TROPICAL CYCLONE AND RELATED METEOROLOGICAL DATA SETS AVAILABLE AT CSU AND THEIR UTILIZATION

BY

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ABSTRACT

This report has been prepared to familiarize the international meteorological community with the comprehensive collection of tropical cyclone and other meteorological data which are available on our research project. We provide a rationale for the research philosophy behind the assembling of these data sets over the last decade, describe the data and indicate how other researchers may use them for their own research purposes. In particular, we summarize the rawindsonde compositing philosophy and the other research techniques employed on our project. We describe our data processing procedures, the various formulations we have used for different research purposes, the coordinate systems employed and the data availability by region. Our research accomplishments, types of compositing runs, and a list of publications are also presented.

These data sets and their software support represent a considerable manpower and financial investment. An investment that is now able (we believe) to provide a high return in the form of new knowledge on tropical cyclones and other weather systems. We are currently exploring a number of exciting avenues. The possibilities are quite broad and we encourage other research workers to help exploit this resource.

OUTLINE

1. NEED FOR MORE OBSERVATIONAL ANALYSIS OF TROPICAL CYCLONES

Tropical cyclones have been a subject of meteorological concern for many centuries. Yet, because of the severe data limitations which exist over the tropical oceans, the broad-scale structure and physical processes of these storms are only now being documented. This report lists the observational information on tropical cyclones that has been compiled at Colorado State University for the purpose of documenting the various aspects of the tropical cyclone and its environmental flow patterns. This report discusses the research potential available from the expanded data handling capacities of modern computers that are able to process vast amounts of rawinsonde data from many storms at many time periods. This enables us to document and analyze the persistent features of tropical cyclones and increases our knowledge of the basic structure of these storms together with their large structural and behavioral variability. Despite recent knowledge gains, there is still much more that needs to be learned about the physical processes of the tropical cyclone. It is now possible to obtain new observational facts which can increase our understanding of these storm systems. Progress requires that one piece together observational information and physical inferences derived from a variety of different storm behavior characteristics.

Justification. Growing population densities along tropical coastlines are increasing the damage potential of tropical cyclones. At the same time the general population explosion in tropical countries has made the economic impact to agriculture of tropical cyclone rainfall crucial. Agricultural activity in India, China and the southeast US and other locations is influenced by the seasonal variability of tropical cyclones. Maritime interests are often affected by these cyclones. It is important that man gains more knowledge about tropical cyclones so that he is better able to understand and predict their behavioral characteristics. From a global modelling and forecasting point-of-view it is necessary that the broad-scale influences of tropical cyclones be properly incorporated into these models.

The main reason for our ignorance of these storms is that they are grossly undermeasured. Since tropical storms occur where rawinsonde station density is thin, it is quite difficult to quantitatively sample an individual tropical storm at an individual time period. Typically, there are only 1-5 rawinsonde reports (or less) within 10 degrees of the center of a tropical storm at a particular time. Quantitative analysis requires that one resort to some form of rawinsonde compositing procedure.

There has been a large expenditure of resources over the last 20-30 years to establish a network of rawinsonde stations throughout the tropics. The data collected have been almost exclusively utilized for real time tropical analyses, they then sit in US and foreign archives and are only rarely utilized for tropical weather research. When one considers the large costs of collecting the rawinsonde data over and around the tropical ocean basins in the last 20-30 years (probably between 100-200 million dollars) one questions the cost effectiveness of not utilizing these data sources for research on tropical weather systems. Studies utilizing already collected and stored rawinsonde data are much less expensive than the original cost of taking such observations or devising new programs for additional data collection such as GATE, BOMEX, LIE, etc.

Computer Technology Advances and Increased Research Potential. We have been fortunate in the last 10-15 years with the advances made by the semi-conductor electronics industry. This has led to the advent of new and innovative methods to store and retrieve meteorological data on magnetic tape and disks. Without this technology development the research methodology here discussed could not be undertaken. One must realize that the development of this computer technology may prove as beneficial or even more beneficial for meteorological research than the already accepted and established use of the numerical computer for primitive equation and other numerical modelling. We are optimistic about what may be accomplished in observational research advancement and forecasting improvement through the use of this growing computer technology.

