INTENSITY CHANGES OF RECURVING TYPHOONS
FROM A POTENTIAL VORTICITY PERSPECTIVE

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Andrew S. Levine

Thesis Committee:

Gary M. Barnes, Chairperson
Thomas A. Schroeder
Yuqing Wang
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ABSTRACT

Potential vorticity (PV) interactions are evaluated in fourteen recurving typhoons to assess its usefulness as a forecast tool for intensity change. PV fields are derived from the large scale data in the ECMWF Global Advanced Operational Analysis data set.

A deformation of the 1 potential vorticity unit contour around the typhoon on the 330 K isentropic surface coincides with the weakening of three typhoons, and may prove to be a useful forecast guideline for all recurring typhoons.

Five typhoons have a trough with high PV on the 345 K isentropic surface approach within 10° radial distance. For these five typhoons, PV is not useful for forecasting intensity in isolation from other variables. The PV fields are too subtle by themselves to show a significant difference among typhoons which intensify, weaken or remain steady. Because of this, vertical shear of the horizontal wind and maximum potential intensity (MPI) are included with PV to examine intensity changes.

Vertical shear of the horizontal wind calculated between 850-200 hPa in an intensifying typhoon is ≤ 15 m/s, while shear in a weakening typhoon is ≥ 25 m/s. Shear increases as a PV anomaly propagates closer to the typhoon center. Weakening is associated with the upper PV anomaly passing within 5° from the center of the typhoon. When over fairly constant sea surface temperature (change of ≤ 1°C), two typhoons close to their MPI weakened. The typhoon which was far from its MPI intensified.

Guidelines for forecasting intensity change using these parameters are presented.
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CHAPTER 1:
INTRODUCTION

1.1 Background

Tropical cyclone intensity, defined as the minimum sea level pressure in the eye, continues to be a challenging forecast. Numerical models are not much better at forecasting intensity than climatology and persistence models (CLIPER), and statistical models do not address rapid deepening or filling. The mean absolute forecast intensity errors at the Joint Typhoon Warning Center (JTWC) are presented in Fig. 1. Errors grow from 3.6 m/s at 12 hours to 11.7 m/s by 72 hours. Intensity errors also lead to errors in track, especially in the early stages of a tropical cyclone’s life. Track forecasts utilizing a deep layer mean depend on accurate intensity forecasts to determine how to weigh different flow levels.

After track, the intensity forecast dictates the level of response. Underestimation of intensity results in more injuries, deaths, and damage, some of which may have been avoidable. Overestimation of intensity results in unnecessary evacuation of people and equipment. Sociologically, such errors result in a loss of credibility with the public.

For the United States military, the yearly cost of response is particularly high for the northwest Pacific (especially when compared to the Atlantic basin). The basin is very active with an average of 26 tropical cyclones (TCs) per year, which is more than twice the amount in the Atlantic. Additionally, it is over twice as expensive to evacuate aircraft in the western north Pacific since they must fly farther to reach safety. Intensity forecasts are significant for ships as they need
sufficient warning time to evade a swell created by a tropical cyclone (Brand and Bleloch 1975).

Forecasters at JTWC currently use a systematic approach to tropical cyclone forecasting aid (SAFA). This tool assists track forecasting by identifying systematic model errors, but, intensity guidance is not included in SAFA. However, JTWC forecasters have guidelines they follow based on flow regimes and physical processes. Table 1 is an example of some of the guidelines. It is apparent that there is no solid understanding of how to forecast a typhoon's intensity during and after recurvature. From 1988-2000, there were 231 typhoons, and 68 (30%), recurved over water. Of these 68 recurvers, 22 intensified (32.4%), 22 weakened (32.4%), 18 remained steady (26.4%), and 6 did not fall under any category as they both intensified and weakened (8.8%). Fourteen of these typhoons are examined in this study. The forecast errors for the fourteen typhoons are presented in Fig. 2. A further understanding of the causes of intensity change during recurvature may help lower these values.

The basis for potential vorticity (PV) was developed in the early 20th century by Bjerknes (1901), which resulted in the derivation of the Bjerknes circulation theorem:

$$\frac{dC_a}{dt} = \int \frac{dp}{\rho}$$

where $C_a$ is the absolute circulation, $p$ is the pressure, and $\rho$ is the density. Bjerknes' theorem states that circulation is driven by pressure gradients from differential heating. The usefulness of this equation is best exemplified in a sea breeze circulation where surface heating over land during the day results in a sea
breeze, and cooling over land at night reverses the circulation to a land breeze. Rossby or Ertel's derivation of PV each start with this basic concept, and then eliminate the solenoidal term: Rossby (1940) with a barotropic assumption, and Ertel (1942) with the use of potential temperature as a vertical coordinate.

Before the work of Rossby and Ertel, Shaw (1933) suggested the use of potential temperature as a vertical coordinate. In the 1930's, Rossby (1937) and Namias (1939) made use of isentropic maps to describe atmospheric motion in a Lagrangian sense, where an individual fluid element is labelled by a distinguishing property. The major assumption was that diabatic heating was of little importance on the synoptic scale. Despite the attempts of Rossby, Shaw and Namias to advocate the use of isentropic surfaces as the vertical coordinate of choice, pressure became the primary vertical coordinate. The major problem of using isentropic surfaces as a vertical coordinate was the excessive time it took to produce the maps.

With the work of Hoskins et al. (1985), who advocated the use of potential vorticity as a forecast tool in the midlatitudes, and the advance of computers which made calculations easier, PV has recently gained widespread popularity. Hoskins et al. (1985) showed the usefulness of the invertibility principle. With the invertibility principle, when the proper balance condition is applied to a global distribution of PV, the temperature, pressure, and wind fields can be determined. This dynamical way of thinking is termed isentropic potential vorticity (IPV) thinking, a way in which vertical motions are not needed explicitly to explain cyclogenesis.

There are four qualitative points to IPV thinking. First, the circulation
induced by the PV anomaly is of the same sense as the anomaly itself. A cyclonic (positive) PV anomaly will induce a cyclonic circulation, and an anticyclonic (negative) anomaly will induce an anticyclonic circulation. Second, the induced fields are governed by a scale effect. A large scale PV anomaly will induce a relatively strong wind field, while a small one will induce a relatively weak wind field. A large upper level positive PV anomaly can induce a cyclonic circulation through the depth of the entire troposphere. Third, both static stability and relative vorticity are anomalously high within a positive upper level PV anomaly, and low within a negative upper level PV anomaly. Finally, the static stability anomalies have the opposite sense to the PV anomalies above and below that anomaly. Below an upper level positive PV anomaly, static stability is anomalously low, and below an upper level negative PV anomaly, static stability is anomalously high.

Using the invertibility principle, Thorpe (1986) illustrated how a circulation may be induced by a given PV anomaly. In a cross section through a cold core upper tropospheric positive PV anomaly, the following features are observed: a relatively cold troposphere, low tropopause, and warm stratosphere. There is convection ahead of the anomaly as a result of vortex tube stretching and rising air forced along the uplifted isentropic surfaces. The size and strength of the PV anomaly determines how unstable the region is, and thus, the depth of the convection.

1.2 Previous studies on PV in tropical cyclones

Most intensity research utilizing PV revolves around the role of an upper
level positive PV anomaly associated with an approaching trough. Bosart and Bartlo (1991) described the three stages of cyclogenesis for Tropical Storm Diana (1984) from a PV perspective. The first stage was the fracture of a cold trough as it approached the east coast of the United States. This resulted in a small positive upper level potential vorticity maxima left behind over central Florida. The fractured piece of PV aloft maintained the cold temperature of the trough, and viewing the isentropes, looked like a dome of cold air. Next, low level PV was generated below the latent heating associated with convection, which was located ahead of the upper PV maximum. The induced circulation at the surface arising from the generation of PV increased cyclonic vorticity at the surface. Cyclogenesis was completed with the dissipation of the upper level positive potential vorticity maximum, and the associated cold dome.

In addition to explaining tropical cyclogenesis, PV has been used to evaluate the effect a trough can have on tropical cyclone intensity. A key aspect of PV for this area of research is the ability to effectively define the tropopause. Danielsen (1968) argued that a definition of a tropopause in terms of PV is more useful than a lapse rate definition. The ability to define a tropopause and the conservative nature of PV makes its evaluation useful to distinguish, and follow, troughs and ridges. This conservative aspect of PV has made it a popular framework with which to study trough interactions with a TC.

In some cases, the PV anomaly associated with a trough has been observed to thin and fracture as it approaches the TC. When this thinned or fractured portion of the PV anomaly superposes over the TC center, it can have
a positive affect on intensity. Molinari et al. (1995, 1998) noticed a rapid intensification of Hurricane Elena (1985) and Tropical Storm Danny (1985) after the superposition of a relatively small scale upper level positive PV anomaly over the TC. The eyewall formed in Danny just as it moved under an upper PV anomaly. For Elena, intensification occurred in an environment which did not appear favorable for rapid deepening. The TC was within 200 km of land and over constant sea surface temperature (SST).

Elena was discussed in detail by Molinari et al. (1995). The key to intensification, according to Molinari et al., was the mutual interaction between the synoptic scale trough and the mesoscale outflow of the hurricane, where the outflow anticyclone acts as a blocking high. This interaction resulted in the deformation, and a narrowing of the approaching upper PV anomaly associated with the trough (Fig. 3b,c), similar to Rossby wave breaking as described by Thorncroft et al. (1993).

