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Local severe storm monitoring and prediction using satellite data

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सार – इस शोध पत्र में उपग्रह से प्राप्त आँकड़ों के आधार पर 0–6 घंटों की समय अवधि में प्रचंड तूफानों और उनकी तीव्रता का पूर्वानुमान लगाने के बारे में बताया गया है। मौसम और मौसम से संबद्ध परिघटनाएँ मापक्रमों के विस्तृत क्षेत्र के भी पार कर जाती है, मौसम विज्ञान में सिनॉप्टिक स्केल और मेसोस्केल के मध्य संपर्क बहुत बार स्थानीय मौसम की तीव्रता को नियंत्रित करने में मुख्य भूमिका निभाता है। केवल भूस्थैतिक उपग्रह ही प्रेक्षण का ऐसा साधन है जो इन स्केलों पर (और स्केलों के परस्पर संबंध) मौसम का मानीटरन करने की क्षमता रखता है। जैसे ध्रुवीय कक्षा–उपग्रहों से प्राप्त चित्र से सिनॉप्टिक स्केल परिघटना को पहले से समझने में सहायता मिली है वैसे ही भूस्थैतिक उपग्रहों से लिए गए चित्र से मेसोस्केल के बारे में जानकारी में वृद्धि हो रही है। भूस्थैतिक उपग्रह से प्राप्त चित्र के उपयोग से हुई कुछ महत्वपूर्ण खोजों का मेसोस्केल मौसम विज्ञान पर अभूतपूर्व प्रभाव पड़ा है और उसके परिणामस्वरूप आरंभी चंडवात पंक्ति के क्षेत्र ; टोरनेडो और प्रचंड तूफानों के अधिक संभावना वाले क्षेत्रों का पता लगाना ; मेसोस्केल संवहनीय मिश्र ; तथा भारी संवहनीय वर्षा वाले क्षेत्र जैसी आपदा संबंधी मौसम की घटनाओं के लिए अल्पावधि पूर्वानुमान और चेतावनी देने की क्षमता पर भी अभूतपूर्व प्रभाव पड़ा है। अगले कुछ वर्षों में प्रचलन मे आने वाली उपग्रह प्रणालियाँ मौजूदा क्षमताओं से कहीं अधिक क्षमता उपलब्ध कराने में सक्षम होंगी।

ABSTRACT. This paper addresses using satellite data for nowcasting severe storms and their intensity in the 0-6 hour time frame. Weather, and weather related phenomena extend across a broad range of scales. In meteorology the link between the synoptic scale and the mesoscale is many times a key factor in controlling the intensity of local weather. The only observing tool capable of monitoring weather across those scales (and those scales interactions) is the geostationary satellite! Just as imagery from polar orbiting satellites helped advance understanding of synoptic scale phenomena, imagery from geostationary satellites is advancing our understanding of the mesoscale. A number of important discoveries using geostationary satellite imagery have had a dramatic impact on mesoscale meteorology and, in turn, our ability to provide short term forecasts and warnings for disaster related weather events, including: areas of incipient squall line development; location of regions with high probability of tornadoes and severe thunderstorms; mesoscale convective complexes; and, areas with heavy convective rainfall. As exciting as current capabilities are, satellite systems that will come into being during the next several years will provide capabilities well beyond the present ones.

Key words – Satellite monitoring, Local severe storms, Prediction, Mesoscale convective systems, Remote sensing.

1. Preamble

When using space based remote sensing data four critical questions must be addressed. In the context of the application area under investigation they all deal with resolution. Those resolutions are: (*i*) spatial – what picture element size is required to identify the feature of interest, what is its spatial variability, and over what scale must it be observed; (*ii*) spectral - each spatial element has a continuous spectrum that may be used to analyze the earth's surface and atmosphere, what spectral resolution(s) is (are) needed for a particular application; (*iii*) temporal – how often does the feature of interest need to be observed; and, (*iv*) radiometric – signal to noise, or how accurately does an observation need to be. For some applications, particularly the topic addressed in this paper, optimal resolutions may not be attainable from any one satellite but in some cases may be approached using data from a series of satellites, such as rainfall[1].

2. Current capability

Early work with polar orbiting satellite imagery showed that important synoptic scale features such as jet

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[1] The TRMM project provides 3-hourly global rainfall maps derived from TRMM active radar data and infrared data from geostationary satellites (http://trmm.gsfc.nasa.gov/). The value of those data have led to planning for a much more accurate and powerful system known as the Global Precipitation Measurement (GPM) Mission (http://gpm.gsfc.nasa.gov/).

streams, mid-troposphere trough and ridge lines, vorticity centers and hurricanes were readily located in the images - the capability of using geostationary satellite data to track their development and evolution was almost immediately realized (Anderson, 1974). Satellite system improvements over the years resulted in better data and products that led to refinement of those early techniques, culminating in an excellent book, "Images in weather forecasting," that provides a practical guide for the interpretation of satellite and radar imagery (Bader, *et al*., 1995). Local severe storm monitoring and prediction is in many aspects mesoscale in nature, and it is here that satellite data can provide great benefit. While observations from polar orbiting satellites often detect mesoscale phenomena at the needed spatial resolutions, they lack the temporal resolution required for many nowcasting applications. For example, sounder data from polar orbiting satellites, particularly HIRS data[2], provide high spatial resolution data that can be used to derive information on atmospheric instability over land in cloud free areas generally once every 6 hours. Those data are valuable for assessing the broad scale features such as axes of deeper moisture and instability that may support convection, however, their temporal resolution is not optimal for convective nowcasting. Prior to geostationary satellites, the mesoscale was a "data sparse" region; meteorologists were forced to make inferences about mesoscale phenomena from macro-scale observations. Today, over the United States, geostationary sounder data provides high spatial resolution hour-by-hour information of the atmosphere's ability to support (and inhibit) deep convection. Today's geostationary satellites provide multispectral high-resolution imagery at frequent intervals, generally between 15 and 30 minutes depending on the satellite operator[3]. Those data reveal meso-meteorological features that are infrequently detected by fixed observing sites. The clouds and cloud patterns in a satellite image provide a visualization of mesoscale meteorological processes. When cloud imagery (and products derived from sounding data such as lifted index) is viewed in animation, the movement, orientation, and development of important mesoscale features can be observed. Furthermore, such animation provides observations of convective behavior at temporal and spatial resolutions approaching the scale of the mechanisms responsible for triggering deep and intense convective storms. As valuable as today's geostationary systems are, they are of greater value when combined with more conventional observations such as surface and upper air data, surface based radar and other satellite data sets, as addressed in Bader *et al*., (1995) but beyond the scope of this paper.

