (1988). Symbol T refers to temperature while T_d to dew point at various pressure levels.

LLHI TLR $T_{950} - T_{850}$	**STerm**	**LLHI DP $T_{850} - T_{d850}$**	**MTerm**	**MLHI TLR $T_{950} - T_{850}$**	**STerm**	**MLHI DP $T_{850} - T_{d850}$**	**MTerm**
3˚C or less	*1*	*5˚C or less*	*1*	*5˚C or less*	*1*	*5˚C or less*	*1*
4˚ to 7˚C	*2*	*6˚ to 9˚C*	*2*	*6˚ to 9˚C*	*2*	*6˚ to 12˚C*	*2*
8˚C or more	*3*	*10˚C or more*	*3*	*10˚C or more*	*3*	*13˚C or more*	*3*

The original Low-Level Haines Index (LLHI) defined originally as LASI (Lower Atmosphere Severity Index) in Haines (1988) comprises two terms: (a) the temperature lapse rate (TLR) between two atmospheric levels, and (b) the difference between temperature and dew point (dew point depression) at the upper level (DP).

Based on predefined thresholds each component, namely: Stability Term (STerm) and Moisture Term (MTerm), gets integer values from 1 to 3 contributing to the calculation of the index by summation. The possible values of LASI (LLHI) can range from 2 to 6, with the higher values indicating low stability of the atmospheric flow, so, greater fire danger. In the Sweden fire case, two of the Haines Index formulations were used: the low and the mid elevation one (details are shown in Table 3.1.1). Besides the original formulation of LASI there also exists its continuous formulation (Mills and McCaw, 2010), based mainly on the desire to provide greater discrimination of HI values. The Continuous Haines Index (CHI) eliminates abrupt transitions between categories and offers greater discrimination at high values, rather than topping out at 6. It also allows a more realistic evaluation of the contributions of atmospheric instability and dew point depression to the overall score.

Considering the STerm and MTerm (Table 3.1.1) of the Mid-Level Haines Index (MLHI), then a set of linear functions of temperature lapse rate and dew point depression for these components can be derived as:

$$STerm = 0.5\,(T_{850} - T_{700}) - 2.0 \qquad (1)$$

$$MTerm = 0.3333\,(T_{850} - T_{d850}) - 1.0 \qquad (2)$$

where STerm (MTerm) is the continuous form of Stability Term (Moisture Term), and adding the two provides the so-called "Continuous Haines Index", hereafter CHI:

$$CHI = STerm + MTerm \qquad (3)$$

In practice, due to occasional very large dew point depressions, together with the non-linearities of the hypsometric equations, the Moisture Term might become disproportionately large, and that is why the following (4) & (5) conditions should be applied:

$$\text{if } (T_{850} - T_{d850}) > 30^\circ C, \text{ then } (T_{850} - T_{d850}) = 30^\circ C \qquad (4)$$

if MTerm > 5.0, then MTerm = 5.0 + (MTerm - 5.0) / 2.0 (5)

Concerning the upper limit of STerm component, it seems to exist a natural upper boundary value of ~6 as being imposed by the dry-adiabatic lapse rate (Simpson *et al,* 2014). This upper boundary seems to be in agreement with the range of temperatures usually being experienced in Mediterranean latitudes (representing the central zone area of this study). On the other hand, for MTerm component the imposed conditions (4) & (5) result in an upper bound of MTerm value of ~7, so, the upper bound of CHI to be ~13.

Table 3.1.2. Mid-Level CHI extremity categories as defined in Tasmanian Bushfires Report, 2013.

CHI	Likely fire behavior and fire prediction reliability
0 - 4	*Fires are easily controlled. Modeling is highly likely to over-predict fire travel.*
4 - 8	*Fires may be difficult to control and fire behavior may be erratic (transition phase of fire behavior). Modeling is likely to be close to actual fire behavior.*
8 - 10	*Fires will be difficult to control and fire behavior will be erratic. Modeling is likely to under-predict fire behavior.*
10 - 13	*Fires will be uncontrollable and extremely difficult to extinguish. Modeling is highly likely to dramatically under-predict fire behavior.*

Summarizing, CHI values can provide a measure of atmospheric stability, and this may be used to help determine fire danger ratings, based on its values ranging between zero (0) and 13. This area is still the subject of research and final validation of the index is expected to take place as knowledge increases. Following suggestions by Marsdem-Smedley taken from the Tasmanian Bushfires Inquiry Report (2013), it is possible to construct Table 3.1.2 referring on how CHI values could provide a measure of atmospheric stability, and this could be used to better determine fire danger ratings.

Concerning fire danger indices, the Fire Weather Index (FWI) was utilised from EFFIS in both diagnostic (analysis) and forecast mode. The fire danger forecast module of EFFIS besides the analysis (day 1) it also generates daily maps of 2- to 10-day projected fire danger level in both European and global scale.

3.2 Model gust factors

Since unstable air amplifies the vertical growth of the plume by enhancing the strength of the updrafts (Werth *et al,* 2011), this results to an increase of combustion rates by supplying more oxygen to the fire. As the height and strength of the plume increases, the potential for gusty surface winds also increases. In order to assess the accuracy of ECMWF surface wind forecasts emphasis was given to the model gust factors (besides the instantaneous wind fields). In NWP (Numerical Weather Prediction) models winds at the 10-meter level is computed for post-processing because it is the standard level for SYNOP observations.

Gusts on the other hand, are defined as wind extremes and constitute an important forecast parameter. The processes leading to their formation, such as boundary-layer turbulence, deep convection, mountain waves and wake phenomena are generally not resolved in NWP models, so frequently parametrisations and diagnostic formulae are used to predict gusts based on more coarse grained output from NWP and/or limited observations (Sheridan, 2011). For many years the gust formulation had been based on an assessment of the turbulent gustiness in the boundary layer.

However, this takes no account of gustiness associated with convective situations. The typical wind output of NWP models is a set of instantaneous wind fields, i.e., fields that are valid for a specific time of the forecast horizon. To simulate gusts the standard deviation of the horizontal wind at 10-meter height (F_{10}) is estimated on the basis of the similarity relation as described by Panofsky (1977). The resulting wind gust (F_{gust}) is given by the equation

$$F_{gust} = F_{10} + C_{ugn}\, u_* \tag{6}$$

with parameter C_{ugn} = 7.71 and u_* from the surface stress as computed in the vertical turbulent transport code (Beljaars, 1987). From the controlling parameters it is clear that the effects of surface friction (through surface roughness) and stability are captured. However, the approach is not adequate for gusts in baroclinic situations (and where gusts are due to strong convective events.

