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Cyclone wind threat estimates for the Bay of Bengal*

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सार – चक्रवात के आने पर की जाने वाली तैयारियों के संबंध में सरकारी कर्मचारियों की बार-बार निर्णय लेने की आवश्यकता पड़ती है। प्रतिरक्षा के लिए निर्णय लेने के लिए वे सरकारी पूर्वानुमान का ही अनुसरण करते हैं फिर भी पूर्वानुमान में त्रुटि की पूर्ति के लिए गुंजाइश बनाए रखना चाहिए। उपयोगकर्ता को पूर्वानुमानित पवन वितरण और चक्रवात गमन पथ में त्रुटियों के जटिल संबंधों की जानकारी के अभाव से यह एक विशिष्ट कठिन समस्या बन जाती है। इस शोधपत्र में खतरे की मात्रा को ज्ञात करने के लिए पवन के प्रहार की चेतावनी की संकल्पना दी गई है। साथ ही साथ सभी प्रकार की त्रुटियों के लिए भी प्रावधान रखा गया है। निष्कर्ष निकालने में ऐसी संभावनाओं का उपयोग करने के कुछ सरल उदाहरण प्रस्तुत किए गए हैं और प्रहार के आकलन के लिए प्रतिदर्श को प्रस्तुत किया गया है।

ABSTRACT. Public officials are frequently required to make decisions relative to cyclone preparedness actions. For such decisions to be defensible they usually adhere to an official government forecast, yet some allowance for forecast error must be made. Complex relationships between errors in track and in the forecast wind distribution confused by lack of user familiarity makes this a particularly difficult problem. This paper introduces the concept of wind threat as a means of quantifying the risk thereby allowing simultaneously for all types of errors. Some simple examples of the use of such probabilities in decision making are presented and the model which makes the threat estimates is described.

1. Introduction

Tropical cyclones include the hurricane (in oceans bordering North America), typhoons (northwestern Pacific Ocean) and the cyclones of the south Pacific and Indian Oceans including the Bay of Bengal and Arabian Sea. Historically the great disasters have been in the Bay of Bengal. The November 1970 Bangladesh cyclone is estimated to have killed over 200,000 people (Economic and Social Commission for Asia and the Pacific, League of Red Cross Societies, World Meteorological Organization, 1977) and the November 1977 Andhra Pradesh cyclone killed perhaps 20,000.

The problem in the Bay of Bengal is partly attributable to the distribution of population in low lying and unprotected areas along the Bay, but more important is the configuration of the Bay which results in large cyclone induced storm surges. These surges are an elevation of the sea surface because of the "barometer effect" (pushing up the water into cyclone's central low pressure) combined with the build up of wind-driven water along the coast. These are superimposed on the astronomical tides which have a 12-hourly period (two highs and two lows per day) and a large tidal range at least with some combinations of the solar-lunar cycle. An unfortunate coincidence of a large storm surge and high tide can increase the mean water level by several metres, thus inundating large coastal areas with devastating effects. These problems are well recognized and have been discussed in the literature in relation to prediction (Ghosh 1977) and modeling (Das 1974).

The great killer, then, is the storm surge. While this work does not deal with storm surge, it does deal with cyclone winds which directly (but not exclusively) determine the storm surge.

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This work further involves the introduction of probability into interpreting cyclone forecasts in time of threat.

Forecasts tell in very specific language where the cyclone should be, at what time, and describe its configuration (size and wind distribution). If it were not for inaccuracies in these forecasts, specifying the impact of a cyclone on a locale would be rather straightforward. However, inaccuracies are a fact of life even with advanced forecasting capability. Forecast errors have gradually been reduced over the past few decades, but they still persist and their reduction seems to have leveled off in the decade of the seventies (Jarrell *et al.* 1978; Neumann 1978). This was most pronounced in regions of the world where observations improved, *i.e.,* with the use of aircraft reconnaissance in the late 1940's supplemented increasingly after 1964 by meteorological satellites.

