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## TROPICAL CYCLONE TRACKING AND FORECASTING. I

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### 1. INTRODUCTION

1.1 The format for the issuing of tropical cyclone warnings for shipping and aviation are given in WMO Publication No. 49 Technical Regulations, Volumes I (Annex VI) and II.

1.2 In Annex VI, it is specified that warnings on tropical cyclones should have the following content:

- (a) Date and time of reference;
- (b) Type of disturbance with information on central pressure;
- (c) Location of disturbance in terms of latitude and longitude;
- (d) Extent of affected area in terms of wind and sea/swell conditions;
- (e) Direction and speed of movement of disturbance;
- (f) Other appropriate information such as future positions of disturbance and intensity change.

A typical tropical cyclone warning form used in the Royal Observatory Hong Kong is shown in the Appendix.

1.3 Items (a) to (d) concern the tracking of tropical cyclones and will be the subject of discussion in this paper I. Items (e) and (f) which are on tropical cyclone forecasting will be dealt with in sister paper II.

### 2. TROPICAL CYCLONE TRACKING

2.1 Tropical cyclone tracking consists of

- A) the determination of the present location of the centre of the tropical cyclone (items (a) and (c) of para. 1.2);
- B) the determination of the present intensity, in terms of its
  - i) central minimum sea-level pressure (item (b))
  - ii) maximum surface wind (item (d)), hence its type (item (b))
  - iii) wind and sea extent (item (d)).

2.2 It is important for forecasters to know precisely the present or initial location and intensity of the tropical cyclone because the prediction of the future movement and intensity of the tropical cyclone and the area forecasts of rainfall, wind, wave/swell and storm surge are nothing more than the usual initial-value problems. Knowledge of the actual present weather conditions also helps the forecasters in nowcasting, that is, in the making of very short-range forecasts.

### 3. DETERMINATION OF LOCATION OF CENTRE

3.1 The definition of a tropical cyclone, as given in WMO No. 182.TP.91 International Meteorological Vocabulary, reads as follows:

Cyclone of tropical origin of small diameter (some hundreds of kilometres) with minimum surface pressure, in some cases less than 900 mbar, very violent winds, and torrential rain;

sometimes accompanied by thunderstorms. It usually contains a central region, known as the "eye" of the storm, with diameter of the order of some tens of kilometres, and with light winds and more or less lightly clouded sky.

3.2 In view of the above characteristics, the eye of a tropical cyclone can be determined by locating the pressure centre, the wind centre or the rain centre.

3.3 By assuming a symmetrical pressure profile, several points of equal pressure (as reported by land stations or ships) can be selected from the current observations in the vicinity of the eye and the perpendicular bisectors drawn. These bisectors may not always pass through one centre but would form a polygon. The centroid of the polygon can be regarded as the tropical cyclone eye.

3.4 Takahashi (1939)/1/ established that the pressure profile of a tropical cyclone can be expressed approximately by the following empirical formula

$$P(r) = 1015 - \frac{1015 - P_c}{1 + r/r_0} \quad (1)$$

where  $P(r)$  is the pressure in mbar at radius  $r$ ,  $P_c$  the central pressure in mbar and  $r_0$  the radius of the isobar ( $P_c + \frac{1}{2}(1015 - P_c)$ ). Equation (1) can be re-written as

$$\frac{1}{1015 - P(r)} = \frac{r}{r_0(1015 - P_c)} + \frac{1}{1015 - P_c} \quad (2)$$

For a steady-state tropical cyclone, both  $r_0$  and  $P_c$  are constant and so  $1/(1015 - P(r))$  varies linearly with  $r$ . A diagram which is used for determining  $P_c$  and the pressure profile in accordance with Equation (2) is called the Takahashi Diagram. The procedure for determining the location of the eye is as follows:

- Step 1. From a previous surface chart analysis, select a few points with known  $P(r)$  (corrected for diurnal variation) and  $r$ . Using these values on a Takahashi Diagram, draw the best straight line which defines the latest pressure profile of the tropical cyclone.
- Step 2. From the current surface chart, select a few positions with weather reports near the centre of the tropical cyclone. Using their  $P(r)$  (corrected for diurnal variation) and assuming that the tropical cyclone is at steady-state, read off the  $r$  values from the straight line graph developed under Step 1.
- Step 3. Draw arcs from the above positions with the distances obtained. The arcs may not always intersect at the same point but the eye can be taken as the mean position of all the intersecting points.

