Appears in Preprints, *15th Conf. on Wea. Analysis and Forecasting* (Norfolk, VA), 19-23 August 1996, Amer. Meteor. Soc., pp. 28-31.

MULTISPECTRAL GOES-8 AND NOAA/AVHRR OBSERVATIONS OF GREAT PLAINS STORMS

Charles A. Doswell III#, Robert M. Rabin#, Martin Setvák*, Vincenzo Levizzani+

#NOAA/ERL National Severe Storms Laboratory
Norman, Oklahoma

*Czech Hydrometeorological Institute
Prague, Czech Republic

+CNR/FISBAT
Bologna, Italy

1. INTRODUCTION

The GOES-8/9 channel 2 (3.78 - 4.03μ) and the NOAA Advanced Very High Resolution Radiometer (AVHRR) channel 3 (3.55 - 3.93μ), are quite sensitive to microphysical properties of clouds (Levizzani and Setvák 1996). Early NOAA/AVHRR observations of convective storms over Europe have shown that some of these exhibit a significant increase of the 3.7μ cloud top reflectivity and that the observed features fall into two broad classes (Setvák and Doswell, 1991):

a. Areas which are either spot-like, typically located close to overshooting tops, or more widespread with fuzzy or blurred edges. These features range in size from that of a single AVHRR pixel to the extent of the entire convective storm's anvil top.

b. A plume-like shape, emanating from a source the size of a pixel, typically located downwind from the coldest storm tops and into embedded IR warm spots (Levizzani and Setvák, 1996).

The present work extends the research to U.S. Great Plains storms. The broader range of observational tools available in the U.S. can help link the observed cloud top features to storm internal processes and to accompanying weather phenomena. Also, the GOES-8/9 satellites (Menzel and Purdom, 1994) enable us to document the evolution of these cloud top features.

2. DATA SOURCES AND PROCESSING

2.1. Satellite imagery

The AVHRR data sets obtained from NOAA were processed (calibrated and georeferenced) by software written at the Czech Hydrometeorological Institute (CHMI) for MS-DOS platforms. Daytime data in the AVHRR channel 3 have been converted into 3.7μ reflectivity by

Corresponding author address: Dr. Charles A. Doswell III, National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069. Internet: doswell@nssl.noaa.gov [*no longer valid*]

an algorithm developed at CHMI (Setvák and Doswell, 1991).

The GOES-8/9 imagery were processed using the University of Wisconsin Man Computer Interactive Data System (McIDAS). Daytime reflectivity at 3.9μ (GOES-8/9 channel 2) was computed from measured radiance at 3.9μ and 11μ (channel 4) following the same methodology used for the AVHRR data.

2.2. Other data

Radar data (WSR-88D) were obtained from radar sites that recorded data in level-II format. Reflectivity and radial velocity data were displayed using the Radar and Algorithm Display System developed at NSSL.

Surface observations of hail, high winds, and tornadoes were obtained from the log of severe weather maintained by the Storm Prediction Center and displayed using software Severe Plot on a PC. Supplementary surface and rawinsonde observations obtained during the 1995 Verfication of the Origins of Rotation in Tornadoes EXperiment (or VORTEX; see Rasmussen et al. 1994) in the southern plains of the United States augmented routine meteorological data during this period.

3. OBSERVATIONS

3.1. NOAA/AVHRR observations

Examination of about 30 AVHRR data sets from 1994 and 1995 has shown that 3.7μ features, observed for European storms, are also found over U.S. Great Plains convective storms. Preliminary results indicate higher plume frequency than in Europe. Most of the plumes are detectable in visible and near infrared channels only (no increase of the 3.7μ reflectivity).

3.2. Data calibration

Cross-calibration tests have been performed for processed NOAA and GOES data, showing close agreement between them. The brightness temperatures from both instruments are within about 0.5 K at both ends of the temperature range (warm ground surface and cold tops of storms). This is in much better agreement than found previously from AVHRR/NOAA versus METEOSAT cross-calibration tests (Levizzani et al. 1992) where the differences were as high as 7 K in the low temperature range (~ 200-220 K), due to resolution differences and calibration uncertainty at low temperatures on METEOSAT.

