Satellite Observations of Atmospheric and Surface Meteorological Phenomenas

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Abstract: In this paper is introduced the atmospheric and surface meteorological phenomenas very important for determination and identification satellite images. In the first place are included particulars regarding clouds and their low, middle and high levels. Then are described characteristics of atmospheric depressions and storms satellite data and in particulars are depicted tropical and extratropical cyclones, severe thunderstorms and lightning. This paper will also introduce the additional phenomenas of intertropical convergence zone, cold front structure and warm front structure.

Keywords: NWP, Clouds, ISCCP, WCPR, Storms**,** Lightning, ITCZ, Weather Fronts Structures, Warm Front Structure

1. Introduction

The satellite meteorological observations and imaging network help to visualize atmospheric phenomenas, including clouds in the real-time basis, atmospheric depressions, convergences and frontal structures. These important observations have been used for not only weather forecasting, but also climate change detection and atmospheric research. With the advance of sensor technology, the temporal, spatial and spectral resolution of satellite observation continues to be improved.

The receives observation data from polar and geostationary meteorological satellites has been used to generate various above stated meteorological products, including atmospheric motion vector, sea surface temperature, fog stratus, Asian dust, cloud information, etc. The products as well as imagery data are distributed to forecasters and users through Internet and Intranet, as soon as processed. Some of these products are also ingested into the data assimilation of Numerical Weather Prediction (NWP) models, which are the form of weather model data most familiar with on a day-to-day basis.

The detection of certain important meteorological or other phenomena when viewed alone are not optimal, which can be detected only in image products combined with two or more spectral bands. With an introduction to the characteristics of meteorological satellite imagery and some of the sources for error, now it is possible to look at examples of the phenomena that can be identified from the imagery. Several references are available that give detailed analysis techniques for identifying specific phenomena on a satellite image.

It is well known that the information about the vertical profile of the atmosphere is essential for understanding atmospheric conditions and accurate weather forecasting, which concerns pressure, geopotential height, temperature, dew point temperature, wind direction and wind speed twice a day (0000 UTC, 12 00 UTC) under regular weather conditions and four times a day (0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC) under severe weather conditions.

2. Clouds

Clouds are visible meteorological collections of particles of water or ice suspended in the air and aerosol comprizing a visible mass of minute liquid droplets, frozen crystals or particles suspended in the atmosphere above the atmosphere at an elevation above the surface of the Earth. Clouds are the single most informative feature on the satellite image and in some cases the most difficult to analyse. Thus, the presence of clouds is often the only clue to provide a significant meteorological process occurring in the atmosphere.

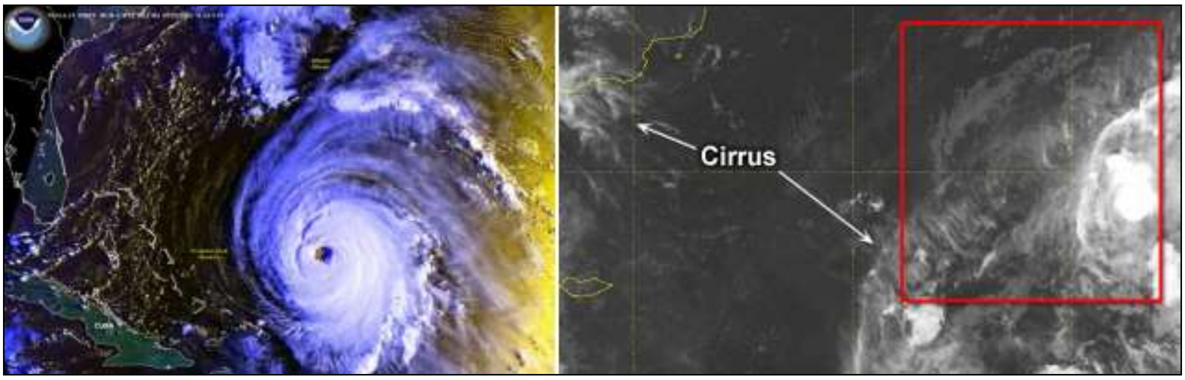

Figure 1. VIS Imagery of Hurricane Isabel and DMSP OLS Nighttime IR image over the Arabian Sea – Courtesy of Manuals: by NOAA/UCAR

The droplets and crystals may be made of water or various chemicals. On Earth, clouds are formed as a result of saturation of the air when it is cooled to its dew points, or when it gains sufficient moisture (usually in the form of water vapor) from an adjacent source to raise the dew point to the ambient temperature. They are seen in the Earth's homosphere, which includes the troposphere, stratosphere and mesosphere. Nephology is the science of clouds, which is undertaken in the cloud physics branch of meteorology.

