Geostationary Operational Environmental Satellite (GOES)-14 super rapid scan operations to prepare for GOES-R

Timothy J. Schmit
Steven J. Goodman
Daniel T. Lindsey
Robert M. Rabin
Kristopher M. Bedka
Mathew M. Gunshor
John L. Cintineo
Christopher S. Velden
A. Scott Bachmeier
Scott S. Lindstrom
Christopher C. Schmidt

Geostationary Operational Environmental Satellite (GOES)-14 super rapid scan operations to prepare for GOES-R

Timothy J. Schmit,[a] Steven J. Goodman,[b] Daniel T. Lindsey,[c] Robert M. Rabin,[d] Kristopher M. Bedka,[e] Mathew M. Gunshor,[f] John L. Cintineo,[f] Christopher S. Velden,[f] A. Scott Bachmeier,[f] Scott S. Lindstrom,[f] and Christopher C. Schmidt[f]

[a]NOAA Center for Satellite Applications and Research, Advanced Satellite Products Branch, 1225 West Dayton Street, Madison, Wisconsin 53706
Tim.J.Schmit@noaa.gov
[b]NOAA/NESDIS GOES-R Program Office, NASA GSFC Code 417, Greenbelt, Maryland 20771
[c]NOAA Center for Satellite Applications and Research, 3785 Laporte Avenue, Fort Collins, Colorado 80523
[d]NOAA/NSSL, 120 David L. Boren Boulevard, Norman, Oklahoma 73072
[e]Science Systems & Applications Inc., NASA Langley Research Center, Climate Science Branch, 1 Enterprise Parkway, Hampton, Virginia 23666
[f]University of Wisconsin-Madison, Cooperative Institute for Meteorological Satellite Studies, 1225 West Dayton Street, Madison, Wisconsin 53706

Abstract. Geostationary Operational Environmental Satellite (GOES)-14 imager was operated by National Oceanic and Atmospheric Administration (NOAA) in an experimental rapid scan 1-min mode that emulates the high-temporal resolution sampling of the Advanced Baseline Imager (ABI) on the next generation GOES-R series. Imagery with a refresh rate of 1 min of many phenomena were acquired, including clouds, convection, fires, smoke, and hurricanes, including 6 days of Hurricane Sandy through landfall. NOAA had never before operated a GOES in a nearly continuous 1-min mode for such an extended period of time, thereby making these unique datasets to explore the future capabilities possible with GOES-R. The next generation GOES-R imager will be able to routinely take mesoscale (1000 km × 1000 km) images every 30 s (or two separate locations every minute). These images can be acquired even while scanning continental United States and full disk images. These high time-resolution images from the GOES-14 imager are being used to prepare for the GOES-R era and its advanced imager. This includes both the imagery and quantitative derived products such as cloud-top cooling. Several animations are included to showcase the rapid change of the many phenomena observed during super rapid scan operations for GOES-R (SRSOR). © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JRS.7.073462]

1 Introduction

The Geostationary Operational Environmental Satellite (GOES)-14 was operated by the National Oceanic and Atmospheric Administration (NOAA) in an experimental super rapid scan 1-min mode to emulate the high-temporal resolution sampling of the future Advanced Baseline Imager (ABI) on the next generation GOES-R series. This test took place from August 16, 2012, to October 31, 2012, with a gap during parts of September and October. Imagery was acquired of many phenomena including severe convection, fires, smoke, and hurricanes. During typical GOES

operation, images are collected every 15 or 30 min. The 1-min imagery allows users to visualize phenomena while they are happening, as opposed to what has already happened.

Previously, 1-min GOES images have been shown to be useful during postlaunch science tests (PLT) and other nonoperational periods to monitor fog, clouds, rapidly developing convection, and a distinct "aircraft dissipation trail" (otherwise known as "distrails" or "hole punch clouds").[1] Often the PLT super rapid scan data represent just a few days of data.[2,3] In the fall of 2006, 1-min data were collected during the GOES-10 traverse of the continental United States (CONUS) as the satellite was positioned to a longitude of 60 deg West, from 135 West. During this time, "a forecaster at the Nashville, Tennessee, National Weather Service (NWS) Weather Forecast Office (WFO) had access (via the Internet) to the experimental GOES-10 1-min visible satellite animation" and used the information to correctly reduce the size of a watch box,[1] showing the potential value of the rapid refresh mode in warning decision making.

The 2012 GOES-14 1-min data are a unique resource since the 2006 GOES-10 data, though extensive, were collected while GOES-10 was changing its subpoint and after GOES-10 had been operational for approximately 8 years. The GOES-10 image quality was affected by an increased satellite inclination. These high time resolution image sequences bring the satellite image temporal frequency on par with that from other datasets, such as from radar, lightning mapping, and other remotely sensed and *in situ* measurements.

Demonstrations in the GOES-R Proving Ground with the NWS, including the National Hurricane Center (NHC), Storm Prediction Center (SPC), and the Ocean Prediction Center (OPC) have shown forecasters the benefit of these fine time resolutions in rapidly changing environments.[4] In the Proving Ground, products are demonstrated with, and receive feedback from, forecasters using proxy and simulated datasets. Some of the key products that are very useful for high impact weather forecasts and warnings include cloud and moisture imagery, hurricane intensity, convective initiation, overshooting convective cloud top (OT) detection, and lightning detection.

A deficiency in these product demonstrations is the inability to more fully demonstrate the added utility of the GOES-R imagery products at the higher 30 s to 1 min mesoscale refresh rate that will be routinely possible with the ABI. This is especially applicable when dealing with rapidly changing phenomena. In the demonstrations, NWS forecasters evaluate the planned and future capabilities of GOES-R in the context of their current and planned suite of observing systems and numerical weather prediction models. For example, at the Hazardous Weather Testbed in Norman, OK, the forecasters have access to simulated cloud and moisture imagery products, convective initiation, overshooting tops, cloud-top cooling rate, and 1-min Oklahoma total lightning mapping array (LMA) density maps while at the same time having access to dual polarization radar and National Weather Radar Testbed Multifunction Phased Array Radar rapid refresh 1-min volume scans.[5] Therefore, unique datasets can be collected in central Oklahoma consisting of the GOES-14 super rapid scan operations for GOES-R (SRSOR) proxy data for the GOES-R ABI and the Oklahoma LMA proxy data for the GOES-R Geostationary Lightning Mapper (GLM) concurrently with the radars forecasters rely on for nowcasting and warning of high impact and severe weather.[6] While not covered in this article, GOES-14 also acquired SRSOR images during the summer of 2013 on select dates in June and August.

1.1 Characteristics of GOES Imagers

The two Earth viewing sensors on the current GOES series are the imager and the sounder.[7] The nominal field of view is approximately 1 km at nadir for the imager visible band, although the detectors are oversampled in the east-west direction.[7] The technical aspects can be found in the GOES N/O/P data book.[8] Many operational products from these sensors are derived, such as the cloud products (height, properties, etc.), atmospheric motion, biomass burning, smoke, and surface properties (e.g., land surface temperature). Current plans call for GOES-14 to become an operational satellite in 2015. The GOES-14 imager has five spectral bands (Fig. 1); see Fig. 6.1 of Ref. 3 for a plot of the visible spectral response function. The current GOES imager routine operational schedule scans a full disk (FD) image every 3 h as well as a CONUS or "extended Northern Hemisphere" sector as often as every 15 min. In contrast, for one scan mode, the ABI on the GOES-R series will provide FD images every 15 min, plus
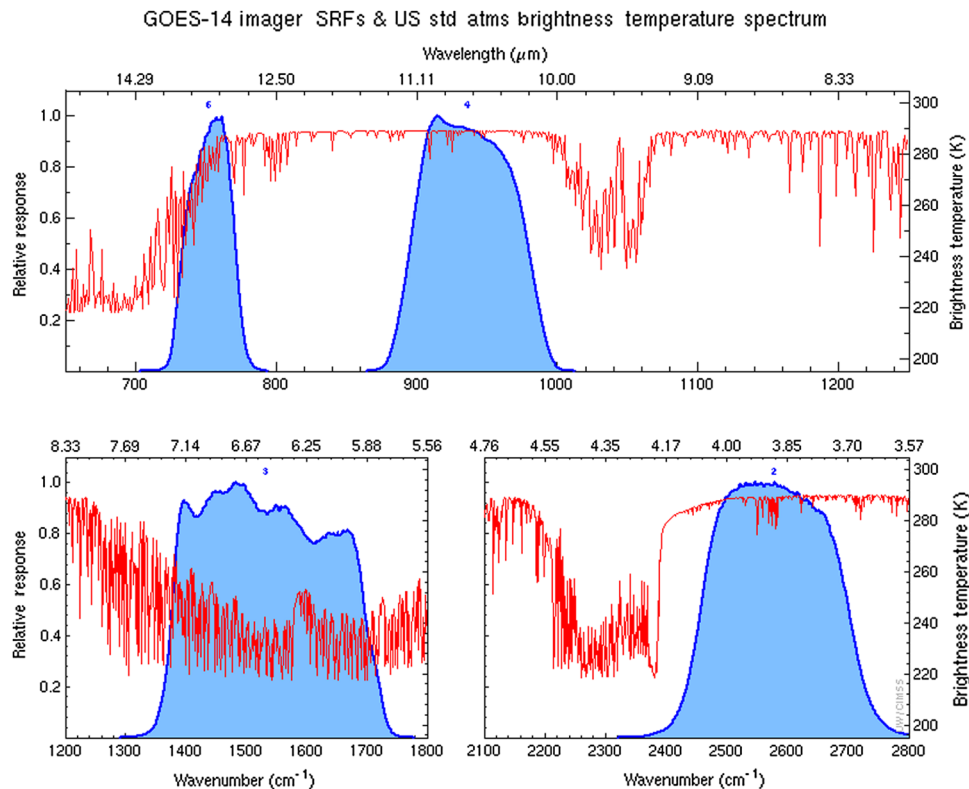
Fig. 1 GOES-14 imager spectral response functions (SRF) for the infrared (IR) bands. For the reference, a high-spectral resolution Earth-emitted spectrum (for the US standard atmosphere) is also plotted. The visible band (1) centered at 0.63 μm is not shown.

