JOINT CENTER FOR SATELLITE DATA ASSIMILATION

NO. 58, WINTER 2018

JCSDA Quarterly

NOAA | NASA | US NAVY | US AIR FORCE

https://doi.org/10.7289/V5CJ8BR2

NEWS IN THIS QUARTER

SCIENCE UPDATE

New Era of Lightning Data Assimilation using Observations from Space

The first satellite in Geostationary Operational Environmental Satellite R-series (GOES-16) hosts the Geostationary Lightning Mapper (GLM). The GLM is the first step in the operational space-based observing constellation for continuous measurements of total lightning on a global scale. It builds on a legacy of optical lightning observations from low earth orbit from the NASA Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM, 1997-2015) and the Optical Transient Detector (OTD) on the OrbComm-1 satellite (1995-2000). The GOES-16 GLM is the first of four instruments that will provide lightning mapping over most of the western hemisphere through 2036.

The ground processing algorithms are an extension of the algorithms developed for the earlier OTD and LIS research instruments (Mach et al. 2007). Concepts for the GLM have been explored since the early 1980s, culminating with the single telescope design having high-detection efficiency for total lightning with near uniform storm-scale spatial resolution owing to the variable pitch pixel detector array design (Goodman et al. 2013). The high-detection efficiency is made possible by the data telemetry bandwidth of 7.7 mbps. This allows the GLM to be set at more sensitive (lower) detection thresholds allowing up to 100,000 events per second (nominally 40,000 lightning events and the remainder noise) to be transmitted to the ground where the ground processing algorithms filter out the non-lightning events.

(continued on page 2)

IN THIS ISSUE

Calibration and validation efforts are critical and challenging, because the GLM is the first instrument of this type to operate in geostationary orbit. Pre-launch and on-orbit checkout of the instrument performance and algorithms employs a variety of space, airborne, and ground-based instruments. Public, private, and international partnerships provide extensive lightning reference data sets for post-launch testing and validation. The methodologies, validation tools, and correlative data needed during on-orbit checkout and for continued monitoring were developed and tested well before launch. These cal/val efforts help ensure that a quality product is provided to users of these valuable data.

The GLM differs from the ground-based lightning detection networks most familiar to researchers and forecasters, so focused efforts are required to guide the application of these new data. The GLM provides continuous, full disk total lightning measurements with coverage to 54° N/S and <20 sec product latency. The primary GLM applications include (1) Lightning Jump – Rapid increase in total lightning that signifies an increased threat for severe weather, (2) Lightning Safety –GLM provides insights beyond point observations, revealing the spatial extent and distance lightning flashes travel, and (3) Situational Awareness – Rapidly updating GLM data reveal convective storm development and evolution throughout the GOES-16 field of view. The GLM allows forecasters to detect electrically active storms (Intra-Cloud (IC) precedes Cloud-to-Ground (CG)), determine the areal extent of the lightning threat, track convective cells embedded in larger features, identify strengthening and weakening storms, monitor convective mode and storm evolution, and supplement radar data where coverage is poor.

The GLM data also show great promise for data assimilation, and the GOES-R Risk Reduction (R3) program has supported lightning assimilation research for several years. For example, Fierro et al. (2012) assimilated total lightning data to help initiate convection at cloud-resolving scales within a numerical weather prediction model. The authors used a nudging function for the total lightning data, which locally increases the water vapor mixing ratio (and hence relative humidity) via a simple smooth continuous function using gridded pseudo- GLM flash rate and simulated graupel mixing ratio as input variables. Assimilation of the total lightning data for only a few hours prior to the analysis time significantly improved the representation of the convection at analysis time, as well as the 1-h forecast. They showed this simple and computationally inexpensive assimilation technique to have promising results and suggested it could be useful when applied to events with moderate to intense lightning activity.

Fierro et al. (2014) evaluated the short-term forecast (≤6 h) of the 29–30 June 2012 derecho event using two data assimilation techniques at cloud-resolving scales (3-km horizontal grid). The authors used a smooth nudging function for lightning, along with a three-dimensional variational technique (3DVAR) that assimilates radar reflectivity and radial velocity data. Although the 3DVAR simulations best represented the storm's radar reflectivity structure at the analysis time, the authors showed that the relatively simple nudging scheme

(continued on page 3)

complements the more complex variational technique. The much lower computational cost of the lightning scheme may permit its use alongside variational techniques in improving severe weather forecasts on days favorable for the development of outflow-dominated mesoscale convective systems.

Mansell (2014) demonstrated the potential benefit from ensemble Kalman filter (EnKF) assimilation of synthetic GLM total lightning data. The author showed that the assimilation of pseudo-GLM data at 8-km horizontal resolution can effectively modulate the convection simulated at 1-km horizontal resolution by sharpening the location of reflectivity echoes and the spatial location probability of convective updrafts. The tests with zero flash rates showed that the lightning assimilation can help to limit spurious deep convection, and that pseudo-GLM observations at 1 km further sharpen the analyses of location (updraft and reflectivity) of the relatively simple storm structure.

Allen et al. (2016) used the EnKF to assimilate pseudo-GLM flash extent density (FED) observations at convection-resolving scale for a nonsevere multicell storm case (6 June 2000) and a tornadic supercell case (8 May 2003). The best results were obtained when assimilating 1-min temporal resolution data using any of three observation operators that utilized graupel mass or graupel volume. Each of the three observation operators performed well for both the weak, disorganized convection of the multicell case and the much more intense convection of the supercell case.

Fierro et al. (2016) evaluated the performance of the assimilation of total lightning data within a 3DVAR framework for the analysis and short-term forecast of the 24 May 2011 tornado outbreak. Assimilation of radar data with 3DVAR and a cloud analysis algorithm (RAD) also were performed as a baseline for comparison and in tandem with lightning to evaluate the added value of this lightning data assimilation (LDA) method. When both the lightning and radar data are assimilated, the 30-min forecast showed noteworthy improvements over RAD in terms of the model's ability to better resolve individual supercell structures and still maintained a 1-h forecast similar to that from the LDA. These results chiefly illustrate the potential value of assimilating total lightning data alongside radar data.

Zhang et al. (2017) used the empirical relationship between flash rate, water vapor mixing ratio, and graupel mixing ratio to adjust the model relative humidity, which was then assimilated by using a 3DVAR system. The authors found that 60 min was the appropriate assimilation time-window length for this case. Forecasts of 1-h accumulated precipitation during the assimilation period and the subsequent 3-h accumulated precipitation were significantly improved compared with the control experiment without LDA. The positive effect from LDA began to diminish after 72 min of the forecast. Overall, the improvement from LDA can be maintained for about 3 h.

This JCSDA Quarterly newsletter presents two recent examples of LDA research. Fierro et al. discuss "Assimilation of total lightning with GSI and NEWS3DVAR to improve short-term forecasts of high-impact weather events at cloud-resolving scales." Their initial results using multi-sensor data assimilation

(continued on page 4)

techniques (including lightning) revealed forecast improvements relative to forecasts with only Weather Surveillance Radar (WSR-88D) radar data assimilation. Apodaca and Zupanski describe "Variational and Hybrid (EnVar) methodologies to add the capability to assimilate GOES-16/GLM observations into GDAS." Their results indicate that LDA helps forecast models predict lightning flash rate in the less observed mountainous regions of Mexico, clearly illustrating that satellite-based lightning measurements can be particularly useful in data-sparse regions. These studies highlight the important role that GLM observations can play in improving convection resolving model forecasts. Studies on LDA will become even more important as new GLMs extend coverage beyond the Western Hemisphere.

Scott Rudlosky (NOAA/NESDIS/STAR)
scott.rudlosky@noaa.gov

References

Fierro, A.O., E.R. Mansell, C.L. Ziegler, and D.R. MacGorman, 2012: Application of a Lightning Data Assimilation Technique in the WRF-ARW Model at Cloud-Resolving Scales for the Tornado Outbreak of 24 May 2011. Mon. Wea. Rev., 140, 2609–2627, https://doi.org/10.1175/MWR-D-11-00299.1

Fierro, A.O., J. Gao, C.L. Ziegler, E.R. Mansell, D.R. MacGorman, and S.R. Dembek, 2014: Evaluation of a Cloud-Scale Lightning Data Assimilation Technique and a 3DVAR Method for the Analysis and Short-Term Forecast of the 29 June 2012 Derecho Event. Mon. Wea. Rev., 142, 183–202, https://doi.org/10.1175/MWR-D-13-00142.1

Fierro, A.O., J. Gao, C.L. Ziegler, K.M. Calhoun, E.R. Mansell, and D.R. MacGorman, 2016: Assimilation of Flash Extent Data in the Variational Framework

