INTERACTION BETWEEN A WILDFIRE AND A SEA-BREEZE FRONT

Deborah Hanley[1], Philip Cunningham[2], and Scott Goodrick[3]

[1] Division of Forestry, Florida Department of Agriculture and Consumer Services, Tallahassee, Florida
[2]Department of Meteorology, Florida State University, Tallahassee, Florida
[3]USDA Forest Service, Southern Research Station, Athens, Georgia

1. Introduction

The effect of weather on fire behavior is one of the most important and most difficult factors to understand and predict. Rapid changes in wind speed and direction can quickly affect the rate and direction of fire spread as well as fire intensity. Changes in humidity may also cause unexpected changes in fire activity. Florida experiences sea breezes, lake breezes, and bay breezes almost every day during the year and also sees a combination of many of these breezes. Most wildfires in Florida experience some effect from these breezes.

The nature of the interaction between sea breezes and wildfires is relatively unknown. Previous studies of sea breezes depended upon a network of observation sites at different locations in the area of the sea breeze or used numerical models to simulate the sea breeze. More recently, radar and satellite imagery have been shown to be useful in tracking the evolution and timing of the movement of sea-breeze fronts. Radar and satellite have also been used in recent studies to observe smoke plumes from fires and other sources of particulate emissions (i.e. volcanoes, dust storms, industrial emissions, etc).

This study will offer a unique opportunity to study the interaction between a wildfire and a sea-breeze front in April 2004 in the Apalachicola National Forest in the Florida Panhandle using a combination of data sources including observations from the Remote Automated Weather Station (RAWS) network and the National Weather Service (NWS), as well as NWS radar imagery.

2. Data and methodology

The goal of this study is to provide an improved understanding of the interactions between wildfires and the sea breeze, based both on observations of a fire event and on idealized numerical simulations that describe the interaction between a buoyant plume and a density current.

a. Case study

The details of the atmospheric conditions at the time of the fire are described through a combination of surface observations, upper-air soundings and radar data (both base reflectivity and radial velocity). Description of the fire is more problematic, as no direct measurements of the fire are available, except for daily estimates of area burned. As an alternative, we focus on the behavior of the smoke plume as observed by the Weather Surveillance Radar-1988 Doppler (WSR-88D) instrument as a surrogate, since Hufford et al. (1998) found high reflectivities to be associated with more intense burning.

The East Fork Fire burned over a period of about two weeks in early April 2004; however, this study focuses on the early stages of the fire, specifically the afternoon of April 5. The location of the East Fork Fire and the nearby weather stations are shown in Fig. 1. Observations of temperature, relative humidity, wind speed and direction are used to track the passage of the sea-breeze front. A high-pass filter was applied to the temperature and relative humidity time series to filter out any signals with periods greater than or equal to 24 h. The high-pass filter was accomplished using a Fourier decomposition of a 96-h time series for each station and recomposing the time series with the longer wave periods excluded.

During the period of interest, the WSR-88D site in Tallahassee, Florida, was operating in clear-air mode, which is its most sensitive mode of operation. The antenna has a slower rotation rate than it does in precipitation mode, increasing the radar sensitivity and therefore its ability to sense smaller objects in the atmosphere. Most of the signal in this mode will be the result of airborne dust and particulate matter.

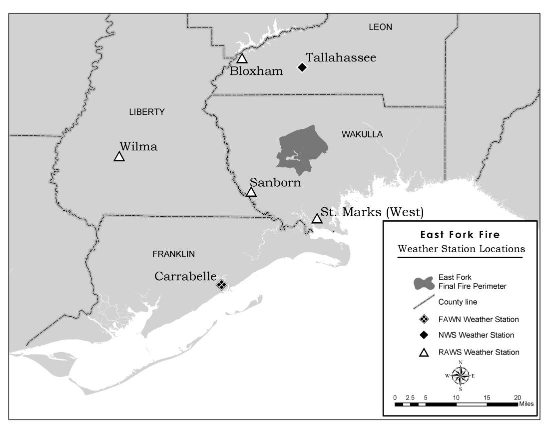

Fig. 1. Locations of the East Fork Fire (dark gray shading) and the weather observation stations.