CONUS images every 5 min and mesoscale images every half minute (or two locations of approximately 1000 km × 1000 km every minute).[9] Hence, the special 1-min imagery of GOES-14 foreshadows what will be routinely available from the ABI on the next generation geostationary satellite series (GOES-R), scheduled to be launch ready in 2016, and operational in early 2017. GOES-S, the second in the series, is currently slated to launch in 2017 and become operational in 2020. A second possible scan mode is that the ABI only scan FD images, but do so every 5 min. The ABI will be better than the current imager in a number of significant ways. For example, faster coverage rate, improved spatial resolution (by a factor of four), on-orbit calibration of all bands, improved bit depth, more spectral bands (by over a factor of three), and improved Image Navigation and Registration.[9] This means the imagery from the ABI will not have the gaps that the current SRSOR has when a FD is scanned. Nominally, the period for a given low Earth orbiting satellite is approximately 90 min, although there are multiple polar-orbiters. There is little overlap between orbits over the mid-latitudes and tropics so these observations primarily provide snapshots of the atmospheric state and cannot capture the rapid evolution of phenomena as is routinely captured by satellites in a geostationary orbit.

1.2 *Super Rapid Scan Operations for GOES-R*

The GOES-R imager will be able to routinely take mesoscale images every 30 s (or swapping between observations of two widely separated phenomena every minute—e.g., an Atlantic hurricane and a Great Plains supercell tornadic storm). These images from the ABI can be acquired even while concurrently scanning larger areas, such as the continental United States and the FD. In general, the SRSOR schedule from GOES-14 consisted of 26 images every 30 min, with the exception of the 30-min gap every 3 h during FD images and during stray light (SL) testing (04:45 to 09:14 UTC). There was no SL outage during the late October collection of Hurricane Sandy (known as "Super Storm Sandy" in some media outlets) data, since the special

scans needed for the SL correction algorithm had already been collected. The SRSOR allows for more rapid imaging than the standard Rapid Scan Operations (RSO) or even the SRSO. While the SRSOR scans an area nominally each minute, the RSO is only as fine as 5 min (and at times only 10 or 30 min). The SRSO has 1-min imagery periods that are broken up by other longer scans of approximately 5, 9, and 30 min. All these schedules require a FD imaged every 3 h, which leaves the 30-min gaps. The 1-min sectors from the current GOES imagers are approximately 1100 km × 1900 km over the mid-CONUS (Fig. 2). More information on these operational scans can be found at NOAA's Office for Satellite and Product Operations (OSPO) web page: http://www.ospo.noaa.gov/Operations/GOES/schedules.html, while http://www.ospo.noaa.gov/Operations/GOES/14/srsor.html lists the scans associated with the SRSOR 2012 experiment. For most of the experiment, GOES-14 was positioned at a longitude of 105 deg west, although the images of Hurricane Sandy were scanned from approximately 90 deg west. The location of the scanned area was determined the preceding afternoon, based on a number of factors such as the SPC outlooks. These coordinates were then communicated with the satellite operators. In general, the same schedule and center point were operated for 24 h.

The schedule that was run during the SRSOR test varied due to a number of factors, including the potential weather, other satellite schedules, and out-of-storage planned testing (Table 1). The "default" schedules allowed for testing of changes to the routine schedules. The Continuous East Full Disk is a schedule that takes successive FDs, nominally every 30 min. More information, such as the daily schedule, coverage area, and satellite animations, on the SRSOR in 2012 can be found at the University of Wisconsin-Madison's Cooperative Institute for Meteorological Satellite Studies (CIMSS) web page: http://cimss.ssec.wisc.edu/goes/srsor/GOES-14_SRSOR.html. Scientists at the Cooperative Institute for Research in the Atmosphere collected the SRSOR data in the real time, converted it to the proper format, and sent it to the SPC in Norman, Oklahoma, where it was displayed in their National Advanced Weather Information Processing System. This supplemental real-time 1-min data feed assisted the SPC forecasters by providing more frequent scans of preconvective clouds.

As can be seen in Table 1, GOES-14 data collection continued until September 24, 2012, at 10:14 UTC when GOES-14 was needed for the operational service during a major anomaly (outage) of GOES-13. From that moment until GOES-13 was restored to service October 18, GOES-14 operated as the operational east satellite. "The root cause of the GOES-13 anomaly unusual large Filter Wheel vibration as the root cause for the sounder east/west scan motor overload. The large vibration disturbance was further transmitted onto the imager/sounder optical bench which was also affecting imager East/West scan control system." (NOAA National Environmental Satellite, Data, and Information Service (NESDIS) memo: "GOES-13 Anomaly Report—September 23, 2012 Imager and Sounder Instrument Scan Motor Overload," January 2013).
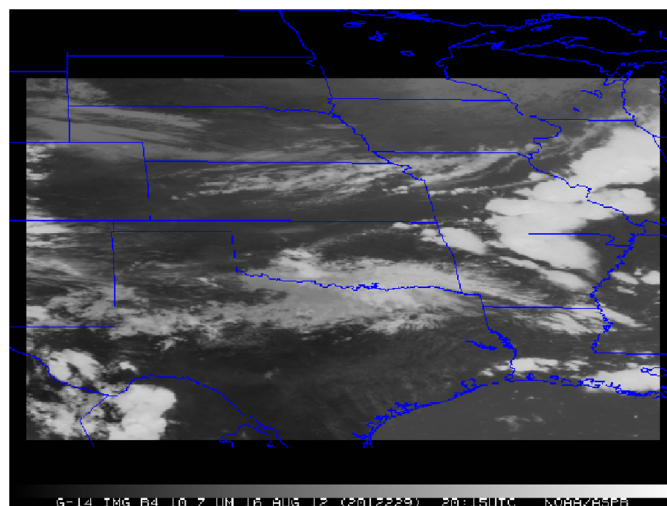

Fig. 2 GOES-14 imager sample displaying the spatial coverage during 1-min imaging. Image start time of 20:15 UTC on August 16, 2012.

Table 1 Starting day (with ordinal day number), schedules, and location with SRSOR from GOES-14 during 2012.

Starting date	Schedule	Duration	Center point	Comments
October 31 [305]	SRSOR	305/11:14:30 UTC to 305/22:44:30 UTC	41N 78W	Sandy
October 30 [304]	SRSOR	304/11:14:30 UTC to 305/11:14:30 UTC	41N 76W	Sandy
October 29 [303]	SRSOR	303/11:14:30 UTC to 304/11:14:30 UTC	38.5N 73W	Sandy (landfall)
October 28 [302]	SRSOR	302/11:14:30 UTC to 303/11:14:30 UTC	34N 73W	Sandy
October 27 [301]	SRSOR	301/11:14:30 UTC to 302/11:14:30 UTC	31N 76W	Sandy
October 26 [300]	SRSOR	300/11:14:30 UTC to 301/11:14:30 UTC	27.5N 77W	Sandy
October 25 [299]	SRSOR	299/17:44:30 UTC to 300/11:14:30 UTC	25N 76W	Sandy
...	...	...	...	No SRSOR due to GOES-13 anomalies
September 24 [268]	Default	268/01:30:30 UTC to 269/10:14:30 UTC	–	No SRSOR due to GOES-13 anomalies
September 23 [267]	SRSOR	267/10:14:30 UTC to 268/01:30:30 UTC	39W 113W	Truncated due to GOES-13 anomalies
September 22 [266]	CEFD	266/10:14:30 UTC to 267/10:14:30 UTC	—	30-min full disk
September 21 [265]	SRSOR	265/10:14:30 UTC to 266/10:14:30 UTC	39N 116W	Pacific NW
September 20 [264]	SRSOR	264/10:14:30 UTC to 265/10:14:30 UTC	37N 93W	OK and eastern US
September 19 [263]	SRSOR	263/10:44:30 UTC to 264/10:14:30 UTC	37N 93W	OK and eastern US
September 18 [262]	SRSOR	262/10:14:30 UTC to 263/10:44:30 UTC	37N 82.5W	East coast, convection.
September 17 [261]	Default	261/10:14:30 UTC to 262/10:14:30 UTC	—	—
September 16 [260]	Default	260/11:14:30 UTC to 261/10:14:30 UTC	—	—
September 15 [259]	SRSOR	259/11:14:30 UTC to 260/11:14:30 UTC	37N 82W	East Coast Frontal System.
September 14 [258]	CEFD	258/11:14:30 UTC to 259/11:14:30 UTC	—	Testing FD schedule.
September 13 [257]	SRSOR	257/10:14:30 UTC to 258/10:14:30 UTC	35N 97W	Convection over Norman.
September 12 [256]	SRSOR	256/10:14:30 UTC to 257/10:14:30 UTC	39N 99W	Fire potential over MN
September 11 [255]	SRSO	255/10:14:30 UTC to 256/10:14:30 UTC	39N 102W	SRSO testing.
September 10 [254]	SRSO	254/10:14:30 UTC to 255/10:14:30 UTC	38N 105W	SRSO testing (No data 09:05 to 20:05 UTC)
September 09 [253]	SRSOR	253/10:14:30 UTC to 254/10:14:30 UTC	39N 116W	Fires, convection, etc.
September 08 [252]	SRSOR	252/10:14:30 UTC to 253/10:14:30 UTC	37N 82W	Thunderstorms over East Coast
September 07 [251]	SRSOR	251/10:14:30 UTC to 252/10:14:30 UTC	27N 63W	Leslie
September 06 [250]	SRSOR	250/14:14:30 UTC to 251/04:14:30 UTC	32N 91W	Slight risk over OK and '90L' in Gulf
September 05 [249]	RSO	249/04:14:30 UTC to 250/14:14:30 UTC	—	Standard RSO testing

Table 1 (*Continued*).

