MODULE 6.3H

MESOSCALE PROCESSES I
Tropical Storms and Hurricanes

Table of Contents

Introduction

Hurricanes are a dramatic demonstration of thermally produced circulations. Although there is a global average of only about 50 hurricanes per year, far fewer than the number of extratropical storms, the extensive damage to life and property associated with hurricanes ensures their detailed study. Hurricanes and tropical storms are tropical phenomena, but they can often affect the weather patterns over Canada. This document will focus mainly on tropical systems forming in the Atlantic basin, since those are the ones that most often affect Canadian territory.

Hurricanes develop only over warm ocean surfaces and in regions where the baroclinicity of the basic current is weak. Their main energy source is the release of latent heat, and the systems have a distinctive warm core. In contrast, extra-tropical storms occur in association with existing baroclinic zones and are thus manifestations of energy conversions between pre-existing available potential and kinetic energies.

Stages of Hurricane Development

There are three stages in the development of hurricanes:

1. Tropical depression

This occurs when a cluster of convective clouds in the tropics begins to take on a rotating motion about a centre of low pressure. As long as the maximum sustained surface (10 metre) winds remain below 34 knots, the system is considered a tropical depression. In the north Atlantic, each tropical depression is numbered consecutively in each calendar year.

2. Tropical storm

When the winds in a tropical depression reach a maximum of 34 knots or more (but less than 64 knots), the depression becomes a tropical storm. At this point, the storm is given a name by the U.S. National Hurricane Center (NHC) in Miami, Florida.

3. Hurricane

When the maximum winds in a tropical storm reach 64 knots or more, the system is classified as a hurricane. There are five categories of hurricane, according to the Saffir/Simpson scale (Table 1).

Broadly favourable conditions for hurricane formation exist over large parts of the tropics. Figure 1 indicates the main regions where tropical cyclone genesis occurs. It should be noted when observing this figure that the same system is given a different name

Category	Central Pressure Millibars	Winds (Mph)	Storm Surge (Feet)	Damage
1	$\geq$980	74-95	4-5	Minimal
2	965-979	96-110	6-8	Moderate
3	945-964	111-130	9-12	Extensive
4	920-944	131-155	13-18	Extreme
5	<920	>155	>18	Catastrophic

Table 1 Saffir/Simpson Hurricane Scale Ranges

depending on where it occurs. What is called a hurricane in the north Atlantic and eastern Pacific oceans is called a typhoon in the western north Pacific, and a cyclone in the Indian and south Pacific oceans.

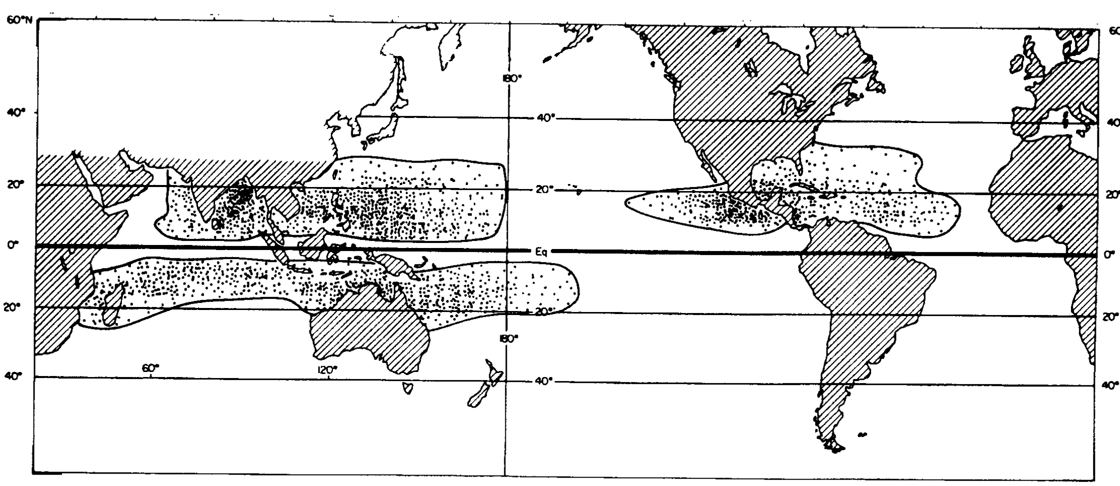

Figure 1. Location of first storm origin for 20 years of data (1952-71). From Gray (1975).

Required Conditions for Development of Tropical Systems

There are several necessary conditions hurricane forecasters look for when forecasting the development of tropical systems:

- A warm sea surface temperature of at least 26^{o}C with a deep oceanic mixed layer
- The presence of a pre-existing region of low surface pressure
- Weak vertical wind shear over the genesis region
- A conditionally unstable atmosphere with mean upward motion
- High mid-tropospheric humidity
- Generally, a distance of greater than 4-5 degrees of latitude removed from the equator

These conditions are present somewhere in the tropics at any time of the year. In the north Atlantic (and eastern north Pacific), the hurricane season is generally considered to last from June to November, with a peak in August and September.

As is always the case with intense weather systems, the above necessary conditions require a 'kicker' to set off development. In the case of tropical systems the kicker is an area of low level convergence that can come from one of the following:

- In tropical waves which propagate westward in the trade wind belt
- Within the inter-tropical convergence zone (ITCZ)
- Monsoonal low pressure troughs
- A wave along an old cold front or trough in the subtropics (this is the dominant "kicker" for early season storms in May and June)
- An occluded extratropical low which has drifted over warm (>26C) waters

The first factor, tropical waves, seems to be the most common kicker. These waves are similar to the short waves seen in the mid-latitude westerlies, except that they are low-level phenomena.