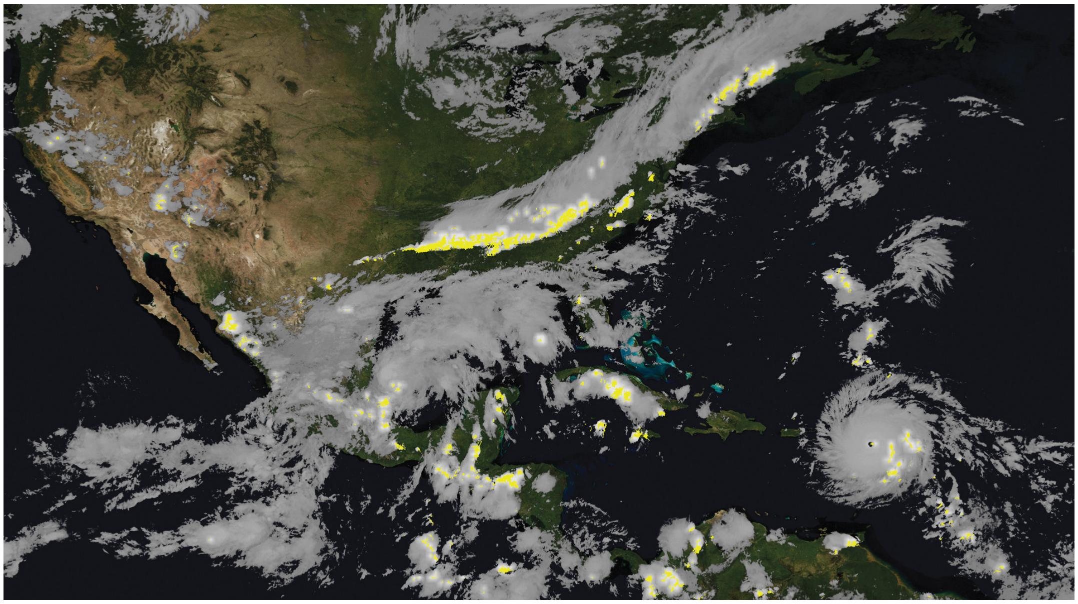


Figure 1. *Depiction of clouds and lightning as viewed by the GOES-16 Advanced Baseline Imager (ABI) and Geostationary Lightning Mapper (GLM) during Hurricane Irma (2017).*

(continued on page 5)

at Convection-Allowing Scales: Proof-of-Concept and Evaluation for the Short-Term Forecast of the 24 May 2011 Tornado Outbreak. Mon. Wea. Rev., 144, 4373–4393, https://doi.org/10.1175/MWR-D-16-0053.1

Mansell, E.R., 2014: Storm-Scale Ensemble Kalman Filter Assimilation of Total Lightning Flash-Extent Data. Mon. Wea. Rev., 142, 3683–3695, https://doi.org/10.1175/MWR-D-14-00061.1

Allen, B.J., E.R. Mansell, D.C. Dowell, and W. Deierling, 2016: Assimilation of Pseudo-GLM Data Using the Ensemble Kalman Filter. Mon. Wea. Rev., 144, 3465–3486, https://doi.org/10.1175/MWR-D-16-0117.1

Zhang, R., Zhang, Y., Xu, L. et al. J Meteorol Res (2017) 31: 731. https://doi.org/10.1007/s13351-017-6133-3

Goodman, S. J., and Coauthors, 2013: The GOES-R Geostationary Lightning Mapper (GLM). Atmos. Res., 125–126, 34–49

Assimilation of Total Lightning with GSI and NEWS3DVAR to Improve Short-Term Forecasts of High-Impact Weather Events at Cloud-Resolving Scales

Introduction

Real-time data assimilation methods used in numerical weather prediction (NWP) models at convection allowing (~3-4 km) or finer scales have proven critical for decision making during short-term (~6h) forecasts of high-impact weather events. In that respect, assimilation of volumetric datasets from ground-based radar networks has played a prominent role in recent years. Radar data assimilation, however, suffers from limitations when storms evolve in regions with poor or no coverage by the radar network, such as mountainous terrain or over oceans. For instance, a real-time implementation of a three-dimensional variational (3DVAR) system using only radar data, which was systematically evaluated by National Weather Service (NWS) forecasters within the Hazardous Weather Testbed (HWT) (Clark et al. 2012; Gao et al. 2013; Smith et al. 2014), became less useful when operations occurred in regions having poor radar coverage, because the analyses became dominated by the smoothed mesoscale background derived from the (12-km) forecast fields of the North American Mesoscale (NAM) model (Calhoun et al. 2014).

(continued on page 6)

The assimilation of high-temporal resolution, total lightning data from a ground-based network (e.g., Earth Networks; ENTLN) or from the Geostationary Lightning Mapper (GLM) can help fill this gap. Initial development and testing of lightning data assimilation (LDA) methods involving nudging (e.g., Fierro et al. 2012, 2014; 2015), 3DVAR (Fierro et al. 2016) and EnKF (Mansell 2014; Allen et al. 2016) techniques in cloud-resolving models suggest that assimilating GLM data would produce improvements in forecasts comparable to those from assimilating Weather Surveillance Radar (WSR-88D) data.

Initial results from simulation tests using each of these methods revealed forecast improvements overall comparable to forecasts from assimilating only WSR-88D data. Based on total flash density products derived from ground-based networks (here, ENTLN), the 3DVAR LDA of Fierro et al. (2016) imposes water saturation within a fixed depth above the lifted condensation level. This LDA method is an outgrowth from previous work by investigators at the National Severe Storms Laboratory (NSSL) and the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) using WRF-ARW (Fierro et al. 2012, 2014, 2015), which demonstrated that increasing the water vapor mass mixing ratio (Qv) at observed lightning locations using a simple nudging method effectively enhances local thermal buoyancy, ultimately leading to the initiation of convection.

Current work on assimilating lightning data by NSSL and CIMMS adapts our previous techniques to make them compatible with NWP models used by the NWS operational centers. A major effort focuses on developing, improving, and evaluating the variational LDA method of Fierro et al. (2016) within the framework of the Gridpoint Statistical Interpolation (GSI) system. Additional efforts include implementing and testing this LDA method within NSSL's 3DVAR prediction system (NEWS3DVAR, Gao et al. 2013) for a quasi-operational test there next spring.

The Environmental Modeling Center (EMC) at the National Centers for Environmental Prediction (NCEP) has been working on LDA since May 2015, and has made significant efforts to use lightning data in their NDAS/NAMRR system (Liu et al. 2016; 2017). Their work uses a statistical model developed to ingest radar reflectivity observations over the contiguous United States (CONUS) using lightning data from the National Lightning Detection Network (NLDN). This statistical model first uses an empirically-developed relationship to convert the NLDN observations to radar reflectivity profiles, which are then used by the existing NCEP GSI analysis system to modify hydrometeors and temperature to initialize NCEP's high resolution forecast model. The scheme developed by NSSL and CIMMS differs from the one used at EMC. The chief differences between these two schemes are: (a) The NSSL/CIMMS scheme uses total lightning data (as will be provided by the GLM) in lieu of cloud-to-ground lightning data of the NLDN; (b) The NSSL/CIMMS scheme converts the lightning data into pseudo Qv observations, while the NCEP scheme converts lightning data into proxy radar reflectivity; and (c) The NSSL/CIMMS scheme adjusts only Qv, whereas the EMC scheme adjusts hydrometeor mixing ratios and temperature.

(continued on page 7)

Much of our recent efforts have been geared toward better understanding the details behind both the NSSL/CIMMS scheme and the EMC scheme through case studies of selected high-impact weather events. Following Fierro et al. (2016), the pseudo Qv were derived from the lightning density rates observed by the ENTLN. Based on these flash density fields data, near water saturation conditions (relative humidity = 95%) were imposed within a fixed layer depth (set here to 3 km) above the lifted condensation level (LCL). The DA experiments employed only one GSI analysis. It is relevant to note that owing to the large default horizontal decorrelation length scale (H) used by GSI (~100-120 km; Liu et al. 2016; 2017), the LDA coefficients of Fierro et al. (2016) were purposively set to notably more conservative values to lessen the impact of the LDA; their study assumes relative humidity = 100% over a deeper layer between the LCL and a fixed height of 15 km.

In this study, a series of quasi real-time 24-h forecasts at convection-allowing scale (dx = 4 km) from initial conditions created by the LDA algorithm implemented within GSI and in NEWS3DVAR were performed for selected high-impact weather cases during Spring 2017 within one domain covering the eastern 2/3rd of CONUS (no nesting, Fig. 1). The initial and boundary conditions were based on the NAM 12-km forecasts and the model physics were infused from Fierro et al. (2015). Because the results with GSI and NEWS3DVAR were qualitatively very similar, only the results for GSI are shown. To quantify and gauge the impact of the LDA, the evaluation included standard domain-wide, bulk forecast metrics for selected accumulated precipitation fields (APCP, Fierro et al. 2015) or reflectivity thresholds and influence radii, such as the frequency biases, equitable threat scores and fraction skill scores.

These tests primarily focused on evaluating the forecast (APCP and reflectivity) from LDA analyses using convective scale H values (≤10 km) against the default mesoscale value (H~100-120 km) used by GSI. These tests also evaluated forecasts benefiting from the assimilation of the standard PREPBUFR dataset with and without lightning. For all experiments, the observations and background error (standard deviation) were set to a relative humidity of 3% and 10%, respectively. It is relevant to highlight that at the time of this writing only a handful of the case studies utilized a multiscale approach, which remains the subject of ongoing research. For the sake of brevity, only the results from one representative case study are presented, namely 6 April 2017. We deemed this case broadly representative, because the lightning-producing convection in the warm sector of this low-pressure system was synoptically forced and, hence, already well captured by the control simulation (which did not assimilate any data). Consequently, this was a challenging forecast to improve.

