chapter nine

The Skilled Interpretation of Weather Satellite Images: Learning to See Patterns and Not Just Cues

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Contents

Keywords: *weather satellites, image interpretation, perceptual learning, atmospheric dynamics, radar, weather maps*

9.1 Introduction

The purpose of this chapter is to describe how an expert learned to perceive patterns (i.e., organized and discernible arrangements) in the weather satellite images used in forecasting, and now commonly seen on televised weather broadcasts. This skill—some would call it an art—is only now coming to be taught more widely in college-level course work on meteorology. A great many forecasters—old-schoolers who began in the days of hand chart analysis and witnessed the advent of weather satellite imagery—have spent decades interpreting images. They have developed an extensive new vocabulary, rich in terms that make sense describing patterns as seen from the vista of space but that do not fit well (or at all) with the traditional ground-based descriptors. From space you see patterns called "popcorn," "comma clouds," "leading edge gradients," "enhanced-V's," and "plumes," each of which suggests specific causal dynamics.

To explain the interpretation skills of the expert, I have covered them in this chapter through a format familiar to meteorology—the case study. Throughout, weather satellite images (in many formats—some familiar, some not), radar displays, weather maps, and other visual information will be used as illustrations. On most images, there will be many more patterns present than can be addressed in the text. As a result, some images may be referred to several times for different reasons. Information about each image, including Web addresses, as appropriate, is included.

9.2 A life story

When I was asked to write about pattern recognition for meteorological applications, I had to ponder how I ever came to do it well. Some would say that I am justified in regarding myself as a very good pattern recognizer, having spent 10 years teaching image interpretation at the Training Branch of the National Environmental Satellite Data and Information Service, an arm of the National Oceanic and Atmospheric Administration (NOAA). I was of the generation that was not formally instructed in the process, although that is what I do now with students of all age groups—from school children through adults. The easy answer to the question of how I became good at it was that I began studying clouds at a very early age, and kept on doing it for some 45 years.

From my family's 14th-story Manhattan apartment I used to watch the clouds. I was especially intrigued by clouds that lined up in "rows" or "streets." I watched snow showers march down the Hudson River. I recall being fascinated by how the clouds hid the sun and moon, and at other times, how the sun or moon could be seen through the clouds. I started counting the seconds for each type of event by day (sun) and night (moon). I discovered that the moon was visible through the clouds more often than the sun. I also noticed that the sun was more easily hidden by thin cirrus clouds than the moon was.

When we moved to the borough of Queens, I discovered that tides provided patterning experiences. Water came up from the nearby bay and occasionally flooded the streets. I remember being fascinated with how the water moved into and out of our neighborhood. I would note the high water marks and eagerly await the next event to see if the level rose even higher.

I understood none of these patterns at the time, but I consciously knew that I had become a watcher. A watcher is someone who looks for patterns and can see them within a larger frame of reference. This can often be accomplished due to contrast when one is able to distinguish color variations, shape variations, and/or movement variations. This was step one in becoming skilled at pattern recognition—noticing differences.

Step two developed over the years. I became a counter. A counter is a person who is always counting things or creating patterns or designs with numbers. I would count the numbers on license plates and add them. I would make a game out of the number of cars we passed vs. the number that passed us. I counted the exits until we reached South of the Border's "Pedro" at the North Carolina-South Carolina border on Interstate 95. (Billboards were strategically placed about 1 mile apart for 100 miles.)

Steps three through five, which will be described throughout the rest of this chapter, involve the linking of pattern recognition with principled understanding, and using that understanding for some purpose (usually analysis and/or forecasting).

- Step three is linking patterns to some process (i.e., physical understanding).
- Step four involves linking the pattern to some future event.
- Step five is bringing the understanding and prediction together.

Thus, if I know why a pattern is like it is, then I can use pattern recognition and go beyond simple observation or noticing of isolated cues.

9.3 Steps three to five: Linking patterns, principles, and prediction

9.3.1 The development of understanding

In high school, I took the New York State Regents' diploma curriculum. This program was for students planning to go to college and involved lots of math and science. In science we studied many concepts including the periodic table of the elements, planetary orbits, and rock formations. All of these were filled with patterning. Also in my math courses, almost everything keyed on patterning (but no one never really stated it that way). We worked number sequences, geometric proofs, and algebraic relationships and formulas. I was literally in heaven (and never had a clue).

Although I am avid cloud and weather watcher (see http://www.weatherworks.com/cool_clouds.html), I was always fascinated by other patterns in nature. This led me into photography and videography, where I can now capture my images of patterns for later study and enjoyment. In photography, I noticed that I was starting to look for the artistic aspects of scenes, not just the cloud types that were present. This artistic facet often involves recognizing and showcasing some type of pattern. It might have been the rolling hills, how haze in mountain areas increased with optical depth, or even how a row of parked aircraft at a terminal building presented a pattern. It also often involves taking photographs of mountain, river, and urbanization patterns from as high as 39,000 feet as I fly to various cities across the U.S. and the world. Figure 9.1 shows the pattern of streets and houses in an urbanized area from an aerial perspective. Figure 9.2 shows the patterning created by wave action interacting with human constructed structures in New York City. The pattern is especially clear because there is little vegetation to block the view or to protect the ground from erosion.

However, it is weather patterns that have driven me since the fourth grade. I recognized that a certain cloud sequence foretold a certain type of weather event. I knew that when the wind blew from a certain direction, a corresponding (and seasonally appropriate) temperature change followed. And during a winter storm along the mid-Atlantic coast, I knew that a wind from the northeast was more likely to mean snow than a wind from the southeast. I remember drawing weather maps at a young age, showing wave cyclone evolution. One of these appears in Figure 9.3. The low pressure center

Figure 9.1 An aerial photograph of an urban residential area. Not only are the houses patterned, but the meandering character of the natural, tree-lined river valley is quite evident.

Figure 9.2 An aerial photograph of a high-density urban center (foreground) and barrier island (upper right). There is active sand/silt transport here (from background toward foreground) as shown by collection of sediment behind the closest jetty. Notice the scalloped pattern on the water side of the sand deposits (and associated wave action on the water surface).

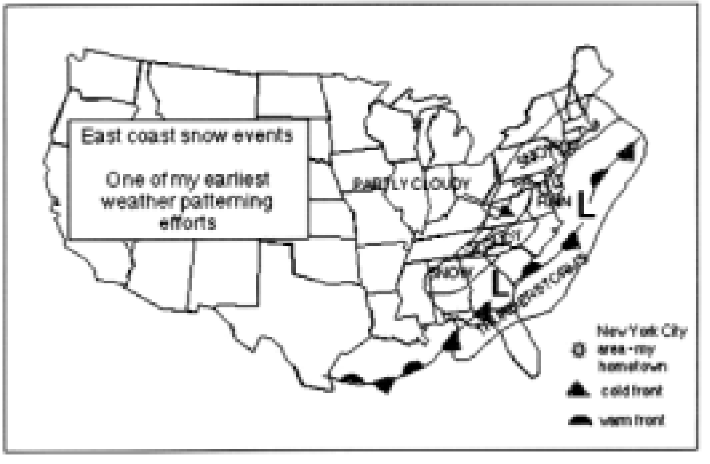


Figure 9.3 Here is a weather forecast I map made as a seventh grader. Note that a series of low pressure systems lies along the east coast and snow is forecast for New York City (my hometown) and parts of the Deep South. The low over Georgia would be the next snow-maker for New York. The symbols are those that typically appear on weather maps.

was always to the south of where I lived, the winds were always blowing from the northeast, and the temperatures were always cold enough for snow.

My interest arose some 6 years before the first weather satellite was launched and some 30 years before I became interested in weather satellite imagery. It is satellite imagery that can make it especially easy—today—for people to start forecasting even at a young age. The waviness of the jet stream, the circular banding of hurricanes, and the shape of a middle-latitude low pressure system with its "legs" (warm and cold fronts), all present and easy to recognize patterns.

At Florida State University (where I earned both undergraduate and graduate degrees in meteorology) I learned a great many more weather patterns, and how the patterns related to the underlying causal dynamics—thunderstorm structure, mesoscale meteorology, tornado characteristics, hurricane evolution, climatology and singularities, and much more. In 1971, I began my formal career at NOAA (I had worked as a trainee while at college during summer months in the late 1960s). It was then that perhaps the most notable pattern event in my life occurred. One evening while watching the evening television weather report, the local weatherman described a line of showers and thunderstorms on radar off to the northwest of Washington, D.C. The weatherman noted that heavy rain was likely in that area. At 11:00 P.M., the weatherman voiced concern that the line of thunderstorms had not moved in five hours and that flooding was probably occurring. He obviously did not fully understand atmospheric processes. The atmosphere was too stable to support the formation of thunderstorms. All that he knew was that he saw a pattern, recognized what he believed the pattern to be, and reported his observation (plus his incorrect interpretation). Most unfortunately, the weatherman did not know about radar "ground clutter." (A glance ahead to Figure 9.16 on page 259 will give the reader some idea of the clutter that appears in radar images.) Furthermore, the weatherman did not understand how local geographical patterns can cause and enhance clutter. He was not seeing thunderstorms at all, but rather the radar reflection off the eastern range of the Appalachian Mountains! Topography is illustrated in Figure 9.4. In this Geostationary Operational Environmental Satellite (GOES) image we have a clear view of the terrain of much of the eastern U.S. One can see the topography of the Appalachian Mountains revealed in the snow-cover pattern.

This event was significant to me because it showed me that a pattern could be caused by different things. The shape shown on the radar image that evening could have been thunderstorms, but it could also have been false echoes or ground clutter. Without the understanding behind pattern recognition, prediction or even simple interpretations can be seriously flawed.

