Chapter 7

Satellite Interpretation

Since the launch of the first satellite in 1960, satellite imagery has been a primary source of weather information, particularly in areas which lack surface and upper air observations. One image provides an instant glimpse of what is happening in the atmosphere, at least from a qualitative perspective. Combining individual images into an animated series provides additional insights for the analysis process. Using special techniques information on winds and precipitation amounts, among other things, can be derived from satellite data.

The purpose of this chapter is to describe how satellites operate, identify the three main types of satellite imagery that are used in operational forecasting, examine the basic features of the three main image types, and to provide pattern recognition schematics to help identify synoptic-scale features on satellite images.

Physical Principles

Satellites contain a set of instruments that look down at the Earth and measure the electromagnetic radiation emitted from the Earth's surface, cloud tops, and the atmosphere itself. Most satellite sensors are passive in that they focus in a particular direction and measure radiation for a specific wavelength band. Most satellite imagery used in operational forecasting comes from passive sensors. There are active satellite sensors, but they will not be addressed here.

Unlike solids and liquids, gases only absorb or emit radiation at certain wavelengths. These wavelengths depend upon the gas and its molecular structure. As a result, when you look at the absorption by the atmosphere as a function of electromagnetic radiation wavelength, you find a series of strong absorption bands due to water vapor, ozone, and carbon dioxide along with other wavelength bands that have minimal absorption. Specifically, there is:

- A very strong absorption band (near 100%) due to water vapor between 5.5µ and 8.3µ.
- A strong absorption band due to ozone between 9.3µ and 10.2µ.

- Strong absorption due to carbon dioxide above 13.4µ.

If you are looking at the Earth with a passive sensor and want to sense the Earth's surface, you need to look in wavelength bands with low absorption. Bands where absorption is weak and the atmosphere looks almost transparent are called *atmospheric windows*. There are three main windows used by satellite sensors:

- One from 0.3µ to 0.8µ.
- One around 4µ.
- Another in the 10µ to 13µ range.

The first window is in the visible portion of the electro-magnetic spectrum and correlates well with the peak in solar radiation. The third window is in the infrared portion of the electromagnetic spectrum and correlates well with the peak in terrestrial radiation. These two windows are used for the visible and thermal infrared imagery described below.

Types of Meteorological Satellites

There are two types of meteorological satellites: polar-orbiting and geostationary. Polar-orbiting Operational Environmental Satellites (POES) pass near the poles on each orbit and cross the equator at local noon (called sun-synchronous orbit). They are approximately 850 km above the Earth's surface and have a viewing swath approximately 2,600 km wide. The swaths overlap at the poles and are nearly adjacent at the equator. For one satellite 14 orbits each day provide global coverage twice a day.

Geostationary Operational Environmental Satellites (GOES) orbit the Earth once a day and rotate at the same rate as the Earth rotates. As a result, the satellite remains over the same spot above the equator and views the entire Earth. It is located approximately 35,800 km above the Earth's surface and does a full Earth scan every 25 minutes.

The main advantage of GOES is increased temporal resolution (new image every 30 minutes). In special weather situation, e.g., severe thunderstorms outbreaks, new imagery can be obtained every 15 minutes or less. The main disadvantage with GOES is limited polar coverage with useful data only available equatorward of 70^{o} latitude (due to viewing angle).

There are five geostationary satellites above the equator that provide continuous global coverage (at least from 70^{o}N to 70^{o}S latitude). These satellites are located at the following longitudes:

- 75^{o}W (GOES-E, operated by the U.S.)
- 135^{o}W (GOES-W, operated by the U.S.)
- 140^{o}E (GMS, operated by Japan)
- 75^{o}E (INSAT, operated by India)
- 0^{o} (MESOSAT, operated by Europe)

Satellite Imagery

When a sensor looks down at the Earth, it senses the radiation from an elliptical area within the sensor's field of view. As the sensor scan across the landscape, the individual fields of view are composited into the geographical image used by forecasters.

This field of view determines the image resolution. Strictly speaking, resolution refers to the smallest viewable area at the satellite's subpoint. The field of view gets larger as you move away from that subpoint. Resolution varies with wavelength and instrument type. In general, visible imagery resolution is around 2.5 km while IR imagery resolution is around 5 km.

Single satellite images are useful in analyzing what is happening in the atmosphere, but a series of images, shown in sequence, i.e., animated, often reveal features that may not be obvious from one image alone. When you view image animation, do not try to capture the entire image at one time. Focus on one feature and follow it for several loops. Then switch to another feature and view it. This approach allows you to see more detail in the satellite animation.

Operational forecasters use three main types of satellite imagery: visible (VIS); infrared (IR); and water vapor (WV).

Basic Interpretation of Visible Imagery

Visible imagery is derived from solar radiation reflected from the Earth and atmosphere. It is radiation in the 0.4µ to 0.7µ range. The imagery is available during daylight hours. Some satellites can sense low intensity visible light at night, but these data are not routinely used by operational meteorologists.

The standard VIS imagery is black and white. White is used for the brightest and most reflective energy received by the sensor while black displays the least reflective values. Shades of gray are used between the two extremes. The brightness sensed by the satellite depends upon several things:

- The albedo of the underlying surface
- The intensity of the solar beam (which is a function of the day of the year and the solar angle)
- The relative position of the Sun and the satellite

The relative brightness implies something about what you are viewing on the VIS image. Low brightness is associated with the ocean, lakes and the background Earth while medium brightness values come from land, including forests and deserts. Clouds produce high brightness, displayed in white or light gray.

