ESCI 344 – Tropical Meteorology
Lesson 10 – Tropical Cyclones: Motion and Analysis

References: *A Global View of Tropical Cyclones*, Elsberry (ed.)
The Hurricane, Pielke
Forecasters' Guide to Tropical Meteorology, Atkinsson
Forecasters Guide to Tropical Meteorology (updated), Ramage
The Use of Satellite Imagery in Tropical Cyclone Analysis, WMO

Reading: *The Hurricane*, Pielke, Chapter 3 (e-reserve)
The Use of Satellite Imagery in Tropical Cyclone Analysis, WMO, Chapter 5 (e-reserve)

GENERAL

- **Tropical cyclone motion can be thought of as the cumulative effect of the following three influences:**
  - **Environmental steering**
  - **The *beta* effect**
  - **Asymmetrical convection**
- **Of the three, environmental steering is usually of primary importance, followed by the beta effect.**
  - **Asymmetrical convection is mainly responsible for short term "eye wobble", but is of little importance for long term motion.**

ENVIRONMENTAL STEERING

- **To a first approximation, environmental steering can be thought of as "cork-in-a-stream", with the tropical cyclone merely advected by the mean environmental flow.**
- **The environmental flow can be represented by various means, either through a single level, or through a mass-weighted mean flow.**
  - **A deep-layer mean is best for intense, mature cyclones.**
  - **A medium-layer mean or even shallow-layer mean is more suited to weak systems, especially if they are highly sheared.**
- **In any case, the cyclone circulation needs to be removed from the wind field, in order to determine the environmental flow.**
- **Synoptic-scale influences are very important for the environmental steering currents.**

- An approaching trough can alter the steering current such that the cyclone recurves, or at least tracks more northerly.
- A strong subtropical ridge will keep a cyclone entrenched in the trade winds, and tracking westward.

- **An adjacent tropical cyclone can influence the steering flow.**
  - **This is called the Fujiwhara effect, and can result in some unusual tracks as the cyclones spiral around each other, occasionally even merging.**

LINEAR BETA EFFECT

- **The beta effect refers to the tendency of a circulation to move, even in the absence of a mean flow, due to the conservation of absolute vorticity**
- **The quasi-geostrophic barotropic vorticity equation is**

$$\frac{\partial \zeta_g}{\partial t} + \vec{V}_g \bullet \nabla \zeta_g + \beta v_g = f \nabla \bullet \vec{V}_z \qquad \textbf{(1)}$$

where the terms are the local vorticity tendency, advection of relative and planetary vorticity, and divergence.

- **When equation (1) is linearized the phase speed for the waves it supports (called Rossby waves) is**

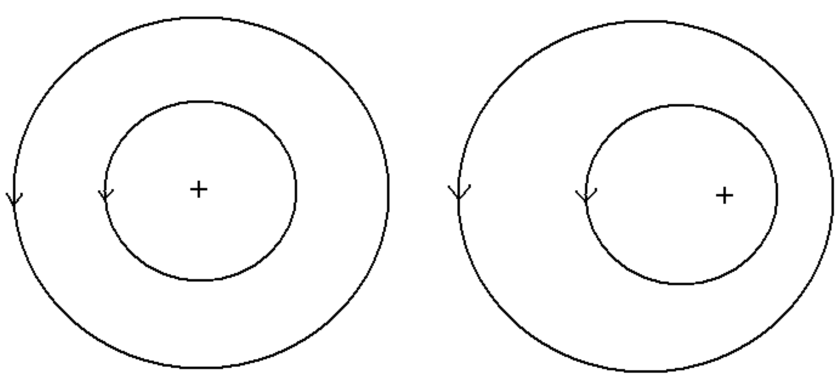
$$c = \bar{u} - \frac{\beta}{k^2 + l^2} \qquad \textbf{(2)}$$

where $\bar{u}$ is the speed of mean zonal flow, and *k* and *l* are the zonal and meridional wave numbers.

- **The dispersion relation (equation 2) shows two important characteristics of Rossby waves:**
  - **They will move westward in the absence of a mean flow.**
  - **They are dispersive, with the shorter waves moving more slowly than the longer waves.**
- **If a tropical cyclone is thought of as the superposition of several different linear Rossby waves, then in the absence of a mean flow the cyclone would be expected to move westward.**
- **This tendency for the cyclone to move westward in the absence of a mean flow is known as the *linear beta effect*.**

NONLINEAR BETA EFFECT

- **If the Rossby waves comprising the cyclone were truly linear, there would be no interaction between the different wavelengths, and the waves would just pass through each other, with the longer waves moving faster.**
- **However, if nonlinear interactions are allowed, the resultant motion of the cyclone is not only westward, but also poleward.**
  - **This is known as the *nonlinear beta effect*.**
- **The nonlinear beta effect can be explained somewhat qualitatively by imagining that the cyclone is comprised of two Rossby waves.**
  - **The outer cyclone is represented by a long wavelength (small wave number) wave while the inner cyclone is represented by a short wavelength (large wave number) wave.**
- **We will imagine that initially the cyclone is symmetric, and the vorticity isopleths will be concentric with the streamfunction contours (see left side of diagram below).**
  - **There will initially be no advection of relative vorticity.**
  - **The cyclone will move westward due to the advection of planetary vorticity.**
- **Since Rossby waves are dispersive, at some time later the outer Rossby wave will have traveled farther westward than the inner Rossby wave.**
  - **The cyclone is no longer symmetric, and the vorticity maximum will no longer be in the center of the cyclone (see right side of diagram).**



