chapter eight

The Role of Remote Sensing Displays in Earth Climate and Planetary Atmospheric Research

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Contents

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8.1 Introduction

The communities of scientists who study the Earth's climate and the atmospheres of the other planets barely overlap, but the types of questions they pose and the resulting implications for the use and interpretation of remote sensing data sets have much in common. Both seek to determine the characteristic behavior of three-dimensional fluids that also evolve in time. Climate researchers want to know how and why the general patterns that define our climate today might be different in the next century. Planetary scientists try to understand why circulation patterns and clouds on Mars, Venus, or Jupiter are different from those on Earth. Both disciplines must aggregate large amounts of data covering long time periods and several altitudes to have a representative picture of the rapidly changing atmosphere they are studying. This emphasis separates climate scientists from weather forecasters, who focus at any one time on a limited number of images. Likewise, it separates planetary atmosphere researchers from planetary geologists, who rely primarily on single images (or mosaics of images covering the globe) to study two-dimensional planetary surfaces that are mostly static over the duration of a spacecraft mission, yet reveal dynamic processes acting over thousands to millions of years.

Remote sensing displays are usually two-dimensional projections that capture an atmosphere at an instant in time. How scientists manipulate and display such data; how they interpret what they see; and how they thereby understand the physical processes that cause what they see, are the challenges I discuss in this chapter. I begin by discussing differences in how novices and experts in the field relate displays of data to the real world. This leads to a discussion of the use and abuse of image enhancement and color in remote sensing displays. I then show some examples of techniques used by scientists in climate and planetary research to both convey information and design research strategies using remote sensing displays.

8.2 Novices vs. experts

The problems beginning students face in interpreting remote sensing displays have much in common with those they encounter with any mathematical representation of the real world:

1. Novices often cannot translate their own observations of the real world into more abstract representations of the larger-scale picture. For example, after a lecture on the forces that determine the flow around low and high pressure, and how that relates to the isobars displayed on a weather map, students in an introductory climate course at Columbia University and Barnard College went outside to measure pressure and wind direction. Afterwards, the students were shown a schematic weather map with a high-low pressure pair and corresponding isobars,

including arrows indicating the approximate flow. Fewer than half the students could identify where on that map we were minutes earlier when we watched the wind carry a balloon away, noted the sky condition, and confirmed that pressure was rising. This presages the problems that more advanced students have in trying to express physical statements as mathematical equations, or to see the ramifications of an equation or symbolic diagram for the behavior of the physical system it describes.

2. Novices tend to seek out isolated features of any data set they examine, and rarely think in terms of the superposition of several phenomena to explain what they see. For example, the students in the same class were asked to draw a graph of the temperature one would measure on a three-day trip from New York to Florida in winter. Many students drew a simple straight line with an increasing trend. Some added an oscillatory pattern to indicate day-night changes. Only a few recognized that there would also be random day-to-day changes as weather systems passed. Later in the semester, the students were given a data set showing the change in Earth's global surface temperature over the past 100 years. Asked to describe the graph's salient features, most could only say that temperature had risen over the past century and attributed this to rising concentrations of greenhouse gases. Few noticed that from 1940–1965 temperatures had actually cooled slightly, a possible indicator of ocean circulation effects or solar luminosity changes that had been discussed in class. Fewer mentioned the random year-to-year variability superimposed on the pattern.

These general difficulties carry over to the realm of remote sensing displays. Given an image of a planetary atmosphere or a false-color contour map of a climate parameter, the novice—with no background in the physics of the system under study—often simply does not know what to look for and what questions to ask. The situation is something like opening the book, *Where's Waldo?* and trying to find Waldo without having seen what he looks like first. The difference between novice and expert here seems to be that the expert goes in with a mental image of what the remote sensing display might look like, based on his current understanding of the system, and thus can react to the actual display with questions about how it departs from expectations.

As an example, students in the climate system course are asked to interpret Earth Radiation Budget Experiment (ERBE) false-color maps of the geographic distribution of absorbed sunlight (see Figure 8.1). They tend to focus on the decrease of sunlight from equator to pole (indicated by the transition from red / orange in the tropics to blue in the polar regions), which is fundamental but is of little interest to the researcher, who takes that well-understood aspect of the map for granted. The expert instead focuses on less obvious longitudinal variations in absorbed sunlight over a homogeneous

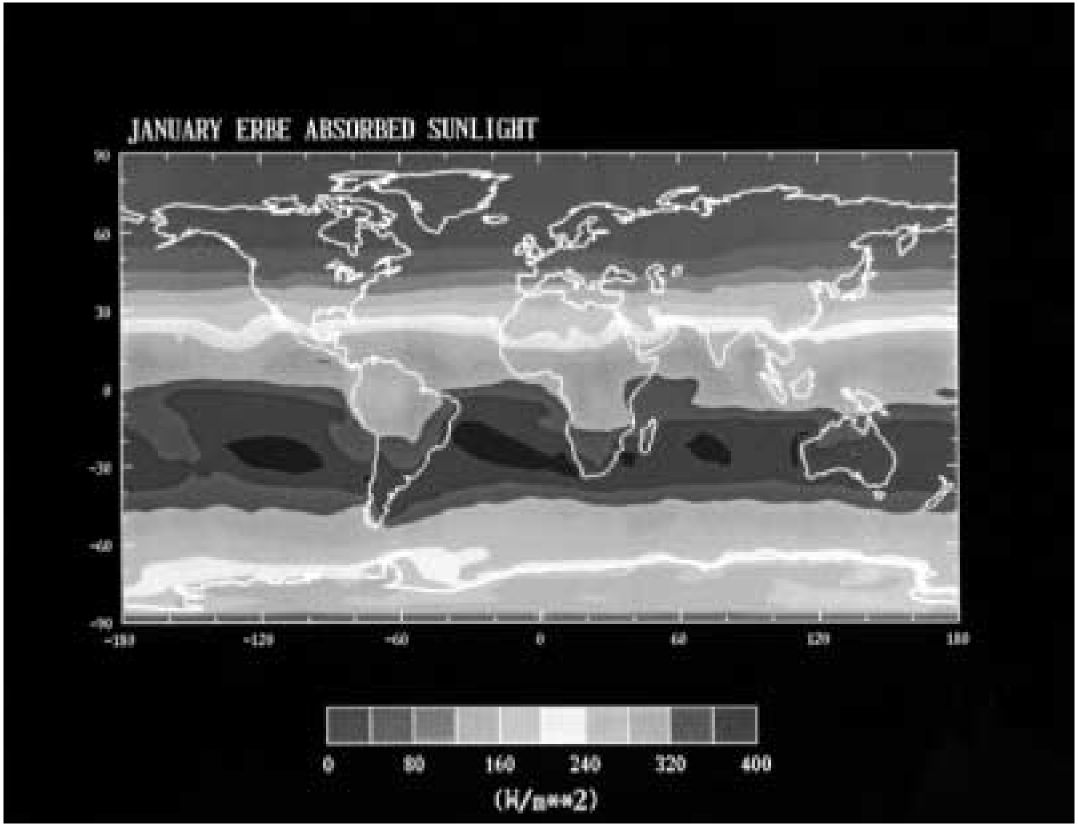

Figure 8.1 False-color contour map of the five-year mean values of solar radiation flux absorbed by the Earth in January (in units of W/m^2), derived from satellite measurements made by the Earth Radiation Budget Experiment (ERBE). See color version of this figure in the color section following page 114. (Photo courtesy of NASA.)

surface (e.g., the ocean), which are diagnostic of poorly understood variations in clouds that are of more interest. In Figure 8.1, e.g., the subtle transition south of the equator from the deeper reds in the mid-Pacific and mid-Atlantic to orange just off the west coasts of South America (20°S, 70°W) and Africa (15°S, 10°E) reveals the presence of climatically important low-level stratus cloud decks in the eastern oceans. The expert starts with a mental model (the intensity of incident sunlight varies with latitude because of Earth's spherical shape and axial tilt) and a resulting expectation (uniform solar heating at a given latitude over the ocean because the ocean is approximately equally reflective everywhere), and looks for deviations from the expectation to learn something. The novice, without a prior mental model, simply "draws" a mental caricature of the display that emphasizes the major features and misses the details.

A related bias of the novice is to pay inordinate attention to an obvious or spectacular feature of a satellite image, at the expense of the more numerous but more amorphous features that are more important indicators of the climate (the same is apparently true of novice interpretation of weather maps[7]). Students, for example, enjoy studying pictures of extreme weather events such as hurricanes. But these storms are rare and affect a relatively limited area, so their contribution to the seasonal mean temperature and total rainfall of a region is usually negligible. In the absence of such storms, most students would guess that skies are clear. But on average, the sky is not much less cloudy over high pressure centers than over the low pressure centers we associate with storms. Mainly the type of cloudiness changes, from deep thick rain clouds in storms to innocuous cirrus or low stratus or fair-weather cumulus before or after a storm. Storms are present a small fraction of the time, so the more frequent fair-weather cloudiness may be just as climatically important, but this is rarely anticipated by the novice.

