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Recognizing the Potential for Dangerous Nocturnal Fire Growth and its Implications on Fire Weather Products and Services

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Abstract

Recognition of conditions which support nocturnal extreme fire behavior (EFB) can pose a challenge to forecasters, especially since numerical weather prediction (NWP) tools are limited in their ability to initialize highly dynamic, but relatively small-scale features. Large fires can drastically alter nocturnal stability which can quickly lead to nocturnal EFB and directly impact public safety. During the night of 22-23 Apr 2009 the Highway 31 Fire in Horry County, SC exhibited EFB when NWP indicated a stabilizing environment. In a matter of a few hours, the fire consumed 2000 ha, destroyed 76 homes and damaged another 96 structures. To assess the potential for nocturnal EFB, it is imperative forecasters conduct an analysis which includes: antecedent conditions, ventilation rate, visual observations, National Weather Service (NWS) Weather Surveillance Radar (WSR-88D) imagery, and stability profiles. This research provides weather forecasters with factors that contributed to the nocturnal EFB observed during the Highway 31 Horry County fire, an overview of a Nocturnal Fire Growth (NFG) sounding, how to assess potential nocturnal EFB through a decision tree, and the Impact-based Decision Support service (IDSS) implications for the 22-23 Jun 2011 Juniper Road fire in Pender County, NC.

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1. Introduction

NWS fire weather forecasters provide an average of 45,000 Fire Weather Forecasts (FWFs) and 21,000 Spot Forecasts (Spots) each year across the United States (L. Van Bussum, National Interagency Fire Center (NIFC), 2018, personal communication). These forecasts directly support local, state, and federal agencies tasked with responding to wildfires or managing controlled burns. Due to the varied fire weather conditions across the U.S., there are a number of regional and local challenges. Across the coastal plain of the Carolinas, forecasters occasionally have to provide forecast weather information for large fires that may directly impact life and property. These fires are influenced by the type and availability of fuel, recent rainfall trends, and complex atmospheric conditions, even across areas with little variability in terrain. The Highway 31 fire that began in Horry County, SC, on 22 April 2009 is an example of a large Carolina coastal plain fire that created life-threatening conditions resulting in unique forecast and decision support challenges, especially regarding the extreme nocturnal fire growth observed during the first night of the fire.

Extreme Fire Behavior (EFB) has been thoroughly researched and it is known that a favorable synoptic pattern (Brotak and Reifsnyder 1977), strong winds (Byram 1954), a dry atmosphere, and deep mixing (Werth et al. 2011; Potter 2002) can contribute to explosive fire growth. However, investigations specifically pertaining to conditions supportive of nocturnal EFB is very limited. Large wildfires can directly modify the atmosphere leading to complex fire behavior as the heat added to the surrounding atmosphere can inhibit the development of stable nocturnal environments. Subsequently, conditions conducive to nocturnal EFB can be created, which can significantly increase the risk to the safety of the public and responders. In addition, the current suite of operational models used by NWS fire weather forecasters do not initialize with atmospheric contributions from wildfires. As a result, it is critical for NWS fire weather forecasters to understand the parameters which may lead to nocturnal EFB despite models predicting the development of a stable atmosphere in the vicinity of a large wildfire.

For this analysis, the antecedent precipitation trends and fuel conditions, visual and radar observations, trends in mixing height/ventilation rate, and atmospheric stability are discussed. In addition, the concept of a Nocturnal Fire Growth (NFG) sounding is introduced to understand how changes in the atmospheric profile and stability affected the nocturnal EFB during the Highway 31 event. Also, a decision chart was developed for forecasters to account for all factors that may combine to increase the potential for nocturnal fire growth. The chart can be especially useful during cases when Numerical Weather Prediction (NWP) suggests that stabilization will occur, potentially creating a misrepresentation of the actual environment in the vicinity of a large fire. Ultimately, a comprehensive review containing a more robust dataset of large fires would be needed to accurately develop a forecast tool to predict a potential increase in nocturnal winds. In the meantime, the decision chart will assist forecasters with considerations for using enhanced wording in fire weather products and decision support briefings. The enhanced wording would alert Fire Behavior

Analysts (FBANS), emergency managers, and fire crews to develop specific contingency planning to account for nocturnal EFB. An analysis of the environment of the Highway 31 fire which led to extreme nocturnal fire growth was applied to the Juniper Road fire in Holly Shelter, NC in 2011 to highlight the potential application of the decision chart.

2. Overview of the Highway 31 Fire – Horry County, SC April 2009

On 22 April 2009 at approximately 1624 UTC, a residential burn had become out of control approximately 13 km east of Conway, SC. The Horry County Emergency Management reported the fire moved for 10 km to the east during the afternoon of 22 April 2009. Conditions again became favorable for explosive fire growth during the early morning hours of 23 April 2009. During this nocturnal acceleration toward the northeast, the fire quickly consumed 2000 ha and posed a direct threat to lives and property. Fire crews estimated wind gusts of 18 to 27 m s^{-1} (Randy Webster, Personal Communication, 2012) in the vicinity of the fire during the late night and early morning hours of 22-23 April 2009.

Overall, the fire consumed approximately 7769 ha (Fig. 1), destroyed 76 structures and damaged 97 additional buildings in and near North Myrtle Beach, SC. The majority of the structural damage occurred on the night of 22-23 April 2009 (McLeod III et al. 2009). As many as 4,000 residents were evacuated during the height of the fire, including 2,500 people that were evacuated during the overnight hours of 22-23 April 2009. During the evacuation, several residents were in the process of getting into their vehicles to flee as their homes caught fire. Fortunately, no injuries or fatalities were reported. Property losses were estimated at $25 million, and forested woodland damage was estimated at $15-20 million. The fire in this location occurred on the "Buist Tract" which has a notorious wildfire history given its composition of Carolina Bay fuels (waxy and oily foliage with a deep layer of peat) and proximity to several communities.

Figure 1. Map of NWS Wilmington NC County Warning Area (CWA) bright green, Highway 31 fire in Horry county, SC (red outline), Charleston (CHS) upper air site, Shallotte, NC (KLTX) doppler radar site, North Myrtle Beach ASOS (KCRE), and Supply, NC RAWS site (NATN7).