Both the character and the extent of the clouds are important, as well as the specific location of the cloud mass. Besides, in some cases the absence of clouds is more significant than the occurrence of clouds. It will be possible to look at some of the characteristics of clouds and examine how they can be detected. There is a possibility also to examine some of the clouds properties that occasionally make them difficult to detect.

Clouds indicate the presence of moisture and some type of cooling mechanism. Thus, the most common cause of cooling is upward vertical motion (convection) that causes adiabatic expansion. Less common, but important for cloud formation, are radiative cooling and the advection of warm, moist air over a cool surface or cold air over a warm, moist surface. The presence of clouds indicates that one of these mechanisms is or has been, occurring. The type of cloud and its height present further clues about the process that is responsible for it.

To understand cloud, it will be necessary to examine the characteristics of clouds in standard height categories. The commonly accepted layers are low, middle and high clouds, with some clouds, such as cumulonimbus, spanning all three atmospheric layers. In midlatitudes low clouds are typically found below 3 km, middle clouds between 3 and 7 km, and high clouds between 7 and 12 km, with cumulonimbus occasionally extending beyond 20 km. Thus, the placement of clouds in the three layers is normally done using infrared imagery to assign heights based on cloud top temperature, but some cloud types are best observed in visible imagery. In this case, it also will identify some clouds that require the use of both the visible and infrared imagery for proper identification, and it will be necessary to look at the use of other channels, such as the water vapour absorption bands.

2.1. Low Level Clouds

The three main low cloud types, such as cumulus, stratus and stratocumulus, each of them exhibit characteristics that allow us to identify them on a satellite images. Cumulus clouds most often appear as individual cells or clusters of cells that are on the order of 1 kilometre in diameter, whereas stratus covers a large area, sometimes hundreds of kilometres in extent and are normally smooth in texture. Stratocumulus is normally found in bands, called streets or in large clusters. The tops of cumulus and stratocumulus also have a more "lumpy" texture than stratiform clouds.

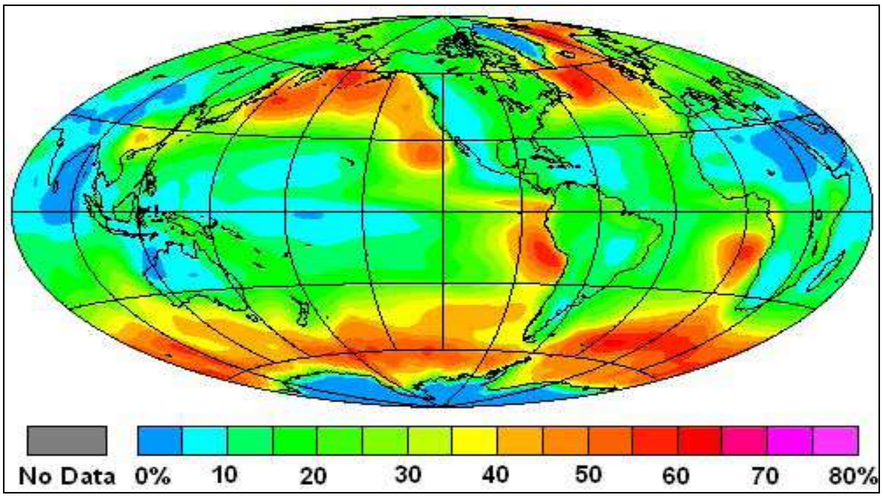

Figure 2. Low Level Annual Cloud Amount – Courtesy of Manual: by WCPR

Some low clouds are difficult to identify without the use of a visible image or knowledge of the underlying surface. Thus, in **Figure 1 (Left)** visible image shows low-level stratus clouds together with high-level clouds around centre or cyclone. However, **Finure 1 (Right)** is showing DMSP OLS Nighttime IR image over the Arabian Sea, which is unable to detect tropical cyclone circulation features due to lack of thermal contrast between low level clouds and water surface, taken at 1605 UTC (local evening) on 12 November 1997. In the same picture produced by the Air Force Weather Agency (AFWA) are depicted two areas of high level clouds cirrus. In fact, deep convection or thick cirrus cloud is both cold and optically thick and therefore is bright in either a visible or an infrared image. Because the infrared image is a display of radiative temperatures, the cloud and ground may appear nearly the same temperature on the infrared image (in some cases where a strong temperature inversion exists, the clouds may even appear warmer than the underlying surface). In the visible, however, the clouds most often appear bright because of the high Albedo of the cloud tops compared to that of the land or water surface.

