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Remote Sensing Applications
P. S. Roy
R. S. Dwivedi
D. Vijayan
इसरो isro
nrsc
Remote Sensing Applications
National Remote Sensing Centre

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Cyclones

11.1. Introduction

A cyclone is a low pressure area in the atmosphere in which winds spiral upward. A cyclone can cover an area as large as half of the United States. All cyclones are characterized by: (1) low pressure at the centre, and (2) winds spiraling toward the center. The direction of the spiral is unique because in the northern hemisphere the winds blow counter-clockwise and in the southern hemisphere they blow clockwise. Cyclones are formed from simple thunderstorms. However, these thunderstorms can only grow to cyclone strength with cooperation from both the ocean and the atmosphere. First of all, the ocean water itself must be warmer than a threshold say, 28 °C. The heat and moisture from this warm water is the source of energy for cyclones. Cyclones will weaken rapidly when they travel over land or colder ocean waters — locations where their heat and/or moisture sources do not exist. High relative humidities in the lower and middle troposphere are also required for cyclone development. These high humidities reduce the amount of evaporation in clouds and maximizes the latent heat released because there is more precipitation. The vertical wind shear in a tropical cyclone's environment is also important. Wind shear is defined as the amount of change in the wind's direction or speed with increasing altitude. When the wind shear is weak, the storms that are part of the cyclone grow vertically, and the latent heat from condensation is released into the air directly above the storm, aiding in development. When there is stronger wind shear, the storms become more slanted and the latent heat release is dispersed over a much larger area.

Cyclones are characterized as tornadoes, hurricanes and typhoons. A tornado is a smaller kind of cyclone. When a cyclone forms over tropical waters in the North Atlantic or eastern North Pacific oceans and has winds of 119 km/hr or more it is called a Hurricane. If the cyclone forms in the western Pacific with winds of 119 km/hr or more it is called a Typhoon. All of these storms are generally accompanied by high winds, heavy rains, severe thunder, and lightening. In the north Indian Ocean they are simply called as tropical cyclones.

A typical mature tropical cyclone is a warm core vortex in the atmosphere (anti-clockwise vortex rotation in the Northern Hemisphere and clockwise in the southern), cyclonic in the lower troposphere and anti-cyclonic in the upper troposphere. The circulation extends horizontally to some 1000 kilometers from the centre and vertically to about 15 km above sea level. There is an 'eye' at the centre of the cyclone of radius 5 to 50 kilometers. The eye is rain-free with light winds. It is surrounded by a 'wall cloud' made up of tall cumulo-nimbus clouds rising upto an altitude of 15-18 km, the wall cloud thickness being about 10-15 km radially. Below the wall cloud are found the strongest surface winds of the cyclone (V_{max}) with heaviest rain. Beyond the wall cloud, surface wind speeds decrease gradually with the radial distance from the centre and rainfall is confined to the regions covered by the inward spiraling cloud-bands (composed of cumulo-nimbus clouds and some cumulus clouds at large distances from the centre) that are seen within a radial distance of about 400 km from the centre of the cyclone.

As one moves from the periphery to the centre of the cyclone, the sea level atmospheric pressure falls continuously, the largest radial pressure gradients of 2-4 hPa/km, occurring in the wall cloud region. Under the influence of frictional forces, the low-level wind direction, which is almost tangential to the nearly circular isobars of the cyclone field at about 1-km above sea level, cuts the isobars at about 25° towards low pressure at sea level. The low level winds rich in moisture thus possess strong tangential and radial component causing the air parcels to spiral inwards from the peripheral regions of the cyclone towards its centre. In consequence, their rotational velocity (tangential wind) increases rapidly due to partial conservation of its angular momentum. The radial component of the wind converges large amounts of moisture to the central regions of the cyclone, which ascends and condenses in cloud formations there, keeping the central regions warmer than the surrounding tropical atmosphere. This warm anomaly which reaches a maximum of about 15°C at 300-200 hPa level (9-12 km altitude) reduces the radial pressure gradients at these high altitudes. The cyclically rotating air parcels rising up in the central regions of the cyclone move outwards in the upper troposphere, under the action of unbalanced centrifugal forces (with reduced pressure gradients) and conserving angular momentum, begin to reverse their cyclonic rotation as they move further away from the centre. Satellite pictures of tropical cyclones indeed show both the inward spiralling (anti-clockwise) low level clouds and the outward moving (clock-wise) cirrus clouds at the upper levels in the northern hemisphere.

