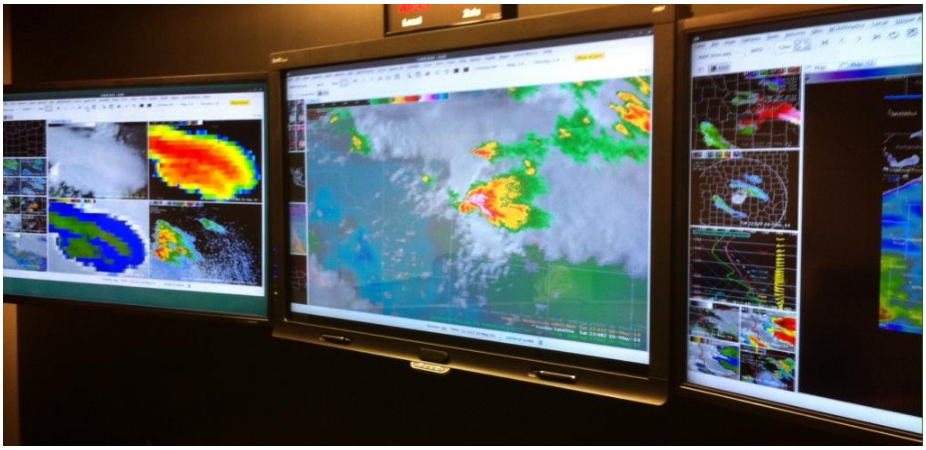
NWS Operations Proving Ground
Operational Readiness Evaluation Report

Evaluating the Usefulness of High-Temporal Satellite Imagery for NWS Operations in the GOES-R Era



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Executive Summary

Between February and April of 2015, the National Weather Service (NWS) Operations Proving Ground (OPG) hosted and facilitated an Operational Impact Evaluation (OIE) focused on the usefulness of 1-min satellite imagery for NWS operations in the Geostationary Operational Environmental Satellite (GOES)-R Series era. The overarching goal of the evaluation was to provide quantitative and qualitative guidance to NWS senior leadership, including the regional NWS Scientific Services Division Chiefs, on how satellite imagery with a refresh rate of 1 minute impacts NWS forecaster decision making. In total, seventeen NWS forecasters completed eight simulations that were developed using imagery from the 2013 and 2014 GOES-14 Super Rapid Scan Operations for GOES-R (SRSOR). Six additional forecasters participated in a follow-up assessment using live 2015 SRSOR imagery.

During the OIE simulations, forecasters evaluated 1-min and 5-min satellite imagery scanning modes while completing tasks ranging from aviation forecasting and wildfire decision support services to monitoring where convective initiation would occur and integrating the imagery into the convective warning decision-making process. Each week, feedback was gathered to assess whether the satellite imagery had influence on forecaster decision making, if the satellite imagery provided forecasters with more confidence in making those decisions, to what extent they could effectively assimilate the data into operational practices, and whether forecaster workload was adversely impacted.

Participating NWS forecasters overwhelming felt that 1-min satellite imagery improved their environmental analysis and increased their confidence to make effective forecast and warning decisions in a variety of simulations. Many forecasters found that animating the satellite imagery while integrating it with other decision aids revealed important insight on how the atmosphere was evolving, which allowed them to anticipate and predict short-term trends. During most simulations, participants expressed that they were able to internally assimilate the imagery with ease. However, when forecasters were asked how easy the imagery was to use in convective warning operations, the feedback was mixed. Some forecasters felt that it was difficult to incorporate the satellite imagery with radar data while issuing convective warnings, while others believed that with sufficient training and experience the satellite imagery would be invaluable in warning operations. Participants unanimously agreed that in order for forecasters to understand how to accurately interpret atmospheric processes using 1-min satellite imagery, the development and delivery of timely, effective training resources is essential. Many forecasters felt these training materials need to focus on effective practices, be layered to maximize forecaster retention, and be integrated into the NWS Distance Learning Operations Course. The evaluation led to seven findings and ten recommendations that focused on preparing NWS forecasters to use high-temporal satellite imagery in the GOES-R era.

1. Evaluation Purpose and Goals

From February through April of 2015, the National Weather Service (NWS) Operations Proving Ground (OPG) hosted a series of six week-long evaluations to assess the operational impact of high-temporal resolution satellite imagery. During each weekly session, NWS forecasters completed eight realistic Weather Forecast Office (WFO) simulations that integrated 1-min and 5-min resolution satellite imagery, imagery that will routinely be available in the Geostationary Operational Environmental Satellite (GOES)-R era, into a variety of analysis, forecast, and warning tasks, in a diverse range of geographic locations.

The overarching goal of the evaluation was to provide quantitative and qualitative guidance to NWS senior leadership on how 1-min satellite imagery may impact NWS forecaster decision making in the context of convective and non-convective situations. For the purpose of this evaluation, the primary question posted was: does high-temporal satellite imagery impact the NWS forecaster's ability to make effective forecast and warning decisions? Efforts were made to address this question by assessing how high-temporal satellite imagery added value to forecaster decision making and how forecasters assimilated the imagery in real time.

In addition to the primary goal, a second objective was to obtain a representative WFO forecaster perspective on the preferred GOES-R operational scanning strategy. As the launch date for the GOES-R Series approaches, one of two operational scanning strategies for the new satellite, either continuous full disk mode or flex mode, will be chosen as the routine scanning strategy. In continuous full disk mode, a full disk image would be received every five (5) minutes. By comparison, in flex mode, images of the full disk, Contiguous United States (CONUS), and mesoscale domains (i.e., two at 1000x1000 km) would be received every 15, 5, and 1 minute, respectively (Schmit et al. 2013). The importance and urgency of these priorities prompted the OPG to develop the high-temporal satellite imagery forecaster evaluation described as follows.

2. Participant Selection and Assessment Methodology

NWS forecasters were selected to participate in the OPG 1-min satellite imagery evaluation by the four CONUS NWS Regional Offices. This resulted in 17 forecasters that included two females and fifteen males from NWS Weather Forecast Offices (WFO) located in Eastern (4 forecasters), Central (5 forecasters), Southern (2 forecasters), and Western Regions (6 forecasters). Years of NWS work experience between the six journey forecasters, seven lead forecasters, and one science and operations officer ranged from 4 to 29, with an average of 14 years of service. These participants represented a broad cross section of NWS forecasters that was important to obtain when evaluating a capability that will impact the NWS operational workforce. Three NWS forecasters participated in each of the six week-long evaluation sessions, except for the last week when only two participated because one was forced to cancel due to a family emergency.

For many forecast and warning decisions, satellite imagery is not the primary dataset for a forecaster's decision making. For example, during the convective warning decision-making process, although 1-min satellite imagery may enhance a forecaster's understanding and confidence of storm-scale evolution, forecasters use WSR-88D radar data to make their warning decisions. Therefore, instead of placing emphasis on improvements with warning and forecast lead times while incorporating the high-temporal satellite imagery, it was more important to focus the majority of this evaluation on capturing the forecaster's conceptual understanding, reasoning, decision making, and trigger points with their simulation decisions. During each of the week-long evaluations, four methods were used to extract this qualitative information: virtual decision logs, recent case walk-throughs (RCW), group discussions, and an anonymous online survey.

During each simulation, forecasters used a virtual decision log to document their confidence and observations for each decision they made. These decisions ranged from issuing a convective warning, to updating a terminal aerodrome forecast (TAF), to notifying relevant NWS partners via NWSChat of imminent high-impact weather. These decision points were logged and used to understand the thoughts of the forecaster as the simulation was unfolding. In addition, for the convective initiation (CI), convective warning operations, and mesoanalyst simulations, these decision points were used to develop a timeline of each forecaster's thoughts and actions, which ended up being used in a cognitive task analysis retrospective method called the RCW.

The RCW was successfully applied in the Phased Array Radar Innovative Sensing Experiments by Heinselman et al. 2015. In preparation for a RCW, the forecaster's desktop was recorded using the RecordMyDesktop® software. When the simulation concluded, forecasters were presented with a playback of their recorded actions. Here, forecasters were asked to recollect what they were seeing, thinking, and doing during the simulation while OPG facilitators documented their thought processes. In Heinselman et al. 2015, facilitators completed the RCW with participants using three sweeps or passes; one built the decision making timeline, another refined the timeline, and the third deepened the timeline. For the RCWs in this evaluation, a preliminary timeline was built in real time with information from forecasters' virtual decision logs. Therefore, it was decided to complete one thorough sweep to allow forecasters to deepen the timeline. Although the RCW methodology can be time consuming, it provides an opportunity to document the qualitative thought process of the forecaster with more accuracy and depth than many other methodologies.

After each simulation, a group debrief was conducted with the forecasters to discuss their experience with the high-temporal satellite imagery and how they integrated it into their forecast and warning processes. Emphasis was placed on having forecasters articulate details concerning the usefulness of the 1-min imagery, interesting or unexpected ways it contributed to aspects of their decision making, insights gained from fusing the imagery with other data sets, and their ability to assimilate the data effectively for the assigned task. The discussions were recorded and detailed accounts were extracted to provide an additional layer of assessment. Finally, on each Friday morning, forecasters completed an anonymous comprehensive survey that allowed them to rate and discuss their experiences using the satellite imagery. The results presented in sections 3 and 4 are a combination of the four methods discussed here.

3. Evaluation Simulations and Key Forecaster Observations

To achieve the most comprehensive assessment of the high-temporal resolution satellite imagery, it was important to select cases for each simulation that would represent a variety of meteorological phenomena and forecasting tasks. Therefore, forecasters evaluated the 1-min satellite imagery with tasks that ranged from monitoring CI for impact on TAFs to providing critical impact-based decision support services (IDSS) during a high-impact wildfire. Each week, forecasters completed the simulations in the same order and on the same days to minimize any potential biases.

In each simulation, forecasters received satellite imagery that was collected during the 2013 and 2014 Super Rapid Scan Operations for GOES-R (SRSOR) experiments. This imagery was used as a proxy (i.e., 26 consecutive images every 30 min) for the temporal resolution that will be available with the Advanced Baseline Imagery (ABI) on GOES-R. In addition, satellite image latency to the forecaster during the simulations was similar to what it would be in the GOES-R era (i.e., approximately 45 sec for a 1-min resolution domain). Although not possible to simulate during this evaluation, in addition to the temporal resolution improvements on the ABI, the spatial resolution will be improved by a factor of four.