The satellite era is just emerging in the Bay of Bengal and we may expect to see improvement in forecasting capability there. Forecast accuracies equivalent to those of Atlantic and Eastern Pacific hurricanes and Western Pacific typhoons should be expected in the immediate future. Even with the expected improvement in forecast accuracy, the need to deal with forecast errors will always be with us. The aim of this research was to develop a reliable estimate of the probability of 20, 33 and 50 ms^{-1} winds for points under threat of a tropical cyclone, thus making current forecasts with their inherent inaccuracies more usable.

2. Use of Probability

Why Use Probability? The reduction of fore cast error associated with tropical cyclones appears to be leveling off once the improved observational methods have been incorporated into a particular oceanic basin (Jarrell *et al.* 1977). The use of probability is introduced to improve the usability of current forecasts given their inherent errors.

We use probability as a means of quantifying the risk of an event occurring. Often events can be expressed as binary (choice of two) outcomes, *i.e.,* the event *will* or *will not* occur. In this context, for a given case the real probability (presently unknown) is either 0 (the event will not occur) or 1 (the event will occur). Any other outcome is impossible.

If we take a long term perspective of the problem then a number between 0 and 1 can represent the proportion of a large number of like cases which will result in the event occurring. It is this point of view that is usually advocated in decision theory. The techniques used are those which maximize the long term outcome, not necessarily the immediate decision at hand. For example, if evacuation of personal property (*i.e.,* a fishing boat) is considered, all the costs must be weighed against the savings.

The following loss table illustrates the trade-off between evacuation and non-evacuation.

Contingency Loss Table

Preparation Actions	Outcome: Hit	Outcome: Miss
Evacuate	Costs of Evacuation (C)	Costs of Evacuation (C)
Do not Evacuate	Avoidable Losses (L)	None

If we want to minimize probable losses we will want to evacuate only when the probable loss with evacuation is less than the probable loss without evacuation. Note that *unavoidable* losses are not a relevant part of the problem.

If P is the probability of a "hit" of sufficient magnitude to necessitate evacuation then the expected or probable losses with evacuation would be the costs of evacuation (C) and those without evacuation, P times avoidable losses (L). We want to evacuate only if $C < P \times L$ or, rearranging we evacuate when $P > C/L$.

To illustrate this principle with a simplistic example let us suppose the boat owner is considering moving his boat to an inland shelter. Let's say the boat is worth $10,000 and it costs $500 to move it. With $C = 500$, $L = 10{,}000$, he would not want to move it unless the probability (P) of its being lost exceeded the ratio of these numbers :

$$P > C/L = 5 \text{ per cent}$$

His "critical probability" P_c is 5 per cent.

The boat owner can now evaluate the other factors involved in evacuation knowing that when the probability of tropical cyclone strike is 5 per cent or greater his personal property risk of loss is not cost beneficial with his boat exposed. Other considerations may involve timing or when to move the boat to safe harbour. Here again probability may be an effective tool. Suppose, again, that the maximum winds in which his craft can maneuver safely is about 40 knots (20 mps). A run of the model herein proposed tells him that there is a high probability (50 per cent or more) of winds of at least 20 mps within 24 hours but a small probability within the first 12 hours. This gives him a time window within which to work to get his boat to safety. Thus he has '*tools*' with

