Applications of Remote Sensing in Weather Forecasting and Warnings

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Preamble

For many decades, man has been trying to unravel the complexity of the ever-changing weather. Equipment of various types and intricacies has been developed to detect the weather. There are conventional equipment like anemometers to measure the winds, thermometers for taking the temperatures, barometers for pressure measurement and rain gauges for rainfall recording. Many of the conventional equipment can only record the weather conditions over a localized region. As most part of the earth is covered by water, the weather conditions of many places on the globe are left undetected by the equipment. This is where remote sensing equipment comes into play. Since remote sensing equipment can detect the weather conditions at a distance, they are now widely used to monitor the weather all around the globe to support the weather forecasting and warning services.

The purpose of this note is to give an introduction to the applications of remote sensing technology in weather forecasting and warnings. In the first part of the note, the basic theory of remote sensing is briefly described. Various types of remote sensing equipment are mentioned. The basic principle of operation of meteorological satellites and weather radars are also introduced. The second part of the note is devoted to the applications of meteorological satellites and weather radars in weather monitoring.

Part I Basic Theory and Principle of Operations

A. What is Remote Sensing?

Remote sensing refers to the activities of obtaining information about an object by a sensor without being in direct contact with the object. In the realm of meteorology, the information of interest includes, among others, the location and development of weather systems such as clouds, rainstorms, tropical cyclones, cold and warm fronts. Information needs a physical carrier to travel from the object to the sensor through an intervening medium. In remote sensing, the information carrier is the electromagnetic radiation (Figure 1). The output of a remote sensing system is usually an image representing the object being observed. The way the image looks depends on the source of electromagnetic radiation from the object and on the interaction of the electromagnetic radiation with the intervening medium.

Applications of remote sensing span a wide range of fields. These include
meteorology, hydrology, oceanography, mapping and cartography, land-use planning, agriculture, fisheries, archeology, geologic studies, etc. Typical remote sensing equipments for meteorological uses include meteorological satellites that detect clouds and moisture in the atmosphere, and weather radars that probe rain areas.

To understand the principle of operation of remote sensing in meteorology, it is necessary to know the source of electromagnetic radiation and the way electromagnetic radiation interacts with the atmosphere.

B. Electromagnetic Radiation

Electromagnetic radiation and its interaction with other matters form the core of remote sensing. Every object emits electromagnetic radiation. This is called blackbody radiation. A sensor not only receives the blackbody radiation emanating by an object but also the reflected radiation from an external source by the same object. For objects on the earth, the primary external source of radiation is the sun.

Every object, including the sun and the earth, does not emit electromagnetic radiation in just one frequency but in specific ranges of frequencies called spectrum. The radiation spectrum of an object depends on its temperature. An object with a higher temperature emits higher energy radiation at shorter wavelengths, whereas an object with a lower temperature emits lower energy radiation at longer wavelengths. Figure 2 illustrates the radiation spectra of the earth, the sun and the sun's radiation at the earth. The earth's radiation is mainly in the long wavelength portion of the infrared spectrum, known as the thermal infrared region. The sun's radiation, or solar radiation, is more intense at all wavelengths than that of the earth's radiation. Unlike the earth's radiation, the sun radiates the most in the visible spectrum.

![Figure 2](image-url)  
*Figure 2  Schematic diagram showing the spectrum of the earth (---), the sun (---) and the sun’s radiation at earth (—-—).*
Electromagnetic radiation emanating from an object interacts with the atmosphere before reaching the sensor. In particular, electromagnetic radiation is absorbed by the atmosphere due to the presence of gases like ozone, carbon dioxide and water vapour. As a result, only part of the electromagnetic radiation can pass through the atmosphere. Figure 3 shows the transmissivity, or the transparency, of the atmosphere at various wavelengths of electromagnetic radiation. Transmissivity of 100% at a wavelength means that the electromagnetic radiation at that wavelength can pass through the atmosphere without being absorbed. Those wavelength bands with high transmissivity are more useful to remote sensing. These bands are known as the atmospheric transmission windows. These windows are found in the visible, near-infrared, thermal infrared and the microwave regions.

![Figure 3](image)

**Figure 3** Transmissivity of the atmosphere. Transmissivity of 100% at a wavelength means the electromagnetic radiation at this wavelength can penetrate through the atmosphere without being absorbed.

### C. Passive and Active Remote Sensing

Remote sensors can be classified into active and passive type in accordance with the source of electromagnetic radiation. Some sensors rely on the radiation emitted or reflected from the object. This type of sensors is called passive sensors. Typical example is meteorological satellites. The other type of sensors shines electromagnetic radiation onto the object and receives the reflected radiation. They are called active sensors. Weather radar falls into this type. It operates by radiating microwave into the atmosphere and receiving the reflected radiation from water droplets in the air. Detailed principle of operation of meteorological satellites and weather radars will be described later.