It is quite important that studies be made with these already collected and stored rawinsonde data sets, especially when one considers the gradual but steady deterioration of the number of tropical rawinsonde stations which is occurring due to the general belief that the new weather satellites can supply most of the needed oceanic observations at lower cost. Unfortunately, satellite measurements at this time are not able to provide the necessary information needed for in-depth quantitative understanding of tropical weather systems.

There is no question that the weather satellite has had a profound influence on tropical cyclone forecasting and research. The satellite has taught us:

1) how different the cloud patterns of the hurricane and weaker tropical systems can be from one storm system to another,

2) how storm cloud amounts are not well related to storm intensity

3) how cyclone centers can form in regions away from the primary deep convection area, and

4) how large the diurnal range of hurricanes and weaker cyclone system cloudiness can be.

Despite its unique usefulness as a locator and tracker of hurricanes, the satellite observational information has to this date been level restricted. This makes it very difficult or impossible to perform the types of quantitative analysis of the mass, energy, momentum fields, etc. which are necessary for a basic physical understanding of these systems. It is hoped that this level restriction on the satellite information may be gradually reduced as the new satellite vertical sounder systems become more useful in coming years and as we learn more about the hurricane (from rawinsonde compositing) so that we can better interpret these new satellite sounder systems.

Our CSU tropical meteorology research group has been advocating the utilization of rawinsonde composite studies of hurricanes and weaker tropical systems for over a decade. We believe that a great deal has already been learned about the hurricane and weaker tropical cloud clusters from our rawinsonde composite studies. A summary of a good portion of our composite studies to date is contained in a recently issued World Meteorological Organization (WMO) report titled 'Recent Advances in Tropical Cyclone Research from Rawinsonde Composite Analysis', 407 pp. Yet, only a fraction of the potential of this methodological approach has so far been exploited. As we expand our data sets and make more studies we are confident that much new quantitative information on the tropical cyclone can be obtained which will be of both theoretical and operational value.

Besides the desired understanding of the physical processes of tropical storms, there is also the larger and probably more important practical needs of the tropical cyclone forecaster. It is important to distinguish from weather maps which physical parameters best differentiate between developing and non-developing tropical disturbances, which parameters are associated with weather system intensity change, and which factors are most related to the alteration of cyclone motion, etc. Although ambiguity may persist about the scientific interpretation of the relevant physical processes of the tropical cyclone it is important that a general consensus be reached on the surrounding empirical parameter differences which cause cyclone behavioral differences.

When firmer relationships are established between tropical cyclone behavior and surrounding environment conditions through the types of rawinsonde composite analyses being advocated, then justification can likely be made for special aircraft flights, dropsondes, special satellite measurements, etc. to supply the necessary individual case information so that better individual storm forecasts can be made. This is the ultimate purpose of our research philosophy.

2. RAWINSONDE COMPOSITING PHILOSOPHY AND METHODOLOGY

2.1 Overview

The best method of analyzing an atmospheric phenomenon from observations is to perform detailed, quantitative case studies of a large sample of similar systems and then statistically compare the cases. This provides information on both the mean characteristics and the variability of individual systems. However, in practice there are a number of problems to this approach for the study of tropical storms and other oceanic phenomena , the most serious of which is the inevitable scarcity of data available for individual case situations. An ideal case study requires quality data in four dimensions with an appropriate spatial density as well as adequate time resolution. The resolution that is required depends upon the nature of the phenomena to be studied. Ideally, for tropical cyclones and other tropical weather systems of meso to synoptic scale, one would want sufficient data to resolve significant organized convective elements. This would require sampling resolutions on the order of 1-10 km spacing and a few minutes in time. Since the relevant domains extend to thousands of kilometers, merely handling such data would be impractical even if they were available (and, of course, they are not).

One method of improving spatial data resolution is the compositing of data from weather systems showing similar behavioral characteristics. The hypothesis is that by combining data from many systems one can:

a) Improve the effective spatial resolution of the data,

b) Focus on the features common to all systems while averaging out unimportant idiosyncrasies, and

c) Average out sampling noise resulting from measurement errors and subgrid scale influences.

But there are difficulties with compositing as well:

1) variable features of individual systems are lost,

2) time resolution is seriously degraded, and

3) each system exists in a somewhat different mean state from the others. This introduces the possibility of surrounding region biases.