Over the next 30 years, I further built my pattern recognition skills by working at various National Weather Service (NWS) facilities across the country. Following in the footsteps of many who preceded me, I made a concerted effort at understanding the physical processes behind what I could see in weather maps, data from balloon-borne sensors (radiosondes), and

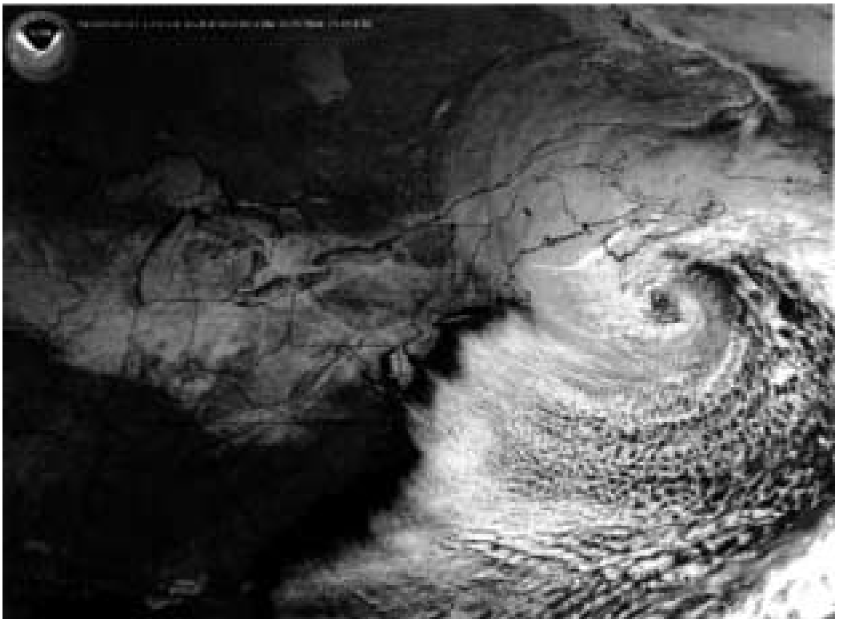


Figure 9.4 As shown in this multispectral satellite image, an intense winter storm (with an eye-like center) spins off the New England Coast on January 21, 2000. Strong northwesterly winds (blowing cold air over relatively warmer waters) are contributing to "lake effect" snow bands and cloud streets off the coast (including longer cloud bands at the exits of larger bays where over-water trajectories are longer). Due to differences between forested and unforested ground, snow cover variations highlight the Appalachian ridge-valley pattern from Pennsylvania to Virginia. There are also some mountain wave clouds present in Virginia due to the wind flow perpendicular to the ridge axes. (GOES Image courtesy of NOAA.)

radar patterns. My work at the National Severe Storms Forecast Center (NSSFC), now known as the Storm Prediction Center (SPC), led to many insights. The myriad patterns created by wind currents at different levels in the atmosphere, moisture variations, and associated pressure, temperature, and dew point changes showcased how the atmosphere could prime itself for a severe weather outbreak.[9,10,32,37] The depiction of how weather parameters *change* can be as important as the raw numbers, since changes often pinpoint where significant thunderstorm development and/or tornadoes are most likely to occur.[17,30]

In all my years of forecasting since working at NSSFC, I always searched for and tracked small and large scale pressure change centers on weather maps.[31] I did this because I recognized the pattern and its association with severe weather; but I also knew that surface pressure change provided an integrated measure of all the pressure variations going on above ground level; this process cannot be measured directly level by level in the atmosphere.

Thus, I came to add physical understanding to the pattern recognition-prediction couplet. Doswell,[9,10] Lemon and Doswell,[26] and Moller et al.[32] have applied similar approaches to forecasting severe mesoscale weather events. Burgess and Lemon,[5] Wilson and Fujita,[47] Forbes,[16] and Petit[39] are among those who have applied pattern recognition techniques to understanding and forecasting radar-based severe weather signatures.

In 1981 I moved to San Francisco. My job was to forecast for a large part of the west coast. After noticing just how little weather data was available for the eastern Pacific Ocean, my comment to the lead forecaster my first day on the job was, "How do you forecast anything out here? There's no data!" His reply was, "We use satellite data." From that moment on, I began to examine clouds from the viewpoint of space on a daily basis. Lacking other data sets to prove or disprove my assessments, I began to see myriad patterns including storm swirls, weather fronts, different cloud types, and snow coverage.

The jet stream (a band of high speed winds at altitudes generally above 20,000 feet) is often quite evident in weather satellite images. It can appear as a meandering band of bright clouds in all three types of imagery—visible, infrared, and water vapor. In multispectral imagery (where different bandwidths are superimposed on the same image), cirrus often appear as a thin purplish shade. Jetstream bands in multispectral imagery are illustrated in Figure 9.5.

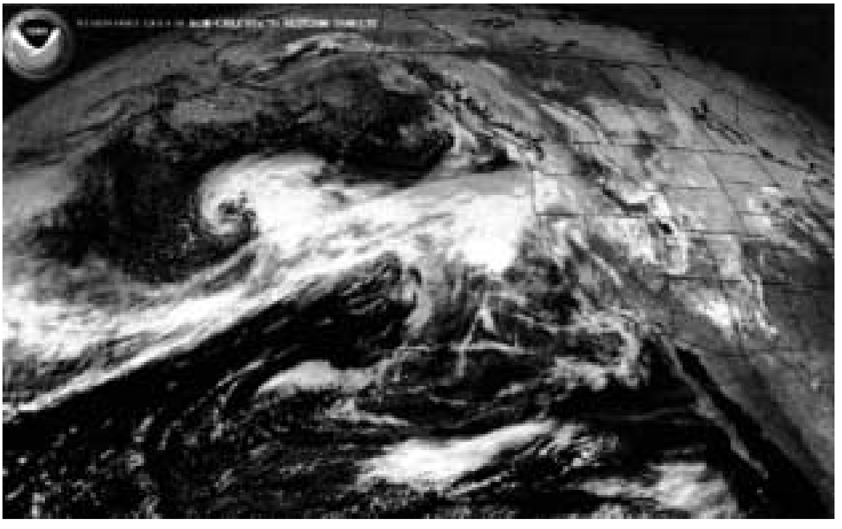


Figure 9.5 Large comma cloud in the central Pacific Ocean shows the presence of another ocean storm. The thin band cutting across the comma at nearly a right angle (on this February 25, 2000 multispectral image) indicates cirrus associated with a jet stream. In addition, the snow-covered mountains in the western United States have a much different pattern than the clouds in the region. The snow-covered Sierra Nevada Mountains of eastern California help to highlight the adjacent Sacramento-San Joaquin Valley. (GOES Image courtesy of NOAA.)

The subtropical jet stream is the easiest to recognize. Moving at 35,000 feet or more around 30° latitude, this relatively low amplitude wave often has large sheets of cirrostratus clouds on its equatorward side. The polar jet, typically at much lower altitude, but higher latitude and much greater ampli-

weather pattern. The polar jet stream is often associated with stronger weather fronts and low pressure or storm systems. However, the polar jet is often more discontinuous and cuts across the sharp cloud edges of middle-latitude storms and frontal systems at varying angles. In Figure 9.5, the polar jet is cutting almost directly across the frontal band that lies to the south of the low pressure system.

9.3.2 Patterns at larger and smaller scales

While large-scale patterns on satellite images often "jump out at you," smaller scale features require more scrutiny. For example, in Figures 9.6 and 9.7 notice the effects of coastal geography on fields of low-lying fog and stratus clouds near the California coast (Figure 9.5 also shows the mountain valley pattern). Tule fog, the name given to fog that fills most or all of California's Central Valley after a winter rain, is another fog feature that is relatively easy

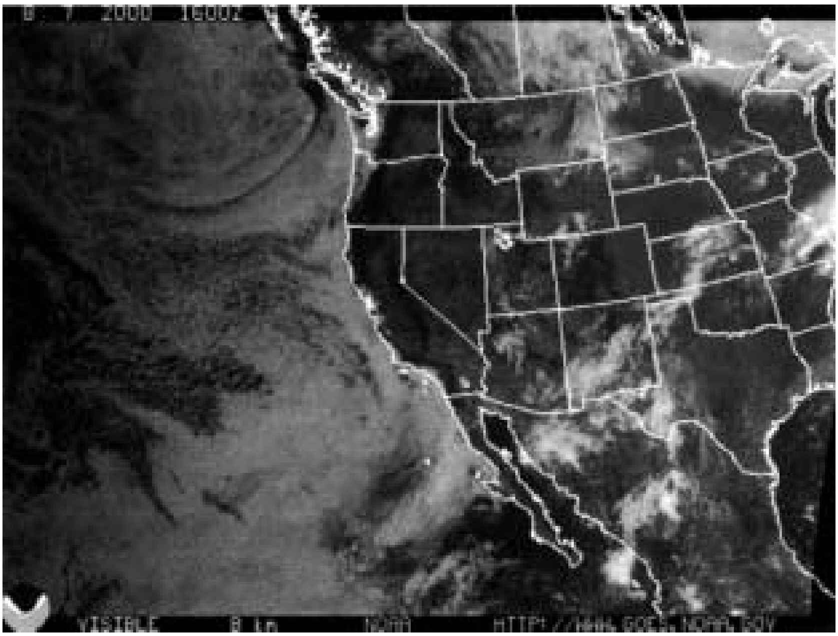


Figure 9.6 This visible image shows how mountains and valleys constrain the inland movement of coastal fog and stratus in central California. Also vegetation differences make California's Central Valley easy to locate. (GOES Image courtesy of NOAA.)

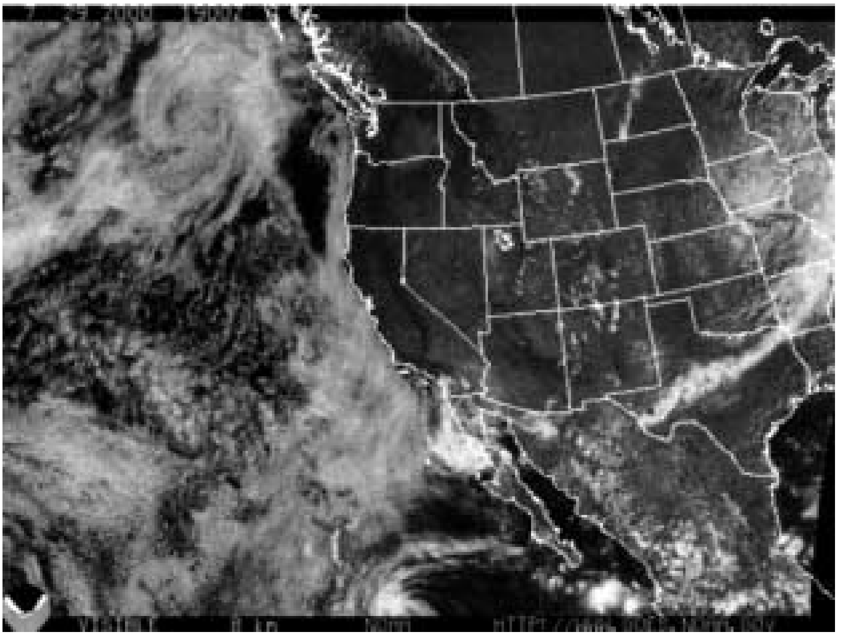


Figure 9.7 This visible image shows how coastal fog and stratus tend to hug the west Coast throughout the day. This patterning is significant in understanding microclimates of the region. As in Figure 9.6, vegetation differences make California's Central Valley easy to locate. (GOES Image courtesy of NOAA.)

to see. It literally fills the central valleys of California (seen as gray shades in Figure 9.7). The mountains that surround the rain-cooled air help to frame the fog, creating an image that looks like a giant bathtub filled with soap bubbles. Animated imagery sequences often show how the fog sloshes in the valley, driven largely by differential solar heating on nearby hillsides.

