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AN INVESTIGATION OF EQUIVALENT POTENTIAL TEMPERATURE AS A MEASURE OF TROPICAL CYCLONE INTENSITY

by
CAPT CHARLES R SIKORA

MARCH 1976

FLEET WEATHER CENTRAL
JOINT TYPHOON WARNING CENTER
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CONTENTS

ABSTRACT

Several investigators of tropical and mid-latitude sounding data have attempted to differentiate between the "disturbed" and the "undisturbed" states of the atmosphere. One parameter, which has been used to approximate the total energy of a parcel of air, and thus distinguish between these two states, is the equivalent potential temperature (Θe).

Radiosonde data from Clark Air Base in the Republic of the Philippines and tropical cyclone dropsonde data have been analyzed for Θe. It is shown that a mid-tropospheric minimum in total energy vanishes as a tropical cyclone approaches Clark Air Base, with subsequent increases in Θe extending through 400 mb. From an analysis of dropsonde data obtained in tropical cyclone centers, large values as well as rapid increases in Θe were observed for tropical cyclones which deepened explosively. Since these changes in Θe are not the product of synoptic scale motions nor horizontal advective processes, it is proposed that they result from the direct mechanical lifting of heat and moisture in the form of convective "hot towers". A procedure for forecasting explosive deepening is postulated.

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1. INTRODUCTION

Tropical energetics involve a continuous transfer of latent and sensible heat between the earth-ocean and the tropical atmosphere in the form of turbulent-scale and synoptic-scale motions and convective processes. These energy transfers may be thought of as occurring during "disturbed" and "undisturbed" states of the tropical troposphere. Garstang et al. (1967) in an evaluation of tropical sounding data attempted to differentiate between these two states, and although small temperature differences and relatively large and variable moisture differences were observed, these differences still did not adequately describe the varying energy states.

A variable which has been used by Garstang et al. (1967) and others (Hutchinson, 1962; Darkow, 1967; Biltoff et al., 1968; and Rasmussen et al., 1969), in both tropical and mid-latitude analyses, is the equivalent potential temperature (Θe). The lower tropical atmosphere is normally potentially unstable during periods of undisturbed weather (e.g., Θe decreases with height) and then becomes potentially stable as convection increases, accompanied by corresponding increases in Θe in the mid-troposphere resulting from vertical transfers of latent and sensible heat.

Madden and Robitaille (1970) have shown that Θe may be derived from the first law of thermodynamics in the form

$$Cp \frac{dT}{T} - R_d \left(\frac{dp}{p}\right) + \left(\frac{Lq}{T}\right) = 0 \qquad (1)$$

where C_p is specific heat of air at constant pressure, T is temperature, R_d is gas constant for dry air, p is pressure, L is latent heat, and q is mixing ratio. Integration of (1) yields

$$\Theta e = \Theta d \exp \frac{(Lq)}{C_p T_s} \qquad (2)$$

where T_s is temperature at the lifting condensation level and Θd is potential temperature. Thus, Θe is highly conservative with respect to saturated and unsaturated adiabatic processes.

2. PURPOSE

The first purpose of this paper is to determine if single-station analysis of Θe can be utilized to define the extent of the Θe field associated with a tropical cyclone. Single-station analysis is quite useful in tropical regions where significant horizontal advective processes do not occur in the nearly homogeneous tropical atmosphere. Clark Air Base (CAB) located at 15.2N/120.5E in the Republic of the Philippines was chosen for this analysis because of the large number of tropical cyclones which approach from the east and pass within 555 km (300 nm) each year. According to statistics derived from Fleet Weather Central/Joint Typhoon Warning Center (FWC/JTWC) Annual Typhoon Reports (1960-1974), an average of 7.8 tropical cyclones [sustained surface winds of 15.4 m sec^{-1} (30 kt) or greater] pass within 555 km (300 nm) of CAB. Based on observed values of Θe, time-height cross-sections of Θe were evaluated for a tropical cyclone of typhoon intensity passing directly over CAB.

