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SIMULATION AND ANALYSIS OF A TROPICAL CYCLONE WARNING SYSTEM.(U)
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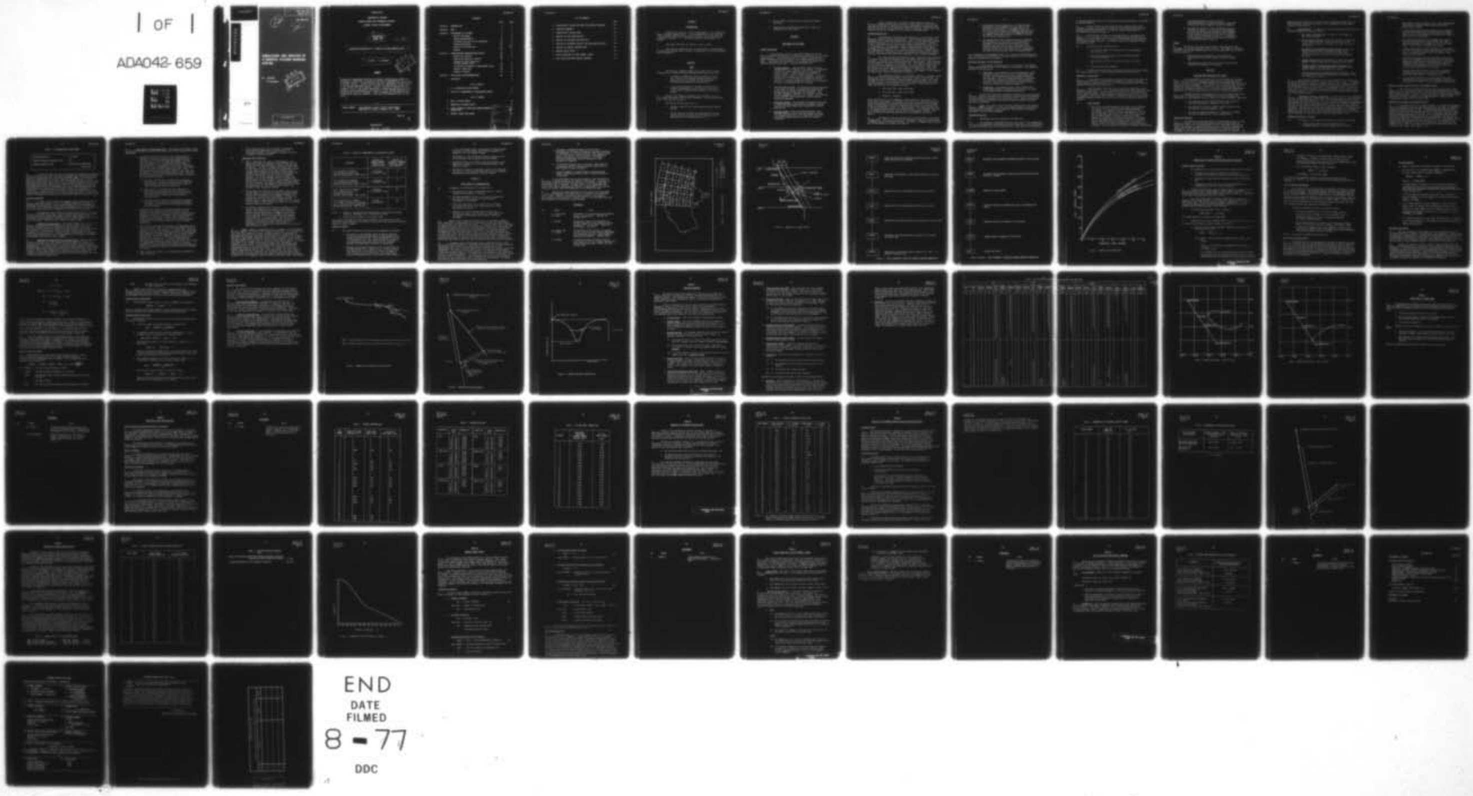

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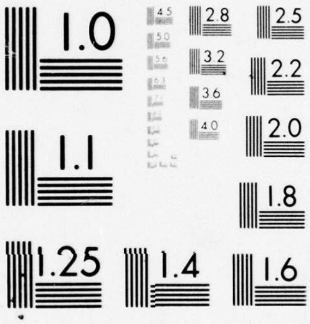
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SIMULATION AND ANALYSIS OF A TROPICAL CYCLONE WARNING SYSTEM

By J.W. Moll
A.J. Donohoe

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SIMULATION AND ANALYSIS OF A TROPICAL CYCLONE WARNING SYSTEM

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J. W. Moll A.J. Donohoe

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SUMMARY

An empirical mathematical model of the Tropical Cyclone Warning System was developed to investigate the potential benefits of improvement to the cyclone measurement system. It was found that the model indicated little sensitivity in warning 'quality' (defined in broad terms) to improvements in some aspects of the cyclone observation system. Despite this lack of sensitivity, the assumption of U.S. cost figures applicable to communities affected by cyclones produces a result favourable to participation in the Japanese Geostationary Meteorological Satellite program. Areas of weakness in the model have been identified as requiring attention in any continuing program of work in this field.

POSTAL ADDRESS: Superintendent, Central Studies Establishment
Department of Defence, Canberra, A.C.T. 2600.

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SECTION 1

INTRODUCTION

1. Reference [1] reported a study of improvements to the Queensland Tropical Cyclone Warning Service. One recommendation of that study was 'that a detailed study should be carried out of the costs resulting from a community receiving ...... inaccurate warning of the approach of a cyclone.'

2. This report describes the results of such a study.

3. The study was conducted under the sponsorship of the Department of Science and Consumer Affairs and was co-ordinated by the Cyclone Research Steering Committee.

SECTION 2

AIMS

4. The Steering Committee agreed that a study of the economic consequences of inaccurate cyclone warnings should have as its aims:

   a. to develop a methodology that can be used to relate the accuracy of the cyclone prediction system to the degree of effective warning the system provides to the community throughout the cyclone area;

   b. to use this methodology to examine the implications of potential improvements in the prediction accuracies on the level of effectiveness achieved in the warnings issued.

5. However, the Committee recognised the formidable nature of such a study and agreed that CSE should undertake a 'pilot investigation' as the first part of the study.

6. The aims of the CSE study were to:

   a. develop a model of the cyclone observation and warning system;

   b. use the model to determine the improvement in warning quality (accuracy, warning time etc) brought about by improvements in the observation system;

c. use the model to assess costs of inaccurate cyclone forecasts;

d. identify those areas where further work or data are required for the main study.

SECTION 3

DEVELOPMENT OF THE MODEL

General Philosophy

7. It was decided at CSE that the model required to meet the first of the above aims should be a computerised simulation of the cyclone warning system. This simulation had to be capable of representing a number of different aspects related to the cyclone warning system as a whole. Each aspect was considered to be a separate sub-model of the complete warning system model. They are described here:

a. Cyclone Dynamics. This sub-model simulates cyclone variables which are relevant to the study. The variables include the cyclone position, speed of movement and central pressure. When required, this sub-model produces 'true' values for these variables. It must be stressed that the model was to be completely empirical, based solely on the statistical behaviour of previous cyclones. Detailed climatology could not be incorporated because this information was not available.

b. The Observation System. The observation system represented in the model is limited to observations involving the cyclone position, motion and central pressure. This sub-model generates 'observed' or 'estimated' values of these parameters from the 'true' values. The 'observed' values represent those available to the forecasters issuing the warnings.

c. Prediction System. This sub-model represents the process of predicting future cyclone motion, landfall, central pressure and surge height (where appropriate) from the observations.

d. Warnings Issued. From the predictions above, this sub-model generates gale, storm and landfall warnings for appropriate sections of the Queensland coast and a storm surge height prediction is made for landfall situations.

8. Since the model was to be based on the behaviour of previous cyclones, appropriate statistical data from a small sample of these cyclones was gathered and used to develop the necessary probability distributions from which the stochastic cyclone parameters could be simulated. Annex A gives the technical details of the model, but an outline is described below.

System Representation

9. The geographical setting for the simulation is an extension of the Queensland tropical cyclone warning region. The area considered ranged from longitude 135°E to 165°E and latitude 5°S to 30°S. Some of this area includes the mainland and not all of it is in fact used in the simulation. However it was a convenient area for division into 30 grid squares (GS), each of size 5° of latitude by 5° of longitude. Figure 1 shows the grid squares which encompass the geographical setting. Those variables which are considered to have dependence on location, e.g. cyclone positioning errors, cyclone central pressure estimates and motional errors, are analysed and simulated on a GS by GS basis, thus effectively preserving something of their location dependency.

10. For study purposes the Queensland coast, regarded as most vulnerable to cyclones, was taken as extending from a latitude of 15°S (just north of Cooktown) to latitude 25°S (between Bundaberg and Maryborough). This coastline was represented in the model as a straight line. Two lines were drawn parallel to this 'coast' to seawards at distances of 100 to 50 n miles. These lines were used to define Gale and Storm warnings as described later. The 'coast' was divided into twenty segments each spanning 0.5 degrees of latitude and warnings were issued to the appropriate segments. Each segment is approximately 35 n miles long. Figure 2 illustrates the geometry.

11. Each simulation provided, at six-hourly intervals, a forecast of the position and central pressure which a cyclone will attain 12 hours hence. By extrapolation from the predicted track and speed of the cyclone, the position and time at which it will cross the 100 n mile coastline parallel, 50 n mile coastline parallel or the coastline can be calculated. These positions and times form the basis for warnings as follows:

a. 100 n mile line - gale force winds

b. 50 n mile line - storm force winds

c. coastline - landfall.

Actual cyclones vary in the diameters of their gale force (34 kn) and storm force (50 kn) wind bands. To represent this variation in the model would have required the gathering of further data and greater complication in the model. Bureau of Meteorology officers had suggested that radii of 50 n mile and 100 n mile were reasonably 'typical' for storm and gale force winds and hence all of the simulated cyclones had these characteristics. It is contended that this is a reasonable approximation for the present investigative purposes. More detail concerning the warnings generated by the simulation is given in Annex B.

12. The length of the coast issued with cyclone warnings is termed the 'warning zone'. The size of this zone in the model is taken as a whole number of segments each of 0.5 degrees latitude. The number of segments comprising the zone is determined by the sum of two factors:

a. the radius of cyclone influence - viz. 100 n miles or approximately three segments north and south of the predicted cyclone centre for the gale warning zone; 50 n miles or approximately two segments north and south of the predicted cyclone centre for storm warning zone; the segment containing the predicted landfall position for the landfall warning zone;

b. the possible error due to position forecast inaccuracy - this contribution to the size of the warning zone is determined by the expected time before the cyclone influences the coast and the time coefficient (β) of position inaccuracy (in the basic situation as derived from the cyclone data, this coefficient is approximately 10 n miles for each forecast hour to cyclone arrival).

In the analyses to be described in para. 36 et seq. the contribution due to para. 12.b above will be modified to be more consistent with the prediction inaccuracies produced with the model.

Structure and Logic of the Simulation

13. In this section a description of the structure of the computer program and the logical flow of the simulation is presented. The simulation consists of two main parts:

a. First Part. This simulates the true movement and central pressure variations of the cyclone. It generates, from the true cyclone parameters and appropriate stochastic distributions, a set of estimated parameters to represent the 'observed' parameters available to the forecaster. Finally it develops a cyclone motion and central pressure prediction using these estimated parameters;

b. Second Part. This generates gale, storm, landfall and storm surge warnings for appropriate sections of the coast as determined from the simulated predictions.

14. Because the information potentially available from these generated warnings is diverse, different output quantities and statistics are developed for the different investigations to be described later. Annex B illustrates the basic information available from which the more specialised statistics used later are derived.

15. Logic. The logical flow of the main subroutines of the computer program is shown in Figure 3. An executive program controls the calling of the subroutines and updates time as required. The sequence of events is described in the following paragraphs.

Program Description

16. The program starts by reading the relevant data.

17. The procedures, described in Annex A, that occur at the commencement of the cyclone simulation (establishing the starting position, starting direction and speed of movement etc.) are then carried out. This advances the simulation

to the point where the first set of predictions and hence warnings, if required, are issued (Annex B).

18. Time is updated by three hours and the program executes those procedures in Annex A which produce subsequent true, estimated and predicted positions and central pressures. If required, cyclone surge height is calculated by the method in Annex C.

19. The procedures of para. 18 are repeated but at alternative time updates (i.e. at six hourly intervals), simulated warnings are generated for segments of the Queensland coast if necessary and previous warnings cancelled if no longer relevant (Annex B). The times of issue or cancelling of these warnings are stored.

20. The above process continues until:

a. the cyclone crosses the Queensland coast as represented in the model; or

b. the cyclone goes outside the area of interest defined by the grid squares; or

c. an estimated position is outside the area of the grid; or

d. 100 hours have been simulated.

21. The whole process may then be repeated to simulate further cyclones, with results appropriate to the investigation being printed (Annex B).

Analysis of Cyclone Data

22. It was stated in the previous section that actual cyclone data was analysed for such inputs to the simulation program as cyclone positioning errors, speeds, central pressures etc. This section describes these data and shows how the analyses were carried out.

23. Below the words 'true' and 'actual' are used to describe cyclone parameters. The 'actual' or 'true' cyclone parameters are those produced by the Bureau of Meteorology in a post-cyclone analysis, when all the relevant data can be readily reviewed. These parameters represent the best estimate of the true history of the cyclone and can differ considerably from the corresponding parameters estimated during the life of the cyclone when observations may be sketchy.

24. Data Analysed.

a. The bulk of the data analysed was obtained for the previous CSE cyclone study [1] and hence was readily available to the authors. It consists of data on the tracks of 23 of the cyclones which occurred off the Queensland coast in the period from March 1964 to May 1972. For each cyclone data were provided showing the actual position and central pressure as measured at three hourly intervals. For about 20% of these measurements estimates and 12 hour predictions, made by the Tropical Cyclone warning centre, of position, central pressure and speed of movement of cyclones were also available. As it was gathered hurriedly by manually transcribing from issued warnings, the scope and the comprehensiveness of the data are limited. Data from [2] were also used to augment the above information.

b. The method of analysis of the true position data is described in Annex D. The analysis of the estimated position data is described in Annex E, while analysis of the predicted position data and speed of cyclone movement data is described in Annex F. A description of the analysis of the data on the central pressure of the cyclones is given in Annex G.

Summary

25. The first of the aims stated in para. 6 has been met by the development of the model described in this Section. This model as presently developed, has some shortcomings which will be discussed later, but it served the dual purpose of:

a. demonstrating the feasibility of the approach for analysing cyclone warning systems, (see next section) and

b. highlighting the areas that will require special effort in any future extension of this work.

