APPLICATIONS OF FULL SPATIAL RESOLUTION SPACE-BASED ADVANCED INFRARED SOUNDING IN THE PRE-CONVECTION ENVIRONMENT

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ABSTRACT: Advanced infrared (IR) sounders such as the Atmospheric InfraRed Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) provide atmospheric temperature and moisture profiles with high vertical resolution and high accuracy in pre-convection environments. The derived atmospheric stability indices such as convective available potential energy (CAPE) and lifted index (LI) from advanced IR soundings can provide critical information 1 ~ 6 hours before the development of severe convective storms. Two convective storms are selected for the evaluation of applying AIRS full spatial resolution soundings and the derived products on providing warning information in the pre-convection environments. In the first case, the AIRS full spatial resolution soundings revealed local extremely atmospheric instability 3 hours ahead the convections on the leading edge of a frontal system, while the second case demonstrates that the extremely low atmospheric instability is associated with the local development of severe thunderstorm in the following hours. These cases suggest that the AIRS full spatial resolution LI product shows the atmospheric instability 3.5 hours before the storm genesis.

The CAPE and LI from AIRS full spatial resolution and operational AIRS/AMSU soundings along with Geostationary Operational Environmental Satellite (GOES) Sounder derived product image (DPI) products were analyzed and compared. Case studies show that full spatial resolution AIRS retrievals provide useful warning information in the pre-convection environments for determining favorable locations for convective initiation (CI) than the coarser spatial resolution operational soundings and lower spectral resolution GOES Sounder retrievals

1. INTRODUCTION

High spectral resolution infrared (IR) sounders such as the Atmospheric InfraRed Sounder (AIRS) and Infrared Atmospheric Sounding Interferometer (IASI) provide three-dimensional fields of atmospheric moisture and temperature with great vertical resolving power (Chahine et al., 2006; Clerbaux et al., 2007; Smith et al., 2009). Improved information about the clear-sky horizontal and vertical water vapor and temperature in the pre-convection environment leads to substantial improvements in monitoring characteristics of the mesoscale environment such as atmospheric stability and boundary layer structure (Li et al., 2011). Such data are important for severe storm nowcasting and short-range forecasting and other applications, although with limited temporal resolution and spatial coverage. Operational high spectral resolution IR sounder retrievals are performed with coarser spatial resolution microwave sounder observations to reduce the impact due to clouds. On the other hand, the current geostationary operational environmental satellite (GOES) Sounder has fewer channels than the high spectral IR sounders onboard the polar-orbiting satellites so that the vertical resolution of GOES Sounder is limited. Therefore, the full-spatial resolution (or single-field-view; SFOV) high spectral resolution IR soundings are needed for mesoscale applications, and are critical for measuring the degree of atmospheric instability which is highly related to the storm genesis.

Several potential applications from high temporal and high spectral resolution IR data were discussed by Sieglaff et al. (2008). They showed how the spectral 'on-line' and 'off-line' absorption features in the IR window region of the spectrum are related to low-level temperature and moisture. Schmit et al. (2009) showed that the equivalent potential temperature differences between 800 and 600 hPa are indicative of thunderstorm potential. The advanced IR sounder is able to depict an unstable region similar to the "truth" field in a simulation using an International H2O Project (IHOP) case (Li et al., 2011). Equally important is that the atmospheric stability derived from an advanced IR sounder may suggest the region of stable air. This characteristic is important for reducing false alarms when forecasting the convective events. Full spatial resolution advanced IR soundings can also be assimilated in a regional numerical model to improve severe storm forecasts, e.g., the hurricane track and intensity forecast can be improved when the

AIRS full spatial resolution soundings are assimilated into a regional numerical weather prediction model (NWP) (Li and Liu 2009; Liu and Li 2010).

In this paper, applications of AIRS full spatial resolution IR soundings for two convective storms were investigated to reveal the advantage of using higher spatial and spectral resolution AIRS SFOV retrievals. In the first case (Case A) the convective storm was developed between 17:00 and 22:00 UTC across parts of Iowa, Minnesota, and Wisconsin on 28 August 2007. This is a linear mesoscale convective system that caused a large cluster of thunderstorms in north-central/northern Wisconsin. The convection produced several reports of hail (up to 2.5 cm in diameter) and wind gusts of 95 - 130 km per hour (km/hr) according to NOAA Storm Prediction Center (SPC) reports. The second convection (Case B) was a cluster of severe thunderstorms that propagated southeastward across far northwestern South Dakota on 19 July 2010. This case produced a long-duration wind and hail events that resulted in a remarkably long and wide damage path. According to the NOAA/SPC storm reports, the largest hail size was 6.4 cm in diameter, and the maximum wind gust was 110 km/hr in that particular region. The report also mentioned wind-driven hail duration of 15 - 30 minutes, which exacerbated the crop damage.