3. Extreme Nocturnal Fire Growth Considerations

a. Drought and Recent Rainfall Trends

As with any large fire, rainfall deficit plays a crucial role to the availability of fuels to burn. Although an official drought as rated by the U.S. Drought Monitor (USDM) is not a requirement for all large fires (Werth et al. 2011), relative dryness does help fires grow more quickly. It makes sense that wet fuels will burn more slowly than dry fuels, thus allowing for better control and a lesser chance for any rapid-fire development. Understanding the antecedent hydrologic conditions is crucial to diagnosing the potential for large fires. However, forecasters and FBANs need to be aware that there is a temporal lag in the USDM assessment and should not rely solely on this analysis. Since official drought designation is not necessarily a method to diagnose large fire potential, forecasters must rely on other methods to understand the risk. There are two methods to understand the hydrologic conditions and the effect on available fuels. One is recent rainfall compared to normal, and the other is the deficit compared to Penman Evapotranspiration (ET).

The closest precipitation observation station to the Highway 31 fire is the Automated Surface Observing System (ASOS) at North Myrtle Beach, SC (KCRE) located approximately 3 km east of the fire. The period from several months to two weeks before the fire was dry, but not excessively so, hence no drought designation from USDM. However, in the two weeks leading up to fire initiation, KCRE received only 7 mm of rainfall, 19 percent of normal, and only 0.25 mm, 2 percent of normal, fell in the week before ignition. These percentages of normal are well below those for the 30, 60, 90, and 120 day periods and, combined with abnormally warm temperatures the week of ignition, allowed the 10 hour fuels, consisting of plants, sticks, and twigs between ¼ inch and 1 inch in diameter, as well as the fine fuels (anything smaller) to dry out quickly, enabling the environment to become conducive to rapid fire growth.

Perhaps more important to potential fire growth than recent rainfall deficit, is the amount of rain relative to ET, computed at the nearest Remote Automatic Weather Station (RAWS). ET calculations incorporate the effects of solar radiation, wind, air temperature, and relative humidity on evaporation and transpiration for a "well-watered and managed" reference crop (M.B. Breckner, Western Region Climate Center, 2008, personal communication.) Although a RAWS currently exists in Conway, SC, in 2009 the nearest RAWS was in Supply, NC (NATN7) approximately 50 km from the fire. Examination of ET data from NATN7 revealed that the 30-day rainfall was only 51% of the measured ET. However, most of this deficit accumulated in the two weeks before the onset of the Highway 31 fire as rainfall in the two weeks prior to the fire was 9% of ET. Using the NATN7 ET as a proxy for KCRE suggests that soils in the area lost approximately 142 mm of water in the 90 days prior to ignition, with 64 mm, or 45%, being lost in the 14 days before the event.

b. Trends in Mixing Height and Ventilation Rate

While antecedent hydrologic conditions are critical to diagnosing large fire potential, the meteorological conditions are equally important. A fire after a very dry period is less likely to become explosive if winds are light and mixing heights are low, than if the reverse was true. Thus understanding the relative fire weather conditions is very important. It is known that EFB requires strong winds (Byram 1954), a dry atmosphere, and deep mixing (Werth et al. 2011; Potter 2002), but the exact values of these parameters can vary. In the Carolinas, the National Weather Service will issue a Red Flag Warning (RFW) if winds are forecast to reach 9 m s^{-1} or gust to 13.4 m s^{-1}, in conjunction with RH falling to 25% or less. However, not all RFW days are accompanied by large fires, and thus it is clear that other parameters, including transport wind, ventilation rate, and mixing heights, are also critical to large fire maintenance and potential EFB.

Although no direct verification of these parameters is available, the NWS Wilmington, NC compiled a forecast climatology of data for fire weather parameters, which has led to a better understanding of the extreme fire potential environment. The forecast climatology was developed using daily FWF data from NWS Wilmington, NC. This data represent an average of expected conditions across the Cape Fear region which includes Brunswick, New Hanover, and Pender Counties. The analysis used seven years of data (15 March 2005 – 2 March 2012) which includes the Highway 31 Fire.

Identifying these long-term forecast trends allowed for statistical analysis of the environmental data, enabling the calculation of anomalies for mixing heights, transport winds, and ventilation rates. Anomalies are frequently used by meteorologists to determine extreme environments and the potential for significant weather events, and this same process can be used to diagnose the potential for EFB. A RFW day with extremely anomalous values would be more likely to drive EFB than a standard RFW day with near-threshold values, so understanding relatively how extreme the environment is can be crucial to forecasters.

Although not known at the time of the event, the environment on the morning of the ignition of the Highway 31 Fire was one of the most extreme in the entire dataset. The day the Highway 31 fire initiated, the forecast ventilation rate (41000 $m^2 s^{-1}$) was the second highest of any day studied (Fig. 2). This was due to both strong forecast transport winds, and the highest forecast mixing height (3700m) in the data set. Ventilation rate is the product of the mixing heights and transports winds. These significant anomalies combined with a Haines Index of 5 suggested moderate potential for rapid fire growth (Haines 1988).

Anomalies would have helped better diagnose the fire potential on 22 April 2009. While the forecast ventilation rate and mixing height were at or near all-time highs for the area, this was not known at the time of the forecast. The data shows that the forecast mixing height was nearly 4.5 standard deviations above the mean, in conjunction with a forecast ventilation rate of 3.7 standard deviations over the mean for April. If the forecaster had been able to recognize this at the time, stronger wording could have been written into the FWF and RFW to alert foresters of fire growth potential. After looking at the anomalies, it is no surprise that a major fire occurred on this date. With the forecast climatology now available, forecasters will be able to better identify this potential and alert foresters more efficiently in the future.