The second and primary purpose of this paper is to examine the relationship between Θe and tropical cyclone intensity. Several detailed studies of Hurricane Helene in 1958 (Palmén and Newton, 1969) indicated that the wall cloud or ring of heaviest precipitation (where low-level convergence and upward vertical motion were the greatest) was also identical with the outer boundary of the thermal "eye wall". Colón (1964) found that even though this eye wall band had a higher temperature than the surrounding rain bands, this temperature was still lower than that observed at the edge and in the center. The fact that Θe within the eye wall and in the eye itself was nearly constant with height inferred that the source for the air found in this region was a direct result of the sea-to-air transfer of heat and moisture from low-level inflow.

The overall purpose of this paper is to demonstrate that Θe is an extremely useful parameter for describing the varying energy states of tropical cyclones, especially in the form of the "hot tower" concept. Time-height cross sections of dropsonde data obtained from tropical cyclone center fixes have been analyzed for Θe in order to evaluate a possible relationship between changing values of Θe and tropical cyclone intensity. Note throughout this paper that Θe is not being used in the sense of a stability index, since changes in Θe in cumulus clouds are the result and not the cause of increased convective activity (Atkinson, 1971).

3. SINGLE-STATION ANALYSIS OF Θe

Time-height cross-sections of Θe (surface through 400 mb) have been analyzed for the months of June, July, November, and December of 1974 and November of 1973, but only results from November will be presented here. This radiosonde data is normally available at 0000Z and 1200Z, but whenever tropical cyclones approach to within 555 km (300 nm) of CAB, it is made available every 6 hr to FWC/JTWC, Guam. Values of Θe were determined graphically from the temperature and dew-point data plotted on Skew-T, Log P diagrams at the standard reporting levels of surface, 850 mb, 700 mb, 500 mb, and 400 mb with additional values determined from the 900 mb, 800 mb, and 600 mb levels by interpolation of the plotted temperature data.

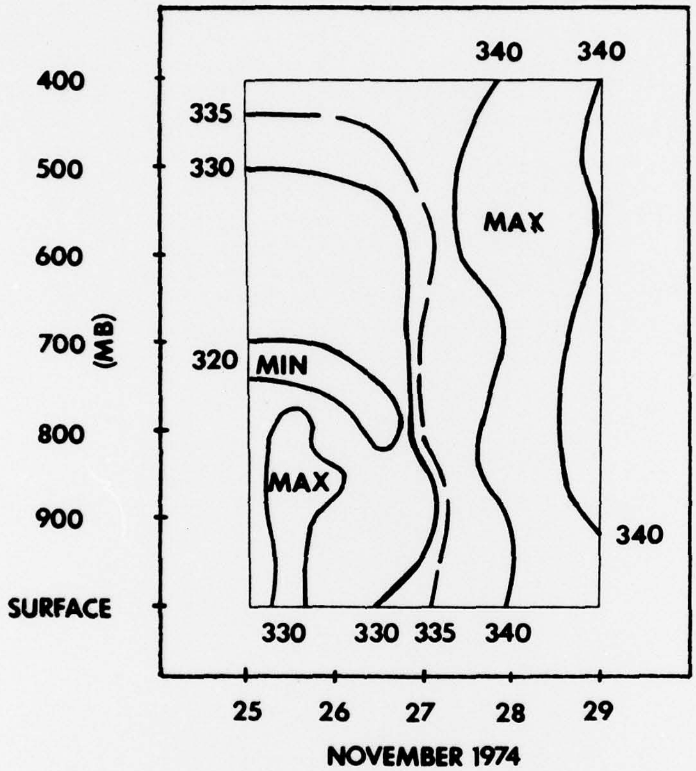

FIG. 1. Time-height cross section of Θe(K) at Clark AB during the passage of Typhoon Irma

