Performance of Satellite Fog Detection Techniques With Major, Fog-related Highway Accidents

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Abstract

Five multi-vehicular highway accidents caused by low visibilities in fog were examined as to the ability of Geostationary Operational Environmental Satellite (GOES) techniques to detect the fog in advance. All of the accidents occurred near or shortly after sunrise on major U. S. or Canadian highways and resulted in numerous injuries and some fatalities. Multi-spectral infrared and visible channel data were used in the evaluation. In most cases, fog was detectable from GOES products but the lead time was usually short (1-3 hours). All were mesoscale events that would have required use of all available forms of observational data from satellites and surface mesonets to properly diagnose. Benefits and shortcomings of satellite-based techniques are described, along with technology improvements planned for future spacecraft.

1. Introduction

There are approximately 700 highway fatalities per year in the United States caused by driving in areas of dense fog (visibilities ¼ mile or less), and around 50 fog-related highway fatalities per year in Canada (Whiffen et al. 2004). While these do not seem like large numbers, fog-related highway fatalities are nevertheless ten times the number of deaths due to tornadoes. Within the past ten years, the number of fog-related accidents resulting in injury or death has stayed about the same, whereas the total number of weather -related highway accidents has declined (Figure 1) (Goodwin, 2002). A similar trend has been observed in Canada (Whiffen et al. 2004). Specifically, do satellite image products from Geostationary Operational Environmental Satellites (GOES) detect fog in the vicinity of major accidents and provide sufficient lead time for warnings? If not, what are the deficiencies of the satellite detection techniques? Five major fog-related accident events were evaluated with these questions in mind. While smaller, less dramatic events are no less important, information on the larger accidents was easier to obtain via media reports, and most likely represent the worst possible driving conditions.

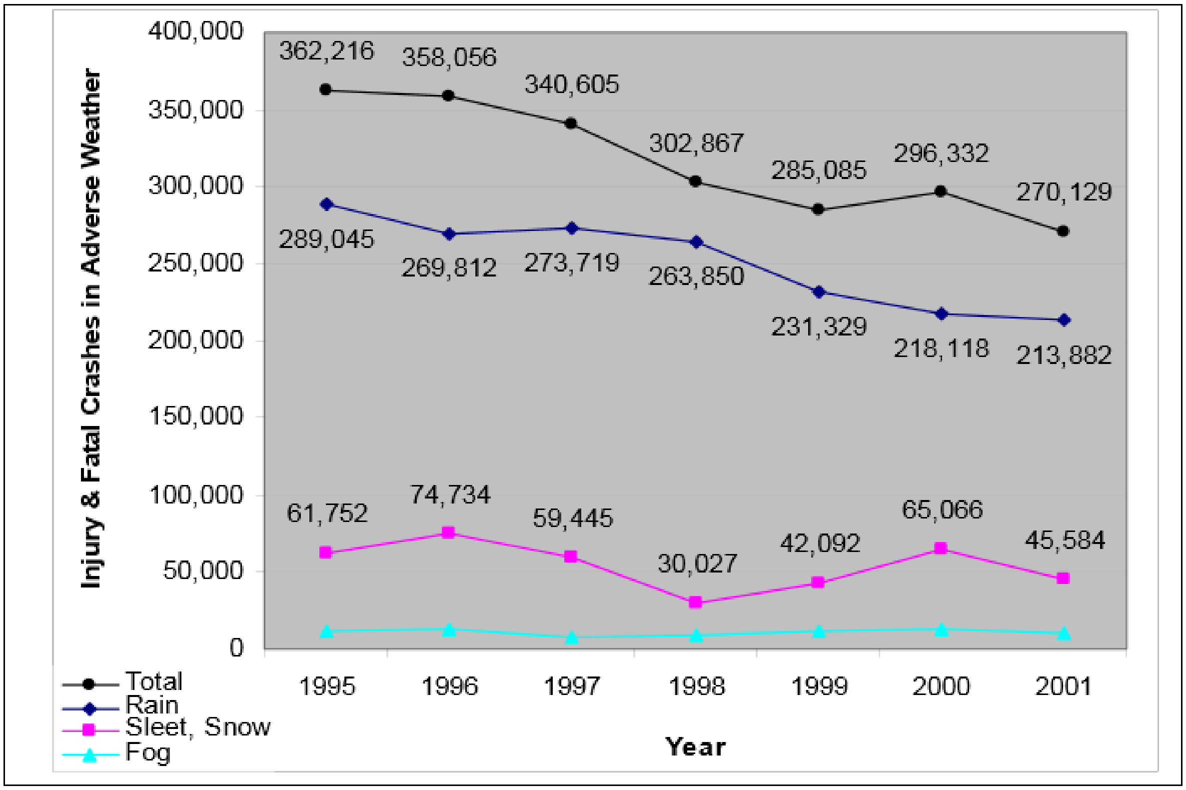

Fig. 1. *Annual trend of serious (injury or fatal), weather-related automobile accidents from 1995-2001 (Goodwin, 2001)*

Among many possible reasons for the continued high accident rate in foggy conditions are the following: (1) Despite steady improvements in automobile safety equipment, traffic volumes continue to rise, along with average speeds. (2) Drivers are commuting longer distances to their jobs, introducing the fatigue factor, especially in the early morning hours when fog is most often found.. (3) Finally, the occurrence of very dense fog (that reduces visibility to a few car lengths) is relatively rare; so many drivers do not have the experience of driving in conditions of very low visibilities.

The purpose of this paper is to examine the ability of meteorological satellites to detect fog and provide useful information to weather forecasters or transportation officials for the purpose of local warnings and advisories.

2. Data and Analysis

GOES products used in this analysis include single band Infrared (IR) in the 11 µm and 3.9 µm wavelength channels (IR4 and IR2 respectively), 0.6 µm Visible images during daytime periods, and the derived "fog product" at night (based on the 11 µm – 3.9 µm brightness temperature difference (BTD)) (Ellrod 1995). There is also a special fog depth color enhancement that can be applied directly to the fog product that helps determine where fog or low clouds are particularly thick and will likely persist for several hours after sunrise. The fog product is available to National Weather Service forecasters on the Advanced Weather Interactive Processing System (AWIPS), and can also be viewed on the Web at several sites (see appendix). It should be stressed that the nighttime fog product highlights all stratiform clouds consisting of water droplets, regardless of altitude, so careful interpretation and use of supplemental data from METeorological Aviation Reports (METAR) or aircraft pilot reports (PIREPs) is critical.

Single band GOES images as well as animations were evaluated to determine if fog was detectable prior to the time of the accidents. Detection of fog using the GOES two-band IR fog product usually requires a BTD value of at least 2K. This threshold can be lower in areas of marine stratus due to the micro-physical effects of larger droplet sizes found with those types of clouds systems (Lee et al. 1997). Thresholds can also be lower in situations where dense fog with small droplets is present, but is geometrically very shallow, resulting in smaller observed BTD. Generally, the synoptic conditions leading to those two scenarios are quite different; allowing a forecaster to determine which of the two is most likely. The value of animated GOES imagery is to show trends in area coverage and thickness. GOES data were obtained at 15 to 30 min intervals.

In this study, several major fog-related highway accident events were analyzed using archived GOES data. The accidents all involved at least dozens of vehicles, numerous injuries, and in many cases, fatalities. All occurred in the early morning hours, shortly after sunrise. The cases are summarized in Table 1.

TABLE 1.
Summary of Accident Cases Analyzed

Location	Highway	Date	# of Vehicles	Injuries	Fatalities
Mobile, AL	I-10	20 Mar ‘95	193	91	1
Windsor, Ont.	401	2 Sep ‘99	145	150	8
Cedar Grove, WI	I-43	11 Oct ‘02	38	38	10
Caliente, CA	CA58	3 Jan ‘02	77	15	1
Long Beach, CA	I-710	3 Nov ‘02	194	40	0

3. Results

a. Mobile Bay Alabama, 20 March 1995

The Mobile, Alabama "Bayway " accident that occurred early on 20 March 1995 is considered the largest in U. S. history, involving around 200 vehicles, and resulting in more than 90 injuries . The meteorological aspects of this crash were first described by Croft et al. 1997. Interstate highway 10 (I-10) crosses the extreme north side of Mobile Bay in an east-west direction (Figure 2). In the early spring, bay and offshore water temperatures are quite cool along the Gulf Coast, fed by cold water from southward flowing rivers such as the Alabama River that empties into Mobile Bay. When warm, moist air flows northward from the Gulf of Mexico in a stable environment, fog often results.

Animated GOES imagery and surface wind data showed that on the morning of 20 March 1995, the flow of air in the central Gulf Coast was from the warm Gulf of Mexico northward toward the coast. A single band IR4 image at 1032 UTC (4:32 AM CST) (Figure 3) showed several dark gray regions, including one in the vicinity of Mobile. The dark areas can indicate the presence of either warm, Moist, cloud-free air, or fog or low stratus (e.g. Gurka 1995), so the use of IR4 imagery alone can be ambiguous. Animated GOES fog product imagery (Figure 4) clearly showed however, that low clouds or fog (shown by the whiter areas) covered Mobile Bay and then extended well inland. The fog increased in area coverage with time as the clouds were spread inland by the southwesterly flow (image navigation, and thus the map overlay, was offset slightly to the east on this morning).

Fig. 2. *Road map of Mobile Bay showing I-10 Causeway, site of 20 Mar 1995 accident*

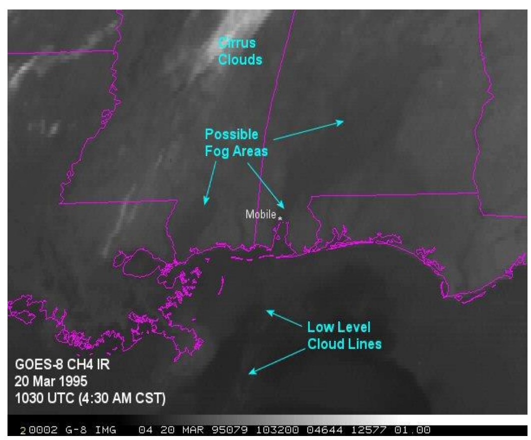

Fig. 3. *GOES-8 IR 4 image at 1032 UTC, 20 Mar 1995.*

The fog was detected in GOES imagery well before sunrise, although it was somewhat difficult to see over Mobile Bay due to the geographic overlay. Along I-10, the thickest fog near Mobile was confined to the bay northward, so motorists driving at high speed on I-10 would have encountered the fog rather suddenly as they crossed the causeway.

Some fog was also present over the Florida Panhandle to the east, but based on IR fog depth imagery (visible imagery was not available for this case), the fog was most likely shallower, although quite extensive (Figure 5).

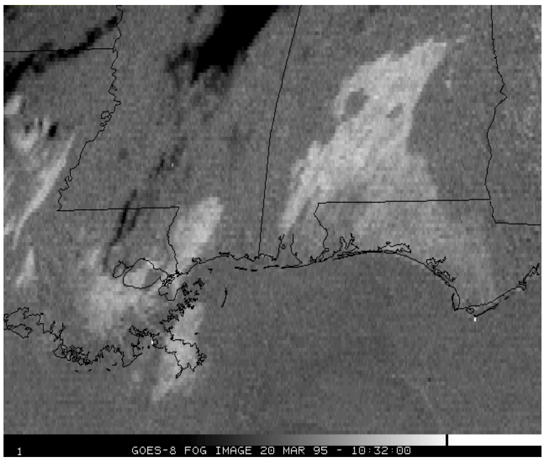

Fig. 4. *GOES-8 fog product image at 1032 UTC, 20 Mar 1995 (Click image for animation)*

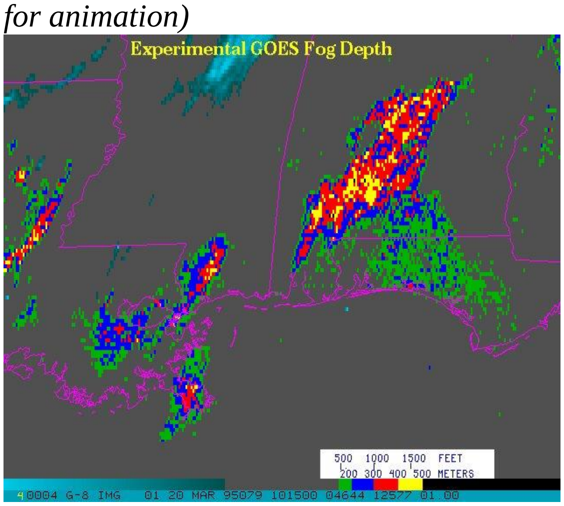

Fig 5. *GOES-8 fog product image with depth enhancement at 1032 UTC, 20 Mar 1995 (Click image for animation)*

b. Windsor, Ontario, 3 September 1999

The Windsor, Ontario accident occurred around 8 AM EDT on 3 September 1999 on Highway 401, a busy corridor connecting the major cities of southwest Ontario with Detroit and other cities in the northern Midwest (Figure 6). This was a very serious vehicle pileup that resulted in 8 fatalities and 150 injuries. A detailed analysis of this case is provided in Pagowski et al. 2004. A weak high pressure area centered over southwest Ontario resulted in light east to northeast winds across Lake St. Clair, just to the north of route 401.

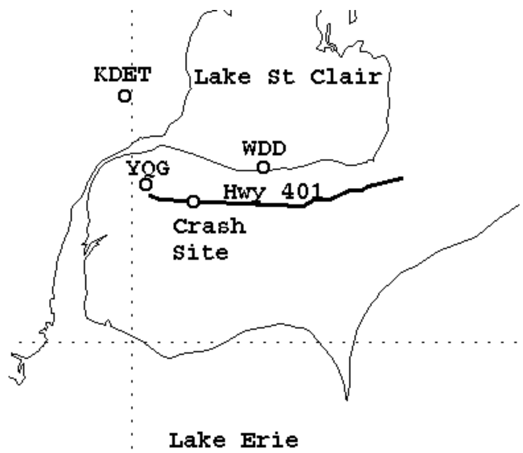

Fig.6. *Map of southwest Ontario showing location of accident near Windsor on 3 Sep 1999 around 1200 UTC.*

Animated GOES IR fog product imagery (Figure 7) showed that a patch of fog or low clouds developed over the western part of Lake St. Clair and drifted southward toward the Ontario peninsula (the crash site location is annotated on the images). Reports of extremely low visibilities from Mt. Clement, Michigan, at the northern tip of this cloud bank, suggested that this was likely dense fog. The last image in the loop (at 1215 UTC, close to the accident time) was shortly after sunrise, and exhibited a BTD reversal which resulted in the fog patch turning a dark gray shade (Figure 7). An animation of close-up GOES visible images (Figure 8, courtesy of Patrick King, Meteorological Service of Canada) beginning at 1200 UTC revealed that the fog patch grazed the north side of the peninsula (and Highway 401), then continued drifting southwest, dissipating by 1400 UTC except for a small area over Lake St. Clair. The fog patch appeared to be slightly larger in visible images than was revealed by the IR fog product prior to sunrise.

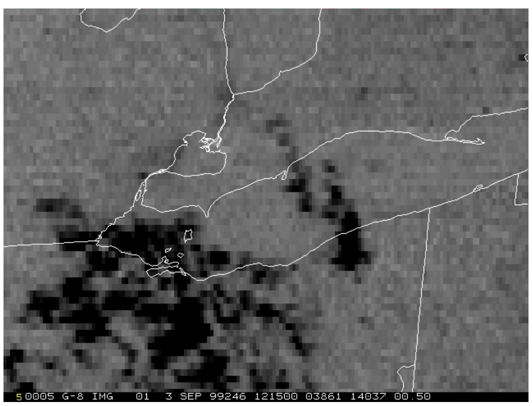

Fig. 7. *GOES-8 fog product image at 1215 UTC, 3 Sep 1999 (Click for loop)*

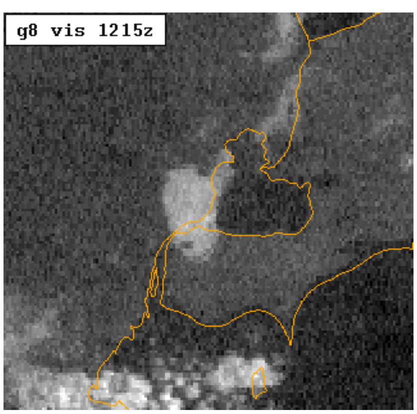

Fig. 8. *GOES-8 visible image at 1215 UTC, 3 Sep 1999 (Click image for loop)*

In this case, GOES images detected the fog prior to the accident, but only careful analysis of animated GOES IR images could have led to the expectation that the fog would impact Highway 401. An encouraging aspect of this case is that the Penn State University/National Center for Atmospheric Research MM5 mesoscale model (Grell et al. 1995) was able to simulate the fog formation and development reasonably well (Pagowski et al. 2004), providing some hope of the future ability to forecast such events using high resolution models.

c. Cedar Grove, Wisconsin, 11 October 2002

Highway I-43 runs north-south along the western shore of Lake Michigan and connects small to medium sized cities such as Green Bay and Manitowoc in northeastern Wisconsin with Milwaukee and Chicago to the south (Figure 9). On the morning of 11 October 2002, motorists encountered dense fog near the town of Cedar Grove that resulted in a multi-vehicle accident that killed 10 persons and injured 38. A previous study was completed on the satellite detection capabilities for this case by Lindstrom (2004). Inspection of animated GOES fog product images (Figure 10) showed some hint of fog development prior to the accident, which occurred just after sunrise. Based on the movement of the fog, there appeared to be a light onshore breeze along the west side of Lake Michigan. However, the BTD threshold for the bi-spectral images was 1-2K, which is slightly lower than is normally observed for significant fog or low clouds using this technique. Even the visible image at 1300 UTC (Figure 11) barely showed the fog due to its shallowness (Lindstrom 2004). For this case, it is doubtful that a warning could have been issued based on GOES satellite data alone.

Fig. 9. *Road map of eastern Wisconsin showing approximate location of severe accident on 11 Oct 2002 near Cedar Grove, WI*

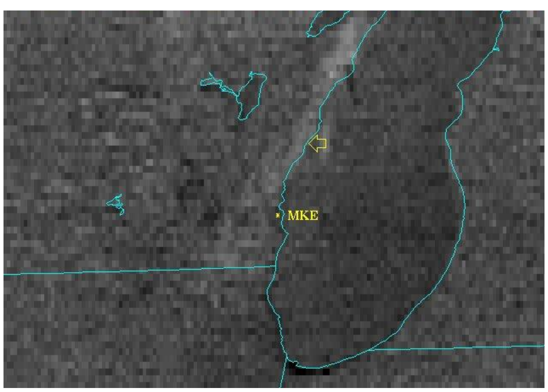

Fig 10. *GOES-8 fog product image, 1215 UTC 11 Oct 2002 (Click on image for animation)*

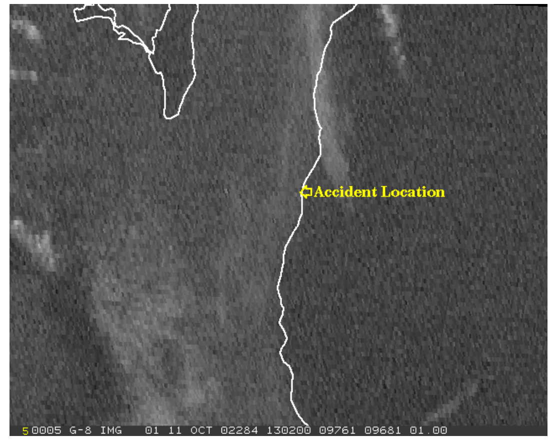

Fig 11. *GOES-8 visible image at 1300 UTC*

d. Caliente, California, 3 January 2002

The fourth case is the Caliente, California accident on state highway CA58 on the morning of Monday, 3 January 2002. CA58 connects the lower San Joaquin Valley and Bakersfield metropolitan area with the Mojave Desert to the southeast (Figure 12). Seventy-seven vehicles were involved in this accident, resulting in 15 injuries and 1 fatality. A multilayered, frontal cloud system with some precipitation had just passed through the region, as shown in the GOES-10 IR image (Figure 13) at 1400 UTC. Much of the valley to the north of Caliente was seen covered by a dark gray region in the unenhanced IR image, suggesting either warm moist air or low clouds, but most likely the latter given the synoptic situation. An animation of the two-band IR fog product showed that low stratus was forming and moving down the valley toward Caliente in the northwesterly flow following the front (Figure 14). The final image of the sequence is at 1400 UTC, about 1 hour prior to the accident, so it is likely that fog enveloped the accident scene just before sunrise.

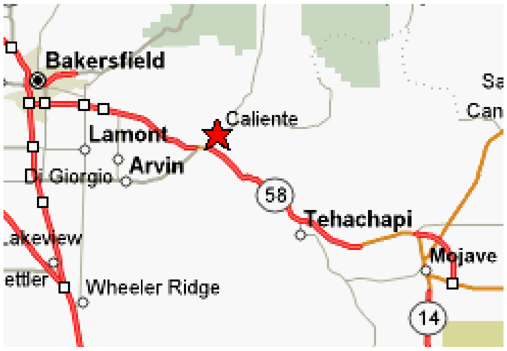

Fig. 12. *Road map of southern San Joaquin Valley, site of roadway accident near Caliente on 3 Jan 2002*

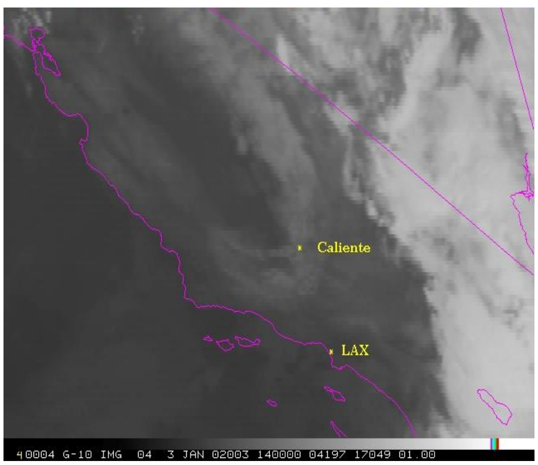

Fig. 13. *GOES-13 IR image at 1400 UTC, 3 Jan 2002*

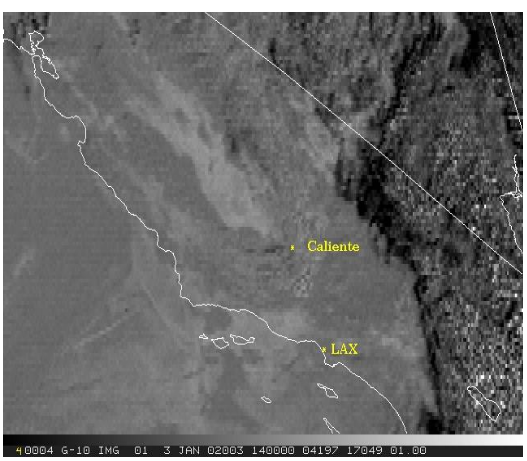

Fig. 14. *GOES-13 fog product image at 1400 UTC, 3 Jan 2002*

e. Long Beach, California, 3 November 2002

The fifth and final case occurred on I-710, a north –south freeway near Long Beach, California (Figure 15) shortly after sunrise (1500 UTC) on the morning of Sunday, 3 November 2002. The accident involved 194 vehicles, and resulted in 40 injuries, 9 of which were critical.

Animated GOES fog product images observed the fog develop in the pre-dawn hours in the area near Long Beach, and the southern portions of Los Angeles (Figure 16). However, the fog was quite patchy, and tended to form rapidly in some locations, while dissipating in others. The area of fog that caused the accident formed in a northwest to southeast band to the north of Long Beach by around 1200 UTC, and then drifted southwestward over I-710, expanding in area coverage as it moved. Since the fog was not widespread, motorists would likely have encountered the fog suddenly while enroute to or from Long Beach. A close up view of the area provided by a GOES-10 visible image after sunrise (1530 UTC) (Figure 17) showed that the IR fog product provided reliable information about the location of the fog during the pre-dawn hours.

Fig. 15. *Road map of Long Beach, CA, site of 3 Nov 2002 accident on I-710*

4. Satellite Analysis Summary

Analysis of the five major accident cases showed that GOES satellite image products were able to observe fog or low clouds at or near the accident location in most cases. The one possible exception is the I-43 event, where fog was difficult to detect because it was too shallow. The fog was observed in GOES images typically 1 to 3 hours in advance of the accidents, allowing a short period of time to provide some warnings or advisories. The sudden onset of fog was no doubt a factor in the severity of most of these accidents. The resulting rapid decrease in visibility was caused by the limited extent of the fog, which was in patches or narrow bands, along with either movement or development. In other words, these were truly mesoscale events, which require high resolution, high frequency data to resolve, predict, and provide warnings.

A mitigating factor in all cases was that the events occurred shortly after sunrise, at a time when GOES IR products used in fog detection become less useful due to contamination by solar reflectance, and

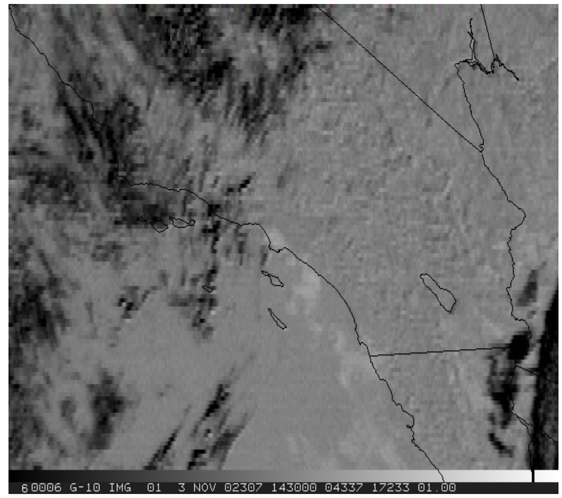

Fig. 16. *Fog product image at 1430 UTC, 3 Nov 2002 (click on image to animate)*

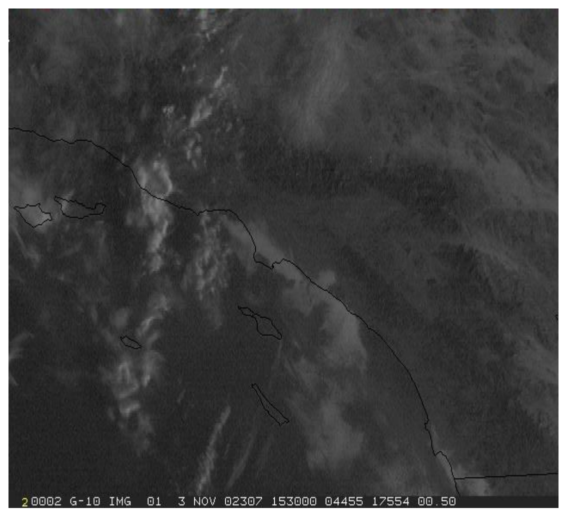

Fig. 17. *GOES-10 visible image at 1530 UTC, 3 Nov 2002*

visible imagery is still somewhat limited by low sunlight conditions. Thus, some extra effort is required to observe and analyze both types of image products during the transition period from night to day.

Lastly, there is the nagging uncertainty caused by the inability of

GOES products to detect low visibility conditions at the surface. While some progress has been made in determining the likelihood of a low cloud base using GOES and surface temperature data (e.g. Ellrod 2002), low cloud bases do not necessarily correlate well with low visibilities at the surface. Thus, GOES data must be supplemented with surface visibility reports such as those from Road Weather Information Systems. Demonstration of the complementary use of satellite and surface data in fog detection and analysis was shown by Fischer et al. 2003. The existing METAR system provides weather and visibility observations from airports but is not adequate for highway fog warnings. In the cases described in this report, there were often METAR observations that showed fog in the region, but not in the immediate vicinity of the accident (e.g. Mt. Clement, Michigan for the Ontario crash).

5. Upcoming Technological Improvements to GOES

Some technological improvements are scheduled to be implemented on GOES that should help with fog detection and advisories. Some near-term improvements will come about starting with the GOES-N (GOES-13) spacecraft due to be launched early 2006. An increased power supply will allow the Imager to operate throughout the satellite eclipse periods in fall and spring, eliminating nighttime blackout periods during severe storms, hurricanes, and fog formation. A star tracker navigation system will be deployed, allowing an increase in mapping accuracy from 6 km to 2 km at night.

Even greater improvements will come with the launch of GOES-R (circa 2012) and the modernized Advanced Baseline Imager (Schmit et al. 2005). The most notable improvements will be: (1) the faster scanning capabilities, allowing routine 5-minute interval observations of the Continental United States and southern Canada, (2) higher spatial resolution, with 2 km IR and 0.5km visible imagery, (3) improved signal to noise ratio (SNR) in the shortwave IR channels, that will allow better discrimination of fog from background surfaces at night, especially with colder surface temperatures.

The latter two upgrades have been simulated using high resolution polar satellite data from the NOAA Advanced Very High Resolution Radiometer (AVHRR) and NASA Moderate-resolution Imaging Spectroradiometer (MODIS) instruments. Figure 18 approximates the improved resolution that will be attainable from the ABI during fog episodes using AVHRR 1 km fog imagery reduced to 2 km resolution. It can be seen that the precise coverage of valley fog in the Central Appalachian Mountains is much more easily determined with the 2 km data. Figure 19 compares MODIS fog product imagery (with a fog depth color enhancement) with GOES for a case of extensive fog and stratus in the Great Plains of the U. S. The MODIS image has a better definition of the fog edges, especially for the fog filament in eastern South Dakota. The GOES-R ABI will have an SNR value

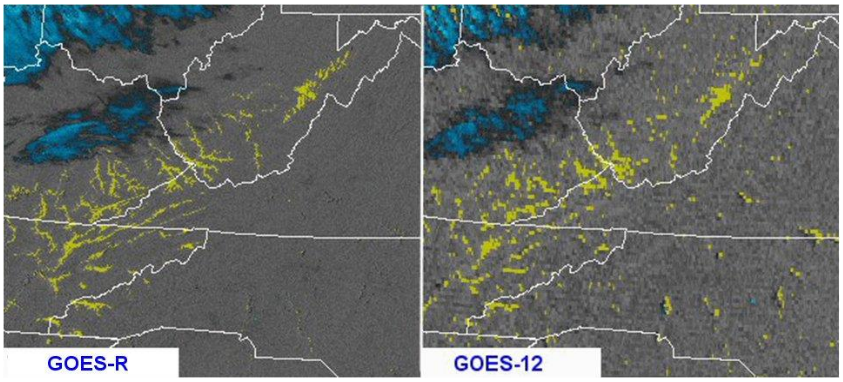

Fig.18. *Fog product images from AVHRR (left) and GOES-12 (right) to simulate difference between future ABI on GOES-R and current GOES.*

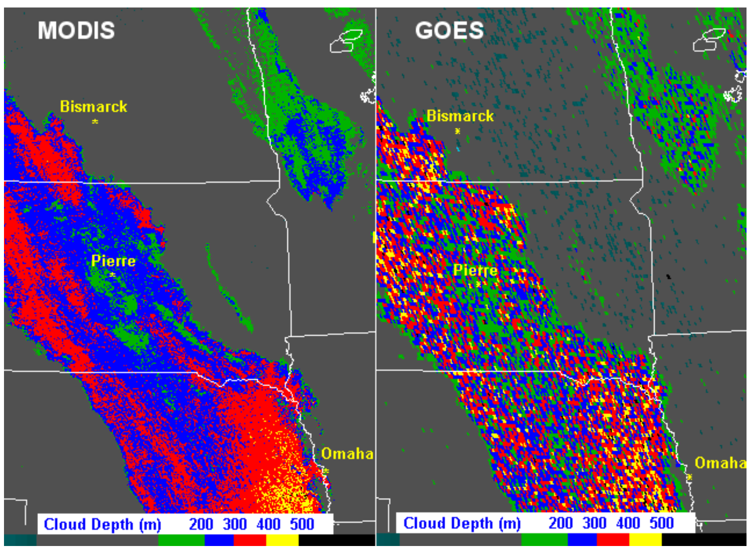

Fig. 19. *Fog depth image enhancement from 1km resolution MODIS (left) versus current 4km GOES (right)*

that is better than current GOES, but slightly worse than shown by the MODIS example (left panel).

6. What's needed To Improve Highway Fog Warnings?

In addition to the technological improvements to GOES previously noted, there are a number of steps that are needed to provide a better system to warn motorists about hazardous fog situations. Many of these recommendations were outlined in a recent forum on Weather and Highways (American Meteorological Society 2003). More environmental sensors are needed along roadways to detect low visibilities and quickly provide the information to Road Weather Information Systems for use by traffic officials and weather forecasters. National Weather Service (NWS) offices need to have direct access to this data to help with the timely issuance of Hazardous Weather Advisories similar to those for snow or ice, excessive heat, high winds, etc. Unfortunately, some states have very few (or no) RWIS, and must rely on on-site reports from motorists or highway patrolmen. Although RWIS' are somewhat expensive to install and maintain, their benefits can more than outweigh costs, especially on roadways with high traffic volume.

Once a dense fog event has been observed, the use of Variable Message Signs (VMS) and dynamic speed limits can then be used to help reduce the large variation of travel speeds that can occur, decreasing the risk of collisions. Finally, better driver education courses and public safety messages on radio and television would increase driver awareness of the dangers of dense fog and offer helpful advice on how to reduce the risk of accidents, such as adherence to VMS posted speed limits, use of emergency flashers, etc. The incorporation of GOES (and other types of) satellite data into highway warnings while feasible, appears to be a long way off due to shortcomings previously described. GOES image products nevertheless can contribute to the situational awareness of traffic officials and weather forecasters by providing information on the extent, movement, and possible duration of dense fog.

Acknowledgment

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References

American Meteorological Society, 2003: Weather and highways. Final Report on policy forum held 4-5 November 2003, Washington, DC, available at: http://www.ametsoc.org/atmospolicy/documents /WxHighwaysFinalReport .pdf .

Grell, G. A., J. Dudhia , and D. R. Stauffer, 1995: A description of the fifth generation Penn State/NCAR Mesocale Model (MM5). NCAR Tech. Note NCAR/TN-392+STR, 122pp.

Gurka , J. J., 1995: Fog and low cloud. In: Images in weather forecasting: A practical guide for interpreting satellite and radar imagery. Ed.: M. J. Bader, G. S. Forbes, J. R. Grant, R. Lilley, and A. J. Waters. Cambridge University Press, U. K., 445-456.

Ellrod, G. P., 1995: Advances in the detection and analysis of fog at night using GOES multispectral infrared imagery. *Weather and Forecasting* , **10** , 606-619.

___________ 2002: Estimation of low cloud base heights at night from satellite infrared and surface temperature data. *National Weather Digest* , **26** , 39-44.

Fischer, K. W., G. P. Ellrod, M. R. Witiw, J. A. Baars, and T. J. Ashman, 2003: Validation of GOES Imager experimental low cloud data products for terrestrial free space optical telecommunications. *Proc. 12 th Conf. on Satellite Meteor. and Oceanography* , Paper P1.17, 9-13 February 2003, Long Beach, California, American Meteor. Soc., Boston.

Goodwin, L. C., 2002: Analysis of weather-related crashes on U. S. highways. Mitretek Systems, Washington, DC, available at: http:/ /www.ops.fhwa.dot.gov/Weather/best_practices/CrashAnalysis2001. pdf

Lee, T. F., F. J. Turk, and K. Richardson, 1997: Stratus and fog products using GOES-8-9 3.9-µm data. *Weather and Forecasting* , **12** , 664-677.

Lindstrom, S., 2004: Challenges in routine fog detection from current satellite data. National Highway Visibility Conference, Madison, Wisconsin, 18-19 May 2004.

Pagowski,M.,I. Gultepe,and P.King, 2004: Analysis and modeling of an extremely dense fog event in Southern Ontario. *J. Appl . Meteor.* , **43** , 3-16.

Schmit,T.J.,M.M.Gunshor,W.P.Menzel,J.J.Gurka,J.Li,and S. Bachmeier , 2005: Introducing the next-generation baseline imager on GOES. *Bull. Amer. Meteor. Soc.*, **86** , 1079 -1096.

Whiffen , B., P. Delannoy , and S. Siok, 2004: Fog: Impact on road transportation and mitigation options. National Highway Visibility Conference, Madison, Wisconsin, 18-19 May 2004.

Appendix: Internet Sources of Satellite-derived Imagery for Fog Detection

NOAA/NESDIS Office of Research and Applications
http://www.star.nesdis.noaa.gov/smcd/opdb/aviation/fog.html
NOAA/NWS Western Region
http://www.wrh.noaa.gov/satellite/
Naval Research Laboratory, Monterey (provided at night in place of visible images)
http://www.nrlmry.navy.mil/sat-bin/epac_westcoast.cgi