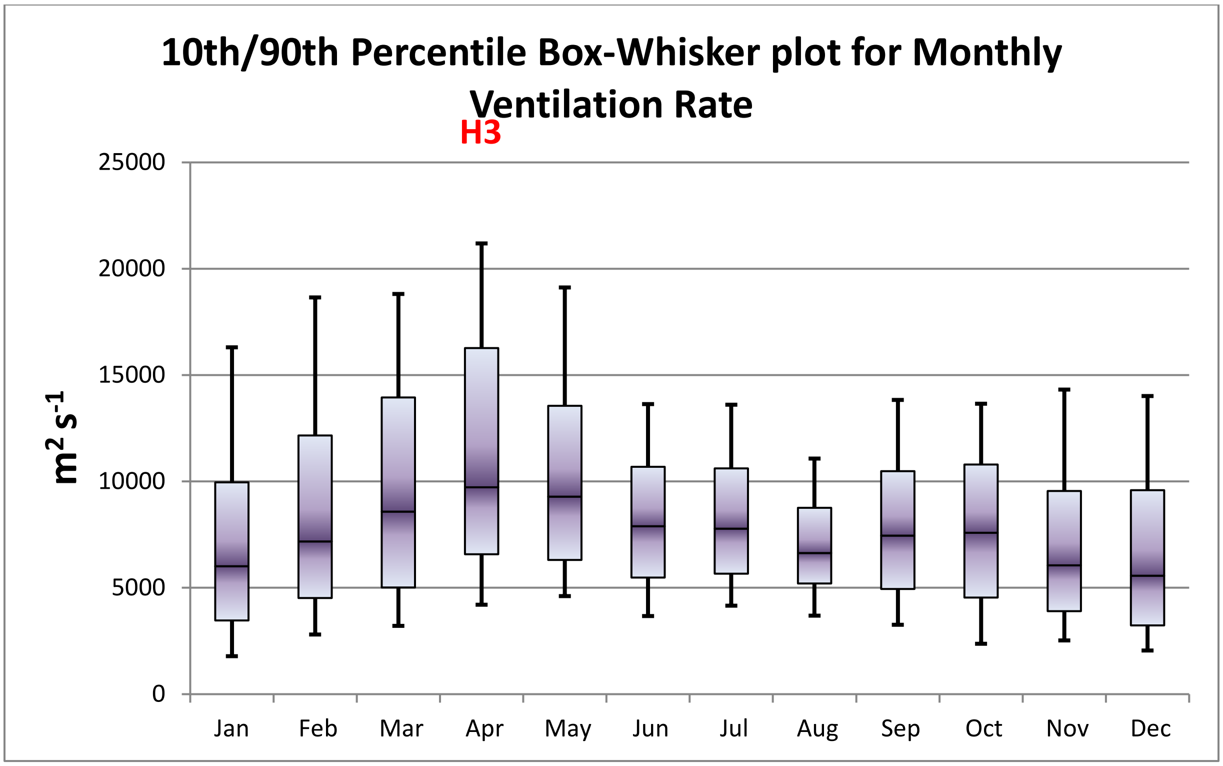

Figure 2. Monthly forecast ventilation rate box and whisker plots. H3 represents the Highway 31 Fire, which was over 41000 $m^2 s^{-1}$. This ventilation rate is at the very high end of the chart and was recorded as the second highest in the entire data set.

c. Visual clues and Radar Analysis

The main convective column exhibited by the Highway 31 fire became extremely large during the afternoon and early evening of 22 April 2009 before the period of significant nocturnal fire growth. Based on the Weather Surveillance Radar (WSR-88D) imagery, located in Shallotte, NC (KLTX), the plume vertically exceeded 4 km at times. The convective column of the plume (Fig. 3) exhibited sharply defined pyrocumulus along with an asymmetric tilt downwind which enhanced the transport of larger particulate similar to descriptions observed by Small and Heikes (1988). The presence of a large plume was important since it would likely promote local changes in the atmosphere, including the erosion of inversions and an increase in winds (Penner et al. 1986).

Also, the Highway 31 fire sustained a large plume into the evening of 22 April 2009. The fire remained large enough to modify the otherwise stabilizing nocturnal atmosphere, supporting additional turbulent transfer and mixing of stronger winds aloft to the surface. Another reason for the gusty winds observed by fire personnel was likely a result of strong downdrafts influenced by the dry and unstable low-level atmospheric profile noted in sounding data. The collapse of a convective column, particularly on a large fire such as this, suggested that a period of gusty winds were likely (Werth et al. 2011).

KLTX WSR-88D Base Reflectivity cross sections of the plume (Fig. 4) for the period preceding and during the nocturnal fire growth showed very intense lofting of larger particulates. During the peak of nocturnal fire growth, 55 dBZ echoes were observed lofted over 600 m. Vertically, the plume exceeded 3600 m during the afternoon, before dropping to less than 1800 m in the early evening as the atmosphere attempted to stabilize. The vertical structure then regained intensity overnight as the low-level wind field eventually increased. The depth of the most intense reflectivity returns occurred after 0300 UTC on 23 April 2009 concurrent with the fastest rate of spread based on fire crew reports. This fire also exhibited a cycle of plume collapse and regrowth, in which Werth et al. (2011) indicates that periods of gusty winds are associated with a collapsing plume (Fig. 5). In addition to the impressive vertical structure shown in KLTX imagery, the spatial extent of the plume was very significant. During the afternoon prior to the nocturnal EFB, the plume length exceeded 100 km, and when the plume became re-established during the overnight hours of 23 April 2009 it exceeded 75 km as observed in Fig. 6.

Figure 3. The Highway 31 fire in Horry County, SC 22 April 2009 from the Horry County Emergency Management photo collection.

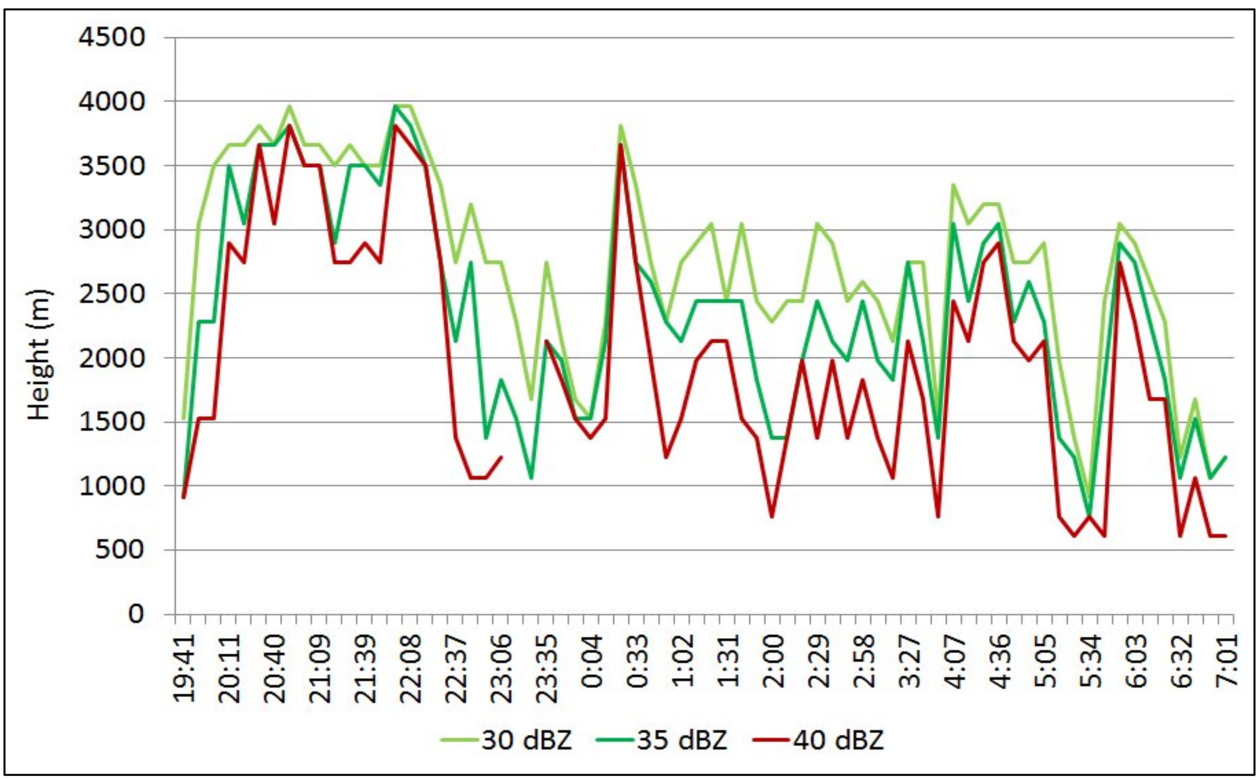

Figure 4. KLTX WSR-88D reflectivity (dBZ) plot of height (m) vs. time (UTC) of the Highway 31 fire 22-23 April 2009.

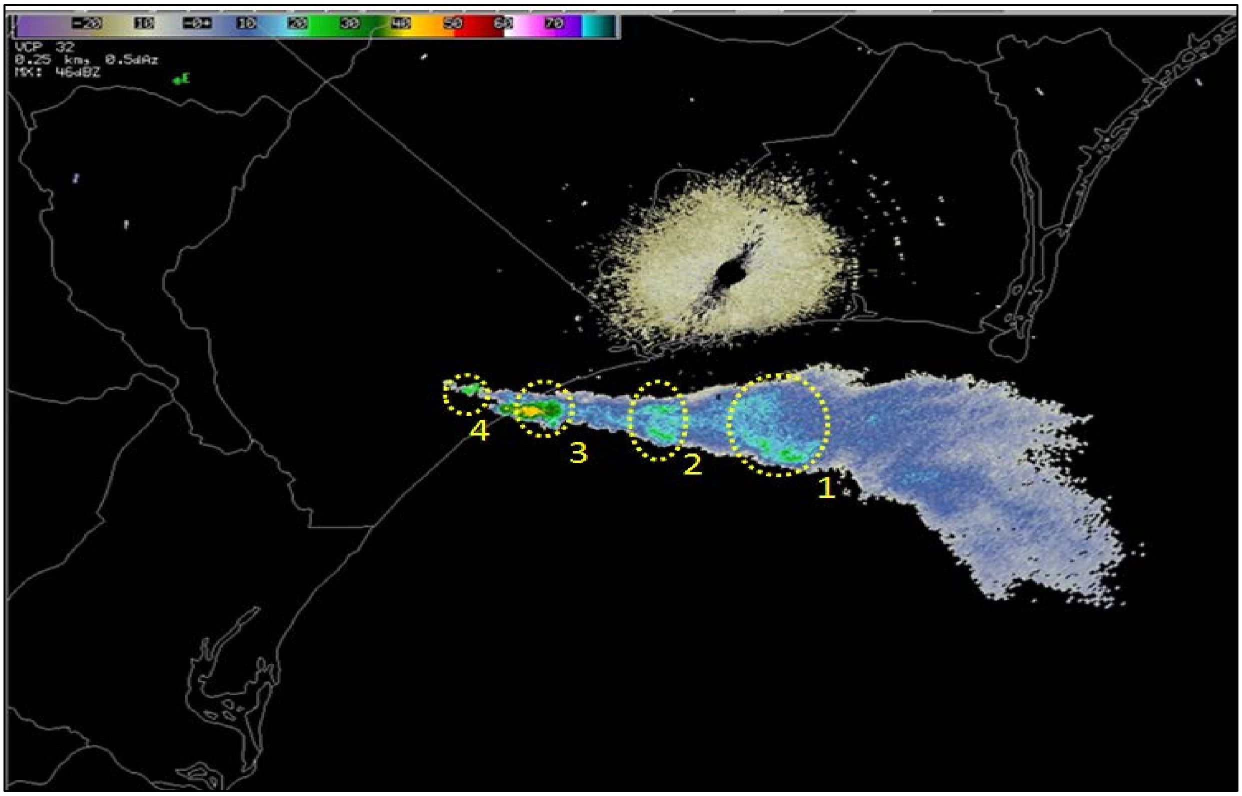

Figure 5. 2344 UTC 22 April 2009 WSR-88D KLTX 1.5° base reflectivity image showing the "pulsing", indicated by the 4 yellow dashed circles, of the Highway 31 fire in Horry County, SC.

