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Thermodynamic Profiling and Humidity Mapping for Local High-Impact Weather Prediction

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Abstract

Early stage convection has been detected in temperature and humidity parameters derived from ground-based microwave radiometer profiler observations. This capability can be extended to regional scales using combined GNSS[1] and radiometer data for three-dimensional humidity mapping. We present examples of radiometer-derived thermodynamic parameters during early stage convection and tornadic supercell analysis including 1DVAR radiometer profiles, and describe opportunity for humidity mapping evaluation in a hazardous weather testbed.

Convective Storms

Convective storms are initiated by vertical motion of humid air due to converging winds, thermals, or wind passage over rising terrain. Air cools and expands as it moves upward, triggering water vapor condensation. Latent heat released by the condensation causes the air parcel to continue rising. The rising air draws additional lower level humid air upward, releasing more latent heat. During typical convection, each 10 cubic meters of air releases roughly the amount of energy in a cubic centimeter of gasoline, generating a familiar mushroom-shaped convective storm. The total energy release in a typical convective storm that creates gust front winds, lightning, hail and rain can be 25 kt TNT or more.

Boundary Layer Measurements

It is widely recognized that a practical and cost effective way to improve high impact local weather forecasting is via enhanced thermodynamic (temperature and humidity) and wind monitoring in the boundary layer where severe weather originates and exacts its personal and economic tolls. The U.S. National Research Council recommends a

[1] Global Navigation Satellite System

400-site national wind and thermodynamic monitoring network to improve high impact local weather forecasting (NRC 2008, 2010, 2012).

The economic impact of convective storms in the U.S. totals tens of billions of dollars per year (Lazo et al, 2011) -- better forecasting of these events would provide greater productivity and reduce personal hazard and economic loss.

Continuous Thermodynamic and Liquid Profiling

Radiosondes typically provide twice-daily high resolution temperature, humidity and wind soundings, whereas radiometers provide continuous temperature, humidity and liquid soundings (Campos et al, 2014; Serke et al, 2014; Ware et al, 2013; Cimini et al, 2011). Radiosonde soundings are routinely assimilated into numerical weather models and can also be used to generate traditional forecast indices for local high impact weather forecasting. However, radiosonde sampling intervals are typically inadequate to effectively forecast convective and other local weather events that develop on time scales of several hours. This presents an opportunity to improve local high impact weather forecasting using continuous boundary layer thermodynamic and wind information.

Severe Storm

The June 29, 2012, Derecho was one of the most destructive and deadly fast-moving severe thunderstorm events in North American history. It produced torrential rains and wind gusts approaching 150 km/hr in Washington, D.C., on the evening of June 29, 2012. It caused 22 deaths and widespread damage that left millions without power for nearly a week.

Radiometer observations from a private network[2] 30 km northwest of Washington, D.C., show an extremely unstable atmosphere with hurricane strength wind potential more than six hours in advance (Figure 1). CAPE (Moncrieff and Miller, 1976) and Windex (McCann, 1994) derived from radiometer and radiosonde (30 km away) soundings are shown in Table 1.

Table 1. CAPE and Windex derived from Germantown radiometer and Dulles radiosonde (30 km apart).[3]

Date Time	Sensor	CAPE (J/kg)	Windex (kt)
29Jun12 12Z	Radiometer	0	26
	Radiosonde	125	18
30Jun12 00Z	Radiometer	3,465	62
	Radiosonde	4,409	71

[2] http://earthnetworks.com/Products/BoundaryLayerNetwork.aspx
[3] RAOB analysis (www.raob.com).

The radiometer and radiosonde soundings show good agreement, in spite of their 30 km separation.