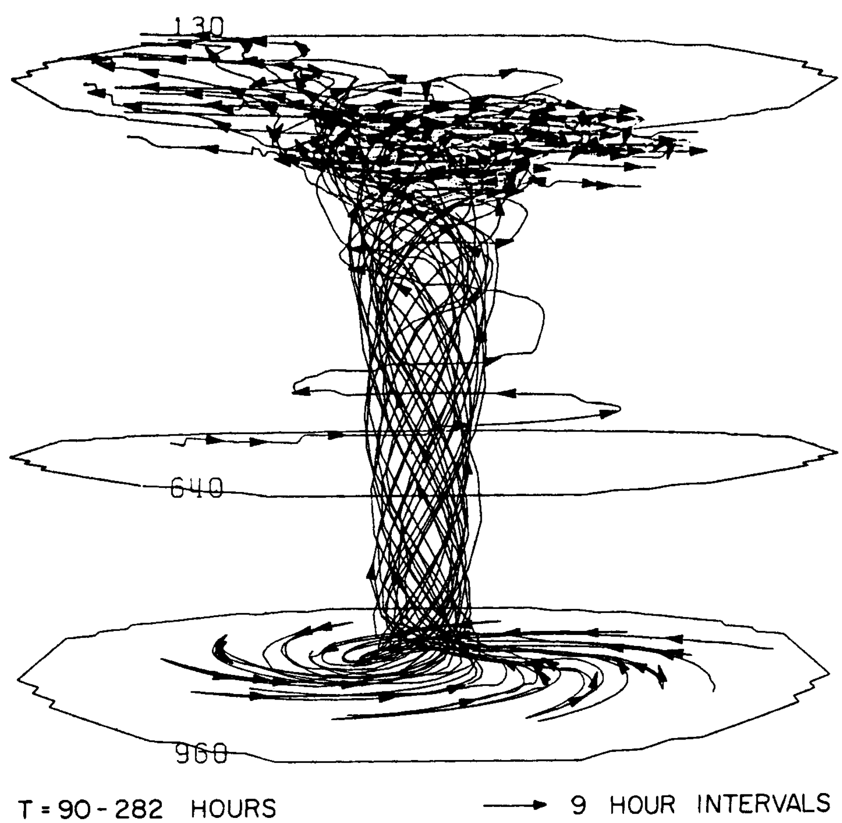

Figure 2. Particle trajectories calculated from a numerical model of a hurricane. From Anthes and Trout (1971).

Once a tropical depression has developed, it will travel slowly westward in the tropical easterlies. Its further development will depend on the continued presence of the atmospheric conditions required for its initial formation. Some of the more common factors which inhibit development are movement over water less than 26°C, movement into an area of strong wind shear, and advection of cool, dry air into the mid-levels of the system. When conditions are right, and the tropical system develops to the intensity of a hurricane, it tends to be a persistent weather feature which lasts for several days.

Structure of a Hurricane

The paths of selected air parcels in a hurricane are illustrated in figure 2, which is generated from a computer simulation. In general, you can see that air in the lowest levels is drawn toward the low pressure in the centre of the storm. The parcel takes on a rotation as a result of the coriolis force, and turns rapidly and cyclonically as it rises in the eyewall. Air parcels exit and turn anticyclonically at high levels.

We will examine the three dimensional structure of a mature hurricane using a series of diagrams taken from Hawkins and Ludlam (1964).

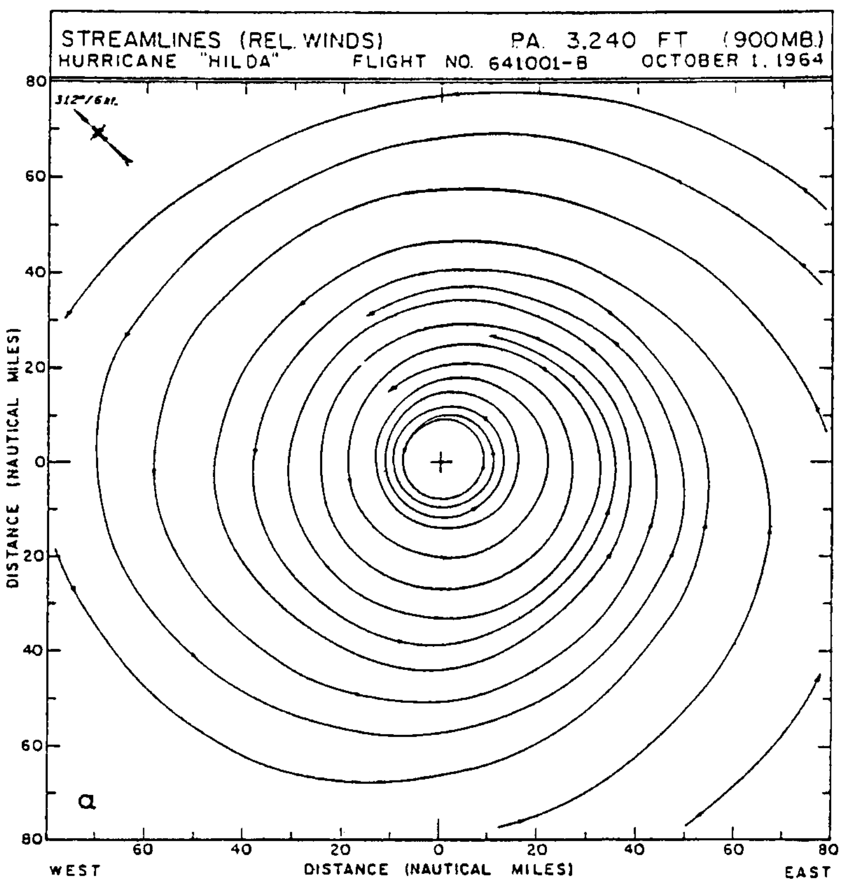

Figure 3. Low level streamlines of air motion in Hurricane Hilda. Note the stong convergence along the eyewall.