3.3. GOES-8 observations

Seven GOES-8 data sequences showing severe storm development have been examined for the presence of spots or plumes of increased 3.9μ cloud top reflectivity. As expected, areas of increased 3.9μ reflectivity were found over some of these storms. One of the first results of this study was rejection of speculations based on earlier European observations that indicated a possible link between hail and increased 3.7μ reflectivity (Setvák, 1989). Some of the storms, which are known to have produced significant hail on VORTEX days, have shown no significant increase of 3.9μ reflectivity at all. However, many of the storms did produce enhanced reflectivity spots of varying size, persistence and magnitude. Lifetimes of these spots ranged from few minutes (as determined from the occasional 1 minute data scans) to about two hours. The size of these varied from a single GOES-8 channel 2 pixel (4x4 km) up to about 20-30 km across. The highest observed 3.9μ reflectivity was about 0.20 (i.e., the surface reflects 20 percent of the incident radiance), while the typical "background" value for the anvils was about 0.02–0.04 (all at brightness temperatures below 215K).

3.4. Comparison of the 3.9μ observations with WSR-88D data

Spots of increased 3.9μ reflectivity do not seem to be linked uniquely to overshooting tops. To try to determine their possible sources, we looked at WSR-88D radar reflectivity and radial velocity data. Though only four data sets have been considered in this way to date, some interesting observations have been made.

Most of the small scale spots appear over areas with relatively weak radar reflectivity, lasting at most up to somewhat less than one hour. When spots appear above storms organized in lines, they typically develop near a ridge of overshooting tops and later drift over the "stratiform" part of the anvil.

Another category of spots appears linked to mesocyclones or deep bounded weak echo regions (BWERs). However, their behavior and location with respect to a nearby mesocyclone can vary substantially. For example, on 07 May 1995, a spot of high 3.9μ reflectivity appeared above a mesocyclone and deep BWER at 2145 UTC, (Fig. 1—all times UTC), which was also near the time and location of first touchdown of an associated tornado. Since the previous 3.9μ image that is available from 2130 shows no trace of this spot, an uncertainty of up to 15 minutes remains for the time of its onset. The spot persisted in the anvil for almost 2 h, disappearing after 2330. In this case, the spot drifted away from its "parent" cell, as determined by radar observations (Fig. 2).

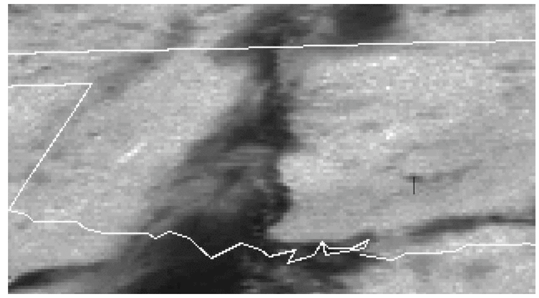

Fig. 1. Enhanced 3.9μ image on 07 May 1995 at 2145 UTC, showing the increased reflectivity as the dark spot in southeastern Oklahoma.

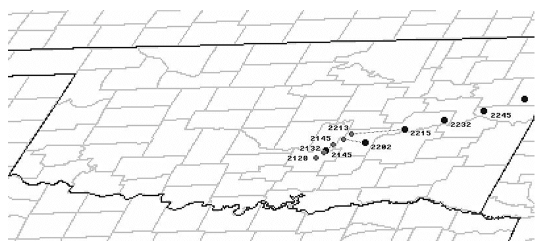

Fig. 2. Diverging paths of (a) the 3.9μ dark spot (filled circles) and (b) the mesocyclone (* symbols), labelled with times (UTC).

A second example of a spot that occurred above a mesocyclone and BWER occured on 02 June 1995. In this case, the spot first appeared at about 2330 (the mesocyclone was first detected at 2246). It increased in magnitude and size by 0015, attaining a diameter of about 15 km. The spot remained in close proximity to the mesocyclone during this period. In this case, a nearby tornado touchdown was reported at 2300, followed by 3 more between 2343 and 0000. There was no trace of the spot on the next image at 0045, and the mesocyclone dissipated around 0030.