SECTION 4

INVESTIGATIONS UNDERTAKEN AND RESULTS

26. The investigations using the model can be divided into two broad types. The first series of investigations was aimed at determining how the overall 'quality' of cyclone warnings changed when improvements were made to the observation system performance. The 'quality' of a cyclone warning is a multi-dimensional concept involving for example the amount of warning time, the accuracy of the predicted effects etc. A means was devised which would permit comparisons to be made between observation systems of different capability.

27. Whereas the above investigations were of an exploratory nature the second type of investigation to be attempted concentrated on potential improvements in some important specific aspects of cyclone warnings. These were:

a. the occurrence of false alarms defined as the receipt of unnecessary warnings by segments of the coast;

b. the occurrence of 'hit-not warned' events, defined as the non-issue of a required warning; and

c. the error in predicted landfall as a function of forecast time and the implications on the 'warning zone'.

Sensitivity Analysis

28. To establish the relative quality of the warnings issued a scoring system was devised. This system (described in Annex H) awards points in proportion to how 'poor' the warning was; that is, the larger the score the 'worse' the warning. A sensitivity analysis was carried out to determine if improvements to the observation system contributed to improvement in the components of the score representing the various dimensions of 'quality'. The

results are mainly from the 'two point' model of prediction rather than the 'multiple point' smoothed model (Annex A), but essentially the two models produced the same results.

29. Scoring System. In summary the scoring system awards points for the following dimensions of warning 'quality':

a. The length of warning time - the shorter the warning the more points allotted.

b. The accuracy of warning - points are allotted in proportion to the temporal error in arrival and the error in the predicted surge height, if relevant (i.e. Eqns [2] and [7] of Annex H).

c. The warning is withdrawn when still required - points are awarded in proportion to the length of time between withdrawal and time of arrival of the cyclone and in inverse proportion to the length of time the warning was in effect.

d. Warning required but not issued (i.e. a 'hit - not warned' event) - a single fixed score is allotted if this occurs.

e. Warning issued but not required and not withdrawn (i.e. a false alarm) - a single fixed score is allotted if this occurs; the score is less than for d. above.

f. Warning issued but not required and later withdrawn - points are allotted in this case proportional to the length of time the warning was in effect.

30. Each simulation segment of the coast situated in the warning zone is awarded appropriate scores on the above basis for each cyclone. Furthermore, the scores are weighted according to whether gale, storm or landfall warnings (in increasing order of severity) happen to be appropriate, and the total of each of the above scores is obtained for each simulated cyclone. The six score (para. 29 a.-f.) totals represent a quantitative estimate on an ordinal scale of warning 'quality' for each cyclone (see Annex H for a more complete description of the scoring system).

31. Sensitivity Analysis - Procedure. A set of scores for the sensitivity analysis was obtained from a simulation of 200 cyclones using statistics derived from the original Queensland data. (Note that only approximately half of these 200 cyclones came sufficiently near the coast to require warnings to be generated.) This set will be referred to hereafter as the 'basic' set. A similar number of cyclones, with different observation errors were then simulated and the scores calculated. The two sets of scores were compared by means of a Mann-Whitney test (Annex H) to determine if there was any statistically significant difference between the two; if there was a difference the sum and mean of the scores were used to determine if this difference represented improvement or not.

Sensitivity Analysis - Results

32. The results of the sensitivity analysis revealed the following:

a. although improvements to the observation system (through reduction of the observation errors) produced improvements to warning quality, few of these improvements were found to be statistically significant for the cyclone sample tested;

b. of those improvements that were significant the change of false alarm rate with size of warning zone was the most sensitive (as the warning zone was decreased the number of false alarms also decreased);

c. when the warning zone was at its minimum (i.e. equal to the influencing diameter of the cyclone) there was no significant increase in the number of 'hit - not warned' events. (This result is somewhat surprising);

d. eliminating position and speed estimation errors reduced the 'hit - not warned' events significantly but only if the size of the warning zone and hence the number of false alarms was kept constant;

e. reducing the estimation errors within 100 n miles of the coast (as is possible with radar observations) produced no significant improvements in warning quality. (It must be remembered that the scores are derived from simulated forecasts made throughout the life of the cyclone - not just over any small portion of its path);

f. equating observation system errors to those currently attainable in the US [3, 4], see Table 1, produced no significant improvements in warning quality;

g. no significant difference in warning quality was found between scores derived using the 'two-point' method or the 'multiple-point' method of cyclone prediction (see Annex A).

Analysis of False Alarms and 'Hit - Not Warned' Events

33. The sensitivity analysis showed an inter-reaction between 'false alarms' and 'hit - not warned' events as warning system parameters are varied. Because these two types of events are two of the most serious results of cyclone forecasting inaccuracies they were investigated further. Annex I summarises the results for the basic situation (i.e. using parameters derived from the 23 Queensland cyclones and from Coleman [2]).

Sensitivity to Changes in Observation Errors

34. The sensitivity of the results in Annex I to changes in positioning errors was examined by repeating the simulations with the errors in estimated position halved and also put to zero. No significant difference was found between the occurrence rates of false alarms in either case with half or zero positioning errors and the original case. This is consistent with the result from the scoring investigation. For the 'hit - not warned' events the only significant difference was detected when the positioning errors were put to zero and the difference occurred only in the landfall 'hit - not warned' events. In the latter case the occurrence rate was 3.0 ± 0.3 (i.e. between 2 and 4) segments per 100 cyclones (cf. 4.8 ± 0.5 segments per 100 cyclones for the original case). Again this agrees with the previously described sensitivity analysis on the scores. (See subpara. 32.b.).

Table 1. US OBSERVATION SYSTEM ERRORS

Positioning Error	=	13 n miles
Central Pressure Estimation Error	=	3 mb
Speed Estimation Errors	=	Not available (Australian Data used)

35. It should be noted that one of the reasons the significant difference could be detected in the 'hit - not warned' landfall case with zero errors was that such a large number of cyclones were simulated (1866). In practice this number of cyclones would occur over a period of around 400 years. In any short-term study period, say 10 years, this difference would not appear as being significant because only about 40 to 60 cyclones would be expected to occur in the Queensland tropical cyclone region. Also, it is impossible to reduce the positioning error to zero in actual practice, because the pinpointing of the cyclone centre from observation will always be subject to some degree of uncertainty. It can be concluded that, for all practical purposes, the model indicates false alarms and 'hit - not warned' events, measured in terms of their rates of occurrence, are insensitive to reductions solely in positioning errors.

Landfall Prediction

36. A further statistic which was examined using the model was that of landfall prediction accuracy. This is a parameter particularly relevant in determining the effectiveness of the warning system since it encompasses the most severe threat situation arising from an impending cyclone - the passage of the cyclone sufficiently near to communities to cause severe destruction.

37. Improvements to the observation system should result in increasing accuracy for landfall predictions. This investigation was designed to examine the sensitivity of the predicted landfall errors to improvements in the observation system quantified by decreases in the cyclone position and velocity estimation errors. Comparison with a similar US study is made.

38. Landfall Error Definition. For forecast times of 6, 12, 18, 24 and 30 hours, the distance between predicted and actual landfall position was extracted from many runs of the simulation. The root-mean-square (RMS) of these errors was calculated to provide a suitable statistic for landfall error as a function of forecast time. Note that these forecast times are not necessarily the actual times to landfall because of inaccuracies in estimated cyclone speed and direction, e.g. a nominal forecast of six hours to landfall may eventuate as 20 hours to actual landfall.

39. Dependence of Landfall Error on Forecast Time. Figure 4 shows the variation of the RMS error with time for the basic situation in which the cyclone positioning errors were derived from the original data collected in Queensland [1]. All results shown are derived from the 'two point' prediction unsmoothed model rather than the 'multiple point' smoothed model (Annex A) since the latter showed little difference in results for the basic case. Also shown on Figure 4 are the RMS landfall errors calculated by the model when the estimated cyclone position errors are reduced to half and one-quarter of those of the basic situation respectively.

40. Implications for Queensland Coast. The implication of Figure 4 will be discussed in terms of evacuation operations which may be initiated in coastal communities:

a. The present evacuation plans for major centres such as Townsville, Mackay etc. require a final implementation of the plans at 6 hours before expected landfall. We can note from Figure 4 that the model RMS landfall error for six hour forecasts (not necessarily six hour-to-go to actual landfall) is approximately 100 n miles. This means that 85% of cyclone landfalls will occur within ±150 n miles of the six hours predicted landfall position. In the following analysis the predicted landfall, ±150 n miles will be assumed as the six hour landfall warning zone. This may well be an overestimate of the warning zone used in practice for the following reasons:

   (1) The model uses the data collected for the original study [1] which noted the possibility that these data may represent a pessimistic view of the accuracy of today's Queensland cyclone predictions.

   (2) Specifically, no allowance has been made for the radar chain covering the coast out to 100 miles or more which would be expected to significantly reduce the landfall error associated with the shorter forecast periods.

   (3) The model does not represent the essentially dynamic situation of the forecaster having varying degrees of confidence in the forecast and adjusting the warning areas accordingly.

b. Without trying to refine this analysis beyond the level dictated by the quality of the model results, one can postulate from Coleman [2] that an average of eight cyclones crossed each 60 miles of Queensland coast (from Cooktown to Brisbane) in the 30 years to 1969. This translates to 0.0045 cyclones/mile/year. This value will also be used as an estimate of the average frequency of cyclone landfall predictions.

c. Since Figure 4 indicates approximately 10% improvement in the six hour forecast landfall error when the estimated position errors are halved, this implies a 2 x (10% of 150) = 30 n mile decrease in the six hour warning zone would still maintain the 85% probability of communities subject to the actual landfall being warned. Hence each community would be subject to an average of 30 x 0.0045 = 0.135 fewer warnings per year or one warning in seven years. It is also calculated that arbitrarily decreasing the warning zone 30 n miles (i.e. without any improvement to the observation system) in the given situation of the nominal 150 n mile warning zone increases the chance of an unwarned community being affected by the landfall by around 4%.

d. Table 2 shows the results of the same analysis performed in other situations.

e. The 12 hour forecasts will be relevant to evacuation of much greater populations in future years; US evacuation procedures are presently initiated at 18 hour or longer to expected landfall.

41. Comparison with US Results

a. Table 2 shows that the effect of improvements to the observation system, as measured by the decrease in false alarms, is small when expressed in terms of forecast time to landfall. In order to compare the present model with results from a US source [4] (which are expressed in terms of true time-to-landfall rather than forecast time-to-landfall) some results were extracted from the model runs specifically relating to a true 12 hour to landfall forecast. The cyclone movement velocity estimate was assumed to be its true movement velocity in these runs. Unfortunately, because the model is not designed to express results in terms of true time-to-landfall the sample size for this particular investigation is smaller than for those described above, but the results shown in Table 2 are believed to have reasonable validity.

b. The US results [4] indicate that the RMS 12 hour forecast landfall position error with the basic positioning errors we have used as appropriate to Queensland should be 127 n miles (cf. 180 n miles from our model). Halving these positioning errors in the US model produces an RMS landfall error of approximately 60 n miles (cf. 132 n miles from our model). Table 2 shows the results of the landfall analysis using the US figures.

c. The absolute landfall errors are not as important to this study as the sensitivity to changes in the observation system. Both analyses which use true time-to-landfall indicate greater sensitivity to changes in positioning errors than the analysis with our model using forecast time-to-landfall. But the US model indicates greater sensitivity than our present model. Yet in operational terms it is the forecast time-to-landfall which would determine the warning zone and it would seem that improvement to the observation system should be justifiable from this point of view.

42. Costs. Table 2 expresses the effect of changes to the observation system in terms of the effect on the landfall warning zone. It is desirable to cost this effect (benefit) in order to compare the cost of improving the observation system with the benefit derived therefrom. Unfortunately costs associated with warnings applicable to Australian conditions are not available. However, a rough benefit costing is given in Annex J using US derived costs; the applicability of these costs to Australian conditions is unknown. It may be noted that if the assumed values given in Annex J were applicable to the Queensland coast, or were to overestimate these costs, the maximum annual benefit found (for 12 hour time-to-landfall from the US model) would be considerably below the annual running costs of a squadron of specialised weather reconnaissance aircraft [1]. On the same basis, the annual benefits shown in Annex J are all comparable with or greater than the annual costs associated with receiving data from the Japanese Geostationary Meteorological Satellite [1], even assuming a satellite life of only three years; note however

Table 2. EFFECTS OF IMPROVEMENTS TO OBSERVATION SYSTEM

SITUATION	DECREASE IN AVERAGE WARNING FREQUENCY FOR A GIVEN LOCATION	INCREASE IN CHANCE OF WARNING NOT BEING ISSUED WHEN REQUIRED[1]
6 hr forecast to landfall. Estd. position error halved. (Nominal Warning Zone ≃ 300 n miles)	0.135/year ≃ 1 Warning/7 years	4%
12 hr forecast to landfall. Estd. position error halved. (Nominal Warning Zone ≃ 500 n miles)	0.180/year ≃ 1 Warning/5 years	3%
12 hr time-to-go[2] to landfall. Estd. velocity error = 0. Position error halved. (Nominal Warning Zone ≃ 500 n miles)	0.65/year ≃ 2 Warnings/3 years	25%
12 hr time-to-go[2] to landfall. (U.S. Model). Position error halved. (Estd. velocity error presumed zero. Nominal Warning Zone ≃ 380 n miles)	0.9/year ≃ 1 Warning/year	34%

Notes: 1. Relates to situation where warning zone is arbitrarily decreased without an improvement to the observation system.

2. Actual time-to-landfall - not forecast time.

that absolute costing over such a short timescale is unrealistic since the calculated benefits may not accrue within a given three year period, the benefits being only annual averages.

Summary of Results

43. The results derived in this section are summarised as follows:

a. The quality of the warnings issued during the simulated cyclones is relatively insensitive to improvements in the cyclone observation system. Some improvement in the rate of occurrence of 'hit - not warned' events was noticed if the positioning errors were reduced but for practical purposes this improvement would not be significant.

b. Reduction of the positioning errors has a small effect on the RMS landfall error. However, for a six hour forecast this small effect is sufficient to reduce the number of false alarms by one per seven years if the positioning errors are halved with only a 4% increase in the chance of a 'hit - not warned' event. Any attempt to further reduce the number of false alarms significantly increases the number of 'hit - not warned' events.

c. Improvements in the observation system to decrease errors in the forecast time-to-landfall are justifiable.

d. Limitations exist in the model which tend to make it less sensitive to changes in cyclone warning parameters than similar US models.

e. Aircraft for cyclone reconnaissance are not cost effective but such is not the case for participation in the Japanese Geostationary Meteorological Satellite program.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

44. In summary, the conclusions of this paper are:

a. The approach of using a deterministic model to analyse cyclone warning systems is feasible.

b. The model developed for this study needs refinement and more cyclone data is needed if a more vigorous investigation is attempted.

c. Within the limitations of the model cyclone warnings are relatively insensitive to improvements in cyclone observation accuracies.

d. Aircraft for cyclone reconnaissance are not cost effective but such is not the case for participation in the Japanese Geostationary Meteorological Satellite programme.