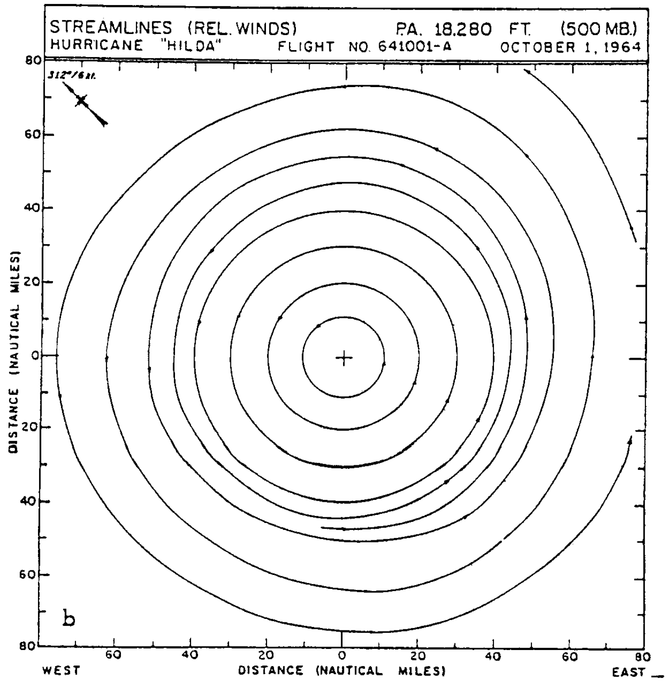

Figure 4. Mid level (500 mb) streamlines in Hurricane Hilda. Notice the cyclonic rotation is still present, in comparison with a mid latitude cyclone where westerlies increase with height.

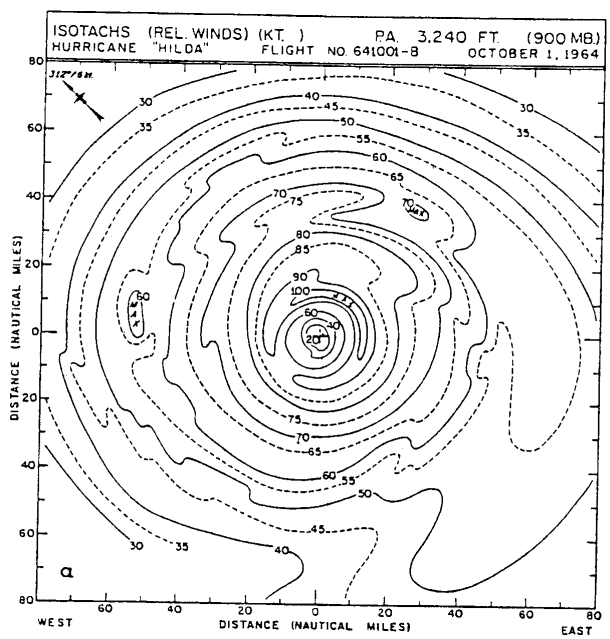

Figure 5. Low level winds in Hurricane Hilda - winds are measured relative to the motion of the storm's eye. Note the general symmetry of the wind field, but the strongest winds are on the northeast side of the storm.

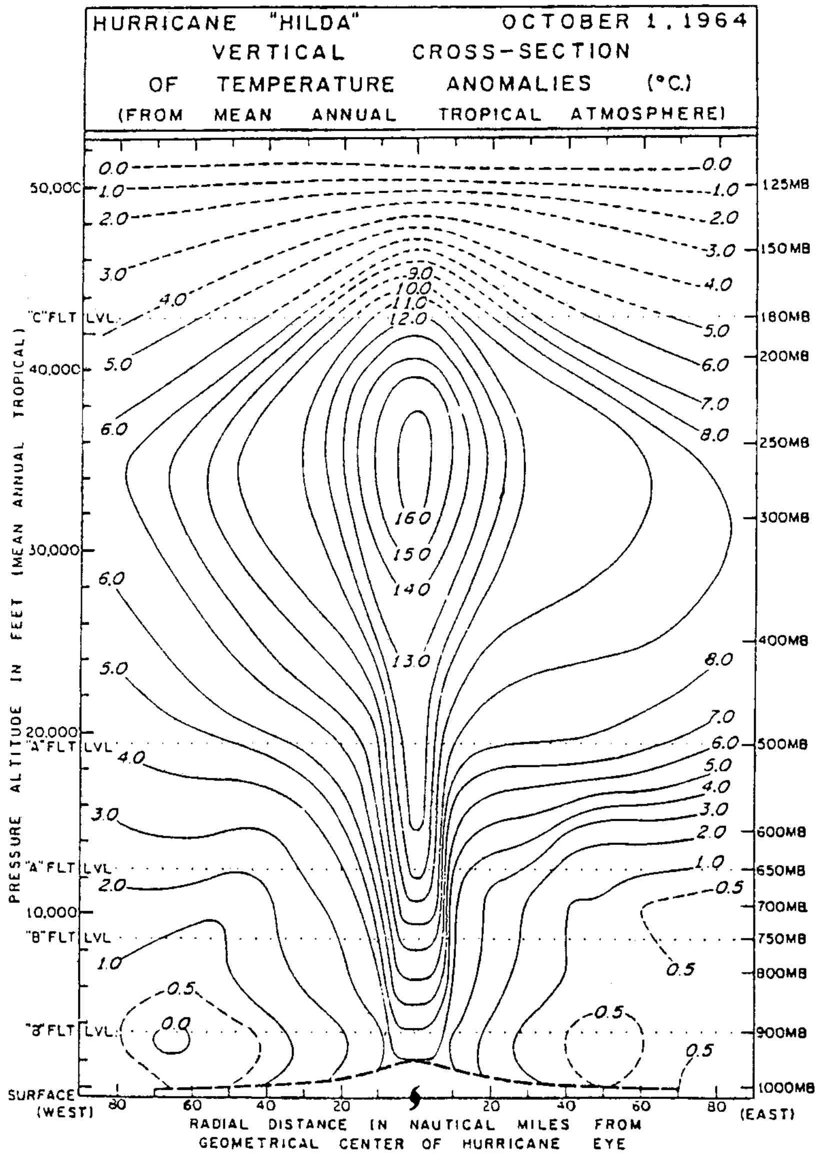

Figure 6. Vertical cross section of temperature anomaly in Hurricane Hilda prepared from soundings. The anomalies are departures from normal tropical airmass values. Note the strong anomalies in the warm core. Maximum anomaly occurs aloft at the height of strongest latent heat release.