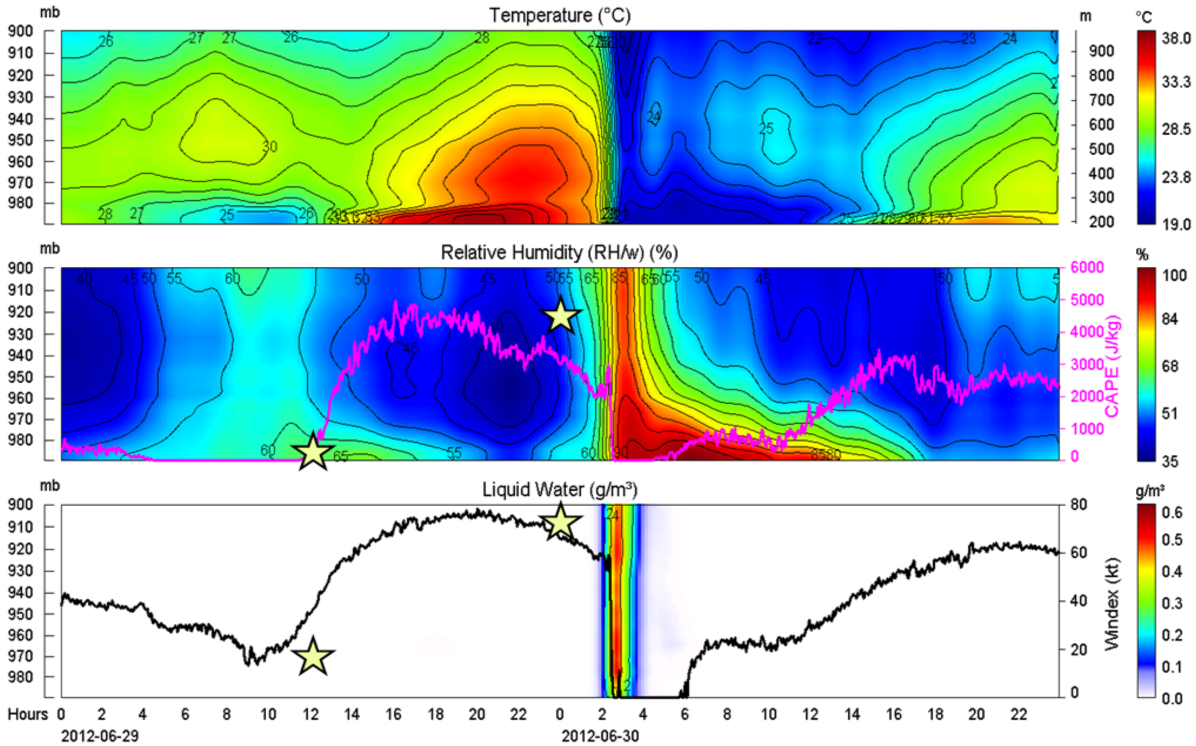

Figure 1. Radiometer profiles to 1 km height with superimposed CAPE and Windex derived from radiometer and radiosonde (stars)[4].

In this case, knowledge of extremely unstable atmospheric conditions (CAPE = 5,000 J/kg) and hurricane force wind potential (Windex = 80 kt = 148 km/hr) more than 6 hours in advance could have contributed to more accurate severe weather warnings. However, relatively large CAPE and Windex maxima are seen the following day and severe weather did not follow. This suggests that additional information such as that described in the following sections may be required to avoid false alarms.

Lightning Prediction Hours in Advance

Good agreement has been reported between thermodynamic parameters derived from collocated radiometer and radiosonde soundings at a tropical station (Madhulatha et al, 2013; Ratnam et al, 2013). An algorithm was developed using radiometer data from 26 thunderstorm cases that combined thermodynamic parameters associated with the occurrence of thunderstorms. Included were K index, humidity index, precipitable water, stability index and equivalent potential temperature lapse rate. Algorithm testing on an independent set of nine thunderstorms demonstrated that thermodynamic indices derived from radiometer soundings can be used to predict thunderstorms at least two hours in advance.

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[4] RAOB (www.raob.com) analysis and display.

Electric field mill (EFM) measurements (Evans and Velkoff, 1972) commonly used to assess lightning risk for space launch operations are shown in Figure 2, along with collocated boundary layer thermodynamic measurements.