Case A indicates a stationary developing convection while Case B represents moving convection associated with two high-pressure super cells. In these two cases, the AIRS observed the atmospheric instabilities in the pre-convection environments 1 ~ 3.5 hours ahead of storms genesis. During the pre-convection storm environment, the current regional NWP model has limited capability on forecasting the local storm genesis and development, while radar can provide important information only after the storm is initiated.

2. AIRS FULL SPATIAL RESOLUTION SOUNDINGS

Satellite-based high spectral resolution (or advanced) IR sounding measurements are a principal source of atmospheric water vapor and temperature data over areas where conventional in situ observations are relatively sparse. Hyperspectral IR sounders, such as the AIRS onboard the NASA's EOS Aqua platform and the IASI onboard the Europe's Metop-A satellite, are providing unprecedented global atmospheric temperature and moisture profiles with high vertical resolution and accuracy. Along with the Advanced Microwave Sounding Unit (AMSU), which provides atmospheric temperature profiles in most cloudy regions, AIRS is able to provide soundings (Susskind et al., 2003) with much better vertical resolution and higher accuracy (1 K for temperature, 15% for water vapor mixing ratio) (Tobin et al., 2006); such improvements are very useful for global numerical weather prediction (NWP) and climate applications (Reale et al., 2008). Since the AIRS/AMSU soundings are based on the AMSU footprint that has a spatial resolution of ~50 km at nadir, the application of AIRS/AMSU soundings on mesoscale weather forecast might be limited. Although the GOES Sounder provides 10 km spatial resolution soundings (Ma et al., 1999; Li et al., 2008), with relatively broad-width and fewer spectral channels, GOES Sounder does not provide enough vertical resolution and accuracy compared with the advanced IR soundings. Therefore, full spatial resolution AIRS soundings are needed for mesoscale applications. The SFOV retrieval approach was first developed for the processing of ultra-spectral data obtained by the NPOESS Airborne Sounding Testbed-Interferometer (NAST-I) (Zhou et al., 2002; Smith et al., 2005). For satellite sounding applications, the Cooperative Institute for Meteorological Satellite Studies (CIMSS) hyperspectral IR sounder retrieval (CHISR) algorithm has been developed to retrieve the atmospheric temperature and moisture profiles from the advanced IR sounder radiance measurements in clear skies and some cloudy sky conditions on a SFOV basis. The CHISR algorithm has three steps: the first step is the IR sounder sub-pixel cloud detection using a high spatial resolution imager cloud mask product (for example, the AIRS cloud mask can be derived from the MODIS cloud mask product (Li et al., 2004), while the Advanced Very High Resolution Radiometer (AVHRR) cloud mask can be used for IASI cloud detection); the second step is to perform an eigenvector regression on the hyperspectral IR radiance measurements for a first guess of temperature and moisture profiles (Weisz et al., 2007; Liu et al., 2008); and the final step is to update/improve the first guess by performing a one-dimensional variational (1DVAR) retrieval algorithm with a Quasi-Newtown iteration technique. Radiance measurements from all good IR channels are used in the sounding retrieval process. The retrieved profiles have the root-mean-squared difference (RMSD) 1K in temperature and less than 2 g/kg in moisture ratio when compare with ECMWF analysis dataset (Kwon et al., 2011). The CHISR algorithm can be applied to hyperspectral IR sounder radiances for atmospheric profiles in non-cloudy pre-convection environments with full spatial resolution (12 ~ 14 km at nadir) for nowcasting purposes. These full spatial resolution soundings are crucial for measuring the degree of atmospheric instability which is highly related to the storm genesis, and can be used to analyze the pre-convection environment. The results will be compared with the science team AIRS/AMSU (Chahine et al., 2006) and the current GOES Sounder retrievals (Ma et al., 1999; Li et al., 2008).