When we image other planets, the playing field becomes more level for the expert/novice comparison. Our understanding of the other planets is primitive compared to that of the Earth. Most planets have cloud features that do not resemble those of the Earth. Figure 8.2 shows Venus, for example, devoid of the swirling midlatitude storm clouds so well-known to us on Earth. We understand this as a result of Venus's slow rotation period (243 days), which eliminates the instability that produces our midlatitude storms. So we expect not to see such features on Venus. But in the absence of that process, what other processes prevail on Venus? Can we see evidence of them in the image? At first glance, the eye is drawn to the planet-sized dark feature shaped like a sideways letter "Y" that spans the equatorial region. Analysis of several years of such images by the author has identified this feature as a particular type of wave and documented its characteristics.[3] Unfortunately, I concluded that this feature is secondary among the processes that maintain the surprisingly strong winds that blow on Venus. The most important processes occur below the visible clouds, hidden from our view. We have been fooled into overinterpreting what we see, because it is all we

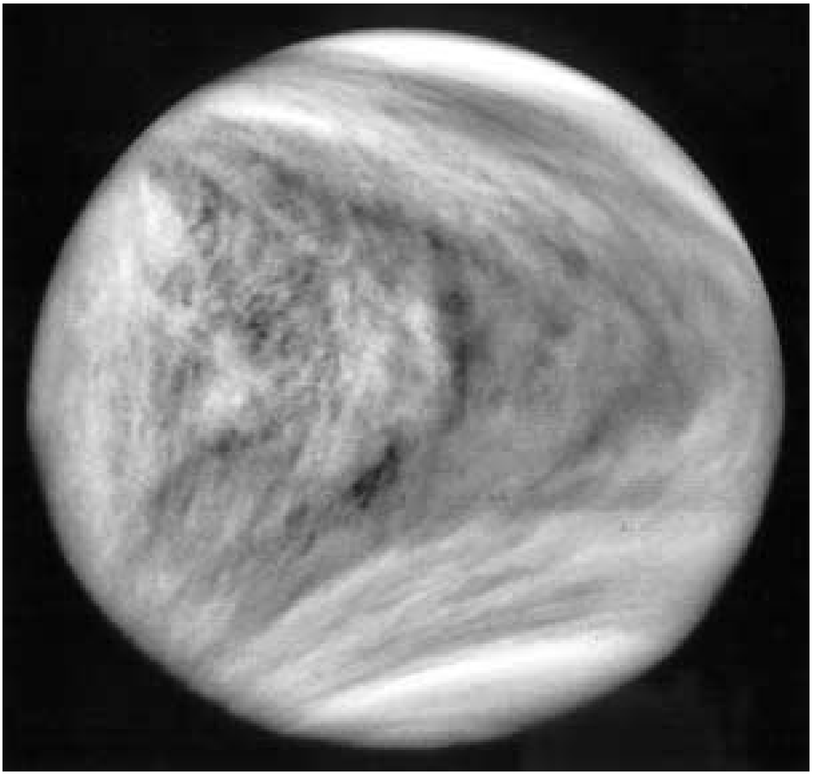

Figure 8.2 An image of the planet Venus taken through an ultraviolet filter by the Pioneer Venus Orbiter Cloud Photopolarimeter Experiment. The bright regions are clouds composed of a concentrated solution of sulfuric acid in water. The dark regions are locations in which other sulfur compounds have been lifted into view. (Photo courtesy of NASA.)

have to go on! In other words, the other planets can make novices out of experts because their behavior is at least partly unfamiliar to all of us.

The challenge, then, is to manipulate and display remote sensing data in ways that optimize transmission of information, whether in a research or an educational setting. In the next section I describe some common approaches to this problem.

8.3 Image enhancement and color

The image of Venus just discussed does not represent how Venus would look to the human eye. Venus is covered with whitish sulfuric acid clouds; it looks like a featureless tennis ball. However, other sulfur compounds in the clouds absorb ultraviolet (UV) radiation, and when viewed through a UV filter, places where such compounds are lifted up above most of the bright sulfuric acid veil show up as slightly dark regions in a gray-scale image of reflected UV light, which is the Figure 8.2 image. In the "raw" version of this image, even the dark areas are so faint as to be barely detectable by the human eye, both because the contrasts are inherently small and because sunlight falling on a sphere produces larger variations in brightness over the disk, i.e., the image is bright where the Sun is directly overhead, and darkens toward dawn or dusk. The latter effect impedes scientific analysis of the individual features that reveal Venus's weather. Thus, planetary scientists routinely first use a computer algorithm to subtract out global brightness variations due to the different angles at which sunlight falls on different locations. This in turn requires us to know enough about the clouds of Venus to anticipate how well sunlight is reflected as a function of the angle at which it enters and the angle at which we view it.

The next challenge is to enhance the weather features that are really present. This depends on what one wishes to see. In Figure 8.2 we can see both dark regions that span the planet, such as the "Y," and local cloud blobs and streaks reminiscent of things we can see in our own sky. To emphasize one or the other, we filter the image, i.e., we mathematically separate the brightness variations into small and large spatial scales, mathematically boost the strength of the scales we wish to see, and then reconstruct the image. This is the visual equivalent of turning up the bass vs. the treble on one's sound system. In Figure 8.2 a high-pass filtered version of the image (which emphasizes the small features) was added back to the original image (in which the "Y" dominates), to produce a product in which all spatial scales are visible. This makes the image more pleasing for public relations purposes, but it also enhances the scientist's insight—the more irregular nature of small features within the dark arms of the "Y" compared to the more linear nature of the small features in the bright regions to either side contains clues about the processes that form the features and the stability of the underlying atmosphere. This is an example of constructive image manipulation.

Not all such efforts are as successful. Black-and-white imagery is frowned upon by the public relations offices at NASA centers. On a planet such as Venus that does not cooperate by providing much color, one must resort to false colors. A misguided attempt of this sort can be seen on the March 29, 1974 cover of *Science*[12] magazine, which showed a UV image of Venus obtained by the Mariner 10 spacecraft. This image was false-colored blue and white (with the dark regions in Figure 8.2 appearing as blue) to resemble "blue planet" pictures of Earth. The result is visually striking but scientifically misleading (as are many of the planetary images seen by the public[11]): On Earth, clouds (which are white) form in updrafts, while the blue ocean below is visible mostly in places where air sinks and clouds evaporate. On Venus, dark places instead are where the UV absorber is lifted above the bright sulfuric acid, while the bright places are likely to be regions of descending motion. Thus, a terrestrial bias led to a display that obscured the proper scientific interpretation of the image.

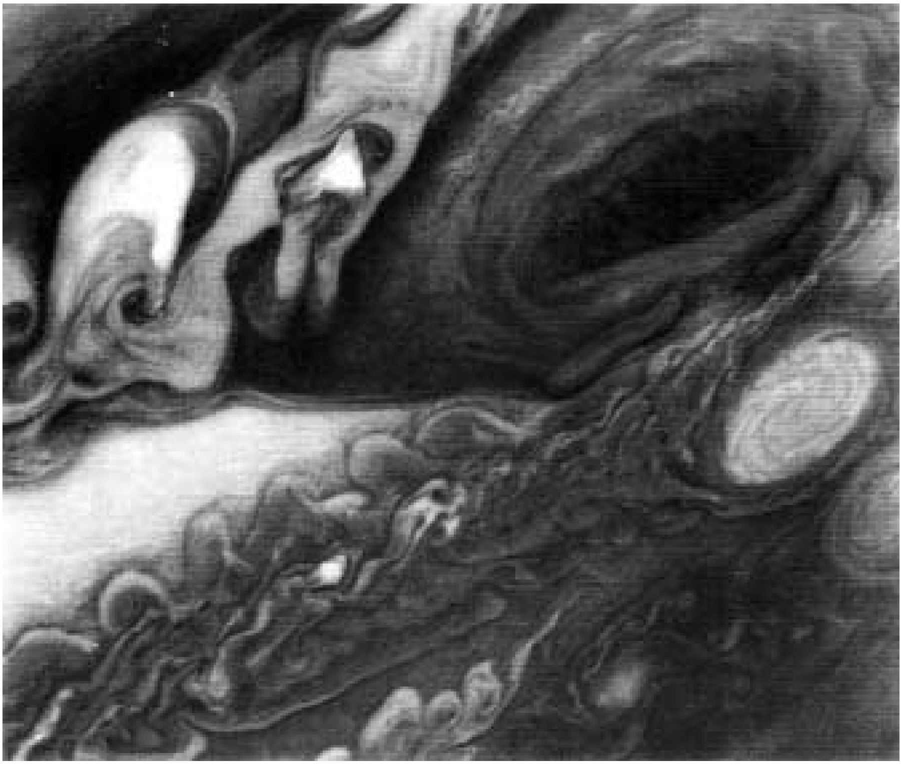

Figure 8.3 A false-color composite image of the clouds of Jupiter taken by the Voyager 1 imaging system. The Great Red Spot is visible in the upper right. See color version of this figure in the color section following page 114. (Photo courtesy of NASA.)