The first step was a time-cross section analysis of this data as depicted in Fig. 1. During the period 25-29 November 1974, Typhoon Irma was moving towards CAB and at 0700Z on the 28th passed over CAB with a peak gust of 42.7 m sec^{-1} (83 kt) recorded at 0500Z. For comparison, an example of "undisturbed" weather is shown in Fig. 2. Examination of this data and similar data from other months (not presented here), leads to the following conclusions: (1) the surface values of Θe are highly variable on a diurnal basis during periods of both disturbed and undisturbed weather. These variations can be attributed to boundary layer fluxes of heat and moisture in the form of differential heating, radiation processes, and frictional effects; (2) a mid-tropospheric (approximately 700 mb) minimum in total energy normally exists during periods of undisturbed weather. This characteristic minimum in Θe is a result of strong subsidence suppressing convection and radiational losses from the top of the moist layer; (3) since low values of Θe are characteristic of undisturbed weather, a change in Θe from 313K to 323K is not nearly as significant as a change from 333K to 343K during a period of tropical cyclone activity. When the mid-tropospheric minimum in Θe disappears and Θe increases above 340K from the surface through 400 mb, a tropical cyclone is approaching and is within 555 km (300 nm) of CAB; and (4) inflow of Θe

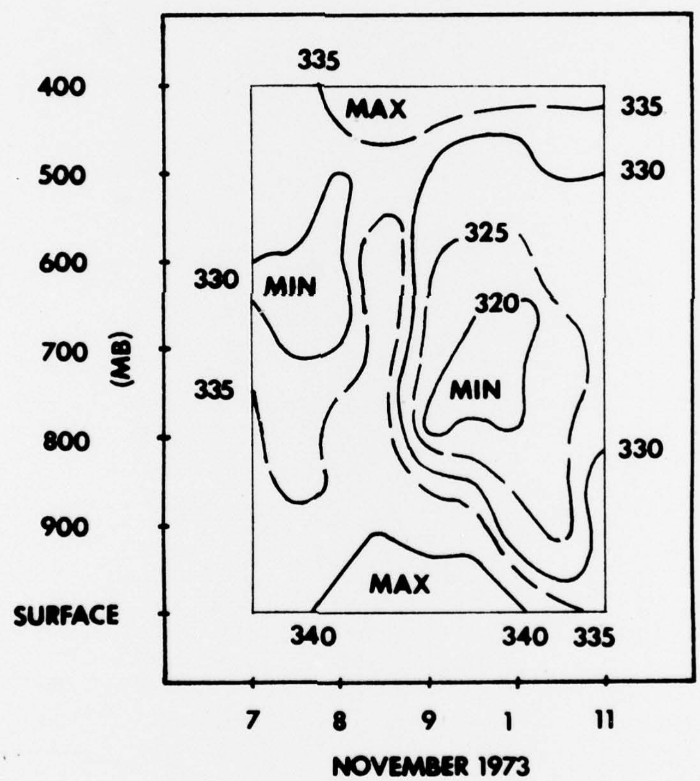

FIG. 2. Time-height cross section of Θe(K) at Clark AB during a period of "undisturbed" weather.

is not observed at intermediate levels along the 340K isotherm which was selected as the dividing line between disturbed and undisturbed states. If simple mixing (lateral in the form of entrainment and vertical in the form of heating and convection) occurs in the vicinity of tropical cyclones, then these isotherms should be observed. However, air parcels with high values of energy (Θe) rising in small cumulus clouds, would be diluted by mixing with the surrounding low-energy environment, while a parcel rising in the core of a large-diameter updraft (cumulonimbus cloud) would conserve its energy (Pálmen and Newton, 1969). Riehl and Malkus (1958) postulated that moist adiabatic ascent occurs primarily in the region of rapidly ascending "hot towers" rather than in a uniform and gradual ascent of the entire mass. The cumulonimbus clouds found in the feeder bands of tropical cyclones may be considered insulated cores or "hot towers" capable of accomplishing the required vertical lifting of boundary-layer air into the upper atmosphere while conserving Θe. As a result of this very intense mechanical lifting, there is little opportunity for significant entrainment to occur.