17-79 051108002 132N 912E 90 142N 805E 105 147N 769E 60 48

FOR CYCLONE 17-79 FROM 110800Z

PROBABILITIES OF EVENTS WITHIN	0HRS	12HRS	24HRS	36HRS	48HRS
HOURS OF DARKNESS	+	*****	+	*****	+ ***
STRIKE WITHIN SRI LANKA	.000	.000	.001	.005	.014
WINDS OF AT LEAST 20 MPS	.000	.000	.004	.014	.032
WINDS OF AT LEAST 33 MPS	.000	.000	.002	.008	.018
WINDS OF AT LEAST 50 MPS	.000	.000	.001	.003	.008
STRIKE WITHIN TAMIL NADU	.003	.062	.125	.172	.209
WINDS OF AT LEAST 20 MPS	.009	.182	.336	.431	.504
WINDS OF AT LEAST 33 MPS	.004	.098	.170	.228	.273
WINDS OF AT LEAST 50 MPS	.000	.019	.058	.091	.116
STRIKE WITHIN AN PRADESH	.006	.172	.289	.388	.446
WINDS OF AT LEAST 20 MPS	.009	.196	.414	.553	.642
WINDS OF AT LEAST 33 MPS	.009	.169	.349	.463	.528
WINDS OF AT LEAST 50 MPS	.001	.042	.138	.209	.248
STRIKE WITHIN ORSA+W.BEN	.000	.000	.001	.008	.017
WINDS OF AT LEAST 20 MPS	.000	.000	.019	.052	.079
WINDS OF AT LEAST 33 MPS	.000	.000	.002	.011	.023
WINDS OF AT LEAST 50 MPS	.000	.000	.001	.005	.010
STRIKE WITHIN EAST INDIA	.009	.193	.415	.567	.671
WINDS OF AT LEAST 20 MPS	.009	.193	.416	.573	.687
WINDS OF AT LEAST 33 MPS	.009	.192	.413	.565	.669
WINDS OF AT LEAST 50 MPS	.001	.061	.195	.302	.370

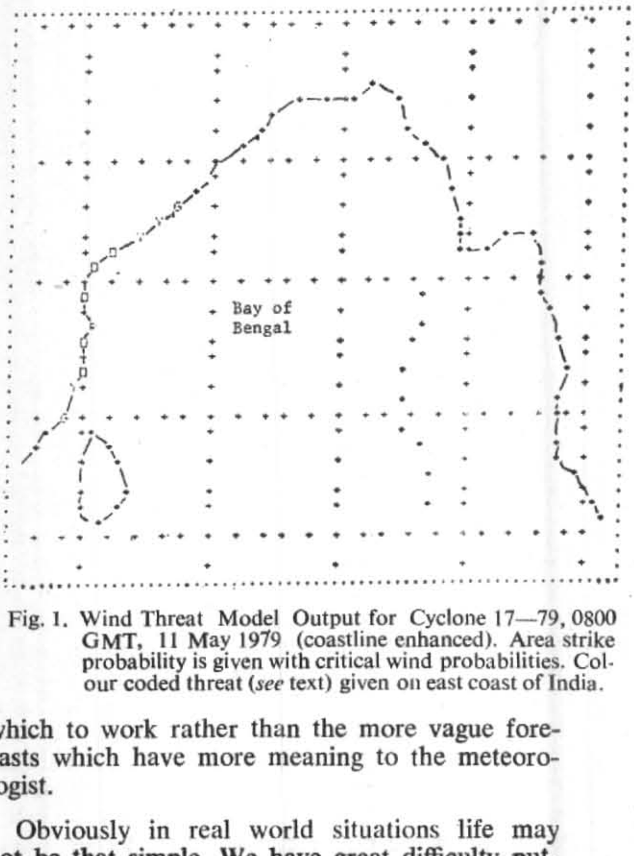

Fig. 1. Wind Threat Model Output for Cyclone 17—79, 0800 GMT, 11 May 1979 (coastline enhanced). Area strike probability is given with critical wind probabilities. Colour coded threat (*see* text) given on east coast of India.

which to work rather than the more vague forecasts which have more meaning to the meteorologist.

Obviously in real world situations life may not be that simple. We have great difficulty putting monetary values on both evacuation costs and losses because of a host of complexities. Note that it is necessary that both C and L be expressed in the same units, but not necessarily monetary units. They could, for example be used by planners to evaluate the potential loss of an entire economic sector such as the entire fishing fleet and resultant costs over a period of time.

