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Assimilating synthetic hyperspectral sounder temperature and humidity retrievals to improve severe weather forecasts

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ABSTRACT

Assimilation of hyperspectral sounder data into numerical weather prediction (NWP) models has proven vital to generating accurate model analyses of tropospheric temperature and humidity where few conventional observations exist. Applications to storm-scale models are limited since the low temporal resolution provided by polar orbiting sensors cannot adequately sample rapidly changing environments associated with high impact weather events. To address this limitation, hyperspectral sounders have been proposed for geostationary orbiting satellites, but these have yet to be built and launched in part due to much higher engineering costs and a lack of a definite requirement for the data.

This study uses an Observation System Simulation Experiment (OSSE) approach to simulate temperature and humidity profiles from a hypothetical geostationary-based sounder from a nature run of a high impact weather event on 20 May 2013. The simulated observations are then assimilated using an ensemble adjustment Kalman filter approach, testing both hourly and 15 minute cycling to determine their relative effectiveness at improving the near storm environment. Results indicate that assimilating both temperature and humidity profiles reduced mid-tropospheric both mean and standard deviation of analysis and forecast errors compared to assimilating conventional observations alone. The 15 minute cycling generally produced the lowest errors while also generating the best 2–4 hour updraft helicity forecasts of ongoing convection. This study indicates the potential for significant improvement in short-term forecasting of severe storms from the assimilation of hyperspectral geostationary satellite data. However, more studies are required using improved OSSE designs encompassing multiple storm environments and additional observation types such as radar reflectivity to fully define the effectiveness of assimilating geostationary hyperspectral observations for high impact weather forecasting applications.

1. Introduction

Many advancements in numerical weather prediction (NWP) have been made that can be attributed to the assimilation of satellite data to improve the analysis of the atmospheric state where traditional observations are not available (Derber and Wu, 1998; Le Marshall et al., 2007). Satellite observations include, but are not limited to, cloud-track winds (CTWs), retrieved temperature and humidity profiles, precipitation estimates, and recently lightning observations (Velden et al., 1998; Hou et al., 2004; Reale et al., 2008; Mansell et al., 2007; Schmit et al., 2008a, 2008b). Each of these observation types can be assimilated into a NWP model to improve certain aspects of the model state. In recent years, assimilating information from hyperspectral sounders via infrared radiances or temperature and humidity retrievals has become a key component in NWP models (e.g., McNally et al., 2006; Reale et al., 2008; Li and Liu, 2009; Migliorini, 2012; Jones and Stensrud, 2012). One of the most significant limitations of NWP is the lack of observations describing the vertical structure of the atmosphere at high spatial and temporal scales. A partial solution to the current data void is provided by hyperspectral infrared spectrometers including the 2378-channel Atmospheric InfraRed Sounder (AIRS), the 8461-channel Infrared Atmospheric Sounding Instrument (IASI), and the 1305-channel Cross-track Infrared Sounder (CrIS). Temperature and humidity profiles can be retrieved from both instruments with high vertical resolution in clear to partly cloudy conditions from near the surface into the stratosphere (Aumann et al., 2003; Susskind et al., 2003, 2006). With such large channel sets, these instruments can substantially decrease the uncertainty of retrieved vertical profiles compared to other sounding instruments, which typically have no more than a few dozen channels.

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Studies of assimilating retrieved profiles from polar orbiting sounders into NWP models have generally found a positive impact on model analyses and forecasts at various temporal and spatial scales (e.g., Le Marshall et al., 2006; Chou et al., 2007; Reale et al., 2008). Several studies focused on the impact of assimilating hyperspectral profiles on tropical cyclone track and intensity forecasts (Wu et al., 2006; Li and Liu, 2009; Liu and Li, 2010; Pu and Zhang, 2011; Atlas and Pagano, 2014). For example, Li and Liu (2009) and Liu and Li (2010) show an improvement to 12–96 hour track forecasts resulting from a better analyses of the mid-tropospheric temperature and mixing ratio while smaller, but still significant improvements, are present for intensity forecasts. Pu and Zhang (2011) found similar results while noting the possible need for bias adjustments in the assimilated profiles to further reduce forecast error. Additional research has been conducting focusing on the impacts of assimilating hyperspectral sounder profiles for severe weather events. Chou et al. (2010) describe an event in eastern Texas on 12–13 February 2007 in which AIRS profiles improved the characterization of the thermodynamic near storm environment leading to more accurate 6 hour precipitation forecasts. Jones and Stensrud (2012) further analyzed the impact of assimilating AIRS profiles on two Southern Plains events and found that even assimilating a single overpass of high-resolution temperature and humidity retrievals could significantly improve the analysis and forecast of the pre-storm environment, which should result in better forecasts of convective initiation and storm evolution. As in these cited severe weather studies, this research is primary concerned with the impact of retrievals on the representation of the environment, not the internal characteristics, of severe storms, and the subsequent impact on the evolution of the storms.