While forecasts of convection cover a spectrum of time periods, this paper addresses using satellite data for nowcasting severe storms and their intensity in the 0-6 hour time frame. Nowcasting may be addressed statistically, with numerical models, or expert systems. Historically it has been primarily based on extrapolation of radar echoes or satellite images (Browning, 1982). Nowcasting studies have consistently shown that accuracy decreases very rapidly within the first few hours and that the reason for this rapid decrease is the rapid evolution of the precipitation field (Wilson *et al*. 1998). This rapid evolution of the precipitation field is often due to boundary layer and convective scale processes, such as outflow boundary development and interaction with other convergence boundaries. This highly non-linear character of convective development and evolution over short time periods must be understood if significant advances are to be made in local severe storm monitoring and prediction. Indeed, such understanding has been the focus of numerous field studies dating from WWII, beginning with the Thunderstorm Project in 1946-47 (Byers and Braham, 1948) whose basic goal was to understand the thunderstorm and factors influencing its initiation. Nearly 50 years later, the basic goals of the International Water Vapor Project, that took place in 2002, were: improved characterization of the four-dimensional distribution of water vapor and its application to improving the understanding and prediction of convection, improved understanding of convective initiation and boundary layer processes, and improved prediction of convective rainfall[4]. That this topic has been so intensely investigated for nearly half a century with arrays of sophisticated instrumentation attests to the inherent difficulty posed by local storm monitoring and prediction.

Forecasting the development and evolution of convection is one of the most difficult tasks in meteorology today. There are a variety of reasons for this, one being the lack of observations on the mesoscale and the other being the highly non-linear aspects of convective evolution. For purposes of this paper, it is assumed that the forecaster is in a situation where convection is anticipated and that data from satellites will be used as an aid in the required nowcasting tasks. Mandatory for this activity are basic conceptual models that are used as guides for understanding (Browning, 1982 ; Bader, *et al*., 1995).

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[2] Use of microwave data, such as from AMSU, for derivation of soundings over land is very difficult due to variable surface emissivity.

[3] For information on current status of all operational satellites visit the WMO satellite activities web page accessible through http://www.wmo.ch/index-en.html

[4] http://www.atd.ucar.edu/dir_off/projects/2002/IHOP.html

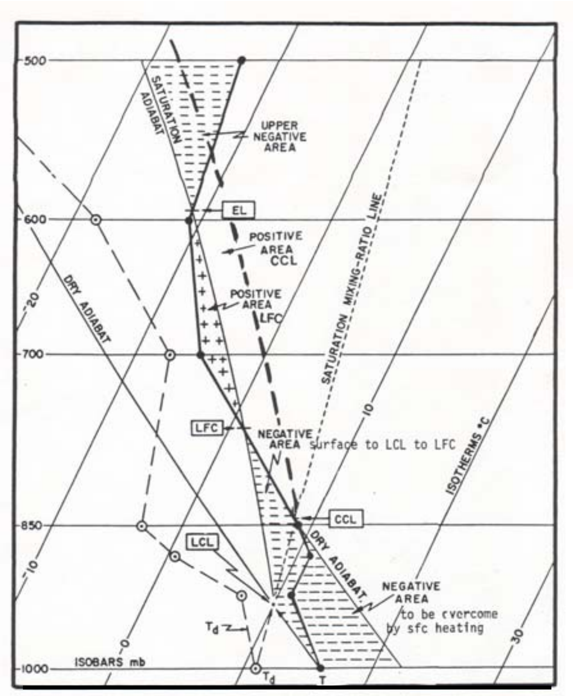

Fig 1. Skew-T Log-P diagram

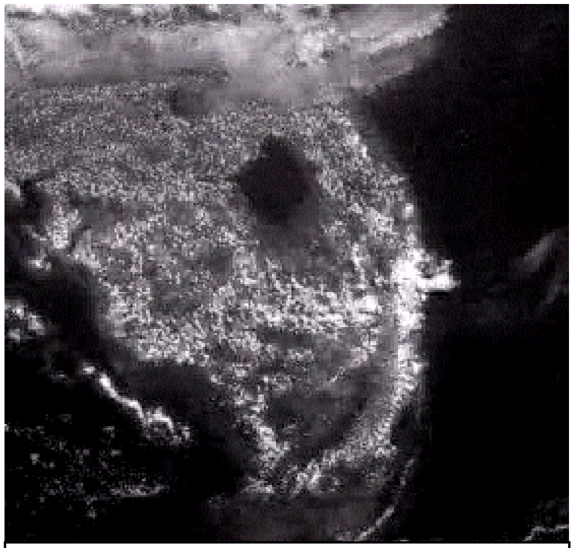

Fig 2. Sea-breeze over South Florida, 2 July, 1995 at 1700 UTC. Note enhanced convection along sea-breeze convergence zone

Fig 3. Picture illustrating variability across a convective cloud field, taken by the author from an aircraft window

3. Convection and convective development

3.1.1. *Development under weak synoptic scale forcing*

When convection forms under conditions of weak synoptic scale forcing, two factors exert a major influence on its development: instability and low-level convergence. It is informative to inspect a thermodynamic diagram and envision deep convection as it grows. Fig. 1, a typical early morning Skew-T Log-P diagram, shows a moist and stable boundary layer with the potential to fuel deep convection. In the simplest sense, to realize that convective potential: (*i*) surface heating and mixing can bring the sounding to an unstable state by reaching a convective temperature; (*ii*) through lifting, low level air reaches a lifting condensation level (LCL) where convection will form, then through further lifting reach a level of free convection (LFC); or, (*iii*) a combination of the two. If one develops a simple perturbation form of the vertical equation of motion, $\delta(w^2/2) = -g\ (\Delta T/T)\ \delta z$, as Pielke (1984), and integrates the equation from the LCL to LFC using realistic numbers from a sounding (average negative $\Delta T = 0.5°$ C, an average environmental T of 290° C over a height of 290 meters and assumes a vertical motion of 0.1 m/s at the LFC) then the vertical motion input required at the LCL is approximately 3.4 m/s: How can this come about? To support deep convection when synoptic scale forcing is weak requires substantial low level forcing. Such forcing is most often confined to organized convergence zones that develop due to differential heating. A number of such convergence zones will be readily recognized by the reader: land-sea breezes (Fig. 2), mountain breezes, urban effects, [Pielke (1984)] and cloudy *versus* clear boundaries (Segal, *et al*., 1986).