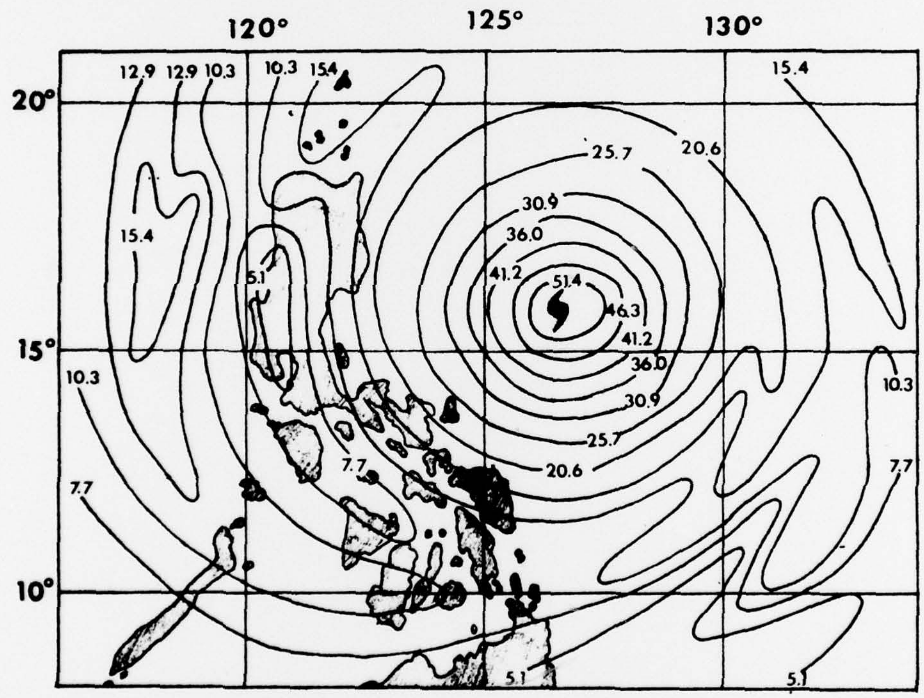

FIG. 3. Isotach analysis (m sec^{-1}) for Typhoon Irma in the Philippine Sea, 270000Z November 1974.

In November 1974, between the 27th and 28th (Fig. 1), mid-tropospheric values of Θe increased considerably at CAB during the appraoch of Typhoon Irma. A detailed isotach analysis at 270000Z (Fig. 3) supported this increase as winds of 15.4 m sec^{-1} (30 kt) began skimming the east coast of Luzon. In Fig. 1, the values of Θe increased steadily beginning at 270000Z [Irma was still 630 km (340 nm) east of CAB] and remained abnormally high until the 29th when Irma moved into the South China Sea.

Garstang et al. (1967), using island and ship sounding data, had similar findings which indicated Θe is one parameter which strikingly reflects the vertical and temporal energy fluxes occurring in the tropical atmosphere, especially in relation to tropical cyclone activity. Parameterization of Θe could represent a significant contribution to tropical meteorology. For example, a network of rawinsonde stations coupled with aircraft reconnaissance data could provide a three-dimensional Θe field and hence valuable information on the structure and future intensification of tropical cyclones.

4. ANALYSIS OF AIRCRAFT DROPSONDE DATA

Dropsondes are routinely released by weather reconnaissance aircraft, while penetrating tropical cyclones, to gather meteorological data. These soundings do not usually extend higher than 700 mb, although occasionally special soundings are dropped from above 700 mb. Due to the nature of the operational requirements for aircraft reconnaissance of tropical cyclones, meteorological observations are only made in the eye or center of these storms and none are accomplished in the area of the eye wall or wall cloud. Observations are normally available every 6 hr (under certain circumstances, every 3 hr), but gaps in the data of 12 hr or more occur. A detailed analysis then becomes extremely difficult in view of the rapidly changing structure of tropical cyclones. Thus, the relatively large number of tropical cyclones initially available for study is quickly reduced to an extremely small number which have continuous dropsonde coverage.

As the first step in an evaluation of this data, time-height cross sections of Θe were examined for several typhoons. The initial conclusions drawn from these data were: (1) the values of Θe at levels below 700 mb fluctuate considerably and are generally higher than the values near 700 mb and (2) the values of Θe in the vicinity of 700 mb increase steadily with continued development of a tropical cyclone--dramatic increases were noted when rapid intensification occurred. Based on this latter observation and the fact that the majority of the tropical cyclone center fixes are made by weather reconnaissance aircraft at 700 mb, it was decided to concentrate on this level in an attempt to derive some meaningful relationship between Θe and tropical cyclone intensification.