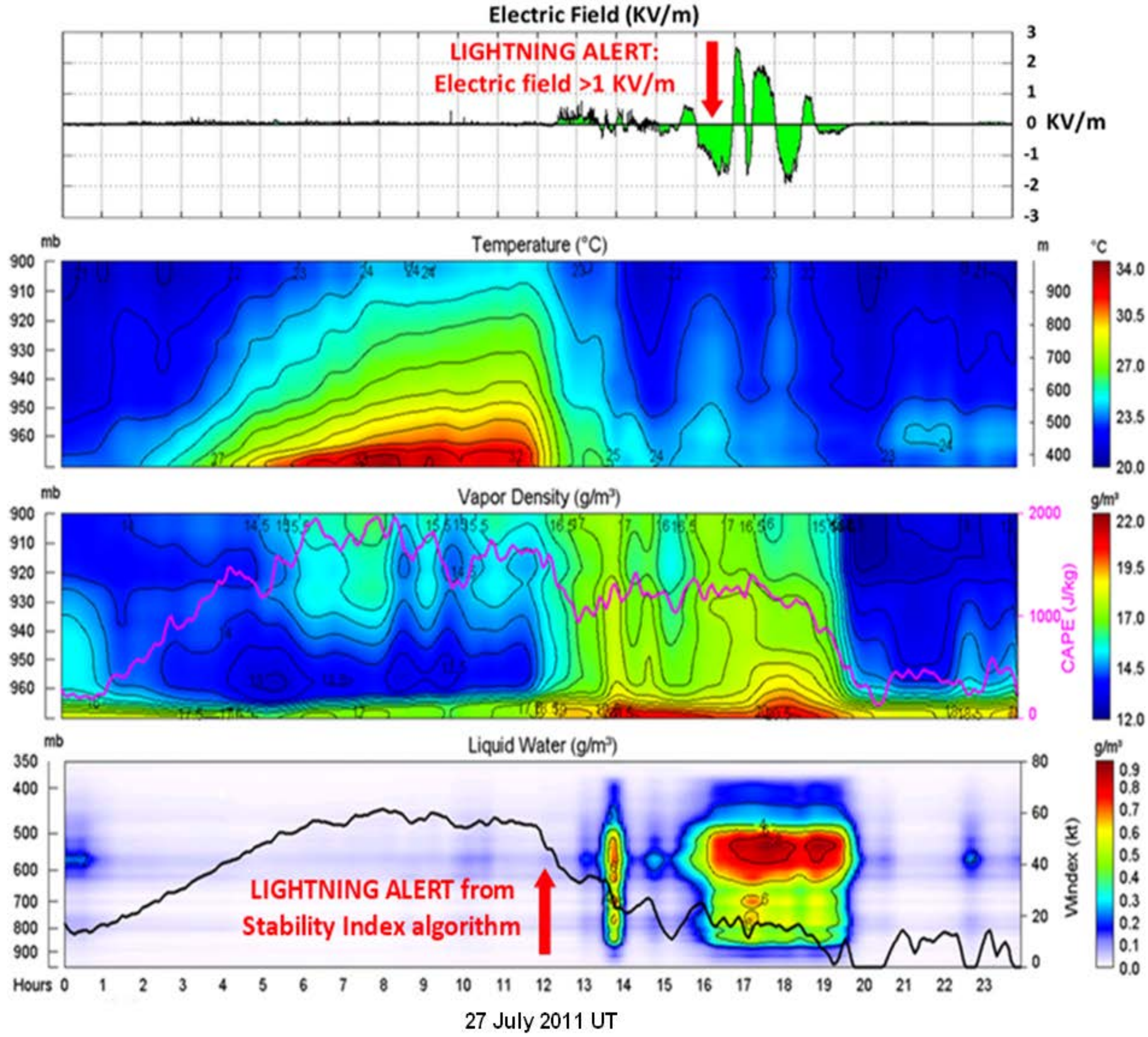

Figure 2. Lightning alerts from electric field and thermodynamic measurements.[5]

At 1615 UT the electric field exceeded 1 kV/m, a threshold that mandates a scrub decision for India space launch operations. CAPE and Windex forecast index time series are superimposed on the contour plots in the bottom two panels. These indices fall by nearly 40% from 1200 to 1300 UT, correlated with large boundary layer temperature and vapor density variations. These signatures precede the traditional electric field warning threshold by more than three hours. Similar plots for the same radiometer dataset are presented by Madhulatha et al (2013) that did not employ

[5] RAOB (www.raob.com) analysis and display.

radiometer observation and retrieval methods optimized for accurate performance during rain (Xu et al, 2014).