A critical use of probability would be evacuation planning for populations in dangerous low lying coastal areas subject to storm surge potential or in flood zones. A planning team, knowledgeable in local evacuation routes and evacuation problems, could set probability criteria before hand for strike or wind conditions and then act once the probability reached the critical level. For example an evacuation route may become unusable once tropical cyclone winds reach a critical level. Again the model (Fig. 1) would provide a time window and a probability for a critical wind speed [Darkness may add a complicating factor (*i.e.*. increase evacuation time) and thus is output in the program]. With the advantage of such planning tools a time sequenced evacuation plan could be enacted at opportune times with the approach of a tropical cyclone.

The above extends easily to choosing between several courses of action. The difficult part of applying such methods is obtaining the probabilities. Providing the probabilities is the subject matter of this research.

Basis for Probabilities

In the Bay of Bengal probabilities are available based on climatology. For example, Neumann and Mandal (1978) describe an analog scheme which models such a probability. This probability is solely based on climatology biased to persistence. The actual probabilities will almost certainly differ substantially from these. The most obvious reason is that the forecaster, having access to information other than climatology and persistence, will have decided on a forecast somewhat different in track and/or timing from the analog. The maximum likelihood positions are along this forecast track rather than the analog track as currently available probabilities would indicate. A less obvious but more serious drawback to the analog probabilities is that they were based on postanalysis data; hence the uncertainties of initial position and motion (for persistence) are not considered.

The scheme which will be introduced is based on the actual forecast and derives probabilities from the assumption that the statistical behaviour of past forecast errors will be observed in the future. In addition, this model includes allowance for wind forecast errors and an implicit allowance for the size of the area of strong winds. Lastly the threat model uses the concept of time summation or time integration so that the threat over a period of time can be estimated. These are all features not presently available with the analog probability system.

3. The model

Statistical Model Basis

The probability estimation model is based on a study of tropical cyclone forecasts issued by

TABLE 1

Summary of results of statistical study of errors in JTWC forecast for the Bay of Bengal related to tropical cyclone heading to sectors 1 & 2

	Sector 1			Sector 2			Combined		
	0 hr	24 hr	48 hr	0 hr	24 hr	48 hr	0 hr	24 hr	48 hr
Error manitude									
Mean (km)	100	320	465	100	280	519	100	296	502
Std Dev (km)	79	183	211	89	181	274	83	183	256
S-N Error (En)									
Mean (km)	31	39	133	20	28	19	24*	31*	56*
Std Dev (km)	83	230	365	70	198	359	76	211	361
W-E Error (Ee)									
Mean (km)	11	76	4	—50	—157	—324	—26*	—63*	—217*
Std Dev (km)	87	283	346	102	220	341	96	248	343
Wind Error (Ew)									
Mean (ms^{-1})	0	4	6	—1	—1	1	—1	1	3
Dev (ms^{-1})	5	8	11	4	7	11	4	8	12
Correlations									
Ee to En	0.40	0.37	0.22	—0.06	0.17	0.15	0.07	0.26	0.22
Ee to Ew	—0.16	—0.25	—0.51	—0.25	—0.00	0.19	0.02*	0.00*	0.04*
En to Ew	0.03	—0.18	—0.23	0.09	—0.16	—0.05	0.01*	—0.15*	—0.10*
Case count	56	55	26	81	81	54	137	136	80

*assumed to equal zero on the model

Sector 1 — Tropical cyclones with headings between 340° clockwise to 180°. Mostly recurving and post recurvature cases.

Sector 2 — Tropical cyclones with headings between 180° clockwise to 340°. Mostly pre recurvature cases.

the United States Joint Typhoon Warning Center (JTWC) on Guam during the seven years beginning with 1971.