Other datasets that forecasters received during each simulation, unless specifically discussed below, were WSR-88D radar data from sites within the simulation County Warning Area (CWA), Meteorological Terminal Aviation Routine (METAR) surface weather reports, High Resolution Rapid Refresh (HRRR) model output, Rapid Refresh (RAP) model output, and during the Mesoanalyst, Monsoon Flash Flooding, and Severe Weather Outbreak simulations GOES-R Overshooting Top (OT) and Convective Cloud-Top Cooling (CTC) output. Prior to beginning each simulation, participating forecasters viewed a prerecorded weather briefing. The weather briefing attempted to provide each forecaster with an understanding of the meteorological environment along with their roles and responsibilities for the simulation.

a. Convective Simulations

1) Convective Initiation

This simulation occurred in the Kansas City/Pleasant Hill, MO (EAX) NWS CWA on 10 May 2014 between 1840 and 2010 UTC. At the start of the simulation, a cumulus field was present across the western portion of the EAX CWA and a Storm Prediction Center (SPC) Mesoscale Discussion was given to the participants that stated "rapid intense thunderstorm development appears possible by around 20-21Z…". During the second half of the simulation, agitated cumulus clouds developed across southeastern NE and northwestern MO that resulted in two significant thunderstorms. The thunderstorm that developed across northwestern MO produced 1 ¾" hail.

Forecasters were told to work individually and monitor the CWA for CI, issue any necessary NWS products, including how convective evolution may impact the TAF for three NW Missouri airports (St. Joseph, MO; Kansas City, MO International; and Downtown Kansas City, MO Executive Terminal), and communicate potential impacts to any appropriate NWS partners. All products were issued with either the Advanced Weather Interactive Processing System (AWIPS) Warning Generation (WarnGen) or the Aviation Forecast Preparation System (AvnFPS) software packages.

Key Forecaster Observations:

Animating 1-min and 5-min satellite imagery, in near real-time, was deemed extremely valuable for visualizing and understanding three dimensional atmospheric flow and, in particular, the evolution of cumulus growth and convection. Forecasters continuously mentioned that these animations revealed many insightful details about fluid atmospheric motions and fine-scale cloud interactions that are nearly impossible to perceive in lower temporal resolution imagery (i.e., 15-min imagery or greater). For example, animating 1-min visible (0.65 μm) satellite imagery made it possible to visualize mesoscale undulations propagating through the developing cumulus field. Monitoring these small scale perturbations made it possible to anticipate and predict growth and decay cycles within the cumulus field. Several forecasters noted that the ability to observe these types of features and make mental connections to their conceptual models led directly to improving their situational understanding and operational decisions.

An important lesson for many forecasters was learning to identify the appearance of an "orphan anvil" (i.e., cirrus spissatus cloud) and understand how to interpret its significance in the context of CI. Here, an orphan anvil is associated with an updraft that briefly penetrates a capping inversion, but cannot maintain the strong, deep vertical motion field necessary to continue developing into a mature cumulonimbus cloud. Once such an updraft decouples from the boundary layer, the midlevel cirrus spissatus cloud is carried downstream by the environmental wind. Being able to identify the presence of orphan anvils can be extremely useful when anticipating CI because it is evidence of a local weakness in convective inhibition and may serve as a signal that deep, moist convection is imminent. The high-temporal resolution satellite imagery allowed forecasters to identify this phenomenon as it was occurring and trace the process back to its source, enabling identification of specific locations to scrutinize for CI.

Some forecasters attributed better forecast decisions and greater lead time to the 1-min satellite imagery. For example, by tracking the leading edge of the agitated cumuli, forecasters could quickly determine the impact on aviation operations and, if necessary, issue timely amendments to the impacted TAF sites well before radar echoes would suggest a reason for concern. Some forecasters credited the high-temporal resolution imagery with enabling them to anticipate how the short-term forecast would evolve:

"[This allowed me to] get ahead of the game by composing social media posts, informing EMs and media partners via NWSchat, and performing other DSS activities to be better prepared to take on warning responsibilities. […] Without this type of real-time, rapid refresh animation, I would have been reacting to initial development [on radar] and trying to catch up once we shifted to warning mode."

Another forecaster discussed a similar experience:

"My workflow completely changed by watching this coming together in near real-time. I started to put out special media products, updated AFDs, amended TAFs before ever seeing anything on radar. My normal workflow at the office would be to see something on radar and scramble to get everything else out after getting that confirmation."

These statements are significant because it is deemed possible that increasing the temporal resolution of satellite imagery may place stress on the operational forecaster workload. For this forecaster, the opposite occurred as the 1-min satellite imagery allowed them to better anticipate initial convective development which in turn placed less stress on workload.

A number of forecasters noted that analyzing cloud-top temperatures from infrared (IR; 10.7 μm) 1-min and 5-min satellite imagery was useful in identifying which convective updrafts were growing most rapidly. This information allowed forecasters to quickly determine areas where CI was most likely. One forecaster discussed the usefulness of the IR imagery for CI after completing this simulation:

"In this simulation, I used the visible more than the IR but the IR definitely had some useful information. Initially, I used the visible to observe the bubbling cumulus to see initial development. Then as the towers began to grow I could observe them in the IR imagery. It gave me confirmation that these towers are strong and things are starting to get going here."

Another forecaster mentioned the transition from visible to IR imagery:

"Once things started to show up on radar and became mature enough to show up in IR [imagery], I was able to compare the storms and their heights. Once things get going and become muddled on visible, IR [imagery] becomes a lot more useful."

2) Convective Warning Operations

This simulation occurred in the Kansas City/Pleasant Hill, MO (EAX) NWS CWA on 10 May 2014 between 2100 and 2230 UTC, fifty minutes after the CI simulation ended. When the simulation began, a SPC Severe Thunderstorm Watch was in effect and severe thunderstorms were occurring across northern MO. Thunderstorms were also developing just north of Kansas City, MO and became quickly severe by 2120 UTC. Forecasters were instructed to work individually and their sole responsibility was to, if necessary, issue convective warnings for the convection developing near Kansas City. The severe thunderstorm farthest to the south moved east-northeast along a quasi-stationary surface boundary and produced hail as large as 2.50" and an EF-2 tornado at 2216 UTC, 14 minutes before the simulation ended.

<u>*Key Forecaster Observations*</u>:

Three important observations, directly relevant to improving the convective warning decision-making process, were made by many forecasters during this simulation. Each of these observations would be repeated and reinforced multiple times as the week progressed, but they were first observed while forecasters completed this simulation.

The first observation identified was that high-temporal satellite imagery, especially 1-min satellite imagery, can allow forecasters to anticipate storm-scale evolution before confirming the presence of storm structures in WSR-88D radar data. One example occurred during this simulation as forecasters observed a feeder cloud cluster of cumulus congestus being ingested into the southernmost storm's main updraft (Fig. 1). Feeder cloud clusters, discussed in detail in Mazur et al. (2009), are organized cumulus clusters that are situated within a thunderstorm's warm sector inflow that converge on the main updraft. In this case, forecasters observed feeder clouds that transitioned to feeder cloud clusters just south of the thunderstorm's main updraft at approximately 2130 UTC. Fifteen minutes later, the feeder cloud cluster had converged with the updraft and at 2147 UTC considerable cooling was observed in IR temperatures. As the updraft intensified, the storm's structure became more organized as the magnitude of the 0.5° reflectivity inflow gradient increased, an inflow notch developed, and moderate midlevel rotation appeared in the 0.5° storm-relative velocity data. By 2159 UTC (Fig. 2), cloud-top temperatures approached -65 C and the low-level storm-relative velocity couplet continued to strengthen prior to tornadogenesis at 2216 UTC. This sequence of events led one forecaster to discuss why they issued a tornado warning:

"At 2158 UTC I issued a tornado warning. The circulation continued to strengthen and I noticed enhanced velocity/inflow into the storm. The visible satellite imagery also indicated enhanced inflow feeder clouds into the storm and I felt that it was only a matter of time before this storm produces a tornado."

This example illustrates the value high-temporal satellite imagery can bring to a forecaster's awareness of how the storm-scale landscape evolves and how the convective warning decision-making process can be enhanced. In fact, in cases where a forecaster may be able to anticipate changes in storm structure by analyzing 1-min satellite imagery, some forecasters discussed that it would be possible to prepare an initial warning polygon that can be quickly transmitted if confirmation is received on the next WSR-88D volume scan. For tornado warnings, this could result in a minute or two of additional lead time which may represent a significant, perhaps lifesaving, difference. It is important to note most forecasters did not observe this sequence of events during the simulation. However, during post-simulation discussions, the majority stated that this was due to not understanding the significance of how feeder cloud clusters can influence storm-scale evolution.

As in the CI simulation, forecasters once again found usefulness in analyzing the high-temporal resolution IR imagery. Many discussed how important it was to analyze how storm tops in mature convection were evolving. When integrated with radar data, not only does this information provide confidence that severe convective weather may be occurring but also that storms may be weakening. One forecaster discussed how warming IR cloud-top temperatures provided confidence to cancel a warning:

"For me, the best part of using the 1-min satellite imagery was the ability to identify which cell to focus on by analyzing overshooting tops. Later in the simulation seeing these disappear gave me confidence to cancel a warning."

Some forecasters also observed features and evolution in the IR imagery they had not previously witnessed in satellite imagery from the current GOES series. For example, between 2147 and 2159 UTC cloud-top temperatures associated with the main thunderstorm updraft not only became colder, they also became quasi stationary when compared to the mean ambient environmental flow. Some forecasters hypothesized this evolution was in response to the updraft quickly strengthening while others suggested it may be an indication that updraft rotation was increasing. It is difficult to determine how often this occurs and if there is operational utility in being able to identify a quasi-stationary updraft.