45. Results from the simulation runs do not, on the whole, indicate great sensitivity to improvements in the observation system (and improvements in positioning of the cyclone in particular). In only one aspect was it possible to compare the model results with a US model and, although it is argued that this particular investigation is not strictly appropriate to practical forecasting/warning operations, the sensitivity of the model in this case was markedly increased, but still less than the US model. One of the main criticisms that has been made of the present study concerns the meagre data base used to develop and apply the model; yet the limited sensitivity of the model to changes in input parameters makes it doubtful that the present model with a more reliable statistical base would produce any firmer conclusions than those already produced.

46. It appears that the methodology used in simulating cyclone tracks and in simulating observations is reasonably satisfactory but the application and methodology could be improved by using statistics derived from a more comprehensive data base. The main problem with the model lies with the prediction methodology; in particular the question arises as to whether the Australian cyclone forecasting process is as unresponsive to improvements in the observation accuracy as the model suggests. If further work is to be done, development of the prediction model is essential - simply gathering more data to provide a better data base for the present model is not considered to be worthwhile. Following are the three main directions future work could take:

a. Gathering a considerable amount of data on the performance of the prediction system in the past may permit the development of a better prediction model along the same lines as the present prediction model. The expectation would be that part of the randomness of the present prediction methodology could be replaced by a more deterministic approach.

b. If sufficient relevant data is available, development of an empirical prediction model along the lines of the US model CLIPER [4] may be possible.

c. Close involvement of a meteorologist in the study may enable a completely different form of prediction model to be developed.

47. It has been learnt that a course similar to that advocated in para. 46.b. is being followed by the Bureau of Meteorology. The Bureau is developing an empirical prediction model which is expected to take some considerable time to complete. In view of this, it is recommended that further work aimed at analysing the benefits of improvement to the cyclone observation system, await the completion of this prediction model.

48. Finally, the results presented in this report have been chosen to assist understanding of the model and to be relevant to a cost-benefit type of study. However, the nature of these results is sufficiently wide-ranging to illustrate that a reliable model of this type might have more general application in disaster relief planning.

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No.	Author	Title
1	R.J. Curnow and J.W. Moll	'Improvement of the Tropical Cyclone Warning Service in Queensland'. CSE Note 33. October 1974.
2	F. Coleman	'Frequencies, Tracks and Intensities of Tropical Cyclones in the Australian Region, November 1909 to June 1969'. Bureau of Meteorology. July 1971.
3	R.C. Sheets and P. Grieman	'An Evaluation of the Accuracy of Tropical Cyclone Intensities and Locations determined from Satellite Pictures'. NOAA Technical Memorandum ERL WMPO-20. February 1975.
4	C.J. Newman	'A Statistical Study of Tropical Cyclone Positioning Errors with Economic Applications'. National Hurricane Centre, Miami, Florida. January 1975.

ARRANGEMENT OF GRID SQUARES

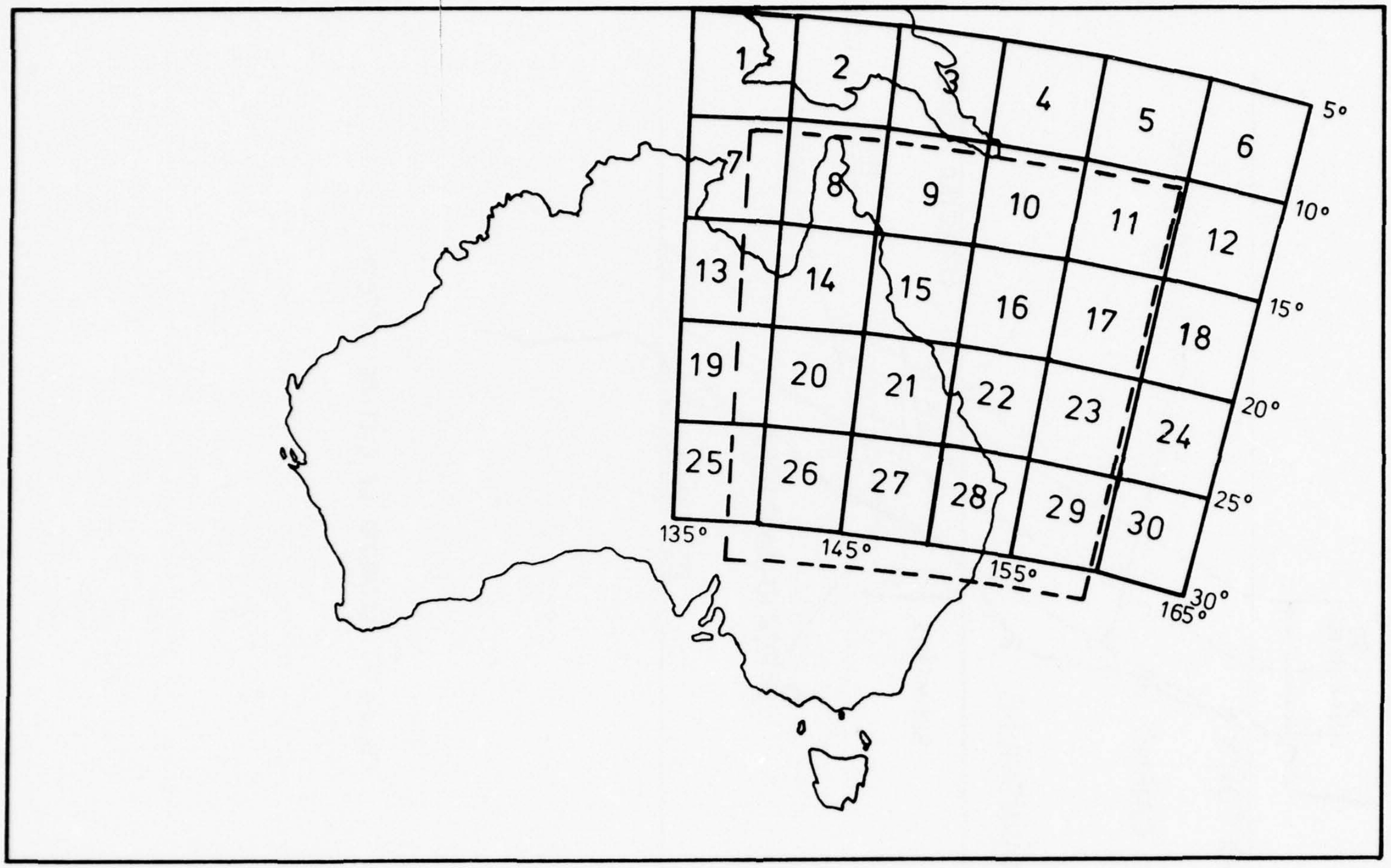


Figure 1. MAP OF CYCLONE REGION

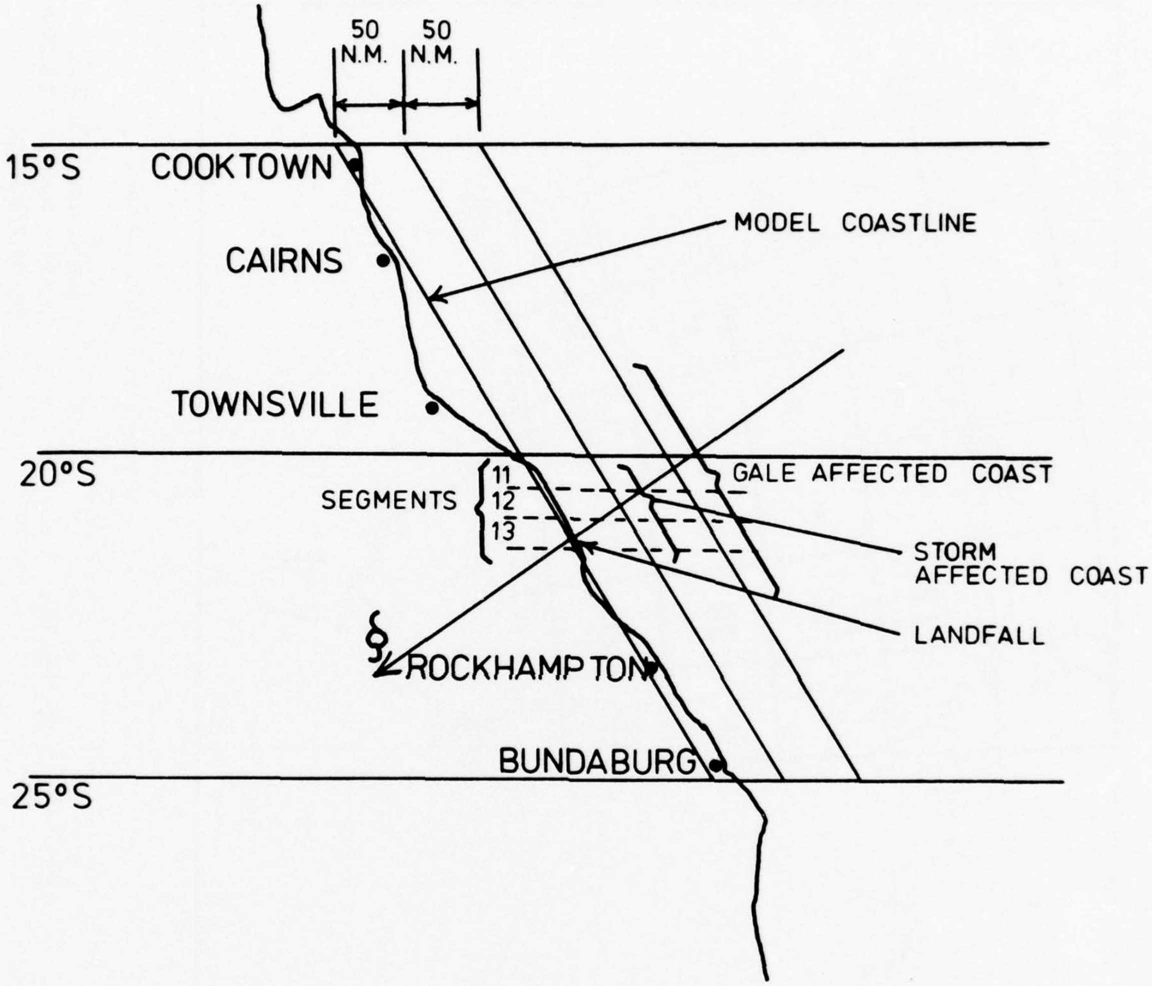
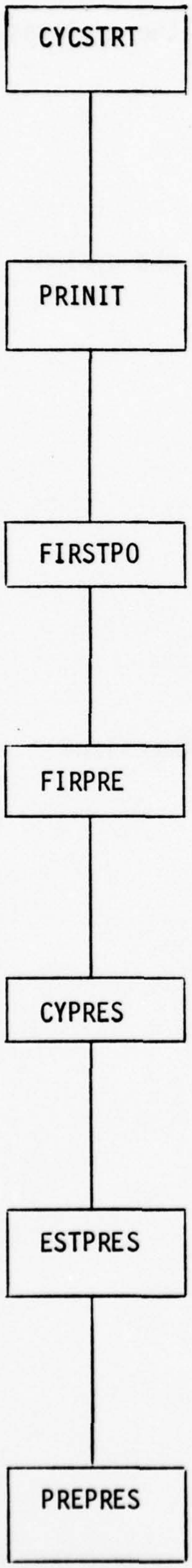


Figure 2. GEOMETRY OF CYCLONE EFFECTS



Starts the cyclone by selecting starting point and initial speed and direction of movement.

Determines the parameter of the central pressure variations with time.

Determines the first estimated position of the cyclone.

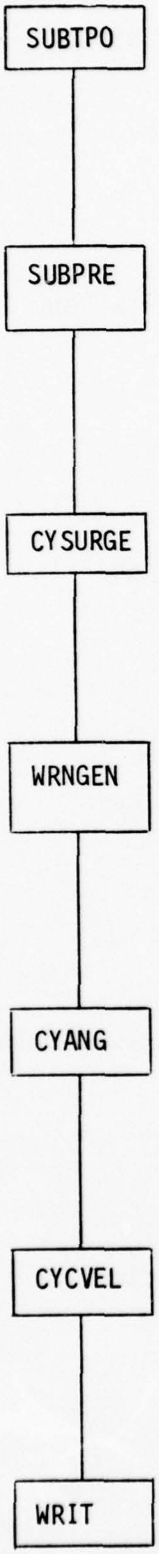
Determines the first predicted position of the cyclone.

Determines the central pressure of the cyclone at present time.

Determines the estimated central pressure of the cyclone at present time.

Determines the predicted central pressure at a time t in advance of present time.

Figure 3. LOGIC DIAGRAM OF SIMULATION SHOWING COMPUTER SUBROUTINES



SUBTPO	Determines the subsequent estimated positions of the cyclones.
SUBPRE	Determines the subsequent predicted positions of the cyclone at time t ahead.
CYSURGE	Determines surge heights.
WRNGEN	Generates warnings to appropriate parts of the Queensland coast.
CYANG	Updates direction of movement of the cyclone.
CYCVEL	Updates speed of movement of the cyclone.
WRIT	Writes the results.

