1.0 INTRODUCTION

A tropical cyclone is a storm system characterized by a low pressure center and numerous thunderstorms that produce strong winds and flooding rain. A tropical cyclone feeds on heat released when moist air rises, resulting in condensation of water vapour contained in the moist air. They are fueled by a different heat mechanism than other cyclonic windstorms such as European windstorms, and polar lows, leading to their classification as "warm core" storm systems. Cyclones form over tropical waters where the winds are light, the humidity is high in a deep layer extending up through the troposphere, and the surface water temperature is warm, typically 26.5°C (80°F) or greater, over a vast area. These conditions usually prevail over the tropical and subtropical North Atlantic and North Pacific oceans during the summer and early fall; hence, the hurricane season normally runs from June through November.

The term "tropical" refers to both the geographic origin of these systems, which form almost exclusively in tropical regions of the globe, and their formation in Maritime Tropical air masses. The term "cyclone" refers to such storms' cyclonic nature, with counterclockwise rotation in the Northern Hemisphere and clockwise rotation in the Southern Hemisphere. Depending on their location and strength, tropical cyclones are referred to by other names, such as in western North Atlantic, central and eastern north Pacific, Caribbean Sea and Gulf of Mexico they are called hurricane. In western north pacific they are called typhoon. In the Bay of Bengal and Arabian Sea they are called cyclones. In western south pacific and south east and West Indian Ocean they are called tropical cyclones.

While tropical cyclones can produce extremely powerful winds and torrential rain, they are also able to produce high waves and damaging storm surge. They develop over large bodies of warm water and lose their strength if they move over land. This is the reason coastal regions can receive significant damage from a tropical cyclone, while inland regions are relatively safe from receiving strong winds. Heavy rains, however, can produce significant flooding inland, and storm surges can produce extensive coastal flooding up to 40 kilometers (25 mi) from the coastline. Although their effects on human populations can be devastating, tropical cyclones can also relieve drought conditions. They also carry heat and energy away from the tropics and transport it toward temperate latitudes which make them an important part of the global atmospheric circulation mechanism. As a result, tropical cyclones help to maintain equilibrium in the Earth's troposphere.

Many tropical cyclones develop when the atmospheric conditions around a weak disturbance in the atmosphere are favorable. Others form when other types of cyclones acquire tropical characteristics. Tropical systems are then moved by steering winds in the troposphere; if the conditions remain favorable, the tropical disturbance intensifies, and can even develop an eye. On the other end of the spectrum, if the conditions around the system deteriorate or the tropical cyclone makes landfall, the system weakens and eventually dissipates. A tropical cyclone can become extra tropical as it moves toward higher latitudes if its energy source changes from heat released by condensation to differences in temperature between air masses. From an operational standpoint, a tropical cyclone is usually not considered to become subtropical during its extra tropical transition.

Tropical cyclones can bring hazardous weather to affected areas, including high winds and heavy rain. The fact that a tropical cyclone spends the majority of its life over the tropical ocean, where few data are available, has forced the meteorological community to pioneer adaptive observing strategies to provide critical observations for the operational forecast and research. In addition, these techniques have evolved to include measurements of the upper-Ocean and atmosphere in the vicinity of the
storm. Continuing to improve our tropical cyclone forecasting capabilities will require sustaining and fostering this synergism between observations and NWP models.

If intelligent action is to be taken to avoid the full flurry of a tropical cyclone, early determination of its location and direction of travel is essential. This is possible when the cyclone is monitored from its development stage, maturity up to the dying stage. Monitoring is done using two methods, remote sensing and in situ.
2.0 MONITORING CYCLONES

Tropical cyclones are weather phenomena that destroy both lives and property. High winds from tropical cyclone cause destruction of buildings, trees, power and telephone lines, and turn debris to projectiles. Storm surges can provoke a temporary rise in sea level which can flood coastal areas and damage buildings on the shoreline and cause mudslides. This destruction in property and loss of human lives is what drove researchers to begin monitoring the occurrence of the cyclones such that the information obtained would be given to areas that are usually affected for earlier preparations.

Various observational platforms and sensors are used to monitor and analyze the atmospheric and oceanic environment in and around a tropical cyclone. Operational capabilities of monitoring tropical cyclone system have improved significantly since the inception of the tropical cyclone forecasting centers. These operational capabilities require specialized atmospheric and oceanic observations from many platforms and sensors, both in situ and remote.