Sometimes a planet does contain intrinsic color, though, and false color can be used to create a dramatic and less misleading image. The Voyager 1 image of Jupiter's Great Red Spot and surrounding regions in Figure 8.3 is a good example. This image has a certain basis in truth, because it is a superposition of three monochromatic images sensitive to different colors. But not all colors were included in the Voyager camera filters, so the image is biased. The Jupiter that one views through a telescope is really much more yellow-green and lower in contrast[11]; the Great Red Spot is really a pale pink. Of more concern is how the color scheme influences one's interpretation. Dark regions such as that between the Great Red Spot and regions of swirling white clouds to the west look to the human eye like clearings between the clouds in which we see to great depth, and are thus regions of sinking air. Two decades later, this interpretation is still open to question. Recent Galileo images of lightning on Jupiter suggest that the canonical view of where air is moving up and down on Jupiter may have to be revised.[5]

Aside from images, false color is used to display contour maps of remote sensing retrievals of weather and climate parameters. It is often overlooked that remote sensing retrieval techniques are not perfect—photons emitted or reflected by a planet and received by a detector in space are converted by a computer algorithm to the numerical value of some physical parameter. The algorithm used may be simply empirical, based on observations at one location that are not valid globally. It may assume that other physical parameters that also affect the radiation observed are constant, when in reality they are varying. Or the algorithm may be a physical model of the atmosphere that makes simplifying assumptions. But the result, a color contour map with a title indicating the parameter displayed (e.g., precipitation) immediately attains an air of legitimacy and certainty among scientists who know, but sometimes forget that it is not a direct measurement of raindrops collected in a bucket. The intervals chosen for changes in color sometimes have little relationship to the inherent uncertainty in the algorithm that produced the data set, and users often do not ask how large the errors are. This is a different take on the novice vs. expert issue—professional users of data may be naive about how the data displayed were produced, and hence, erroneous scientific conclusions may sometimes be reached.

The preferred choice of colors depends on the quantity displayed. Sometimes the choice seems obvious based on common associations—e.g., red for warm and blue for cold on a temperature map, or brown for drier and green for wetter on a map of drought severity. When a particular color scheme is not obvious, an effective choice is to color extreme high values red, which draws the eye's attention. Maps of differences (e.g., between a satellite data set and a climate model prediction, or between El Niño years and the mean climate[8]) are commonly used to highlight changes in the real world or errors in a model. A useful color choice in such maps is white for the interval spanning zero, in which changes / differences are too small to be of concern because they are physically unimportant or within the error bar of the data. Figure 8.4 shows such an example. The left side shows a climate model prediction of the coverage of cirrus clouds, with the red areas drawing the eye to the cloudiest places on Earth. The right side shows differences between the model's prediction and the cirrus cloud cover inferred from satellite remote sensing of visible and infrared radiation. It is immediately obvious where the model seriously over- and underestimates cirrus. The spatial pattern of the differences suggests possible causes of the problem to the model developer.

Of more importance than color choice is the parameter interval over which the color changes. Consider precipitation, which varies by an order of magnitude from the tropics to the deserts and polar regions. The novice might choose to display this field using, e.g., 6 colors with equal spacing at precipitation intervals of 2 mm / day, producing a map that resembles a more exaggerated version of the left side of Figure 8.4. For the novice, such a display conveys information, namely that rainfall is highest near the equator and on the western sides of ocean basins. To the expert, though, this is

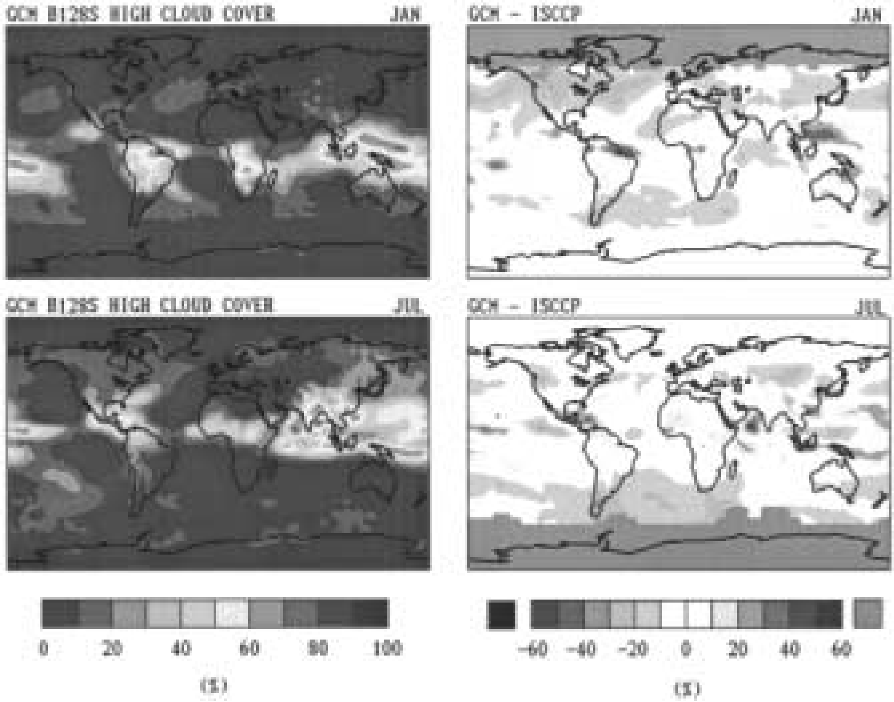

Figure 8.4 Left: Color contour map of monthly mean cirrus cloud coverage (%) simulated by the NASA Goddard Institute for Space Studies global climate model for (upper) January and (lower) July. Right: Differences in cirrus cloud coverage between the simulations at the left and data acquired from visible and infrared satellite imagery by the International Satellite Cloud Climatology Project (ISCCP). The color contour resolution of 10 percent is comparable to the accuracy of the ISCCP satellite retrieval of cloud cover. See color version of this figure in the color section following page 114. (Photos courtesy of NASA.)

well-known and therefore of no research interest. A nonlinear scale that resolves 0.5 mm / day differences in dry regions while sacrificing detail at the high end reveals subtle but interesting variability at middle and high latitudes relevant to drought occurrence and climate changes in ocean currents.

This example points out two other differences between the novice and the expert. The expert is aware of what is already known and selects display characteristics to bring out the unknown, while the novice starts with no such knowledge base and thus makes default choices for a display. Also, novices tend not to appreciate that percent differences are more important than absolute differences, and thus that a 1 mm / day anomaly in a region whose mean rainfall rate is 2 mm / day is more significant than a 2 mm / day anomaly in a region whose mean rainfall rate is 10 mm / day. Similar thinking pervades the general public—100 point daily swings in the Dow Jones Industrial Average were news when the average was near 1,000, but it has taken the media many years to realize that a 100-point swing in today's 10,000-point Dow is cause for neither alarm nor excitement.

With these general concepts as background, we next discuss some of the specific techniques that scientists use to manipulate and display remote sensing data to understand Earth's climate.

8.4 Earth remote sensing for climate research displays

8.4.1 Displays of the atmosphere's variation with time

Satellite imagery is a static display of a dynamic field, and it is the dynamics that best reveals the underlying physical processes. Remote sensing scientists use a variety of techniques to gather and represent dynamic information. A climate expert can deduce a great deal just from the morphology of clouds in a single image. For example, a well-defined comma-shaped cloud pattern is good evidence of the mature stage of a strong midlatitude storm. But patterns in single images are sometimes ambiguous—an amorphous cloud pattern may either be the beginning stage of such a storm or a minor disturbance that never organizes into something stronger. Only animation of a series of images can distinguish the two possibilities.

