Use of Geostationary Super Rapid Scan Satellite Imagery by the Storm Prediction Center*

WILLIAM E. LINE

Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, and NOAA/NWS/NCEP/Storm Prediction Center, Norman, Oklahoma

TIMOTHY J. SCHMIT

NOAA/NESDIS/Center for Satellite Applications and Research/Advanced Satellite Products Branch, Madison, Wisconsin

DANIEL T. LINDSEY

NOAA/NESDIS/Center for Satellite Applications and Research/Regional and Mesoscale Meteorology Branch, Fort Collins, Colorado

STEVEN J. GOODMAN

NOAA/NESDIS/GOES-R Program Office, Greenbelt, Maryland

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ABSTRACT

The *Geostationary Operational Environmental Satellite-14* (*GOES-14*) Imager was operated by the National Oceanic and Atmospheric Administration (NOAA) in an experimental rapid scan 1-min mode during parts of 2012, 2013, 2014, and 2015. This scan mode, known as the Super Rapid Scan Operations for GOES-R (SRSOR), emulates the high-temporal-resolution sampling that will be provided by the Advanced Baseline Imager on the next-generation GOES-R series. NOAA/National Weather Service/Storm Prediction Center (SPC) forecasters utilized the 1-min imagery extensively in operations when available over convectively active regions. They found it provided them with unique insight into relevant features and processes before, during, and after convective initiation. This paper introduces how the SRSOR datasets from *GOES-14* were used by SPC forecasters and how these data are likely to be applied when available operationally from GOES-R. Several animations, included as supplemental material, showcase the rapid change of severe weather–related phenomena observed during the 2014 and 2015 SRSOR campaigns from the *GOES-14* Imager.

1. Introduction

The Geostationary Operational Environmental Satellite R series (GOES-R) represents the next generation of geostationary weather satellites that will provide coverage for the Americas and surrounding oceans. The series includes four satellites to maintain operational continuity through the mid-2030s. GOES-R will introduce significant technological advancements for the observation of Earth's atmosphere from space via two Earth-pointing instruments: the Advanced Baseline Imager (ABI) and the Geostationary Lightning Mapper (GLM). As indicated by Schmit et al. (2005), the ABI will improve upon the current GOES Imager by providing over 3 times the spectral resolution (16 spectral channels vs 5 currently), up to 4 times the horizontal spatial resolution (2 km × 2 km for infrared channels vs 4 km × 4 km currently; 0.5 km × 0.5 km for a visible channel vs 1 km × 1 km currently), and up to 5 times the temporal resolution (5-min full-disk coverage vs 25 min currently). The GLM is the first operational

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Corresponding author address: William E. Line, NOAA/NWS/NCEP/Storm Prediction Center, 120 David L. Boren Blvd., Norman, OK 73072.
E-mail: bill.line@noaa.gov

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instrument of its kind and will provide near-uniform continuous total lightning detection coverage day and night over much of the full disk below the satellite (Goodman et al. 2013). The first GOES-R satellite is scheduled to launch in late 2016.

There are two scan modes currently planned for the ABI. Mode 3, or ''flex mode,'' will provide concurrent 15-min coverage over the full disk with 5-min coverage over the continental United States (CONUS) and 30-s coverage over one mesoscale sector, or two mesoscale sectors having 1-min coverage. The mesoscale sector represents a 1000 km × 1000 km (at the satellite subpoint) relocatable domain. Mode 4, or ''continuous full-disk mode,'' simply provides a full-disk image every 5 min. It is envisioned that the flex mode will be the default scan strategy, with the two mesoscale sectors most likely viewing geographically separated areas. The two baseline ABI scan modes have been described, but additional scan modes are possible from the instrument and could be implemented in the ground system. One such scan strategy is similar to the flex mode but provides a full-disk image every 10 min instead of every 15 min.

The GOES-R Proving Ground was established, in part, to prepare end users for the new and enhanced products and capabilities that will be available in the GOES-R era through the development and demonstration of proxy datasets (Goodman et al. 2012). An important end-user stakeholder that is expected to benefit considerably from GOES-R products and capabilities derived from ABI and GLM data is the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service (NWS)/Storm Prediction Center (SPC) in Norman, Oklahoma. Responsible for monitoring severe weather activity across the entire CONUS, the SPC has long considered rapidly updating observational datasets to be a vital component to the analysis and forecast process. In particular, SPC forecasters rely heavily on geostationary satellite data during all stages of their convective analysis and forecasting and are experts in satellite-imagery interpretation. As part of the GOES-R Proving Ground effort at the SPC, experimental super rapid scan satellite imagery has been made available to forecasters in the SPC operational National Centers for Environmental Prediction (NCEP) Advanced Weather Interactive Processing System (NAWIPS) data visualization system in real time during select periods since 2012. These experiments allowed SPC forecasters the unique opportunity to gain valuable experience integrating very-high-temporal-resolution satellite data into their analysis and forecast methodology, identifying features and processes not before diagnosable in traditional satellite imagery.

This paper focuses on the use of very-high-temporal-resolution satellite data in SPC operations, starting with background on how SPC forecasters use current satellite data when making their forecasts. The paper continues with examples of how they have already been utilizing the experimental 1-min imagery in operations, and it ends with a discussion on the envisioned use of GOES-R ABI super rapid scan data in the SPC.

2. SRSOR overview

The *GOES-14* Imager was operated by NOAA in an experimental 1-min mode during parts of August, September, and October 2012; June and August 2013; May and August 2014; and May, June, and August 2015. This scan mode, known as the Super Rapid Scan Operations for GOES-R (SRSOR), demonstrates the high-temporal-resolution sampling capability of the GOES-R ABI when operating in mode 3. However, there are differences between the *GOES-14* Imager SRSOR and GOES-R ABI. Specifically, data from the *GOES-14* SRSOR do not supply the improved spatial or spectral attributes of the ABI. Also, the mode-3 mesoscale-sector scanning of the ABI will provide imagery every minute (when looking at two locations), whereas in general the SRSOR from *GOES-14* only scans 26 images every 30 min; plus, there are two 15-min outages each day. In addition, *GOES-14* SRSOR does not produce the full derived product suite in real time that the ABI will (e.g., cloud microphysics).

The SRSOR campaign of 2012 included approximately 38 days of data, including more than 6 days during Hurricane Sandy in late October (Schmit et al. 2013). The SRSOR campaign of 2013 included approximately 14 days of data (Schmit et al. 2015). Thirty days were captured in 2014, including 16 days in May, during which the imagery was demonstrated at the Hazardous Weather Test Bed (HWT) Spring Experiment in Norman (Table 1). Last, the 2015 campaign included 36 total days, with 24 days in May and June in support of the Plains Elevated Convection at Night experiment and, once again, the HWT Spring Experiment (Table 2). Examples of phenomena captured during the four years of *GOES-14* SRSOR experiments include clouds, fog, nonsevere and severe convection, southwestern U.S. monsoon moisture, wildfires and smoke, and tropical cyclones. Additionally, more detailed analyses of certain processes such as cloud updrafts and atmospheric flow are under way (e.g., Mecikalski et al. 2016; Apke et al. 2016, manuscript submitted to *J. Appl. Meteor. Climatol.*).