The particular forecasts were 205 motion and maximum wind forecasts for cyclones in the north Indian Ocean; however, there were only 137 forecasts where the nowcast position was actually in the Bay of Bengal. This number of forecasts is barely adequate to support a statistical study. In a similar motion forecast study for Western Pacific typhoons, Nicklin (1977) had over 6000 cases. Jarrell (1979) studied wind forecast errors also in the Western Pacific and had a sample of over 2000 cases. The large difference in sample size is somewhat reduced because the Bay of Bengal forecasts were issued at 12-hour intervals *versus* 6-hour intervals in the Western Pacific, thus consecutive forecasts are more nearly independent. Additionally, the general characteristics of the error distributions are known to a good approximation from these and other earlier studies. This study was more to confirm similarity rather than break new ground.

An attempt was made to stratify forecasts into difficulty classes. The most successful stratification was on the basis of forecast direction of motion. Errors are usually smaller for cyclones moving west and larger for cyclones moving northeast. These directions represent typical tracks before and after recurvature. Recurvature is a term signifying a transfer from control by the near equator easterly air currents to the westerly currents of the mid-latitudes. Per-recurvature tracks in the easterlies are typically west-northwest while post recurvature tracks are typically toward the northeast. The westerlies are much stronger and hence cyclone forward speeds after recurvature are much greater. Larger errors are associated with larger forward speeds. The best directional separation occurred at about 340 deg. (northnorthwest), *i.e.,* directions from 340 deg. to 180 deg. appeared to behave differently from the remainder of the cyclones. Some statistical summary results are shown in Table 1. The group with headings 340 deg. clockwise to 180 deg. consists mainly of post recurvature cases and is shown as Sector 1 in Table 1.

Sector 2 forecasts (pre-recurvature-headings 180 deg. to 340 deg.) are the most common forecasts.

In Sector 1 the mean west-east error is somewhat positive (east) while the mean south-north error is significantly positive (north), since these forecasts are typically for north to northeast motion, this represents a speed overforecast. For Sector 2, the west-east mean error is significantly negative (west), while the mean south-north error is slightly positive (north). Again these are overforecasts in speed along the track. These speed errors may in part be attributable to the lack of a good climatology for the area and hence the Guam forecaster relies on his experience with faster moving Pacific typhoons.

For this sample, the average forward speed was 2.8 ms^{-1}, if we add the average 24 hour speed overforecast (1.5 ms^{-1}) to that, we arrive very close to the average typhoon forward speed of 4.6 ms^{-1}. This appears to be correctable bias. Without this bias, there appears to be no significant difference in the difficulty classes, hence an artificial set of statistics based upon the removal of this bias is used in the model and the directional discrimination is eliminated.

This permits the pooling of cases for maximum statistical stability. The correlation coefficients are of some passing interest. The correlation between the error components is small but comparable to those found in the Western Pacific by Nicklin (1977) and in various studies (*see,* for example, Neumann 1975 and 1978). Notice the small correlation between the error in maximum winds and displacement errors components. Since none of these in the pooled sample are significantly nonzero, these errors were treated as independent in the model.

While we are satisfied with the stability of the forecast error statistics, we would have preferred a longer period of record. We have also seen a rather severe bias in the Guam forecasts which we assume will be corrected. The presence of this bias serves to flag the risk in applying statistics derived from forecasts from one source to forecasts of another source. For this reason we recommend that the statistical package be derived from and tailored for the deriving forecasts. For example, if one of the nations on the Bay chooses to adapt this model relative to its own forecasts, a statistical package derived from those forecasts should be substituted for the Guam statistics. In some cases this may also provide a more extensive basis.

Model Operation

Like most models the wind threat model can be described in three stages; input, computation and output. Input and output are perhaps of most concern to the user because of their visibility, but the important work goes on in the computation stage. It is here that underlying mathematical relationships are expressed and exercised and it is here that any simplyfying assumptions are made. The latter, together with input, primarily determine the validity of the output. The following description provides information which the user should understand in order to fully appreciate the output information.