The deformation led to a trough fracture which created a small scale anomaly apart from a larger pool of PV. From PV thinking, this led to two positive factors for intensification. First, a smaller PV anomaly will be destroyed quicker from diabatic heating. This will reduce the amount of time high vertical shear affects the TC. Additionally, the vertical extent of the induced circulation of a PV anomaly is proportional to the horizontal length scale of the anomaly. Therefore, the reduction in size of the PV anomaly likely reduced the duration and penetration depth of the vertical shear affecting Elena, preventing a negative influence on intensity.
Once the small scale PV anomaly reached the TC center, Elena began to intensify (Fig. 3d). Intensification was attributed to the combination of constructive interference between the upper and lower PV anomalies, and to enhanced surface circulation associated with the upper PV anomaly which triggered the wind induced surface heat exchange (WISHE) mechanism (Emanuel 1986). This last conclusion appears speculative, without any physical basis supporting it.

Hanley et al. (2001) made a composite of trough interactions with 121 Atlantic tropical cyclones in an attempt to differentiate between troughs which lead to intensification (good trough), and those which lead to decay (bad trough). Trough interactions were separated into three categories. In the superposition case, there is an upper positive PV maximum within 400 km of the TC center. Inside of 400 km, flow is still cyclonic around the storm center in the upper levels. A distant interaction occurs when an upper positive PV maximum is between 400 km and 1000 km from the TC center. This is where flow is anticyclonic in the upper levels. No trough interaction is considered to occur when an upper PV maximum is at a distance greater than 1000 km. They found 78% of TCs with a superposition and 61% of TCs with a distant interaction deepened. In superposition cases, the composite showed a small scale upper PV anomaly approach the TC center and dissipate before crossing the TC center, similar to the results of Molinari et al. (1995, 1998). It was concluded for the superposition cases that a larger and stronger upper PV anomaly (bad trough) induces more vertical shear than a small scale PV anomaly (good trough), and has a negative impact on TC intensity.
Some studies have been unsuccessful using PV to explain intensity changes of maritime cyclones. Elsberry and Kirchoffer (1988) used data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to determine if PV can be used operationally in forecasting pressure changes of maritime cyclones, particularly explosive cyclones which had a deepening rate of 1 hPa/h for 24 hours. They examined twenty-three explosive and non explosive deepeners from the western north Atlantic and western north Pacific regions. PV and jet streak analysis at 300 hPa was evaluated in an attempt to find precursor PV conditions that could be used to forecast explosive deepening storms 12-36 hours in advance. It was shown that narrow zones of PV which exist during cyclogenesis could not be distinguished due to poor horizontal and vertical resolution. It was concluded that forecasting 12 hour pressure falls using PV and wind fields was difficult. Wu and Chen (1999) also found little evidence that the intensification of typhoons Flo and Gene were directly associated with the superposition of a positive PV anomaly as described by Molinari et al. (1995,1998) and Hanley et al. (2001).

The PV papers discussed support Hoskins et al. (1985) in that PV is useful in determining trough interactions, but its usefulness as a predictor for TC intensity is still not proven. Although the conclusions in Molinari et al. (1995,1998) are difficult to support, it seems to be a repeatable signal in Atlantic TC intensification cases. Perhaps the only way to fully understand the physics would be to have aircraft reconnaissance flights during a PV interaction.
1.3 Previous studies on the intensity of recurving typhoons

Riehl (1972) used storm data from 1957 to 1968, and found that nearly one third of the typhoons recurved. He studied intensity in relation to the storm's point of recurvature (p.o.r.), which was defined as where the storm reached its western most position, and found that most typhoons achieved maximum intensity at or slightly before the p.o.r.. It was concluded that most of the TCs decrease in intensity during recurvature was due to latitudinal changes in the Coriolis parameter, with a small fraction due to other causes, such as a cooler SST. The process described can be thought of in terms of conservation of PV, where dry static stability is assumed constant. As the storm moves north, the Coriolis parameter increases, therefore, relative vorticity must decrease, or acquire an anticyclonic sense of rotation. Riehl's (1972) finding was later repudiated by Bao and Sadler (1982), who found 20% of recurving typhoons achieved maximum intensity at least 18 h after recurvature, and Guard (1983), who found over 30% of typhoons intensify after recurvature.

Guard (1983) looked at tropical storms and typhoons which intensified after the p.o.r.. The data set included 18 years of tropical cyclones (TCs), from 1965-1982. There were 478 tropical storms and typhoons, and 181 (38%) were considered recurvers. This included TCs which recurved over land, as long as they did not dissipate. Intensifiers were chosen to be TCs which had an increase in intensity by at least 2.5 m/s at least 6 hours after recurvature. Sixty of the recurving typhoons met this criterion. It was found that tropical cyclones which had an intensity greater than 46 m/s at, or before, the p.o.r. typically did not intensify
significantly after recurvature. As Huntley (1981) and Bao and Sadler (1982) found, super typhoons reach their maximum intensity one to three days prior to recurvature. Guard (1983) concluded that SSTs played a large role in intensity after recurvature, with cooler temperatures encountered the farther north the typhoon recures. Therefore, mean latitude of recurvature could be used as a reference point to assess the potential for intensification after recurvature.

These earlier papers on recurving TCs use a climatological approach, but recently there have been some case studies. Wu and Chen (1999) looked at environmental influences on the intensification of Typhoons Flo (1990) and Gene (1990). In Flo's case, values of vertical shear of the horizontal wind (hereafter vertical shear) were very low, but vertical shear in Gene was above 10 m/s. This seemed to be the difference in why Flo became a super typhoon, and Gene only reached a maximum intensity of 41 m/s. Upper level flow enabled the formation of an effective outflow jet during the intensification of Typhoon Flo, while vertical shear prevented Gene from becoming more intense.

Titley and Elsberry (2000) looked at eddy flux convergence, and how it affected the intensification of Typhoon Flo (1990). The authors described a "preconditioning" phase, where several favorable conditions such as a decrease in vertical wind shear in the upper levels, an increase in cyclonic wind within 600 km of the center at 200 hPa, and an increase in outflow occurred simultaneously. After the preconditioning phase, Flo rapidly intensified (23 m/s in 18 hours), reached a peak intensity of 74 m/s, and then filled rapidly (25 m/s in 30 hours). Favorable environmental conditions appeared to exist during the rapid
decay phase everywhere but in the midlevels. Rapid decay was attributed to mid-level horizontal shear, caused by a midlatitude jet with a large vertical extent, which forced outflow in the mid-levels (400-500 hPa layer). The large vertical extent of eddy flux convergence was hypothesized to create a shallower circulation, which decreased the radial temperature gradient between the circulation center and the environment.

1.4 Vertical shear of the horizontal wind

The good trough versus bad trough scenario was examined further in a modelling study that idealized hurricane-trough interactions (Kimball and Evans 2002). Four types of trough interactions were modelled, three cases in a shallow layer: a weak low (2 potential vorticity units (PVU)), a slightly stronger low (4 PVU), the strongest low (6 PVU), and the fourth case: a weak low (2 PVU) through a deep layer. Surprisingly, the strongest low led to the most intense hurricane. However, the results may not be entirely realistic. Westerly shear imposed in the strongest low was only 6.5 m/s, which may be less than that observed in a weak trough. The weak trough interaction described for Typhoon Gene by Wu and Chen (1999) brought wind shear values of over 10 m/s over the storm.

Even though the results of Kimball and Evans (2002) may be questionable, it does point out the need to understand thresholds of vertical shear for existing tropical cyclones. Zehr (1992) determined a threshold of 12.5 m/s, beyond which TCs in the western North Pacific typically do not form. However, a threshold has
not been determined for existing typhoons. As a result, JTWC forecasts for intensity change based on vertical shear are done subjectively.

1.5 Maximum potential intensity

Maximum potential intensity (MPI) is the maximum intensity a TC could achieve assuming no negative kinematic environmental interactions. It is a thorough view of the thermodynamic environment around the tropical cyclone which incorporates SST, tropopause temperature, and relative humidity. There are several theories that exist regarding MPI. Emanuel's theory (1986, 1991), which views the tropical cyclone as a Carnot heat engine, will be used in this study, but it has its limitations. One obvious limitation is that an existing tropical cyclone will change its MPI by lowering SST, raising the tropopause temperature, and changing the relative humidity in the storm region. Holland (1997) pointed out how sensitive Emanuel's calculations can be to different parameters (Table 2), especially relative humidity, which is typically assumed constant in Emanuel's calculations. Despite its limitations, model simulations performed by Camp and Montgomery (2001) show it still produces a good estimate of MPI.

1.6 Goals

Can potential vorticity be used to forecast typhoon intensity during recurvature? PV estimated for the upper troposphere may provide evidence for an interaction between a midlatitude trough and the TC. If the PV associated with the trough is particularly strong I expect that the TC will weaken. If the PV field
is weaker, and fragments, I expect the TC will intensify.

I will also estimate PV for levels in the midtroposphere. I expect that this will reveal midlevel shear which will weaken the TC. Deformation of the 1 PVU contour around the TC will provide evidence of midlevel shear, and the removal of mass from the outer core of the TC.

After examining PV at upper and middle levels, I will combine it with other variables such as deep layer vertical shear and MPI. In the latter case, I assess thermodynamic forcing that may be responsible for TC intensity change. Examination of PV and deep layer vertical shear will help stratify positive and negative kinematic influences associated with the approaching trough. Vertical shear will be calculated within 3° from the center of the TC to determine if the cyclonic portion of the outflow is affected by high shear. This will inhibit outflow, and lead to the decay of the TC. I expect a strong PV anomaly to bring high vertical shear values over the TC, and weak PV anomalies to bring lower shear values.