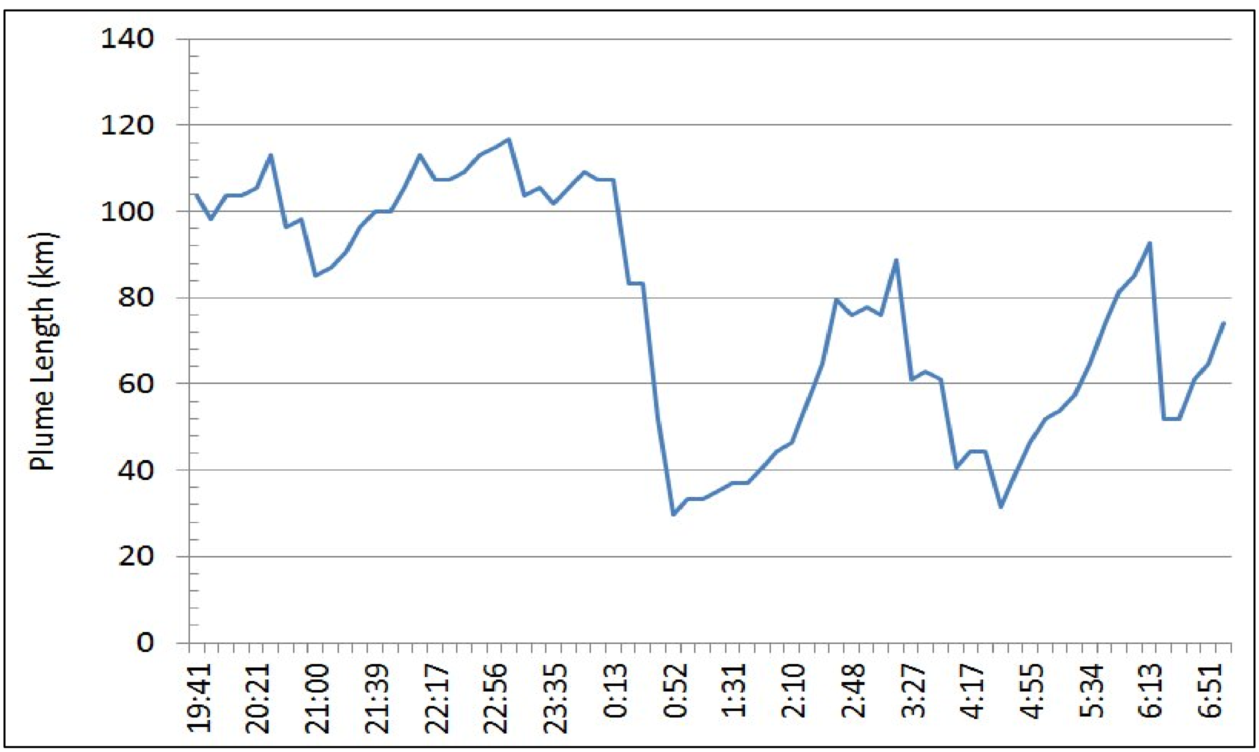

Figure 6. Plume length distance (km) vs. time (UTC) plot of the Highway 31 fire 22-23 April 2009.

d. Atmospheric Stability

Atmospheric stability plays a crucial role in the potential for EFB with greater instability resulting in lower relative humidity (RH) and higher wind (Brotak and Reifsnyder 1977). Often these parameters influence each other as instability promotes mixing, leading to lower surface RH, counter to the typical nocturnal rise in RH associated with a decoupled wind field. Also, Werth et al. (2011) indicate that the low RH eventually reduces fuel moisture, increasing the potential for ignition and spreading. The increasing wind further dries fuels downwind of a fire leading to an increased rate of spread (Werth et al. 2011). Since intensely burning fires can modify the stability in the vicinity of the fire sufficiently to promote the mixing of stronger winds aloft to the surface, it is at this point where NWP tools could become very misrepresentative. This may lead to forecast inaccuracies if localized stability modifications are not fully considered or anticipated with the presence of a large fire. Best (2002) notes that resolution limitations with NWP do not adequately portray the influence of heat islands. Similarly, an extreme and highly variable heat island, such as a wildfire, would be poorly resolved by NWP.

Since the 0000 UTC 23 April 2009 Charleston, SC (CHS) sounding was diurnally influenced the 1200 UTC 23 April 2009 Charleston, SC (CHS) sounding was utilized as a proxy for the 22-23 April 2009 Highway 31 fire (Fig. 7) given a better representation of the conditions to develop the night of EFB. The CHS sounding is located approximately 150 km south-southwest of the fire. Forecasters providing spot forecasts and model sounding analyses should consider several conditions which were observed in the 1200 UTC CHS 23 April 2009 sounding. The CHS sounding exhibited a 7^{o}C inversion below 950 hPa extending to the surface and the existence of an Elevated Mixed Layer (EML) between 950 hPa and 680 hPa. Very dry air was also noted in the low-levels with a greater than 10^{o}C dewpoint depression, and winds were shown to increase from the surface (3 ms^{-1}) to 700 hPa (20 ms^{-1}). The existence of a low-level inversion, EML, dry layer, and increasing winds are needed for a NFG sounding profile (Fig. 7).

The presence of a NFG sounding suggests a greater potential for EFB especially if the negative buoyancy supported by the inversion can be overcome by the intensity of a fire. As a result the fire will be capable of tapping into: higher instability available through the EML (create/support stronger updrafts), the dry low-level air to enhance downdrafts (entrainment), and stronger winds aloft (supporting turbulent transfer). If model soundings indicate the development of a NFG sounding after the onset of a nocturnal inversion, then forecasters must not fall trap to the unrealistic stabilization in the presence of large fires. Ultimately, forecasters must remain vigilant to the potential of nocturnal EFB during these situations, especially if the radar characteristics and visual clues indicate the fire has maintained its size and intensity into the evening.