Passive sensors can only be used to detect radiation when the radiation is available. Remote sensing of objects that reflect solar radiation is possible only when the sun is illuminating the earth. Since there is no reflected radiation available from the sun at night, cloud images in the visible channel are only available in the day. On the other hand, remote sensing of objects in the thermal infrared channel can be performed day or night, as long as the objects radiate enough amount of thermal infrared radiation.

Active sensors have the advantage of being independent of solar radiation and the time of the day. It can be used for examining objects in wavelengths that are not sufficiently provided by the sun, such as microwaves. However, active sensors require the generation of a fairly large amount of radiation to adequately illuminate an object.
D. Ground-based and Spaceborne Remote Sensing

To enable a sensor to collect and record electromagnetic radiation from an object, the sensor must reside on a stable platform away from the object. Platforms for remote sensors may be located on the ground, on an aircraft, or on a satellite outside the earth’s atmosphere. **Ground-based** sensors such as weather radars are those located on the ground. These sensors are used to record information of an object near the surface of the earth. Restricted by their fixed location, the coverage of these ground-based sensors is usually limited to the vicinity of the sensor. **Spaceborne** sensors are located outside the earth. One example of spaceborne sensors is meteorological satellite. Since satellite circles the earth continuously, the coverage of a satellite is larger than that of ground-based sensors.

E. Introduction to Meteorological Satellites

The launching of satellites is a key milestone in remote sensing. The word ‘remote-sensing’ actually emerged from the development of satellite observations. Sensors onboard meteorological satellites are pointing towards the ground, enabling them to have bird eye view of the globe from the space. There are two types of meteorological satellites characterized by their orbits. They are *geostationary* satellites and *polar-orbiting* satellites (Figure 4).

As the name suggests, a geostationary satellite is stationary relative to the earth. That is, it moves above the equator at the same rate as the earth’s rotation so that all the time it is above the same geographical area on the earth. In this manner, it is capable of taking cloud images of the same area continuously, 24 hours a day. As it is some 35,800 kilometres from the earth, it is capable of taking cloud pictures covering part of the whole globe. Table 1 contains a list of geostationary meteorological satellites in operation. These satellites together provide full coverage of the earth. In Hong Kong, satellite broadcast from both Japan's **Geostationary Meteorological Satellite-5** (GMS-5) and the Chinese **Fenyun-2B** (FY-2B) are received.

Polar-orbiting satellites are low-flying satellites circling the earth in a nearly north-south orbit, at several hundred kilometers above the earth. Most of them pass over the same place a couple of times a day. As they operate at a distance closer to the earth, they are only capable of taking cloud images of a limited area of the earth each time. Compared with geostationary satellites, polar-orbiting satellites offer fewer and smaller cloud pictures. However, the advantage is that the cloud pictures obtained are of much higher resolution. Table 2 is a list of some polar-orbiting meteorological satellites.
Table 1  List of geostationary meteorological satellites

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Location (longitude)</th>
<th>Coverage</th>
<th>Operating country/agent</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMS</td>
<td>140°E</td>
<td>Western Pacific, Eastern Asia, Australia</td>
<td>Japan</td>
</tr>
<tr>
<td>FY-2</td>
<td>105°E</td>
<td>Asia, Indian Ocean, Western Pacific, Australia</td>
<td>China</td>
</tr>
<tr>
<td>GOMS</td>
<td>76°E</td>
<td>Asia, Indian Ocean, Eastern Africa, Eastern Europe</td>
<td>Russia</td>
</tr>
<tr>
<td>INSAT</td>
<td>74°E</td>
<td>Asia, Indian Ocean, Eastern Africa, Eastern Europe</td>
<td>India</td>
</tr>
<tr>
<td>INDOEX</td>
<td>63°E</td>
<td>Asia, Indian Ocean, Africa, Europe</td>
<td>EUMETSAT</td>
</tr>
<tr>
<td>METEOSAT</td>
<td>0°E</td>
<td>Eastern Atlantic, Europe, Africa</td>
<td>EUMETSAT</td>
</tr>
<tr>
<td>GOES-E</td>
<td>75°W</td>
<td>Northern America, Southern America, Atlantic Ocean</td>
<td>USA</td>
</tr>
<tr>
<td>GOES-W</td>
<td>135°W</td>
<td>Eastern Pacific, Northern America</td>
<td>USA</td>
</tr>
</tbody>
</table>