Fog was not the only weather pattern I discovered while working in San Francisco. As the persistent northwest surface winds interact with the coast and nearby islands, circulations or spins (similar to those of tornadoes and large scale low pressure systems) are created. A striking example of this is in Figure 9.8. There is an outstanding animation of this phenomenon (created as winds flow past Guadeloupe Island off the Baja California coast) at the University of Wisconsin Web site (http://cimss.ssec.wisc.edu/tropic/temp/eddy/eddy.html). Generation of eddies by other phenomena is discussed by Chen (see Web site http://www.eng.umd.edu/~chenjh/wakes/wakes.html).

The effect of the western mountains on weather amazed me. The Sierra Nevada Mountains provided me with insights into mountain induced cirrus and cumulus cloud formation, thunderstorm evolution, and snow cover patterning. (See Figure 9.5 for an example of snow coverage over the entire

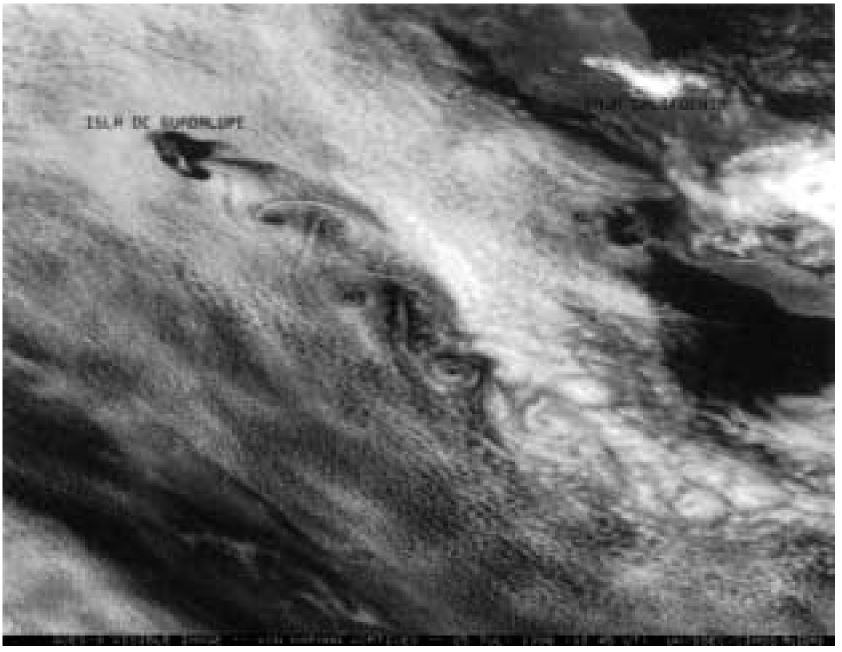


Figure 9.8 As northwest winds blow across and around Guadeloupe Island (off the Baja California Coast), the wind field is disrupted. Due to the persistence of the winds, both in speed and direction, island eddies often form and move downwind from the island. A string of these eddies (called von Karman vortices) can be seen in the stratocumulus cloud layer. (GOES Image courtesy of the University of Wisconsin—http://cimss.ssec.wisc.edu/goes/misc/von_karman.gif.)

western U.S. Differences in color—purplish vs. whitish hues—reveal clouds vs. snow cover.)

Meteorologists (both forecasters and researchers) have discovered an array of additional patterns in satellite imagery. Ellrod and Nelson,[14] Maddox et al.,[28] Purdom,[40] and Scofield et al.[42] have led efforts at applying pattern recognition of satellite cloud signatures to severe weather and/or heavy convective rainfall events. Ellrod has used satellite imagery to detect fog at night[13] and also assess clear air turbulence.[12] Dvorak[11] and Smigielski and Mogil[43] have developed decision-tree approaches which allow meteorologists to look at satellite imagery almost exclusively to obtain estimates of the central pressure inside tropical and middle latitude oceanic cyclones, respectively. Figure 9.9 contains two multispectral images of Hurricane Alberto in the summer of 2000. The top figure shows Alberto as it was "spinning up" and the bottom figure shows the subsequent organization of the storm and a well-defined eye. Alberto would have been classified as a strong storm using the Dvorak Technique and was measured as a strong storm by hurricane hunter aircraft.

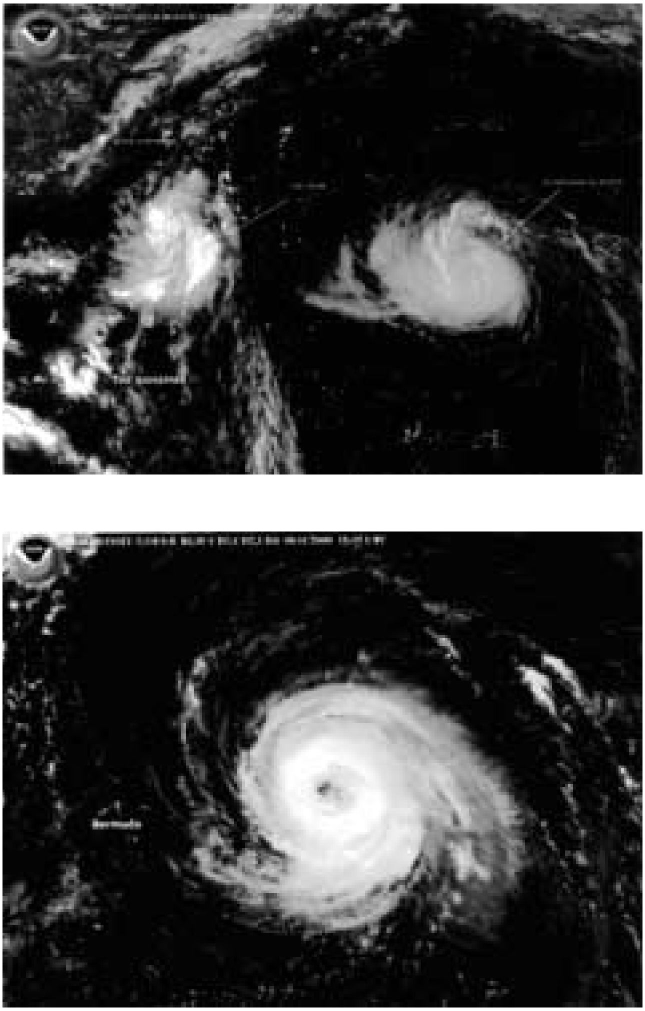


Figure 9.9 Hurricane Alberto undergoes changes in its cloud pattern from the afternoon of August 10, 2000 to August 11, 2000. In this multispectral image pair, notice how the circulation is more rounded and an “eye” has appeared by the August 11 image. According to NOAA, the sustained winds in Alberto had reached hurricane force by the time of the August 11 image. (GOES Image courtesy of NOAA.)

Pattern recognition also plays a role when one takes an even-larger scale perspective. Leonard Snellman, head of the NWS Western Region Scientific Services Division in the 1970s and 1980s, demonstrated relationships between the location of high altitude long wave troughs (low pressure centers) and ridges (high pressure centers). He used the word “teleconnections” to describe how weather patterns in one place can be related to patterns in other places.[44] A teleconnection is a "recurring and persistent, large-scale pattern of pressure and circulation anomalies that spans vast geographical areas"[46] (see also [1,34]).

Gray uses a similar approach to produce his annual forecast of Atlantic Ocean hurricane frequency and storm strength.[22,23] He relies on the strength of El Niño, the presence and strength of westerly winds at high altitudes in the tropics, and African rainfall among his key predictors.

Recently, patterns such as El Niño and La Niña have gained international attention. These patterns are revealed in displays of the type shown in Figure 9.10. The patterns involve variances from average sea surface temperatures in the tropical eastern Pacific Ocean and are part of a larger-scale teleconnections pattern known as the El Niño Southern Oscillation (ENSO).

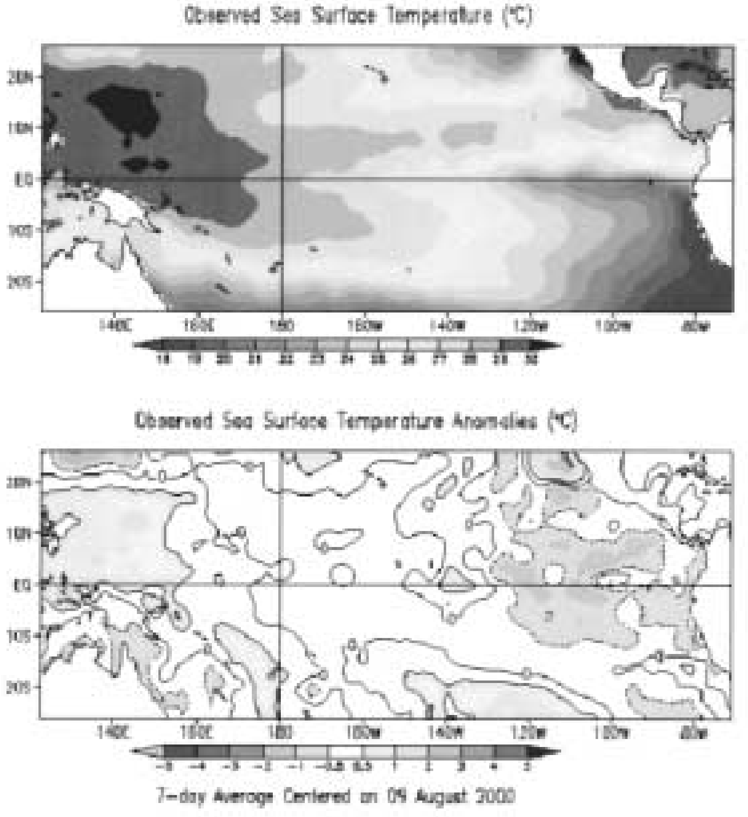


Figure 9.10 Using satellites, ships, and data buoys, NOAA scientists create maps showing sea surface temperatures and departures from average in order to monitor the onset and demise of events such as El Niño and La Niña. See color version of this figure in the color section following page 114. (Maps courtesy of NOAA's Climate Prediction Center—
http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/.)

One way to measure the pattern is by examining images of sea surface temperatures in the tropical eastern Pacific Ocean which are created from satellite imagery, ship reports, and data buoys. The most current analysis of sea surface temperatures can be found at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/.