2.1 IN SITU

In situ measurements require that the instrument be in physical contact with phenomenon under study. A number of in situ sensors can be grouped according to where they are located (platform) e.g. land stations provide data for wind speed and direction that helps in the determination of the intensity of TC (tropical cyclones), moored buoys, drifting buoys and ships provide sea surface temperature (SST), barometric pressure and wind speed and direction. In addition, there are reconnaissance aircraft that drop dropwindsonde which provide wind, temperature and moisture data from the flight level to the surface. Unfortunately they cannot provide three dimensional data required for hurricane track forecasting. Dropwindsondes also have time delay such that they take a long time to relay the information in real time.

The main advantage of in situ measurements is their accuracy at the point of measurement hence can be used to validate other observational methods. The disadvantages are they are costly to run, prone to observer errors and have limited aerial coverage.

2.2 REMOTE SENSING

Remote sensing is the study of a phenomenon whereby the sensor in use is not in physical contact with the phenomenon that is being studied. There are various platforms on which remote sensing instruments can be mounted. These are on the ground, in the air abode aircrafts and in space abode both spacecrafts and satellites.

Satellite observations play a critical role at all tropical cyclone warning centers as aircraft observations are only routinely available in the Atlantic Basin for storms threatening land and in the Pacific for storms threatening Hawaii. Thus, satellite data are the primary source of tropical cyclone information for the majority of tropical cyclones around the globe that are out of range of coastal radars (270 km/150 nm). Satellite data are used in two primary ways. First, the data are used for tropical cyclone monitoring including estimation of current position and intensity, projection of short-term trends in position and intensity, wind structure, rainfall rate and inner-core structure analysis, and storm-environment analysis. Second, the satellite observations are assimilated into numerical forecast models to obtain more accurate estimates of the initial values for the model state variables.
The remote-sensing meteorological instruments provide much useful information about the wind distribution around the tropical cyclone as well as the interaction between the high winds and the complex terrain. Such data are available at high temporal and spatial resolutions, which could not be achieved with the conventional, in situ meteorological measurements obtained with ground-based anemometers and upper-air ascents (e.g. radiosondes). Moreover, the continuous availability of weather data over a wide region enables the processing of the data using sophisticated mathematical algorithms in the identification of hazardous weather areas, such as the abrupt wind changes, that may adversely affect the operation of the aircraft.

Environmental satellites can be classified into two basic types, geostationary and low Earth-orbiting (including polar-orbiting). The geostationary satellites are operational systems that measure radiation in the visible and infrared (IR) portions of the electromagnetic spectrum. All tropical cyclones around the globe have geostationary coverage from systems maintained by the United States (the Geostationary Operational Environmental Satellite [GOES] System), the European Space Agency (Meteosat), Japan (Multifunctional Transport Satellite [MTSAT] series), and China (FY-series satellites). The polar-orbiting satellites, some of which are operational missions while others are experimental, measure the microwave portion of the spectrum in addition to the visible and IR. There are also specialized satellite systems that contain active or passive microwave instruments for estimating the surface wind speed and the height of the ocean surface. The microwave measurements are of great utility for tropical cyclone analysis because they provide information below the cloud tops that are normally present over tropical cyclones. The geostationary satellites provide near-continuous temporal coverage from the equator to about 65° north latitude, while the polar systems generally provide about two passes per day over a fixed point on the earth (more near the poles, less near the equator). The satellite instruments include imagers, which generally have higher horizontal resolution with fewer spectral channels, and sounders (IR and microwave), which have lower resolution but more and spectrally narrower channels. The imagers are utilized for feature analysis, while the sounders provide vertical profiles of temperature and moisture. Some quantitative analysis is also performed with the imagers, such as rainfall and wind estimation.

The three major portions of the electromagnetic spectrum that are utilized in monitoring of tropical cyclones are Visible, Infra-Red (IR) and Microwave (w.v) spectrums.

2.2.1 MICROWAVE IMAGERY

Principle of Observation with Microwave Imagery

A microwave radiation usually refers to an electromagnetic wave with a frequency of 3 to 30 GHz or a wavelength of 10 to 1 cm. Satellite observation using microwaves requires a frequency range that is significantly lower (or with a longer wavelength range) than that for infrared sensors with geostationary meteorological satellites (10-µm range, which is called the infrared range hereinafter) or for visible sensor (0.6 µm range). Therefore, with limited influence of cloud particles, microwave observation can tell atmospheric conditions under the cloud top. This advantage of microwave sensors that has not been achieved by infrared or a visible sensor presents an absolutely new viewpoint for the analysis of weather phenomena. On the other hand, information that has been accumulated through analysis using infrared and visible imagery may not be applied...
to analysis with microwaves directly. Therefore, it is important to know the characteristics of the new method with microwaves.