In the convective atmosphere rarely, if ever, is there uniform instability across an area. Gray (1973) showed that on large scales there must be compensating downward motion in the vicinity of convection, envisioned in the form of gradual broad-scale sinking. In

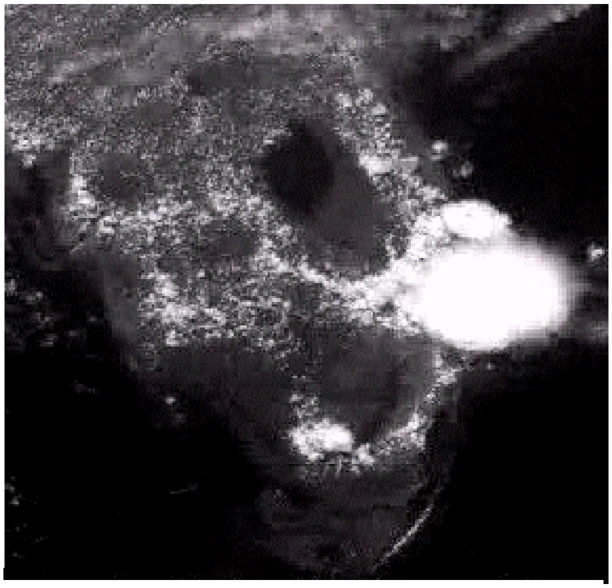

Fig 4. Sea-breeze over South Florida, 2 July, 1995 at 1830 UTC. Notice large thunderstorm has developed where the sea-breeze intersected enhanced convection

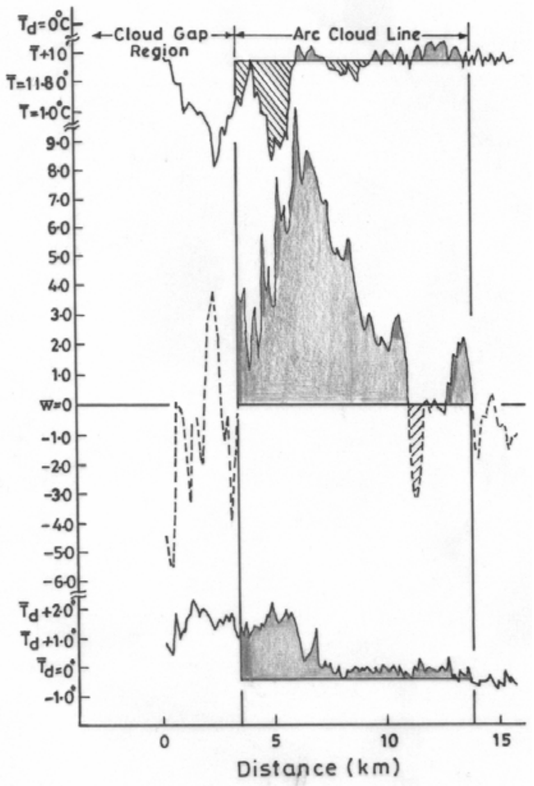

Fig 5. Data from flight under an arc cloud line (Sinclair and Purdom, 1984)

the case of deep convection this may be envisioned in the form of subsidence around the convective storm as well as downward moving air associated with the storm's precipitation area (Zipser, 1977). Further, one needs but observe cloudiness outside an aircraft window (or satellite image) to observe the variability in the atmosphere's instability as reflected through its cloud cover, Fig. 3. This is not new to forecasters, indeed as was pointed by Schereschewsky (1945) long before the beginning of the satellite era: "Clouds are now considered essential and accurate tools for weather forecasting. Every feature of the air masses (discontinuity, subsidence, instability and stability, etc.) is reflected in the shape, amount, and structure of the clouds."

Because of the inherent stability of the atmosphere, the growth from cumulus cloudiness being the predominant type cloud along the convergence zone to cumulonimbus generally is a process taking several hours. It would be a rare thunderstorm indeed that formed without precursor cumulus clouds. Thus, using sequential geostationary satellite imagery to monitor cumulus developing in convergence zones represents one of the primary uses of those data to nowcast deep convective development. Further, in the context of conceptual models, Betts (1973) showed the importance of cumulus growth and decay in destabilization of the atmosphere through moistening of the cloud layer, thus reducing entrainment as sequential cumulus grew in the same region[5]. "In satellite imagery it has been noted that where two convergence zones merge locates a favored place for early and strong thunderstorm development (Purdom, 1976), as in Fig. 4, taken 1 ½ hours after Fig. 2. Thus, when nowcasting, one can locate regions where convection is expected to develop sooner and be more intense by identifying merger areas".

3.1.2. *Outflow boundaries and convective scale interaction*

When nowcasting convection, use of the cloud field as an indicator of the atmosphere's ability to support deep convective development is very important. This is especially true when vertical forcing is imposed upon the local environment, as occurs with thunderstorm outflow boundaries. Fig. 5, aircraft data from research flights made by the author, reveals a narrow band of strong vertical motion, approximately 7 km wide exists above the narrow convergence zone associated with the outflow

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[5] This points to the importance of vertical wind shear with respect to the convergence zone: if the flow above the convergence zone is parallel to that zone then as cumulus penetrate into dry air above and die a favorable moist regime will develop, where as if that flow is perpendicular to the zone that will not be the case.

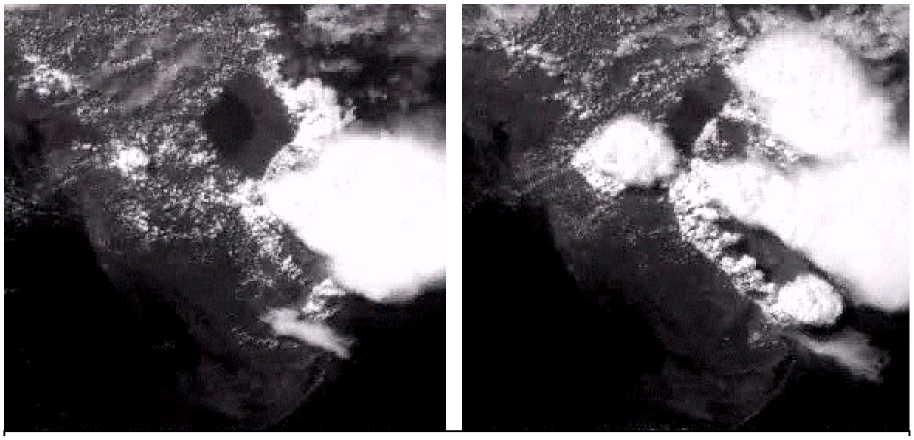

Fig 6. Over South Florida, 2 July, 1995 at 1945 UTC (left) and 2045 UTC (right). Notice large thunderstorm outflow boundary moving west from original thunderstorm has triggered new convection where it intersects sea-breeze to its north and south. Also note new thunderstorm along west coast sea-breeze with evidence of small outflow on its southwest edge