Table 2  List of some polar-orbiting meteorological satellites

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Altitude of orbit</th>
<th>Operating country</th>
<th>Area of applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA series</td>
<td>830-870 km</td>
<td>USA</td>
<td>Cloud observation</td>
</tr>
<tr>
<td>FY-1 series</td>
<td>870 km</td>
<td>China</td>
<td>Cloud observation</td>
</tr>
<tr>
<td>TRMM</td>
<td>403 km</td>
<td>USA, Japan</td>
<td>Tropical rainfall observation</td>
</tr>
<tr>
<td>QuikSCAT</td>
<td>803 km</td>
<td>USA</td>
<td>Sea winds observation</td>
</tr>
</tbody>
</table>

Onboard meteorological satellites are a collection of different sensors, each with a specific purpose. Most sensors of meteorological satellites are passive sensors that receive reflected sunlight and thermal radiation from the earth. For instance, the GMS-5 of Japan carries a Visible Infrared Spin Scan Radiometer (VISSR). This equipment is specially designed to take cloud pictures of the earth in the visible and infrared frequency bands. A total of 4 channels are available. They fall in the atmospheric transmission windows described in Section B above. Some characteristics of these channels are given in Table 3. Application of these channels in weather monitoring and forecasting will be discussed in Part II of this note. Figure 5 is an example of satellite image in the infrared channel captured by GMS-5. The clouds over the western Pacific, Asia and Australia at 11:32 UTC on 24 January 2001 can be seen simultaneously in a single image.
Table 3  Characteristics of the four channels of VISSR in GMS-5.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength (µm)</th>
<th>Horizontal resolution</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS (visible)</td>
<td>0.55-0.90</td>
<td>1.25 km</td>
<td>Distribution of clouds, ice and snow at daytime</td>
</tr>
<tr>
<td>IR1 (infrared 1)</td>
<td>10.5-11.5</td>
<td>5 km</td>
<td>Temperature of cloud top, sea surface and land surface</td>
</tr>
<tr>
<td>IR2 (infrared 2)</td>
<td>11.5-12.5</td>
<td>5 km</td>
<td>Sea surface temperature, volcanic ash</td>
</tr>
<tr>
<td>WV (water vapour)</td>
<td>6.5-7.0</td>
<td>5 km</td>
<td>Water vapour in the atmosphere</td>
</tr>
</tbody>
</table>

**Figure 5**  Satellite cloud image in the IR1 channel captured by GMS-5 at 11:32UTC on 24 January 2001. Distribution of clouds over the western Pacific, Asia and Australia can be seen in a single image. (The image was originally captured by GMS-5 of Japan Meteorological Agency).

**F. Introduction to Weather Radar**

Radar is an acronym for 'RAdio Detection And Ranging’. Its primary function is to detect and locate object of interest. It was developed for military use in World War II, mainly for detection and location of aircrafts. Advancement of signal processing technology and improvement in computing hardware after the war enabled rapid development in radar.
Radar is now widely used in many applications including weather monitoring and air traffic control.

Radar is a ground-based and active remote sensing equipment. It emits microwave radiation from a fixed location into the atmosphere and receives the reflected radiation called echoes from water droplets in the air. Microwave is not intense in the solar radiation and the earth's emission spectrum. Therefore the background radiation level in the microwave frequencies is not high and it usually does not affect the operation of the radar. Microwave frequencies can be divided into a number of frequency bands. Table 4 contains a list of band designation in the microwave frequencies. Many weather radars operate in the S and C bands.

<table>
<thead>
<tr>
<th>Band designation</th>
<th>Nominal frequency</th>
<th>Nominal wavelength</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1-2 GHz</td>
<td>30-15 cm</td>
<td>Radar for air traffic control</td>
</tr>
<tr>
<td>S</td>
<td>2-4 GHz</td>
<td>15-8 cm</td>
<td>Weather radar</td>
</tr>
<tr>
<td>C</td>
<td>4-8 GHz</td>
<td>8-4 cm</td>
<td>Terminal weather radar</td>
</tr>
<tr>
<td>X</td>
<td>8-12 GHz</td>
<td>4-2.5 cm</td>
<td>Radar for airport ground traffic control, Police speed radar</td>
</tr>
<tr>
<td>K_u</td>
<td>12-18 GHz</td>
<td>2.5-1.7 cm</td>
<td>Spaceborne radar</td>
</tr>
<tr>
<td>K</td>
<td>18-27 GHz</td>
<td>1.7-1.2 cm</td>
<td>Spaceborne radar</td>
</tr>
<tr>
<td>K_a</td>
<td>27-40 GHz</td>
<td>1.2-0.75 cm</td>
<td>Spaceborne radar</td>
</tr>
</tbody>
</table>

There are various types of radars. A pulse radar is one that emits pulses of radiation while a continuous wave (CW) radar radiates radiation continuously. Weather radars are commonly of pulse type. They measure the time required for a pulse of microwave to travel from the radar to an area of rain and back to determine the distance of the rain area from the radar. This is the basic principle of operation of conventional type of weather radar.
There is also Doppler weather radar that generates microwave at a fixed frequency. After hitting an area of rain, the frequency of the microwave pulses is shifted. This phenomenon is known as the Doppler effect. The change in frequency, or Doppler shift, is proportional to the velocity of the rain area in the direction of the radar, known as the radial velocity or the Doppler velocity. By measuring the frequency change between the transmitted and reflected microwave pulses, the radial velocity of the rain area can be determined (Figure 6(b)).