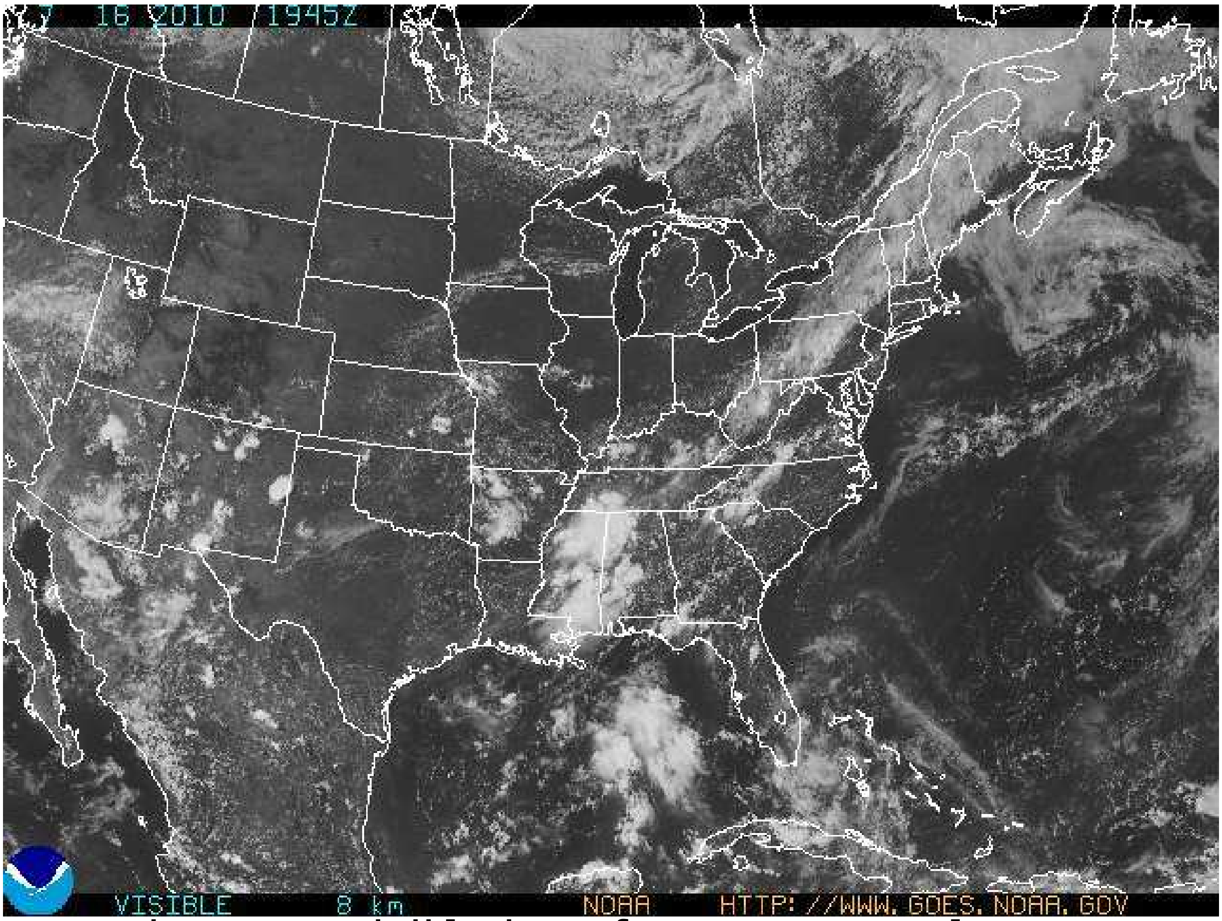

Figure 7-1: Visible image for 1945 UTC 16 July 2010.

With the better resolution available in VIS imagery, you often see some vertical structure in the clouds and cloud layers. For example, the shadow of one layer upon another is frequently seen around sunrise and sunset when the solar angle is low. Thunderstorm tops that protrude above the anvil can also be seen. Cloud texture and cellular patterns are easily distinguished. Cellular patterns are typical of cumuliform clouds while a flat structure indicates stratiform clouds. Wispy clouds are seen with cirrus. Figure 7-1 shows an example of a visible satellite image. The white clusters over the Gulf of Mexico and over Mississippi-Alabama are thunderstorms. The band of paler white that extends from Vermont to West Virginia is an example of a front.

There are a few areas where interpretation can be tricky. Low clouds and snow are difficult to separate on VIS imagery. Animation is the best way to do this. The clouds tend to move over time while snow does not move.

Small convective clouds that are below the resolution of the satellite sensor show up as a relatively uniform field due to the averaging the energy within the satellite’s field of view.

High thin cirrus clouds have a low albedo and do not show up well on visible imagery. In the IR these clouds are depicted as a flat sheet of clouds while they are frequently invisible in the visible. This illustrates why you should look at multiple sensor sources before deciding what is happening in the atmosphere.

Basic Interpretation of Infrared Imagery

IR (or conventional thermal infrared) imagery is derived from terrestrial radiation emitted by the Earth, cloud tops and the atmosphere in the 10μ to 12μ range. It is available 24 hours a day. Values are a measure of the temperature of the emitting surface, with some modification due to absorption and re-emission as the radiation passes through the atmosphere.

The standard IR display was black and white in the early days of satellite imagery, but has been modified with color enhancement for easier interpretation. On the black and white scale, white is used for the colder temperatures and black for the warmer clouds. This scale choice allows clouds, which have colder tops, to appear white, similar to the white associated with clouds on visible imagery. Temperatures also allow the relative height of the cloud tops to be estimated.

Image enhancement is a process that modifies the infrared temperature values with colors or shades of gray to emphasize specific features and improve interpretation. The concept of image enhancement is used with many image types including radar and non-weather data.

The enhancement process displays specific colors (or shades of gray) for specific temperature bands. Colors for adjacent bands are selected to maximize the contrast between bands. This selection of colors tends to emphasize or enhance specific features on the image. Figure 7-2 shows an example of an enhanced IR image. Note the color-temperature enhancement scale on the right side of the image.