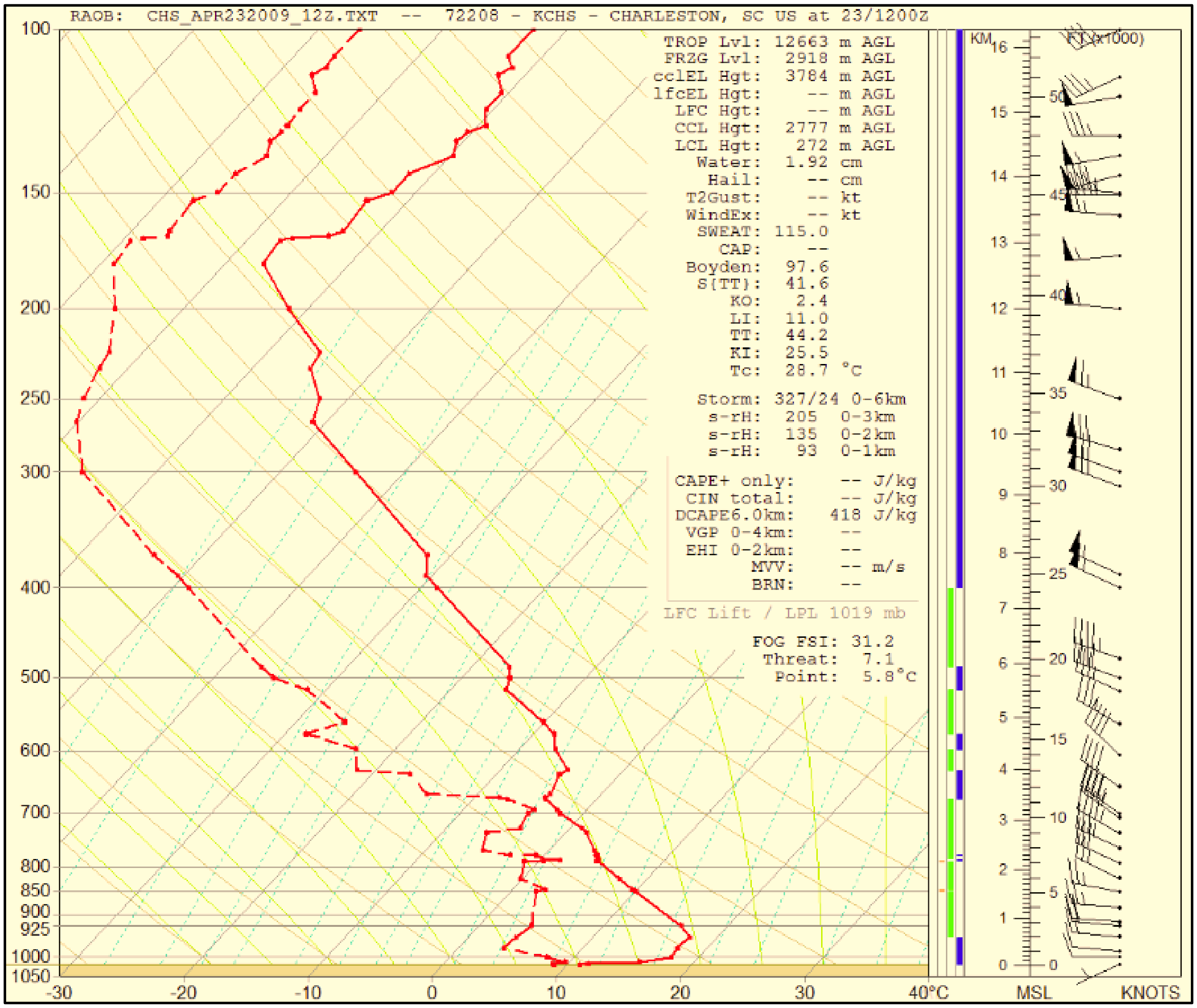

Figure 7. 1200 UTC 23 April 2009 Charleston, SC (CHS) sounding is characterized by strong surface-based inversion, dry low-levels, EML, and increasing winds above the inversion.

4. Implementation of a Nocturnal Fire Growth Decision Chart

Not all fires pose a risk for nocturnal EFB. However, those that do exhibit this potential will require enhanced wording through briefings, forecasts, and other decision support services. Forecasters can begin a diagnosis by obtaining information regarding antecedent hydrologic conditions (regardless of drought status) and the fuel environment. Also, the identification of anomalous forecast mixing height and transport winds will prove valuable when assessing the potential for significant ventilation rates. As a fire evolves any available visual observations of the fire structure and plume characteristics exhibited via radar imagery will assist the ability of forecasters to determine a fire's intensity. Lastly, if forecasters determine the development of a NFG profile in the vicinity of a large fire, then it is expected that significant modifications to the local stability will occur, creating a high potential of nocturnal fire growth. A Nocturnal Fire Growth Decision Chart for the Carolina coastal plains (Fig. 8) has been developed to assist forecasters to go through the process in determining the potential for nocturnal fire growth, with considerations for the factors listed above.

Specific antecedent factors detailed in the decision tree include the existence of rainfall compared to ET (<20%), the availability of sufficient dry fuels, and anomalous forecast values of mixing heights/transport winds/ventilation rates. Visual and radar observations include: the identification of a large plume - characterized by sharply defined pyrocumulus, radar observations of 30 dBZ scatterers lofted more than 9 km, and a plume length exceeding 37 km persisting into the nocturnal period. Lastly, the decision chart incorporates all NFG characteristics developing overnight. The potential development of stronger winds overnight resulting from a nocturnal jet, coastal jet, or increasing synoptic flow are other factors to consider, especially with a NFG sounding in place or expected to develop. If all, or most, of these factors, are in place, then it is strongly recommended that enhanced wording be utilized to highlight the potential for nocturnal EFB in decision support briefings and forecasts.