boundary (arc cloud line). In the figure, the thunderstorm that produced the outflow is 10s of kilometers to the west (left in figure) of the arc cloud line. Particularly interesting is the cool moist negatively buoyant air that exists within the arc cloud's sub-cloud updraft (left of vertical motion maximum): due to mixing of rain-cooled air from the thunderstorm with environmental air. This mixed updraft region is evidence of a solenoidal circulation confined to the leading edge of the outflow boundary (Sinclair and Purdom, 1984), and will be shown later to be an important factor in severe storm development. The confinement of upward vertical motion to a narrow region beneath arc cloud lines was typical of flights beneath them, with the vertical motions becoming weaker the older and more remote the arc cloud line was from its source (Sinclair and Purdom, 1983).

It was from satellite images that the importance of convective scale interaction, manifested through thunderstorm outflow boundary interaction, became recognized.

Purdom (1973) first pointed out that in satellite imagery, the leading edge of the meso-high (Fujita, 1959) [thunderstorm outflow boundary] appears as an arc shaped line of convective clouds associated with thunderstorm activity, Fig. 6, and that the majority of new convective activity would form along that boundary. Purdom (1976) later introduced the concept of convective scale interaction and discussed its role in controlling the development and evolution of deep convection through the intersection of arc cloud lines with other convective areas, lines and boundaries. It would be five years later before the importance of such interactions were first recognized by Doppler radar (Wilson and Carbone, 1984).

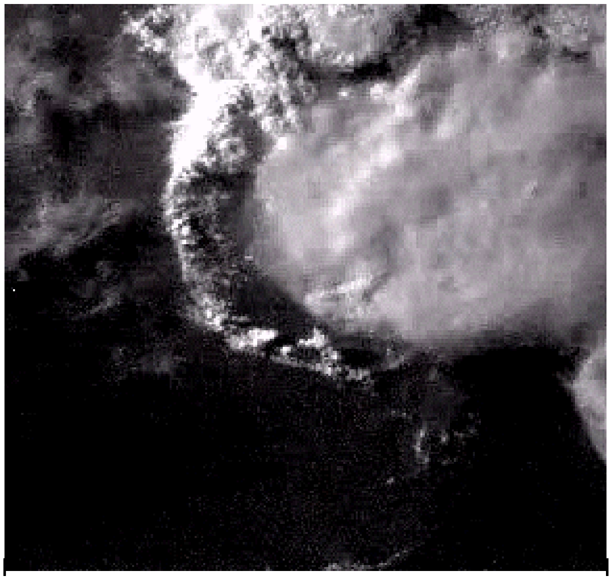

Fig 7. Over South Florida, 2 July, 1995 at 2315 UTC. Late in the day, the effect of stabilization of the boundary layer is evident (see text)

Recognition of outflow boundaries and understanding their role in triggering new convection is important for nowcasting. It is precisely this non-liner aspect in the development and evolution of convection that makes it so difficult to nowcast. Obviously the initiation of convection, timing of its outflow production and characteristics of the convective field and instability ahead of it are required for precise nowcasting. This is one of the major reasons that precision forecasting ability for of this type convection decreases so rapidly as a function of

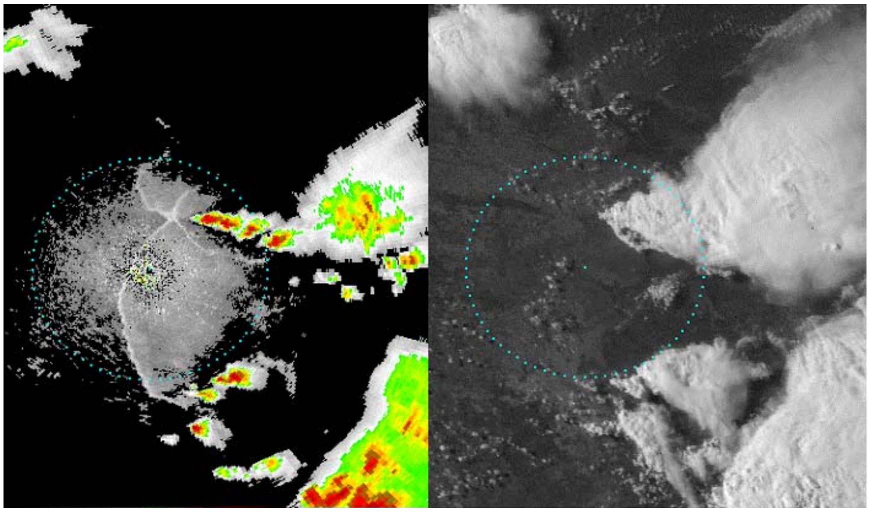

Fig 8. Over Texas, 31 May 1995 at 2345 UTC. Radar (left) reveals outflow boundaries late in the day, while insufficient vertical motion and instability make them difficult to detect in satellite image. Radar elevation 0.5 degrees, circle is 100 km radius from radar center

time (Wilson *et al*., 1998). Observe the following: the arc cloud line appears as a line of cumulus and cumulus congestus clouds, not as thunderstorms, precisely because as the boundary moves into clear skies there is insufficient vertical motion along it to couple with environmental instability and cause a thunderstorm to develop. It is where instability ahead of the arc cloud line is manifest by cumulus development that less vertical forcing is required and the outflow boundary may successfully force that air to a level of free convection: thus the preferred region for thunderstorm development. In the early evening, thunderstorm activity often decreases and cloudiness along the thunderstorm's outflow boundary decays as the atmosphere into which it moves stabilizes, as in Fig. 7. At times the boundary may not be visible to the naked eye due to its lack of cloudiness (weak vertical motion field); however, it is often still detectable by radar as a density discontinuity, as in Fig. 8. This is important, because the following morning, after surface heating begins, remnants of old outflow boundaries are often trigger points for early thunderstorm activity. The reason for this is not well understood, but may well be that the difference in the low level temperature and moisture fields on opposite sides of the boundary result in the boundary layer heating at different rates which leads to a rebirth of the local solenoidal circulation previously mentioned.