The shape of a midlatitude storm cloud pattern is immediately interpreted dynamically by the expert, who recognizes the tail of the comma as the cold front, knows that southwesterly flow of warm humid air and northerly flow of cold dry air (if the storm is in the Northern Hemisphere) usually lie to the east and west, respectively, and sees the cloudiest regions as locations of upward motion. The novice may recognize the pattern shape but make no dynamical associations. Understanding can be enhanced for the novice by superimposing other fields on the image, e.g., vectors indicating wind direction and strength and color contours displaying temperature. However, unless a prior mental model of the dynamics exists, the observer has difficulty integrating the individual parts into a comprehensive picture.[7]

Sometimes there is no alternative but to display the time dimension itself. Increasingly, animation is used to track movements of features and to reveal interactions between different geographic regions. Only in a movie can one appreciate the "rivers" of upper troposphere moisture that originate in the tropics and flow all the way to midlatitudes. Figure 8.5, for example, shows a Geostationary Operational Environmental Satellite (GOES) water vapor image. It is obvious to the novice and expert alike that high humidity along the east coast of the U.S. on this day is spatially linked to convection (the bright specks of humidity seen throughout the tropics) occurring near 10°N, 120°W, and that a similar relationship exists between convection west of Hawaii and the Pacific Northwest U.S. The expert has a mental model that transforms this static display into a dynamic interpretation: updrafts in tropical thunderstorms loft moisture to high altitude, and the prevailing winds near the tropopause in the tropics move this humid air poleward, ultimately affecting the sky condition and weather in the U.S. The novice, with no

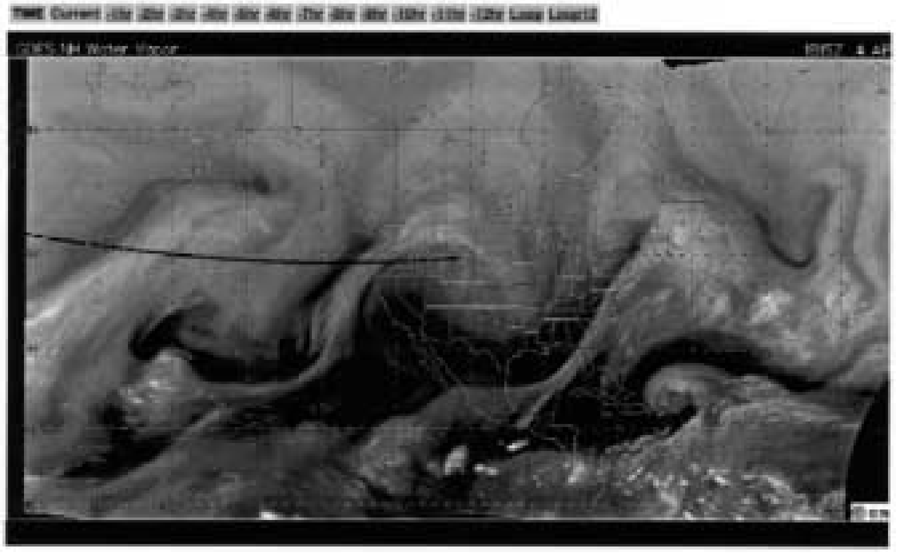

Figure 8.5 Northern Hemisphere GOES water vapor channel gray-scale image for April 4, 2000. Brighter pixels indicate regions of enhanced upper troposphere humidity and high-level cloudiness. (Photo courtesy of NOAA.)

mental model, cannot tell whether the tropics is affecting the midlatitudes or vice versa, or whether the pattern just forms as a single entity at all locations at the same time. By animating the images, though, the novice can watch variations with time in the tropical convection and see how their effects move along the “river” to higher latitudes. The cause-effect link is established via the animation.

Another important aspect of time variation is characterizing propagating wave features. A common way to do this is to construct a Hovmöller diagram: A latitudinally thin (5–10°) strip covering a broad range of longitudes is extracted from a satellite image. A similar strip from the next day’s image is placed directly above, and the process is repeated for perhaps a month or more. The result is a composite image in which many two-dimensional arrays of longitude vs. latitude have been converted into a single display of longitude vs. time. In a Hovmöller diagram, a propagating wave shows up as lines of clouds tilted with respect to the horizontal, with the sense and angle of tilt indicating the direction and phase speed of propagation. Persistent stationary features are solid vertical lines, while nonpropagating oscillations are the image equivalent of a dashed vertical line, with the length of the dashes indicating the period of oscillation. False-color Hovmöller displays of tropical Pacific monthly sea surface temperature over several years have become a common means of portraying the onset and decay of El Niño.[8]

Figure 8.6 shows Hovmöller diagrams of GOES visible, water vapor, and “window” (outside the wavelengths of strong water vapor absorption) infrared imagery for a region in Oklahoma over the month of June 1999.

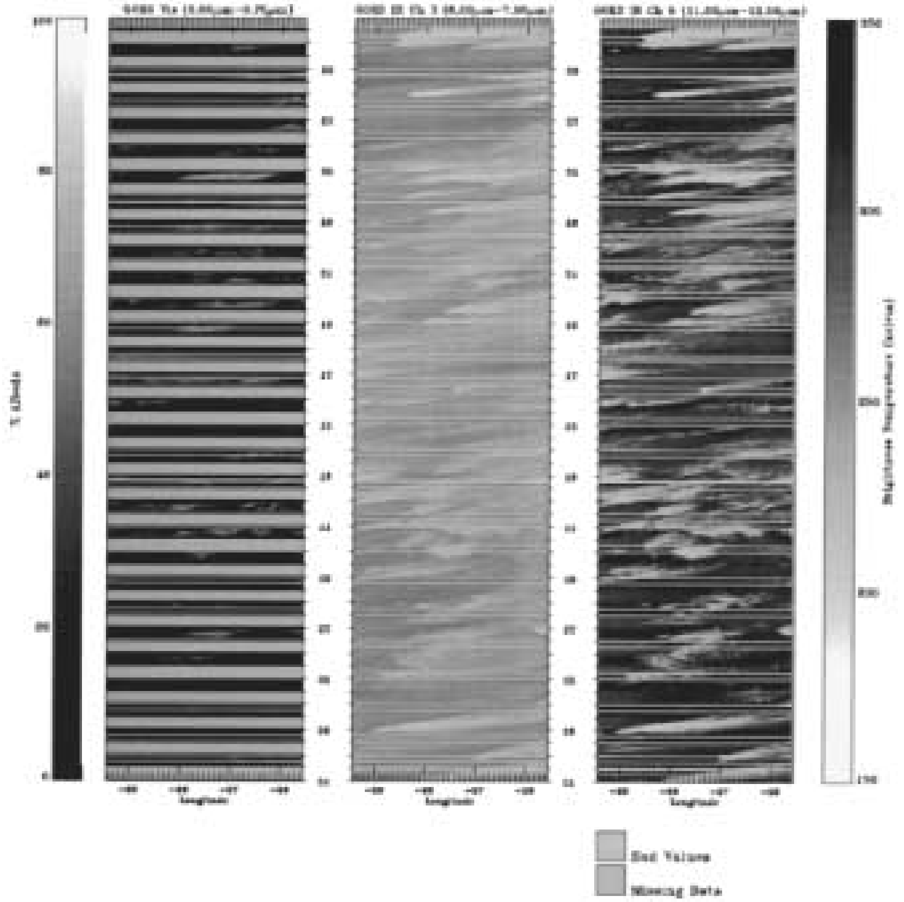

Figure 8.6 Hovmöller diagrams constructed from visible (left), water vapor channel (center), and window infrared (right) GOES-8 hourly imagery of northern Oklahoma for June 1999. The ordinate indicates time (in days of the month), increasing from bottom to top. The abscissa is west longitude in degrees. Bright areas in the visible images represent reflective clouds at any altitude. Bright areas in the window infrared indicate mid- and high-level cloudiness usually associated with synoptic storms. (Figure courtesy of U.S. Department of Energy.)

Storm cloud patterns (the bright features in the middle and right images) tilt from lower left to upper right, indicating that the storms propagate from west to east with time. The degree of tilt tells us how fast the storms move. For example, the storm that originated near 98°W on June 28 had moved to 95.5°W (a distance of about 225 km) by the end of the day, giving a propagation speed of about 2.6 m / sec. Another advantage of the Hovmöller diagram is the ease with which the observer can mentally assimilate missing data. Horizontal lines in the image are times at which the satellite did not acquire or transmit useful data, yet even the novice should be able to guess what the missing data would have looked like by mentally connecting the pattern below the horizontal line to the pattern above.

As mentioned earlier, real atmospheres are a superposition of processes occurring on different temporal and spatial scales. Separation of the different contributions to what we see can be difficult for novices and experts alike, especially when a subtle long-term climate trend must be detected in a parameter that fluctuates more strongly on shorter time scales. Mathematical techniques such as empirical orthogonal function (EOF) analysis separate space-time data sets into a few characteristic modes of variation.[6] The EOF displays the spatial pattern; it is accompanied by a function of time, the principal component (PC). The decomposition is mathematical and is not guaranteed to provide physically meaningful results, but the combined display of the EOF and the PC can often be interpreted as a physical process by the expert. For example, an analysis of monthly sea surface temperature (SST) anomalies has a first EOF showing anomalies of opposite sign north and south of the equator, with an accompanying PC that is sinusoidal with a period of one year. To novice and expert alike, this is obviously capturing the seasonal cycle. The second EOF may show large anomalies in the tropical east Pacific and a PC that oscillates somewhat irregularly with a time scale of a few years; this is El Niño.