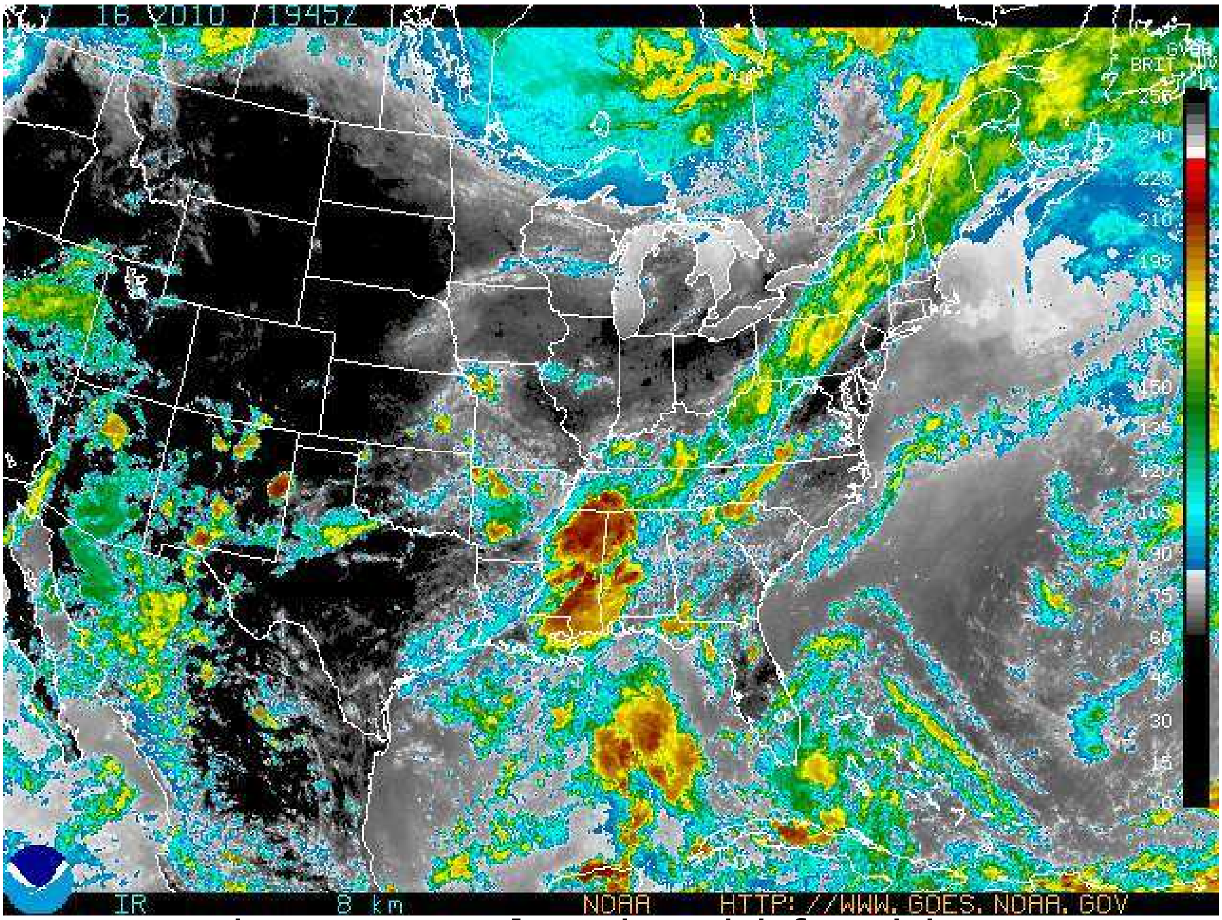

Figure 7-2: A color-enhanced infrared image for 1945 UTC, 16 July 2010.

Interpretation difficulties in the IR arise from the lower resolution of the IR images (relative to VIS). This makes cloud texture difficult to see. Also, low clouds and fog are hard to identify to due similar emission temperatures from the top of the stratus cloud and the Earth. Other sensor channels are now used to help see fog and stratus.

Basic Interpretation of Water Vapor Imagery

Water vapor imagery is derived from radiation emitted by water vapor at wavelengths not in an atmospheric window (6µ to 7µ range). It is available 24 hours a day. The stronger the signal seen by the WV sensor, the higher in the atmosphere is the moisture located. Most WV radiation originates from moisture in the upper troposphere (600-300 mb layer). If the upper troposphere is dry, WV radiation can come from layers are low as 800 mb.

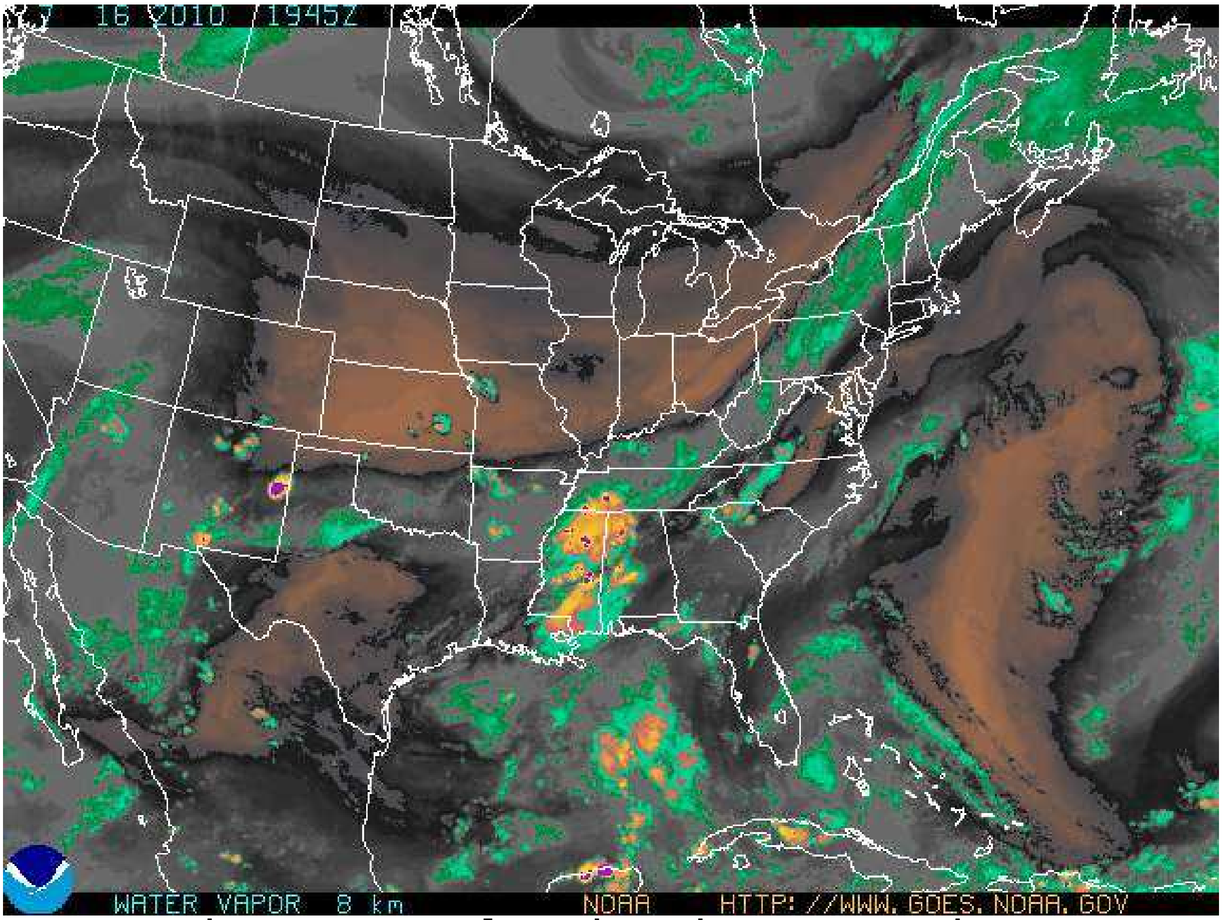

Figure 7-3: A color-enhanced water vapor image for 1945 UTC, 16 July 2010.