In line with Fierro et al. (2016), the LDA increases Qv at observed lightning locations with the most optimal results seen for convective scale H = 6 km (Fig. 1c). When the default H from GSI is used (H~100 -120 km), the impact of the LDA is spread over too wide of an area (Fig. 1d). The assimilation of PREPBUFR data slightly reduces Qv where lightning-producing storms are observed (Fig. 1b). To alleviate the overspread of Qv

(continued on page 8)

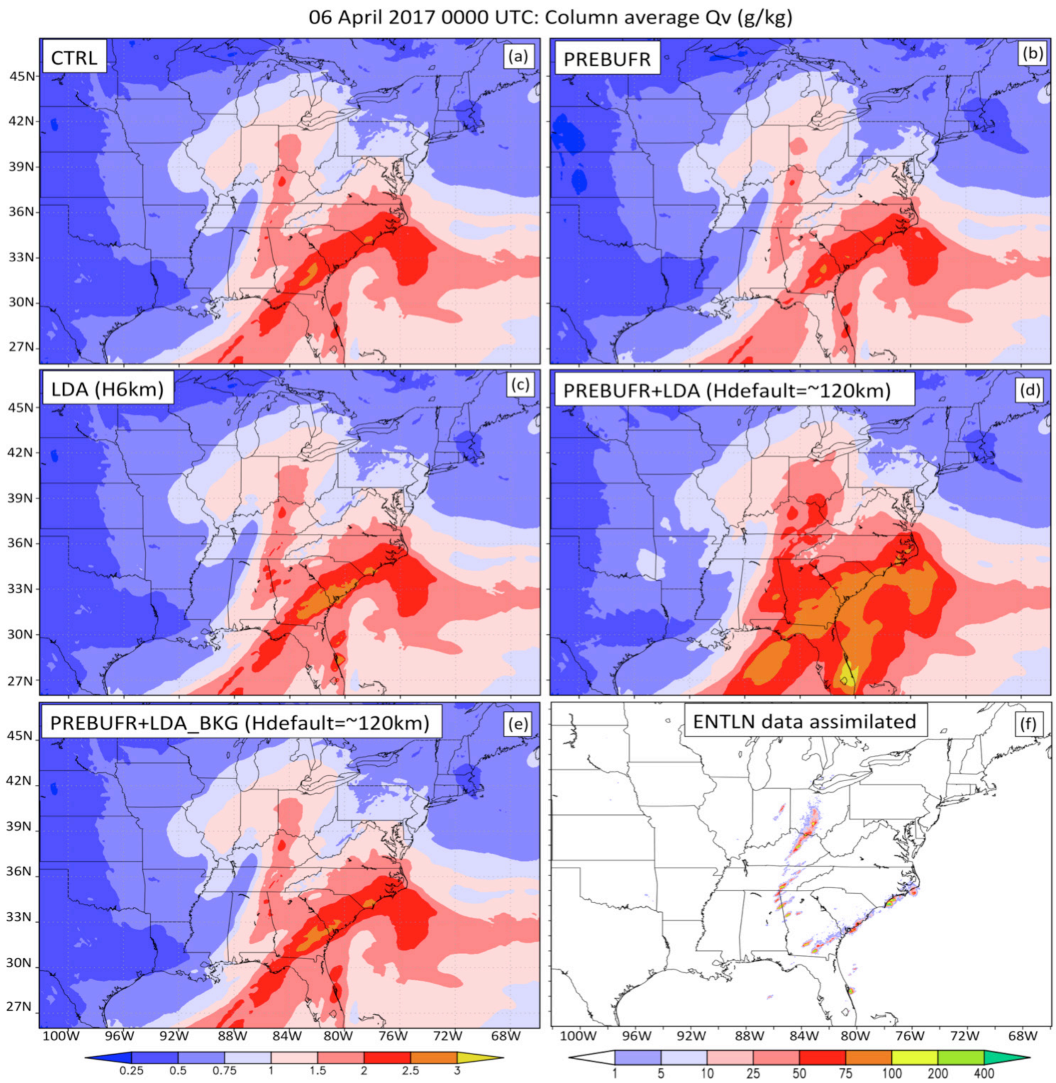


Figure 1. *Horizontal cross-section of column-averaged Qv (variable assimilated as proxy for lightning, following Fierro et al. 2016) at the analysis time (0000UTC) for: (a) control run (NO DA, CTRL), (b) case assimilating standard NCEP PREPBUFR datasets (PREBUFR), (c) lightning data assimilation only with H = 6km (LDA), (d) lightning data and PREPBUFR data are both assimilated with the default H = ~100 -120 km and (e) as in (d) but treating the nonlightning areas (i.e., zero lightning) as zero innovation instead of missing values for Qv (which confines horizontal spread, cf. Fierro et al. 2016). For reference, the 0000-0100 UTC accumulated ENTLN data that were assimilated in the LDA experiments are displayed in (f) (i.e., location of deep convection in the observations). The horizontal cross-sections cover the entirety of the simulation domain.*

by the LDA in Fig. 1d for the default H in GSI, an additional experiment was devised wherein the nonlightning areas treated the innovations for Qv as zero (i.e., background Qv values were assimilated) instead of assuming missing values for Qv (Fierro et al. 2016). As shown in Fig. 1e, this has for main effect to confine the horizontal spread of the Qv increase and generate an analysis (and forecasts) that is qualitatively equivalent to the LDA run with H = 6 km (Fig. 1c). One salient disadvantage of this practice, however, is the significant increase in CPU cost, because every grid point in the domain must be accounted for during the minimization. Additionally, forcing the analysis close to the background Qv in nonlightning areas has the potential to degrade the analysis resulting from the assimilation of other types of observation that also adjust Qv.

The respective increases in Qv in Fig. 1 translate well with the 24-h APCP forecasts in Fig. 2. Consistent with Fierro et al. (2015), the improvements in the APCP (Fig. 2, 3) and reflectivity (not shown) forecast in the lightning-active areas are noteworthy

(continued on page 9)

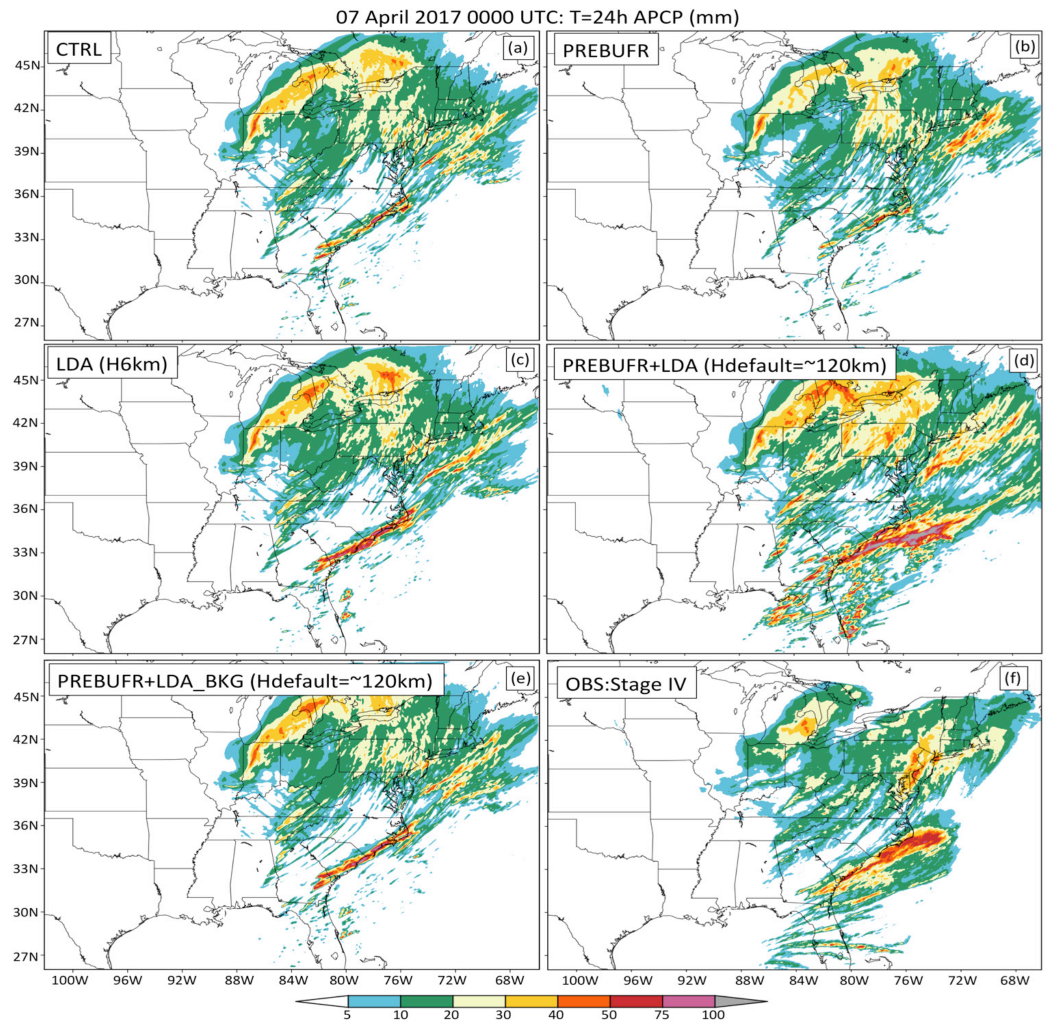


Figure 2. *As in Figure 1 but for the simulated 24-h accumulated precipitation (APCP). For reference, the observed (Stage IV) 24-h APCP fields are shown in (f).*

during the first few hours but wane after ~6 h with very little difference/gain seen at or after that (Fig. 3). As evidenced in Figs. 1 and 2, when the default H of GSI is used, the Qv increase is spread over too wide of an area yielding to notably larger-than-observed APCP in the forecast (Fig. 2) and, consequently, large wet biases (Fig. 3).

Domain wide fit-to-obs statistics (not shown) such as total bias and root mean square errors for Qv, temperature and horizontal wind speed reveal that, with the exception of the experiment using the default H, all other DA runs produce negligible changes in these quantities when evaluated against CTRL. This result is encouraging as it indicates that the LDA does not incur noticeable additive noise/error later in the forecast (i.e., ≥12 h) – an issue that often prevails in long term (≥24 h) forecast if convective-scale information (such as lightning or radar data) is assimilated (Shun Liu, personal communications, 2016).