Input

The input is taken exclusively from the JTWC cyclone warnings. It consists of cyclone identification information, used for output labelling, and forecasts of latitude, longitude and maximum wind at 0, 24 and 48 hours after forecast valid time. Table 2 illustrates an actual forecast of tropical cyclone 17—79 originated by the JTWC at 0800 GMT on 11 May 1979. The bottom line in Table 2 is the necessary input information extracted from the warning. The information (except the second entry, month : 5 = May) is underlined in the warning. This cyclone warning will be used again as an output example.

Computations

The actual computations are carried out on a grid of points spaced at 111 km intervals along the periphery of the Bay of Bengal and along the Andaman Island Chain. These computations are executed at 3-hour time steps from forecast initiation (nowcast) time out to 48 hours. The following assumptions are implicit in the computations :

(*a*) That the forecast represents the mean of all possible outcomes, that the deviation of the actual position from this mean is a random variable pair described by a bivariate normal frequency distribution whose parameters are given in Table 1.

(*b*) That the actual maximum wind is a normally distributed random variable about the forecast, with parameters given in Table 1.

(*c*) When landfall is forecast, the accompanying reduction in the maximum wind forecast is solely attributable to land influence, otherwise, a trend established prior to landfall would have continued. If no trend can be inferred from the forecast, it is assumed the nowcast wind would have continued in the absence of landfall.

(*d*) That probabilities can be adequately interpolated in space between representative points spaced 111 km apart.

(*e*) That the forecast positions and the statistical parameters valid for 0, 24 and 48 hours can be interpolated to 3-hour time steps and

TABLE 2

An actual cyclone warning issued by joint Typhoon Warning Center on Guam for cyclone 17-79 on 110800 GMT May 1979

WTXX31 PGTW 111000

TROPICAL CYCLONE 17—79 WRNG NR 20

POSIT 13.2N6 082.3E3 at 110800Z

ACCURATE WITHIN 40 NM

BASED ON EYE FIXED AT 13.3N7 082.7E7

AT 110615Z BY SATELLITE

PRESENT MOVEMENT : WEST-NORTHWEST AT 05 KTS

PRESENT WIND DISTRIBUTION :

MAX SUSTAINED WINDS 90 KTS NEAR CENTER WITH GUSTS TO 110 KTS

RADIUS OF OVER 50 KT WINDS 75 NM

RADIUS OF OVER 30 KT WINDS 150 NM OVER WATER

REPEAT POSIT 13.2N6 082.3E3 at 110800Z

FORECASTS :

12 HRS VALID 112000Z 13.8N2 081.5E4

MAX WINDS 100 KTS WITH GUSTS TO 125 KTS

RADIUS OF OVER 50 KT WINDS 80 NM

24 HRS VALID 120800Z 14.2N7 080.5E3

MAX WINDS 105 KTS WITH GUSTS TO 130 KTS

RADIUS OF OVER 50 KT WINDS 90 NM OVER WATER

RADIUS OF OVER 30 KT WINDS 175 NM OVER WATER

EXTENDED OUTLOOK :

48 HRS VALID 130800Z 14.7 N2 078.9E4

MAX WINDS 30 KTS WITH GUSTS TO 45 KTS

DISSIPATING OVER LAND

NEXT WARNINGS AT 111600Z, 112200Z, 120400Z and 121000Z

REMARKS : LATEST SATELLITE DATA INDICATES TC 17—79 HAS CONTINUED TO INTENSIFY OVER THE PAST 12—24 HOURS, WITH SLOW INTENSIFICATION EXPECTED UNTIL LANDFALL, TC 17—79 HAS SLOWED TO 05 KTS, HENCE AN ADDITIONAL 06 HOURS WAS ADDED TO THE WARNINGS VALID PERIOD. TC 17—79 CONTINUES TO OSCILLATE ABOUT AN OVERALL WEST-NORTHWEST TRACK, HENCE, THE FIX POSITION WAS NOT USED VERBATIM.

