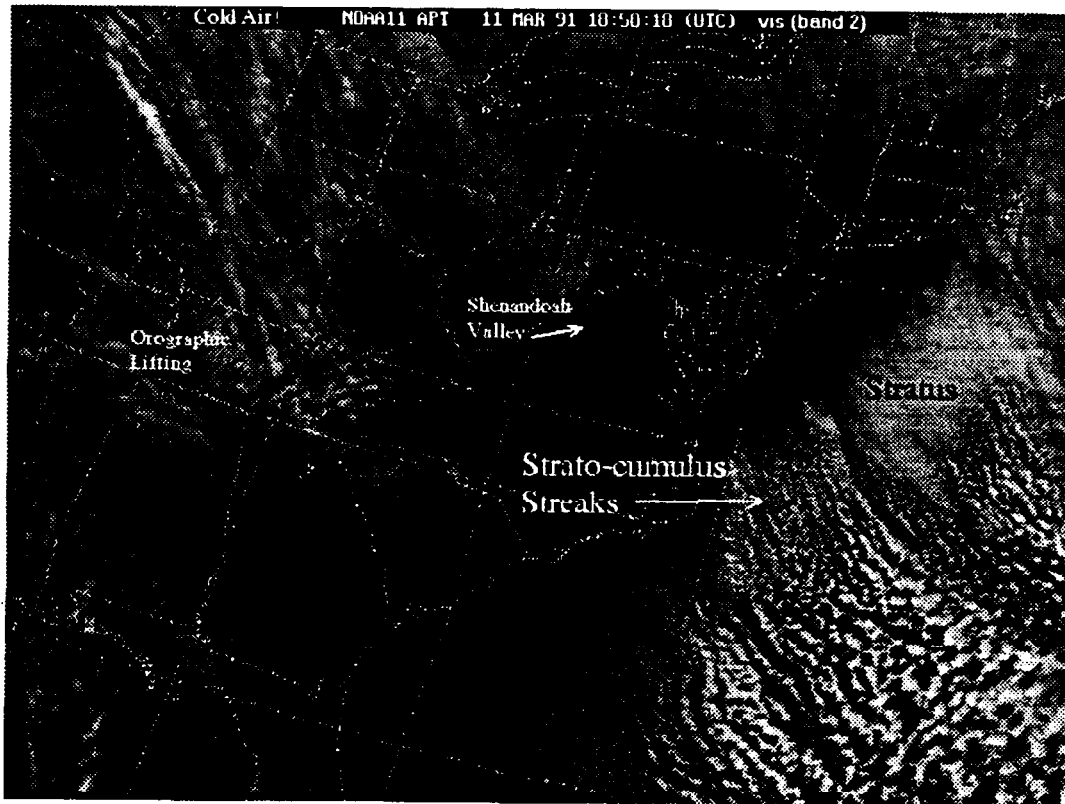


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# TEACHERS' GUIDE FOR USING APT SATELLITE IMAGERY TO TEACH SCIENCE AND MATH



This work is the result of research sponsored in part  
by the National Oceanic and Atmospheric Administration,  
U.S. Department of Commerce  
Sea Grant No. NA9OAA-D-SG840

Tri-Space, Inc.  
P.O. Box 7166  
Mc Lean, Virginia 22106

This work is a result of research sponsored in part by the National Sea Grant College Program of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, under Grant No. NA86AA-D-SG042 to the Virginia Marine Science Consortium and the Virginia Sea Grant College Program. The U.S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notation that may appear hereon.

# **TEACHERS' GUIDE FOR USING APT SATELLITE IMAGERY TO TEACH SCIENCE AND MATH**

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July 1991

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## Acknowledgements

This work could not have been undertaken without the assistance of the Virginia Space Grant Consortium, a coalition of five Virginia colleges and universities, NASA, state educational agencies, museums, private industry associations, and other institutions with diverse education and aerospace interests. Throughout this effort the Consortium has worked diligently on enhancing public awareness of the benefits of space related research and in the use of satellite APT imagery to enhance science and math curricula. Their promotion of strong science and math programs is to essential to the success of this Guide.

I wish to extend my gratitude to Jim Fletcher, who not only contributed the Unit on Agricultural Applications, but devoted many hours to capturing the west coast images used throughout the Guide. His interest in the Guide and encouragement along the way were invaluable. I extend my thanks also to Hank Brandli who provided most of the meteorological annotation and interpretation for the images used herein. Hank also provided substantial insight and guidance on the content of the meteorological units. Thanks also to my husband Jim for his patience while this book was in preparation, his suggestions and careful editing of the document.

This work was sponsored in part by NOAA, Sea Grant, Department of Commerce, under Grant NA90AA-D-SG840. The image of twin hurricanes off the coast of the Baja Peninsula was provided courtesy of Lockheed Missiles and Space, Austin Division. The GOES image was provided courtesy of Thomas Jefferson Science High School, Fairfax County, Virginia.

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## Introduction

### Overview:

Welcome to the exciting world of the Automatic Picture Transmission (APT) user. This Guide is intended to be a companion to your satellite APT receiving station. With it you will learn to explore Earth's environment from the broad perspective of space. Installation and operation of your APT station are not topics here. Rather, our purpose is to explain the *science content* of APT images and to demonstrate ways to extract the maximum benefit in terms of developing needed science and math skills in the classroom.

We have chosen to focus on the polar orbiting series of satellites operated by the United States Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) and the Soviet Union. The U.S. satellites are called the TIROS-N series and the Soviets call their satellites the Meteor series. Both series broadcast satellite images via APT links. APT images are inexpensive to capture and are of higher resolution than images broadcast from geostationary weather satellites - satellites that remain stationary over a fixed spot on the equator. Polar orbiting weather satellites broadcast pictures that can be received with little more than an FM television antenna, an radio receiver and a computer.

New technology must play a vital role in devising new strategies and creative approaches to learning science and math. It is equally important to stress the unknown and unfamiliar as intellectual challenges rather than intimidating concepts to avoid. APT satellite technology offers a marvelous opportunity fulfill both needs. However, it is essential first to instruct educators about using satellite imagery and digital data as effective instructional tools. This Guide is aimed specifically at that objective.

### Learning Objectives:

Each unit in this Guide has a specific set of learning objectives. Units may also include suggested activities, problems, and discussion topics. You will find a Summary Discussion at the end of each unit that lists important ideas and concepts that were presented.

#### ■ The first two Units present the fundamentals of remote sensing. ■

Unit 1 presents the fundamental concepts of image processing. After finishing Unit 1 you will be able to identify the building blocks of a digital image and understand the mechanical and statistical tools used for processing an image. You will be shown how to extract the maximum information content from an image using statistical analysis techniques to optimize image processing. Through Unit 1, you will see how APT satellite imagery can help develop skill in handling large volumes of data through statistical analysis.

Unit 2 focuses on the physics of remote sensing. Using the laws of electromagnetic radiation and radiative transfer, Unit 2 presents the scientific basis for what can be seen in visible and infrared satellite images. After completing Unit 2, you will be able to identify

objects in a image by their physical properties; reflectance and thermal emissivity. You will also be able to explain the influence of the atmosphere on radiation reflected and emitted from Earth. The information presented in Unit 2 will assist you in developing a learning environment where students' critical thinking and problem solving skills are challenged.

■ **Satellite Meteorology is the subject of Units 3 through 6.** ■

Unit 3 describes the physical properties of the atmosphere. The relationship between these properties is used to explain how clouds are formed. After finishing Unit 3, you will understand how the temperature and pressure of an air mass must change to cause clouds to develop and dissipate. You will be able to locate regions of rising and sinking air on a satellite image and to draw inferences about local and regional circulation patterns. The material in Unit 3 will help develop skills in detecting change and in analysis of relational databases.

The objectives of Unit 4 are to be able to recognize clouds in satellite images and explain their implications as they relate to prevailing weather conditions. Cloud shape, content, and height are used to explain the appearance of a variety of cloud types on visible and infrared satellite images. Skills in pattern recognition and comparison are emphasized throughout this unit.

Unit 5 examines upper level atmospheric air flow and its relationship to surface weather conditions. The objectives of this unit are to be able to classify the upper level patterns on a satellite image and then draw inferences about changing weather conditions at the surface. This unit provides an opportunity to extend pattern recognition skills to interpreting patterns, and inferring change.

Unit 6 presents the concepts of weather prediction. The objectives are to learn to identify combinations or systems of patterns and to predict their change. After completing this unit you will be able to locate weather fronts and various types of storm conditions in satellite images. By understanding the scientific principles of storm development, you will be able to predict changes.

■ **Units 7 and 8 illustrate the application of satellite imagery to real-world problems.** ■

The objectives of unit 7 and unit 8 are to show how remotely sensed satellite data can provide solutions to actual real-world problems. Unit 7 describes the value of infrared ocean images to maritime industries. The role of the ocean's in Global Change is also introduced. Satellite imagery as it applies to various agricultural activities is explained in Unit 8.

**Vocabulary:**

This Guide presents many new words in remote sensing and earth science. Important words whose meanings should be learned are printed in **bold faced type**. If you don't recall the

meaning of a word, you can look it up in the Glossary at the back of the Guide.

### Symbols:

Meteorology has its own symbolic language. Many of these symbols should be familiar to you from reading the weather map in your local newspaper. They are used throughout this Guide. You must be able to read these symbols in order to understand the image analyses presented. If you are not sure what a symbol means, check the list of symbols in the table provided at the right.




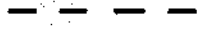

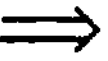


### Some Comments on Your Computer Graphics Capability:

Computers come with a variety of graphics capabilities and some may not be able to take advantage of the information available in 256 pixel values assigned to each image. An Extended Graphics Adapter (EGA) will process and display up to 16 different colors. Most VGA systems will process 256 colors and display 64 shades of grey. The number of rows and columns displayed also differs from computer to computer. Screen size will not effect the information content of the display as long as various portions of the image can be brought into view. Some common graphics formats include;

- o CGA 320 x 200 x 4 colors
- o EGA 640 x 350 x 16 colors
- o VGA 640 x 480 x 64 grey shades or 256 colors
- o SVGA 600 x 800 x 64 grey shades or 256 colors

You may wish to check your computer graphics capability now. To extract the most information from your APT station, you will need a VGA display. Although oceanographic and geographic features can be investigated with EGA graphics, it is very difficult to study weather phenomena without a display of at least 64 grey shades.

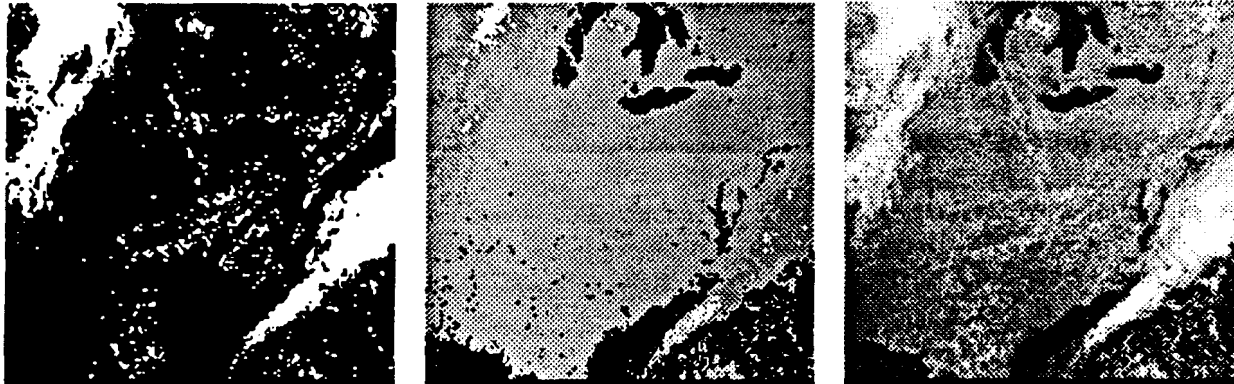
## Symbols

Stratus	(St)
Stratocumulus	(Sc)
Cumulus	(Cu)
Cumulonimbus	(Cb)
Alto cumulus	(Ac)
Altostratus	(As)
Cirrostratus	(Cs)
Cirrocumulus	(Cc)
Cirrus	(Ci)
Cold Front	
Warm Front	
Stationary Front	
Troughline	
Ridgeline	
Winds Aloft	
Surface Winds	
Rain	



## 1.2 The value of grey shades

Each pixel in an image has a brightness value which can be assigned a grey shade (or color). In the previous example the “tics” were white and the “tocks” were black. Most printed text, like the “NOAA” sign and page you are now reading, is produced in black and white. Although satellite images can be interesting and artistic in black and white, the information contained in a picture increases with increasing shades of grey (or color). Notice how the information content of the image below increases as more shades of grey are used in the printing process.

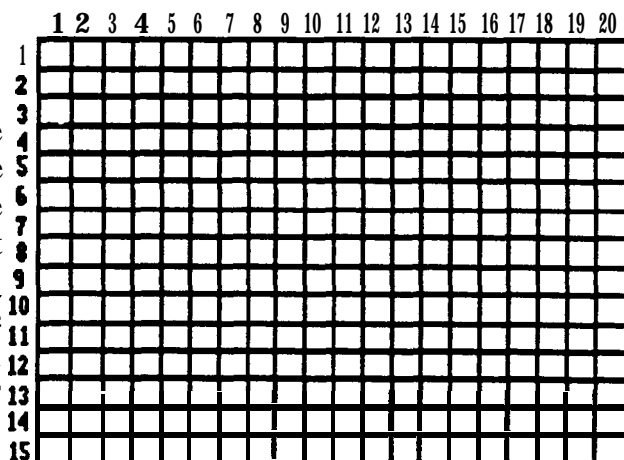


**Image 1.1 Increasing the grey shades increases the information in an image display.**

As they are transmitted from satellites, each APT pixel has a brightness value ranging from 1 to 256 which can be displayed using colors or grey shades ranging from black to white. Each shade relates to the brightness, and thus the physical characteristics of objects within the pixel area. A change in grey shade from one pixel to the next adjacent pixel means that the brightness has changed, corresponding to a physical change in the scene. If more grey shades are contained in an image display, more changes in physical conditions can be detected.

### Activity: Grey is Informative!

The graph paper shown here has 15 lines and 20 columns. Using a pencil to create dark and light grey, draw a picture on the paper by filling in the pixels. An example might be a picture of white sky and light grey grass with a black tree overlapping both. Your picture should have three shades; black, grey, and white. Can you imagine your picture in black and white? Did the grey shade increase the information content of the image? Discuss what information content would be lost without the three colors.

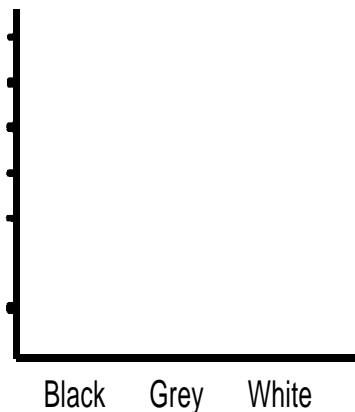
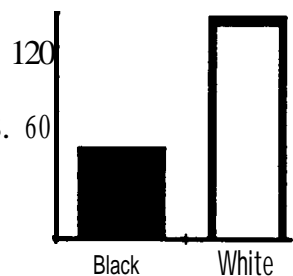


### 13 Intermediate Study: Understanding Histograms

Not all 256 brightness values may be present in an image. For example, there may not be anything in a scene that has a very low brightness value that would be displayed using black or charcoal grey shades. By knowing which brightness values an image contains and how many pixels of each value, many physical characteristics of objects in an image can be determined.

**Histograms** are statistical graphs of a picture showing the number of shades of grey used to display the picture and the frequency of occurrence of each shade. Histograms are usually displayed as bar graphs. Each grey shade in a picture is represented by a vertical bar. The height of the bar shows the number of pixels of that shade.

The NOAA sign created in “What is a pixel?” contained 8 rows and 24 columns totalling 192 pixels. Each of the 192 pixels was either black or white. Thus a histogram of the NOAA sign would have two bars. If you count the black pixels you will find that there are 58. How many are pixels white? A histogram of the NOAA sign looks like the graph at the right. The height of the bar representing black pixels is 58 units high. The height of the bar representing white pixels is 134 units high.



Activity: Histogram Grey is Informative!

In the space provided at the left, sketch a histogram of the picture you created in the “Grey is Information” Activity. Notice that each grey shade corresponds to a different object in your picture. (Hint: the picture had  $15 \times 20 = 300$  pixels.)

How many bars would the histogram have? \_\_\_\_\_

Number of black pixels? \_\_\_\_\_

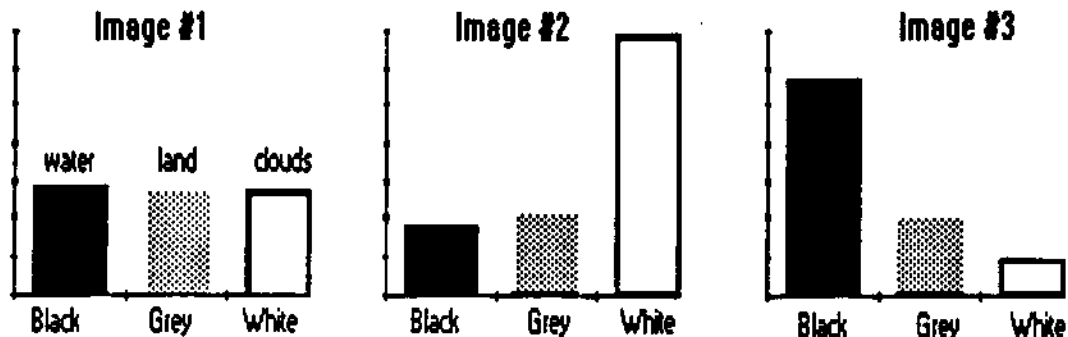
Number of grey pixels? \_\_\_\_\_

Number of white pixels? \_\_\_\_\_

### Activity: Interpreting Histograms

Consider a picture that shows water (black), clouds (white), and land or vegetation (grey). Several possible histograms of this picture are shown below.

- Circle the histogram would correspond to a rainy day.
- Underline the histogram that corresponds to a sunny day image.
- In which image is there likely to be lots of water?



### 1.4 Advanced Study: Image Enhancement/Contrast Stretching

Look closely at a television screen and you will notice that the picture is made up of many rows of dots and that each dot has a different brightness. Adjusting the television's brightness knob changes the brightness values of the dots and also the information content of the display. In image processing, the dots are like **pixels**. Increasing a TV screen's brightness is similar to **stretching** a satellite image. Stretching means enhancing the contrast of an image over a selected range of pixel values. Stretching brings out features in an image that are not readily apparent otherwise.

If the histogram of an image tells us that there are no features in a scene that are either very dark or very bright, then we can **stretch** an image over the grey shades available to the computer graphics display. Image 1.2 at the top of the next page was captured from a Soviet Meteor satellite. It is printed using grey shades ranging from black (0) to white (256). The histogram shown over the page helps explain why we can see very little in the top image. Almost all of the pixels range in value from about 24 to 64 (dark greys). There are almost no pixels brighter than a pixel value of 96. Image 1.3 at the bottom of the page is the same as Image 1.2 except that it has been **stretched** over a range from 24 to 64. All pixel values less than 24 are black, and all values greater than 64 are white in the display. By stretching the image we are able to see features that were not apparent before including the swamplands on the northern Florida panhandle and in southern Georgia, farmlands in the fertile river valleys, and bright sandy beaches along the Gulf Coast.



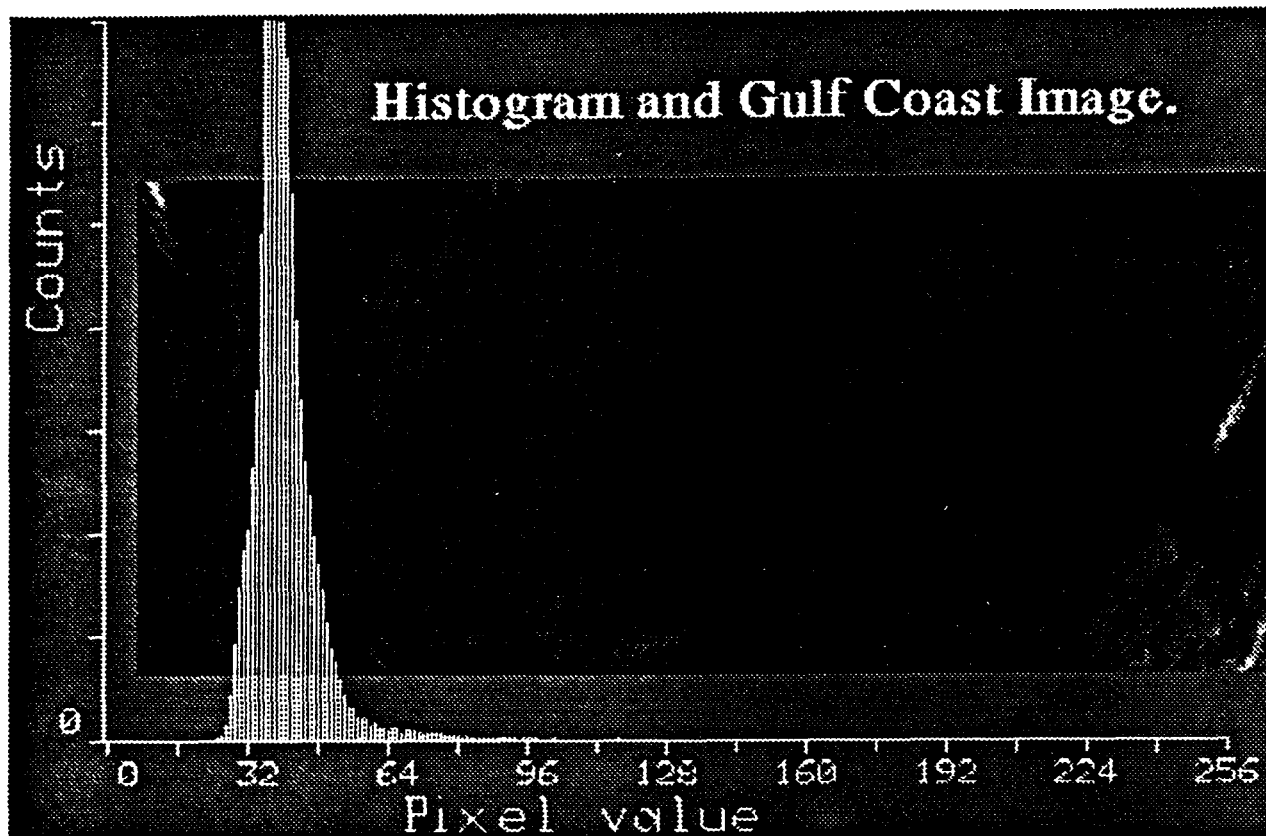


Image 1.2 Histogram and Soviet Meteor image of the United States' Gulf Coast.

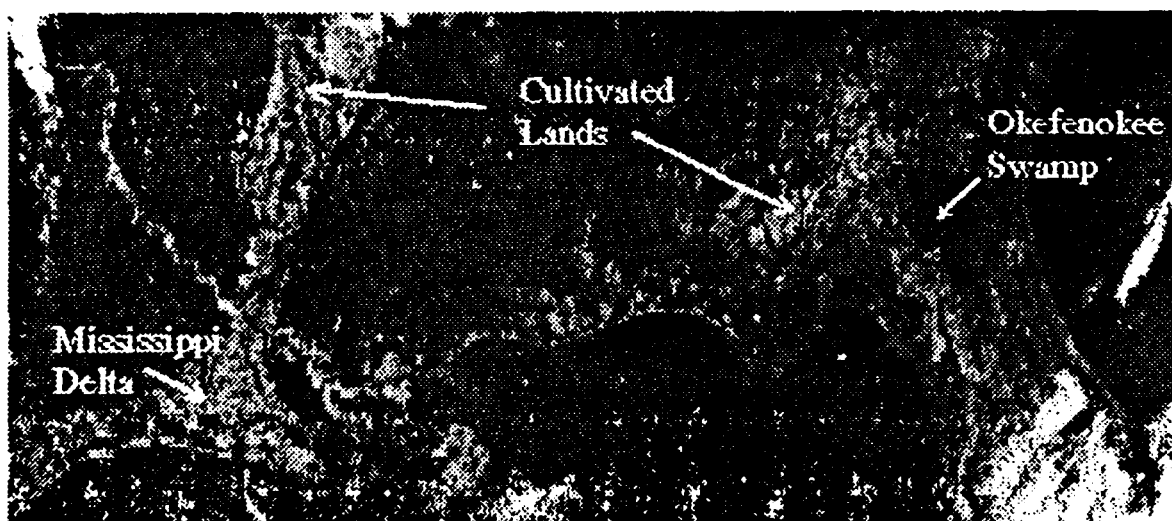


Image 1.3. The same Meteor image stretched over a range of pixel values from 24 to 64.

### **1.5 Summary Discussion**

You have learned that **pixels** are the fundamental building blocks of a satellite image, defining both the spatial resolution and the brightness (grey scale) of each picture element. The information content of a picture is increased by increasing the number of grey shades. Statistical representations of images in the form of histograms, are helpful in understanding the content and the changes taking place in an image. Finally, image processing techniques like contrast stretching can bring out information content of an image that might not otherwise be apparent.

At this point you have begun to develop skills in handling large volumes of data through statistical analyses. You should be able to apply concepts of computer processing to digital data analysis. Further exploration of image processing techniques might include finding out how resolution and scale affect detectability and recognizability of features in a scene.

## Unit 2: Remote Sensing - Electromagnetic Radiation

**Remote sensing** is the process of collecting information about material objects without coming into physical contact with them. Your eyes are a good example of remote sensors. They collect enormous amounts of information about the world around you without actually making physical contact. Satellite instruments are a lot like eyes. Both rely on waves of scattered and emitted **electromagnetic radiation** as their means for gathering information. In this unit you will learn about the nature of electromagnetic radiation and how the radiative properties of the earth and atmosphere are recorded in satellite imagery. The principles of radiation-matter interactions are presented and the radiative properties of four major classes of landscape features - water, clouds, vegetation, and soil - are summarized. This unit serves as the cornerstone for all further exploration of remote sensing.

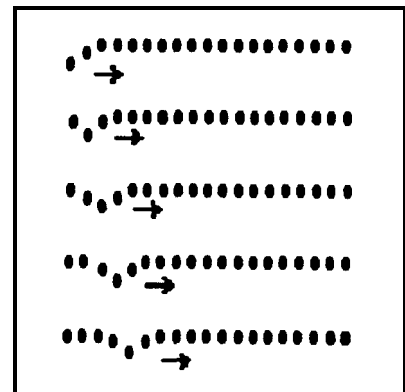
### 2.1 Waves are Patterns not Matter

Various types of waves and wave motion are described throughout this Guide. This unit deals with electromagnetic waves which are detected by satellite remote sensing instruments and form the basis for satellite images. The units on weather examine atmospheric waves which can have wavelengths that span the entire country. Wave phenomena are also an important component of ocean circulation, described in unit 7. Some fundamental characteristics of all waves are presented here.

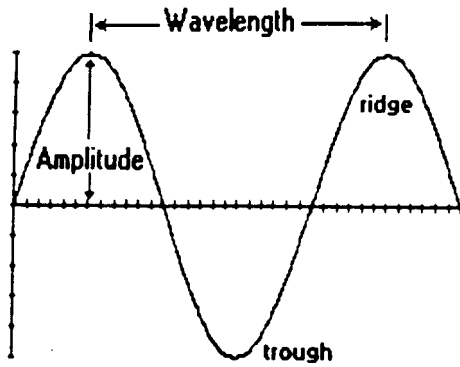
A **wave** is not a material object but a **pattern**. A wave can transport energy from one place to another, but it does not have mass. Some wave patterns are easily visualized. Water waves and waves on the strings of musical instruments are two common examples of wave motion that we can see. **Electromagnetic radiation** is more difficult to visualize because it consists of alternating electric and magnetic fields. Examples of radiation include radio and television waves and visible light.

#### Activity: Visualize a Wave

Have your students form two long single lines facing each other. Students in one line are asked to clap their hands at a constant beat. Each student in the second line is given the instruction, “Watch the person on your right and do what he does one beat later.” Then go to the left end of the second line and ask the first student to bend his knees and then straighten up again. The effect will be a “bump” that travels down the line from one end to the other. Yet, not one student will have moved either to his left or right showing that the wave is a pattern without mass.



The most important wave phenomena are not individual “bumps” but repeated identical waves. The parts of a repeating wave are defined and shown in the figure on the next page.



**Ridge** - a region of upward displacement. The maximum upward displacement is at the peak of the wave.

**Trough** - a region of downward displacement.

**Wavelength** - the interval at which the wave pattern repeats itself. Can be measured from peak to peak or trough to trough.

**Amplitude** - size of the vertical displacement produced by a wave.

**Frequency** - the number of waves passing a given point per unit time.

Activity: Measure a Wave. Weather systems move in waves across the country. Weather waves can often be visualized in the cloud patterns associated with them. A weather wave has been drawn on the satellite AFT image shown below.

1. Place an **R** on the ridge and a **T** on the trough.
2. Each degree of latitude is about 100 kilometers long at the earth's surface. Using this fact, estimate the wavelength and the amplitude of the wave in kilometers. To convert to miles multiply kilometers by 0.6.

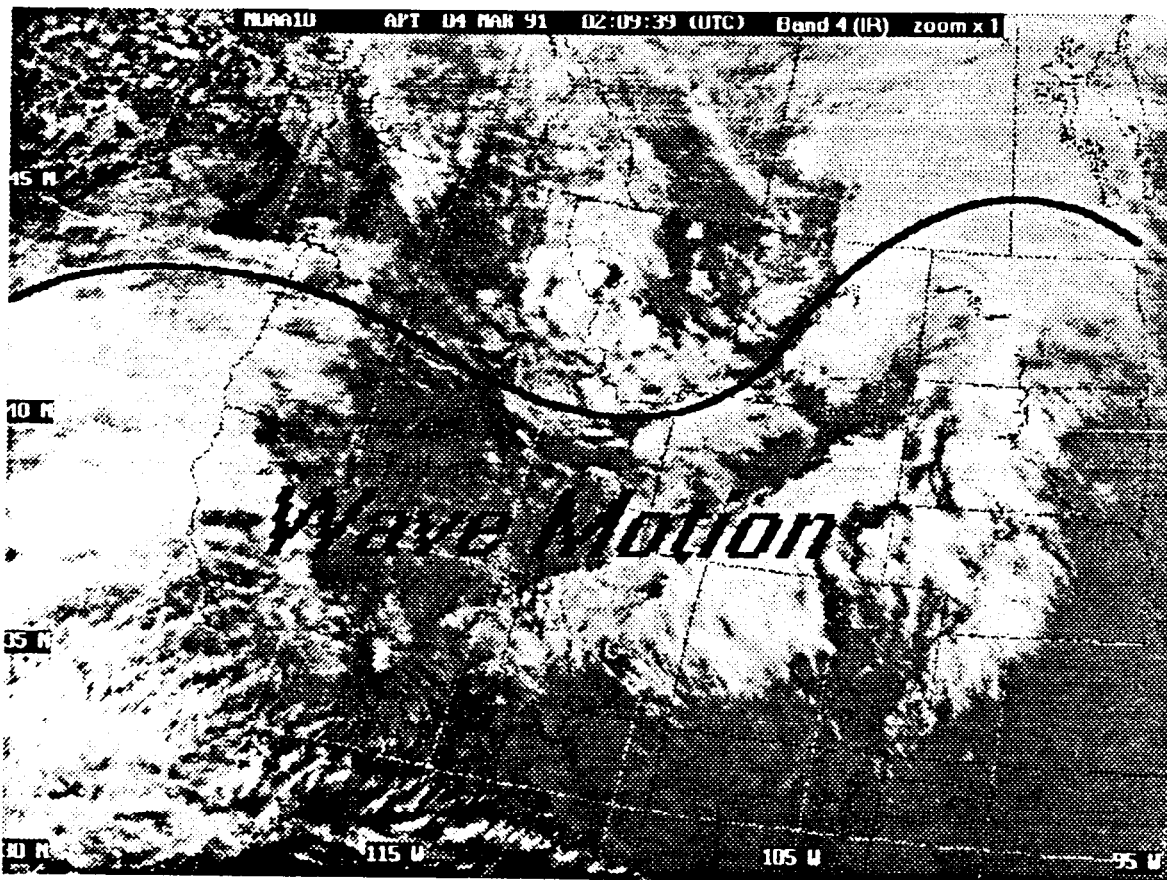


Image 2.1 Illustration of an upper level wave over the Western United States.

## 2.2 Electromagnetic Spectrum

All objects that are not at absolute zero temperature emit electromagnetic radiation in the form of waves of energy. Electromagnetic radiation occurs over a continuum of wavelengths from very long radio waves to extremely short gamma rays. The ordered arrangement of electromagnetic radiation as a function of wavelength is called the **electromagnetic spectrum**.

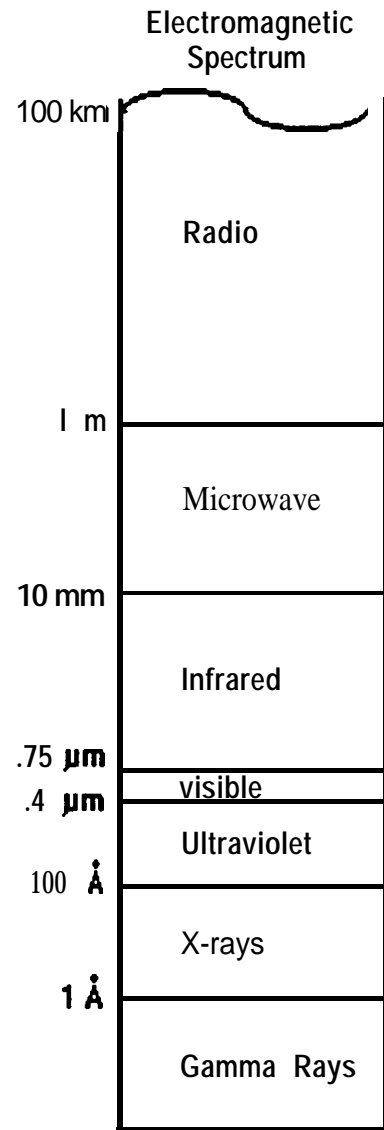
We are exposed to a variety of familiar forms of electromagnetic waves in our daily lives. A radio station emits very long radio waves which travel through space and can be received by radio antennas. Microwaves are shorter, from 10 millimeters to 1 meter, and are used for communications. If you hold your hands over a fire or a burner on the oven you are receiving infrared, or heat, radiation. Your eye is sensitive to a small set of wavelengths called the visible spectrum, wavelengths from .4 to .75 microns. A micron is one millionth of a meter long. At the very shortest end of the spectrum are ultraviolet rays, X rays, and gamma rays. These are measured in Angstroms or  $10^{-10}$  meters. Astronomers look for energy at these tiny wavelengths to learn about the stars.

## 2.3 Planck's Law and the brightness of the Sun and Earth

All material objects radiate a continuous spectrum of electromagnetic waves that is characteristic of its temperature. Some portions of this spectrum are brighter than others. **Brightness** refers to the radiated energy flux entering a remote sensor's field of view from an object. Planck's radiation law describes the brightness of objects over the full spectrum of emitted wavelengths. Planck's law states that the maximum brightness of an object occurs at shorter and shorter wavelengths as the temperature of the object increases. The relationship between the wavelength and the temperature of an object at its maximum brightness can be expressed as;

$$\text{wavelength(in microns)} = 2832 / \text{Temperature(in degrees Kelvin)} \quad (\text{eq. 2.1})$$

where Kelvin (K) is a unit of temperature scaled from absolute zero. Using this relationship, it is easy to calculate that the maximum brightness of the sun which has a temperature of 5900 degrees Kelvin (**°K**), occurs at a wavelength of .48 microns, approximately the middle of the visible region of the electromagnetic spectrum. The brightness maximum for the earth and ocean temperature (300°K) occurs at about 9.6



microns, in the infrared portion of the spectrum.

To measure the temperature of objects on earth, remote sensing satellite instruments often designed to collect electromagnetic radiation in infrared band covering wavelengths between 8 to 12 microns. Because the average temperature on earth is about 300°K the earth emits the maximum radiation and has its maximum brightness at these wavelengths. Therefore the signal energy received at the satellite will be the strongest in these bands unless there is interference as the radiation travels from the earth to the satellite.

#### Example Problem: The Human Body Spectrum!

At what wavelength in the electromagnetic spectrum will a human body whose temperature is 98.6 degrees Fahrenheit emit the most energy (i.e. be brightest)? Hint: The conversion from the Fahrenheit scale to the Kelvin scale is

$$\text{Kelvin} = (\text{Fahrenheit} - 32) \times .5555 + 273.16 \quad (\text{eq. 2.2})$$

Activity: Hot objects on earth are easily sensed from satellites that collect energy from the right wavelengths. Many remote sensing satellites including NOAA TIROS-N satellites collect images over a wavelength band from 3.5 to 4.0 microns. Use the form of Planck's law provided in equation 2.1 to calculate the temperature of objects that have their maximum brightness in this band of the electromagnetic spectrum. Discuss what kinds of scenes on earth would have this temperature. It may be helpful to convert Kelvin to Fahrenheit using the following equation:

$$(\mathbf{K} - 273.16) \times (9/5) + 32 = \mathbf{F} \quad (\text{eq. 2.3})$$

Forest fires, industrial exhaust, and natural gas waste flares have all been detected using the 3.7 micron band 3 channel of the AVHRR. Because the pixel resolution for APT satellite images is 4 kilometers, these hot spots must either be very hot or very large in order to be detected.