One research value of such a decomposition is that if the dominant features of the EOF and PC suggest a particular physical process to the person viewing the display, unanticipated spatial relationships can be discovered. For example, Figure 8.7 shows the first PC and EOF of the twentieth-century record of precipitation for rain gauge stations over all land areas of the globe, after subtraction of the seasonal cycle.[1] The first PC time series is seen to be well-correlated with observed SST anomalies over the east equatorial Pacific, which are known to be caused primarily by El Niño. The corresponding EOF shows some well-known geographic effects of El Niño: negative precipitation anomalies (drought) over eastern Australia, the Amazon Basin, and equatorial Africa, and wet anomalies over the western half of the U.S. But the EOF also suggests more subtle "teleconnections" to places thousands of miles away that were not previously known to be affected by El Niño, e.g., wetter than normal conditions in Europe and western Asia. The second PC (not shown) is an upward trend over the century that might be an effect of anthropogenic global warming but which is undetectable in a simple animation of the data due to the large El Niño signal. The corresponding EOF indicates that midlatitudes have become wetter and the tropics a bit drier over the past century.

8.4.2 The use of displays in computer algorithm development

As noted above, short-term climate changes such as El Niño produce large weather perturbations in certain parts of the world that are clearly noticeable to people (e.g., the flooding in usually dry California in 1997–1998). Long-term anthropogenic global warming due to building concentrations of greenhouse

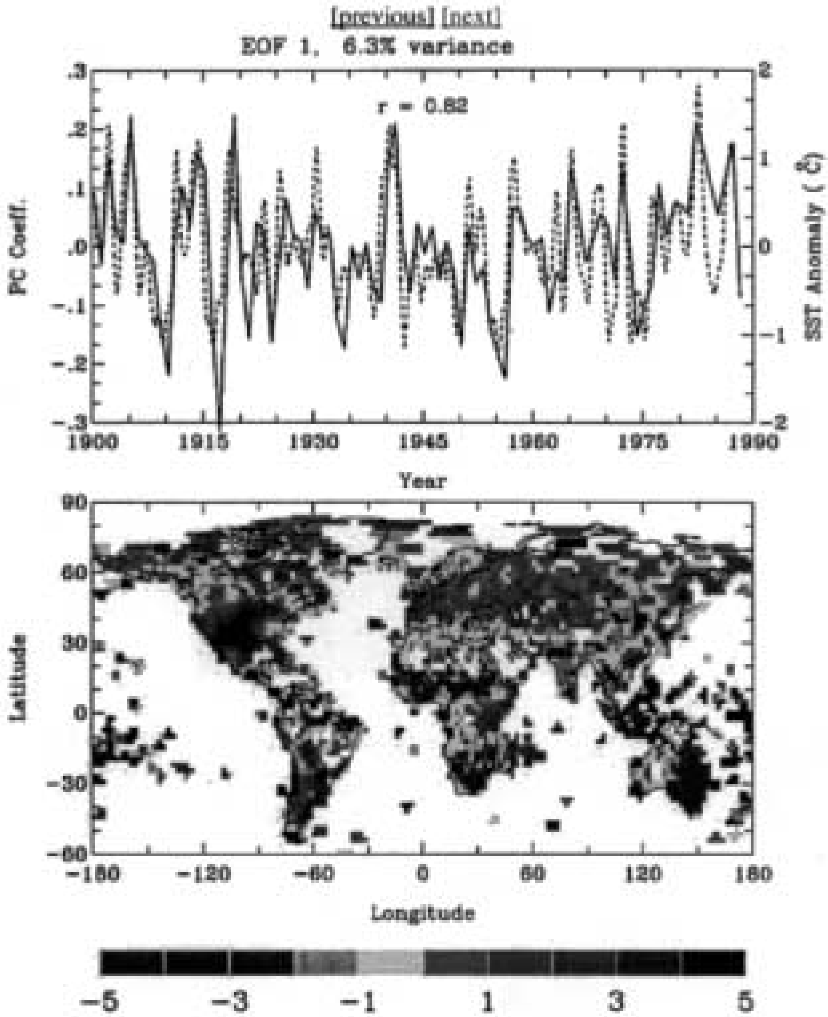

Figure 8.7 Top: The first PC of the record of observed monthly precipitation variations over land for the Twentieth Century (solid line), and the time series of SST anomalies in the equatorial east Pacific, an indicator of El Niño (dashed line). Bottom: The corresponding first EOF of the Twentieth Century land precipitation record, with blue indicating wetter than normal conditions at times when the PC coefficient is positive, and orange/red indicating drier conditions at these times. See color version of this figure in the color section following page 114. (From Dai, A., et al., *J. Climate,* 10, 2943–2962, 1997. Photos courtesy of NASA.)

gases is more gradual and smaller in magnitude. Thus, it is detectable only as a subtle change in the frequency of occurrence of unusual weather, e.g., more or fewer droughts or strong storms over decades. These changes may be barely noticeable, but collectively they have the potential to impact society via the availability of water, the growth of crops, the spread of diseases, erosion of shorelines, and summer electricity demand. Remote sensing scientists use satellite data to understand how the climate responds to changes in temperature, but such changes are much smaller than day-to-day fluctuations in weather. The human eye-brain combination cannot sense such changes reliably, since (1) it notices the obvious, spectacular aspects of an image at the expense of the more mundane but numerous features that weigh more heavily in determining the climate change, (2) many images spanning seasons or even years must be analyzed to get a statistically significant result, and (3) visual displays of 8-bit data, which resolve 256 brightness levels, cannot easily communicate net shifts of only a few brightness levels that represent the collective sum of slight brightenings in some pixels and slight darkenings in others.

Climate researchers therefore resort to the computer to tally statistics for them in an unbiased, representative fashion. But the scientist needs to program the computer to look for the right thing. A current project involving New York City high school students and teachers working with NASA scientists seeks, for example, to determine whether clouds in midlatitude storms are systematically different in either visible brightness, cloud top height, or coverage under warmer vs. colder conditions, and in years when the temperature difference between the tropics and poles is larger vs. smaller. To do this we require a program that recognizes and tracks storms as they grow and decay; this is done objectively using ancillary data on surface pressure patterns to locate storm centers. How big an area of the satellite image should we include in our definition of a storm, though? In other words, where does a storm begin and end? For some storms, with vigorous cold fronts and clear skies behind, the rear boundary of the storm is obvious. For others in which low-level cloud "debris" remains after frontal passage and gradually dissipates, the choice is more problematic. Pattern recognition techniques are not yet sophisticated enough to encompass all possible storm cloud morphologies, especially the less organized ones.

Thus, the student observers determine a plausible storm definition by visually examining a number of images, and we incorporate their subjective impressions into the computer algorithm that compiles the statistics. We then must address Mark Twain's "lies, damn lies, and statistics" warning about being skeptical of what we cannot see. We run the computer algorithm for a month of images and use displays to see whether it detects anything our eyes tell us is not really a storm or misses things we would identify as storms. As a final check, we can test the sensitivity of any conclusions to the assumptions we have made by rerunning the program with an altered storm definition. In this way, the human and the computer work hand-in-hand to do what neither can do alone.

8.4.3 Displaying vertical structure in the atmosphere

Another challenge for Earth remote sensing is the vertical dimension. Images project a 3-D world into two dimensions, and the scientist must know what altitude is being observed, because understanding sometimes depends on knowing how things going on at one level in the atmosphere are influenced by things happening at a lower level or at the surface. Atmospheres usually work from the bottom up—the warm dense lower atmosphere is the "dog" wagging the "tail" that is the cold, tenuous upper atmosphere. For example, an increase in cirrus clouds near the tropopause observed in isolation cannot be interpreted, but that observation combined with the knowledge that temperature or humidity near the Earth's surface had increased at about the same time might enable the scientist to explain the change in clouds, since the expert knows that warm moist air near the ground destabilizes the atmospheric column, and that thunderstorms that originate near the ground and transport moisture to high altitudes are the atmosphere's response to this.