The final key observation made during this simulation was the value of fusing multiple datasets to enhance the forecaster's situational intelligence. Although this visualization capability was introduced to forecasters during the training simulation, the majority first discussed its importance during this simulation. In the Common AWIPS Visualization Environment (CAVE), the most familiar method to fuse two images is to use the image combination feature. There are visualization limitations with this method, most notably that each image is only partially visible at the same time. For this evaluation, forecasters were taught how to change the transparency for only portions of the upper layer image so it is possible to analyze the lower layer image in the transparent areas. For example, if a forecaster loads the 1-min visible satellite imagery and the gridded 2-m dewpoint field from the HRRR model into CAVE, the visible imagery clear sky pixels can be made transparent to analyze the underlying HRRR field (Fig. 3). One forecaster discussed how important this AWIPS capability is:

"Data fusion was quite useful to show various parameters and their relation to satellite features. Moisture flux, CAPE, and helicity [fields] fused with satellite imagery really aided in seeing if storms were moving into more/less favorable environments as well as which environment will be (un)favored for convective development."

The observations forecasters made during the simulations, and discussed here, led to numerous discussions on how high-temporal satellite imagery can reshape the convective warning decision-making process in the GOES-R era. Each of these observations would be repeated and reinforced multiple times as the week progressed, but they were first observed while forecasters completed this simulation. It is important to note that every participating forecaster felt that integrating high-temporal satellite imagery into the warning decision-making process is only possible with low latency. Latency on the order of seconds, not tens of minutes, is crucial to being able to integrate the imagery in real-time convective warning operations.

While the evaluation participants unanimously felt the high-temporal satellite imagery was useful for the warning decision-making process, many discussed the difficulty with internally assimilating and then using the imagery for decision making during this simulation:

"It was most difficult to incorporate 1-min satellite imagery as the warning forecaster. Not because it's not useful, but rather, when storms are firing all over the place and there's a half a dozen warnings already out, I generally fall back to what I'm comfortable with – radar data."

Another forecaster stated this opinion:

"I think in extreme convective cases, assimilating satellite imagery into the warning process is, by far, most difficult for the warning forecaster. […] The mesoanalyst can do this task, without the pressure of issuing the warnings, and feed the information to the warning forecaster so they can have greater situational awareness and subsequent confidence in their warnings."

3) Mesoanalyst

This simulation occurred in the Raleigh, NC (RAH) NWS CWA on 18 August 2014 between 2100 and 2230 UTC. As the simulation began, a west-east oriented stationary front was bisecting an area of strong thunderstorms moving into the northwestern portion of the RAH CWA and a north-south oriented coastal front was across eastern NC. The presence of these boundaries, along with steep low-level lapse rates, would increase the difficulty for forecasters to determine convective evolution and to identify which storms were most concerning. By the end of the simulation, numerous thunderstorms, some severe, were present in the northern and eastern portions of the RAH CWA. Forecasters were told to work individually as the forecast office mesoanalyst, monitoring existing and developing convection within the CWA. They used a virtual decision log to communicate these observations, very similar to how a mesoanalyst would relay significant information to a warning forecaster. In addition to 1-min visible and IR satellite imagery, forecasters also integrated the GOES-R CTC (Sieglaff et al. 2014) and overshooting top (OT; Bedka et al. 2012) products into their decision making.

Key Forecaster Observations:

During this simulation, participants were given the opportunity to interrogate the satellite imagery without the responsibility of directly integrating the imagery into the warning forecaster's decision making. Even with numerous thunderstorms for the mesoanalyst to analyze during the second half of the simulation, opinions regarding the benefit of 1-min satellite imagery during this simulation were unanimously positive. Most forecasters mentioned that the 1-min satellite imagery was critical for conducting intelligent triage on the thunderstorms. Forecasters discussed the importance of being able to quickly diagnose developing and mature convection with both the GOES-R algorithms and the satellite imagery. This allowed forecasters to identify which thunderstorms needed to be interrogated more closely in the WSR-88D data. One participant remarked:

"At one point I counted 13 individual cells that looked interesting in plan-view radar reflectivity, but using the 1-min [satellite] imagery enabled me to narrow down the list of those with severe potential to four. I quickly examined those storms on my four-panel and all-tilts display procedures to determine whether [the warning forecaster] needed to worry about severe thunderstorm warnings. […] Keeping up with such a complex and rapidly evolving event like this was made a lot more manageable by having 1-min [satellite] imagery available in real-time."

Another forecaster noted:

“It was much easier to discern and predict potential ‘hot spots’ using animations of 1-min [satellite] imagery. Monitoring boundary motions and impending interactions made it possible to anticipate potential development and aberrant storm motions more accurately. If I had been the warning forecaster, I think I could have generated more representative polygons too, because it was easier to pinpoint areas where intensification was likely to take place, as well as being able to identify areas where the air mass was worked over and stabilizing.”

4) Monsoon Flash Flooding

This simulation occurred in the Las Vegas, NV (VEF) NWS CWA on 14 August 2014 between 1730 and 1900 UTC. When the simulation began, the western extent of the monsoon moisture boundary extended from central Utah southwestward across the Las Vegas Valley and into the high desert of southeast California. Boundary layer air within the monsoon circulation was characterized by rich low-level moisture, precipitable water values near 1.5”, and steep lapse rates to 700 hPa. During the simulation, strong thunderstorms developed near Boulder City, NV and in northern Mohave County, AZ. At 1845 UTC flash flooding and severe thunderstorm wind damage was reported at Lake Mead Recreational Area in Clark County, NV. During this simulation, forecasters were instructed to work individually as the convective warning forecaster and issue convective warnings as necessary. During this event the Las Vegas WSR-88D (KESX) was out of service. Therefore, forecasters only used the 1-min satellite imagery, HRRR, RAP, surface observations, and storm reports to use in their decision-making process.

Key Forecaster Observations:

The impact of losing radar data is a significant detriment to the warning decision-making process. In fact, it could be argued that the impact is more adverse in the western United States than in other areas. The overlap of WSR-88D coverage that partially mitigates outages east of the Rocky Mountains does not exist in the west because the average distance between radars is far greater. The impact is further compounded due to the fact that many western United States radars are sited on or near mountaintops, thus lower levels are not sampled. Given these difficult conditions, it was not surprising that forecasters were unanimous in their opinion that 1-min satellite imagery contributed directly to their warning decisions. One forecaster discussed the importance of this simulation:

“This was a very important simulation because we had to use what we know about satellite [imagery] to make warning decisions. I realized that we have a lot of ways to quantify the degree of [thunderstorm] severity using radar, but nothing, or very little using satellite, especially 1-min [satellite imagery].”

Most forecasters felt that their inability to analyze radar structure, along with satellite parallax concerns, caused them to be liberal with their warning polygonology (i.e., larger warning polygons). However, one participant felt that with proper training, issuing convective warnings without WSR-88D data is possible:

“This simulation demonstrated that with proper training, it is possible to issue proper flash flood and severe thunderstorm warnings for instances where the radar is out of service.”

After completing this simulation, some forecasters discussed how the character of convection in the 1-min satellite imagery was different than in the previous convective simulations. For example, some noticed that 1-min IR cooling rates were weaker in this environment, yet still ended up being significant. This is not surprising when the monsoon environment is compared to traditional severe weather thermodynamic profiles. In spite of this, forecasters felt that analyzing convective cooling rates using the IR imagery and CTC algorithm was beneficial:

“[The CTC algorithm] was the most useful in this case I think. In the beginning [of the simulation] it helped to say, ‘hey, look at me over here’ to get you focused on a particular storm. It really helped maintain your situational awareness.”

Other forecasters noticed that the cirrus anvils and OTs were warmer than in other simulations. They ended up realizing that signals that may appear to be modest, or even insignificant, for one geographical region could be meaningful in another. Noting these differences, forecasters discussed that it will be necessary to normalize some of these diagnostic signals for each region, season, and situation. This realization generated excitement because it represents a tremendous opportunity for forecasters to meaningfully contribute to the body of operational research.

5) Severe Weather Outbreak

The final simulation during each evaluation week occurred in the Hastings, NE (GID) NWS CWA on 11 May 2014 between 1815 and 2200 UTC. At 1815 UTC, the GID CWA was in a SPC moderate risk for severe weather with a 10% probability for a tornado within 25 mi of any given location and a Mesoscale Discussion was in effect that suggested a Tornado Watch would be issued by 2000 UTC. The storm-scale environment was extremely unstable with steep midlevel lapse rates and deep-layer shear to support all convective modes. A west to east oriented warm front bisected the CWA and a well organized cumulus field was established south of the warm front. At approximately 1850 UTC, most forecasters observed the first of two orphan anvils and towering cumuli were present along the warm front about 30 minutes later. CI occurred around 1945 UTC and most simulation teams were in convective warning operations by 2000 UTC. A cyclic supercell developed shortly afterward, producing four tornadoes before the end of the simulation. One of those tornadoes produced EF-3 damage and, at times, was 0.75 mi. wide. Other severe thunderstorms developed to the southwest along a cold front that extended from southern NE to the Texas panhandle.

This simulation was designed as a culminating experience, intended to synthesize many of the observations, techniques, and lessons learned from the previous convective scenarios. At the beginning of the simulation, forecasters were told to work collaboratively as they monitored the storm-scale environment while communicating short-term CI forecasts with NWS partners (e.g., emergency managers and local media). Once CI occurred, forecasters were instructed to take on one of the following roles: mesoanalyst and IDSS, primary warning forecaster, and follow-up warning statement forecaster. The primary warning forecaster was responsible to adjust work assignments if they felt it was necessary.

Key Forecaster Observations:

After the final simulation, most forecasters discussed how many of the observations they made earlier in the week had been reinforced during this simulation. Once again, forecasters discussed the importance of integrating 1-min satellite imagery with HRRR model output. They specifically discussed how signals in the 1-min satellite imagery (e.g., observing orphan anvils) gave them confidence in the short-term HRRR CI forecasts. These precursors to CI, that most forecasters believe are now observable when analyzing 1-min satellite imagery, allowed them to confidently communicate to NWS partners that CI would occur in a particular area during this simulation. One forecaster summed up the CI portion of the simulation with the following:

"The 1-min satellite imagery can be useful when you observe indicators of an explosive event. When there are 5 minutes between [radar] volume scans, a lot of things can happen. In an explosive environment, it takes about 15 minutes for these storms to develop and start producing. Being able to see that, see the triple point outline, watch the cumulus field develop, it helps you to pinpoint an area to focus on."