The standard WV display is in black and white but, as with the IR, is usually color enhanced to highlight specific features. On the black and white scale, white is used for higher sensor values implying more moisture in the upper troposphere. Darker colors indicate that the upper troposphere is dry and that radiation from moisture in the lower parts of the troposphere is reaching the satellite. Figure 7-3 is an example of a water vapor image for the same time and date as the VIS and IR images in Figures 7-1 and 7-2. The greens represent the higher radiation values while the browns are the drier values.

Water vapor imagery shows the synoptic scale flow very well. The location of main ridges and troughs are easily seen in the cloud patterns. Features like the jet stream axis are easily located. Subsidence in the middle to upper troposphere appears as darker areas.

The one disadvantage of water vapor imagery is that moist air or clouds in the lower troposphere are not well depicted on this type of imagery.

Image Limitation and Caveats

Two limitations should be noted when using satellite imagery: displacement and foreshortening.

Displacement is the poleward shift of the cloud location due to viewing angle geometry and the projection of the higher cloud tops onto the two-dimensional depiction of the Earth’s surface. This poleward displacement is strongest for thunderstorms and cirrus, and usually less than 10 km.

Foreshortening is the effect of the Earth’s curvature on the resolution of the satellite image. As you move toward the edge of an image, the image pixel covers a much larger area than at the satellite subpoint. For geostationary satellites, this means that data poleward of 60 degrees latitude is poor.

Synoptic-Scale Pattern Recognition

Although digital data are available from satellite sensors and algorithms are used to process these data into a variety of information, the main operational use of satellite imagery is qualitative. The method used to interpret imagery is called *pattern recognition*. Pattern recognition uses the fact that specific cloud patterns are commonly associated with specific weather features. If you recognize a particular pattern, it can be correlated with other data as your analysis takes shape.

Shown below are a handful of synoptic-scale cloud patterns that have been used for decades to identify synoptic-scale features in satellite imagery. A more thorough and exhaustive set of satellite patterns can be found in Bader *et al* (1995).

Remember that satellite imagery provides an integrated view of all scales of the atmosphere from the mesoscale through the planetary on one image. You need to mentally separate these scales are you interpret the image and correlate this information with other data.

Fronts and Mid-Latitude Cyclones: Fronts and mid-latitude cyclones are a very common and easily recognized feature on satellite imagery. Figure 7-4 shows the typical cloud pattern associated with a mature cyclone. There is a relatively narrow band of cloud along the cold front associated with the lift along that feature. A more extensive cloud shield is found on the cold side of the warm front in the vicinity of the warm conveyor belt. This cloud shield wraps around the low pressure center forming a “comma” head. The rotation associated with this feature is usually obvious in animation. The center of this circulation may be associated with an upper low or surface low, depending upon the situation.

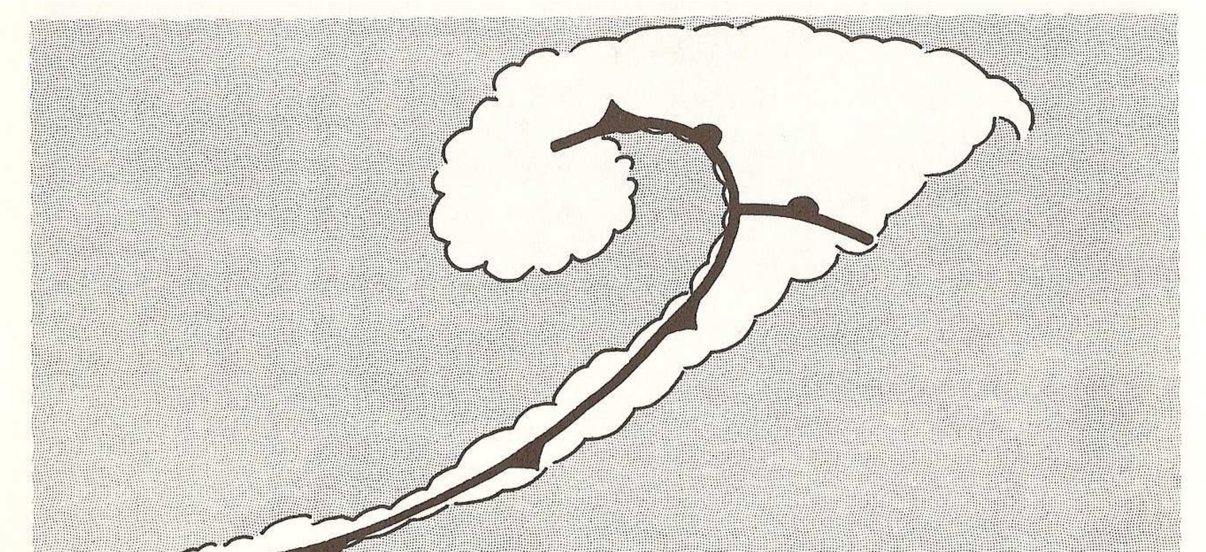

Figure 7-4: Schematic of the typical cloud pattern associated with a mid-latitude cyclone and its fronts. (source: Anderson et al, 1969)

Figures 7-1 through 7-3 show a cold front extending from just north of Maine along the Appalachian Mountains to Tennessee. The cloud shield and comma are cutoff by the top of the image.

Comma Cloud: A cloud formation often seen in mid-latitudes takes the shape of a comma, hence the name “comma cloud” (Figure 7-5). The exact shape of the comma depends upon the wind flow into the comma and the stage of development of the system. The *head* is the main area of clouds and upward vertical motion. The *cusp* is located near the center of rotation or the mid-level vorticity maximum. The *tail* extends equatorward from the head, and during latter stages of the mid-latitude cyclone development is associated with the cold front. An upper level trough is placed on the west side of the comma as shown in Figure 7-5. Note the common features between the comma cloud and the frontal cloud pattern shown in Figure 7-4.