BT

*"17—79", 5, 1108, 132, 823, 90, 142, 805, 105, 147, 789, 30, 48

*Extracted information used for model input (*see* text)

further that linear interpolation of probabilities between 3-hour time steps is valid.

(*f*) That probabilities can be summed over time, (*i.e.*, the probability of an event occurring within a 3-hour timestep is the sum of the probabilities at the two end points less the probability of an occurrence at both times), and can be determined from a geometric parameterization of probability along the forecast track (*see* Jarrell 1979).

TABLE 3

Probabilities (%) of cyclone being within various circles displaced to the northwest of the 24 hr forecast position

Circle Radius (km)	Distance of circle centre NW of forecast point: 0 km	185 km	370 km	555 km
93	13–*11*–9.3	7.8–*7.1*–6.5	1.8–*2.1*–2.4	.15–*.29*–.43
185	42–*36*–31	28–*25*–23	8.2–*9.0*–9.6	1.0–*1.6*–2.1

Standard deviations for forecast errors are assumed to be 90%, 100% and 110% of those calculated (probabilities given in italics for 100%)

(*g*) That wind errors and forecast position errors, notwithstanding the landfall case in (*c*) above, are independent.

(*h*) That the shape of the mean wind radial profile is similar to that of Western Pacific typhoons and is related to maximum wind speed.

Validity of Assumptions

The validity of all the foregoing assumptions has not been established herein, nevertheless there is considerable evidence to support most of them.

The concept expressed in assumptions (*a*) and (*b*) have been firmly established in the development of the U.S. Navy Pacific typhoon STRIKP and WINDP progrems (Jarrell 1979). The actual values of the statistical parameters in Table 1 are subject to error. This can reasonably be as great as 10 per cent in the important standard deviations. As an illustrative example of the impact of a 10 per cent error, we estimated the probability that a cyclone, after 24 hours would actually be within circles of radius 93 and 185 km centred on a 24 hr forecast. The probabilities of the cyclone actually being within these circles (where it is supposed to be) were computed at 11 per cent and 36 per cent respectively.

To demonstrate that these are reasonable, we examined the 24 hr forecast errors for 1978 (independent data) for comparison. There were only 28 such forecasts, but of these 14 per cent and 39 per cent actually verified within 93 and 185 km respectively of the 24 hr forecast point. We estimate that *any* point 185 km removed from the forecast point has 2/3 the chance of being struck as does the forecast point and a point 370 km away has 1/5 as great a chance. It is not true (as has been stated) that the forecast point is the safest place to be, but it is also clear that a great many other points are also threatened. *Being able to quantify that threat is the unique capability of this model.*

To simulate the effect of a 10 per cent error in the standard deviations we computed several probabilities using standard deviations of 90 per cent, 100 per cent and 110 per cent of those in Table 1. The probabilities estimated are for a cyclone being within circles of radius 93 and 185 km centred on the forecast point (as before) and removed to the northwest distances of 185, 370 and 555 km. These estimates are given in Table 3.

Of the sets of three numbers given in Table 3, the first is that based on the smaller standard deviations, the second uses standard deviations given in Table 1 and the third is associated with the larger standard deviations. This should give the reader some sense of the limits on the accuracy of our probability estimates. It is doubtful that the uncertainty introduced by imperfect knowledge of the statistical parameters is great enough to be imoprtant for most purposes.

The above simulation also provides some insight into what happens to probabilities when forecast accuracy improves (and the error standard deviations decrease). Those probabilities near the track (distance small) increase while those far from the track (distance large) decrease. For perfect forecasting, those along the forecast track would be 1.0 while those far from the track would be zero.

Assumption (*c*) is based upon the author's knowledge of the practicalities of forecasting and is a rather straightforward mechanism for removing a foreseeable bias.

Assumptions (*d*) and (*e*) are the result of testing and are considered to represent the minimum space and time model resolution without significant distortion of the results. Finer resolution would not materially affect the output, but for purposes other than the present (*e.g.*, storm surge) a finer resolution in both time and space may be required.