Forecasters also discussed, and reiterated from earlier simulations, the usefulness of the 1-min satellite imagery once convective warning operations began:

"I think the 1-min [satellite] imagery is necessary [during this simulation]. I could see really strong overshooting tops. They would come up and they would come down, but you could capture that with the 1-min satellite imagery. When this occurred you would have more confidence to say that this is a strong storm and you should keep warning or keep an eye it."

Another forecaster discussed how the satellite imagery was giving them confidence to continue or cancel convective warnings.

"When we were monitoring for CI, I was relying more on the satellite [imagery] because it was the highest resolution dataset available. But then once things started to get going I was interrogating the storms [on radar] and glancing at satellite imagery to [internally] say 'Yep, the overshooting top is still there and I should probably continue the warning.' However, if I didn't observe the overshooting top I would think 'OK, maybe it is not that severe anymore and I shouldn't reissue' [another warning]."

While many of the observations noted by the forecasters during this simulation reinforced concepts they observed and documented previously, it is important that they are being observed during multiple simulations and during multiple weeks. When forecasters witness the satellite imagery sensing complex storm-scale behavior in a similar manner, it provides them with confidence to use the imagery for forecast and warning operations. Forecasters also repeatedly discussed the operational research opportunities in the GOES-R era, in particular with high-temporal satellite imagery. They felt that being able to observe meteorological phenomena in real time, with more precision than ever, will provide the potential for forecasters to make important and meaningful contributions to operational research.

b. Non-Convective Simulations

1) Wildfire/Air Quality IDSS

This simulation occurred in the Reno, NV (REV) and Sacramento, CA (STO) NWS CWAs on 22 August 2013 between 1645 and 1815 UTC and focused on monitoring the central California Rim Fire. The Rim Fire, which began on 17 August near Yosemite National Park, nearly doubled in size on this day. During the simulation, surface winds shifted from south to southwesterly near the fire that amplified the upslope component into the Sierra Foothills and resulted in vigorous fire growth on the eastern perimeter of the complex. In fact, pyrocumulus clouds were observed in the 1-min visible satellite imagery beginning at 1730 UTC. As a result of the rapidly expanding fire, excessive amounts of smoke were carried aloft and to the northeast into the Lake Tahoe and Reno, NV area. Near the end of the simulation, visibility was reduced and hazardous air quality conditions were observed in the Lake Tahoe Valley. Although each forecaster had clear responsibilities during this simulation, they were asked to share meteorological insights and work together as a team. One forecaster was assigned to support the Rim Fire on-site incident meteorologist (IMET) with critical meteorological information, another was assigned to an IDSS air quality role with the factious Reno-Tahoe Health District, and the third was assigned to monitor three aviation sites and issue any amendments necessary to assure TAFs were representative.

Key Forecaster Observations:

Early in the simulation, the Rim Fire IMET notified forecasters that crews digging fire lines near Cherry Lake Camp, CA were observing pyrocumulus clouds forming to their southeast. The IMET went on to inform forecasters that the incident commander may need to modify the attack plan and move resources to another area of the fire. During each evaluation week, forecasters assigned to the IMET support role were able to quickly analyze the 1-min visible satellite imagery to provide the IMET with critical supporting information. For example, using the visible satellite imagery, forecasters could determine, in near real-time, that smoke plumes on the eastern side of the fire were more buoyant than the plumes on the western edge. This gave them confidence that low-level relative humidity observations just north of the fire may not have been representative of the environment over the foothills to the east. One of the forecasters discussed this further:

"By having 1-min satellite imagery, I could see the plume characteristics change. That enabled me to identify development that was potentially threatening in time to convey sufficient warning [to the IMET]. In that situation, with a large wildfire in complex terrain, waiting another five or ten minutes could be too late. It's the difference between people escaping and people getting trapped."

Opinions about the value of data fusion were similar to those shared following the convective simulations. In particular, the IMET support forecasters expressed positive impressions about the usefulness of fusing 1-min satellite imagery with high-resolution gridded datasets for enhanced environmental situational awareness. Here, many fused the visible satellite imagery with surface wind and dewpoint forecasts from the HRRR. Fusing the datasets allowed forecasters to understand the advection of marine air was responsible for suppressing the western perimeter of the fire. This gave some forecasters the confidence to use the short-term HRRR 10-m wind forecasts to predict that the fire may expand eastward into the foothills above the marine layer.

During the first portion of the simulation, forecasters assigned to monitor air quality and aviation impacts in Lake Tahoe, CA and Reno, NV did not feel the dense smoke plume would affect those areas. However, once the character of the fire changed and pyrocumulus clouds extended into higher winds aloft the impact quickly became apparent. Many forecasters contacted the Reno-Tahoe Health District via NWSchat and issued an air quality special weather statement, one forecaster discussed this:

"The 1-min satellite imagery was definitely adding more than just confidence to my decisions; it was driving a lot of them. I was trying to get ideas from [the high-resolution] models about what time I thought the airborne smoke plume would arrive and then I would go to the satellite and compare. […] It added exceptional value to my ability to collaborate with the Health District about putting out an accurate and timely Air Quality Alert."

Forecasters monitoring the smoke plume for possible TAF impacts also discussed how the 1-min satellite imagery was responsible for the majority of their decision making:

"You can see the persistence of the features so much more easily in the 1-min satellite imagery. The detail makes certain aspects [of the smoke plume] so much more identifiable. In this

simulation, it added to my confidence levels when coordinating and making a forecast. It also added a new dimension to situational awareness."

2) Fog and Low Stratus/Aviation Support

In 2014, based on passenger count, the San Francisco International Airport (SFO) was the 7th busiest in the United States (FAA 2014). In order for SFO to operate at its maximum traffic flow rate capacity (i.e., approximately 60 in-bound flights per hour), air traffic control must utilize side-by-side landings on its northwest-southeast oriented parallel runways (Hilliker and Fritsch 1999). However, maximum flow rate at SFO is affected by exceeding visual flight rules (VFR) conditions (i.e., ceilings less than 3000 ft or visibility less than 5 SM) because the parallel runways are only 750 ft apart and the 2400 ft tall San Mateo Bridge spans across the final approach. When marginal VFR conditions exist, safety measures are put in place that can range from reduced flow rate (i.e., 30 planes per hour) to a full ground stop. Between 2006 and 2010, warm-season low stratus was responsible for over half of the air traffic delays at SFO (Reynolds et al. 2012). Therefore, providing the most accurate guidance to the Federal Aviation Administration (FAA) and air traffic control on the formation and dissipation of fog and low stratus at SFO is critical to the National Air Space.

This simulation occurred in the San Francisco/Monterey Bay, CA (MTR) NWS CWA on 22 August 2013 between 1630 and 1800 UTC and focused on providing aviation forecast support for the San Francisco Terminal (SFO). When the simulation began, the San Francisco Bay area was covered in an 1800-ft stratus deck, which was causing arrival delays at SFO. Around 1700 UTC, vertical mixing started to thin the stratus across the higher terrain of the Santa Cruz Mountains and by 1730 UTC expanded across the southern portion of San Francisco Bay. By 1810 UTC, ten minutes after the simulation ended, the stratus mixed out from SFO to San Jose, CA (SJC) and the SFO METAR returned to VFR conditions at 1900 UTC. Forecasters inherited the 1200 UTC TAFs for SFO, SJC, and the Oakland International Airport (OAK) that indicated 1500-ft ceilings would clear after 2000 UTC. They were instructed to monitor the low stratus with the 1-min satellite imagery, update and amend TAFs, and, if necessary, use NWSchat to communicate ceiling changes with the SFO Air Traffic Control Tower.

<u>*Key Forecaster Observations*</u>*:*

Forecasters found animating the 1-min satellite imagery, with negligible data latency, invaluable to their situational intelligence and decision making while monitoring the low stratus during this simulation. Many forecasters felt that being able to observe how the mixing process evolved, drove their decisions:

"In this simulation, the satellite [imagery] was directly influencing the decisions. You couldn't make them without [using the] satellite [imagery]."

Other forecasters felt that, when comparing 1-min and 5-min satellite imagery, 1-min satellite imagery was not necessary when monitoring the low stratus:

"In this case, I am having a hard time justifying the 1-min satellite imagery versus the 5-min imagery. The 5-min [imagery] may be good enough. [. . .] I have the feeling that I could almost make the same decision looking at 5-min imagery."

Another forecaster shared a similar view:

"Looping the 1-min satellite imagery was directly influencing my decisions in this simulation. I couldn't have made the call to [forecast visual flight rules which would allow the FAA to] lift the ground delay program that soon without it. But, in this case, I'm not sure 1-min [satellite imagery] was necessary. I could have made the same call with 5-min imagery."

Despite the difference of opinion on whether 1-min satellite imagery was essential or if 5-min resolution imagery was sufficient, it is clear that the high-temporal resolution satellite imagery significantly impacted forecaster decisions during this simulation. In fact, several forecasters stated that their decision to confidently update the SFO forecast to VFR conditions was driven exclusively by the 1-min satellite imagery. Between 1726 and 1800 UTC, fourteen of seventeen forecasters documented their decision to update the SFO TAF and relay that information to the SFO Tower. Furthermore, all but four forecasters predicted accelerated improvement to VFR conditions between 1800 and 1830 UTC. The economic impact that these short-term forecasts have on the aviation industry is often forgotten. For example, one estimate provided by a FAA Command Center NWS National Aviation Meteorologist indicated it can cost $76 for each minute an aircraft is grounded. Applying this estimate to the simulation and assuming that arrivals at SFO were reduced to 30 planes per hour when impacted by the stratus deck, an accurate short-term forecast suggesting VFR conditions at SFO would occur 90 minutes early by fourteen forecasters would have saved the aviation industry approximately $200,000.

In addition to the observations discussed above, during this simulation in particular, several forecasters found it useful to manually bend the IR color table in AWIPS. Since the traditional 11.0-3.9 μm satellite fog product was not available during the SRSOR experiment, this allowed forecasters to highlight warm liquid clouds associated with low stratus that would have been difficult to discern using the default color table. Once the color table was modified and a new IR temperature threshold was set, many forecasters used the IR satellite imagery to highlight areas where clouds were quickly evaporating. This technique was also applied during other simulations and for other datasets, such as HRRR model output fields.