A new formulation has been developed which overcomes this limitation (Bechtold and Bidlot, 2009). The algorithm for estimating gusts takes into consideration the vertical momentum exchange, based on the shear forecast at low levels, only applying the algorithm where deep convection is diagnosed within the NWP model. Therefore, in the presence of deep convection, a convective contribution as a function of the vertical wind shear is added to the turbulence gustiness so that the total gustiness becomes:

$$F_{gust} = F_{10} + C_{ugn}\, u_* + C_{conv}\, max\,(0, U_{850} - U_{950}) \tag{7}$$

where the convective mixing parameter C_{conv} = 0.6, and U_{850} and U_{950} are the wind speeds at 850 and 950 hPa, respectively. Parameter F_{gust} is computed every time step and its maximum since the last post-processing is written out for archiving.

3.2 Hi-Res simulations of HI, CHI, wind speed (WS) and gust factor (GF)

Hourly calculations of Haines Index were made utilizing NWP simulations by ECMWF model with different configurations. Both components (STerm & MTerm) of HI and CHI were assessed focusing onto the critical interval of fire blow-up during 4 August 2014. Besides the various formulations of HI/CHI indices, different configurations of ECMWF model are shown in Table 3.3.1. The operational configuration of the High-Resolution (HIRES) ECMWF forecast utilises the comprehensive scheme of the 4th Dimensional Variational Assimilation (4DVAR) in order to construct an optimal set of initial conditions (analyses). This scheme refers to both H_01 and H_02 and H_33 configurations.

Besides 4DVAR (Liu *et al,* 2008, 2009) there exists another analysis scheme that utilizes a longer assimilation window (Andersson *et al,* 2005, Kalnay *et al,* 2007), the so-called Long DA (Data Assimilation), and it is referring to the rest of the experiments. Both 4DVAR and Long DA model configurations had been formulated mainly to the HIRES horizontal resolution of 16x16 km.

Finally a scheme of even finer horizontal resolution was considered for the HI simulations. As an exception, the H_13 and H_23 configurations had been implemented with an experimental resolution scheme, the so-called "Cubic", referring to the capability of integrating ECMWF model utilising a horizontal resolution of 8x8 km (Yessad *et al,* 2014). All formulations mentioned in Table 3.3.1 are referring to a vertical discretization (Simons *et al,* 1989) comprising 137 model levels.

Investigating over extreme values of critical parameters such as HI/CHI, Wind Speed (WS), Gust Factor (GF) and FWI, long series were constructed as a set of 30-year time series (1980 to 2009) by utilising ECMWF ERA-Interim (ERA-I) reanalysis data base for all 1,135 fire centroids of interest. The European ERA-I database that has been produced by the European Centre for Medium Range Weather Forecasts (ECMWF) is the latest global atmospheric reanalysis platform with such capabilities. The ERA-I is a global reanalysis dataset covering the data-rich period since 1979, and continuing in real time. As ERA-I continues forward in time, updates of its archive are taking place on a monthly basis. The ERA-I project was initiated in 2006 to provide a bridge between ECMWF's previous reanalysis, ERA-40 (from 1957 to 2002), and the next generation extended reanalysis envisaged at ECMWF (Berrisford *et al,* 2009, Dee *et al,* 2011).

Table 3.3.1 Basic characteristics of ECMWF model configurations and HAINES Index simulations

Form	Index	Level	DA / RES	Res. (km)	Date	Time	Horizon
H_01	HAINES	Low	4DVAR	16	20140803	00 UTC	T+72
H_02	HAINES	Low	4DVAR	16	20140804	00 UTC	T+48
H_03	HAINES	Low	Cubic	8	20140804	00 UTC	T+48
H_11	HAINES	Low	Long DA	16	20140803	00 UTC	T+72
H_12	HAINES	Low	Long DA	16	20140804	00 UTC	T+48
H_13	HAINES	Low	LDA / Cubic	8	20140804	00 UTC	T+48
H_21	HAINES	Mid	Long DA	16	20140803	00 UTC	T+72
H_22	HAINES	Mid	Long DA	16	20140804	00 UTC	T+48
H_23	HAINES	Mid	LDA / Cubic	8	20140804	00 UTC	T+48
H_31	C-HAINES	CHI-Mid	Long DA	16	20140803	00 UTC	T+72
H_32	C-HAINES	CHI-Mid	Long DA	16	20140804	00 UTC	T+48
H_33	C-HAINES	CHI-Mid	4DVAR	16	20140804	12 UTC	T+24

Summarising, the ERA-I atmospheric model and reanalysis system has a spatial horizontal resolution of 0.7° × 0.7° and a vertical discretization of 60 atmospheric layers. In order to construct the desired climatological PDFs (Probability Density Functions) over the 1,135 selected points an inverse distance weighting (interpolation) technique was applied that estimates the value of each weather variable resorting to the inverse of the distance to each known point ("amount of proximity").

The resulted value (after assigning weights) represents the weighted average of the corresponding variable at the 4 surrounding ERA-I grid point (nodes). All daily values used for the time series cover the period from 1 January 1980 to 31 December 2009 referring to four windows: 00- 06- 12- and 18 UTC, with a total extent of 10,950 records. Such a set up allows the estimation of the mean (daily) values by averaging 00, 06, 12 and 18 UTC values, while max and min values are estimated by considering the max and min of intra-daily values.

4. Results

The idea to study a connection between atmospheric stability and extreme fire behavior appeared firstly in Foley (1947) and later in Crosby (1949), and Byram and Nelson (1951). All these authors connected instability to fire erratic behavior through turbulence and high winds whereas authors as Brotak and Reifsnyder (1977), Haines (1988) and Potter (2002) also included some measure of moisture aloft in their efforts to assess the instability of atmospheric flow.

In simple words, an unstable atmosphere provides less resistance than a stable one to the ascent of hot air in the fire's plume and greater efficiency of mixing air between the ground and regions higher up. A clear effort to establish a correlation between low moisture aloft and large fire occurrence at the ground was made by Brotak and Reifsnyder (1977) and resulted to the inclusion of the so-called Moisture Term (MTerm) in the Haines Index.

In this work an investigation was made for a possible link between the instability of air as expressed by Haines Index and the occurrence of large fires over European and MENA countries during the last six years. Based on the exact position of each fire centroid the so-called CHI (Continuous Haines Index) was calculated based on ECMWF analysis fields. The maximum value of 00- 06- 12- and 18 UTC CHI analysis was kept as a measure of the daily atmospheric instability. Based on such daily values Figure 4.1 was constructed for the set of 1,135 fire cases.

Additional graphs were also made for its accompanied set of 2,480 days of fires. This was done since the set of fire cases refer to the first day of fire whereas the set of fire days contains all days of active fire.