3. SPC mission overview and pre-GOES-R use of satellite data

The SPC mission states, ''The Storm Prediction Center maintains a high-achieving staff using innovative

TABLE 1. Starting days (with yearday in parentheses), schedules, and locations with SRSOR from *GOES-14* during parts of May and August 2014. All starting times are 1114:30 UTC except for the 27 Aug RSO sector testing, which has a starting time of 1014:30 UTC.

Starting date	Schedule	Center point
8 May (128)	SRSOR (no FD)	38°N, 95°W
9 May (129)	SRSOR (no FD)	35°N, 92°W
10 May (130)	SRSOR (no FD)	36°N, 92°W
11 May (131)	SRSOR (no FD)	37°N, 96°W
12 May (132)	SRSOR (no FD)	36°N, 92°W
13 May (133)	SRSOR (no FD)	36°N, 85°W
14 May (134)	SRSOR (no FD)	35°N, 85°W
15 May (135)	SRSOR (no FD)	36°N, 81°W
16 May (136)	SRSOR (no FD)	39°N, 104°W
17 May (137)	SRSOR (no FD)	39°N, 111°W
18 May (138)	Routine East	—
19 May (139)	SRSOR (no FD)	39°N, 101°W
20 May (140)	SRSOR (no FD)	39°N, 107°W
21 May (141)	SRSOR (no FD)	38°N, 101°W
22 May (142)	SRSOR (no FD)	38°N, 84°W
23 May (143)	SRSOR (no FD)	38°N, 83°W
24 May (144)	SRSOR (no FD)	36°N, 105°W
25 May (145)	Routine East	—
14 Aug (226)	SRSOR (no FD)	39.5°N, 114.5°W
15 Aug (227)	SRSOR (no FD)	39.5°N, 97°W
16 Aug (228)	SRSOR (no FD)	37°N, 97°W
17 Aug (229)	SRSOR (no FD)	37°N, 85°W
18 Aug (230)	SRSOR (no FD)	38°N, 83°W
19 Aug (231)	SRSOR (no FD)	18°N, 120°W
20 Aug (232)	SRSOR (no FD)	39°N, 93.5°W
21 Aug (233)	SRSOR (no FD)	33°N, 85°W
22 Aug (234)	SRSOR (no FD)	39°N, 98°W
23 Aug (235)	SRSOR (no FD)	39°N, 98°W
24 Aug (236)	SRSOR (no FD)	23°N, 75°W
25 Aug (237)	SRSOR (no FD)	20°N, 117°W
26 Aug (238)	SRSOR (no FD)	31°N, 72°W
27 Aug (239)	RSO sector testing	—

TABLE 2. As in Table 1, but for parts of May, June, and August 2015. All starting times are 1114:30 UTC except for 15 Aug, which has a starting time of 1214:30 UTC.

Starting date	Schedule	Center point
18 May (138)	SRSOR (no FD)	37°N, 85°W
19 May (139)	SRSOR (no FD)	36°N, 99°W
20 May (140)	SRSOR (no FD)	34°N, 96°W
21 May (141)	SRSOR (no FD)	32°N, 85°W
22 May (142)	SRSOR (no FD)	37°N, 105°W
23 May (143)	SRSOR (no FD)	36°N, 98°W
24 May (144)	SRSOR (no FD)	34°N, 96°W
25 May (145)	SRSOR (no FD)	37°N, 95°W
26 May (146)	SRSOR (no FD)	37°N, 85°W
27 May (147)	SRSOR (no FD)	39°N, 98°W
28 May (148)	SRSOR (no FD)	37°N, 97°W
29 May (149)	SRSOR (no FD)	39°N, 115°W
30 May (150)	Routine East	—
31 May (151)	SRSOR (no FD)	39°N, 81°W
1 Jun (152)	SRSOR (no FD)	39°N, 106°W
2 Jun (153)	SRSOR (no FD)	39°N, 102°W
3 Jun (154)	SRSOR (no FD)	39°N, 102°W
4 Jun (155)	SRSOR (no FD)	39°N, 102°W
5 Jun (156)	SRSOR (no FD)	39°N, 104°W
6 Jun (157)	SRSOR (no FD)	39°N, 96°W
7 Jun (158)	SRSOR (no FD)	39°N, 92°W
8 Jun (159)	SRSOR (no FD)	37°N, 84°W
9 Jun (160)	SRSOR (no FD)	36°N, 81°W
10 Jun (161)	SRSOR (no FD)	37°N, 94°W
11 Jun (162)	SRSOR (no FD)	37°N, 97°W
10 Aug (222)	SRSOR (no FD)	39°N, 82°W
11 Aug (223)	SRSOR (no FD)	37°N, 84°W
12 Aug (224)	SRSOR (no FD)	40°N, 116°W
13 Aug (225)	SRSOR (no FD)	34°N, 84°W
14 Aug (226)	SRSOR (no FD)	16°N, 110°W
15 Aug (227)	SRSOR (no FD)	40°N, 101°W
16 Aug (228)	SRSOR (no FD)	31°N, 87°W
17 Aug (229)	SRSOR (no FD)	39°N, 102°W
18 Aug (230)	SRSOR (no FD)	39°N, 95°W
19 Aug (231)	SRSOR (no FD)	33°N, 90°W
20 Aug (232)	SRSOR (no FD)	35°N, 84°W
21 Aug (233)	SRSOR (no FD)	15°N, 54°W
22 Aug (234)	Routine East	—

science and technology to deliver timely and accurate watch and forecast products/information dealing with tornadoes, severe thunderstorms, lightning, wildfires, and winter weather for the United States to protect lives and property.'' To complete this mission, forecasters must rely on quick-updating, low-latency observational datasets given the rapid evolution of mesoscale phenomena that lead to the development of thunderstorms and severe thunderstorms. Geostationary satellite information is one such dataset because it provides near-continuous viewing of the CONUS and has proven vital for the composition of effective SPC forecast products. Satellite imagery in particular is utilized by SPC forecasters for tracking weather systems several days before a hazardous-weather event through the initiation and eventual dissipation stages of convection. SPC forecasters enhance their understanding and utilization of the satellite imagery by viewing it in conjunction with other relevant datasets such as surface METAR and radiosonde observations, lightning observations, radar data, and numerical weather prediction (NWP) fields, among others.