b. Idealized numerical simulations

As an initial step towards understanding the interaction between wildfires and sea-breeze circulations, in this study we employ a large-eddy simulation (LES) model designed to explore the dynamics of buoyant plumes from intense heat sources in an effort to gain insight into the processes associated with the interaction of a sea-breeze front with a buoyant plume from a wildland fire. The results from this study will then motivate further investigation using a coupled atmosphere–fire model (e.g., Linn et al. 2002), in which the response of the fire itself can be examined.

The LES model to be used is described by Cunningham et al. (2005), and is based on the dynamical core of the Weather Research and Forecasting (WRF) model in physical height coordinates (Skamarock et al. 2001). The domain used in these simulations is a rectangular box of size 800 x 3200 x 1000 m in the x, y, and z directions, respectively, with a uniform grid spacing of 10 m in all three dimensions. Boundary conditions are periodic in the x-direction and open-radiative in the y-direction. Other details of the LES model are identical to those described by Cunningham et al. (2005).

There is significant evidence that sea-breeze fronts can be interpreted as density currents (e.g., Simpson 1994), particularly when the ambient wind is in the offshore direction. Density currents have been explored extensively using numerical models, in an atmospheric context primarily in connection with thunderstorm outflows (e.g., Droegemeier and Wilhelmson 1987), but also in general fluid mechanics contexts (e.g., Härtel et al. 2000). In the simulations shown here we initialize the density current via a cold pool located at the surface that is localized in the y direction at one end of the domain and that is uniform in the x-direction. An ambient wind is imposed in the negative y-direction, such that the simulations attempt to represent the inland advance of a sea-breeze front in the presence of offshore winds.

Finally, we emphasize that the goal of the idealized modeling portion of this study is not to reproduce the behavior in the observed case, but is to attempt to gain insight into the basic dynamical processes associated with the interaction between a sea-breeze front, as represented by a density current, and a buoyant plume representative of those seen with wildland fires.

3. Case Study

The East Fork fire began late on April 4, 2004, or early on April 5, 2004, and is suspected to have been started by human causes, either accidental or arson. The fire burned in timber and southern rough fuel groups. According to the National Interagency Coordination Center Reports, by April 7 the fire reached 7,000 acres (28.3 km^2) and was only 20% contained. Spotting of up to 0.25 mile (0.4 km) ahead of the main fire front was observed with rates of spread of 20–30 chains per hour (0.11–0.17 m s^{-1}) reported. This observed fire activity continued and by April 8, the area burned had increased to over 8,400 acres (34.0 km^2). By April 13, the fire had consumed almost 20,000 acres (80.9 km^2) and was only 70% contained. The fire ultimately consumed over 26,000 acres (105.2 km^2) of wilderness area and was 90% contained by the April 15. The total area burned was increased by back burning activities of the fire suppression crews in an effort to remove fuels ahead of the active fire front and help containment.

On April 4, 2004 a dry cold front moved through the panhandle of Florida between 1200 UTC and 0000 UTC on April 5. The passage of the cold front brought cooler and drier air to the region, dropping dew point temperatures from 4.4°C to -1.7°C. Upper-air soundings from Tallahassee for April 5 (not shown) reveal a weakening of the northwesterly flow above 850 hPa and pronounced drying below 800 hPa.

Hourly surface observations were used to examine the passage of the sea-breeze front. The raw time series are dominated by the normal diurnal cycle; in an effort to remove this cycle and to identify more clearly the passage of the sea-breeze front, a high-pass filter was applied as noted above. The reconstructed time series for temperature and relative humidity are shown in Figs. 2a and 2b, respectively. Sanborn, the closest of the four stations to the coast, shows the earliest decrease in temperature and increase in relative humidity (1400 EDT) associated with the passage of the sea-breeze front, while the changes at the other stations occur 2–3 h later.