**Characteristics of the Microwave Range**

The microwave range is in a significantly lower-frequency range (or longer-wavelength range) than the visible or infrared ranges. As with the case of the infrared range, the microwave range acts as the atmospheric window, and is suitable for satellite observation with limited influence of the atmosphere. However, the energy within microwave range is significantly small; the scale is a ten-billionth of that of the infrared range. Therefore, satellites equipped with microwave sensors orbit at the altitude (400 to 900 km) significantly lower than geostationary orbit (about 36000 km) to achieve gain.

As shown in Figure 2-1, influences by the earth’s surface conditions and atmosphere, and various types of particles in the atmosphere, on a microwave depend on its wavelength. This means that it is necessary to select a suitable wavelength to observe a target object. The atmosphere is nearly transparent to a wavelength of 10 GHz or lower. The sea surface temperature is sensitive to the same-wavelength range. The higher the wavelength, the lower the response to the surface temperature. On the other hand, the higher the wavelength, the higher the response to water clouds. Water vapor affects the response of the entire microwave range.

![Figure 2-1 Rates of changes in radiation temperature of microwave radiation to various changes in objects to be observed with microwave remote sensing (NASA, 1987)](image)

**Atmospheric Influences**

Satellite observation of the earth, including that with microwaves, is performed by receiving radiation energy from the earth by satellite sensors, which measure physical quantities with the dimension of energy. Radiation energy emitted from the earth is affected by the air, cloud particles, and raindrops on its way to a satellite sensor. According to usage, energy detected by such sensors is converted into radiance temperature, or effects of the air on the energy are estimated to retrieve physical quantities.
The microwave range generally has high atmospheric transmittances, so it is easy for microwave radiation from the earth’s surface to reach a satellite sensor. This means that information about the surface is easily obtainable. Microwave radiation with a suitable-frequency transmits clouds, which is nearly opaque to the infrared region, so that conditions inside clouds can be clear. For clouds, satellite observation can tell not only the top using the infrared region, but also the inner structure using the microwave range. To understand the observation mechanism for the inner structure of clouds, it is necessary to know the influences by cloud particles, raindrops, and snow particles on microwaves. Particles of water and ice absorb, emit, and scatter microwave radiation. The degree of influence is greatly different between water and ice particles, and depends greatly on the frequency of an incoming wave.

Generally, water clouds have a high microwave absorptivity, and therefore, a high emissivity. This feature and the low emissivity of the sea surface are reasons for the higher radiation temperature of water clouds than that of the sea surface. Ice particles such as snow and hail are good scattering bodies of microwaves. This property becomes more significant with an increase in microwave frequency. A high scattering property reduces the volume of radiation that reaches a satellite sensor, leading to lowered radiation temperature. Therefore, well-developed convection clouds in which many ice particles are present above the melting layer are recognized as a region of low radiation temperature, especially in a high-frequency band of the microwave range.

**Emissivity of the earth’s surface**

Generally, an object emits an electromagnetic wave with reference to its temperature. A black body has an emission rate of 1. This means that the radiance temperature calculated using the strength of an electromagnetic wave emitted from the body is equivalent to the temperature of the body itself.

In the infrared region, for example, ground surface, which can be considered a black body, has an emissivity of approximately 1. This suggests that the radiance temperature of unclouded areas in the infrared range is considered to be the temperature of the ground surface.

In the microwave range, on the other hand, the ground surface cannot be considered a black body. Depending on the frequency, the emissivity in the microwave range is basically lower than 1 (Figure 2-2). This indicates that the radiance temperature of the ground observed with a microwave is lower than the actual temperature of the ground surface. This decrease is significant especially on the sea surface where the emissivity is much lower than 1. This influence is further pronounced on a low-frequency band of the microwave range, with which the radiance temperature of the sea surface is found to be extremely low. Great differences in radiance temperature are observed between the sea surface (extremely low radiance temperature), and water clouds (relatively high radiance temperature achieved by radiation from the clouds, which have an emissivity of approximately 1). Therefore, water clouds appear as regions of high radiance temperature, and can be easily distinguished from the sea surface.
**Polarization (vertical and horizontal)**

A microwave is a type of electromagnetic wave and is a transversal wave with its electric and magnetic fields oscillating at right angles to each other (Figure 2-3). An electromagnetic wave whose electric field oscillates at a right angle to the reflection surface (ground surface) is called the vertical polarization. An electromagnetic wave whose electric field oscillates in a plane horizontal to the ground surface is called the horizontal polarization.