Here is shortly introduced the International Satellite Cloud Climatology Project (ISCCP) established as the first project of the Word Climate Research Program (WCPR), which began in 1982 as a project to develop climatology of cloud radiative properties. Low clouds over the ocean are extremely important for the energy balance of Earth because their Albedos are much higher than that of clear sky over ocean and they have only a small effect on escaping longwave radiation. In **Figure 2** is illustrates the **a**nnual ISCCP C2 inferred status cloud amount percent, which slows the annual mean abundance of clouds with tops at or below the 680 MB level (heights less than about 3 km) from ISCCP. Low clouds are abundant over the oceans and are especially common in high latitudes and over the eastern margins of the oceans where low sea surface temperatures and atmospheric subsidence encourage their presence. Also shown is the annual mean net cloud radiative forcing, the amount by which the clouds that are present in the current climate change the net energy balance at the top of the atmosphere.

There is a remarkable similarity between the distribution of the fractional area coverage by low clouds and the net forcing of the climate by clouds. This is because the low clouds are relatively abundant where they occur. They have a strong negative effect on the energy balance because they reflect a lot of solar radiation and yet their tops are warm enough that they have only a small effect on the amount of emitted thermal radiation. The amount and optical properties of low stratiform clouds are sensitive to both atmospheric and oceanic large-scale properties and to the abundance of cloud condensation nuclei, which may be affected by human activities such as the burning of fossil carbon.

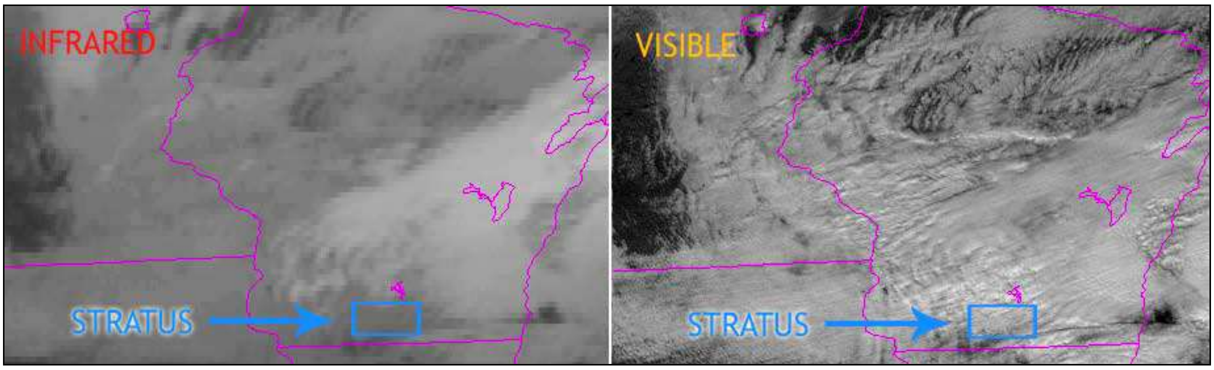

Figure 3. Infrared and Visible Low Level Clouds – Courtesy of Manual: by NOAA

These sensitivities combined with their strong effect on the radiation balance give them the potential to play a major role in climate change. Stratus clouds are shown in **Figure 3 (Left) as** IR satellite image that measures thermal energy, and in **Figure 3 (Right)** is shown visible that using reflected light. Stratus clouds are usually uniform and featureless, appearing gray or dullish white rather than blue.

2.2. Middle Level Clouds

Characteristics of middle-level clouds are similar to those of low clouds, except that they are not as difficult to distinguish from the underlying surface on an infrared image because they are much colder than the surface, which is shown in **Figure 1.** Exceptions are extremely cold wintertime outbreaks over high and midlatitudes, and mountainous terrain where the surface reaches middle cloud altitudes. Middle clouds can be either stratiform (altostratus) or cumuliform (altocumulus) used to infer processes that extend into the midtroposphere.
The prefix “alto” indicates middle-level clouds. Mid-level clouds offer scientist information about the middle part of the troposphere. Recall that the troposphere is the lowest part of the Earth's atmosphere where conditions support living organisms, although the stratosphere, mesosphere, and thermosphere also play their part supporting life on Earth.
Altostratus clouds develop when the middle layers of the atmosphere are moist and are lifted slowly. They generally appear as a flat, featureless dark gray sheet. They rarely block out the sun and are fairly uneventful, although may be the precursors of a rain event. Altocumulus clouds tell a completely different story. The presence of altocumulus clouds in the sky means that convection is occurring quite high up. In the summer, altocumulus clouds that rise up in little castle-like turrets (castellanus) may be a precursor to severe weather. In **Figure 4 (Left)** is shown conus IR satellite image of altocumulus clouds that measures thermal energy, and in **Figure 4 (Right)** is depicted conus visible image of the same clouds using reflected light, both done by the GOES East satellite sensors.