The problem, though, is that satellites view a planet top down, and we cannot always see through the complete atmosphere. Climate scientists deal with this difficulty in a number of ways:

1. By simultaneously observing at two wavelengths, one a "window" of weak absorption in which the atmosphere is transparent and we see to the surface, the other a wavelength of strong absorption by atmospheric gases in which we "see" only part of the way down, we can sense both top and bottom.
2. By looking up from the ground with surface-based remote sensing instruments, we see lower levels better locally but not globally.
3. Clouds are at least partly opaque to the short and moderate wavelengths of most planetary radiation, so active remote sensors such as radars, which emit their own long-wavelength radiation that penetrates through clouds, now fly on spacecraft.
4. The atmosphere changes faster than the Earth's surface beneath it, so we can observe the surface by waiting for the clouds to clear.

Figure 8.8 shows an example of the latter technique, a single frame of an animation of three months of operational weather satellite data.[10] The analysis uses visible and window-infrared images to distinguish clouds from the underlying surface. The visible channel analysis makes use of our knowledge that clouds are brighter than most surfaces, and the infrared analysis uses the knowledge that cloud tops are usually colder than the surface because temperature decreases upward in Earth's troposphere. Figure 8.8 uses four color bars, one each for clouds, ice / snow-cover, continents, and open oceans, with different hues for each type and different levels of saturation distinguishing higher vs. lower temperature. The simultaneous polar projections allow us to compare clouds in the two hemispheres. When the display is animated, even beginning students are able to detect temporal and spatial relationships between surface and atmosphere, e.g., the increase in high thick tropical clouds in the midafternoon when the temperature of the land surface is warmest, and the association of persistent high clouds in the equatorial west Pacific with the warm sea surface temperatures there.

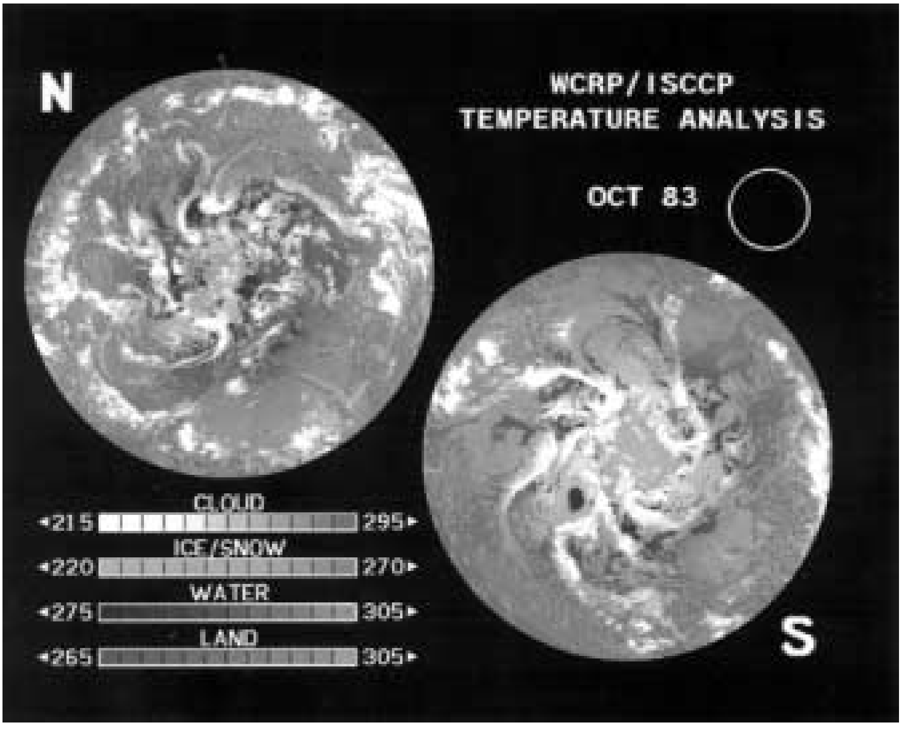

Figure 8.8 Northern and Southern Hemisphere polar projection false-color temperature maps for October 1, 1983, derived by the International Satellite Cloud Climatology Project from operational satellite infrared imagery. Separate color bars differentiate temperatures at cloud tops, ice / snow-covered surface regions, oceans, and continents. Temperatures are expressed in units of kelvin, which are identical to degrees Celsius but shifted upward in value by 273.15. For example, the freezing point of water is 32°F = 0°C = 273.15 K. See color version of this figure in the color section following page 114. (Photo courtesy of NASA.)

This works as long as one can distinguish cloud from surface. In the polar regions this is difficult, because snow and ice are just as bright as clouds in the visible channel analysis and the atmosphere can be warmer than the surface, which can confuse the interpretation of infrared images. The apparent absence of clouds near the North and South Poles in Figure 8.8 is partly a failure to detect them. Such regional errors in remote sensing data sets wreak havoc among climate scientists who are remote sensing novices. At one extreme, the naive user accepts Figure 8.8 as fact and worries needlessly that his climate model produces "too much" polar cloudiness. At the other extreme the skeptic who knows that the error bars in the polar regions are large, dismisses good data in other parts of the world and refuses to use the data set at all. In my experience, both types exist in the supposedly objective, meticulous scientific community.

A recent trend is to use multispectral microwave emission to separate cloud from snow / ice effects in the polar regions, since higher microwave frequencies are more sensitive to clouds and lower frequencies to sea ice.[4] Unfortunately, the separation is not complete, and ambiguity remains. Thus, at any instant a bright region in an image may be a cloud, an ice-covered ocean location, or ice hidden beneath a cloud. Animation allows both novice and expert to use the different morphologies of cloud systems and sea ice, and the different time scales of variation (days for clouds, weeks for sea ice) to separate the two. The observer can see a spiral cloud shape over the dark ocean disappear as it passes over ice and then reappear over the ocean downstream and link the two as the same entity. The observer can separate the primarily north-south seasonal growth and decay of sea ice from the primarily west-east movement of cloud systems. Whether such interpretation capabilities can be translated to the computer to enable the processing of years of such data remains to be seen.

Challenging as it is to understand Earth remote sensing data, we at least have the advantage of everyday experience and routine surface weather observations to guide our development of effective display strategies. When we remotely sense another planet, though, the same rules may not apply, and our approach therefore is somewhat different.

8.5 Remote sensing of planetary atmospheres

In principle, remote sensing of other planets is no different from remote sensing of Planet Earth, but in practice this is not the case. The volume of data on all the other planets combined is a small fraction of that for the Earth, although the advent of long-term planetary orbiters has finally begun to create a data volume issue in planetary research. In any event, our conceptual understanding of other planetary atmospheres still greatly lags that of our own atmosphere. Consequently, even the expert is something of a novice, attempting to make sense of cloud patterns that bear little resemblance to those we see on Earth (Figures 8.2, 8.3). The expert draws upon terrestrial experience to interpret these cloud features. For example, the Voyager imaging team routinely referred to isolated small white clouds (such as that below and to the left of the Great Red Spot of Jupiter in Figure 8.3) as "convective clouds," i.e., scientific jargon for thunderstorms, because of their resemblance to such features in Earth imagery. But this association implies the presence of a specific type of instability, and in truth there was no independent corroborating evidence to assure us that convection was indeed the process producing the clouds. Theoretically, we expect convection to exist sporadically on Jupiter, but to this day we cannot demonstrate why those clouds appear different from the surrounding larger-scale clouds tinged with pink, brown, or blue/gray. Depending on the final outcome of this story, the expert's experience may turn out to have been a boon or an obstacle to true understanding.

The other major difference between Earth and other planetary atmospheres is that most of the other planets are completely cloud covered (Venus, Jupiter, Saturn, Titan, Uranus, and Neptune) and we therefore either cannot see the surface, or no solid surface exists. This has two implications. First, since atmospheres work from the bottom up, what we see with remote sensing on other planets is only the tail of the dog, and it is hard to know what the rest of the dog looks like. Second, since atmospheres are dynamic entities, we have no fixed reference for mapping, and thus there is no such thing as a map of the world for planetary atmospheres. Figure 8.9 shows an attempt to create a rectangular world cloud map of Venus by digitally combining Pioneer Venus images spaced to correspond to the mean rotation rate of the "Y" feature.[2] The result is partly a success, partly a failure (note the discontinuities at image boundaries), because from one day to the next individual clouds grow and decay, and because the rotation speeds of the atmosphere and its waves are different at different latitudes. This is less of a problem on Jupiter, where the rotation rate of the planet far exceeds any fluctuations due to winds.