Our current knowledge of the structure of tropical cyclones has come from studies made over a hundred years of different cyclone-prone regions of the world. Early studies using ship reports and measurements from coastal and island observatories gave a reasonably good picture of the surface level features of the cyclone, but that of their three dimensional structure has been derived mainly from reconnaissance flights using specially equipped aircrafts that were flown into the cyclone at various levels, measuring winds, temperatures, humidity and pressure. Direct sensing as well as remote sensing methods were used. Compositing of data from routine balloon soundings of the atmosphere has also yielded a wealth of information. Details regarding the eye, wall cloud and the spiral cloud bands were obtained from satellite pictures (polar orbiting and geo-stationary) as well as cyclone detection radar systems installed at coastal and island .

11.2. Life Cycle of Tropical Cyclones

Cyclones evolve through a life cycle of stages from genesis to dissipation. A tropical disturbance in time can grow to a more intense stage by attaining a specified sustained wind speed. Cyclones can often live for a long period of time — as much as two to three weeks. They may initiate as a cluster of thunderstorms over the tropical ocean waters. Once a disturbance has become a tropical depression, the amount of time it takes to achieve the next stage, tropical storm, can take as little as half a day up to a couple of days. The same may occur for the amount of time a tropical storm needs to intensify into a cyclone. Atmospheric and oceanic conditions play the major role in determining these events.

There are several schemes that describe the life-cycle of an average TC. The four stages shown below are not really discrete entities, rather they represent a continuous process. Individual stages may even occur more than once during the life-cycle of a particular storm.

Formation or Genesis Stage:

Since the nature of Tropical Cyclone (TC) development is continuous, features associated with earliest stages of the TC life-cycle can overlap. To complicate the issue, there is no standard language for these initial stages. For example, some meteorologists prefer the term “genesis” to describe both the earliest stages of the life-cycle and progression to a mature hurricane or typhoon. Others use the term “genesis” to describe the earliest stages and “formation” to somewhat later stages in the life-cycle.

Intensification or Deepening Stage:

In this stage, the TC central pressure falls and the maximum surface wind speed increases. An eye may develop at the center of the TC if the stage continues.

Mature Stage:

The mature stage of a TC is usually associated with the period in which the TC reaches maximum intensity. The central pressure has reached a minimum, and the surface winds have reached a maximum.

Decay Stage:

When a TC decays, the central pressure increases and the maximum surface winds weaken. Usually, the decaying process is the result of a TC moving over land, moving over cool water, recurving and assuming extratropical characteristics, or a combination of these processes. Even though the TC is decaying, it can produce high winds and heavy rains.

11.3. Classification of Cyclonic Disturbances

Tropical cyclones have great socio-economic concern for the Indian subcontinent that is the only region in the world having two cyclone seasons within a year. A vast coastline of India with high density of population is exposed to these natural threats, making it one of the worst cyclone-affected regions in the world in terms of the loss of lives. Due to the varying coastal bathymetry of the Indian coast, the severity of the storm surge created by the cyclones vary from place to place for the same intensity of the cyclone. Classifications of cyclonic disturbances for the Bay of Bengal and the Arabian Sea region for the exchange of messages among the panel countries are given below:

Weather system	**Maximum wind speed**
• Low pressure area	Wind speed less than 17 kt (31 km/h)
• Depression	Wind speed between 17 and 33 kt (31 and 61 km/h)

• Cyclonic storm	Wind speed between 34 and 47 kt (62 and 88 km/h)
• Severe cyclonic storm	Wind speed between 48 and 63 kt (89 and 118 km/h)
• Severe cyclonic storm	Wind speed 64 kt (119 km/h) or more with a core of hurricane winds
• Very severe cyclonic storm	Wind speed 64 and 119 kt (119 and 221 km/h)
• Super cyclonic storm	Wind speed 120 kt and above (222 km/h)