The Southern Oscillation Index (SOI) is another measure of the El Niño and La Niña pattern.[35,36] Here, the large-scale fluctuations in air pressure occurring between the tropical western and eastern Pacific (i.e., the state of the Southern Oscillation) are examined. Traditionally, this index has been calculated based on the differences in air pressure anomaly between Tahiti and Darwin, Australia. The inverse relationship between the SOI and sea surface temperatures anomalies in the eastern Pacific shown by the time series in Figure 9.11 is striking. Notice too that the cycle of the ENSO has an average period of about four years, even though in the historical record the period has varied between two and seven years. The 1980s and 1990s featured a very active ENSO cycle, with five El Niño episodes (1982–1983, 1986–1987, 1991–1993, 1994–1995, and 1997–1998) and three La Niña episodes (1984–1985, 1988–1989, 1995–1996) occurring during the period. This period also featured two of the strongest El Niño episodes of the century (1982–1983 and 1997–1998), as well as two consecutive periods of El Niño conditions during 1991–1995 without an intervening cold episode.

The wide-reaching impacts of these ENSO patterns are well-recognized and even predictable to a large extent. The thought that haunts me is whether the science which describes their formation is sound enough. Presently, scien-

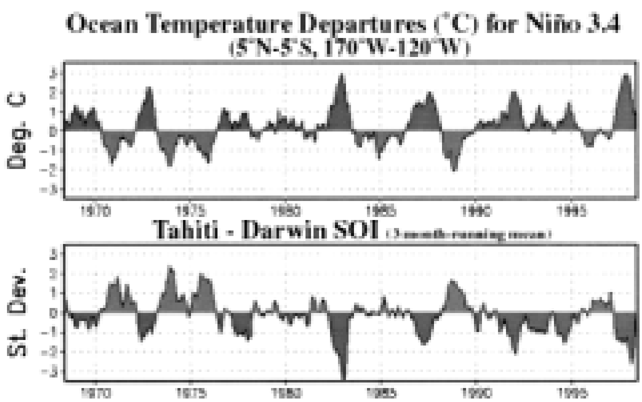


Figure 9.11 The SOI index (the difference in air pressure anomaly between Tahiti and Darwin, Australia) can be compared to the sea surface temperature anomalies (departures from average) found in the tropical eastern Pacific Ocean. The inverse relationship between the SOI and sea surface temperature anomalies in this time series is dramatic. (Graphs courtesy of NOAA's Climate Prediction Center—http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/soi.html.)

tists note the SOI pressure pattern and its associated link to a weakening of the easterly winds in the southeastern North Pacific Ocean. This, in turn, leads to a decrease in upwelling (rising of cold bottom ocean water due to wind stress on the ocean's surface). However, at this time, no one seems to know exactly what causes these pattern changes to occur. Without completing the entire picture (the understanding to support the pattern recognition), the forecasting of these climatological scale oscillations is still in its infancy.

Finally, there are long-term climatic patterns. While satellite imagery (and other forms of remote and *in situ* sensing) may begin to help us understand these, the data record is incomplete, at best. Clearly, with global warming in the news almost daily, there are many valid reasons to document and understand and long- and short-term climatic trends. Some of these include the effects of climatic change on agriculture, water resources, energy use, the potential rise in sea level, insect populations, and spread of disease.[15]

9.3.3 Repeating patterns

During my years working at the NWS, I also learned another aspect of how pattern recognition (on scales shorter than climatic or El Niño) applies to forecasting. It seems that once a certain pattern becomes established, it often repeats itself over time. Even if the pattern weakens or changes, it often quickly re-establishes itself. This was evident during the drought in the eastern U.S. during the summer of 1999 and the cool, wet pattern in the Great Lakes-New England regions during the summer of 2000. There are also some classic semipermanent weather patterns that are often very evident in satellite imagery:

- *The east coast's "Bermuda High,"* a high pressure system which is located near Bermuda during the summer months. With its broad clockwise wind circulation, this weather feature brings warm, humid air (and scattered afternoon thunderstorms) to large parts of the eastern U.S. This is illustrated in Figure 9.12.
- *"Lake effect" snow bands* usually occur throughout the late fall and winter months (and sometimes into spring) when northwest winds blow persistently across the warmer waters of the Great Lakes. As the cold air flows over the warmer waters, it picks up heat and moisture, destabilizing the atmosphere and allowing convection to occur where it normally would not. Due to their narrow nature, the bands often produce large snowfall gradients—excessive snowfall on one part of town and clear skies a few miles away. Figure 9.4 shows these bands extending from the Great Lakes all the way to the Delaware and Chesapeake Bays in the wake of a large winter storm.
- *The "four corners high"* is a semipermanent wintertime high pressure system found near the intersection of Colorado-New Mexico–Arizona-Utah. This high brings light winds and cold temperatures to much of

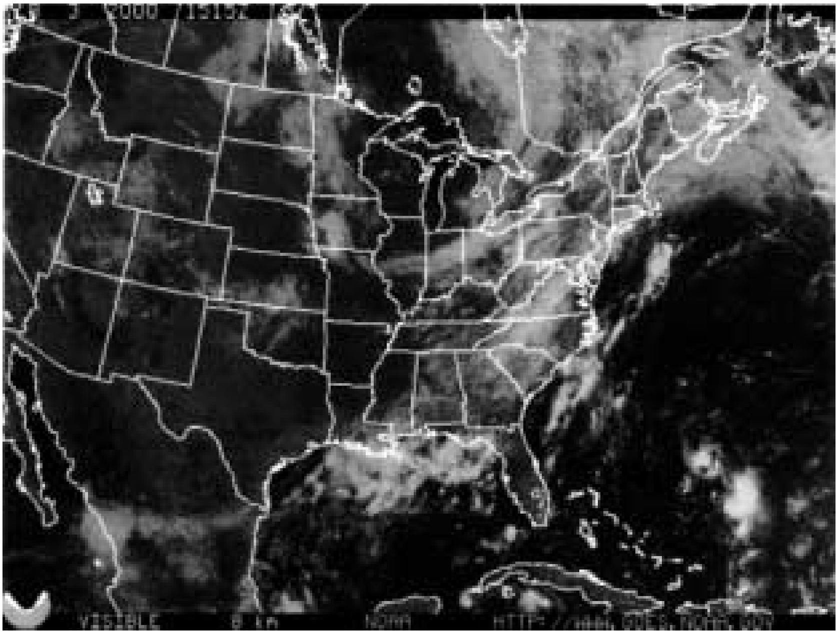


Figure 9.12 This visible image shows a large, mainly cloud-free area off the U.S. East Coast. Suppression of cloud development over warm ocean waters is one key to the presence of a large high pressure system. Some small cloud lines extend in a curved arc from north of Puerto Rico northwestward toward a few small thunderstorms and then recurve toward the northeast. These cloud lines often reflect the low-level wind pattern. This counter-clockwise curve to the clouds is another clue to the presence of a high pressure area. Because this high is located near Bermuda, it is referred to as the "Bermuda High." (GOES Image courtesy of NOAA.)

the intermountain west. If it shifts to the west slightly, it can alter the normal pressure pattern along the southern California coast and create Santa Ana winds—hot, dry downslope winds that occasionally blow into the Los Angeles basin and nearby locales. Any coastal fog that may be around is quickly swept out to sea by these winds. A similar pattern can occur when a high pressure system builds into the northern and central Rockies and causes onshore winds in California to weaken or shift to an easterly component.[6]

- *The normal pressure pattern along the U.S. west coast* (San Francisco-San Diego) has higher pressure offshore. Likewise, temperatures are much colder offshore, especially in summer. This combination of factors results in an almost constant sea breeze, especially along the central California coast, and most noticeably in the San Francisco Bay Area. As cooler ocean air moves inland toward the hot interior region of

California's Central Valley, it has only one way to go geographically—through the Golden Gate Bridge area, past Alcatraz and Angel Islands, northward through San Pablo Bay, and then eastward through Suisan Bay and the Carquinez Strait. This creates a perpetual "wind tunnel" in the area where onshore winds of 20 to 30 mph are common. Not surprisingly, comments such as "the coldest winter day I ever experienced was a summer day in San Francisco" have been widely ascribed to the weather in the City by the Bay. Null[38] notes that Mark Twain apparently never said these words; nonetheless, the value of this urban legend is inescapable. Ask the hapless tourists who are caught in shorts and tee shirts as the fog rolls in through the Golden Gate Bridge. Figure 9.6 shows how the coast fog and stratus field has moved ashore overnight to fill nearly all the coastal valleys of the central California coast.

- *The "dry line" from west Texas northward to western Nebraska* is a semi-permanent boundary between dry, desert-like air to the west and warm, humid Gulf of Mexico air to the east. The dry line often migrates to the east when a large-scale storm system develops over Colorado and moves into the Great Plains and is occasionally accompanied by blowing dust. The dry line is often readily detected in surface observations, but when cumulus and cumulonimbus (thunderstorm) clouds develop along the boundary and/or wind picks up dust to the west of the dry line, it becomes observable in satellite imagery. This is illustrated in Figure 9.13. Both boundary clouds and dust to the west of the dry line can be seen in Figure 9.13, across north Texas and southern Oklahoma where the dust cloud is actually hiding land features. To the east of the dust plume (and to its far northwest), contrasts between different types of land features (including forests and rivers) are evident. As the storm moves away, the dry line usually returns to its usual position in west Texas. Many significant tornado outbreaks in the central U.S. are linked to the dry line.[33]

9.3.4 Dynamic patterning

As the above examples suggest, the patterns in weather can be discussed in terms of the configurations of cues and cue relationships in a particular data set (i.e., a GOES image), but they can also be regarded as dynamic and evolving due to the underlying cause-effect relations, which end up leaving their traces in the static images (or dynamic image loops).