3.5 Using the wind directions reported by ships or land stations within the circulation of the tropical cyclone, the wind centre can be determined by assuming that the wind profile is symmetrical and that the angle of inflow is constant at 20 degrees. (This is in accordance with the findings of Malkus and Riehl (1960)/2/ who found that the angle of inflow for a moderate model tropical cyclone can be taken as 20 degrees for distances exceeding 100 km from the centre.) The procedure to locate the eye is therefore to draw straight lines from the above points at an angle of  $110^\circ + \theta$  where  $\theta$  is the direction of the reported wind. The centroid of the polygon formed by these straight lines can be regarded as the tropical cyclone eye.

3.6 Another way of identifying the eye location is by determining the position of the rain-free centre on the radar. This is normally done by fitting spiral overlays of suitable angles of inflow onto the radar echoes. While determining the radar eye position, forecasters should also take notice of the organization of the eye and measure its diameter. By comparing the degree of organization and the eye diameter with those taken in a previous radar observation, it is possible to deduce the change in the intensity of the tropical cyclone. (See paper II). The eye diameter is an important parameter to know because from this we can estimate the radius of maximum wind (approximately half of the eye diameter) which is one of the controlling factors in the computation of storm surge.

3.7 The rain-free and lightly clouded eye of a tropical cyclone can often be seen clearly on the meteorological satellite picture in the visible spectrum. Forecasters however must be on the alert for possible errors when trying to use an infrared picture to fix the eye because what they identify may sometimes be just an upper-air centre which could well be displaced from the low-level eye position (based on which tropical cyclone warning is issued) in a strong vertically-sheared situation. Details of procedures for identifying the cloud system centre are described in the TOPEX Operational Manual (1981) [3] published by WMO. With the advance of techniques in digitizing satellite data, it has now become possible to use computers to extract the low-level high resolution satellite data and identify the surface centre with reasonably good accuracy.

3.8 The most reliable form of fixing the position of a tropical cyclone is by means of a reconnaissance flight. A high degree of confidence can usually be put in by forecasters when such data are available.

#### 4. DETERMINATION OF CENTRAL PRESSURE

4.1 Whenever a tropical cyclone warning is in force, all the ships in the vicinity of the tropical cyclone will try to evade from its centre. Hence the availability of a report giving the central minimum pressure inside the eye is normally very scarce. But from time to time, a ship may pass quite close to the centre or the cyclone may hit an island station, in which case valuable central pressure and maximum surface wind data would become available.

4.2 By using the Takahashi Diagram and Equation (2) as described in paragraph 3.4, the central pressure  $P_c$  can be estimated by reading the ordinate once the centre of the tropical cyclone is fixed and the pressure profile is determined.

4.3 The minimum sea-level pressure is most accurately measured by the use of dropsondes released from reconnaissance flights.