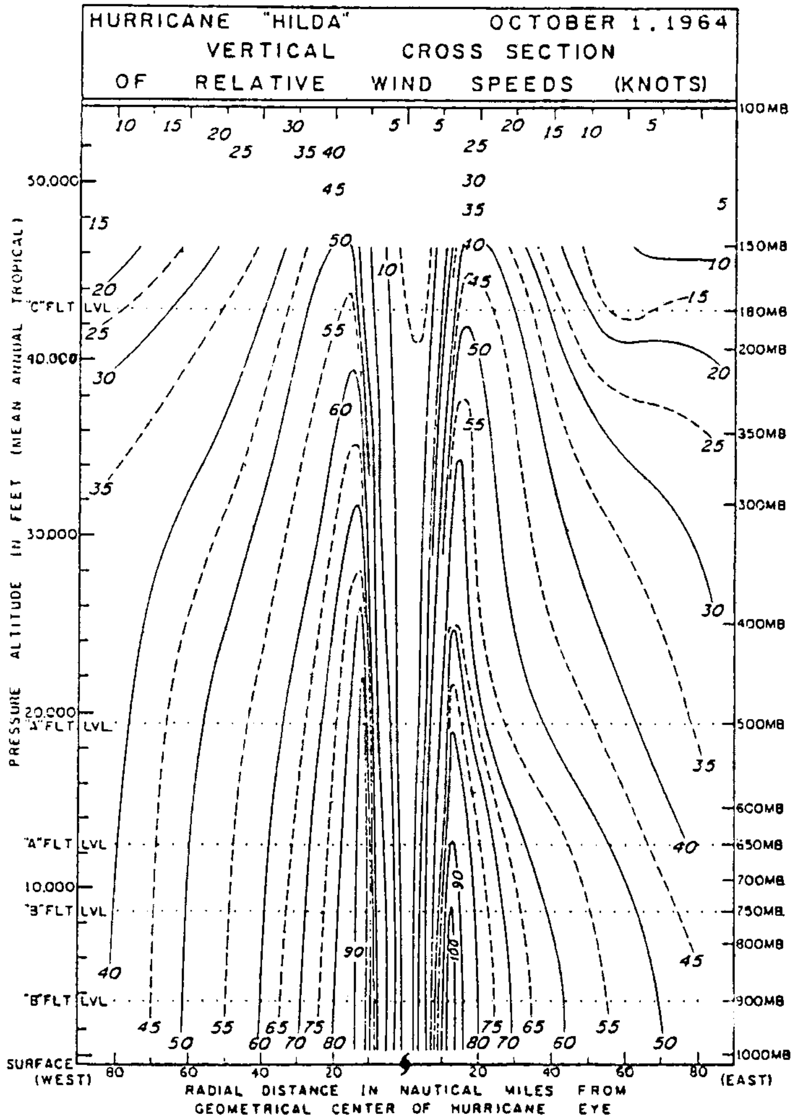

Figure 7. Vertical cross section of wind speed relative to the moving eye of Hurricane Hilda. Strongest wind speeds occur just above the boundary layer, then decrease with height. Compare with an extratropical cyclone where westerlies increase with height. Also notice the strong gradient of wind speed along the inner eyewall, and the relatively light winds in the eye.

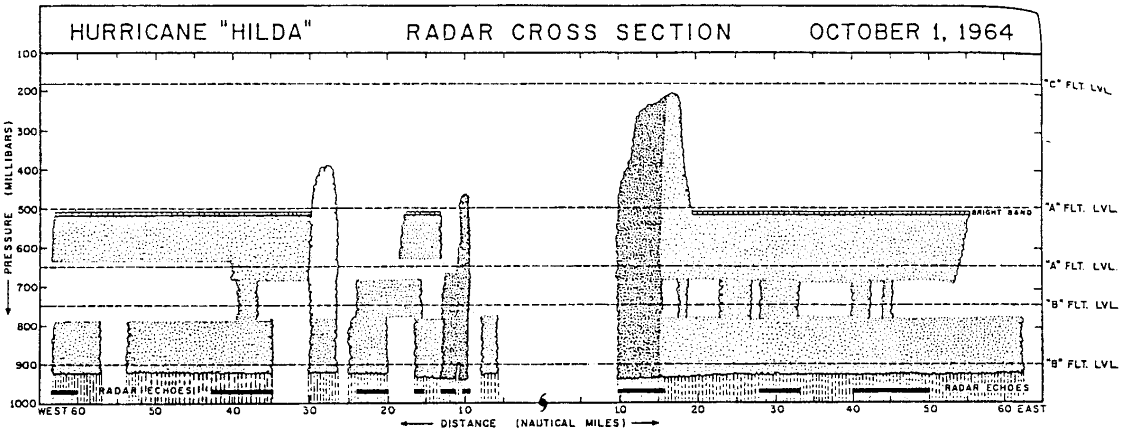

Figure 8. Vertical cross section of radar precipitation echoes. Notice the rough symmetry and the banded nature of the precipitation pattern.