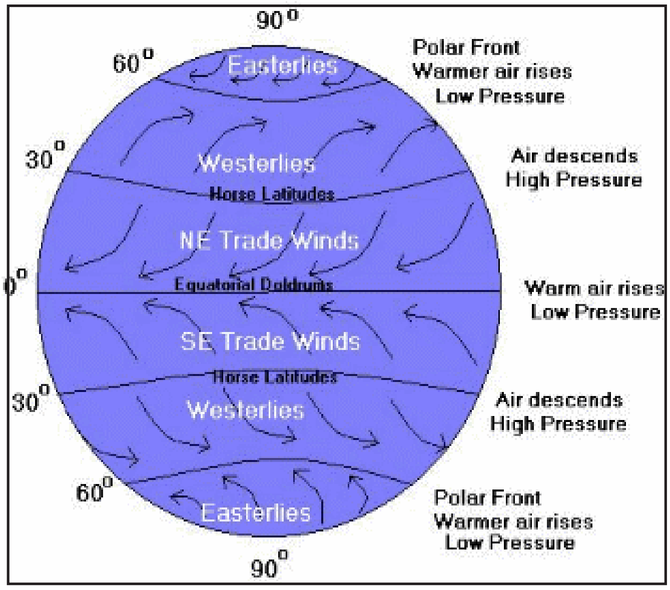

Figure 11.1: Global wind patterns (source: www.weatherwizkids.com/weather-winds.html)

11.4. Movement of Cyclones

Winds steer the cyclones. The global wind pattern is also known as the "general circulation" and the surface winds of each hemisphere are divided into three wind belts (figure 11.1).

Polar Easterlies: from 60-90 degrees latitude, prevailing westerlies: from 30-60 degrees latitude, tropical easterlies: from 0-30 degrees latitude. The easterly trade winds of both hemispheres converge at an area near the equator called the "Intertropical Convergence Zone (ITCZ)", producing a narrow band of clouds and thunderstorms that encircle portions of the globe. The path of a cyclone greatly depends upon the wind belt in which it is located. A cyclone originating in the eastern tropical Pacific, for example, is driven westward by easterly trade winds in the tropics. Eventually, these storms turn northwestward around the subtropical high and migrate into higher latitudes. Some times the local steering winds may not exactly follow this pattern.

11.5. Cyclone Intensity

Many of the physical processes associated with TC intensification and decay are difficult to observe and poorly understood. Hence, cyclone intensity prediction is a relatively difficult problem compared to the track prediction. Some of the factors that influence the TC intensities are:

11.5.1. Upper Tropospheric Anticyclones

As viewed by satellites (and satellite cloud-tracked winds and water-vapor-tracked winds), upper-troposphere circulation patterns associated with intensification are the easiest to identify because the upper tropospheric clouds usually obscure shallower clouds. These upper-troposphere patterns can define the outflow at the top of the TC, which indicates mass removal from the center of the storm (figure 11.2).

Figure 11.2: Mechanism of Tropical cyclone formation (Source: http://www.mspsofworld.com/hurricane/machanism-of-tropical-cyclone-formation.html)

In general, a mesoscale anticyclone is located directly over or near the center of the TC. This represents the location in the upper wind field where there is a buildup of mass from rising convective motion within the center of the cyclone. On the other hand, another larger, synoptic scale anticyclone is often found that pre-existed within the vicinity of the intensifying TC. The location of this larger anticyclone can vary depending upon many environmental factors, including the lower-level forcing mechanisms that are helping to create the cyclone. The relative location of this large-scale anticyclone with respect to the TC will help dictate the direction of outflow patterns around the cyclone. These outflow patterns can be identified from satellite infrared cloud imagery, especially when the imagery is animated. These outflow patterns can be classified into one of three basic categories depending on the number of channels:

- Single-channel Outflow. The single-channel outflow may be divided into two subcategories based on direction of the outflow channel. Tropical cyclones with single-channel poleward outflow pattern generally intensify at an average maximum rate of 15 to 20 kt/6 hr. Tropical cyclones with single-channel equatorward outflow pattern generally intensify at an average maximum rate of 25 to 28 kt/6 hr
- Dual-channel Outflow. Tropical cyclones with a dual-channel outflow pattern generally intensify at an average maximum rate of 35 kt/6 hr
- No Outflow Channel. Tropical cyclones with little outflow generally intensify at a very slow rate as they are unable to evacuate mass

11.5.2. Tropical Upper Tropospheric Trough

A strong upper level (250-200 hPa) cyclonic circulation to the north or northwest of a TC, namely the tropical upper tropospheric trough (TUTT or TUTT Cell), is a common occurrence during July and August in the northern Pacific. This type of upper-level circulation pattern is favorable for vigorous outflow to the north. In addition, this pattern generally occurs as the cyclone nears the western edge of the subtropical ridge where enhanced equatorward outflow is common. The combined effects of the northward and southward outflow often lead to rapid deepening.