While weather radar can measure the distance of rain areas, there is a limit to the effective range of detection of weather radar. The reason is as follows: weather radar transmits a pulse of microwave and waits for the pulse to return to determine the distance to a rain area. This microwave pulse shall come back before the next transmitted pulse to make the measurement meaningful. Otherwise, microwave coming back at a time after the transmission of the next pulse will confuse the weather radar as being the return pulse of the next transmitted pulse. Therefore the effective range of detection of rain areas, $D_{\text{max}}$ is limited by the time interval between successive transmitted pulses, known as the pulse repetition time, $\Delta T$ by the equation:

$$D_{\text{max}} = \frac{c \Delta T}{2}$$

Here $c$ is the velocity of light. $D_{\text{max}}$ is called the maximum unambiguous range. It is proportional to the pulse repetition time, $\Delta T$. The larger the pulse repetition time, the larger will be the maximum unambiguous range.

Likewise, there is also a limit to the measurement of the Doppler velocity. Doppler weather radar does not measure the Doppler shift in the return microwave pulses directly. Instead, it measures the phase change in successive return microwave pulses. Figure 7(a) is the plot of phase angles against time. This is used to determine the Doppler shift, $f_D$.

![Plot of phase angles of successive return microwave pulses (blue circles) for phase change of](image)

(a) phase change of $0.3 \pi$ radians in successive return microwave pulses
(b) phase change of $\pi$ radians in successive return microwave pulses

**Figure 7** Plot of phase angles of successive return microwave pulses (blue circles) for phase change of (a) $0.3 \pi$ radians and (b) $\pi$ radians. In (a), the variation in phase angles with time enables the determination of the Doppler shift, $f_D$. (b) illustrates the case where the phase change is $\pi$ radians and where the maximum velocity a Doppler weather radar can be detected unambiguously.
The maximum velocity a Doppler weather radar can detect unambiguously, $v_{\text{max}}$, is equal to the velocity which just produces phase shift of $\pi$ radians (re. Figure 7(b)). This maximum velocity can be expressed as:

$$v_{\text{max}} = \frac{\lambda}{4 \Delta T}$$  \hspace{1cm} (2)

Here $\lambda$ is the wavelength of the transmitted microwave and is fixed. $v_{\text{max}}$ is called the **maximum unambiguous velocity**. It is inversely proportional to the pulse repetition time, $\Delta T$. The larger the pulse repetition time, the smaller will be the maximum unambiguous velocity.

The combination of maximum unambiguous range and maximum unambiguous velocity forms two constraints on the selection of the pulse repetition time for use with Doppler weather radar. Increasing the pulse repetition time will increase $D_{\text{max}}$ at the expense of decreased $v_{\text{max}}$. This constitutes what is known as the 'Doppler dilemma'. Careful selection of the pulse repetition time is therefore required to maintain a balance between $D_{\text{max}}$ and $v_{\text{max}}$.

Despite their limited range of detection, weather radars prove to be very useful in measuring the intensity of rain areas. It is done by measuring the **radar reflectivity factor** of rain areas. Radar reflectivity factor, or simply the reflectivity, $Z$, is a measure of the fraction of radiation reflected back by rain area. This is determined by the power of the transmitted microwave from the radar, $P_t$, and the power of the reflected microwave from the rain area, $P_r$ by the **radar equation**:

$$P_r = \alpha P_t Z$$  \hspace{1cm} (3)

Here $\alpha$ is a variable depending on the physical parameters of the weather radar such as the dimension of the antenna, the width of the radar beam and the wavelength of microwave in use.

Once the reflectivity $Z$ is known, the rainfall intensity, $R$, can be calculated by an empirical relationship, called the **Z-R relationship**:

$$Z = a R^b$$  \hspace{1cm} (4)

Here $a$ and $b$ are constants. It should be noted that $R$ is not directly determined from $Z$, and $Z$ is also not directly determined from $R$. They are instead determined separately by measuring the size and number of rain drops in the rain. When $Z$ and $R$ are determined, the constants $a$ and $b$ can be calculated. For stratiform rain, $a$ is 200 and $b$ is 1.6. This is known as the **Marshall-Palmer relationship**:

$$Z = 200 R^{1.6}$$  \hspace{1cm} (5)

There are other values of $a$ and $b$ for other types of rain.