Forecasting of Hurricanes and Tropical Storms

The NHC issues an official 72 hour track and intensity forecast every six hours for all tropical cyclones in the Atlantic and eastern Pacific Oceans. Many computer models are available to the forecaster to aid in forecasting the motion of systems. Models are relatively weak, however, in the area of intensity forecasting.

Motion Forecasting

The first step in forecasting the motion of a tropical system is to get an accurate fix on its current location and velocity. This is not always a simple task, since tropical systems are often moving quite slowly and can exhibit wobbles in their motion. Satellite imagery is the tool most heavily used to establish the current position of a system, but many times wind shears mask the precise location of the low level centre. Additional data sources, when available, include ship and coastal surface observations, as well as occasional reconnaissance aircraft flights.

When an initial location and motion are determined, the data are used to initiate objective model guidance. There are two primary types of guidance models, statistical and dynamical, although some models can be a hybrid of the two methods.

Statistical models are based on regression equations using a developmental data set of historical motions of tropical systems. The main advantage of these types of models is they are fast running and give quick results. Their biggest disadvantage is they are far too dependent on the initial conditions. If the hurricane forecaster makes a small adjustment to the initial location and velocity of a system, the statistical model forecast will give quite different results.

Dynamical models used to forecast the motion of tropical systems vary from fast running, simple physics models to fine mesh full physics nested grid models. For example, the beta advection model (BAM) utilizes a large scale numerical model to advect an ideal vortex. On the other hand, the quasi-Lagrangian model (QLM) is a full three dimensional primitive equation nested grid model that derives its lateral boundaries from the U.S. Aviation Model.

In each case, several of these computer models will be run, and it is up to the hurricane forecaster to choose which is the best solution for the forecast track. A common approach is to use a simple ensemble solution comprised of the average solution from the best two or three dynamical models. The intensity forecast is based upon factors such as consideration of the large scale synoptic conditions in which the storm is travelling. The final decision of the hurricane forecaster is a difficult one at the best of times, and is often made under the intense scrutiny of large media attention.

Baroclinic Influence

Occasionally tropical storms form in the presence of baroclinic zones in the subtropical latitudes between 25 and 35 degrees north. In their early stage of development, these systems are referred to as "subtropical cyclones.". Subtropical cyclones typically originate from high latitude cut-off lows which drift southward over warm sea surfaces. This happens in two ways:

a) when a *vertically-oriented cold low* transforms into a warm core as latent heat from convection, fuelled by large sensible heat fluxes, becomes more abundant near the centre of the circulation (bottom-up development).
b) when a *500-mb low* imparts a cyclonic circulation upon a surface trough or cold front. This enhances surface convergence which aids convection and development of a warm core structure (top-down development).

Subtropical cyclones with maximum sustained winds less than 18 m s^{-1} (34 kts) are called *subtropical depressions*. Subtropical cyclones with winds exceeding this threshold are called *subtropical storms* unless they have undergone significant modification such as to achieve winds of 33 m s^{-1} (64 kts) or more, in which case, they are simply classified as hurricanes. The radius of maximum winds in a subtropical storm is often much larger than in a purely tropical storm. Correspondingly, the central pressure is often lower than the maximum winds would suggest. As the storm evolves into a hurricane, the radius of winds tends to contract.

Often during the latter part of the season (October and November), hurricanes will interact with troughs embedded in the mid-latitude westerly flow. Frequently this results in the demise of the hurricane as shear processes rob the storm of its thermodynamically-driven structure. However, there are times when the trough interacts favourably with the hurricane, enhancing outflow in the upper atmosphere, resulting in further intensification. It is necessary for the interaction to occur over the subtropics while there is a sufficient region of warm sea surface temperatures ahead of the storm track. These less common cases are referred to as baroclinically-enhanced (BE) hurricanes. They differ from the baroclinic influence on subtropical cyclones because the incipient low may be of purely tropical origins. To distinguish the two forms of baroclinic influence, hurricanes of subtropical origin are sometimes called baroclinically-initiated (BI) hurricanes.

BI and BE systems are normally found over the western part of the North Atlantic not far south of Canadian waters (Elsner and Kara, 1999), so it is no surprise they frequently cross our marine and public forecast regions.

Extratropical Transition (ET)

Unlike the subtropical systems discussed in the previous section, most purely tropical systems in the north Atlantic follow the same general path. After forming, they move westward in the tropics. As they approach the Americas, they begin to turn more northerly around the Bermuda high. Moving farther north, they then begin to interact with the mid-latitude westerlies, adopting more extra-tropical characteristics—through a process known as extratropical transition (ET)—as shear influences become greater and sea surface temperatures lower. Thereafter, they tend to move rapidly eastward. In their extratropical stage, these systems are sometimes referred to as “post-tropical” to distinguish them from disturbances of purely extratropical origin.

Although usually much weaker than those in the tropics, storms of tropical origin can still pose a threat to life and property when they approach Canadian territory. Despite the fact they are seldom as fierce as Canadian winter storms, they tend to occur during months when many Canadians are participating in outdoor activities such as camping or boating. This leaves people vulnerable to the heavy rain and high winds that accompany these tropical systems.

There has been comparatively little study done on the changes that tropical systems undergo as they move to higher latitudes. Observations have shown that tropical vortices entering the mid latitude westerlies undergo significant changes in their structure. There is also a problem with tropical systems contributing to the development of intense extratropical lows (a process often referred to as re-intensification). This type of regeneration is common near the North American east coast, usually late in the hurricane season, when outbreaks of polar-air masses start to penetrate into lower latitudes. Such rejuvenated tropical cyclones may survive as intense storms for several days, occasionally reaching the European west coast or even as far north as Iceland, with some residual characteristics of tropical disturbances. Some of the most severe storms occurring in September over these regions, far from the tropics, originate in this way.