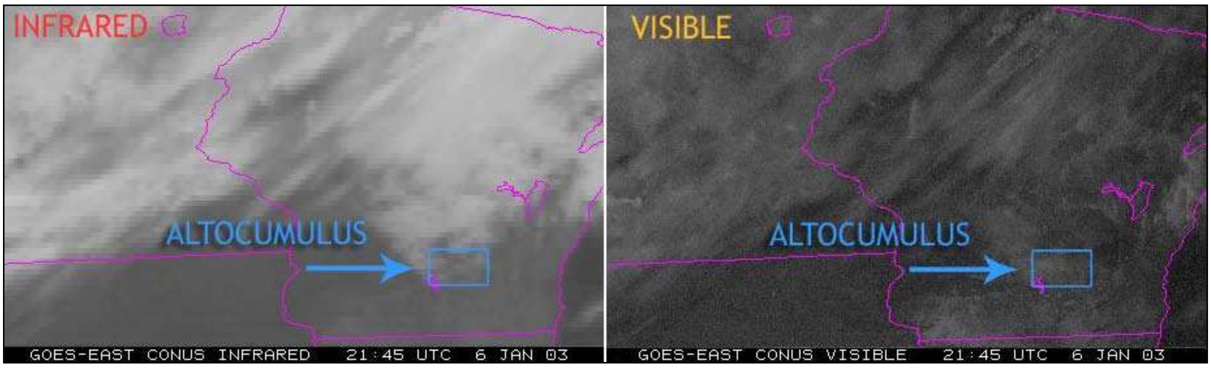

Figure 4. Infrared and Visible Middle Level Clouds – Courtesy of Manual: by NOAA

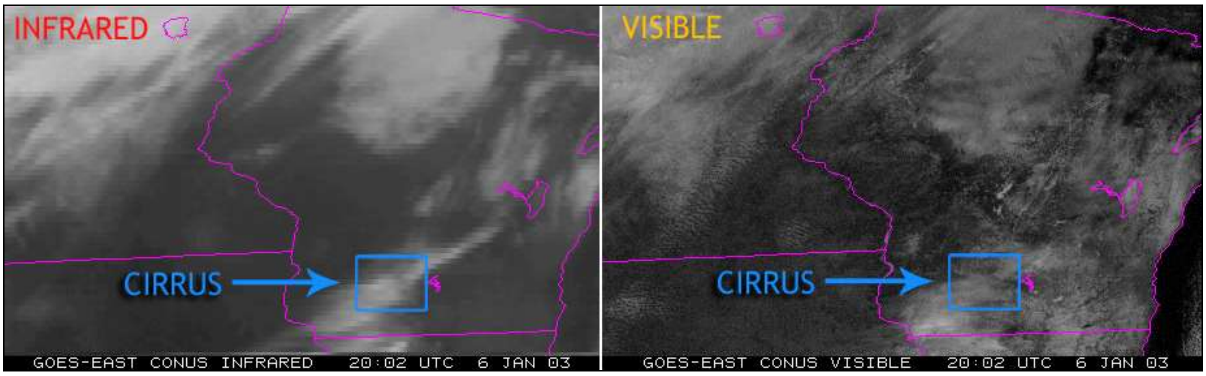

Figure 5. Infrared and Visible High Level Clouds – Courtesy of Manual: by NOAA

2.3. High Level Clouds

The biggest distinction between high clouds and other levels is the fact that they are made up of ice crystals and not water droplets. Thus, the two most common high clouds are cirrus and cirrostratus. High clouds are composed exclusively of ice crystals, and some exhibit quite unique characteristics. The majority of the high clouds are stratiform in texture (cirrostratus) and of large extent. Some cirrus can be so thin that they do not appear on the visible image. In this case, however, the infrared signature is often distinct because the ice-crystal clouds are very cold and contrast with the warmer background, which is shown in **Figure 1.**
Cirrostratus clouds are like sheets of cirrus, high, thin and continuous. They are responsible for halos and other beautiful atmospheric phenomena (a "sundog" can be seen in this picture) because the thin blanket of ice crystals causes sunlight to refract (bend) and spread out into colors of the rainbow.
Cirrus clouds are thin and wispy as can be seen in the following photos and satellite images. They are a common cloud type that occurs in vertical motions ahead of large-scale weather patterns. Cirrus are associated with all weather systems. They can also be generated by flow over mountains or in regions with strong winds, such as the jet stream. They often occur as wisps aligned in the same direction and generally do not completely cover the sky. In Figure **5 (Left)** is depicted an IR satellite image that measures thermal energy, while in **Figure 5 (Right)** is illustrated a visible satellite image using reflected light.

3. Storms

Storms are some of the most dramatic things captured in satellite meteorological data, which are de facto any disturbed state of an environment or in an astronomical body’s atmosphere especially affecting its surface and strongly implying very severe weather conditions. It may be marked as strong wind, tornados, hail, thunder, lighting, heavy precipitation (rain storm), heavy freezing rain (ice storm), strong winds (tropical cyclone, windstorm) and so on. In this section will be presented several selected types of storms.