3. WARNING INFORMATION FROM AIRS FULL SPATIAL RESOLUTION SOUNDINGS

3.1 Linear Mesoscale Convective System in the Upper Midwest on 28 August 2007 (Case A)

A linear convective system was developing across parts of Iowa, Minnesota, and Wisconsin on 28 August 2007. The individual cumulonimbus towers build in northeastern Iowa between 21:00 and 22:00 UTC, and can be identified from GOES visible image in Figure 1. The larger cluster of thunderstorms in north-central/northeastern Wisconsin produced several reports of hail (up to 2.5 cm in diameter) and wind gusts of 90 - 130 km/hr (NOAA/SPC storm reports). The high spatial resolution MODIS observation provides useful information on clouds in cloudy areas while the high spectral resolution AIRS measurements can provide atmospheric thermodynamic structures in clear skies. A MODIS 11.0 µm IR image around 19:10 UTC depicted cloud-top brightness temperatures as cold as -79º C in north-central Wisconsin, with numerous clouds to ground lightning strikes. The AIRS observed the atmospheric instability at ~19:10 UTC 28 August 2007 in the pre-convection environment, around 3 hours before the storm genesis. Figure 2(a) shows the clear sky Convective Available Potential Energy (CAPE) (color regions) from AIRS SFOV soundings overlaying on the AIRS 11 µm brightness temperature image (black and white) at 19:10 UTC 28 August 2007. The local northeastern Iowa (center of the circle) has CAPE values exceed 4000 J/kg (magenta color), while Figure 2(c) is the calculated CAPE from the science team AIRS/AMSU retrieved profiles. Figure 2(b) is the GOES-12 Sounder Derived Product Images (DPI) of CAPE at 17:00 UTC for comparison. It should be noted that the CAPE images from AIRS CHISR algorithm (Figure 2a), science team AIRS/AMSU retrievals (Figure 2c), and GOES Sounder DPI (Figure 2b) are 3, 3 and 5 hours respectively ahead of the GOES-12 visible image in Figure 1.

CAPE in the unit of Joule (J) per kilogram (kg) (energy per unit mass) provides the integration of the positive area on a skew-T sounding. The positive area is that region where the theoretical parcel temperature is warmer than the actual temperature at each pressure level in the troposphere. The theoretical parcel temperature is the lapse rate(s) a parcel would take if raised from the lower surface level. The higher CAPE means storm will build vertically very quickly. The updraft speed depends on the CAPE environment as well. Operational significance of CAPE suggests the hail potential increases when CAPE exceeds above 2500 J/kg, and large hail requires very large CAPE values. The CAPE can be used together with other products such as Lifted Index (LI), convective inhibition (CIN), K index (KI), total precipitable water (TPW), and derived atmospheric motion vectors (AMVs) to improve the severe storm nowcasting. In this study, we compared the CAPE values from atmospheric temperature and moisture profiles from CHISR algorithm, operational AIRS/AMSU, and GOES Sounder retrievals, respectively, at the each observational spatial resolution. This will help to evaluate the atmospheric stabilities in the pre-convection environment, instead of the profile information at various vertical resolutions.

The colored area in Figure 2 denotes the CAPE values; most area has significant CAPE values, while the circled area is extremely unstable. Although Figure 2(b) (GOES-12 DPI CAPE) image shows the atmospheric instability in an earlier time, the CAPE from SFOV AIRS soundings in Figure 2(a) does reveal more severe instability and concise areas when compared with the low spatial resolution science team AIRS/AMSU retrievals in Figure 2(c) for the development of this liner mesoscale convection. Although CAPE images from different retrievals suggest that certain regions are unstable, in particular the science team AIRS/AMSU soundings in Figure 2(c), the Figure 2(a) (full spatial resolution AIRS retrievals) does provide higher correlation to the convection induced high wind, tornado and hail locations on Figure 2(d) when the CAPE is exceed than 4000 J/kg.

3.2 Large hail damage across northwestern South Dakota on 19 July 2010 (Case B)

A cluster of thunderstorm developed and swept across southeastward far western South Dakota on 19 July 2010 during 18:15 UTC and 23:45 UTC. This case caused approximately square meter (m2) of corn field damage according to NOAA/SPC reports. The enhanced GOES-13 10.7 µm brightness temperature image in Figure 3 shows the cluster of severe thunderstorm at 22:10 UTC. Note that the darker red color enhancement of coldest brightness temperature is as cold as -63º C, and the "enhanced-V" storm top signature in western South Dakota. This is a typical severe thunderstorm but it nonetheless produced a long-duration wind and hail event that resulted in a remarkable long and wide damage path. Figure 4(a) shows the clear sky LI (color regions) at SFOV spatial resolution overlaying on the AIRS 11 µm brightness temperature image (black and white) at 19:20 UTC 19 July 2010 in the pre-convection environment, while Figure 4(b) is the LI from the science team AIRS/AMSU retrievals. The local northwestern South Dakota area has LI values less than -15 (dark red color) from AIRS SFOV soundings, and AIRS observation time was approximately 1 hour ahead of the peak of severe storm in Figure 3. The LI from GOES-13 DPI (not shown) suggests that the GOES-13 Sounder has instrumental striping problem that might cause the incorrect cloud mask.