Figure 8 illustrates an example of radar display showing the rainfall intensity of the rain...
bands associated with Typhoon Yutu in the morning of 25 July 2001 when it was located about 200 kilometers to the south of Hong Kong. Regions of more intense rain are represented in yellow to orange colours while areas of lighter rain intense are shown in blue to green colours. In Part II, various types of radar products and their application in weather monitoring and forecasting will be discussed.
Part II Applications in Meteorology

A. Interpretation of satellite images

The most common types of satellite images are visible, infrared and water vapour images. For illustration purpose, the interpretation of satellite images in these channels from the GMS-5 satellite is given below:

(i) Visible satellite images:

Visible satellite images of GMS-5 cover the wavelength range of 0.55-0.90µm. They record sunlight as reflected back from clouds and the earth's surface. Thick clouds and snow have higher reflectivity, or albedo, and show up in bright white colour in the images. Land and sea without any cloud cover have low albedo and appear in dark grey. It is difficult to distinguish between high and low clouds as they can have a similar albedo. Since the source of visible light comes from the sun, visible satellite images are not available at night. Besides the intensity of reflection from any clouds and the earth's surface vary with solar altitude. Figure 9 is a visible satellite image captured by GMS-5 in the morning of 8 September 2000 when Typhoon Wukong was located over northern part of the South China Sea. The image reveals the circular eye of Wukong. The spiraling rainbands surrounding Wukong in bright white colour are also clearly discernible.

(ii) Infrared images:

Infrared images of GMS-5 cover two wavelength ranges, i.e. 10.5-11.5µm (IR1 images) and 11.5-12.5µm (IR2 images). The infrared radiation recorded on the images is a measure of temperature. Since temperature generally decreases with height in the atmosphere, high clouds are colder and emit less infrared radiation than low clouds. Infrared images are therefore useful in differentiating between high and low clouds.
Infrared images also allow estimation of tropical cyclone intensity (see next Section B of this part). This makes them very useful in monitoring the intensity change of tropical cyclones. As a tropical cyclone intensifies, more high clouds develop near its centre, resulting in lower temperatures on the top of the tropical cyclone. Figure 10 depicts an infrared image of Typhoon Wukong. The colours of the image are enhanced. Dark gray and white colours represent low temperatures in the region of -80°C while medium gray represents higher temperatures. Surrounding the centre of Wukong, the colours were dark gray and white. The low temperatures there suggest that the storm attained considerable strength. In fact, Wukong at that time was a Typhoon. Infrared images are made available 24 hours a day, making them suitable for round-the-clock monitoring of the development of tropical cyclones.

![Figure 10](image-url)  

*Figure 10*  Same image as Figure 8 but captured in the infrared channel. It displays cloud temperatures in different shades of grey. The dark grey and white areas surrounding the eye of Wukong indicate temperatures as low as -80°C, suggesting that Wukong attained considerable strength. (The image was captured by GMS-5 of Japan Meteorological Agency)

(iii) **Water vapour images:**

These images record radiation emitted from water vapour in the range of 6.5-7.0μm. As absorption by water vapour is strong in this band, radiation from the low clouds and the earth's surface do not normally reach the satellite. The intensity of the radiation received at
the sensor depends on the amount of water vapour in the mid and upper atmosphere as well as the temperature of the radiation source. If the upper atmosphere is moist, radiation emitted from water vapour there will be received by the sensor and appears in brighter shades. When the upper atmosphere is dry, radiation originating from water vapour in the middle atmosphere will reach the radiometer and will appear in darker shades. Therefore, darker colors indicate drier air while the brighter colours indicate more moisture in the mid and upper atmosphere. Figure 11 is a water vapour image at 11:32 UTC (07:32 a.m. Hong Kong Time) on 15 October 2001. This illustrates that Typhoon Haiyan to the east of Taiwan contained substantial amount of moisture near its centre. Over southern China and the northeastern part of the South China Sea, however, water vapour was scarce in middle to upper atmosphere. The weather was general fine in these areas.

![Figure 11](image.png)

**Figure 11** Water vapour image at 11:32 UTC (07:32 p.m. Hong Kong Time) on 15 October 2001. Typhoon Haiyan to the east of Taiwan contained substantial amount of moisture around its center (moist zone in bright white colours). Meanwhile, water vapour was scarce over southern China and the northwestern part of the South China Sea (dry zone in dark gray to black colours). (The image was captured by GMS-5 of Japan Meteorological Agency).