3.1.3. *Mesoscale convective climatologies*

Forecasters have long understood the importance of various climatological regimes in weather forecasting. Over a number of years various satellite products have been developed that may be used to anticipate convection and rainfall locations when certain climatological signals are strong. Well known is the influence of el Nino and la Nina on rainfall over portions of the United States and Asia. Recently, scientists have begun to develop mesoscale convective climatologies from geostationary satellite data. Such climatologies serve as valuable aids for anticipating where convection will develop and grow and are normally stratified by time of day, month and direction of boundary layer flow (Connell, *et al*., 2001).

3.2. *Development under strong synoptic scale forcing*

Intense convection may take on a variety of characteristics (super cell, multi-cell, or mesoscale convective complex) depending on the instability, the vertical distribution of moisture, and the characteristics of the vertical wind profile (Fankhauser, 1971, Maddox, 1980, Marwitz, 1972; Routunno, *et al*., 1988, Zipser, 1982). When performing local scale forecasting of intense convection, it is important to recognize which type of convection is expected with respect to the particular synoptic regime and then use the satellite data as an aid in nowcasting a storm's or storm system's development and evolution.

3.2.1. *Instability*

Thermodynamic instability exerts a strong influence on the atmosphere's ability to support strong convection,

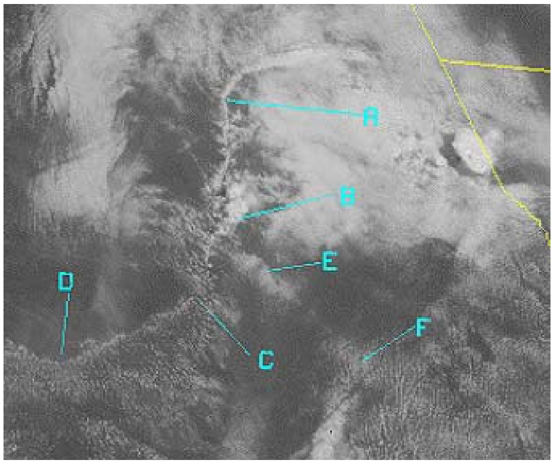

Fig. 9. GOES-West view. 1 km visible image at 1745 UTC over Texas on 27 May, 1997, showing organized convection along convergence zone ABCD, with convection being triggered at B by gravity wave EF

and its relative importance may be classified by synoptic regime (Miller, 1972). When synoptic scale forcing is strong, the effects of moisture transport and surface heating play important roles in its evolution (op cit). With today's broad spectral resolution satellite sounder data, various thermodynamic products can be derived to aid the forecaster in the task of local scale forecasts. Those products do not have the high vertical resolution information that can be derived from rawinsonde data, however, with their higher spatial and temporal resolutions they are able to be used in a relative sense to locate gradients in the thermodynamic field and regions of more or less instability (Purdom and Menzel, 1996). While hourly geostationary sounder data are more relevant to short-term nowcasting of strong convection due to their being able to capture the diurnal cycle and monitor the development of instability (Menzel, *et al*., 1998; Weaver *et al*., 2002), six hourly polar orbiting data are able to locate tongues of higher moisture content that can be valuable for assessing the atmosphere's ability to sustain strong convection. Two products that have been found particularly useful are total column precipitable water and Lifted Index (op cit). Those products, as well as individual soundings, may be derived using polar orbiting sounder data with the International ATOVS processing package (CIMSS, 2000), or viewed using the NESDIS Office of Research and Application Polar Orbiting Satellite Sounding Evaluator (Posse) system, see http://poes.nesdis.noaa.gov/index.html.

3.2.2. *Large scale forcing and development of convergence zones*

Strong thunderstorm activity is often associated with frontal zone or pre-frontal squall lines (Miller, 1972). The front or squall line most often is associated with organized surface low pressure, a surface convergence zone, and with highly unstable air within the warm sector. Upper level support in the form of a short wave trough and jet-streak is often present (Uccellini, 1980). Synoptically, the upper level features are normally revealed by conventional upper air analyses with their future positions fairly well forecast by numerical weather prediction models. The major use of satellite data in diagnosing the upper air system is to verify the initial upper air analysis and monitor the movement of the jet-streak or vorticity center into the expected storm outbreak area and as necessary make modifications to the timing of the outbreak. As the upper level trough moves toward the outbreak area, the upper level wind and mass fields may become so far out of balance that gravity waves are shed by the system and move across the convective region triggering thunderstorm activity and influencing severe storm development (Tepper, 1950) – such triggers have been observed using frequent interval GOES satellite data (Fig. 9). It is common for the low level winds to increase in response to an approaching trough and deepening low pressure system, thus generating a strong low level jet that transports moist unstable air into the outbreak area – the necessity of using rapid interval geostationary satellite imagery to track such a strong low level cumulus flow has been documented (Velden, *et al*., 2000). Most often, the organized convergence along the front or developing pre-frontal squall line is readily detected in satellite imagery, Fig. 9, and along with the warm sectors stability can be monitored to nowcast storm genesis.

3.2.3. *Severe thunderstorms*

Severe thunderstorms that produce hail, tornadoes and damaging winds form under a variety of synoptic scale conditions (see references in section 3.2). Depending on the large scale forcing, instability and vertical wind shear, they can take the form of long-lived super cells that may produce incredible damage (Routunno, *et al*., 1988). Satellite imagery can be used to help identify super cells as well as identify certain tornadic storm triggering mechanisms. (Adler, and Fenn 1979; Heymsfield *et al*., 1983; Purdom, 1993).

3.2.3.1. *The importance of low level boundaries*

Miller (1972) pointed out that in a severe thunderstorm situation when meso-highs were present that the probability of tornado activity increased dramatically. It was Purdom (1976) who first showed that such boundaries were detectable using satellite imagery and often triggered severe weather. Maddox, *et al*., (1980) and Purdom (1976,1993) pointed out that other organized mesoscale boundaries can serve as the trigger mechanism

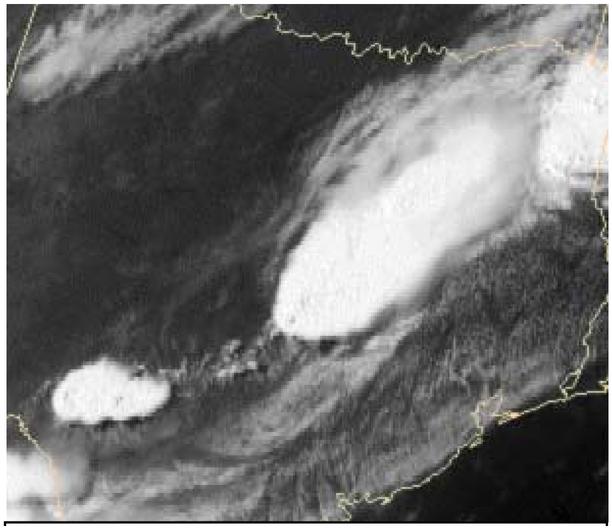

Fig. 10. GOES-East view. Visible image of developed squall line over Texas on 27 May, 1977, see Fig. 9