Figure 3 (Contd). LOGIC DIAGRAM OF SIMULATION SHOWING COMPUTER SUBROUTINES

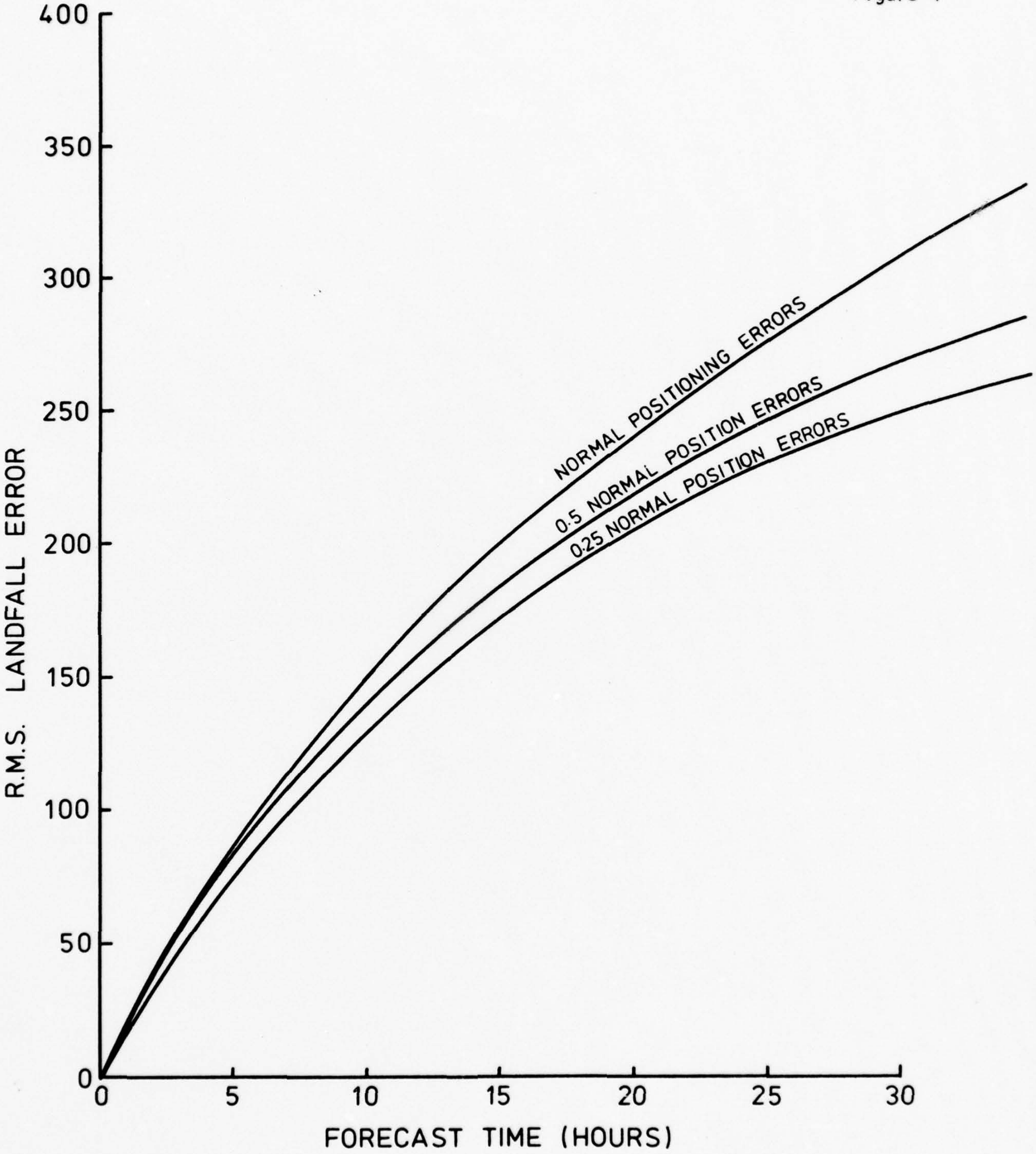


Figure 4. LANDFALL PREDICTION ERRORS

Annex A

SIMULATION OF CYCLONE POSITIONS AND CENTRAL PRESSURES

Cyclone Position (Actual)

1. The simulation of the actual motion of the cyclone centre involves:

   a. defining a start position and direction of motion; positions are expressed in terms of latitude and longtitude;

   b. updating the cyclone centre's position at 3-hourly intervals; and

   c. redefining, at each time step, the speed and direction of movement during the next 3-hourly interval.

2. Expressed symbolically, the grid square (Figure 1 of main text) in which the cyclone starts, START SQUARE, is sampled from an empirical distribution and a position START POINT chosen randomly within it. START POINT is the first simulated position of the cyclone.

3. The initial direction of movement, START DIRN, is obtained by sampling from a Normal distribution with mean and standard deviation derived from actual data. The initial speed of movement, START SPEED, is then obtained by sampling from a direction-dependent probability distribution derived from recorded velocities of past cyclones.

4. The second true position is then a distance

$$\text{START SPEED} \times 3.0 \text{ (hours)}$$

from START POINT in the direction of START DIRN.

5. Subsequently, any true position $TPOSN_i$ of the cyclone at time step i, is found from the previous position $TPOSN_{i-1}$ as follows:

   a. Firstly the direction of movement (measured anticlockwise with East as zero) is found:

$$DIRN_i = DIRN_{i-1} + \Delta_i$$

where $DIRN_i$ is the direction of movement between $TPOSN_{i-1}$ and $TPOSN_i$,

$DIRN_{i-1}$ is the direction of movement between $TPOSN_{i-2}$ and $TPOSN_{i-1}$; and

Δ_i is sampled from an autocorrelated time series of Normal variates with mean and standard deviation themselves chosen stochastically prior to the start of each cyclone simulation.

b. Secondly, the speed of cyclone movement, $SPEED_i$, whilst moving from $TPOSN_{i-1}$ to $TPOSN_i$ is sampled from the same direction dependent distribution that was used to define START SPEED, except that subsequent speeds are autocorrelated.

c. The true position $TPOSN_i$ is then a distance

$$SPEED_i \times 3.0 \text{ (hours)}$$

from $TPOSN_{i-1}$ in a direction $DIRN_i$.

All positions are defined in terms of a Cartesian Co-ordinate system of longitude and latitude. No account is taken of earth curvature in the area of interest.

Cyclone Position (Estimated)

6. The actual or true cyclone position is generally not known accurately at the time of forecast. The estimated position on which the forecast is based must therefore be derived. The distance between the first estimated position, $EPOSN_1$, and START POINT is obtained by sampling from a grid-dependent Rayleigh distribution with parameters derived from the collected cyclone data. The first estimated position lies on a line which is at an angle, $EANG_1$, to START DIRN. $EANG_1$ is found by sampling from a grid-dependent Normal distribution with mean and standard deviation also found from cyclone data.

7. Subsequent estimated positions are found as follows:

a. The distance between the true position, $TPOSN_i$, and the estimated position, $EPOSN_i$, is a distance $EDIST_i$ which is obtained by sampling from the grid-dependent Rayleigh distribution mentioned above.

b. The estimated position is located in the direction defined by $EANG_i$ to the direction defined by $TPOSN_{i-1}$ and $TPOSN_i$. $EANG_i$ is obtained by sampling from a grid-dependent autocorrelated time series of Normal variates with means and standard deviations obtained from analysis of actual cyclones.

Figure 1 illustrates the geometry described here.

Cyclone Position (Predicted)

8. Two methods have been investigated for finding the predicted position. The first developed uses the last two estimated positions to define a speed and direction to project ahead in time whereas the second method uses a number of estimated positions with smoothing to define the projection speed and direction. Both methods are described below. As discussed in the main text neither method is particularly satisfactory primarily because track curvature is not adequately represented in deriving forecast position. Time has precluded an adequate development of this sub-model.

9. Two Point Method

a. Figure 2 illustrates the geometry relevant to this section.

b. At time step i the estimated speed $ESPEED_i$ is obtained from the true cyclone speed of movement ($SPEED_i$) by:

$$ESPEED_i = SPEED_i + \Delta_i$$

where Δ_i = ERROR $SPEED_i$

an ERROR $SPEED_i$ is obtained by an autocorrelated sampling of grid-dependent Normal distributions whose means and standard deviations were obtained by analysing the observed velocity errors in the cyclone data.

c. A 12 hour predicted reference point, REF PT_i is located at a distance $ESPEED_i$ x 12.0 from $EPOSN_i$ in the direction defined by $EPOSN_{i-1}$ and $EPOSN_i$.

d. The 12 hour predicted position $PPOSN_i(12)$ is then a distance $PDIST_i$ (which is sampled from a Rayleigh distribution) from REF PT_i at an angle $PANG_i$ (which is obtained by autocorrelated sampling from a Normal distribution) to the direction defined by $EPOSN_{i-1}$ and $EPOSN_i$.

e. The predicted position for any other forecast period T, $PPOSN_i(T)$, is a distance $ESPEED_i$ x T from $EPOSN_i$ in the direction defined by $EPOSN_i$ and $PPOSN_i(12)$.

Multiple Point Method

10. The main advantage of this method is that it allows more than two estimated positions to influence the projection. The projection is based on what is effectively a smoothed fit to a number of estimated positions. Any estimated position that is excessively in error tends not to have such a marked influence on the location of the predicted position. This method is restricted to use when there are two or more estimated positions on which to base the projection.

11. Overall this method is similar to that of the two point projection method. The difference lies in the way the 12 hour predicted reference point is determined. In this method the latitudinal and longitudinal co-ordinates of the estimated positions are considered to be independent time series. The following recursive formulae which represent a double coefficient smoothing process are used to derive a straight line approximation to the series of latitude and longitude co-ordinates (formulae for longitudinal components are presented here but similar formulae are used for the latitudinal co-ordinates):

$$L_i = a_i + \bar{b}_i \; t$$

$$\text{where } \bar{a}_i = (1 - \alpha_1)\,\bar{a}_{i-1} + \alpha_1 a_i$$

$$\bar{b}_i = (1 - \alpha_2)\,\bar{b}_{i-1} + \alpha_2 b_i$$

$$b_i = \frac{L_i - L_{i-1}}{t_i - t_{i-1}}$$

$$a_i = \frac{t_i L_{i-1} - t_{i-1} L_i}{t_i - t_{i-1}}$$

and α_1 and α_2 are smoothing constants (between 0 and 1) whose magnitudes in effect determine the degree of smoothing produced (e.g. when $\alpha = 1$ no smoothing results, the coefficients being determined solely by the last two points i, i-1). Note that $\bar{a}_o$ and $\bar{b}_o$ have to be defined; in this simulation $\bar{a}_o$ is taken to be the first estimated longitude or latitude and $\bar{b}_o$ is determined from the first estimated position co-ordinates and the first predicted position co-ordinate. However a_1 and b_1 are determined from the first two estimated positions.

12. Once the projection line has been established the 12 hour reference point is located a distance along it, proportional to either the longitudinal or latitudinal component of the speed of movement of the cyclone; this distance is measured from the last estimated co-ordinates. Once the 12 hour predicted reference point has been determined the 12 hour predicted position and predicted positions for any other forecast time are found in a similar manner to that for the two point projection method described above.

<u>Central Pressure (Actual)</u>

13. Examination of the cyclone data sample indicated that the central pressure histories during the life of a cyclone tended to possess a characteristic time development shown in Figure 3. This characteristic was represented analytically by

$$\text{TPRES(T)} = \text{STPRES} - (\text{STPRES} - \text{MINCP}) \exp \left[-0.69 \left(\frac{\text{T-TMIN}}{\text{HALF}}\right)^2 \right]$$

where TPRES(T) = the true central pressure at time T

STPRES = the base reference pressure of the cyclone

MINCP = the minimum central pressure attained during the life of the cyclone

T = the time in hours

TMIN = the time at which the minimum central pressure is attained

HALF = the half width (in hours) at half depth of the variation in central pressure.

14. STPRES, TMIN and HALF are obtained by sampling from Normal distributions with means and standard deviations derived from analysis of the pressure variations of actual cyclones. MINCP is obtained by sampling from an experimental distribution also derived from actual cyclone statistics.

Central Pressure (Estimated)

15. The estimated central pressure at time T, EPRES(T), is found from

$$\text{EPRES(T)} = \text{TPRES(T)} + \Delta$$

where Δ is sampled from a grid-dependent, autocorrelated time series of Normal variates with mean and standard deviation derived from actual data.

Central Pressure (Predicted)

16. The predicted central pressure for any time FT ahead of present time T is found as follows:

a. A rate of change of estimated pressure is defined from

$$\text{RATE} = \frac{\text{EPRES(T)} - \text{EPRES(T-3)}}{3}$$

b. A temporary reference central pressure, TEMP PRESS, at a point in time 12 hours in advance of T, is found from

$$\text{TEMP PRESS} = \text{EPRES(T)} + \text{RATE} \times 12.0$$

c. The predicted pressure at 12 hours ahead of T, PPRES (12), is found from

$$\text{PPRES (12)} = \text{TEMP PRESS} + \Delta$$

where Δ is obtained by sampling from an autocorrelated time series of Normal variates with means and standard deviations derived from actual cyclone prediction error data.

d. The predicted pressure at any other time, FT, is found by firstly calculating an amended rate of pressure change, RATE^1.

$$\text{RATE}^1 = \frac{\text{EPRES(T)} - \text{PPRES (12)}}{12.0}$$

the predicted central pressure at time FT, is then

$$\text{PPRES (FT)} = \text{EPRES(T)} + \text{RATE}^1 \times \text{FT}.$$

(Note that this procedure precludes obtaining a predicted central pressure for the first point of a cyclone).

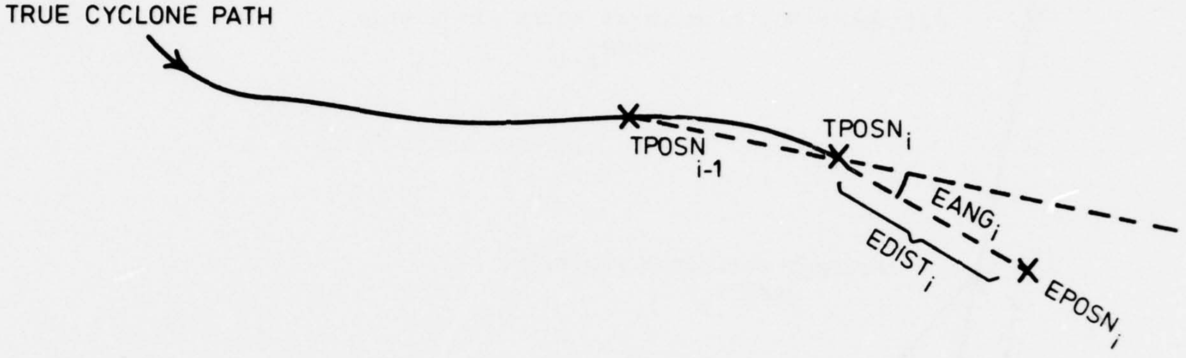
Comments on the Model

17. The model has been presented with little argument or justification for its details. This is in line with the mostly empirical approach taken in this study. The aim was to develop a simulation which would reproduce certain relevant statistical characteristics of previous cyclones and the present model represents a pragmatic approach which appeared to be qualitatively acceptable. Some comments will now be made concerning a few of the aspects of the model.

18. Autocorrelated Variables. In presenting the model the use of autocorrelated random variables is indicated in a number of instances. No analysis was made of the available cyclone data to determine the order of autocorrelation, this being chosen arbitrarily in the simulation to simply provide for 'smooth' fluctuation of certain stochastic parameters. The overall results were not sensitive to the degree of smoothing over a large range.

19. Probability Distributions. Two main forms of distribution were employed; Normal and Rayleigh. Where no particular distribution was expected from the physical nature of the random parameter in question a Normal distribution was fitted to the available data. Some significance tests were performed to verify that the available data was statistically compatible with this distribution. The Rayleigh distribution was used for distance errors, where the quadrature components could be hypothesised to follow a Normal distribution.

20. Position Predictions. In the sub-model for determining the predicted position, a so-called reference point is defined. Its rationale is that the forecaster, having estimations available of cyclone speed, and past and present positions, would predict the position of the cyclone to be at the reference point in 12 hours if he used linear extrapolation - i.e. assumed persistence of straight line motion. In line with the pragmatic approach to the model development it seemed reasonable to analyse the predictions in the data sample in terms of this reference point and to subsequently simulate predictions with respect to this point.