The sea-breeze front can be seen clearly on the Tallahassee 0.5° elevation radar reflectivity imagery (Figure 3). The East Fork Fire is visible approximately 40 km southwest of the radar location and is indicated by high values of reflectivity. The sea-breeze front moves inland during the time period and by 1927 UTC (Fig. 3a) the smoke plume from the fire increases in intensity with reflectivities reaching 28–32 dBZ for a brief period prior to the arrival of the sea breeze front.

At 2124 UTC (Fig. 3b), the sea-breeze front has reached the fire, as evidenced by the humidity increase indicated at Sanborn. Despite this increasing humidity, the plume intensifies to levels not previously seen with a large core of the plume now displaying reflectivities in the 28–32+ dBZ range (Fig. 3b). Upper-level winds that are carrying the plume back toward the coast and may be increasing due to the upper-level return flow of the sea breeze circulation. The reflectivity of the plume decreases from this peak over the next several hours as the fire begins to respond to the decreased temperature and increased moisture of the marine air, leading to a decrease in fire activity (Fig. 3c).

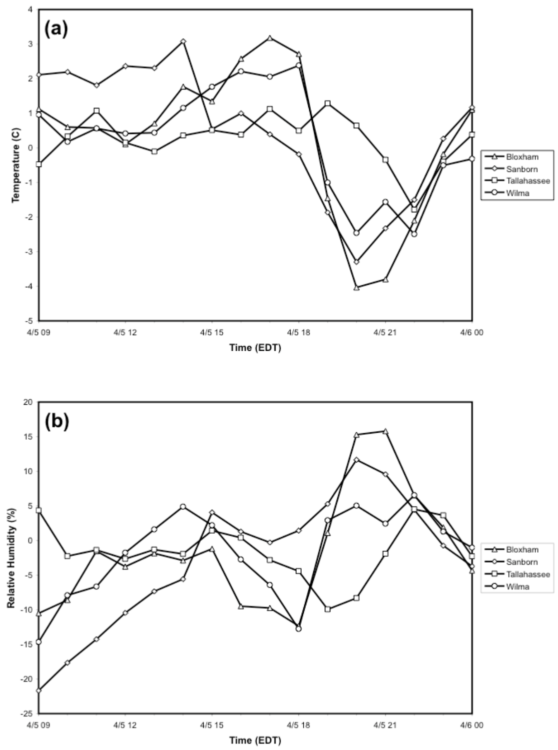

Fig. 2. Time series of surface observations on 5 April 2004 with high-pass filter applied as described in the text: (a) temperature, and (b) relative humidity.

4. Numerical Simulations

In this section, we present three simulations to explore the nature of the interaction between a density current and a buoyant plume: two simulations in which a density current and a plume are examined in isolation, and one simulation in which both are present and they are allowed to interact.

The density current is initialized with a cold pool at one end of the domain. When the simulation is started, the cold pool adjusts under gravity and initiates a density current that travels in the positive y-direction. The ambient winds are directed in the negative y-direction, representing an offshore flow situation. The cold pool is initially uniform in the x-direction, but rapidly becomes three-dimensional with the development of lobe and cleft instabilities (not shown). Figure 4a depicts the potential temperature, vertical velocity, and wind field in the y–z plane. The Kelvin–Helmholtz billows characteristic of the interface between the density current and the ambient atmosphere are apparent, as is the enhanced vertical motion and return flow associated with the current.