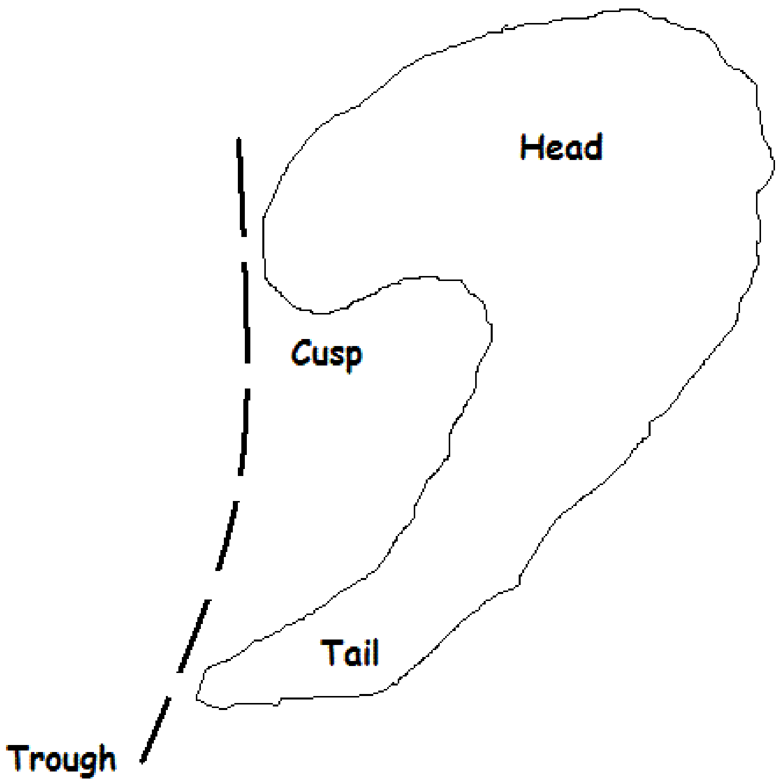

Figure 7-5: Schematic of a comma cloud and an upper level trough

Cyclone Development: As a mid-latitude cyclone intensifies from the initial frontal wave, through the wave cyclone stage, to an occluded system, the cloud pattern changes as the upward vertical motion increases. Figure 7-6 shows the typical evolution of the cloud pattern. In the left frame, the clouds are stretched along the front while a comma cloud and upper level trough is seen to the east of Kamchatka Peninsula at the western end of the Aleutian Island chain.

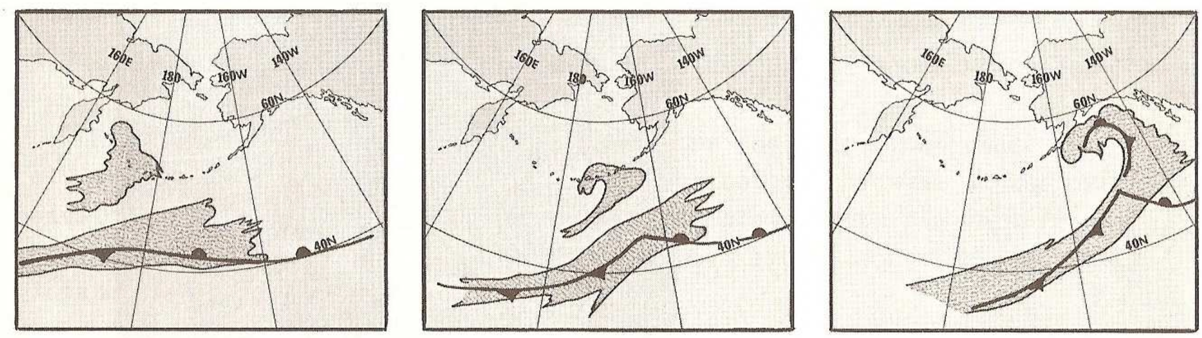

Figure 7-6: Schematic of the cloud pattern associated with the development of a mid-latitude cyclone (source: Anderson et al, 1969)

As the upper level trough moves closer to the frontal wave, the surface low intensifies, and the comma cloud more closely resembles Figure 7-5. As the system occludes, the cloud pattern from the front and upper level trough merge to show the typical occluded frontal pattern seen in Figure 7-4. The cloud pattern for evolving mid-latitude cyclones varies somewhat depending upon the flow into the developing system and available moisture.

Jet Axis Location: Figure 7-7 shows the location of the jet stream axis relative to an upper tropospheric cirrus shield. This cirrus shield often has an anticyclonic curvature and has a well-defined poleward edge. The jet axis is within 1^{o} of latitude of the cloud edge.

Open and Closed Cells: Figure 7-8 shows several features associated with a mature mid-latitude cyclone. Of particular interest is a pattern known as open cells and closed cells. *Open cells* are a pentagonal pattern of convective clouds with clear centers. In other words, there is more clear sky than cloud seen on the satellite image. Closed cells are a pentagonal shaped cloud element covering most of the cloud area. Closed cells and open cells can be compared to positive and negative photographs of the same cloud field. These convective cells are typically found in the cold advection to the west of a low center. The jet stream axis is found along the boundary between the two cell