11.5.3. Other Factors Affecting Intensity

There are a few other observable phenomena that can affect TC intensity:

- Cumulus convection. Satellite cloud imagery can show whether convection is increasing or decreasing, and whether the TC cloud patterns become more or less organized. The convective activity implies the stage of TC development. Therefore, cumulus convection should be monitored continuously by the forecaster
- Sea surface temperature (SST): A SST of 26.5 °C is generally considered to be the minimum for TC formation. Anomalously high SST can cause more heat and moisture flux from the ocean to the atmosphere. This condition favors further development of the TC. Rapid deepening is more likely once the SST is higher than 28.5 °C
- Vertical wind shear: Weak vertical wind shear aids TC intensification while strong vertical wind shear inhibits TC intensification
- Low-level circulations: Low-level cyclonic circulations are favorable regions for TC intensification. The summer monsoon trough in the western North Pacific is an area where low level cyclonic circulations are abundant. The Earth’s rotation (i.e., Coriolis effect) can also contribute to cyclonic circulation
- Low-level convergence: Low-level convergence zones such as the Inter-Tropical Convergence Zone (ITCZ), are suitable areas for TC intensification
- Land, coast, and mountain effects: These effects can be quite complex. In general, a TC that moves over land decays. A TC decays much faster when it passes over mountainous regions, such as Taiwan or Luzon, than it does over flat land. Also, a TC often re-intensifies when it re-enters a marine area
- Tropical cyclone transformation: A TC that enters into the mid-latitudes either decays rapidly or transforms into an extratropical cyclone. A decaying TC may still produce heavy rain, especially when it moves over mountainous areas. When a transformation from TC to extratropical cyclone occurs, forecast responsibility is transferred from the TC forecast center to another forecast office
- Oceanic heat content: While a threshold SST is required for the cyclogenesis, oceanic heat content plays a prominent role in the intensification or dissipation of the cyclones

11.6. Cyclone Track Prediction

Predicting the tropical cyclones has been a challenging problem. Several models and methods have been developed to predict the position of the cyclone accurately so that appropriate warning can be issued for disaster management. Mohanty and Gupta (1977) and Gupta (2006) described in detail different track prediction techniques. The most devastating impact of the tropical cyclone, particularly, for the Indian coastal regions is the storm surge. Because of the highly varying bathymetry of the Indian region, even a slight error in the prediction of landfall point can lead to a totally different storm surge height. The objective track prediction of tropical cyclones may be grouped into four categories (Elsberry 1995): (i) empirical, e.g., climatology, persistence of past motion, climatology and persistence (CLIPER), and analogue techniques, (ii) statistical-synoptic, in which additional meteorological information is incorporated, usually via statistical regression using grid-point values from synoptic analysis available at the forecast time, (iii) statistical-dynamic, in which grid-point values from synoptic predictions are also incorporated, and (iv) dynamic, in which a global or regional numerical weather prediction (NWP) model is integrated as an initial value problem to provide a track forecast. The empirical track forecasts are easy to understand given the simple inputs. On the other hand, the statistical models have additional complexity and are not easy to interpret because the grid-point predictions are generally not available to the forecaster. The dynamical models are even more complex and difficult in which steering influences at many levels and various physical processes such as advective, diabatic and frictional effects may be contributing to TC motion.

Traditionally, modeling a dynamical system requires one to derive the equations of motion from first principles, to measure initial conditions and, finally, to integrate the equations of motion forward in time. Alternatively, when such an approach is not feasible due to some reasons, e.g., the model may be far from perfect, and initial conditions may be erroneous or even the required computing resources are not available, empirical laws governing the physical processes can be obtained by model-fitting approaches based on the observed variability of the system evolution. Nowadays, it is known that not all random-looking behavior is the product of complicated physics but it may result from the chaotic nature of a nonlinear and deterministic dynamics involving few degrees of freedom. In such cases, it is possible to exploit this determinism to make short-term forecasts that are more accurate than those obtained employing a linear stochastic model. Deterministic models directly built from observations of the system evolution carry out these forecasts. If we assume that random movement of the cyclone can be modeled from the chaotic nature of a nonlinear and deterministic dynamics, forecasting of the cyclone track is possible. These forecasts use deterministic models directly built from observations of the system evolution. Using the chaos theory, Pal (1991) suggested the possibility of predicting the position of the cyclone from the past six positions. One of the main requirements of a robust statistical technique is its ability to predict the correct track within a short time. Ali *et al.*, (2007) used 31 years (1971-2001) cyclone positions at 6 hourly intervals for developing and validating the artificial neural network model.