3.1. Tropical Cyclones

Tropical cyclone is the generic term for a low-pressure system over tropical or sub-tropical waters, with organized convection (called thunderstorm activity) and winds at low levels circulating either anticlockwise (in the northern hemisphere) or clockwise (in the southern hemisphere). The whole storm system may be five to six miles high and 300 to 400 miles wide, and it typically moves forward at speeds as fast as 60 km/h. At its weak stages it is called a Tropical Depression, but when the winds reach 70 km/h it is called a Tropical Storm.

Figure 6. Tropical Cyclone Rita – Courtesy of Manual: by NOAA

Thus, if the wind should reach 120 km/h or more the tropical storm is called a Hurricane in the Atlantic and the eastern North Pacific or a Typhoon in the western North Pacific. In other parts of the world, such as the Indian Ocean and South Pacific the term Cyclone or Tropical Cyclone is used. Therefore, a tropical cyclone is a circular air movement over the warm ocean waters in the warm part of Earth near the equator. Most tropical cyclones create strong winds and heavy rains. While some tropical cyclones stay out in the sea and others pass over land. This can be dangerous because they can cause a lot of damage whilst picking up lawn chairs, lumber, garbage cans, sheets of metal, small boats and more they get tossed around at high speeds of 252 km/h.
With its unmistakable spiral shape and central eye, the tropical cyclone, including hurricanes and typhoons, is the most memorable feature on any satellite image on the Internet or such as shown in **Figure 6.** This image was taken on early 22 September 2005 by GOES-12, while hurricane Rita was at peak intensity. Indeed, if weather satellites detected nothing else besides these monster storms, they would be well worth the money invested in them. Thus, a number of techniques have been developed to estimate the movement and intensity of tropical cyclones from satellite images. One of the most widely accepted is the Dvorak technique (Dvorak, 1984), which assigns an intensity based on the size and shape of the dense cloud shield adjacent to the centre of the storm (see Loops of tropical cyclones are quite interesting. In high-resolution visible imagery, one can see low clouds spiraling inward and high clouds spiraling outward, so no tropical cyclone anywhere on Earth has gone undetected since weather satellites became operational in the mid-1960s.

3.2. Extratropical Cyclones

Perhaps the second most memorable thing in satellite imagery is the extratropical cyclone. The midlatitude cyclone model first described by Bjerknes in 1918 has been dramatically supported by weather satellites, from the cloud bands at warm and cold fronts to the swirl of clouds at the centre of a mature cyclone.

Figure 7. Extratropical Cyclone – Courtesy of Manual: by NOAA

Extratropical cyclone**,** also called wave cyclone or midlatitude cyclone depression, is a type of storm system formed in middle or high latitudes, in regions of large horizontal temperature variations called frontal zones. Extratropical cyclones present a contrast to the more violent cyclones or hurricanes of the tropic regions, which form in regions of relatively uniform temperatures.

In general, extratropical cyclones can bring mild weather with a little rain and surface winds of 15–30 km/h or they can be cold and dangerous with torrential rain and winds exceeding 120 km/h in large area, sometimes referred to as windstorms in Europe.

In **Figure 7** is shown the clouds associated with a large midlatitude cyclone storm that swept across the center of the United States. This image, taken by the GOES satellite on 26 October 2010, shows the storm system circling around the area of extreme low pressure. Thus, such extratropical cyclones form over the United States in the spring and fall, when the temperature difference from north to south is large. Cool, high-pressure air rushes toward the warmer, low-pressure air. Because the Earth is rotating, the air moving in ends up circling the area of low pressure, creating the cyclone shown in the image. The intensity of the storm is determined by the pressure difference between the center and the outer edges. In a such a way, extreme low pressure in the center of the storm, therefore, is an indicator that the storm was very intense.

However, evidence of a warm front can barely be seen at the limb of this image, but the cold high-pressure system over the central United States behind the cold front is quite evident because of the clear weather it has produced. Weldon (1983) reports on the results of a large effort to identify the relationship between cloud patterns and frontogenesis, cyclogenesis, and wind fields in general.

3.3. Severe Thunderstorms

Severe thunderstorms and potential tornadic thunderstorms can be identified on satellite imagery by several interesting signatures. Severe thunderstorms quickly extend to the top of the troposphere or beyond and are identifiable on infrared images by very cold cloud tops and by rapid areal expansion of the anvil region**.** A severe thunderstorm warning is issued by meteorologists in any local national weather office for forecast service, to eliminate a serious threat to life and property to those in the path of the storm.