#### **2.4 The Tiros-N AVHRR is a Radiometer**

The camera on the United States TIROS-N satellites is called the Advance Very High Resolution Radiometer (AVHRR). A **radiometer** is an instrument that measures radiation brightness within a fixed band of wavelengths. The AVHRR collects images in five spectral bands simultaneously. However APT broadcasts from NOAA satellites contain only two spectral bands. The choice of which bands are broadcast to APT users is made by NOAA and is posted on the NOAA electronic bulletin board. The bands broadcast at any given time are also encoded within the signal being transmitted from the satellite. Usually, the solar infrared band 2 and the thermal infrared band 4 are broadcast during the day, and thermal infrared bands 3 and 4 are broadcast at night. The characteristics of the five bands are shown in Table 2.1. Bands 1 and 2 of the AVHRR instrument collect the sun's electromagnetic energy as it is reflected off objects within its field of view. Bands 2, 3, and 4 collect thermal energy radiated from objects in the infrared portion of the spectrum.

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<u>Band</u>	<u>Wavelength (um)</u>	<u>Description</u>	<u>Purpose</u>
1 <sup>1</sup>	58 - 0.68	Visible - green to red	Emphasizes cultural features, such as metropolitan areas and cultivated land.
2	.725 - 1.10	Near infrared	Emphasizes land-water boundaries. Penetrates atmospheric haze.
3	3.55 - 3.93	Infrared	Cloud heights. Transparent to water vapor.
4	10.30 - 11.30	Infrared	Thermal mapping
5 <sup>2</sup>	11.50 - 12.50	Far infrared	Thermal mapping. Water vapor correction

<sup>1</sup> Soviet Meteor Satellites broadcast 0.5 to 0.7 micron image at 2 kilometers resolution.

<sup>2</sup> The AVHRR on NOAA-10 has only the first four bands.

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Table 2.1. Each spectral band on the AVHRR has a special purpose. Bands 2, 3, and 4 are broadcast on NOAA APT channels.

### 2.5 Reflectance is the Key to Meteor and Band 2 Images

Band 2 collects energy in the solar infrared portion of the electromagnetic spectrum, adjacent to the visible spectrum. Although band 2 is not truly a visible band, the AVHRR detects the reflection of sun's light scattered off objects beneath rather than the amount of radiation emitted from objects due to their temperature. Because the human eye also detects reflected sunlight, band 2 is often referred to as a visible band even though technically it is in the near infrared.

The major classes of features we can see in band 2 images include water, vegetation, soil, and clouds. Weather systems, major water bodies, and soil/vegetation zones can be distinguished because each of these features has a characteristic **reflectance**. Each reflects, absorbs and transmits radiation in a different way. When we define the reflectance, absorbance, and transmittance of a feature, we say that we have defined its **spectral signature**.

Table 2.2 provides rule-of-thumb reflectance values for four broad classes of landscape features. Low reflectance values mean that these features will appear dark in satellite

images. Objects with high reflectance values are bright. Because the human eye responds to light in much the same way as AVHRR band 1 and Soviet Meteor instruments, reflectance properties of materials in this band are “intuitive”. Band 1 images are not broadcast on the APT link. Until they are enhanced using the procedures learned in Unit 1, Meteor images often appear to have only two shades, light clouds and dark earth.

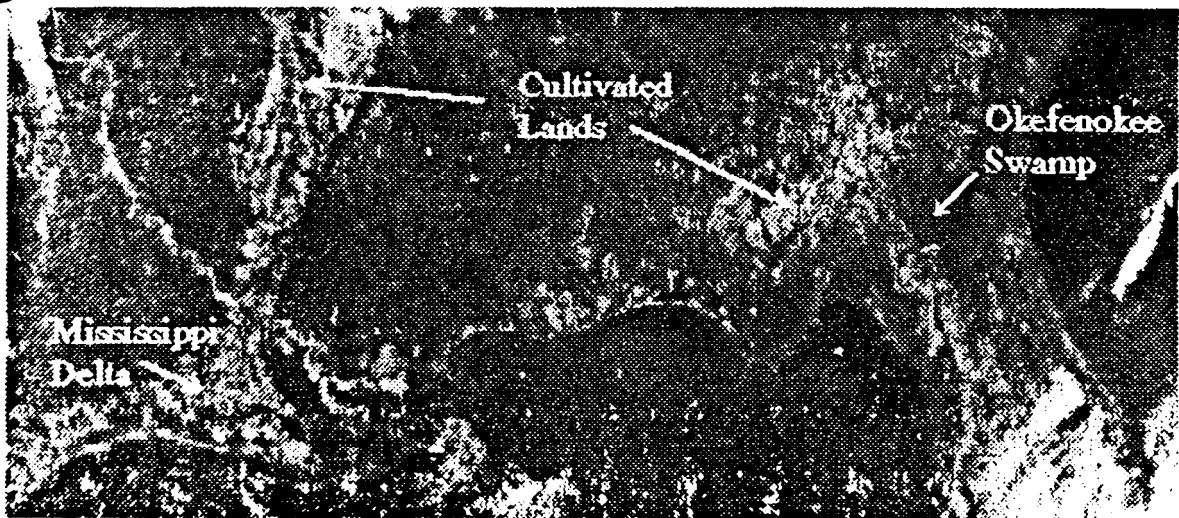
Band 2 is broadcast during the day from NOAA’s AVHRR instruments. Unenhanced band 2 images often appear to have three broad classes of objects. Clouds are very bright, land masses and vegetation are darker, and bodies of water are very dark. Both band 1 and 2 images have the most contrast when the sun is high and the contrast will change with the season.

**Table 2.2 Reflectance values for four broad classes of landscape features.**

Band	Water	Vegetation	Soil	Clouds
1 & Meteor	low (5%)	low (10-30%)	low (10-30%)	high (>70%)
2	low (5%)	medium (50%)	medium (50%)	high (>70%)

In general the reflectance of land surfaces increases with the extent of development. Forests appear very dark and cultivated farmlands are somewhat brighter. Urban areas comprised of concrete are lighter than the surrounding vegetation in band 1 images, but can be darker in band 2 if the city is set in grasslands or other reflective vegetation.

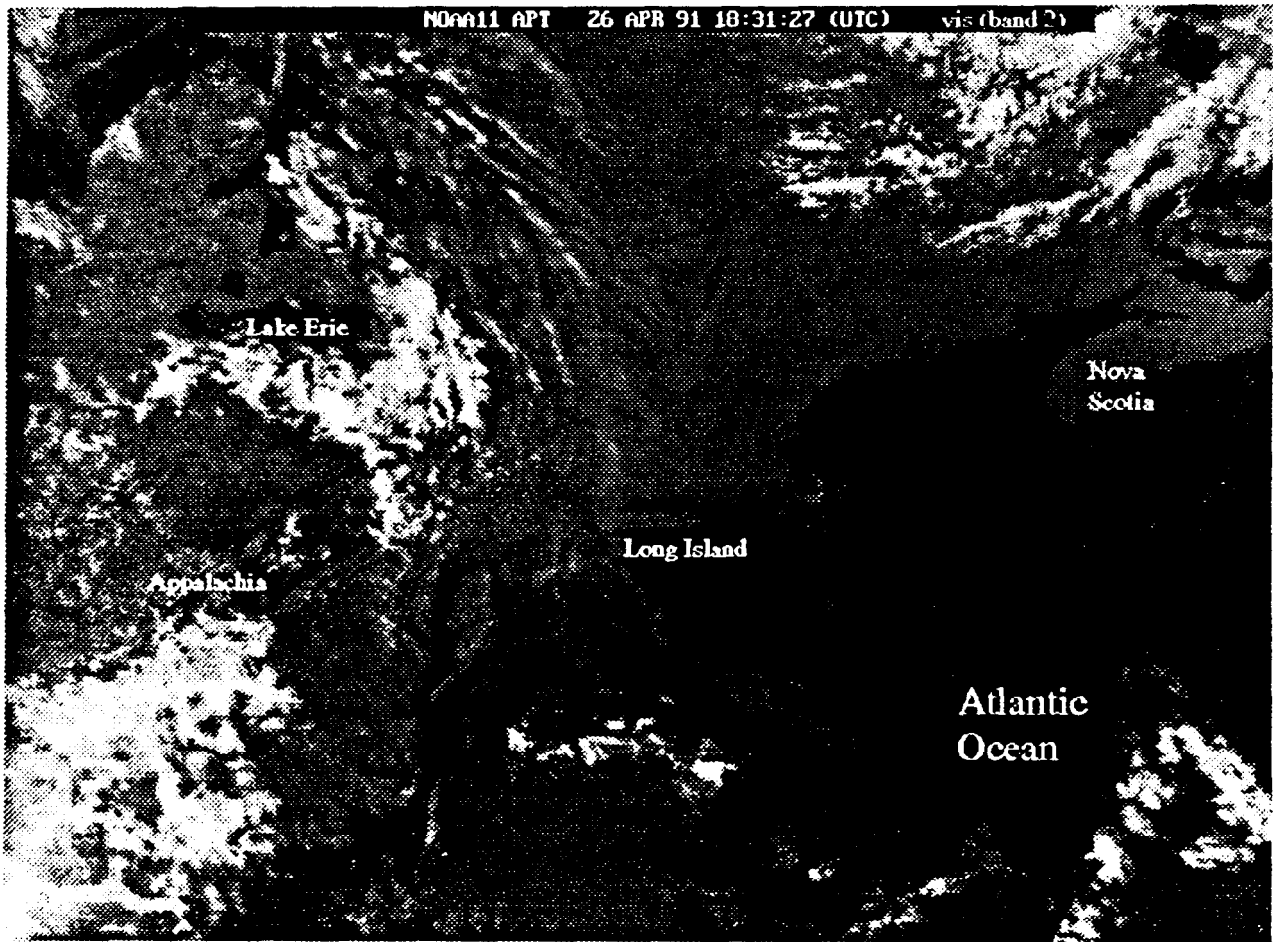
The Soviet Meteor image shown in Image 2.2 was *stretched* from a low pixel value of 24 to a high pixel value of 64. Assume, qualitatively, that the grey scale from 0 to 256 is equivalent to reflectance from 0 to 100 percent. Then the maximum *stretched* value of 64 is roughly representative of 25 percent reflectance. Stretching the image over pixel values from 24 to 64, displays the reflectance range from about 10 to 25 percent. Notice how vegetation and soils features are enhanced.



**Image 2.2 Stretched Meteor image of the Gulf Coast of the United States.**



This Band 2 image, captured from a NOAA 11 pass on April 26th, 1991 shows the Northeastern United States on a clear spring day. Characteristic of very low reflectance, the darkest objects in Image 2.3 are water bodies. Many large water bodies are evident including the Atlantic Ocean, Lake Erie, Lake Champlain, and a bit of the Saint Lawrence Seaway. Land areas are an intermediate shade of grey. Land areas that can be easily identified include Long Island, Nova Scotia, and Cape Cod. The smaller islands of Martha's Vineyard and Nantucket are also visible. Highly reflective clouds over western New York, Pennsylvania., and New Brunswick are the brightest components of Image 2.3.



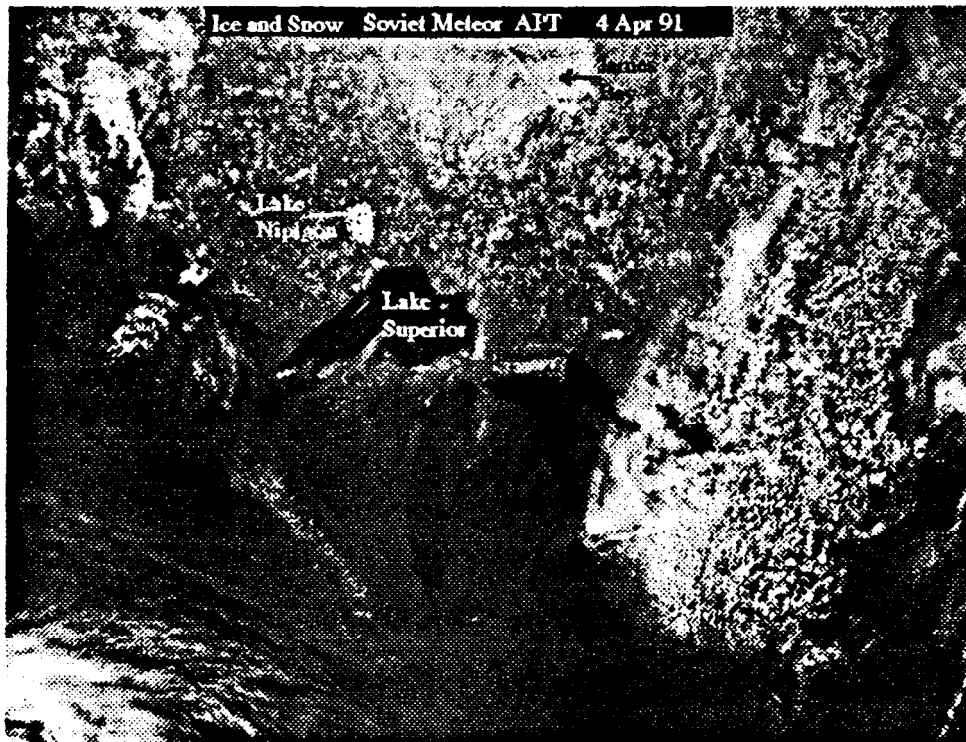
**Image 2.3 Visible (band 2) image of the Northeastern United States on a clear day.**

Visible and solar infrared wavelength reflectance of some common materials found on the earth's surface are described in the following pages. These are provided to give an indication of what values are found in some areas. When examining a specific location in detail, "ground truth" measurements are important. Field trips are a good way of collecting ground truth. Aerial photography and resource maps are other important tools. These should be available from the District Department of Interior office in your region.

**Clouds, Snow, and Other Forms of Water:**

Water in its various states has a dominant influence in all AFT images. In liquid form, water reflects very little of the light incident on it and is consequently the darkest element in any satellite image. Because cloud droplets scatter sunlight, they appear white in satellite images. In general, snow reflects more light than ice does. The liquid water content of snow and ice influences spectral reflectance - the greater the water content, the lower the reflectance.

<u>Snow, Ice, Water</u>	<u>Band 1</u>	<u>Band 2</u>
Fresh dry snow	80 - 90%	60-70%
Wet snow	65 - 75 %	50-60%
Brash and pack ice	35 - 45 %	20 - 40 %
New ice	15 - 25 %	< 20 %
Ocean	< 5 %	< 1 %
Lake water	3 - 10 %	< 5 %
Clouds	70 - 75 %	60-70%

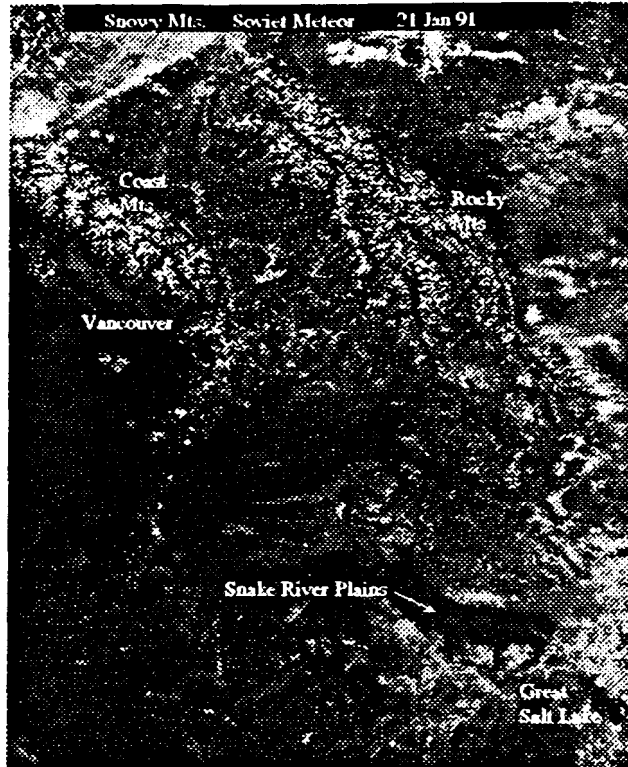


**Image 2.4 Meteor visible image showing reflectance characteristics of ice, snow and water.**

The Soviet Meteor image shown above was captured in early April and shows light snow cover blanketing the northeastern United States and Canada. Lake Nipigon, north of Lake Superior, and the James Bay are ice-covered and overlain with a dusting of new snow. The Great Lakes are not frozen and therefore appear very dark. A layer of thin cirrus clouds covers the region from Lake Erie to the Saint Lawrence Seaway.

A common snow pattern seen in satellite imagery is a **dendritic** pattern. Dendritic means a tree-like or branching pattern. The pattern is caused by mountain valleys, rivers, and tree lines which contrast sharply with snow covered areas.

This Meteor image from 21 January, 1991 shows dendritic snow patterns in the western Canadian Rockies. Snow also covers the Coast Mountains of British Columbia. The flat plains of the Snake River are also apparent. The discerning eye can also spot the tops of numerous mountains in the Cascades including Mt. Rainier, Mt. Hood and Mt. Saint Helens.

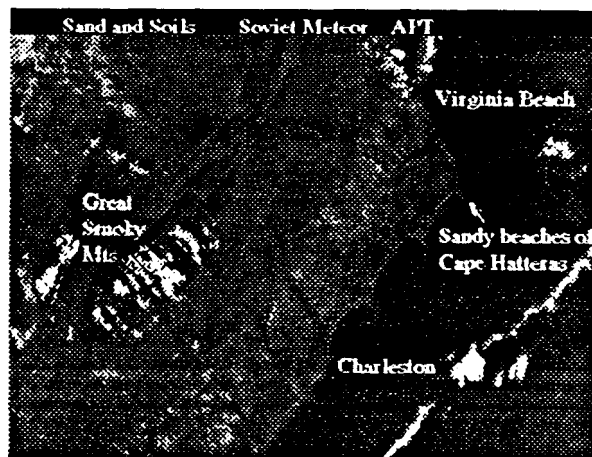


**Image 2.5 Meteor image showing the dendritic pattern of snow.**

**Soils:**

The spectral reflectance of soil is controlled for the most part by moisture content. Fine clay holds water and is thus less reflective than sand or well drained silt. Better-drained soils are more reflective. Particle size distribution also effects reflectance to some extent. Notice that the finer the particle size, the more reflective the sand.

	<u>Band 1 &amp; Meteor</u>	<u>Band 2</u>
Dark soil	5 - 15 %	10- 15 %
Gray soil	15 - 35 %	10- 15 %
Dry sand	25 - 50 %	60-80%
Coarse sand	60 - 65 %	60-70%
Medium sand	70 %	75 %
Fine sand	75 %	80%
Wet sand	15 - 30 %	
Concrete	15 - 40%	50 - 55 %



**Image 2.6 Meteor image showing the reflectance of sand and soils**

This Soviet Meteor image shows the bright fine sands of Cape Hatteras and the sandy coastline of the Carolinas. Also apparent, are forested areas in the Great Smoky Mountains and cultivated flatlands along the Atlantic Coast.

### Vegetation:

Examples of spectral reflectance values for various vegetation types are shown below. Vegetation is less reflective in band 1 than in band 2. The range of vegetative reflectance values from species to species is broader in band 2, ranging from 18 to 80 percent.

<u>Species</u>	<u>Band 1 &amp; Meteor</u>	<u>Band 2</u>
Fir	5 %	18%
Pine	10 %	30%
Birch	15-25%	50 - 70%
Grasslands	20 - 30 %	60-80%

As suggested by the data in the table, coniferous forests are generally less reflective than deciduous forests, due primarily to the density of water versus air in the leaf structure. In band 2, healthy deciduous vegetation reflects more light than concrete. Thus urban areas should appear darker than the surrounding grasslands. Urban areas surrounded by conifers will appear brighter than their surroundings.

Image 2.7 of Florida illustrates the importance of water content on the reflectance of areas beneath. The Everglades ecosystem depends on fresh water flow from Lake Okeechobee across south Florida into the Gulf of Mexico. The pathway for the water flow, called the Shark River Slough, is readily apparent in this image because it is wetter, and thus darker, than the surrounding higher ground.

Vegetative spectral reflectance in band 2 is directly correlated with water content in the leaf structure. Monocots and young leaves are generally compact and have a high water content. Dicots and older leaves have less water and more air in their structure.

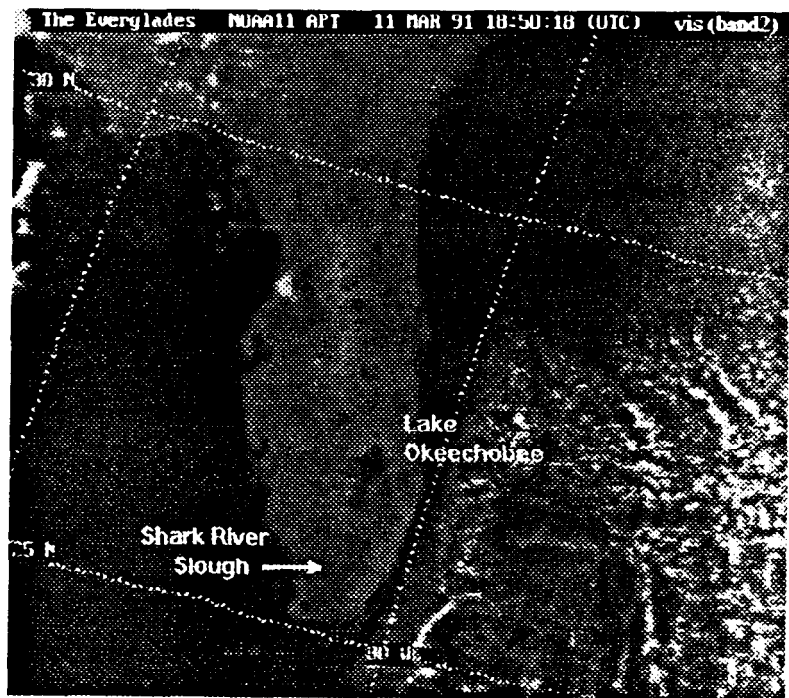


Image 2.7 TIROS-N band 2 image showing the reflectance of everglades vegetation.

The change in reflectance from band 1 to band 2 suggests that the ratios of reflectance measured in one band to another might be a very good indication of species.

## 2.6 Temperature is the Key to Bands 3 and 4

Band 3 and 4 infrared images show temperatures and temperature differences of the landscape beneath. Cold objects appear bright and warm objects are dark.

Image 2.8 is a thermal infrared image from NOAA 10. The darkest areas of the image are the warmest and the lightest areas are the coldest. The coldest objects in the image are clouds. The circular cloud pattern centered over Missouri and Illinois is a low pressure system. Low pressure systems are correlated with stormy weather which is fed by the mixing of warm and cold air masses. A warm tongue of air from the Gulf of Mexico is feeding the frontal system followed by colder air over Kansas and Oklahoma which is entering the system from the west. The Gulf Stream current is a warm water current in the Atlantic Ocean. It is visible in this image located about 100 kilometers off the coast of Virginia. You can estimate distances on images that have latitude and longitude markings by remembering that one degree latitude is about 100 kilometers.

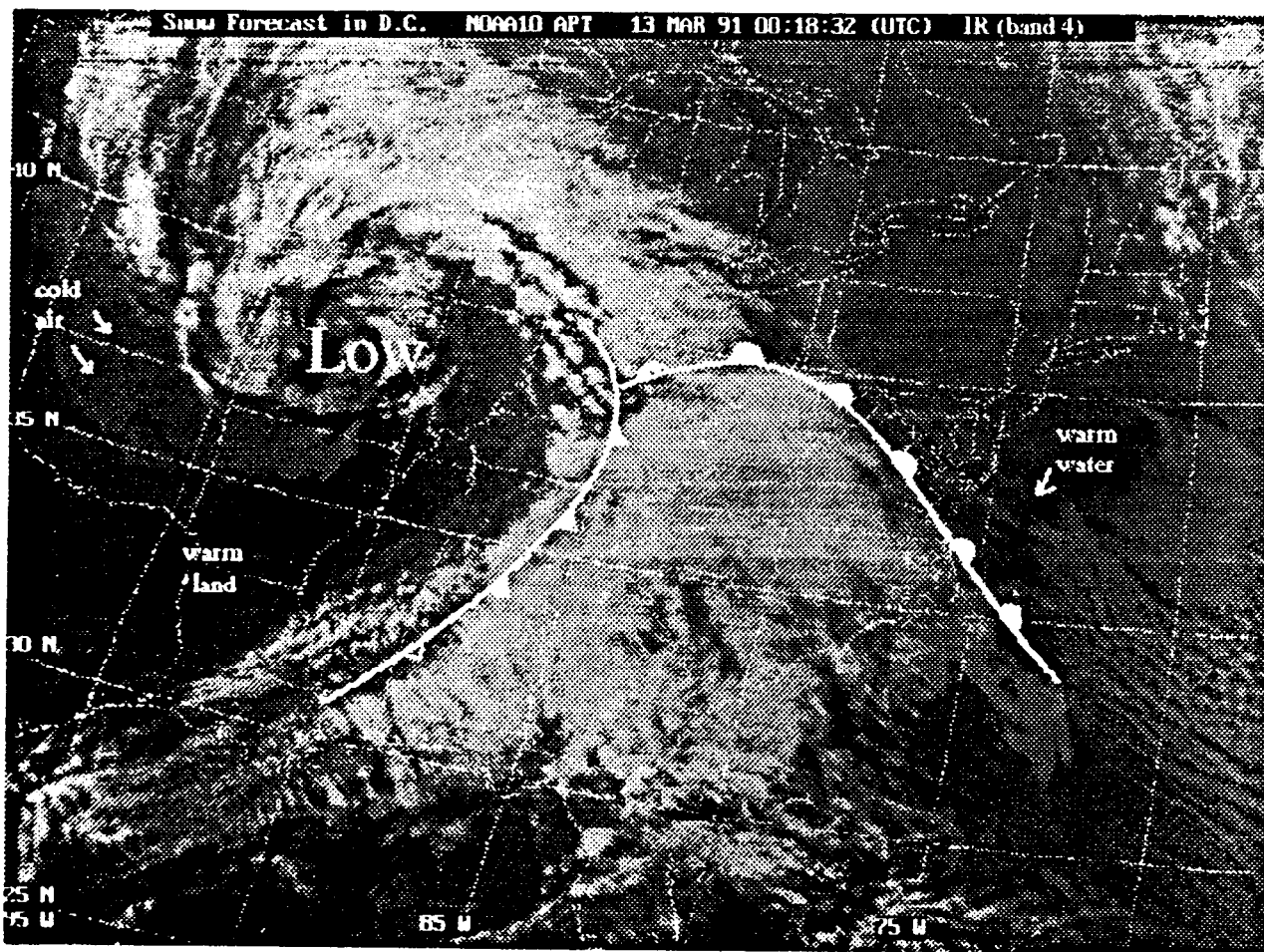


Image 2.8. In thermal infrared images, warm features are black and cold objects are white.

Infrared remote sensing depends on detecting the radiation emitted from objects in a scene rather than on radiation from reflected sunlight. Thermal energy emitted from the earth and ocean is a maximum in the wavelength intervals between 10 and 11 microns. Brightness values measured in band 4 are almost linearly dependent on temperature, and thus grey-shade steps in an image are uniform temperature steps as well. The relationship between brightness and temperature is not quite linear for band 3. APT images are broadcast with calibration data for converting measured brightness values to temperatures.

The band 4 infrared image below shows two large hurricanes named Herman and Iselle. They are fed by the warm water of the Pacific Ocean beneath them. The wind speed near the center of Herman measured 150 knots. Winds near the center of Iselle measured 100 knots. You can use the latitude and longitude lines to estimate the diameter of the eye of each hurricane. The smaller very cold cloud masses over the Gulf of California and southeastern Arizona are thunderstorms. The desert areas of southern California and the Baja Peninsula appear very warm. Tropical storms are covered more extensively in Unit 6 - Weather Systems.

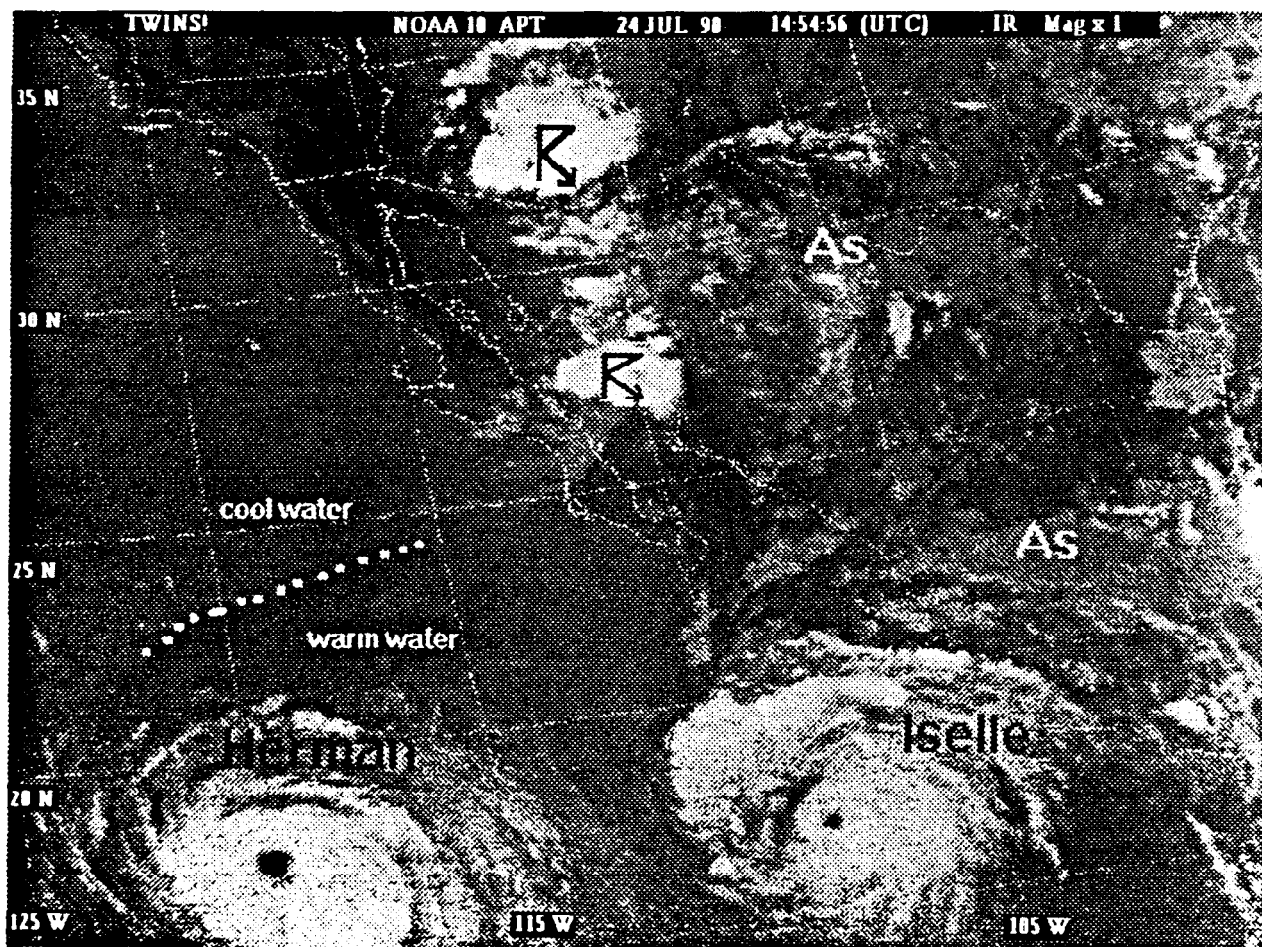


Image 2.9 TIROS-N infrared image of twin hurricanes off the West Coast of Mexico.

## 2.7 Intermediate Study: Black Body Radiation

A **black body** is an object that emits an amount of radiation equal to the amount it absorbs. Only black bodies are perfect emitters of radiation; most real objects are not. Most objects radiate somewhat less energy than if there were perfectly black. The parameter relating the observed brightness of an object to an ideal black body emitter is termed **emissivity**. **Emissivity ( $\epsilon$ )** is defined as the ratio of the observed brightness ( $B_{\text{observed}}$ ) to the ideal energy flux ( $B_{\text{black}}$ ). The actual temperature of an object is

$$T_{\text{actual}} = T_{\text{brightness}} \epsilon^{-1/4} \quad (\text{eq 2.4})$$

Because remote sensing instruments like the AVHRR measure the brightness temperatures of objects in a scene, the emissivity of the object is required in order to derive the actual temperature.

Surface emissivities of some common materials are shown in the Table 2.3. Calculations of actual temperature and brightness temperature have been entered in the Table for the extreme cases of asphalt and water. **You should complete the table as an exercise.** Note that actual temperatures are warmer than measured temperatures. Brightness temperatures of dark rocks can be in error by as much as 10°K. However for water, the difference between the temperature measured by the satellite and the actual temperature is within 1°K. Therefore satellite derived ocean temperatures should be quite accurate without correcting for emissivity of water.

The importance of emissivity to accurate measurement of surface temperature can be noted by observing that a one percent change of emissivity produces a change in surface temperature of slightly under 1° Kelvin. Therefore, in order to measure the temperature of an object on earth to within 1°, emissivity must be known to within one percent.

**Table 2.3 Emissivity and Brightness Temperature of Selected Materials.**

Material	$\epsilon$	$\epsilon^{1/4}$	$T_{\text{actual}}$ if $T_{\text{brightness}}$ is 300° Kelvin	$T_{\text{brightness}}$ if $T_{\text{actual}}$ is 300° Kelvin.
Rock: Asphalt	0.86	0.963	311.5° Kelvin	288.9° K
Granite	0.90	0.974	308.0° K	
Basalt	0.92	0.979		
Concrete	0.97			
Soil: Dry sand	0.91	0.977		
Wet sand	0.94	0.985	304.6° K	
Water:Ice	0.95	0.987	303.9° K	
Fresh/Salt	0.99	0.997	300.9° K	299.1° K

### Activity: Infrared Photography

Infrared film is available for 35 mm cameras at most professional camera shops. Try taking pictures from high places of grassy parks, asphalt playgrounds, water bodies and other landscapes. Have the film developed and make comparisons with AFT imagery. Try this day and night. What changes? What remains the same?

## 2.8 The Atmosphere's Content

The earth's atmosphere is a mixture of

- gases which are relatively constant in concentration, called permanent gases,
- gases which vary in concentration, and
- solid and liquid particles.

About 99 percent (%) of our atmosphere is comprised of permanent gases, which include nitrogen (78 %) and oxygen (21 %). These gases are nearly transparent to radiation over the broad visible and infrared wavelength bands monitored by weather satellite instruments. Therefore they are not readily detected in APT satellite images. Gaseous molecules do scatter some sunlight, particularly at shorter (blue and ultraviolet) wavelengths.

Variable gases cause changes in weather and climate as their concentrations change. The most dynamic variable gas is water vapor which may occupy as much as four percent of the volume of humid air but be nearly absent in arid areas. The Atmosphere's water vapor content can change rapidly causing dramatic changes in weather conditions. Other variable gases are carbon dioxide and ozone. All three variable gases play a role in global change because they absorb electromagnetic radiation. As the amount of variable gases increases, more radiation can be absorbed, resulting in warmer temperatures on Earth.

Radiation emitted or reflected from the earth's surface interacts with the atmosphere's variable gases in two ways: by absorption and scattering. Both effects change the amount of electromagnetic radiation that is received at the satellite sensor from what is reflected or emitted at the earth's surface. Because of the presence of variable gases, satellite brightness measurements are different from what is actually reflected or emitted from the earth's surface.

Ozone and water vapor absorb electromagnetic radiation in the infrared portion of the spectrum. The effect of these variable gases on infrared remote sensing' is that satellite measured temperatures are colder than the actual temperature at the earth's surface. The magnitude of this effect can range from 2° to 10° K and varies from day to day and from place to place depending on the atmosphere's water vapor content. Fortunately, absorption minima are found at 3.5, and 12 microns, Bands 3 and 5 of the AVHRR instrument. The absorption caused by water vapor is less in Band 3 than in Band 4.

The AVHRR instrument scans Earth from side-to-side as it orbits the earth. At the center of the scan, the satellite is looking straight down. This is called a **nadir view** because it is



the shortest distance to earth. At the edges of the scan, the distance to earth is greater. Therefore the geometry of Earth viewing during the sensor scan effects the length of the path through the atmosphere. Because of the curvature of the earth, light from the left and right edges of an APT image must travel further through the atmosphere to reach the satellite than light from the center of the picture. This has the effect of slightly lowering measured temperatures measured at the edges of the image. Actual temperatures can be as much as 3° K during warmer humid weather conditions.