11.7. Cyclone Intensity Prediction

Various dynamical and statistical models have different rates of success for cyclone intensity prediction. In addition to atmospheric parameters and sea surface temperature (SST), another important parameter that enhances the understanding of the intensification of the cyclones is the upper ocean heat storage that is generally reflected in the oceanic eddies and dynamic topography. Sea surface height anomalies (SSHAs) from radar altimeters can provide information on this parameter. The relationship between the SSHAs and the associated hydrographic structure, particularly of eddies, is discussed by *Ali et al.,* (1998), *Gopalan et al.,* (2000) and *Gopalakrishna et al.,* (2003). Because of these changes in hydrographic features caused by SSHAs, warm (cold) core oceanic eddies have more (less) heat content compared with their surroundings.

The importance of SST in the formation and maintenance of tropical cyclones has long been known. *Palmen* (1948) showed that hurricanes cannot form unless the SST is greater than 26º C, though this is not the only necessary condition. Latent heat release through evaporation fuels the cyclone system. After the passage of a cyclone, SST reduces due primarily to the cyclone-induced mixing. While this negative feedback regime tends to decrease the storm intensity, pre-existing mesoscale features like warm core eddies and the deeper mixed layer provide the heat source for intensification of cyclones.

Patterns of lower atmospheric anomalies are more consistent with the upper ocean thermal structure variability than just with SSTs (*Namias and Canyan,* 1981). Using a coupled ocean-atmospheric model, *Mao et al.,* (2000) reported that the rate of intensification and final intensity of cyclones are sensitive to the initial spatial distribution of the mixed layer. *Shay et al.,* (2000) described details of the response of the hurricane to a warm core eddy. Thus, a well-mixed upper ocean layer, due either to the mixing processes or to eddies, may be a more effective means of assessing oceanic regimes for tropical cyclone studies.

Sudden unexpected intensification of Hurricane Opal from 965 to 916 hectopascals in the Gulf of Mexico over a 14-hour period (*Shay et al.,* 2000) after passing over a warm core eddy is a classic example of the influence of oceanic features on cyclones. Ali *et al.*, (2007) have demonstrated impact of SSHAs on the intensity of the Bay of Bengal cyclones.

11.8. Satellite Technologies

New technologies have been employed to grasp each of these factors when attempting to make an intensity or track forecast. The earliest attempts aimed at tropical cyclone prediction began with the development of a 2-dimensional axi-symmetric cyclone models at Space Applications Centre (SAC), Ahmedabad (Narayanan and Kishtawal, 1984). Although these models had limited or no applicability for real-time forecasting needs, they provided the basic insight into the physical processes within a tropical cyclone and helped in interpreting the satellite observations. The advent of next-generation satellite observations, mainly the wind scatterometer onboard first European Remote Sensing (ERS-1) satellite provided a boost to tropical cyclone studies (Rao *et al.*, 1994). Some of earliest attempts to demonstrate the impact of assimilation of scatterometer surface wind observations on the prediction of cyclone tracks was carried out jointly between SAC and NCMRWF (National Centre for Medium Range Weather Forecasting) (Joshi *et al.*, 1998). The period during the late nineties was very significant for the development of tropical cyclone studies with the advent of the most important international satellite missions like Tropical Rainfall Measuring Mission (TRMM) that provided much awaited insight into the tropical cyclone structure (Falguni *et al.*, 2004). This, added with the availability of larger computing resources and also the development and availability of more sophisticated meso-scale numerical weather prediction models like MM-5, and WRF, helped the tropical cyclone research community. Active use of satellite observations has always been the prime concern for all the modeling activities. Some of the early applications of satellite observations in tropical cyclone forecasting experiments based on mesoscale models is by use of a synthetic vortex in model initial conditions (Singh *et al.*, 2007) where the tropical cyclones were relocated in model fields in consistence with the satellite observations. Later, more sophisticated data assimilation techniques like 3-D variational (3D-VAR) approaches were applied to optimally assimilate the satellite derived information for improving tropical cyclone prediction (Singh *et al.*, 2008). Initially, these experiments were based on satellite observations like cyclone location and intensity, ocean surface and upper level winds, and atmospheric water vapor were obtained from international satellite missions like TRMM, DMSP, Meteosat and the data assimilation experiments clearly proved the value of these observations in improving the track and intensity prediction of tropical cyclones. Since the retrieval of geophysical parameters from Indian satellites is one of the most significant scientific activities, there was a logical concern to use these data in numerical models for improving tropical cyclone predictions. The latest development in data assimilation research includes the assimilation of INSAT-derived cloud motion winds, and the radiances from imaging sensors. Considerable impetus in tropical cyclone related data assimilation research can be expected in coming few years with the order of magnitude enhancement of satellite data from state-of-the art Indian satellite missions (e.g., atmospheric sounder onboard INSAT-3D, SAPHIR onboard Megha-Tropique, and a wind scatterometer onboard Oceansat-2). At present only existing INSAT data is being used for cyclone studies. During MSMR (Multifrequency Scanning Microwave Radiometer) time frame, the geophysical parameters from Oceansat-1 were also used in