One key limitation of polar orbiting hyperspectral instruments is their poor temporal resolution relative to the time scales of high impact weather events. The importance of high temporal resolution hyperspectral information has been demonstrated by Aune et al. (2000) and Bingham et al. (2013). High impact weather events in particular are likely to be associated with a rapidly changing environment, which is poorly sampled by current observations. If the initial model representation of the environment is incorrect, then any potential forecasts will suffer. Even if the initial conditions are correct, it is unlikely the model will accurately capture the evolution of the near storm environment without high spatial and temporal resolution observations to update the model in a timely manner. A key hypothesis of this research is that improvements to the thermodynamic environment from assimilating hyperspectral sounder profiles translate to improvements in short-term forecasts of convection.

This research uses the Ensemble Adjustment Kalman Filter (EAKF) data assimilation scheme (e.g., Kalman, 1960; Anderson, 2001; Anderson and Collins, 2007; Yussouf and Stensrud, 2010), rather than the more traditional variational approach (e.g., Barker et al., 2004). The primary advantage of the EAKF approach is that it provides a flow dependent and dynamically evolving estimate of the multivariate background error covariances that is updated at each assimilation cycle. This is an important consideration for rapidly moving and developing weather phenomena and allows observations of one variable (say temperature) to influence other variables including those not observed (winds in the present study and potentially cloud microphysics variables).

Since there is no geostationary hyperspectral profiler that currently provides high spatial resolution temperature and humidity profiles over North America, this research uses the Observing System Simulation Experiment (OSSE) methodology to simulate such observations from a nature run and then to quantify impacts by comparing data assimilations and forecasts that include and exclude these data. Specifically, this study employs a "Quick OSSE" approach (Atlas et al., 2015) and an experimental setup similar to that of Jones et al. (2013a). Geostationary hyperspectral profilers would be expected to provide a temporal resolution of approximately 15 min with a spatial resolution on the order of 10 km or better. A case study approach is used based on the 20 May 2013 central Oklahoma (OK) tornado event that produced a violent tornado in Moore, OK and weaker, short lived tornadoes in southern OK. A very unstable, high shear environment was present over the Southern Plains during this day with convection forming along a frontal boundary in central OK and a connecting dryline further to the south. NWP experiments assimilating real radar and satellite observations of this event have shown some skill at forecasting the severe convection, but many uncertainties remain which were likely due to the lack of information on the near storm environment being assimilated in the model (Wheatley et al., 2015; Jones et al., 2016). An objective of this research is to assess whether assimilating near-storm environment information can, in fact, improve the model analyses, leading to better short-term (0 − 3h) forecasts of high impact weather events. However, these experiments only describe the impact for a single case using an OSSE system that is not fully validated and without the benefit of other high-resolution observations such as radar data. As a result, the applicability of these results to realistic settings remains uncertain.

Following this introduction, Section 2 describes the nature run created to simulate the 20 May 2013 event with Section 3 describing the synthetic simulated observations derived from the nature run. Section 4 provides an overview of the experiment design and Section 5 discusses the results of these data assimilation experiments. Finally, concluding remarks are given in Section 6.

2. Nature run

A nature run for the 20 May 2013 event was created from a deterministic forecast initialized from the Global Forecast System (GFS) analysis at 1200 UTC 14 May. The nominal GFS resolution in 2013 was 0.5° with 27 vertical levels which are downscaled to a 4 km resolution for the nature run. The nature run used a 1400 × 1200 grid point domain covering the continental United States (CONUS) with 56 vertical levels extending from the surface to 10 hPa (Fig. 1). The nature run was continuously integrated forward in time until 0000 UTC 21 May using the Advanced Weather Research Forecasting (WRF-ARW) model version 3.6.1 (Skamarock et al., 2008). Ferrier 3-class (cloud water, rainwater, and snow mixing ratios) cloud microphysics is used along with GFDL shortwave and longwave radiation schemes, MYJ boundary layer physics, and the NOAH land surface model with 4 soil layers (Ferrier et al., 1996; Chou and Suarez, 1994; Janjic, 2002; Ek et al., 2003). Note that cumulus parameterization is unnecessary at a 4 km convection permitting resolution and is not used. Boundary conditions created from the operational GFS forecast initiated at 1200 UTC 14 May were applied at 3 hour intervals through the duration of the nature run. The length of the nature run is dictated by the need for the characteristics of the simulated 20 May event to be as independent from the initial conditions as possible, but still retain enough predictability to capture an event similar to that which occurred in reality.

3. Synthetic observations

Conventional and hyperspectral IR observations are simulated as described in the following. WSR-88D radar observations were not used in this study since the primary goal of this study is to isolate the impacts of assimilating high resolution satellite retrievals to the near storm environment. The impacts of assimilating radar reflectivity and Doppler radial velocity into high resolution NWP models is well understood and has been the focus of many studies. In particular, Wheatley et al. (2015) provide an overview of radar data assimilation for the 20 May event using a similar model configuration to the one being used here.

3.1. Conventional

Simulated observations are generated from the nature run for a variety of conventional observation types including Automated Surface Observing System (ASOS), Aircraft Communications Addressing and