Initial streamfunction and vorticity max   Later streamfunction and vorticity max

- **The result of the dispersion is that there is now positive advection of relative vorticity poleward of the cyclone, which will cause the cyclone to move poleward.**

- **The net result of the nonlinear beta effect is a westward and poleward cyclone track in the absence of a mean flow.**
- **Some qualities of the nonlinear beta effect are:**
  - **It is the size and strength of the outer region that are most important for determining the beta effect.**
  - **Larger cyclones will have a stronger beta effect.**
  - **The intensity of the inner core has little influence on the beta effect.**
- **The beta effect acts in addition to the mean flow steering.**
  - **The interaction between the beta effect and the mean flow steering may not be linear.**

ASYMMETRICAL CONVECTION

- **Though the inner core of a tropical cyclone has large inertial stability, there are asymmetries in convection.**
- **The asymmetrical convection can be due to several factors, including**
  - **SST gradients**
  - **Differential stress (different surface roughness, especially near land).**
- **The asymmetrical convection can lead to local pressure falls in the eyewall, which essentially can displace the eye in the direction of the pressure falls.**
- **This leads to short-term "eye wobble" often seen in tropical cyclone tracks.**
- **This eye-wobble is one reason why the longer term tropical cyclone motion should not be estimated from two eye positions, but should be based on a longer term average of several positions or *fixes*.**

INTERACTION WITH MOUNTAINS

- **Topography can influence tropical cyclone motion. The prime example is the Island of Taiwan, which is very mountainous.**
- **As tropical cyclone cross Taiwan, the eye is sometimes seen to "jump" to the other side, presumably due to pressure changes induced by the lee of the topography.**

ANALYSIS

- **One important key for a successful prediction of the cyclone track and intensity is an accurate analysis of the current position and intensity of the cyclone.**
- **Location is determines primarily by satellite imagery, except near land, when radar and aircraft can be brought to bear.**
- **Synoptic fixes (positioning based on adjacent synoptic observations) was the staple of location techniques in the pre-satellite era, but is now a "quaint" pastime for bored analysts.**
- **Satellite imagery can give a very accurate fix when there is an eye, or an easily visible, exposed low-level circulation center.**
- **Positions based on curved cloud features or when the eye is obscured by a central dense overcast (CDO) are less accurate.**
- **The best intensity estimate is a direct observation from an aircraft penetration.**
  - **The aircraft can not only measure flight-level winds, which can be extrapolated to surface winds, but pressure measurements can also be made using drop sondes.**
- **If the cyclone is close enough to land, Doppler radar observations can be used to estimate intensity.**
- **In the absence of aircraft observations or Doppler radar observations, the *Dvorak* technique is the staple for determining intensity, and is described below.**

DVORAK ANALYSIS

- **The Dvorak technique is based on appearance of the storm from IR and visible satellite imagery.**
- **The Dvorak technique assigns a *T-number* based on the appearance from the satellite imagery.**
  - **The *T*-number is itself a combination of a *CF* (central feature) number and a *BF* (banding feature) number.**
- **The "*T*-number", along with some rules which are formulated to avoid wildly differing intensity estimates from one observation to the next, are used to assign the *current intensity*, or *CI*.**

- **The *CI* is usually close to the *T-number* for developing storms, but is higher for weakening storms.**
    - **The assumption is the cloud features dissipate faster than the momentum of the circulation.**
- **The relation between *CI* and intensity is shown in the table below.**

CI	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**
Intensity (knots)	**25**	**25**	**30**	**35**	**45**	**55**	**65**	**77**	**90**	**102**	**115**	**127**	**140**	**155**	**170**

- **A CI of 2.5 implies a tropical storm, while a CI of 4.0 implies a hurricane/typhoon.**

TRACK PREDICTION

- **There are several different methods for predicting tropical cyclone tracks.**
- **The historical progression of forecasting techniques began with *persistence*, which is useful in the first few hours of the forecast.**
- **Later, methods based on *climatology* were developed, such as finding analogs, or past storms that had similar characteristics and synoptic environments.**
- ***Statistical* methods use regression techniques to correlate information about the storm and its environment with the likely track.**
    - **The earliest successful prediction technique was a statistical blend of persistence and climatology, called CLIPER.**
        - **CLIPER had no dynamical input, and yet was very successful. It is often used as the reference by which new methods are judged. If they can't do better than CLIPER, then they aren't worth the effort.**
- **Those statistical techniques that use dynamical properties as independent variables are known as *statistical-dynamical* methods.**
- **As understanding of the physical processes affecting motion was gained, pure *dynamical* methods were developed.**
    - **Examples of the dynamical methods are**
        - **Numerical models**
        - **BAM (*Beta plus Advection Models*) which used output from numerical models to define the steering flow, to which calculations of the beta effect were added.**

- **FBAM, MBAM, and SBAM stood for full BAM, medium BAM and shallow BAM, and denoted whether a deep-layer, medium-layer, or shallow-layer mean was used for the steering flow.**

- **Output tracks from numerical models are also ensembled, in a sense creating a type of statistical dynamical method.**

INTENSITY AND SIZE PREDICTION

- **Methods for intensity and size prediction have lagged those for track prediction.**
- **While track prediction has progressed into the dynamical methods stage, intensity and size prediction are still in the climatology and statistical stages, owing to an incomplete understanding of the processes that result in intensity or size changes.**