### B. Applications of meteorological satellites

Meteorological satellites are indispensable in weather forecasting and warning services. Because of their huge areal coverage, meteorological satellite images can be used to keep track of weather systems days before they come close to an area. This is particularly useful
in monitoring severe weather systems like tropical cyclones. The very basic application of meteorological satellite is in identification of clouds. Clouds can be broadly classified into three categories according to the cloud base height, namely, low, medium and high clouds. Some clouds, such as cumulonimbus (a type of thundery clouds), span the three layers. Different clouds have different characteristics in terms of shape and pattern and have different tones in the visible and infrared images. These differences enable the identification of clouds using a combination of the visible and the infrared images. For instance, fog and low dense clouds are characterized by their sharp boundary and smooth texture on satellite image. They appear in bright white to medium gray tone on the visible image, but in dark to medium gray colour on infrared image (Figure 12). Thundery clouds such as cumulonimbus, however, contains abundant moisture and extends to great height. They appear in globular shape and are in very bright tone on both the visible and infrared images (Figure 13).

**Figure 12** Fog is characterized by sharp edge and smooth texture in white to medium gray tone on the visible image (a) and dark to medium gray tone on infrared image (b). (The images were captured by NOAA-15 at 00:21 UTC on 23 October 2001).

**Figure 13** Cumulonimbus is globular in shape and appears in very bright tone on both visible and infrared images. (The images were captured by NOAA-16 at 06:08 UTC on 26 October 2001).
Apart from identification of clouds, meteorological satellites are widely used in many areas of applications. Here below are some examples:

(i) Monitoring of tropical cyclones:

Tropical cyclones cause loss of properties or lives in many parts of the world every year as a result of their devastating winds and torrential rain. The fact that tropical cyclones develop and spend most of their lifetime over the sea has made it difficult to measure their winds directly, especially when they are still far away from the coast. Remote sensing equipment like meteorological satellite is useful in tracking the evolution and movement of tropical cyclones. With its remarkable circular shape with possible central eye, tropical cyclones are easily identifiable on satellite images. In addition to tracking the locating and movement of tropical cyclones, meteorological satellites also enable the estimation of the intensity of tropical cyclones. The method is called the D’vorak analysis, namely after V.F. D’vorak who developed it. This method is based on the fact that tropical cyclones at different development stages have different features such as the shape, the size and the temperatures of the cloud mass adjacent to their centres. By identifying these features on the infrared satellite images, the strength of tropical cyclones can be estimated quite accurately. To carry out the analysis, the colour tone in the infrared image has to be enhanced. Figure 10 above is an example of such enhanced infrared image for use in D’vorak analysis. This method is a proven technique widely used nowadays around the world.

(ii) Monitoring of thunderstorms:

Thunderstorms usually come with heavy rain. Severe thunderstorms can even bring hail or tornado. Meteorological satellite is a means to identify areas of thunderstorms,
As mentioned above, thundery clouds are easily identifiable on both visible and infrared images. Intense thunderstorms tend to cluster together, which can be easily spotted on satellite image. Figure 14 illustrates intense thunderstorms and heavy rain extending from Hainan Island to the Pearl River Estuary in the evening of 1 September 2001. They brought heavy downpour in Hong Kong.

(iii) Monitoring of flooding:

In mid-September 2000, torrential rain caused widespread flooding in Cambodia. The flooded area can be easily discernible on satellite image (Figure 15). In this figure, the area of flooding, in deep blue tone, was nearly eight times the size of Tonle Sap (Great Lake), the boundary of which is in red colour. Meteorological satellite therefore enables close monitoring of widespread flooding and estimation of the extent of flooding, which would not otherwise be easily accomplished by other means.

(iv) Observation of sandstorms:

Apart from clouds and thunderstorms, satellite images can also be used to observe sandstorms. In Figure 16, the sandstorm, in hazy shade, spread over the Yellow Sea at around noon time on 22 March 2001. It should be noted that sandstorms can only be observed when they are not obscured by rain or clouds. Besides, they are more easily observable on visible image than on infrared image because they are hardly distinguishable from low clouds on infrared image.

(v) Detection of areas of clear air turbulence

Turbulence is very often associated with thundery clouds or warm and cold fronts. Aircraft entering a region of turbulence would experience bumpiness and might even go momentarily out of control. Apart from thundery clouds and warm and cold fronts, turbulence may also occur in clear air conditions, i.e. without clouds around. This is known as clear air turbulence. One of the causes of clear air turbulence is strong downward movement of air. Descending air dries up on its way, enabling it to be recognized on water vapour satellite image. Figure 17 illustrates possible occurrence of clear air turbulence near Macau around noon time on 17 October 1999. Drying up of the atmosphere by descending air within the area was evident by the changing of colour from dark purple to light purple on the satellite image.
(vi) Observation of volcanic eruption