Based on these tests, it was deemed de rigueur to place emphasis on tests aimed at improving shorter term convective scale forecasts (NEWS3DVAR during HWT). Additional work with GSI will focus on

(continued on page 10)

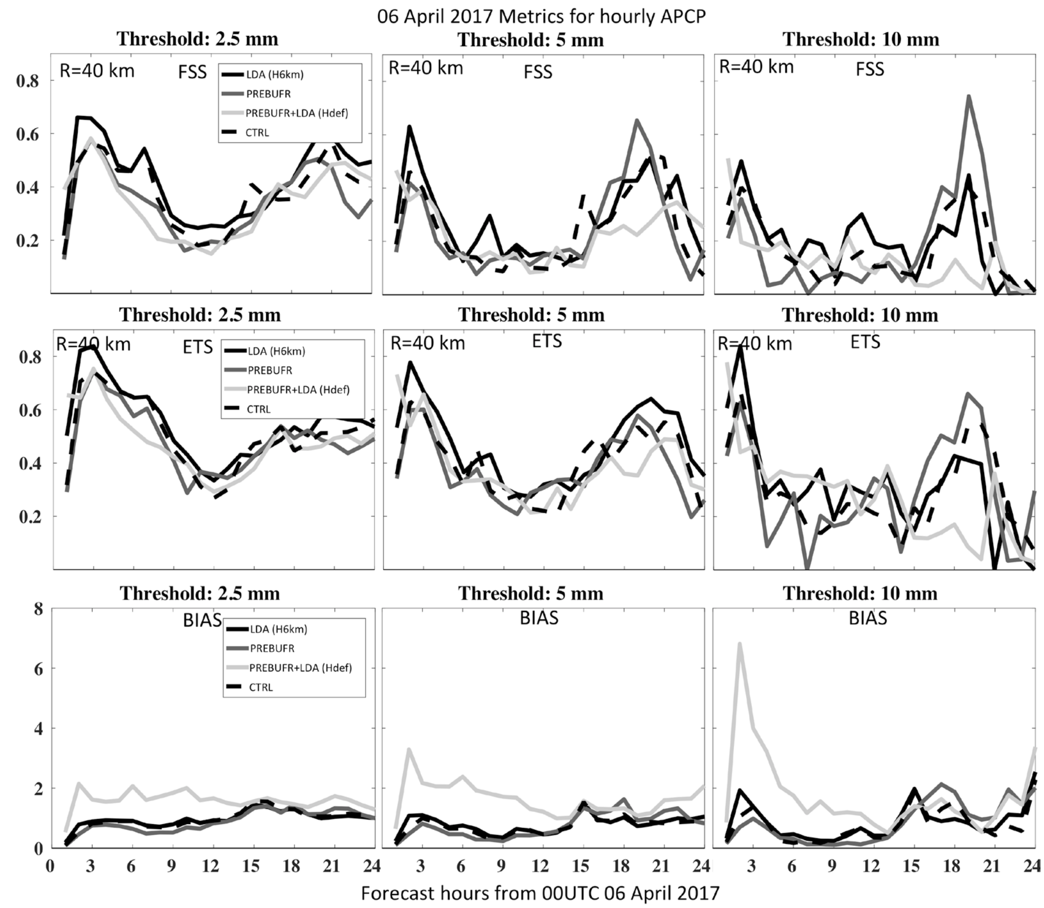


Figure 3. *Domain wide fractions skill score, equitable threat score, and frequency bias for various simulated APCP thresholds for LDA (H6km), PREBUFR, PREBUFR+LDA (Hdefault) and the control run (CTRL).*

performing more systematic forecasts with a multiscale DA approach (i.e., H~100 km for PREPBUFR and H~10 km for lightning; Fierro et al. 2016). Using the aforementioned multiscale approach (not shown), preliminary results for this representative case study reveals forecast improvements that are quantitatively similar to the convective-scale LDA (H6km) experiment in Fig. 2c. This is because PREBUFR incurred overall small adjustments to the Qv field relative to CTRL, as evidenced by Figs. 1a, 1b. Evaluations of the LDA within NEWS3DVAR and GSI will be pursued with GLM and/or with ENTLN data.

Alexandre O. Fierro, Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma and NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma | alex.fierro@noaa.gov

Gang Zhao, Center of Analysis and Prediction of Storms, Norman, Oklahoma

Shun Liu, NOAA/National Centers of Environmental Prediction, College Park, Maryland, I. M. Systems Group, Inc., Rockville, Maryland

Yunheng Wang, Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma and NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

(continued on page 11)

Jidong Gao, NOAA/National Severe Storms Laboratory, Norman, Oklahoma

Kristin M. Calhoun, Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma and NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

Conrad L. Ziegler, NOAA/National Severe Storms Laboratory, Norman, Oklahoma

Edward R. Mansell, NOAA/National Severe Storms Laboratory, Norman, Oklahoma

Donald R. Macgorman, NOAA/National Severe Storms Laboratory, Norman, Oklahoma

Acknowledgments

The authors thank Dr. Ying Lin for providing the Stage IV rainfall data. The authors also gratefully acknowledge Bill Callahan, Stan Heckman, and Jim Anderson from Earth Networks for providing the ENTLN total lightning data. Funding was provided by NOAA/Office of Oceanic and Atmospheric Research under NOAA–University of Oklahoma Cooperative Agreement NA11OAR4320072, U.S. Department of Commerce. This work was further supported by the GOES-R program under Grant opportunity #NOAA-NWS-NWSPO-2016-2004610(Award #NA16NWS4680024). The simulations were conducted on the NOAA HPC "Jet" resources housed in Boulder, Colorado. Auxiliary computer resources were provided by the Oklahoma Supercomputing Center for Education and Research (OSCER) hosted at the University of Oklahoma.

References

Allen, B. J., E. R. Mansell, D. C. Dowell, and W. Deierling, 2016: Assimilation of pseudo-GLM data using the ensemble Kalman filter. Mon. Wea. Rev., 144, 3465–3486.

Calhoun, K. M., T. M. Smith, D. M. Kingfield, J. Gao, and D. J. Stensrud, 2014: Forecaster Use and Evaluation of Real-Time 3DVAR Analyses during Severe Thunderstorm and Tornado Warning Operations in the Hazardous Weather Testbed. Wea. Forecasting, 29, 601-613.

Clark, A. J., and Coauthors, 2012: An Overview of the 2010 Hazardous Weather Testbed Experimental Forecast Program Spring Experiment. Bull. Amer. Meteor. Soc., 93, 55–74.

Fierro, A. O., J. Gao, C. Ziegler, K. Calhoun, E.R. Mansell and D. R. MacGorman 2016: Assimilation of pseudo GLM flash extent data in the variational framework at convection allowing scales: Proof-of-concept and evaluation. Mon. Wea. Rev., 144, 4363-4393.

Fierro, A. O., A. J. Clark, E. R. Mansell, D. R. MacGorman, S. Dembek and C. Ziegler, 2015: Impact of storm-scale lightning data assimilation on WRF-ARW precipitation forecasts during the 2013 warm season over the contiguous United States. Mon. Wea. Rev., 143, 757-777.

Fierro, A. O., J. Gao, C. Ziegler, E.R. Mansell, D. R. MacGorman and S. Dembek 2014: Evaluation of a cloud scale lightning data assimilation technique and a 3DVAR method for the analysis and short term

(continued on page 12)

forecast of the 29 June 2012 derecho event. Mon. Wea. Rev.,142, 183-202.

Fierro, A. O., E.R. Mansell, C. Ziegler and D. R. MacGorman 2012: Application of a lightning data assimilation technique in the WRF-ARW model at cloud-resolving scales for the Tornado Outbreak of 24 May 2011. Mon. Wea. Rev., 140, 2609-2627.

Fierro, A. O and J. M. Reisner, 2011: High Resolution Simulation of the Electrification and Lightning of Hurricane Rita during the period of Rapid Intensification. J. Atmos. Sci, 68, 477-494.

Gao, J. and CoAuthors, 2013: A Real-time Weather-Adaptive 3DVAR Analysis System for Severe Weather Detections and Warnings. Wea. Forecasting, 28, 727–745.

Liu, S., J. Carley, W. Wu, E. Rogers, J. He, B. Ferrier, D. Parrish, G. DiMego and J. Derber, 2017: WSR-88D radar data and NLDN lightning data assimilation at NCEP. 21st conference on integrated observing and assimilation system, 22-26 January 2017, Seattle, WA.

Liu, S., J. He, G. DiMego and X. Liang, 2016: Assimilation of Lightning data at NCEP. 2016 International Lightning Detection Conference/6th international Lightning Meteorology Conference, San Diego, CA, 17-22 April, 2016.

Smith, T. M., and Coauthors, 2014: Examination of a real-time 3DVAR analysis system in the Hazardous Weather Testbed. Wea. Forecasting, 29, 63–77.

Variational and Hybrid (EnVar) Methodologies to Add the Capability to Assimilate GOES-16/GLM Observations into GDAS

The launch of new observing systems offers tremendous potential for advancing the operational weather forecasting enterprise. However, "mission success" is strongly tied to the ability of data assimilation systems to effectively process new observations not previously used in operations. One such example are the new measurements of lightning activity by the Geostationary Lightning Mapper (GLM) instrument aboard the Geostationary Operational Environmental Satellite (GOES-16). Essentially, the GLM instrument provides "pictures" from which the frequency, location, and extent of lightning strikes can be estimated. Hence, these measurements can be regarded as two-dimensional fields that indicate where lightning events occur at a given time and at a significantly coarser resolution, as compared to ground-based lightning detection networks (LDN). Therefore, how can it be possible to capitalize

(continued on page 13)

on the information provided by these pictures of lightning events for the benefit of operational numerical weather prediction models and in particular at the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service?