4. Overall Results

To conclude each evaluation week, forecasters completed a 90-min anonymous online survey which asked them to rate and discuss topics including, but not limited to, confidence, assimilation, and usefulness of the high temporal satellite imagery and derived products (i.e., CTC and OT algorithms) during the simulations. Following completion of the online survey, forecasters participated in a final group discussion with OPG facilitators.

In the first portion of the survey, forecasters rated, on a scale from one to ten, if their confidence increased (one being no increase in confidence and ten being a significant increase) and if they noticed improvement (one being no improvement and ten being significant improvement) in the decisions they made using the satellite imagery during the simulations. Overall, forecasters felt their confidence and improvement in the decisions they made increased substantially (Fig. 4). On a scale from one to ten, with one being no increase in confidence or improvement and ten being a significant increase, on average the seventeen forecasters rated the increase in confidence 8.59 and the increase in improvement 8.29. One forecaster stated:

"The 1-min imagery was extremely useful in making forecast and warning decisions during the various weather scenarios by improving confidence during the forecast process."

Another forecaster made an attempt to quantify the influence of satellite imagery on decisions made:

“[…] In fact, I estimate that many of the decisions and warnings I relayed and issued this week came a lot sooner (on the order of 5-10 min) than perhaps I would have made without the 1-min satellite imagery.”

Forecasters were asked to rate their increased comfort and confidence in using the 1-min satellite imagery throughout the evaluation. Fifty-nine percent of forecasters felt their comfort using the satellite imagery significantly grew during the evaluation and only one forecaster rated their growth below eight out of ten (Fig. 4). Many forecasters went on to discuss how their comfort grew throughout the week:

“I learned a lot in just a few days and I am confident that further experience with the 1-min GOES-R satellite imagery will continue to improve my interpretation skills.”

Another forecaster discussed how their comfort changed after integrating the 1-min satellite imagery throughout the week for convective events:

“At first, [using the 1-min satellite imagery] was a bit overwhelming. Gradually, my confidence in interpreting and applying the imagery increased. By the end of three days I was completely sold on the idea of using the imagery to issue warnings, fulfill IDSS requests, and anticipate IDSS needs, etc. Many times, I'd see something about to happen, or a small thing happening such as cumulus forming ahead of a storm which radar could not pick up due to weakness of the echoes or beam height problems, and I knew an outflow was moving out [from the storm].”

These results are not surprising, since evaluating a new capability can be thought of as an exercise in “learning-by-doing”. Although forecasters are not formally participating in a training exercise, their comfort and understanding in applying the 1-min satellite imagery after using it during the evaluation is due to applying it in real situations. This being said, forecasters were asked how essential training resources for 1-min satellite imagery will be in the GOES-R era. All seventeen forecasters rated the importance of training resources a nine or ten with an average of 9.76. One forecaster discussed the importance of learning how to use 1-min satellite imagery for convective applications early, when forecasters learn how to interrogate radar for the forecast and warning decision-making process in the NWS Distance Learning Operations Course (DLOC):

“If you could get the [1-min satellite imagery] training in DLOC, where you learn and form your habits in the earliest training you could take those habits with you the rest of your career. I am sure the concepts you learned at DLOC you still use to this day. […] To me it is almost like learning a second language. If you learn English first it will always be your primary language, but if you learn another language at the same time [as English] you become bilingual. This is similar. If you learn radar first, it is going to be your primary source [for thunderstorm interrogation] and satellite will always be second, but if you incorporate them together from the beginning it is almost like bringing up a new generation of forecasters, fluent in using both tools simultaneously.”

Overall, forecasters felt that a variety of easily accessible, focused, and well-designed training resources are crucial in being able to adopt and apply 1-min satellite imagery for forecast and warning decisions.

Forecasters were also asked which scanning strategy should be default in the GOES-R era and for which tasks it is absolutely critical to have 1-min satellite imagery. The majority of forecasters, thirteen of seventeen, felt having continuous full disk mode would be sufficient for

NWS operations. Having flex mode "on demand" would allow some National Centers for Environmental Prediction, such as the Aviation Weather Center and Satellite Analysis Branch, to have 5-min satellite imagery available to monitor atmospheric hazards outside of the CONUS domain. When asked to identify tasks for which 1-min satellite imagery is absolutely necessary, thirteen of seventeen mentioned monitoring the development and evolution of thunderstorms, ten of seventeen forecasters discussed analyzing and forecasting wildfire behavior, and five of seventeen said monitoring fog and low stratus.

During the mesoanalyst, monsoon flash flooding, and severe weather outbreak simulations, forecasters integrated the 1-min satellite imagery with output from the GOES-R CTC and OT algorithms into their warning decisions. When they were asked how useful the CTC product was in increasing situational awareness during these simulations, the average rating from forecasters on a scale from one (i.e., not useful) to ten (i.e., extremely useful) was 7.24. One forecaster discussed how they used the CTC product to estimate the strength of developing convective clouds:

"The CTC product was very useful in the simulations it was provided. It helped to quantify the initial strength of the updraft and allowed us to compare [the output] to other storms in the area. The only time it wasn't as useful was in the Hastings, NE simulation where it flagged several glaciating cloud objects north of the warm front. Overall, I was impressed by its utility during these simulations."

Another forecaster voiced concerns about the inconsistency that was, at times, observed with the CTC output:

"After completing the pre-simulation training I was very enthusiastic about this algorithm and saw it potentially becoming a very important tool in the warning forecasters toolkit, pointing forecasters to where [their] attention is needed most. After using the tool it appeared very scattered and uncoordinated in its detections for most of the simulations. […] To be useful, this tool will need to perform better or forecasters will turn it off and not utilize it. But I think if this tool is worked on and improved it can be extremely useful."

It should be noted that the CTC product is a GOES-R demonstration product that has been optimized using the current GOES series during the routine scanning schedule. Therefore, the product may not perform consistently when using data from the SRSOR experiment. When forecasters were asked how useful the OT product was in increasing situational awareness during convective events, the average rating was 6.82. Some forecasters felt the OT product provided excellent situational awareness:

"The OT algorithm was very useful in being the 'deciding factor' in borderline severe storms based on radar. It provided a huge benefit in helping me target those few cells that were intense, rather than having to weed through the multiple storms simply through radar."

Some forecasters felt the information they could process from analyzing the IR temperatures provided them better situational awareness than the OT algorithm:

"I was not impressed with the OT algorithm. […] I was able to detect an OT in the Las Vegas simulation that helped me in my confidence of the warning [I issued] but the OT algorithm did not detect this short lived OT."

This forecaster went on to discuss the importance of displaying the algorithm output intelligently in the forecaster's display:

"The display of the OT product, a large white square placed over the OT, was not that useful. Perhaps an icon overlaid on the image would be better."

This type of approach would allow forecasters to recognize when an OT was detected by the algorithm while still being able to analyze the cloud-top temperatures in the IR imagery. The mixed CTC and OT feedback suggests that, while many forecasters find the added layer of information from the algorithms useful while interrogating convective evolution, it will be important for product developers to continue investigating the quality and appearance of algorithm output once GOES-R data is being used. Forecasters also rated the importance of all satellite-based products and algorithms in the GOES-R era. On a scale from one, not important, to ten, extremely important, the average rating was 8.82. One forecaster explained why they feel these algorithms are important:

"In the GOES-R era, there will be so much more data (temporally and spectrally) than we can handle that properly developed algorithms will be needed to provide forecasters the information they need instead of having forecasters mining all the data and determining which is unique. Proper post processing research will be vital to the success of this great new technology."

Finally, based on the simulations completed in this evaluation, forecasters rated how easy it was to assimilate 1-min satellite imagery for the range of tasks assigned during the evaluation. Most forecasters felt it was relatively easy to assimilate the satellite imagery and use it to make decisions for monitoring fog and low stratus and providing fire weather support (Fig. 5). As the mesoanalyst, the results were similar but more forecasters, three, rated the ease of assimilation seven or below. However, as the warning forecaster the results were much different. Ten forecasters rated the ease of assimilation below seven and six rated it five or below. One forecaster discussed the difficulty in using the 1-min satellite imagery as the warning forecaster and why having a mesoanalyst is important for warning operations:

"I think in extreme convective cases, assimilating satellite imagery into the warning process is, by far, most difficult for the warning forecaster. […] The mesoanalyst can use the imagery without the pressure of issuing warnings and feed that information to the warning forecaster so they can have greater situational awareness and confidence in their warnings."

Another forecaster discussed how assimilating the satellite imagery as the warning forecaster was difficult at first, but became easier the more they used it:

"The only time it seemed somewhat difficult to incorporate 1-min satellite imagery was into radar/warning operations. Since I am not used to using satellite imagery this way, it took a little adjustment to incorporate it into my operations and divert from the way warning operations are typically done. However, once I made that adjustment it was much easier to use the satellite data as a warning forecaster."

It is difficult to determine the reason(s) why many forecasters had difficulty assimilating and integrating the imagery to help make decisions as the warning forecaster because the online survey was anonymous. It could be hypothesized that the majority of forecasters with difficulty were from Western Region where opportunities as the warning forecaster are limited due to the low climatological occurrence, when compared to other areas of the CONUS, of severe convection. It is also possible that it is too difficult to integrate the satellite imagery into the warning decision-making process.

Prompted by this specific discrepancy in opinions, the OPG decided to extend its investigation into whether NWS forecasters can effectively integrate these data into the convective warning decision-making process. For one week in May and another in June, during the 2015 SRSOR experiment, six NWS Central Region forecasters were invited to the OPG with the express purpose of trying to assimilate 1-min satellite imagery into their decision making as the warning forecaster. These forecasters were chosen by their WFO management because they are experienced warning forecasters. While issuing convective warnings in real time, forecasters were told to continuously think about the usefulness of the 1-min satellite imagery and how easy (or difficult) it was to assimilate the imagery as the warning forecaster. During each of the weeks, the forecasters completed an interactive training session on Monday afternoon, completed real-time warning operations on Tuesday through Thursday, and debriefed with OPG staff on Friday morning. Forecasters issued convective warnings in ten NWS CWAs on days where the SPC categorical convective outlooks had slight and enhanced risks for severe thunderstorms.