In a third case, 08 June 1995, one of several 3.9μ spots appeared to be associated with a mesocyclone, although in this case, the mesocyclone did not produce a tornado. This spot persisted from 2045 to 2115. The rest of the spots had lifetimes of only 15–30 min, which made linking their presence to radar-observed structures difficult.

On the basis of satellite imagery alone it is impossible to distinguish among different types of 3.9μ spots, nor to infer the existence of radar reflectivity and velocity field features. Examination of many cases is required to determine the fraction of 3.9μ spots associated with radar-observable features.

There might be a possible link between 3.9μ spots and "stratospheric" cirrus, as Fujita (1982) observed from aircraft flying at anvil top levels. Though Fujita has reported the stratospheric cirrus to extend at greater distances from its source (25 km or more), one of authors of this paper (Setvák) has observed (on 24 May 1996, Alabama, Georgia) similar "jumping cirrus." Persistence of these "crests" was on the order of several minutes. Location of these and their typical lifetime are close to those of the 3.9μ spots. Perhaps some of the 3.9μ spots also could be attributed to pileus clouds. Though this might explain most of the observed 3.9μ spots, it cannot explain those spots with longer lifetimes.

3.5. Plumes above storm tops

European observations, summarized in Setvák and Doswell (1991) and Levizzani and Setvák (1996), though based on "snapshots" from the NOAA/AVHRR instrument only, have shown several important characteristics of plumes that occasionally develop over convective storm anvils. Space does not permit listing these characteristics; the reader should consult the references.

The most pronounced plume of increased 3.7μ reflectivity found in the U.S. AVHRR data sets, is shown in Fig. 3. In the AVHRR channel 3 reflectivity image, the plume extends well beyond the edge of the anvil. Notice the almost "point like" source of this plume.

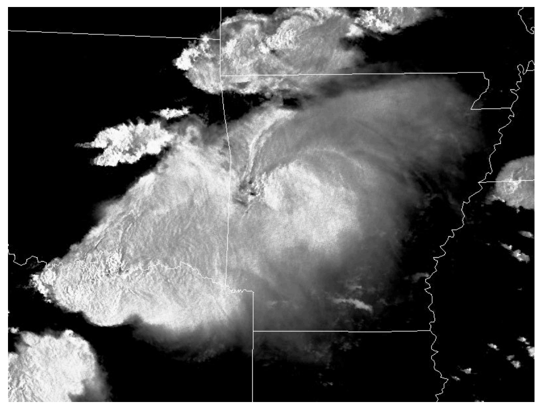

Fig. 3. Enhanced 3.7μ AVHRR image, showing plume over northern Arkansas on 26 April 1994 at 2250 UTC.

Some examples of plume-like structures were observed on 22-23 May 1996. By mid-afternoon, several isolated storms were developing in the High Plains (Fig. 4). From GOES-8, two of the storms (northeastern Colorado and southwest Nebraska) had notably higher 3.9μ reflectivity than other storms within the image. There are differences between the GOES-8 and GOES-9 reflectivity: GOES-9 values are as much as 20% higher, presumably due to lower viewing angles. There is less small-scale detail visible from GOES-9; however, the differences between storms are visible from both satellites.

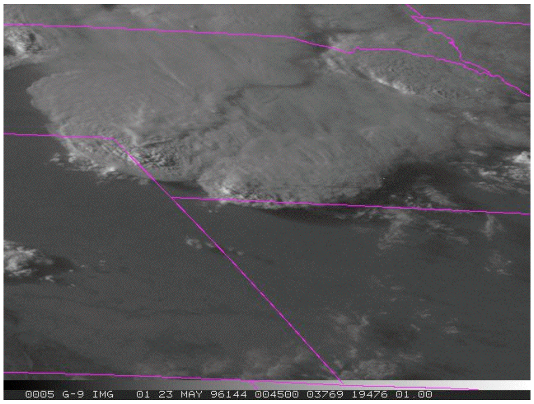

Fig. 4. GOES-9 visible image showing plumes over anvils of storms in southwestern Nebraska and northeastern Colorado on 23 May 1996 at 0045 UTC.