As on Earth, we use multispectral imaging to sense different altitudes of other planetary atmospheres, but with greater ambiguity. UV filters show sunlight scattered from small haze particles at high altitudes in the stratosphere, while near-infrared filters probe beneath the high hazes to sense sunlight reflected from clouds deep in the troposphere. Longer wavelength thermal infrared radiation senses the planet's own emission, which increases with temperature and therefore depth below the highest cloud tops. Maps of such thermal features side-by-side with images of reflected sunlight tell the expert whether a specific cloud feature is higher or lower in the atmosphere, or perhaps not a cloud at all. We can observe a planet with a filter that admits radiation at a wavelength at which a specific gas is known to absorb (e.g., methane band imaging of the Jovian planets). The higher the cloud top, the less overlying gas there is to absorb, and therefore the brighter the feature in the image. Finally, we can image the nightside of a planet in visible filters, looking for lightning flashes that mark the locations of thunderstorms at great depths that might otherwise be hidden from our view by the overlying cloud layers. Figure 8.10 shows such an example from the Galileo mission to Jupiter. Although this image is a view of the nightside, one can see both the lightning flashes from deep levels and the clouds at upper levels, because the latter are weakly illuminated by moonlight from Jupiter's closest satellite Io.

In all of these cases, interpretation is almost impossible for the novice. It depends on having not just a mental model of the weather of the atmosphere, but also a mental model of how specific types of electromagnetic radiation interact with a specific type of atmosphere. The expert must know the source of the radiation (reflected sunlight vs. the planet's emitted heat), the composition of the atmosphere and whether the gases present absorb or not at the wavelength being observed, and whether the atmosphere contains small haze particles (which reflect short wavelengths well but long wavelengths

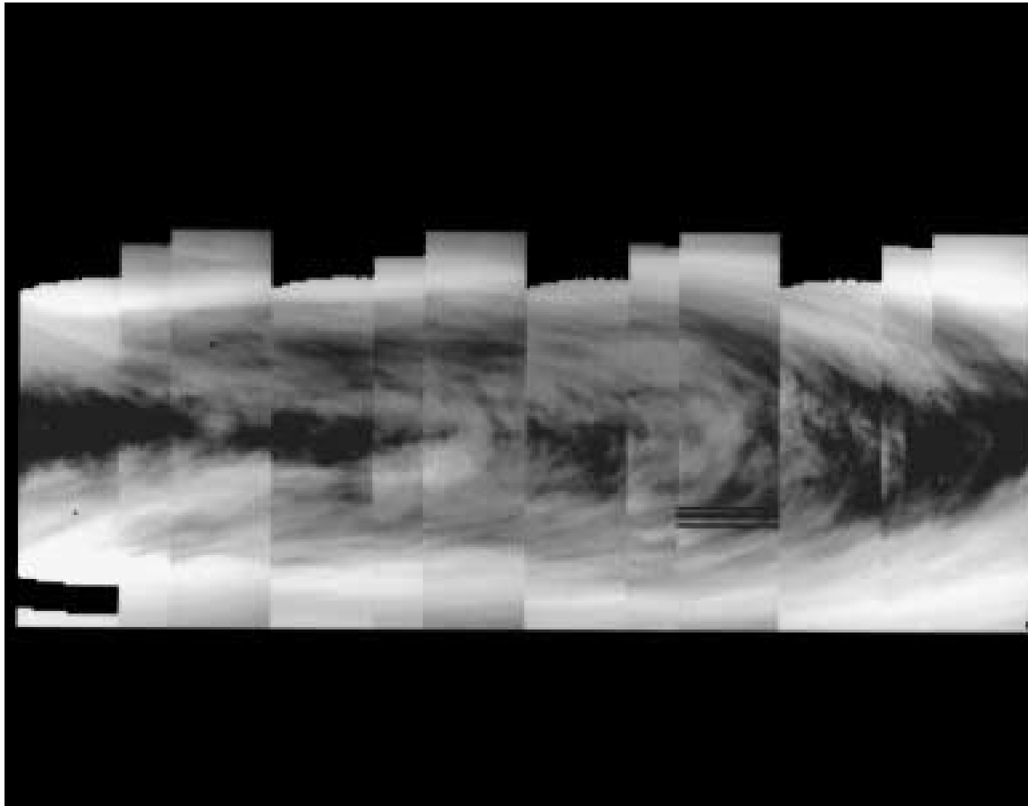

Figure 8.9 A rectangular projection world “map” of UV cloud features on Venus constructed by compositing the central sectors of 12 consecutive Pioneer Venus images acquired over a 4-day period, the nominal rotation period of planetary-scale cloud features. Discontinuities visible at image boundaries are caused by evolution of cloud features over time intervals of a few hours and by departures of the atmosphere’s rotation period from 4 days at some latitudes. Solid black areas represent missing data. (Photo courtesy of NASA.)

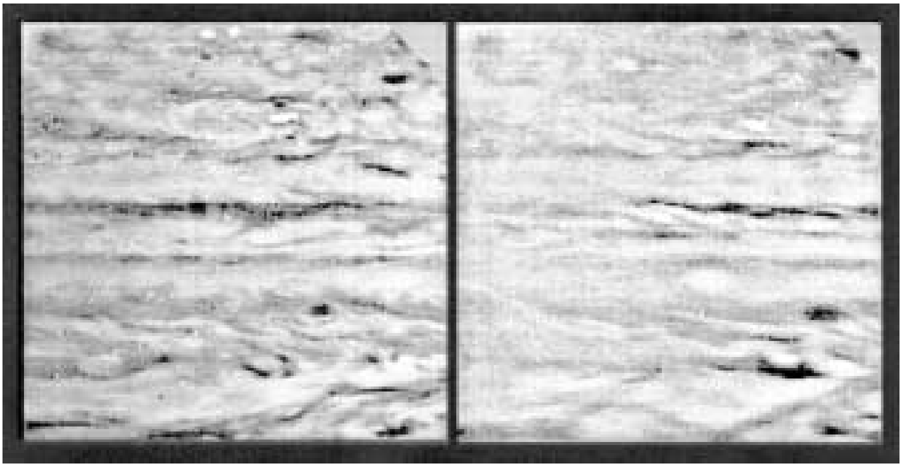

Figure 8.10 Galileo Orbiter visible images of the nightside of Jupiter. Bright specks indicate lightning flashes from water clouds located at depth below the visible cloud deck, while the background shows clouds at higher altitudes illuminated by moonlight reflected by Jupiter's innermost satellite Io. (Photo courtesy of NASA.)

poorly) as opposed to large cloud droplets (which reflect all wavelengths well but may be hidden below the reflective hazes in a short-wavelength image). If there are multiple haze/cloud layers of different particle size and composition (as is the case in most planetary atmospheres) and a heterogeneous planetary surface, the interpretation can be ambiguous even for the expert. Is a near-infrared feature in a Hubble Space Telescope image of Titan evidence of surface topography or ice, a tropospheric methane cloud, or a local thinning of the overlying stratospheric haze? Only by comparing images at different wavelengths and tracking motions over time can such ambiguities possibly be resolved.

Since we do not routinely launch weather balloons into other planets' atmospheres, most of our knowledge of these planets' circulations comes from tracking the motions of cloud features. The novice can do a fairly good job of tracking cloud motions by observing the same cloud shape in two images acquired several hours apart but displayed simultaneously. However, once the zeroth-order information has been gathered and higher accuracy is needed to detect subtle variations in the flow, the limitations of the novice emerge. For example, planetary-scale cloud features (such as the Venus "Y") move at slightly different speeds than the small cloud features in Figure 8.2 because the large features are propagating waves, and the up-down motions that produce wave crests and troughs look to the eye like horizontal motions of the air but are not (imagine, e.g., spreading ripples from a rock thrown onto a pond). It is easy to train the novice to focus only on small features more indicative of the true wind speed, and to avoid alternating dark-bright series of linear features that are obviously small-scale waves.

It is much harder, though, to train the human eye to detect both well-defined cloud objects and disorganized fields of brightness variation. Thus, even the expert detects only some of the possible cloud features that might provide information, given a sparse sample of the wind field. Even worse, since the human is drawn to certain types of features and develops an expectation of how far and in what direction features should move, the resulting wind field may be biased. Finally, from recent multiyear planetary orbital missions, thousands of images have been obtained, and the time it would take a human to process all images from a single mission becomes prohibitive.

We therefore use automated digital tracking algorithms, based on cross-correlations of image brightness fields for limited areas of a pair of images, to try and objectively map wind speeds in planetary atmospheres.[9] This maximizes the information from each image and allows large volumes of data to be processed, giving the statistics needed to answer some current research questions. As with the Earth storm-tracking program, though, the human and the computer must work together to optimize the algorithm. For example, we use visual impressions of cloud feature sizes that provide the most reliable wind estimates to specify the size of the array of pixels that the algorithm tries to cross-correlate. We define a minimum acceptable correlation coefficient by visually inspecting the kinds of feature motions the algorithm derives under different conditions (ideally we would like perfect correlations, but real clouds change shape with time). Most important, after the fact we can look at a frequency histogram of wind speeds derived by the algorithm. This will appear as a well-behaved Gaussian distribution of speeds, plus secondary distributions of outliers that are clearly not part of the main population of vectors. By visually displaying the cloud features that the computer tracked to obtain each outlier, we can throw out the spurious vectors (which may be due to periodic features that fool the algorithm, large-scale brightness gradients not removed in our image enhancement phase, etc.) and retain the “real” outliers for in-depth analysis. This iterative procedure allows us to refine the algorithm so that fewer outliers appear in future versions.