By comparing the temperature of the cloud top to the tropopause temperature we can determine whether the top has reached or penetrated the tropopause. Lines of thunderstorms, called squall lines, often form at or in advance of a rapidly moving cold front, and can easily be detected on satellite imagery. Satellite loops clearly show the movement of squall lines and most often show the movement of individual cells within the line.

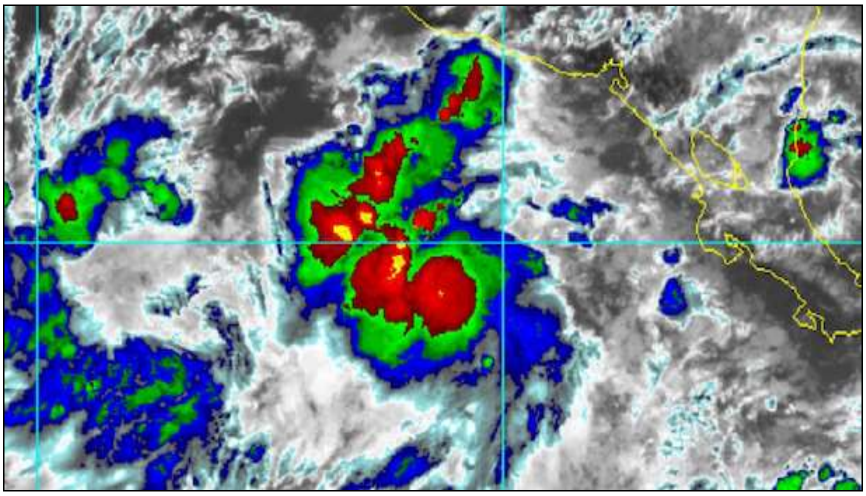

Figure 8. Thunderstorms with Lightings – Courtesy of Manual: by NOAA

3.4. Lightning

Although not a storm, lightning is an indicator of thunderstorms. Thus, a special low-light nighttimes visible sensor on board the DMSP satellite can detect lightning, even though its designers never envisioned that it would do so.

In fact, the visible sensor on the Operational Linescan System (OLS) instrument was designed to be sensitive enough to detect clouds illuminated by moonlight. Because of its sensitivity, the sensor is momentarily saturated when a bright lightning flash occurs as it scans across a thunderstorm.

Very strong thunderstorms (shown in red) with dramatic lightings are increasing around the disturbance labeled 90E in infrared satellite image taken at 1647pm UTC on Tuesday, 9 May 2017 is illustrated in **Figure 8. W**hat could become the earliest tropical storm on record in the Northeast Pacific Ocean is continuing to gradually organize in the open waters south of El Salvador and west of Costa Rica. In a special Tropical Weather Outlook issued at that time on Tuesday, the NOAA/NWS National Hurricane Center gave the disturbance dubbed 90E a 90% chance of development. Rotation was becoming more evident in satellite imagery of the cluster of showers and thunderstorms at the heart of 90E, and the system might already contain depression or even storm-strength winds.

4. Intertropical Convergence Zone (ITCZ)

The Intertropical Convergence Zone (ITCZ) is an easily recognizable, intermittent band of cloudiness that circles the Earth in the vicinity of the equator. Sailors know it as the doldrums that appears as a long band of clouds, usually thunderstorms, in area encircling Earth near the Equator with northeast and southeast trade winds converge.

The position of the ITCZ varies with the seasons, and lags behind the Sun’s relative position above the Earth’s surface by about 1 to 2 months, and correlates generally to the thermal equator. Since water has a higher heat capacity than land, the ITCZ propagates poleward more prominently over land than over water, and also over the Northern than the Southern Hemisphere. In July and August, over the Atlantic and Pacific, the ITCZ is between 5o and 15o N of the Equator, but further north over the landmasses of Africa and Asia.

In eastern Asia, the ITCZ may propagate up to 30o N of the Equator. In January, over the Atlantic, the ITCZ generally sits no further south than the Equator, but extends much further south over South America, Southern Africa, and Australia. Over land, the ITCZ tends to follow the Sun’s zenith point.

Figure 9. Intertropical Convergence Zone – Courtesy of Manual: by NOAA

Therefore, the ITCZ region is also called equatorial convergence zone, belt of converging trade winds and rising air that encircles areas near the Equator, where the trade winds of the Northern and Southern Hemispheres come together. Besides, the ITCZ shifts north and south seasonally with the Sun, and especially Indian Ocean it undergoes especially large seasonal shifts of 40° to 45° of latitude. The intense sun and warm water of the equator heats the air in the ITCZ, raising its humidity and making it buoyant. Aided by the convergence of the trade winds, the buoyant air rises. As the air rises it expands and cools, releasing the accumulated moisture in an almost perpetual series of thunderstorms.
For instance, seasonal shifts in the location of the ITCZ drastically affect rainfall in many equatorial nations, resulting in the wet and dry seasons of the tropics rather than the cold and warm seasons of higher latitudes. Thus, longer-term changes in the ITCZ can result in severe droughts or flooding in nearby areas. In **Figure 9** is illustrated combination of cloud data from NOAA’s newest GOES-11 satellite and color land cover classification data. The ITCZ is the band of bright white clouds that cuts across the center of the image.