MPI will determine how much potential a TC has for intensification. I expect TCs far from their MPI to intensify with a trough nearby. TCs close to their MPI are expected to weaken or remain steady. When a TC is close to its MPI, there is not much more potential to intensify. An MPI parameter is calculated to determine how close a TC is from its MPI. The parameter will be used to quantify the percentage of MPI the TC has realized.
2.1 Experimental design

2.1.1 Definitions

Recurvature is considered to be occurring when the TC has a heading between 315° and 45° (Fig. 4). The point of recurvature is where the TC has a heading of 360°, which is also when the TC will be at its farthest westerly point. During recurvature, the TC must have attained at least typhoon intensity and must have been over water for the entire recurve period.

Recurving TCs are split into those that intensify, those that weaken, and those that remain constant. Operationally, intensity is estimated using the Dvorak technique (Dvorak 1975), which determines a prescribed T number. A typhoon must increase or decrease by at least one T number to be classified as an intensifying or a weakening TC, respectively. Steady storms either do not have a change in T number, or only increase or decrease by .5 T number. A further discussion on the Dvorak technique will be given in the following section.

2.1.2 Track and intensity

Tropical cyclone best track data were obtained from the Annual Tropical Cyclone Reports (ATCRs) which are published by the Joint Typhoon Warning Center (Honolulu, Hawaii) at the end of each calendar year. These reports include a final best track analysis for all TCs which occurred in the Northwest Pacific basin throughout the year. Each TC is reevaluated to determine a final best track, which incorporates data not available at the time of the original forecast. This evaluation removes inconsistencies which may have occurred during a hectic forecast period.
Dvorak intensity estimates were also obtained from the best track analysis from the ATCR. The Dvorak method is a nine-step procedure using cloud pattern recognition and set guidelines to determine storm intensity, which is determined through a designated T number. Steps 1 and 2 use satellite observations to determine an objective intensity estimate, or Data T number (DT). Steps 3-6 find a model expected intensity T number (MET), which is based on the expected intensity change and set guidelines. These independent analyses are combined to determine a final intensity, or final T number (steps 7 - 9). Table 3 shows T numbers, maximum sustained 1 minute winds (in m/s), minimum central sea level pressure (in hPa), and storm category. Important T numbers are 1.5 (tropical depression), 2.5 (tropical storm), 4.0 (typhoon), and 6.5 (super typhoon).

If there is a clear-cut cloud pattern the DT determines intensity. When the cloud pattern is not so obvious, the intensity estimate is biased toward the MET number. After all rules and constraints are applied, the final T number is determined, which must be within one T number of the MET. This implies possible ambiguities in intensity estimates may arise when a storm intensity changes by less than one T number. Therefore, I conservatively constrain the determination of intensity change.

2.2 ECMWF

The ECMWF Global Advanced Operational Spectral Analysis data set is used for PV and vertical shear calculations. The ECMWF model is a spectral
model with a triangular truncation at wave number 106 (T106), which gives a horizontal resolution of 1.125° X 1.125°. This data set was chosen over the coarser National Centers for Environmental Prediction (NCEP) data set (2.5° X 2.5°). Since the radius of maximum winds is usually less than 50 km in a tropical cyclone, ECMWF analysis can not resolve the inner core region. PV analysis will reveal synoptic scale interactions, and the outer TC environment.

The operational data analysis is uninitialized. Uninitialized data means that they start with the 6 hour model forecast and run an objective analysis with current observations using the model forecast as a first guess field. Initialized data are obtained when the uninitialized run is subjected to dynamic and diabatic constraints. The dynamic initialization alters the objective analysis so that height and winds obey balance laws. The diabatic initialization adds a divergent component based on model derived diabatic heating.

ECMWF uses a four-dimensional variational data assimilation scheme (4DVAR). In variational assimilation, error statistics are obtained from comparing observations with the model output, and statistically weighted observational data are incorporated into the data assimilation (Jarvinen et al. 1999). Statistical weighting determines how much influence data will have in the assimilation process based on how accurate the data are believed to be. Unstable flow, such as that seen in and near tropical cyclones are given a higher weight in the assimilation (ECMWF Newsletter number 78-winter 1997/1998). The analysis scheme incorporates observations obtained over a six hour period, within ±3 hours of the model run time. These observations are compared in variational
analysis to hourly model output.

The advantage of 4DVAR is the ability to incorporate observations in time and space, so synoptic data can be incorporated (ECMWF Newsletter number 78-winter 1997/1998). After data assimilation, the data are then subject to an initialization process, and then another model run is made for the next 6-hour first guess field. This process runs in a continuous cycle, and is run four times daily. Thus, data are available four times daily at 00Z, 06Z, 12Z, and 18Z. Model forecast errors of TC position are near 100 km when compared to best track data (ECMWF Newsletter 85-Autumn 1999). Since ECMWF does not bogus in a tropical cyclone vortex, position differences between the best track and operational data set may be off by one grid point.

Thirteen pressure levels were used for PV calculations: 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70 and 50 hPa. One difficulty in analysis is the poor vertical resolution in the upper levels. Since upper level resolution near the tropopause level is only 50 hPa, tropopause folding is not well represented. Tropopause folding is typically found in association with troughs, and represents the deformation of the tropopause where it may be found in two places in the vertical plane (see Fig. 5, from Bluestein 1993). This is a major drawback in evaluating PV interactions since larger gradients are found in the tropopause region which may not be evident with the levels archived in the data set.

An excellent example of how much detail is lost with this upper resolution is shown in Fig. 6. This figure is taken from Elsberry and Kirchoffer (1988) and shows a comparison of a vertical cross section made from rawinsonde data versus
one made from ECMWF data. PV values are considerably lower in the ECMWF analysis. However, PV anomalies at jet levels are still evident (Elsberry and Kirchoffer 1988).

The advantages of using ECMWF data for studying tropical cyclones were discussed by Molinari et al. (1992). The tangential winds around the tropical cyclone are well represented, but the divergent part was underestimated, although the sign was correct (Molinari et al. 1992). Underestimation of the divergent part of the wind was due to the model's failure to effectively represent cloud formation, and therefore, diabatic heating. However, in 1995, ECMWF incorporated a new cloud parameterization scheme which produces a more realistic cloud representation (ECMWF Newsletter Number 70-Summer 1995). This improved the divergent representation in the upper levels of the tropical cyclone environment (Molinari-personal communication 2001). For this reason, all storms chosen for PV analysis in this study occurred in 1995 or later.

2.3 PV

2.3.1 PV calculations

PV is calculated as:

\[ PV = -g(\zeta_\theta + f) \frac{\partial \theta}{\partial p} \]

where PV is potential vorticity, g is gravity, \( \zeta_\theta \) is relative vorticity calculated on an isentropic surface, f is the Coriolis parameter, and \( \partial \theta/\partial p \) is dry static stability. In a frictionless, adiabatic environment, \( dPV/dt = 0 \). The minus sign in the equation is to make the typical value of PV positive in the northern hemisphere. The
equation represents the ratio of absolute vorticity to the depth of the vortex. We expect to see high values of PV in highly stable regions, such as at the tropopause and in the stratosphere. Additionally, high PV values will be found in areas of high vorticity in the troposphere such as tropical cyclones. With that in mind, PV is dominated by the static stability term in the upper levels, and by vorticity in the lower levels.

Potential vorticity is calculated on isentropic surfaces between 310 K and 370 K. First, potential temperature is computed on pressure surfaces. Next, the u and v components of the wind, and pressure are linearly interpolated to isentropic levels. Potential vorticity is then calculated on isentropic surfaces.

Derivatives for dry static stability are calculated using centered finite differencing, centered on an isentropic surface:

$$\frac{\partial \theta}{\partial p} = \frac{(\theta+5)-(\theta-5)}{\Delta p} = \frac{10 K}{\Delta p}$$

Calculations are made every 5 K from 315 K through 365 K. Since data are needed above and below the isentropic surface to calculate using centered finite differences, and the 305 K and 375 K surfaces are not calculated, one sided differences are used on the 310 K and 370 K surfaces.

$$\frac{\partial \theta}{\partial p} = \frac{(\theta+5)-\theta}{\Delta p} = \frac{5 K}{\Delta p}$$

For the 310 K surface, where \( \theta=310 \) K, and

$$\frac{\partial \theta}{\partial p} = \frac{\theta-(\theta-5)}{\Delta p} = \frac{5 K}{\Delta p}$$

For the 370 K surface, where \( \theta=370 \) K.

PV is calculated on isentropic levels from 310 K-370 K, given that my focus is the interaction of the TC with environmental flow. Potential temperature is not
used at 305 K since that isentropic surface may often run below ground in the tropics, or at 375 K since this surface is already into the stratosphere.

2.3.2 Implications of conservation

The tropopause level decreases with height toward the poles. The 345 K isentropic surface (~285 hPa) is typically in the stratosphere in the midlatitudes, and in the troposphere in the tropics. This means higher PV values will be found on the 345 K surface to the north. Therefore, relative maxima in PV are brought equatorward from the poles in the form of troughs, and minima are brought from the equator to the poles in the form of ridges. High values of PV in the troposphere represent stratospheric air brought into that layer, and are associated with cyclonic curvature and shear in troughs, and cool air in the troposphere (Bluestein 1993). The conservative nature of PV works well on the synoptic scale. Diabatic and frictional sources and sinks are small in the upper levels well outside the hurricane core. Therefore, PV maxima (troughs) and minima (ridges) can be useful as a tracer for upper tropospheric research on tropical cyclones.