Starting date	Schedule	Duration	Center point	Comments
September 04 [248]	SRSOR	248/14:14:30 UTC to 249/04:14:30 UTC	37N 85W	Convection over WI, AL, etc.
September 03 [247]	SRSOR	247/19:44:30 UTC to 248/04:14:30 UTC	37N 85W	Afternoon convection
September 02 [246]	SRSOR	246/19:44:30 UTC to 247/04:14:30 UTC	37N 85W	Afternoon convection
September 01 [245]	SRSOR	245/11:44:30 UTC to 246/02:44:30 UTC	40N 107W	Fire weather, convection, smoke
August 31 [244]	SRSOR	244/09:44:30 UTC to 245/04:14:30 UTC	35N 88W	Isaac
August 30 [243]	SRSOR	243/09:14:30 UTC to 244/04:44:30 UTC	32N 92W	Isaac
August 29 [242]	SRSOR	242/09:14:30 UTC to 243/04:44:30 UTC	30N 90W	Isaac
August 28 [241]	SRSOR	241/09:44:30 UTC to 242/04:44:30 UTC	29N 89W	Isaac
August 27 [240]	SRSOR	240/09:44:30 UTC to 241/04:44:30 UTC	27N 85W	Isaac
August 26 [239]	SRSOR	239/09:44:30 UTC to 240/04:44:30 UTC	25N 81W	Isaac
August 25 [238]	SRSOR	238/09:44:30 UTC to 239/04:44:30 UTC	22N 77W	Noisy (due to thunderstorms near Wallops)
August 24 [237]	SRSOR	237/09:44:30 UTC to 238/04:44:30 UTC	19N 72W	Isaac
August 23 [236]	SRSOR	236/09:14:30 UTC to 236/15:11:30 UTC	18N 68W	Isaac and east-west Maneuver
August 22 [235]	SRSOR	235/09:44:30 UTC to 236/04:44:30 UTC	39N 116W	Pacific NW, fires, smoke etc.
August 21 [234]	SRSOR	234/21:44:30 UTC to 235/04:44:30 UTC	37N 115W	Maneuver: no data before ∼21:45 UTC
August 20 [233]	SRSOR	233/09:14:30 UTC to 234/02:44:30 UTC	39N 107W	Convection over CO, etc.
August 19 [232]	Default	—	—	—
August 18 [231]	SRSOR	231/09:14:30 UTC to 232/04:44:30 UTC	23N 97W	Tropical (Helene)
August 17 [230]	SRSOR	230/09:14:30 UTC to 231/02:44:30 UTC	35N 85W	Convection over AL, etc.
August 16 [229]	SRSOR	229/11:14:30 UTC to 230/01:44:30 UTC	35:13N 97:27W	Norman, OK w phased-array radar

After GOES-13 returned to operations, the 1-min imaging from GOES-14 was not resumed. As Hurricane Sandy neared Jamaica, track forecasts increasingly suggested an impact with the United States East Coast was imminent. At the suggestion of researchers at CIMSS and NOAA NESDIS in Madison, Wisconsin, a request was sent to satellite operations warning of an "epic storm along the east coast" the following week. At this time, GOES-14 was slated to be placed back in storage mode within a few hours, when the request for special 1-min data from the GOES-14 imager of Hurricane Sandy through landfall was approved. NOAA NESDIS OSPO restarted the 1-min special SRSOR scans within 24 h. During the SRSOR time frame in 2012, GOES-14 collected approximately 30,000 images (or over 500 GB).

2 Animations of GOES-14 SRSOR

The SRSOR animations give the best representation to date of what the routine mesoscale imaging from the ABI will be like. NOAA had never before operated a GOES in continuous 1-min

mode, from a consistent orbit for so long a period, making this an unique dataset. Animations of visible and infrared (IR) imagery at 1-min intervals provide a unique perspective of atmospheric and other environmental phenomena. A viewer can witness the dynamic nature of the atmosphere as seen from space and watch as features develop and eventually dissipate or move out of the scene. The high-temporal resolution of these stunning images provides scientifically valuable information that researchers are currently studying.

2.1 Convection

The effect of "varying temporal sampling" was investigated in relation to several severe storms, showing the importance of rapid scanning, given that "storms evolve significantly on time scales shorter than the current GOES operational scan strategies."[10] Many applications regarding severe weather will benefit from more rapid imaging.[11]

The GOES-14 imager captured convection developing extremely rapidly over Missouri and Arkansas on August 16, 2012, the first day of the SRSOR experiment (Fig. 3). A time sequence of 90 min of 10.7-μm IR window channel imagery demonstrates the rapid convective development of the storm in Arkansas circled in Fig. 3 and magnified in Fig. 4. Note the cold cloud top pixels associated with over shooting cloud tops. The corresponding high-temporal (1 min) resolution animation shows rapidly developing convection over the region (Video 1). According to the NOAA Storm Reports, the storm in Fig. 3 had a severe wind report with it at 18:27 UTC ("A tree was blown down onto Highway 10"). The NOAA Storm Reports for this day from the SPC can be found at http://www.spc.noaa.gov/climo/reports/120816_rpts.html.

The cloud top rapid cooling for the storm circled in Fig. 3 as seen in the 1-min data is not well represented when the data are subsampled in time to represent operational RSO (blue line) or normal operations (red line) (Fig. 5). The cloud-top emissivity (ordinate) represents the cloud compared to an optically thick cloud at the tropopause, where the emissivity "ε_{tot} is a measure of how close the cloud radiative center is to the tropopause."[10] This higher time resolution is
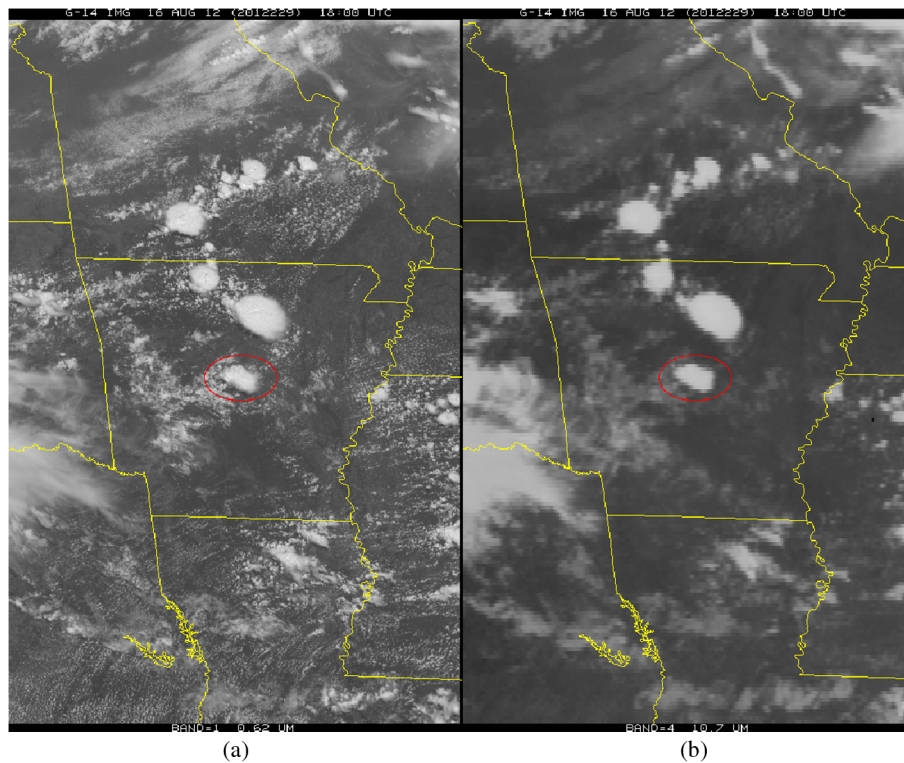

Fig. 3 GOES-14 imager of one storm (near the center of the state of Arkansas, USA) for two of the spectral bands: visible band (a) and IR window (b). The image start time is 18:00 UTC on August 16, 2012.
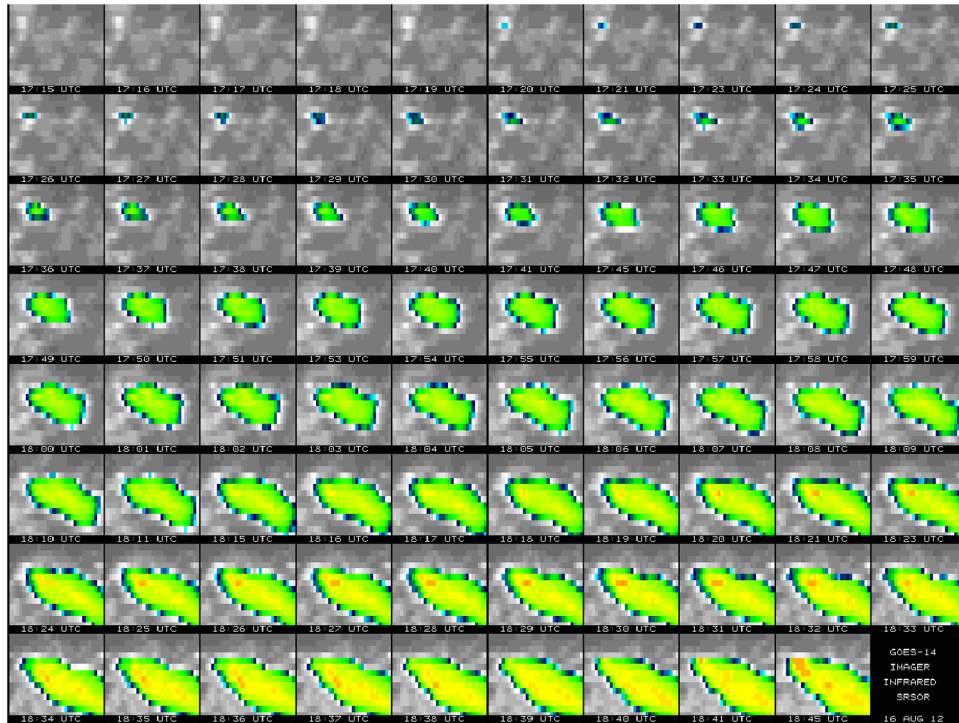
Fig. 4 GOES-14 imager of one storm over a 90-min time window. The image series start time is 17:15 UTC on August 16, 2012, while the end time is 18:45 UTC. The IR window (band 4) is shown for each frame, with the coldest brightness temperatures (BTs) color-enhanced.

especially important when monitoring rapidly developing storms. The time change in ε_{tot} can be interpreted as a cloud-top cooling rate.