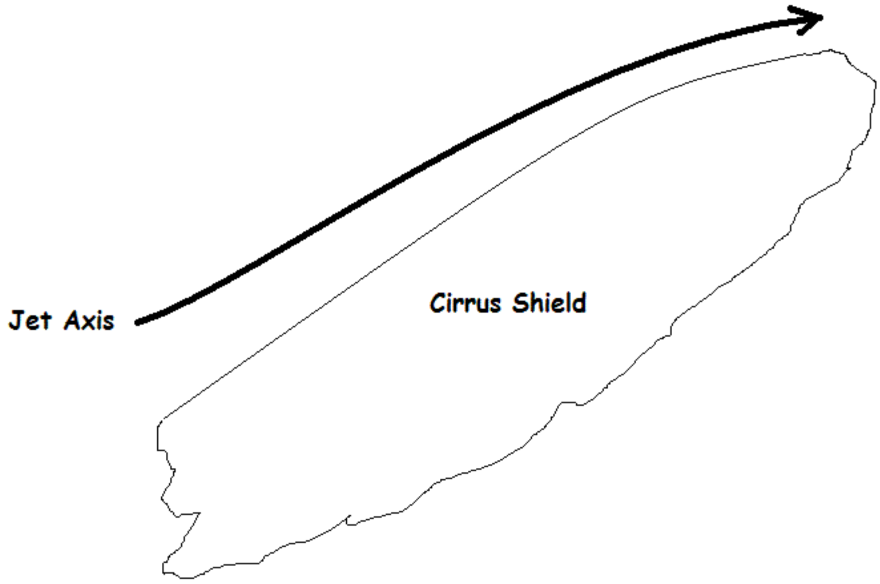

Figure 7-7: Typical location of the jet stream axis relative to a cirrus shield

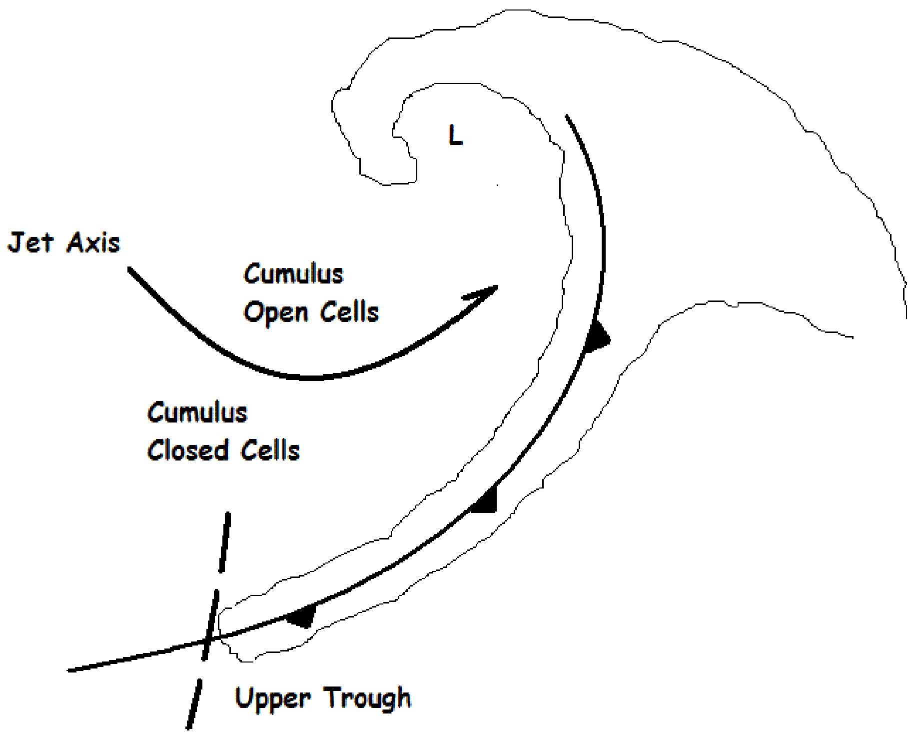

Figure 7-8: Various features associated with a mature mid-latitude cyclone

patterns shown in Figure 7-8. This particular pattern is found over ocean areas more often than over land.

Another feature shown in Figure 7-8 is the upper level trough crossing the frontal cloud band. When this occurs the cloud band along the front changes from continuous (ahead of the upper trough) to scattered or broken coverage. This indicates a change in the middle and upper tropospheric vertical motion.

Surface Ridge Location: The changes in vertical motion associated with surface ridges create a variety of cloud patterns in satellite imagery. Anderson et al (1969) divided these patterns into three types: A, B and C. Figures 7-9a, 7-9b, and 7-9c show the change in cloud type on either side of the surface ridge.

For large quasi-stationary high pressure centers over the ocean, where there is little or no wind, you can sometimes see the sun reflecting off the sea surface. This feature is called *sun glint*. It appears as a bright spot on visible imagery.

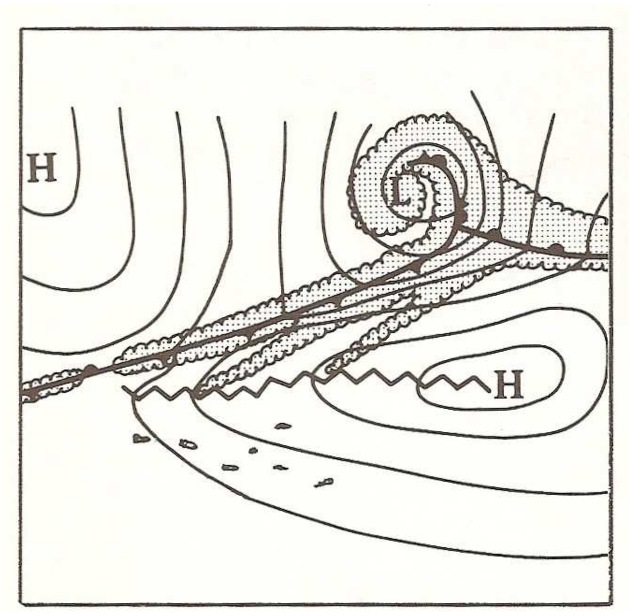

Figure 7-9a: Schematic of a surface ridge – Type A (source: Anderson et al, 1969)

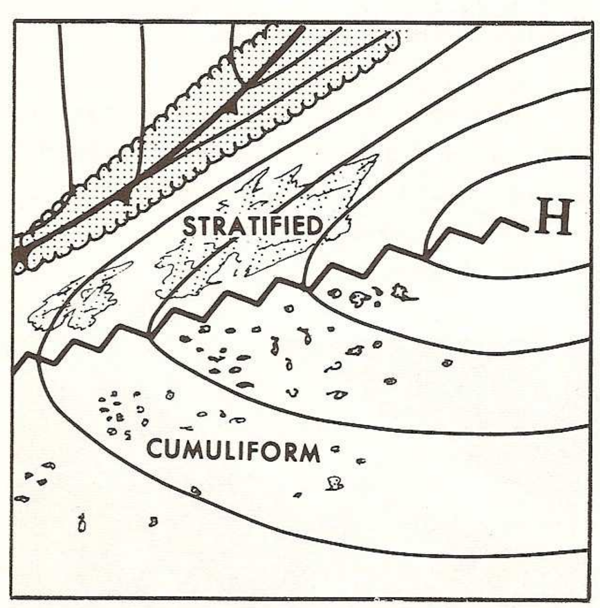

Figure 7-9b: Schematic of a surface ridge – Type B (source: Anderson et al, 1969)

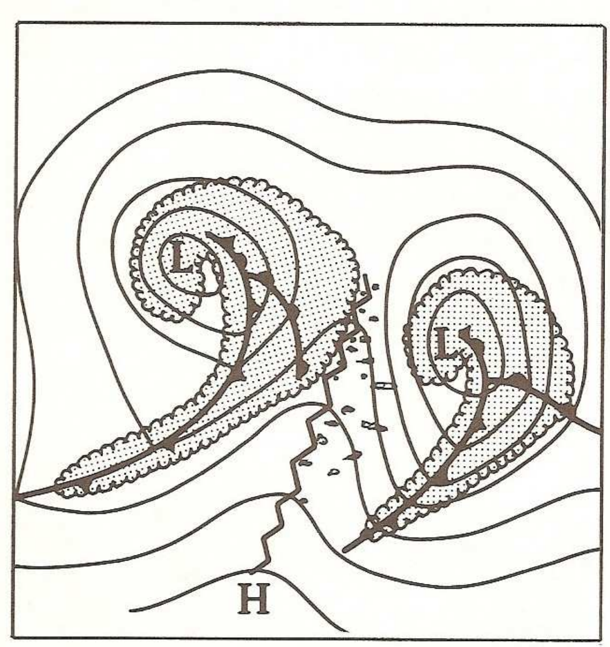

Figure 7-9c: Schematic of a surface ridge – Type C (source: Anderson et al, 1969)

Satellite Imagery Examples

Shown below are three infrared images for the same time and date in three different enhancements: linear IR; MR IR; and SABIR.