The objectives of compositing are to maximize benefits a-c while minimizing difficulties 1-3.

Even though rawinsonde compositing will not answer all relevant questions in individual storm cases it will, if used properly, greatly improve our general and basic knowledge of weather systems. Compositing is particularly valuable at showing physical differences between systems with different behavioral characteristics. For instance, one can determine quantitative parameter differences between intensifying and weakening storm systems, between right turning vs. straight moving storms, etc., by subtracting the composite data for one type of system from the composite data for the other type of system. In these cases all systematic data biases will likely be in both systems and will be eliminated through the subtraction process. What remains are the true physical differences between systems.

We really have no other choice at this juncture of tropical meteorological development than to try to fully exploit the information available with this compositing methodology. Alternate suggestions for quantitative research advancement will be appreciated!

Rawinsonde compositing has been performed on our CSU research project with both cylindrical and rectangular grids, which extend horizontally to 1500-2000 km for the cylindrical grid and 10000 km for the rectangular grid and vertically from sea level to 50 mb, about hundreds of tropical cloud clusters and tropical storm systems in three different ocean basins. The weather system circulation center for the lowest level is located at each time period and positioned at the grid center. Whenever a rawinsonde report at a given period for a given storm is available within the confines of the grid being used the sounding is positioned relative to the storm center and then averaged with other soundings which fall within the same grid space. Since the relative position of the storm center and the balloon change due to their respective motions during the balloon's ascent, the position of each is recalculated at every pressure level.

2.2 Cylindrical Grid

The basic compositing grid used for studying the tropical cyclone is a 15° latitude radius cylindrical grid extending from sea level to 50 mb. The cylindrical grid consists of eight octants of 45° azimuthal extent and eight radial bands extending from 0-1°, 1-3°, 3-5°, 5-7°, 7-9°, 9-11°, 11-13°, 13-15° as shown in Fig. 2.1. Octant 1 points to the north or to the direction that the storm is moving. The specific pressure levels being composited vary with the data region and are delineated in Chapter 3. For finer detail, wind and budget parameters are also averaged for 2-4° and 4-6°, and thermodynamic parameters for 1° increments from 0-7° to give the radial belts described in the output displays discussed in Chapter 5.

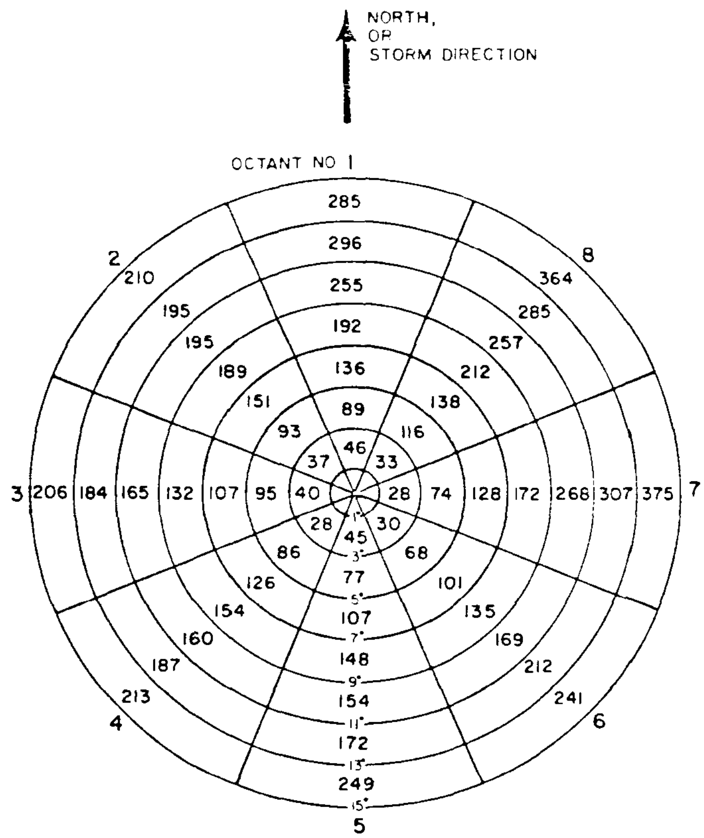

Fig. 2.1. Compositing grid (15° latitude radius) with the number of rawinsonde reports in each octant and each 2° radial band for a typical stratification. Azimuthal octant numbers are outside the circle, 3 to the left, 7 to the right, etc. Arrow points north in NAT and MOT coordinate systems and in the direction of the storm in the ROT and MOTROT systems.