The SPC is responsible for issuing convective outlooks for days 1, 2, 3, and 4–8. Imagery from the GOES 6.5-μm water vapor channel provides the outlook forecaster with valuable information related to the evolution of synoptic-scale atmospheric phenomena. Forecasters are able to monitor and track long-wave trough and ridge patterns, short-wave troughs and vorticity maxima, moisture distribution (e.g., moisture plumes and dry slots), jet streaks, and regions of convergence and divergence, all of which play an important role in convective development and evolution (Weldon and Holmes 1991). On the basis of the evolution of synoptic-scale features as observed by satellite, SPC forecasters use their scientific knowledge and extensive operational experience to aid in predicting how such features will evolve in the future, often highlighting those details in their convective-outlook products. Similarly, satellite-derived precipitable-water fields are utilized days in advance to track the recent evolution of moisture in the atmosphere. Comparisons of observed water vapor imagery and atmospheric motion vectors (AMVs) with model analysis and forecast fields provide the forecaster with an idea of how well a particular model cycle is handling the given weather scenario. Also, long temporal loops of GOES 0.63-μm visible and 10.7-μm infrared (IR) channel imagery are viewed during this period to monitor the longer-term cloud-field evolution over the past few days and to determine how certain features have influenced recent convective-storm occurrence.

Water vapor imagery continues to be utilized in a similar manner during the day-1 SPC forecast period, which has traditionally been a key focus of SPC forecasting efforts. This includes the preparation of the 0600, 1300, 1630, and 2000 UTC day-1 convective outlooks. During the day-1 period prior to afternoon convective development, forecasters are also analyzing visible and IR imagery to diagnose cloud-cover trends and to assess their impact on future diurnal heating. The forecaster determines whether persistent cloud cover will prevent destabilization from occurring or if sufficient clearing will occur to allow for convective initiation. Similarly, SPC forecasters will identify areas of differential heating that could potentially lead to the development of relevant boundaries to focus subsequent convective initiation. Prior to sunrise, forecasters must rely on IR imagery to complete these tasks. Satellite imagery also helps to discern between low- and mid/upper-level clouds. Mid/upper-level clouds can be a sign of large-scale ascent and, when combined with NWP vorticity/height and thermal-advection fields, provide a detailed representation of the synoptic and mesoscale environmental setup. Satellite-derived precipitable-water imagery and the evolution of boundary layer clouds in visible imagery allow a forecaster to assess the return of low-level moisture into regions of interest.

The careful analysis of satellite imagery, especially the visible spectrum, becomes particularly vital during the period immediately prior to convective initiation at the lead, mesoscale, and mesoscale-assistant forecast desks in the issuance of "Mesoscale Discussions" (MDs) and severe thunderstorm and tornado watches. As one SPC forecaster states, "during the day, visible satellite imagery is the workhorse." In some instances, forecasters will note wave and billow cloud formations as indicators that a stable layer is present and limiting surface-based deep convection. The erosion of these cloud features is evidence that convective inhibition is weakening, and the development of a cumulus (Cu) field is a sign that the atmosphere is destabilizing. Forecasters are constantly monitoring cloud-character trends within the Cu field for signs of vertical growth and potential convective initiation. They will often reference the "clumping," "deepening," "agitation," or "towering" of cumulus clouds (transition from cumulus humilis to cumulus mediocris to cumulus congestus) in areas of enhanced Cu development where initiation is appearing more imminent. In some situations, "orphan anvils" will appear to blow off from individual updrafts representing failed attempts at convective initiation. However, this can be a sign that the capping inversion is weakening, and successful initiation may subsequently occur. During the day, visible imagery is most often the first source of information from which a forecaster can visualize where and when convective initiation has occurred and is sustaining itself (the transition to cumulonimbus). At night, forecasters monitor brightness temperature trends in IR imagery to diagnose the initiation and vigor of the updraft, although storm-updraft processes are not resolved as well by the IR data.

Satellite imagery continues to play an important role after convective initiation as the SPC forecaster watches for signs of strengthening, maintenance, and dissipation. The appearance of storms from the satellite view can help to influence the decision of whether to issue a new watch on mature convection, or issue an MD, noting continued strengthening or weakening trends. Continued streaming of boundary layer Cu (e.g., cloud streets) into mature convection is a sign that moist low-level inflow into the storm is occurring that may enhance storm intensity and longevity. Forecasters can determine from satellite imagery on the basis of cloud motion whether convection is elevated or is rooted in the boundary layer, which may help to determine potential hazards (e.g., elevated severe storms are less likely to produce tornadoes or severe wind gusts). The apparent bubbling or texture at the storm top suggests the continued presence of a vigorous updraft, whereas the cessation of this process may reveal the early stages of storm weakening and dissipation. Overshooting tops (OTs) are indicators of particularly strong updrafts and associated areas of potentially strong to severe storms (Bedka et al. 2010, 2015; Dworak et al. 2012). Alternatively, decreasing trends in previously persistent OTs imply that the hazard may be waning. Other cloud-top features relevant to the SPC forecaster as indicators of significant weather include enhanced Vs and above-anvil cirrus plumes (McCann 1983; Levizzani and Setvák 1996). Forecasters continue to monitor satellite imagery for the organization of convection into linear systems and upscale growth into mesoscale convective systems and vortices and their movement. Especially at night, forecasters will analyze IR satellite imagery for cooling/expansion of cloud tops as evidence of continued development and strengthening, and warming as evidence for convective decay (Roberts and Rutledge 2003).

Prior to and after convective initiation, identification and tracking of boundaries in visible and IR imagery are important tasks for the SPC forecaster. Boundaries will often appear as a line of enhanced/congested Cu, a contrast in cloud character and motion, and/or a sharp temperature gradient observed in the IR imagery. Examples of boundaries for which SPC forecasters are looking include warm and cold fronts, drylines, sea breezes, prefrontal troughs, differential heating zones, and the leading edge of convective outflow. Forecasters examine satellite imagery for the interaction of these boundaries with existing Cu fields, other boundaries, and mature convection. Along a boundary, signs of convective initiation and continued development downstream of existing convection are analyzed. Similarly, the identification and tracking of gravity waves are important because these features will often influence convection. Not surprisingly, the location of boundaries can affect the issuance and wording of MDs as well as the placement of watch boxes.