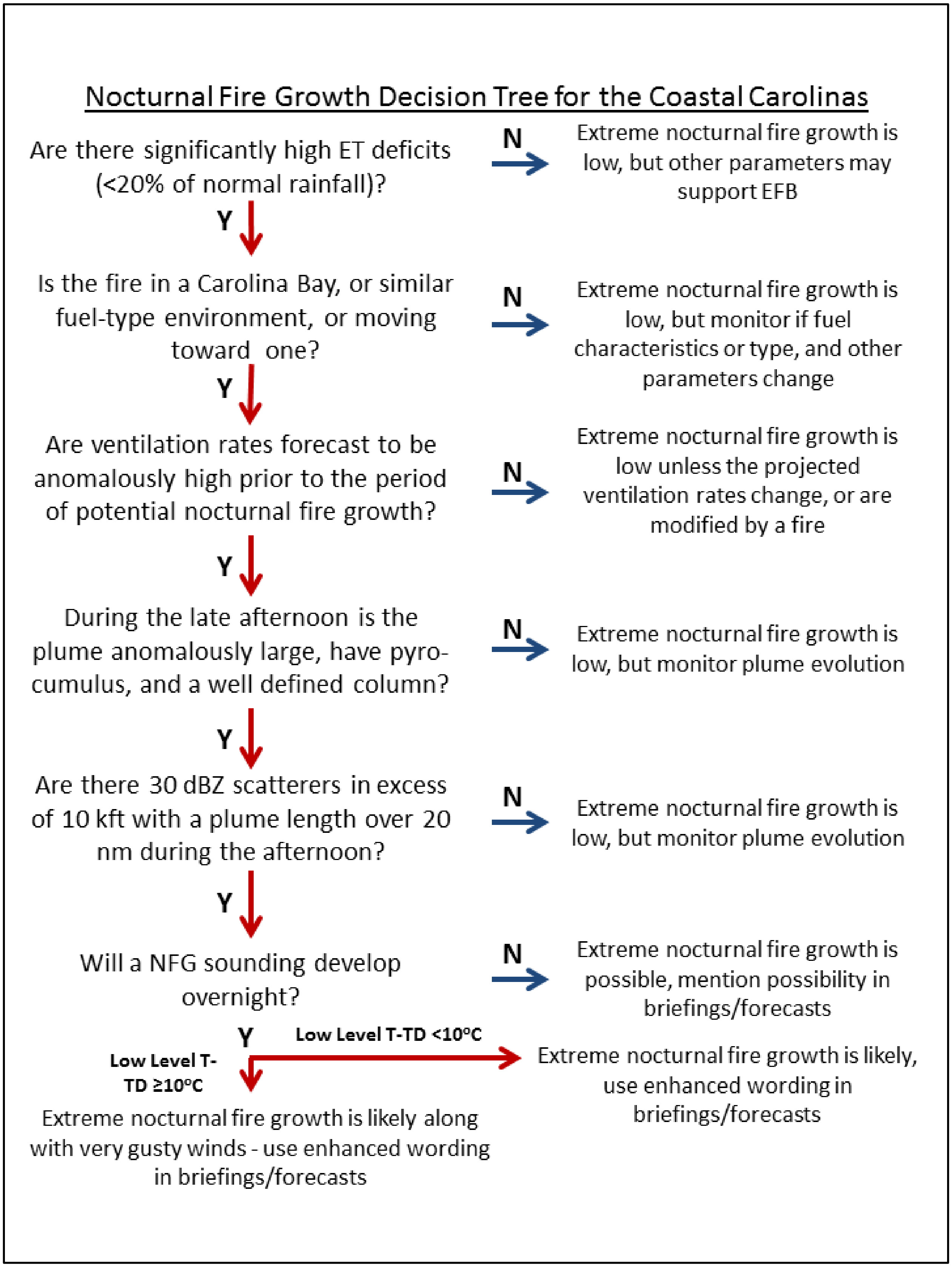

Figure 8. Nocturnal Fire Growth Decision Tree for the Coastal Carolinas.

5. Applications Utilized During the Juniper Road Fire – Pender County, NC

On 19 June 2011 WFO Wilmington NC initiated multi-day FBAN support for the Juniper Road fire (Fig. 9) in the Holly Shelter Game Preserve in Pender County NC, which ultimately consumed 12140 ha before it was brought under control. The fire had ample fuel with which to work as it was situated in the middle of the game preserve consisting of 20000 ha of dense Carolina Bay fuels. Over the 30 day period prior to the Juniper Road fire, 13 mm of rainfall was measured at the Back Island RAWS (BKIN7), located in the Holly Shelter Game Preserve. The BKIN7 observed rainfall amounted to approximately 6 percent of ET computed for the site. In the two weeks leading up to the fire, rainfall as a percentage of ET was only 5 percent. In addition, the projected ventilation rate was well above the 90th percentile for the afternoon of 21 June 2011 for all June ventilation rates. In fact, the ventilation rate reached 2.9 standard deviations above the mean for June.

During the late afternoon of 21 June 2011, before the period of significant nocturnal spreading, the plume became very large and exhibited sharply defined pyrocumulus. KLTX radar imagery indicated 30 dBZ scatterers lofted more than 3500 m with a plume length in excess of 40 km. The 1200 UTC 22 June 2011 Morehead City, NC (MHX) sounding (Fig. 10) located approximately 80 km northeast of the fire exhibited NFG sounding characteristics. Specifically, the sounding showed a 5^{o}C surface-based inversion to 900 hPa, an EML in the 900 to 600 hPa layer, and a dry column, especially at the top of the inversion where the dewpoint depression was 16°C. In addition, the low-level wind field increased with height through the depth of the EML to 15 m s^{-1}.

Many of the Extreme Nocturnal Fire Growth Decision Chart parameters suggested a period of significant nocturnal EFB was possible during the night of 21-22 June 2011. As a result, WFO Wilmington NC included enhanced wording to highlight the potential hazard in briefings sent to the FBAN, Emergency Management, and responders during the afternoon prior to the night of significant fire growth. Specifically, the briefings stated that "*A concern exists that this fire is hot/large enough to tap the developing low-level jet resulting in an increase in winds local to the fire allowing it to run at night.*" The nearby RAWS BKIN7 located just west of the fire indicated wind gusts approaching 16 m s^{-1} and a drop in RH from near 100 percent to 70 percent. These trends suggest that turbulent mixing was occurring in the vicinity of the fire. Ultimately, gusty winds developed and the fire made a significant nocturnal run during 21-22 June 2011 consuming an additional 1618 ha of the preserve.

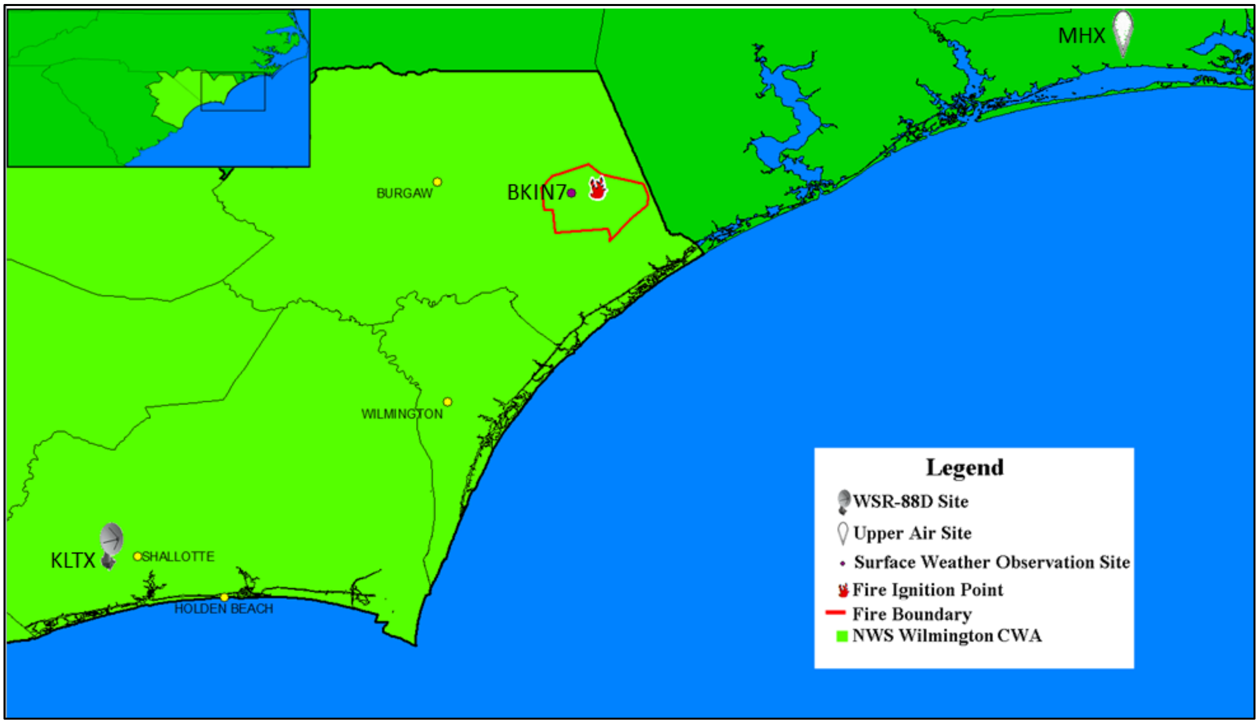

Figure 9. Map of NWS Wilmington NC CWA (bright green), Juniper Road fire (red outline), Morehead City, NC (MHX) upper air site, Shallotte, NC (KLTX) doppler radar site, and BKIN7.