Unlike terrestrial images, where the expert can visualize the dynamics from the static display of a familiar feature, no such baseline of knowledge exists for less familiar planetary cloud features. Thus, movies are becoming an important tool for the planetary fluid dynamicist. Movies of rotating vortices on Jupiter and Neptune allowed Voyager scientists to watch individual vortices merge or pass by without interacting, and to detect individual vortices wiggling as they rotated. This in turn provided information about the otherwise unobserved vertical structures of these atmospheres.

Thus far, I have discussed remote sensing display as an after-the-fact exercise: a spacecraft instrument observes a planet, the data are processed and displayed, and the scientist manipulates and observes the display to understand what the planet *was* doing at the time of the observation. But (albeit in a limited way) we can also use displays to look into the future. This becomes important when scientists plan specific observations they are going to take during a planetary mission. We next discuss the use of displays in planning planetary observations.

8.6 The future: remote sensing displays as planning tools

Unlike Earth-orbiting satellites, which cover the globe and have regular, repeating orbits, planetary missions are either one-time flybys of one or two satellites or orbiter missions in which each orbit has a different shape and orientation to meet multiple scientific objectives (e.g., nearly circular vs. highly elliptic, closest approach to the planet on the dayside vs. the nightside, etc.) Instructions to point the spacecraft in a specific direction, image through a specific filter, set an exposure time, and shutter the camera at a certain moment must be relayed to the spacecraft far in advance of the time the image is taken (because of human limitations in planning and execution and the finite travel time of radio waves to a distant planet). The Voyager imaging team would not have acquired the image of the Great Red Spot in Figure 8.3 if they had not had some idea in advance when and where the Spot was going to come into view.

Such observation planning can of course be done by examining graphs of a spacecraft's latitude, longitude, distance from the planet, and time of day as a function of time during the mission. What we would really like, though, is to be able to visualize what the planet is going to look like from the vantage point of the spacecraft at any future moment, so we know when the most useful imaging opportunities arise and what type of observation is warranted. Projects such as the Cassini-Huygens mission to the Saturn system, already launched for arrival at Saturn in 2004, are using computer software that allows that to be done.

Figure 8.11 is a schematic example of what Saturn will look like to the Cassini Orbiter about a day before it goes into orbit. We can visualize what latitude and longitude are in direct view, where the day-night boundary is, how good a view of Saturn's rings we have at that time, and whether any of Saturn's moons are visible. The superimposed square representing the camera's field of view tells us whether a single image frame will cover the planet or whether we need a mosaic of many images to see everything. Once Cassini gets close enough to do an initial imaging survey of Saturn and its moons, the schematic diagram can be replaced by a projection from a data base of previous images, allowing us to use remote sensing displays to *predict* what Saturn and its moons will look like to Cassini at any time. No one is an expert on the future—since atmospheres evolve in time, these simulated images will only be educated guesses. But they will allow us to optimize the science return by planning the right type of image at the right time.

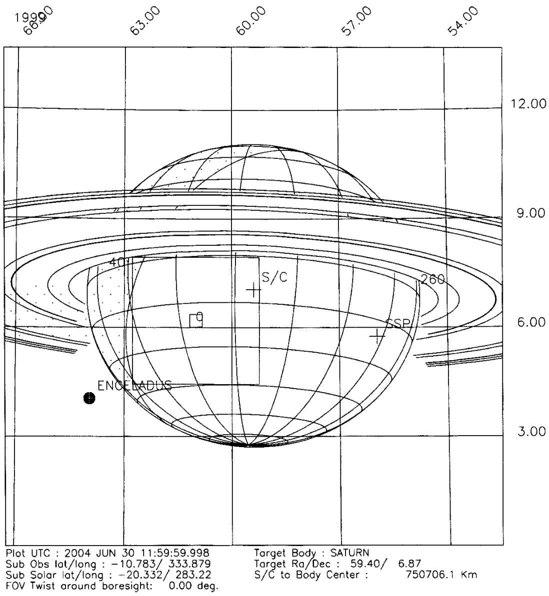

Figure 8.11 A schematic view of the appearance of Saturn as it will be seen by the Cassini Orbiter spacecraft the day before it goes into Saturn orbit on July 1, 2004, computed using the Cassini Sequence Planner (CASPER) algorithm developed by the project for planning mission observations. The superimposed squares are the fields of view of the Cassini Imaging Subsystem Wide and Narrow Angle Cameras. Dotted areas on the left represent the nightside of the planet. “SSP” indicates the point on Saturn directly beneath the Sun, and “S/C” the point directly beneath the spacecraft. According to CASPER, Saturn’s moon Enceladus will also be in view just to the lower left of Saturn at that time. (Figure courtesy of NASA.)

8.7 Conclusion

Consider three people looking at a yellow layer cake with chocolate icing: one has never seen a cake before, another has eaten cakes but never made one or seen a recipe, and the third has baking experience. Only the third would know most of the ingredients used to make the cake. Furthermore, there are limits to experiental learning: placed in a fully stocked kitchen, neither of the first two people would be likely to stumble upon the recipe in any reasonable amount of time.

The second person starts out with some advantages over the first: previous experience that although only chocolate icing is visible, there is probably cake and a layer of icing or fruit inside, and that usually the cake is either yellow or chocolate. The first person can advance to the expertise level of the second simply by cutting into the cake, looking at the inside, and tasting it.

Both are then in a position to think about what might make the cake yellow, perhaps leading to an inference about the use of eggs, and so on, although they will never reach the expert level on their own.

The novice in remote sensing display and analysis is in much the same situation. What lessons can be learned to make remote sensing display a more useful learning tool?

1. A prior mental model must exist. It may not be wise to have students use displays until they have some basic background in the subject. There is also no substitute for curiosity, a trait that seems to diminish from childhood to adulthood. Novices must be trained first and foremost to ask questions and encouraged to "play" with data displays.
2. Flexibility in display is crucial. Most atmospheric remote sensing data are two-dimensional (latitude vs. longitude, or horizontal-vertical cross-sections) and time-varying. It should be possible to look at the data from all angles (latitude vs. longitude at a given time, latitude vs. time at a specific longitude, animations that blend both spatial dimensions with time) via menu choices. It should be possible to select subsets of the data (e.g., geographic regions) to view in more detail. Color bar design should permit selection of a large number of colors from a palette, flexible choices of dynamic range, and variable data range definitions for different colors. Each of these features can be found in existing commercially available graphics packages; rarely are all found in the same package.
3. The display software should permit a variety of mathematical manipulations of the data: Anomalies with respect to a user-defined baseline, frequency histograms, lag correlations, spectral analysis, filtering with user-defined bandpass, EOF and/or related orthogonal function analysis, and mathematical function capability, i.e., the ability to calculate and display a function of two or more existing display data sets.
4. Novices must be trained not only how to use all the "bells and whistles," but also why they might want to use each one. For example, a novice who notices the big midlatitude comma cloud patterns but tends to miss the small cloud blobs indicating thunderstorms must be trained not only how to use the filtering function, but why he or she might want to notice both the big things and the small things in an image. Analogies to other fields might help, e.g., the importance of both bass and treble to the overall impact of music.
5. In meteorology and climate, the whole is greater than the sum of the parts. Remote sensing displays should permit the user to superimpose multiple fields on the same display. Satellite image gray-scale displays with superimposed color maps highlighting precipitation, contour maps of pressure and temperature, and wind vectors can be a useful way to allow the student to think about physical relationships, especially if the display can be animated. Simultaneous display of

fields at different altitudes, such as that in Figure 8.8, can be used to help students see how one part of the atmosphere does or does not communicate with another.

6. Novices must be trained to describe what they see in more detail than that to which they are accustomed. An exercise replicating the experience of someone describing a criminal to a police sketch artist might be useful. Two novices, one viewing a display and the other not having access to it, work together. The first describes the display to the second, whose job it is to draw the display only from the description offered by the first.

These points highlight the need especially for training documentation written from the standpoint of the novice user, rather than from the standpoint of the expert. A common flaw of software manuals is that they are so intent on demonstrating all the capabilities of the software, they overwhelm the novice who wishes to get started doing a few basic tasks and has no idea why the advanced capabilities even exist. Meeting the users at their level of expertise is and will continue to be the most effective strategy for widening the novice-to-expert bottleneck.

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