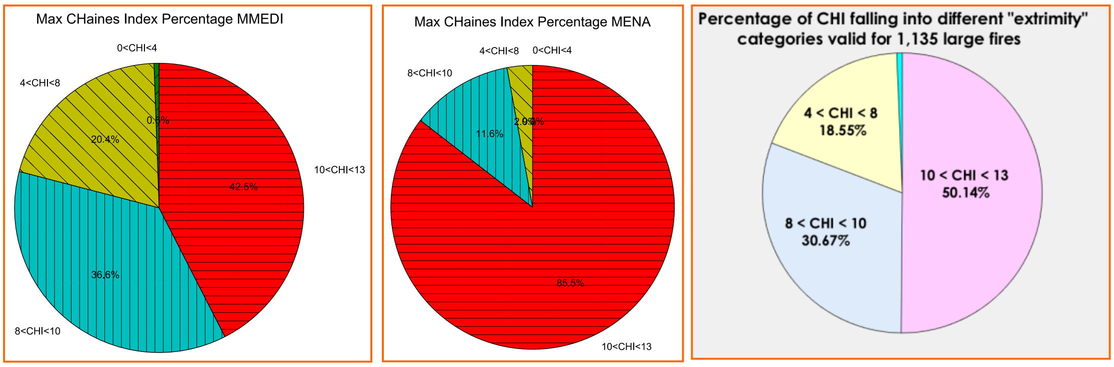

Figure 4.1. Percentage of Haines index values falling in different categories of "extremity" for MMEDI (a), for MENA (b) and for all European & MENA countries (c).

Very similar results were found for both sets of fire cases and fire days suggesting that more than 80 % of the total number of large fires was falling in the two top extremity categories of CHI, as shown in Figure 4.1 (c), although this number was not uniformly spread over European and MENA countries.

For instance over the main Mediterranean countries (Portugal, Spain, France, Italy and Greece) this percentage found to be equal to 79.1% as shown in Figure 4.1 (a), while it was reaching to a maximum value of 97.1% for MENA countries, as depicted in Figure 4.1 (b).

Based on such considerable high percentage values it seems more than likely that low stability conditions had been accompanied most of the large fires taken place over Europe and MENA during the last six years.

4.1 Assessment of critical weather elements

Analyzing the full set of hourly simulations for HI/CHI and daily simulations for FWI the possibility of such values to be considered as alarm bell signals for a potential fire blow-up was examined. FWI provides a description of the fire suppression difficulty, whereas, HI/CHI combines stability and dryness of the atmosphere to measure the atmosphere's contribution to the growth potential of a forest fire as one of the driving forces behind significant fire blow-ups.

Long time series of both FWI and CHI values were obtained for the exact position of Sweden's fire centroid (59.91N/16.16E). These "pinpoint" values were estimated by the methodology of inverse distance weighting (interpolation) technique as explained in the previous Section 3. In Figure 4.1.1 (a) the daily maximum CHI versus FWI daily values are plotted over a period of 30 years (1980 to 2009). Points corresponding to day 1, day 2, day 3, day 4, day 5 and day 6 of the Sweden large fire (Megafire) are plotted as individual dots using different color, with day 5 dot corresponding to the blow-up event of 4 August 2014. The same "raw" values from day 1 to day 6 expressed as percentile values are plotted in Figure 4.1.1 (b). It becomes clear that both FWI and CHI values were at "saturated" mode during the blow-up event as they were reaching to their top 99% percentile value.

It should be highlighted also that in the case of FWI such saturated values could have been available as forecast guidance to the fire manager at least five days (T+120 hours) before the blow-up event. In the case of CHI, such information was unavailable since there has not been any implementation of an operational forecasting scheme for CHI in Europe yet. Nevertheless, a series of CHI forecast was constructed by utilising ECMWF HIRES model simulations over various forecast horizons investigating if some useful guidance could have been available to the fire manager prior the blow-up event.

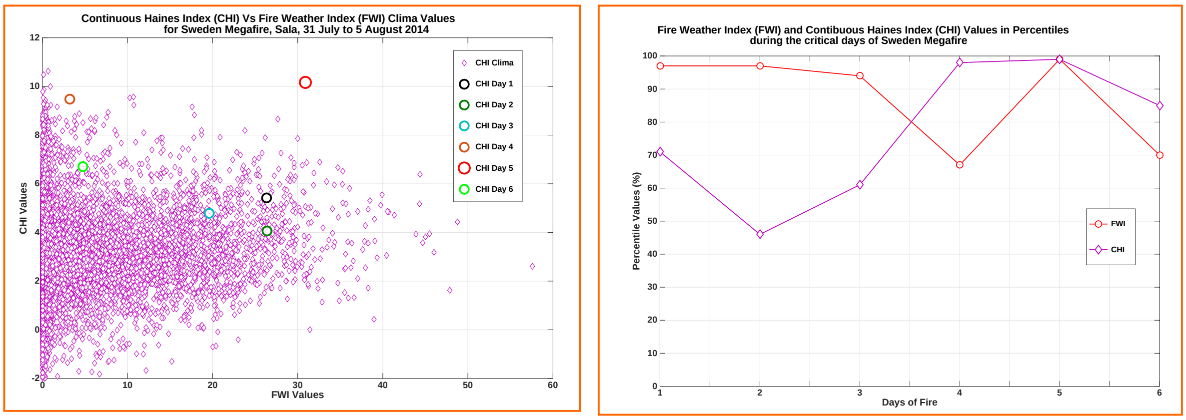

Figure 4.1.1. (a) Daily maximum CHI versus daily FWI values over a period of 30 years (1980 to 2009). Larger dots (points) corresponding to day 1, day 2, day 3, day 4, day 5 and day 6 of Sweden Megafire are plotted as individual dots using different colors, with day 5 dot corresponding to the blow-up event of 4 August 2014. (b) CHI and FWI values expressed as percentiles during the first 6 days of fire.

It was found that values overshooting the 97% CHI percentile would have been forecasted at least 156 hours (6.5 days) prior the event. It should be noted that instead of using "raw" values of FWI and CHI referring to various rigid "extremity" categories, percentile values seem to be more appropriate as the ones shown in Figure 4.1.1 (b).

Concerning the "raw" HI/CHI values the full set of hourly simulations over the critical interval of the fire blow-up as described in Table 3.3.1 was considered. For all simulations, the values for 00, 06, 12, and 18 UTC over the fire centroid were verified against both corresponding HIRES operational analysis and ERA-I reanalysis values. The H_13 (original scheme of low-level HI) and H_32 (continuous scheme of HI) formulations were found as the ones closest to both analysis/reanalysis and considered as HI and CHI reference data sets.