EANG$_i$ - *Angle selected from grid-dependent autocorrelated Normal distribution.*

EDIST$_i$ -*Distance selected from a grid-dependent Rayleigh distribution.*

Figure 1. GEOMETRY OF ESTIMATED CYCLONE POSITION

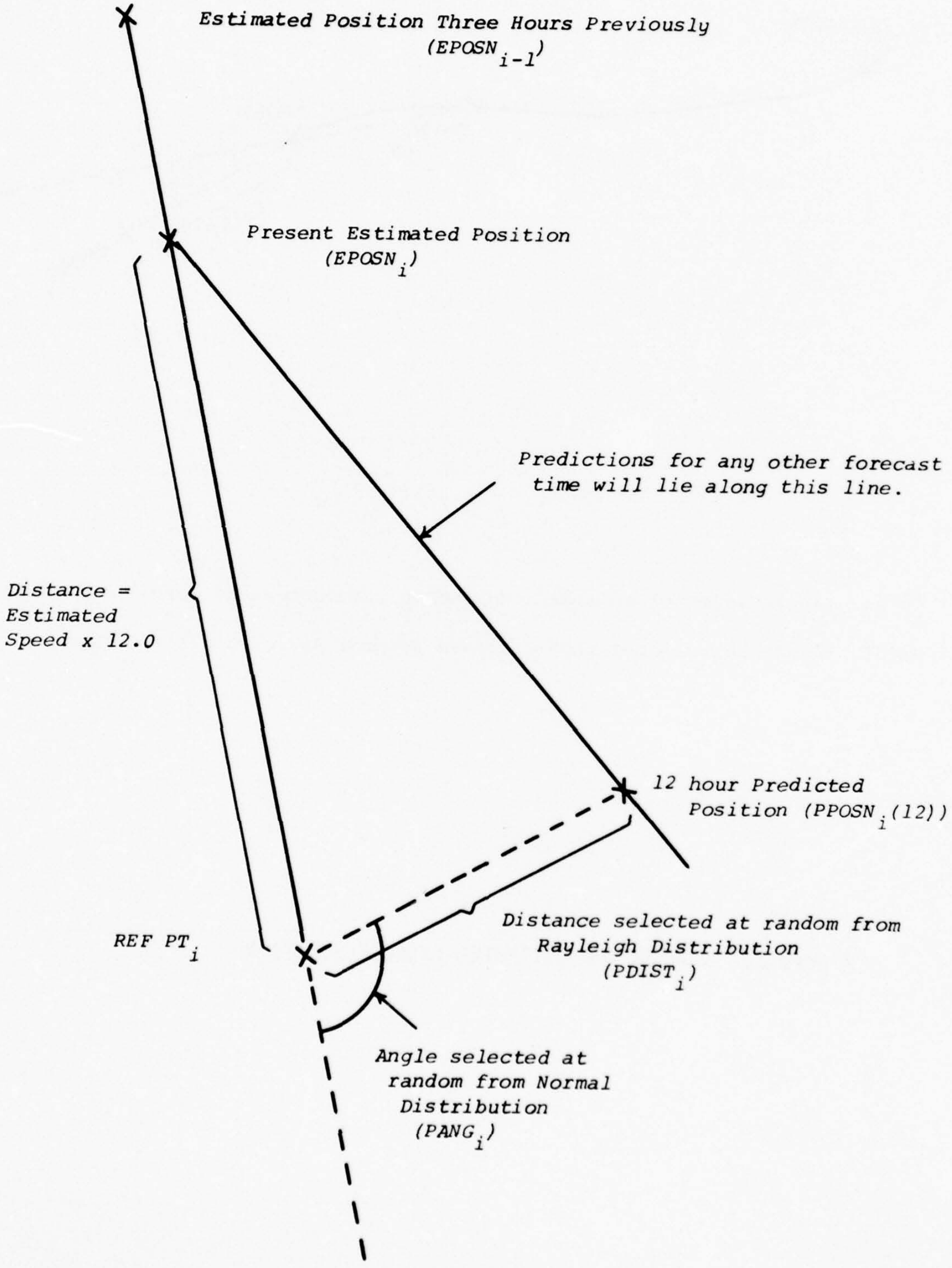


Figure 2. PREDICTED POSITION GEOMETRY

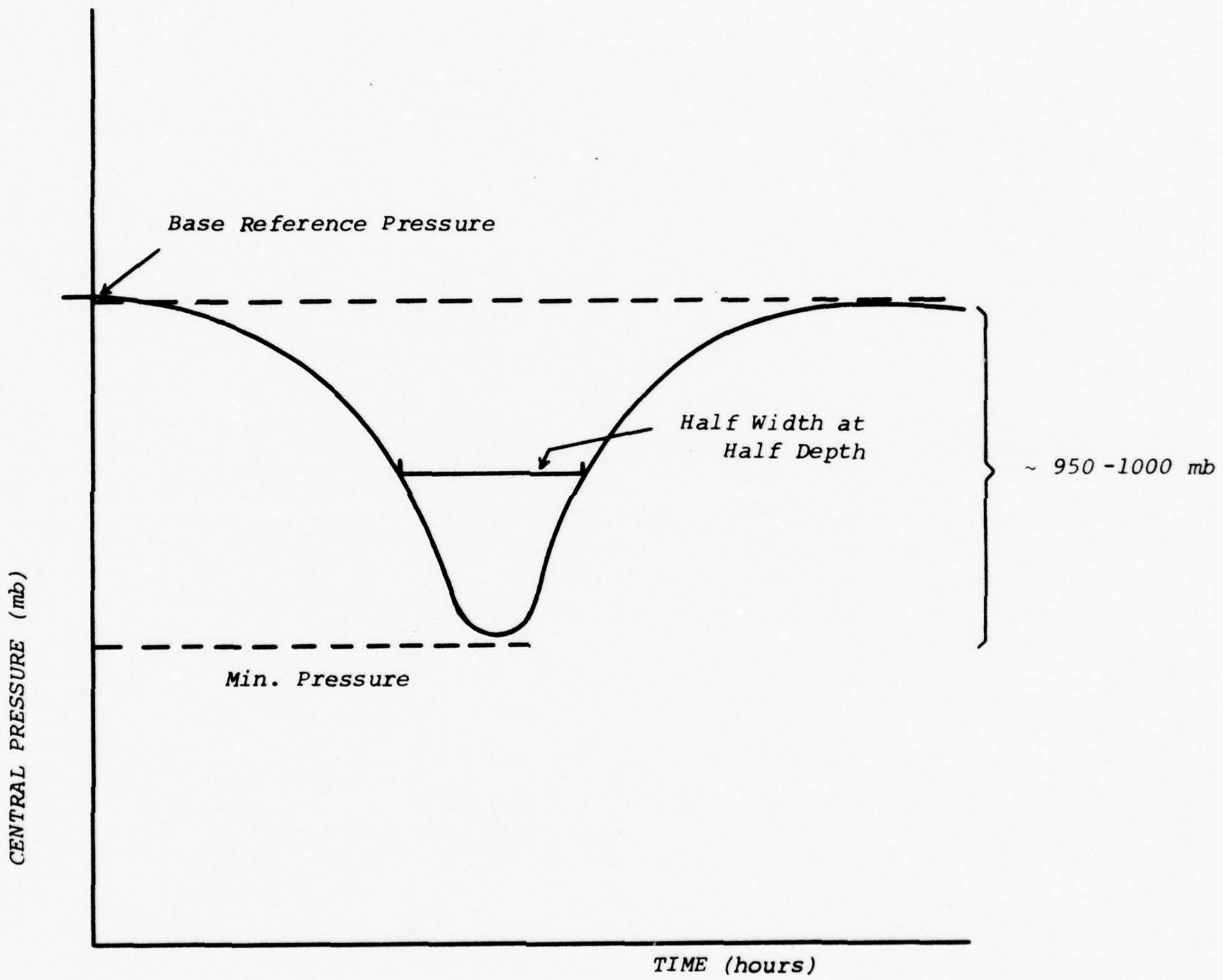


Figure 3. CENTRAL PRESSURE CHARACTERISTIC

Annex B

SIMULATED WARNINGS

1. The approach taken in developing the simulation of warnings was to produce initially a comprehensive summary of warning information for each simulated cyclone. The comprehensive summary, which will be described in this Annex, contains the basic information used in the different investigations described in this report.

2. Table 1 illustrates the type of basic information available from the simulation. Output in this form was not produced for the specific investigations described in this report: Table 1 simply indicates the basic warning information calculated. The information comprising the various columns will be described individually below (to assist the interpretation of Annex H, the variables used in that Annex are indicated where appropriate):

a. Cyclone Number. This is the number of the simulated cyclone.

b. Segment Number. The coastal segments used in the simulation have been described in the main text (Para.10, Figure 2). The twenty segments are numbered sequentially from North to South and the warning information pertinent to each of these segments is given.

c. Warning Required. If a segment required a Gale, Storm or Landfall warning, this is indicated by unity in these columns. As described elsewhere, the criteria are:

(1) if during the life of a cyclone its centre came within 100 n miles of a segment then that segment required a gale warning.

(2) if during the life of a cyclone its centre came within 50 n miles of a segment then that segment required a storm warning.

(3) if cyclone landfall occurred in a particular segment then that segment required a landfall warning.

d. Warning Received. Unity in these columns indicates that gale, storm or landfall warnings as appropriate have been received by a segment (which may or may not have required them, see previous column). This column merely indicates whether a warning was issued for the segment - not how long the warning remained in force.

e. Stated Minimum Warning Time (FWT). When a segment receives a warning, the warning contains information on the time expected before the effects of the cyclone are experienced. This column represents the minimum time a segment was told it would have before the effects would be experienced. It therefore represents the time scale to which the communities situated in the segment should react in taking precautions against the cyclone.

f. Actual Warning Time (TWT). This represents the time a segment requiring and receiving a warning actually has to prepare for the onset of the cyclone's effects. The value is the interval between the time the segment received its first pertinent warning and the onset of the cyclone.

g. Cancelled Warnings. These are warnings issued at some time but not renewed (at a later time) when the segment is no longer expected to suffer the cyclone effects predicted in the warnings. There are two situations to be distinguished.

(1) If the segment did not need a warning it received (because the cyclone effects were not experienced) the value computed (WINRLWS) is the time between its first warning and the time the warning was finally cancelled (i.e. not renewed).

(2) If the segment was affected by the cyclone the value computed is the time between the segment becoming affected and the time the warning had (incorrectly) lapsed.

h. Minimum Predicted Surge (MINSG). A surge prediction is made in conjunction with all landfall warnings. For a particular segment receiving updated landfall warnings the surge predictions are also updated using the latest central pressure information. This column shows, for those segments in receipt of a landfall warning, the minimum surge height value predicted for the segment.

i. Maximum Predicted Surge (MAXSG). As above except the maximum predicted surge height is given.

j. Actual Surge (ACTSG). For those segments which actually experienced cyclone landfall, the associated surge is calculated from the Central Pressure at landfall. These true and predicted surges ignore tides, and depth correction factors (the latter are set to unity).

k. Termination. The code for termination of a simulation run is as follows:

(1) '1' The simulated cyclone passes outside the grid squares.

(2) '2' The estimated cyclone position lies outside the grid squares.

(3) '3' The cyclone has crossed the coast.

(4) '4' A period of 100 hrs has been simulated.

3. Results for two cyclones are shown in Table 1 and discussed below:

a. Cyclone 1. This cyclone did not cross the coast - 100 hrs were simulated (Col. 21 of Table 1). Gale warnings were issued for the whole of the coast being considered (Col.4) and storm and landfall warnings for most of this coast (Cols. 9 and 14). None of the cyclonic effects were actually experienced on the coast and all warnings were cancelled after approximately 50 hrs in force.

Figure 1 which shows the cyclone path relative to the Queensland coast indicates the reason for this warning pattern. The cyclone initially approached the coast, turned and moved parallel to the coast before veering away. Warnings were issued in anticipation of the approach and cancelled when the change in track was confirmed.

b. Cyclone 2. This cyclone crossed the coast in segment 19 (Col. 13) with a surge of 3.4 ft (Col. 20). Segment 19 had received warning requiring precautionary measures to be taken within 27 hrs (Col. 15) but the cyclone crossed the coast 36.7 hrs after the initial warning (Col. 16). Although the segment at some time during the cyclones' progress should have reacted to the 27 hr timescale subsequent warnings may have been issued revising the expected time of landfall to more accurately reflect its true value. These revisions are not noted - only the minimum reaction time given to the communities in the segment is indicated by Col. 15. All the other segments affected by the cyclone received a warning and some segments were unnecessarily warned - and of the last, some warnings were cancelled after some time in operation. Figure 2 illustrates the cyclone's path across the coast.