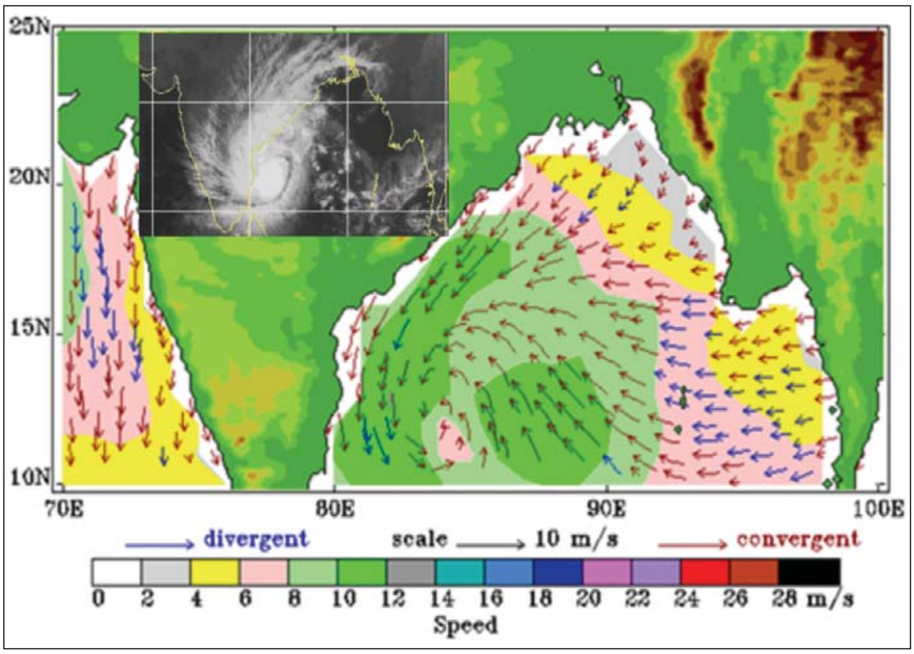

Figure 11.3: Quickscat derived wind vectors over a Bay of Bengal cyclone (inset: cloud imagery form INSAT)

numerical weather forecasting models. The wind magnitude for MSMR was found to be in good agreement with ERS-1 observations (Falguni *et al.*, 2005).

TRMM Microwave Imager (TMI) data has emerged as an exceptional tool for measuring atmospheric water vapor content, liquid cloud water, and precipitation rates in the tropics. Clouds are transparent at 10.7 GHz - one of the frequencies used by TRMM - and so it is a useful tool for monitoring SST on a daily basis even when clouds normally obscure the view. Although SST and atmospheric relative humidity have been used in idealized models to study the Maximum Potential Intensity (MPI) in the past, they have not been used to examine the interactive nature of tropical cyclones with SST and moisture variability. Kishtawal *et al.*, (2005) used genetic algorithm technique to estimate the cyclone intensity using multichannel TMI data. Since the cyclones are greatly influenced by the upper ocean heat content or the cyclonic heat potential (Goni and Trainanes, 2003), SSHAs representing this parameter have the potential towards a better forecasting of the cyclone track and intensity. INSAT visible channel is used to locate and track the cylones. Scatterometer wind vectors have shown great impact on cyclone studies, particularly, in cyclone models. A typical picture of the Bay of Bengal cyclone observed from INSAT visible imagery and Quickscat scatterometer winds is shown in figure 11.3.