Among microwave sensors, many types of imagers measure different polarizations for each frequency. Intensities of different components are measured because different components have different properties, which allow estimation of atmospheric influences, especially scattering influences. On a plane horizontally homogeneous and smooth, the emissivity of a vertical polarization is higher than that of a horizontal polarization because of Fresnel’s law and Kirchhoff’s law. This means that when a calm sea surface is observed with a microwave, the brightness temperature of a vertical polarization is higher than that of a horizontal polarization. The difference in brightness temperature between these two waves depends on the frequency of a microwave, but the brightness temperature of a vertical wave is always higher than that of a horizontal wave. If vertical and horizontal polarizations are affected by scattering particles on their way to a satellite sensor, scattering changes the oscillating direction of the electric field of a wave in various directions. Therefore, scattering effects on a microwave decreases the difference in brightness temperatures between its vertical and horizontal polarizations. Using this property, it is possible to distinguish between the sea surface and well-developed convection clouds using a measurement of radiance temperature for the region.
Types of microwave sensors and satellites

Orbits of satellites equipped with a microwave sensors

Satellites equipped with a microwave sensor orbit at an altitude of approximately 400 to 900 kilometers. They take 90 to 100 minutes to make an orbit of the earth. Unlike geostationary meteorological satellites, which are in stationary orbit of the earth and take images of the same area, many satellites equipped with a microwave sensor make an orbit of the earth in a short cycle, and observe strip-shaped areas several-thousands-kilometer wide.

Because this observation method limits the area that can be observed while a satellite make an orbit, in most cases, a slight change is made to a satellite’s orbit when it has made an orbit so that images taken in different orbits cover almost the entire earth. Many satellites orbit over both poles of the earth. Such orbits are called polar orbits, and satellites that take polar orbits are called polar orbiter. Typical polar orbiter equipped with a microwave sensor include the Aqua satellite, DMSP satellite series, and NOAA satellite series. These satellites orbit the earth while keeping the angle between their orbital planes and orientations toward the sun the same. Such orbits are called sun-synchronous orbits. Its advantage is that an area can be observed twice a day at the same local times. This reduces the influences of changes in sunlight. An orbit in which a satellite returns to its starting point within 24 hours after it has made some orbits is called a recurrent orbit. An orbit in which a satellite returns to its starting point after more than 24 hours and within several days is called a sub-recurrent orbit. Most polar orbiter take the sub-recurrent orbit because the coverage of satellites is wide and they return to the starting point regularly.

In summary, the above-mentioned orbit of polar orbiter can be called the sun-synchronous sub-recurrent orbit. This orbit possesses many advantages: a satellite in this orbit returns to the starting point in a cycle of several days while it observes the same area at the same local time under the same conditions where a satellite keeps its positional relationship with the sun the same. On the other hand, the TRMM satellite does not take the polar orbit. The angle between the satellite’s orbit plane and the equatorial plane is 35 degrees. It observes the area ranging between 35 degrees north and 35 degrees south of the equator. This satellite is not sun synchronous because it observes day changes in the rainfall in the tropical region at different local time.
Passive and Active Sensors

Satellite observation with a microwave is roughly classified into two according to the sensor types: a passive sensor or an active sensor. A passive sensor receives microwave radiation that is emitted naturally from the earth. This is the same observation mechanism as for infrared imagers for geostationary meteorological satellites. As mentioned earlier in this paper, the energy of the microwave range by earth radiation is very small. Generally, the energy received by an antenna is proportional to its diameter, and inversely proportional to the distance to the observation object. Therefore, in order to achieve gain, satellites are orbited at a low altitude or equipped with a large antenna. However, despite these efforts, the temperature resolution of passive sensors is still lower than that of infrared imagers.

Typical passive sensors for the microwave range are: AMSR-E, loaded on the Aqua satellite; SSM/I, loaded on the DMSP satellite series; TMI, loaded on the TRMM satellite; and AMSU-A, AMSU-B, and MHS, loaded on the NOAA satellite series. Data obtained with these passive sensors are used to analyze weather phenomena using their brightness temperatures. This is described in detail later. An active sensor itself emits a microwave like a radar, and observes a wave reflected by an object. For example, SeaWinds, loaded on the QuikSCAT satellite, measures the direction and speed of winds over the sea by detecting the scattering state of a microwave, which is scattered in a different way according to the sea surface state. The TRMM satellite has a 14-GHz precipitation radar to observe precipitation. The CloudSat satellite has a 94-GHz radar to detect the three-dimensional structure of clouds. As represented by these examples, an active sensor is used to obtain specific physical products, such as wind or rain.