On September 08, 2012, there was an EF0 tornado reported in the Queens borough of New York City at approximately 15 UTC: http://www.spc.noaa.gov/climo/reports/120908_rpts.html. GOES-13 (operational GOES-East at the time) also viewed this cell. Unfortunately, the touch-
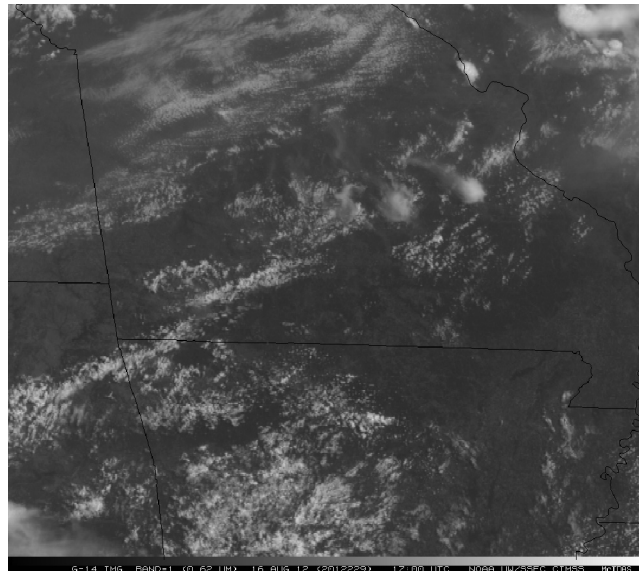
Video 1 GOES-14 imager visible band image animation of rapidly developing convection over the state of Arkansas, USA, on August 16, 2012 (QuickTime, 6 MB) [URL: http://dx.doi.org/10.1117/1.JRS.7.073462.1] (Also available at http://remotesensing.spiedigitallibrary.org/data/Journals/APPRES/926148/JARS_7_1_073462_ds001.mov).
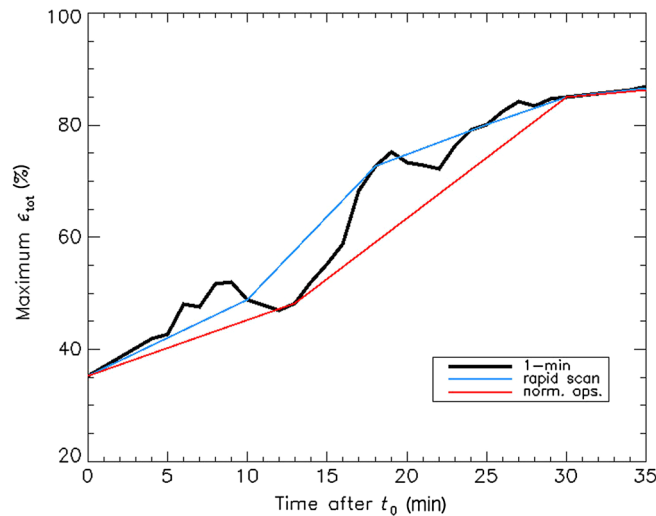
Fig. 5 Time series of maximum 10.7 μm cloud-top emissivity (ordinate) as seen from the GOES-14 imager of the one storm circled in Fig. 3 from August 16, 2012, as a function of time after t_0 (17:15 UTC). Note that the rapid cooling associated with the pulsating updrafts depicted with the data each minute.

down occurred when GOES-13 was performing a routinely scheduled full-disk image and only collected imagery at 14:45 UTC, 15:15 UTC, and 15:45 UTC (housekeeping on GOES-13 was performed for 10 min starting at 15:34 UTC). Nevertheless, the animation of the visible and IR imagery shows the development of the tornadic cell along the convergence line. The 30-min gap between images, however, makes computation of convective predictors complementary to radar such as cloud-top cooling ineffective. GOES-14 was in SRSOR on September 8, and its (almost) every minute imagery captured the evolution of the tornadic cell very well. The 1-min imagery allows careful scrutiny of the cloud-top temperature as the cells evolve. The loop, from 14:45

(a)   (b)
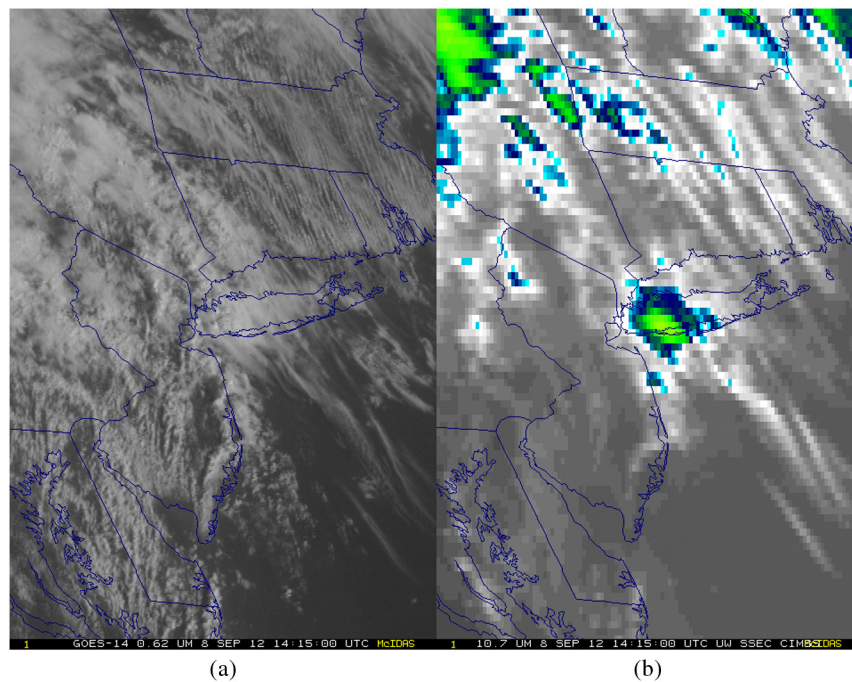
Video 2 GOES-14 imager visible (a) and IR window (b) bands animation of convection over the state of New York, USA, on September 08, 2012 (QuickTime, 4 MB) [URL: http://dx.doi.org/10.1117/1.JRS.7.073462.2] (Also available at http://remotesensing.spiedigitallibrary.org/data/Journals/APPRES/926148/JARS_7_1_073462_ds002.mov).

(a)   (b)
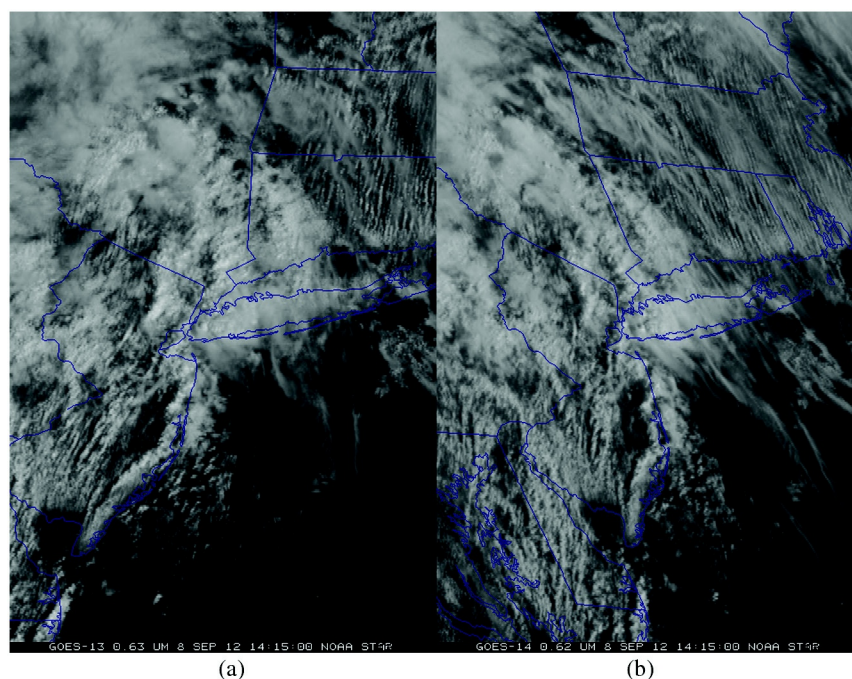
Video 3 GOES-13 (a) and GOES-14 (b) imager visible band image animation of convection over the state of New York, USA, on September 08, 2012 (QuickTime, 6 MB) [URL: http://dx.doi.org/10 .1117/1.JRS.7.073462.3] (Also available at http://remotesensing.spiedigitallibrary.org/data/ Journals/APPRES/926148/JARS_7_1_073462_ds003.mov).