Four coordinate systems are in use. Each offers a different viewing perspective of the storm system. The systems are:

1) With respect to the (instantaneously fixed) cyclone center given by the best track position in a N-S or geographical coordinate system with Octant 1 pointing due North - Natural or <u>NAT</u> system.

2) With respect to the cyclone center in a geographical coordinate system with cyclone motion subtracted out of all the winds (portrayal of data relative to the moving cyclone center in geographical coordinates) - Motion or <u>MOT</u> system.

3) With respect to the (instantaneously fixed) cyclone center with Octant 1 oriented in the direction to which the storm is moving - rotated or <u>ROT</u> system.

4) With respect to the cyclone center and the direction to which the storm is moving with the cyclone motion subtracted out of all the winds - <u>MOTROT</u> system.

Figure 2.1 shows the grid system and the number of soundings per grid space for a typical tropical system stratification. All the parameters to be composited, whether directly measured or computed are determined at the individual station locations for 16 to 21 pressure levels and assigned to a point at the center of the grid box in which the sounding falls. All soundings which fall in that grid space for the particular composite are averaged. Checks are made so that obviously biased data are removed from the data sample.

The following parameters are observed or computed at each level for each sounding:

Wind Parameters	Thermodynamic Parameters	Thermodynamic Parameters (cont'd)
Zonal wind (u)	Height (H)	Relative humidity (RH)
Meridional wind (v)	Temperature (T)	Specific humidity (q)
Radial wind (V_r)	Virtual temperature (T_v)	Dry static energy (s)
Tangential wind (V_θ)	Potential temperature (θ)	Moist static energy (h)
Total wind speed (V)	Saturated moist static energy (h*)	Equivalent potential temperature (θ_E)

The above parameters are composited at each grid space at each level. The composite wind values are then used to compute the derived quantities of divergence, vorticity and other wind related parameters for each grid space. Similar derived quantities are computed from the basic thermodynamic variables.

<u>Budget Calculations</u>. The best technique for estimating the values of horizontal transports of various parameters for use in budget studies is to compute the radial flux of that quantity for each sounding at each level. The radial winds (V_r) are initially composited and mass balanced

from the surface to 100 mb by adding a small constant correction factor (ΔV_r) to each individual radial wind in a given radial band. The mass balance correction is applied to the computed V_r for each observation and the product of the corrected V_r and the quantity (e.g., Q) being analyzed is computed at each level. These products are then composited as before, giving a mean transport value for each octant at each level, $\overline{V_r Q}$, where the bar denotes time and space averaging of the $V_r Q$ products. By subtracting the product of the mean $\overline{V_r}$ and the mean $\overline{Q}$ one can achieve a good estimate of horizontal eddy transport, thus

$$\overline{V'_r Q'} \approx \overline{V_r Q} - \overline{V}_r \, \overline{Q} \qquad (2.1)$$

The types of radial fluxes so far computed are:

$V_r h$ (moist static energy)

$V_r s$ (dry static energy)

$V_r q$ (specific humidity)

$V_r V_\theta r$ (relative angular momentum)

$V_r (fr^2/2)$ (earth momentum)

$V_r V^2$ (kinetic energy)

Vertical Resolution. Vertical motion and budget analyses require sufficient vertical resolution to permit accurate integration of kinematic divergences. Based on experience with numerous composites of tropical convective systems it is desirable to have 25-50 mb vertical resolutions from the surface to 900 mb, 50 mb resolution between 300-100 mb and 100 mb resolution at intermediate levels. Some data above 100 mb should also be included. When this vertical resolution is accomplished with reasonable data density, then the tropospheric vertically integrated divergence closely approximates zero and the vertically integrated mass balance corrections are quite small.

Horizontal Resolution. This should be fine enough to allow computation of gradients (r,θ) on the scales of interest but the grid spaces must be large enough to encompass sufficient observations for meaningful averages. For cylindrical composites eight azimuthal octants and 100-200 km radial resolution has proven satisfactory.

