Tropical Cyclone Forecasting and Monitoring

Introduction

Tropical cyclones are monitored primarily utilizing remotely-sensed observations. Geostationary and polar-orbiting satellites are the primary tools by which these remote observations are obtained. To first order, satellite observations can be categorized into three types based upon the wavelength of the emitted radiation measured (or sensed) by a given satellite instrument. These three types are visible, infrared, and microwave. Later in this lecture, we focus upon describing the Dvorak technique, a robust method for estimating tropical cyclone intensity using remotely-sensed observations, and on detailing some available scatterometry and microwave satellite products and their utility to tropical cyclone monitoring. Note that there exist other means by which tropical cyclones are monitored, including via land-based or ocean-based (buoys, oil rigs, etc.) observation platforms and aircraft reconnaissance missions. However, as the utilization and application of such data are fairly straightforward in nature, these are not discussed in great length here.

Guidance used in support of operational forecasts of tropical cyclone track and intensity takes many forms. These forms include dynamical models, both regional and global in scope; consensus models, whether corrected or otherwise; trajectory models, used to guide motion forecasts; statistical-dynamical models, utilizing statistical relationships between parameters obtained from dynamical model forecasts; and statistical models, primarily utilizing climatology and persistence to guide forecasts. Later in this lecture, we describe the formulation and utility of each of these numerical guidance products.

Key Concepts

- What in situ and remote sensing tools do forecasters routinely use to monitor tropical cyclones?
- What are the capabilities of these tools?
- What are the different types of guidance used by forecasters to make forecasts of tropical cyclone track and intensity?

Tropical Cyclone Monitoring: Intensity Estimation Using the Dvorak Technique

The Dvorak technique (e.g., Velden et al. 2006) relies on four distinct properties that relate organized cloud patterns to tropical cyclone intensity. Two of these are kinematic, vertical vorticity and vertical wind shear, while two are thermodynamic, related to deep, moist convection and inner core temperature. The strength and distribution of the circular winds (and, by implication, vertical vorticity) in a tropical cyclone organizes the clouds into patterns that the Dvorak technique relates to the intensity of the cyclone. Vertical wind shear acts to distort the cloud pattern, with the magnitude of the distortion directly related to vertical wind shear magnitude. Convective cloud depth, as assessed using satellite-measured infrared cloud-top temperatures in the tropical cyclone inner core, is also directly related to intensity. For tropical cyclones with eyes, the Dvorak technique also relates the differential in temperature between the eyewall and eye to intensity, with a greater (smaller) differential being associated with stronger (weaker) intensity.

To first order, the Dvorak technique relies on empirically-derived relationships between tropical cyclone intensity and the corresponding satellite depiction of the tropical cyclone. A given tropical cyclone is allowed to fit into one of four primary cloud organization patterns: curved band, shear, central dense overcast, or eye. Once the appropriate pattern has been determined, an analyst then utilizes the empirically-derived relationship appropriate to that pattern to obtain an intensity estimate. Such an intensity estimate is given in terms of what is known as a “T-number” or “CI” number, with the latter used to obtain an estimate of the maximum sustained winds. An appropriate wind-pressure relationship is then used to obtain an estimate of the minimum sea level pressure. Note that there is a large degree of subjectivity to both the pattern identification and intensity estimation stages of the Dvorak process.

Through the years, the Dvorak method has proven to be a skillful means of estimating tropical cyclone intensity. Approximately 50% of the intensity estimates obtained using the Dvorak method are within 5 kt of reconnaissance aircraft measurement-aided best track intensity estimates. Similarly, 75% (90%) of the errors are 12 kt (18 kt) or less. As a result of its skill and the lack of routine reconnaissance aircraft missions into tropical cyclones over large portions of the globe, the Dvorak technique is the chief method for estimating the intensity of nearly all tropical cyclones. That said, the Dvorak technique is not without its limitations. One of the most limiting factors in the Dvorak technique is its reliance on infrared satellite imagery (when visible satellite imagery is not available) in which cirrus clouds can obscure tropical cyclone organization and thus result in underestimates of tropical cyclone intensity. It also struggles during eyewall replacement cycles, when tropical cyclones rapidly weaken over cold waters, with subtropical cyclones, during extratropical transition, and with tropical cyclones that form in the midst of larger-scale phenomena such as monsoon troughs and gyres.