The atmosphere's liquids and solid particles are a result of water vapor condensation, sea salt, volcanic eruptions, wind blown dust, man made pollution or other sources. Liquids and solids in the atmosphere are they are easily observed in visible satellite images because they scatter light. Smoke plumes from slash burning can often be observed in Meteor and band 2 images.

#### Activity:

A flashlight and an atomizer can be used to illustrate the effects of light scattering by particles. Fill an atomizer with water. Then spray the air and shine the flashlight on the spray. Repeat the process in a dark room. A discussion of your findings might include a discussion of why automobile headlights can be ineffective on foggy nights.

### **2.9 Advanced Study: Radiative Transfer in the Atmosphere**

Scientists refer to the collective effects of scattering and absorption of light in the atmosphere in terms of **optical thickness**( $\tau$ ). Optical thickness depends on the wavelength of light and the size distribution of the gases and particles causing the scattering. When the wavelength is about equal to the size, scattering is the greatest. Since molecules of gas are very small, they scatter the shortest wavelengths in the visible spectrum most efficiently. A lot of blue light scatters, but much less red and infrared light is scattered by gases.

Aerosols such as sea salt, particles from volcanic emissions, and some forms of air pollution consist of particles that are about the same size as the wavelengths monitored by AVHRR Bands 2 and 3. Therefore these bands can be noticeably influenced by aerosol scattering. The optical thickness of the atmosphere is usually reported as the sum of gaseous and aerosol contributions ( $\tau = \tau_{\text{gas}} + \tau_{\text{aerosol}}$ ).

The **transmittance** of the atmosphere ( $T_a$ ), the probability that light reflected or emitted from the earth's surface will arrive at the satellite, is related to the optical thickness in the following way:

$$T_a = \exp[-\tau \cos\theta] \quad (\text{eq. 2.5})$$

where the optical thickness is represented by the greek letter tau( $\tau$ ) and theta( $\theta$ ) is the viewing angle from the satellite to earth. Zero  $\theta$  means that the satellite is looking straight down - a **nadir** view. The optical thickness of the atmosphere on a clear day is about 0.17. Using equation 4.1 the transmittance can be shown to have a value of .84. This means that

84 percent of the light reflected from the surface in band 2 will reach the satellite. Since the sunlight being reflected has to travel two ways through the atmosphere (down and back), the probability of two way transmission is  $T_a^2$  or 0.71.

Example Problem 1:

Using a typical hazy day optical thickness of .7 for band 2, calculate the two way transmittance of the atmosphere on hazy days.

Example Problem 2:

A typical cirrus cloud is about 1 kilometer thick and 75 percent of all cirrus clouds are less than 2 km thick. The total two way propagation path for near infrared light through cirrus clouds can be calculated from the following model equation:

$$T_a^2 = \exp[-.28 L^2] \quad (\text{eq. 2.6})$$

where  $L$  is the thickness of the cirrus layer in kilometers. What is the two way transmission probability for a 1 kilometer thick cirrus cloud?

## 2.10 Summary Discussion

The materials presented in Unit 2 are fundamental to remote sensing and are a prerequisite to comprehending the information content of any remotely sensed scene. The objective of this unit was to build an understanding of electromagnetic radiation and the relationship between electromagnetic energy flux and remote sensing signatures. The concepts of waves and wave motion have been presented as have been the nature of electromagnetic radiation and radiative transfer. You should be able to define the parts of a wave and relate these parts to the electromagnetic spectrum.

You have learned that waves of electromagnetic energy are reflected and emitted from all objects in different quantities depending on the object's material content and physical characteristics. You should be able describe the relationship between and object's reflectance, its temperature, and its brightness as recorded in satellite imagery. By knowing how the reflectance and temperature of material objects influence the appearance of satellite images, you should be able to recognize major features in an image and be able to interpret and compare visible and infrared images.

The influence of scattering and absorption by gases in the atmosphere on the quality of satellite images of Earth has been examined. This advanced topic of radiative transfer through the atmosphere can be explored in much greater depth than presented here, particularly as it relates to global change and warming.

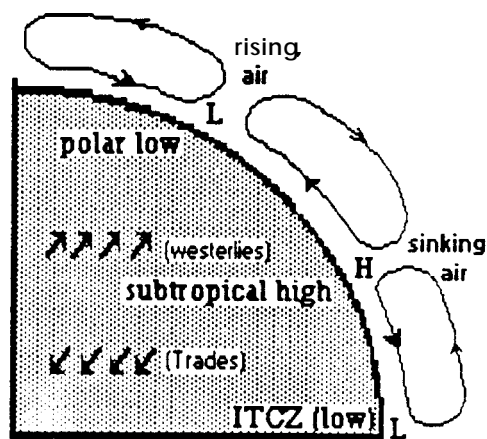
This Unit should challenge the resourcefulness and academic capacities of its readers. Opportunities for problem solving in physics, geography, geometry, algebra, and statistics are abundant.

## Unit 3: The State of the Atmosphere - How Clouds Form

### 3.1 Temperature and Atmospheric Circulation

Temperature differences from place to place on the earth's surface result in convective air flow, or winds. When a gas is warmed its volume expands and it tends to rise. You can observe this on a small scale by placing your hand over a pan of boiling water or by measuring the air temperature at the top and the bottom of a heated or air conditioned room. The physical law that states that the volume of a gas is proportional to its temperature is called the *ideal gas law*. The mathematical relationship is the equation of state. The equation of state is presented in section 3.3.

Global wind patterns begin when air at the equator is heated by the sun. This hot humid air expands and rises to a height of about 20 kilometers (12 miles). It then flows toward the colder polar regions where it sinks again at about 30 degrees latitude. The regions of sinking on either side of the equator are called subtropical high pressure areas. Because of the earth's rotation underneath the atmosphere, low level air flow back toward the equator appears to have an easterly (from the east) orientation. These easterlies are called **trade winds**. Winds flowing away from the equator from the subtropical high are called **westerlies**. Westerlies occur in the mid-latitude bands of the earth.



Thermometers for measuring temperature are scaled by the melting point of ice and the boiling point of water. On the Celsius scale, the difference between the boiling and freezing is divided into 100 parts, or degrees Celsius ( $^{\circ}\text{C}$ ), where zero is freezing and 100 is boiling. On the Fahrenheit scale, the difference between freezing and boiling is divided into 180 parts or degrees Fahrenheit ( $^{\circ}\text{F}$ ). The temperature of melting ice is marked at  $32^{\circ}\text{F}$  and boiling water at  $212^{\circ}\text{F}$ . The universal temperature scale is called the Kelvin scale. Degrees on the Kelvin scale are equivalent to degrees on the Celsius scale. However, zero on the Kelvin scale is set at absolute zero, the temperature at which molecules stop moving and there is no heat at all. Zero degrees Kelvin is  $-273.16^{\circ}\text{C}$  or  $-459.4^{\circ}\text{F}$ .

### 3.2 Pressure and Atmosphere

Air has weight. One simple way to prove it is to balance two balloons on a yard stick. Prick one and watch what happens. The weight of the atmosphere over a one inch square patch of land at sea level is 14.7 pounds. Using this information you can compute that the weight of air on your shoulders (about 1 square foot or 144 square inches) is over one ton! We don't feel it because we are used to it.

**Pressure** is defined in terms of the weight of the atmosphere per unit area. Semi-permanent high and low pressure areas occur at various locations on earth. These locations are related to the global circulation pattern described above. Over the equator, where moist tropical air rises due to the sun's heating, is a permanent belt of low pressure called the Intertropical Convergence Zone (ITCZ). At 30 degrees north and south of the ITCZ are belts of high pressure called subtropical highs. Semi-permanent high pressure systems also reside over each of the poles. These two high pressure areas are separated by a low pressure belt sometimes called the **polar front**. The polar front occurs at about 60 degrees latitude but meanders toward the equator during the cold season. These high and low pressure belts are marked on the figure above.

Atmospheric pressure is measured with a barometer. One common type of barometer consists of a glass tube about 800 millimeters long. The tube is filled with mercury, inverted, and placed in a dish of mercury. The level of mercury falls until the force per unit area on the mercury in the dish supports the mercury in the tube. At sea level about 760 millimeters of mercury should remain in the tube. As the atmospheric pressure on the mercury in the dish rises and falls, the mercury level in the tube will rise and fall.

Pressure is sometimes reported in fractions of normal sea-level atmospheric pressure, or fractions of an atmosphere (atm). On this scale, 1 atm is the weight per unit area of the atmosphere above land at sea level. Units of pressure which are equivalent to 1 atm are 1013.25 millibars, or 760 millimeters of mercury or 29.9213 inches of mercury.

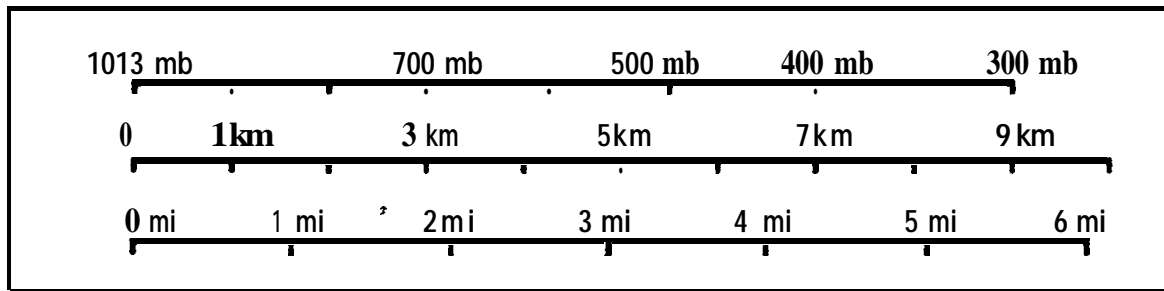
### 3.3 Thermodynamics

Atmospheric pressure decreases with height above the earth. Our bodies detect changes in atmospheric pressure when they take place. You may have experienced the effects of pressure drop with height causing your ears to pop as you drive over a mountain. Meteorologists often report the height of weather phenomena above the earth's surface in units of pressure rather than length. The relationship that describes how pressure changes with height is called the hydrostatic equation. A simple form of this equation, which is only valid near the surface of the earth where the density of the air is also constant (about the first 5 kilometers), can be written as follows:

$$P_{\text{at height } h} = 1013 - h/10 \quad (\text{eq. 3.1})$$

where **P** is pressure in millibars and the height **h** is measured in meters, the value of the constant is 10. The hydrostatic equation was used to develop the conversion ruler shown on the next page. You may wish to develop a conversion ruler from "millibars" to "feet" as a classroom activity.

The study of the solid, liquid, and gaseous states of a system is called **thermodynamics**. The properties of state, sometimes called the variables of state, are pressure, temperature, and volume. The **equation of state** defines the relationship between state variables when a



system is in equilibrium. The equation of state for a constant fixed volume of gas is:

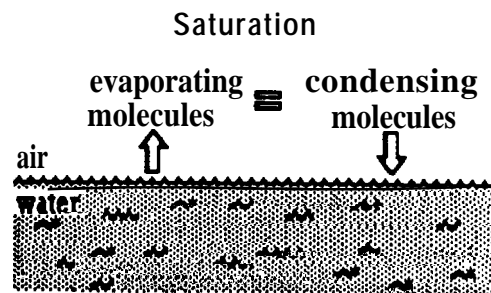
$$\text{Pressure(millibars)} \times \text{Volume} = \text{Constant} \times \text{Temperature(Kelvin)} \quad (\text{eq. 3.2})$$

In section 3.1 we explained the relationship between the temperature of a gas and its volume. The equation of state also says that if the pressure on a gas is increased, the gas will heat and if the pressure decreases, that gas cools. This law explains why a bicycle pump feels hot when it compresses air, and why a fire extinguisher gets frosty cold when it is used. For meteorological purposes, the ideal gas law when combined with the hydrostatic equation states that the temperature of the atmosphere must decrease with altitude.

As a general rule, the temperature of dry air decreases at a rate of  $10^{\circ}\text{C}$  per kilometer above the ground. This is called the dry **adiabatic** lapse rate. The temperature of saturated air decreases more slowly, at a rate of about  $5^{\circ}$  to  $7^{\circ}\text{C}$  per kilometer. Meteorologists refer to this as the moist adiabatic lapse rate. The term **adiabatic** refers to a thermodynamic process which takes place without gain or loss of heat.

### 3.4 Water Vapor

The atmosphere's water content varies in time and place. Because water at atmospheric temperature readily changes state from solid ice to liquid drops to gas, it can be easily picked up, transported, and deposited from place to place around the world. Dry air soaks up water by converting it to its gaseous state, called water vapor. However, like a sponge which cannot hold an unlimited amount of water, the atmosphere cannot hold an unlimited amount of water vapor. The maximum possible amount a volume of air can hold depends on temperature and pressure. The higher the temperature or the pressure, the more water vapor air can hold.



Perhaps you have noticed how sidewalks dry out in the sun after a rain, or how water condenses on grass on cold evenings. This figure depicts an air water interface. Water molecules can evaporate leaving the water and entering the air and they can condense from the air back into the water. Saturation occurs when evaporation equals condensation. The temperature to which air must be cooled to reach saturation is called the **dew point temperature**. If air is cooled

beyond the dew point, then the excess water vapor condenses into droplets. If the temperature rises above the dew point, then water will evaporate.

Relative humidity is another measure of the air's water vapor content expressed as the ratio of the actual atmospheric water vapor to the maximum possible. If a volume of air with a relative humidity of 50 % is cooled, the relative humidity will increase until it reaches 100 %. Further cooling will result in fog, rain or another form of precipitation.

### 3.5 How Clouds Form

Clouds form when moist air cools beyond its dew point temperature and the excess water vapor condenses. There are two main ways to cool air to bring about condensation; radiative cooling and adiabatic expansion as a result of vertical motion. The various causes of vertical motion include; lifting of air over mountains, **convection** caused by the sun's unequal heating at the earth's surface, convergence of air flow, and frontal ascent or **advection**. Clouds dissipate either when air is heated above its dew point, or if the moisture falls out as precipitation.

#### Radiative Cooling:

Radiative cooling occurs on clear evenings after the sun has set. Ground temperature rapidly falls as heat is radiated away. Then the air in contact with the land is cooled causing condensation if the temperature drops below the dew point. Radiative cooling results in dew, fog, and, if its cold enough, frost. Fog appears in visible satellite images as a uniform textured area. Depending on the sun angle and the thickness of the layer, fog can appear white or grey in visible images. Boundaries are sharply defined and often outline the topography, such as coast lines, mountains and valleys. Fog is not easy to identify on infrared images because the temperature difference between fog and its surroundings is not large.

Both images shown here are from early morning Soviet Meteor passes. Image 3.1 on the left shows a thick fog layer covering the San Joaquin Valley in central California. Image 3.2 shows fog settled into the valleys of Yellowstone National Park and other mountain valleys of the Rocky Mountains.

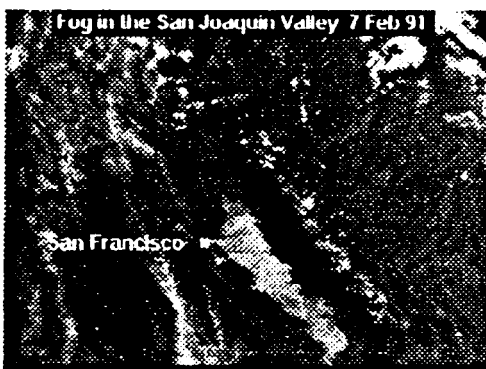


Image 3.1 Fog in San Joaquin Valley.

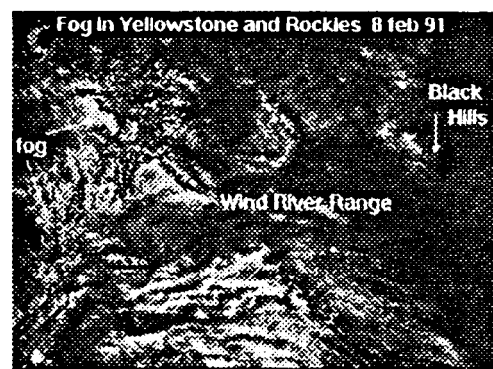
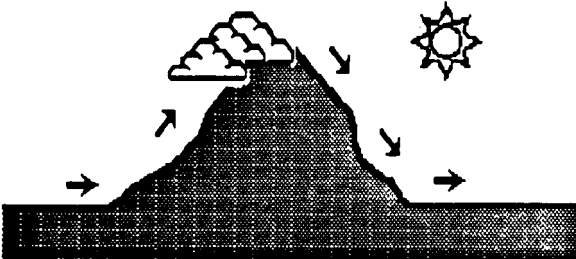


Image 3.2 Fog in Rocky Mt. Valleys.

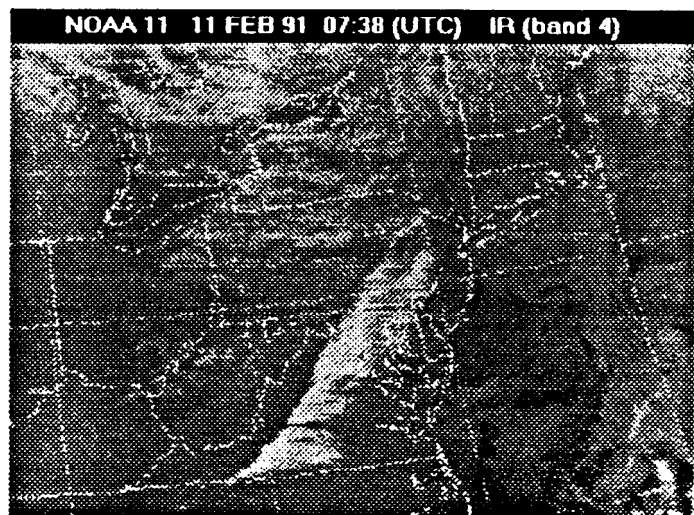
### Orographic Lifting:

Meteorologists call the rise of air as it flows over topographic barriers is called **orographic lifting**. The temperature of dry air decreases at about  $10^{\circ}\text{C}$  per kilometer as it is lifted. If the air cools beyond its dew point temperature, then condensation takes place and clouds form. Saturated air cools at a little more slowly as it is lifted because when water vapor condenses it gives off a bit of extra heat, called **latent heat**. Therefore, saturated air cools at rate of about  $5^{\circ}$  to  $7^{\circ}\text{C}$  per kilometer.

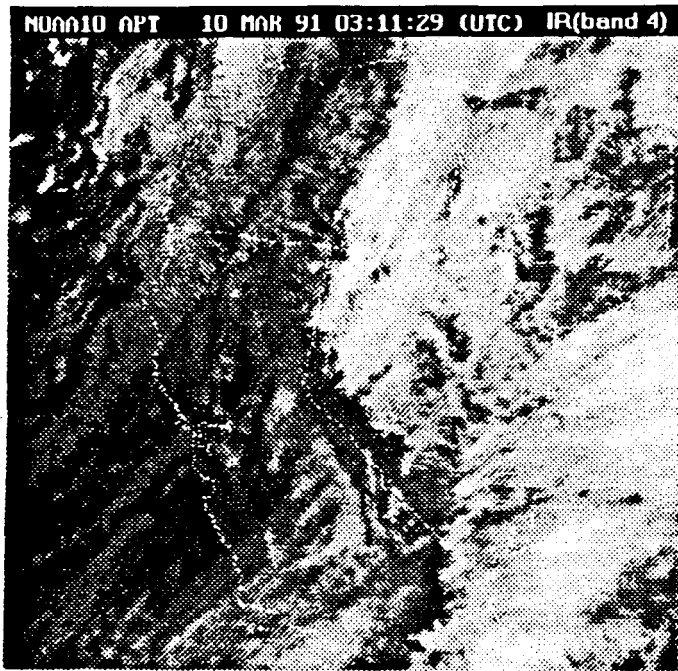


leeward side of the mountain it heats up at a rate of  $10^{\circ}\text{C}$  per kilometer to  $29^{\circ}\text{C}$  at the base. The air parcel is both warmer and drier on the leeward side of the mountain.

Cloud formation due to orographic lifting is readily apparent in both visible and infrared images. The effects of the Appalachian mountains on cloud formation is clearly depicted in this NOAA 11 APT satellite image captured on February 11th 1991. This is a relatively clear cold day.



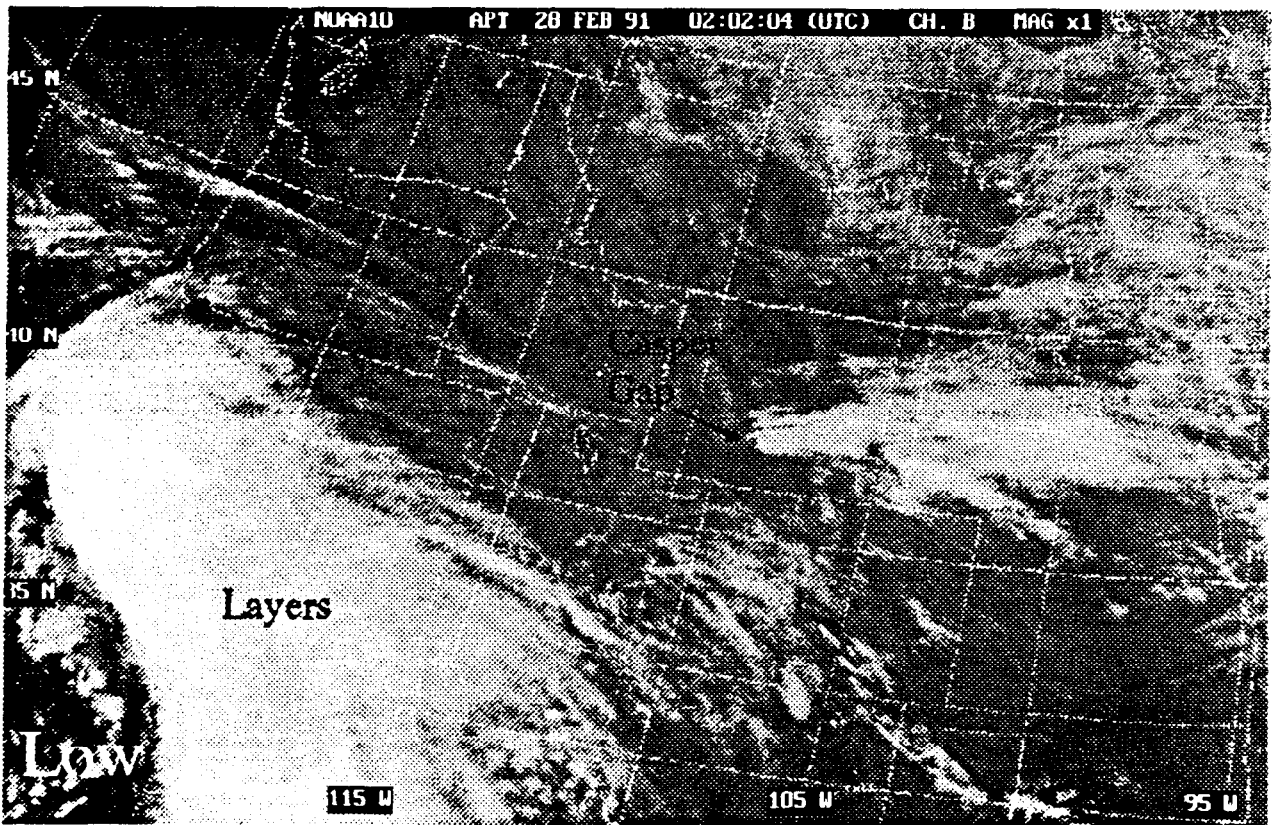
**Image 3.3 Clouds form due to orographic lifting over the Blue Ridge Mountains.**



**Image 3.4** Cloud dissipation on the leeward side of the Sierra Nevadas.

Image 3.4 of the western United States, was captured from a NOAA 10 pass on March 10, 1991. Moist air from the Pacific Ocean is lifted up the west side of the Sierra Nevadas in eastern California. As it lifts it cools below its dew point temperature and water vapor condenses forming clouds. The air mass dries out as it descends down the other side of the mountains into Nevada.

An unusual variation of orographic effects is shown in Image 3.5. Here, air is constrained by high mountain ranges to the north and south, forcing it to pass through the Casper Gap in central Wyoming. As moist air approaches the gap it converges and is forced to rise causing the cloud formation seen in this image.

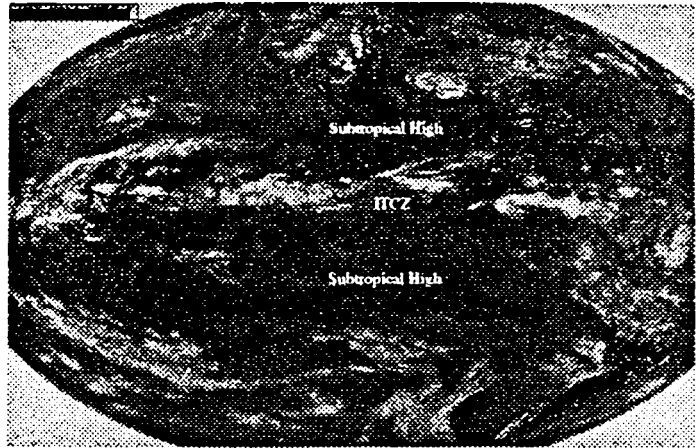


**Image 3.5** Lifting due to converging air as it passes through the Casper Gap,



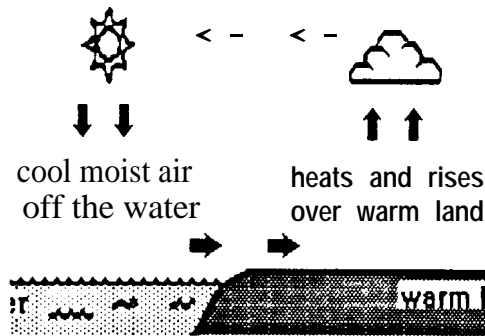
### Rise of thermals

As explained by the ideal gas law, air expands and rises as the sun heats it. Since the sun's heating effects are the greatest at the equator, air rises there. We might expect a semi-permanent cloud band to form along the ITCZ. This GOES image composite from May 9, 1991 shows the expected cloud band at the equator and clear areas at +30 degrees and -30 degrees latitude where sinking air results in subtropical high pressure areas.



**Image 3.6 GOES infrared image showing the ITCZ and subtropical high pressure belts.**

### Sea Breezes



### Lake and Sea Breezes

Whenever there is differential heating of an area, local circulation systems will develop. Differential heating is common along coastlines. During the day, the sun causes the land to heat up faster than the water. The cool moist air over water moves inland, heats up, and rises. If the moisture content of the air is high enough, clouds will form and precipitation may occur. Lake and sea breeze circulation will be stronger when prevailing large scale weather systems are weak. If the prevailing wind is blowing against the sea breeze, then the localized circulation may not develop.

An example of sea breezes along the coast of Lake Michigan is shown in the image to the left.

**Image 3.7 Sea breezes.**

Another example of differential heating resulting in cloud formation is when cold continental air flows offshore over the warmer ocean water. As the cold air reaches the warm water it rises resulting in stratus or strato-cumulus cloud streaks (see Unit 5 for more on cloud types). As shown in Image 3.8 from NOAA 10 captured on March 11th, 1991 the cloud edge off the east coast is often a good predictor of the location of the warm waters of Gulf Stream. Other feature of this image include some topographic cloud formation over the Great Smoky Mountains and a glimpse of the Shenandoah Valley. A light dusting of snow streaks the countryside from Michigan through West Virginia. The Great Lakes appear to be warmer than the surrounding land indicating not only that this is a cold day but the spring is on its way.

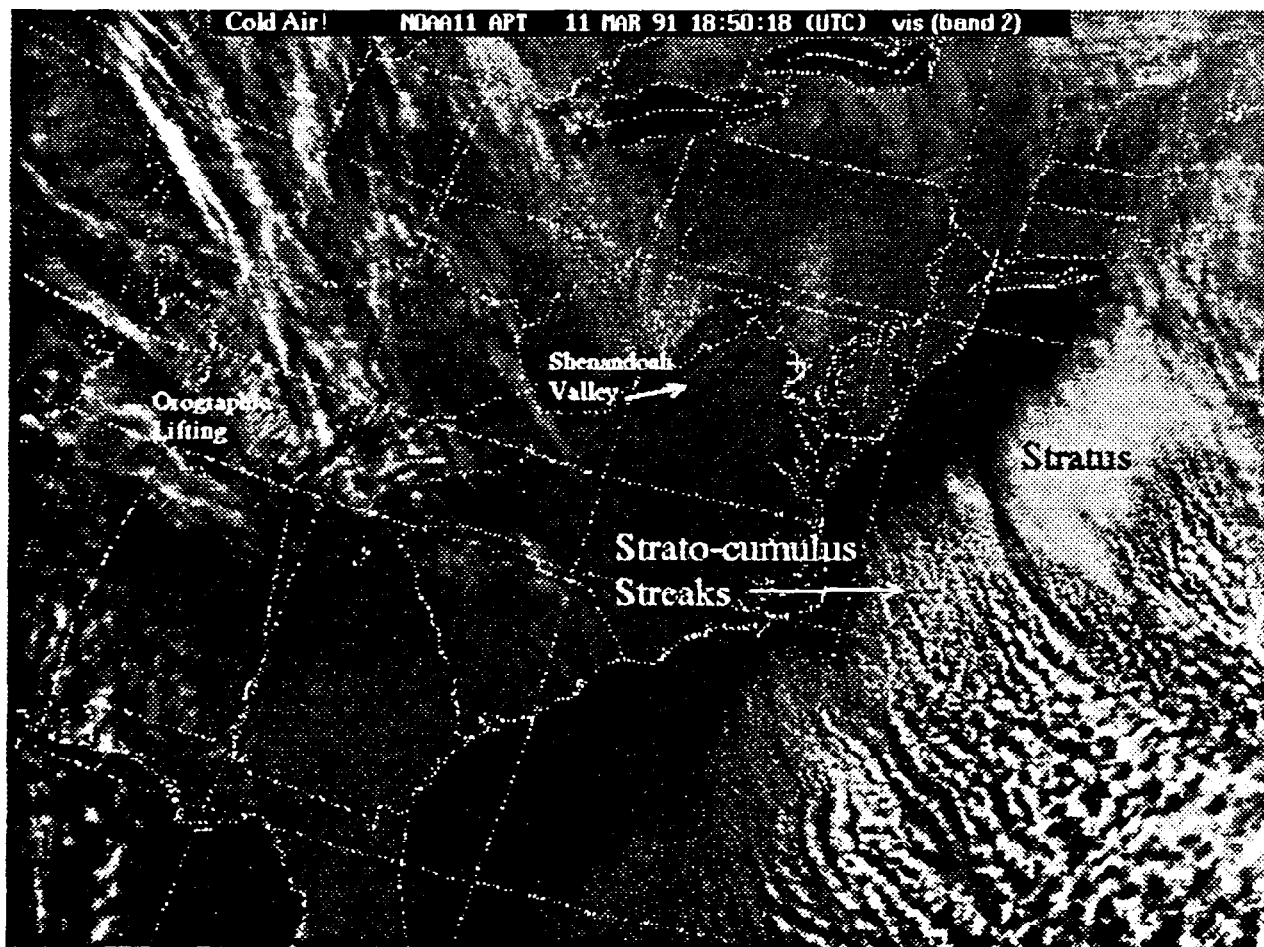
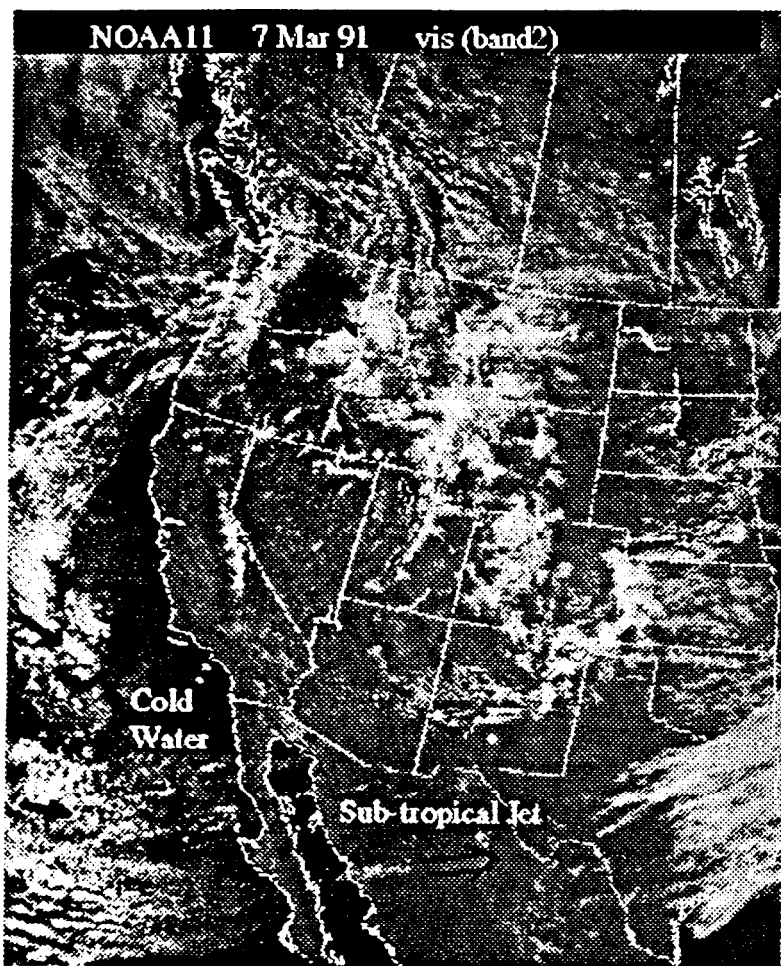


Image 3.8 Cold continental air rising over warm Gulf Stream water.



The opposite effect is shown in this NOAA 11 image captured on the afternoon of March 7, 1991. Here we have hot dry air moving from land out over the Pacific Ocean. Easterly winds at the ocean surface result in cold upwelling water off the coast of California.

This situation is likely to lead to nighttime advection of warm moist ocean air back to the east over the colder coastal water. As the air approaches the California coast it will cool and condense into morning low level stratus clouds and fog, common to the area from late winter through early summer.

**Image 3.9 Santa Ana winds cause upwelling cold water off the coast. Air is sinking in the clear areas.**

### 3.6 Summary Discussion

The objective of this unit was to explain how the physical properties of the atmosphere result in cloud formation. First the physical properties were presented together with common units and measurement techniques. Then the laws pertaining to their relationship with each other were described in the context of cloud formation. Finally visual examples were provided from selected APT imagery.

At this point you know that there are two ways of cooling moist air to cause cloud formation; radiative cooling and adiabatic expansion. The first results in fog and dew near the ground. The second is the most important mechanism for cloud formation. You should be able to explain how unequal heating produces convective circulation and results in cloud formation. You should be able to identify regions of rising and sinking air on satellite imagery.

## Unit 4: Cloud Types - How Do We Recognize Them

The most common features seen on meteorological satellite images are clouds and cloud systems. In this Unit you will learn to recognize cloud types and determine their nature, extent, height and movements. You will be shown how separate out low, middle and high clouds, and to determine the height and intensity of weather phenomena by comparing visible and infrared imagery.

### 4.1 Classifying Clouds

Nine cloud types presented in this unit are listed in the table below. The abbreviated symbols in the table are used to denote cloud types and mark them on satellite images. Clouds are generally classified by

- shape,
- content, and
- height above the ground.

#### Cloud Shapes:

There are two main categories of cloud shape; cumuliform and stratiform.

Cumuliform, or heap, clouds look like fat puffy cotton balls. They can be fair weather indicators. They are likely to have strong vertical motions within them and they can have considerable vertical depth. Cumuliform clouds develop in an *unstable* atmosphere. Their appearance on satellite images is visual evidence of convection in the atmosphere.

<u>Type</u>	<u>Content</u>	<u>Base Height</u>
<b>Cirrus(Ci)</b>		
<b>Cirrocumulus(Cc)</b>	Ice	6 to 18 kilometers
<b>Cirrostratus(Cs)</b>		(20,000 to 60,000 feet)
<hr/>		
<b>Altostratus(As)</b>		
<b>Altostratus(As)</b>	Mixed Water and Ice	2 to 6 kilometers
<b>Cumulonimbus(Cb)</b>		(6,500 to 20,000 feet)
<hr/>		
<b>Cumulus(Cu)</b>		
<b>Stratocumulus(Sc)</b>	Water	less than 2 km
<b>Stratus(S)</b>		(less than 6,500 feet)

Stratiform clouds are layered and spread like sheets across the sky. They develop in a *stable* atmosphere and generally have less vertical motion and less turbulence associated with them. When they appear in satellite images they give evidence of widespread cooling, usually as a result of advection of moist air over a cooler air mass or land surface beneath.