Table 1. RESULTS FROM TWO CYCLONE SI

		GALE					STORM				
CYCLONE NO.	SEGMENT NO.	WARNING REQUIRED	WARNING RECEIVED	STATED MIN W.TIME	ACTUAL WARNING TIME	CANCELLED WARNINGS	WARNING REQUIRED	WARNING RECEIVED	STATED MIN W.TIME	ACTUAL WARNING TIME	CANCELLED WARNINGS
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	1	0	1	28.6	-	48.0	0	1	30.8	-	36.0
	2	0	1	28.6	-	48.0	0	1	32.0	-	42.0
	3	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	4	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	5	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	6	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	7	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	8	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	9	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	10	0	1	28.6	-	48.0	0	1	32.0	-	48.0
	11	0	1	28.6	-	54.0	0	1	32.0	-	48.0
	12	0	1	28.6	-	54.0	0	1	32.0	-	48.0
	13	0	1	28.6	-	54.0	0	1	32.0	-	48.0
	14	0	1	28.6	-	54.0	0	1	32.0	-	48.0
	15	0	1	28.6	-	54.0	0	1	32.0	-	6.0
	16	0	1	28.6	-	54.0	0	1	32.0	-	6.0
	17	0	1	10.6	-	6.0	0	1	32.0	-	6.0
	18	0	1	10.6	-	6.0	0	0	.0	-	.0
	19	0	1	10.6	-	6.0	0	0	.0	-	.0
	20	0	1	10.6	-	6.0	0	0	.0	-	.0
2	1	0	0	.0	-	.0	0	0	.0	-	.0
	2	0	0	.0	-	.0	0	0	.0	-	.0
	3	0	0	.0	-	.0	0	0	.0	-	.0
	4	0	0	.0	-	.0	0	0	.0	-	.0
	5	0	0	.0	-	.0	0	0	.0	-	.0
	6	0	0	.0	-	.0	0	0	.0	-	.0
	7	0	0	.0	-	.0	0	0	.0	-	.0
	8	0	0	.0	-	.0	0	0	.0	-	.0
	9	0	1	24.6	-	6.0	0	0	.0	-	.0
	10	0	1	24.6	-	6.0	0	1	28.8	-	6.0
	11	0	1	21.5	-	18.0	0	1	28.8	-	6.0
	12	0	1	20.7	-	.0	0	1	28.8	-	6.0
	13	0	1	20.7	-	.0	0	1	23.0	-	.0
	14	0	1	20.7	-	.0	0	1	23.0	-	.0
	15	0	1	20.7	-	.0	0	1	23.0	-	.0
	16	0	1	20.7	-	.0	0	1	23.0	-	.0
	17	1	1	20.7	24.0	.0	0	1	23.0	-	.0
	18	1	1	20.7	24.0	.0	1	1	23.0	36.0	.0
	19	1	1	20.7	24.0	.0	1	1	23.0	36.0	.0
	20	1	1	21.5	24.0	.0	1	1	23.0	36.0	.0

2

Annex B to
CSE Note 42
Table 1

35

TS FROM TWO CYCLONE SIMULATIONS

		LANDFALL								
ACTUAL WARNING TIME (11)	CANCELLED WARNINGS (12)	WARNING REQUIRED (13)	WARNING RECEIVED (14)	STATED MIN W.TIME (15)	ACTUAL WARNING TIME (16)	CANCELLED WARNINGS (17)	MIN PREDICTED SURGE (18)	MAX PREDICTED SURGE (19)	ACTUAL SURGE (20)	RUN COMPLETE INDICATOR (21)
-	36.0	0	1	34.5	-	36.0	7.3	10.4	.0	
-	42.0	0	1	34.5	-	36.0	7.3	10.4	.0	
-	48.0	0	1	34.5	-	36.0	7.3	10.4	.0	
-	48.0	0	1	35.4	-	42.0	.7	10.4	.0	
-	48.0	0	1	35.4	-	42.0	.7	10.4	.0	
-	48.0	0	1	35.4	-	48.0	.2	10.4	.0	
-	48.0	0	1	35.4	-	48.0	.2	10.4	.0	
-	48.0	0	1	35.4	-	48.0	.2	7.3	.0	4
-	48.0	0	1	35.4	-	48.0	.2	7.3	.0	
-	48.0	0	1	35.4	-	48.0	.2	7.3	.0	
-	48.0	0	1	35.4	-	48.0	.2	7.3	.0	
-	48.0	0	1	35.4	-	48.0	.2	7.3	.0	
-	48.0	0	1	35.4	-	48.0	.2	.7	.0	
-	48.0	0	1	35.4	-	48.0	.2	.7	.0	
-	6.0	0	1	35.4	-	48.0	.2	.7	.0	
-	6.0	0	0	.0	-	.0	-	-	.0	
-	6.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	
-	.0	0	0	.0	-	.0	-	-	.0	3
-	6.0	0	0	.0	-	.0	-	-	.0	
-	6.0	0	0	.0	-	.0	-	-	.0	
-	6.0	0	1	32.9	-	6.0	-	-	.0	
-	.0	0	1	32.9	-	6.0	-	-	.0	
-	.0	0	1	32.9	-	6.0	-	-	.0	
-	.0	0	1	25.3	-	36.0	.5	13.9	.0	
-	.0	0	1	25.3	-	36.0	.5	13.9	.0	
-	.0	0	1	25.3	-	.0	.5	13.9	.0	
36.0	.0	0	1	25.3	-	.0	.5	13.9	.0	
36.0	.0	1	1	27.2	36.7	.7	.5	6.6	3.4	
36.0	.0	0	1	27.2	-	36.0	.5	6.6	.0	

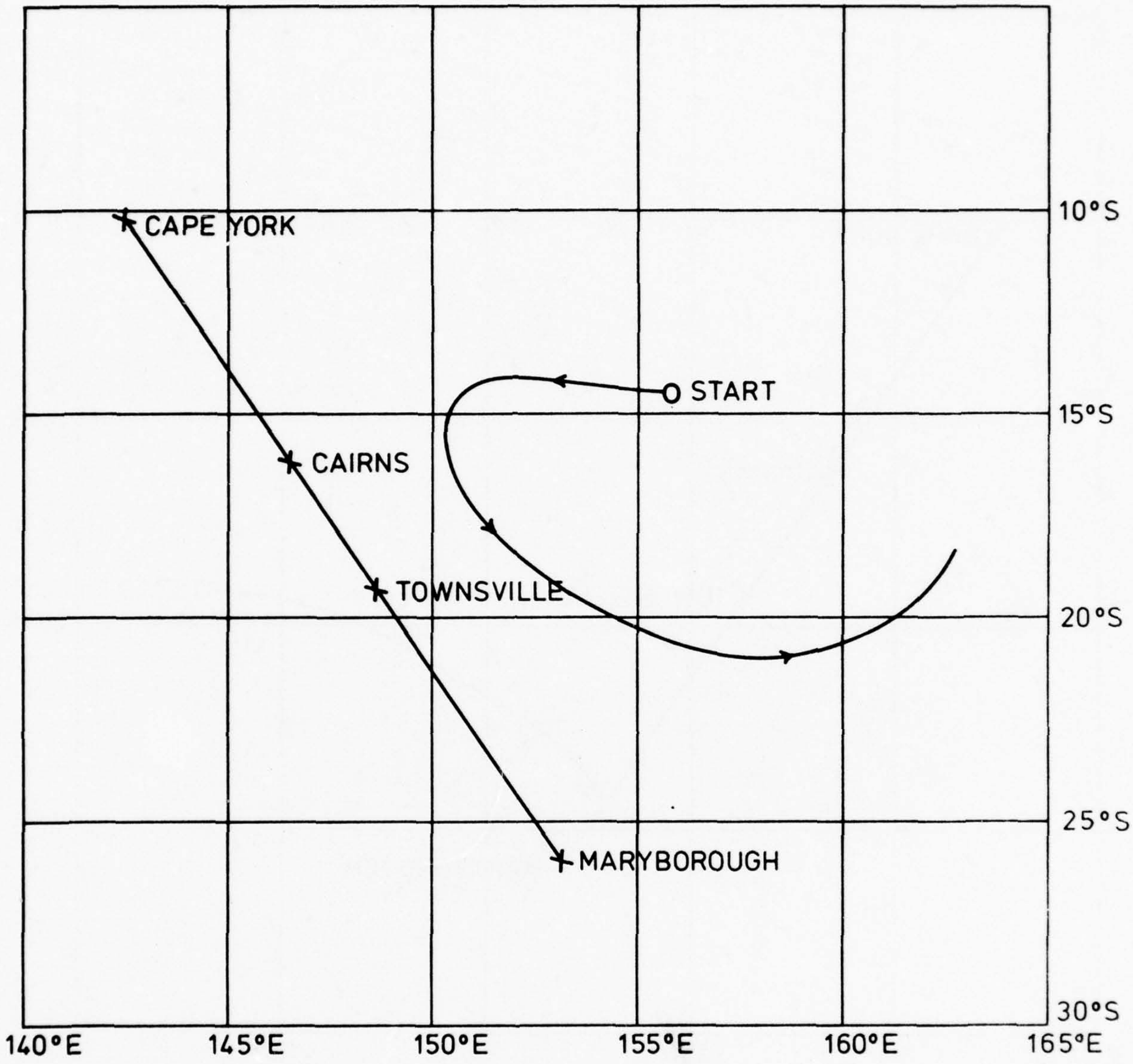


Figure 1. SIMULATED CYCLONE TRACK. TRACK OF CYCLONE 1

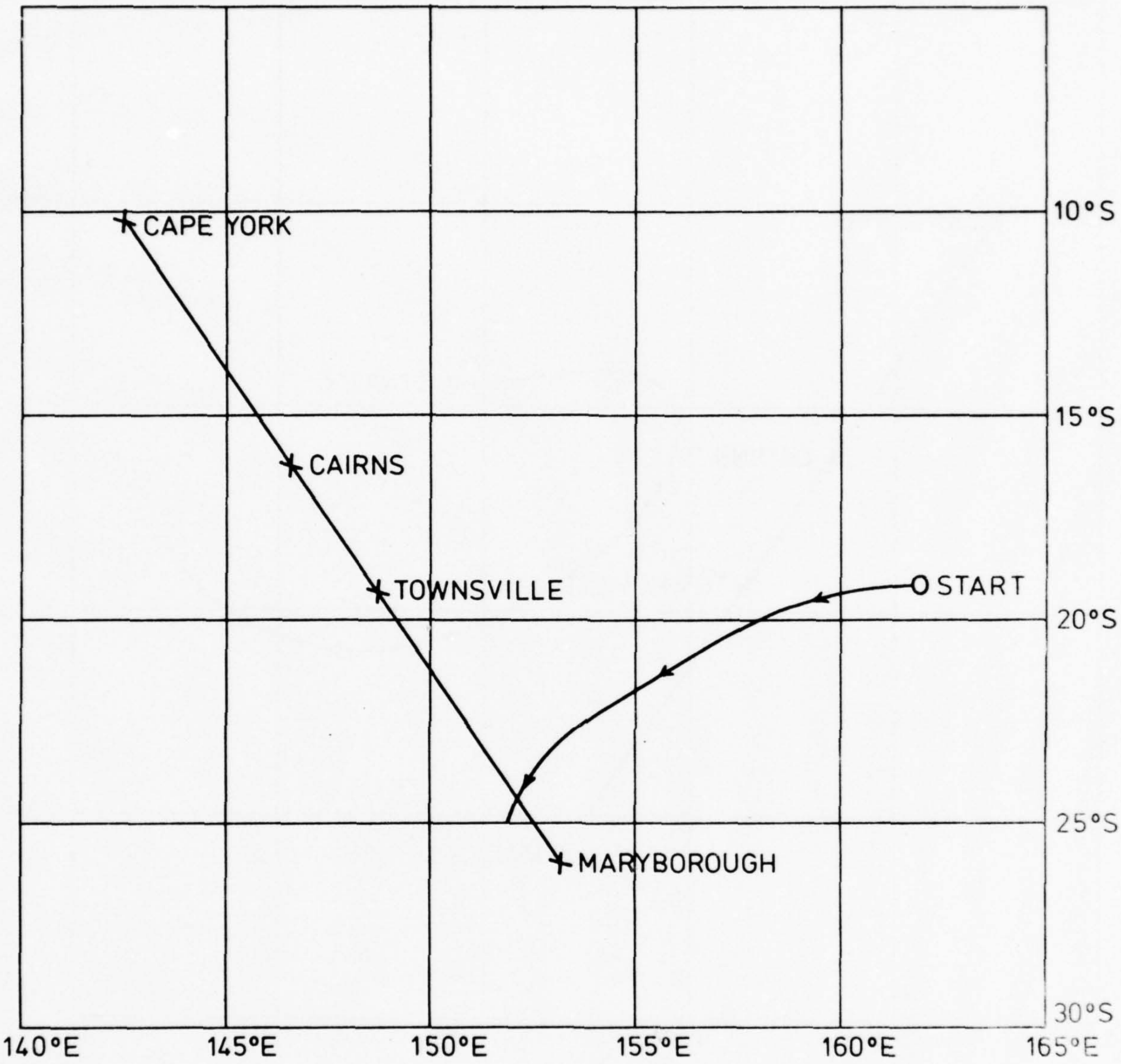


Figure 2. SIMULATED CYCLONE TRACK. TRACK OF CYCLONE 2

Annex C

SIMULATION OF CYCLONE SURGE

1. The method used to simulate the cyclone surge is that of Trajer [1] which is a modification of the simplified method developed by Jelesnianski [2]. For the simulation program developed to date the following assumptions were made:

   a. The depth correction factors are all unity.

   b. Only the surge height at point B (the maximum height attained by the surge along the coast) is calculated.

   c. Tides are not considered.

2. Figure 2 of [1] was converted for use by the computer in the following manner:

   a. The grid in Figure 1 of [1] was further divided into a smaller grid with 4 smaller boxes taking the place of one of the larger.

   b. Any portions of the lines that went through these smaller boxes were given the co-ordinates of the bottom left-hand corner of the box.

Thus the continuous distribution was converted into a discrete one.

REFERENCES

No	Author	Title
1	F.L. Trajer	'A Manual Storm Surge Forecasting Scheme for the Australian Tropics'. Research and Development Division, Bureau of Meteorology.
2	C.P. Jelesnianski	'Special Program to List Amplitude of Surges from Hurricanes'. 1. Landfall Storms. NOAA Tech Memo. NWS TOL-46. April 1972.

Annex D

ANALYSIS OF TRUE POSITION DATA

Start Position and Initial Direction of Movement

1. To obtain appropriate statistics for the start position of cyclones, the grid squares containing the start of all of the tracks shown in Coleman [1] were analysed. Hence for each square the probability that a cyclone would originate in that square was calculated (Table 1) and used to derive the starting squares of the simulated tracks. The actual start positions were randomly chosen within the squares.

2. The statistics of the directions of movement at the origins of the cyclone tracks were analysed from Coleman [1] and followed Normal distributions whose parameters are given in Table 1 for each grid square.

Speed of Movement

3. The speed of movement of the cyclones was analysed from data in Coleman [1]. This reference provides direction - speed roses for actual cyclones. These were converted to speed distributions for each of the 8 major points of the compass; these speed distributions are given in Table 2. Note that these speed distributions were assumed to be independent of the cyclone position, that is, the data were not grouped for each grid square.

Direction of Movement

4. After some preliminary work to find a way of representing the statistical properties of cyclone centre movement it was decided this could most readily be done by considering the change in direction of cyclone movement at each synoptic hour as a stochastic variable.

5. The change in the direction of movement at each synoptic hour was calculated for each of the 23 cyclones and the mean and standard deviation (SD) calculated (Table 3). An assumption was made that the angle change from one synoptic hour to the next is Normally distributed - significance tests did not reject this assumption.

6. The results of Table 3 were manipulated to produce empirical probability distributions which are sampled independently prior to each cyclone simulation to provide the mean and standard deviation of angle change for that cyclone. No correlation between these two parameters is assumed.

7. As an observation it may be noted that the values in Table 3 tended to produce a considerable number of simulated cyclones with a high degree of track curvature. Qualitatively, the number of cyclones produced with such track curvature appeared to be larger than occurs in practice. This reflects the meagre data base used to produce Table 3 (and the other Tables) and a simulation sample more representative of actual cyclone tracks would be achieved if Table 3 were developed from a larger cyclone data base.

REFERENCES

No.	Author	Title
1	F. Coleman	'Frequencies, Tracks and Intensities of Tropical Cyclones in the Australian Region. November 1909 to June 1969'. Bureau of Meteorology Publication. July 1971.

Table 1. CYCLONE STARTING DATA

GRID SQUARE	PROB. OF CYCLONE STARTING IN G.S.	MEAN START ANGLE (rad)	STD DEV OF START ANGLE (rad)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0.018	2.28	0.53
6	0	0	0
7	0	0	0
8	0	0	0
9	0.17	2.16	1.17
10	0.158	2.23	1.02
11	0.1	2.25	1.01
12	0.073	2.59	1.56
13	0	0	0
14	0	0	0
15	0.079	1.75	1.02
16	0.127	2.23	1.24
17	0.067	1.6	0.98
18	0.067	2.31	1.52
19	0	0	0
20	0	0	0
21	0	0	0
22	0.079	1.51	0.71
23	0.036	1.59	0.48
24	0.018	3.18	0.21
25	0	0	0
26	0	0	0
27	0	0	0
28	0	0	0
29	0.006	1.08	0
30	0.006	3.23	0

Table 2. CYCLONE SPEED DATA

DIRECTION	SPEED (kn)	PROBABILITY	DIRECTION	SPEED (kn)	PROBABILITY
EAST	0 - 5	0.16	WEST	0 - 5	0.24
	6 - 10	0.29		6 - 10	0.30
	11 - 15	0.26		11 - 15	0.26
	16 - 20	0.16		16 - 20	0.13
	21 - 25	0.10		21 - 25	0.02
	26 - 30	0.01		26 - 30	0.05
	31 - 35	0.03		31 - 35	
SOUTH EAST	0 - 5	0.16	NORTH WEST	0 - 5	0.22
	6 - 10	0.32		6 - 10	0.37
	11 - 15	0.27		11 - 15	0.25
	16 - 20	0.11		16 - 20	0.05
	21 - 25	0.08		21 - 25	0.11
	26 - 30	0.05		26 - 30	
	31 - 35	0.01		31 - 35	
SOUTH	0 - 5	0.27	NORTH	0 - 5	0.34
	6 - 10	0.42		6 - 10	0.29
	11 - 15	0.79		11 - 15	0.37
	16 - 20	0.10		16 - 20	
	21 - 25	0.01		21 - 25	
	26 - 30	0.01		26 - 30	
	31 - 35			31 - 35	
SOUTH WEST	0 - 5	0.25	NORTH EAST	0 - 5	0.19
	6 - 10	0.47		6 - 10	0.28
	11 - 15	0.18		11 - 15	0.26
	16 - 20	0.10		16 - 20	0.23
	21 - 25			21 - 25	
	26 - 30			26 - 30	0.04
	31 - 35			31 - 35	

Table 3. CYCLONE ANGLE CHANGE DATA

CYCLONE	MEAN ANGLE CHANGE/3HR INTERVAL THROUGH CYCLONE (rad)	S.D. OF ANGLE CHANGE (rad)
1	0.04	0.29
2	-0.01	0.41
3	0.17	0.37
4	-0.02	0.25
5	-0.06	0.20
6	0.07	0.30
7	0.00	0.43
8	0.05	0.31
9	-0.06	0.26
10	0.04	0.18
11	-0.03	0.30
12	0.13	0.65
13	0.09	0.35
14	-0.02	0.57
15	-0.11	0.18
16	-0.06	0.41
17	-0.13	0.14
18	0.04	0.72
19	-0.05	0.38
20	0.08	0.72
21	0.04	0.33
22	-0.01	0.28
23	0.04	0.31

Annex E

ANALYSIS OF ESTIMATED POSITION DATA

1. Errors in the estimation of cyclone location at the time of preparing a forecast form an integral part of the cyclone simulation program. These represent the uncertainties in observation affecting the forecast during the life of a cyclone. Consequently estimation errors used in the cyclone simulation should reflect the practical situation as far as possible.

2. The data for estimated position (i.e. the position of the cyclone as estimated at the time of making a forecast) were analysed to determine a relationship between the estimated positions and the true positions. Two aspects of this relationship were considered:

a. the distance between the true and the estimated positions, and

b. the angle between the direction defined by the true and estimated positions and the true direction of movement of the cyclone at the true position.

3. The means and standard deviations of these distances and angles were found for all the grid squares. The reasoning behind the grouping was that cyclones passing through certain squares may be subject to more accurate observation resulting from improved instrumentation. The distances were postulated to follow a Rayleigh distribution and the angles a Normal distribution about the means; a Kolmogorov-Smirnov test was used to test these hypotheses which were found to be consistent with the available data. Table 1 gives the means and standard deviations mentioned above.

Table 1. CYCLONE ESTIMATED POSITION DATA

GRID SQUARE	MEAN DISTANCE (n miles)	S.D. DISTANCE (n miles)	MEAN ANGLE (rad)	S.D. ANGLE (rad)
1[1]	25.0	14.0	-0.7	1.6
2	9.0	3.0	-0.7	1.8
3	41.6	25.5	-0.67	2.2
4	115.2	33.0	-1.88	2.3
5	72.7	42.0	1.49	2.3
6[1]	50.0	24.0	1.25	1.5
7[1]	25.5	16.0	-0.7	1.5
8[1]	26.0	18.0	-0.7	1.5
9	43.8	34.1	-1.48	1.2
10	94.2	123.8	0.0009	1.9
11	59.8	56.6	-0.2	2.0
12	28.3	6.6	1.07	0.6
13	46.6	32.2	-0.89	2.0
14[1]	47.0	31.0	-0.1	1.9
15	47.8	30.3	0.64	1.8
16	42.0	66.4	-0.17	1.6
17	40.1	31.5	-0.18	2.0
18	52.2	34.1	0.98	1.6
19[1]	36.0	25.0	-0.7	1.8
20[1]	27.0	17.0	-0.5	1.7
21	8.0	2.8	-1.09	1.5
22	25.4	13.8	0.30	1.9
23	59.1	54.4	0.30	1.6
24	64.3	45.3	-0.27	1.6
25[1]	28.0	18.0	-0.5	1.8
26[1]	23.0	12.0	-0.2	1.7
27[1]	20.0	7.0	0.1	1.8
28	32.0	12.8	1.23	2.1
29	56.7	28.9	0.22	1.9
30	56.6	43.2	0.45	0.2

Note: 1. No cyclones in the data sample passed through these grid squares. Hence interpolations were made using the parameters of adjoining squares to estimate appropriate values for these squares.

Annex F

ANALYSIS OF ESTIMATED VELOCITY DATA AND PREDICTED DATA

Estimated Speed

1. Two methods were used to examine the estimated speed of movement of the cyclone. One involved using two consecutive estimated cyclone positions 3 hrs apart to determine a speed. The other analysed the estimated speed directly from the recorded data sample. The results showed that using the 'estimated speed' method produced a smaller mean and standard deviation of the distance between the predicted reference position (see following section) and the actual predicted position than the method using two consecutive estimated positions to obtain the speed. Thus it was decided that the 'estimated speed' method should be used in the proposed simulation. The means and standard deviations of the difference between the true speed and estimated speed of the 23 cyclones were obtained for all the grid squares. These results are shown in Table 1.

Predicted Position

2. An integral part of the cyclone simulation is the prediction of the location of the cyclone at some time in the future; such information is required to enable warnings to be issued. The simulation method derived a predicted position from

a. the estimated speed of movement,

b. the direction defined by two successive estimated positions and

c. a point which is constructed from these two quantities. This point is termed a '12 hour predicted reference point'. (Annex A). The actual predicted position was then defined relative to this reference point by means of error distribution in distance and angle.

3. Direction of movement was derived from the estimated positions at times T and T-3 hours.

4. The estimated speed of movement was used to project ahead to a 12 hour predicted reference point. The direction of projection was that defined in Para. 3 and the length of time over which the projection was made was the forecast time given in the data on the 23 cyclones; note that in general this was 12 hours but sometimes varied by an hour or so, i.e., '12 hour predicted reference point' is somewhat of a misnomer.

5. The 12 hour predicted reference point defined in Para. 4 was then compared with the actual forecast position given in the data on the 23 cyclones. This comparison was made by calculating both the distance between the two positions and the angle between the line joining the two positions and the direction of movement defined in Para. 3. The geometry of the situation is shown in Figure 1.

6. The analysis produced means and standard deviations of the distance and angle between the two positions defined in Para. 5. In this case the

results were not grouped into boxes because the errors in prediction were assumed to be the same, irrespective of the location of the cyclone. The results are shown in Table 2. In the simulation the actual data was grouped into an empirical distribution which was sampled for the predicted distance error; this obviated the use of an assumed distribution. However the angle data was compared with a Normal distribution and found not to differ significantly; hence a Normal distribution was used in the simulations.

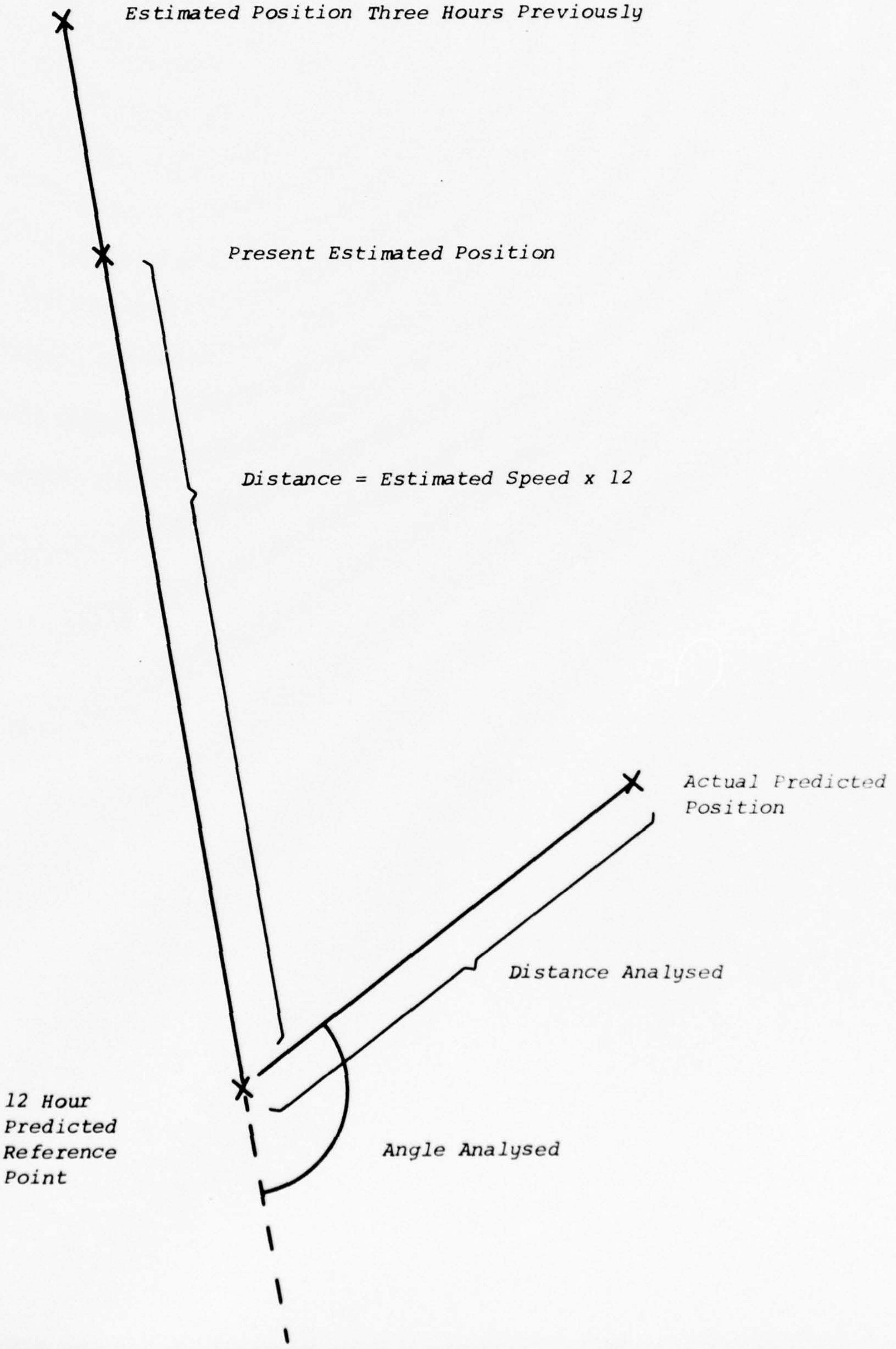
Table 1. PARAMETERS OF ESTIMATED VELOCITY ERROR

GRID SQUARE	MEAN ABS ERROR (kn)	S.D. OF ERROR (kn)
1	0.5	1.8
2	0.5	0.5
3	1.0	3.2
4	2.0	2.3
5	8.0	1.4
6	2.5	1.5
7	0.2	1.4
8	0.9	1.0
9	1.3	1.6
10	1.2	3.5
11	0.6	2.5
12	2.5	1.5
13	2.0	0.8
14	1.1	1.7
15	0.2	2.6
16	0.1	3.8
17	1.1	3.2
18	1.0	3.0
19	1.4	1.1
20	0.8	1.4
21	0.7	1.2
22	0.6	2.1
23	2.1	2.5
24	1.2	2.5
25	1.0	1.6
26	0.6	2.1
27	0.4	2.8
28	0.2	4.5
29	0.7	5.7
30	4.0	3.0

Table 2. PARAMETERS OF PREDICTED POSITIONS

ADOPTED METHOD OF SIMULATION[1]	DISTANCE FROM REF. POINT TO PREDICTED POS'N (n miles)	ANGLE OF PREDICTED POS'N AT REF. POINT (rad)
ESTIMATED SPEED DATA TWO POINT PROJECTION	45.9 ± 62.9	0.08 ± 1.90
MULTIPLE POINT PROJECTION	42.6 ± 36.0	-0.1 ± 1.83

1. See Annex A.



GEOMETRY OF ANALYSIS OF PREDICTED POSITION

Annex G

ANALYSIS OF CENTRAL PRESSURE DATA

1. Originally it was considered that the central pressure variations during the life of a cyclone could be simulated by selecting the starting pressure and then effecting changes to this pressure by random, though biased, increments that depended on the grid square in which the cyclone was located. To this end the means and standard deviations of the changes of central pressure at each three hourly intervals were found for the 23 data cyclones. These data were grouped into the grid squares.

2. However, it was realised that such a simulation technique could produce unrealistic central pressures if the changes over a period of time became biased in one direction. For example, if the random fluctuations in pressure were all positive then central pressures over 1,050 mb for example might arise if no constraints are employed. Consequently it was decided that a method not dependent on random variations, rather than a 'constrained' random method, would be used to generate cyclone central pressure. The chosen method was based on the observation that the central pressure variations during the life of a cyclone could be represented by a curve in the form of an inverted Normal distribution whose characteristic parameters (depth, half width at half depth, location of the minimum and the reference base) would be set for each cyclone (see Figure 3 to Annex A).