11.9. Operational Scenario

India Meteorological Department (IMD) is the nodal agency to provide operational cyclone forecast to Bangladesh, India, Maldives, Myanmar, Pakistan, Sri Lanka, Sultanate of Oman and Thailand. INSAT imagery is used to identify and locate the various stages of the cyclone and to estimate the intensity and position using objective Dvorak Technique. The Dvorak technique is based on the analysis of cloud patterns in visible and infrared imagery. The cloud patterns obtained from INSAT for the Orissa Super Cyclone is shown in Figure 11.4 wherein the eye of the cyclone is clearly seen. A quasi-lagrangian model (QLM) is used by IMD for cyclone track prediction. The model provides track forecast up to 72 hours in advance. The initial analysis and the lateral boundary conditions are generated at 00 and 12 UTC from global T-80/T-254 model sigma fields operationally run at NCMRWF.

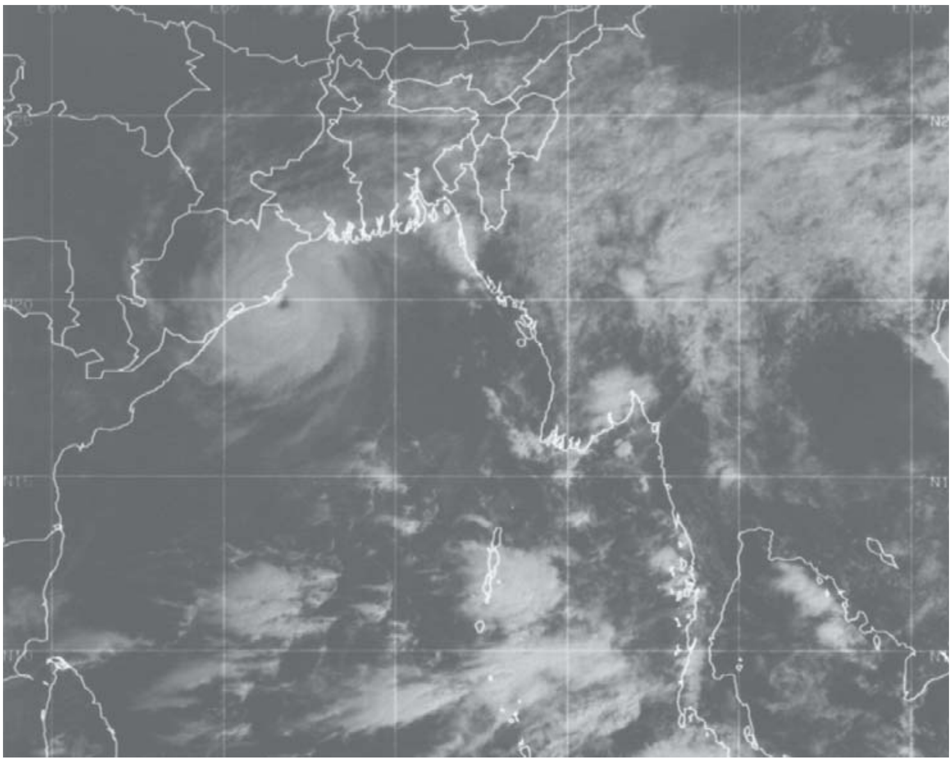

Figure 11.4: October 1999 Orissa Super Cyclone as viewed by INSAT

Operational cyclone forecasts are also available from Joint Typhoon Warning Centre, US Department of Defence, Hawaii, USA, though these forecasts are primarily meant for the US government agencies. Although not an official member or participant in the United Nations World Meteorological Organization (WMO), JTWC continually attempts to maintain cordial relations with WMO tropical cyclone forecast centers to minimize the issuance of conflicting information. JTWC monitors, analyzes, and forecasts tropical cyclone genesis, development, and movement across more than 110 million square miles of the Pacific and Indian Oceans from the west coast of the Americas to the east coast of Africa. This area of responsibility encompasses more than 90% of the world's tropical cyclone activity. JTWC uses the 1-minute mean wind speed to determine maximum sustained surface winds, as required by the US National Hurricane Operations Plan. Other countries, however, use the 10-minute mean wind speed to determine maximum sustained surface wind speeds. The difference generally means that JTWC will report