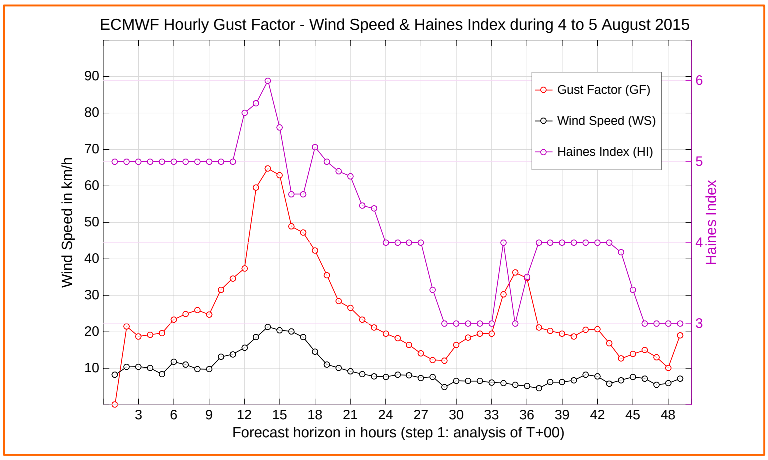

Figure 4.1.2. HI, WS and GF hourly simulations based on H_13 ECMWF Cubic High-Resolution based on 00 UTC of 4 August 2014. Maximum forecast horizon: T+48 hours. Step 1 corresponds to analysis.

Besides H_13 and H_32 HI/CHI values over the fire centroid, an additional set of hourly values over 72 (HIRES) selected grid points spread uniformly spread around fire centroid were also obtained. These 72 data sets were investigated referring to their maximum and minimum HI/CHI values during the 48-hour critical time interval (from 4 to 5 August 2014). This was done since the resolution of ECMWF model is considered relatively low (16 km as HIRES / 8 km in its Cubic configuration) to describe with very high detail local weather fire characteristics. Nevertheless, the impact of the horizontal resolution on simulating various Haines Index formulations was also investigated. It was found that both 16- and 8-km integrations managed to produce quite comparable results. In a similar way (as in HI/CHI case), 72 plus one (centroid) set of values were constructed for the Fire Weather Index (FWI), wind speed (WS) and model gust factor (GF) parameters for further studying and inter-comparisons.

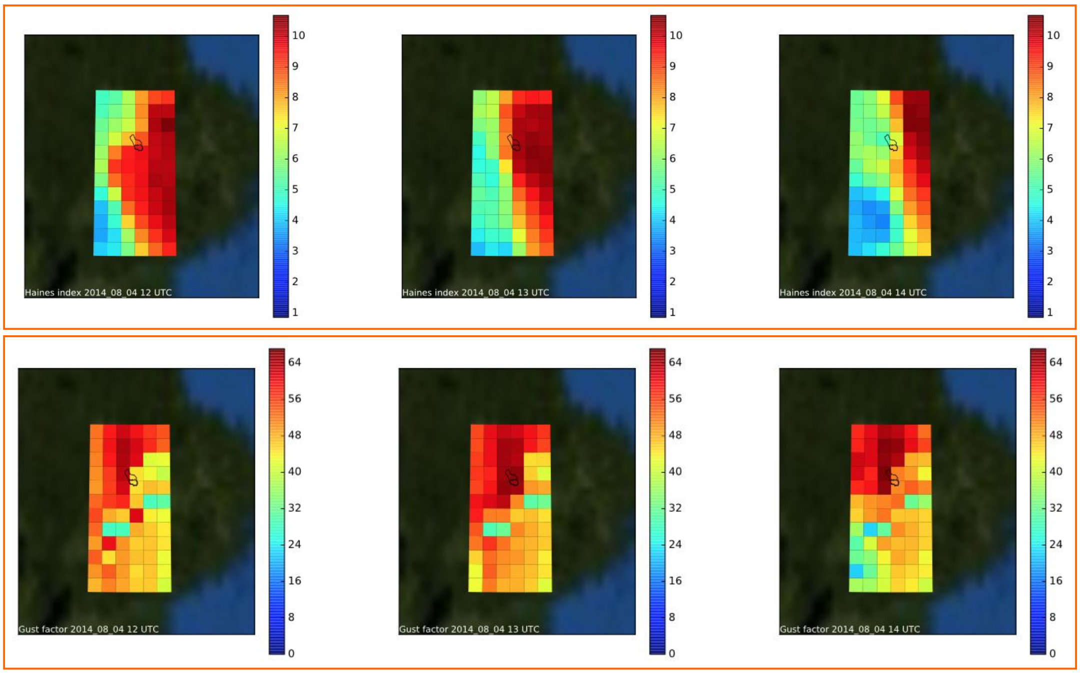

Figure 4.1.3. CHI (upper panels: a, b, and c) and GF (lower panels: d, e and f) H_32 simulation values over 72 grid points valid for 12-, 13- and 14 UTC of 4 August 2014. GF values are given in km/h.

Investigating over the evolution of HI, WS and GF parameters during the interval of 4 to 5 August, from Figure 4.1.2 it becomes clear that at the early morning hours of 4 August very high and at times (noon hours) “saturated” values of Haines Index were advected/prevailing over the area of interest. The highest value of HI (equal to 6) seems to be reached at 13 UTC (corresponding to T+13 of H_32 simulation). At the same time both instantaneous wind (WS) and model gust factor (GF) values reach to their maximum levels. Their difference also appears to get its maximum value as well.

For a better discrimination of HI categorical type of values, CHI values were considered over the total domain of interest as defined by 72 plus one (centroid) reference grid points. Details of CHI evolution can be seen in Figure 4.1.3 (a) to (c) while GF corresponding values are shown in the same Figure 4.1.3 from (d) to (f).

From Figure 4.4.3 it is obvious that very high values of CHI were advected during the noon hours of 4 August mainly from southeast retaining a north/north-eastern direction following closely a short-wave trough most pronounced at 700 hPa, as shown in Figure 2.2.2 (b), whereas the gusty components of air at surface linked to a Secondary Low-Level Jet (SLLJ) - cantered at 950 hPa - were exhibiting a different trajectory mainly from south/southeast to northwest following closely the position of the SLLJ’s streak (area of maximum winds) as shown in Figure 4.1.6 (a) & (b).

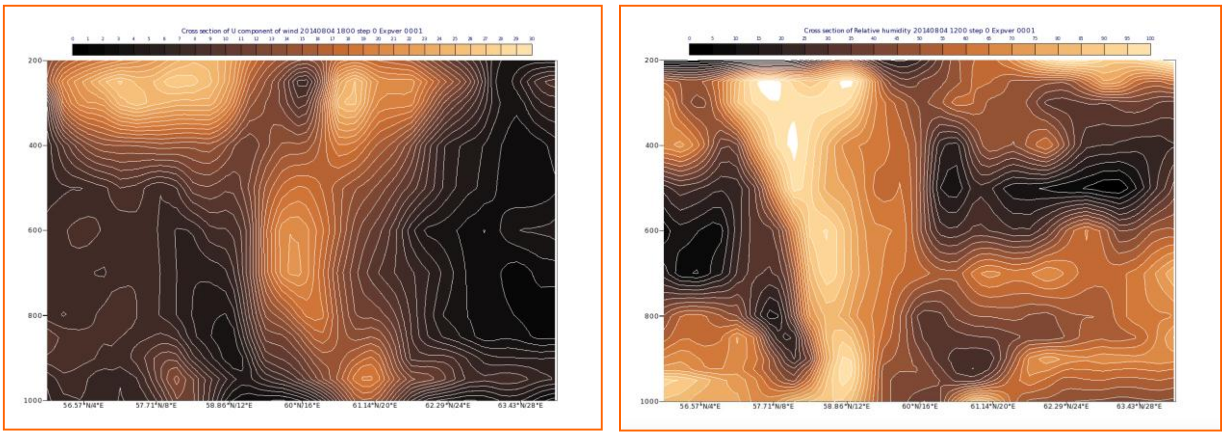

Figure 4.1.4. (a) The existence of three characteristic jets over the greater area of Sweden fire centroid (~60N / 16E). The tropospheric one at about 300 hPa, the Low-Level Jet (LLJ) at about 700 hPa and the Secondary LLJ (SLLJ) centered at about 950 hPa at 18 UTC. (b) RH vertical cross section at 12 UTC.

Constructing and examining a vast set of relevant cross-sections centered on fire centroid the existence of three characteristic jets was certified as shown in Figure 4.1.4 (a). Figure 4.1.4 (a) refers to a cross section passing over the position of fire centroid (~60N / 16E) in a SW–NE direction (from 56N / 2E to 64N / 30E) utilizing analysis maps of 18 UTC.

It is obvious that the first jet had been a typical upper-level tropospheric jet stream at about 300 hPa, the second was a Low-Level Jet (LLJ) at about 700 hPa (positioned just ahead of the approaching cold front from southwest) and the last and seemingly most important one had been a Secondary LLJ (SLLJ) centered at about 950 hPa (just ~550 meters above the fire).

It should be noted that till noon hours of 4 August, the fire appeared to exhibit a plume-type behaviour justifying the considerably high values of HI, but due to the advancing SLLJ and its accompanied kernel of maxima winds (jet streak) linked to intense surface gust components, a transition to wind-driven behaviour seems to had taken place, resulting to an abrupt expansion (blow-up) of fire towards northwest.

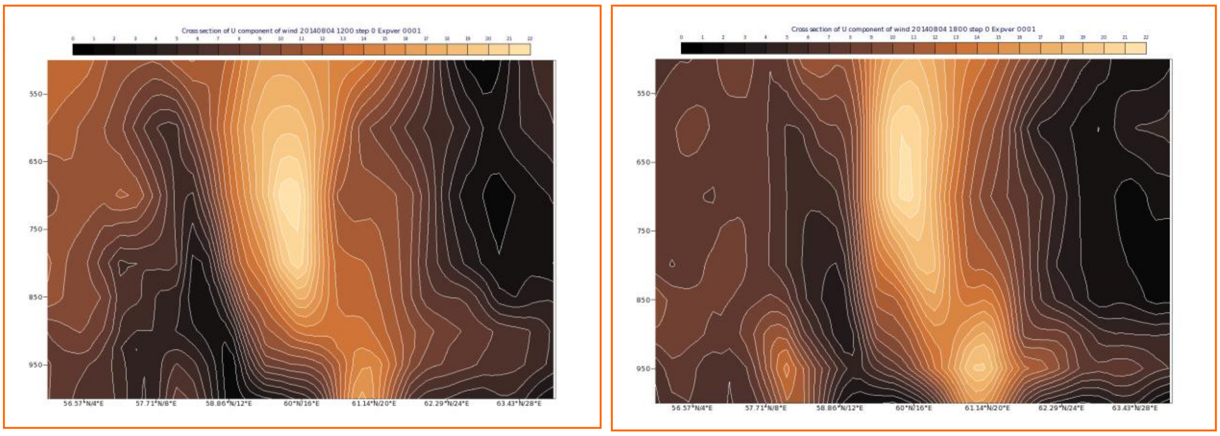

Figure 4.1.5. Position of LLJ at 700 hPa and SLLJ at 950 hPa at 12 (a) and 18 UTC (b) analysis maps.

Furthermore, in the beginning of the blow-up event (noon hours of 4 August), a core maximum belonging to a LLJ of 21.5 m/s (77.4 km/h) was suited over the fire centroid at the level of 700 hPa as shown in Figure 4.1.5 (a) containing the vertical cross section of wind speed at 12 UTC. It is important to notice that till then the presence of any SLLJ is not evident.

The SLLJ had been visible for the first time at the T+02 (hours) simulation of the operational HIRES H_33 forecast (initiated from 12 UTC) valid for 14 UTC and it kept intensifying till T+06 (hours) simulation. This seems to be in agreement with the cross section shown in Figure 4.1.5 (b) based on the analysis of 18 UTC that reveals the exact position and structure of SLLJ. Details of the evolution of both LLJ and SSLJ based on operational HIRES analyses and simulations are contained in Table 4.1. From Table 4.1 it becomes clear that the SLLJ stops to be evident at the analysis of 24 UTC (midnight hours of 4 August).

Table 4.1. Analysis and simulation values of LLJ – SLLJ & RH

Analysis	CUBIC	LLJ (m/s)	SLLJ (m/s)	RH (SLLJ)	RH (SFC)
00 UTC		20.35	-	27	85
06 UTC		16.15	-	35	75
12 UTC		21.50	-	25	35
	T+00	21.50	-	25	35
	T+01	20.85	-	26	25
	T+02	20.50	17.45	25	29
	T+03	20.50	17.75	25	33
	T+04	20.50	18.50	26	38
	T+05	21.35	19.75	28	43
	T+06	21.25	20.15	31	49
18 UTC		21.50	19.75	29	49
24 UTC		-	-	33	85

This should be the main reason behind the dramatic slowing down of the fire during the early morning hours of 5 August. On the other hand the presence of the main LLJ (at 700 hPa) was still evident in the analysis maps of 5 August 00 UTC. Details of the SLLJ (at 950 hPa) palced at the east of fire centroid and moving towards northwest can be seen in Figure 4.1.6 (a) while details of its slowing down behaviour are shown in Figure 4.1.6 (b).

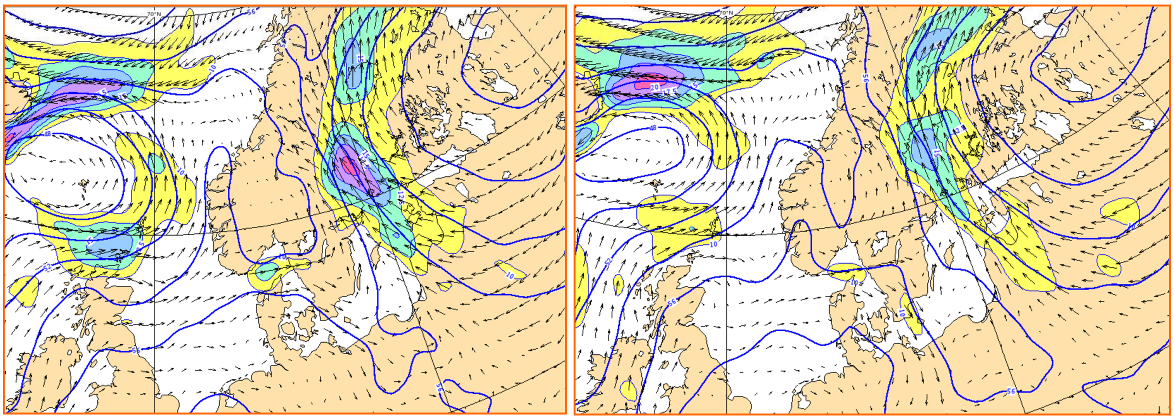

Figure 4.1.6. Details of SLLJ on 18 UTC (a) and 24 UTC (b) from 950 hPa analysis maps of 4/8/2014.