**FIGURE 2-4** Arrows show surface winds spinning counterclockwise around Hurricane Dora situated over the eastern tropical Pacific during August, 1999. Colors indicate surface wind speeds. Notice that winds of 80 knots (92 mi/hr) are encircling the eye (the dark dot in the center). Wind speed and direction obtained from QuikSCAT satellite. (NASA/JPL
Imager and sounder

As with an infrared sensor, a microwave passive sensor is classified into an imager and a sounder. An imager is observational equipment that converts data into images with a relatively high horizontal resolution. Typical imagers include: AMSR-E, loaded on the Aqua satellite; SSM/I, loaded on the DMSP satellite series; and TMI, loaded on the TRMM satellite. For each observation frequency, these imagers observe its vertical and horizontal polarizations, and convert obtained data into images.

A sounder is equipment to observe different frequencies in order to obtain vertical profiles of physical quantities for a purpose, such as air temperature distribution and water vapor distribution. A sounder is configured to observe many frequencies at and around a specific absorption line according to a physical quantity to be obtained. For its high wavelength resolution, a sounder trades off horizontal resolution. Generally, a sounder has a lower horizontal resolution than an imager.

Typical sounders of microwave sensors are AMSU-A, AMSU-B, and MHS, loaded on the NOAA satellite series. AMSU-A is designed to obtain temperature profiles, while AMSU-B and MHS are designed to obtain vertical water vapor profiles. Unlike an imager, a sounder is designed mainly to obtain vertical profiles of physical quantities, so it observes either a vertical polarization or a horizontal polarization. To analyze a meteorological phenomenon using its graphic information, an imager is more suitable. It is possible to use a sounder using a selected frequency in the same way as an imager, but a lower horizontal resolution than that of an imager is produced. A sounder has a disadvantage in that polarization information is unavailable. Observation with a microwave sensor is performed with insufficient frequency, so the use of microwave data obtained with a sounder is of value.

Analysis with microwave imagery

A microwave sensor uses many frequencies for observation. However, not all data converted into graphic data are suitable for the analysis of meteorological phenomena. Therefore, it is necessary to select frequencies suitable for the operational application of tropical disturbance analysis (Kato et al., 2004) performed at the Meteorological Satellite Center.

Frequency bands are named from the observation frequencies of AMSR-E. Slightly different frequencies are used in other sensors for observation (e.g., 89 GHz is used for AMSR-E, while 85.5 GHz is used for SSM/I). Observation frequencies are different according to the sensor, but are selected essentially within the frequency band that has the same characteristics. Differences in observation frequencies selected in this way have few effects on the analyses described later, so the same name is given to the selected observation frequencies for the sake of convenience. The 89-GHz and 36-GHz bands are selected to analyze tropical cyclones.

Characteristics of the 89-GHz band

The 89-GHz band is a relatively high-frequency band of the microwave range with a relatively high horizontal resolution (about 6 kilometers for AMSR-E). The main characteristic of the band is that it is greatly scattered by ice particles such as snow or hail. Therefore, well-developed convection clouds are found to be areas of extremely low radiance temperature.

Based on this property, especially in tropical disturbance analysis, the area of the strongest convection stands out in a well-developed convection cloud such as the Cb band, and is easily identifiable. Other characteristics can be explained by the previously described properties of the microwave. As compared with the land (with an emissivity of about 1), the sea surface (with an emissivity of lower than 1) is
found to be a region of lower radiation temperature. Because of absorption and scattering by water cloud particles or raindrops, water clouds below the melting layer are found to be a region of relatively higher radiation temperature than that of the sea surface.

Using these characteristics, the main analytical work using these frequency bands is tracking of areas of low radiation temperature of well-developed convection clouds. Generally, it is useful to limit the object to be observed with a microwave to the sea surface. However, because well-developed convection clouds stand in sharp contrast to the land, which appears as a region of high radiation temperature, it is possible to keep track of such clouds over the land. It should be noted that well-developed convection clouds and a sea surface with low surface temperature may be confused because their radiation temperature is found to be similar. For example, a typhoon over a sea area with low surface temperature should be carefully analyzed.

To avoid this kind of confusion, a good method is comparison of radiation temperature between the vertical and horizontal polarizations. If a microwave is sufficiently scattered in a convection cloud, the radiation temperature of the vertical polarization will be nearly the same as that of the horizontal polarization. Therefore, well-developed convection clouds are distinguishable from the sea surface, which makes a great difference in radiation temperature between the vertical and horizontal polarizations of a microwave.

An example of this is shown in Figure 2-5. In Figure 2-5 (A) of infrared imagery, no clouds are observed over the Yellow Sea or sea area in the southern part of Okinawa. The radiation temperature is about 283 K and 293 K, respectively, which makes a difference of about 10 K. Looking at the microwave imagery of Figure 1-8 (B) and (C), the brightness temperature of the Yellow Sea is found to be much lower than that of the sea area in the southern part of Okinawa, and almost the same as that of the convection cloud accompanied by Typhoon No. 200601 around the Philippines. These figures clearly show some change in radiation temperature between the vertical and horizontal polarizations in the region of low brightness temperature caused by the active convection cloud accompanying the typhoon. And in the Yellow Sea, the brightness temperature of the horizontal polarization is lower than that of the vertical polarization, which makes a great difference between them.