4. Use of *GOES-14* SRSOR imagery in SPC operations

All of the features and processes described in the previous section are more easily diagnosed and tracked as the temporal resolution of satellite imagery is increased. During SRSOR campaigns of 2013, 2014, and 2015, the 1-min visible and IR imagery was increasingly viewed in SPC operations at the lead, mesoscale, mesoscale-assistant, and outlook forecast desks. Feedback from SPC forecasters on their use of the SRSOR imagery was collected by the authors through verbal and e-mail communications and a short voluntary survey. As forecasters gained experience in viewing the SRSOR data, it became evident that the high-temporal-frequency imagery aided them in analyzing the preconvective environment, identifying convective initiation, and monitoring mature convection. As one forecaster explained, ''the 1-min data gives a more continuous depiction of how meteorological features are evolving, versus the 'snapshot' approach of coarser temporal resolution images.''

Forecasters viewed animations to monitor the evolving atmospheric state, including display loops with anywhere from 30 to over 200 SRSOR images in NAWIPS, animated at fast rates for a fluid visualization of the atmospheric phenomena. Additionally, the latency of the imagery from time stamp to arrival in NAWIPS was typically 3–4 min versus the 5–9 min of routine imagery via direct broadcast and 10–12 min via the Satellite Broadcast Network. The decreased latency was, in part, due to the relatively small spatial size of the sector being scanned by the *GOES-14* Imager.

Forecasters have remarked that the addition of 1-min satellite imagery has aided in severe thunderstorm watch and tornado watch decisions, including starting the product issuance process sooner (lead time) and improved focusing of the watch area (less potential for a false alarm). Additionally, mesoscale forecasters stated that the 1-min imagery has provided them with more confidence and lead time in the issuance of MDs, often referencing the 1-min data in the MD text. Very little training was needed for the forecasters to routinely use SRSOR information because the higher-temporal-resolution imagery fit well within the existing workflow. Examples follow of how the 1-min satellite imagery has benefited SPC forecasters in operational decision-making.

a. *Midwest convective initiation and SPC convective watches on 18 August 2015*

SPC forecasters routinely commented that the 1-min satellite imagery has allowed them to anticipate areas of new convective development sooner and has led to faster recognition that convective initiation has taken place. The 1-min imagery allows for easier/more accurate tracking of individual cloud elements as they evolve, especially when partially obscured by upper-level cloud cover. This includes observations of the initial development of a Cu field, clumping of Cu, areas of a Cu field becoming agitated or deepening, individual Cu growing into towering Cu, failed convective-initiation attempts, and successful convective initiation. The improved evaluation of cloud character and trends in the 1-min imagery has also led to higher confidence in the diagnosis of boundaries (especially convective outflow) and gravity waves, including their location and motion, the potential for convective initiation along them, and their influence on upshear storms. Such evolution becomes less evident with longer time between scans, making it difficult to interpret important trend information and forcing forecasters to make inferences as to what has occurred.

The 1-min satellite imagery from *GOES-14* proved to be especially valuable to SPC forecasters during the early stages of an 18 August 2015 severe weather event as *GOES-15* (GOES-West) underwent a scheduled maneuver, causing a data outage between 1630 and 1759 UTC. More significant to the SPC was that *GOES-13*

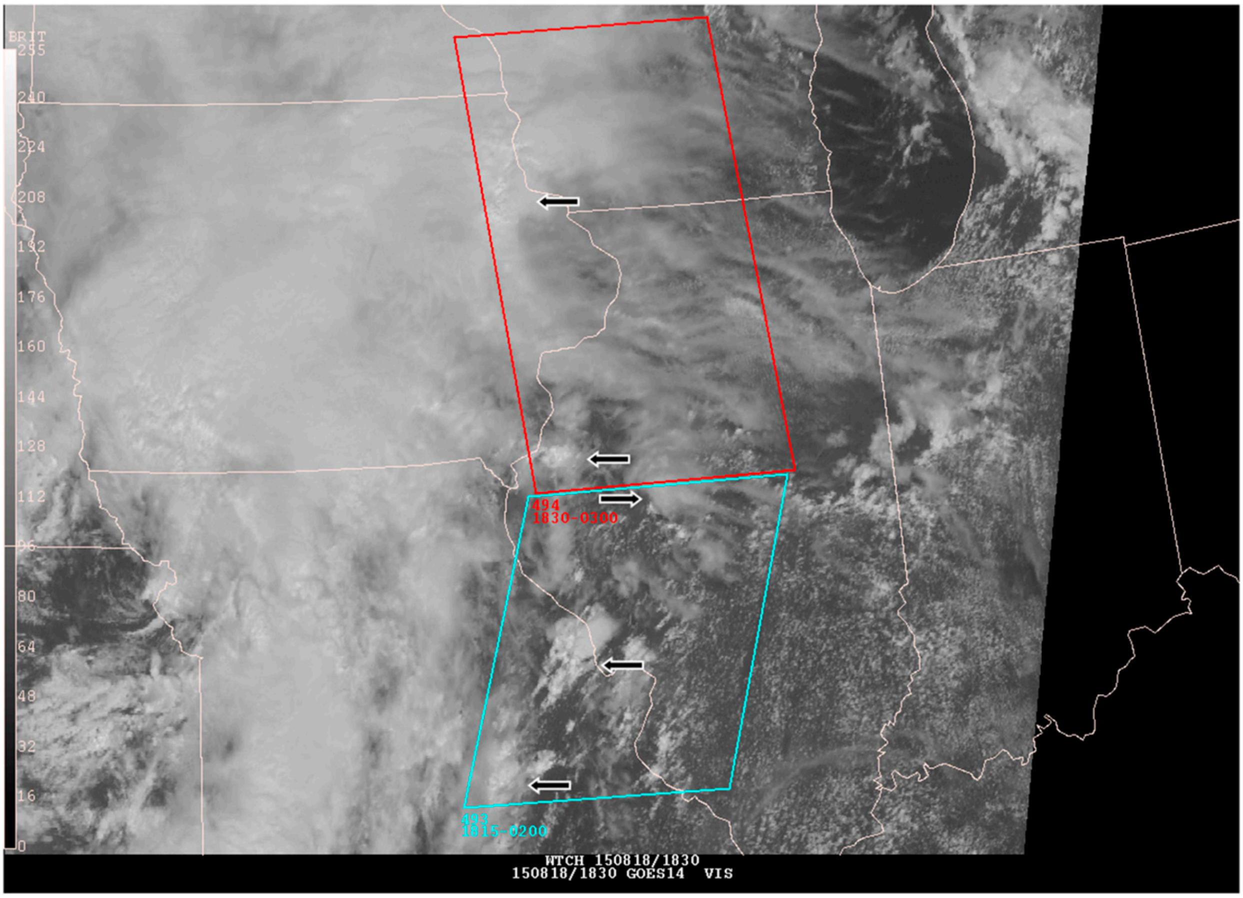

FIG. 1. The 1830 UTC 18 Aug 2015 *GOES-14* visible-channel image and SPC tornado (red) and severe thunderstorm (blue) watch polygons with time of issuance and expiration. Arrows point to features described in the text. Note the developing convection throughout the severe thunderstorm watch area and in the southwestern part of the tornado watch and the mature convection within the tornado watch along the Iowa–Wisconsin border (an animation is available in the online supplemental material: video 1).

(GOES-East), to cover for the GOES-West outage, operated in full-disk mode, collecting images only every 30 min (instead of the typical 15 min) from 1615 to 1815 UTC. During this period of 30-min imagery, convection developed and intensified in a corridor of prefrontal destabilization ahead of a midlevel short-wave trough advancing through the central United States where the SPC day-1 convective outlook included a slight-risk area.

Analyzing the 1-min visible imagery, the lead forecaster noted that Cu developing under a broken upper-level cloud deck in east-central Missouri were clearly becoming enhanced by 1715 UTC as a gravity-wave feature traversed the area. Over the next hour, the deepening Cu quickly evolved into towering Cu before sustained initiation was obvious by 1800 UTC in far east-central Missouri. In animations of the 1-min imagery, the forecaster was able to recognize soon after initiation that updrafts were being sustained. A severe thunderstorm watch (No. 493) centered over the area of first initiation was issued at 1815 UTC.

At the same time, the forecaster analyzed additional convective initiation to the north along the southeastern Iowa–Illinois border under a more opaque region of high clouds. Convection could be seen extending through the cloud deck by 1820 UTC. Farther north in northeastern Iowa, the forecaster had been tracking several areas of convection over the previous couple of hours. The 1-min imagery allowed for the diagnosis of continued bubbling and texture through the opaque/smooth cloud shield as storms advanced into an environment more favorable for severe weather, including tornadoes. The forecaster issued a tornado watch (No. 494) at 1830 UTC to cover this convection along with the newer development to the south (Fig. 1).[1]

[1] All satellite images included in this paper use color tables that are operationally available in the SPC NAWIPS system. Although these images may contain less detail than do those available from other sources, they accurately represent the imagery that is viewed by SPC forecasters.

The features and processes mentioned are best visualized in the animation (video 1) of *GOES-14* SRSOR visible imagery that is available in the online supplement for this article.

The quick-updating, seamless animations of 1-min imagery provided the forecaster with enhanced lead time and confidence for areas of ongoing and subsequent convective initiation. This type of continuous real-time analysis was not possible when viewing only the 30-min imagery available from GOES-East. Storms in both SPC watches would continue to strengthen, eventually producing severe wind, hail, and a few tornadoes.[2]

b. Nebraska convective initiation and SPC day-1 convective-outlook update on 11 May 2014

The 1-min visible satellite imagery also influenced forecaster decision-making on 11 May 2014 in a moderate-risk area in southeastern Nebraska prior to a localized tornado outbreak. SPC forecasters were monitoring the 1-min visible imagery for signs of convective initiation near the Nebraska–Kansas border while the 2000 UTC day-1 convective-outlook update was being prepared. A west–east-oriented warm front that was draped across southeastern Nebraska and an associated north–south-oriented cold front through central Kansas were made apparent in the visible imagery by distinct breaks in cloud character. Wave-cloud formations in place north of the warm front indicated a stable atmosphere while cloud streets south of the warm front and east of the cold front implied destabilization within the warm sector.

By 1855 UTC, an orphan anvil was generated within an area of towering Cu near the intersection of the two boundaries and could clearly be seen blowing off from an updraft (Fig. 2). The quick progression of the orphan anvil is evident in the animation (video 2) of *GOES-14* SRSOR visible imagery that is available in the online supplement for this article. This progression represented a failed convective-initiation attempt but also indicated that an updraft had managed to temporarily break through the capping stable layer. Given the short time scale, the feature was not as easily observed in the operational GOES-East satellite rapid scan imagery. Shortly thereafter, by 1925 UTC, successful convective initiation was apparent in the region of the towering Cu and orphan-anvil origin. The character of the Cu field and appearance of the orphan anvil provided forecasters with noteworthy lead time that storm initiation was imminent in that location. This was important because forecasters knew that, once convection started, storms would strengthen rapidly in the exceedingly unstable air mass. Given the favorable environment and rapid initiation thereafter, the outlook forecaster increased the tornado probabilities from 10% to 15% over a small corridor, writing: "THE LATEST 1 KM VISIBLE SATELLITE IMAGERY SUGGESTS STORM INITIATION IS TAKING PLACE NEAR THE SFC [surface] TRIPLE POINT IN WEBSTER COUNTY NEB" in reference to the 1-min visible imagery. Although the 1-min imagery alone did not lead the forecaster to that decision, it did increase early confidence in where and when initiation was forthcoming. Convection that developed within the area of the upgrade went on to produce a number of tornadoes, with the first report at 2040 UTC.

c. Mature convection and SPC MD on 21 May 2014

After convective initiation, SPC forecasters continued to experience value in the 1-min imagery. The intensity of individual convective updrafts can be monitored with more efficiency since significant fluctuations at the storm top become evident as they occur and are not likely to be missed between images. Forecasters highlighted their improved analysis of overshooting and collapsing storm tops, storm-top divergence, and storm-anvil character. Additionally at this stage, convectively driven outflow boundaries, cold-pool evolution, and flanking-line development could all be investigated with more clarity, leading to higher confidence in the timing and location of additional storm development. Forecasters specifically commented that new convective development along a flanking line is often hard to visualize with longer time between satellite images since anvil clouds typically obscure that activity quickly.

The 1-min visible satellite imagery was utilized by a mesoscale forecaster while monitoring the evolution of severe convection on 21 May 2014 across western Texas. A severe thunderstorm watch had been issued at 2155 UTC as convection just began to develop, the main threat being severe wind gusts. By 0015 UTC 22 May 2014, a broad north–south-oriented line of deep convection was in place across western Texas, already producing severe wind and hail (Fig. 3). The strongest updrafts within this broad convective system were identified, and their intensity was monitored by the forecaster who was assessing trends in the 1-min visible imagery. There was no question whether these updrafts were sustaining themselves, because the 1-min data clearly showed constant bubbling at the storm top that is less obvious in current routine imagery. Persistent OTs and above-anvil cirrus plumes were also clues to areas of particularly robust convection. Furthermore, a new area of convection was sampled as it rapidly developed

[2] Preliminary storm-report data may be found on the SPC Internet site (http://www.spc.noaa.gov/climo/online/), and official storm-report data may be found on the National Centers for Environmental Information (formerly the National Climatic Data Center) Internet site (https://www.ncdc.noaa.gov/stormevents/).