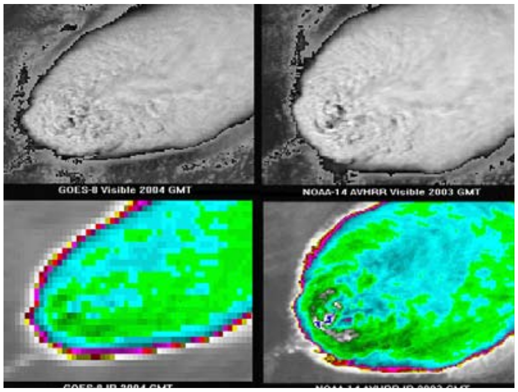

Fig. 11. GOES (left) and AVHRR views of severe thunderstorm top. Upper panels visible images, lower panels infrared images with light blue as warm, green colder, and dark to white to very dark blue colder yet. North is up

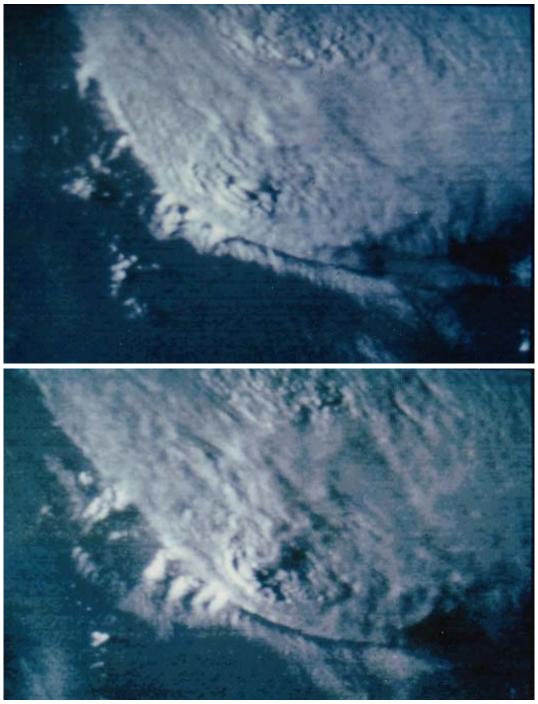

Fig. 12. Super cell storm over Texas on 10 April, 1979 at 2345 UTC (top) and 30 minutes later (bottom). This view from GOES West at 135°W provides an oblique view into the back side of the storm which is at 100° W

that causes a storm to evolve to its tornadic phase, although their role was not well understood. For example, cases were documented where very heavy rains (from the previous evening) produced a boundary with which a severe storm interacted resulting in tornadic activity[6]. That boundary was detectable in satellite imagery as a marked transition zone between stable boundary layer air (low level waves in a stratiform cloud field) and cumulus in the unstable air to its south (Bader *et al*., 1995, pg 431). Similarly, a lake breeze front (Bader *et al*., 1995, pg 433) was shown to be the trigger mechanism for a tornado near Chicago. Later a conceptual model was proposed to explain the role that low-level boundaries played in a severe storm's evolution to the tornadic phase (Purdom, 1993). The mechanism pointed out the importance of vorticity concentrated along the outflow boundary being converged and tilted into the severe thunderstorm's updraft, resulting in a concentration of low level vorticity at that intersection point. The important point is that the intersection of a severe thunderstorm with a low level boundary marks a point with a very high potential for intense thunderstorm activity: under the right conditions, the storm will become tornadic.

3.2.3.2. *Supercells*

Under the proper vertical wind shear and instability conditions (Rotunno, *et al*., 1988), exceptionally intense thunderstorms form that are almost steady state in nature and last for several hours. Such storms, known as supercells, are responsible for the most intense tornadoes, and are more often than not characterized by large hail,

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[6] This is the storm referred to in the Heymsfeld *et al*., 1983, reference.

Fig. 13. The tornado was over one mile wide at times – the entire black cloud in the photo on the right is the funnel, note its size in relationship to the buildings it is about to destroy

heavy rainfall and very strong downdraft winds. These storms can often be identified in satellite imagery by several common characteristics: (*i*) they are long lived; (*ii*) their strong updrafts are revealed by intense overshooting tops above the thunderstorm anvil; (*iii*) they often have long plumes of downstream cirrus emanating from the overshooting top region and extending far downstream above the broad cirrus anvil; (*iv*) there may be an enhanced cold "V" with a warm central region extending downstream from the overshooting top region [often coinciding with the plume in (*iii*) above]; and, (*v*) multiple low level cloud lines can be detected feeding into the upwind flank of the storm, flanking cloud lines. Fig. 11 shows cloud top characteristics of the very large storm shown in the center of Fig. 10. That storm produced one of the most violent tornadoes on record, F5 (Fujita, 1981) intensity, that ripped up street pavement and totally leveled houses and trees. In both the visible AVHRR and GOES image, Fig. 11, note the overshooting top region near the back western edge of the storm, and smooth textured cirrus extending eastward from the OST region across the broader anvil cirrus. The images reveal colder temperatures associated with the OST region, and a "V" notch characteristic. It is of interest that the coldest OST area in the AVHRR image is over 10° C colder than that revealed by GOES. The two images were taken less than 15 seconds apart – the reason for the colder temperature in the AVHRR image is its better spatial resolution: 1 × 1 km *versus* 4 × 4 km resolution. Conceptually, referring back to Fig. 1, the AVHRR infrared image is much more representative of the storm's strength with its top shooting well above the equilibrium level-this storm had a large positive energy area and a very intense updraft, a strong indicator of severe convection. The long cirrus plume above the anvil is indicative of a continuous strong overshooting top region (a long lived storm with a very intense updraft).