4.4 Occasionally, only the minimum 700 mbar height over the eye is available during aircraft reconnaissance. In such cases, the central pressure can be estimated in accordance with the following empirical formula developed by Jordan (1958) [4]:

$$P_c = 0.115h_{700} + 645 \quad (3)$$

where  $h_{700}$  is the 700 mbar height in gpm and  $P_c$  the central pressure in mbar, or other established forms of the  $(P_c, h_{700})$  relationship such as that developed by Bell and Tsui (1973) [5]:

$$P_c = 0.122h_{700} + 624 \quad (4)$$

4.5 During reconnaissance flights, very often the state of the sea near the eye-wall of the tropical cyclone can be observed. From this, the maximum wind  $V_m$  (in knots) can be deduced. The central pressure  $P_c$  can then be computed according to the empirical formula established by Atkinson and Holliday (1977) [6]

$$V_m = 6.7(1010 - P_c)^{0.644} \quad (5)$$

There are other forms of the ( $V_m$ ,  $P_c$ ) relationship. One was established by Fletcher (1955) [7] as follows:

$$V_m = 16\sqrt{P_n - P_c} \quad (6)$$

where  $P_n$  is the outside pressure in mbar. Another empirical formula reported in the Joint Typhoon Warning Center's Annual Typhoon Report (1968) [8] was:

$$V_m = (12 - \lambda/8)\sqrt{1007 - P_c} \quad (7)$$

where  $\lambda$  is the latitude of the centre of the tropical cyclone.

4.6 Dvorak (1975) [9] developed a technique of tropical cyclone intensity analysis using satellite imagery. This was subsequently modified with the introduction of enhanced satellite data (see Dvorak and Wright (1978) [10]) and further improved by Dvorak (1980) [11] using digital means. In all his methods, Dvorak related the estimated current intensity number (in steps of 0.5) to the minimum sea-level pressure through a statistical table. Recently, this table has been updated by Skewchuck and Weir (1980) [12]. The accuracy of the central pressure so determined is reasonable but in general not as high as that provided by reconnaissance flights.

## 5. DETERMINATION OF MAXIMUM SURFACE WIND

5.1 It is important to know the maximum surface wind of a tropical cyclone in order to be able to determine its type according to the regional classification practice. In Hong Kong, for example, tropical cyclones are called tropical depressions if their maximum surface winds are below 34 knots, tropical storms if they are between 34 and 47 knots, severe tropical storms if they are between 48 and 63 knots and typhoons if they are 64 knots or more.

5.2 The maximum surface winds are occasionally reported by ships passing close to the eye-wall or by island stations hit by the tropical cyclone.

5.3 During reconnaissance flights, visual observations of the state of the sea near the eye-wall are often taken by the pilots. From these sea conditions, the maximum surface winds can be assessed.

5.4 If the minimum sea-level pressure  $P_c$  is known, for example, when measurements by dropsondes in the eye of the tropical cyclone are made, the maximum surface wind can be computed by the use of Equation (5) or other applicable empirical formulae such as Equations (6) and (7).

5.5 A number of techniques have been developed to determine the maximum surface winds by the use of satellite data. Fritz et al (1966) [13] devised a classification system based on satellite

cloud data and used the diameter of the central overcast to compute the maximum surface winds in the case of Stage X tropical cyclones. The methods of Dvorak (1975, 1978, 1980) [9, 10, 11] are more sophisticated and are therefore more commonly used by forecasters. From the estimated current intensity number, the maximum surface wind can be obtained by the use of a statistical table. Details of the methods will not be presented in this paper as they have already been extensively covered in proceedings of a number of recent WMO seminars like the Regional Training Seminar on the Interpretation, Analysis and Use of Meteorological Satellite Data, Tokyo, 23 October to 2 November 1978, International Conference on Tropical Cyclones, Perth, 25-29 November 1979, Symposium on Typhoons, Shanghai, 6-11 October 1980 and Seminar on the Application of Satellite Data to Tropical Cyclone Forecasting, Bangkok, 24 May to 4 June 1982. Fang and Zhou (1980) [14] proposed a scheme for computing a tropical cyclone intensity number  $T$  using infrared satellite pictures based on the position of the centre relative to the deep convective cloud, the characteristics of the eye (form, size, degree of clearness), the size of the central convective overcast and the characteristics of the spiral cloud bands. The maximum surface winds  $V_m$  in knots can then be calculated according to the following empirical formula:

$$V_m = 15.187(T - 1) \quad (8)$$

5.6 The maximum surface wind of a tropical cyclone can be calculated by estimating the radar echo motion outside the eye-wall (see Wong (1981) [15]). Huges (1952) [16] showed that just outside the eye-wall

$$V_r r^\alpha = \text{constant} \quad (9)$$

where  $\alpha$  is a constant (with magnitude about 0.5 to 0.7) that can be determined experimentally for the tropical cyclone by

$$\alpha = \frac{\log_{10} \frac{V_{r_1}}{V_{r_2}}}{\log_{10} \frac{r_2}{r_1}} \quad r_1 \neq r_2 \quad (10)$$

where  $r_1$  and  $r_2$  are the distances of two radar echoes from the centre and  $V_{r_1}$  and  $V_{r_2}$  their measured speeds of motion. Once  $\alpha$  and the radius of maximum wind  $R$  (— can be taken as half of the eye diameter) are known, the maximum surface wind can be calculated by the use of Equation (9) in the following form:

$$V_m = V_{r_1} (r_1/R)^\alpha \quad (11)$$

#### 5. DETERMINATION OF EXTENT OF WIND AND WAVE

5.1 The radius of over 33 knot winds (gales), over 47 knot (storm force) winds, over 63 knot (hurricane force) winds and over 2 metre waves in the various quadrants from the eye of the tropical cyclone can be determined by the use of the current surface synoptic charts where ship observations are plotted.

5.2 Where surface observations are scanty, climatological data, compiled from observations made during tropical cyclones of similar intensity over similar months in the same sea area, can be used as a substitute.

## 7. CONCLUDING REMARKS

7.1 In this paper, we have described how the various tropical cyclone tracking parameters can be determined. It is up to each national instructor to decide whether part or all of the methods are applicable in his/her own forecasting centres. They should also draw up appropriate flow charts to assist the operational forecasters in obtaining the best results in the most expeditious manner.

7.2 One of the commonest questions asked by forecasters is how to decide on giving an "official" value to a parameter based on the many determined by various methods. The general rule is very simple. If the accuracy of one of the methods is very much superior to the rest, we should by all means take its result as the "official" value. In the case when the various accuracies are more or less of the same level, the mean value can then be computed and used in the issuing of the tropical cyclone warning.

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## TROPICAL CYCLONE TRACKING AND FORECASTING. II

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### 1. INTRODUCTION

1.1 In "Tropical Cyclone Tracking and Forecasting-I" (Tsui, 1982) [1], I have discussed in detail the various methods for tropical cyclone tracking. Here in this paper, I shall concentrate on the other important aspect: tropical cyclone forecasting, upon which community preparedness and disaster prevention is dependent.

1.2 By tropical cyclone forecasting, it is meant:

- A) forecasting of tropical cyclone movement;
- B) forecasting of tropical cyclone intensity;
- C) forecasting of wind, rainfall, sea wave/swell and coastal storm surge caused by a tropical cyclone for a specified area or geographical point.

### 2. TROPICAL CYCLONE MOVEMENT FORECAST

2.1 It is well-known that accurate tropical cyclone movement forecast is one of the most challenging tasks to achieve. Throughout the years, a lot of efforts have been put in by forecasters and meteorologists to improve the forecasting techniques and devise more objective or computerised methods in order to eliminate errors associated with subjective assessment. Unfortunately up till now, the annual mean 24-hour forecast position error is still disappointingly large and well above 160 km for most warning centres (see Bell (1980) [2] and Chin (1980) [3]).