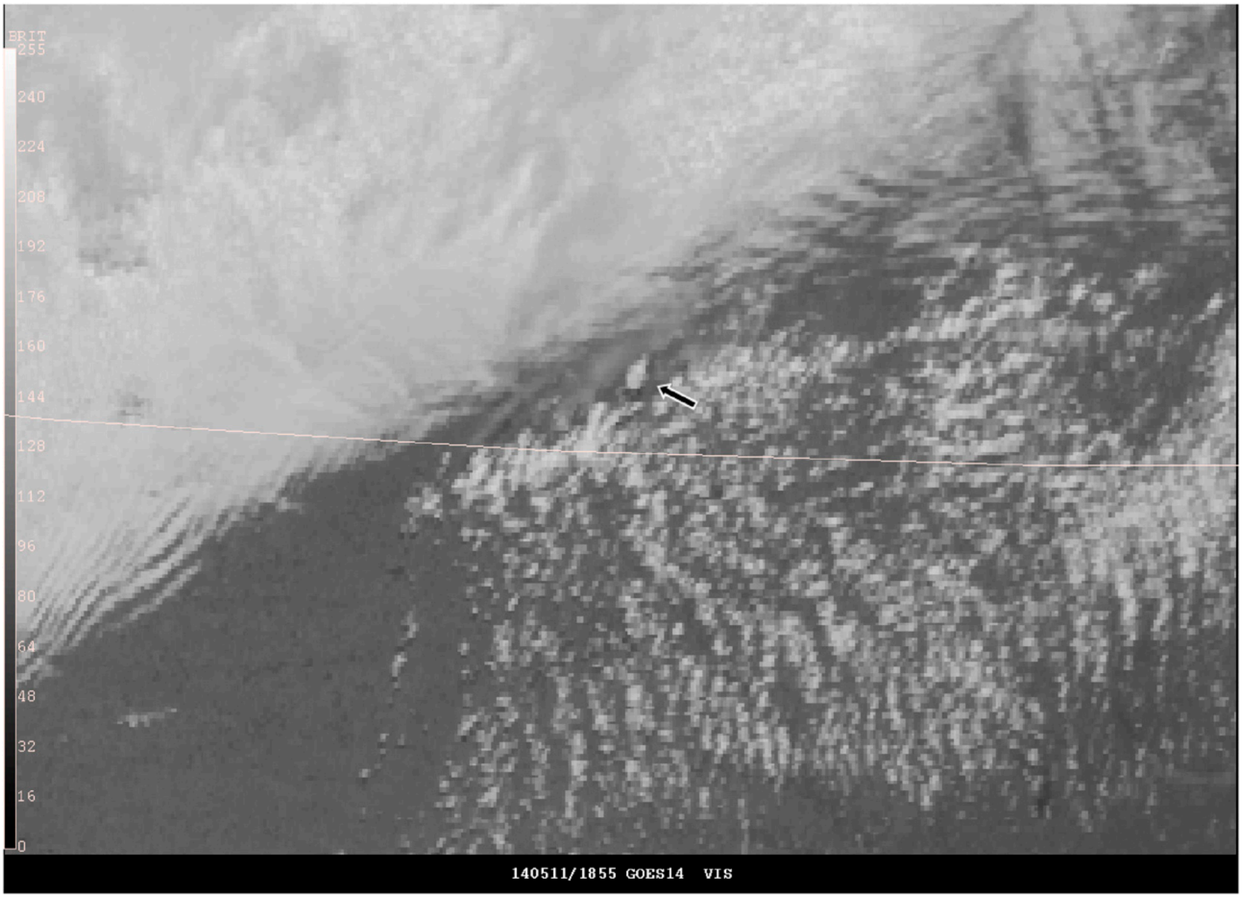

FIG. 2. The 1855 UTC 11 May 2014 *GOES-14* visible-channel image. The arrow points to the orphan anvil described in the text. Note the towering Cu just southwest of the orphan anvil where convection would initiate shortly thereafter (an animation is available in the online supplemental material: video 2).

farther to the south. In a watch update MD (No. 0647) issued at 0015 UTC, the mesoscale forecaster wrote: "GOES 14 ONE-MINUTE IMAGERY SHOWS CONTINUED UPDRAFT GENERATION WITHIN A MORE MATURE CLUSTER JUST E OF AMA [east of Amarillo]...AND ADDITIONAL TSTM [thunderstorm] DEVELOPMENT W OF MAF [west of Midland]...SUGGESTIVE OF A CONTINUED SVR [severe] HAIL/WIND THREAT FOR AT LEAST THE NEXT 1-2 HRS." (Note that the ellipses are in the original material.) The evolution of convective activity is apparent in the animation (video 3) of *GOES-14* SRSOR visible imagery that is available in the online supplement for this article.

d. *Convective dissipation and SPC MD on 23 May 2015*

There were also instances in which the 1-min satellite data aided in the recognition of weakening convection. Decreasing trends in OTs and lack of texture at the storm top could be identified more rapidly in loops of visible 1-min imagery, indicating that updrafts were no longer being sustained. An additional early clue to the decay of convective activity included the detection of rapid warming in the 1-min IR imagery, which is especially important to forecasters at night in the absence of visible imagery.

One such event occurred during the early morning hours of 23 May 2015 in the Texas Panhandle. A mesoscale forecaster was monitoring the evolution of a quasi-linear convective system (QLCS) in the 1-min IR satellite imagery during the predawn period. Damaging winds with this line of convection had been reported between 0945 and 1015 UTC, including a measured gust of 71 mi h^{-1} ($\sim$32 m s^{-1}). By 1038 UTC, the forecaster issued an MD (No. 0721) remarking on the potential for the QLCS to produce additional damaging wind gusts but stressing that the structure should weaken as it moved into a more stable air mass. This assessment was confirmed by observations in the 1-min IR imagery as he went on to write, "1-MIN IR IMAGERY SUGGESTS THIS MAY ALREADY BE UNDERWAY AS THE AREAL EXTENT OF