Lightning can be related to state variables through an observation operator that can transfer the impact of lightning observations via data assimilation to standard model fields, among others, humidity, temperature, pressure, and wind. To that end, we enhanced the National Centers for Environmental Prediction (NCEP) operational Gridpoint Statistical Interpolation (GSI) data assimilation system (Parish and Derber, 1992, Kleist et al. 2009) by adding a lightning assimilation capability (based on Apodaca et al. [2014]) to the Global Data Assimilation System (GDAS), which is suitable for the current-operational Global Forecasting System (GFS) with its intrinsic coarse resolution and simplified cloud microphysics and by following a variational framework (the GSI-GOES-16/GLM lightning assimilation package, hereafter).

As a starting point, we used surface-based Lightning Detection Network (LDN) data from the World Wide Lightning Location Network (WWLLN) as a GLM-proxy, from which the real-earth longitude and longitude and timing of total lightning strikes were extracted in a way similar to what the GLM instrument detects (Fig. 1). These data are subsequently converted into the Binary Universal Form (BUFR) format required for assimilation by the GSI system and are ingested as a cumulative count of geo-located lightning strikes, within a typical assimilation time window, which for the NCEP/GFS global system is six hours. The GSI-GOES-16/GLM lightning assimilation package has been prepared to

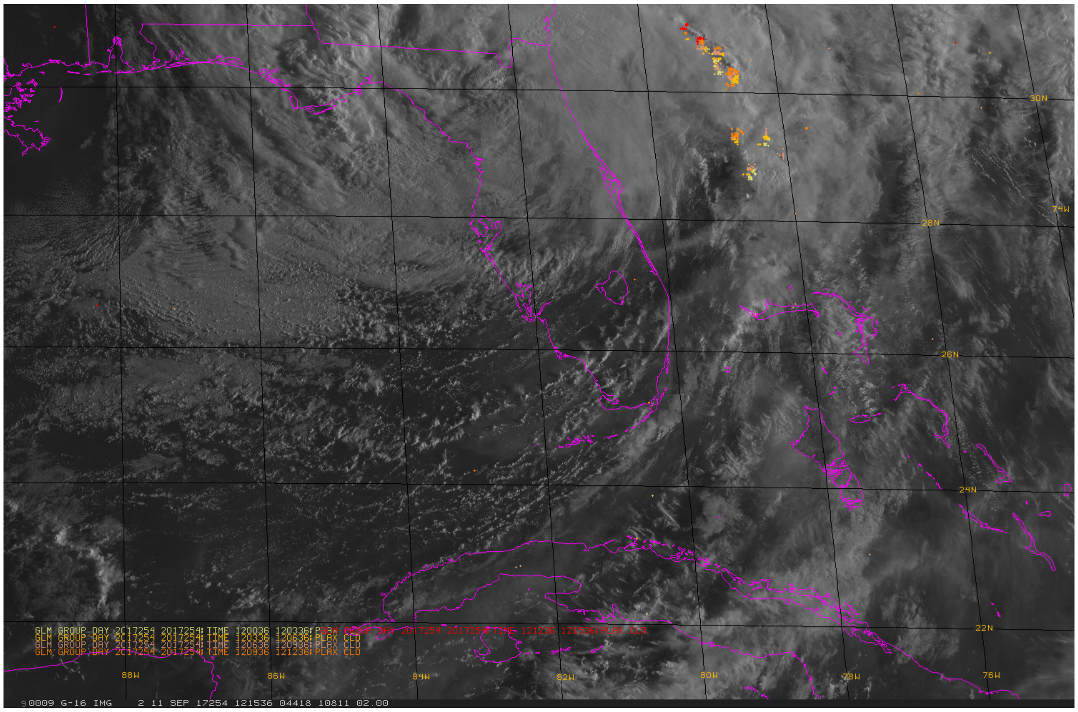


Figure 1. *Groups of GOES-16/GLM observations during tropical cyclone Irma (2016) (Courtesy: University of Wisconsin/CIMSS and Colorado State University/CIRA).*

(continued on page 14)

handle actual GLM observations once these are well-curated, suitable for testing, and readily available to the public.

Given that lightning flash rate (*FR*) is commonly used for data assimilation and forecast threat estimation, it is necessary to transform the raw GLM-proxy geo-located strike data to lightning flash rate, which is calculated as the number of strikes (*NS*) per square kilometer, per hour ($FR=NS/km^2hr$). Such derived FR observations are defined on a gridded domain with a horizontal resolution corresponding to the average resolution of the GLM instrument (i.e. 10 km). The calculation of lightning *FR* is conducted in the vicinity of each grid point without overlapping.

In order to obtain the "model version" of the lightning flash rate observations (i.e., a forward observation operator), a lightning flash rate observation operator based on the vertical updraft regression in Barthe et al. (2010) was adopted in the GSI system (Eq. 1), where α and β are empirical parameters derived from satellite climatologies. This represents a challenge since updraft speed *(w)* is not a prognostic variable in the GFS model, therefore, it needs to be calculated and is given by (Eq. 2), where g is the gravity constant, Φ is the geopotential height, σ is the vertical sigma coordinate, and ∇_σ denotes the horizontal gradient on a constant sigma surface. Note that a modified version of the continuity equation is employed where the geopotential time tendency term is neglected, because updates in sequential assimilation algorithms like the GSI only occur at a single time step. Since vertical updraft speed is related to other model variables through the continuity equation, (Eq. 1) can take the form of (Eq. 3), where T is the temperature, q is the specific humidity, u and v are the components of the wind, and the subscript k denotes model vertical layers that vary over horizontal points. Given that these are the standard control variables in atmospheric data assimilation, lightning observations can be assimilated without introducing new control variables into the GSI system. The maximum updraft is calculated for each horizontal grid point where clouds are detected via a cloud mask implying that lightning flash rate is a two-dimensional horizontal field.

(1), $$FR = h_{updraft} = \alpha[w_{\max}]^{\beta}$$

(2), $$w = \frac{1}{g}\frac{\partial\Phi}{\partial t} = \frac{1}{g}\left[V \bullet \nabla_\sigma \Phi + \dot{\sigma}\frac{\partial\Phi}{\partial\sigma}\right]$$

(3), $$h_{updraft} = \alpha[w(T_K, q_K, u_K, v_K)]^{\beta}$$

Variational data assimilation methods require the derivation of tangent linear (TL) and adjoint (AD) operators. In the GSI system, the TL and AD operators are given by a set of coefficients. In this case, they are obtained by taking the first variation of (Eq. 3). The TL of the lightning flash rate observation operator is

(4), $$\delta h_{updraft} = s_T\delta T_K + s_q\delta q_K + s_U\delta u_K + s_V\delta v_K$$

where s_T, s_q, s_u, and s_v are elements of the observational Jacobian matrix in the GSI and are given by:

(5), $$S_T = \alpha\beta\left[w_{\max}\right]^{\beta-1}\frac{\partial w}{\partial T_K}$$

(6), $$S_q = \alpha\beta\left[w_{\max}\right]^{\beta-1}\frac{\partial w}{\partial q_K}$$

(7), $$S_u = \alpha\beta\left[w_{\max}\right]^{\beta-1}\frac{\partial w}{\partial u_K}$$

(8), $$S_v = \alpha\beta\left[w_{\max}\right]^{\beta-1}\frac{\partial w}{\partial v_K}$$

(continued on page 15)

The AD operator simply follows from the TL in the form of:

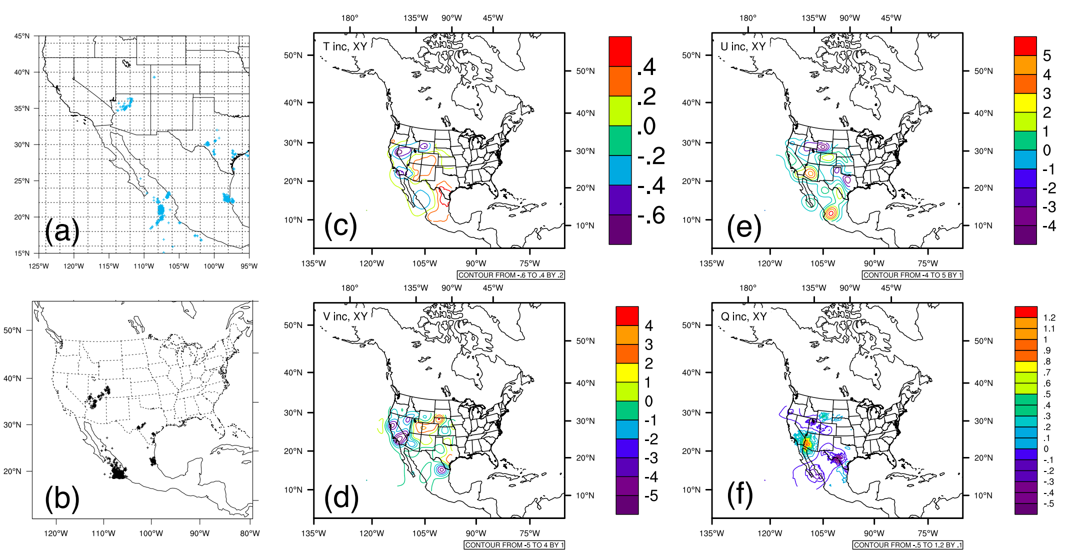
$$(9), \quad S\hat{h}_{updraft} = \mathbf{R}^{-1}[\mathbf{y}-H(\mathbf{x})]$$

where the (^) indicates the adjoint of a variable, **y** is the vector of lightning flash rate observations, *H* is the nonlinear observation operator for lightning flash rate, and **R** is an observation error covariance matrix.