This was the case with hurricane Hazel over Toronto in 1954. This destructive hurricane (the deadliest in Canada in the 20th century) moved in across the east coast of the United States on October 15, 1954. Simultaneously a very deep cold-air outbreak occurred over the central and eastern parts of the continent. The expected weakening of the hurricane over land never took place. The warm, humid, unstable air associated with Hazel contributed to the energetics of the ensuing extratropical cyclone, and the storm remained very destructive while moving northward into Canada.

Abraham et al (1991) produced a study of hurricane Hugo, which moved northward over eastern North America in September, 1989. Their paper produced the following conclusions regarding the transformation of tropical cyclones in the mid latitudes:

- The evolution of the system from post-tropical to extratropical is accompanied by a change of track from anticyclonic to cyclonic.

- The region of heavy precipitation shifts ahead and to the left of the storm track.

- Maximum precipitation rates and potential for flash floods is most likely during the time that initial interaction is taking place.

- Mesoscale convergence lines may be observed well ahead of the tropical storm centre. Upper air support or "collision" with the post-tropical system may trigger very heavy rainfalls along this line.

- The presence of a relatively stable boundary layer may preclude the observation of extreme winds, despite the fact that hurricane force winds may still reside just above this level.

- Rapid re-intensification, although not a frequent occurrence, can be devastating. The conditions necessary for such a development are the same as those required for formation and intensification of extratropical cyclones. It is then the incipient extra-tropical cyclone that uses the warm, moist and unstable environment of the tropical system for extreme and rapid intensification, although the phasing between the two systems is critical. Evidence suggests that, for intensification to occur, the tropical disturbance must interact ahead, but within five degrees latitude of the mid-latitude trough. However, if the tropical feature encounters a significant steering flow before interacting with the trough, it will be whisked away as a stable or decaying tropical system. This suggests then that the key zone of interaction is near the base of the trough where vorticity is high and shear is weak.

Hurricanes and other tropical storms are complex phenomena that pose significant forecast problems for operational meteorologists. Constant monitoring of their motion and intensity changes is required to ensure that citizens are warned of their potential impact.

Climatology of Extratropical Transition

Fogarty and Gyakum (1999) compiled a climatology of transitioning tropical storms in the western North Atlantic from 1963 to 1996. All tropical storms and hurricanes which underwent transition and passed through a specified area south of Nova Scotia were chosen for the study. Data were collected from the NHC best track archives as well as from the National Meteorological Center (NMC) and the National Centers for Environmental Prediction (NCEP) from which the extratropical phase of the storm tracks were derived. Composites of the storm tracks for each of the 45 cases are shown in figures 9 and 10. Note the high frequency of transitions occurring south of Nova Scotia where sea surface temperatures are colder than 26°C. Figure 11 shows (a) the frequency of ET by month, and (b) the sampled life times of these systems.

Some of the conclusions drawn from their work include:

- A statistically significant 1000-500 mb warm anomaly over central North America was noticed during the week prior to the transition

- A north-westward ridging of the subtropical Bermuda high over the Maritime provinces two days prior to the arrival of the cyclone

- A mobile 500-mb synoptic-scale trough often accompanies the transition over eastern North America

- The tropical cyclone’s warm core and convectively unstable airmass are maintained after transition

- A significant drying-out in the 850-500 mb layer during the transition process

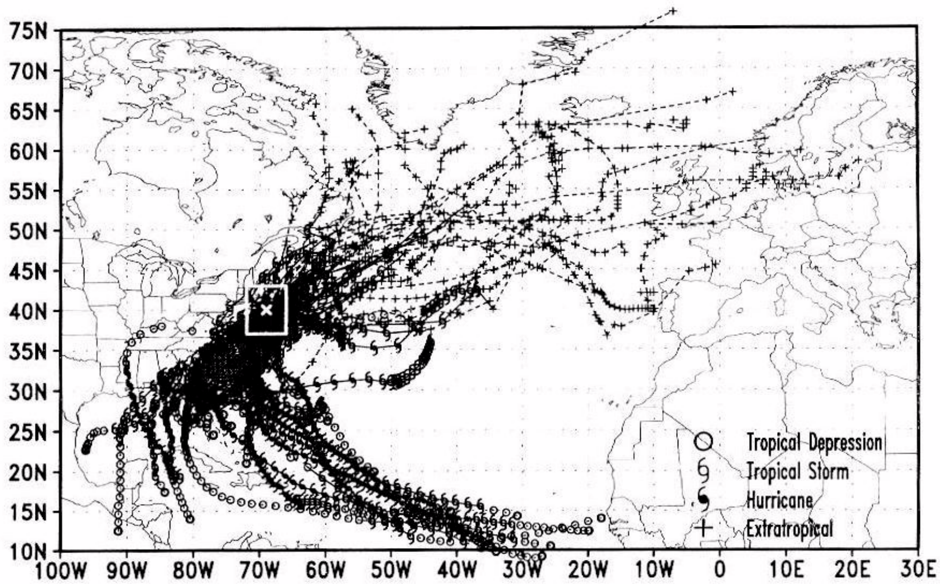

Figure 9. Tracks of 45 ET events between 1963 and 1996 based on NHC, NMC and NCEP data. Only cases tracking through the 6 degree latitude-longitude reference box (centered on 40.0 N, 69.0 W) were chosen.