In addition to the above limitations, the inherent subjectivity to the Dvorak method can be viewed as a limitation in the technique. The most skillful Dvorak-based estimates of tropical cyclone intensity often come from forecasters with decades of experience utilizing the technique. More unnerving, however, is that two equally-skillful, equally-experienced forecasters can obtain intensity estimates that differ from one another by 5-15 kt when independently given the same satellite imagery! This motivated the development of the Advanced Dvorak Technique (ADT; Olander and Velden 2007) to attempt to reduce the subjectivity inherent to the Dvorak technique. The ADT is an entirely objective, automated means of estimating tropical cyclone intensity using extensions to the principles underlying the Dvorak technique. The skill of the ADT is typically on par with that of the best subjective Dvorak intensity estimates, making it an attractive tool to operational forecast centers across the globe.

Like the Dvorak technique, the ADT first classifies a tropical cyclone by its cloud organization pattern. As compared to the four possible patterns of the Dvorak technique, a total of eight possible patterns (hereafter referred to as scene types) exist within the ADT. These eight possible scene types are comprised by three eye scene types (eye, pinhole, and large) and five cloud region scene types (uniform CDO, irregular CDO, embedded center, curved band, and shear). Once the scene type has been determined, the intensity estimate is calculated utilizing either regression-based intensity estimates (all but curved band and shear scene types) or traditional Dvorak technique-based satellite-derived pattern matching techniques (for the curved band and shear scene types only). From the resultant intensity estimate, a T-number and CI are obtained, after which any appropriate corrections (e.g., for latitude, basin, land, etc.) are applied before the tropical cyclone intensity estimate is finalized.

Tropical Cyclone Monitoring: Structure and Intensity Assessment via Scatterometers

Scatterometers, or microwave-wavelength remote-sensing instruments on polar-orbiting satellites, relate ocean roughness (as caused or manifest by waves) to surface wind speed and direction. The MetEd module, "Using Scatterometer Wind and Altimeter Wave Estimates in Marine Forecasting," provides a comprehensive introduction to the physical basis for and interpretation of the output from scatterometry. A given scatterometer can provide, at most, two passes over a given region per day due to its polar orbit. Furthermore, as individual swaths from a scatterometer do not overlap, a feature of interest might fall between swaths, whether in whole or in part. Gaps between swaths are largest within the tropics. Currently operational scatterometers include ASCAT-A and ASCAT-B, onboard the European Space Agency's METOP-A and METOP-B satellites, and RapidScat, onboard the International Space Station.

Scatterometers typically emit radiation at wavelengths of 0.84, 2, or 5 cm. The 5 cm band is that which is used by ASCAT; this band is relatively insensitive to rain. The 2 cm band is that which is used by RapidScat; retrievals from RapidScat are thus somewhat less reliable in areas of precipitation. Rain-contaminated estimates are typically denoted in black on scatterometer output charts. Overall, scatterometer retrievals are reliable up to approximately 50 kt, with ASCAT in particular having a slight weak bias for wind estimates above approximately 35 kt. Thus, scatterometers are best used for assessing the current intensity of weaker tropical cyclones and for assessing the size and asymmetry of the tropical cyclone's gale- and storm-force wind fields.

Independent of whether a scatterometer estimate is taken in a region of precipitation or not, there typically is some uncertainty in wind direction manifest within each retrieval. Thus, in addition to the processed wind speed and direction product, analysts should also consider the ambiguity product, which provides a graphical interpretation of the range of possible wind directions from the retrieval. This is particularly important where wind direction changes rapidly and where wind speed is light. Typically, an analyst will interpret the ambiguity product in light of the appropriate conceptual model for atmospheric motions and/or relative to wind direction estimates at nearby locations. An example is provided in the accompanying lecture materials.

Tropical Cyclone Monitoring: Structural Assessment via Microwave Satellite Imagery

Microwave satellite imagery enables those monitoring tropical cyclones to "see" salient tropical cyclone structures that may otherwise be hidden beneath a tropical cyclone's cirrus or convective canopy and are thus undetectable using conventional infrared and/or visible satellite imagery. Of particular benefit to tropical cyclone monitoring operations are two specific frequency bands within the microwave spectrum: the 36-37 GHz and 85-91 GHz bands. The 36-37 GHz band is sensitive to lower tropospheric water or rain droplets and insensitive to frozen hydrometeors in the upper troposphere. The inverse is true for the 85-91 GHz band. The combination of information from each frequency band enhances our ability to detect a tropical cyclone's center, inner and outer rain bands, convective organization, and primary and secondary eyewall presence and integrity.

In both frequency bands, the primary meteorological variable of interest is brightness temperature (T_b). Brightness temperature is a measure of the temperature that a blackbody would have in order to produce the signal perceived by the satellite. Recall that a blackbody is a perfect emitter (i.e., emissivity ε = 1). The Earth's emits radiation toward outer space over a wide range of frequencies. Water (in frozen, solid, and gaseous states) absorbs, scatters, and re-emits portions of this radiation, again over a wide range of frequencies. As water is not a perfect emitter, the amount of radiation energy reaching the satellite in outer space is less than that emitted by the Earth's surface. We know that the amount of radiation energy associated with a blackbody emitter is exclusively a function of temperature (or, more specifically, the fourth power of temperature). If we assume a perfect emitter, the brightness temperature is merely the estimated temperature associated with the sensed amount of radiation energy.

For a perfect emitter, $T_b = T$. For liquid water, $T_b < T$. For frozen water, $T_b \ll T$. This information enables us to determine regions of warm rain (e.g., moat regions, where T_b is high) and deep, moist convection (where T_b is low) associated with a tropical cyclone. As noted above, such information is particularly useful when these structures are obscured by some phenomenon, most commonly associated with cirrus canopies. At 36-37 GHz, radiation emitted from the Earth's surface is absorbed and largely re-emitted by cloud and rain droplets in the lower troposphere. It is largely unaffected by ice particles in the upper troposphere. Therefore, the satellite senses relatively high brightness temperatures. At 85-91 GHz, radiation emitted from the Earth's surface is rapidly depleted by water droplets and ice particles in the upper troposphere within deep, moist convection. This depletion of radiation energy results in the satellite sensing relatively low brightness temperatures. Both channels are largely insensitive to ice contained within cirrus canopies. In the aggregate, these characteristics enable salient tropical cyclone structures to be detected underneath cirrus canopies and other obscuring features.

Examples of tropical cyclone structures as inferred from both the 85-91 GHz and 36-37 GHz frequency bands are contained within the accompanying lecture materials. In the following, we seek to briefly detail some of the strengths and weaknesses of each band. In the 85-91 GHz range, cloud-free land, a near-perfect emitter, always appears warm (with higher brightness temperatures) whereas cloud-free ocean, an imperfect emitter, always appears cold. Owing to the radiative principles described at the outset of this section, dense water vapor and low cloud bands appear relatively warm while deep, moist convection appears relatively cold. Because both cloud-free ocean and deep, moist convection appear cold, care must be taken when analyzing 85-91 GHz data to ensure that one is not being mistaken for the other. This is often accomplished through analysis of conventional satellite imagery and/or utilization of derived microwave-based imagery. In the 36-37 GHz range, liquid water always appears warm whereas areas lacking liquid water appear cold. This enables the detection of cirrus-covered eyes, with relatively cold brightness temperatures, and lower tropospheric clouds and rain, with relatively warm brightness temperatures. When used in conjunction with 85-91 GHz imagery, a near-complete characterization of tropical cyclone convective structure can be obtained.

Tropical Cyclone Forecasting: Available Guidance

Dynamical Models

Using a variety of numerical methods and initial representations of the atmospheric state, dynamical models make forecasts of tropical cyclone track and intensity by solving the primitive equations governing atmospheric motions. There exist two categories of dynamical models used for tropical cyclone forecasting: global models, such as the GFS, ECMWF, UKMET, and NOGAPS; and regional models, such as the GFDL and HWRF, that provide forecasts following a given tropical cyclone. The former are typically run at relatively coarse (>20-30 km) horizontal grid spacings whereas the latter are typically run at fine (< 5 km) horizontal grid spacings. Global models typically provide skillful track guidance but unskillful intensity guidance whereas regional models typically provide skillful intensity guidance. Improvements to global and regional dynamical models over the last twenty years have resulted in substantial improvements to tropical cyclone track forecasts; however, the same cannot be said as of yet for tropical cyclone intensity forecasts. Nevertheless, with a few exceptions as described below, dynamical models are typically the most skillful of all available guidance.