Sometimes a weather pattern will establish itself and a series of storms may bring excessive rain to one part of the nation, while another part remains dry. Then the pattern "flips" and the storm track shifts to another place. The winter of 1995–1996, for example, exhibited such a persistent pattern, with storm after storm bringing the northeast record-breaking snows. The winter of 1996–1997 was almost the reverse, with record snows falling

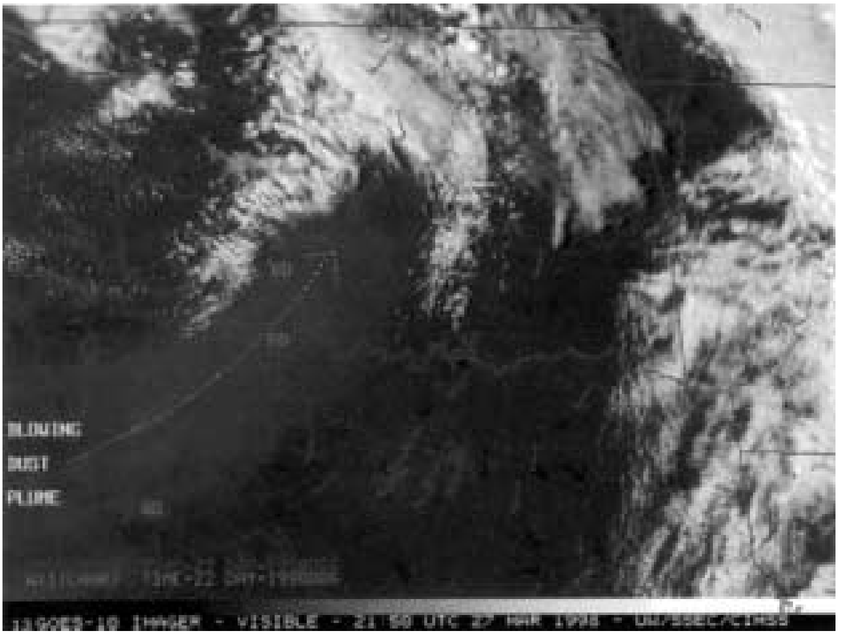


Figure 9.13 A satellite image that reveals the "dry line" in two features—boundary clouds and a dust plume to the west of the dry line (shown in a gray shade subtly lighter than the land). BD signifies blowing dust. Wind flags showing direction and speed are those typically used on weather maps. (GOES Image courtesy of the University of Wisconsin—http://cimss.ssec.wisc.edu/goes/misc/980327_2150_vis.GIF.)

over the northern plains states. The establishment of a pattern could easily be linked to the presence of a snow cover. Once established, the snow on the ground often affects the larger-scale air temperature pattern such that storm tracks move along the snow-no snow cover boundary. Ensuing precipitation events over snow-covered areas tend to be more often of the frozen variety. The boundary becomes further enhanced due to the effects of radiational cooling and reflection of sunlight from different surfaces. This unwritten rule works very well east of the Rocky Mountains. In short, snow often begets more snow!

Dryness (and a record number of forest fires) was the rule over the western U.S. during the summer of 2000. The cause-effect relationships have not been well-established (and are likely very interrelated). For some reason, dry areas tend to remain dry. The 2000 drought could be related to lowered evapo-transpiration rates as well as an associated large-scale high pressure or upper air ridge weather pattern due to decreased cloudiness. Conversely, rainy areas (with higher evapo-transpiration rates and a large scale low pressure system or upper level trough) tend to continue to receive rain.

Daily national high temperatures across the U.S. are most frequently observed in the desert southwest, Texas, and Florida. This pattern is driven by latitude, sun angle, and amount of cloud coverage. The chilliest spots are in northern states and/or in mountain areas of the west where latitude and altitude factors prevail.

Yet, even persistent patterns can and do change. Meteorologists sometimes refer to this as "flip-flopping." Periods of heavy rainfall may be followed by periods of dry or even drought conditions, only to be followed by periods of heavy rains.

Each year, the classic hurricane and tornado seasons occur during expected time periods. And *within* these trends one can easily find subpatterns involving the concentration of storminess in certain areas, the movement of storms, and the number of storms. For example, hurricane frequency was high along the U.S. east coast in the 1950s. It was not until the 1990s that the east coast frequency peaked again. Fujita[20] noted a periodic, clockwise migration of the tornado frequency centroid across the central U.S.

In addition to the generally repetitive daily weather cycle pattern (cold in the morning and warmer in the afternoon), periods of warm air for several days are often followed by periods of cold air for several days before the warmer air returns. Seasonally, the colder months are followed by warmer ones and then that pattern repeats itself. These ground-based weather patterns are linked closely to similar changes in the upper level wind and pressure patterns.

Have you ever heard the expression, "It always rains in Seattle"? Well, the pattern of prevailing storm tracks and Seattle's special geographical flavor make Seattle a rather cloudy and damp place. Although it rains often, Seattle does not receive a large amount of rain each year, and summertime in Seattle is often not marked by precipitation. Southern California's sun-filled beaches are generally sunny, but only after the nighttime and morning coastal low cloudiness "burns off" or evaporates due to solar heating.

All these instances of dynamic patterning show that the patterns perceived in data and imagery (of any type) are related in a direct way to the underlying causal dynamics. The achievement of expertise at interpreting data and/or imagery means that the person no longer perceives only the information shown. The expert interpreter *sees* the data or the image, and can tell you things about it (e.g., there is a coffee stain in the left corner). *But what the expert perceives is the underlying causal dynamics*. It is because of the expert's understanding of the underlying causal dynamics that the expert can perceive patterns that the novice cannot. Fronts do not appear on satellite images, but the expert can tell you where the fronts are. The jet stream leaves its footprint on both weather charts and satellite imagery. High and low pressure systems, upper-air disturbances, the list goes on and on—these are things that can be *perceived* in the images, but cannot be *seen* in the images.

Let me illustrate.

9.4 *Skywatching*

Of all the weather possibilities, clouds (from the ground up) first hooked me on patterning. Clouds offer an incredible array of patterns even within the basic set of cloud types. Looking up from the ground, cumulus clouds are puffy, often with white tops and darker bottoms; stratus clouds appear flat; cirrus clouds are wispy; and altocumulus and stratocumulus often have alternating dark and light bands or cloud bands interspersed with clear areas (see http://www.weatherworks.com/cool_clouds.html). Although each cloud type may be different, each one is formed by an associated weather pattern and its appearance is linked closely to physical processes.

Classic cloud patterning involves winter storms (east of the Rockies) and thunderstorms. High-flying cirrus clouds often herald the arrival of a winter storm. The cloud sequence—cirrus-cirrostratus-altocumulus-fractostratus—followed by snow or rain is what is typically observed. As is true in the interpretation of cloud patterns from a space viewpoint, the patterns seen from the ground hinge on the underlying dynamics—they are keyed to a gradual uplifting of moving air, followed by falling precipitation that moistens air below cloud level. As the air between cloud and ground becomes saturated, fractostratus clouds form; this signals that falling precipitation is almost ready to reach the ground.

Look at an approaching thunderstorm (in most parts of the U.S.), and it often involves a description such as "dark west." This is expected since towering thunderstorm clouds are blocking the late afternoon sun (most thunderstorms occur during the time of maximum solar heating of the ground) and the cloud we see is really shadowed (most sunlight has been reflected back toward the sun). No wonder that with five to eight miles of cloud between a ground observer and the sun, a thunderstorm cloud really appears dark!

Cumulus clouds, which generally form in late morning and dissipate around sunset, are the result of a repeating daily pattern associated with solar heating and radiational cooling of the Earth's surface. Land-sea breezes and mountain-valley breezes are driven by this same cold-warm-cold daily temperature cycle and differential heating or cooling related to land-water temperature differences or terrain variations.

Contrails (condensation trails or cirrus-type clouds formed by high-flying jet aircraft) mark the highways in the sky that jet planes use. That is why so many of the trails parallel each other and you can see planes follow planes across the sky. If the contrails last for a long time, chances are the air at flight level was already moist; if the contrail disappears almost as fast as it forms, the air aloft is likely dry.

I have also noticed that some cloud types had patterns within them. Altocumulus usually have alternating bands of clouds and clear spaces. Stratocumulus are similar, but with larger individual cloud elements. Sometimes there are two patterns that seem to crisscross in these layered cumulus-type clouds. At the time I first noticed these subtle patterns, I did not fully appreciate the interactions taking place in these wave pattern clouds. Now that I have taken trips to the beach, seen a tidal bore in Alaska, and watched raindrops splashing in puddles, this patterning seems almost too obvious for me not to have not recognized earlier. Basically, these events all involve transverse wave patterns. Either air or water rises in one place, and sinks in another. The ripple marks left behind in sand or soil by moving water or wind show the presence of the same type of wave pattern. Ripple marks found in wind-blown snow are not much different.

9.5 Patterns in weather analysis

Since I have been largely focusing on satellite image interpretation, I should point out that the understanding of weather involves looking at many different data types (including—but not limited to—clouds from the ground up, radar maps, surface and upper air weather maps, and data from balloon-borne sensors). All of these data types are rich with patterns and one can achieve expertise at interpreting them. An example would be the "meteogram," which depicts the weather for a specific location as a time series. The meteogram shown in Figure 9.14 (from the U.S. Weather Web site—http://www.uswx.com/us/wx/) provides an easy-to-see example of patterns and pattern relationships among weather variables for a 10-day period for Rapid City, SD. (By visiting the U.S. Weather Web site, one can find similar meteograms for cities across the U.S. for 2-, 10-, 30- and 60-day periods.

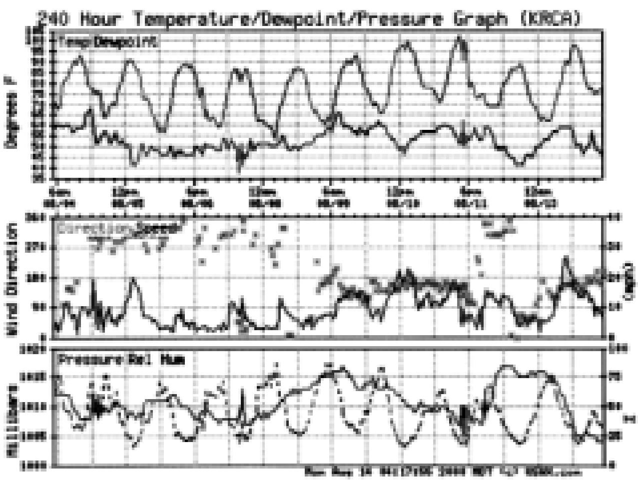


Figure 9.14 A meteogram for 10 days in August 2000 for Rapid City, SD. Notice the daily patterns for temperature, dew point and relative humidity. (Graphs courtesy of the U.S. Weather Web site—USWX at http://www.uswx.com/us/wx/.)

To find the meteograms, click on any city, once you get to the state map page you are interested in. The two day meteogram will initially appear at the bottom of the page; you can toggle among the other three choices.)

Patterns abound in weather charts. There are isotherm bands, warm and cold fronts, and the ongoing progression of highs and lows. One can see jet stream meanders. One can see squall lines go through a formation-decay process that repeats itself over and over again. One can see the preferred locations for highs and lows to form, tracks for them to take, and places for them to die.

Storm chasing provides another venue in which pattern perception plays a major role. Before storm chasing began formally in 1970, meteorologists noted recurring patterns in photographs of tornadic thunderstorms.[21] As a result, the basic structure of tornado-producing storms was specified. This became the basis for the ensuing storm chase programs operated by NOAA, universities, and other organizations. Photography, videography, and *in situ* and remote sensing data were examined to determine patterns and revise our models of storm structure. Photographic evidence provided by storm chasers supported hypotheses developed concerning the dynamics of multivortex tornadoes (smaller tornadoes rotating around the main tornado).[8,18] Most recently, Doppler radar evidence confirmed the existence of this phenomenon.[4] Richardson[41] was correct when he suggested that "big whirls have little whirls which feed on their velocity; little whirls have smaller whirls and so on to viscosity."