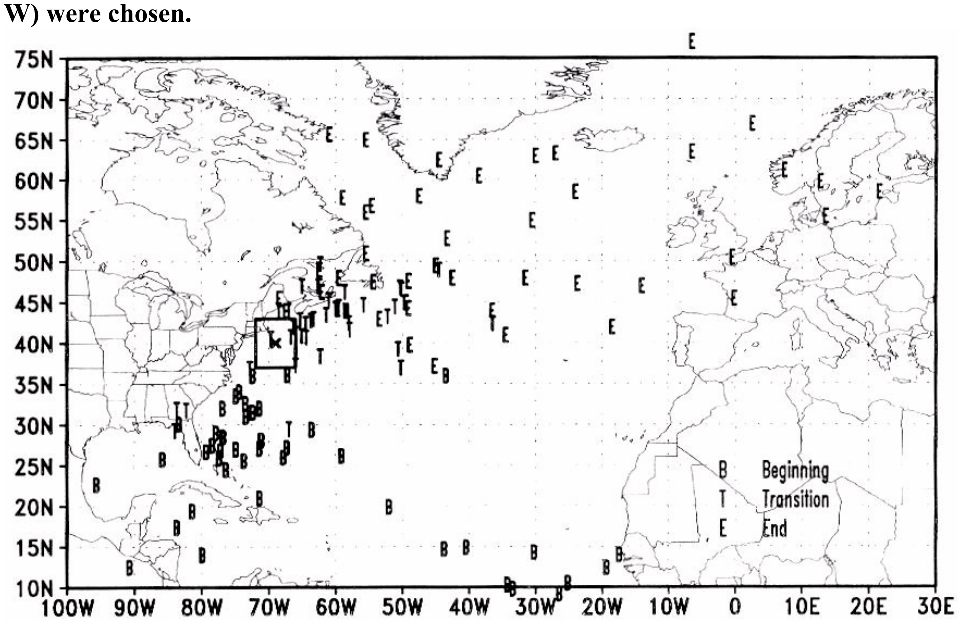

Figure 10. Location markers for beginning, transition and ending for all 45 ET cases occurring between 1963 and 1996 which passed through the 6 degree latitude-longitude reference box shown.

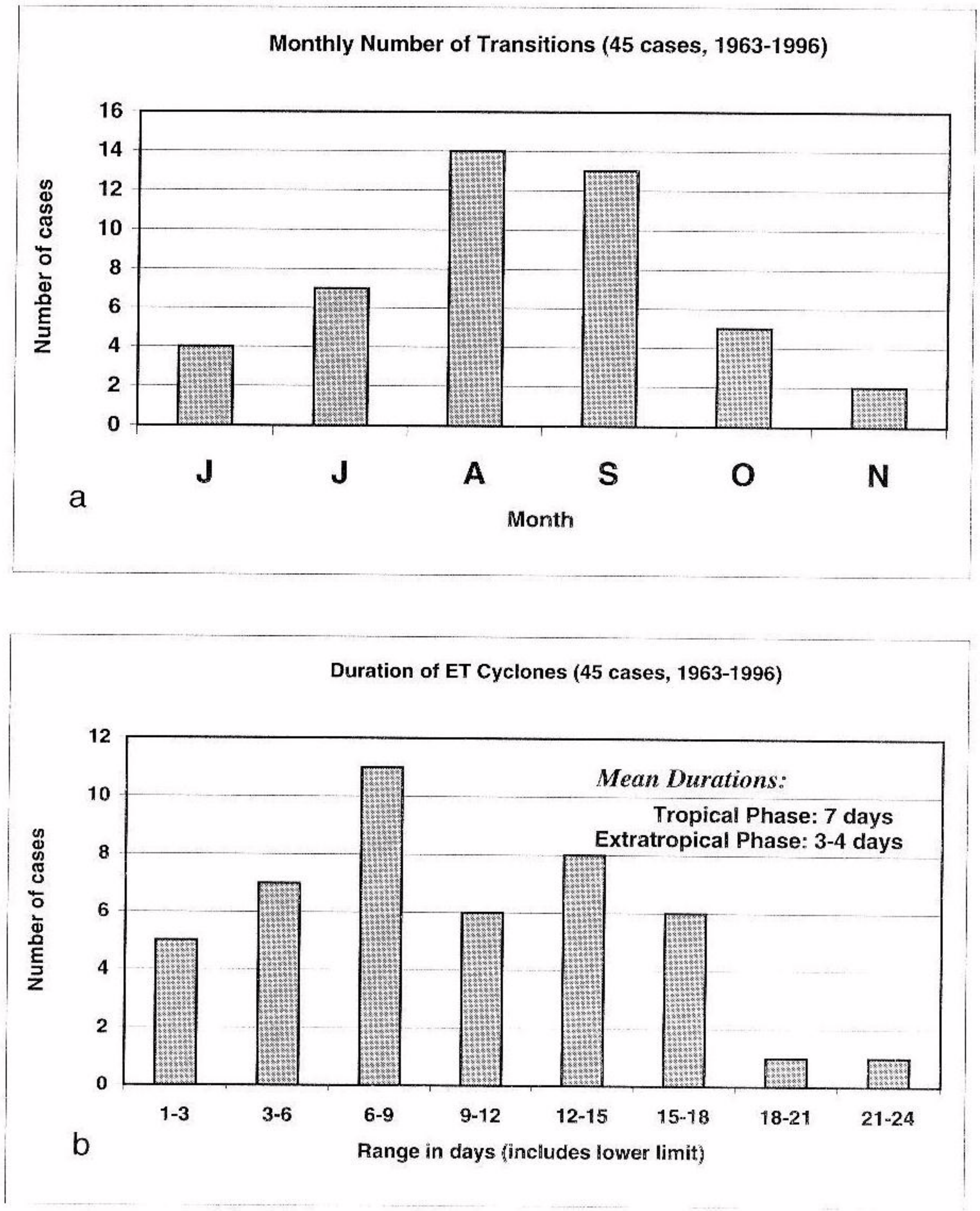

Figure 11. (a) Monthly number of ETs during the Atlantic Basin hurricane season. The months are June through November. (b) Duration in days of all cyclones studied, from beginning of their tropical to the end of their extratropical phases.