From Figure 4.1.6 it is also clear that the fire centroid during the afternoon hours of 4 August had been under the influence of the left entrance region of the SLLJ. This is an area that dry air could be brought down to a fire through wind-induced mixing by means of negative vertical wind shear (Potter *et al,* 2002). In everyday forecasting such potential source of descending (and gusty at surface) dry air involves descent associated with bands (streams) of high-speed wind maxima, known as "jet streaks" that accelerate/decelerate as shown in Figure 4.1.7 (a).

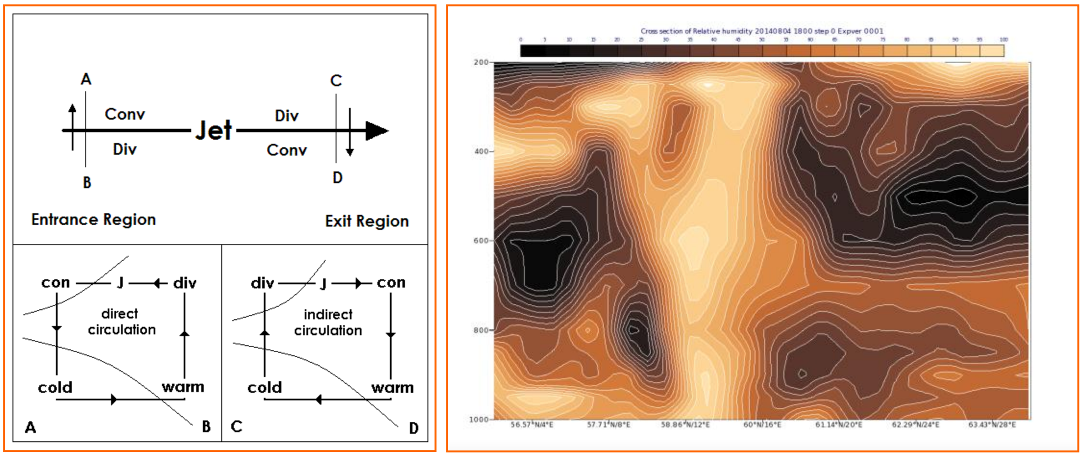

Figure 4.1.7. (a) Transverse ageostrophic wind components and patterns of divergence associated with the entrance and exit regions of a straight jet streak (adapted from Ucellini, 1990). (b) 18 UTC RH low values of RH reaching at ground level.

Investigating closely over the position of the left-side entrance of the SLLJ (linked to convergence and downward motion of air) it became evident that this was suited over and affecting directly the fire centroid. It is important to point out that such set up would have allowed a direct circulation pattern as shown in Figure 4.1.7 (a) to feed dry air the fire during the critical hours of 4 August.

The existence of dry air and its contributing effect to a fire blow-up was investigated once more by utilizing appropriate vertical cross sections of Relative Humidity as the one shown in Figure 4.1.7 (b) revealing low values of RH reaching to ground level at 18 UTC.

Additional cross-sections based on ECMWF model analysis and simulations referring to the critical hours of blow-up revealed a dry air intrusion lying directly over the region of fire's centroid. Values of very dry air as low as 25% of relative humidity appear to touch the ground level over the exact position of fire centroid. Details of RH values can be seen in Table 4.1 referring to the upper pool of minimum RH values at the level of SLLJ and at surface level (just over the fire centroid).

The characteristic descent of dry air (at T+01 simulation) from its upper pool centered at 950 hPa down to the ground as shown in Figure 4.1.8 (a) seems to be in harmony with the orientation of potential temperature surfaces that appear to be bended and oriented towards fire's centroid as shown in Figure 4.1.8 (b). The SLLJ lies directly above this dry air intrusion, suggesting strong positive momentum transport downwards, along the sloping isentropes, towards the fire.

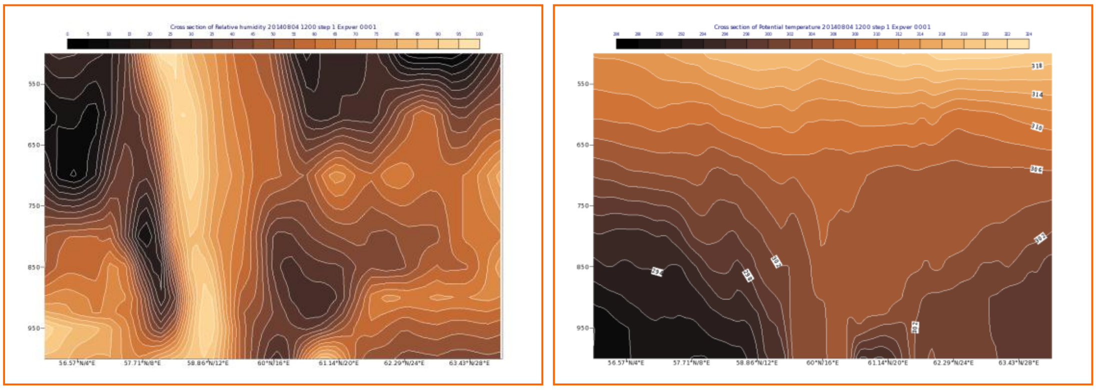

Figure 4.1.8. (a) T+01 Cubic simulations for RH. (b) Potential temperatures based on 12 UTC (4/8).

It should be noted that such potential temperature surfaces act as streamlines revealing the vertical descent of the atmospheric flow. It is important to notice that the 304˚K potential temperature surface extends from the level of 700 hPa downwards directly through the dry air intrusion illustrating the relationship between the tilted isentropes and the dry air intrusion that results from the forced descent in this region. This could justify how dry air from above is been injected to the fire.

Furthermore, the LLJ lies directly above this dry air intrusion. This circumstance is suggestive of strong positive momentum transport downwards, along sloping isentropes, towards the fire. Such descent is the reason behind the upper level origin air to follow downward motion along isentropes that have been tilted into the vertical. Upper level troughs are regularly associated with upper level processes of frontogenesis particularly in the presence of an upper-level jet feature as they are associated with maxima of potential vorticity and a characteristic tendency of descent at upper levels.