UTC to 15:09 UTC, spans the time of tornadic activity, and the initial cloud-top cooling and subsequent anvil spreading is readily apparent (Video 2). Note that the GOES-13 is animated with the normal time between images (15 or 30 min), while the GOES-14 is in SRSOR (Video 3).

Total lightning flash detections from northern Alabama Lightning Mapping Array (NA-LMA) and Earth Networks Total Lightning Network (ENTLN) were monitored at 1-min intervals within 15 km of the center of an overshooting cloud-top producing storm cell south of Huntsville, Alabama, on September 2, 2012 (Fig. 6). OTs were detected by the GOES-R algorithm for 30 consecutive GOES scans, though an OT was evident in visible imagery prior to 23:33 UTC. Radar vertically integrated liquid (VIL) and enhanced echo top height were analyzed from the Huntsville and Birmingham, Alabama, Weather Surveillance Radar 1988, Doppler. The ENTLN network did not transmit valid data for 3 min from 00:00 to 00:03 UTC (i.e., 24:00 to 24:03 on the ordinate) on the 3rd. Lightning activity began to increase in association with (1) IR cloud-top cooling and ascending cloud top height and (2) an increase in radar echo top height and VIL. The NA-LMA and ENLTN lightning time trends follow each other quite well. Lightning maximized near the time of a severe wind report at 23:56 UTC. The minimum IR brightness temperature (BT) preceded the maximum flash rate by approximately 7 min, though a secondary maximum in echo top and IR BT occurred at the time of severe wind. Although detection of continuous OTs for an extended period did not clearly indicate a particular time of significant weather, the combined presence of continuous OTs, high/increasing VIL, and high/increasing flash rate may be indicative of impending high impact weather and may improve the forecaster's situational awareness.

2.2 Fires/Biomass Burning

The geostationary perspective allows one to monitor the diurnal signatures of a number of phenomena, including wildfires. The SRSOR is a great improvement over the operational RSO (Ref. 12). The "start" of a fire is observed in both the visible loop (Video 4) and shortwave IR window loop (Video 5). Both spectral bands also show the smoke plumes from the fires. It should be noted that the BT of some fires is fairly constant over time, while other fires
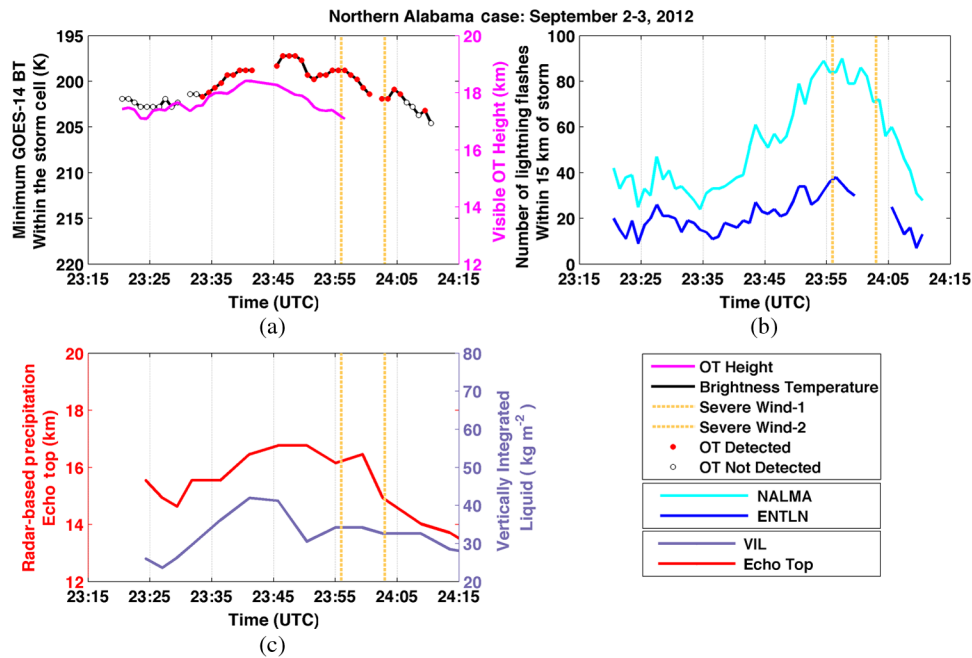
Fig. 6 An analysis of the co-evolution of GOES-14 SRSOR, WSR-88D, and total lightning observations for an individual storm cell over northern Alabama on September 2–3, 2012. (a) GOES-14 SRSOR minimum IR BT within the storm cell, GOES-R overshooting cloud top (OT) detection algorithm output, and cloud-top height derived from the length of shadow produced by OT penetration above the surrounding anvil combined with the 16.1 km equilibrium level from the Birmingham, Alabama, sounding at 00 UTC on 3 September. (b) Total lightning flash detections from the NA-LMA and ENTLN within 15 km of the storm cell center. (c) The maximum WSR-88D derived vertically integrated liquid and precipitation echo top height within the storm cell.
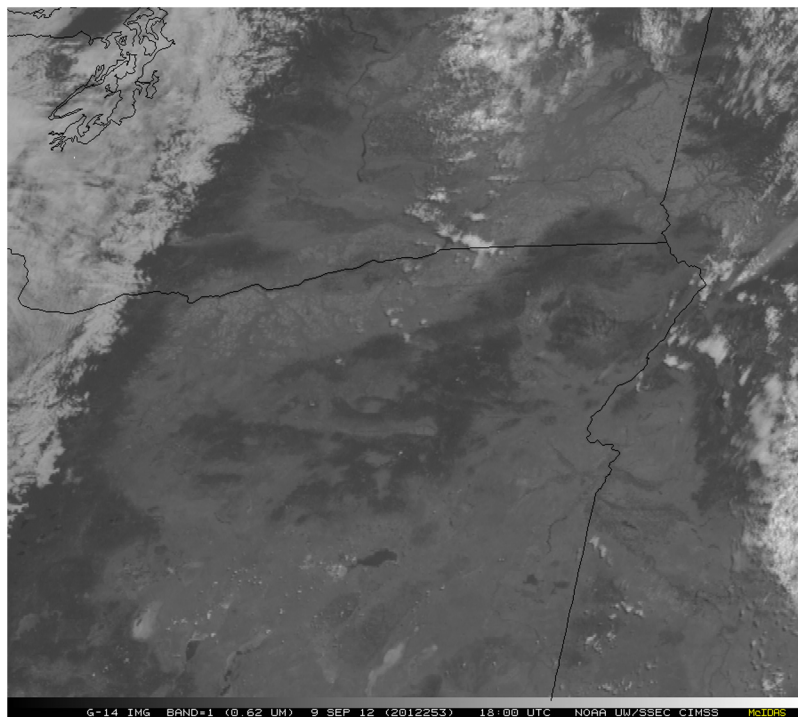
Video 4 GOES-14 imager visible band image animation of smoke over the states of Oregon, Washington, and Idaho, USA, on September 9, 2012 (QuickTime, 8 MB) [URL: http://dx.doi .org/10.1117/1.JRS.7.073462.4] (Also available at http://remotesensing.spiedigitallibrary.org/ data/Journals/APPRES/926148/JARS_7_1_073462_ds004.mov).
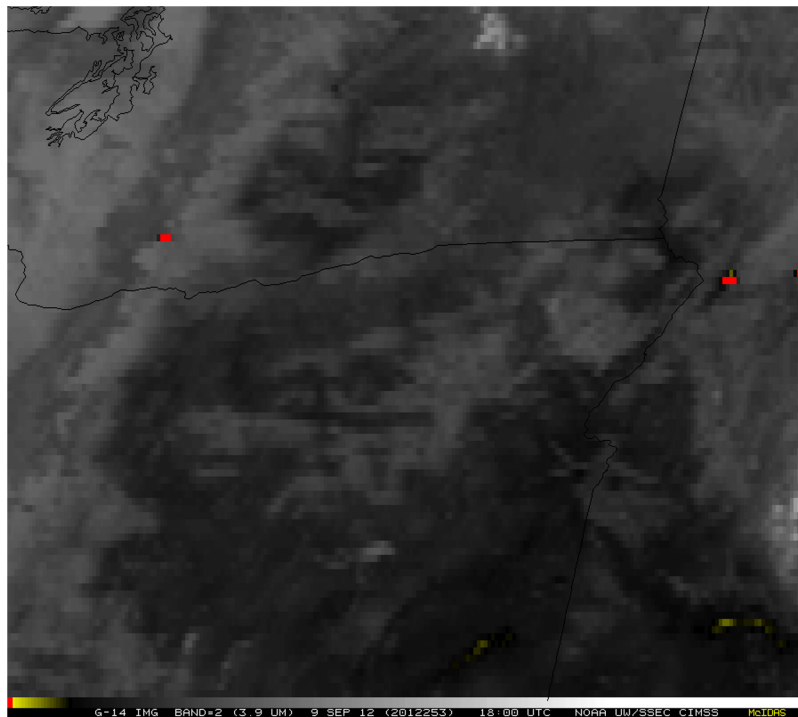
Video 5 GOES-14 imager near-infrared band 2 (3.9 μm) image animation of fires and smoke over the states of Oregon, Washington, and Idaho, USA, on September 9, 2012. The hottest pixels are color-enhanced (QuickTime, 3 MB) [URL: http://dx.doi.org/10.1117/1.JRS.7.073462 .5] (Also available at http://remotesensing.spiedigitallibrary.org/data/Journals/APPRES/926148/ JARS_7_1_073462_ds005.mov).

have widely varying BTs. Of course rapid scan images of fires can help monitor these changes and understand how they are associated with changes of wind speed/direction, moisture, fuel loads, etc. This may have implications in air quality models, to make sure the fire properties that are being assimilated are not aliased. How the same fire can rapidly change is demonstrated with GOES-12 RSO from 15:15 UTC May 9, 2007, to 04:15 UTC May 11, 2007. This is from the Bugaboo-Scrub fire in Georgia, USA. As can be seen in Fig. 7, the BT of the 3.9-μm band varies tens of Kelvin over just minutes. The 10.7-μm band does not show these rapid changes. The 3.9-μm band saturates at approximately 342 K for this imager, yet the similar band on the ABI at will be increased to 400 K. So, the ABI will improve not just the dynamic range, but also the spatio-temporal attributes.