2.2 Amongst the objective methods commonly used are:

- A) Extrapolation: The simplest is persistence (P) which is linear extrapolation of the present movement. In some forecast centres, extrapolation with acceleration included is sometimes used especially after recurvature.
- B) Climatology (C): The climatological forecast moves the tropical cyclone in the climatological resultant direction at the climatological mean scalar speed which are functions of the location (latitude and longitude) and the time of the year.
- C) Analogue: In this technique, "similar" tropical cyclones or analogues are chosen according to certain specified criteria, such as position separation less than 2.5 degrees latitude, time of occurrence within 15 days, directions of movement differing by less than 22.5 degrees and speeds of movement differing by less than half the speed of the tropical cyclone. Examples are the HURRAN and TYFOON of the USA, CYCLOGUE of Australia (ref. WMO No. 528 [4]) and the TYAN 73 of Guam (ref. JTWC's 1981 Report [5]).
- D) Statistical Methods:
  - a)  $\frac{1}{2}(P + C)$ : This simple technique of giving equal weights to P and C was described by Bell (1962) [6] and is still one of the best methods available to the operational forecaster. Guam's HPAC and BPAC (see JTWC's 1981 Report [5]) are based on the same concept. In the Philippines, there are methods

in which unequal weights are given to P and C (see TOPEX Report No. 4 [7]).

- b) PC Regression: Japan's PC Method (ref. TOPEX Report No. 2 [8]), USA's CLIPER (ref. WHO No. 528 [4]) and Hong Kong's Regression Method (ref. TOPEX Report No. 4 [7]) are examples of this kind.
- c) Arakawa's Method: see Arakawa (1964) [9].
- d) Modified Veigas-Miller Method: see Bell (1962) [6] and TOPEX Report No. 4 [7].
- e) Tse's Method: see Tse (1966) [10].
- f) Various NHC models: see WMO No. 528 [4].

E) Dynamical Methods: These are the various kinds of numerical weather prediction models for tropical cyclones, for example, the balanced barotropic model, moving multi-nested grid model and the multi-level primitive equation model (see Gentry (1973) [11]).

F) Statistical-dynamical methods: Both the Model Output Statistics Method and the Perfect Prognosis Method have been used to develop forecasts based on numerical modelling results. Examples include China's SD75 (ref. Wu and Xu (1980) [12] and TOPEX Report No. 4 [7]), Guam's HATRACK, MOHATT and CYCLOPS (ref. JTWC's 1981 Report [5]) and Japan's SNT and SNT-Correction Methods (ref. TOPEX Report No. 4 [7]).

G) Steering: It has often been hypothesised that tropical cyclones would move along with or be steered by the basic environmental flow. Various procedures have been adopted to evaluate such a steering current. Typically the tropical cyclone vortex is first removed from the geopotential fields which are then smoothed to reveal the large scale pattern (see Tung and Liu (1965) [13] and TOPEX Report No. 4 [7]). The geostrophic space mean flow is then determined. Sometimes the flow at a single level is used for the tropical cyclone movement forecast, in which case the level is taken as a "steering level". In Hong Kong, a volume mean is also calculated using the flows at the surface, 700, 500 and 300 mbar and this technique is called MUSIC (Multi-level Steering by Integrated Current) (ref. TOPEX Report No. 4 [7]). A space mean regression method has also been developed. Bell and Lam (1980) [14] however have shown that the simple concept of geostrophic steering flow is not adequate to fully account for the movement of tropical cyclones. Yeh (1950) [15] has also shown that the flow resulting from superposition of a tropical cyclone vortex on a steering current is nonlinear and explained why trochoidal tracks are sometimes observed. Forecasters are therefore advised to take note of these possible deviations when applying the steering concept.

H) Synoptic Methods: Most of the synoptic methods are subjective. Chin (1974) [16] however managed to develop two objective schemes by the use of computer, namely a fixed control point method and a variable control point method, using synoptic data from objective analyses.

2.3 Subjective assessments are still important in the forecasting of tropical cyclone movement. It is quite impossible to tabulate here all the valuable experiences of the forecasters. The following hints are however worthy of mentioning:

A) Rossby Effect: When the tropical cyclone is quasi-stationary, the difference in the Coriolis parameter across the tropical cyclone (- a dynamical effect) may cause a poleward drift of about one degree of latitude in 30 hours (see Rossby (1949) [17]).