2.3.3 Units

PV units are defined from midlatitude synoptic scale flow as per Hoskins et al. (1985):

\[ PV = -g f \frac{\partial \theta}{\partial \phi} \]

Using typical midlatitude values, the units for PV can be determined:

\[ PV = -(10 \text{ m s}^{-2})(10^{-4} \text{ s}^{-1})(-10 \text{ K} / 100 \text{ hPa}) \]
\[ = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1} = 1 \text{ PVU} \]

The tropopause is defined as a value of 1.5 PVU.
2.3.4 With heating and friction

Potential vorticity is not conserved due to diabatic heating and friction. Bluestein (1993) derives the equation for the change in PV with time. He starts from the isentropic form of the equations for absolute vorticity and continuity, and arrives at:

\[
\frac{dPV}{dt} = PV \frac{\partial}{\partial \theta} \left( \frac{D\theta}{Dt} \right) - g \frac{\partial \theta}{\partial p} \nabla_\theta \cdot \mathbf{F}_{\text{fric}}
\]

where \( \mathbf{F}_{\text{fric}} \) is friction. Looking at the first term on the right hand side, PV >0 almost always in the northern hemisphere. Below the heating anomaly maximum, \( \frac{D\theta}{Dt} \) increases with height, so PV increases with time, and, above the heating anomaly maximum, \( \frac{D\theta}{Dt} \) decreases with height, and PV decreases with time. Diabatic heating is a PV source (sink) below (above) the heating maximum. The second term on the right hand side of the equation may be written as,

\[
-g \frac{\partial \theta}{\partial p} \nabla_\theta \cdot \mathbf{F}_{\text{fric}} = -g \frac{\partial \theta}{\partial p} \left( \frac{\partial F_x}{\partial x} - \frac{\partial F_y}{\partial y} \right)
\]

Horizontal differences in friction may be a source or sink for PV.

2.4 Vertical shear

Vertical shear is calculated using the ECMWF data set. A deep layer shear is calculated as:

\[
\text{vertical shear} = v_{200} - v_{800}
\]

After vertical shear is calculated, it is evaluated inside a radius of 3° around the center of the TC. This value is chosen since it represents the inner portion of the outflow layer where flow is still cyclonic based on a composite of northwest Pacific TCs from Frank (1977) (Fig. 7). Since the typhoons are recurving, and entering
into the westerlies, shear will usually increase from the west. If high shear values from the westerlies pass inside the TCs cyclonic upper level circulation in the northwest quadrant, it will oppose the flow, force sinking motion, and prevent the "ventilation" of this lower angular momentum air. In this case, lower angular momentum air will remain in the storm's environment. Since storm placement differences between the best track and ECMWF data set can be off by a grid point, the center of the storm is determined as the center of circulation defined at the surface in the ECMWF fields.

PV evaluation in the midlevels (particularly at 330 K), reveals a deformation of the 1 PVU contour in the northeast quadrant of some weakening typhoons. From previous studies, it appears the deformation may be the result of both vertical and horizontal shear. Titley and Elsberry (2000) discussed the rapid decay of Typhoon Flo as it approached a midlatitude jet which increased vertical shear in the midlevels. This shear initiated midlevel outflow which led to the weakening of the typhoon. In Holland and Wang (1995), an anticyclonic gyre to the east/northeast of a TC during recurvature was found to create a shearing deformation in the northeast quadrant. The deformation is particularly evident in the vorticity field in the midlevels. Therefore, midlevel shear is calculated vertically between the 400-700 hPa levels, and horizontally on the 330 K isentropic surface.

2.5 MPI

MPI is calculated using surface and tropopause data from the NCEP reanalysis data set. This data set is chosen over the ECMWF data set due to the
readily available tropopause temperatures which are required for MPI calculations.

From Emanuel (1991), MPI is calculated as:

$$MPI = P_{env} e^{-x}$$

$$X = \frac{eT_s \Delta S_{max} - \frac{f^2 r^2}{4}}{R_d T_s}$$

$$\epsilon = \frac{T_s - T_{out}}{T_s}$$

$$T_s \Delta S_{max} = R_d T_s \ln \frac{P_{env}}{P_c} + L_v (q_c - q_{env})$$

$$q_c = \frac{3.802 \text{mb}}{P_c} \exp \left[ \frac{17.67 (T_s - 273.15)}{T_s - 29.65} \right]$$

where $P_{env}$ is environmental pressure, $P_c$ is central pressure of the TC, $T_s$ is the surface temperature (taken as sea surface temperature), $S$ is entropy, $f$ is the Coriolis parameter, $r$ is the radius of the outer closed isobar (taken as 500 km), $R_d$ is the gas constant for dry air, $T_{out}$ is the outflow temperature (taken as the tropopause temperature), $L_v$ is the latent heat of vaporization, $q_c$ is the water vapor mixing ratio in the center of the typhoon, and $q_{env}$ is the environmental water vapor mixing ratio. The first term in the numerator in $X$ is the increase in entropy in the inflow resulting from the difference in relative humidity between the tropical cyclone center and the ambient environment multiplied by the thermodynamic efficiency based on inflow and outflow temperature. The second
term in the numerator represents energy lost to the outflow anticyclone. The denominator is energy gained from isothermal sensible and latent heat fluxes.

Environmental relative humidity is chosen to be 80%, following Emanuel (1986). Based on the average surface relative humidity in the northwest Pacific Ocean between 1995 and 2000 (Fig. 8), this is not a bad estimate. Even though this relative humidity value may be below the observed values in the boundary layer of a hurricane, Camp and Montgomery (2001) argue that this value may be an acceptable choice. In addition to this simplification, the large scale SST fields used in the calculation are constant under the TC. This is not correct as the boundary layer is not isothermal toward the center of a TC (Cione et al. (2000), Barnes and Bogner (2001)). Using observed values in Hurricane Mitch (1998), Camp and Montgomery (2001) compare equivalent potential temperature calculated with an isothermal boundary layer temperature, and a relative humidity of 80% with a calculation with the observed nonisothermal boundary layer temperature, pressure, and increasing relative humidity. Both cases result in the same value of equivalent potential temperature. Boundary layer cooling and the increase in relative humidity in the TCs boundary layer appear to offset each other in entropy calculations.

A parameter to determine the percentage of MPI which has been realized by the typhoon is calculated as:

\[
\text{MPI PARAMETER} = \frac{1000 - P_{TC}}{1000 - MPI}
\]
The smaller this parameter is, the further the TC is from its MPI. Bosart (2000) speculated that TCs which are further from their MPI will tend to have a favorable trough interaction.

2.6 TCs

Fourteen TCs are used in this study: four intensified, four weakened, four remained constant, and two that both intensified and weakened (Table 4). The TCs that both intensified and filled on the same recurve path are chosen to see PV evolution when a TC falls under both extremes during recurvature. In order to assess how useful PV is for forecasting the intensity of typhoons with a trough nearby, the typhoons are further stratified by the distance of an upper level PV anomaly to the center of the typhoon. How can this stratification be made? A short discussion of previous work on TCs and troughs is necessary to answer this question.

DeMaria et al. (1993) defined a trough interaction to occur when eddy flux convergence (EFC) of angular momentum by azimuthal eddies, averaged within 600 km of the TC center, is greater than 10 m s\(^{-1}\) day\(^{-1}\). Molinari et al. (1995) derived the relationship between PV flux and Eliassen-Palm (E-P) flux divergence in cylindrical coordinates. Within 1000 km of the TC center, the eddy PV flux field was found to be a direct measure of the E-P flux divergence term. In Hanley et al. (2001), a value of EFC greater than 10 m s\(^{-1}\) day\(^{-1}\) was always associated with an upper PV anomaly within 1000 km from the TC center. Following their methodology, I shall examine cases where PV associated with a trough is within
10° from the TC center. Five TCs have a trough come within 10°; one intensifies, two weaken, and two remain steady. Even though I did not calculate eddy momentum flux, Hanley et al. (2001) suggest that it is not necessary to calculate these fluxes to determine if there is a trough interaction. They argue that the relative approach of a trough and TC will generate large EFC values.
3.1 PV in the upper levels with a trough nearby

Is there a difference in the PV fields during intensity change which can be used to assist in forecasting? In order to answer this question, I will examine PV at 345 K for the five cases which have a trough come within 10° of the TC center, and one other TC that has no trough nearby. For ease of comparison, from here on, the typhoon name will be followed by (I) for intensifying, (W) for weakening, (S) for steady, and (I/W) for intensifying and weakening cases.

3.1.1 Intensifying typhoons

Typhoon Bing (I) (1997) intensified from 40 m/s to 67.5 m/s as a trough approached. The PV associated with the trough thins and eventually fragments (Fig. 9). At 00Z 31 August, there is a deformation of the PV field associated with the trough as it is stretched in the southwest-northeast direction (Fig. 9a). The PV anomaly associated with the trough is being thinned as a portion of high PV is being stretched from its main reservoir. Over the next 24 hours, Bing (I) intensified 22.5 m/s as it approached the high PV gradient associated with the thinning trough (Fig. 9b,c). Also during this period, the trough fracture is complete as a small scale PV anomaly (with PV still greater than 1 PVU) has separated from the main PV body. This interaction looks very similar to that of Elena as discussed in Molinari et al. (1995).

3.1.2 Weakening typhoons

Ward (W) (1995) and Shanshan (W) (2000) both weakened with a PV
anomaly associated with a trough nearby. Typhoon Shanshan (W) weakens by 17.5 m/s during recurvature. At 00Z 22 September 2000 (Fig. 10a), Shanshan (W) is at its peak intensity of 65 m/s. At this point, the 1 PVU contour of the approaching anomaly is at a distance of 8° from the center of the TC. This anomaly has a greater zonal extent than the PV anomaly discussed in Bing (I), and has a slightly greater magnitude. At 12Z 22 September 2000 (Fig. 10b), Shanshan (W) weakens 7.5 m/s, as the 1 PVU contour approaches to ~ 5° from the center. The approaching PV anomaly has not distorted, and the magnitude is still as large as 12 hours earlier. Over the next 24 hours (Figs. 10c and 10d), intensity decreases by 12.5 m/s as the upper PV anomaly superposes (Fig. 10d) over Shanshan (W). Shanshan (W) starts to weaken as the upper PV anomaly approaches to within 5° from the center of the TC. This is a significant number, and its implications for forecasting will be discussed in the next chapter.