LI in units of degrees Celsius (C) provides an estimate of the atmospheric stability in cloud-free areas and is one of the most popular satellite derived products. The LI (Galway, 1956) expresses the temperature difference between a lifted parcel and the surrounding air at 500 hPa. The parcel is lifted dry adiabatically from the mean lowest 100 hPa level to the condensation level, and then wet adiabatically to 500 hPa. When an air parcel is lifted adiabatically from the surface, the atmosphere is considered potentially unstable if the parcel's temperature at 500 hPa is less than its environment (i.e. LI<0). In general, the LI has the following meteorological implications for storm development: LI > 0 K for stable, -3 K < LI < 0 K for marginally unstable, -6 K < LI < -3 K for moderately unstable, -9 K < LI < -6 K for very unstable, and LI < -9 K for extremely unstable. The likelihood of severe thunderstorm development increases as the LI becomes more negative, with LI values less than -6 K indicating very favorable thermodynamic conditions for severe thunderstorm development. Similar to CAPE comparisons in Case A, LI comparisons are applied for this case, and the LI values are also from the integration of retrieved profiles information.

Although Figure 4(b) and GOES-13 Sounder DPI reveal the low atmospheric stability in the same region in Figure 4(a), the low LI areas in the eastern North Dakota span to the eastern South Dakota, where there was no convection in the following hours. This is the advantage to distinguish stable and low stability area by applying SFOV soundings in regional short-term forecasting and nowcasting. Using the high spectral resolution AIRS soundings at its full spatial resolution; we may have advantage not only on the accuracy of atmospheric thermodynamic profiles but also finer vertical resolution at each observation point. These will reduce the false-alarm possibility as presented in this case.

4. SUMMARY

The derived atmospheric instability (e.g., LI and CAPE) from AIRS full spatial resolution soundings provided earlier warning information, approximately 1 hour before a local genesis of severe thunderstorm (Case A), and 3 hours before severe convections (moving synoptic systems in Cases B and C). IASI has the similar sounding capability of AIRS, full spatial resolution IASI soundings will also be processed so that AIRS and IASI can be used together to improve the temporal coverage for storm warning. This study also demonstrates the needs of an advanced IR sounding system from the geostationary orbit that provide high temporal resolution. Although the vertical resolution from advanced IR sounder has improved from the legacy GOES Sounder, the near-surface resolution is still not necessary high enough to adequately capture convective parameters. Atmospheric sounding measurements from the high spectral resolution IR sounders, however, still provide critical pre-convection atmospheric destabilization information that can be used together with other measurements and regional numerical weather prediction model for nowcasting the storm genesis and development.

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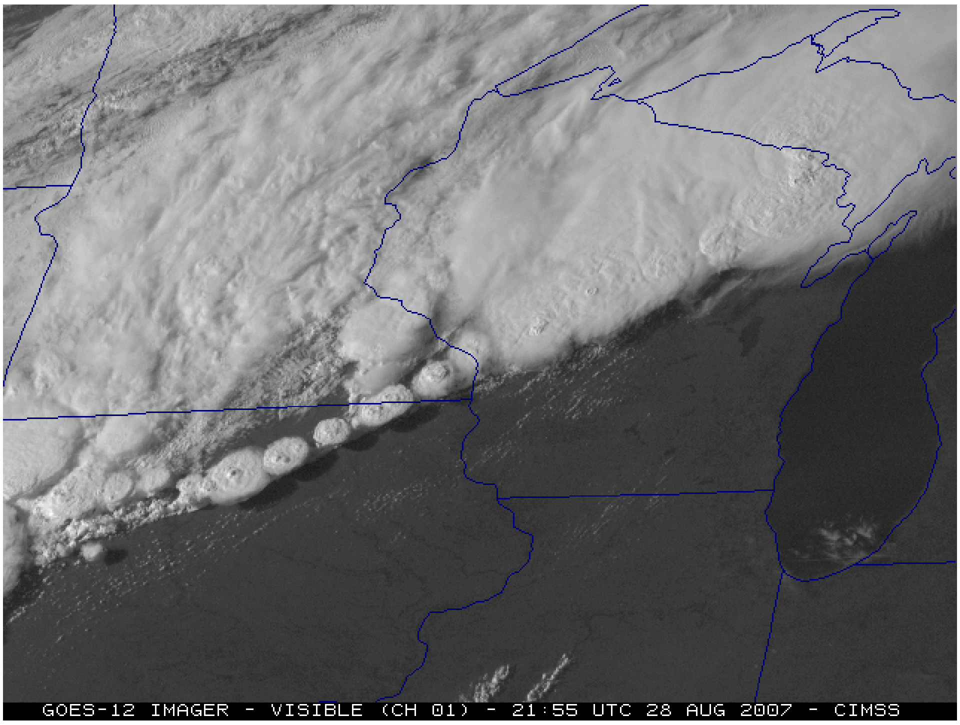