In order to standardize tropical cyclone intensity and eliminate various sources of error, a relationship between the 700 mb height and minimum sea level pressure (MSLP) (Jordan, 1957) was used for determining tropical cyclone intensity. This derived MSLP is accurate to $\pm$5 mb.

During the period 1973-1975, Θe at 700 mb (Θe 700) was calculated for a sample of twelve tropical cyclones which attained typhoon strength. All of these typhoons deepened very gradually to maximum intensity. Values of Θe 700 and a corresponding MSLP were determined from dropsonde data until each typhoon reached its peak intensity and began filling. These typhoons were categorized as average strength with maximum sustained surface winds ranging from 33.4 m sec^{-1} (65 kt) to 54.0 m sec^{-1} (105 kt) with corresponding MSLP's between 980 mb and 943 mb. For 77 dropsondes taken east of the Philippines and south of 25N, Θe 700 was less than 370K in all cases and less than 365K in 71 cases.

In contrast to these "average" typhoons was the category of very intense typhoons with maximum sustained surface winds from 61.7 m sec^{-1} (120 kt) to 82.3 m sec^{-1} (160 kt) and MSLP from 930 mb to 876 mb. Several general conclusions concerning the relationship between Θe 700 and intensification rate will be drawn after a brief discussion of the life cycles of five of these typhoons.

For Typhoon Irma in November 1971, weather reconnaissance aircraft were scheduled every 3 hr resulting in frequent dropsonde data. During the early stages of Irma, when the MSLP had reached 973 mb, Θe 700 was 368K. Two hours later, Θe 700 was 383K, and in the ensuing 18 hr, Irma intensified at an explosive rate to a MSLP of 884 mb. Coincident with this MSLP was an increase in subsidence in the eye region and a rapid decrease in Θe 700 to values near 360K. This finding agrees with Jordan's (1961) conclusions that an intense tropical cyclone is at or near peak intensity once strong subsidence occurs in the eye. The phenomenal drop in MSLP of 87 mb had transpired during a period of only 18 hr after the occurrence of an extremely high value of Θe 700. According to Holliday (1973), this was one of the most extreme rates of deepening on record for a tropical cyclone.

Holliday (1971) in his documentation of the rapid deepening of tropical cyclones used a MSLP intensification rate of 30 mb per 24 hr (-1.25 mb per hr) as the criterion for rapid deepening. He found that in 81 percent of the cases, deepening began when the MSLP was between 989 and 960 mb. In 75 percent of the cases, rapid deepening occurred within 36 hr after typhoon strength was attained. "Explosive" deepening was defined to occur when intensification rates of -2.5 mb per hr and -5 mb per hr were observed over 12 hr and 6 hr periods, respectively.

During Typhoon Billie in July 1973, early aircraft reconnaissance data indicated that the MSLP was 988 mb and Θe 700 was 355K. The next available dropsonde data some 12 hr later indicated that Θe 700 was 381K and the MSLP had dropped 10 mb to 978 mb. Eighteen hours later the MSLP was 921 mb, a drop of 57 mb since the initially high value of Θe 700.

During the 1975 typhoon season, Typhoons Nina, Elsie, and June all fell in the category of explosive deepeners, but detailed data for determining Θe 700 was only available for June. June intensified steadily and when the MSLP had reached 965 mb, the maximum sustained surface winds were 43.7 m sec^{-1} (85 kt) and Θe 700 had increased to 372K. Twelve hours later, the MSLP was 919 mb, and in the ensuing 12-hr period, the MSLP plummeted to 876 mb with maximum sustained surface winds estimated at 82.3 m sec^{-1} (160 kt). This extremely low MSLP eclipsed the previous record low of 877 mb measured in Typhoons Ida in 1958 and Nora in 1973 (Holliday, 1976).

In Table 1, the occurrence of abnormally high values of Θe 700 served as an indication that subsequent explosive deepening would occur. These anomalously high values indicated that active hot towers were prevalent near the core of the tropical cyclone and served to pump tremendous amounts of energy into the upper atmosphere. Using the relationship developed by Atkinson and Holliday (1975), a MSLP of 920 mb corresponds to maximum sustained surface winds of 61.7 ± 5.1 m sec^{-1} (110 to 130 kt). In Table 1, explosive deepening was considered to have occurred when the MSLP dropped below 920 mb. Using these findings as a general guideline, Holliday's previous definition of explosive deepening was modified. For those typhoons with a MSLP $\leq$960 mb, an explosive deepening of -2.5 to -5 mb per hour can be expected within 6 to 18 hr of the occurrence of θe 700 values ≥370K, while for a MSLP above 960 mb, this deepening can be anticipated within 12 to 24 hr.