#### Cloud content:

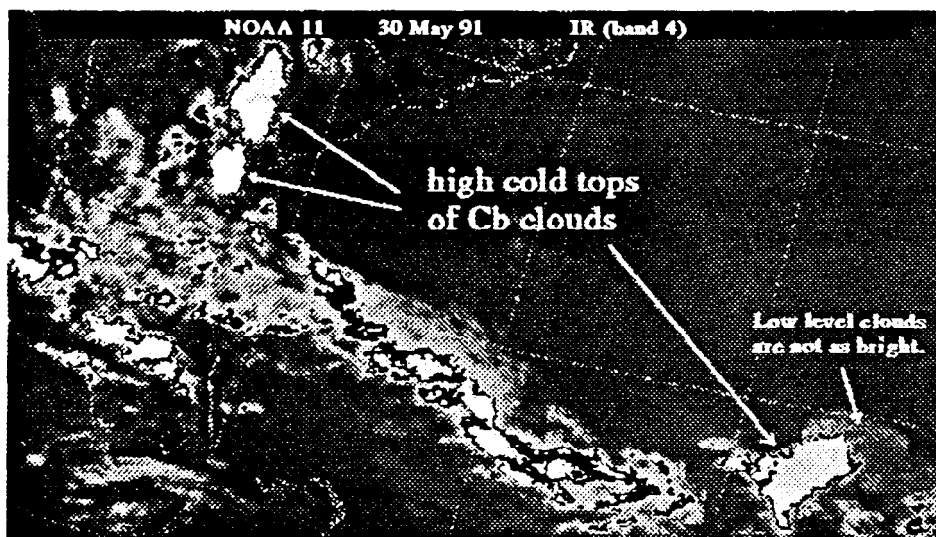
Clouds contain water, ice, or a mixture of both. Cumulus (Cu) and stratus (S) clouds are fairly warm, usually above 0° C, and comprised of water. Water clouds can be distinguished in satellite images by their sharp boundaries. Clouds composed of a mixture water droplets

and ice crystals are known as mixed clouds. Mixed clouds are usually undergoing strong vertical development, such as that which occurs in thunderstorm clouds called cumulonimbus (Cb) clouds. Below  $-38^{\circ}\text{C}$  only ice crystals form by condensation. Ice crystal clouds, which have fibrous structure, are easily identified in satellite images. They look like they have been painted on with a dry brush. Cirrus clouds are made of ice crystals.

### Cloud Height:

The third way of classifying clouds is by their average base height above the ground. Meteorologists speak of three main height categories; low clouds, middle clouds and high clouds. Low clouds are those that have base heights from the earth's surface up to about 2,000 meters (about 6,500 feet). Middle clouds are found between about 2,000 and 6,000 meters (6,500 to 20,000 feet), and high clouds are higher than about 6,000 meters (20,000 feet) above the ground. The cloud layer of the atmosphere stops at about 15 to 18 kilometers (10 miles or 60,000 feet). This layer of the atmosphere is known as the **troposphere**. Base heights described here are representative of mid-latitudes. In the tropics, base heights are a bit higher and they are lower near the poles.

Because the atmosphere cools with height, cloud temperatures also decrease with height. Meteorologists have found that the temperature at the base of low clouds is usually in the range between  $0^{\circ}$  and  $25^{\circ}\text{C}$ . The base temperature of middle clouds ranges from  $0^{\circ}\text{C}$  to  $-25^{\circ}\text{C}$  and high cirrus clouds are almost always colder than  $-25^{\circ}\text{C}$ . Of course satellites measure temperature at the top of a cloud, not its base. Nevertheless, cloud top temperatures can be used to help identify cloud types. Because stratiform clouds do not develop vertically, their tops are likely to be lower and warmer than cumuliform clouds. Cumuliform clouds are accompanied by strong vertical development. Depending on the strength of convective activity, the tops of cumuliform clouds can extend through the entire troposphere. The tops of Cumulonimbus (Cb) thunderclouds are often colder than  $-50^{\circ}\text{C}$ . In Image 4.1 pixels in the temperature range from  $-50^{\circ}\text{C}$  to  $-55^{\circ}\text{C}$  are blackened.



**Image 4.1 Cloud height relates to temperature on infrared images.**

**Appearance on satellite images:**

In visible satellite images the brightness of clouds depends on cloud thickness and the sun's angle of reflection off the cloud tops. Thick clouds have roughly equal brightness in visible imagery regardless of their height or content. Very thin clouds can appear grey because they are partially transparent. Not all of the sunlight is reflected back toward the satellite sensor. Sunlight is readily transmitted through thin cloud layers. (Refer to Unit 2, section 9 for a more detailed discussion of cloud transmittance.) High icy clouds are most likely to be thin and appear grey in visible satellite imagery.

In thermal satellite images (AVHRR bands 3 or 4), the brightness of clouds depends on temperature. Ice clouds like cirrus (Ci) are cold and appear much brighter than clouds comprised of warmer water like fog and stratus (S). Because the atmosphere's temperature decreases with height, higher clouds are almost always colder than low level clouds. Therefore, the temperature of cloud tops as determined by the brightness of infrared imagery provides a qualitative measure of cloud height. When visual imagery is used together with thermal infrared imagery, cloud discrimination is most easily accomplished.

Date: <u>Nov 12</u>	Cloud Photo # <u>23</u>
Time: <u>9:30 am</u>	Camera Direction:
Location: <u>School</u>	N NE E <b>(SE)</b>
	s SW w NW
Stratiform <u>✓</u>	Wind Speed: <u>4 mph</u>
Cumuliform <u>   </u>	Wind Direction: <u>SE</u>
S <b>(Sc)</b> Cu Cb As	Temp: <u>49°F</u> Precip: <u>—</u>
Ac Cs Cc Ci	Pressure: <u>29.8"</u>
	RH: <u>83% / 0</u>

**Activity: Cloud Atlas** The best way to become familiar with cloud types and to relate them to weather is to create your own cloud atlas. The materials needed include a camera, 3 x 5 cards, photo-album, compass, and a cloud chart available from the National Weather Service. Photograph clouds and collect data on 3 x 5 cards in a format similar to the one shown here. Initially, it will seem like there are an endless variety of cloud types. However, before long patterns will become apparent and you will be able to identify and classify clouds quickly. By including surface weather conditions in your log, you will learn to relate each cloud type to impending weather. The data cards should be mounted in the album on the same page as the photo.

## 4.2 Low Clouds

Low clouds occur in the lowest level of the atmosphere. Their heights do not generally reach above 2,000 meters (6,500 feet). These clouds include fog, stratus (S), cumulus (Cu), and stratocumulus (Sc) types.

Stratus (S) and fog are the lowest cloud types. The only difference between the two is that fog touches the ground. Both are caused when air near the ground cools after sunset or when warm air is **advected** over cooler land, water or air near the ground. **Advection** is the process of heating or cooling an air mass by transporting it horizontally over an area of different temperature. From a satellite's vantage point, fog and stratus clouds look the same. They both look uniform in shade and they have very little texture although their edges are sharply defined. In visible images, brightness depends on cloud thickness and sun angle. A thick stratus layer will appear very bright.

In infrared images, stratus and fog appear grey. They can be hard to distinguish from background because their temperature is not much different than their surroundings. In fact, the air on the top of stratus and fog layers is often warmer than the cloud layer itself. This is caused when upper level air sinks down on top of the fog layer and is called a subsidence inversion or temperature inversion. Infrared Image 4.2 shows stratus clouds blanketing most of northern and central Florida. Other low level clouds; stratocumulus streaks and open cell cumulus clouds are also visible.

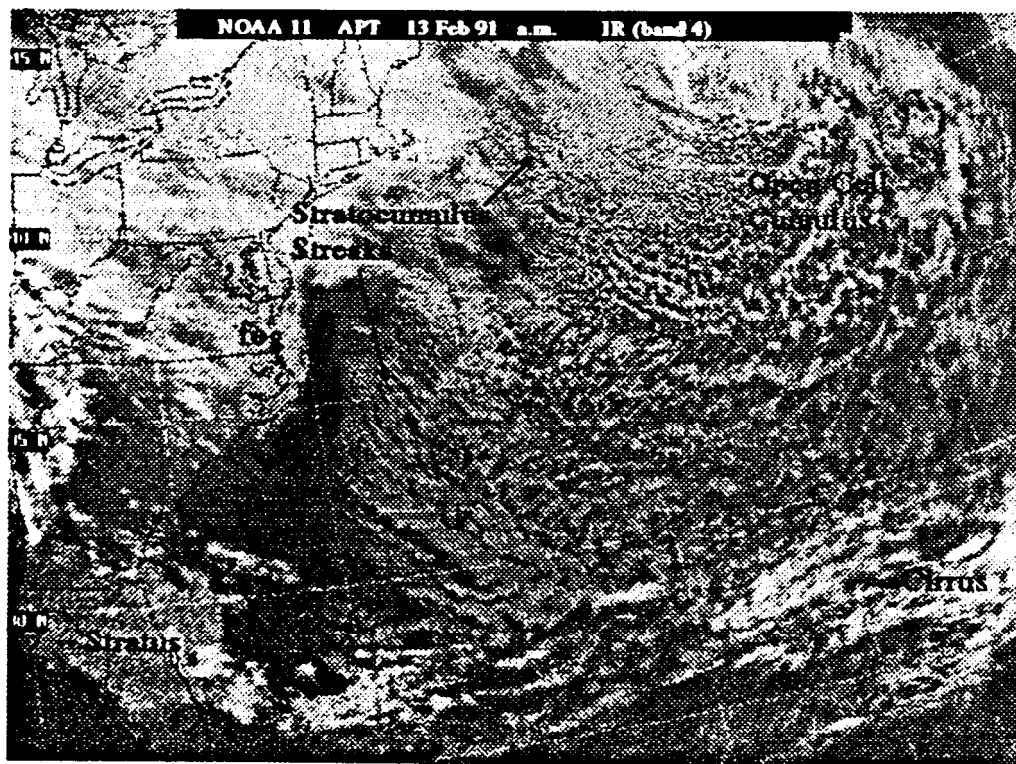
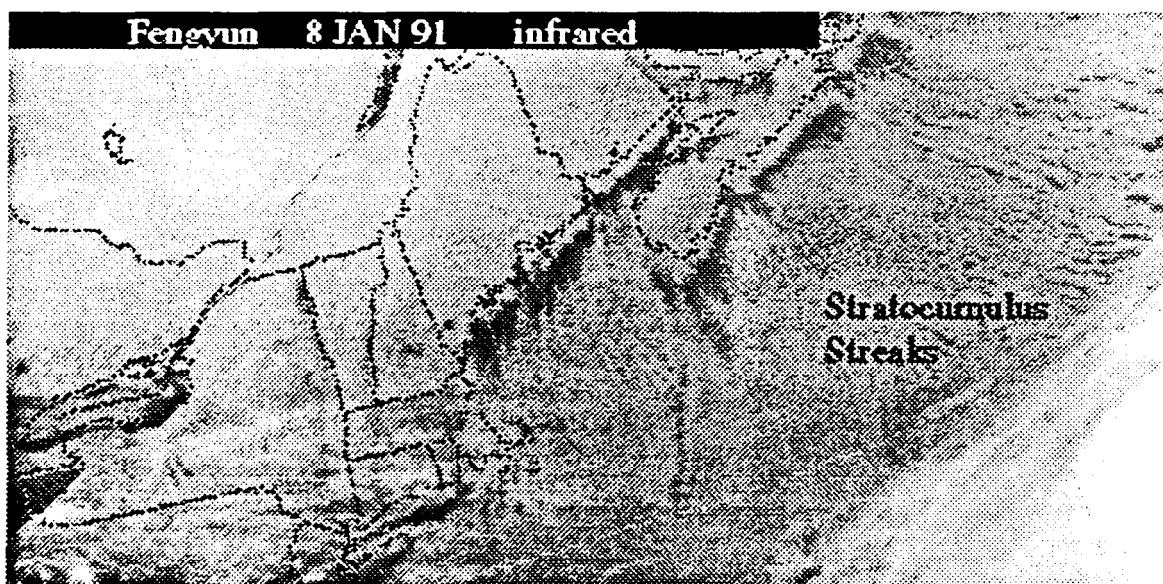


Image 4.2 Infrared view of low level cumuliform and stratiform clouds.

Stratocumulus (Sc) cloud patterns are easily recognized on weather satellite imagery by their characteristic lumpy pattern. Cloud bases for stratocumulus(Sc) clouds are from 500 to 800 meters. The smallest stratocumulus elements are 2 to 4 kilometers in diameter while the largest are 15 to 40 kilometers in diameter. Often, Stratocumulus (Sc) clouds are limited from growing vertically by the presence of warm air aloft. Because the temperature inversion blocks vertical development, the clouds will spread laterally forming rows aligned with the wind. This formation can be observed as cold air moves off the continents and flows over warmer water. Then streaks of stratocumulus clouds form over the warm water, aligned with the low level wind flow.

An example of stratocumulus streaks is shown in this infrared AFT image from the Chinese FengYun Satellite. Cold continental air is flowing southeast from the snow-covered lands of New England and eastern Canada toward the warmer waters of the northern Atlantic Ocean. Over warm water condensation takes place and clouds form. However, three dimensional vertical development of the clouds is constrained by warm air aloft. This results in streaks of stratocumulus clouds which are aligned with the wind.



**Image 4.3 FengYun infrared view of stratocumulus cloud streaks.**

Cumulus(Cu) clouds are very common small puffy fair weather clouds. Most individual fair weather cumulus clouds are too small to be seen in AFT images. Cumulus clouds usually have bases of 600 to 900 meters (2,000 to 3,000 feet) with cloud tops anywhere from 1.5 to 3 km (5,000 to 10,000 feet). Those with tops above 3 km (10,000 ft) are called towering cumulus and are large enough to be identified in visible images. Once they reach this height they can also be identified in thermal imagery. Examples of cumulus clouds in visible and infrared imagery are shown in Images 4.4 and 4.5 captured from an afternoon NOAA 11 pass on May 2, 1991.



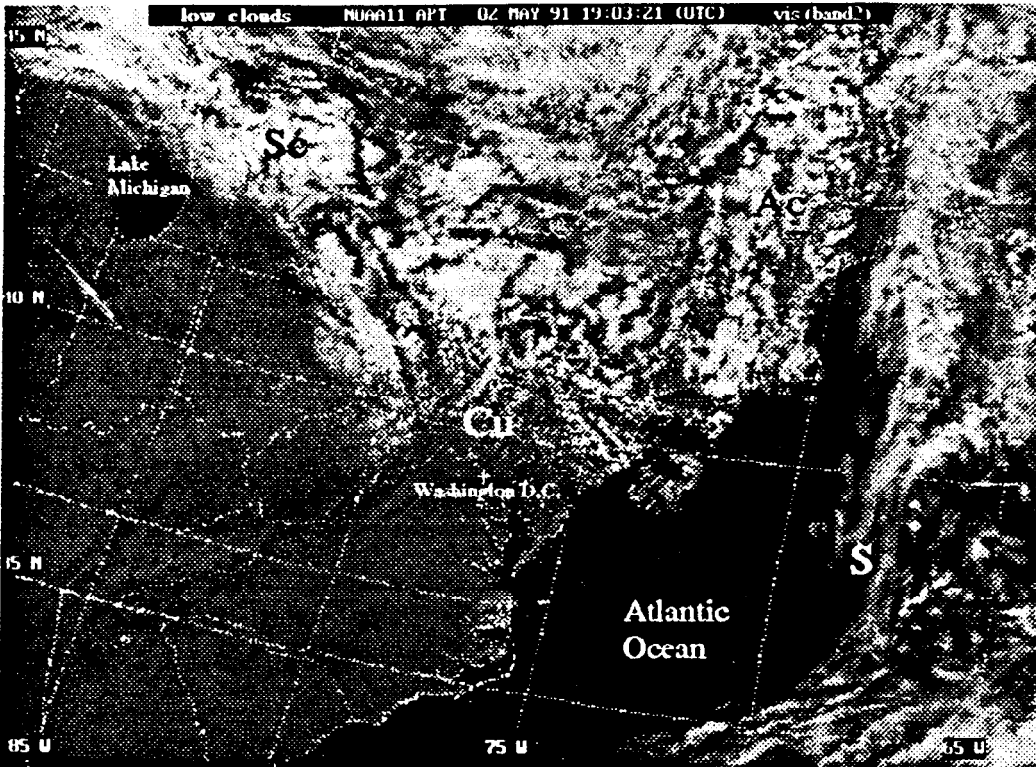


Image 4.4 Visible image of various cumulus and stratus clouds over the Northeast.

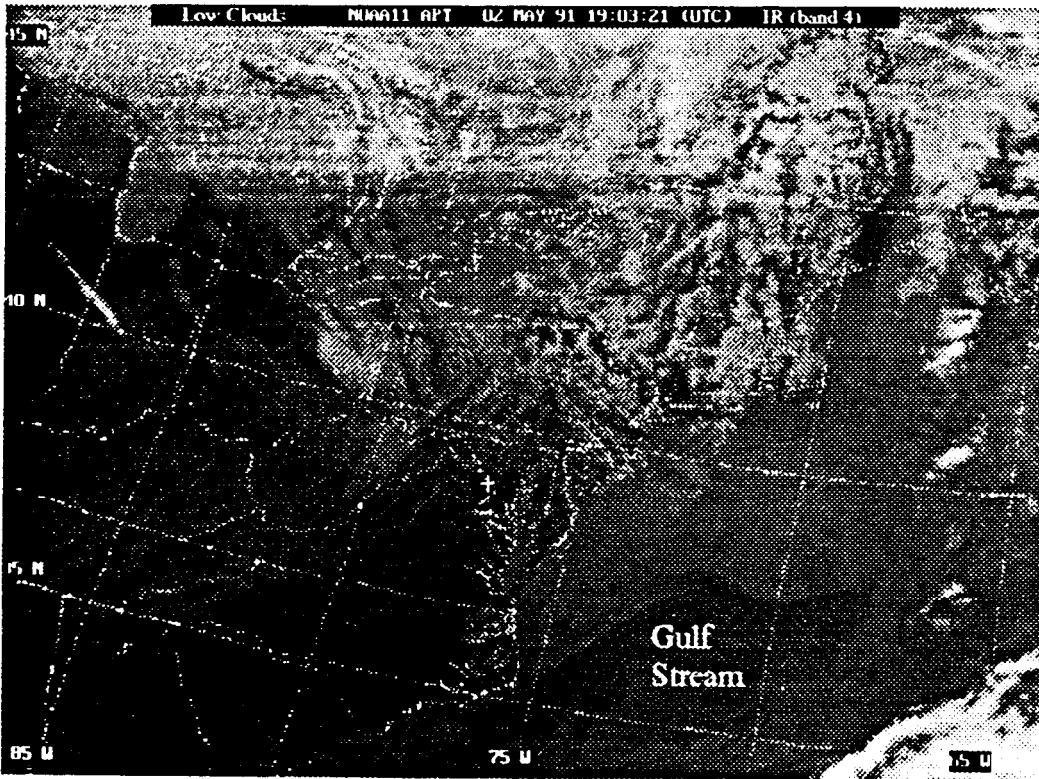


Image 4.5 Infrared image of cumulus and stratus cloud forms.

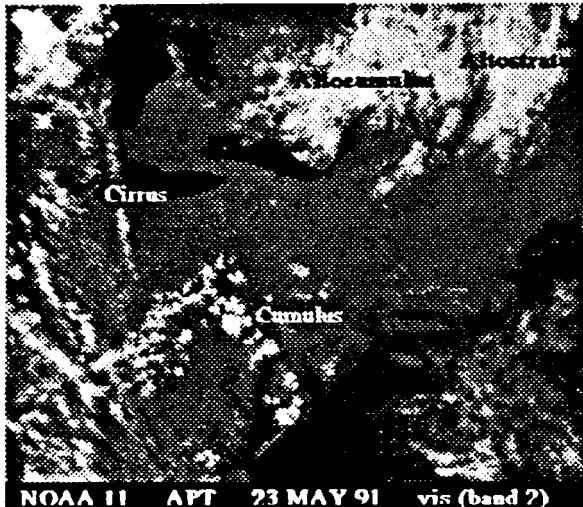
Cumulus clouds can form in “open cell” patterns that resemble geometric shapes such as polygons or ellipses. Upward vertical motion occurs where clouds are present and downward sinking motion occurs in the clear cells. Typically, open cell cumulus patterns are found behind fast moving cold fronts and often suggest low level turbulence. Open cell cumulus patterns are prevalent in Image 4.6 of the West Coast captured on March 14th, 1991.



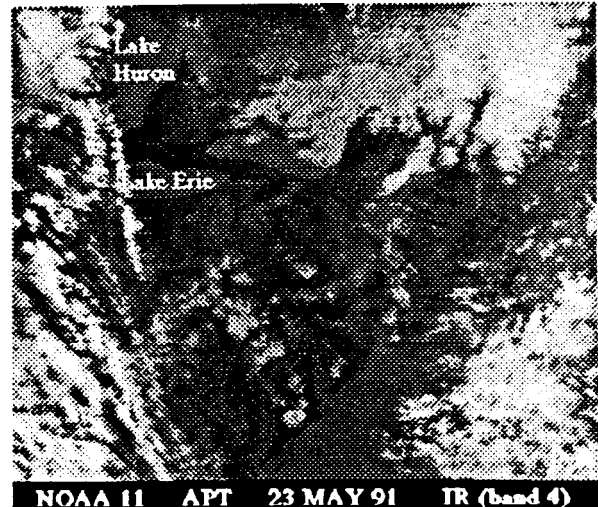
**Image 4.6 Open cell cumulus over the Pacific Ocean from NOAA 11.**

### 4.3 Middle Clouds

Middle level clouds are infrequently seen in satellite images because they usually occur in layers in frontal systems, hurricanes, typhoons, and other weather systems where higher level cirrus clouds obscure them from view. Mid level clouds include altocumulus (AC) and altostratus (As). Altocumulus (AC) clouds are stratocumulus clouds that are higher up. The transition from one form to the other is very fluid. Similarly, altostratus(As) clouds are cirrostratus(Cs) clouds that are a little lower and more dense.



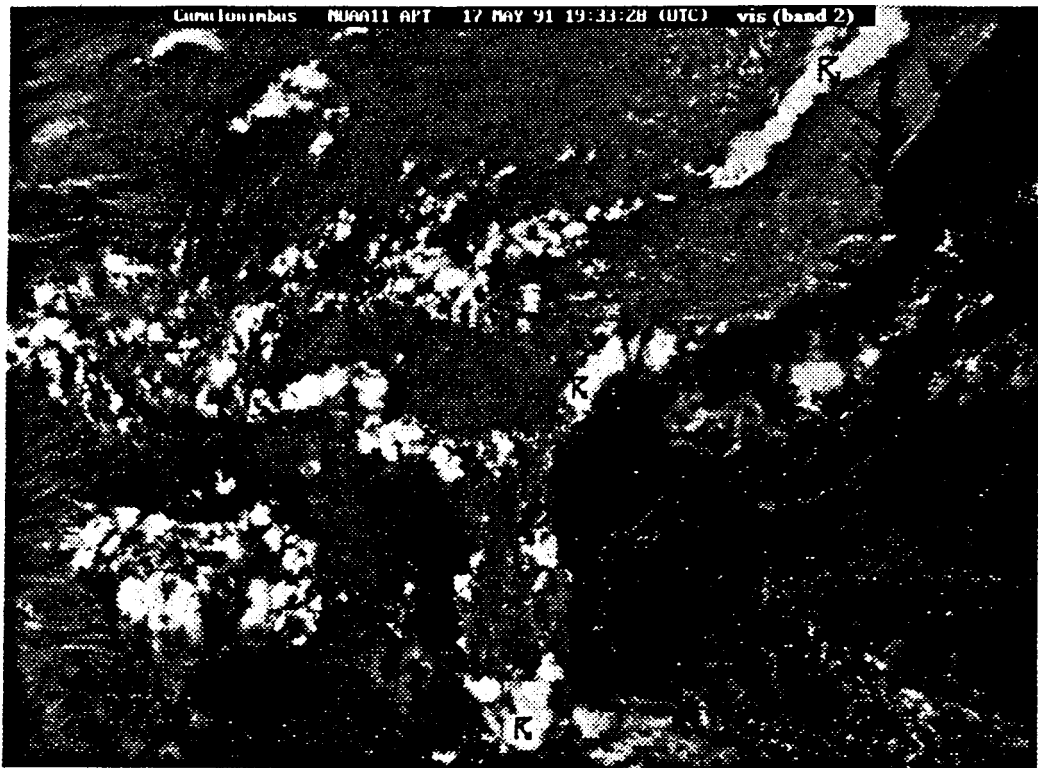
**Image 4.7 Band 2 view of mid level clouds.**



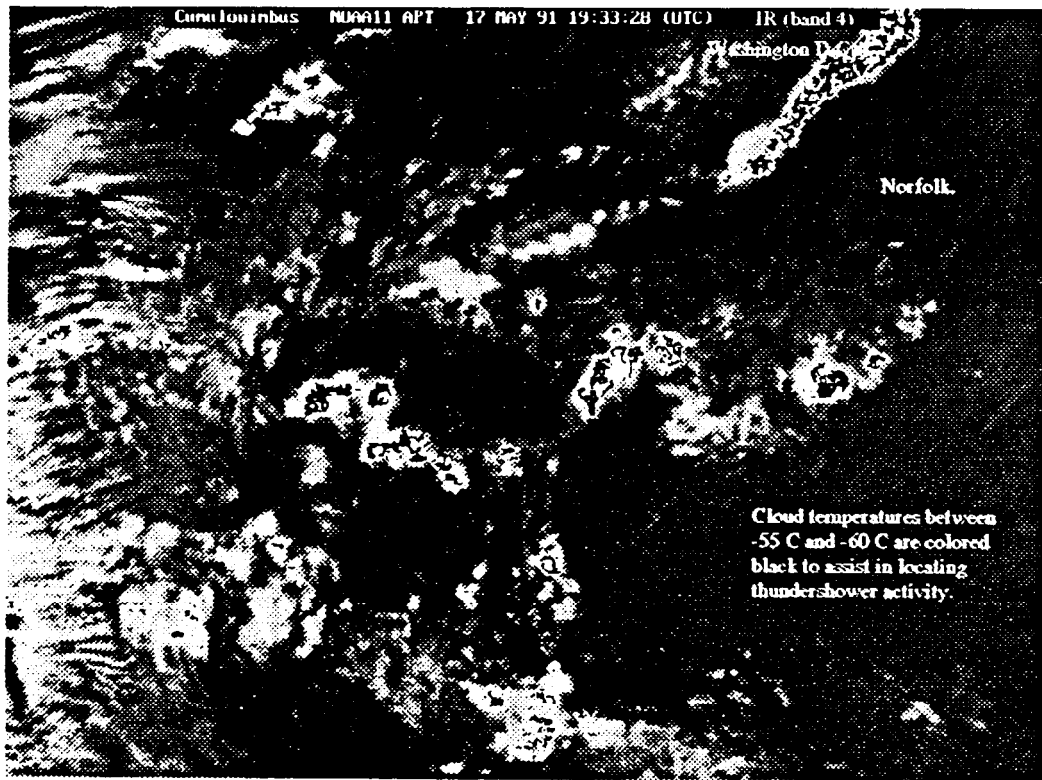
**Image 4.8 Infrared view of mid-level clouds.**

On hot days the temperature of water is colder than land. As the sun heats the land, the overlying air becomes warm and light. It rises and cooler air off the nearby water moves inland producing a sea breeze front. If there is enough moisture in the warm rising air, water vapor will condense producing clouds and possibly thunderstorms inland from the shore. This was the situation on May 17, 1991.

A pair of band 2 and band 4 images from the afternoon pass of NOAA 11 on May 17, 1991 are shown on the next page (Images 4.9 and 4.10). Numerous puffy white cumulus clouds have developed across the Southeast. The largest white billows are cumulonimbus(Cb) clouds. Cumulonimbus clouds are very unstable with strong updrafts and downdrafts resulting in thundershowers. When the tops of these clouds turn to ice, thundershowers begin. Infrared Image 4.10 has been processed to display temperatures between -55°C to -60°C in black. About 90 minutes after these images were captured, lightning struck a Lacrosse field in downtown Washington D.C. killing one spectator and hospitalizing 9 players.



**Image 4.9 Visible image of cumulonimbus storm clouds.**



**Image 4.10 Infrared image of cumulonimbus clouds with coldest cloud tops blackened.**

## 4.4 High Clouds

High clouds are those with bases above 6 kilometers and extending to the top of the troposphere. Clouds at these heights are comprised primarily of ice. They include cirrus (Ci), cirrocumulus (Cc), cirrostratus (Cs), and the tops of cumulonimbus (Cb) cloud formations.

Cirrus and cirrostratus clouds are thin, fibrous or veil-like layers of ice which are nearly transparent in the visible spectrum. Because cirrus clouds are found in very thin layers, they do not appear bright white but are more likely to be grey when viewed in visual imagery. However, since cirrus clouds are comprised of very cold ice crystals, they will always appear as bright white clouds on thermal imagery.

Images 4.11 and 4.12 are visible and infrared images from the afternoon pass of NOAA 11 on March 13, 1991. They illustrate the advantage of having both spectral bands when identifying cirrus clouds. These images of the west coast of the United States show a subtropical jet marked by cirrus and cirrostratus clouds along the bottom of the images. Also, a cold front off the coast of Washington is marked by cirrus clouds in advance of the low lying stratocumulus frontal system. Open cell cumulus clouds cover a large portion of the eastern Pacific Ocean.

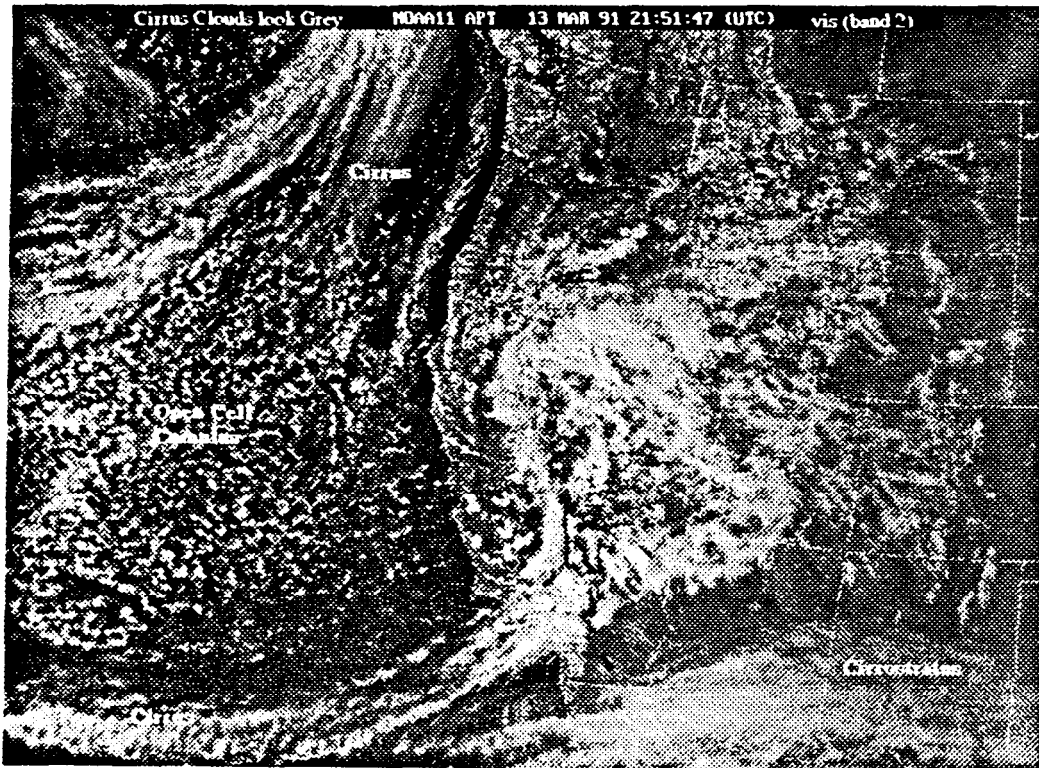


Image 4.11 Band 2 image of cirrus and cirrostratus clouds.

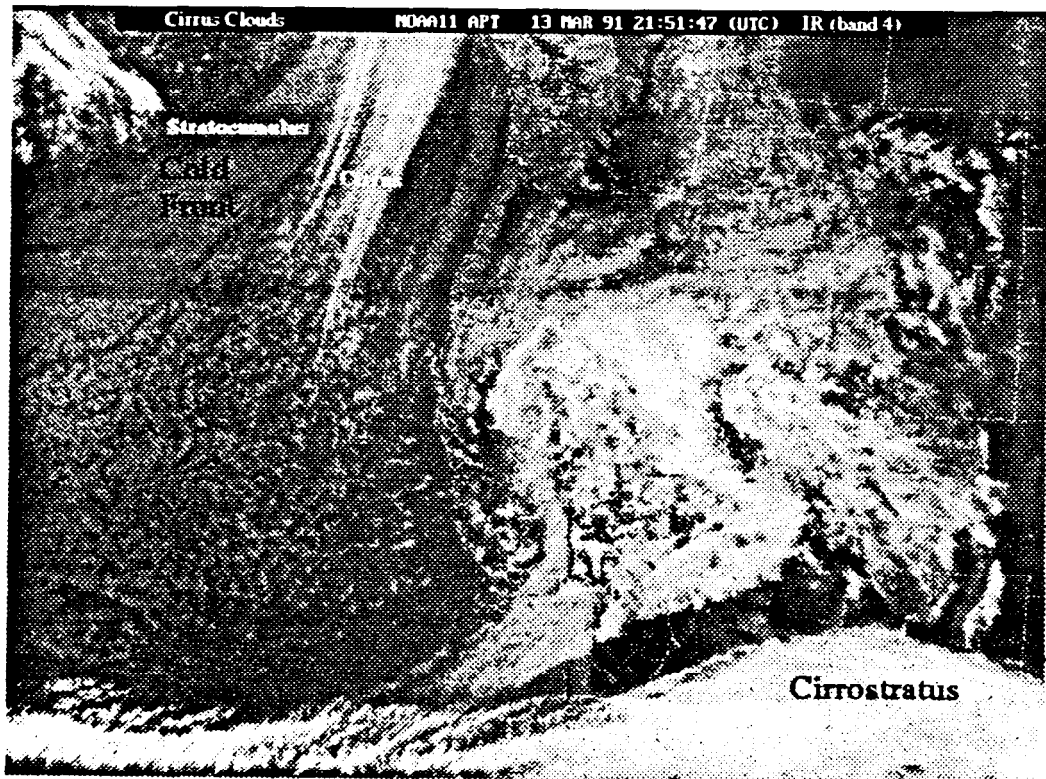


Image 4.12 Infrared image of cirrus and cirrostratus clouds.

When thunderstorms reach their fully developed stage, cirrus clouds will have developed at the top. When strong winds are also present, they will blow the cirrus off the top of the thunderstorms. New cirrus will continue to develop at the top of the thunderstorm and the constant outflow of cirrus will form a characteristic cirrus plume that is oriented with the high level wind flow. Hurricane Bertha, shown in the tropical storm section of this unit shows cirrus blow-off.

High level cirrus clouds are found alone or in conjunction with numerous weather situations. The approach of a storm is usually indicated by the appearance of high cirrus clouds, followed successively by cirrostratus, altostratus, nimbostratus, and stratus clouds. In this Guide we refer to this cloud formation as “layers” and use the word “layers” to mark on satellite images. After the layers pass, the cumulonimbus clouds move in resulting in thunderstorms. (note: The presence of high cirrus does not necessarily lead to storms. They must be accompanied by weak zonal flow. See Unit 5)

#### **4.6 Summary Discussion,**

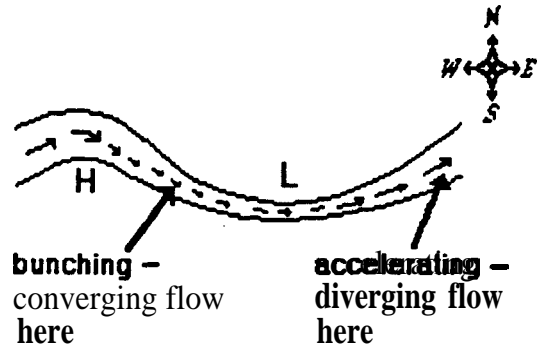
In this unit you have learned to identify cloud types on visible and infrared images. Cumuliform clouds are recognized by a heaped appearance and clear-cut outlines. Their presence is an indication of vigorous convection and vertical development. Stratiform clouds are generally spread widely over a region and often have diffuse boundaries. Their presence indicates weak vertical motion. They are often caused by warm air advection over colder land, ocean, or air masses. Cirrus type clouds are precipitating ice crystals and they appear fibrous or though they were painted with a dry brush.

You should be able to explain the visual appearance of any cloud in an image based on its physical characteristics: shape, content, temperature, thickness and height above the ground. On visible images the brightest clouds are the thickest. On infrared images, the brightest clouds are the coldest and probably the highest off the earth’s surface.