During this interaction, the approaching PV anomaly associated with the trough does not decrease in size or strength, contrasting the PV anomaly in the case of Bing (I). However, comparing the PV field for Shanshan at 12Z 23 September with the composite of intensifying TCs in Hanley et al. (2001) shows strong similarity in the size and strength of the PV anomaly (Fig. 11). The PV pattern for the weakening interaction behaves much like the intensifying composite in Hanley et al. (2001).

Upper level PV fields for Typhoon Ward (W) are similar to those of Shanshan (W) in many ways: there is no deformation of the approaching PV anomaly in the interaction, it has a large zonal extent, and it is strong (with high
values of PV). There is a distinct difference in the structure of the approaching PV anomaly between Bing (I) and Shanshan (W) and Ward (W).

### 3.1.3 Steady typhoons

Typhoon Zane (S) (1996) did not significantly change in intensity during the entire recurve time, which was over 42 hours (Fig. 12). The approaching PV anomaly did not have a deformation associated with it, but there is a significant difference between this situation and the ones that weakened. The PV anomaly does not pass inside of 5° of the TC center during recurvature. In Zane’s (S) case, 1 PVU contour on the 345 K isentropic surface associated with the PV anomaly reaches within 5° from the typhoon’s center on 12 Z 29 September, which was the last 12 hour period of recurvature (Fig. 12d). Only then does the TC decrease in intensity 2.5 m/s.

Typhoon Zeb (S) (1998) had an upper PV structure similar to Zane (S). Zeb’s (S) intensity was steady at 40 m/s during recurvature. The upper PV anomaly did not have a deformation, and the PV anomaly associated with the trough did not pass within 7° of the typhoon center during the entire recurve path.

### 3.2 PV in the upper levels without a trough nearby

Nine typhoons did not have a PV anomaly within 10° from the typhoon center during recurvature. Out of the nine cases, four intensified, two weakened, two remained steady, and one intensified and weakened. An example is Typhoon Bart (I) (1999), which increased in intensity from 40 m/s to 55 m/s during
recurrence (Fig. 13). At 12Z 20 September (Fig. 13a), the upper PV anomaly is located 15° away from the center of the typhoon. Intensification occurred over the next 12 hours, and at 00Z 21 September (Fig. 13b), the upper PV anomaly is still greater than 10° from the center of the typhoon. Each of the nine TCs had similar PV structure on the synoptic scale. Since there is no trough nearby, PV analysis on the 345 K isentropic surface is not useful for forecasting in these TCs.

### 3.3 PV in the midlevels

In three typhoons which weakened, a deformation of the 1 PVU contour on the 330 K (≈480 hPa) isentropic surface is observed. In each case, the contour around the storm is initially circular, then there is a large deformation in the northeast quadrant, downstream of the westerlies. The typhoons which have the deformation do not need to have a PV anomaly in the upper levels associated with a trough nearby.

The deformation of PV on the 330 K isentropic level for Shanshan (W) is presented in Fig. 14. At 12Z 22 September (Fig. 14a), intensity decreases 7.5 m/s, and a slight deformation of the 1 PVU contour in the northeast quadrant of the typhoon is just beginning to appear. Twelve hours later (Fig. 14b), intensity decreases another 7.5 m/s, and the deformation of the 1 PVU contour has become much more obvious.

Ward (W) also has a similar deformation of the 1 PVU contour around the TC on the 330 K isentropic surface. In each case, the slight deformation of the 1 PVU contour on the 330 K isentropic surface coincides with the approach of the
PV anomaly, at 345 K, to 5° from the storm center. Once the anomaly propagates inside 5°, the deformation becomes more severe.

Ginger (I/W), which does not have a PV anomaly within 10° of the TC center, also has a deformation of the 1 PVU contour on the 330 K isentropic surface during weakening. This deformation looks similar to the structure seen in both Shanshan (W) and Ward (W) (Fig. 15). The first period when filling is noticed coincides with the first time a significant deformation of the 1 PVU contour is observed. This agrees with the findings of Holland and Wang (1995) and Titeley and Elsberry (2000), as they show a trough does not need to be present for midlevel shear to occur.

### 3.4 PV at 345 K and vertical shear

There is a significant difference in structure of the PV anomaly near Bing (I), and the TCs which weaken. Nevertheless, it is difficult to use PV fields by themselves as a predictor for intensity change. The comparison between Shanshan (W), and the composite for intensifying TCs in Hanley et al. (2001) is a perfect example. An approaching trough will subject the TC to vertical shear. The big question which can not be answered just by looking at PV structure is: how much vertical shear? Since PV is not useful for forecasting without a trough present, the following sections will focus on the five typhoons which have a PV anomaly within 10° of the TC center. A deep layer vertical shear is examined within 3° of the center of these TCs.
3.4.1 Intensifying typhoons

Bing (I) encounters vertical shear of 15 m/s during intensification (Fig. 16). There are two significant differences in shear between Bing (I) and the typhoons which either weakened or remained steady. First, vertical shear in Bing (I) is significantly lower than the other TCs. Next, vertical shear values remain constant during the interaction, while in the other cases vertical shear increases as the PV anomaly comes closer to the TC.

Bing (I) began to recurve at 00Z 31 August with an intensity of 35 m/s. At this time, an effective outflow channel is located in the northern half of the typhoon. High shear values outside of 3° from the typhoon center are seen ahead of the PV anomaly, and represents the outflow channel (Fig. 17). During the intensification period, these high shear values persist outside of 3°, but do not increase inside of 3°. The low vertical shear inside of 3° observed in this case matches the results by Molinari et al. (1995, 1998) that the thinning of the PV anomaly reduces vertical shear affecting the typhoon.

3.4.2 Weakening typhoons

Ward (W) and Shanshan (W) have a steady increase of shear with time during recurvature as the PV anomaly propagates from ~8-10° from the center of the TC to inside of 5° (Fig. 16). Tables 5 and 6 show the distance of the 1 PVU contour from the center of the typhoon and the associated vertical shear within 3° of the typhoon center for Ward (W) and Shanshan (W), respectively. Once the upper PV anomaly reaches 5° from the center, the typhoons start to weaken.

Vertical shear increases in the northwest quadrant coinciding with the
inward propagation of the upper PV anomaly as shown in Fig. 18, which displays the 345 K PV analysis for Shanshan (W) overlayed on vertical shear. As the upper PV anomaly is within 4° from the center, vertical shear increases significantly from 25 m/s to 35 m/s within 3° (Fig. 18c). The negative effect of vertical shear is evident in a satellite picture taken 8 hours after Shanshan (W) exits recurvature (Fig. 19). Note the partially exposed center, located at approximately 31° N, 170° E.

3.4.3 Steady typhoons

Similar to Ward (W) and Shanshan (W), Zane (S) and Zeb (S) have increasing vertical shear during recurvature (Fig. 16). Tables 7 and 8 shows vertical shear and the distance of the 1 PVU contour from the center for Zane (S) and Zeb (S). Each typhoon encounters vertical shear values of 30 m/s by the end of recurvature. Despite the increase in vertical shear, intensity for Zeb (S) and Zane (S) remains constant. The primary difference between these two typhoons and Ward (W) and Shanshan (W) is the distance of the upper PV anomaly from the center of the TCs. The upper PV anomaly does not reach inside 5° of the typhoon center for Zane (S) and Zeb (S).

3.5 PV at 345 K, MPI and SST

SST is a variable commonly used to forecast intensity, additionally, I use MPI since it offers a more complete view of the thermodynamic environment. Recently, it has been suggested that TCs closer to their MPI are less likely to have a favorable trough interaction than those further from their MPI (DeMaria et al. 33
1993, Bosart et al. 2000). This section focuses on PV with SST and MPI. SST, MPI, and the MPI parameter as a function of time are presented in Figs. 20, 21, and 22, respectively.

3.5.1 Intensifying typhoons

Bing (I) is over water temperature near 28°C, and SST cools to 27°C during recurvature (Fig. 20). Looking at just SST, it would appear Bing (I) should weaken. Based on the MPI parameter (Fig. 22), Bing (I) is far from its MPI entering recurvature (MPI parameter = .35), and has plenty of potential to intensify. With a trough nearby, low vertical shear inside of 3° from the center, and a low MPI parameter, Bing (I) intensifies to a super typhoon.

3.5.2 Weakening typhoons

Shanshan (W) remains over constant SST of 27°C, while Ward (W) remains over SST above 27°C during recurvature (Fig. 20). Without looking at the complete thermodynamic environment, particularly for Shanshan (W), it would appear that intensity should not decrease. MPI for Shanshan (W) is higher than all of the other typhoons (Fig. 21), and the MPI parameter is above .9 (Fig. 22). The MPI for Ward (W) (Fig. 21) is only 3 hPa more than that for Bing (I). However, the MPI parameter for Ward (W) is 1 (Fig. 22). Both Ward (W) and Shanshan (W) are much more intense than Bing (I). These typhoons weaken when a trough approaches while Bing (I) intensifies. This lends support to the findings of DeMaria et al. (1993) and Bosart et al. (2000).