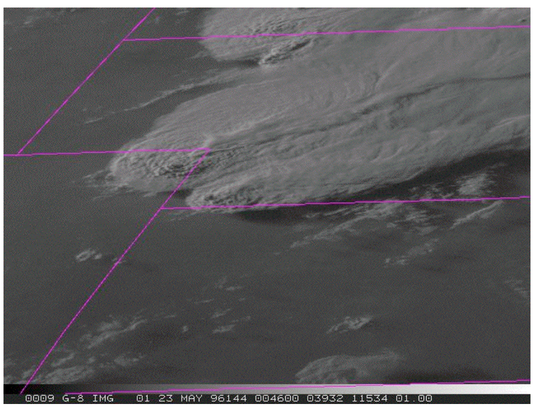

Fig. 5. GOES-8 visible image showing plumes over anvils of storms in southwestern Nebraska and northeastern Colorado on 23 May 1996 at 0046 UTC.

Unlike the plume-like structures previously observed, nearly the entire anvils (extending at least 500 km) of these storms have high reflectivity. These features persisted through the remaining hours of daylight; at least 3 h total. Near sunset (2330-0100, Fig. 5) the imagery reveals narrow plumes, similar to those observed in previous studies. In both cases, shadows cast from the plumes indicate they are above the anvils. The 3.9μ reflectivity appears to be locally higher in these plumes than over the surrounding anvil cloud. However, this may be an artifact of varying solar illumination.

The detection of plumes from visible imagery is greatly enhanced at low solar angles. Correspondingly, the existence of these features earlier in the afternoon hours is uncertain. Data from the 3.9μ channel do not reveal enhanced reflectivity from these plumes.

4. RADIATIVE TRANSFER STUDIES

The potential of theoretical and experimental studies on the optical properties of nonspherical atmospheric ice crystals of the last two decades (e.g., Liou 1972a,b; Asano and Sato 1980) is far from being fully exploited. Satellite multispectral techniques for the analysis of cloud microphysics have been developed; e.g., Ou et al. (1993) and Rao et al. (1995) using either the 3.7μ channel alone or combined with the 10.9μ channel. Radiative transfer models have been coupled to radiometric observations for the identification of cirrus and stratiform cloud optical properties, which are of great relevance for the radiation budget and global warming issues. See Stephens (1980) on cirrus cloud properties in the infrared, Stone et. al (1990) on thin cirrus clouds in the near infrared and infrared from satellite with simultaneous observations with lidar and lirad, and Kleespies (1995) on marine stratiform cloud in the 3.9μ channel.

Little of this activity has been devoted to convective storms cloud top studies. Scattering computations and radiative transfer theory currently represent the only available "probe" for the identification of the microphysical composition of the AVHRR channel 3 plumes. A radiative model of plumes is presently under construction for the simulation of AVHRR channel 3 response to varying sun-satellite-cloud geometries. Numerical modeling of the storm's structure is needed to investigate the dynamical and microphysical origin of the spots and plumes, as well as their evolution in time. The Wisconsin Dynamical Microphysical Model (Johnson et al. 1993; 1994) is being considered, given its very detailed microphysical parameterization.

5. DISCUSSION

These preliminary studies have revealed a veritable "bestiary" of phenomena at the tops of deep convective clouds, including: warm spots, U-shaped regions of cold tops, plumes, spots of enhanced 3.7/3.9μ reflectivity, etc. The observations do not seem to be tied to any particular form of severe weather. At this point, we do not have any definitive explanations for the observations, either. Any effort to understand the meaning of such signatures must include: 1) a study of the radiative transfer properties of storm tops, 2) a multisensor look at the storms that exhibit these features and those which do not, to look for clues about what distinguishes signature producing storms from those that do not, and 3) an accurate knowledge of the weather events the storms have produced.

Practical forecasting applications of these observations must await a definitive explanation of their origins and the establishment of connections (if any) between the signatures and the observed weather. In situ measurements of the microphysical properties of storm tops, as well as high-altitude aircraft observations above the storm anvils would be of considerable help in understanding what is happening.