## Unit 5: Upper Level Air Flow

### 5.1 Ridges and Troughs

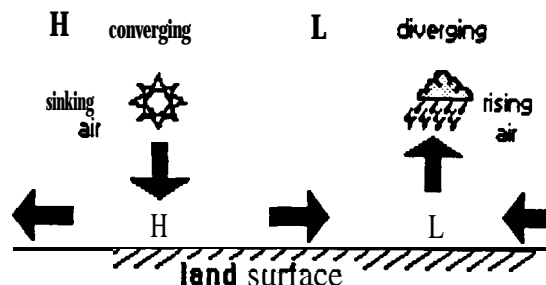
Imagine a super highway in the sky like the one in the figure at the right. Imagine that traffic always flows from west to east, clockwise around **High** and counter clockwise around **Low**. Suppose that there are six lanes of traffic around **High** which converge to three lanes at **Low**. The smooth flowing traffic around **High** will begin to back up as it approaches **Low**. After passing **Low**, the traffic stretches out again, or diverges, as the highway widens.



In the mid latitudes, upper level air flow is like this imaginary highway. Air flow is from west to east, and is referred to as “westerly flow” or “the westerlies.” The location where upper level air flow changes direction from northwesterly to southwesterly around a low pressure zone, is called a **trough**. (In the Southern Hemisphere, the wind shifts from southwesterly behind the troughline to northwesterly ahead of it.) The line where the wind shift takes place is the **troughline**. Trough lines are marked on an image with a dashed line (· \_ \_ ·). The location where the curvature of air flow around a high pressure zone is greatest is called a **ridge**. The marking for a ridge line is a saw-tooth line (^ ^ ^ ^ ^ ^ ^ ^).

The major difference between the ‘highway in the sky’ and upper level air flow is that traffic can only move horizontally from west to east, never vertically. But air can move up and down in the vertical direction as well. As air moves away from the high pressure ridge towards the trough, it can move down a level to avoid bunching up. Like the highway traffic example, when air leaves the low pressure area it will stretch out again. To the right of the troughline, air will rise up from below to fill in the spaces.

Vertical air flow beneath the “highway in the sky” is depicted here. Sinking air results in high pressure at the surface and rising air results in a surface low pressure area. Surface pressure patterns are shifted to the east of the upper level pressure zones. Troughs and ridges shift at each level so that the troughline itself may be sloped or tilted, usually to the west. To see this effect, connect the L’s on the picture to the right with a dashed line and the H’s with a saw-tooth line. Because of vertical air flow patterns, both troughs and ridges can be identified in satellite images.





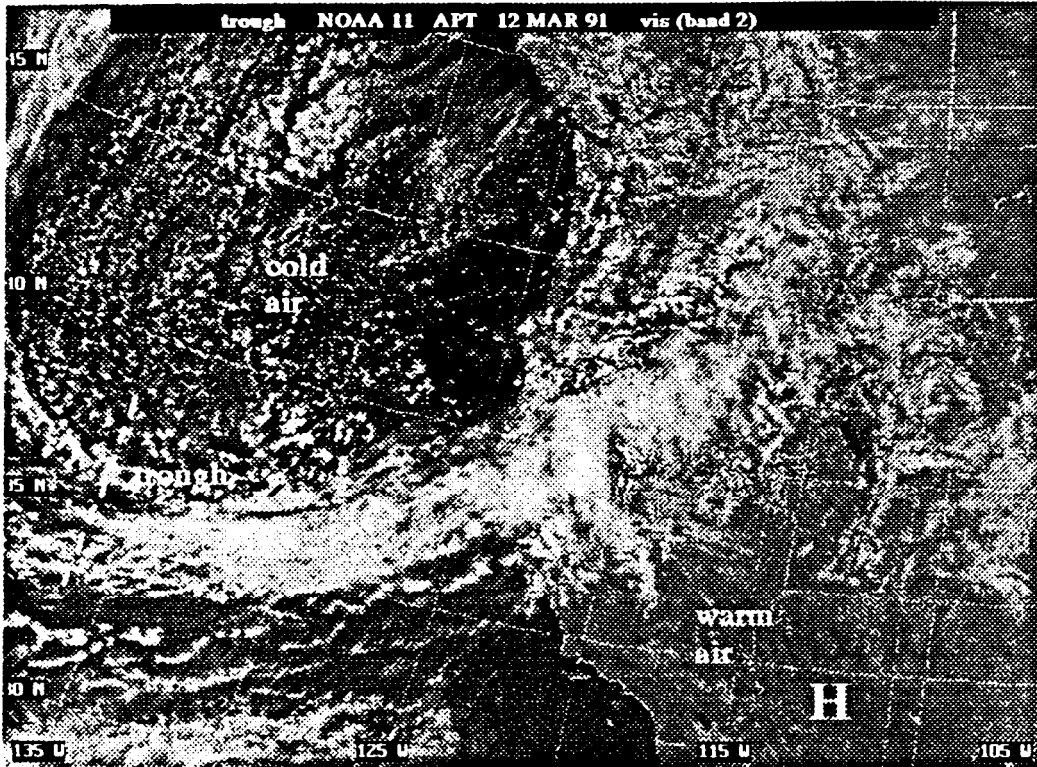


Image 5.1 Troughline over the Pacific Ocean seen in a band 2 image.

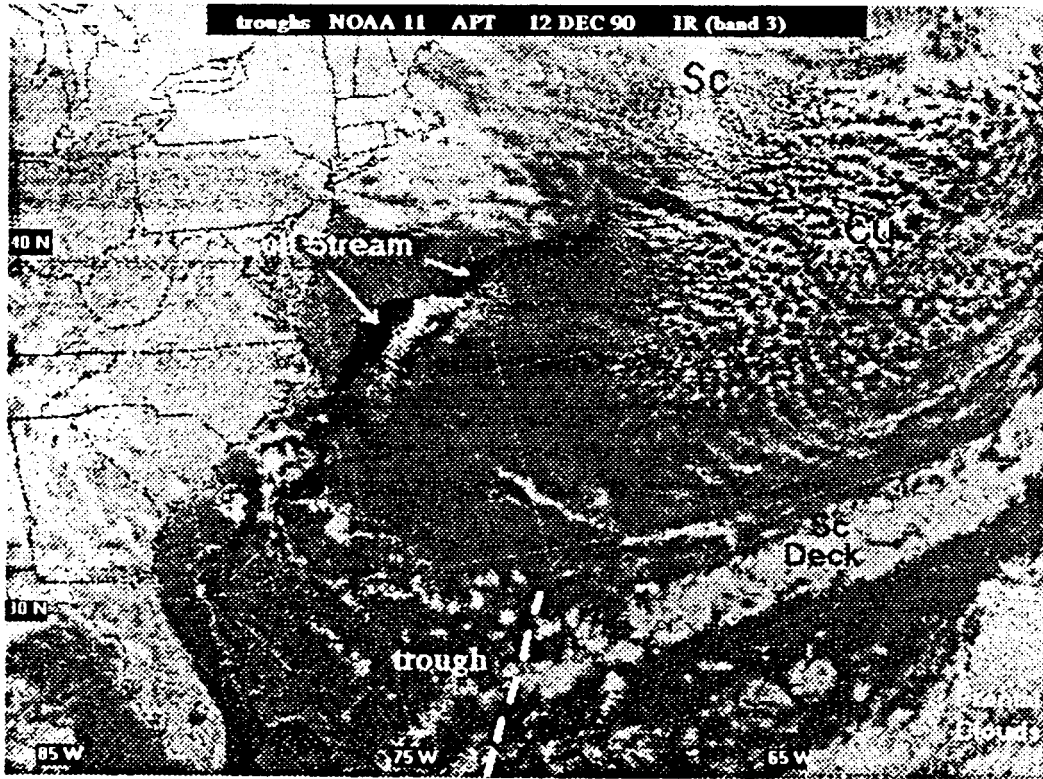


Image 5.2 Troughline over the Atlantic Ocean seen in an infrared image.

### **Troughs:**

Strong vertical motions associated with troughs result in distinct cloud patterns. Air sinks to the west of a trough and, in accordance with the ideal gas law, compresses and warms. If this sinking air is not saturated, or if it warms above its dew point temperature, the air will be clear. To the east of the troughline air rises from below and often cools below its dew point temperature resulting in cloud formation. Based on these vertical motions, troughlines can be located by finding;

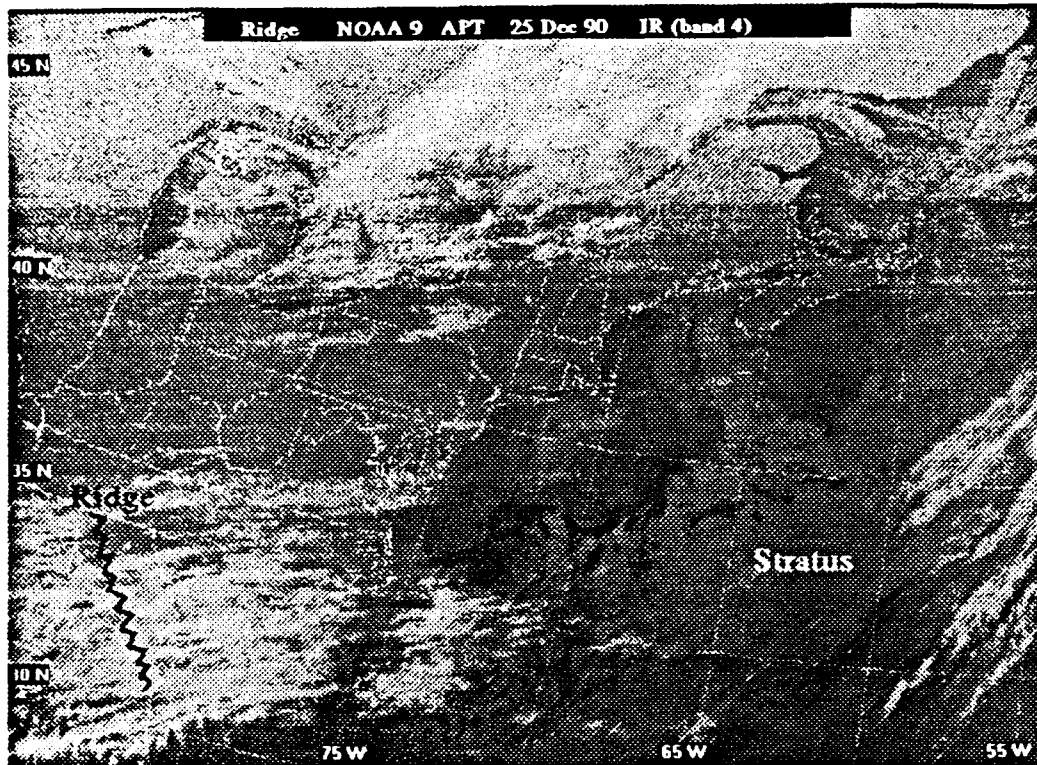
- the place on the upper level wave pattern where air flow appears to shift from the northwest to the southwest direction,
- clear areas to the left or west, and  
cloudy areas to the right or east.

Upward vertical motion to the east of the troughline marks the location of the surface low pressure system which often triggers the development of storm systems.

Both satellite images used as examples for locating troughs are over oceans. Oceans present a flat surface to the air masses flowing over them. There are few distortions due to terrain, differential heating, and other perturbations caused when air flows over land areas. Once you are comfortable locating troughs over oceans, it will be easy to adapt your skill to weather conditions influenced by land areas.

Image 5.1 is a visible band image of the West Coast of the United States and the eastern Pacific Ocean from a NOAA 11 pass on March 12, 1991. You can almost feel the cold air mass out over the ocean where open cell cumulus clouds are abundant. On this day the maximum temperature in Los Angeles was 71° F compared to 57° F in San Francisco and 46° F in Seattle. The location where warmer air over the southwestern United States meets colder air is called a **cold front**. Regions north of San Francisco experienced mixed rain and snow. The troughline is located where the wind shifts from a northwesterly direction to a southwesterly direction. Can you guess whether showers were forecast for Los Angeles on March 13th? The answer is yes, as the cold front passed through the area.

Image 5.2 is an infrared image of the East Coast of the United States and the western Atlantic Ocean from a NOAA 11 pass on December 12, 1990. The troughline where the wind shifts from the northwest to the southwest is marked by clear air to the west and a cloudy frontal region to the east.



**Image 5.3** Ridgelines are marked by upper level cirrus clouds.

### Ridges:

Ridgelines can be a little more difficult to locate on satellite images because vertical motions are generally weaker around high pressure systems and the air tends to be drier and therefore less cloudy. Various clues for identifying clockwise the direction of air flow (in the Northern Hemisphere) on satellite imagery can be used to position ridgelines.

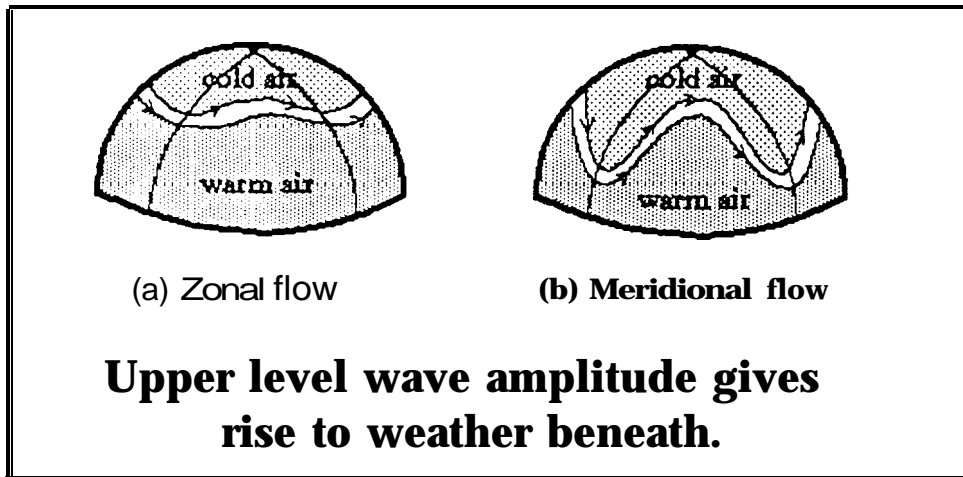
Most are oriented in a north-south direction. Upper level ridgelines can be located from cirrus cloud patterns or plume blowoff from cloud formations which indicate a clockwise flow. Because cirrus clouds are easier to see on infrared images, ridgelines are easier to see.

The ridgeline in Image 5.3 captured on the December 25th has a north-south orientation across the State of Georgia. This ridge is visible because of the cirrostratus cloud pattern which marks the clockwise flow. The ridgeline occurs where the change in curvature of the flow is a maximum. In this image we also observe the gulf stream edge and low lying stratus clouds which have formed over the warmer waters to the east.

### **5.2 Waves**

In Unit 2 we described wave motion in the atmosphere and we estimated the wavelength and the amplitude of an upper air wave pattern. The wavelength of most mid-latitude weather wave patterns ranges from about 50 degrees to 75 degrees of longitude (about 5,000

kilometers or 3,000 miles). Wave amplitudes typically vary from 5 degrees to 25 degrees latitude. The amplitude of upper air wave patterns has a direct bearing on weather conditions below.



When the amplitude of an upper level wave is low, air masses tend to move in an east-west direction. This is called **zonal flow** referring to air flow from time zone to time zone. As illustrated in the figure above, low amplitude waves aloft do not result in much mixing of colder northern air with warmer air to the south. Low amplitude waves are generally associated with strong westerly winds aloft called a jet stream. Usually when there is a low amplitude wave aloft, weather at the surface tends to be mild. Low pressure storm systems are either very weak or non-existent.

When the amplitude of a wave pattern aloft is large, troughs and ridges are deep. During these conditions, cold polar air moves southward filling into the trough and warmer tropical air moves north into the ridge. This condition is referred to as **meridional flow**. Eventually, the amplitude increases until the wave breaks up, leaving pools of cooler air in the south and warmer air in the north. Meridional flow tends to result in stormy weather at the surface.

Images 5.1 and 5.2 are good examples of high amplitude wavelike meridional flow. In both cases the wave amplitude exceeded 15 degrees latitude. Examples of low amplitude zonal flow are shown in Images 5.4 and 5.5. Image 5.4 was captured on February 10, 1991. The streaks of high cirrus clouds across the southern states and over the Gulf of Mexico mark the location of the jet stream. On this day the jet stream at 200 millibars was in excess of 100 knots. Surface winds across the middle of the country ranged from 10 to 20 miles per hour under clear sunny skies.

Image 5.5 showing upper level zonal flow over the southwestern United States was captured from NOAA 11 on March 5, 1991. Although there were no storm systems in the region on March 5th, moisture from the Pacific Ocean produced heavy snow in west-facing slopes in the mountains of the southwest.

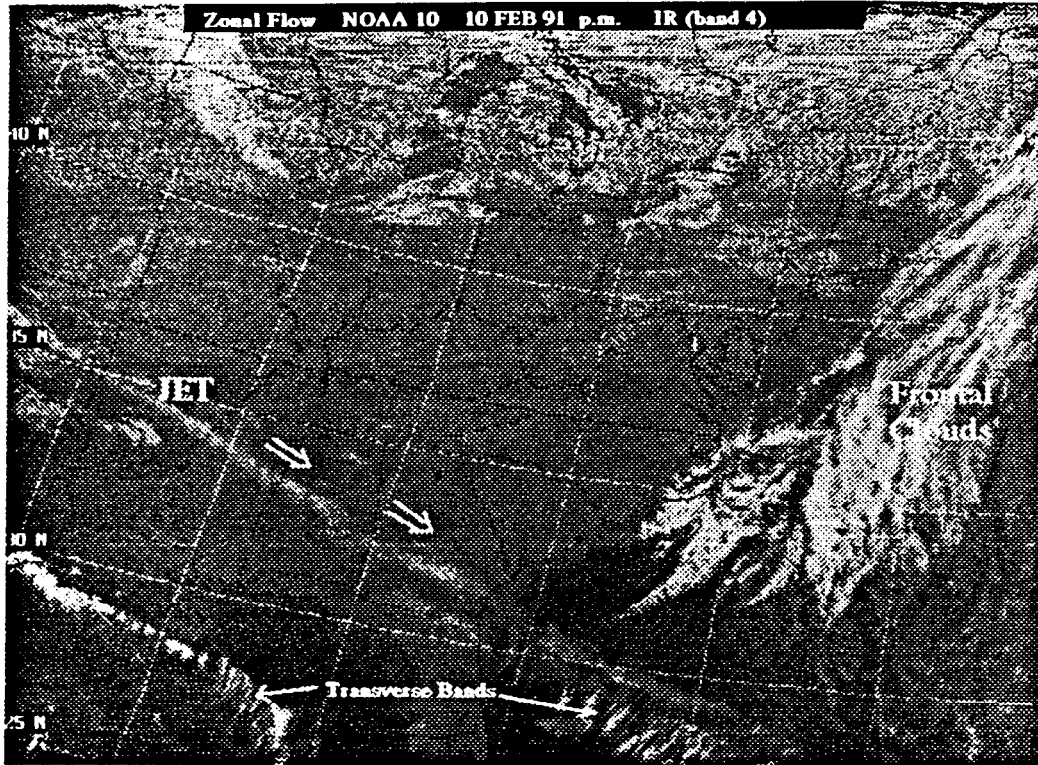


Image 5.4 Zonal Flow over the eastern U.S. marked by cirrus clouds in the jet stream.

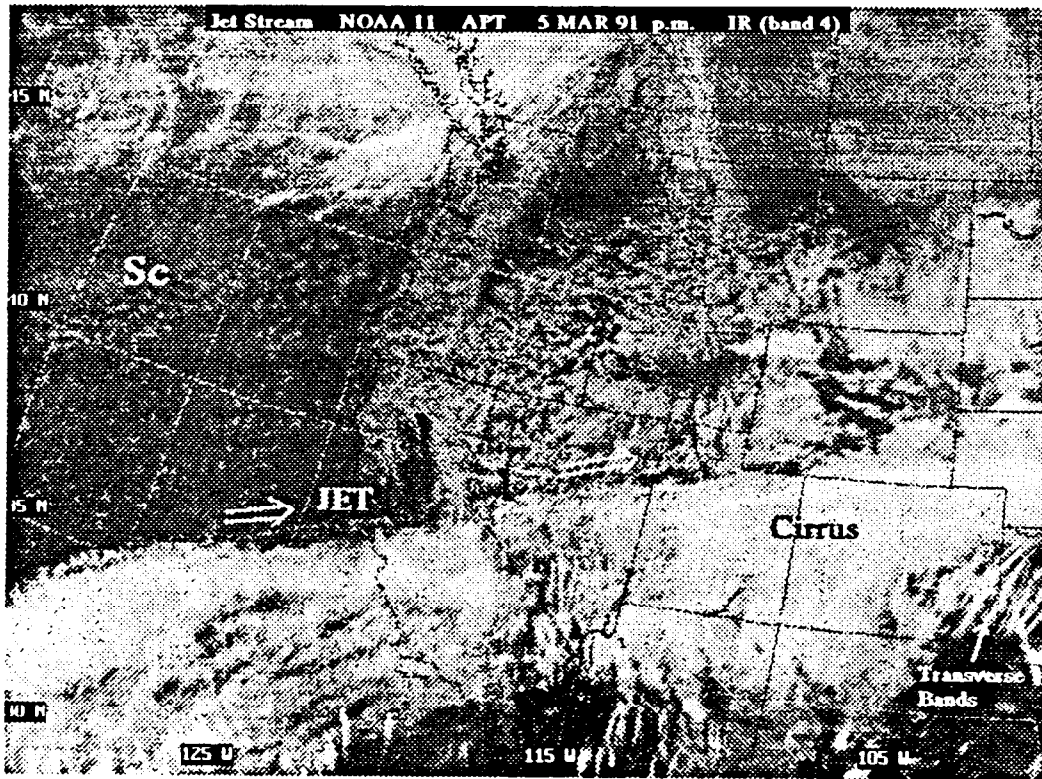


Image 5.5 Zonal Flow over the western U.S. marked by the jet stream.

### 5.3 The Jet Stream

The **jet stream** is a belt of strong westerly winds aloft which flow along the polar front. Although jet stream winds have been known to exceed 200 knots, the average jet is about 75 to 150 knots. It varies in height from 9 to 15 kilometers (30,000 to 50,000 feet) above sea level. The jet stream tends to be stronger and to migrate toward the equator during the winter. In the summer the jet stream is generally weaker, about 50 to 100 knots, and is usually confined to higher latitudes.

Conventional meteorological analysis has shown that a cirrus cloud shield will form to the right of and above jet streams (Northern Hemisphere). On satellite images the upper level jet stream is located in the clear area approximately 1 degree away from the edge of the cirrus shield.

Many satellite images of the jet stream exhibit bands of clouds that are perpendicular to the flow. These **transverse bands** indicate extremely high wind speeds, usually greater than 70 knots, which cause the air flow to become turbulent. The effect of turbulence is vertical motion, which we have learned, causes cloud formation. One way to imagine turbulent breakup is to watch water flow from a faucet or hose. When the water is flowing slowly the stream is smooth. However, as the flow increases turbulence will eventually cause the water to break up into droplets.

Images 5.6 and 5.7 were captured from a NOAA 11 pass on February 21, 1991. The jet stream is marked by the presence of cirrus clouds which appear grey on visible image 5.6 but are cold and bright white on infrared image 5.7. The altostratus (As) and cirrostratus (Cs) cloud band to the south of the jet is thick and white in the visible image but warm and grey in the infrared image. The weather in Washington D.C. on February 21 was sunny but breezy. The Gulf Coast from New Orleans to the Florida Panhandle experienced fog and drizzle.



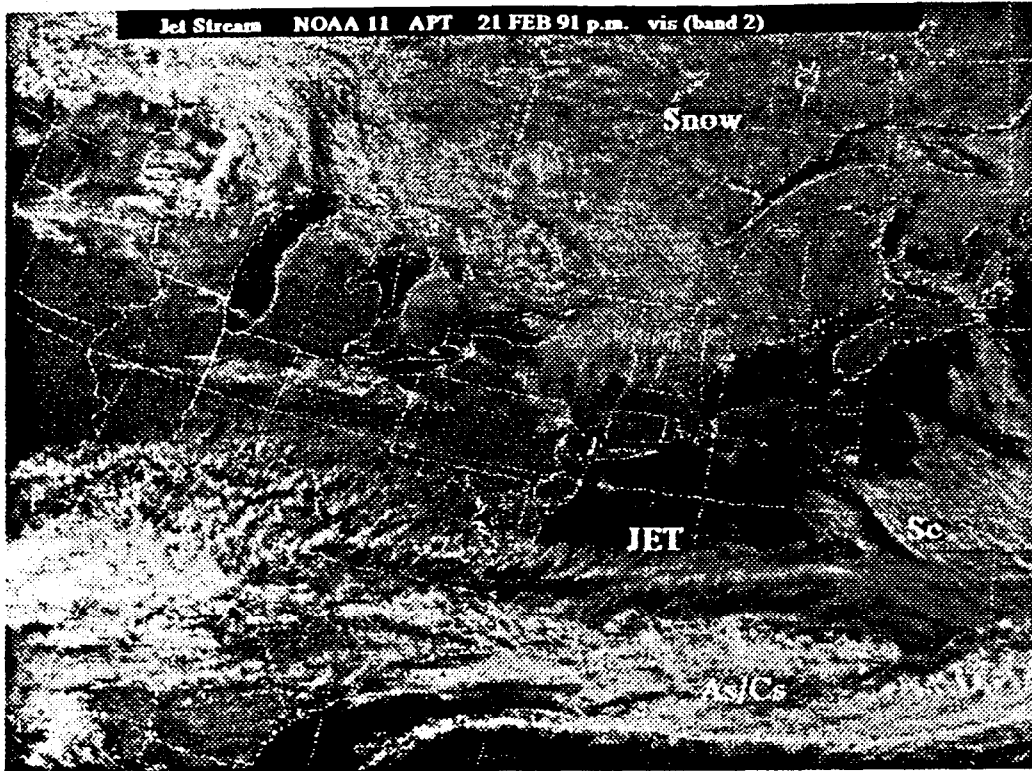


Image 5.6 Jet stream cirrus clouds are grey in a visible image.

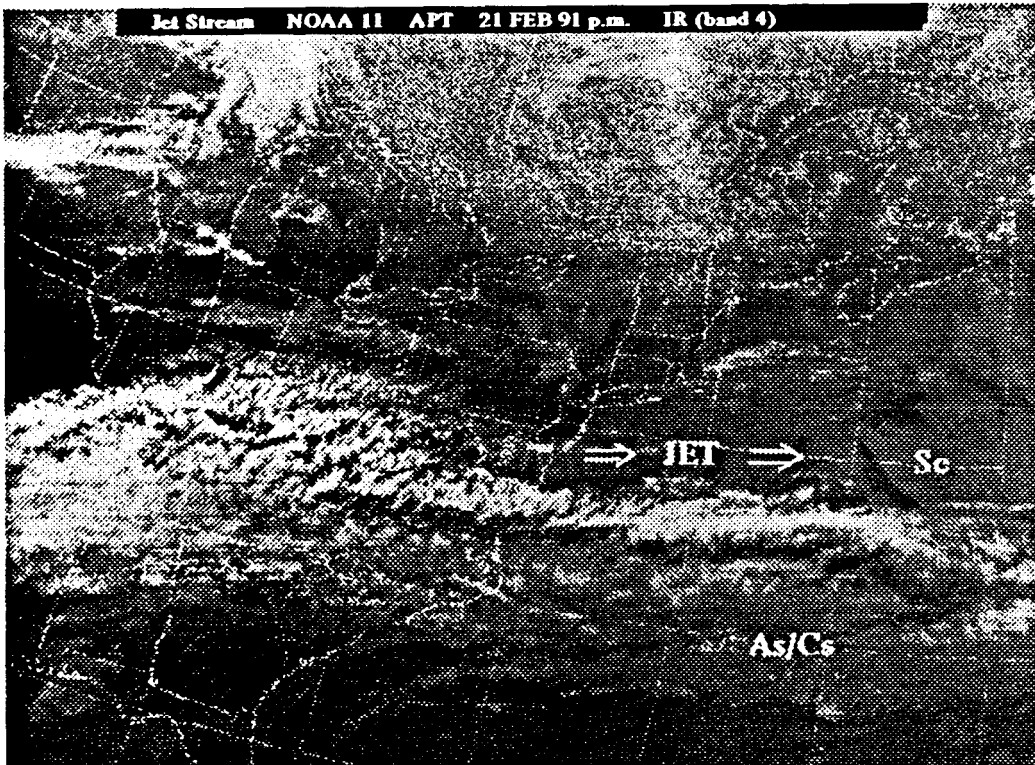


Image 5.7 Jet stream cirrus clouds are white in infrared image.

### Activity 1: Weather Cycles

The purpose of this activity is to test the hypothesis that the transition from zonal to meridional flow is has a predictable cycle. Construct a graph with the days of the month along the x axis and wave amplitude on the y axis. This activity will require about 90 days and you should allow for wave amplitudes ranging from 500 to 2500 kilometers. Capture an APT image at least twice each week for a period of several months. Estimate the amplitude and the wavelength of the upper level flow from each image and plot your data on the graph. After you have finished collecting your data analyze it for patterns. Elementary school students may prefer to rely on visual data analysis and the most advanced students might like to try Fourier transforms and statistical analyses. Alternatively you may wish to try an intermediate approach. Record on a sheet of paper,

- the number of days between each amplitude maximum observed
- the number of days between each amplitude minimum observed

Is the average number of days between maximums (or minimums) at least 6 days or longer? If not, then your hypothesis may be true but you did not collect enough data to test it. You need to collect data at twice the frequency for which you can test for a cycle or pattern.

Are the number of days between amplitude maximums all about the same within a day or two days? If your answers to both questions are yes, then you have proved your hypothesis that weather comes in predictable cycles.

Patterns discovered during this activity will change depending on the season and the location of the investigator. More ambitious investigators may wish to include other data sets in their analyses. Precipitation and precipitation rate are good candidates. This activity is a good opportunity to present the concepts of mean, standard deviation, correlation coefficient, and other statistical methods as appropriate.

### **5.4 Summary Discussion:**

In this unit you have been introduced to the concept of upper air flow. You should understand how convergence and divergence of air aloft are connected to weather patterns on the surface. You should be able to locate the jet stream and to identify upper level ridges and troughs on satellite images from cloud patterns. Measuring the amplitude of the upper level wave, should enable you to determine the strength of surface weather systems beneath. If you cannot answer the following questions, you may wish to review this unit before proceeding further.

1. A surface low pressure system would be found to the (right, left) of the troughline.
2. It is most likely to be raining to the (right, left) of the troughline.
3. Downward or sinking air would be found to the (right, left) of the trough.
4. A ridgeline is the place where upper level air flow has its maximum (clockwise, counterclockwise) curvature.
5. The jet stream tends to migrate (poleward, equatorward) in winter.
6. Meridional flow is usually accompanied by (stormy, mild) weather.

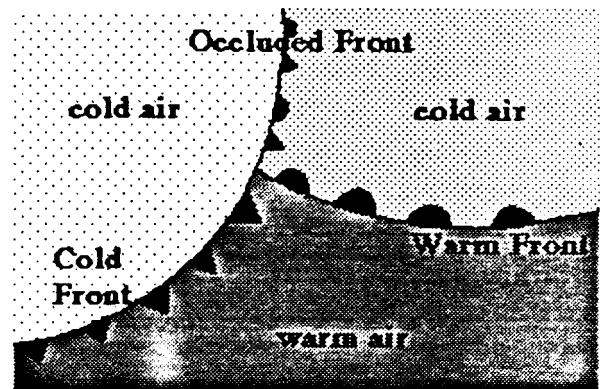


## Unit 6: Weather Systems

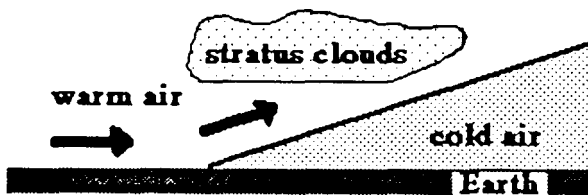
Weather systems can be characterized by the types of clouds and cloud patterns that are associated with them. All weather systems from large scale storms and hurricanes to small lake breezes display characteristic cloud patterns. The more violent a weather system is, the more prominent are the cloud patterns. Large expanses of cloud free areas or areas that contain widely dispersed cumulus clouds are indicative of mild weather. Large bands of clouds that move in formation from west to east (in the northern hemisphere) are characteristic of frontal systems. Tropical storms and hurricanes are highly organized swirling cloud eddies that spin as they move along their path. In this unit you will learn to determine the type of weather system that exists over a given area by interpreting cloud types, patterns, and movements as observed from satellite images.

### 6.1 Fronts

An air mass is a volume of air that has similar properties; temperature, pressure, wind and moisture. When two air masses with different properties come in contact with each other, the transition zone is called a *front*. At the front, rapid changes take place. The major types of front are cold fronts, warm fronts and occluded fronts. Well developed frontal systems show up as large-scale bands of clouds on satellite imagery. Weather map symbols for fronts are depicted in the figure to the right. Lines with semi-circles represent warm fronts and lines with points represent cold fronts.



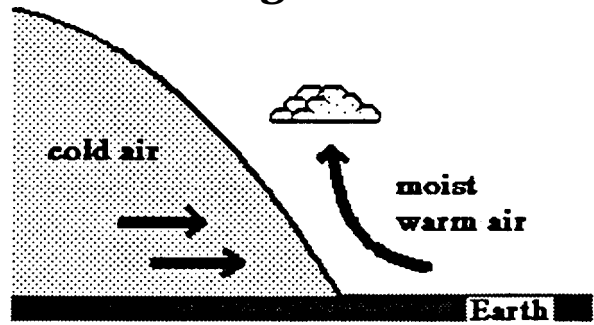
### Advancing Warm Front



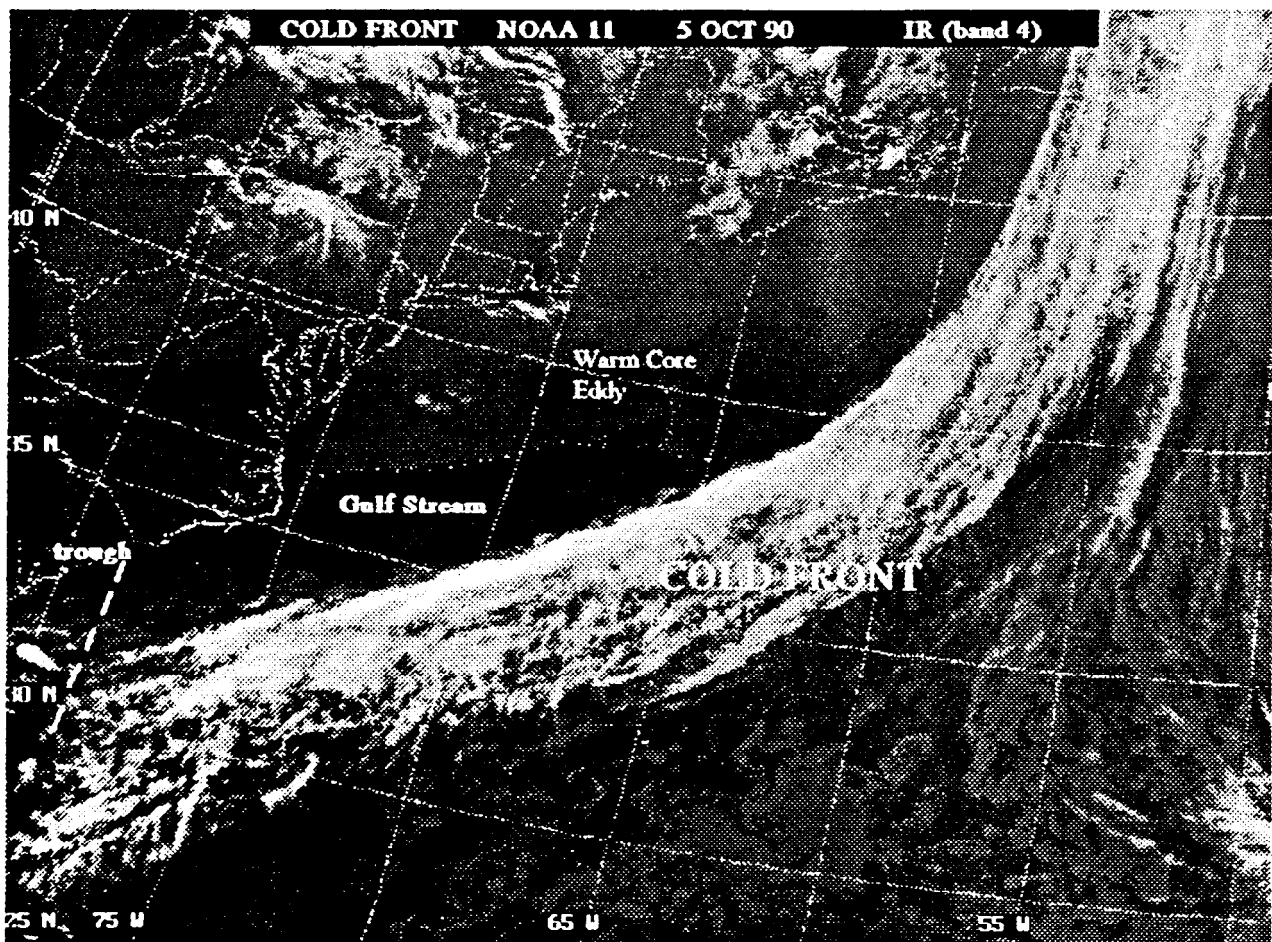
with very little structure evident. Warm front weather is less intense than weather associated with cold fronts, and will generally cover a wider area. A typical warm front moves at about 15 miles per hour.