One additional component of the GSI-GOES-16/GLM lightning assimilation package is the inclusion of an online bias correction scheme based on optimal parameter estimation. The goal is to correct any skewness on the probability density function statistics of the normalized vectors of departures at observation points (innovations). Skewness can indicate that observed values are considerably larger than a first guess. This online bias correction scheme is described in detail in Apodaca et al. (2014).

The GOES-16/GLM lightning assimilation package has been fully incorporated in the GSI system, and this new capability is currently undergoing testing in global parallel experiments with the NCEP/4DEnVar system to verify impacts to forecast step. Thus far, an assessment on the processing of lightning observations and on the impacts to the initial conditions of some of the dynamical fields of the GFS model seems promising. Plots of the spatial distribution of the raw lightning strikes (Fig. 2a) and the lightning flash rate density (# hits km^{-2} 6-hours^{-1}) for the remnants of tropical storm Ivo, valid at 2013-08-27_12:00:00 indicate that the locations of the raw lightning observations coincide with the lightning flash rate observations processed by the GSI system (Fig. 2b). Two experiments were conducted with the GSI system, one with the assimilation of lightning (light) and another without (control). A panel of analysis increments or a difference between both experiments for the selected set of control variables (temperature, the u and v components of the wind, and specific humidity) in the GFS model is shown in Fig. 2 (c, d, e, f). Regions of adjustments to

Figure 2. *(a) Raw lightning observations from the WWLLN network, (b) assimilated lightning flash rate, both valid at 12 UTC 27 August 2013. Analysis increments of (c) temperature (K), (d) u-component of wind (m/s), (e) v-component of wind (m/s), and (f) specific humidity (g/kg) from a GFS/GDAS lightning data assimilation experiment.*



(continued on page 16)

the control variables, by the assimilation of lightning observations, are evident, and these regions coincide with the areas with high densities of lightning flash rate observations shown in Fig. 2(b). The most pronounced increments can be seen on the Nevada-Arizona region and over the South-Central/US-Mexico border region of Texas, in the United States, with additional increments off the coast of the states of Jalisco and Colima in Mexico. For verification, we used observed 24-hour accumulated surface precipitation from the National Weather Service for the continental Unites States (Fig. 3), also valid at 2013-08-27_12:00:00. This plot shows areas of flash flooding produced by the remnants of tropical storm Ivo (2013) in the Southwestern United States. For these development efforts and experiments, only regional lightning datasets were made available to us, and for this particular tropical storm/remnant case study we only had lightning observations from 15 to 45 degrees North and from 95 to 115 degrees West. Therefore, the impact of the lightning assimilation could not be tested nor verified for the systems over the Great Lakes and Northeastern United States (Fig.3).

In preparation for the NOAA/NGGPS FV3-based Unified Modeling System, we anticipate to further develop the GSI/GOES-16/GLM lightning assimilation package following a hybrid (EnVar) methodology and by incorporating a prototype version that is fully functional in the Colorado State University/Maximum Likelihood Ensemble Filter (Zupanski, 2005). This prototype was tested with the non-hydrostatic/cloud resolving WRF-ARW model. This prototype is capable of updating both dynamical and cloud control variables through the use of a new observation operator that exploits the relationship between lightning FR and the maximum upward flux of graupel in the mixed phase region (–15 °C), as well as the gridded vertically integrated mixing ratios of cloud ice, graupel, and snow (McCaul et al. [2009]). The WRF-ARW-MLEF data assimilation system can be tested at resolutions of 9, 3, and 1 km with

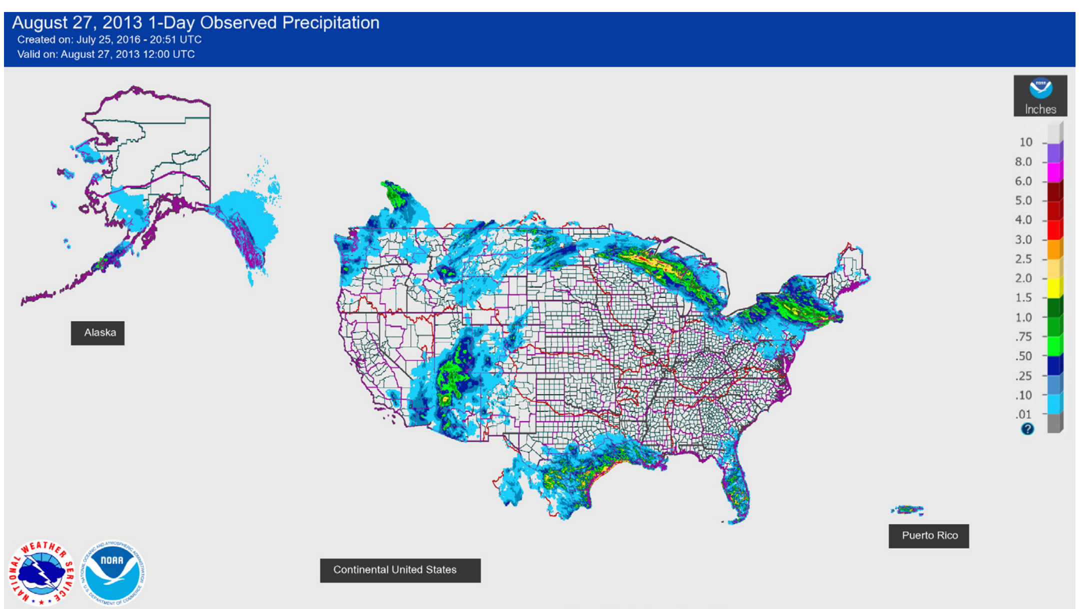


Figure 3. *24-hr precipitation valid at 2013-08-27_12:00:00 (Courtesy: NWS). Note the region of maximum precipitation near the Arizona-Nevada border, which coincides with the region of a positive analysis increment in specific humidity shown in Fig. 2. The assimilation of lightning observations has a positive impact in the initial conditions of the GFS model.*

(continued on page 17)

an ensemble size of 32 members and cycling windows of 1–3 hours. A single observation test (1-OBS) was conducted to evaluate the impact of a single lightning flash rate observation on the analysis increments of a subset of the control variables (cloud vapor mixing ratio, temperature, and the u and v wind components) and to implicitly illustrate the complex structure of a flow-dependent forecast error covariance. Fig. 4, shows the analysis increments of (a) water vapor mixing ratio (kg kg-1), (b) temperature (degrees K), and (c) wind (m sec-1) at 850 hPa. It can be seen that lightning can impact the large-scale atmospheric environment at surrounding grid points. The magnitude of the analysis increments indicates non-negligible adjustments on dynamical variables and an impact to the initial conditions of this cloud-resolving model.

The assimilation of GLM-proxy lightning data was also tested for a tropical cyclone case (Ivo [2013]) to illustrate the capability of this assimilation/modeling system in the prediction of lightning activity. By including hydrometeors as control variables, updates to cloud mixing ratio fields are possible (Fig. 5). The assimilation of lightning on top of conventional data (red line) leads to decreases in both ice and snow hydrometeors, while increasing cloud water mixing ratio. These adjustments are relevant since it is well known that some of the microphysical schemes implemented in cloud-resolving models (e.g. WRF-ARW) tend to overestimate ice-phase species.

The plots in Fig. 6 show 3-hour forecasts after data assimilation using the WRF-ARW model at 3 km resolution for an

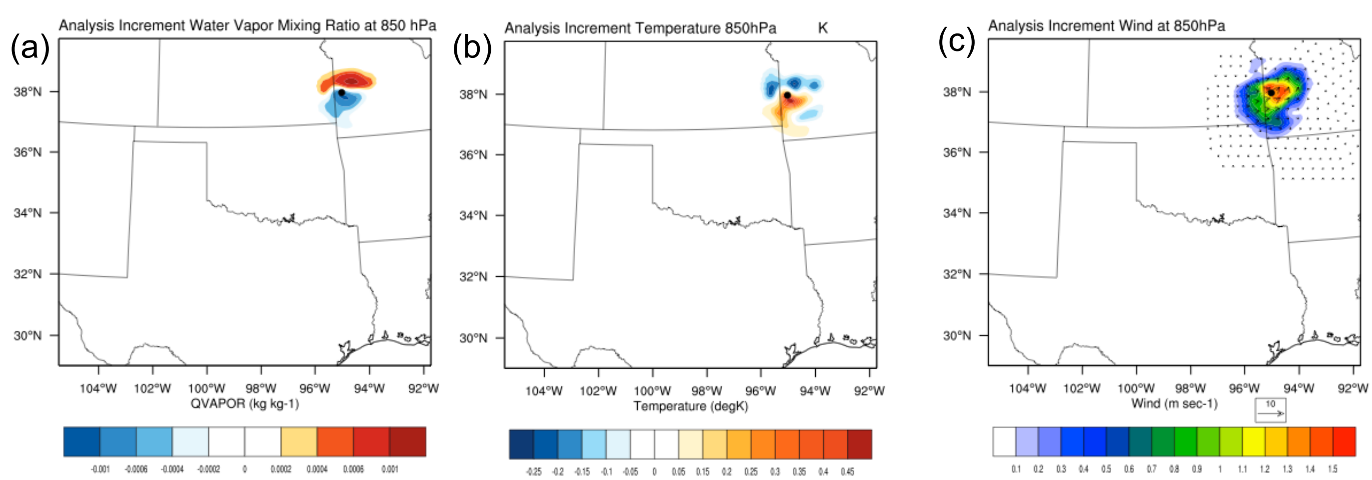


Figure 4. *Analysis increments of (a) water vapor mixing ratio (kg kg-1), (b) temperature (degK) and (c) wind (m sec-1) at 850 hPa. The black dot shows the location of a single lightning observation (37 N, 95 W). Dipoles of positive and negative analysis increments can be observed at either end of the single observation in the specific humidity and temperature plots but with opposite signs. 850 hPa winds show a positive analysis increment with maximum values coinciding with the region of positive temperature increment, and anti-cyclonic circulation can be observed around the location of the single observation. These increments are a clear indication of the information content a single lightning strike can spread horizontally into the analysis.*