Apart from monitoring weather systems, satellite images can also be used to observe volcanic eruption. When there are no clouds covering the volcano, the ash erupting from the volcano is normally discernible on satellite images. When the volcano is obscured by clouds, an "IR2 minus IR1" image, representing differences in the received radiation

Figure 17  Water vapour images on 17 October 1999. Wet zones are shown in gray, green and red colours, and dry zones are depicted in purple colour. The driest region is in light purple colour. In the region of suspected clear air turbulence (yellow circle), drying up of the atmosphere was clearly discernible with colours there turning from dark purple to light purple. (The images were captured by GMS-5 of Japan Meteorological Agency)

Figure 18  (a) IR1 infrared satellite image at around 1130UTC on 29 February 2000. Volcanic ash erupting from Mount Mayon in the Philippines is obscured by clouds. (b) "IR2 minus IR1" image showing ash clouds (indicated by a red arrow) erupting from Mount Mayon. (The images were captured by GMS-5 of Japan Meteorological Agency)
between the IR2 and IR1 channels, sometimes offer an excellent tool in unravelling volcanic ash beneath clouds. The operating principle is that volcanic ash and clouds exhibit different characteristics in the IR1 and IR2 infrared images. Figure 18 is an example of "IR2 minus IR1" image showing volcanic ash erupting from Mount Mayon in the Philippines in February 2000.

C. Applications of weather radars

As mentioned in Part I, Section F, weather radars can measure rain reflectivity as well as Doppler winds. Since weather radars have higher spatial resolution than many meteorological satellites (100-300 m for typical weather radars vs. 1-5 km for many meteorological satellites), weather radars can reveal finer details on the rainfall intensity variation within rain bands. Besides, weather radars usually take images more frequently than meteorological satellites (1 image in a few minutes for typical weather radars vs. 1 image in half to one hour for most geostationary satellites). Weather radars are therefore ideal for monitoring rapid change in rainfall intensity of rain areas, and prove to be very useful for short-range weather forecasting and warnings.

Some common radar products are: rainfall rate of rain areas at constant height above the ground (CAPPI - Constant Altitude Plan Position Indicator), vertical scan of a section across rain areas (RHI - Range Height Indicator), and maximum height of rain echoes (ECHO TOPS). There are also other specific products. For instance, rain areas can be represented in a 3-dimensional view by means of data processing technique. Some applications of these radar products in weather forecasting and warning are illustrated below:

(i) Monitoring of tropical cyclones:

Like meteorological satellite, weather radar enables the determination of the location of tropical cyclones. It can also indicate the strength of storms, i.e. the maximum winds near their centres. This is made possible by means of the radial velocity images. Figure 19 shows the radial velocity of Typhoon Yutu at 3 km height in the morning of 25 July 2001. From this image, the maximum wind speed

Figure 19  Radial velocity image of Typhoon Yutu at 09:00 a.m. Hong Kong Time on 25 July 2001 when Yutu was located about 200 kilometres south of Hong Kong. The maximum radial velocity near its centre was in excess of 40 m/s.
near the eye of Yutu can be estimated to be more than 40 m/s (144 km/h), suggesting that Yutu has reached the strength of a Typhoon (maximum wind speed $\geq 118$ km/h).

While a single Doppler radar detects the radial velocity, information collected by two Doppler weather radars can be combined to produce a wind pattern. The usefulness of such dual Doppler winds in weather observation was demonstrated in the case of a Tropical Depression (TD) hitting Hong Kong in June 2000. During the night of 18 June 2000, the TD formed over the water just to the south of Hong Kong. The TD headed north towards Hong Kong and then made landfall. Despite the fact that TDs are weakest in strength in the tropical cyclone hierarchy, the distinct circulation of the TD was well captured by the observed dual-Doppler winds of the TD when making landfall (Figure 20). In view of the above, weather radar is a very important tool for the weather forecasters to locate tropical cyclones and facilitate the issuance of tropical cyclone warnings to the general public and aviation users in a timely manner.

(ii) Monitoring of rainstorms:

Tropical region like Hong Kong is frequented with intense rainstorms in the summer season. Weather radar is useful in depicting the location of rainstorms as well as their rainfall intensity. Figure 21(a) shows an example of a rainstorm in the evening of 6 July 2001 when an extensive rainband covered the Pearl River Estuary and brought heavy downpour to Hong Kong. Regions of heavier rain in yellow, orange and red colours were clearly discernible. A 3-dimensional image in Figure 21(b) provides a more vivid view of the rainband and its vertical extent. Regions with larger vertical extent produced heavier rain, matching well with the location with heavy rain in Figure 21(a).