9.6 Patterns in weather forecasting

It is safe to say that weather *is* patterns! From individual and collective clouds to local, national and global weather and climatological scales, meteorologists examine patterns and try to use this information to predict the future state of the atmosphere. Weather forecasters today have an arsenal of pattern-recognition concepts at their disposal. These include pattern concepts developed over the years, statistical techniques driven by computer technology, and even rules for determining which computer forecast model is most likely going to handle a particular weather situation. Yes, forecasters have even recognized patterns in the performance of the many computer models (biases, tendencies, weather situations each model handles well, situations each model does not handle well, etc.), and have integrated these into their forecast process. Discussions of the use of pattern recognition in numerous weather forecasting applications appear throughout meteorological literature. Some of these include:

- Patterns involved in heavy rainfall prediction[28]
- Conditions needed for major east coast cyclogenesis[45]
- The relationship between winter lightning in the southeastern U.S. and heavy frozen precipitation[24]

Most of the forecasting techniques used by NWS forecasters today are based not only on patterning, but also sound scientific principles that support the pattern.

The same types of pattern recognition have forged breakthroughs in how forecasters interpret radar (both conventional and Doppler) and weather satellite imagery to create forecasts and warnings. Techniques key on the shape, movement, intensity, temperature, temperature gradient, and other measurable characteristics in either satellite or radar data. For example, a v-shape signature atop a thunderstorm in satellite imagery often indicates the presence of a strong updraft (and possible overshooting cloud tops) that is blocking the horizontal wind flow.[29] As the wind is forced around the updraft, it creates a v-shaped pattern downwind. This is easily seen in the cloud tops on enhanced infrared satellite imagery (hence its name, "enhanced-V") and may also be evident in visible imagery. Figure 9.15 (top) is a color enhanced infrared image at a 4 km resolution. It shows the temperature pattern associated with an enhanced-V cloud-top signature. The strongly rising air inside the thunderstorm causes environmental winds to split apart and move around the storm. A similar effect happens at the top of the storm. Notice the location match of the "V" with the overshooting cloud top in the corresponding, higher 1 km resolution visible image in the bottom figure. You can also see this type of feature as water flows down a curb and passes over or by an obstacle (see Figure 9.8).

The circulation associated with a tornado can sometimes be seen on conventional radars as a "hook echo." This shape results as rain is curled around the circulation of the tornado's parent mesocyclone. Where rain is not present, the radar detects nothing. The contrast between coiling rain and rain-free areas yields the hook shape in conventional radar reflectivity images. This is illustrated in Figure 9.16.

Here, the green yellow and red colors show increasing reflectivities (which mean heavier rain and/or larger hail are reflecting the radar signals). NEXt generation RADar (NEXRAD) is the new NWS Doppler radar system. While this system can detect rainfall, it also has the added capability of measuring the motion of raindrops (hailstones, other airborne particles) toward or away from the radar site (the Doppler effect). This means that air that is moving quickly toward the radar at one place and moving quickly away from the radar next to it shows two sides of a circulation pattern. Figure 9.16 (bottom) shows a Doppler velocity profile (red = winds moving away from the radar; green = winds moving toward the radar; white = very strong winds moving toward the radar). Depending upon the strength of this "gate-to-gate shear," the phenomenon can be classed as a mesocyclone or the more dangerous tornado vortex signature. These radar images in Figure 9.16 were obtained just before a large F5 tornado struck Moore, OK on May 3, 1999. A similar hook-shaped pattern, although at a much larger scale, is often observed in satellite images. Clouds (and associated precipitation) wrap around a low pressure center in a comma-shape pattern, shown in Figure 9.17 (see also Figure 9.4).

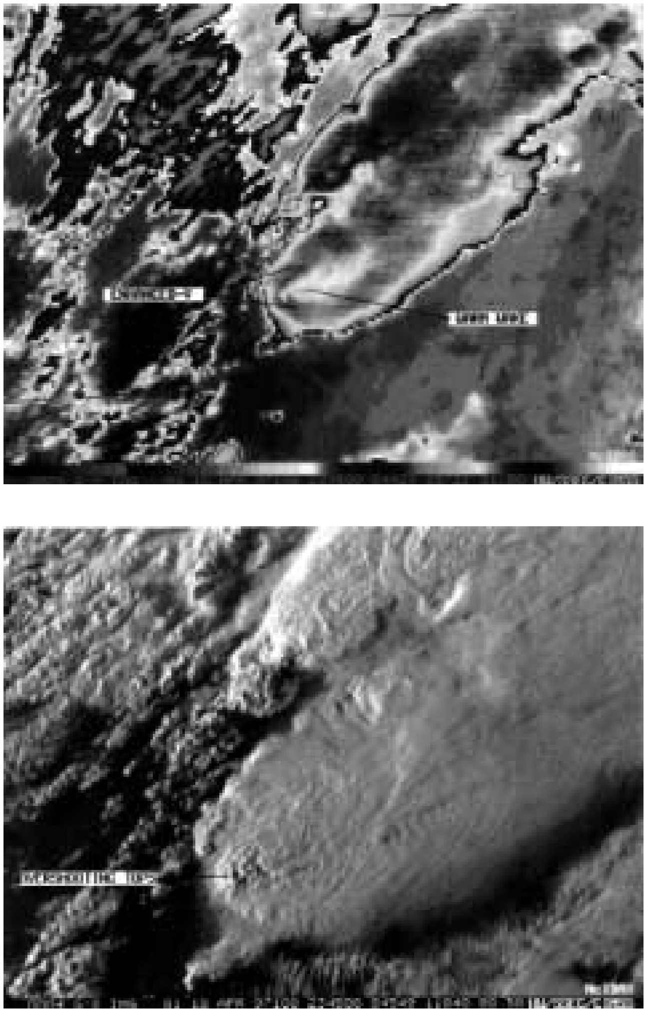


Figure 9.15 Top: A color-enhanced infrared image showing the temperature pattern associated with an enhanced-v cloud-top signature. Bottom: The corresponding visible image. See color version of this image in color section following page 114. (GOES images courtesy of the University of Wisconsin—http://cimss.ssec.wisc.edu/goes/misc/warm_wake.html.)

A cloud pattern that typifies a high pressure system is the meso-scale convective complex (MCC). The meso-scale of weather is for phenomena that are at a scale small in areal extent and which last for periods of only a few hours to a day. An MCC is a large cluster of thunderstorms that persists for a long time. Most commonly observed in the central U.S. during the summer months, MCCs also move off the west Africa coast and can develop into Atlantic hurricanes. Many MCCs produce strong outflow wind patterns

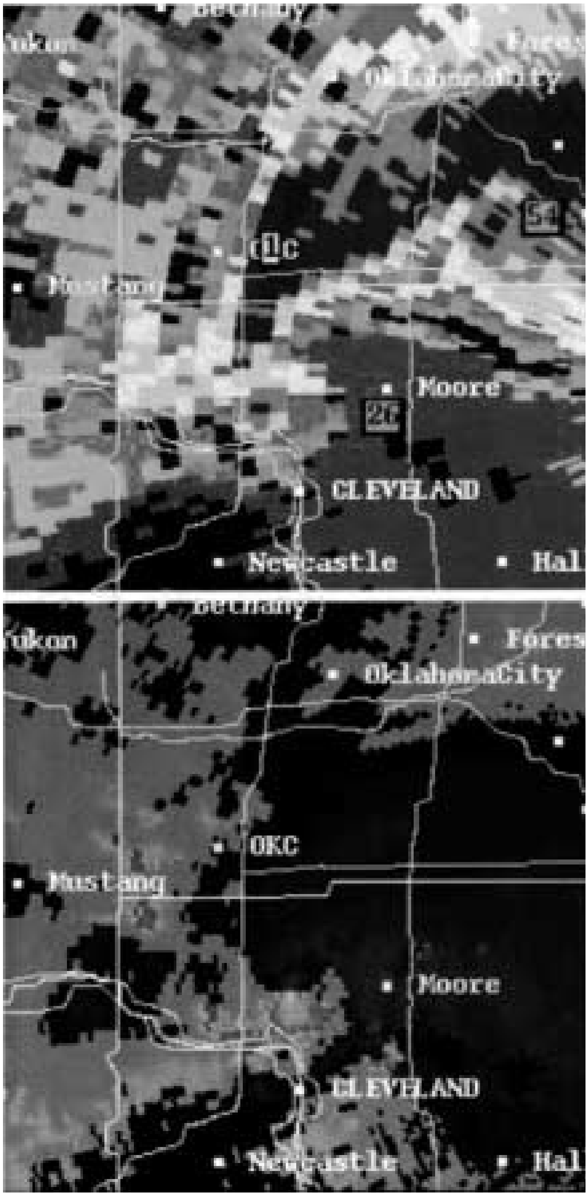


Figure 9.16 NEXRAD base refectivity and velocity images for a major tornado event on May 3, 1999. Base reflectivity shows the classic hook-shaped image associated with a tornado just west-southwest of Moore, OK. Velocity data show a corresponding gate-to-gate (or pixel-to-pixel) shear of velocity inward toward the radar (green) and outward from the radar (red). This wind shear couplet shows two parts of a corresponding complete circulation pattern. See color version of this figure in the color section following page 114. (Image courtesy of NOAA's National Severe Storms Laboratory—http://www.nssl.noaa.gov/~tsmith/may3/0017-8panel.gif.)

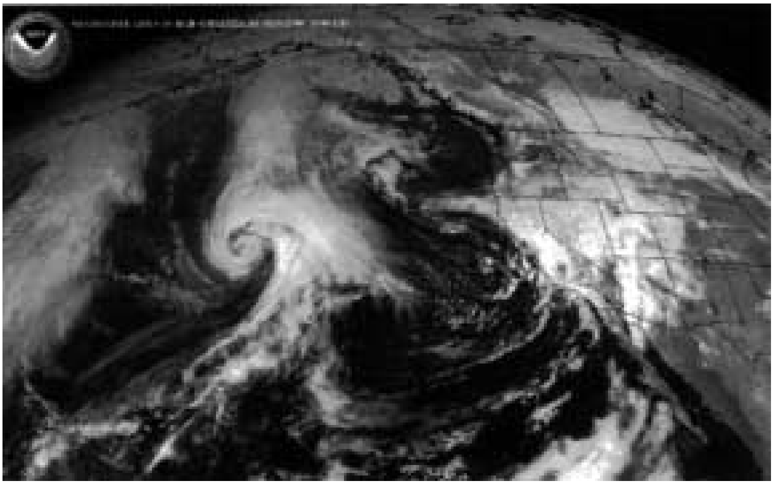


Figure 9.17 Another example of a large comma cloud in the central Pacific Ocean on February 16, 2000. Compare to Figure 9.5. (GOES Image courtesy of NOAA—http://www.osei.noaa.gov/.)

known as microbursts or downbursts. Some produce tornadoes and excessive rainfall. Some give rise to straight-line outflowing winds that in satellite and radar imagery appear as easily recognized patterns known as leading edge gradients or LEGs (in satellite images) and bow echoes (in radar images). Fujita,[19] Johns and Hirt,[25] Maddox,[27] and Bently et al.[2] have described many of the patterns showing MCCs that are evident in surface weather, radar, and satellite data.