3.5.3 Steady typhoons

During recurvature, Zeb (S) passes over SST values which increase from
28°C to 29°C (Fig. 20). Based solely on SST, Zeb (S) should intensify. The warm SST values assist in producing a very low MPI value (Fig. 21), and an MPI parameter of .3, which is equal to Bing (I) at its' start of recurvature (Fig. 22). As shown in the previous section, the significant difference between Bing (I) and Zeb (S) is how much more vertical shear Zeb (S) encounters, 20 m/s, increasing to 30 m/s vs. 15 m/s for Bing (I). For Zeb (S), the positive thermodynamic environment is offset by the negative kinematic influence.

Zane (S) has a decrease in SST of 1°C (Fig. 20). However, the more important value is the MPI parameter. Zane (S) does not have an MPI parameter that is as high as the values in Ward (W) and Shanshan (W), nor as low as the values in Bing (I) and Zeb (S) (Fig. 22). Forecasting the intensity of Zane (S) benefits from the forecast guidelines presented in the next chapter.
4.1 Forecast guidelines

Even though I looked at fourteen typhoons, the majority of the following guidelines are based on the results from the five typhoons which had an upper PV anomaly nearby, which is admittedly a small sample size for solid forecast guidelines. However, there were differences among the different intensity categories that may assist forecasting intensity change. Certain thresholds, such as the MPI parameter, are based on just a few TCs, and are therefore not necessarily robust, so more TCs must be examined to establish firm guidelines. With these caveats, I offer guidelines to test (Table 9).

First, observe PV structure on the 330 K isentropic surface. If there is a large deformation of the 1 PVU contour as observed in Ginger (I/W), Ward (W), and Shanshan (W), forecast the TC to weaken. Deep layer (850 hPa - 200 hPa) vertical shear values in these do not seem to be important. Ginger (I/W), Ward (W), and Shanshan (W) had vertical shear values of 10 m/s, 20 m/s, and 25 m/s, respectively, when they had a deformation in the midlevels.

The next few guidelines involve TCs which have an upper level PV anomaly on the 345 K isentropic surface within 10° of the TC center, and a change in SST of ≤1° C. First, observe the approaching PV anomaly, and determine if there is a large deformation of said anomaly. If so, calculate the MPI parameter. If the MPI parameter is ≤ .35, and if the 850 hPa - 200 hPa vertical shear inside of 3° from the TC center is ≤15 m/s, forecast for intensification. If the anomaly does not have a large deformation, is large in zonal extent, the MPI parameter is > .9,
and vertical shear inside of 3° from the TC center is ≥25 m/s, forecast for weakening.

The last couple of guidelines depend on the distance of the upper PV anomaly from the center of the TC. These work for TCs which do not have a large deformation of the approaching PV anomaly. If the vertical shear inside of 3° from the TC center is ≥20 m/s, look at the distance of the upper PV anomaly to the circulation center of the TC. If the anomaly is > 5° from the center, maintain the intensity of the typhoon. If the anomaly is < 5° from the center, forecast to weaken.

The choice of 5° is not arbitrary. Zane (S) had an MPI parameter of .65 during recurvature. Zane’s (S) intensity did not begin to weaken until the end of recurvature, when the PV anomaly reaches 5° from the TC center. Additionally, Shanshan (W) and Ward (W), even though they had high MPI parameters, first weakened as the upper level PV anomaly reaches 5° from the center of the typhoon. Upper level PV was analyzed on the 345 K isentropic surface, which is at approximately 280 hPa. Looking at a composite of typhoons by Frank (1997) (Fig. 7), flow at that level is cyclonic out to a radius of 5°. Therefore, when the upper PV anomaly approaches inside of 5°, it is starting to oppose the cyclonic circulation. This will inhibit outflow, and prevent the removal of low angular momentum air from the tropical cyclone.

4.2 Midlevel shear

Each typhoon that has a deformation of the PV field on the 330 K isentropic
surface weakened. If one assumes PV is conserved, then the deformation is a reflection of the removal of air parcels from the circular 1 PVU contour, away from the typhoon and toward the northeast, or downshear. It is hypothesized that horizontal midlevel shear is the primary cause for this deformation, but vertical shear may indirectly have an effect as well. In order to test this hypothesis, shear is looked at both in the vertical (between 700 hPa - 400 hPa), and on a horizontal plane (330 K isentropic surface).

In Shanshan (W), high horizontal shear on the 330 K isentropic surface is seen to the east of the TC (Fig. 23). During the course of recurvature, there is an increase in wind speed to the east of the TC from 15 m/s at 12 Z 21 September (Fig. 23a) to 25 m/s at 00Z 23 September (Fig. 23b). This causes a shearing deformation of the 1 PVU contour around the TC on the 330 K isentropic level.

Ward (W) and Ginger (I/W) both have large horizontal shear values to the east of the typhoon which likely deforms the 1 PVU contour. Holland and Wang (1995) show a deformation in the vorticity field occurs in the midlevels in recurving typhoons. They note that an anomalous high pressure cell to the east/northeast of the TC, created by the advection of planetary vorticity, becomes the dominant high cell during recurvature. The deformation is attributed to a shearing deformation from this high pressure cell.

Does midlevel vertical shear contribute to this deformation? Titley and Elsberry (2000) showed that when eddy momentum flux extends down to the midlevels, it creates a shallow secondary circulation leading to midtropospheric
outflow. Deformation of the 1 PVU contour in the midlevels implies outflow. Thus, it may be possible that midlevel vertical shear may play a small role in this deformation to the extent that it can create outflow in the midlevels. Shanshan (W) saw high values of midlevel vertical shear. At 12 Z 22 September, shear values of 15 m/s are seen within the 1 PVU contour around the TC (Fig. 14a). At this time, there is a slight deformation of the 1 PVU contour in the northeast quadrant of the storm. Twelve hours later (Fig. 14b), there is a severe deformation of the 1 PVU contour. Ward (W) and Ginger (I/W) both fail to exhibit substantial vertical midlevel shear approaching from the west. Thus, it does not appear that midlevel vertical shear is a primary cause of the deformation, but it may play an indirect role in some instances by helping initiate midlevel outflow.

Midlevel horizontal shear is the main cause of the deformation of the 1 PVU contour. Since the deformation only occurs in cases which weaken, it appears to be a useful tool in forecasting intensity change, and may be a worthwhile area to study in the future. A threshold shear value can not be determined, and may be an issue to explore with a model.

How can the deformation of the 1 PVU contour weaken the TC? Based on MPI theory, the hypothesis of Titley and Elsberry (2000) raises the outflow temperature and promotes the decay. An alternative physical explanation for the decrease in intensity could be as follows: the process leading to the deformation removes mass from the midlevels downshear of the westerlies. If one assumes conservation of PV, the deformation of the 1 PVU contour, combined with unperturbed PV contours closer to the TC center, implies mass is removed from
the outer circulation of the typhoon. This removal of mass will lower the pressure
at the surface on the outer portion of the typhoon (outside of 130 km from the
typhoon center). This may weaken the pressure gradient in the inner core, and
increase the pressure gradient at larger radii.

4.3 Comparison with other PV studies

The results presented do not necessarily differ from previous studies. Hanley et al. (2001) stratify their cases further into direct superposition (PV
anomaly within 400 km of TC center), and distant interaction (PV anomaly between
400 and 1000 km of the TC center). In this study, Bing (I) and Shanshan (W), fall
under the superposition classification. Typhoon Bing (I), was very similar to the
intensification cases of Hurricane Elena and Tropical Storm Danny discussed by
Molinari et al. (1995,1998). In Bing (I), Elena, and Danny, the approaching trough
was thinned significantly as it came close to the TC, which reduced vertical shear.
Even though Shanshan (W), was shown to have similar PV structure as compared
to the favorable superposition composite presented by Hanley et al. (2001), it was
very intense during the interaction. DeMaria (1993), Bosart et al. (2000), and
Hanley et al. (2001) all noted that the more intense TCs tended to weaken during
a trough interaction.

Three TCs fall under the distant interaction classification. The difference in
PV structure in the favorable distant interaction and unfavorable distant interaction
cases shown in Hanley et al. (2001) was very subtle. Similarly, the case which
weakened, and the two cases which remained steady had subtle differences in PV
structure, which would make it difficult to use as a forecast tool.

The first section in this chapter discussed possible forecast guidelines based on the results of this study. It has been determined that three variables can be used to forecast intensity change: vertical wind shear, MPI, and PV (or a measure of the strength of the approaching trough). The results of this study support the results of DeMaria et al. (1993), who previously hypothesized the same three variables can influence tropical cyclone intensity change, with EFC used as a measure of the strength of the trough interaction.
CHAPTER 5:  
CONCLUSION

5.1 Summary

A major challenge facing JTWC is the forecast of typhoon intensity during recurvature. Potential vorticity was examined to determine its usefulness for solving this problem. The PV fields were derived from the ECMWF Global Advanced Operational Spectral Analysis data set, with a 1.125° X 1.125° horizontal resolution. Intensity estimates are from the best track data set at JTWC, based on the Dvorak technique. Fourteen recurving typhoons are categorized as intensifying, weakening, or steady.

Potential vorticity was analyzed on isentropic surfaces from 310 K - 370 K to determine which levels would be useful for forecasting intensity. PV on the 345 K and 330 K isentropic surfaces are chosen as the focus. The 345 K isentropic surface is in the upper level outflow region at ~280 hPa. This level is useful for observing the presence of a trough, and is used in many studies with trough interactions. Trough interactions have been associated with the presence of an upper level PV anomaly within 10° of a TC center. Five of my cases have PV greater than 1 PVU within 10°. The 330 K isentropic surface is in the midlevels at ~ 480 hPa, and gives a view of the outer core of the TC.