*Cold fronts* result from cold air rapidly advancing and replacing warmer air in a given region. The actual cold front is the transition zone between the cold air mass and the warm air mass it is replacing. The advance of cold air results in rapid uplifting of the warm air it replaces, causing a relatively thin line of cumuliform clouds to develop. These cumuliform clouds appear as clearly outlined, almost cauliflower shaped, white cells on a satellite image. Cold fronts generally move from west to east at about 20 miles per hour in the mid latitudes.

### Advancing Cold Front



An example of a cold front is shown in Image 6.1, an infrared image captured on October 5, 1990. The cloud band across the image is the front. The amplitude of the wave pattern is larger than 20 degrees of latitude, indicating strong meridional flow. The gulf stream is also evident, with a warm core eddy forming about 300 kilometers southeast of Cape Cod.



**Image 6.1** A cold front off the east coast of the United States.

### **Occluded Fronts**

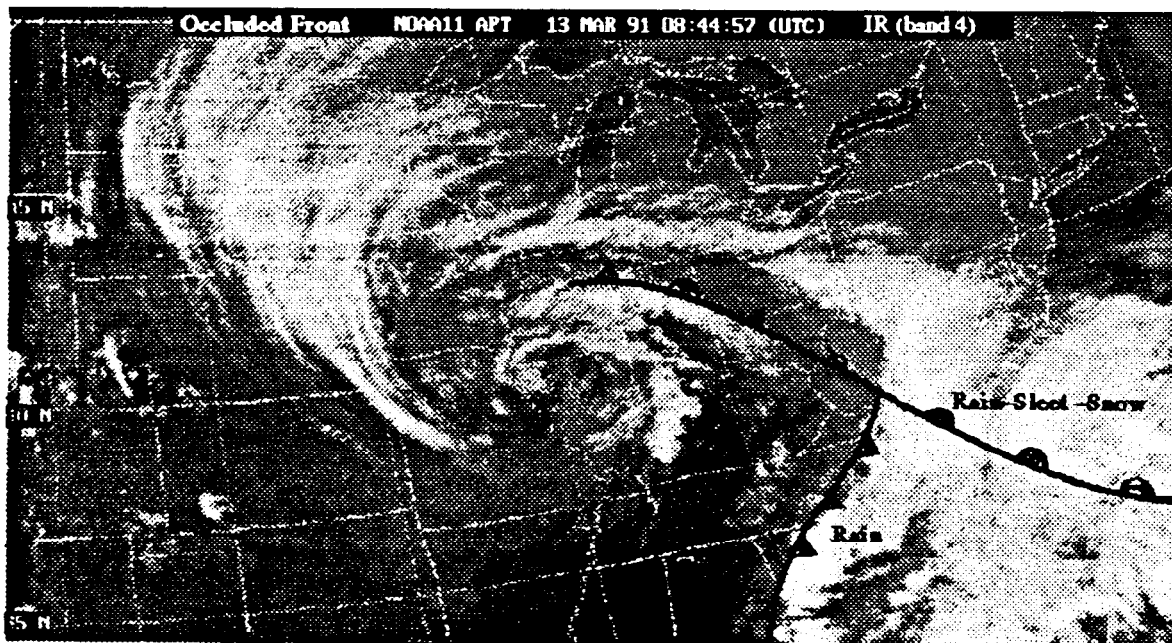
Because cold fronts move much faster than warm fronts, in a normal frontal system the cold front will eventually catch up with the warm front. When the two fronts combine an **occluded front** results. This frontal occlusion will be a mixture of both cold and warm frontal clouds. The occluded front will be a band of clouds with a chaotic blend of stratiform and cumuliform clouds often with embedded cumulonimbus and towering cumulus clouds.

Two examples of occluded fronts are shown here. The image to the right, captured on March 4th, shows an intense low pressure system that swept sheets of rain and strong thunderstorms across the northeast before moving out to sea. A image of this storm system 12 hours earlier is shown in Image 6.9.

Image 6.3 is from March 13th. Note the cumuliform clouds in advance of the cold front and the stratus layers associated with the warm front. Snow, sleet and rain were forecast in Washington D.C. on March 13th but never materialized.



**Image 6.2 An occluded front.**



**Image 6.3 An occluded front with rain and snow forecast.**

### Frontal Rope Clouds

In some cold frontal bands, a well defined cloud line will stand out near the leading edge of the clouds. This cloud line, called a frontal rope cloud, is coincident with the surface position of the cold frontal boundary. Rope clouds stand out vividly over mid-latitude oceans. Over land, the roughness of the terrain and resulting frictional effects often break up the orderly structure of rope clouds. However, rope clouds can sometimes be observed over very flat regions of land like Florida.

Image 6.4 from May 31, 1991 shows a front off the east coast of the United States. A thin line of cumulus clouds marks the frontal line. A series of squall lines have developed in advance of the front. The V shaped cloud marked at the top of the rope is a classic cloud pattern for tornado watches.

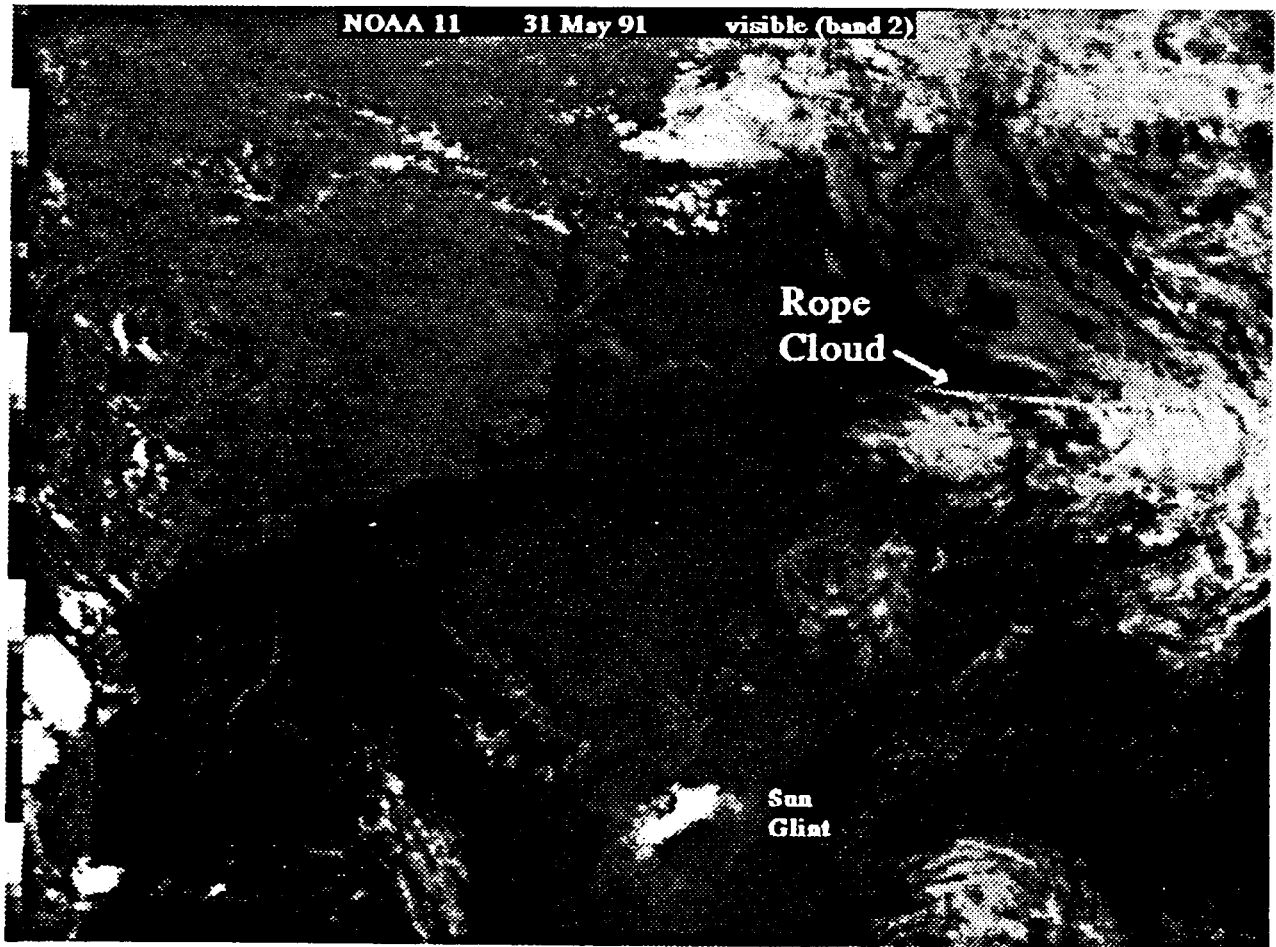
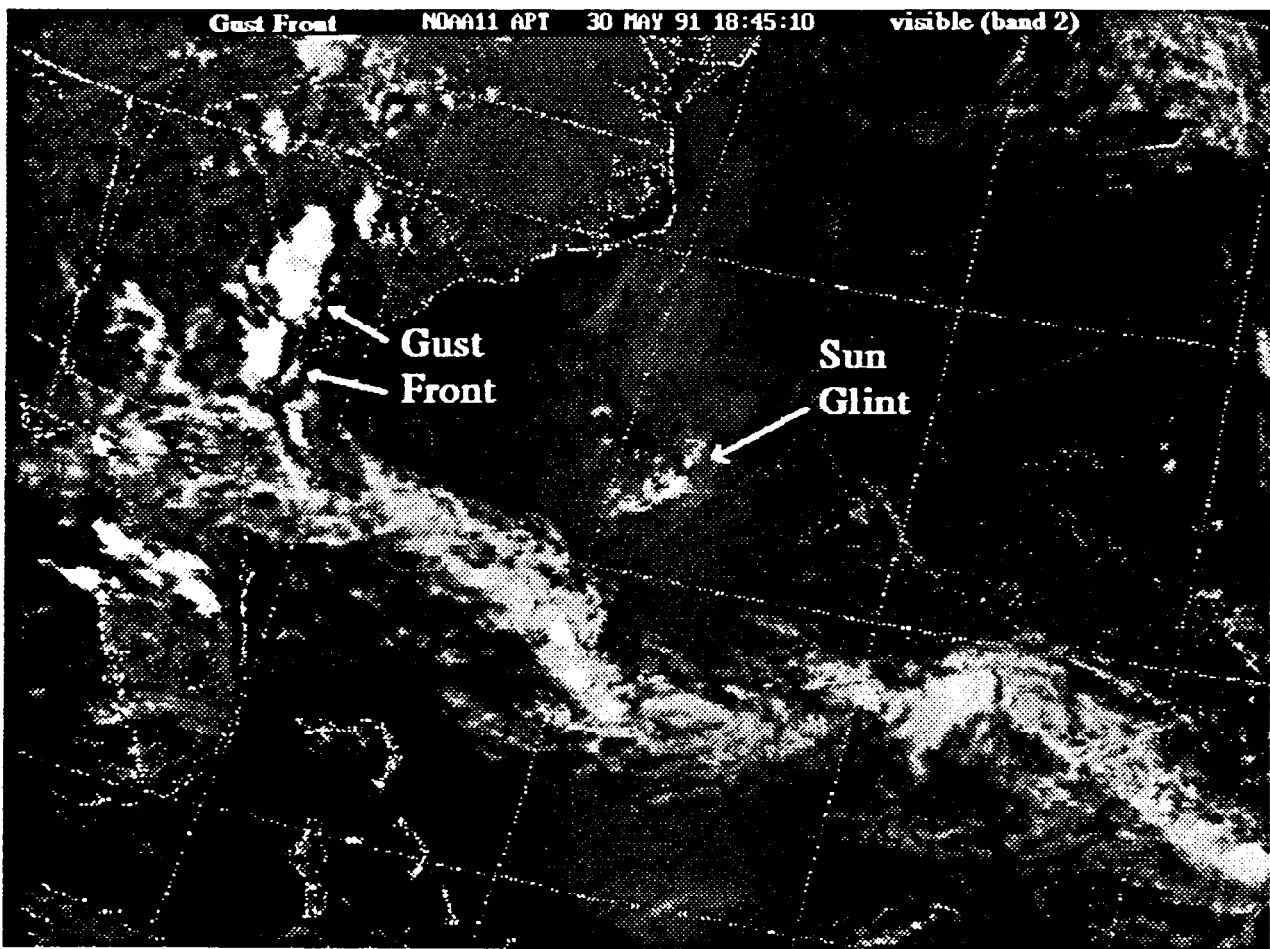


Image 6.4 A rope cloud marks the edge of the frontal system.

### **Gust Fronts**

Thunder storms are regions of intense updrafts and downdrafts. As the storm begins to dissipate, downdrafts flow out the bottom and ahead of the storm. Because of its downward vertical motion, this air is cooler than the surrounding air and thus forms a mini cold front in advance of the thunderstorm itself. The leading edge of the cold air that flows from the bottom of a thunderstorm appears in satellite images as an arc shaped line of convective clouds sometimes referred to as a **gust front**. New thunderstorms can develop along gust fronts particularly where two arcs intersect or where there is already some convective activity. Strong turbulence is generally associated with gust fronts. Wind speeds can easily exceed 20 knots and in some cases have been believed to reach 100 knots.



**Image 6.5 Gust fronts form in advance of thunderstorms.**

## 6.2 Severe Storms

### Squall Lines

Squall lines are intense lines of thunderstorms that form ahead of fast moving cold fronts. The squall line forms due to rapidly converging air ahead of a cold front that leads to severe thunderstorm and tornado activity. Some squall lines are several hundred miles in length. Squall lines are very prominent weather features, and can be seen on visible (Meteor and band 2) satellite imagery. However, the best analysis tool for tracking squall lines is an enhanced infrared image because vertical development can easily be monitored.

An example of squall lines is shown in APT Image 6.6 captured on January 17, 1991. A cold front off the east coast of the United States is marked by a thin rope cloud. A series of squall lines has developed in advance of the front. The V shaped cloud marked at the top of the rope is a classic cloud pattern for tornado watches.

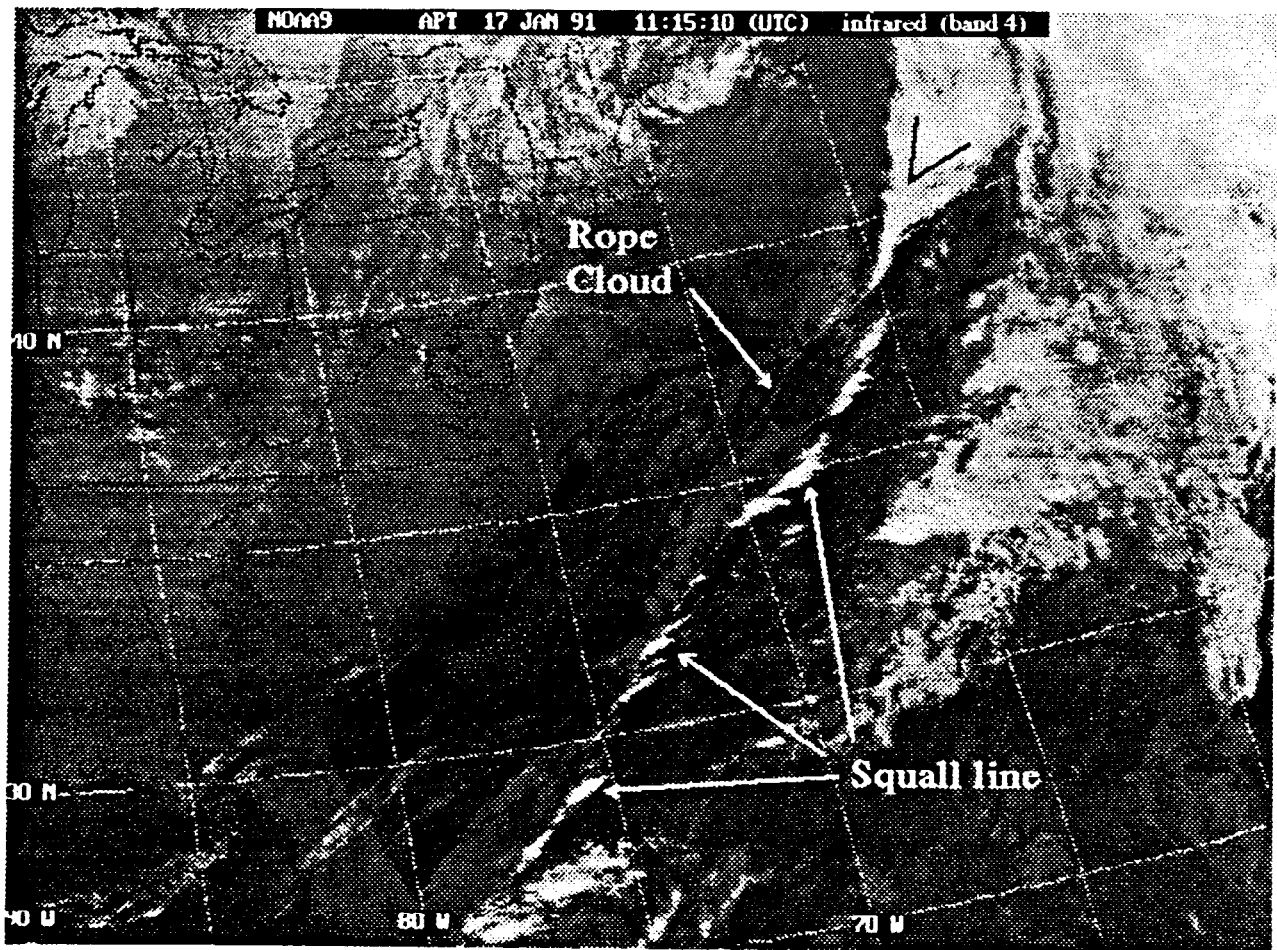


Image 6.6 Squall lines form in advance of fronts.

## Tornadoes

Tornadoes result from extremely severe thunderstorm activity. Well developed squall lines and highly organized cold frontal systems are prime candidates for the development of tornadoes. Once you have observed a well developed squall line in visual imagery, you should then switch to thermal imagery to analyze the detailed cloud structure.

There is a classic V shaped cloud pattern associated with tornado activity. This V pattern, or triangular cloud mass, actually resembles a tornado as when viewed from a satellite's vantage point. Infrared imagery in most cases will show upper level divergence. By tracking the movement of the coldest clouds the situation can be monitored and areas of suspected tornado activity can be outlined. Upper level divergence is usually accompanied by low level convergence resulting in strong updrafts that accompany severe turbulence, icing, and windy surface gusts.

Images 6.7 and 6.8, captured on March 1, 1991 are from the afternoon pass of NOAA 11. The area of potentially severe weather near New Orleans is marked on the infrared view. Heavy thundershowers were reported in the area but no tornadoes were sighted.

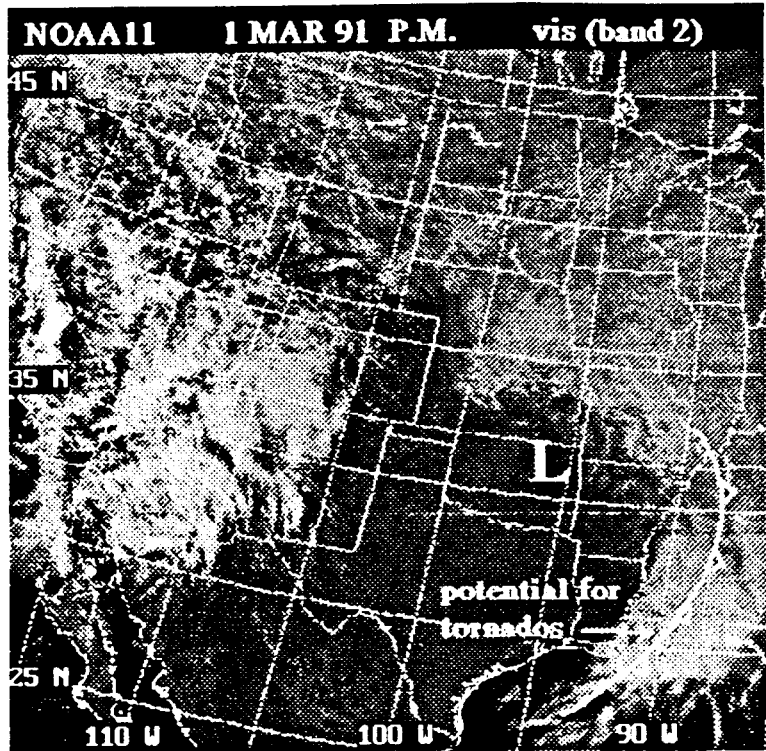


Image 6.7 Visible image of storm system.

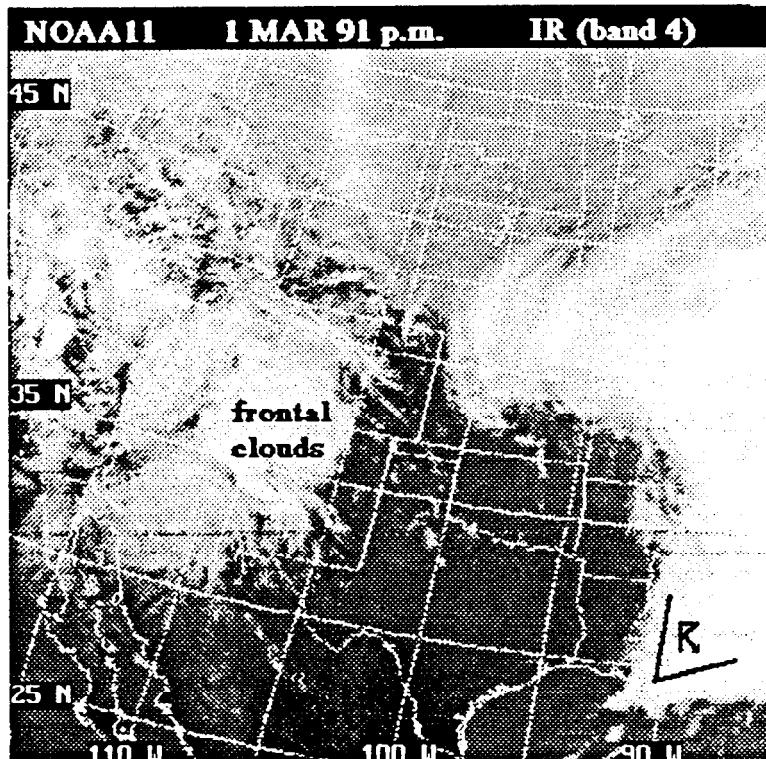


Image 6.8 Infrared image of storm.



### Thunderstorm Detection and Forecasting

Meteorologists forecast weather on several time and spatial scales. Clues about the weather over a region on a scale of one to three days can be derived from watching for changes in the amplitude of upper level air flow. A change from zonal to meridional flow indicates that more mixing of different air masses is likely. The full cycle from zonal to meridional back to zonal flow can take 7 to 10 days. If upper level divergence is strong, a strong surface low will develop to the east of the upper level trough. This area should be watched for thunderstorm development. An illustration of the life cycle of a storm is shown here. The life cycle of a cyclone storm is usually about 3 days.

### Life Cycle of a Frontal Wave

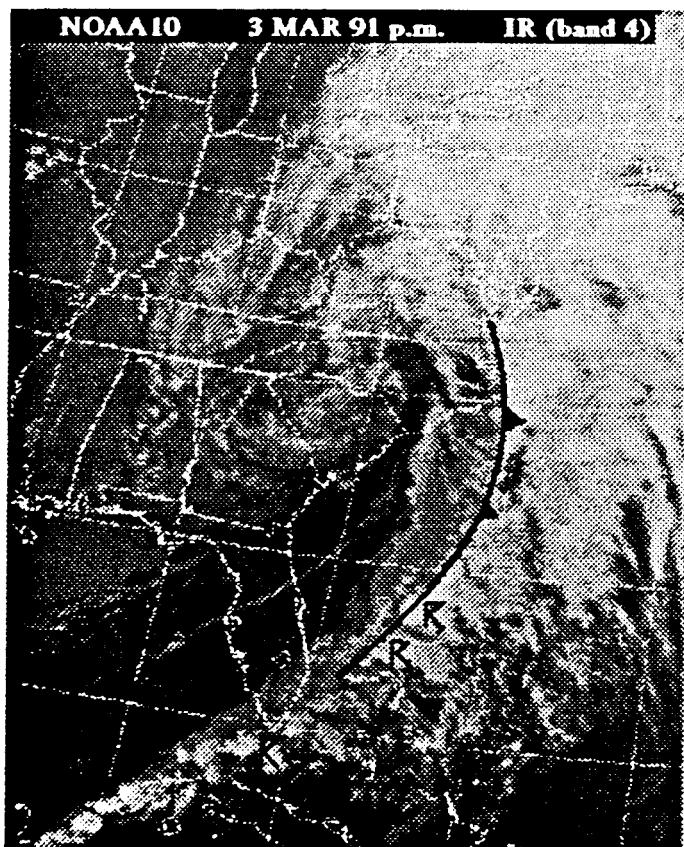
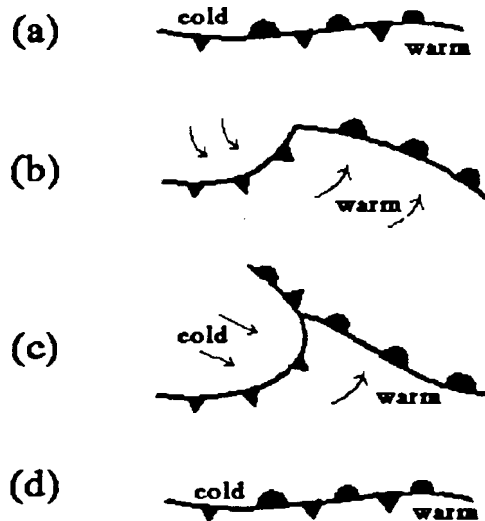


Image 6.9 Cold front with thunderstorm activity.

Thunderstorm activity is both detectable and predictable on much smaller time and space scales. One short term clue is to look for an arc of cumulus clouds marking a line of convective activity in advance of a cold front. Where these arcs cross each other or where there is strong convective activity, thunderstorm development is likely.

Thunderstorm intensity can be estimated by monitoring cloud top temperatures. Cloud tops with temperatures colder than  $-55^{\circ}\text{C}$  are most likely to be producing intense thunderstorms. One simple trick that meteorologists use to visually note which clouds are the coldest is to enhance the image coloring all pixels in a low temperature range, for example from  $-55^{\circ}\text{C}$  to  $-60^{\circ}\text{C}$ , black. The images showing cumulonimbus clouds in Unit 4 were enhanced in this way.



## 6.3 Tropical Storms

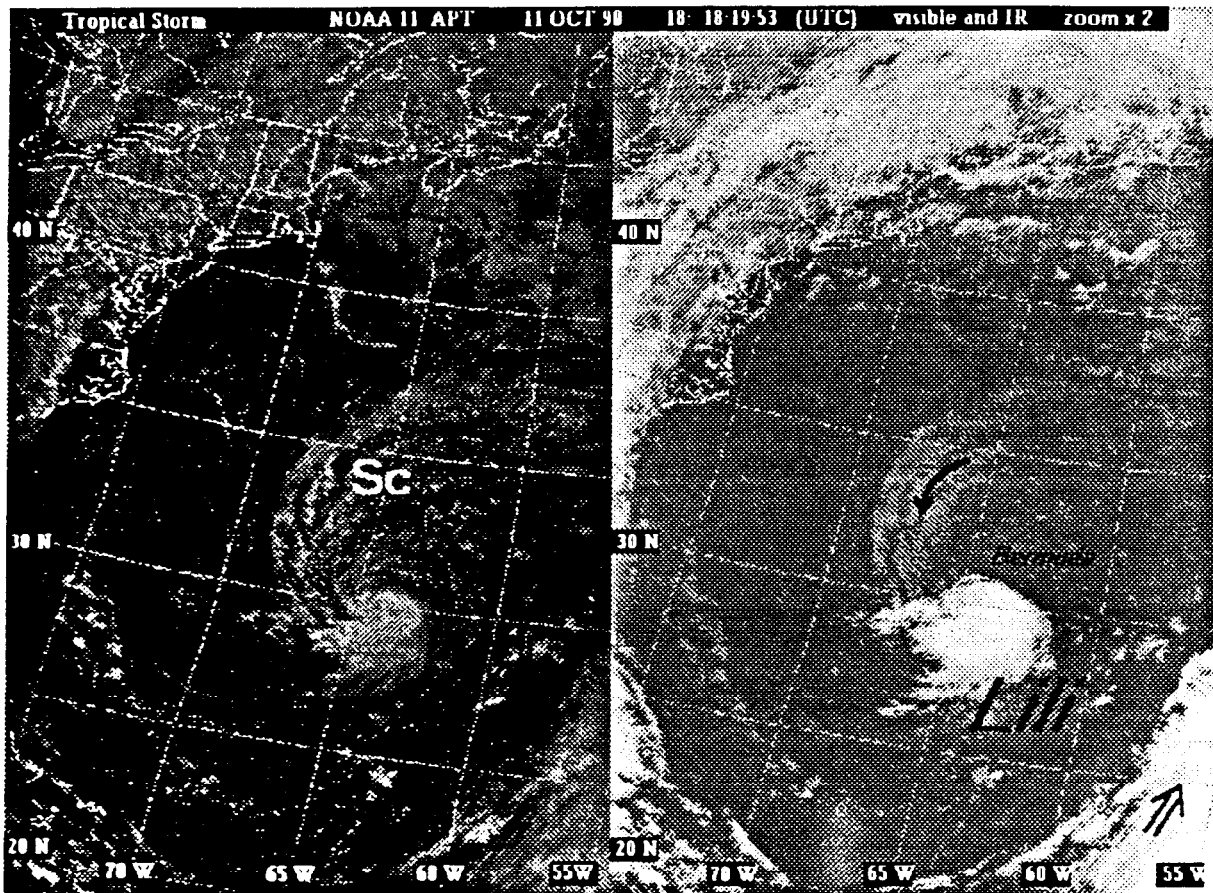
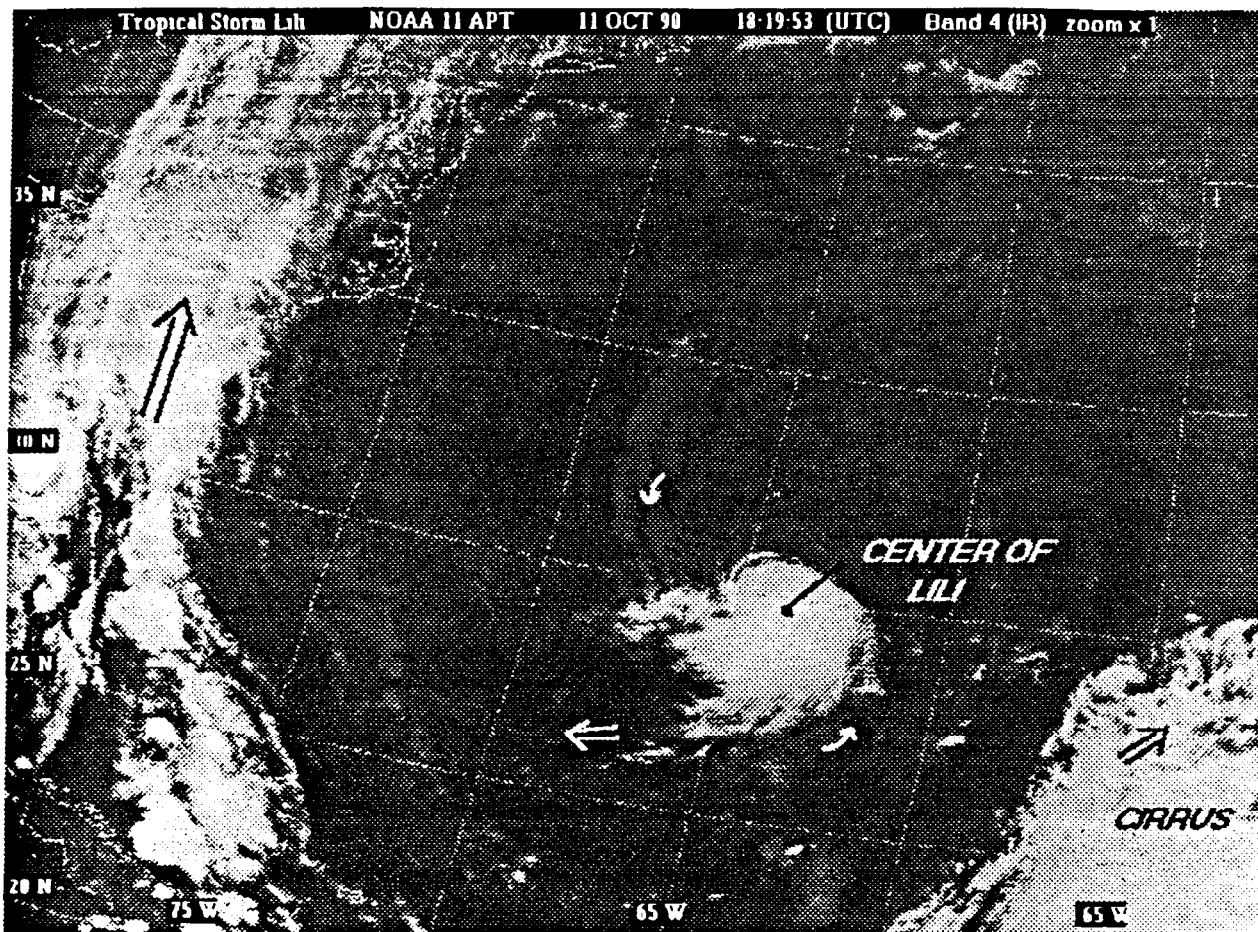


Image 6.10 Tropical storm Lili at about 3 p.m. on October 11, 1991.

A tropical storm begins as a **tropical disturbance**, which is a large low pressure area over warm tropical ocean. If conditions are favorable, an organized pattern of clouds, wind, and rain develops. The first pattern that can be recognized in a satellite image is called a **tropical depression**. Tropical depressions have closed rotary flow at the surface with winds less than 34 knots. When winds increase above 34 knots, the cyclone is classified as a **tropical storm**. When Image 6.10 was captured, Tropical Storm Lili had formed off the coast of Florida.

Tropical storms are more likely to occur in the summer and autumn than during the rest of the year because the three ingredients required to initiate a tropical storm are most likely to occur at the same time and place during the late summer and autumn. They are:

- (1) warm moist converging air,
- (2) warm ocean, and
- (3) latitude away from the equator where the Coriolis force caused by the earth's rotation is strong enough to increase to potential for cyclone development.