(continued on page 18)

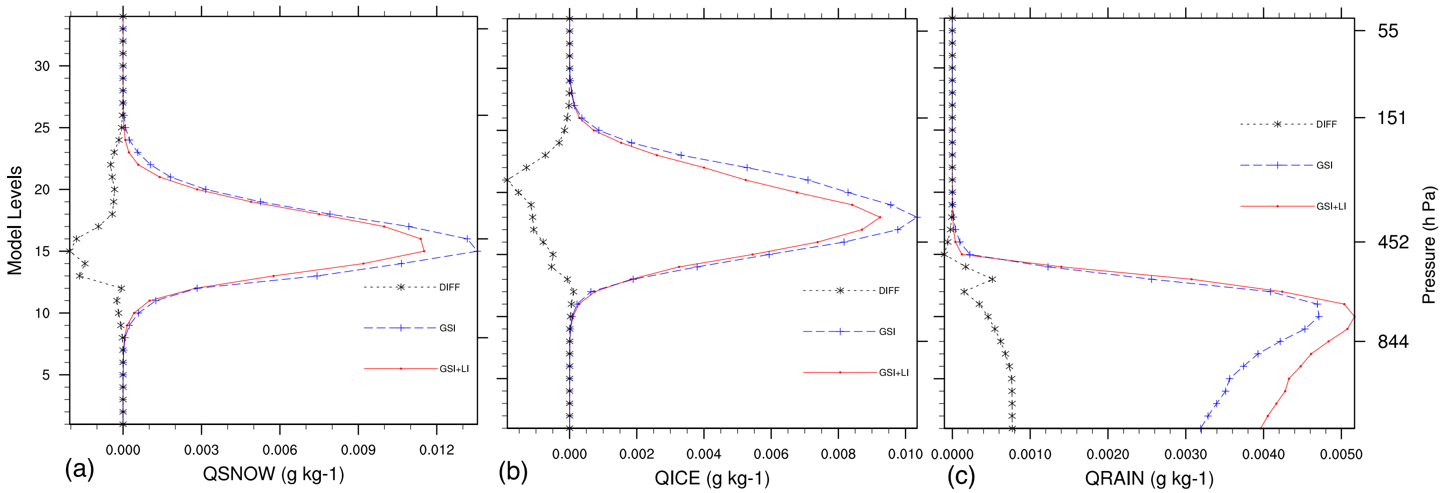


Figure 5. *Valid at 26 AUG 2013 0600 UTC. The blue curve represents the control experiment with the assimilation of conventional observations, only (GSI). The red curve represents the assimilation of lightning and conventional observations (GSI+LI). The black curve shows the difference between both experiments. Note that in (a) and (b) the assimilation of lightning (red) lead to decreases in the concentration of ice and snow mixing ratios, while increasing rain mixing ratio (red) in (c).*

experiment that included the assimilation of conventional observations (Fig. 6a) and another where lightning was assimilated on top of conventional observations (Fig 6b). Results indicate that the assimilation of lightning is capable of predicting lightning flash rate in the less observed mountainous regions of Mexico (Fig. 6b). This example clearly illustrates that satellite-based lightning measurements can be particularly useful in data-sparse regions.

The former are just some examples where the assimilation of lightning observations can lead to updates to moisture and dynamical and cloud microphysical fields by following advanced data assimilation approaches. Verification of the impacts to the forecast are currently undergoing testing in global parallel cycling experiments with the NCEP/4DEnVar system. Once GLM observations are readily available, we will be able to evaluate their true impact with GSI system and to assess their benefit in operational weather prediction at NCEP. Furthermore, as a way to address the implications of employing observation operators that contain empirically-based parameters, we can develop "generic" lightning flash rate observation operators that include meteorologically-driven optimal parameter estimation within minimization, relevant for global/multi-scale models (Zupanski and Zupanski, 2006).

(continued on page 19)

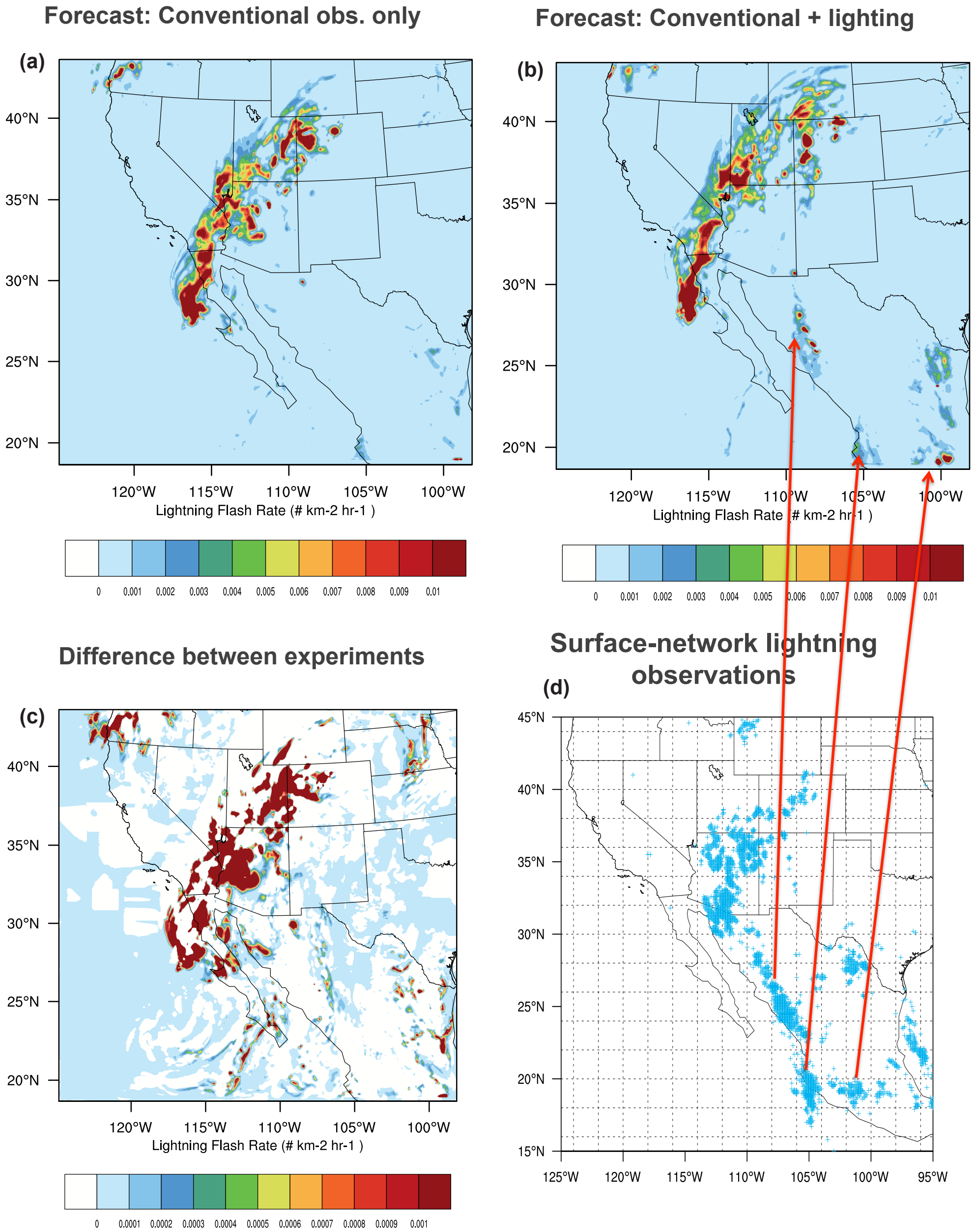


Figure 6. *A 3-hour forecast of lightning flash rate (strikes per km2 per hour) valid at 25 AUG 2013 1200 UTC: (a) after assimilating conventional observations only, (b) after assimilating conventional and lightning observations, (c) the difference between both experiments, and (d) raw WWLLN lightning observations.*

Karina Apodaca (CSU/CIRA and NOAA/OAR/AOML/HRD) Karina.Apodaca@noaa.gov and Milija Zupanski (CSU/CIRA)

Acknowledgements
These projects have been possible thanks to the support from numerous individuals and institutions: CIRA: Robert DeMaria, Louis D. Grasso, Ting-Chi Wu; NCAR/MMM/DAS; NOAA/GOSA group; NCAR/CISL/Yellowstone supercomputing; JCSDA/S4 supercomputing; EMC/DA; Financial support: Sandy Supplemental Award #NA14NWS4830034 and DTC Visitor Program Award.

The authors wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 50 universities and institutions, for providing the lightning location data used in this paper.

References

Apodaca, K., Zupanski, M., DeMaria, M., Knaff, J. A., and Grasso, L. D.: Development of a hybrid variational-ensemble data assimilation technique for observed lightning tested in a mesoscale model, Nonlin. Processes Geophys., 21, 1027-1041, doi:10.5194/npg-21-1027-2014, 2014a.

Barthe, C., Deierling, W., and Barth, M. C.: Estimation of total lightning from various storm parameters: a cloud resolving model study, J. Geophys. Res., 115, D24202, doi:10.1029/2010JD014405, 2010.