3. The 23 data base cyclones were analysed to obtain the means and standard deviations of the reference pressure base, (i.e., the maximum central pressure of the cyclone recorded during its life), the minimum central pressures attained during the life of the cyclone, the half width of the curve at half depth and the time at which the minimum central pressure occurred after the commencement of the cyclone. The results are shown in Table 1 and Figure 1.

4. The simulation also requires a method of representing estimated pressures. To establish this the data were analysed to obtain the mean and standard deviation of the difference between the true and estimated central pressure for the cyclones aggregated in each grid square. These results are shown in Table 2.

5. The predictions of central pressure are made in the simulation in a similar manner to that for predicted positions (see Annex A). To this end the data were analysed by determining the time rate of change of pressure from two consecutive estimated values of central pressure and this rate used to determine a reference predicted pressure at a time corresponding to the forecast period. The mean and standard deviation of the difference between this reference predicted pressure and the actual predicted pressure at this forecast time were then found. This quantity was not resolved into the grid squares because it was considered that the accuracy of such predictions would be independent of the location of the cyclone. These results are shown in Table 3.

Table 1. CHARACTERISTICS OF THE PRESSURE CURVE

Mean of Base Pressure = 1000.5 mb, STD DEV = 3.4 mb
Mean of Time to Min. Pressure = 93.6 hrs, STD DEV = 83.4 hrs
Mean of Half Width at Half Depth = 46.8 hrs, STD DEV = 33.3 hrs

Table 2. CYCLONE ESTIMATED CENTRAL PRESSURE ERROR DATA

GRID SQUARE	MEAN CENTRAL PRESSURE ERROR (mb)	S.D. OF CENTRAL PRESSURE ERROR (mb)
1	-3.0	10.0
2	-1.0	2.0
3	8.0	23.4
4	1.0	13.0
5	-2.6	3.2
6	-2.0	3.0
7	-2.0	6.0
8	-2.5	5.5
9	-4.7	3.6
10	0.2	12.1
11	1.5	8.5
12	-1.0	3.0
13	-1.0	2.7
14	-4.0	9.0
15	-7.1	16.9
16	-3.0	9.8
17	-1.5	6.1
18	-0.3	4.5
19	-4.5	4.0
20	-8.0	5.0
21	-11.7	1.7
22	-8.7	11.2
23	-0.6	2.7
24	5.8	7.4
25	-7.0	4.0
26	-8.5	4.0
27	-9.0	2.0
28	-5.7	2.7
29	-2.1	4.4
30	5.0	5.0

Table 3. CYCLONE PREDICTED PRESSURE DATA

Mean of the Pressure Difference between Reference Predicted Pressure and Actual Predicted Pressure = 0.2 mb

Standard Deviation of this Pressure Difference = 12.1 mb

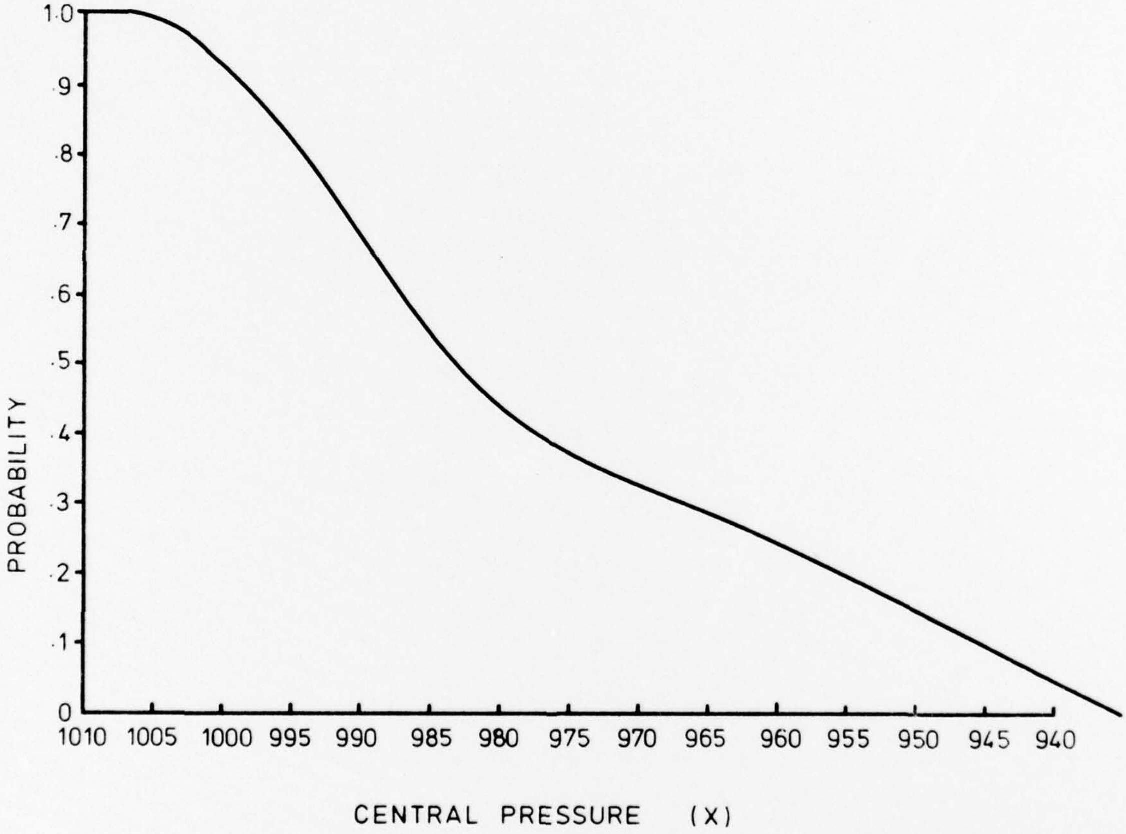


Figure 1. PROBABILITY THAT MIN CENTRAL PRESSURE < X

Annex H

WARNING SCORE SYSTEM

1. The intention of the scoring system is to provide numerical values (scores) for the dimensions which comprise warning 'quality'. This results in an ordinal scale on which the various 'quality' dimensions of a warning issued to a coastal segment can be ranked from 'high' quality to 'low' quality. Statistical tests as described were used to check whether ranks of different samples are significantly different.

2. The scores allotted to various aspects of the warning process are quite arbitrary. However they are based on an intuitive order of ranking; for example, a landfall warning error is assumed to be four times more serious than a gale warning error and a storm warning error is twice as serious as a gale warning error. No attempt is made to relate the different 'quality' dimensions, and hence the need to judge the relative importance of these dimensions disappears. It is only within each 'quality' dimension that the need exists for intuitive judgement concerning the rankings of the individual components of that dimension.

'Measures of Quality'

3. For each coastal segment appropriate scores are allotted as described below; more detail on the variables is given in Annex B.

a. Length of Warning

$$LWS = 40 \exp(-TWT/20) \qquad (1)$$

where LWS = length of warning score

TWT = true warning time

b. Accuracy of Arrival

$$AAS = ABS\ (FWT - TWT) \qquad (2)$$

where AAS = accuracy of arrival score, and

FWT = minimum forecast warning time.

(ABS means absolute value)

c. Warning Withdrawn But Still Required

$$WWSRS = 40(1 - \exp(-(TA-TWR)/(TWT-(TA-TWR)))) \qquad (3)$$

where WWSRS = warning withdrawn but still required score,

TWR = time the warning was withdrawn, and

TA = time of arrival.

d. Warning Required But Not Issued

$$WRNIS = 40 \quad (4)$$

where WRNIS = warning required but not issued score.

e. Warning Issued But Not Required and Not Withdrawn

$$WINRNWS = 20 \quad (5)$$

where WINRNWS = warning issued but not required and not withdrawn score.

f. Warning Issued But Not Required and Later Withdrawn

$$WINRLWS = TWR - TWI \quad (6)$$

where WINRLWS = warning issued but not required and later withdrawn score, and

TWI = time warning was issued.

g. Surge Height Accuracies. The score is derived from

$$SHS = 10 \times (ACTSG - MINSG) + 20 \times (MAXSG - ACTSG) \quad (7)$$

where SHS = surge height score,

ACTSG = actual surge height

MINSG = minimum predicted surge height

MAXSG = maximum predicted surge height.

4. The scores are weighted (see Para. 2) and added for each segment to form the total score for each variable in Para. 3.

The Mann-Whitney Test

5. The Mann-Whitney test is a non-parametric test that can be used to determine if one set of numbers is significantly different from another. It was used in an analysis of the scores to determine if changes made to the cyclone observation and prediction systems significantly affected the scores. A basic set of 200 cyclones were simulated and the scores from these stored. Scores derived subsequently from simulations of the same number of cyclones with different cyclone observation or prediction parameters were compared with the basic set by means of the Mann-Whitney test. If a significant difference was found in any of these tests the means and sums of the scores were compared to determine whether or not this difference represented an improvement in the relevant aspect of the observation or prediction systems. Further information on the Mann-Whitney test can be found in [1].

REFERENCES

No.	Author	Title
1	Siegel S.	'Non-Parametric Statistics for Behavioral Scientists'. McGraw-Hill, 1956.

Annex I

FALSE ALARMS AND 'HIT-NOT WARNED' EVENTS

1. The rate at which false alarms and 'hit-not warned' events occur for the basic situation was determined. The basic situation is defined to be that using the parameters derived from the 23 Queensland cyclones and from Coleman [1]. In this assessment the number of segments warned is determined using the top curve of Figure 4 of the main text and the diameter of the cyclone effect under consideration (see para 12 of main text).

2. False Alarms. The rate at which false alarms occur was determined from a simulation of 1244 cyclones. The averaged results obtained were as follows:

   a. 696 segments per 100 cyclones received a gale 'false alarm' (that is a gale warning was issued when not required).

   b. 694 segments per 100 cyclones received a storm 'false alarm'.

   c. 608 segments per 100 cyclones received a landfall 'false alarm'.

3. 'Hit-Not Warned' Events. In all 1866 cyclones were simulated to derive the 'hit-not warned' event statistics. The results are divided into the three categories - gale, storm and landfall. The initial results given below are for the basic case, using the original Queensland data aggregated, with no specific recognition given to improvements in the observation system over recent times or the improvement in the system capability nearer the coast. Since the sensitivity of the results to changes in the observation data is the prime concern, the possibly pessimistic numerical results below are of secondary importance.

   a. Gale

      (1) An average of 11.4 ± 0.7 (i.e. between 10 and 13) cyclones per 100 cyclones will influence at least one segment of the coast which has not been warned, with a gale effect.

      (2) If a cyclone does influence the coast and there are segments which have not received a gale warning then the average number of such segments affected is 4.0 ± 2.3 (i.e. between 1 and 7 segments).

      (3) On average, 46 segments of the coast per 100 cyclones will experience a gale 'hit-not warned' event.

   b. Storm

      (1) An average of 5.7 ± 0.6 (i.e. between 5 and 7) cyclones per 100 cyclones will influence at least one segment of the coast with a storm 'hit-not warned' event.

      (2) If a cyclone influences the coast and there are segments unwarned but influenced by a storm the average number of such segments affected is 2.6 ± 1.2 (i.e. between 1 and 4 segments).

(3) On average 15.1 segments per 100 cyclones will experience a storm 'hit-not warned' event.

c. Landfall. A cyclone which crosses the coast influences only one segment with landfall effects. Consequently, the average proportion of cyclones that influence the coast with a landfall 'hit-not warned' situation, namely 4.8 ± 0.5 (i.e. between 4 and 6) per 100 cyclones, is also the average proportion of segments that experience a landfall 'hit-not warned' situation per 100 cyclones.

4. Total 'Hit-Not Warned'. The above results are not additive because a cyclone that produces a gale 'hit-not warned' situation for example, may also produce a storm or landfall 'hit-not warned' situation. On average 11.3 ± 0.8 (i.e. 10 to 13) cyclones per 100 cyclones will produce either a gale, storm or landfall 'hit-not warned' situation.

REFERENCES

No.	Author	Title
1	F. Coleman	'Frequencies, Tracks and Intensities of Tropical Cyclones in the Australian Region. November 1909 to June 1969'. Bureau of Meteorology Publication. July 1971.

Annex J

COSTS RESULTING FROM LANDFALL WARNINGS

1. There are no authoritative estimates available of the costs pertaining to the issue of landfall warnings to coastal communities in Queensland. However in order to put the results of Table 1 of the main text in some perspective, certain costs derived from U.S. sources [1] will be assumed. No judgement is made on the relevance of these costs to the Australian context.

2. Costs Assumed. Based on [1] the following summarises the assumed costs.

Protection costs, per person, per cyclone warning = $5

Evacuation costs per person = $10

Assume also:

a. that half the affected population takes protective action on receipt of a landfall warning (i.e. incurs on average $5 expenses);

b. half the population of an affected area is subject to evacuation. Other costs mentioned in [1] (e.g. military, oil rigs, large industry) were not regarded as appropriate to Queensland and hence were not included.

3. Communities. The cost analysis was made for the following communities, Cairns, Townsville, Bundaberg, Gladstone, Mackay, Maryborough, Rockhampton. This results in a total cost of $1.86m if all of these centres were subject to a cyclone warning. Table 1 summarises the expected savings which would accrue in Queensland from the situations indicated in Table 1 of the main text.

Table 1. SAVINGS FROM OBSERVATION SYSTEM IMPROVEMENT

SITUATION	ANNUAL SAVING BY REDUCTION OF LANDFALL WARNING ZONES
6 hr forecast to landfall Estd. position error halved. (Nominal Warning Zone ≃ 300 n miles)	0.135 x \$1.86M ≃ \$250,000
12 hr forecast to landfall Estd. position error halved. (Nominal Warning Zone ≃ 500 n miles)	0.18 x \$1.86M ≃ \$330,000
12 hr true time-to-go to landfall Estd. velocity error = 0 Position error halved. (Nominal Warning Zone ≃ 500 n miles)	0.65 x \$1.86M ≃ \$1.2M
12 hr true time-to-go to landfall (U.S. model). Estd. velocity error presumed = 0. Position error halved. (Nominal Warning Zone ≃ 380 n miles)	0.9 x \$1.86M ≃ \$1.6M

REFERENCES

No.	Author	Title
1	C.J. Neumann	'A Statistical Study of Tropical Cyclone Positioning, Errors With Economic Applications'. National Hurricane Centre, Miami, Florida, January 1975.

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16. SUMMARY or ABSTRACT (if this is security classified, the announcement of this report will be similarly classified):

An empirical mathematical model of the Tropical Cyclone Warning System was developed to investigate the potential benefits of improvement to the cyclone measurement system. It was found that the model indicated little sensitivity in warning 'quality' (defined in broad terms) to improvements in some aspects of the cyclone observation system. Despite this lack of sensitivity, the assumption of U.S. cost figures applicable to communities affected by cyclones produces a result favourable to participation in the Japanese Geostationary Meteorological Satellite program. Areas of weakness in the model have been identified as requiring attention in any continuing program of work in this field.

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