The validity of assumption (*f*), time summation, has been thoroughly demonstrated in the U.S. Navy models, over a wide range of probabilities and circumstances.

The validity of assumption (*g*), independence of position and wind forecast errors is supported by the small correlation coefficients between them in Table 1. Assumpion (*h*) is perhaps the weakest of the attendent assumptions. Unlike the Atlantic and North Pacific, there are virtually no real wind measurements available in and around the Bay of Bengal cyclones. For this reason there is little choice but to assume a maximum wind determined profile. Maximum wind itself is likewise not measured, but is estimated from satellite imagery. Since maximum wind is treated as a random variable (about the forecast) then too is the wind profile. There is little doubt that real data could improve this aspect, and hence the wind probability estimates in general. The absence of this data however is a more serious problem with deterministic forecasts since they do not anticipate inaccuracies in this or any other forecasts.

Output

The wind threat output is in two forms, an area-threat form and a point threat form. These are illustrated for cyclone 17-79 from 0800 GMT 11 May 1979 in Fig. 1.

Darkness — For planning purposes a simple darkness scale has been included in the output (*see* Fig. 1). This defines darkness as after 1800 and before 0600 LST and uses a -6 time zone. Each print position represents two hours.

Area Threat — The area threat is provided to serve the alerting function of government where certain preparatory actions can be taken even before the actual location of a disaster can be pinpointed. Here the threat of 20, 33 and 50 m/s winds now and within 12, 24, 36 and 48 hours is provided. For example in Fig. 1 the 48-hour threat of 33 m/s wind to Andhra Pradesh is 0.528. This can be read as "The probability of at least 33 ms^{-1} winds being observed at some point on the Andhra Pradesh coast between 0800 GMT 11 May and 0800 GMT 13 May is estimated to be 53 per cent."

The reason for the selection of 20, 33 and 50 m/s winds are these:

20 m/s — This is the point where it becomes extremely difficult to perform outdoor tasks, hence when 20 ms^{-1} winds arrive any physical preparations that will be required should be completed.

33 m/s — Aside from being the definition of hurricane force winds, significant wind damage begins to occur and storm surge first begins to be a problem at this level.

50 m/s—Under ordinary circumstances, winds in excess of 50 m/s can signal a major disaster. The intent here is to treat the probability of winds in excess of 50 m/s as the probability of a major disaster occurring. Obviously there are a great many other contributing factors but this is a satisfactory first approximation.

Point Threat — The wind threat to a point is handled somewhat arbitrarily in a way which combines the level of the threat with the urgency of that threat. The threat used here is the probability of winds of at least 33 m/s. To avoid confusion with established warning/watch/readiness conditions in use in parts of the world a system of colour codes is used. Red represents the greatest, and the most imminent, threat and green represents a more remote threat, with orange and yellow in between. The definitions used herein are as follow :

Symbol	*Colour*	*33 ms^{-1}*	*Time*
R	Red	⩾ 20%	24 hours
O	Orange	⩾ 10%	36 hours
Y	Yellow	⩾ 5%	48 hours
G	Green	⩾2·5%	48 hours
*	None	⩽2·5%	No limitations

These are illustrated for points on the Bay in Fig. 1 for cyclone 17-79 on 11 May 1979 at 0800 GMT.

4. Summary

The concept of cyclone wind threat estimation was introduced as a means to allow for all the interacting types of forecast error. The basis for such estimates is the past history of errors relative to the forecast. The history used is that of the United States Joint Typhoon Warning Center, Guam, Mariana Islands from its Bay of Bengal cyclone forecasts 1971-1977. The model which uses this historical data is available through the United States Agency for International Development (USAID), and would require rather minor modification to use forecasts from sources other than Guam. The model is computer based, but has rather modest time and memory requirements so that it could be operated on a desk top system.

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