B) Pressure changes inside the circulation indicate the cyclone's direction during the past few hours but those outside the circulation often indicate future changes in motion. When there are large pressure changes outside the circulation, their effect is to turn the cyclone at right angles to the line connecting the isallobaric centre and the cyclone centre.

C) Interaction:

a) With another tropical cyclone: see Fujiwhara (1921) [18]

b) With land: deflection to the left on encountering land.

D) Recurvature: Recurvature should be considered when there is

a) interaction with an approaching westerly trough. The approach of a westerly trough can be seen on a 500 mbar prognostic chart and on the satellite pictures (see Chan (1974) [19])

b) retreat of the subtropical ridge as shown on a 500 mbar prognostic chart.

2.4 Before forecasters can decide on an "official" forecast movement and give "official" 24-, 48- or 72-hour forecast positions in a tropical cyclone warning, they have to digest all the objective forecast results and subjective prognostic reasonings available to them. Thus the final act is a subjective procedure itself. Experience has shown that the forecaster must verify the performance of the various methods continually and more weights should be given to those methods that are performing better at the time.

### 3. TROPICAL CYCLONE INTENSITY FORECAST

3.1 Up till now, most techniques developed for the forecasting of tropical cyclone intensity are subjective in nature.

3.2 The simplest method is extrapolation, that is, by keeping persistence of the present intensity change which can be determined by comparing the last observed intensity of the tropical cyclone with that at present. Radar observations often provide useful hints as to whether the tropical cyclone has developed or weakened. Changes in the degree of organization of the radar rain echoes imply changes in the intensity. The formation of a concentric eye structure generally means intensification. When the eye diameter shrinks, angular momentum conservation demands that the maximum surface winds at the eye-wall should increase. Conversely, when the eye expands, the intensity of the tropical cyclone must be decreasing.

3.3 If available, climatological data on intensity change (functions of the location and the time of year) would be useful aids to the forecaster.

3.4 As the intensity of a tropical cyclone is very much controlled by the energy input, the following five conditions would affect tropical cyclone intensity:

- i) Land effect: the presence of land means lesser availability of water vapour from the sea (- fuel for the tropical cyclone thermodynamic engine). Therefore when a tropical cyclone encounters land, it normally weakens.
- ii) Sea surface temperature effect: the higher the sea surface temperature, the greater the rate of evaporation would become. Hence, when a tropical cyclone enters into an area of higher sea surface temperature, it intensifies.
- iii) Upwelling of ocean current: When a tropical cyclone is quasi-stationary, the intense cyclonic winds would force the

surface water to move outwards as a result of the Coriolis effect. The resulted upwelling would bring in cooler water from the deep sea below causing a decrease in the sea surface temperature. Consequently the tropical cyclone weakens.

- iv) Dry air intrusion means lesser availability of water vapour in the atmosphere. Slight weakening normally follows.
- v) During autumn, a tropical cyclone may sometimes encounter cold air. Momentarily, the tropical cyclone would intensify when the temperature gradient is accentuated. But when the cold air has finally penetrated into the circulation, the warm-core structure would gradually be destroyed and the cyclonic winds would decrease in strength, which in turn would slow<sup>down</sup> the evaporation process.

3.5 An intense tropical cyclone needs good outflow aloft and weak vertical wind shear. Hence, the upper-air prognosis is extremely important for a forecaster. Good outflow aloft can be identified by the presence of upper divergence, often in the form of an anticyclone at the 200 mbar level. The divergence of heat flux can sometimes be seen on the satellite picture as a plume of middle and high cloud streaming from the centre of the tropical cyclone into the westerlies (see Tsui et al (1977) [20]). Strong vertical wind shear, manifested by the presence of intense upper-level winds in the form of a jet, would lead to the tropical cyclone being sheared off and the distortion of the vertical axis of the cyclone to such an extent that the hydrostatic effect over the centre would be spread over too large an area to permit the development of a concentrated surface vortex. In this case, weakening would follow. The upper-air prognosis also provides indication as to whether the tropical cyclone would be coming to an extratropical environment. If so, transformation into an extratropical cyclone could be forecast.