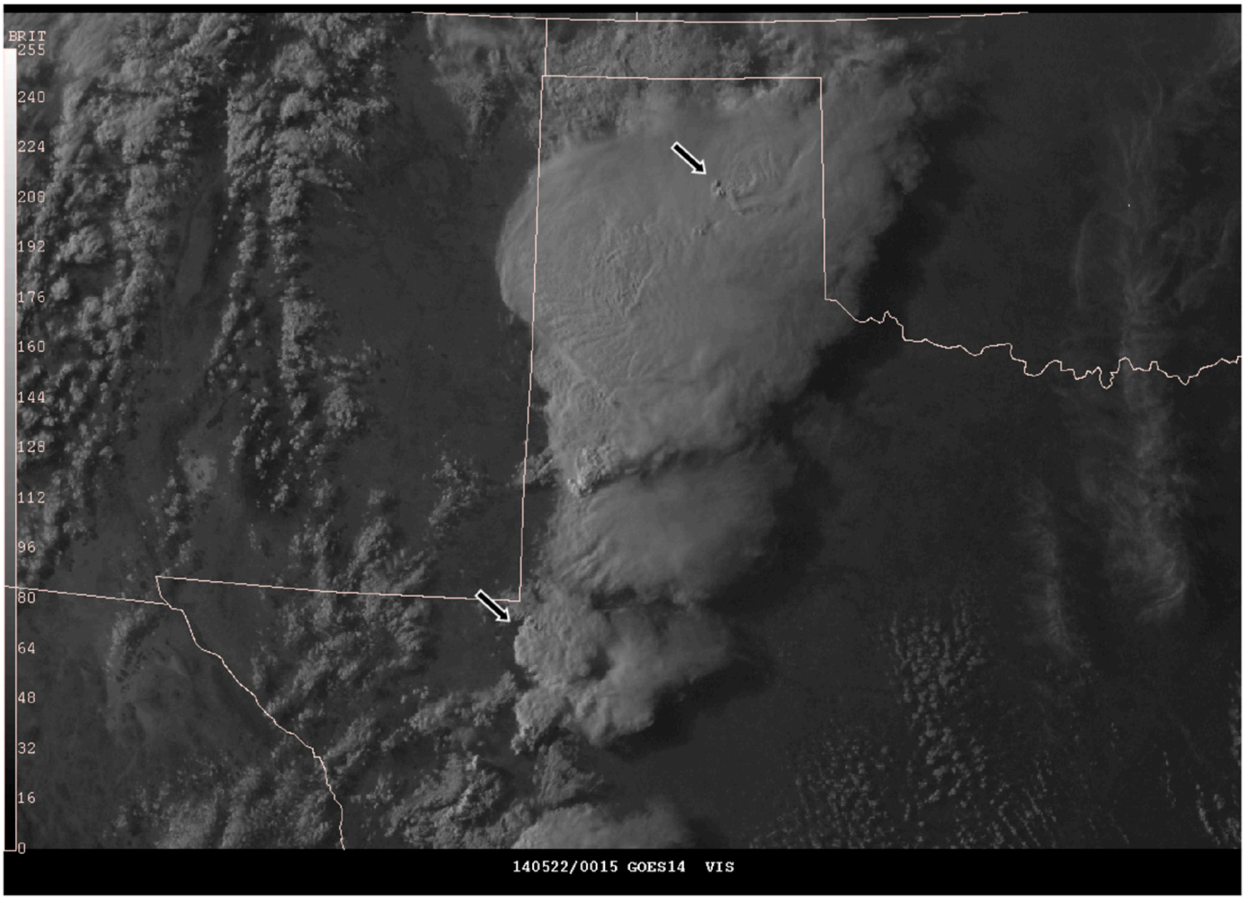

FIG. 3. The 0015 UTC 22 May 2014 *GOES-14* visible-channel image. Arrows point to features described in the text. Note the OTs and texturing that are associated with the northern arrow and the new convective development associated with the southern arrow (an animation is available in the online supplemental material: video 3).

COLDEST CLOUD TOPS HAS BEGUN TO DECREASE IN THE PAST HALF HOUR.'' Rapid warming in the IR imagery continued as the convective system weakened, no longer producing reported severe winds. Figure 4 depicts the warming that occurred in the IR imagery in the 30 min preceding and following the issuance of the MD. The warming is more precisely represented in the animation (video 4) of *GOES-14* SRSOR IR imagery that is available in the online supplement for this article. In this case, the high-temporal-frequency IR satellite imagery allowed the forecaster to diagnose significant warming trends (and implied weakening of convection) earlier than was possible from the available routine imagery.

5. A look to the future

SPC forecasters have benefited from viewing the 1-min visible- and IR-channel satellite imagery that was available experimentally from *GOES-14* and look forward to its operational availability from the ABI in the GOES-R era. It is envisioned, however, that products derived from the 1-min and 30-s data will also provide unique value to the SPC forecaster. Two such algorithms that are currently generated from routine GOES satellite data experimentally and have been viewed by SPC forecasters in operations include the cloud-top-cooling (CTC) algorithm (Sieglaff et al. 2014) and the OT-detection (OTD) algorithm (Bedka et al. 2010). Both the CTC and OTD algorithms have been evaluated in SPC operations as part of GOES-R Proving Ground activities (Line 2015a). Another satellite-based tool that is available to SPC forecasters is the AMV algorithm (Rabin et al. 2004). All three of these satellite-derived products have nonobtrusive, easy-to-understand displays that act to enhance the interpretation and use of satellite imagery. On the basis of feedback from the 2015 Spring Experiment in the HWT, the utility of super rapid scan satellite imagery is further augmented by combining it with other rapid-updating observational

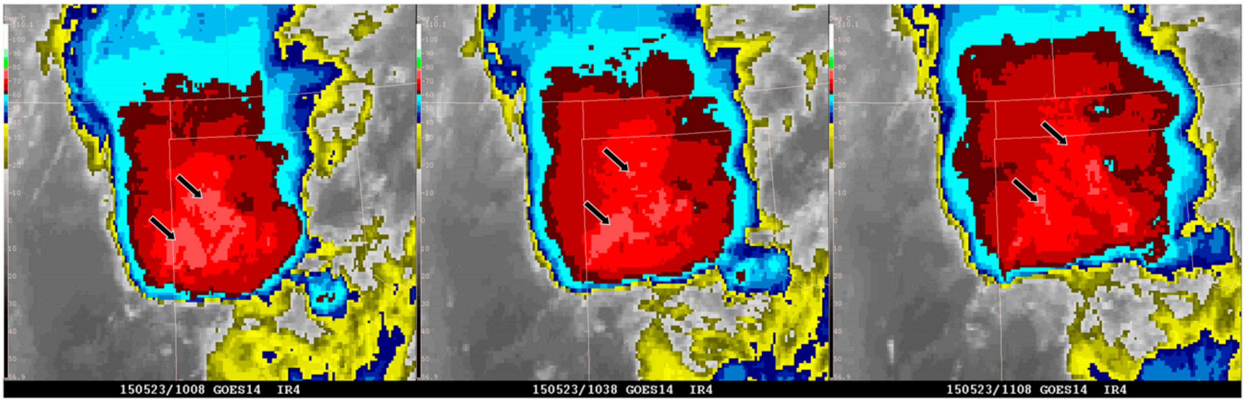

FIG. 4. The (left) 1008, (middle) 1038, and (right) 1108 UTC 23 May 2015 *GOES-14* IR-channel images. Note the warming of the coldest cloud tops as indicated by the arrows (an animation is available in the online supplemental material: video 4).

datasets such as those for lightning and radar (Line 2015b).