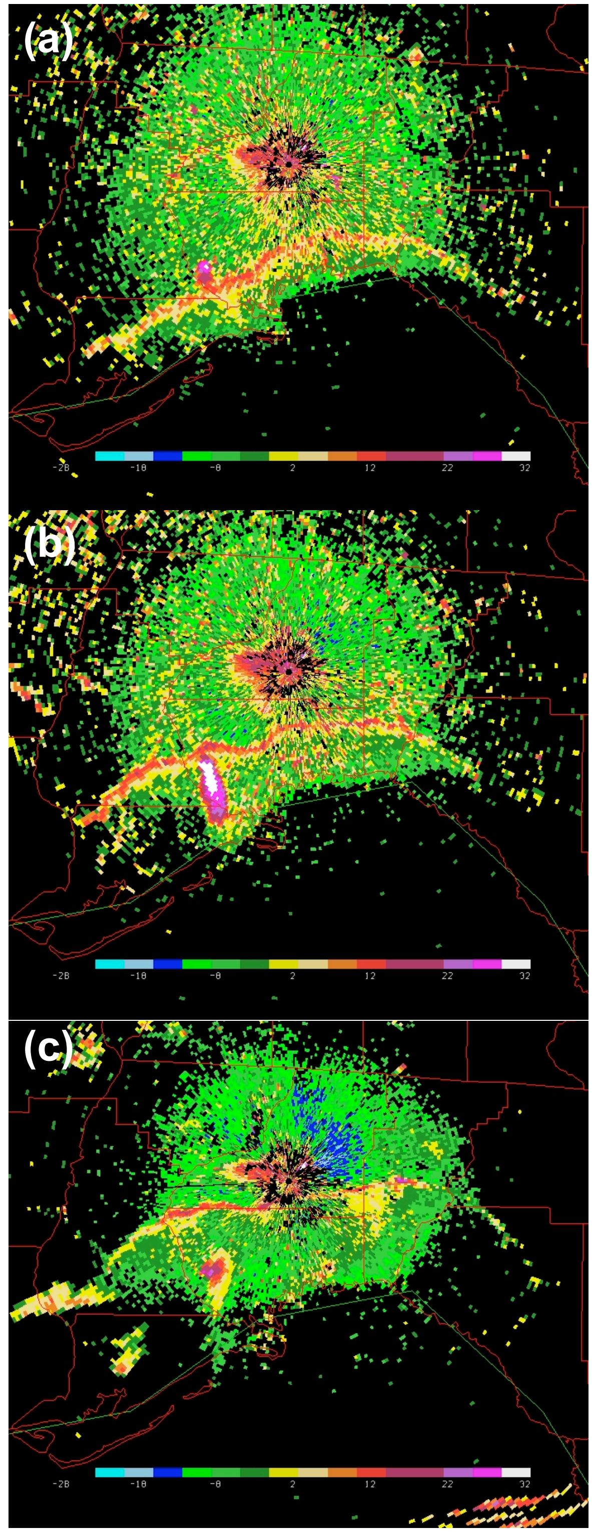

Fig. 3. Radar reflectivity (0.5° elevation) on 5 April 2004 at Tallahassee for (a) 1927 UTC, (b) 2124 UTC, and (c) 2323 UTC.

Figure 4b illustrates the simulation of the plume only. The plume is initiated by a heat source centered at y = 2700 m, the spatial configuration of which is a smoothed top-hat function. Characteristic features of the plume are similar to those described in more detail in the simulations by Cunningham et al. (2005).

The simulation in which both the plume and the density current are present is depicted in Fig. 4c. It is evident that the interaction between the density current and the plume results in the appearance of the intensification of the plume, particularly in the vertical velocity field, in conjunction with the arrival of the circulation associated with the current, and this intensification occurs before the head of the density current reaches the heat source. In addition, the plume becomes more vertical in response to the pressure perturbation that precedes the head of the current and that counteracts the ambient atmospheric flow at low levels (compare Fig. 4b with Fig. 4c).

5. Summary and discussion

Radar observations of a plume associated with a wildfire indicate the possibility that the arrival of a sea-breeze front results in a temporary, but significant, increase in fire intensity. There is insufficient evidence to explain this intensification; however, idealized numerical simulations that examine the interaction of a buoyant plume with a density current suggest that the period of interaction preceding the arrival of the current may result in the intensification of the vertical velocity in the plume. The impact of this interaction on fires is uncertain, however, and further study is required, particularly using coupled atmosphere–fire models, to explore this interaction in more detail.