3.6 The intensity of a tropical cyclone can sometimes be successfully forecast by the use of an intensity development model such as that developed by Dvorak and Wright (1978) [21] using satellite imagery.

#### 4. FORECASTING FOR A SPECIFIED AREA OR GEOGRAPHICAL POINT

4.1 Once the forecast track and the forecast development for the tropical cyclone are fixed, the forecaster can proceed to provide forecasts of wind, rainfall, sea wave/swell and coastal storm surge for a specified area or geographical point.

4.2 The wind can be determined by moving the up-dated wind distribution model of the tropical cyclone along the forecast track, appropriately adjusted to take into account the expected intensification or weakening. Another way to forecast the wind is to use climatological probabilities based on the forecast positions of the tropical cyclone. Analogues, if available, would sometimes yield very useful results.

4.3 Whether rain should be forecast or not can usually be determined by advecting the rain, especially when rain echoes can be seen on the radar. But to forecast the amount of rainfall say in the next 24 hours, one cannot simply multiply the present radar rate of rainfall (per hour) by 24 because of the continuous echo developments. Analogues, numerical weather prediction and

model output statistics can be used to give quantitative precipitation forecasts. So can forecasters use a climatological rain model by moving it along the forecast track. Kwong (1974) [22] devised a climatological method for forecasting 24-hour rainfall at Hong Kong using the position of the tropical cyclone as a variable. In Japan, a statistical method is used to forecast tropical cyclone rainfall based on parameters like the wind speed, orographic vertical velocity, the distance from the centre and the maximum surface wind of the tropical cyclone (see TOPEX Report No. 2 [8]).

4.4 The sea wave/swell conditions can be accurately computed using the Sverdrup-Munk-Bretschneider (SMB) Nomogram (ref. WMO No. 446 [23]) once the wind direction, speed and duration are forecast. A rough estimate of the wave can also be made by using the simple wind speed/wave relation for a fully arisen sea. The wave can also be determined by moving the up-dated wave distribution model of the tropical cyclone along the forecast track, appropriately adjusted to take into account the expected intensity change.

4.5 Besides the wind and the rain, storm surge is a major factor for causing damage in tropical cyclones. Numerical modelling is the usual tool for the forecasting of storm surge at coastal areas (see WMO No. 500 [24]). In Hong Kong, the forecasting of open coast storm surge is by the use of the Jelesnianski SPLASH Model (see Lau (1980a) [25]). The prediction depends primarily on the following six parameters: the central pressure, the direction of movement, the speed of movement, the radius of maximum wind, the distance of nearest approach and the landfalling location. In Hong Kong, a Bay Model has also been developed for the forecast of the propagation of the raised sea-levels shorewards to locations within bays and inlets (see Lau (1980b) [26]). In centres where computer facilities are not available, empirical methods using regression equations can be used to provide peak surge forecasts, for example, using the forecast wind or pressure as the variable (see Cheng (1967) [27] and TOPEX Report No. 2 [8]). Climatological probabilities based on the forecast position and intensity of the tropical cyclone have also been used in the evaluation of peak surge heights. One shortcoming of these empirical methods is that the surge profile with time cannot be determined. Hence the forecaster would have no way to know exactly when the peak surge would occur and compute the peak sea-level.

## 5. CONCLUDING REMARKS

5.1 Numerous methods are in use for tropical cyclone forecasting. In this paper, only a brief outline of the methodologies currently used has been presented. It is up to the national meteorological instructors to decide which should best be applied in their respective forecasting centres.

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