Acknowledgments

This research was supported by the U.S./Czechoslovak Science and Technology Program, grant no. 94067, and also by the Italian Space Agency (ASI), the Italian National Council of Research under the Progetto Strategico for the Mesoscale Alpine Programme (MAP). The authors wish to thank: Pavel Hampl from CHMI for his software support when processing AVHRR data, Julie Adolphson and Patrick Dills of UCAR/COMET, Jim Purdom and John Weaver OF NESDIS/RAMM for providing archived and real-time GOES-8data.

6. REFERENCES

Asano, S., and M. Sato 1980: Light scattering by randomly oriented spheroidal particles. *Appl. Opt.*, **19**, 962-974.

Fujita, T. T., 1982: Principle of stereographic height computations and their applications to stratospheric cirrus over severe thunderstorms. *J. Meteor. Soc. of Japan*, **60**, 355-368.

Kleespies, T. J., 1995: The retrieval of marine stratiform cloud properties from multiple observations in the 3.9-micron window under conditions of varying solar illumination. *J. Appl. Meteor.*, 34, 1512-1524.

Johnson, D. E., P. K. Wang and J. M. Straka, 1993: Numerical simulations of the 2 August 1981 CCOPE supercell storm with and without ice microphysics. *J. Appl. Meteor.*, 32, 745-759.

______, ______ and _____, 1995: A study of microphysical processes in the 2 August 1981 CCOPE supercell storm. *Atmos. Res.*, **33**, 92-123.

Levizzani, V., M. Setvák, J. Krácmar, F. Porcu and F. Prodi, 1992: Multisensor remote sensing analysis of deep convective storms' structure over continental Europe and Mediterranean. Proc., *11th Int. Conf. on Clouds and Precipitation*, IAMAP, Montreal, 1075 - 1078.

______, and ______, 1996: Multispectral, high-resolution satellite observations of plumes on top of convective storms. *J. Atmos. Sci.*, **53**, 361-369.

Liou, K.-N. 1972a: Electromagnetic scattering by arbitrarily oriented ice cylinders. *Appl. Opt.*, **11**, 667-674.

______, 1972b: Light scattering by ice clouds in the visible and infrared: A theoretical study. *J. Atmos. Sci.*, **29**, 524-536.

Menzel, W. P., and J. F. W. Purdom, 1994: Introducing GOES-I: The first of new generation of geostationary operational environmental satellites. *Bull. Amer. Meteor. Soc.*, **75**, 757-781.

Ou, S. C., K.-N. Liou, W. M. Gooch and Y. Takano, 1993: Remote sensing of cirrus cloud parameters using advanced very-high-resolution radiometer 3.7- and 10.9-micron channels. *Appl. Opt.*, **32**, 2171-2180.

Rao, N.X., S.C. Ou and K.N. Liou 1995: Removal of the solar component in AVHRR 3.7-micron radiances for the retrieval of cirrus cloud parameters. *J. Appl. Meteor.*, **34**, 482-499.

Rasmussen, E. N., J. M. Straka, R. Davies-Jones, C. A. Doswell III, F. H. Carr, M. D. Eilts and D. R. MacGorman, 1994: Verification of the Origins of Rotation in Tornadoes EXperiment (VORTEX). *Bull. Amer. Meteor. Soc.*, **75**, 995-1006.

Setvák, M., 1989: Convective storms - the AVHRR channel 3 cloud top reflectivity as a consequence of internal processes. Proc., *5th WMO Conf. on Weather Modification and Applied Cloud Physics*, Beijing, WMO TD-No. 269, 109-112.

______, and C. A. Doswell III, 1991: The AVHRR channel 3 cloud top reflectivity of convective storms. *Mon. Wea. Rev.*, **119**, 841-847.

Stephens, G. L., 1980: Radiative properties of cirrus clouds in the infrared region. *J. Atmos. Sci.*, **37**, 435-446.

Stone, R. S., G. L. Stephens, C. M. R. Platt and S. Banks, 1990: The remote sensing of thin cirrus cloud using satellites, lidar and radiative transfer theory. *J. Appl. Meteor.*, **29**, 353-366.