Fig. 12 provides an interesting view of another super cell storm. This particular storm produced F5 damage while destroying much of Wichita Falls, Texas. Notice the strong overshooting top region, similar to Fig. 11. These images provide an interesting 3-dimensional view of the storm. The flanking cloud lines that "appear" to be to the southwest of the anvil and OST area are actually a new portion of the updraft region that extend vertically into the overshooting top area. Also, notice on the later image evidence of the rain-cooled air left behind by the storm as it moves eastward (the arc shaped line from which the cumulus towers extend into the OST). It is on that boundary that the new updrafts (flanking lines) have formed. Thus the supercell, as it moves eastward, leaves behind a different boundary layer than the well mixed one in which it formed; however, immediately to its south and east, unstable air feeds the updraft region. As with most intense storm situations this is a very complex storm system, but if geostationary sounder data had been available in 1979, based on today's experiences with such data, an observer would have detected dry air to the west of the storm, unstable air to its south and east, and stable air within the interior of the rain-cooled outflow region. Fig. 13 shows two photographs taken from the ground of the tornado funnel as it moved across the city[7]. The funnel was almost a mile wide, and at times had multiple vortices rotating within it (as in left photo). The mechanism that brings about storms of such intensity has been one of intense scrutiny. While the environment in which such storms form is fairly well understood, the precise mechanism that brings forth tornado genesis is not.

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[7] These and other photographs may be viewed at over Internet at http://www.weatherchase.com/wxpics/1979_0410/ , in addition detailed analyses of the outbreak may be gotten from NOAA Natural Disaster Report 80-1, "The Red River Valley Tornadoes of April 10, 1979." Available over Internet at http://www.srh.noaa.gov/oun/storms/1979 0410/index.html

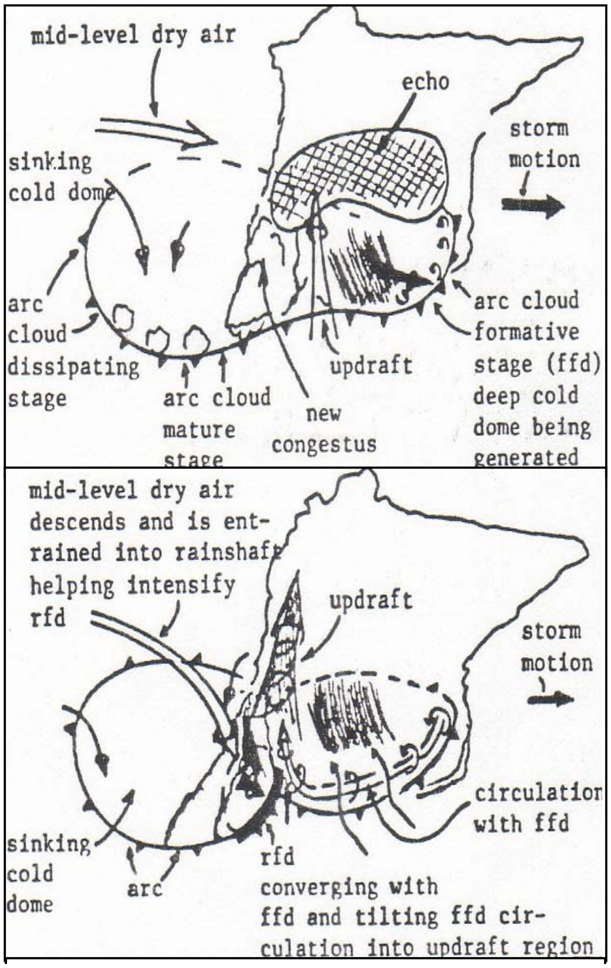

Fig. 14. Early (top) and mature (bottom) stages of super-cell's life

This author put forth a conceptual model based on satellite observations, research aircraft observations and observations from special field programs (Purdom, 1993). In that model, Fig. 14, the early stages of storm evolution are characterized by a vigorous updraft and a strong precipitation core that leaves behind a pool of rain-cooled air while generating a strong forward flank downdraft. The forward flank downdraft would be the location of intense horizontal vorticity due to a solenoidal circulation and vertical shear its interaction with the environment's low level flow. The decoupling of the boundary layer behind the storm (rain-cooled air region) combined with the storm's blocking of environmental flow leads to the entrainment of sinking mid-level dry air into the back side of the storm, fueling an intense rear flank downdraft. That rear flank downdraft penetrates into the sinking cold dome and forces the arc cloud that has been left behind by the storm (rfd) to converge with the forward flank downdraft (this can actually be seen in Fig. 12, where the towers beneath the overshooting top change orientation with respect to the low level cloudiness just beneath the southern edge of the anvil). This strong convergence point – rfd, forward flank downdraft and existing intense updraft is prime for utilizing all available local scale vorticity through tilting, convergence and stretching.

3.3. *Nighttime convection and mesoscale convective systems*

Under weak synoptic scale forcing, nighttime land breezes may generate thunderstorm activity off shore that persists through the night. The mechanism for such convection are well known and have been discussed by Pielke (1987) from a mesoscale modeling perspective and Bader *et al*., (1995) using satellite and radar imagery. One interesting aspect that has been noted by the author is that the land breeze front may exist for several days as a narrow band of cumulus that continues to move away from land, and it may interact with other convective regions to produce convection over the open sea. How such a line can persist is not well understood, but may be due to the inability of the atmosphere to dissipate the solenoidal circulation that would have been generated during its formative stages. At any rate, lines of convection can be seen to last for many hours over the open ocean, and are often trigger points for new thunderstorms.

Local scale monitoring and prediction of nighttime convection over land is a very difficult task. This is particularly true of the genesis stage. When convection from the daytime extends into evening there is often the question of "will it persist, or dissipate." In some cases, satellite data can aid in answering this question. For example if the daytime convection forms in conjunction with strong upper level forcing, then it may persist into the late evening, especially if it is connected to a warm frontal boundary. Convection may also form, or evolve into a Mesoscale Convective Complex (Maddox, 1980) if conditions are right.