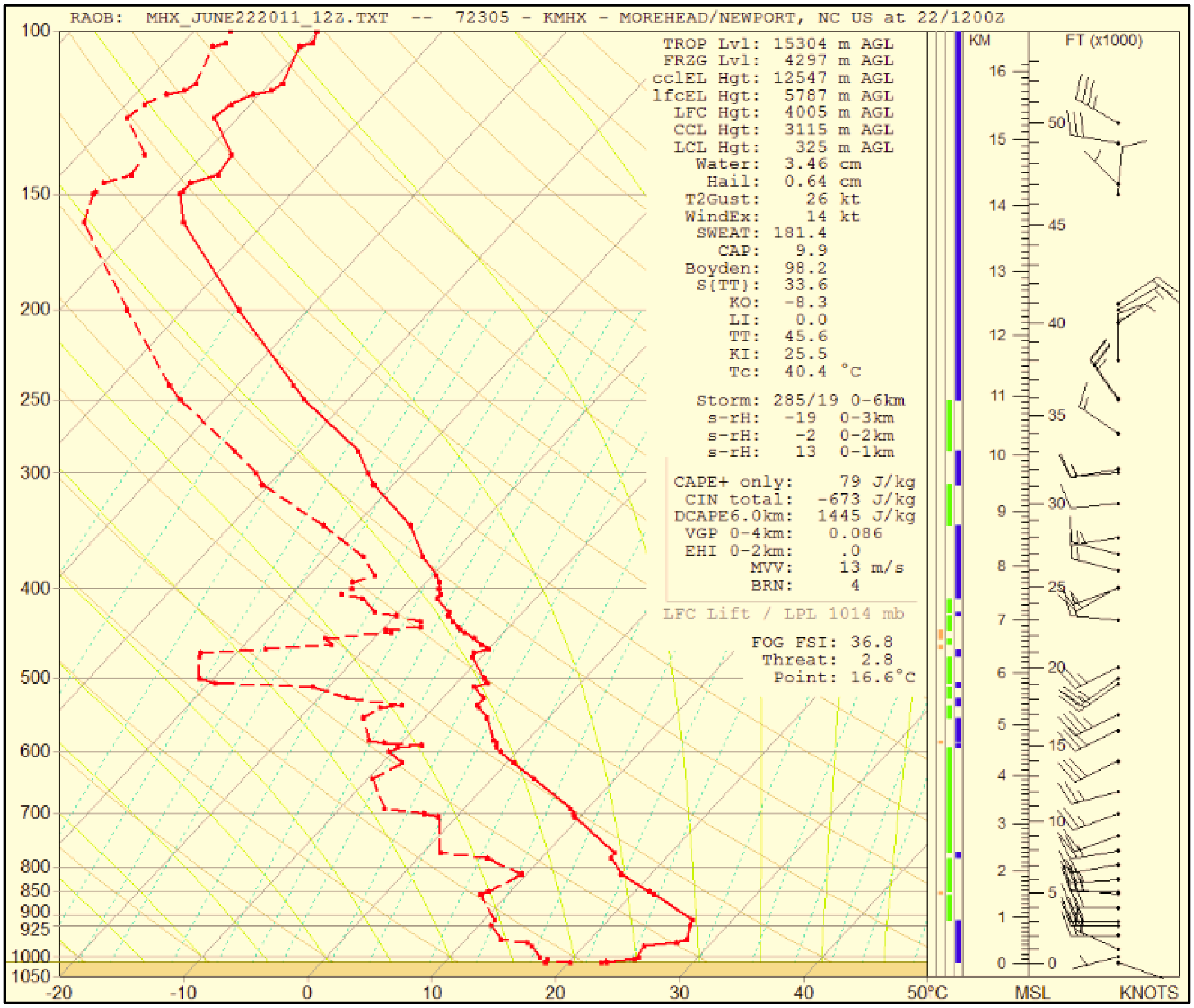

Figure 10. 1200 UTC 22 June 2011 Morehead City, NC (MHX) sounding characterized by a surface-based inversion, dry low-levels, EML, and increasing winds above the inversion.

6. Conclusions

The Highway 31 fire was an extremely large Carolina coastal plain fire defined by dry antecedent precipitation deficits, ample fuel, anomalous forecast ventilation rates, distinct visual and radar characteristics, and a NFG profile. All of these factors yielded dangerous fire growth the night of 22-23 April 2009 with significant public impact and unique emergency management challenges. The Highway 31 fire was also problematic for NWS Fire Weather Forecasters by exposing pitfalls resulting from NWP limitations. It is clear that research on additional large fires would greatly help create a better understanding of the conditions required for nocturnal EFB development. In addition, further research would be needed to simulate the effects of large fires on NWP output to identify how the atmosphere can be modified.

Although current NWP does not adequately represent relatively small- scale atmospheric contributions from large fires due to resolution issues, forecasters can still add value to decision support products and briefings by diagnosing the potential for nocturnal fire growth. In addition, if the stability is not expected to increase overnight, then the typical NFG portion of the decision chart should not be as critical in the overall nocturnal EFB assessment. In the absence of a formal potential nocturnal wind forecast parameter in Spot Forecasts, NWS Fire Weather Forecasters will need to rely on enhanced wording for possible nocturnal EFB through decision support briefings and forecasts. A better understanding of the characteristics that can lead to significant nighttime fire spread through the Nocturnal Fire Growth Decision Chart provided NWS forecasters with the ability to highlight the potential during the 21-22 June 2011 Juniper Road event.

Acknowledgments

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