4.2 Fire evolution simulations

The Sweden case proved to be so extreme and one of the most complex cases that required special handling by the EFFIS fire evolution platform that comprises FireSim, GRASS GIS and FARSITE fire behavior models. Utilizing two of them, (FireSim & FARSITE) an extensive set of simulations were performed.

In preparing FireSim and FARSITE simulations it is important to point out that the fire monitoring of this case using remote sensing had been very difficult due to the poor quality of satellite images. In fact, clouds had covered the active fire area during most of the wildfire's lifetime. A temporal gap in the satellite imagery between 3 and 12 August made possible the identification of the burnt area with a reasonable accuracy.

The FireSim simulator proposed by Bevins (1996) implements the library FireLib that composes the processing as a pipeline structure of four different stages. This simulator uses a cell-based approach, the relationship between neighbors being used to evaluate whether and when the fire may reach a given cell. The model that is being implemented in the kernel of FireLib is the one described by Rothermel (1972 & 1983). The main loop in FireSim operates using a contagion algorithm applied to the 8 neighbors of each cell. Details of FireSim model can be found in Rodriguez-Aseretto (2013).

Same wise, FARSITE simulator requires a set of input data that describes a forest fire scenario. Such input data (components) can be classified depending on the manner being introduced into the simulator. The first component represents the topographic description, i.e., the canopy cover and fuel model map that comprise values that depend on the location and they do not change during the period of simulation. This topographic description is enclosed in a file so called LCP (Landscape FARSITE v4). Details can be found in Finney (2004). The fuel map model being used in FARSITE simulations has been developed in the JRC using a conversion table from 55 different models to 13 fuel models as described by Anderson (1982).

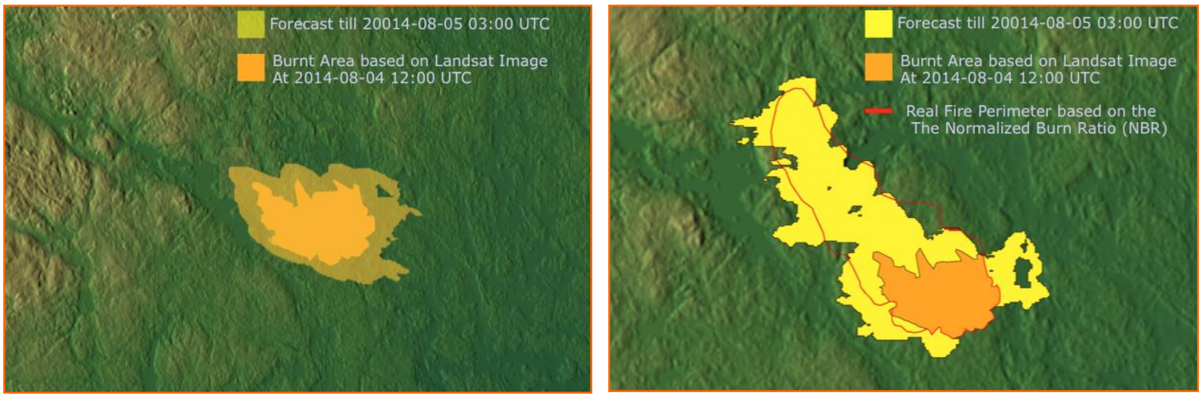

Figure 4.2.1. Fire spread details as being simulated by FireSim utilising WS (a) and GF (b) wind input parameters.

Concerning the input weather elements a full set of data by ECMWF HIRES model are regularly obtained and archived at JRC for the daily operational support of EFFIS. It is worth mentioning that all input weather elements referring to wind speed, wind direction, temperature, relative humidity and precipitation prevailing (analysis and forecast values) over the centroid of fire's perimeter, are interpolated using the inverse distance weighting technique (as described in Section 3). The centroid position is updated every time that a new initial / reference perimeter of a simulation is being introduced. For reasons already explained the set of simulations were focused on the critical interval from 11 UTC (4 August) till 03:00 UTC (5 August) taking into account the distinct fire weather conditions that were prevailing over the area of interest.

The initial fire behavior simulations had been utilizing the typical (practical) approach of inserting instantaneous wind speed values as driving wind terms for FireSim integrations. Results of very poor quality that significantly were underestimating the fire rate of spread in the Sweden fire case led to investigations over possible causes and alternative ways to overcome this problem.

After intense investigation it was found that one of the most important fire weather component that FireSim was the poor quality of wind speed input parameters, since it had been different from the true intensity and gustiness of prevailing winds. This proved to be the reason behind the obvious underestimating results concerning the projection of the burned fire area as shown in Figure 4.2.1

(a). By introducing model High-Resolution Gust Factor (HIRES-GF) values while keeping the same wind directions as provided by instantaneous winds, FireSim simulations were significantly improved as denoted in the same Figure 4.2.1 (b). It became obvious that by utilising model gust factors resulted to quite satisfactory results concerning the critical estimation of fire burned area based on a more accurate simulation of the fire perimeter.

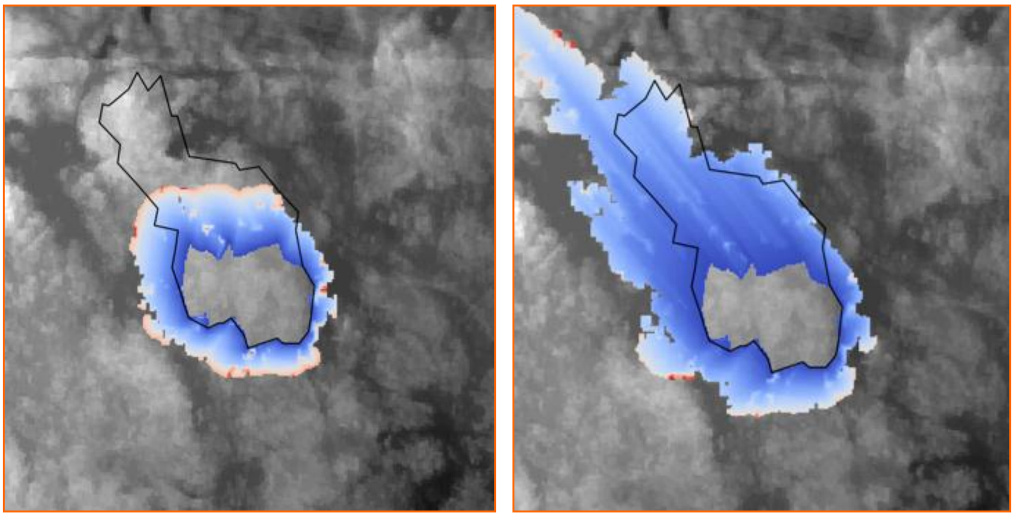

Figure 4.2.2. Fire spread details by FARSITE utilising WS (a) and GF (b) wind parameters – Starting time of simulation: 20140804 11 UTC. End of simulation: 20140805 03 UTC

As in the FireSim, initial FARSITE simulations had been utilising instantaneous wind speed values as forcing wind terms for their integrations. Once more results were of very poor quality as simulations were underestimating considerably the fire rate of spread as clearly shown in Figure 4.2.2 (a). Furthermore, it became evident that results of such poor simulation could not provide useful forecast guidance since they were are completely missing the significant expansion (blow-up) of the fire towards northwest. By introducing model gust factor (HIRES-GF) values while keeping the same wind directions as provided by instantaneous winds we managed to improve significantly FARSITRE simulations as shown in Figure 4.2.2 (b). This HIRES-GF simulation seems to be on the right track with quite satisfactory results concerning the critical fire burned area and its significant expansion (blow-up) towards northwest.