Figure 1. The GOES-12 visible images showed a linear mesoscale convective system at 21:55 UTC 28 August 2007. Note the picturesque shadows cast by the individual cumulonimbus towers building in northeastern Iowa.

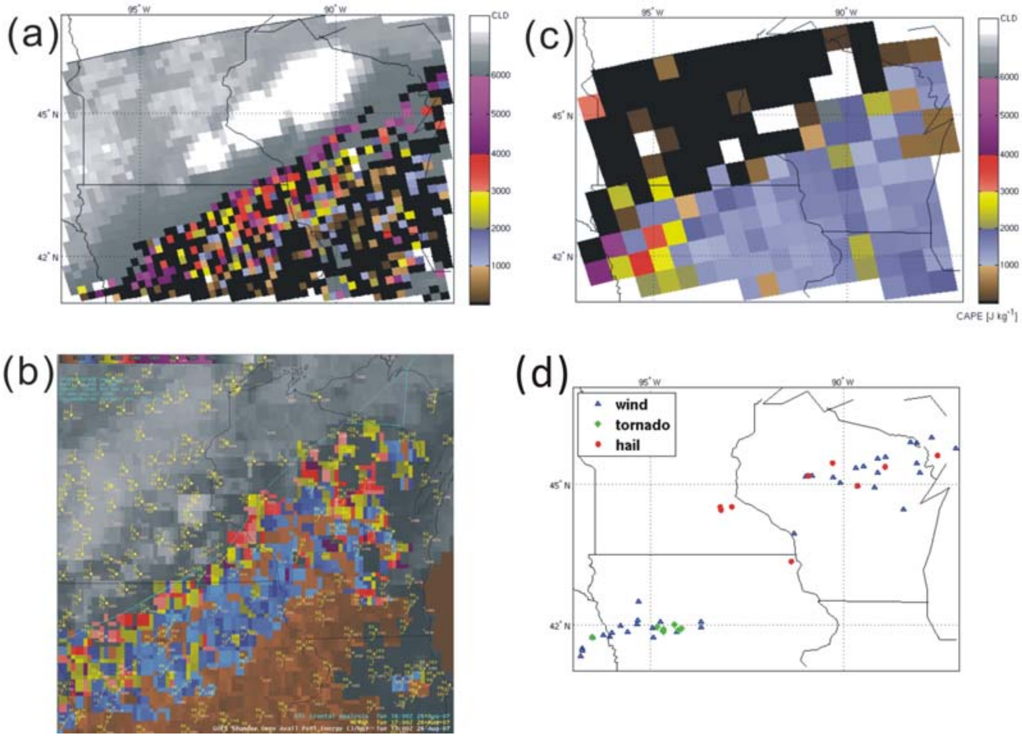

Figure 2. (a) The clear sky CAPE (color regions) from AIRS SFOV sounding overlaying the AIRS 11 µm brightness temperature image at 19:10 UTC 28 August 2007. (b) The clear sky CAPE (color regions) from GOES-12 DPI overlaying GOES-12 window channel brightness temperature image at 17:00 UTC 28 August 2007. (c) Corresponding science team AIRS/AMSU sounding CAPE at 19:10 UTC 28 August 2007. (d) The reported high wind, tornado and hail locations during 17:00UTC and 23:50UTC on 28 August 2007.