PV analysis on the 330 K isentropic surface is useful for forecasting typhoons which weaken. Three cases which weaken have a deformation of the 1 PVU contour around the TC on this level. This deformation is in the northeast quadrant of the typhoon and stretches downshear of the westerlies. Two of the
three typhoons which have this deformation have a trough within 10° of the TC center. For these two TCs, there is a slight deformation of the 1 PVU contour on the 330 K isentropic surface as the upper level PV anomaly moves to near 5° from the typhoon center. As the upper PV anomaly passes inside of 5° of the typhoon center, a more severe deformation is observed.

This deformation also occurs in typhoons which do not have an upper level PV anomaly, associated with a trough, within 10° of the TC center. The third typhoon that has this deformation does not have an upper level PV anomaly within 10° of the typhoon center. Since there does not have to be a PV interaction in the upper levels, the analysis is useful for all typhoons. This is a useful indicator for intensity change since the deformation occurs only in cases which weaken.

When an upper level trough is present, the biggest challenge is to determine how it will affect typhoon intensity. PV analysis on the 345 K isentropic surface is not useful in the absence of a trough, and even with a trough present, it is not useful in isolation from other variables. The structural differences of the PV anomaly at this level are too subtle to provide indications about intensity change.

When there is a change in SST of 1°C or less, PV used in conjunction with MPI and vertical shear can provide additional guidelines for intensity forecasts in specific situations.

The MPI parameter indicates how much potential, based solely on thermodynamics, a TC has to intensify. TCs which are close to their MPI have a high MPI parameter, and are most likely to weaken when an upper PV anomaly is within 10° from the center of the TC. TCs which have a low MPI parameter are
more likely to intensify when an upper PV anomaly is within 10° from the center of the TC. Due to the limited number of cases in this study, further research is necessary to determine a solid threshold for the MPI parameter value.

When comparing PV, vertical shear, and the MPI parameter, the intensifying cases have shown to be quite different from the cases which did not intensify. These are the situations where the approaching PV anomaly has a large deformation. This deformation lowers the amount of vertical shear inside of 3° radius from the typhoon center. When the deformation is combined with vertical shear of ≤15 m/s and a low MPI parameter of ≤.35, the typhoon will intensify.

The three parameters also show a clear signal for weakening cases. These are cases when the approaching PV anomaly does not have a large deformation, and vertical shear over the TC is not lowered. Higher shear values result with the propagation of the PV anomaly toward the center of the typhoon. When this structure is combined with a high MPI parameter ≥.9, and the PV anomaly passes inside of 5° from the TC center, the typhoon will weaken.

The distance of the upper PV anomaly from the center of the TC provides useful guidance when there is little deformation of the approaching trough, and vertical shear is between 20 m/s and 30 m/s within the 3° radius of the TC center. In this situation, a typhoon will either weaken or remain at a constant intensity. The decisive factor is the distance of the upper PV anomaly from the center of the TC. When the distance of the PV anomaly associated with the trough is inside of 5°, the typhoon will weaken. When the distance of the upper PV anomaly remains further than 5° from the typhoon center, the typhoon will remain steady. These
guidelines appear to be most useful for the typhoons which do not have an extremely high (> .9) or low (< .35) MPI parameter.

5.2 Future work

Forecast guidelines were presented based on the results of this study. There were 68 typhoons which recurred between the years 1988-2000, and this study only looked at 14. Included in the 14 were typhoons which had the largest intensity changes. A continuation of this study looking at typhoons with an intensity change of a smaller magnitude would be a good way to test the guidelines offered here. It would also provide the opportunity to further investigate the deformation of the 1 PVU contour in the midlevels, which appears to hold promise for TC intensity studies.

A high resolution model may be useful to further explore the difference between cases which weaken and cases which remain steady. The results of this study suggest that even though deep layer vertical shear may be increasing, intensity may remain steady when the 345 K PV anomaly is further than 5° from the TC center. This may be due to the offset between the positive influence of eddy flux convergence and the negative influence of increased vertical shear. If this result can be duplicated by the model, it will strengthen this hypothesis.

A composite of PV interactions in the Atlantic basin was presented by Hanley et al. (2001). To compare the basins, a composite of the northwest Pacific typhoons which had a PV interaction could be made. All typhoons in the composite must remain over water during the entire PV interaction to ensure there
are no landfall effects. This composite could also be made for the midlevels to further investigate the deformation of the 1 PVU contour on the 330 K isentropic surface. If a composite of weakening typhoons has this deformation, I would have confirmation of its usefulness as a forecast tool.

Finally, a study of trough interactions with hurricanes could provide a 3-D view of an approaching trough and its effect on intensity. The Gulfstream IV could be used on reconnaissance flights at 12 km altitude traversing the approaching trough, and dropping GPS sondes to create the 3-D view of the trough. The upstream rawinsonde network in the eastern U.S. is dense enough to determine trough characteristics. When a trough interaction appears imminent, a reconnaissance mission could be performed for both a strong trough and a weak trough to compare how each affects a TC.
<table>
<thead>
<tr>
<th>Physical Processes and flow regimes</th>
<th>Intensification</th>
<th>Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lower tropospheric cyclonic vorticity, monsoon trough, and wave disturbance</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>2. Upper Tropospheric disturbances, such as midlatitude wave, TUTT</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>3. Strong vertical wind shear</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4. Warm sea surface temperature, deep oceanic well-mixed layer, and upward moisture and heat fluxes from the sea surface.</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>5. Upper-tropospheric organized outflow or outflow cloud patterns</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>6. Fast tropical cyclone motion speed (faster than 10 m/s)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>7. Recurvature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>During</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>After</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

TABLE 1. Physical processes contributing to a tropical cyclone's intensification or decay. The positive and negative contributions are denoted by + and - signs, respectively. For example, a + sign in the intensification category means that flow regime will likely lead to intensification, while the - sign in the decay column means that the flow regime is not likely to weaken the TC, and vice versa.
### TABLE 2. Sensitivity of the MPI predicted by the Carnot cycle of Emanuel (1991) to defined parameters from Holland (1997).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard Value</th>
<th>Range</th>
<th>MPI Range hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{env}$</td>
<td>500 km</td>
<td>50-1100 km</td>
<td>20</td>
</tr>
<tr>
<td>$P_{env}$</td>
<td>1015 hPa</td>
<td>1000-1020 hPa</td>
<td>25 1.2 hPa/hPa</td>
</tr>
<tr>
<td>$RH_{env}$</td>
<td>75%</td>
<td>70%-90%</td>
<td>130 6.2 hPa/%</td>
</tr>
<tr>
<td>$RH_c$</td>
<td>100%</td>
<td>80%-100%</td>
<td>130 -6.2 hPa/%</td>
</tr>
<tr>
<td>SST</td>
<td>30° C</td>
<td>20° - 31° C</td>
<td>115 10.5 hPa/° C</td>
</tr>
<tr>
<td>$T_{out}$</td>
<td>-75° C</td>
<td>-60° to -90° C</td>
<td>120 -4 hPa/° C</td>
</tr>
</tbody>
</table>

Parameter $r_{env}$ is the radius of a tropical cyclone, $P_{env}$ is the pressure in the environment, $RH_{env}$ is the relative humidity in the environment, $RH_c$ is the relative humidity within the cloud, SST is the sea surface temperature, and $T_{out}$ is the temperature at the outer boundary of the model.
<table>
<thead>
<tr>
<th>CI</th>
<th>Maximum Sustained 1-Minute mean winds (m/s)</th>
<th>Minimum central sea-level pressure (hPa)</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-1.0</td>
<td>&lt; 13</td>
<td>1003-1008</td>
<td>Tropical Disturbance</td>
</tr>
<tr>
<td>1.5</td>
<td>13</td>
<td>1001-1002</td>
<td>Tropical Depression</td>
</tr>
<tr>
<td>2.0</td>
<td>15</td>
<td>1000</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>2.5</td>
<td>18</td>
<td>997</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>23</td>
<td>991</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>28</td>
<td>984</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>33</td>
<td>976</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>39</td>
<td>966</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>46</td>
<td>954</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>52</td>
<td>941</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>59</td>
<td>927</td>
<td></td>
</tr>
<tr>
<td>6.5</td>
<td>65</td>
<td>914</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>71</td>
<td>898</td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>79</td>
<td>879</td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td>87</td>
<td>859</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3. Dvorak current intensity chart.
<table>
<thead>
<tr>
<th>Typhoon</th>
<th>Category</th>
<th>PV anomaly &lt;10°</th>
<th>330 K deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ward 1995</td>
<td>Weaken</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Bart 1996</td>
<td>Steady</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Dale 1996</td>
<td>Weaken</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Yates 1996</td>
<td>Weaken</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Zane 1996</td>
<td>Steady</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Bing 1997</td>
<td>Intensify/Weaken</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Ginger 1997</td>
<td>Intensify/Weaken</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Joan 1997</td>
<td>Steady</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Marie 1997</td>
<td>Intensify</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Zeb 1998</td>
<td>Steady</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Bart 1999</td>
<td>Intensify</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Damrey 2000</td>
<td>Intensify</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Shanshan 2000</td>
<td>Weaken</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Xangsane 2000</td>
<td>Intensify</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

TABLE 4. List of typhoons analyzed in the study, with category, if an upper PV anomaly approached within 10° from the center of the typhoon, and if there was a deformation of the 1 PVU contour around the TC on the 330 K isentropic level.
<table>
<thead>
<tr>
<th>Period</th>
<th>Distance of PV ° from center</th>
<th>Vertical shear (m/s)</th>
<th>Intensity change (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>25</td>
<td>-5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>30</td>
<td>-10</td>
</tr>
</tbody>
</table>

TABLE 5. Increase in 850-200 hPa vertical shear inside of 3° radial distance from the center associated with inward movement of upper PV anomaly, associated with a trough, and intensity change for Typhoon Ward. Period is every 12 hours.