Minimum Sample Size. The number of required soundings depends upon the nature of the analysis. Mean large scale wind patterns can be estimated from a relatively small number of soundings since the signal to noise ratio is high. Analysis of thermodynamic fields requires much more data since gradients often are smaller than intersounding errors and true convective (subgrid) scale variability. However, the most critical parameter in the composite cyclone is the radial wind (V_r). In general, the closer the observed vertical profiles of mean radial wind come to achieving mass balance (defined as zero mass flux between the surface and 100 mb), the better the data may be considered. Thus, we use the smallness of these mass balance corrections as a major indicator of the validity of the sample size. These corrections are typically very small (0.1-0.3 m/s), indicating that the instrumental errors and subgrid scale fluctuations are evenly distributed about the mean and cancel out in a reasonably large sample.

Additional Features. One important feature of the cylindrical grid is the ability to eliminate the pressure gradient acceleration at individual radii when one integrates the momentum equation completely around the circle. This is a great aid in isolation of specific wind acceleration influences which is not possible using a rectangular coordinate system.

As discussed earlier rawinsonde composite analysis is an especially powerful tool for distinguishing physical differences between two data sets such as those shown in Fig. 2.2. It is also possible to composite different periods of the life cycle of storms to study the systematic time changes which occur. The potential number of rawinsonde subsets is limited only by the minimum number of data points needed to provide meaningful composites.

Stratifications. Due to the extremely large quantity of rawinsonde data we have assembled, it is possible to form a variety of composites which are stratified according to system behavior characteristics. By compositing storms with different characteristics, it is possible to systematically examine the subtle quantitative structural and dynamic differences which are associated with each behavioral system class.

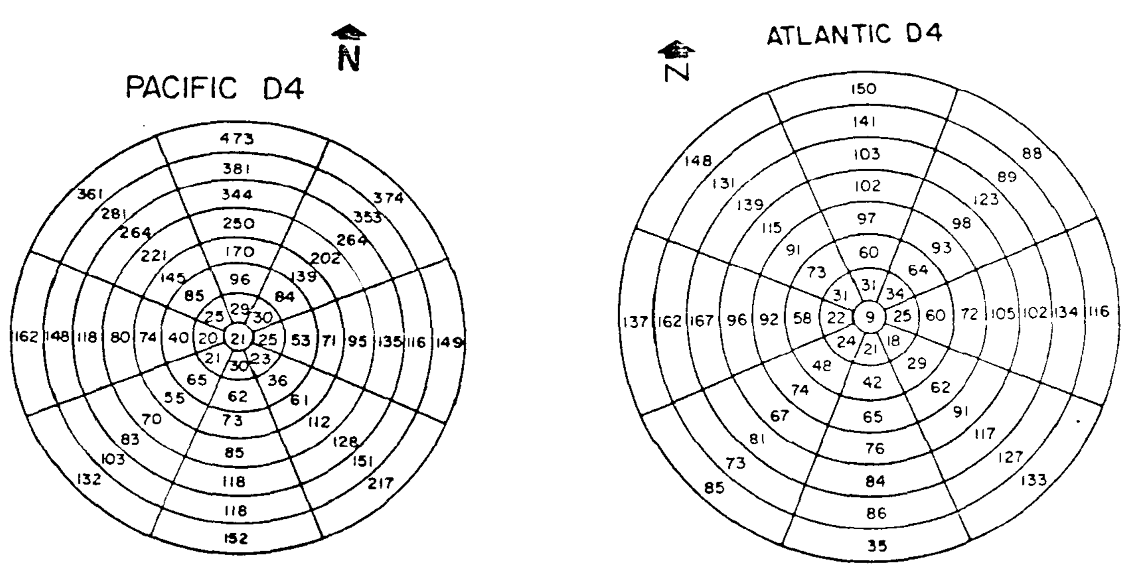

Fig. 2.2. Typical illustration of one of our west Pacific typhoon data sets (left diagram - figures represent number of rawinsonde reports per 2^{o} radial interval per azimuthal octant). The data on the left can be compared with a similar Atlantic hurricane data set (right diagram).

Some of the stratification criteria which have been employed thus far are: