NOWCASTING THUNDERSTORM INTENSITY FROM SATELLITE: A REVIEW

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ABSTRACT

With the advent of higher resolution satellite instruments, renewed interest in applications to severe storm detection and nowcasting is growing. The initial interest in the use of geostationary satellite data to identify thunderstorm growth and intensity took place from the 1970's through the 1980's. Early analyses included stereoscopic and rapid scan observations of storm top morphology such as, measured rates of cloud top cooling and anvil expansion, the evaluation of colliding outflow boundaries related to new thunderstorm development, and the quantitative characteristics of the enhanced "cold-V" signature. Some of this research related to the infrared characteristics of convection has been used in the development of rainfall rate algorithms from satellite. Despite this extensive and very promising early work, satellite observations have failed to become widely used quantitatively in operational severe storm detection.

The basis of these satellite-based approaches will be reviewed and contrasted with developments in radar meteorology, which provided deeper insight into internal properties of storms. Current attempts to apply multi-spectral satellite data to the study of thunderstorm cloud tops and their surrounding environment from GOES and Meteosat Second Generation (MSG) will be discussed. These include the trend analysis of mesoscale convective systems, analysis of thermodynamic instability, and studies of cloud top properties. Recent techniques for nowcasting thunderstorm development from cloud growth rates and estimates of microphysical composition of cloud tops will also be reviewed.

1. INTRODUCTION

The enhanced measuring characteristics of the METEOSAT Second Generation (MSG) will provide observations of clouds and developing storms over Europe and Africa with better resolution than ever before from a geostationary satellite. Many new products will be available to forecasters to help with the monitoring and prediction of a wide range of weather phenomena. Despite the availability of an advanced system of geostationary satellites covering the U.S., the detection of severe or violent thunderstorms has been dependent mainly on radar and storm spotters when available. In Europe and Africa, radar and spotter networks are less developed or even non-existent. The question arises, to what extent can satellite be used for the detection of these severe weather phenomena? A rather extensive history of research into this question is available since the first satellite observations more than 40 years ago in the U.S. The purpose of this paper is to provide a concise review of principle findings from this line of research and of some current applications of the satellite data. The emphasis will be on inferring intensity or severity of existing thunderstorms, which includes the occurrence of high damaging winds, hail, and tornadoes. The estimation of rainfall from satellite imagery and the use of the data in numerical weather prediction are important topics, but beyond the scope of this paper. However, storm initiation and intensification will be covered briefly. It is hoped that this information will be useful in the implementation of severe weather applications of the MSG data.
2. FIRST PICTURES

The year was 1960 and the first pictures of thunderstorms were transmitted to earth from the TIROS-1 (Television Infrared Observation Satellite) low orbiting satellite. These were exciting times, as much was to be learned from extensive pictures of the clouds from above. The first published studies reported on the visible characteristics of thunderstorms. Reading these papers may remind us of our own impressions after seeing satellite images for the first time. For example, Whitney (1963) observed that the storm clouds were “conspicuous and distinctive” and sometimes had sharp, scalloped edges. They were of medium size and not linear in shape. It was also noted that multiple anvils were combined into single, highly reflective cloud tops. Moreover, he noted that these clouds covered a much larger area than the radar echoes and locations of sferics (lightning) associated with the storms. The notion that clear regions adjacent to the storm clouds (compensating subsidence) might an indication of storm severity was proposed.

One of the first studies to propose an index of severity based on cloud characteristics was Boucher (1967). Based on 17 cases from TIROS IV-VII (1962-1964), the diameter of the cirrus shield was suggested to be an index of storm severity. It was noted that diameters of less than about 100 km were rarely severe, while diameters of greater than 250 km often had severe weather. It was also observed that penetrating tops (above the anvil) were not always associated with severe weather. Also, the adjacent clear areas reported by Whitney were not commonly observed.

Some of the first ideas for using satellite imagery in severe weather forecasting and warnings were presented by Purdom (1971). The appearance of squall lines as a wedge shape cloud, narrowing to the south, was noted. Methods to precisely locate the polar and subtropical jet stream, the thermal ridge, and vertical wind shear, which are factors in severe thunderstorm development, were illustrated using NOAA-1 imagery. He also proposed several ideas on how geostationary imagery (from the Applications Technology Satellite, ATS-3) could be used to improve warnings. It was noted that developing squall lines could be detected earlier than from radar, and that specific regions of convective clusters could be identified to be under threat of severe weather (often the southern portion). Finally, the repeated images (as frequent as 11 minutes) allowed measurements of the rate of anvil growth. A pause in the growth was observed to occur at the time of tornado occurrence.

The idea of anticipating thunderstorm initiation, from the location of boundaries and other mesoscale features in high-resolution geostationary imagery, was suggested by Purdom (1976). The effect of terrain (coast lines, rivers, and lakes) was shown on the formation of convective clouds. Precise location of storm outflow boundaries could be made from high resolution GOES (Geostationary Operational Environmental Satellites). Given favorable environmental conditions (stability, etc.), intersecting or merging of boundaries was observed to coincide with new storm initiation or intensification. Some possible mechanisms for such intensification has been explored by Maddox et al. (1980). The utility of locating thunderstorm boundaries and other mesoscale cloud features has been one of the most powerful applications of satellite imagery in severe storm forecasting to date.

3. EXPLORATION OF INFRARED IMAGERY

One of the earlier studies of thunderstorm anvil structure, which made use of the infrared imagery, was that of Anderson (1979). Observations of a few select severe storms suggested anticyclonic rotation and spiral bands with similarity to hurricanes. The cirrus plumes extended downwind but to the right of the upper level flow. The significance of these characteristics to storm severity was not determined. In a latter study, Adler et al. (1981) reported a cyclonic spiral cloud shadow in visible imagery, possibly associated with a mesocyclone observed from Doppler radar.

An early study of overshooting (penetrating) cloud tops from geostationary satellite was reported by McCann (1979). The collapse of overshooting tops had been previously observed by high altitude aircraft and possibly linked to tornado formation (Fujita, 1973; Umenhofer, 1975). In this study, the collapse appeared to be related to enhanced low-level outflow from the storm. In some cases, this coincided with acceleration of the gust front, strong surface outflow (bow-echoes), and occlusion of mesolow, which sometimes precedes tornado genesis. This suggested a possible utility in anticipating strong surface winds, however it was emphasized that the collapsing top was not a direct cause of the tornado.
Maddox (1980) identified a unique class of convective system on the basis of the infrared observations of GOES. Frequenting the Midwest U.S. in summer, these systems, termed Mesoscale Convective Complexes or MCCs, had unique characteristics in the satellite imagery. They were observed to have long life times as compared to individual storms (> 6 hrs), extensive, cold cloud shields (> 100,000 km at <-32 C), and were nearly circular in shape (eccentricity > 0.7). Producing a wide variety of severe weather and heavy rain, these weather systems are still difficult forecast. They occur with weak upper-level forcing and appear to be driven in part by low-level warm air advection.

3.1 GROWTH RATES

One of the first attempts to use geostationary imagery to relate rates of cloud top cooling and anvil expansion to storm severity was conducted by Adler and Fenn (1979). They used 5-minute infrared data from the NASA Synchronous Satellite (SMS 2) to compare a set of severe and non-severe storms from a single day. The severe storms exhibited more rapid growth and colder cloud top temperatures. Storm-top divergence and vertical velocity inferred from rates of cooling and anvil expansion were twice as large for the severe storms. Tornadoes occurred after rapid expansion in several of the storms. It was suggested that a 30-minute lead-time might be possible in anticipating severe weather. Limitations to the measurements were that existing anvils may have obscured new storm growth and that storm heights estimated from cloud top temperature appeared to be underestimated when compared to radar.

These ideas were investigated further by Adler et al. (1985). Using 5-minute imagery from SMS-2 and NOAA’s GOES-1, an index of thunderstorm intensity was developed. The index was computed as the maximum updraft intensity inferred from cloud top ascent rates and expansion rates of isotherms (cloud top temperature). Based on storms on four different days, the index could distinguish most severe from non-severe storms when tested on independent data. The difficulty of identifying growing cloud tops due to existing anvils was reaffirmed in the study. In addition, cold cloud tops sometimes appeared to be too warm because of instrument resolution. The ambiguity in estimating height from cloud top temperature was recognized again.

Reynolds (1980) examined the relationship of cloud top temperature to the occurrence of hail. It was expected that a more direct relationship might exist between inferred updraft intensity and hail than with other types of severe weather. For example, tornadoes depend on other factors such as low-level wind shear. The storms studied developed large, cold cloud tops and were long-lasting (3–5 hours). The onset of hail was related to rapid cloud growth and the cloud tops becoming colder than the tropopause. Maximum hail occurred when the cloud top temperature reached a minimum (and the difference with the tropopause temperature was largest). An enhancement of the infrared imagery was proposed to identify clouds colder than the tropopause.

3.2 “ENHANCED-V” SIGNATURE

From infrared imagery, a distinctive warm spot embedded at top of the anvil cloud was observed with some severe thunderstorms (Mills and Astling, 1977). Hypotheses for the local, warm region of the cloud included greater emissivity, mixing of warm, stratospheric air, and subsidence. When enhancing the imagery to view small temperature differences within the cloud top, McCann (1983) reported on an area of cold cloud top temperature adjacent to the warm spot in the shape of the letter “V”. The orientation of the “V” was related to the upper-level wind with open end pointing downwind. The signature was referred to as an “enhanced-V”.

McCann (1983) used 30-minute infrared imagery from a large number of cases (~900) to investigate the relation between the “V” shaped pattern of cloud top temperature and severe weather occurrence. Most storms with an enhanced-V exhibited some form of severe weather. The appearance of the “V” usually preceded the severe weather; on the average 30 minutes earlier. The false alarm rate (FAR) from warning on the basis of the “V” was about 0.3, similar to current radar methods based on mesocyclone or 3-D reflectivity structure (e.g., Polger et al., 1994). On the other hand, many severe storms did not have an enhanced-V, leading to a relatively low probability of detection (POD), 0.25, which is much less than possible with radar. The enhanced-V occurrence was linked to the combination of strong upper-level wind and
penetrating tops (intense convection). Perhaps, the POD would have been more favorable if the study segregated cases on the basis of upper-level wind speed. The widespread use of this technique for identifying severe weather is unknown.

The causes of the warm spot feature were studied further by Adler and Mack (1986). Using stereoscopic observations from a pair of GOES satellites (1979) and a simple updraft model, they identified three classes of storms. The first class had a vertical updraft with the summit and coldest cloud top located in the center of the anvil. It formed with an isothermal layer above the tropopause, and without horizontal wind shear. The second class was under similar conditions, except for horizontal wind shear near the top of the storm. This class also had a collocated summit and cold cloud top, however a warm spot was located downwind due to subsidence warming. In essence, the cold-warm couplet was a manifestation of the wind shear, which separated the top of the updraft from sinking air downwind. The conditions of the third class of storm were similar to the second, except that the temperature increased with height just above the tropopause. A cold-warm couplet also formed, except that the coldest spot was now located upwind from the summit. This offset between the coldest and highest point is the result of mixing of progressively warmer air as the overshooting top continued to ascend. The effects of the temperature gradient, mixing, and shear above the updraft's equilibrium level explained the uncertainty in estimating cloud top height from radiometric temperature noted in previous studies.

The cloud top temperature structure observed from above severe storms was investigated further by Heymsfield et al. (1984) and Heymsfield and Blackmer (1988). In the first paper, three storms were analyzed in combination with radar data. These storms all had “V” signatures and strong divergence at cloud top level. Similar to other studies, warm areas were observed 10-20 km downwind from the updraft. These formed near the time of tropopause penetration and moved with the storm motion. A subsidence mechanism was again proposed. In some cases, a distant warm area was observed 50-75 km downwind. These areas moved with the upper-level winds. However, no stratospheric cirrus could be identified over those regions to explain the warmer temperatures. In the rapid growth stages, the coldest tops were collocated with the radar echoes. At later stages, these were sometimes displaced from the echo cores. Temporal changes in the cloud top temperature were not always consistent with cloud height change measured from stereographic methods. In the second paper, statistics were gathered from several more cases. It was concluded that 1) the width of the “V” was related to the distance between the cold-warm couplet, and 2) the temperature difference between the couplet was related to the amount of overshoot of the penetrating top. Ingredients for the “V” were believed to be intense updrafts, overshooting tops, and wind shear near the tropopause. Hypotheses included internal cloud dynamics, radiative transfer effects, and flow over and around cloud storm tops. Limited resolution of the satellite imagery, unknown ice crystal and temperature structure, complexity of multi-storms, and simplified 3-D models were identified as factors limiting progress in studies such as this.

The first aircraft measurements directly above intense thunderstorms with enhanced-Vs were collected in 1984 (Heymsfield et al., 1991). Flying about 5 km above cloud summits, a NASA ER-2 aircraft provided high-resolution visible, infrared and cloud height observations. Dimensions of overshooting tops were of the scale of individual GOES pixels (8 km), and cloud top temperatures were found to be as much as 15 degrees too high by GOES. This study pointed out that most thermal couplets were much more pronounced than resolved from the GOES imagery. Observed warm areas did not appear to be due to clouds of reduced optical depth. Above cloud temperature and wind perturbations at 20 km were very significant. For example, a cold dome was observed in the temperature field extending to this height.

Passive microwave measurements from the Special Sensor Microwave/Imager (SSM/I) were used to further study cloud properties of the enhanced-V (Heymsfield and Fulton, 1994). The measurements suggested large spatial variations of ice microphysical characteristics across the anvil. The minimum brightness temperatures at 86 GHz were observed in the convective region and in the region interior to the “V”, where infrared brightness temperatures are locally warm. This was indicative of larger ice crystals dominating both regions. In contrast, polarization differences at 86 GHz varied between the two regions, suggesting fundamental difference in ice crystal orientation. In the convective core, the polarization difference was small, which suggested symmetrical or tumbling ice crystals. The largest polarization differences were in the interior “V” region, which suggested oriented, asymmetrical ice crystals. The difference in these microphysical characteristics partially explained the observed infrared temperature structure.
3.3 PLUMES AND SHORT WAVE INFRARED REFLECTANCE

Short wave infrared imagery from the Advanced Very High Resolution Radiometer (AVHRR) has been observed to contain unusual features above some intense thunderstorms in Europe. The AVHRR is aboard the NOAA series of low orbiting satellites, which limited the observations to fixed times. Daytime images from the AVHRR 3.7 µm band showed regions of enhanced solar reflectivity at or above the anvil surface. Liljas (1984) and Scorer (1986) first reported areas of enhanced reflectivity in vicinity of individual convective cloud elements. Less frequently, the areas were in the shape of plumes, extending from a single point near a penetrating top to long distances downwind over a portion of the anvil (Setvak and Doswell, 1991). The origin of these features were speculated to be from very small ice crystals generated at the top of intense updrafts, however there was no means to test this hypothesis. It was important to note that plumes were often observed without the presence of enhanced “V” signatures. The occurrence of hail with some of these storms raised the question of a practical use of 3.7 µm observations in issuing severe weather warnings.

Additional observations of highly reflective plumes were presented by Levizzani and Setvak (1996). In this study, it was proposed again that the signatures were a manifestation of small ice crystals (~4 µm). The small size could have resulted from limited time for growth in a strong updraft (for example, a the Bounded Weak Echo Region), or from gravitational settling of larger particles. There appeared to be a vertical separation between the anvil and the plumes. A link between the plume source position and close in warm spots was suggested by their common location within storm tops. Hence, the plumes did not appear related to the stratospheric cirrus observed by aircraft above convective domes Fujita (1982). The radiative characteristics of plumes have been simulated by Melani et al. (2003). Demonstrating a strong sensitivity of simulated 3.7 µm reflectance to effective ice crystal size, they confirmed that crystals of 4-7 µm radius size might be typical of the plumes.

The time evolution of highly reflective areas above storm tops was studied with GOES-8 3.9 µm imager data (Setvak et al., 2003). These areas had time scales ranging from minutes to hours, and sizes from individual pixels to entire anvils. In several cases, there was a link to the location and initiation time of mesocyclones as observed from Doppler radar. In one of the cases, the highly reflective spot moved downwind with the speed of the upper-level flow, while in others the spot remained above the mesocyclone. A general relationship between these features and severe weather has yet to be identified.

The plume structure above a storm has been simulated with a 3-dimensional, non-hydrostatic model (Wang, 2003). The source for the water vapor was from the overshooting dome. Water vapor was injected into the stratosphere through the breaking of gravity waves and carried downwind in the shape of plumes. The calculated rate of moisture transport into the stratosphere from these processes was large (~3 tons/s).

Stratospheric water vapor above deep convective clouds has been identified from METEOSAT observations in the Infrared window and water vapor absorption bands (Schmetz, et al., 1997). It was demonstrated that the equivalent brightness temperature in the water vapor can exceed that in infrared window by several degrees because of stratospheric water vapor above cloud top. The use of the difference in brightness temperature between the two bands has been proposed to monitor convective cloud growth and areas of tropospheric-stratospheric exchange.

Research by Rosenfeld and Lerner (2003) has identified characteristic differences in the microphysical structure of pre-storm clouds. Using the 3.7 µm band of AVHRR, hydrometeor size at cloud top has been estimated for cloud clusters at differing stages of growth. In addition, the cloud top temperature at which glaciation occurs was inferred. It was found that the relation between effective radius of hydrometeors and cloud top temperature, and the cloud top temperature of glaciation are uniquely different for severe storms. Strong updrafts in severe storms result in relatively slow growth of hydrometeors. Hence, hydrometeor size increases more slowly as cloud top grows and glaciation occurs at a colder cloud top temperature than in clouds with weaker updrafts. They proposed that hydrometeor size and glaciation temperature of developing cumulus inferred from satellite might be used to help forecast storm severity.
4. RADAR ADVANCES IN STORM DETECTION

There is little doubt that forecasters have made extensive use of satellite imagery in many aspects of severe weather forecasting. However, the extent to which many of the findings cited in Section 3 have been incorporated into the real world of forecasting and warning appears limited. One reason for this was the advent of Doppler radar in the U.S.

While research on thunderstorm cloud top structure and growth rates from geostationary satellites was flourishing, the generation of mesocyclones, and tornadoes was under study with Doppler radar (e.g., Brown et al., 1978). The radar's ability to probe the internal wind and hydrometeor structure of storms made it an obvious tool for the detection hail, high winds, and tornadoes. The implementation of a national network of Doppler radars across the U.S. took place in the 1980's-1990's. Automated algorithms for the detection of mesocyclones, tornadoes, hail, and cell tracking have been used by the National Weather Service to aid in a rapid, uniform scheme for issuing warnings. At the same time, the measurement of cloud top cooling, growth rates, and other measures of storm intensification from satellite have yet to be implemented for automated, routine use. In addition, the identification of features such as the enhanced “V”, and cold-warm couplets have yet to be automated for extended testing.