5. Weather Fronts Structures

Fronts are contact zones between two different air masses, and you can think of the air masses as the advancing armies, just with different pressure, density, temperature and moisture. And just like there's conflict between the battling armies, air masses 'battle' along fronts, creating changes in weather conditions. There are four types of fronts, and the type of front we get depends on which type of air mass, or army, is advancing over the other.

5.1. Cold Front Structure

Formation of cold front structure is defined as the leading edge of cooler air masses that is replacing at ground level warmer air masses, which lies within a fairly sharp surface trough of low pressure. If cold and warm airs are situated next to each other an inclined boundary oriented downward from high to low layers can be found between the two air masses. The main physical process for the development of cold front bands is the movement of the colder against the warmer air. In fact, as a consequence of this movement, and relative to it, the warm air tends to ascend this air mass boundary while the cold air tends to sink below it. This upward motion often leads to condensation and subsequently the development of clouds and precipitation. Cold front structure often brings heavy thunderstorms, rain and hail. It can produce sharper changes in weather and move up to twice as quickly as warm fronts, since cold air is denser than warm air and rapidly replaces the warm air preceding the boundary.

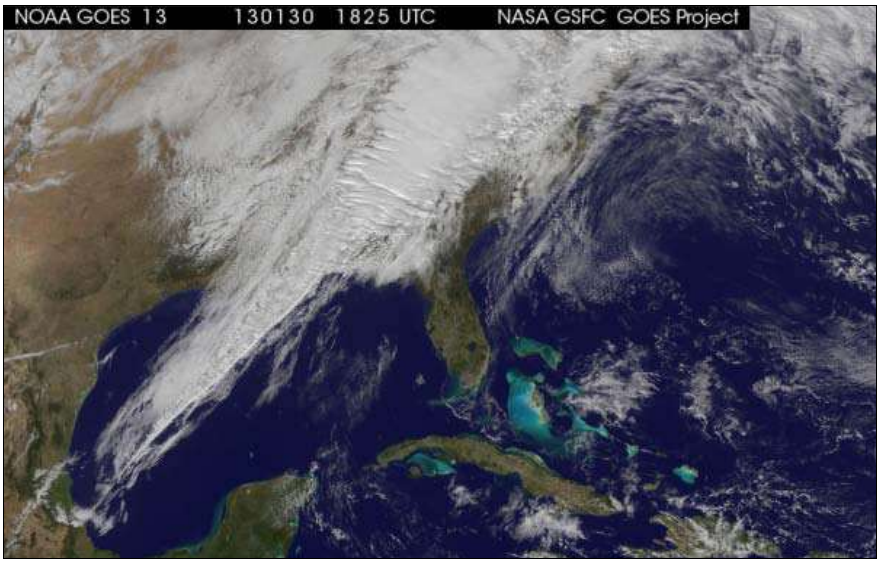

Figure 10. Cold Front Formation – Courtesy of Manual: by NOAA

On weather maps, the surface position of the cold front masses is marked with the symbol of a blue line of triangle-shaped pips pointing in the direction of travel, and it is placed at the leading edge of the cooler air mass. A cold front is located at the leading edge of the temperature drop off, which in an isotherm analysis shows up as the leading edge of the isotherm gradient, and it normally lays within a sharp surface trough.

The concept of colder, dense air "wedging" under the less dense warmer air is often used to depict how air is lifted along a frontal boundary. The cold air wedging underneath warmer air creates the strongest winds just above the ground surface, a phenomenon often associated with property-damaging wind gusts. This lift would then form a narrow line of showers and thunderstorms if enough moisture were present. This concept isn't an accurate description of the physical processes, thus upward motion is not produced because of warm air "ramping up" cold, dense air, rather, front-genetical circulation is behind the upward forcing.

In **Figure 10** is illustrated cold front formation on 30 January 2013 at 1825 UTC, which image was captured an image of clouds associated with the strong cold front by NOAA's GOES-13 satellite.

The visible GOES-13 image shows a line of clouds that stretch from Canada to the US Gulf Coast and contain powerful thunderstorms with the potential to be severe. A powerful cold front moving from the central US to the East Coast of Atlantic Ocean during the summer. When a cold front catches up with the preceding warm front, the portion of the boundary that does so is then known as an occulted front.