The CTC algorithm has been used at the SPC for detecting areas of convective initiation and for distinguishing the most rapidly developing storms. However, such growth is often not identified by the algorithm, owing to the long time intervals between scans with the current operational GOES imager. For example, every 3 h there is a 30-min gap when the imager is scanning a full-disk image. Additionally, data latency combined with the fact that significant growth often occurs between 15- and 30-min scans routinely led to the visual appearance of initiation in the imagery before the CTC product could be updated. A CTC algorithm updating every minute should resolve and quantify updraft growth as it is happening, leading to more precise measurements and timely information for SPC forecasters. It in envisioned that in the GOES-R era CTC would not be a stand-alone algorithm but rather a part of the probability-of-severe algorithm (Cintineo et al. 2014), the convective-initiation algorithm (Walker et al. 2012), and/or a convective toolkit (Gravelle et al. 2016).

The OTD algorithm was utilized by forecasters in operations primarily as a way to track mature convective evolution, providing a quick overview of where the strongest storms were and how they have evolved up to the present. Persistent OTs indicated particularly long-lived strong updrafts, and the dissipation of the OTs clued forecasters to decaying convection and possible short-term wind threat as storms collapsed. However, OTs very often develop and dissipate between satellite scans with current imagery, never being captured by the algorithm or forecaster. The 1-min OTD product will allow forecasters to visualize the complete evolution of individual OTs, with significant increases in updraft strength captured as they occur. Algorithms such as CTC and OTD have been most useful at night (when certain features and processes are difficult to identify in the IR imagery alone) and during busy nowcast situations (during which many storms are present and there is an abundance of data to interpret).

Thirty-minute-updating winds derived from water vapor satellite imagery have also been available to SPC forecasters in operations experimentally. Winds are computed at the upper levels (above 500 hPa), and their primary use at the SPC has been for the identification of jet structures, analysis of divergence and vorticity, and evaluation of NWP model performance. Preliminary forecaster feedback on 10-min-updating winds derived from the *GOES-14* SRSOR data has revealed their potential advantage in severe weather forecasting (Line 2015b). The 10-min-updating winds are computed from visible and IR imagery in addition to the traditional water vapor imagery, leading to more winds being generated both horizontally and vertically through the atmosphere. The abundance of wind vectors allows for the computation of horizontal and vertical atmospheric wind shear in a layer that can extend from the top of the boundary layer to the mid-/upper levels and for a more comprehensive evaluation of NWP model performance. Winds derived from the GOES-R ABI mesoscale-sector imagery are expected to be available at 5-min intervals.

The combination of 1-min satellite imagery with other frequently available observational datasets also helps to further enhance the forecasters' understanding of how the atmosphere and storms are evolving. Single-point, total-lightning data from ground-based networks are already available to forecasters operationally at time scales on the order of a minute. The GOES-R GLM will provide forecasters with continuous near-uniform total-lightning data with 20-s latency or less. High-temporal-resolution lightning data enhance satellite imagery by detecting rapid fluctuations in updraft strength within a storm. When operating in volume coverage pattern 12, a common WSR-88D scan strategy used during severe-weather operations, the low level (0.5°) is scanned every 190–256 s, depending on the Automated Volume Scan Evaluation and Termination function. Recently, WSR-88D instruments were updated to scan in Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS) and meso-SAILS modes, which sample the low-level every 114–147 and 73–89 s, respectively (Daniel et al. 2014). Radar data provide additional details about storm structure and intensity after initial development that are not available from satellite alone. With all three datasets (satellite, lightning, and radar) combined at very high temporal resolution, a forecaster has a more complete and continuous view of thunderstorm structure and evolution.

6. Summary

The *GOES-14* Imager was operated in an experimental super rapid scan 1-min mode during parts of 2012, 2013, 2014, and 2015. These special scans, called SRSOR, emulated the high-temporal-resolution sampling that will be possible from the ABI on the next-generation GOES-R series. SPC forecasters, who already rely heavily on geostationary-satellite imagery, are expected to benefit appreciably from the higher-temporal-resolution data that will be available in the GOES-R era. To prepare them for the future capability and to learn how it might influence severe weather forecasting, the *GOES-14* SRSOR imagery was made available to forecasters in SPC operations. They used the 1-min imagery extensively when it was available over convectively active regions in 2013, 2014, and 2015 and found it to have considerable value in analyzing the preconvective environment, identifying convective initiation, and monitoring mature convective storms. Algorithms using super rapid scan satellite data are expected to supplement the imagery in a quantitative manner, along with other very-high-temporal-resolution datasets such as radar and lightning.

Forecaster insights gleaned from the SRSOR experiments support the recent change in SPC internal guidelines to request current GOES Rapid Scan Operations (RSO; up to 5-min resolution over the CONUS) whenever an enhanced (ENH) risk of severe thunderstorms is included in a day-1 convective outlook. Activating RSO on a more frequent basis using the ENH-risk criterion will improve NWS-forecaster situational awareness on convectively active days and will further help to prepare users for higher-frequency GOES-R data.

When SPC forecasters were surveyed, an overwhelming majority strongly supported the routine operational availability of the 1-min satellite data in the GOES-R era given their experience using it experimentally from *GOES-14*. They commented that the use of very-high-temporal-resolution satellite imagery over time will provide better understanding into processes important to storm development that are not currently diagnosable. Such knowledge will lead to improved severe weather forecasts, which will help the SPC to better fulfill its mission of protecting the lives and property of the American people.

Acknowledgments. More information about the GOES-R series can be found online (http://www.goes-r.gov). More information about the SRSOR campaigns in 2012, 2013 2014, and 2015 is also available online (http://cimss.ssec.wisc.edu/goes/srsor/overview_training.html). Additional information on many of these cases can be found in the CIMSS Satellite blog, under the *GOES-14* category (http://cimss.ssec.wisc.edu/goes/blog/archives/category/goes-14) and in the Satellite Liaison blog, under the SPC category (https://satelliteliaisonblog.wordpress.com/category/spc/). Thanks are given to NOAA/NESDIS for the operation of *GOES-14* in the SRSOR mode; to CIRA/NESDIS/RAMMB, the SSEC Data Center, and NOAA CLASS for ingesting, delivering, and archiving the data; and to the SPC forecasters for providing detailed feedback on their use of the *GOES-14* SRSOR data in SPC operations. Thanks are also given to Robert Rabin (National Severe Storms Laboratory), Israel Jirak (NOAA/NWS/NCEP/SPC), and Steven Weiss (NOAA/NWS/NCEP/SPC). Funding was provided by the NOAA/Office of Oceanic and Atmospheric Research under NOAA–University of Oklahoma Cooperative Agreement NA11OAR4320072, U.S. Department of Commerce. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. government position, policy, or decision.

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