STORM	INITIAL MSLP(MB)	θe (K)	RATE OF DEEPENING (MB PER HR)	TIME ELAPSED (HR)	ABSOLUTE MSLP(MB)
June 75	965	372	3.8	11.7	876
Nora 73	971	372	2.6	23.1	877
Billie 73	978	381	3.1	18.5	916
Amy 71	951	386	3.5	15.0	895
Irma 71	971	383	4.5	13.8	884
Emma 67	944	372	9.0	5.1	898
Sally 64	963	378	2.6	23.5	894
Opal 64	953	374	2.6	19.0	903
Judy 63	946	371	4.2	5.7	914
Opal 62	963	381	2.7	17.7	910
Joan 59	955	370	2.4	13.3	891
Ida 58	938	370	4.3	13.8	878
Faye 57	984	375	2.2	23.1	933
Hester 57	963	383	3.4	15.3	898

TABLE 1. Tropical cyclones which deepened explosively after the initial occurrence of θe 700 ≥ 370K.

In contrast to the typhoons in Table 1, Typhoon Rita in July 1972, although not an explosive deepener, still attained a MSLP of 911 mb. The values of θe 700 were never higher than 362K and a period of 61 hr elapsed between a central pressure of 976 mb and the minimum recorded at maximum intensity. This very gradual deepening, which at no time was explosive, was a direct reflection of the low values of Oe 700.

A final example in the application of θe 700 to forecast explosive deepening illustrates the limitations of this approach. Typhoon Cora in October 1975 was a tropical cyclone which did not deepen explosively after a high value of θe 700 was observed. For the first 48 hr of Cora's life cycle, a 200 mb trough located to the west of Cora was significantly inhibiting the development of a strong outflow channel. The system also lacked good vertical structure and when a θe 700 value of 373K was observed (the MSLP was 966 mb), the 700 mb center was displaced 3.7 km (2 nm) to the east of the surface center.

A MSLP of 943 mb was recorded 30 hr later, for a drop of less than 1 mb per hr. At this time the upper level outflow, as determined from satellite and synoptic data, was excellent in all quadrants except the northwest where a minor trough was still restricting the outflow mechanism and inhibiting rapid development. Cora is an example of when the use of Θe 700 and supporting data did not result in explosive deepening.

5. SUMMARY

The equivalent potential temperature represents a very useful parameter for explaining certain aspects of the complex energetics in the life cycle of a tropical cyclone. Single-station analysis of Θe from sounding data appears to show promise as a possible aid for determining the area of influence of an approaching tropical cyclone. If Θe values (surface through 400 mb) indicate a continually increasing trend to near 340K, then the potential for hazardous weather associated with near-passage of a tropical cyclone must be considered. Considerable work remains to be accomplished to examine those situations where the track of a tropical cyclone has affected the area surrounding a particular station, and the relationship of changes in Θe at the station to the behavior of the tropical cyclone.

The application of Θe 700 derived from dropsonde data appears promising for evaluating the potential of explosive deepening in tropical cyclones. From the data evaluated, the observation of values of Θe 700 greater than 370K appears to correlate well with subsequent explosive intensification. It should be re-emphasized that one of the major problems associated with this study has been lack of frequent dropsonde data. For a multitude of reasons, it is difficult to isolate a sufficient number of cases which not only deepened explosively, but also had timely dropsonde coverage. Therefore, due to this extremely small sample size, more data must be collected in order to establish a procedure which can be used to forecast explosive deepening with a greater degree of confidence.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Several investigators of tropical and mid-latitude sounding data have attempted to differentiate between the "disturbed" and the "undisturbed" states of the atmosphere. One parameter, which has been used to approximate the total energy of a parcel of air, and thus distinguish between these two states, is the equivalent potential temperature (Θe).

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