2.3 *Hurricanes*

GOES-14 SRSOR imagery of four tropical cyclones were acquired in 2012: Helene, Isaac, Leslie, and Sandy. Due to the many days of SRSOR data and the catastrophic impact of Hurricane Sandy on the most populous areas of the east coast of the United States, this case is of the most interest. The multiday 1-min interval scans were collected during Hurricane Sandy, from October 25, 2012, at 17:45 UTC to October 31, 2012, at 22:41 UTC, roughly centered on the storm. Each afternoon the expected coordinates of the storm for the following day were communicated by NOAA NESDIS scientists to the satellite operators for subsequent data collection (Fig. 8).

The SRSOR scans from the GOES-14 imager were the most rapid scan images of a hurricane ever recorded (Video 6). Over 7000 images of Hurricane Sandy were acquired from GOES-14. The loops were shown on the Weather Channel, CNN, NBC, Reuters, and other media outlets, in addition to being used experimentally by NOAA [including OPC, Weather Prediction Center (WPC), NHC, NWS Eastern Region, and NWS Southern Region]. Some of the loops were also posted on YouTube and collectively received over 1 million views. A high-definition
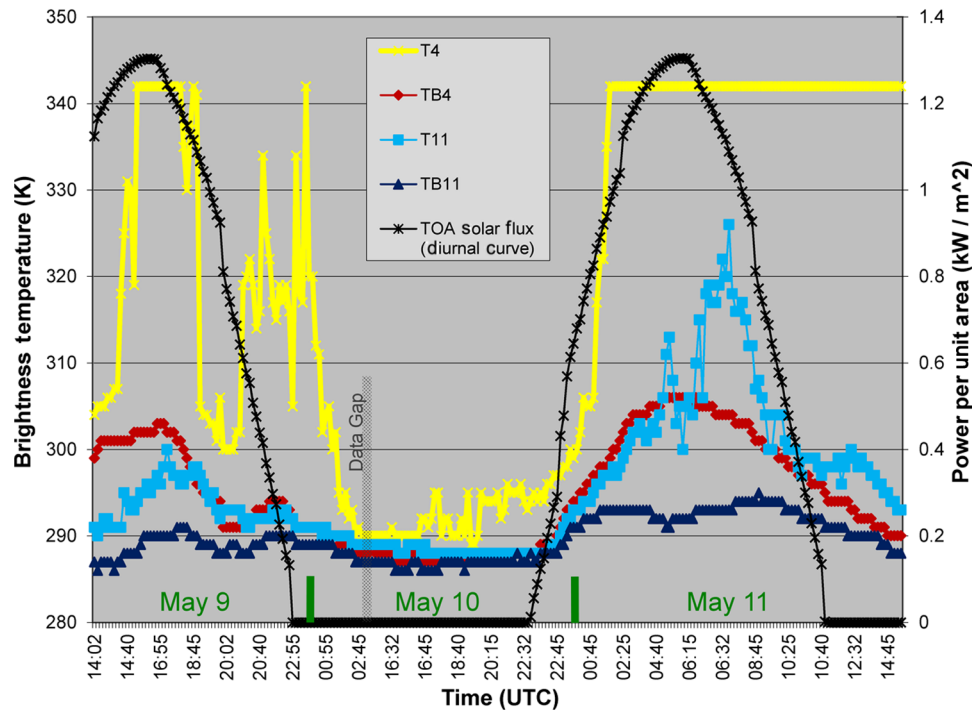
Fig. 7 Time series of the Bugaboo-Scrub fire in Georgia, USA, from 15:15 UTC May 9, 2007, to 04:15 UTC May 11, 2007. The IR window BT values are plotted, where T is the value of the hot spot, TB is the background value and 4 and 11 refer to the 3.9- and 10.7-μm bands, respectively. TOA is the top of the atmosphere solar flux.

YouTube animation of the visible band during daylight hours was posted: http://youtu.be/f2tPHiMAB5U?hd=1 and http://youtu.be/p72XhZT6KdA?hd=1 (the second link is set to play the loop back in 1 min).

The coverage location varies each day following the storm. The animation of the visible band (Video 6) only shows the sunlit hours. On several of the days, the hurricane animations depict wind shear of approximately 180 deg. A more detailed analysis of Hurricane Sandy can be found in Folmer et al.[13]

These nonoperational GOES-14 data of Hurricane Sandy were not acquired by the Comprehensive Large Array-data Stewardship System (CLASS) in real time. So that these unique datasets might be more widely available, the Space Science and Engineering Center (SSEC) Data Center transferred the GOES Variable (GVAR) data to the CLASS. The total amount of Hurricane Sandy data transferred was on the order of 98 GB. These data, along with other SRSOR data from both 2012 and 2013, can be accessed at CLASS or the SSEC Data Center or other sites.
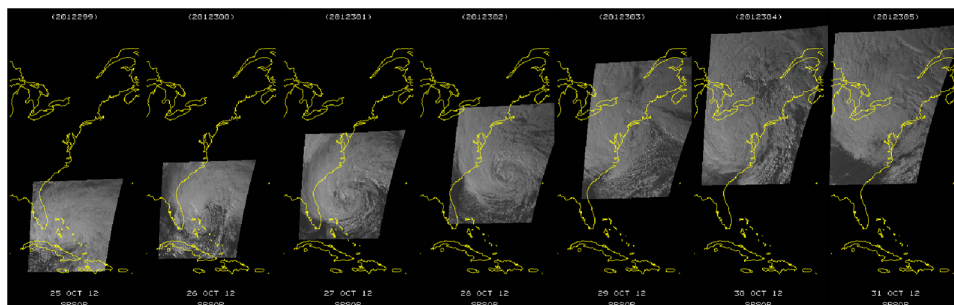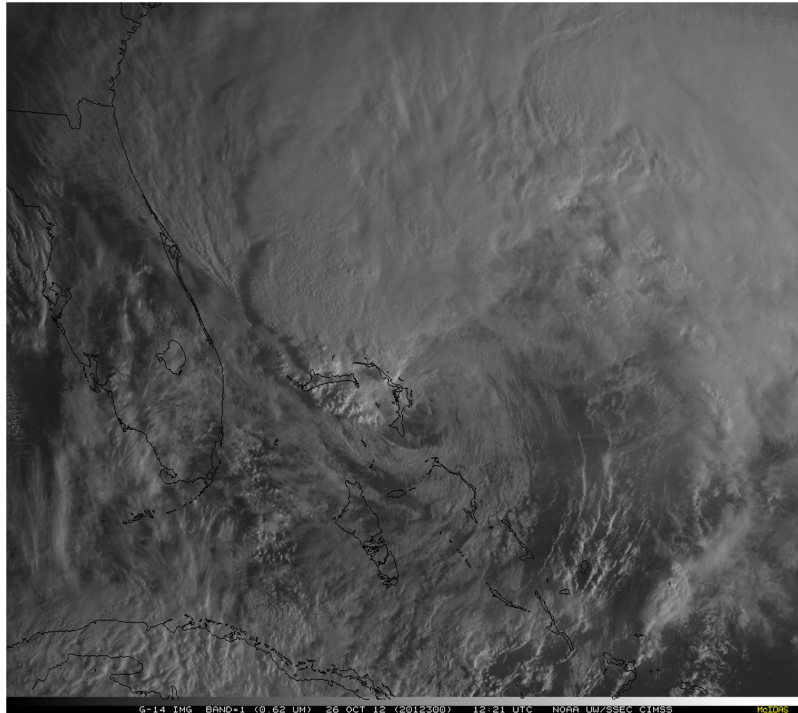

Fig. 8 GOES-14 imager coverage each day of Sandy during the experimental SRSOR. The images have been remapped onto a Mercator projection.

Video 6 GOES-14 imager visible band image animation of Hurricane Sandy from 25 October to 31 October 2012 (QuickTime, 43 MB) [URL: http://dx.doi.org/10.1117/1.JRS.7.073462.6] (Also available at http://remotesensing.spiedigitallibrary.org/data/Journals/APPRES/926148/JARS_7_1_073462_ds006.mov).
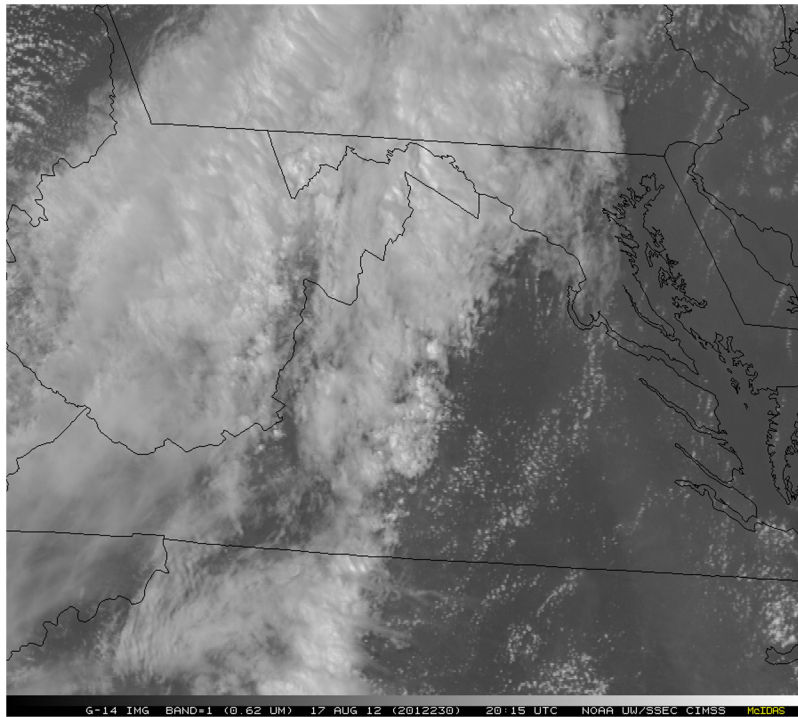
2.4 *Smoke/Cloud Interactions*

While super rapid scan information is most needed to monitor convection that can provide earlier warning for severe weather, it is also useful for monitoring the complex interaction between many other phenomena, such as smoke, clouds, and precipitation. One example shows smoke that appears to suppress the growth of a cumulus cloud field because it reduces the solar insolation necessary to force the convection (Video 7). Smoke is also hypothesized to affect the microphysical processes within clouds, leading to a decrease in precipitation efficiency.[14]

The example in Video 7 highlights how unique 1-min imagery provides visual evidence of what is happening physically in the atmosphere and allows scientists to visualize fine-scale motions. With 15-min imagery, it is difficult to visualize how the smoke interacts with the cumulus cloud field, but in Video 7 the interaction becomes more obvious and provides scientists with a unique perspective.