McCaul, E. W., S. J. Goodman, K. M. LaCasse, D. J. Cecil, 2009: Forecasting Lightning Threat Using Cloud-Resolving Model Simulations. Wea. Forecasting, 24, 709–729.

Kleist, D.T., Parrish D.F., Derber J.C., Treadon T., Wu W., Lord S., Introduction of the GSI into NCEP global data assimilation system, Wea. Forecast. 24 (2009)

Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's spectral statistical-interpolation system. Mon. Wea. Rev., 120, 1747–1763.

Zupanski, D. and M. Zupanski, 2006: Model error estimation employing ensemble data assimilation approach. Mon. Wea. Rev., 134, 1337-1354.

Zupanski, M.: Maximum likelihood ensemble filter: theoretical aspects, Mon. Weather Rev., 133, 1710–1726, 2005.

MEETING REPORT

6th AMS Symposium on the JCSDA

The Symposium was organized under the leadership of the JCSDA's Jim Yoe and conducted as an integral component of the 98th Annual Meeting in Austin, Texas. Organized into 4 topical sessions featuring a total of 20 oral presentations and 12 posters, the Symposium benefited from being scheduled at the peak of the Annual Meeting, with strong attendance and informal discussions that carried on over to supper and into the way late evening hours on Wednesday, January 10. Presentations and posters were offered by staff and contractors of the JCSDA partner agencies, the academic community, and by international representatives.

Jeff Cetola (USAF) and Jim Yoe (NCEP) co-chaired the opening session, which featured six talks on the assimilation of Satellite Data to Improve the Forecasts of Land Surfaces, Oceans, and Air Quality. Another session, chaired by Will McCarty and Krishna Kumar, was devoted to the Development of Innovative Methods for Assimilating Satellite Observations in Environmental Analyses and Prediction, with emphasis on the evolution of the JEDI and the CRTM. Two more sessions, co-chaired by Kathryn Shontz, Tom Auligne, and John LeMarshall, featured impact assessments of assorted satellite observations in a variety of NWP systems. These included an invited keynote presentation by Florence Rabier on the ECMWF.

The JCSDA Symposium again co-sponsored the Student Reception in Satellite Meteorology on the evening of Monday, January 8. This provided an excellent opportunity to meet and interact with students during the "Speed Mentoring" exercise, and to publicize the upcoming JCSDA Summer Colloquium for graduate students and early post-docs. Planning is already underway AMS Symposium on the JCSDA is currently being organized for the 99th Annual Meeting of the AMS in Phoenix, Arizona in January 2019.

PEOPLE

Welcome Dr. Hui Shao

Dr. Hui Shao joined the JCSDA as one of two scientists hired in November 2017. Supporting the scientific mission for assimilating new satellite instrument measurements at the joint center, Hui will focus on assimilation of the Global Navigation Satellite System Radio Occultation (GNSS-RO) observations. The effort will touch on two aspects, data and assimilation, related to available and future GNSS-RO missions. The data aspect includes data pre-processing, data validation, characterization of observation errors, and quality control. The assimilation aspect includes improving data assimilation ethodology, development of new observation operators for assimilation of GNSS-RO, transitioning of available research to operations, and collaborating with the US and international GNSS-RO communities. This effort will help improve operational GNSS-RO assimilation capabilities, accelerate research to operation transitions and, eventually, help improve numerical weather forecasts, as well as other operational applications.

Hui developed an interest in GNSS-RO observations and their assimilation as part of her Ph.D. research. Her dissertation centered on the assimilation of GNSS-RO measurements through various methods, including the ray-tracing method and (local) refractivity and bending angle methods, as well as the non-local refractivity (excess phase) method. Since then, she has continued to develop her knowledge of RO data processing and assimilation and has applied this knowledge to other data assimilation systems and NWP applications. Recently, two of her projects have been related to GNSS-RO observations. One project was to assess RO bending angle and refractivity data quality and errors from commercial satellites. The other project involved development of a forward operator for assimilation of COSMIC RO slant total electron content observations. Besides pursuing her research on satellite data assimilation, Hui recently worked at the Developmental Testbed Center as the Data Assimilation Task Lead. She also served as the DTC liaison at NCEP, supporting NOAA operational Gridpoint Statistical Interpolation (GSI) and Ensemble Kalman Filter (EnKF) data assimilation systems.

Hui has a Ph.D. in Meteorology from Florida State University and M.S. and B.S. in Atmospheric Sciences from Nanjing University, China. Outside of work, one of her favorite things to do in her free time is hiking with her family, including her two boys. She also keeps busy attending her sons' various activities.

Meet Dr. François Vandenberghe

Dr. François Vandenberghe joined the JCSDA in Boulder in November 2017. He will provide science support to verify and validate new-source Global Navigation Satellite System Radio Occultation (GNSS-RO) observations, determine their error characteristics, develop and refine effective data quality control, and quantitatively test the impact of adding these data to NOAA's operational Numerical Weather Prediction (NWP) modeling systems. GNSS-RO provides quasi-vertical soundings of atmospheric properties related to pressure, temperature, and humidity that may be assimilated into NWP models as aggregate observables (refractivity, bending angles or phase delay).

François began to work on GNSS-RO with data from the early GPS/MET experiment during his postdoc at NCAR. With NCEP collaborators, he contributed to the development of the first bending angle (forward and adjoint) observation operator for the GFS model in 1999. He then joined NCAR's Research Applications Laboratory where he worked on data assimilation applications, primarily in support of the Department of Defense. Over his years at NCAR, François has been involved with GPS radio-occultation science in its multiple aspects: space-borne, air-borne and ground-based and for various applications ranging from the government, the military and the private sector. He has collaborated with leading scientists from the U.S., Taiwanese and European GNSS science community and is seated on several Thesis committees.

François has a Ph.D. in Remote Sensing from the School of Mines of Paris, a M.S. in Signal Processing and a B.S. in Electrical Engineering. Apart from science, he is an avid tennis player and enjoys skiing the Rockies.

EDITOR'S NOTE

The JCSDA enters 2018 with considerable momentum and facing a host of opportunities and challenges. As I complete this message, I feel simultaneously nergized and exhausted from the Annual Meeting of the American Meteorological Society in Austin, TX last week. The Sixth AMS Symposium on the JCSDA was a great success, thanks to the contributions of many of you as presenters and as a knowledgeable audience. For those of us who were able to travel to Austin, the meeting may have been most valuable for the opportunities afforded us to meet face to face and to discuss problems of mutual interest, and potential solutions at length.

Fortunately we have a number of other forums to work together in 2018. Some of these are familiar, such as the Annual Science and Technical Workshop in the late Spring, and the JCSDA Summer Colloquium for graduate students and early post-docs at the end of July. But first, the JCSDA Executive Team and all JCSDA Project Leads will meet in Estes Park, CO in early February to complete formulation of the 2018 Annual Operating Plan. Our business practices have been made more efficient, and our science and technical progress more pronounced, through the new planning and operating process instituted in 2017, and thus we look forward to planning the work of 2018 with great enthusiasm.

There is no shortage of work to be done, with several JCSDA "infrastructure" projects including the CRTM, JEDI, and SOCA fully staffed or well on their way to being so. Moreover, there is a glut of environmental satellites newly on orbit or shortly expected, including NOAA-20 (formerly JPSS-1), GOES-16 and GOES-S, COSMIC-2A, KOMPSAT5, Paz, ADM/AEOLUS, just to name a few. At the heart of the JCSDA mission is discovering and developing means to exploit new satellite data in operational environmental prediction models. The new GOES-R series features a sensor that is not simply a new version of an established predecessor, but something truly novel - the GOES-R Lightning Mapper (GLM), which provides near-real time data in a vital but difficult forecasting environment, that associated with strong convection and severe weather. Assimilating GLM data is fundamentally different from assimilating microwave and infrared radiances. Thus, it is appropriate to devote much of this Newsletter to articles describing the GLM and current efforts to assimilate GLM observations. I trust that you will find these articles informative- and inspiring.

Happy New Year - Let's Roll!

SCIENCE CALENDAR

UPCOMING EVENTS

MEETINGS AND EVENTS SPONSORED BY JCSDA		
DATE	**LOCATION**	**TITLE**
May 30-31, June 1, 2018	Boulder, CO	JCSDA Annual Science Workshop
July 22-August 3, 2018	Bozeman, MT	JCSDA Annual Summer Colloquium 2018

MEETINGS OF INTEREST			
DATE	**LOCATION**	**WEBSITE**	**TITLE**
March 5–9, 2018	Munich, Germany	https://isda2018.wavestoweather.de/	6th International Symposium on Data Assimilation
March 25-30, 2018	Copper Mountain, Colorado, USA	http://grandmaster.colorado.edu/~copper/2018/	The Fifteenth Copper Mountain Conference on Iterative Methods
April 8–13, 2018	Austria Center Vienna (ACV) Vienna, Austria	https://www.egu.eu/	The General Assembly 2018 of the European Geosciences Union (EGU)
May 7–10, 2018	Montreal, Canada	http://web.meteo.mcgill.ca/enkf/	8th EnKF Workshop Montreal
July 1–6, 2018	Aveiro, Portugal	http://www.morgan.edu/research_and_economic_development/gestar_adjoint_workshop/first_announcement.html	11th Workshop on Meteorological Sensitivity Analysis and Data Assimilation
July 10–11, 2018	Lisbon, Portugal		2nd International surface working group (ISWG)
December 10–14, 2018	Washington, D.C., USA	https://fallmeeting.agu.org/	AGU fall meeting

CAREER OPPORTUNITIES

Opportunities in support of JCSDA may also be found at http://www.jcsda.noaa.gov/careers.php as they become available.