Early operational use of satellite data was primarily subjective, as most forecast offices did not have access to digital data and were limited by the resolution of imagery. Programs such as the RAMM Advanced Meteorological Satellite Demonstration and Interpretation System (RAMSDIS) advanced the availability of higher quality digital data since the 1990's (Molenar et al., 2000). However, many forecast offices today still lack the means to implement automated schemes using satellite data. An Advanced Weather Interactive Processing System (AWIPS) is now bringing digital data to the forecast offices and may include analyzess from satellite data in the future.

5. CURRENT APPLICATIONS

There are several current attempts to apply some of the early concepts to the routine nowcasting of storms. These do not specifically address identification of current storm severity, but rather initiation and intensification. A few examples are cited here.

Roberts and Rutledge (2003) have developed a technique for the nowcasting of storm initiation and growth using both GOES-8 and Doppler radar data (WSR-88D). The technique is based on observed cloud growth rates over extended periods at three different locations. The onset of storm development depends on surface convergence features such as gust fronts and rolls, utilizing aspects of the earlier work of Purdom. In addition, cloud tops reaching sub-freezing altitudes, and rapid cooling of these clouds are also important factors. Similar to the findings of Adler and others, intensity has been related to the rate of cooling at these early stages of development. The development of 30 dBZ echoes aloft can be anticipated 30 minutes in advance. The concepts of this algorithm are being incorporated into the Auto-nowcast system under development at the National Center for Atmospheric Research (Mueller et al., 2004). The auto-nowcast system uses fuzzy logic to combine predictor information from radar, satellite, surface observations, profilers, and forecast models to provide 0-1 hour nowcasts of storm location. Testing has indicated improvement over extrapolation and persistence. Plans are to include the system into AWIPS.

It is important to note that the multi-spectral capabilities of the current GOES and MSG, can be used to identify the start of glaciation of growing cloud tops to augment the techniques of Roberts and Rutledge (2003). In addition, the sounding capabilities of both satellites can be used to monitor changes in precipitable water and thermodynamic stability (CAPE and CI N) in cloud free areas prior to storm initiation, and within the near-surface inflow to existing storms (for example, Schmit et al., 2002).

A web-based system for the automated monitoring of convective systems has been developed (Rabin and Whittaker, 2004). It identifies and tracks clusters from GOES satellite and WSR-88D radar based on user selected thresholds of cloud top temperature and radar reflectivity. Time trends of size, cloud top temperature, and reflectivity are displayed. After defining inflow regions to the storm, the user may obtain time trends of the environmental parameters in a storm relative frame of reference. These parameters...
include thermodynamic stability and wind shear from the Rapid Update Cycle (RUC) forecast analysis. The usefulness of these time trends in monitoring the evolution of Mesoscale Convective Systems is being explored.

Another automated system for nowcasting convective storms using MSG satellite data is being developed (Morel et al., 2002). Adaptive thresholding of cloud top temperature is used to discriminate convective systems. It tracks and monitors growth and decay of convective systems and time trends of associated lightning.

6. CONCLUSIONS

There has been a long history of research into the development of severe thunderstorms from satellite data. From measurements of cloud top cooling and expansion, there is valuable information on storm initiation and intensification. A serious limitation of the satellite visible and infrared observations is that they only capture the structure of the storm tops. The internal storm structure and subsequent new surface development are often masked by the upper cloud layer. For fully developed storms, inferred processes involve the interaction of the cloud top with upper-level winds. Although the location and strength of the major updrafts can be estimated from information on the overshooting tops, features such as cold-warm couplets, rates of expansion and cloud top cooling, processes in the lower altitudes of the storms cannot be monitored. For example, the wind flow in these lower regions is critical to tornado generation and other strong surface winds.

Other limitations include spatial and temporal resolution. While low-orbiting satellites appear to have sufficient resolution to capture most significant cloud top features in both the visible and infrared, they lack adequate temporal coverage. Geostationary satellites still have less than optimal spatial resolution, however current (MSG) and future (GOES-R) sensors have horizontal resolutions approaching that of earlier low-orbiting data. Data from these sensors should prove valuable in providing additional information on the nowcasting of thunderstorms.

7. REFERENCES