Consensus Models

Consensus forecasts are obtained by combining the forecasts from a collection (or ensemble) of models, where such a collection can either consist of multiple runs of a single model (e.g., the GFS or ECMWF ensembles) or single runs of multiple models (the so-called “poor man's ensembles”). Standard consensus models utilize a linear average of the position and intensity forecasts from its members to obtain a consensus track and/or intensity forecast. Corrected consensus models assign different weights to each member model in an attempt to account for biases of each individual member model, though care must be taken when using such guidance because member model biases are not constant in time or space. On average, consensus forecasts are more accurate than the predictions from their individual model components, particularly for consensus guidance obtained from single runs of multiple models. Such consensus forecasts are more accurate than their individual members because the errors or biases in one member tend to be canceled out by those of the other members of the ensemble. As a result, consensus forecasts are typically the most skillful of all available guidance, particularly for tropical cyclone track.

Trajectory Models

Trajectory models provide tropical cyclone track forecasts based exclusively upon the two largest contributors to variance in tropical cyclone motion: the large-scale steering flow and the Beta effect. In these models, the large-scale steering flow is allowed to evolve through time and is estimated using output from dynamical model forecasts. The trajectory model currently in use at the National Hurricane Center is known as the Beta and Advection Model, or BAM, and is based on large-scale steering flow information from the NCEP GFS global model. To account for variability in the steering flow as a function of tropical cyclone intensity, three different versions of the BAM model are run: shallow (850-700 hPa), medium (850-400 hPa), and deep (850-200 hPa) versions, known as BAMS, BAMM, and BAMD respectively. The skill of the BAM series of trajectory models is strongly dependent upon the quality of the dynamical input from the GFS model. While typically more skillful than climatology and persistence, trajectory models are typically less skillful than dynamical and consensus model forecasts.

Statistical-Dynamical Models

Statistical-dynamical models used to forecast tropical cyclone track and/or intensity are based upon statistical relationships between cyclone behavior and environmental conditions estimated from dynamical model forecasts. The best known of the statistical-dynamical models are the Statistical Hurricane Intensity Prediction Scheme (SHIPS) and Logistic Growth Equation Model (LGEM), both of which are used for tropical cyclone intensity forecasting. SHIPS and LGEM both utilize multiple environmental parameters thought to influence tropical cyclone intensity as estimated from dynamical model forecasts; however, SHIPS (25+) utilizes far more than does LGEM (~5). SHIPS utilizes multiple linear regression between its predictors to obtain an intensity forecast, whereas LGEM utilizes a growth rate coefficient determined from its predictors to obtain an intensity forecast. Through the years, both

SHIPS and LGEM has proven to be skillful guidance for tropical cyclone intensity forecasts. Indeed, SHIPS has historically outperformed most dynamical model intensity forecasts and has traditionally been one of the most skillful sources of intensity guidance for the National Hurricane Center.

Statistical Models

Statistical models used to forecast tropical cyclone track and/or intensity are based upon established relationships between storm-specific information, such as location and time of year, and the behavior of similar historical storms. Put another way, statistical models use information about what a storm has been doing (e.g., persistence) and what other storms like it in the past have done (e.g., climatology) to obtain a forecast. For track, the statistical model in use at the National Hurricane Center is known as CLIPER, or the Climatology and Persistence model. For intensity, the statistical model in use at the National Hurricane Center is known as SHIFOR, or the Statistical Hurricane Intensity Forecast model. Currently, statistical models are most often used only as benchmarks of skill against which other forecasts are compared. Forecasts less accurate than their statistical counterparts are said to be unskillful whereas forecasts more accurate than their statistical counterparts are said to be skillful.

References

- COMET, cited 2012: Polar satellite products for the operational forecaster: using microwave observations for tropical cyclone analysis. [Available online at http://www.meted.ucar.edu/npoess/tc_analysis/print.htm].

- McBride, J. L., 1995: "Tropical cyclone formation." *Global Perspectives on Tropical Cyclones*, R. L. Elsberry (ed.). World Meteorological Organization, Geneva, Switzerland, Report No. TCP-38. [Available online at http://derecho.math.uwm.edu/classes/TropMet/GPTC/tcclimo.pdf].

- NHC, cited 2012: Technical summary of the National Hurricane Center track and intensity models. [Available online at http://www.nhc.noaa.gov/pdf/model_summary_20090724.pdf].

- Olander, T. L., and C. S. Velden, 2007: The Advanced Dvorak Technique: continued development of an objective scheme to estimate tropical cyclone intensity using geostationary infrared satellite imagery. *Wea. Forecasting*, **22**, 287-298.

- Velden, C., and coauthors, 2006: The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.*, **87**, 1195-1210.