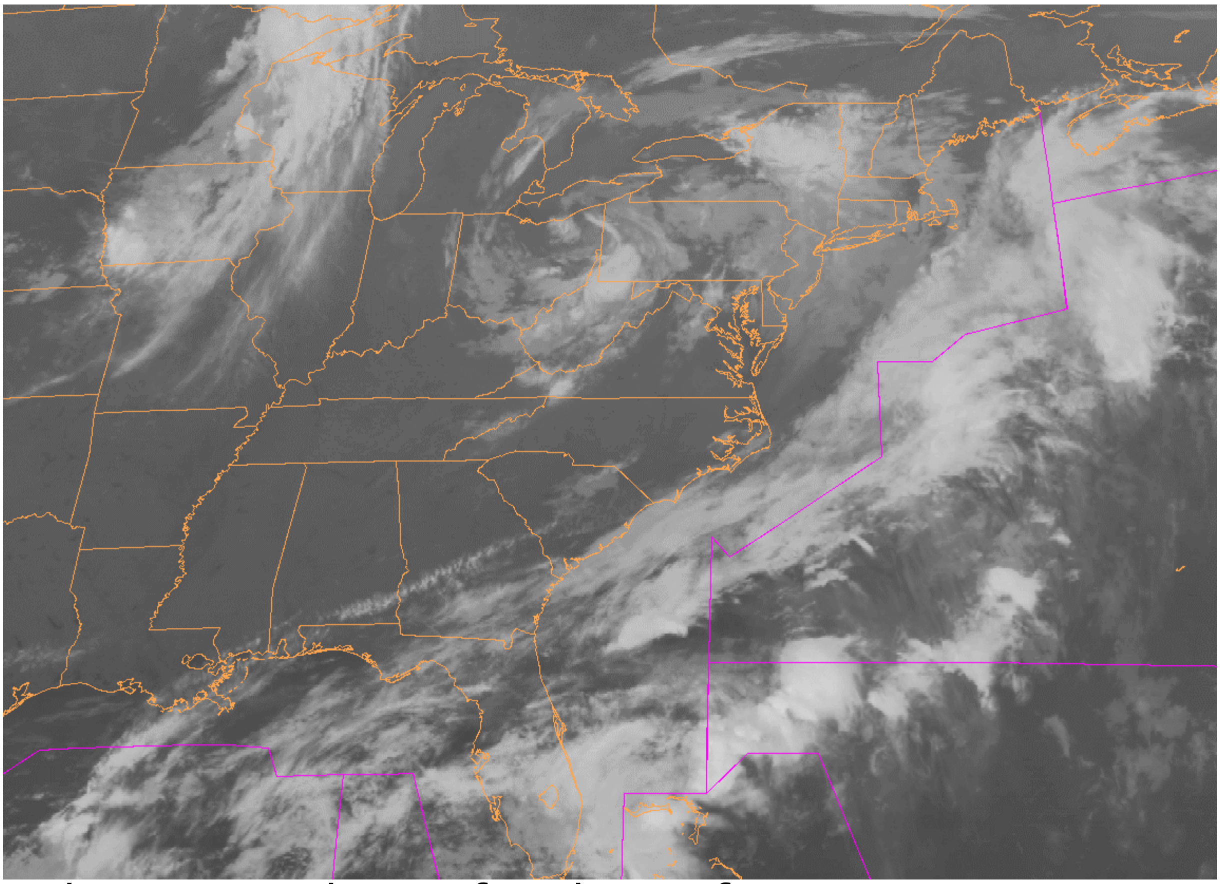

Figure 7-10a: Linear Infrared Image for 0545 UTC, 28 May 2003 (*source: National Weather Service*)

Figure 7-10a shows a linear IR image. In this IR image the warmest sensor temperatures are black and the coldest are white. Shades of gray are determined by a linear scale from black to white. In the image above there is a front that extends from the Florida northeast along the Carolina coast toward Nova Scotia. There is vortex over Ohio with what looks like an occluded front across upstate New York. Another feature, a comma cloud, is located over Iowa and Wisconsin, with an upper level trough from Minnesota into eastern Nebraska.

High clouds are in white while middle level clouds are gray. Low clouds are difficult to see.