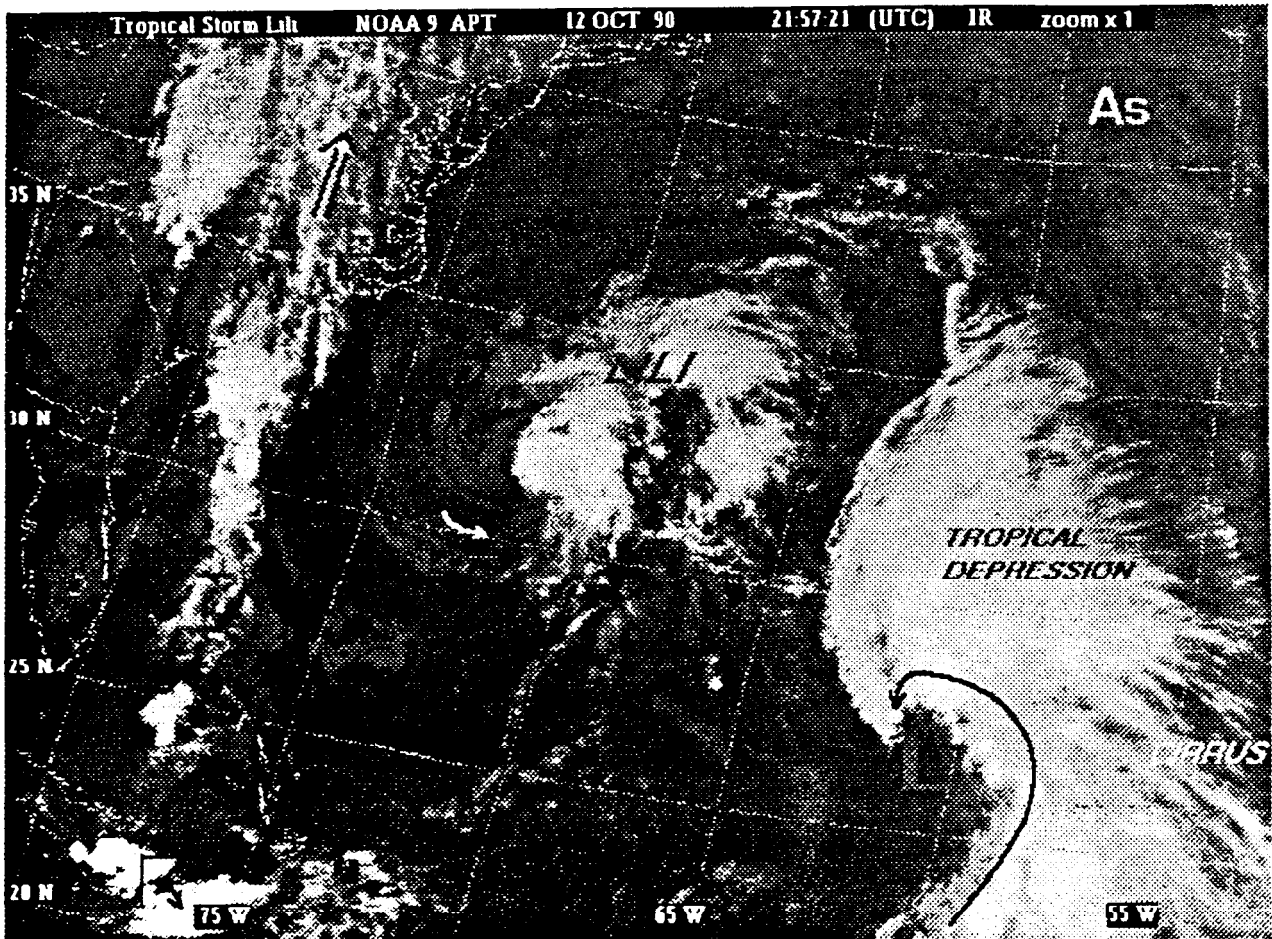


**Image 6.11 Infrared view of tropical storm Lili.**

Tropical storms and hurricanes exhibit a great variety of cloud patterns, but most can be described as having a “comma” shape. As the storm develops, the clouds form bands that wrap around into a center, producing a circular cloud system that often has a cloud-free, dark eye. The number and width of the bands, the solidness of the central dense overcast, and the presence of an eye all enter into the daily assessment of a storm. This closeup infrared view of Tropical Storm Lili shows a comma shape pattern, a dense center but no eye.

Low level winds near the surface of the ocean, shown as solid arrows, flow in a counterclockwise direction into the center of the storm. Winds emerging out of the top of the storm in the upper atmosphere flow in a clockwise direction. Upper level air flow is indicated by double arrows.

Tropical storms begin in the warm converging air of the Inter-Tropical Convergence Zone (ITCZ). They move slowly westward and away from the equator until they reach the subtropical high pressure zone. Then, like a slingshot, they accelerate out of the high into the mid-latitude region.

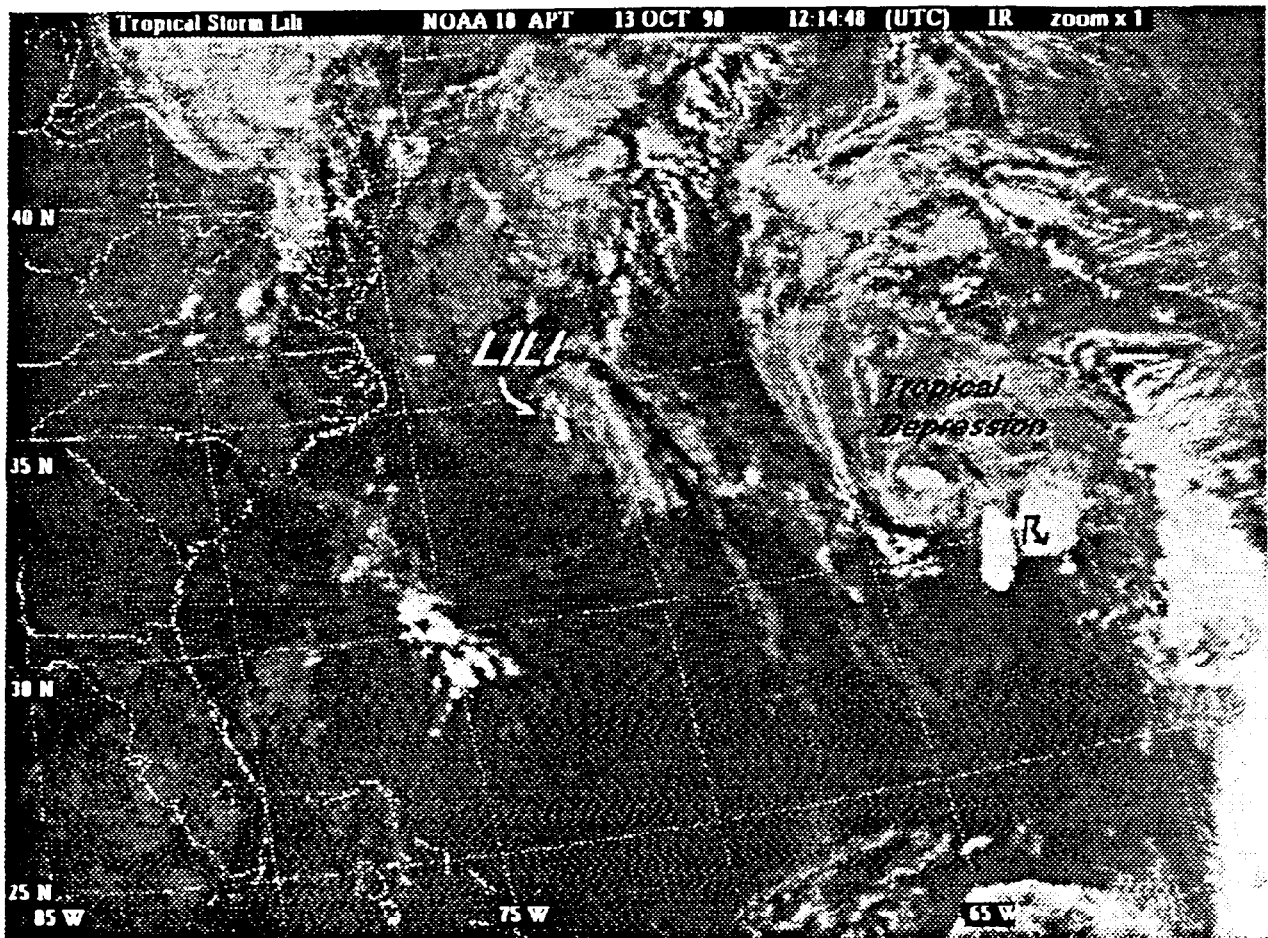


**Image 6.12 Tropical storm Lili late afternoon on October 12, 1991.**

This APT image, captured from a NOAA 9 satellite pass on October 12, 1990, shows Lili about 27 hours after the image on the previous page. Two wide feeders appear to be spiraling into Lily. These feeders can contain intense thunderstorms and tornadoes. Two weather systems now appear in the image. A Tropical Depression has developed to the east of Lili.

Lili has grown larger and has moved about 5 degrees to the north and west. Tropical storms generally move at about 10 to 15 miles per hour in the tropics and pick up speed to 30 to 50 mph as they move to higher latitudes.

Tropical storms are named alphabetically, each season beginning with "A". Alternate names are male and female. How many tropical storms had occurred in 1990 before Lili?



**Image 6.13** By morning on October 13, 1991 tropical storm Lili has burned itself out.

This Automatic Picture Transmission (APT) image was captured from a NOAA 10 satellite pass on October 13, 1990. This is the third day in the evolution of tropical storm Lili. Lili has nearly burned itself out and is moving to off to the north and east.

Tropical cyclones are classified with respect to their state of development.

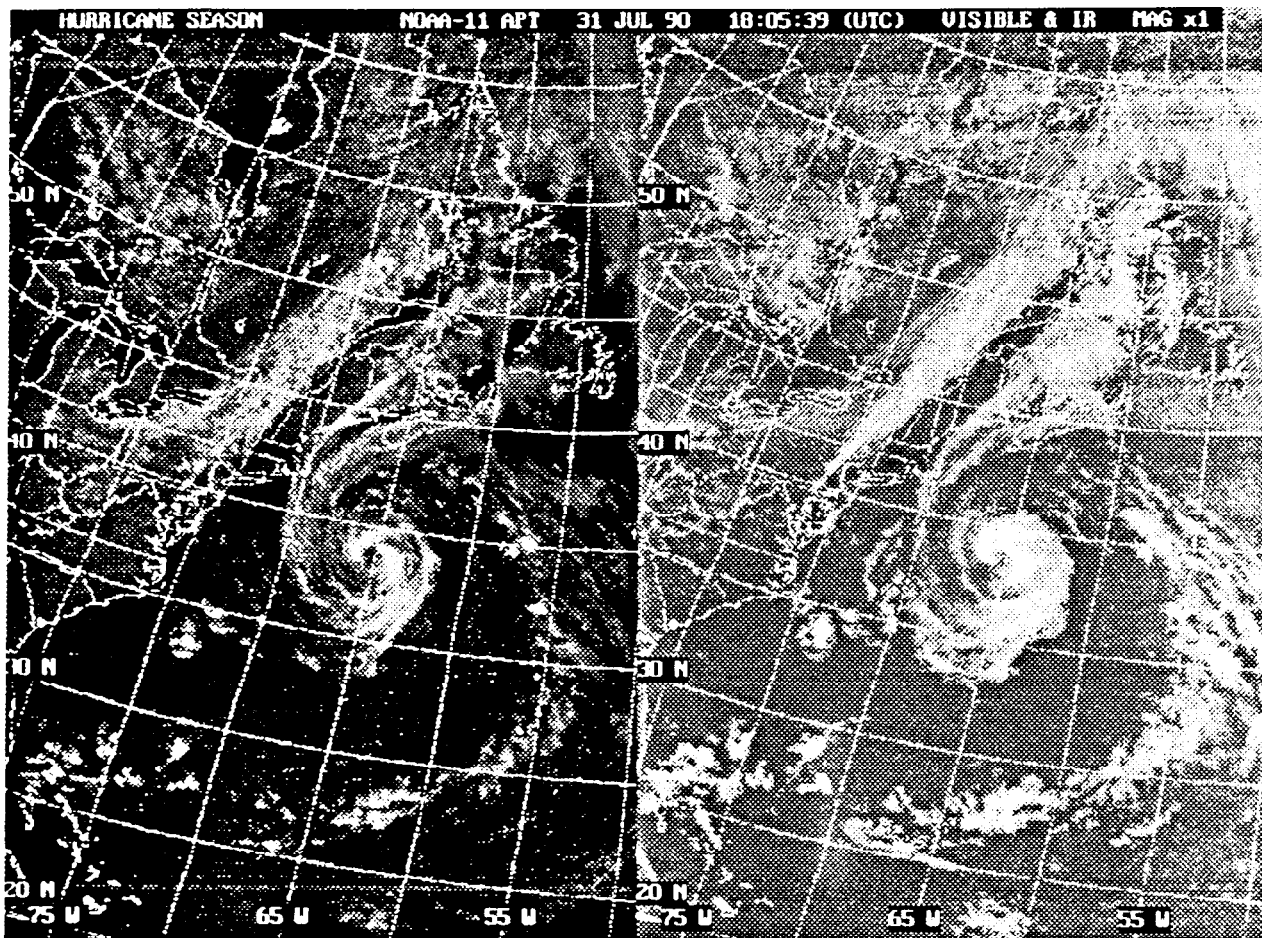
***Tropical Disturbance:*** A weak rotary air circulation 160 to 300 kilometers (100 - 300 miles) across.

***Tropical Depression:*** A closed rotary flow at the surface with wind less than 34 knots (39 mph).

***Tropical Storm:*** A closed rotary flow with winds of 34 to 63 knots (75 mph).

***Hurricane:*** A warm core tropical storm with wind in excess of 64 knots (75 mph).

Activity: Discuss possible reasons why Lili did not develop into a hurricane.

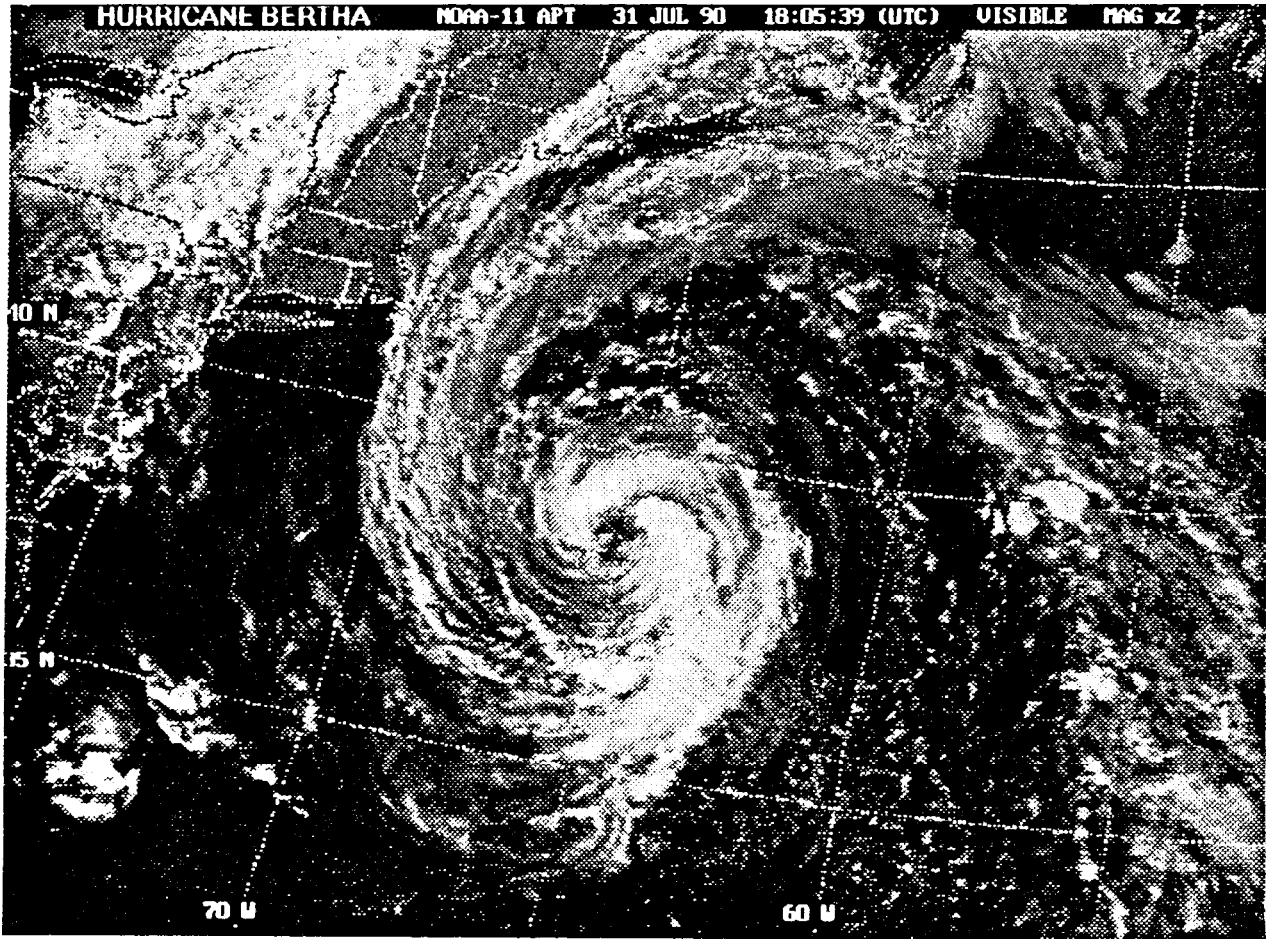


**Image 6.14 Hurricane Bertha on 31 July, 1991.**

When the winds within a tropical storm exceed 64 knots, it becomes a **Hurricane**. This APT image, captured from a NOAA 11 satellite pass on July 31, 1990 shows Hurricane Bertha. Both visible and the infrared channels are displayed side-by-side.

Hurricane Bertha has the classic comma shape with two feeders. From the cloud patterns it can be seen that the wind is swirling in a counter clockwise direction near the surface and a clockwise direction out of the top of the system. Heavy rain and high wind was reported on this day all along the coast of Maine.

Although North Atlantic tropical storms are called hurricanes, in the Pacific, they are called typhoons. In the Southern Hemisphere, storms similar to hurricanes and typhoons affect Australia and Africa as well as many islands such as Madagascar. These are called cyclones. A nickname of "Willy-Willy" has been used to refer to hurricanes in Australia.



**Image 6.15** Close up view of hurricane Bertha in the visible band.

The wind increases and the pressure decreases toward the center of a hurricane. The strongest winds are at a distance of about 6 to 30 miles from the center. The center, called the eye, is a region of relative calm about 6 to 12 miles across.

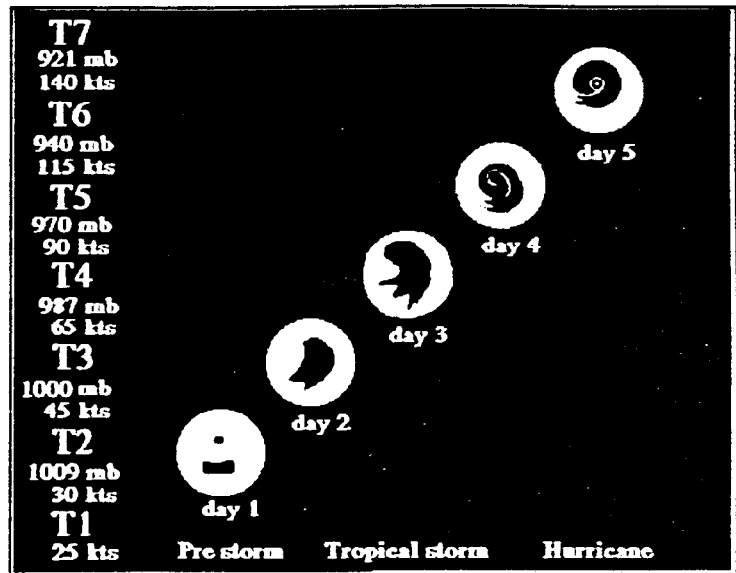
Activity 1: Scale a Hurricane

How big is the eye of Hurricane Bertha? How wide is the hurricane? These lengths can be estimated by using the latitude and longitude grid to develop a map scale. Most hurricanes are about 600 to 800 kilometers (400 to 500 miles) wide. Is Hurricane Bertha typical? (Hint: 1 degree latitude is about 100 kilometers.)



### Activity 2: Intensity analysis of a tropical storm

Meteorologists use a pattern recognition technique to determine the intensity of a tropical storm. This technique is based on a series of patterns that track the history of the cloud pattern to determine the current intensity. The patterns show what the storm should look like as it continues to develop. The intensity numbers for each pattern, called T-numbers, relate to the maximum wind speed and central storm pressure. The patterns and associated T-numbers are shown below. Use them to determine the



approximate pressure and wind speed of tropical storm Lili of October 11, 13 and 13. You can apply the same technique to estimate the intensity of hurricane's Herman and Iselle shown in satellite Image 2.9 in Unit 2.

### 6.4 Summary Discussion

Satellite imagery provides meteorologists with a wealth of information about the position, intensities, and motions of storm systems. In this Unit you have learned about mid latitude and tropical storms. The objectives were to learn to identify combinations or systems of patterns and to predict their change.

Various mid latitude frontal conditions were defined and identified in satellite imagery by their associated cloud types, patterns, and extent. Infrared imagery has been used to determine cloud top temperatures and thereby track determining the intensity of storms. The life cycle of a storm system has been analyzed on two time scales; for development of frontal systems over a period of 1 to 3 days, and development and decay of localized thunderstorms over a period of hours. The key forecast indicators were also examined. The strength of meridional flow is an indicator of storm cyclogenesis. A major key to short range local forecasting is monitoring the outflow boundaries from mature thunderstorms and watching for the development of new thunderstorms in areas where gust fronts intersect.

The ingredients for development of tropical storms were presented and the life cycle of a tropical storm was shown in satellite images. The role of pattern recognition in determining the intensity of tropical storms has been explained.

## **Unit 7: Applications of Infrared Images to Oceanography**

Satellite data are a powerful means for monitoring and forecasting the biological and physical processes in the world's oceans. From a polar orbiting satellite's vantage point the oceans can be mapped every 24 hours. The spatial resolution and areal extent of a satellite pass are well matched to the physical and biological changes taking place on the ocean surface. The only limitation is cloud cover.

Satellites provide a large scale view of oceans which cannot be obtained with sparse measurements from surface vessels. Space and time scales of biological and physical processes in the ocean are compatible with the viewing schedule and resolution of APT imagery. Ocean currents and associated fronts and eddies extend over a range of 10's to 100's kilometers and move slowly, only a few kilometers each day. Plankton communities tend to change over periods of one to ten days across an areas extending from 10's to 100's of kilometers squared. Even with only nighttime infrared image used, the APT broadcast provides a minimum of daily coverage at pixel resolution of approximately 4 kilometers.

Clouds are a drawback to using satellite data in some locations. Over the northern ocean's above 45 degrees latitude, cloud cover is common more than 70 percent of the time. In subtropical areas, cloud cover is consistently less than 50 %. Cloud cover in many mid-latitude areas is seasonal. Fishermen and other maritime industries need to be aware of these trends. In general however, on any given day about 30 to 40 percent of the world's oceans will be covered by clouds. On average, based on capturing one nighttime infrared image every twenty four hours, a cloud free image of a 100 km x 100 km area of ocean should be available every second or third day - sufficiently often to track biological and physical changes in the ocean as they take place.

### **7.1 Tracking Ocean Currents**

Because both the atmosphere and ocean are large fluid bodies on a rotating earth, it should not be surprising that their large scale flow features have many similar patterns. Ocean currents move in a clockwise fashion in the Northern Hemisphere and in a counterclockwise fashion in the Southern Hemisphere. Currents on the western side of oceans are channeled and strong as they move away from the equator. Examples include the Gulf Stream along the eastern coast of the United States and the Kuroshio Current off the eastern coast of Japan. On the eastern sides of oceans currents are generally much broader and slower. They tend to move toward the equator and cause upwelling along the western coasts of continents where water is turned away from adjacent land masses.

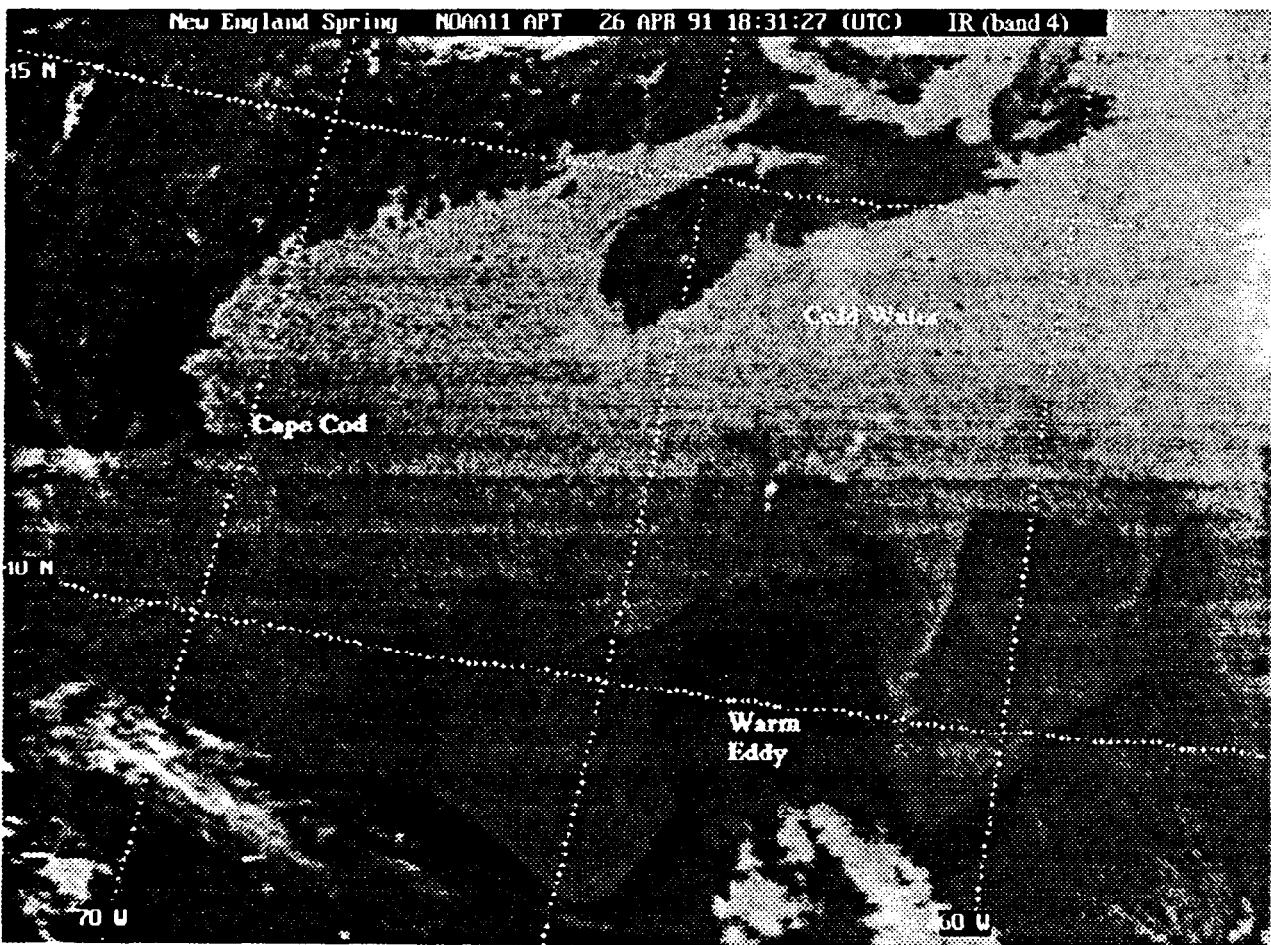
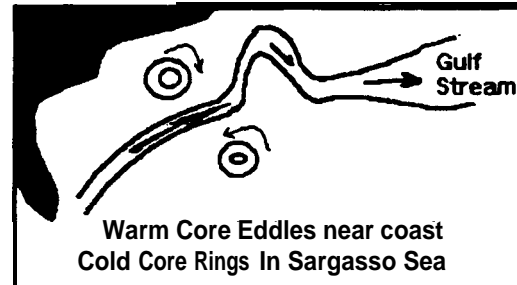
With the advent of thermal satellite imagery, ships at sea can more accurately account for the effects of currents on vessel movements. Selecting an optimum route for ships can save many hours of sailing time and improve safety. In 1975 EXXON and NOAA jointly conducted a Gulf Stream Navigation Experiment that showed how taking advantage of the Gulf Stream flow can result in substantial fuel savings. The western wall of the Gulf Stream is the location of maximum northward current, 2 to 4 knots. Because it has a substantial



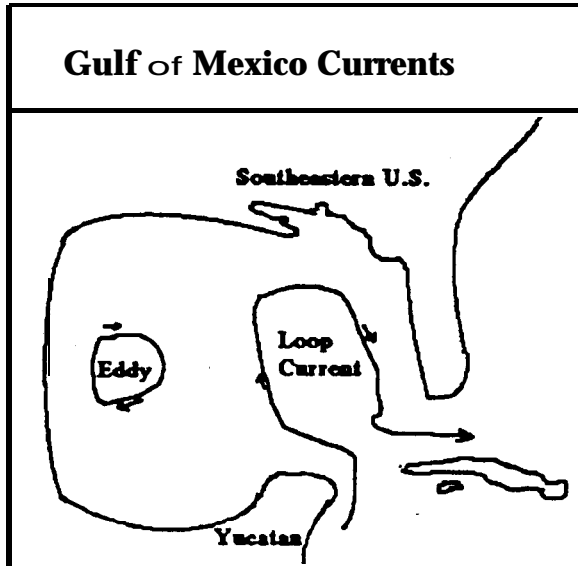
thermal gradient, the Gulf Stream is easily located in infrared satellite imagery. Sailboat racers also take advantage of these data.

## 7.2 Ocean Fronts and Eddies

Like storm systems that develop distinctive flow patterns in the atmosphere, oceans develop circulation systems called warm core eddies and cold core rings. Eddies are formed along the boundary between warm and cold water currents which flow in opposite directions. For example, the shearing effects of Gulf Stream current can cause large cold core rings and warm eddies to be trapped as shown in the figure. These rings and eddies average about 60 kilometers in diameter. Warm core eddies, like atmospheric high pressure systems, flow in a clockwise direction. Cold core rings are like lows, they flow in a counterclockwise direction. Currents in eddies and rings run at about 1 to 2 knots.



**Image 7.1** Warm core eddies and cold core rings developing at the Gulf Stream boundary.



The main current feature in the Gulf of Mexico is called the Loop Current. It can be seen as it enters through the Yucatan Channel and meanders to its eastern extent back along the Tampa Bay. Narrowing of the Loop Current neck indicates the potential for eddy detachment in the next few weeks. As the eddies spin, the nutrients accumulate along the outside edges. The best sports fishing in the Gulf is located along the edges of the Loop Current and warm core eddies.

Detecting the Loop Current with infrared imagery is most challenging during the summer months when the Gulf of Mexico becomes nearly isothermal. Water temperature varies in the narrow range from about 29° C to 31° C

and the pixel to pixel temperature change that can be detected with APT data is about 0.5° C. Relative humidity is also high causing the image contrast to blur. The best opportunity to meet these challenges is to capture the infrared band 3 image from 3 a.m. pass of NOAA 11. Band 3 is less influenced by humidity than band 4, and at this early morning hour the effects of solar heating are minimized.

### 7.3 Locating Fish

Remote sensing of the ocean has played an important role in fishery research since the early 1960's. However, successful operational use of satellite data has been realized only recently. With the emergence of low cost data reception and data processing techniques fishermen can decrease their search time, lower fuel costs, locate the best regions for fishing, and improve their catch.

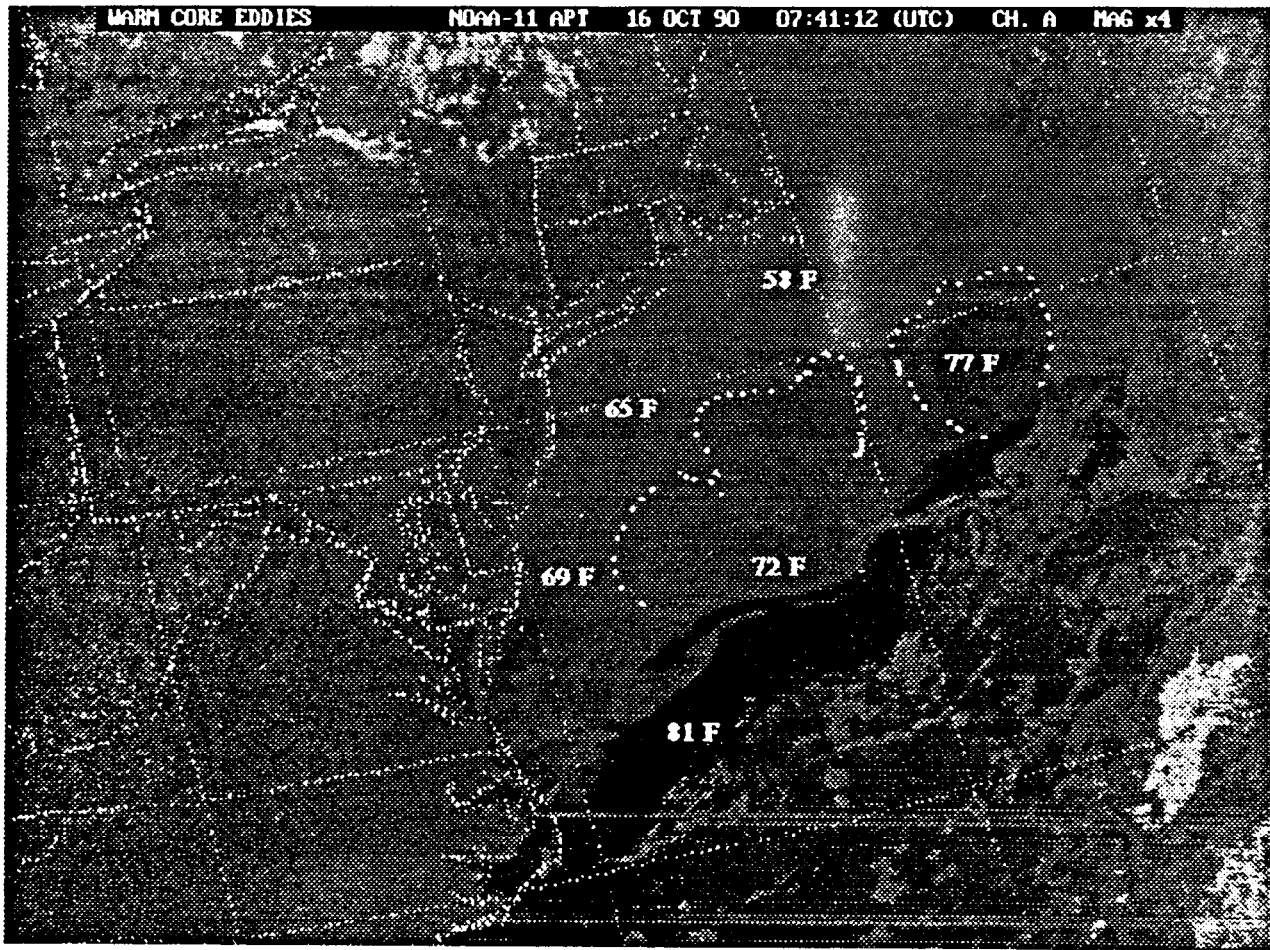
Fish seek water conditions that satisfies their metabolic, physiological, and respiratory requirements for life. By knowing their comfort zone, it becomes possible to predict where fish will be. Temperature is a key factor. Bottom features are also important.

Experiments have demonstrated that many commercially valuable species of fish such as salmon, anchovies, and tuna, have a strong preference for particular ocean temperatures. The Table below illustrates the temperature where selected gamefish are likely to be located. Yellow fin and big eye tuna live in water between 64° and 80° Fahrenheit, but they prefer 73° F. Bluefin tuna like water that is a degree or two cooler. The comfort zone for blue marlin is within 70° to 88° F; whereas white marlin thrive in water that is about 5° cooler.

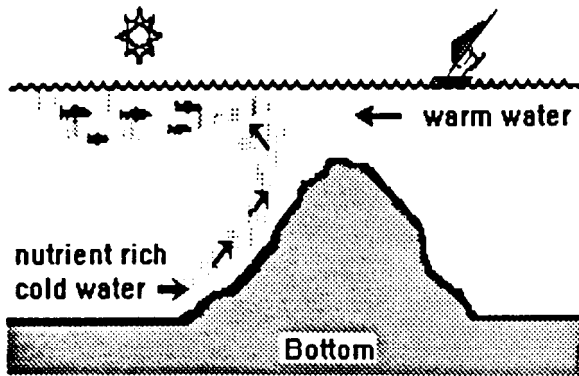
**Temperature Ranges for Some Gamefish (Degrees F)**

Species	Min	<u>Optimum</u>	<u>Maximum</u>
Amberjack	59	65	74
Blackfin tuna	70	74	82
Blue Marlin	70	78	88
Gulf kingfish	58	70	88
Yellowfin tuna	64	73	80
Bluefin tuna	62	71	78

Image 7.2 showing Gulf Stream in the western Atlantic Ocean was captured from an early morning NOAA 11 pass. The temperature of the Gulf Stream is 81° F. Three warm core eddies are apparent in the image. The circulation in the eddies is clockwise. All three eddies lie along the hundred fathom line with the continental shelf along their northern edges. The eddies are moving several miles each day in a southwesterly direction along the 100 fathom curve. Fishermen look for temperatures of about 72° to 77° F, about the temperature of the eddies. They also watch for locations where nutrient rich bottom waters may be lifted up onto the continental shelf.



**Image 7.2 Three Warm Core Eddies Along the Continental Shelf.**



Water temperature can also be used to find the areas where fish are eating or spawning. Areas of vertical upwelling, of deep cold nutrient-rich water can easily detected with infrared imagery. These nutrients, when combined with available sunlight near the ocean's surface, cause an increase in plankton growth and thus mark areas for fish feeding and spawning. Upwelling areas tend to be highly productive and are often the site of important fisheries, such as the anchovy fishery off the coast of California. Upwelling is largely

caused by wind stress and occurs off the west coast of continents. Winds favorable to upwelling vary on a time scale of 3 to 5 days. Upwelling can also be caused by the bottom topography as illustrated in the picture to the left.

Upwelling and its effects on food production have been related to the survival of juvenile salmon after they leave the Columbia River and enter the Pacific. The young salmon tend to stay within 28 kilometers from shore in the narrow belt of the river's plume. However, they count on nutrients from upwelling coastal waters for food production.