Similar to the 6-week evaluation, at the end of each week forecasters completed an anonymous survey that asked them to rate and discuss integrating the 1-min satellite imagery as the warning forecaster. The majority of the six forecasters felt the 1-min satellite imagery had significant impact on their ability to make effective warning decisions which led to increased confidence in those decisions (Fig. 6). With respect to assimilating the satellite imagery in the warning decision-making process, on a scale of one (extremely difficult) to ten (extremely easy), three forecasters rated the ease of assimilating the imagery nine and three rated it seven (Fig. 7). One forecaster concluded that their ability to assimilate the imagery improved with only three days' experience:

"After working three real-time weather events as the warning forecaster, the ability to use 1-min satellite imagery and make it a part of the warning decision process became more comfortable each day. However, even on the first day I was able to quickly integrate and adapt my warning decision process with the 1-min imagery."

Another forecaster discussed what is gained by integrating the satellite imagery into warning operations:

"My confidence increased throughout the week as I compared what I was seeing on radar with what I was seeing in the 1-min satellite imagery. The radar detects and shows the distribution and character of each storm's hydrometeors, which of course is extremely useful. However, the 1-min satellite imagery observes the tops of the clouds that are associated with the hazardous weather and this view is somewhat independent of a storm's hydrometeor character. Knowing there are correlations between these cloud features, associated hazardous weather, and being able to see the cloud features every minute gives me great confidence. When combining [the satellite imagery] with the radar data, I felt like I was provided with another dimension to interrogate the storms within."

Lastly, after using the satellite imagery for three days as the warning forecaster, forecasters were asked how confident they were integrating the imagery directly into their analysis and decision process. The responses they could choose ranged from extremely confident (i.e., they believe they could integrate 1-min satellite imagery into their radar interrogation practices to enhance convective warning decisions right now) to doubtful (i.e., even with considerable practice, they are certain that they could not integrate 1-min satellite imagery into their radar interrogation practices to enhance convective warning decisions). Three forecasters believed they could integrate the satellite imagery right now and three others felt they could integrate the imagery with just a little more practice. Not only does the feedback from these six additional

NWS forecasters continue to reinforce the value of 1-min satellite imagery for interrogating deep moist convection, it suggests that it is possible to successfully integrate this imagery in the warning decision-making process.

5. Evaluation Findings and Recommendations

Finding 1: Animating 1-min satellite imagery reveals important insight on how the atmosphere is evolving and, at times, can allow forecasters to anticipate short-term atmospheric trends.

Recommendation 1: Develop a library of examples that illustrate how 1-min satellite imagery has a direct, positive impact toward improving analyses and forecasts. Examples should include identifying atmospheric features, understanding atmospheric processes, enhancing forecaster decision making, and communicating reliable hazardous weather information.

Finding 2: Fusing high-temporal satellite imagery with other datasets, products, and decision aids (e.g., radar data, HRRR gridded output, and GIS layers) enhances forecaster understanding of the atmosphere.

Recommendation 2: Develop effective practices that focus on integrating high-temporal satellite imagery with supplemental datasets and decision aids to enhance situational intelligence.

Finding 3: Based on the simulations completed during this evaluation, forecasters felt 1-min satellite imagery was, in order of importance, most valuable for: monitoring the development and evolution of severe thunderstorms, analyzing and forecasting wildfire behavior to provide effective IDSS, and identifying short-term evolution of non-convective events such as fog and low stratus and smoke plumes.

Recommendation 3: Establish a prioritized list of meteorological phenomena to use as guidance when assigning 1-min satellite imagery domains in the GOES-R era.

Finding 4: Training needs to be developed that demonstrates how to interpret atmospheric processes in high-temporal satellite imagery and apply that knowledge for forecast and convective warning decision making.

Recommendation 4a: Incorporate 1-min satellite imagery effective practices throughout the GOES-R Training Plan.

Recommendation 4b: Develop layered training materials to maximize forecaster retention. These could include foundational science and applications, supplemental resources that feature in-depth interrogation examples, and just-in-time training to refresh forecasters on core and advanced learning objectives.

Recommendation 4c: Integrate 1-min satellite imagery analysis techniques into the NWS Distance Learning Operations Course to ensure forecasters develop a core understanding of how to use radar data and satellite imagery for interrogating convective structure.

Finding 5: Forecaster insights and questions during simulations suggest many opportunities will exist for meaningful operational research in the GOES-R era.

Recommendation 5a: Appoint a Satellite Focal Point at each WFO that is responsible for advancing the integration of satellite imagery and products into the forecast and convective warning processes.

Recommendation 5b: Science and Operations Officers, Development and Operations Hydrologists, and Satellite Focal Points need to encourage, lead, and guide research to advance operational satellite applications in the GOES-R era.

Finding 6: A clear process to request 1-min satellite imagery domains needs to be developed and understood by NWS forecasters.

Recommendation 6: Ensure NWS forecasters have a voice in developing the process and complete training on how to request 1-min satellite imagery domains in the GOES-R era. Many forecasters do not understand the process to request rapid-scan operations with the current GOES series.

Finding 7: Every forecaster experimented in arranging their personal data displays and integrating the 1-min satellite imagery on the AWIPS workspace to maximize their ability to assimilate the imagery and make effective forecast and warning decisions.

Recommendation 7: Explore and establish effective display procedures for various forecast tasks to enhance the identification of meteorological threats for IDSS and minimize the potential that high-temporal satellite imagery will pose a significant data overload problem for operational forecasters."

6. Figures

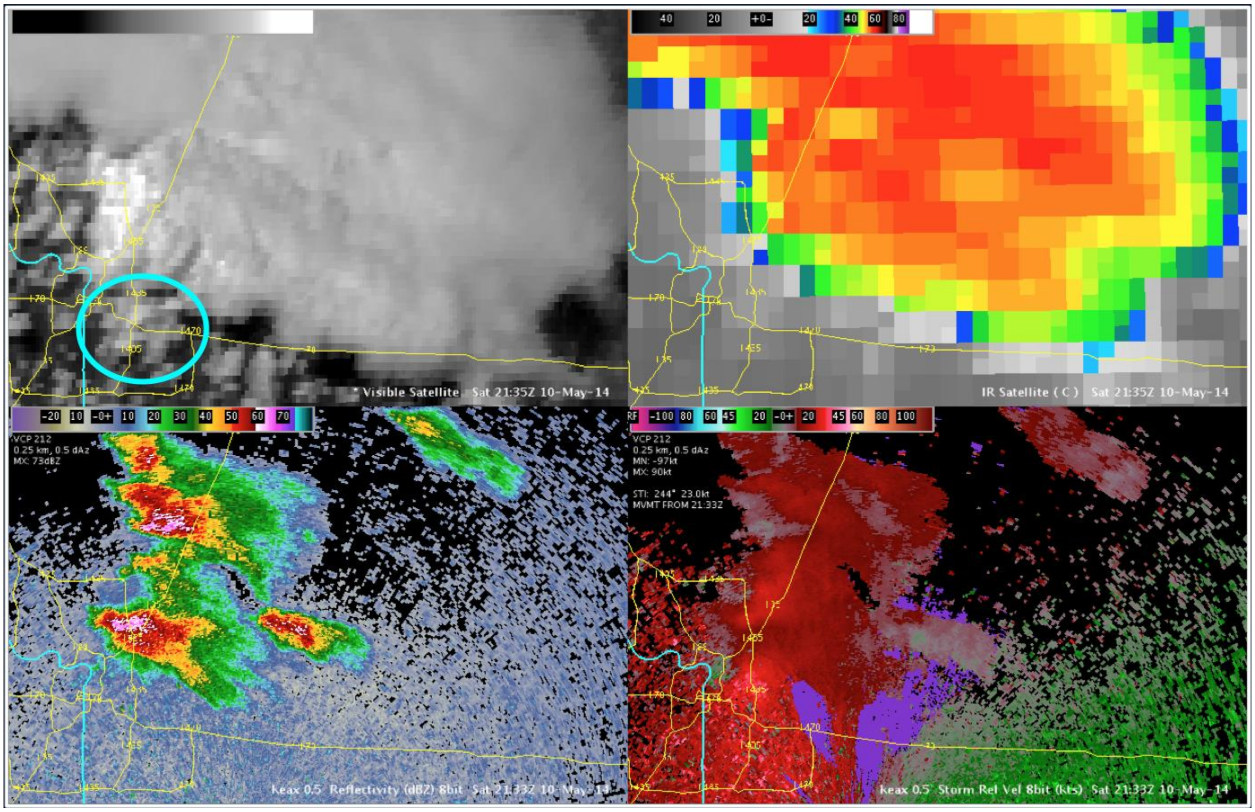

Fig. 1. (top left) 2135 UTC 10 May 2014 visible satellite image from the GOES-14, (top right) 2135 UTC 10 May 2014 infrared 10.7 µm satellite image from the GOES-14 (°C, shaded according to the scale), (bottom left) 2133 UTC 10 May 2014 WSR-88D KEAX 0.5-degree reflectivity (dBZ, shaded according to the scale), and (bottom right) 2133 UTC 10 May 2014 WSR-88D KEAX 0.5-degree storm-relative velocity (kts, shaded according to the scale).