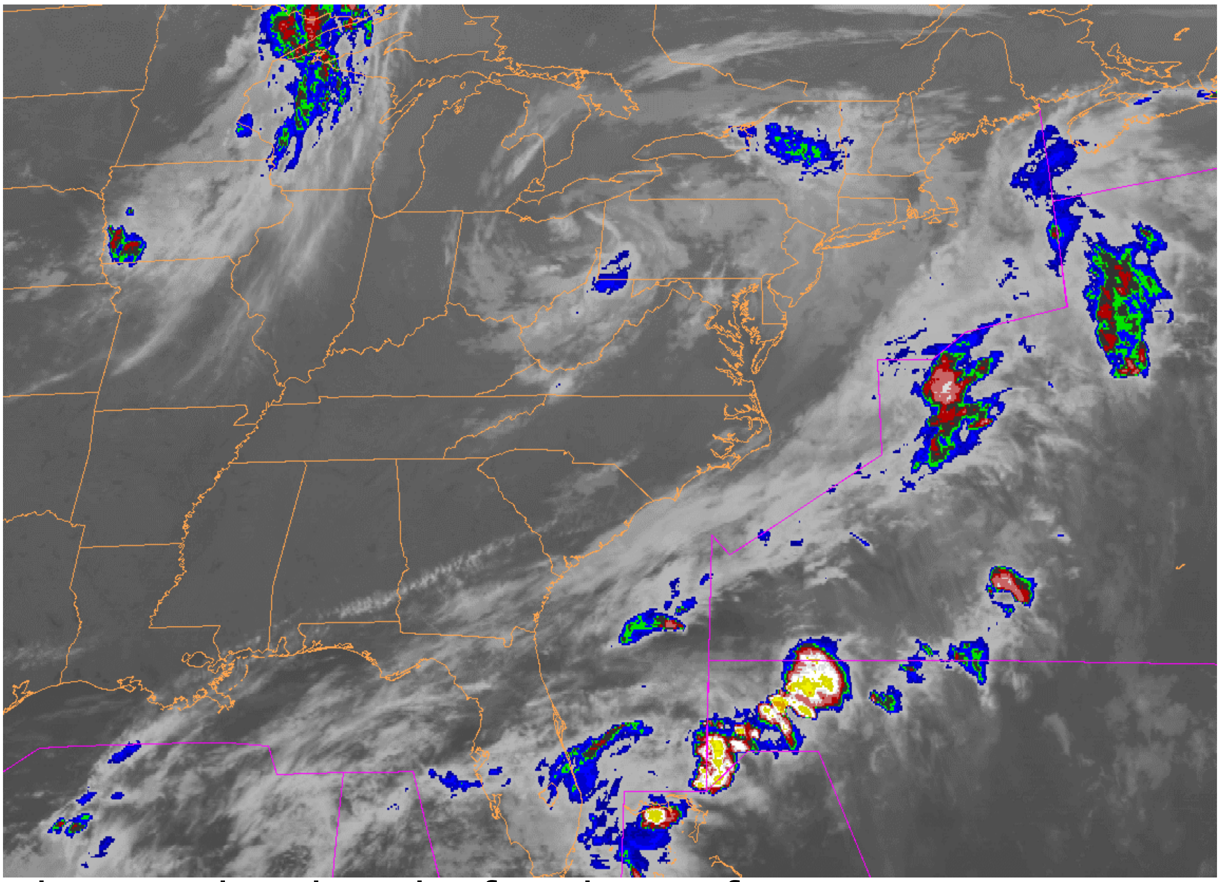

Figure 7-10b: Enhanced Infrared Image for 0545 UTC, 28 May 2003; MB enhancement (*source: National Weather Service*)

The MB enhancement curve was designed to highlight the high level cold tops associated with thunderstorms. High level cirrus clouds are also enhanced by this process. This enhancement is shown in shades of blue, green, red and white, with white being the colder tops in Figure 7-10b. Thunderstorms are seen east of Florida and east of North Carolina.

Figure 7-10c shows a variation on the MB curve developed by NOAA’s Satellite Applications Branch (SAB). It highlights warmer clouds than shown by the MB curve in yellow. The middle clouds around the vortex over Ohio better are defined than the linear IR curve.

Many other enhancement curves have been developed over the years, most for a specific purpose. When you look at a satellite image on the Internet it is often difficult to determine what enhancement curve you are looking at. Hopefully, an enhancement scale is provided with the image.

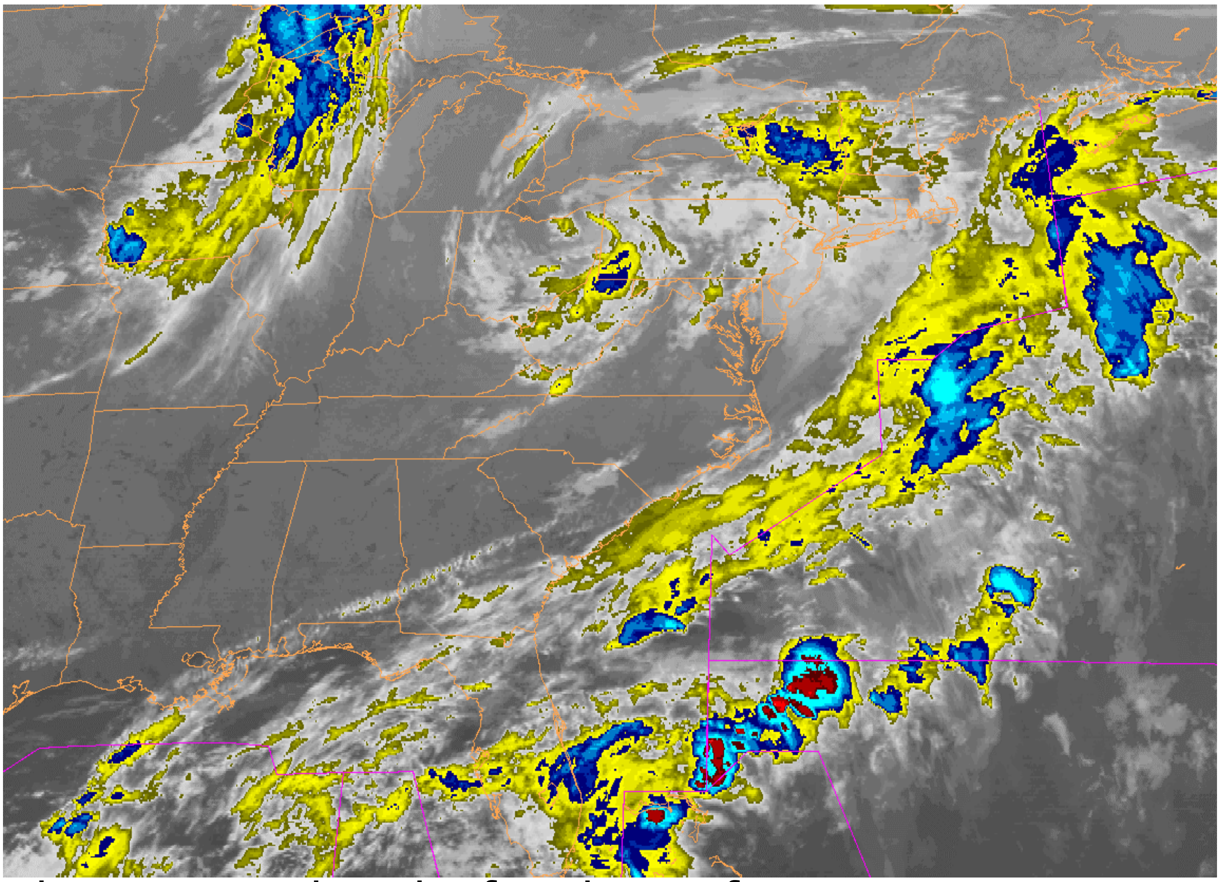

Figure 7-10c: Enhanced Infrared Image for 0545 UTC, 28 May 2003; SABIR enhancement (*source: National Weather Service*)

Concluding Remarks

Even though satellite data are digital, this chapter has focused on the qualitative aspects of interpretation. Many digital applications exist and are readily available to forecasters. These include such things as satellite soundings, the height of cloud tops, precipitation estimates and winds at a limited number of levels.

The interpretation section of this chapter has focused on synoptic-scale features that you see in satellite imagery. There are many mesoscale phenomena that are not addressed here. These include thunderstorms, gravity waves, and sea-breeze boundaries, among others.

An important fact to remember is that satellite imagery should be used in conjunction with other meteorological data to provide the best analysis of what is happening in the atmosphere.

Satellite imagery is a significant part of the meteorologist’s analysis toolbox. Use it wisely!

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