Overall, it is important for a user to realize that FARSITE model has not the capability to take into account explicitly some of the important driving factors behind the fire blow-up during 4 August such as the low-stability of atmospheric flow and the presence of the LLJ and its SLLJ. The results of simulations over the critical interval of 4 to 5 August had also shown the sensitivity of FARSITE in respect to input driving weather data. It was also found that in such a case of intense instability and in presence of other important synoptic weather elements as the existence of an upper-air trough but most importantly with the presence of a low-level jet stream crossing over the fire perimeter, the option of utilizing gusty wind speeds instead of instantaneous components proved to be a more appropriate one. So, even if FARSITE could not resolve the precise low-stability environment at least the introduction of HIRES-GF values resulted to a more accurate simulation.

Nevertheless, low stability has been linked over the past to such cases of gusty winds at the surface level as clearly pointed out in Werth *et al* (2011). In summary, unstable air amplifies the vertical growth of the smoke plume over a fire by enhancing the strength of the updrafts. This increases combustion rates by supplying more oxygen to the fire. As the height and strength of the smoke plume increases, the potential for gusty surface winds, dust devils, and fire whirls also increases.

5. Discussion and conclusions

During the past years, there have been a considerable number of occasions that a forest fire burns with such strong intensity that seems far out of proportion to apparent burning conditions. This proved to be the case for the Sweden fire "blow-up" that took place during the afternoon and night hours of 4 August 2014. Close investigation over critical fire weather parameters showed that a combination of synoptic conditions led to this distinct fire event.

The main weather elements found to be the existence of an upper-air trough linked to a dissolving warm front the previous day (3 August) providing low stability values over the fire centroid and the approach of a cold front from southwest further lowering the stability of atmospheric flow. But above all, the air dryness and the prevailing of strong wind gust components due to a Secondary Low-Level Jet (SLLJ) at 950 hPa (~550 meters above the ground) passing over and to the east of fire centroid made ideal conditions for such an extreme event.

During the noon hours of 4 August, due to a short-wave upper level trough most pronounced at 700 hPa, very high (and at times "saturated") values of HI were advected over the area of interest mainly from southeast retaining a north/north-eastern direction. On the other hand intense surface gusty components of air linked to the SLLJ were exhibiting a trajectory from southeast to northwest following the main direction of the main Low-Level Jet (LLJ) centred at 700 hPa (~3,000 meters above the ground). Till that time, the fire appeared to exhibit a plume-type behaviour, but due to the advancing kernel of wind maxima (jet streak) of SLLJ and its accompanied surface wind gust components, a clear transition to a wind-driven behaviour took place, justifying its final abrupt expansion towards northwest.

The time that the SLLJ was crossing and intensifying found to be in agreement with the position and movement of the area of maximum instability as defined by very high values of Haines index (HI). The HI combines stability and dryness of the atmosphere and provides a simple way to measure the atmosphere's contribution to the growth potential of a forest fire as one of the main driving force behind significant fire blow-ups. Such very high HI values were also combined with an almost "saturated" daily Fire Weather Index (FWI). Fire danger indices as the FWI provide a description of the fire suppression difficulty, so such a combination of almost "saturated" values of both HI and FWI could be indicative of a potential fire blow-up.

Furthermore, such combination of highly unstable weather conditions and gusty wind components proved to contribute significantly to the potential of the Sweden fire to blow-up and cause such significant damage. It is known that in an environment of intense instability fire evolution models significantly underestimate the rate of fire spread. That seemed to be the reason behind the initial poor results of simulating fire's perimeters.

Investigating over the existence of alarm bells for this blow-up event it became clear that the extreme percentile values of both the FWI and CHI could have been considered as the first warning signals for the Fire Manager. But besides this, it was found that two major ingredients for the spread of the Sweden fire's blow-up, i.e., the very dry air and gusty winds, were made available to the fire environment as a result of its proximity to the developing upper level front dynamics forced by the presence of the LLJ. It should be noted that relative humidity (RH) values as low as 25% were found to be injected directly into the fire. Cross-section analysis based on ECMWF model simulations revealed a distinct dry air intrusion lying directly in the region of the most intense sloping of isentropes. The presence of both LLJ and SLLJ directly above this dry air intrusion, suggests a strong positive momentum transport downwards, along sloping isentropes, towards the fire.

Most of initial simulations following the practical approach of utilising instantaneous model wind speed values as driving wind terms for FireSim and FARSITE integrations were inaccurate due to the fact that the true intensity and gustiness of prevailing winds were not used as driving terms. By introducing model gust factor values (instead of instantaneous speeds) while keeping the same wind directions as provided by instantaneous winds significant improvement in accuracy was accomplished in both FireSim and FARSITE simulations.

The Sweden fire proved to be a unique opportunity to explore a variety of meteorological analyses and simulations required to determine that the significant blow-up event taken place on 4 August 2014 was a consequence of a distinct combination of boundary layer instability, air dryness and intense gusty wind speeds due to the existence of a secondary low-level jet. In such distinct unstable environment and under the influence of LLJs/SLLJs the utilization of model gust factors instead of instantaneous winds seems more appropriate. It should be also noted that during the noon hours of 4 August the fire seemed to exhibit a very dramatic change from a fire of plume type with erratic behavior but still low winds to a wind-driven fire with very strong gusts. A critical question seems to be if such plume-type behavior and later its changing to a wind-driven dynamical fire environment could be anticipated by some early warning signals.

The answer is not straightforward. Of course there had been strong signals from HIRES forecasts about significant deviation between instantaneous winds and gust factors. In addition, Haines index values were to become saturated at some time(s) during the critical day. But another important element had been the low-level jet. It is more than likely that the existence and crossing of this LLJ was the main factor behind the gusty behavior of the atmospheric flow that led to this catastrophic blow-up. It also became evident that in such unstable environment and under the influence of such a low-level jet the usage of model gust factors instead of instantaneous winds seems a more appropriate one.

Overall, it is important to consider the concept of atmospheric instability and dryness as key elements in the forest fire management system. That is why it seems of a great importance the consideration of such features, particularly in circumstances conducive to interactions with the planetary boundary layer, may benefit fire weather forecasters and fire managers as they consider risk assessment strategies.

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