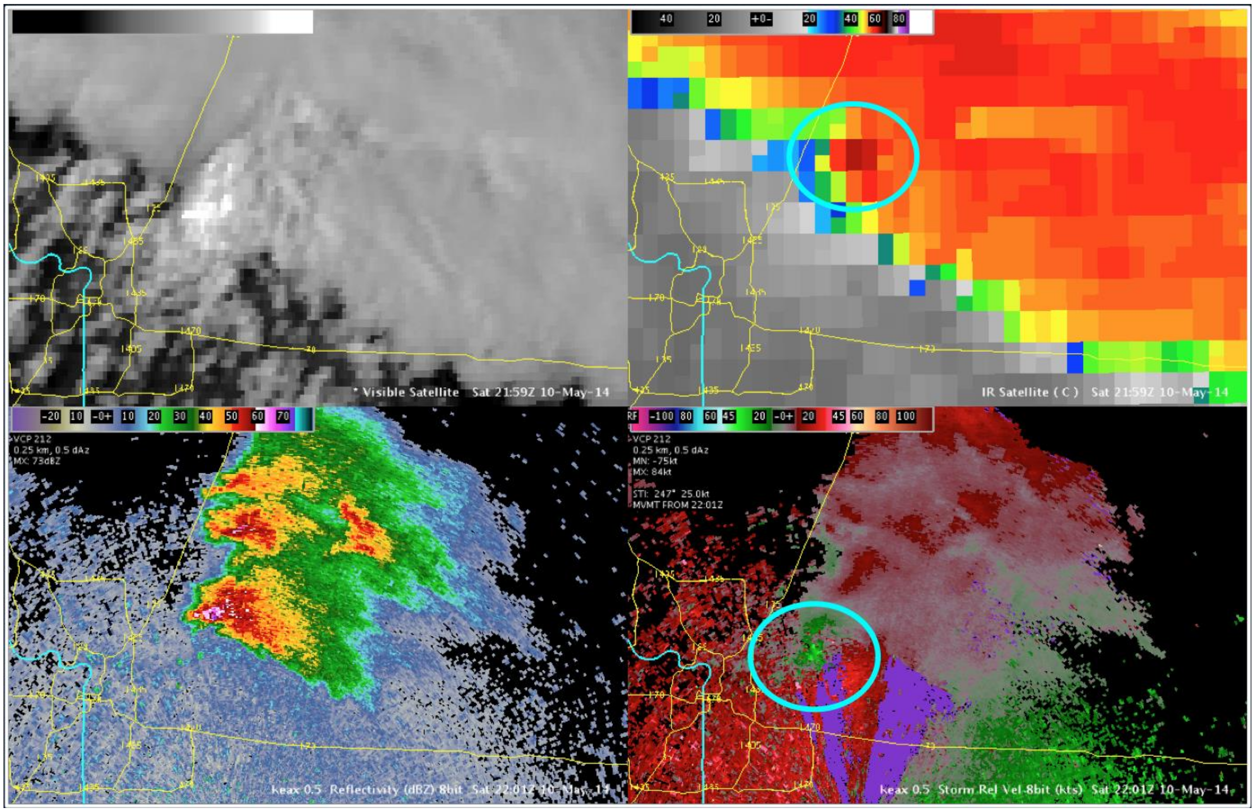

Fig. 2. (top left) As in Fig. 1 top left, except valid at 2159 UTC 10 May 2014, (top right) as in Fig. 1 top right, except valid at 2159 UTC 10 May 2014, (bottom left) as in Fig. 1 bottom left, except valid at 2201 UTC 10 May 2014, and (bottom right) as in Fig. 1 bottom right, except valid at 2201 UTC 10 May 2014.

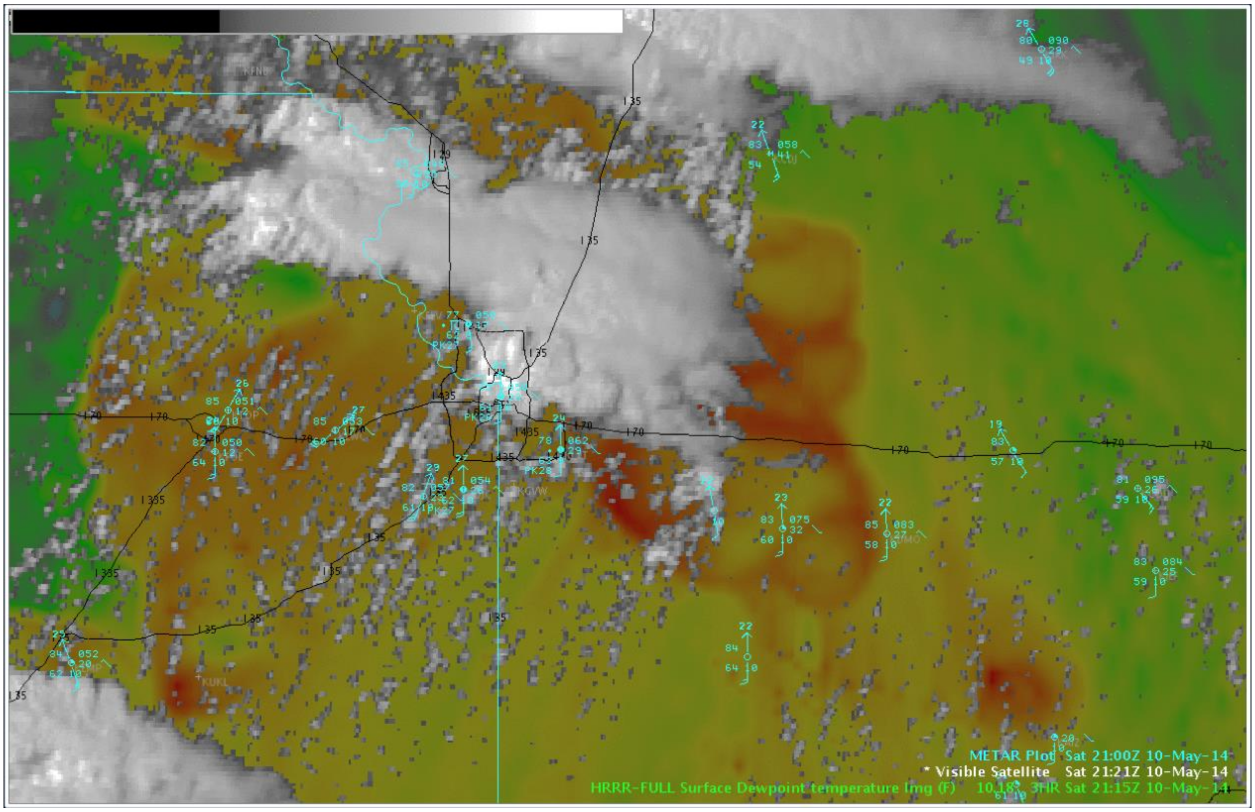

Fig. 3. 2121 UTC 10 May 2014 visible satellite image from the GOES-14, 2100 UTC 10 May 2014 Meteorological Terminal Aviation Routine Weather Reports, and High Resolution Rapid Refresh 2-m dewpoint 3.25-h forecast valid at 2115 UTC 10 May 2014.

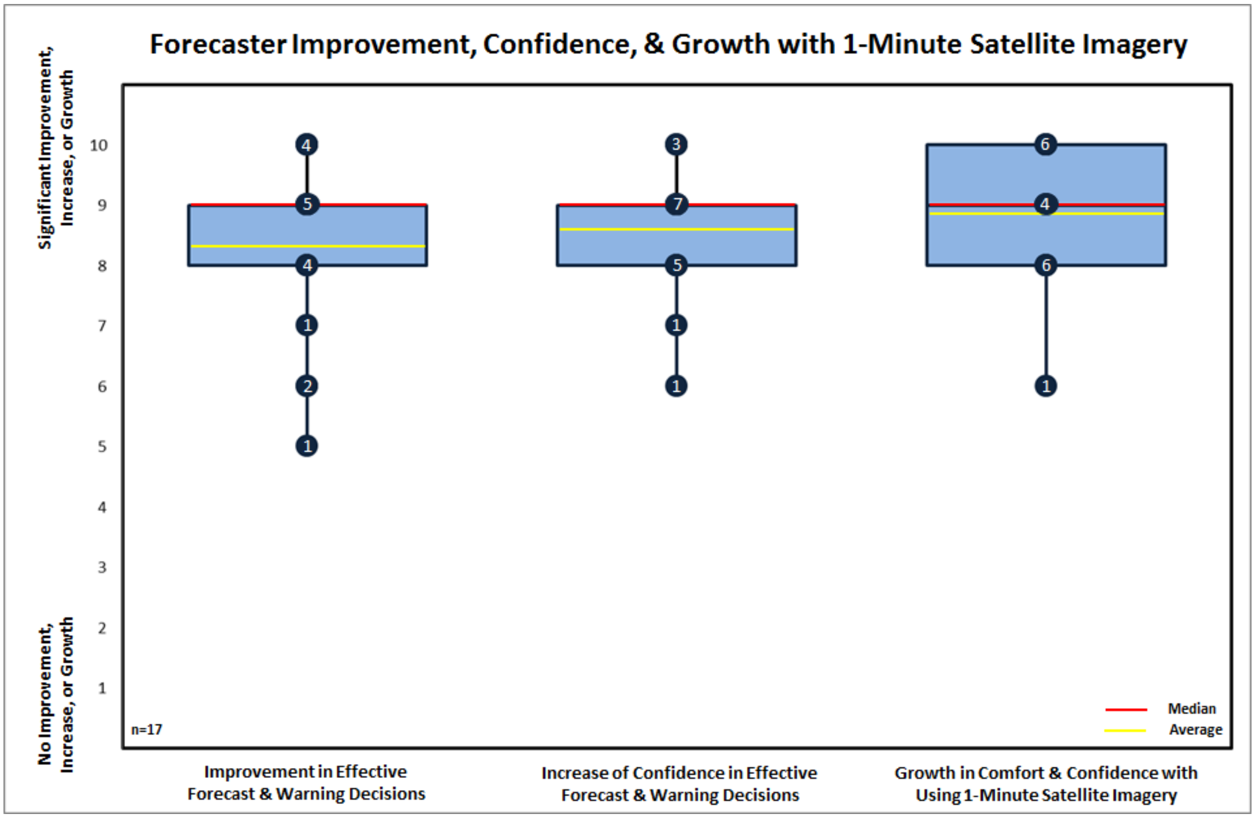

Fig. 4. Box-and-whisker plots of forecaster responses rating their improvement in effective forecast and warning decisions, their increase in confidence with making effective forecast and warning decisions, and their growth in comfort and confidence when using 1-min satellite imagery. The bottom and top of the solid blue box mark the 25th and 75th quartiles, respectively. The yellow bar denotes the median value, the red bar represents the average value, and the values indicate the number of responses chosen for that rating.

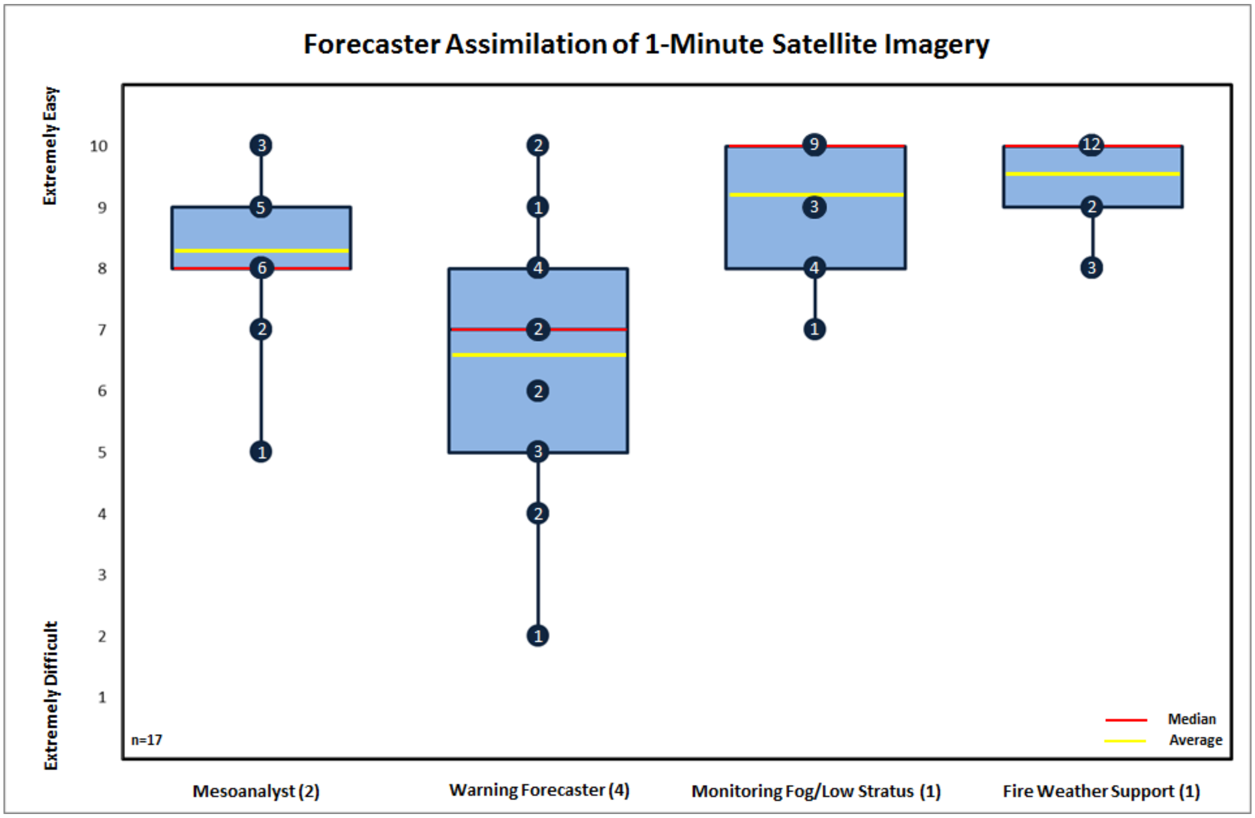

Fig. 5. As in Fig. 4 but for forecaster responses rating the ease of assimilation of 1-min satellite imagery as the mesoanalyst, as the warning forecaster, for monitoring fog and low stratus, and for providing fire weather support.

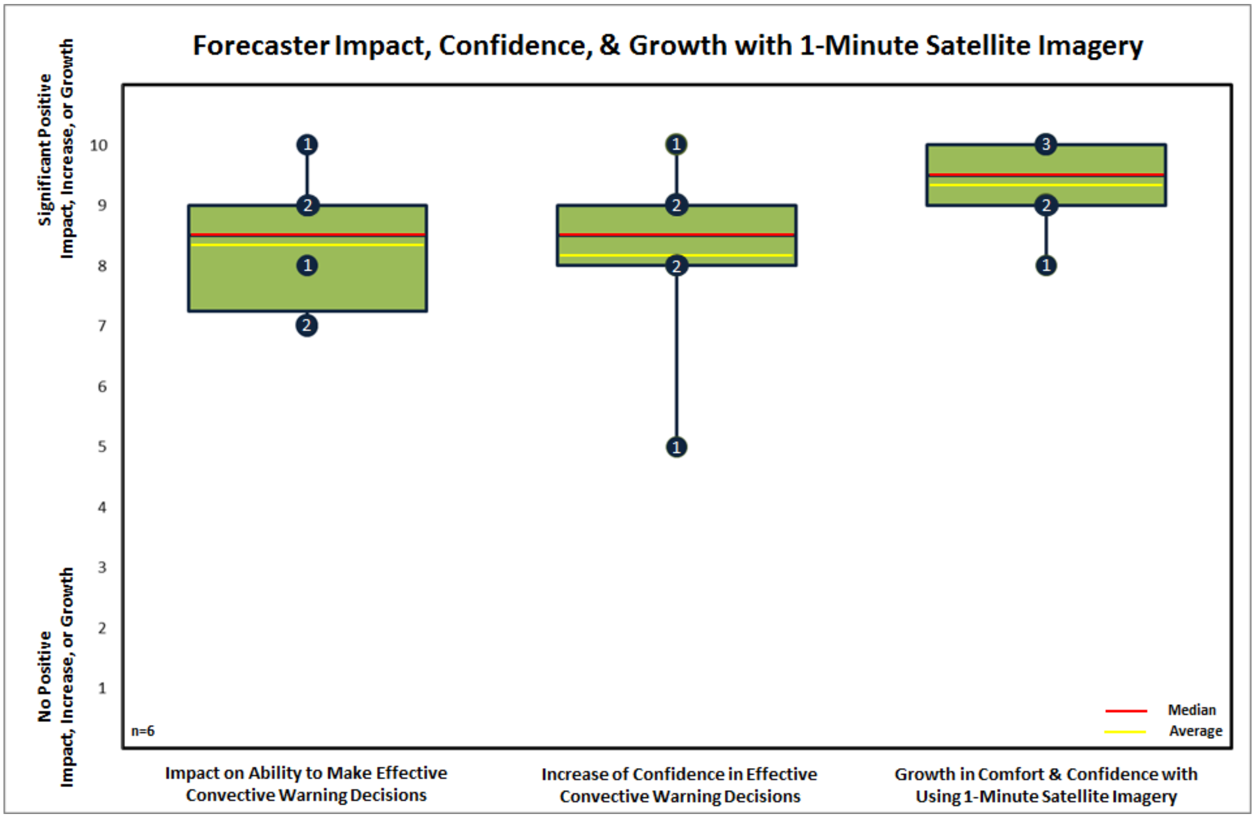

Fig. 6. As in Fig. 4 but for forecaster responses from the 2-week real-time evaluation integrating 1-min satellite imagery into decision making as the warning forecaster.

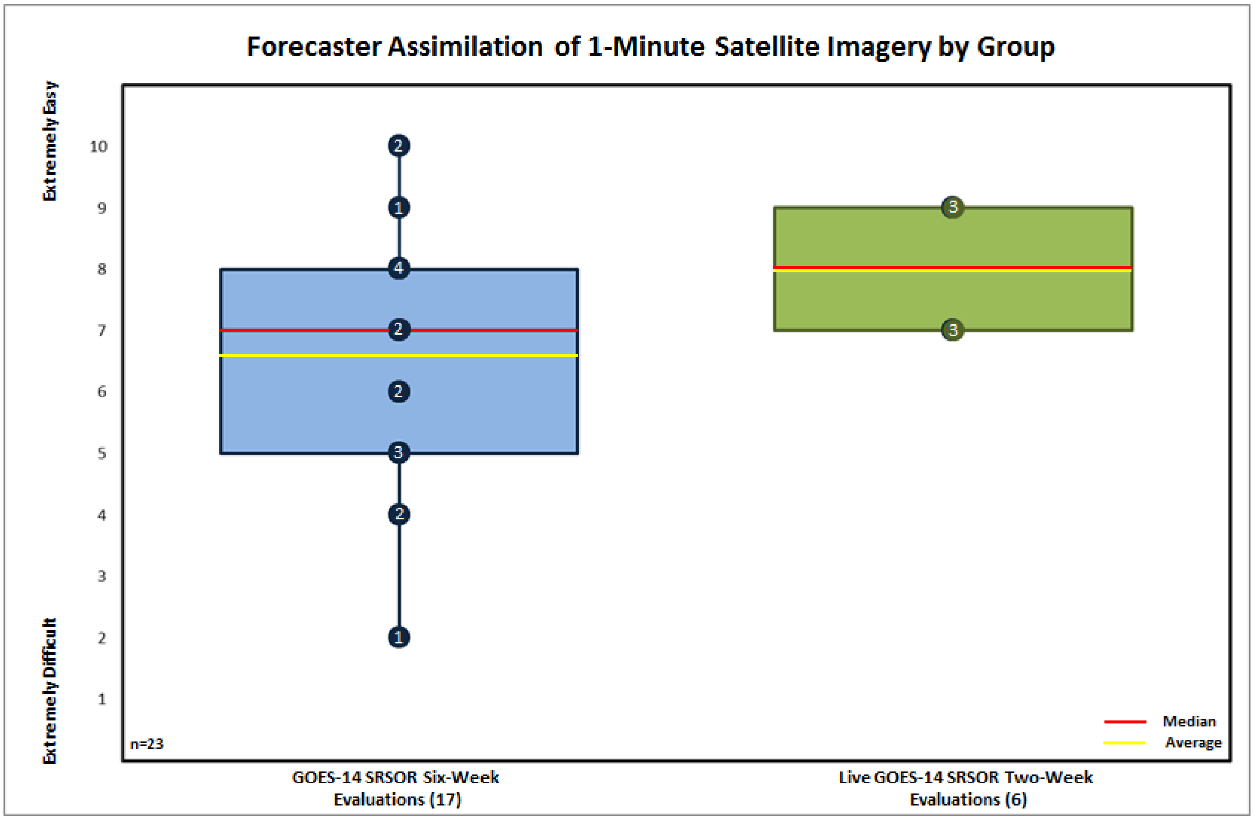

Fig. 7. As in Fig. 4 but for forecaster responses rating the ease of assimilation of 1-min satellite imagery as the warning forecaster during the 6-week evaluation and the 2-week real-time evaluations.

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NWS Operations Proving Ground

Evaluating the Usefulness of High-Temporal Resolution Satellite Imagery for NWS Operations in the GOES-R Era

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