higher maximum sustained surface wind speeds than non-U.S. TCWCs for the same cyclone. Besides the forecasts out to 120 hours, JTWC provides historical data on its site. From the current cyclone season, National Remote Sensing Center (NRSC) has initiated the prediction of cyclones in the Arabian Sea and the Bay of Bengal, primarily, for the Disaster Support Centre of ISRO. Soft-computing techniques developed at SAC and NRSC are being used for the purpose.

NRSC also plays a major role in cyclone damage assessment using Indian Remote Sensing Satellites and Radarsat data. An example of the damage assessment created using IRS-1C and Radarsat data due to the Orissa Super Cyclone is given in Figure 11.5. The procedure adopted is similar to the one for flood inundation map creation, the details of which are given at chapter 12.

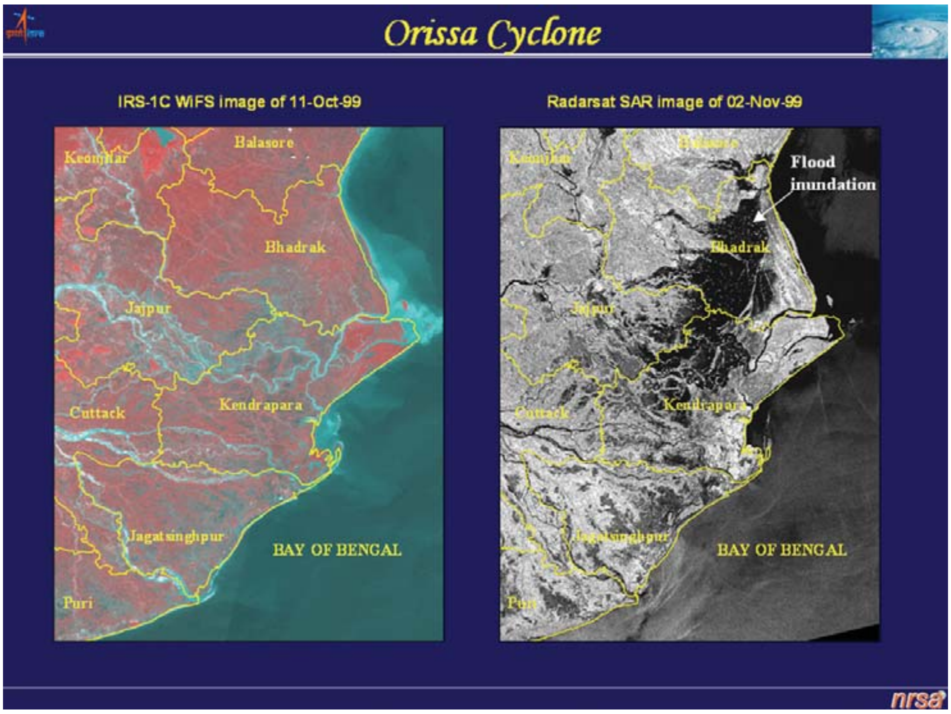

Figure 11.5: Damage assessment created for the Orissa Super Cycone using IRS-1C and Radarsat data

11.10. The Future

Observations from Doppler weather radar systems (DWRS) are very critical, particularly, when the system reaches closer to the land. IMD plans to have a total of 55 DWRS under its modernization plan, in comparison to the existing 5 DWRS. Procurement of the cyclone probing aircrafts under the umbrella of National Disaster Management Authority will give an insight into the understanding of the physics of cyclones. Launching of Indian satellites like INSAT-3D with vertical sounders, Meghatropiques providing radiation budget, temperature and humidity profiles, Oceansat-2 providing wind vectors from a scatterometer and temperature and humidity profiles using radio occultation techniques, would certainly enhance the cyclone modeling capabilities towards a better forecasts. Compared to the track prediction intensity prediction has been more challenging. Incorporation of ocean subsurface thermal information that can be indirectly inferred from remote sensing platforms is likely to reduce this problem, particularly, in the Arabian Sea and Bay of Bengal.

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