MCCs form because thunderstorms transfer large amounts of heat and moisture vertically through the atmosphere. Heat helps to evaporate water from the Earth, oceans, and vegetation. During the condensation process in the clouds, heat is released. As heat builds in these long-lived thunderstorms, it helps to create an upper level high pressure system over the thunderstorm. Often the cloud top pattern associated with an MCC is rounder and contains sharp cloud top temperature gradients. This enhanced infrared image in Figure 9.18 shows many of these features. Figure 9.19 shows a smaller MCC over the Ohio valley in unenhanced infrared imagery. Even without the presence of detailed temperature information, the rounded character of this large thunderstorm system tags it as an MCC.

Figure 9.19 shows the satellite imagery near the onset of an MCC event. Meteograms for that event showing data from Huntington, WV, and Richmond, VA in Figure 9.20 show how the temperature, wind, and pressure changed as the strong wind passed those locations. The storm report map compiled by the NWS's Storm Prediction Center, Figure 9.21, shows the fan-shaped collective of high winds and dense agents resulting from the thunderstorm cluster as it grew and expanded southeastward in an arc-shaped

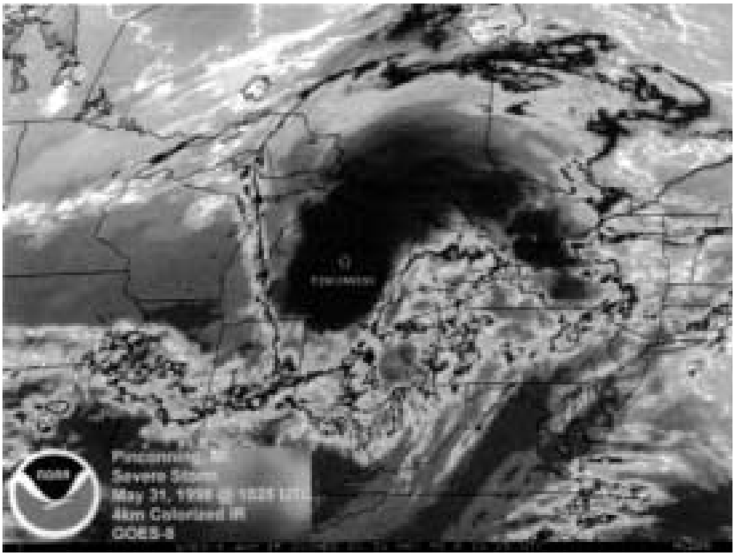


Figure 9.18 A large mesoscale convective complex (MCC) over Michigan on May 31, 1998. In this enhanced infrared image, the coldest and highest cloud tops (and the clouds likely producing the heaviest rainfall) are indicated by purple. Reds also show heavy rainfall. The rounded pattern of this weather feature makes it easy to identify. See color version of this image in color section following page 114. (GOES Image courtesy of NOAA's National Climatic Data Center—http://www.ncdc.noaa.gov/pub/data/images/storm-pincon-19980531-g8ir.gif.)

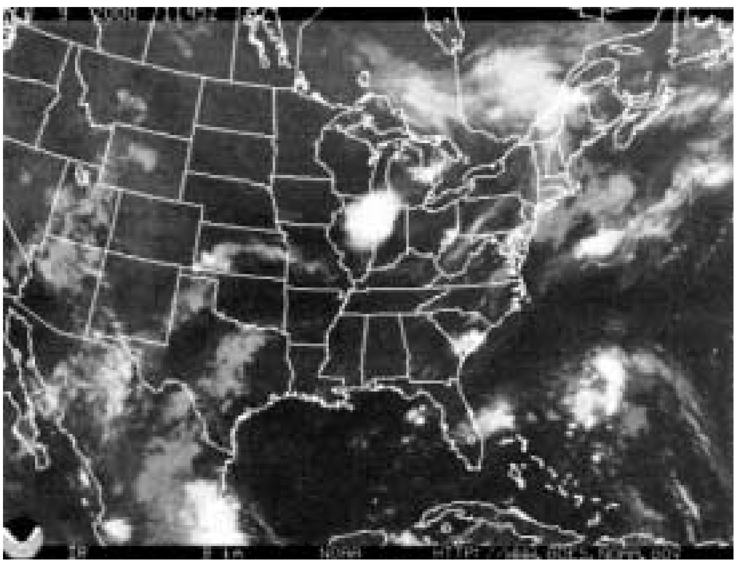
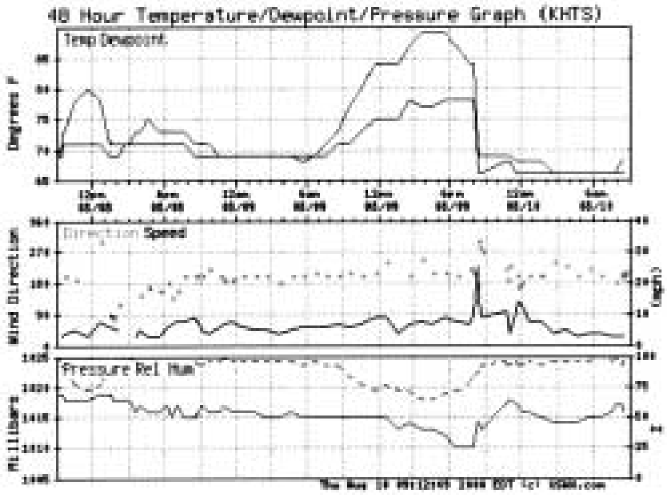
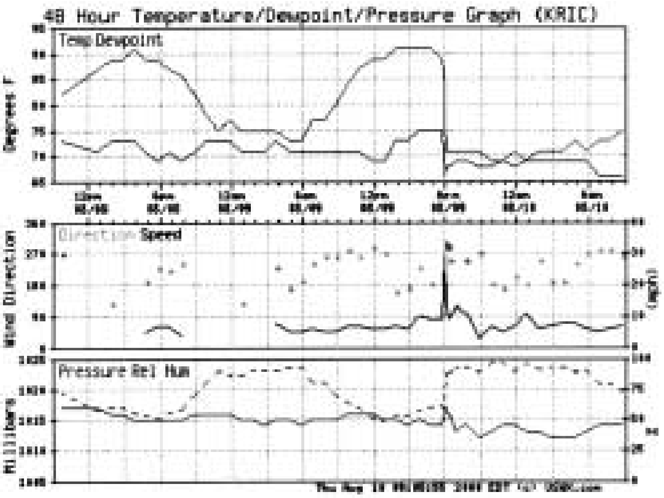


Figure 9.19 A much smaller, but still rounded, MCC over Illinois and Indiana on August 9, 2000. This MCC grew throughout the day and spread severe weather to the U.S. east coast. (GOES Image courtesy of NOAA.)



(a)



(b)

Figure 9.20 Meteograms for 2 days in August 2000 for Huntington, WV, and Richmond, VA. Both locations were impacted by the MCC shown in Figure 9.19. Notice the similar pattern involving a large decrease in temperature and dew point with a rise in pressure and a peak in wind speed. These are the signatures associated with the arrival of a strong thunderstorm and an accompanying small scale high pressure system. (Graphs courtesy of the U.S. Weather Web site—USWX at http://www.uswx.com/us/wx.)

Figure 9.21 NOAA's Storm Prediction Center keeps track of severe weather reports each day. This map summary clearly shows the diverging storm report damage pattern associated with the growing MCC on August 9, 2000. Most reports with this MCC were of strong winds and/or wind damage.

pattern (northern boundary, Indiana to Maryland; southern boundary, Indiana to the western Carolinas).

The book, *An Introduction to Satellite Image Interpretation*[7] provides further background information about basic satellite imagery interpretation and pattern recognition. Similarly, radar interpretation concepts can be found online at the National Severe Storm Laboratory's Operations Training Branch Web page (at http://www.osf.noaa.gov/otb/otb.htm).

9.7 Learning to perceive patterns can be easy

In the natural and man-made world around us, patterns abound. We recognize car types by their characteristics or styling patterns. We assign names to certain housing styles based on their individual characteristics, features, or cues. Identify a bird or a flower, and chances are you will use the patterns associated with it (e.g., wing shape, colors, beak length, and size). Look at the bands in snow drifts or sand dunes, the shapes and designs in icicles, and planted or unplanted fields (especially if snow is present) for still more patterns. Sedimentary rocks afford outstanding examples of patterning, whether they are flat, tilted, or folded. Stir your coffee gently and add some milk to create your own hurricane-like swirls. Stock market investors know about patterns. Simply listen to a market news report and you will hear the reporter talk about "double bottoms," "resistance levels," and more. We live in a world filled with man-made mathematical-based patterns, including bar codes, Web addresses, zip codes, interstate highway numbering, and house numbering.

Our ability to recognize (and understand) the myriad patterns around us helps us survive in our day-to-day world. Yet, we are often not formally taught how to do this. In the case of weather satellite image interpretation, now that we know what some of the patterns are, learning to perceive them can be easy.

Several years ago, my wife and I developed a set of cloud picture cards that we use to teach basic cloud identification to elementary school students. The card set contains three each of cumulus, stratus, and cirrus cloud pictures. Students are instructed to sort and classify the cards according to the three basic cloud families. Not knowing a thing about clouds, or even the names of the clouds, students are able to quickly group the clouds via pattern recognition and provide a list of descriptors that can be used to identify the clouds.

We next replicated the cloud-card concept, and achieved similar results using newspaper weather maps and weather satellite images. Students from elementary through college level (and even some TV meteorologists), were asked to group a set of 12 satellite images (four of each type—infrared, water vapor, and visible, over a 4-day period) by imagery type and cloud features/patterns. Then they were challenged to order the images chronologically, looking for clues in any of the image types to help them determine ordering for all images. The set was chosen to intentionally show a repeating pattern in which day one and day four were remarkably similar. In contrast with the younger participants, many of the college-age students had trouble with this activity at first, because they were not pattern-oriented. (Were they so focused on finding the forest that they could not find the trees, or had pattern recognition been "educated out of them"? We fear that the latter possibility is the truer.) Once they were shown patterning concepts, however, they were better able to perform the activity on another set of images.

Recently, I taught a class of 18 first graders about storms. I keyed on "swirls" as my theme and we examined Hurricane Floyd from a satellite perspective. The students initially patterned the image as representing the globe (because it had all the colors the globe has on it and it was round). This is another great example of how youngsters can develop patterning skills. Then they investigated swirls in a bowl and a pie plate and discovered how swirls form, change, and create smaller swirls inside them. At the end of the hour, students were given take-home copies of weather satellite images in which they were able to pick out storm swirl patterns. They were now ready to explain satellite imagery via pattern recognition to their parents.

In my case (and for others who practice meteorology), there is little doubt that pattern recognition and understanding has played a role in making us better at what we do. It has guided us through the scientific process and helped us uncover relationships we might never have seen otherwise. It also enabled us to take the recognition phase and move into understanding and prediction, thereby advancing the state of knowledge of the science and using it toward a common good. And as Berra once said "you can observe a lot by watching."[3]

Figure 9.22 presents three (unenhanced) satellite images (one visible, one infrared and one water vapor image) from the University of Wisconsin Web page (http://www.ssec.wisc.edu/data/eastsnap.html) showing the Western Hemisphere in the late morning of August 14, 2000. Even if one does not know the meteorological or physical forces that may be creating a particular pattern, it is interesting to see how many patterns can be uncovered. The Reader is invited look at these individually and collectively for patterns, without first looking at Table 9.1, which presents some interpretations.

There are many Web sites that provide real-time satellite imagery in various formats. A list of some of them appears in Table 9.2.

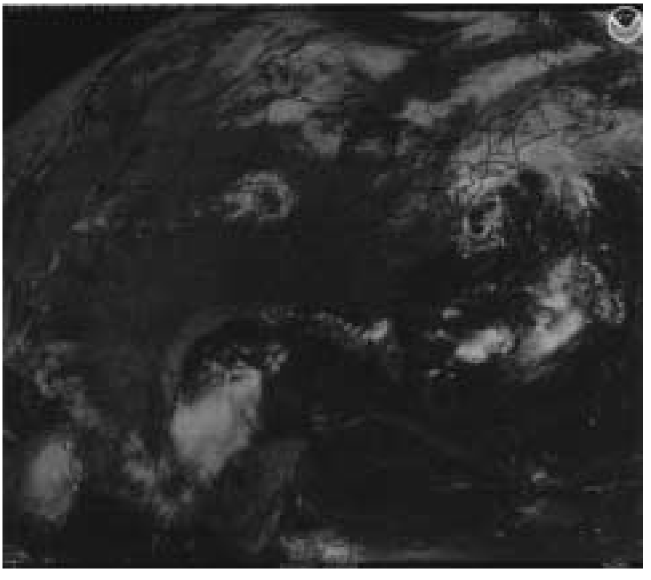


Figure 9.22 This set of images (visible, infrared, and water vapor) shows cloud and weather conditions across the U.S. in the late morning (eastern time) on August 14, 2000. This is a visible light image. (GOES Image courtesy of the University of Wisconsin.)

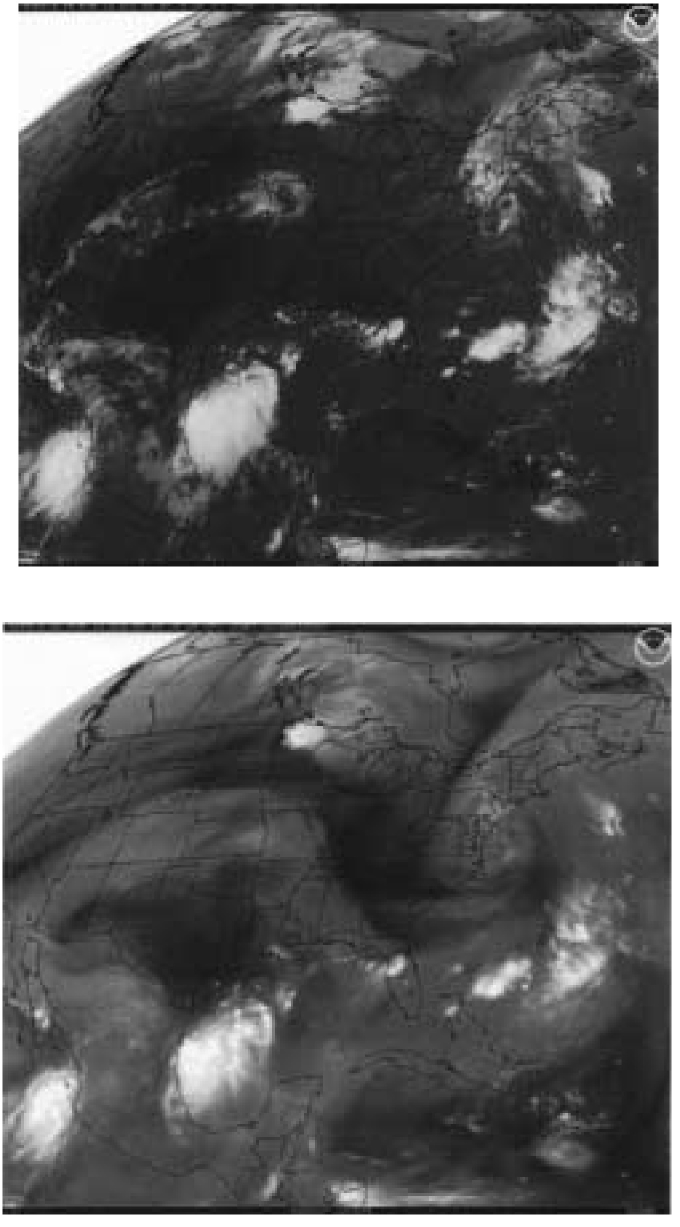


Figure 9.22 (*Continued.*) Top: an infrared image. Bottom: a water vapor image. For an interpretation, see Table 9.1.

Table 9.1 Features Seen in Three Images in Figure 9.22.

Visible light image on page 265 Clouds appear whitish because they reflect solar energy.
• Swirl along middle Atlantic coast. Is this a "Nor'easter?" • Band of speckled clouds from Texas coast eastward to just west of Florida having a distinct "edge" at its northern side. Why? Why is the band inland over Texas but over water in the Gulf Coast? • Two large clusters of clouds on either side of Mexican coast. Are these tropical storms? • Some cloud streaks near Hudson Bay, Canada. • Land is light gray and water in Gulf of Mexico is darker gray. Why? • Dark areas sprinkled throughout southwestern U.S. What are they? • White Sands, NM can be seen.
Infrared image on page 266 (top) Clouds appear whitish because they are radiating infrared energy, but the color code is counterintuitive: cold = white, warm = dark.
• The swirl along middle Atlantic coast now has a "hole" in the center. • Band of small rounded clouds from Louisiana coast eastward to central Florida; clouds are larger over Florida. • The two large clusters of clouds on either side of Mexican coast now have brighter spots embedded in their central regions. What might this indicate? • Why do the cloud streaks near Hudson Bay, Canada look different in the visible image? • Hudson Bay itself is lighter colored than land nearby. Why? • The cloud-free areas in the western U.S. are darker colored than areas in the east. Why? • From Minnesota eastward to New England (and in corresponding regions of Canada), there are definite variations in the gray shades of the clouds. Why? • Outer space looks white. Why?
Water vapor image on page 266 (bottom) The sensor picks up radiated infrared energy that is partially to totally masked by atmospheric water vapor. Clouds appear *very* whitish; areas of water vapor appear milky white; drier regions appear as dark gray—this is related to temperature in the same way as in infrared images (cold = white; warm = dark).
• The swirl along middle Atlantic coast shows circulation well into eastern Canada and southward as far as the Carolinas. The swirl is linked to a larger-scale wave pattern (a "long-wave trough") that extends all the way from central California to northern Nebraska to western Tennessee to the South Carolina-Georgia coast. The thin band of clouds lying along the northern edge of the lighter gray region over the Rockies is a manifestation of the jet stream. • Note the sharp cloud edge from eastern Canada to western Pennsylvania. What might be the cause of this? • The two large clusters of clouds on either side of Mexican coast have many bright spots in them. Might these be storm cells embedded in a tropical storm? • The cloud streaks near Hudson Bay, Canada now appear as rippling layers. Might these be manifestations of the jet streams in those areas? • What are the large areas of light gray and large areas of dark gray? Might they be high altitude moisture and dry air aloft (respectively)?

Table 9.2 URLs of Web Sites Showing Weather Satellite Images.

Site URL	**Notes**
HOWTHEWEATHERWORKS http://www.weatherworks.com/links/satellite_links.html	Current weather Archived images
HOWTHEWEATHERWORKS "Cloud" page http://www.weatherworks.com/cool_clouds.html	Cloud interpretation guidance
Colorado State University http://www.cira.colostate.edu/Special/CurrWx/currwx.htm	Current weather
Colorado State University, Cooperative Institute for Research in the Atmosphere http://www.cira.colostate.edu/ramm/visit/istpds/awips/page1.asp http://www.cira.colostate.edu/ramm/advimgry/enhance0.htm	GOES imagery and how it is processed
NOAA—National Center for Environmental Prediction http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/	Current and archived ocean data
NOAA—National Environmental Satellite Data and Information Service http://goeshp.wwb.noaa.gov/	Current weather
NOAA—National Environmental Satellite Data and Information Service http://orbit-net.nesdis.noaa.gov/arad/fpdt/5_enhan/enhance.html	GOES imagery and how it is processed
NOAA—Operational Significant Event Imagery http://www.osei.noaa.gov/	Archived images
NOAA—National Climatic Data Center Historically Significant Events Imagery Files http://www.ncdc.noaa.gov/ol/satellite/olimages.html	Archived images
University of Wisconsin http://www.ssec.wisc.edu/data/eastsnap.html	Current weather
University of Wisconsin http://cimss.ssec.wisc.edu/goes/ http://cimss.ssec.wisc.edu/tropic/temp/eddy/eddy.html http://cimss.ssec.wisc.edu/goes/misc/interesting_images.html	Archived images
Goddard Space Flight Center http://goes1.gsfc.nasa.gov/	GOES imagery and how it is processed

(*continued*)

Table 9.2 (Continued)

Site URL	Notes
Jeng-Horng Chen's Fluid Dynamics Web Page http://www.eng.umd.edu/~chenjh/wakes/wakes.html	Understanding fluid dynamics of the atmosphere
National Severe Storm Laboratory's Operations Training Branch http://www.osf.noaa.gov	Training in many aspects of meteorology and forecasting
U.S. Weather http://www.uswx.com/us/wx/	One of many sites that provide weather observations and forecast information

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Images from GOES Gallery in this chapter were produced by Scott Bachmeier, Cooperative Institute for Meteorological Satellite Studies, Space Science and Engineering Center, University of Wisconsin–Madison.