Three-Dimensional Humidity Mapping

Humidity convergence during early stage convection can be detected in microwave radiometers and GNSS signals before it generates hydrometeors detectable by radar (Bauer et al, 2011; Liu and Xue, 2006; MacDonald et al, 2002). Integrated water vapor along receiver-satellite lines-of-sight (slant water vapor) can be estimated from ground-based GNSS receiver and surface meteorological data (Ware et al, 1997; 2000). If these estimates are combined with radiometer humidity profiles three-dimensional humidity fields associated with early stage convection can be uniquely mapped (MacDonald et al, 2002).

Tornadic Supercell Analysis

A supercell tornado passed within 14 km of a radiometer at Tateno, Japan, on 6 May 2012. Doppler radar observations and hydrometeor density (rainwater, snow and graupel) analysis including 1DVAR radiometer retrievals[6] are shown in Figure 3 (Araki et al, 2014).

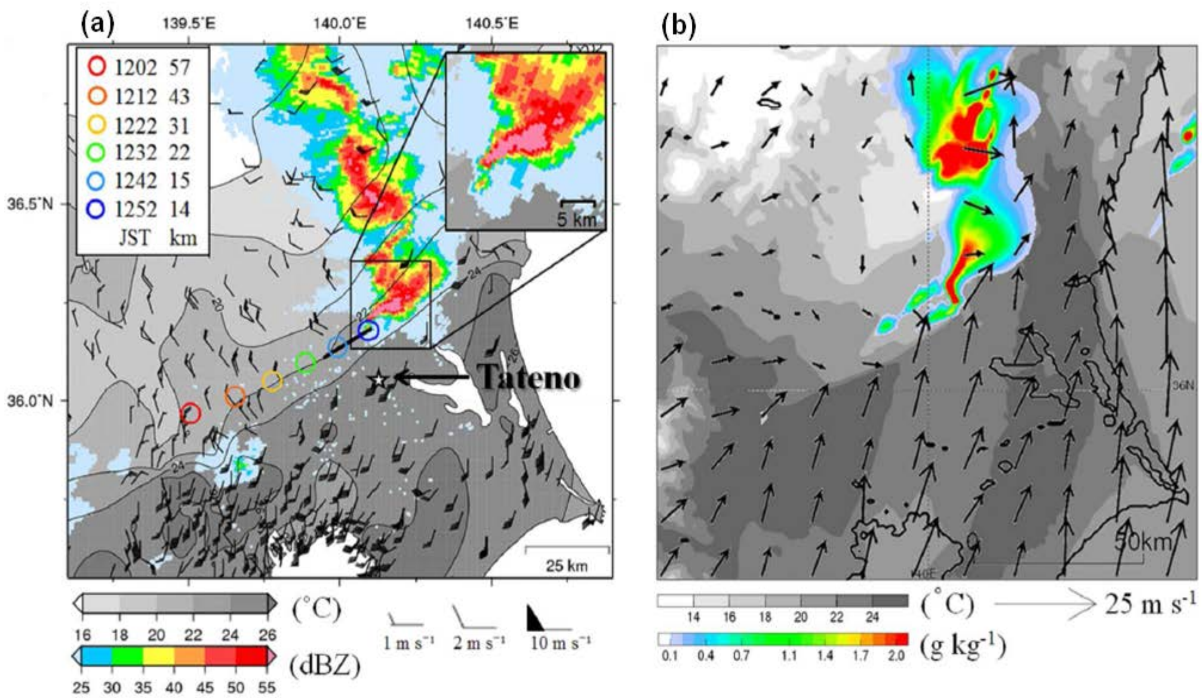

Figure 3. Radar observations (a), and analysis (b) including radiometer data. Hook echoes are evident in (a) with time and distance from Tateno indicated by colored circles, and in (b) at 1245 JST.

[6] One dimensional variational analysis using radiometer and radiosonde derived background error covariance (Ishimoto, 2014: Cimini et al, 2011; Hewison, 2007).

For this case study ten forecast indices were derived from 1DVAR soundings[7]. Ninety minutes before the tornado, the convective available potential energy increased significantly. At the time of minimum distance to the supercell, low-level vertical wind shear and some composite parameters were consistent with Significant Tornadic (SIGTOR) supercell activity. High resolution water vapor density analysis from a 17-km grid GNSS network (Shoji et al, 2014) is similar to the hydrometeor density pattern in Figure 3 (b). This case study demonstrates realistic tornado modeling when continuous radiometer profiles are assimilated, with promise for further improvement if GNSS moisture data are included.