In addition to monitoring tropical cyclones and rainstorms, weather radars also enable the detection of weather phenomena such as hail, gust fronts and microbursts. With advancements in signal processing technology, computer hardware and software, the capability of radars in the observation of weather is ever expanding. Nowadays, weather radar is not just ground-based but is also carried onboard satellites. The next section describes some recent advances in the area of radar and satellite meteorology.
**Quantitative Rainfall Forecast:**

In addition to the monitoring of the location and rainfall intensity of rain areas, radar data can also be used for forecasting of rainfall. This can be achieved by estimating the future location and intensity of rain areas. It is the basis of many rainfall forecast systems used in various countries. In 1997, the Hong Kong Observatory developed such a system called SWIRLS (Short-range Warning of Intense Rainstorms in Localized Systems). This system proves to be very useful for weather forecasters in the forecasting of rainstorms in Hong Kong.

SWIRLS makes use of two consecutive radar images to track the movement of individual rain area by means of correlation method (Figure 22). Based on the past movement of rain echoes, their projected location in the future couple of hours can be estimated. SWIRLS also monitors the change in rainfall intensity of rain areas. This, together with the forecast location of rain areas, enables the estimation of rainfall in the next couple of hours. Figure 23(a) illustrates an example of one hour rainfall forecast.
issued by SWIRLS at 8 a.m. on 9 June 2001. The corresponding rainfall recorded by raingauges in Hong Kong is shown in Figure 23(b). It can be seen that the localized heavy rain over the northern part of Hong Kong is well forecast by SWIRLS.

![Figure 23](image)

Figure 23  (a) An example of one hour rainfall forecast by SWIRLS issued at 8 a.m. on 9 June 2001. (b) The corresponding one hour rainfall accumulation over Hong Kong from 8 a.m. to 9 a.m. on 9 June 2001.

### D. Recent advances in radar and satellite meteorology

Launched in 1997, the TRMM satellite is the first meteorological satellite ever to carry spaceborne radar. TRMM is an acronym standing for Tropical Rainfall Measuring Mission. One objective of this mission is to obtain and study the science data sets of tropical and subtropical rainfall measurements. The TRMM satellite is a polar-orbiting satellite that circles the earth at a height of about 403 km. The radar onboard this satellite, called the Precipitation Radar (PR), operates on the K_α band. While the horizontal resolution of this radar is not as fine as ground-based radars, PR provides radar images of not just a single location but almost every part of the equatorial, tropical and subtropical region. Figure 24 shows an example of the radar image of the rainbands

![Figure 24](image)

Figure 24  Radar image of rainbands of Typhoon Sam at about 4:15 p.m. Hong Kong Time on 23 August 1999 as recorded by the PR on the TRMM satellite. Sam has made landfall near the Pearl River Estuary at this time. Its outer rainbands were still affecting Hong Kong and the neighbouring region. (This image was captured by the TRMM satellite)
of Typhoon Sam as captured by the PR on 23 August 1999.

While Doppler weather radar has the capability to detect winds, meteorological satellite nowadays can also estimate the winds near the sea surface from the space. The meteorological satellite with this capability is called QuikSCAT. This is also a polar-orbiting satellite tracking at a maximum altitude of about 800 km above the earth. Launched in 1999, QuikSCAT carries microwave radar to measures the backscattered microwave signals from the sea waves to deduce near-surface wind speed and direction under all weather and cloud conditions. This is particularly useful to locating and tracking tropical cyclones on the oceans (Figure 25).

The past few years have witnessed substantial boom in the field of radar and satellite meteorology. With the advent of new technology, weather radar and meteorological satellites are expected to find much wider applications in the area of weather forecasting and warnings.

Figure 25  Circulation centre of Typhoon Utor is clearly discernible on the QuikSCAT image at about 21:19 UTC on 2 July 2001. (This image was captured by QuikSCAT)
References on Radar and Satellite Meteorology


Some Internet Resources on Weather Radar and Meteorological Satellite

Geostationary satellite images around the world:
  http://wwwghcc.msfc.nasa.gov/GOES/
  http://www.goes.noaa.gov/
  http://kauai.nrlmry.navy.mil/sat-bin/global.cgi

Geostationary satellite images of Asia and the western Pacific:
  http://weather.is.kochi-u.ac.jp/FE/00Latest.jpg
  http://Radarwww.weather.gov.hk/wxinfo/intersat/satpic_s.htm

QuikSCAT satellite images:
  http://manati.wwb.noaa.gov/quikscat/

TRMM satellite images:
  http://trmm.gsfc.nasa.gov/data/quicklook/last_2_cal.html

Radar images of Hong Kong and Guangdong:

Background information on remote sensing
  http://rst.gsfc.nasa.gov/Front/tofc.html
  http://www.everythingweather.com/weather-radar/principles.shtml