Another effective discrimination method is the use of polarized corrected temperature (PCT) (Spencer et al. 1989). Using calculated PCT values, effects of polarization by the sea surface or water drops can be eliminated to extract a decrease in radiation temperature by scattering, so that convection clouds are easily identifiable. The Meteorological Satellite Center provides calculated results of different radiation temperatures, including PCTs, in real time, but this service is in the trial-and-error stage.
Figure 2-5 Images of vertical and horizontal polarizations of the 89-GHz band (06 UTC, May 11, 2006)
(A) Infrared image, (B) Vertical polarization, and (C) Horizontal polarization
In each image, a darker region (black) indicates a region of higher brightness temperature, and a
lighter region (white) indicates a region of lower brightness temperature.

Characteristics of 36 GHz

The 36-GHz band is a middle-frequency band of the microwave range with a lower horizontal
resolution than that of the 89-GHz band (about 14 kilometers for AMSR-E). The main characteristic of
the band is that the sea surface is found to be a region of low radiation temperature, and microwaves
are strongly affected by water clouds. Because absorption and emission by precipitation particles and
cloud particles affect microwaves in the 36-GHz band more strongly than in other frequency bands,
water clouds are found to be a region of high brightness temperature. The sea surface is found to be a
region of extremely low radiation temperature because of the low emission rate.

These characteristics allow identification of water clouds over the sea as a region of high brightness
temperature with high contrast, so detection of water clouds over the sea is the main analytical work
using the 36-GHz band. However, observation of water clouds over the land is impossible because the
emissivity of the land is high and the radiation temperature is high.

It should be noted that in some cases, effects of scattering by ice particles such as snow or hail on the
36-GHz band are not negligible. A decrease in the radiation temperature of this band is not negligible
for extremely well-developed convection clouds such as a typhoon. In this case, it is necessary to
distinguish whether a region of low radiation temperature comes from the sea surface or a convection
cloud. To distinguish these differences, it is effective to use polarization data, as described in the
section of the 89-GHz band. A region with a great difference in radiation temperature between the
vertical and horizontal polarizations suggests the sea surface and a region with a small difference
suggests a well-developed convection cloud.
Advantages of Microwave Imagery

Primary

- Active microwave energy penetrates clouds and serves as an all-weather remote sensing system
- Synoptic views of large areas, for mapping at 1:250,000 to 1:400,000 satellite coverage of centre of cloud-shrouded countries is possible
- Coverage can be obtained at user-specified times, even at night
- Permits imaging at shallow look angles, resulting in a different perspective that cannot always be obtained using aerial photography
- Serves in wavelengths outside the visible and infrared regions of the electro-magnetic spectrum, providing information about surface roughness, dielectric properties, and moisture content.

Secondary

- May penetrate vegetation, sand and surface layers of snow
- Has its own illumination and the angle of illumination can be controlled
- Enables resolution to be independent of distance to the object, with the size of a resolution cell being as small as 1X1m
- Images may be produced from different types of polarized energy (HH, HV, VV, VH)
- May operate simultaneously in several wavelengths (frequencies) and this has multi-frequency potential
- Can measure ocean wave properties even from orbital altitudes
- Can produce overlapping images suitable for stereoscopic viewing and radargrammetry

Disadvantage

Micro-wave remote sensing has the drawback that, due to its low frequencies (long wavelengths), it requires large antenna and it has, therefore, only been possible to boost such instruments into space on polar-orbiting satellites and other low-earth orbiting platform.

INFRARED AND VISIBLE IMAGERY

IR imagery is the workhorse of the TC analysis because of its 24 hours availability. VIS imagery provides the highest resolution and is the best channel available for detection of surface features that may not be seen in the Visible or Micro-wave imagery.

Why use IR and VIS

Low-level infrared Atmospheric Motion Vectors (AMVs), are utilized to monitor the atmospheric motion in the lower troposphere and near the Earth's surface typically below 600mb by tracking cloud edges over a sequence of visible or shortwave infrared imagery. Low-level wind speeds around tropical cyclones (TC) can be monitored using these AMVs and can be utilized by tropical cyclone (TC) forecasters to help determine current atmospheric conditions that could affect TC development, intensity change, and movement.
Visible imagery has an inherent advantage over other imagery from other satellite channels due to its increased spatial resolution, which allows smaller clouds to be tracked and smaller time periods between imagery to be utilized. This can result in a greater amount of AMVs analyzed from a sequence of images.