With nighttime convection, advection of warm moist low-level air into the convective area is required, and it is here that satellite data may be of value. Nighttime low level jets often fuel warm moist air into nighttime convective areas. When synoptic conditions are strong, a low level jet may have developed during the daytime due to dynamic forcing, only to become invigorated at night when the surface cools and low level air becomes decoupled from surface frictional effects (continuation of daytime convection cited above). In other cases, terrain, coupled with the pressure gradient may make conditions right for low level jet formation (Bonner, *et al*., 1968), but that jet does not form during the daytime due to heating of

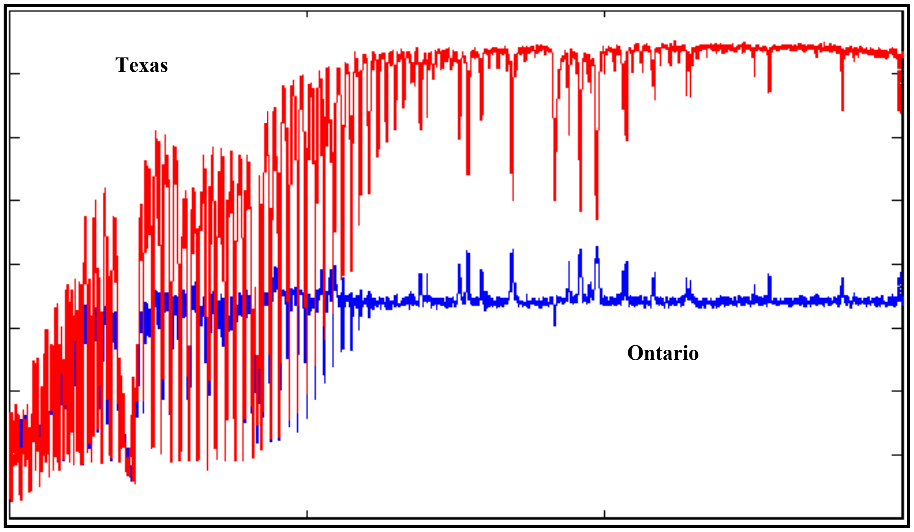

Fig. 15. IMG interferogram over Texas (top) and Ontario (bottom). On the right half of the interferograms note the difference in absorption line orientation (see text)

the surface and vertical mixing of momentum within the boundary layer. In such situations, at nighttime when skies are clear, strong surface cooling result in the rapid formation of a low level inversion, decoupling the warm and moist air within the boundary layer from the effects of friction. In satellite imagery this can often be detected by very rapid cooling of the surface and the movement of warmer low level moisture above it (Bader *et al.*, 1995): however, this is not true in all cases and awaits new technology for its answer, Fig. 15 described below. Such technology is at hand, or on the near horizon, with very high spectral resolution infrared data from NASA's Atmospheric Infrared Sounder (AIRS); the NPOESS' Cross Track Infrared Sounder (CrIS), a Michelson interferometer that will measure radiances from 4 to 15.4 µm; Metop's Infrared Atmospheric Sounding Interferometer (IASI) which is a very high spectral resolution interferometer; and, NASA's Geostationary Imaging Fourier Transform Spectrometer (GIFTS). GIFTS, to be launched in a 2006 timeframe represents an important step forward in earth/space science as it will be the first hyperspectral infrared sounder on a geostationary platform. Fig. 15 shows two interferograms from the Interferometric Monitor for Greenhouse Gases (IMG) instrument that flew on the ADEOS satellite. The spectral region covered is from 700 to 850 cm^{-1} (left to right) with the region of interest being between 770 and 850 cm^{-1}, approximately the right hand portion of the figure. Temperature increases along the vertical axis, approximately 10 degrees C per tic mark, from 210 to 290 °K. The region of interest is an atmospheric window where low level water vapor is an active absorbing gas (up and downward pointing spikes). Notice that over Texas, the surface's skin temperature is approximately 280 °K and the water vapor absorption lines point downward, indicative of cooler temperatures above the surface. The opposite is true over Ontario where the water vapor lines show warmer air above the surface, indicative of a low level inversion.

4. Future satellite systems

During the next several years the polar orbiting component of the operational environmental satellite system will evolve to include at least six satellites in polar sun-synchronous orbits. Those satellites will carry high-resolution multispectral imagers, infrared interferometer sounders, advanced microwave imagers and sounders, improved ozone monitoring instruments and radio occultation (GPS) sensors. As in the early days of satellite meteorology, polar orbiting satellites are again providing valuable information on which we will build the geostationary satellite systems of the future. In the geostationary arena, plans are for similar coverage as today with satellites operated by China, India, EUMETSAT, Japan, the Russian Federation and the United States. The major step forward in the geostationary arena is that many operators are planning for with satellites with greatly improved spectral and temporal coverage for imaging, and the United States is planning to move to hyperspectral infrared sounding. Data from research satellite instruments such as NASA's Moderate Resolution Imaging Spectro-radiometer and AIRS, NASDA's IMG, NASA's Earth Observer-1 with the hyperspectral Hyperion instrument, and ESA's Medium Resolution Imaging Spectrometer are clearly showing that innovative hyperspectral observing is the future for satellite imaging and sounding. Within the next five years, this capability should be demonstrated from geostationary orbit with a satellite known as GIFTS (Geostationary Imaging Fourier Transform Spectrometer). The advantages of hyperspectral data are ubiquitous, and such systems will provide the dream of long-term instrument stability that will support both research and operational users. Planning is underway for an important follow-on mission based on the success of TRMM. That mission, known as the Global Precipitation Mission (GPM), will allow for the derivation of global precipitation at least 8 times a day (more frequent in polar regions due to multiple area coverage from the sun-synchronous satellite observations).

5. Conclusions

Satellite data provides a user with powerful information that can be used to aid in local severe storm monitoring. When using satellite remote sensing data to address this topic, four critical questions must be answered. Those questions all deal with resolution: temporal, spatial, spectral and radiometric. For some applications, optimal resolutions may not be attainable from any one satellite but may be approached using data from a series of satellites. For example, while polar satellite imagery may not have the temporal resolution necessary for severe storm monitoring, it does provide information across scales, and can provide valuable high resolution insight to similar data from a geostationary satellite – thus serving as a valuable additional piece of information. And while polar soundings may not be of sufficient temporal resolutions to monitor rapidly evolving processes, they can provide valuable information that helps place a storm situation into context from a broad thermodynamic perspective. Throughout the paper, the importance of conceptual models to guide the user of satellite data has been emphasized. It has been pointed out that due to the highly non-linear aspects of convective evolution that precise forecasting beyond the nowcast timeframe is an exceptionally difficult task. Innovative products, such as mesoscale climatologies, especially when stratified by synoptic regime and boundary layer flow can serve as valuable tools for anticipating "hot spots" for convective development – it should be noted that such climatologies can also serve as valuable training aids. Monitoring and prediction of rainfall was not explicitly covered in this article. There are several reasons for this, not the least being that an incredible amount of information on that topic exists in the literature. Furthermore, there are numerous rainfall products available to the forecaster (as mentioned earlier with TRMM) and these products and their accuracy will improve with time. If rainfall is to be forecast on local scales, it is important to forecast the thunderstorm that produces it, and that was the focus of this paper.

Finally, the future of space based remote sensing and its applicability to local severe storm monitoring and prediction looks bright. The move toward high temporal and spectral resolution from both imagers and sounders should provide a firm foundation of observations upon which skill in this area can advance.

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