3 GOES-R ABI

A goal during the GOES-R ABI era will be to effectively harness the information from the rapid scan imagery, without requiring forecasters and others to necessarily look at each image/loop. Stated another way, the information from the rapid scan imagery must be extracted, not just the data provided. This can be accomplished via smart decision aids such as those being demonstrated in the GOES-R Proving Ground.[4] For example, the rate of a rapidly cooling cloud top can be used to infer the convections' subsequent intensity.[15] The improved satellite information from the ABI will lead to improvements for many derived products. One such example is the greatly improved atmospheric motion vectors (AMVs) that higher time resolutions allow.[16] Low-level (700 to 950 hPa) vectors have been derived from time sequences of visible band data using the current GOES algorithm (Fig. 9). The AMVs are derived from visible imagery, the delta times (between the first and middle images) are 7.5 and 1 min, respectively. So, the images span 15 and 2 min, respectively. The circulation of the hurricane is better defined with the GOES-R higher

Video 7 GOES-14 imager visible band image animation of smoke/cloud interactions from August 17, 2012 (QuickTime, 3 MB) [URL: http://dx.doi.org/10.1117/1.JRS.7.073462.7] (Also available at http://remotesensing.spiedigitallibrary.org/data/Journals/APPRES/926148/JARS_7_1_073462_ds007.mov).

time resolutions. There are more than an order of magnitude more AMVs for this case/region. Another example will be better monitoring of OTs associated with tropical cyclones.[17] This recent work with rapid scan imagery builds on that of earlier work with GOES-9.[18]

The GOES-R will also have a GLM to monitor total lightning activity.[6] Signatures in the cloud top observed and objectively detected in GOES-R ABI visible and IR imagery will be combined with GLM total lightning observations to better understand dynamical processes occurring within convective storms and improve severe weather forecast lead time. The
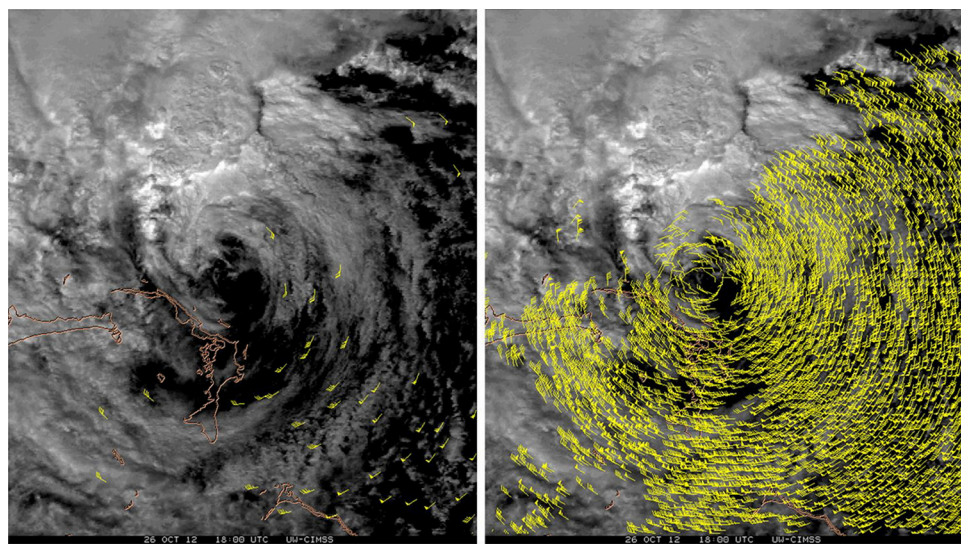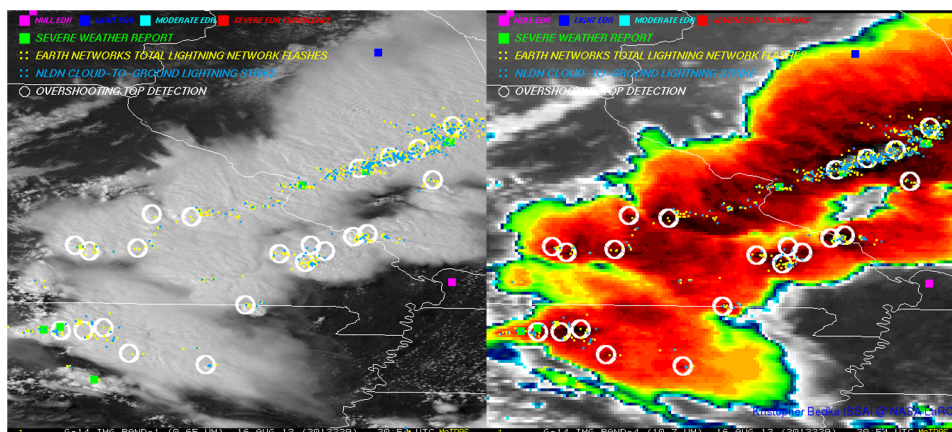

Fig. 9 AMVs from three images 7.5 min apart (GOES sampling) are shown on the left panel, while AMVs from three images that are 1 min apart (mesoscale GOES-R-like sampling) are on the right panel. The images are from Hurricane Sandy, nominally at 18 UTC on October 26, 2012.

Video 8 GOES-14 imager visible and infrared window animation with objective *in situ* Eddy dissipation rate turbulence observations, severe weather reports, in-cloud (Earth Networks Total Lightning Network) and cloud-to-ground (National Lightning Detection Network) lightning flashes, and overshooting cloud top detections over the Central US from August 16–17, 2012 (QuickTime, 20 MB) [URL: http://dx.doi.org/10.1117/1.JRS.7.073462.8] (Also available at http://remotesensing.spiedigitallibrary.org/data/Journals/APPRES/926148/JARS_7_1_073462_ds008.mov).

GLM will map total lightning activity continuously day and night with near-uniform storm-scale spatial resolution of 8 km with a latency of <20 s from flash detection to distribution to user. The GLM will monitor most of the Americas and adjacent oceanic regions in the western hemisphere. As can be seen in Video 8, objectively detected overshooting cloud tops are often found within clusters of in-cloud and cloud-to-ground lightning flashes and occur in advance of severe weather reports.[19] Aviation turbulence observations at high-temporal resolution overlaid upon the SRSOR imagery illustrate that numerous light and moderate intensity events occur as aircraft fly within the outflow of, and gravity waves are generated by, deep convection.

More information about the GOES-R series and the various derived products can be found at http://www.goes-r.gov.

4 Summary

The acquisition of experimental 1-min SRSOR data during the fall of 2012 from GOES-14 provided a unique opportunity to observe many phenomena at high time resolution, including, but not limited to, clouds, convection, fires, smoke, and hurricanes (including Hurricane Sandy). Even while the GOES-14 SRSOR data were experimental, this rapid-scan imagery was shown to have great potential in the operational arena, especially in the area of severe weather monitoring and nowcasting. The animations themselves will help the forecasters to subjectively monitor the progress and structure of convective cell growth and behavior. Many quantitative products will benefit from the rapid 1-min refresh. For example, the OTs, cloud-top cooling rate, AMVs, and turbulence products should all improve in quality and use from a regular rapid-scan schedule. Examples from the SRSOR data included better determining the cyclone center early in the daylight hours by the NHC, improved monitoring of cumulus cloud fields prior to convective initiation by the SPC, utilizing the imagery animations and derived AMVs by the OPC, identifying meso-high locations associated with hurricanes to better assess the rainfall potential by WPC, monitoring smoke plumes by the Satellite Analysis Branch, and OT detection by the forecast offices. Many other possible applications can be utilized in the GOES-R era with high time resolution data from the ABI. The SRSOR data have allowed researchers and operational forecasters to better understand the potential for routine rapid scan imagery, shown either as animated loops or derived products. Many of the rapid scan derived products in the GOES-R era should be valuable to the next generation of real-time/rapid-update-cycle mesoscale data assimilation and high-resolution modeling. These data could be assimilated in forecast models or used to validate model outputs.

The SRSOR digital datasets, in a number of formats, are available in their entirety from several organizations, for example, at CLASS: http://www.class.noaa.gov or the SSEC Data Center (http://www.ssec.wisc.edu/datacenter). These unique data will be used for years to better prepare the United States and others for the improved time resolution of the ABI on GOES-R.

Acknowledgments

References

1. T. J. Schmit et al., "Many uses of the Geostationary Operational Environmental Satellite-10 sounder and imager during a high inclination state," *J. Appl. Remote Sens.* **3**(1), 033514 (2009), http://dx.doi.org/10.1117/1.3099709.