#### 7.4 Summary and Discussion

Thermal infrared imagery is used to locate fish populations, trace ocean current boundaries, optimize ship routes, and support other maritime activities. Sea-surface temperature data from satellite infrared imagery are used to prepare eddy forecasts for offshore oil exploration and production. Temporal changes in eddy size and position and current frontal locations are used to produce routine summaries of eddy positions and the direction of surface currents. Temperature maps can also be used to estimate the global uptake of carbon dioxide, the primary greenhouse gas, by ocean biomass. The productivity of our oceans and coastal environment is a major environmental concern for the 1990's. Marine plankton biomass accounts for at least 30 percent of the total global annual plant storage of carbon dioxide.

You class may want to select one of the following research topics for further study and discussion. How does the temperature of ocean waters effect cloud formation? Hypothesize and test how currents at the surface of the ocean compare with bottom contours? What are the advantages of knowing the location of the Gulf Stream?

Global Change research is now focusing on anomalous warm ocean conditions in the Pacific called El Nino events. These events appear to reduce upwelling along the western coast of the United States. Based on this observation, you might hypothesize how an El Nino event would effect plankton productivity. What would be the possible feedbacks to carbon dioxide storage in the ocean? You can test your hypothesis by collecting, logging, and mapping the change in ocean temperature over the school year.

## **Unit 8: Applications of Visible Images to Agriculture**

This unit examines the role of APT satellite weather data in agricultural applications. The skills learned in earlier units will be applied to interpreting selected APT images captured during the fall and winter growing season of a winter wheat producing area in the Pacific Northwest. The region is diverse in terrain, soil characteristics, and vegetation providing an interesting opportunity to test your image interpretation skills. The objective is to familiarize you with agricultural issues while providing an opportunity to characterize satellite imagery in the visible and infrared spectrum. This unit will assist you in becoming familiar with mapping and charting. You will distinguish snow cover from clouds and appreciate the importance of orographic lifting to producing precipitation along mountain slopes. This unit illustrates to educators and students the importance of timely weather and remote sensing data to the farming community.

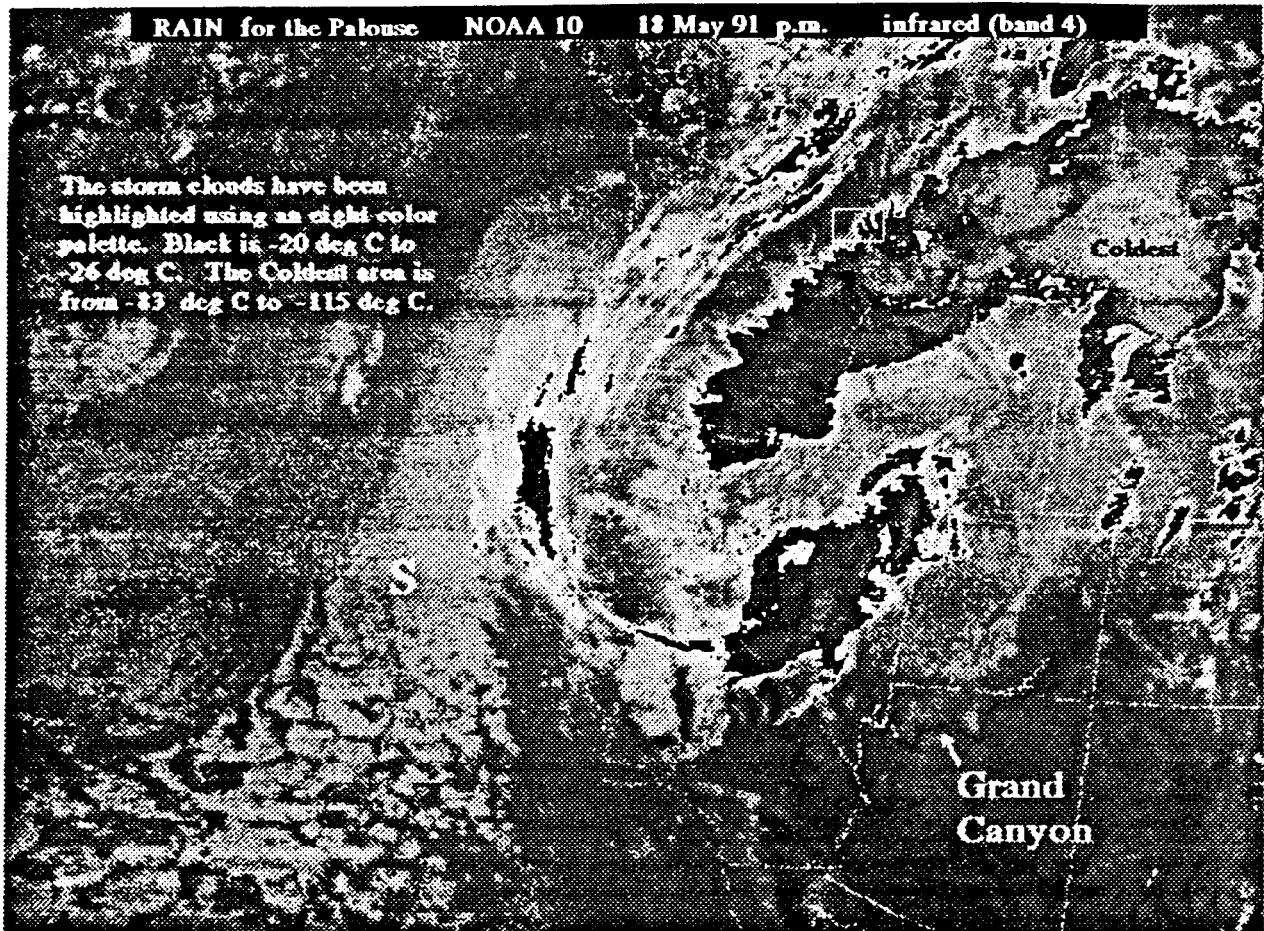
### **8.1 Timing of Tillage and Field Operations**

The use of APT signal reception and imaging from polar orbiting satellites when used in conjunction with WEFAX signal from geostationary satellites allows tracking storm fronts and other significant weather systems. An estimate of the relative intensity of weather systems can be made by monitoring the temperature of the cloud tops. This type of information is useful for scheduling the timing of tillage and other field operations.

Initial spring tillage operations for dryland small grain production in the inland Northwest are ideally begun when soils have drained and firmed enough to minimize compaction from tillage equipment. Soil temperatures should be warm enough to promote germination of planted seeds and the development of a healthy seedling. If initial tillage of over-wintered plowed ground is followed by heavy rains, soils high in clay content will retain that moisture and dry more slowly than if tillage had not occurred. This is due to a relative loss of porosity of the soil mass because larger air pockets created by plowing the previous fall are eliminated by the initial spring tillage. The rough, domed ridges left by plowing are also reduced, producing a finer more uniform soil surface. The total surface area exposed to the air is also reduced, thus reducing the capacity for evaporative drying. The timely delay of the initial tillage until after passage of an impending heavy or prolonged rain can ultimately lead to an overall quicker sequence of tillage operations in preparing the seed bed for planting.

### **8.2 Herbicide Selection and Timing of Application**

Decisions based on recent past and near term future weather conditions contribute to the most economical and environmentally safe use of herbicides used to suppress or eliminate noxious weeds in agricultural fields. Both the crop under cultivation and the herbicide chosen for use on that crop can be sensitive to and respond to changes in weather conditions following the period of application. Extremes of cloudiness (as it affects incoming solar radiation and the resulting level of photosynthetic activity within a plant), temperature,



**Image 8.1 Infrared image of a storm effecting herbicide application.**

rainfall, individually and collectively, influence the activity of the herbicide and the response of weeds and the desired crop to that activity. By tracking weather systems which may pose problems or offer specific benefits to the use of certain selective herbicides, it is possible to alter the timing of application or lessen the concentration of product used. For example, NOAA infrared Image 8.1 depicts a storm affecting the interior West and Northwest on May 19, 1991. The center of low pressure is over Nevada and backwash from the counter-clockwise circulation is moving from Montana through Idaho into the Palouse region of eastern Washington. On May 17 a pre-emergent herbicide application for broadleaf weed control was needed in a seeded field near the Washington-Idaho border. Crop emergence was one to two days away. The storm had been tracked for several days prior to the application date. Based on the intensity of the system as estimated by measuring cloud top temperatures and the general direction of movement, significant rainfall appeared imminent. Because the particular herbicide being applied relies on rainfall to carry it into the root zone of germinating weed seeds and excessive rainfall can carry the product deeper in to the zone of germinating crop seed with the potential for crop damage, a 20 percent reduction in the concentration of product used was made at the time of application. The image shows the storm in the middle of delivering a two day rainfall total of .82 inches as recorded near the application site. This is about 60 percent more rain than necessary to properly place the herbicide within the zone of germinating weeds. To date weed control

has been excellent and there is no evidence of crop damage. Results of the application will continue to be monitored and used in future decision making.

Apart from rate reductions as in the previous example, if a choice of herbicides is available, it may be possible to select a different herbicide which will more closely fit the expected weather condition. In some instances, given impending severe weather conditions, it may be necessary to forgo the application altogether for the sake of crop safety.

### **8.3 Timing of Additional Field Operations**

In the later phases of the production cycle certain crops, such as alfalfa, hay, grass hay and pulses (lentils, dry peas etc.) are mowed or swathed into rows and a period of warm, dry weather is needed for the crop to cure and achieve proper moisture content. This precedes baling in the case of hay or harvesting in the case of pulses. A prolonged period of sustained rains after swathing interrupts the drying process and can cause substantial economic losses from a degradation of crop quality or from spoilage due to the growth of microorganisms such as fungi. Delaying the swathing process to avoid damage from approaching excessive rainfall or high winds is clearly advantageous.

### **8.4 Winter Wheat Season in the Palouse**

The Palouse, in Whitman County of eastern Washington is famous for dryland farming, particularly the production of lentils and winter wheat. Farmers of the Palouse routinely average 60 to 80 bushels of wheat per acre. In years with favorable weather conditions throughout the growing season, areas of the Palouse will average 90 to 100 bushels per acre.

The Palouse, which spans the Washington-Idaho border and lies about 200 miles from Washington's Mount St. Helens, is unusual not only for its agricultural productivity, but because its rolling terrain is rugged for farming. Hilltops in the Palouse, unlike the windswept hills of the midwestern prairies, are still relatively productive. Soil erosion from excessive rains is a problem, but farmers and equipment engineers continue to develop new farming practices and design new machinery to protect that vital resource.

The winter wheat crop is usually planted in September and early October for harvest the following summer. Fall rains are responsible for germinating planted seeds on annually cropped ground. Many farmers regard management of this moisture as a necessary first step in establishing a healthy stand of wheat. Following emergence, the wheat's root system continues to develop and the plant should reach the three to four leaf stage before cold temperatures of late fall and early winter harden the plant and lead it to a state of dormancy.

As we track the weather from planting of winter wheat in September until early spring, we will track the health of the crop as reported in the *Weekly Weather and Crop Bulletin* for the same time period. This publication is produced jointly by the U.S. Department of Commerce and the Department of Agriculture. Each issue begins with a short, general

description of major weather patterns for the nation, then follows with a one paragraph summary of agricultural activities for each state. The agricultural community subscribes to this publication because it gives them a look at general weather conditions in agricultural regions world wide which produce the same crops and thus compete in world markets. For example, Australia raises the same type of wheat (soft white) as farmers in the Pacific Northwest and is therefore a competitor for sales in the Middle East and Southeast Asian markets. Although publications like the *Weekly Weather and Crop Bulletin* are valuable publications, they are not timely. They are usually received several weeks and sometimes up to a month after the fact. Farmers cannot rely on information which is basically historical for time sensitive decisions. This is an area where satellite delivery of images and information really helps out.

The following series of Soviet Meteor images illustrates how snow cover can be monitored in a general way in mountains or in areas of agricultural production. Farmers depend on adequate snow cover to insulate fall seeded wheat and barley plants which have emerged and are vulnerable to damage or winter kill by cold arctic air. The developing crop is especially at risk when strong winds also accompany low temperatures. In addition to causing sever dehydration, fine soil particles and ice crystals can be blown so swiftly along the ground that exposed leaves can be shredded or cut off at the crown of the plant.



September:

Early September through mid-October mark the planting season for winter wheat in eastern Washington. In early September the weather is suitable for fieldwork as illustrated in this September 13, 1990 Meteor pass which covers an area from south central California to British Columbia. A high pressure system persists over the west and clouds cover the north coastal area of the Olympic Peninsula of Washington State. Mounts Olympus, Baker, Rainier, Adams, Hood, Shasta, Lassen and ash laden areas around Mt. St. Helens are visible as white dots on the image attributable to clouds covering their peaks. If you examine this image closely, you should be able to find numerous lakes including Lake Banks, Lake Roosevelt, and the Potholes Reservoir in Washington. It is also possible to discern Pend Orielle and Coeur d'Alene nestled in forested areas of Oregon. Further examination of the image reveals Utah's Great Salt Lake and California's Tahoe, Mono, and Goose lakes and the Snake and Columbia Rivers. Old growth timber of the Olympic National Forest is distinct as well as the channeled scablands of central Washington.

The lighter areas of the image, between the Columbia River and the Blue Mountains of southeastern Washington, are harvested croplands. Harvested areas are also apparent north and east of the Snake River eastward to the foothills of the Clearwater Mountains. This is the Palouse region. Agricultural regions of the Willamette Valley in Oregon also appear lighter as do British Columbia's Okanogan and Frazier Valleys.

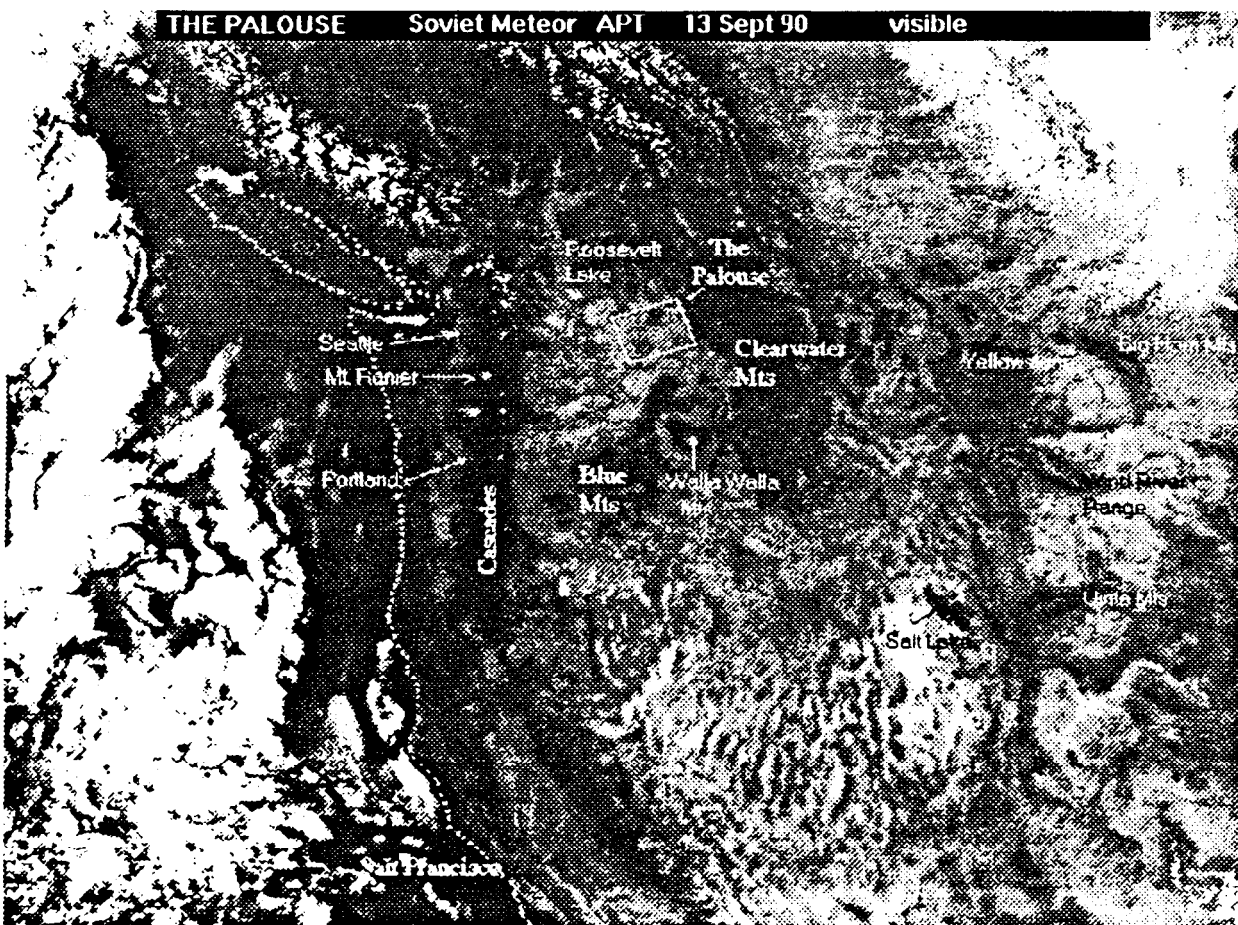
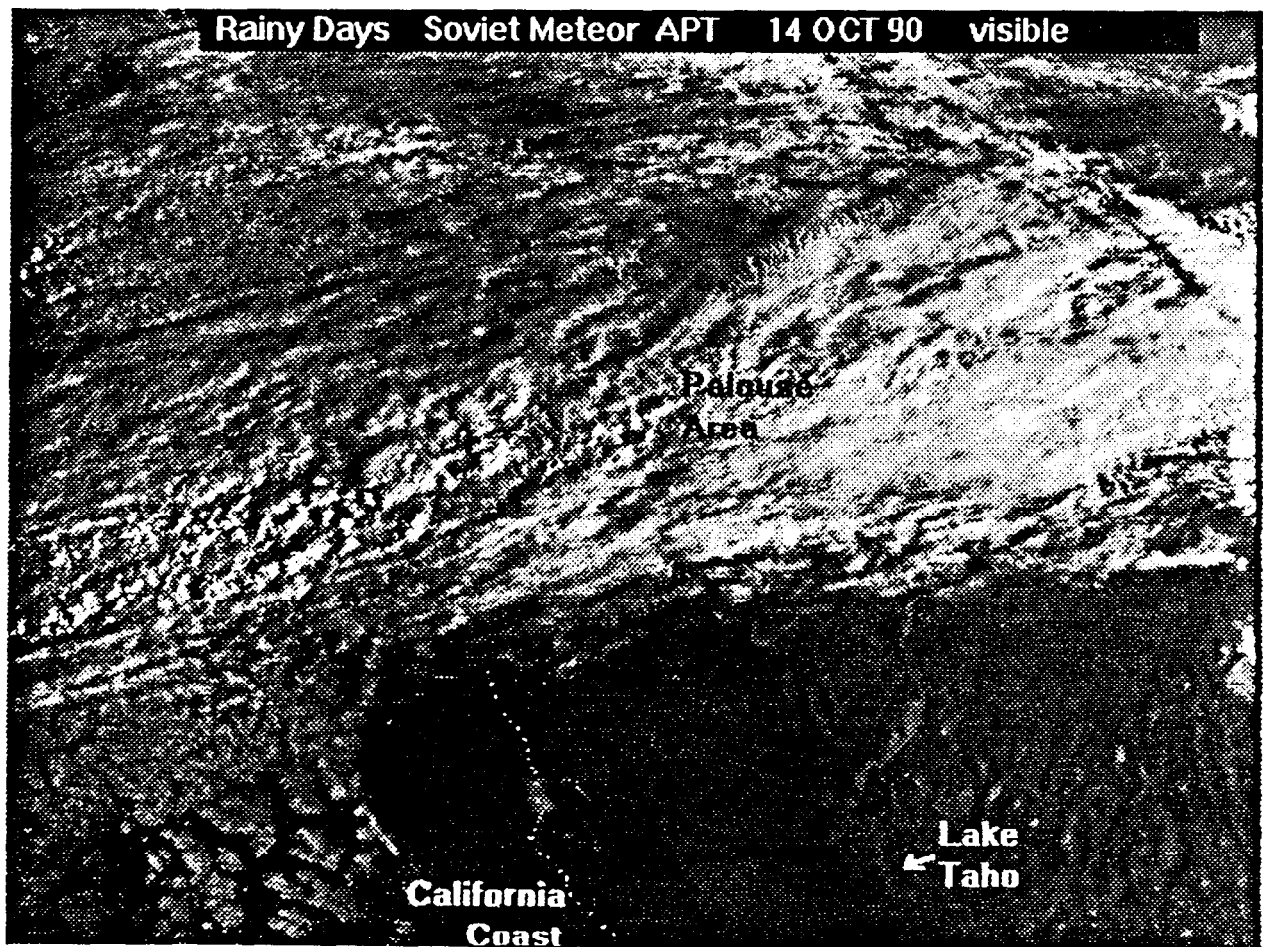


Image 8.2 The Palouse wheat growing region of Eastern Washington

October:

By October the winter wheat has emerged in the Palouse. The *Weekly Weather and Crop Bulletin* for October 23rd indicates that the crop is in good to fair condition across the area. Based on favorable weather conditions, the crop is off to a fine start. This image, captured on October 14th shows overcast conditions. Precipitation measured about .68 inches in near Tekoa in the Palouse. The first snowfall can usually be expected around the end of October.

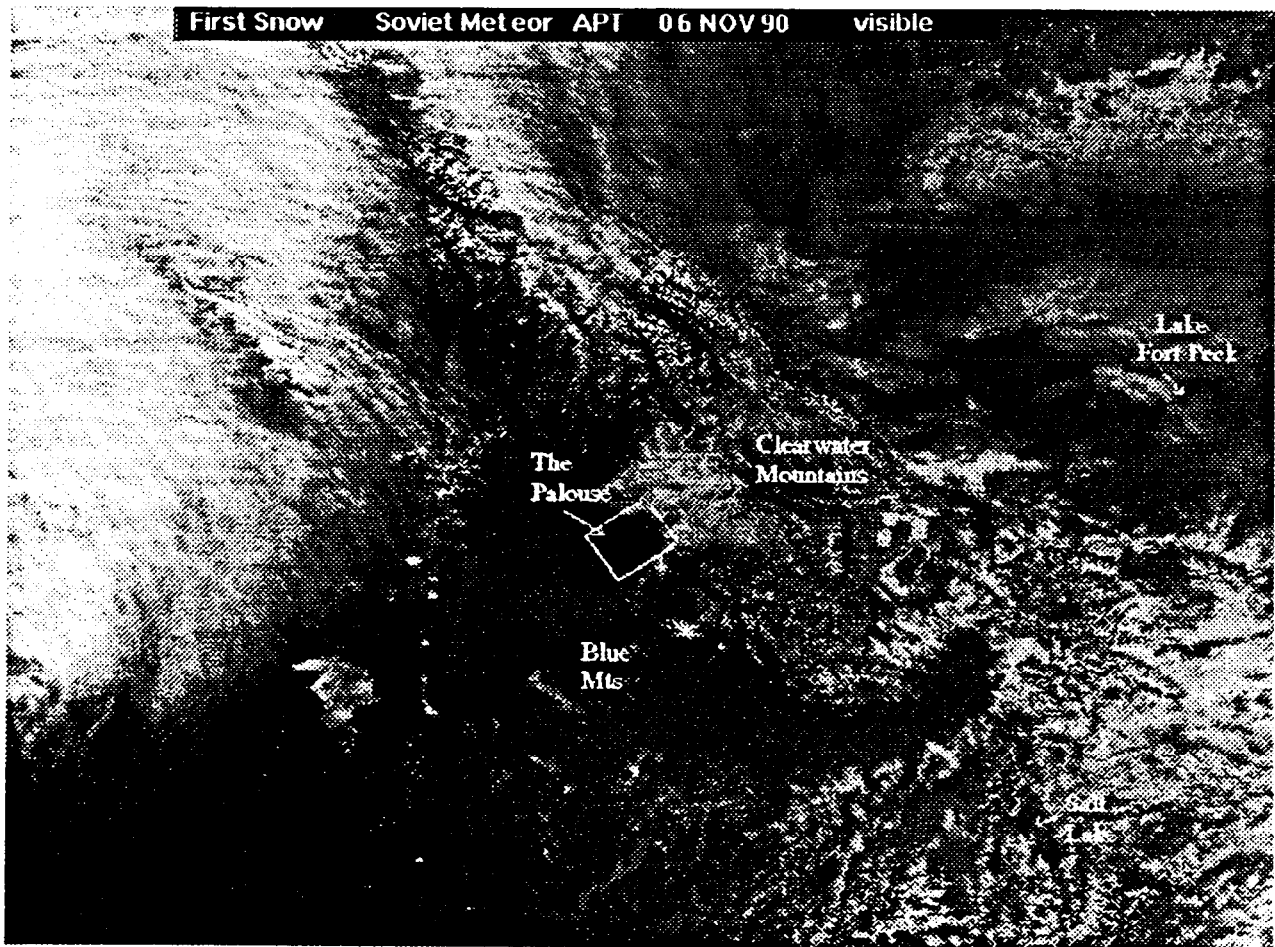


**Image 8.3 Rain after planting starts the crop off right.**

November:

The first snowfall of the season occurred on November 6, 1990. The higher elevations of the Rockies and Cascade range are showing snow accumulation from a previous storm. Some snow cover exists in Montana around Lake Fort Peck and in Saskatchewan in the area north of Lake Diefenbaker around Saskatoon. The cloud mass in the center of the image covers the eastern most portions of the Palouse and the panhandle of northern Idaho. This image illustrates why the Palouse is the prime dryland farming region of Washington State and northern Idaho. Air in the region is generally dry because it has lost its moisture in crossing the Cascades to the east. However, some moisture occasionally remains. As moisture laden air approaches the foothills of the Clearwater Mountains and rises, it cools and precipitation occurs more readily. Normally this produces annual rainfalls which are ideal for the production of small grains (wheat and barley), legumes, and turfgrass seed.

On November 6th 0.07 inches of mixed snow and rain was recorded with a snow accumulation of .5 inches under partly cloudy skies. The high temperature was 44° F and the low temperature was 32° F. The next storm system approaching from the Pacific already obscures the Olympic Peninsula. The *Weekly Weather and Crop Bulletin* lists winter wheat in eastern Washington as 15 percent fair, 65 percent good.

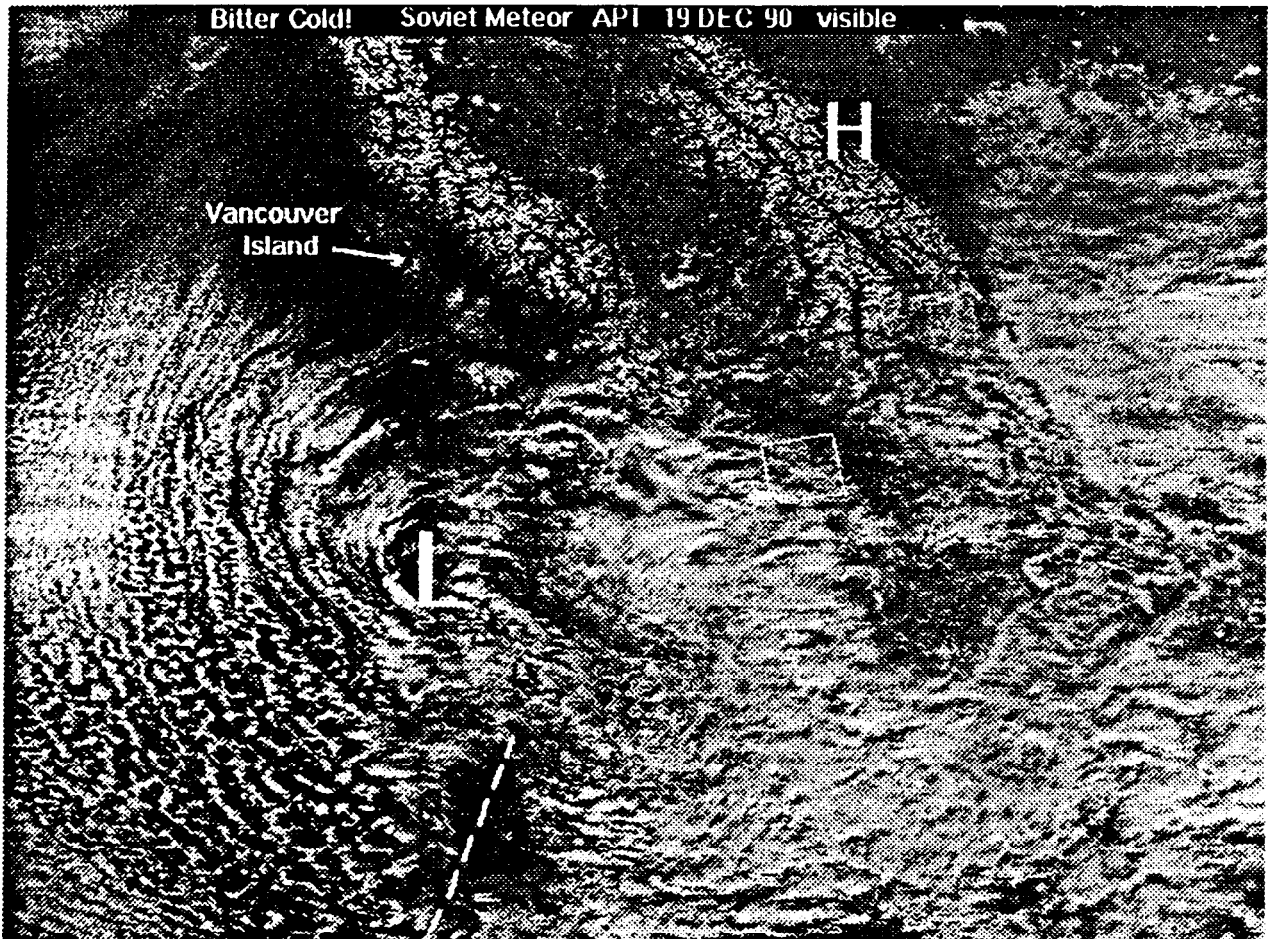


**Image 8.4 November's first snowfall is disappointing at lower elevations.**

The November image reveals how scant snow cover was in the Palouse region of eastern Washington at that time. Good protective ground cover is not observed until we examine the areas around Dayton and Walla Walla in southeastern Washington. Basically this held true until December when depicts arctic air moved into the area from a high pressure system over Canada to a low pressure center in southern Oregon.

December:

On December 19, 1990 a high pressure system was over western Canada and a low pressure system centered over coastal southern Oregon. These are conditions which farmers in the Palouse dread because they cause a frigid air mass to move quickly into the area from the northeast. Winds associated with this air mass are usually strong. Temperature extremes dropped from high a high of 42° F and a low of 30° F on December 17th to a high of 8° F and a low of -2° F on the 19th. Only a trace of snow is recorded leaving most areas of winter wheat exposed to punishing conditions. The depth of frozen soil fell from 4 cm on December 17 th to 40.8 cm on December 25th.



**Image 8.5 December's frigid air and high winds cause widespread damage.**

Just west of the Blue Mountains around Dayton and Walla Walla a heavier amount of snow accumulated providing an insulation layer over the wheat. Overall, though, this storm proved to be very damaging to the developing crop. The *Weekly Weather and Crop Bulletin* of December 16-22 rated Washington winter wheat crop 72 percent good and 8 percent poor to very poor. In January the bulletin reported " Winter wheat has been damaged by strong winds, extreme cold temperature in central, eastern areas." By the end of January the winter wheat crop was rated as 32 percent fair, 60 percent poor, and 8 percent very poor. By February, 58 percent of the winter wheat crop was rated as in very poor condition.

By tracking snow cover in agricultural regions as was done in these APT images, farmers and seed supply companies can monitor how widespread an area is susceptible to damage from arctic air masses if snow cover is not present. This information can serve as an early warning to growers and gives them an opportunity to insure adequate supplies of spring wheat varieties are reserved in case widespread reseeding of winter killed areas is required.

The same arctic front that damaged the winter wheat crop of northeastern Washington, was also responsible for widespread damage to fruit trees in California's San Joaquin and Imperial Valleys during the winter of 1990.

## Glossary of Terms and Acronyms

**Adiabatic** - A thermodynamic process that takes place without external exchange of heat.

**Advection** - Process of heating or cooling an air mass by transporting it horizontally over an object of different temperature.

**Amplitude** - Size of the vertical displacement produced by a wave.

**APT** - Automatic Picture Transmission. Term for the low data rate satellite weather broadcast.

**AVHRR** - Advanced Very High Resolution Radiometer. The name of the instrument on NOAA's TIROS-N satellite series.

**Black Body** - A perfect absorber and emitter of radiation. An object that emits an amount of radiation equal to the amount it absorbs.

**Brightness** - Radiated energy flux entering the satellite sensor's field of view from an object beneath. The direction of radiation differentiates brightness from radiance. Incoming radiation is brightness.

**Convection** - Process of heat transfer through vertical motion caused by unequal heating of the atmosphere.

**Dendritic Pattern** - A tree or branch-like pattern of snow as imaged from a satellite.

**Dew Point Temperature** - The temperature to which air must be cooled to reach saturation.

**Electromagnetic Radiation** - Energy transmitted through space in the form of electric and magnetic wave fields.

**Electromagnetic Spectrum** - The ordered arrangement of electromagnetic radiation as a function of wavelength.

**Emissivity** - The ratio of the observed brightness of an object to the ideal brightness if it were a black body.

**Frequency** - The number of waves passing a given point per unit time.

**Front** - The boundary zone between two air masses with different properties.

**Gust Front** - Arc shaped line of convective clouds ahead of a mature thunderstorm caused by downdrafts out the bottom of the storm.

**Histogram** - A statistical representation of a digital image showing the number of grey shades and the frequency of occurrence of each shade.

**Hurricane** - A warm core tropical storm with winds in excess of 64 knots.

**ITCZ** - Intertropical Convergence Zone. A permanent belt of low pressure around the equator.

**Jet Stream** - A belt of strong westerly winds aloft. The height of the jet stream is typically between 10 to 12 kilometers (6.2 to 7.5 miles).

**Latent Heat** - The heat released or absorbed by a substance when it changes state.

**Latitude** - Distance on the Earth's surface measured in degrees north and south of the equator.

**Longitude** - Distance on the Earth's surface measured in degrees east and west from the prime meridian.

**Meridional Flow** - A condition when the amplitude of upper level flow is large and conducive to mixing of cold and warm air masses.

**Nadir View** - A view directly down from the satellite to the earth at its closest point. This point will be along a line from the satellite to the center of Earth.

**NOAA** - National Oceanic and Atmospheric Administration. A division of the Department of Commerce that operates the National Weather Service and the National Environmental Satellite Data and Information Service.

**Optical Thickness**- The collective effects of scattering and absorption of light in the atmosphere.

**Orographic Lifting** Lifting of an air mass as it is transported over mountains.

**Pixel** - picture element. The smallest resolvable unit of an image. The fundamental building block of a digital image.

**Radiance** - Energy flux leaving a unit area into a cone shaped solid angle defined by the satellite sensor field of view. The direction of radiation differentiates radiance from brightness. Radiance is outgoing energy from an object.

**Radiometer** - An instrument that measures radiation brightness within a fixed band of wavelengths.

**Reflectance** - The ratio of the energy flux reflected from an object to the energy incident on it. If the reflectance = 1, then one energy is transmitted or absorbed by the object,

**Remote Sensing** - A method of measuring properties of objects without making physical contact.

**Ridge** - A region of upward displacement of a wave. In meteorology, the location of maximum clockwise curvature on an atmospheric wave.

**Saturation** - When evaporation equals condensation.

**Spectral Signature** - The reflectance, absorbance and transmittance of an object.

**Stretching** - Enhancing the contrast of an image over a selected range of pixel values.

**Trade winds** - A consistent easterly wind in the tropics. North of the equator the trades are from the northeast. South of the equator they are from the southeast. Trade winds are a major component of the atmosphere's general circulation.

**Transmittance** - The probability that light reflected or emitted from the earth's surface will arrive at the satellite. The probability that light will be transmitted through the atmosphere.

**Thermodynamics** - The study of the solid, liquid, and gaseous states of a system.

**Transverse Bands** - Cloud bands perpendicular to the air flow that are associated with turbulent wind shear along the jet stream.

**Tropical Depression** - Closed rotary flow around a low pressure area over the tropical ocean. Winds less than 34 knots.

**Tropical Disturbance** - Weak rotary air circulation 160 to 300 kilometers across associated with a low pressure area over the tropical ocean.

**Tropical Storm** - A closed rotary flow around a low pressure system over warm tropical ocean. Winds of 34 to 63 knots.

**Troposphere** - The lowest portion of the atmosphere characterized by decreasing temperature with altitude - usually about 15 kilometers (9.5 miles) deep. The layer in which all weather takes place.

**Trough** - A region-of downward displacement of a wave. In meteorology, the location on an upper level wave where the wind shifts from the northwest to the southwest.

**Wave** - A massless pattern that moves with regular oscillations.



**Wavelength** - The interval at which a wave pattern repeats itself. Can be measured from peak to peak or trough to trough.

**Westerlies** - A consistent wind from the west occurring in the mid-latitudes. A major component of the general circulation of the atmosphere.

**Zonal Flow** - A condition when the amplitude of the upper level flow is small.