Hazardous Weather Testbed

The NOAA Hazardous Weather Testbed[8] (HWT) evaluates the operational utility of new science, technology and products. A principal experimental objective is improved understanding of convective initiation (Kain et al, 2013). Radiometer and GNSS data are being collected in the Dallas-Ft. Worth region during spring 2014 (Figure 4). Network station density averages 52 km, adequate to evaluate three-dimensional humidity mapping and detection of moisture convergence associated with early stage convection (MacDonald et al, 2002). Network data assimilation into variational LAPS (Albers et al, 2013; Xie et al, 2011) is planned as part of the spring 2014 HWT experiments.

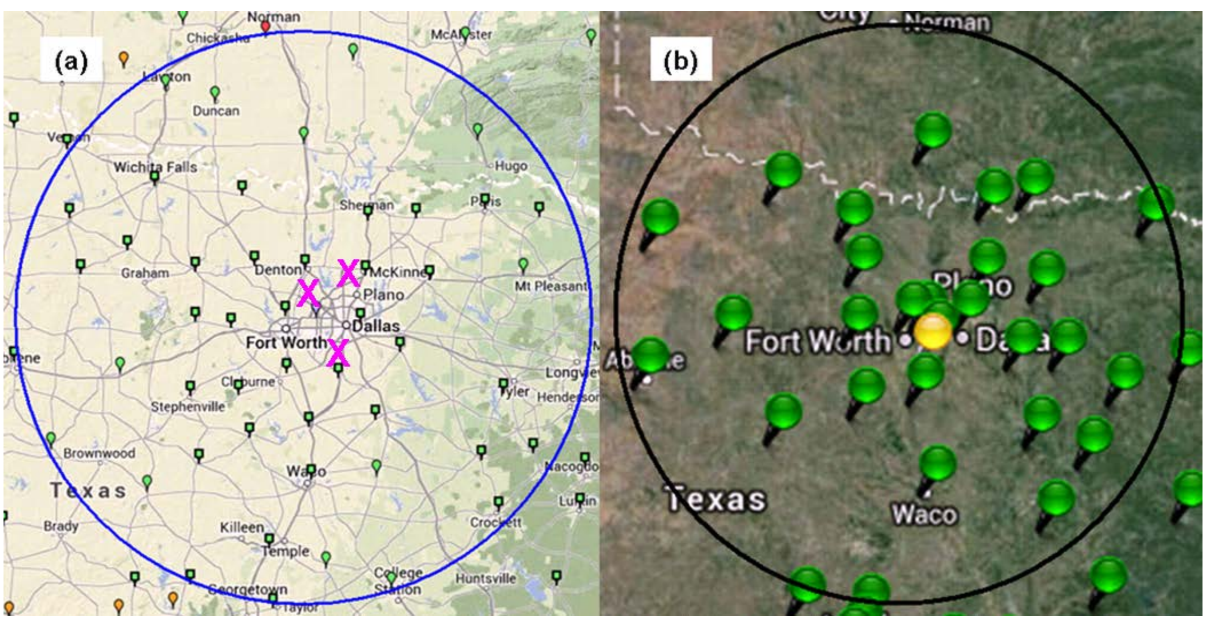

Figure 4. 47 public (a) and 27 private (b) GNSS stations and 3 private radiometer stations (X) within 250 km of Dallas-Ft. Worth.

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[7] Forecast indices were derived from 1DVAR retrievals in this section and in previous sections from radiometer data alone.

[8] http://hwt.nssl.noaa.gov/spring_experiment

Summary

Humidity convergence detection during early stage convection using microwave radiometer and GNSS observations is a promising development. Specifically, predictive thermodynamic parameters associated with early stage convection have been identified in this paper and reports of lightning prediction hours in advance of traditional electric field monitoring methods are discussed. If moisture measurements from GNSS data are included, three dimensional humidity mapping is possible. Experiments to seek convective initiation signatures in radiometer-generated stability index time series and to improve high resolution forecast models via radiometer and positioning satellite network data assimilation are underway. Initial case studies using radiometer data alone demonstrate capability for high impact local weather forecasting several hours in advance.

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