2. D. W. Hillger and T. J. Schmit, "Imager and sounder radiance, and product validation for the GOES-15 science test," *NOAA Technical Report*, NESDIS, 141 (November), 101 (2011).

3. D. W. Hillger and T. J. Schmit, "The GOES-14 science test: imager, and sounder radiance, and product validations," *NOAA Technical Report*, NESDIS, 131, 1–119 (2010).

4. S. J. Goodman et al., "The GOES-R Proving Ground: accelerating user readiness for the next-generation geostationary environmental satellite system," *Bull. Amer. Meteor. Soc.* **93**, 1029–1040 (2012), http://dx.doi.org/10.1175/BAMS-D-11-00175.1.

5. P. L. Heinselman and M. T. Sebastián, "High-temporal-resolution capabilities of the national weather radar testbed phased-array radar," *J. Appl. Meteor. Climatol.* **50**, 579–593 (2011), http://dx.doi.org/10.1175/2010JAMC2588.1.

6. S. J. Goodman et al., "The GOES-R Geostationary Lightning Mapper (GLM)," *Atmos. Res.* **125–126**, 34–49 (2013), http://dx.doi.org/10.1016/j.atmosres.2013.01.006.

7. W. P. Menzel and J. F. W. Purdom, "Introducing GOES-I: the first of a new generation of Geostationary Operational Environmental Satellites," *Bull. Amer. Meteor. Soc.* **75**, 757–781 (1994), http://dx.doi.org/10.1175/1520-0477(1994)075<0757:IGITFO>2.0.CO;2.

8. GOES-N/O/P Data Book, http://goes.gsfc.nasa.gov/text/goes.databookn.html (2006).

9. T. J. Schmit et al., "Introducing the next-generation Advanced Baseline Imager (ABI) on GOES-R," *Bull. Amer. Meteor. Soc.*, **86**, 1079–1096 (2005), http://dx.doi.org/10.1175/BAMS-86-8-1079.

10. J. L. Cintineo et al., "Evolution of severe and non-severe convection inferred from GOES-derived cloud properties," *J. Appl. Meteor. Climatol.* **52**, 2009–2023 (2013), http://dx.doi.org/10.1175/JAMC-D-12-0330.1.

11. R. Dworak et al., "Comparison between GOES-12 overshooting-top detections, WSR-88D radar reflectivity, and severe storm reports," *Weather Forecast.* **27**(3), 684–699 (2012), http://dx.doi.org/10.1175/WAF-D-11-00070.1.

12. J. F. Weaver et al., "Fire detection using GOES rapid scan imagery," *Weather Forecast.* **19**, 496–510 (2004), http://dx.doi.org/10.1175/1520-0434(2004)019<0496:FDUGRS>2.0.CO;2.

13. M. J. Folmer et al., "Use of satellite tools to monitor, and predict "Hurricane Sandy 2012"—current and emerging products," in *Natl. Weather Assoc. Dig.*, submitted for publication (2013).

14. A. Givati and R. Daniel, "Quantifying precipitation suppression due to air pollution," *J. Appl. Meteor.* **43**, 1038–1056 (2004), http://dx.doi.org/10.1175/1520-0450(2004)043<1038:QPSDTA>2.0.CO;2.

15. D. C. Hartung et al., "An inter-comparison of UW cloud-top cooling rates with WSR-88D radar data," *Weather Forecast.* **28**, 463–480 (2013), http://dx.doi.org/10.1175/WAF-D-12-00021.1.

16. C. S. Velden et al., "Recent innovations in deriving tropospheric winds from meteorological satellites," *Bull. Amer. Meteor. Soc.* **86**, 205–223 (2005), http://dx.doi.org/10.1175/BAMS-86-2-205.

17. S. Monette et al., "Examining trends in satellite-detected overshooting tops as a potential predictor of tropical cyclone rapid intensification," *J. Appl. Meteor. Clim.* **51**, 1917–1930 (2012), http://dx.doi.org/10.1175/JAMC-D-11-0230.1.

18. A. F. Hasler et al., "High-resolution wind fields within the inner core and eye of a mature tropical cyclone from GOES 1-min images," *Bull. Amer. Meteor. Soc.* **79**, 2483–2496 (1998), http://dx.doi.org/10.1175/1520-0477(1998)079<2483:HRWFWT>2.0.CO;2.

19. K. M. Bedka et al., "Objective satellite-based overshooting top detection using infrared window channel brightness temperature gradients," *J. Appl. Meteor. Climatol.* **49**, 181–202 (2010), http://dx.doi.org/10.1175/2009JAMC2286.1.

Timothy J. Schmit received his master's degree from the University of Wisconsin—Madison in 1987. He works at the Advanced Satellite Products Branch within NOAA's NESDIS Center for Satellite Applications and Research located in Madison, Wisconsin. His experience with satellite data and processing covers a number of areas, including calibration, simulations, and algorithms for processing satellite data into meteorological/environmental information. He has extensive experience with data and deriving products from the current GOES imager and sounder data. He was involved in the on-orbit science check-out of GOES-8 to 15. His interest in satellite remote sensing includes spectral band selection, trade-off studies, simulating the imager and sounder, calibration, re-broadcast distribution, education, visualization, and product generation, validation, and applications.

Steven J. Goodman received his BS from the University of Wisconsin, his MS from the University of Oklahoma, and his PhD from the University of Alabama in Huntsville. He is the senior scientist for the GOES-R satellite program. His research interests include the global distribution and variability of thunderstorms, lightning, and precipitation physics, and the application of space-based remote sensing to improve the short-range forecasting of severe storms. As the senior program scientist for the GOES-R program, he serves as the primary science authority for the nation's next-generation geostationary environmental satellite program, a joint agency development managed by NOAA and NASA. He is also the team lead for the GOES-R Geostationary Lightning Mapper (GLM) Science Team and a coinvestigator on the NASA Tropical Rainfall Measuring Mission Lightning Imaging Sensor (TRMM/LIS) Instrument Team. Following a 20-year career with NASA and prior to joining the GOES-R Program Office, he served as the deputy

director of the NESDIS Office for Satellite Research and Applications and as the acting deputy director for the Joint Center for Satellite Data Assimilation.

Daniel T. Lindsey received a PhD from Colorado State University and has worked for NOAA since 2004. He works at the Regional and Mesoscale Meteorology Branch (RAMMB) of NOAA/NESDIS in Fort Collins, Colorado, and conducts research on the use of satellite data to improve analysis, forecasts and warnings for regional and mesoscale meteorological events.

Robert M. Rabin received his master's and bachelor's degrees from the McGill University, in Montreal, Quebec, Canada. His PhD on the study of atmospheric boundary layer using Doppler radar was granted by the University Pierre et Marie Curie in Paris, France. His expertise is very diverse, covering passive microwave, infrared, and radar measurements. Most recently, he has specialized in the development of a multisensor algorithm for estimating precipitation from radar, satellite, lightning, soundings, and gauges, as well as applications of GOES satellite and WSR-88D radar for detection and short-range forecasting local convection. He is a research meteorologist who works at the NOAA/National Severe Storms Laboratory (NSSL) in Norman, Oklahoma. He is also an honorary fellow at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison.

Kristopher M. Bedka received his BS degree in meteorology from Northern Illinois University in 2000 and his MS degree in atmospheric science from the University of Wisconsin-Madison in 2002. He was an associate researcher at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) from 2002 to 2009. He is currently a senior research scientist with Science Systems and Applications Inc., who is under contract with the NASA Langley Research Center Climate Science Branch. His current research interests include (1) the use of remotely sensed data to study deep convective clouds, with an emphasis on LEO and GEO satellite imagers and (2) development of long-term cloud property climate data records.

Mathew M. Gunshor received his BSE degree in ocean engineering from Purdue University in 1993 and his MS degree in physical oceanography from Louisiana State University in 1997. He is currently a researcher at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison, Wisconsin, where he has worked on numerous remote-sensing projects since 1997. His current research interests primarily include calibration and validation of infrared meteorological satellite data and assisting the nation in preparing for GOES-R and the Advanced Baseline Imager (ABI).

John L. Cintineo received his BS in atmospheric science from Cornell University in 2009 and his MS in meteorology from the University of Oklahoma in 2011. He has worked as a researcher at the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison since 2011. His current research interests include short-term prediction of severe convection using multisensor algorithms, and operational volcanic ash detection and characterization.

Christopher S. Velden works in Madison, Wisconsin, at the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison. He is a senior scientist and principal investigator and a chief investigator for internationally recognized UW-SSEC/CIMSS Tropical Cyclones Group and Satellite Winds Group.

A. Scott Bachmeier received a master's degree in meteorology from the South Dakota School of Mines and Technology in 1985, then provided meteorological support for Global Tropospheric Experiment field studies at NASA's Langley Research Center from 1985 to 1995, and joined the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison in 1996. He is currently involved in satellite training activities with the Virtual Institute for Satellite Integration Training (VISIT) and Satellite and Hydrology Meteorology (SHyMet) programs. He is instrumental with the CIMSS Satellite blog: http://cimss.ssec.wisc.edu/goes/blog/.

Scott S. Lindstrom received a BS in meteorology and in computer science from the Pennsylvania State University in 1982, and a master's and PhD in meteorology in 1984 and 1989, respectively, from the University of Wisconsin-Madison. He is now an information technologist at the Space Science and Engineering Center at the University of Wisconsin-Madison and also works with VISIT at the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison.

Christopher C. Schmidt received his BA from Lawrence University in Appleton, Wisconsin,, in 1997 and his MS in atmospheric and oceanic sciences from the University of Wisconsin-Madison, Wisconsin, in 2000. He is currently a researcher at the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at University of Wisconsin-Madison, where he has led the biomass burning team as well as algorithm development and implementation for fire detection and characterization and ozone detection for current and future geostationary satellites.