<table>
<thead>
<tr>
<th>Period</th>
<th>Distance of PV ° from center</th>
<th>Vertical shear (m/s)</th>
<th>Intensity change (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>25</td>
<td>+2.5</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>25</td>
<td>-7.5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>35</td>
<td>-7.5</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>35</td>
<td>-5</td>
</tr>
</tbody>
</table>

TABLE 6. Increase in 850-200 hPa vertical shear inside of 3° radial distance from the center associated with inward movement of upper PV anomaly, associated with a trough, and intensity change for Typhoon Shanshan. Period is every 12 hours.
<table>
<thead>
<tr>
<th>Period</th>
<th>Distance of PV ° from center</th>
<th>Vertical shear (m/s)</th>
<th>Intensity change (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>20</td>
<td>-2.5</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>30</td>
<td>0</td>
</tr>
</tbody>
</table>

TABLE 7. Increase in 850-200 hPa vertical shear inside of 3° radial distance from the center associated with inward movement of upper PV anomaly, associated with a trough, and intensity change for Typhoon Zeb. Period is every 12 hours.

<table>
<thead>
<tr>
<th>Period</th>
<th>Distance of PV ° from center</th>
<th>Vertical shear (m/s)</th>
<th>Intensity change (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>30</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

TABLE 8. Increase in 850-200 hPa vertical shear inside of 3° radial distance from the center associated with inward movement of upper PV anomaly, associated with a trough, and intensity change for Typhoon Zane. Period is every 12 hours.
<table>
<thead>
<tr>
<th>PV guidelines</th>
<th>Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation of the 1 PVU contour on the 330 K isentropic surface</td>
<td>Weaken</td>
</tr>
<tr>
<td>@ 345 K</td>
<td></td>
</tr>
<tr>
<td>Upper level PV anomaly associated with a trough inside of 10° from the TC center, change in SST of &lt; 1° C, MPI parameter of ≤.35, large deformation of approaching PV anomaly, 850 hPa - 200 hPa vertical shear inside of 3° from the TC center ≤ 15 m/s</td>
<td>Intensify</td>
</tr>
<tr>
<td>@ 345 K</td>
<td></td>
</tr>
<tr>
<td>Little deformation of approaching PV anomaly, change in SST of &lt; 1° C, 850 hPa - 200 hPa vertical shear inside of 3° from the TC center ≥ 20 m/s, upper level PV anomaly associated with a trough &gt; 5° from the TC center</td>
<td>Steady</td>
</tr>
<tr>
<td>@ 345 K</td>
<td></td>
</tr>
<tr>
<td>Little deformation of approaching PV anomaly, change in SST of &lt; 1° C, 850 hPa - 200 hPa vertical shear inside of 3° from the TC center ≥ 20 m/s, upper level PV anomaly associated with a trough &lt; 5° from the TC center</td>
<td>Weaken</td>
</tr>
<tr>
<td>@ 345 K</td>
<td></td>
</tr>
<tr>
<td>Little deformation of approaching PV anomaly, 850 hPa - 200 hPa vertical shear inside of 3° from the TC center ≥ 25 m/s, MPI parameter of ≥ .9, upper level PV anomaly associated with a trough &lt; 5° from the TC center</td>
<td>Weaken</td>
</tr>
</tbody>
</table>

**TABLE 9. Additional guidelines for JTWC using PV.**
FIG. 1. Northwest Pacific Forecast Intensity Errors for 2000. Courtesy ofJTWC.
FIG. 2. Forecast intensity errors for the 14 typhoons used in this study.
FIG. 3. Wind vectors and Ertel potential vorticity for Hurricane Elena on the 345 K isentropic surface at a) 1200 UTC 30 August; b) 0000 UTC 31 August; c) 1200 UTC 31 August; and d) 0000 UTC 1 September 1985. The potential vorticity increment is $1 \times 10^{-6}$ m$^2$ K s$^{-1}$ kg$^{-1}$ (1 PVU), and values greater than 1 PVU are shaded. Wind vectors are plotted each 2.25° latitude-longitude, one half their resolution in the gridded analyses. The tropical storm symbol represents the observed position of Hurricane Elena from Molinari et al. (1995).
FIG. 4. A schematic of a recurving typhoon. Recurve time is when the track direction is between 315° and 45°, represented by the thicker line.
FIG. 5. Vertical cross section across a middle-upper tropospheric front in the central United States at 0000 UTC, December 3, 1990 from the south (left) at Del Rio, Texas (DRT) through Midland, Texas (MAF), Amarillo, Texas (AMA), Dodge City, Kansas and to the north (right) at North Platte, Nebraska (LBF). Isotherms of potential temperature (solid lines) in K; pennant = 25 m/s; whole wind barb = 5 m/s. Tropopause indicated by thick solid line; note the fold around AMA. Distance from AMA to DDC is approximately 350 km (from Bluestein 1993).
FIG. 6. Vertical cross sections from Green Bay, Wisconsin to Apalachicola, Florida for 0000 UTC 19 February 1979: (a) isentropes (solid, K), geostrophic wind (dashed, m/s) and potential vorticity (heavy solid, where $10 = 10 \times 10^{-6} \text{ K mb}^{-1} \text{s}^{-1}$). (b) Corresponding isentropes (K) and (c) potential vorticity (contour interval $3 \times 10^{-6} \text{ K mb}^{-1} \text{s}^{-1}$) derived from archived ECMWF analyses at mandatory levels only, with horizontal distance in kilometers from Elsberry and Kirchoffer (1988).
FIG. 7. Northwest Pacific composite west-east cross section of tangential winds (m/s) in stationary coordinates from Frank (1977).
FIG. 8. Average relative humidity in the northwest Pacific Ocean from 1995-2000. Contours are every 2%.
FIG. 9. As in Fig. 3 but for Typhoon Bing at a) 0000 UTC 31 August; b) 1200 UTC 31 August; c) 0000 UTC 01 September; and d) 1200 UTC 01 September 1997.
FIG. 10. As in Fig. 3 but for Typhoon Shanshan at a) 0000 UTC 22 September; b) 1200 UTC 22 September; c) 0000 UTC 23 September; and d) 1200 UTC 23 September 2000.
FIG. 10. (continued).
FIG. 11. a) Composite of 200 hPa surface for intensifying TCs with a PV anomaly nearby. PV increment is 0.5 PVU and values greater than 1.5 PVU are shaded, from Hanley et al. (2001); and b) As in Fig. 3 but for Shanshan at 1200 UTC 23 September 2000.
FIG. 12. As in Fig. 3 but for Typhoon Zane at a) 0000 UTC 28 September; b) 1200 UTC 28 September; c) 0000 UTC 29 September; and d) 1200 UTC 29 September 1996.
FIG. 13. As in Fig. 3 but for Typhoon Bart at a) 1200 UTC 20 September and b) 0000 UTC 21 September 1999.
FIG. 14. 400-700 hPa vertical shear and 330 K isentropic potential vorticity for Typhoon Shanshan at a) 1200 UTC 22 September and b) 0000 UTC 23
FIG. 15. As in Fig. 3 but on the 330 K isentropic surface for a) Typhoon Ginger at 1200 UTC 27 September 1997 and b) Typhoon Ward at 0000 UTC 21 October 1995.
Fig. 16. Vertical shear, within a radius of 3° from the circulation center, as a function of time for the typhoons which have a PV anomaly inside of 10° from the TC center. (I), (W), and (S) represents whether the typhoon intensified, weakened, or remained steady, respectively.
FIG. 17. 850 - 200 hPa vertical shear and Ertel potential vorticity on the 345 K isentropic surface for the northern half of a 10° box around Typhoon Bing at 0000 UTC 31 August 1997. Full wind barb is 10 m/s, half wind barb is 5 m/s. Potential vorticity increment is 0.5 PVU and values greater than 1 PVU are shaded. The center of Bing is represented by the 1 PVU contour on the bottom of the figure.
FIG. 18. PV on 345 K isentropic surface and 850 - 200 hPa vertical shear for the 10° X 10° box in the northwest quadrant of Shanshan at (a) 0000 UTC 22 September, (b) 1200 UTC 22 September, (c) 0000 UTC 23 September, and (d) 1200 UTC 23 September 2000. Full barbs are 10 m/s. PV increment is 0.5 PVU and values greater than 1 PVU are shaded. The center of Shanshan is in the lower right corner.
FIG. 19. 2031 UTC 23 September 2000 visible image of Typhoon Shanshan just after exiting recurvature. Convection is located to the northeast of the circulation center, which is partially exposed due to the increasing vertical shear associated with the trough to the west, from JTWC (2000).
FIG. 20. SST as a function of time for the typhoons which have a PV anomaly inside of 10° from the TC center. (I), (W), and (S) represents whether the typhoon intensified, weakened, or remained steady, respectively.
FIG. 21. MPI as a function of time for the typhoons which have a PV anomaly inside of 10° from the TC center. (I), (W), and (S) represents whether the typhoon intensified, weakened, or remained steady, respectively.
FIG. 22. MPI parameter as a function of time for the typhoons which have a PV anomaly inside of 10° from the TC center. (I), (W), and (S) represent whether the typhoon intensified, weakened, or remained steady, respectively.
FIG. 23. Isotachs on the 330 K isentropic surface in Typhoon Shanshan for a) 1200 UTC 22 September and b) 0000 UTC 23 September 2000. Isotach increment is every 5 m/s, and values greater than 20 m/s are shaded. The tropical cyclone symbol indicates the best track position of Typhoon Shanshan.
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