It is also possible that the sea-breeze front can transport smoke from the fire, decreasing air quality substantially further inland, and this possibility is also being explored using the LES model described here.

6. Bibliography

Cunningham, P., S. L. Goodrick, M. Y. Hussaini, and R. R. Linn, 2005: Coherent vortical structures in numerical simulations of buoyant plumes from wildland fires. *Int. J. Wildland Fire*, **14,** 61–75.

Droegemeier, K. K. and R. B. Wilhelmson, 1987: Numerical simulation of thunderstorm outflow dynamics. Part I: Outflow sensitivity experiments and turbulence dynamics. *J. Atmos. Sci.*, **44,** 1180–1210.

Härtel, C., E. Meiburg, and F. Necker, 2000: Analysis and direct numerical simulation of the flow at a gravity-current head. Part 1. *J. Fluid Mech.*, **418,** 189–212.

Hufford, G. L., H. L. Kelley, W. Sparkman, and R. K. Moore, 1998: Use of real-time multisatellite and radar data to support forest fire management. *Wea. Forecasting*, **13,** 592–605.

Linn, R. R., J. M. Reisner, J. J. Colman, and J. Winterkamp, 2002: Studying wildfire behavior using FIRETEC. *Int. J. Wildland Fire*, **11,** 233–246.

Skamarock, W. C., J. B. Klemp, and J. Dudhia, 2001: Prototypes for the WRF (Weather Research and Forecasting) model. Preprints, *Ninth Conf. On Mesoscale Processes*, Fort Lauderdale, FL, J11–J15.

7. Biographies

Dr. Deborah Hanley is the fire weather meteorologist for the State of Florida Division of Forestry.

Dr. Philip Cunningham is an assistant professor in the Department of Meteorology at the Florida State University.

Dr. Scott Goodrick is a research meteorologist for the USDA Forest Service Southern Research Station.

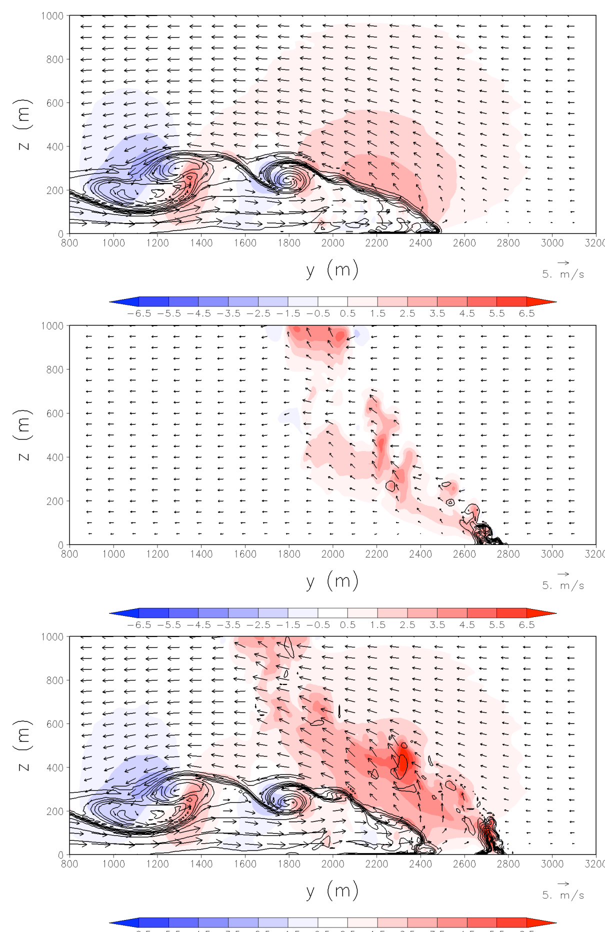

Fig. 4. Vertical velocity (in ms^{-1}, shaded as indicated) and potential temperature (contour interval 1 K) in the y–z plane for (a) the density current only, (b) the plume only, and (c) the density current and the plume. Vectors depict velocity in the plane of the section, with scale at bottom right.