Shortwave infrared (SWIR) imagery can act as a proxy to visible imagery during non-daylight time periods due to its ability to identify and track clouds near the surface (as opposed to long wave infrared imagery which typically "sees" higher in the atmosphere). The spatial and temporal resolution of the SWIR imagery is decreased, as compared to the visible imagery, resulting in a reduced analysis capability.

Visible and SWIR winds can be numerically adjusted to the surface to estimate the actual surface wind speeds around a TC. This can provide TC forecasters with information about TC wind field structure when in situ data from aircraft, buoy, or land observing stations are not available.

In addition, AMVs can be imported into regional and global numerical models to provide information within data sparse regions, such as over the oceans and land regions with little or no atmospheric monitoring capabilities. AMVs have been shown to have a significant positive impact on the accuracies of numerical models. Low-level infrared AMVs are utilized to monitor the atmospheric motion in the lower troposphere.

**Why we’re Interested…**

Infrared (IR) images are a powerful tool for interpreting a variety of weather phenomena. Unlike visible images that require sunlight, IR images are products of electromagnetic emissions that emerge constantly from the earth/atmosphere system. Therefore, IR images are available for interpretation both day and night. As a result, a weather observer can continuously track features such as cold fronts and hurricanes during all hours of the day. In addition, since the IR energy received by the satellite can be directly related to temperature, one can determine the earth’s surface (land, water) as well as atmospheric (cloud top) temperatures within the image. Additionally, the infrared portion of the electromagnetic spectrum covers a much broader band of energy than does visible light. This gives us the ability to glean more information about the different constituents of the atmosphere they all interact to various parts of the IR spectrum in unique ways.
Infrared and Visible Imagery Analysis

Above: Tropical Storm Gaston is about to make landfall on South Carolina. The storm’s most intense components correspond to the coldest cloud tops (depicted here in red). Within the complex cloud features that occur on a regular basis over the United States, the user can quickly key in on the more vertically-developed clouds based on temperature information alone. These clouds are typically associated with lower temperatures, as depicted in clouds with embedded color contours. Note how the infrared-color enhanced image on the right panel displays the storm’s intensive structure (red) much more clearly than the brightness features depicted in the visible image on the left. It is also easier to apply infrared imagery to distinguish the more intensive convective activity from other cloud cover as shown with thunderstorm activity over the southeastern US. Finally, the tiny cloud cells in the Gulf of Mexico provide little information as to the vertical extent within the visible image. Within the infrared (IR) image, the embedded colors within these clouds represent a “tell-tale” sign of cumulus cloud development.

IR imagery looks softer to the eye than visible imagery. Two reasons really, IR sensors cover more earth surface per pixel than visible imagery, and because it is measuring temperatures, which do not change as rapidly as reflected light.

Water vapor imagery

Tropical cyclone forecasters and satellite analysts conduct continuous global monitoring using animated water vapor imagery. Uses for these animations include the following:

- Monitor tropical cyclone steering and outflow patterns
- Assess the relative positions of the polar front and subtropical jet streams, subtropical ridge axis, and cyclonic cells within the Tropical Upper Tropospheric Trough (TUTT)
• Evaluate how these features may impact both the development and movement of tropical cyclones
• Identify potential developing cloud clusters that warrant further interrogation

In addition to intensity, wind structure, and synoptic analysis, satellite data are also useful for estimating the rainfall rate. Microwave data from the polar-orbiting satellites and the geostationary IR data are both utilized for this purpose (e.g., Scofield 2001). Extrapolation techniques provide short-term rainfall forecasts from the satellite rain-rate estimates (Ferraro et al. 2005).

ESTIMATING TROPICAL CYCLONE INTENSITY

A number of techniques have been developed to estimate the movement and intensity of tropical cyclones. One of the most widely accepted is the Dvorak (1984) technique which assigns an intensity based on the size and shape of the dense cloud mass adjacent to the centre of the circulation of the storm. The Dvorak technique relies on image pattern recognition along with analyst interpretation of empirically based rules regarding the vigor and organization of convection surrounding the storm center. The subjectivity of the Dvorak technique is well documented, and an accurate analysis depends largely on the skill and experience level of the satellite analyst. The Dvorak technique is the main tool for determining tropical cyclone strength when it is out of range of reconnaissance aircraft. TC intensity is estimated using VIS and IR imagery.