5.2. Warm Front Structure

Formation of a warm front structure is defined as the transition zone where a warm air mass is replacing a cold air mass. It generally moves from southwest to northeast and the air behind a warm front is warmer and moister than the air ahead of it. When a warm front passes through, the air becomes noticeably warmer and more humid than it was before.

In fact, warm front is a density discontinuity located at the leading edge of a homogeneous warm air mass, and is typically located on the equator-facing edge of an isotherm gradient. Warm front lies within broader troughs of low pressure and move more slowly than cold fronts, usually follow because cold air is denser and less easy to remove from the Earth's surface. In such way, this also forces temperature differences across warm fronts to be broader in scale.

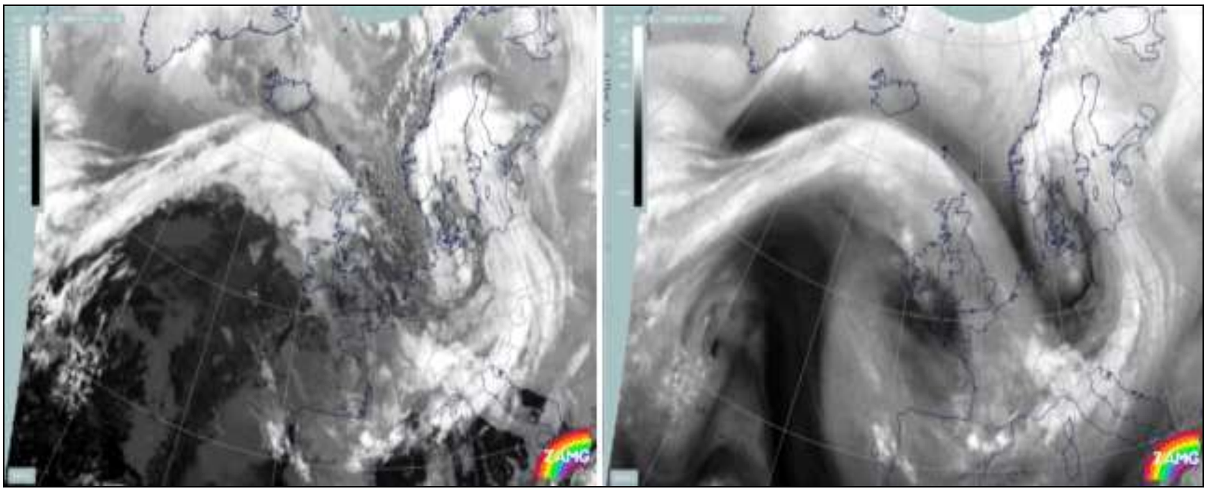
Figure 11. Warm Front Formation – Courtesy of Manual: by Meteosat

Clouds ahead of the warm front are mostly stratiform and rainfall gradually increases as the front approaches. Fog can also occur preceding a warm frontal passage. Clearing and warming is usually rapid after frontal passage. If the warm air mass is unstable, thunderstorms may be embedded among the stratiform clouds ahead of the front, and after frontal passage thundershowers may continue. On weather maps, the surface location of a warm front formation is marked with a red line of semicircles pointing in the direction of travel, while cold front is shown in blue line.

Besides, a warm front marks the leading edge of a warm air mass. The presence of a warm front means that the warm air is advancing and rising up over the cold air. This is because the warm air is “lighter” or less dense, than the colder air. Warm air is thus replacing cold air at the surface. In practice, the cloud band of the warm front can be located in the Infrared (IR) image shown in **Figure 11 (Left)** and in Water Vapor (WV) image shown in **Figure 11 (Right).** Both images are provided 10 January 1995 at 0600 UTC by Meteosat. The warm structure can be spread from the southeastern part of Sweden across the Baltic Sea and the Baltic countries to the Ukraine.

In the IR image it consists of several high, i.e. cold, cloud areas and cloud lines superimposed on dark gray, i.e. warmer, cloud tops. In the WV image a broad white band in the area of the Warm Front indicates high water vapour content, which is bounded by dark stripes on the northern as well as the southern edges. Moreover, the northern stripe represents the dry air on the cyclonic side of the jet. The dark gray area extending from the Benelux countries across Germany and Denmark to Poland is an area of Fog and Stratus cloudiness.

6. Conclusion

Satellite observations of atmospheric and surface meteorological phenomenas, such as clouds and their levels, atmospheric depressions and storms satellite data, tropical and extratropical cyclones, severe thunderstorms and lightning, play a crucial role in regulating the Earth’s weather prediction and climate change.

These atmospheric phenomena can adjust the amount of solar radiation that reaches the Earth’s surface and affect the surface temperature and moisture. The processes involved in cloud formation also influence large-scale atmospheric circulation and can lead to rapid storm intensification.

To accurately forecast the evolving state of the atmosphere, it is important that meteorologists are able to realistically simulate cloud information in weather prediction models.

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