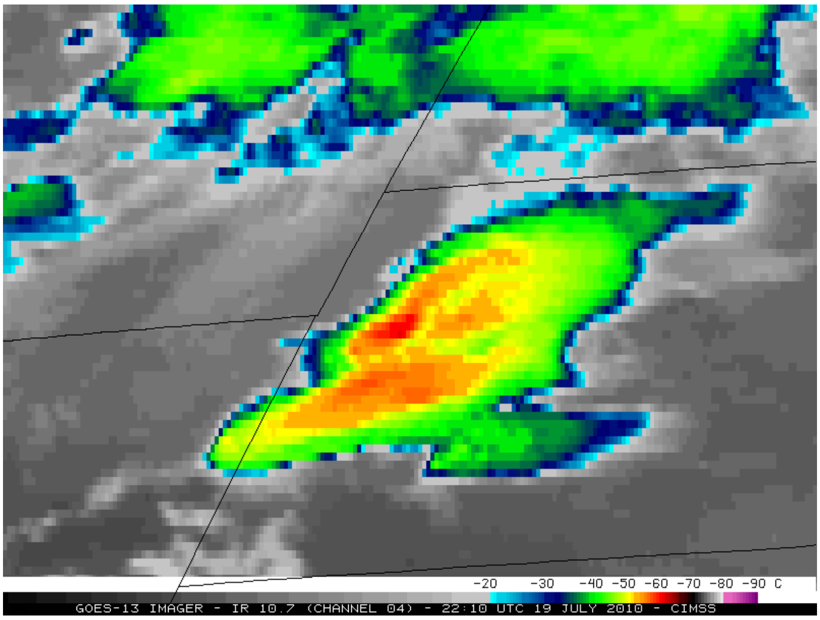

Figure 3. The enhanced GOES-13 10.7 µm images showed a cluster of severe thunderstorm at 22:10 UTC 19 July 2010. Note the darker red color enhancement of coldest brightness temperature is as cold as -63º C, and typical severe “enhanced-V” storm top signature in northwestern South Dakota.

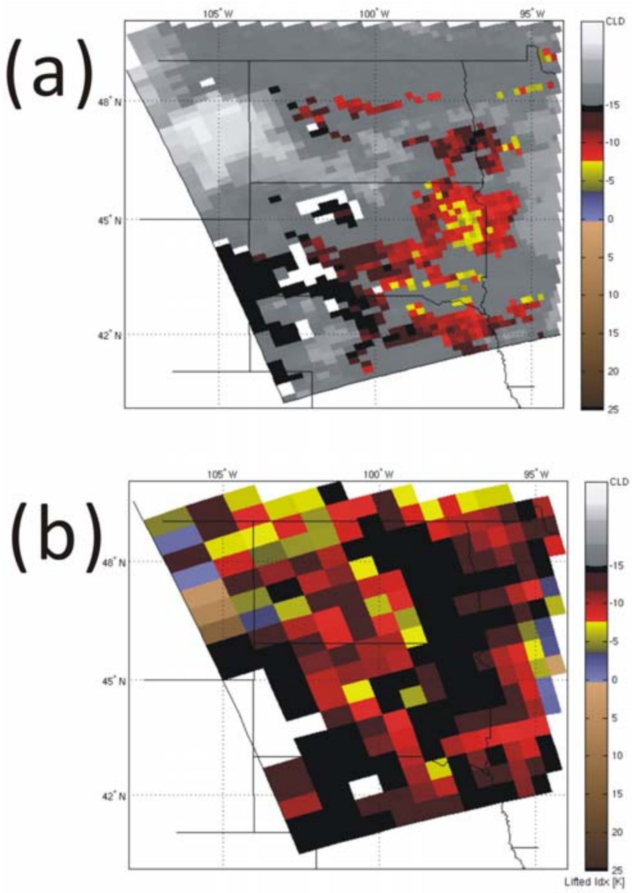

Figure 4. (a) The clear sky LI (color regions) from AIRS SFOV sounding overlaying the AIRS 11 µm brightness temperature image at 19:20 UTC 19 July 2010. (b) Corresponding science team AIRS/AMSU sounding LI at 19:20 UTC 19 July 2010. The remarkable long and wide damage path is located in western South Dakota. Although Figure 4(b) indicates the unstable area, Figure 4(a) gives a more precise area and may reduce the false-alarm area like eastern Minnesota and Iowa.