Forecast Difficulties

While a tropical storm or hurricane is interacting with the mid-latitude westerly flow, its structure will inevitably undergo significant changes. Exactly how and when these changes occur continues to present a forecast challenge for meteorologists today. The first issue that a forecaster should address is the behaviour of the upper level flow. The phasing of any upper level troughs with the storm will play a significant factor in the transition process. There are several things that could happen to a tropical system moving northward:

1. It simply dissipates without completing ET; usually when the upper level flow and low level temperature gradients are weak and/or when the storm moves inland or over cold waters
2. It undergoes ET then weakens (most common).
3. It re-intensifies as a strong extratropical low after undergoing ET.
4. It deepens in response to enhanced upper level outflow in advance of a short wave trough in the westerlies (a so-called BE storm). This is followed by transition to an extratropical low.

Points 3 and 4 are the most difficult, yet, the most important to forecast correctly. They are invariably associated with active short-wave troughs approaching the tropical system as it tracks northward.

The responsibility for forecasting tropical storms moving into Canadian territory falls under the jurisdiction of the Canadian Hurricane Centre (CHC) in Dartmouth, Nova Scotia. The CHC communicates with the regional weather centres whenever transitioning tropical systems pose a threat to their forecast regions. The centre issues special weather discussions on these storms, providing details on storm track, intensity, wind radii, rainfall, sea state, and storm surge.

Forecasting Tropical Storm Interactions With Baroclinic Troughs

A good one to two day forecast of the transition with a baroclinic trough can be based on a thorough look at 500 mb height and vorticity analyses and prognostic maps. Generally speaking, models do a good job predicting the evolution and position of troughs and ridges in the mid troposphere. Experience has shown that the sea level pressure centre associated with the tropical disturbance is not picked up well by synoptic-scale models, particularly over the ocean where data are sparse.

The first step to forecasting transition with a baroclinic trough is to diagnose the motion of the trough and decide whether it is strengthening or weakening. Short wave troughs move much more quickly than long waves, and can potentially move in phase with the storm. Their speed is governed by the *Rossby-wave formula*:

$$c = U - \beta/(2\pi/L)^2$$

where U is the geostrophic wind at 500 mb, $\beta \sim 10^{-11}$ s^{-1} m^{-1}, and L is the horizontal wavelength of the trough. Observing the tilt of the trough often indicates whether it is strengthening or weakening. Negatively-tilted (or diffluent) troughs tend to be deepening or "digging." Secondly, estimate the time in which the low will become embedded in the baroclinic flow. This can easily be done by following the vorticity maximum associated with the tropical disturbance in the 500 mb forecast maps.

The timing between trough and low is critical. If the trough is moving quickly, it may fail to "pick up" the storm. If the trough is moving slowly (i.e. a long-wave), the storm will usually succumb to north-easterly shear and will dissipate. *Cases where the trough and storm meet coincidentally offer an opportunity for intensification—either before or after transition.* As a rule of thumb, the onset of deepening occurs when the hurricane or tropical storm moves to within 5 degrees of latitude of a digging trough. If the trough is weakening, then a standard transition is most likely, with no re-intensification.

After merging with the trough, the storm typically accelerates at speeds approximated by taking 2/3 the speed of the 500 mb geostrophic wind . Prior to re-intensification, the storm's direction is approximated by the orientation of the 500mb contours. If intensification is expected, the direction is approximately 30° cross-contour towards lower heights.

The following is a summary of expected weather accompanying the merger of a tropical disturbance with a baroclinic trough:

- ***Clouds:*** cloud shield becomes elongated with the shear flow; fronts often develop; convection diminishes over the southern part of the storm, exposing the eye to dry air wrapping around its western periphery

- ***Winds:*** radius of gale-force winds expands, especially to the right of the track where the strongest surface winds will be found

- ***Rainfall:*** heaviest amounts occur to the left of the storm track and along frontal zones ahead of the storm; upslope and coastal convergence effects can significantly enhance rainfall; often very little rain falls to the right of the track; rainfalls often underestimated by models (the NHC rule-of-thumb for maximum rainfall is an appropriate first guess: Max.Rain (mm) = 2500 divided by the storm speed (kts).)

- ***Temperatures:*** storm's arrival is precluded by warm and humid conditions while cooler, drier air occurs in its wake

- ***Sea State:*** seas can build to significant heights to the right of the storm track if the storm accelerates such as to match the wave group velocity, creating a 'trapped fetch' phenomenon

Other obvious factors can influence the forecast. If the tropical storm moves far enough inland and loses most of its convection, less energy will be available to initiate transition. Forecasters must beware of transitions that begin further south over warm waters in an atmosphere which is convectively unstable. It will take less baroclinic forcing to initiate transition. In fact, transition may be precluded by a period of intensification, which represents the BE type of storm discussed earlier.

References

Abraham, J., K. Macdonald and P. Joe, 1991: The Interaction of Hurricane Hugo with the Mid-Latitude Westerlies. Preprints of the 19th Conference on Hurricanes and Tropical Meteorology, Miami, Florida, 124-129.

Anthes, R.A. and J.W. Trout, 1971: Three-dimensional particle trajectories in a model hurricane, Weatherwise, **24**, 174-178.

Elsner, James B. and A. Birol Kara, 1999: *Hurricanes of the North Atlantic: Climate and Society,* Oxford University Press, 488 pp.

Fogarty, Chris T. and John R. Gyakum, 1999: A Study of Tropical to Extratropical Cyclone Transition in the Western North Atlantic Ocean, 1963-1996. *Masters Thesis, McGill University,* 62 pp.

Gray, W.M., 1975: Tropical Cyclone Genesis, Fort Collins: Colorado State University, Atmospheric Science Paper No. 234.

Hawkins, Harry F. and Daryl T. Rubsam, 1968: Hurricane Hilda, 1964, Part II. Structure and Budgets of the Hurricane on October 1, 1964. Mon. Wea. Rev., **96**, 617-636.