With a process called composite fixing, forecasters use data from multiple fixing agencies when positioning tropical cyclones. For a composite fix, the forecasters subjectively weight the available data based on a confidence interval assigned by the satellite analyst and use the weighted data to estimate the position of each tropical cyclone. For example, during 2005 satellite analysts at JTWC produced 7,988 position and intensity fixes within the Central and Western North Pacific, South Pacific, and Indian Ocean basins. They processed an additional 6,102 fixes produced by other agencies. Fixes are also made using scatterometer, TRMM, multispectral and special sensor microwave imager (SSM/I) data. IR imagery is the workhorse of the TC analysis because of its 24 hours availability. Multispectral imagery which highlights features both at low and high levels is used to determine TC intensity and position. Satellite fixes of position are added to the fixes database along with fixes from other sources. This is used to develop a Working Best Track and for input of TC bogus into numerical models. A lot of insight has been gained into physical and dynamical progress shaping development of TCs. Satellite imagery has also been very exhaustively used for the analysis of TCs developing in the north Indian Ocean.

The original Dvorak technique was developed more than three decades ago. More recently, the Advanced Dvorak Technique (ADT), developed by UW-CIMSS, creates an automated tropical cyclone position and intensity analysis using enhanced infrared satellite imagery. This robust computer algorithm first determines the position of the tropical cyclone and then applies a series of subroutines to determine tropical cyclone intensity. Finally, the Dvorak constraints are applied to ensure that the storm’s intensity is not increased or decreased too quickly. Whereas manual application of the Dvorak technique yields a position estimate every three hours and an intensity analysis every six hours, ADT estimates can be generated hourly or half-hourly, depending on how frequently new imagery is received. ADT performs well for well-defined systems with a clear, visible eye. Continued improvements are required before this tool can be integrated into operations.
Limitations of Dvorak System.

The Dvorak tech-unique does not directly measure wind, pressure, or any other quantity associated with TC intensity. It infers them from cloud patterns and features. This primary limitation leads to two basic sources of error. First, the technique is physically restricted due to natural variability between the remotely sensed cloud patterns and the observed wind speed. Second, the method is subject to analyst interpretation and/or misapplication. Another common limitation in applying the technique using geostationary satellite imagery involves the scan angle, or the viewing angle from the satellite sub point. At large scan angles, TCs with small eyes can be underestimated using the Dvorak EIR method because the eye and attending warm brightness temperature is partially or fully obscured by the eye wall.

Advantages of Remote Sensing technique

Remote sensing measurements provide three dimensional data required for hurricane track forecasting which cannot be provided by the in situ measurements. The remote-sensing meteorological instruments provide much useful information about the wind distribution around the tropical cyclone as well as the interaction between the high winds and the complex terrain. Such data are available at high temporal and spatial resolutions, which could not be achieved with the conventional, in situ meteorological measurements obtained with ground-based anemometers and upper-air ascents (e.g. radiosondes) while dropwindsondes also have time delay such that they take a long time to relay the information in real time.

Disadvantages of Remote sensing

Remote sensing instruments are expensive to build and operate. Data interpretation can be difficult as it needs one to theoretically understand how the instrument work and the instrument’s uncertainties.

CONCLUSION

This paper has explored a number of channels in practice in the meteorological world used in the monitoring of tropical cyclones. From the microwave, infrared and visible channels all of which have advantages and limitations but all complement each other for the purposes of better monitoring and forecasting of the TCs. Visible imagery has an inherent advantage over other imagery from other satellite channels due to its increased spatial resolution, which allows smaller clouds to be tracked and smaller time periods between imagery to be utilized. On the other hand Infrared (IR) images are a powerful tool for interpreting a variety of weather phenomena unlike visible images that require sunlight, IR images are products of electromagnetic emissions that emerge constantly from the earth/atmosphere system.

It is also clear that the great advantage of microwave (WV) signal is that at the longer wavelength they are not severely absorbed by the clouds and rain in the storm while at higher frequency absorption by clouds and rain provide information about this phenomenon. The paper has also explored the Dvorak technique of measuring the TCs intensity and it relies on image pattern recognition along with analyst interpretation of empirically based rules regarding the vigor and organization of convection surrounding the storm center. So much has been done on this topic and much still need to be done in order to clearly monitor and forecast TCs.
Finally, for purposes of community evacuation, general protection of life and resources, and safe maritime operations, it is important to determine (analyze) and forecast the structure (wind radii) of tropical cyclones. Remote sensing observations play a critical role in the observation and monitoring tropical cyclone cyclogenesis. Several advances have been made from the in situ based observations of monitoring TC to the remote sensing observations despite the set up cost. Although in situ observations are accurate at the point of measurement they, alone, cannot be used to predict and forecast TCs accurately therefore the two methods are used complementarily.
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