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Prediction of tropical cyclone formation in terms of sea-surface temperature, vorticity and vertical wind shear

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The method involves the use of a 'hurricane' index which is a measure of the kinetic energy of any given cyclonic circulation or shear zone. The index is derived from the sea-surface temperature, relative vorticity and vertical wind shear of the broadscale flow in the vicinity of the disturbance, and is used to indicate the potential for such disturbances to develop into tropical cyclones. It is found that when the index is above a certain fixed threshold value, most disturbances develop into tropical cyclones, whereas when it is below this fixed value development into tropical cyclones does not occur.

Introduction

One of the least understood processes in meteorology is the mechanism leading to the formation of tropical cyclones. By contrast, the process of intensification and movement of an already formed cyclone is much better understood. Extensive numerical modelling of cyclone intensification and movement has already been accomplished with reasonable success, and used by centres such as the Joint Typhoon Warning Center in Guam, the Honolulu Weather Service, the European Centre for Medium Range Weather Forecasts and the International Forecasting Unit at Bracknell, United Kingdom, in the routine production of cyclone track and intensity forecasts.

Various authors have related tropical cyclogenesis to the environmental conditions (e.g. Gray 1968, 1970, 1975; Ward 1971, 1973; Revell and Goulter 1986; Zillman et al. 1989; Hastings 1990). However, there remains a pressing need in operational practices to predict the location and time of formation of each individual tropical cyclone with greater accuracy and more advanced warning.

The present article deals with tropical cyclogenesis in the southwest Pacific, and relates the development of individual disturbances to three of the six key environmental parameters used by Gray (1975) in his global view of tropical cyclone genesis. The parameters used in the present work are sea-surface temperature, vorticity and the vertical shear of the broadscale tropospheric flow, whose combined effect on cyclogenesis is represented by a single 'hurricane' index. The methodology closely parallels the work of Zehr (1992) who showed that necessary conditions for tropical cyclogenesis in the northwest Pacific are small vertical wind shear, sufficient low-level convergence and sufficient low-level relative vorticity.

The concept of a hurricane index

In an earlier study (Ward 1973), a regression equation was obtained relating the total tropical cyclone activity in the southwest Pacific (150°E–150°W) for any given season, represented by a hurricane index H, to the mean sea-surface temperature, T, in the main development area (10°S–15°S, 150°E–150°W), and an intensification potential, I, obtained from the relative vorticity and tropospheric vertical shear of the broadscale flow. This was based on the findings of Gray (1968) that genesis only occurs in pre-existing cyclonic disturbances, and does not occur in regions of high vertical shear because the moisture and temperature anomalies necessary to lower surface pressure are advected away.

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Hurricane index was defined by:

$$H = \Sigma V^2 \times 10^{-3} \qquad \ldots 1$$

where V = strength in knots of the maximum sustained wind of each disturbance, the summation being carried over all major cyclones occurring in a given period or season. This somewhat arbitrary index gives an approximate measure of the kinetic energy of the cyclones. The kinetic energy of systems with maximum sustained winds less than 50 knots, neglected in this earlier study, is comparatively small.

The regression equation obtained in this earlier study was:

$$H = 20(T - 27.6)I + 1.5 \qquad \ldots 2$$

where I was defined by Eqn 3 below, and T and I were measured in five-degree squares in the main development area (10°S–15°S, 150°E–150°W) and then averaged over that area. If T is less than 27.6°C, H = 0.

Following Gray (1968, 1970), intensification potential, I, was defined by

$$I = \frac{\bar{\eta}}{|\bar{u}_2 - \bar{u}_{10}|} \qquad \ldots 3$$

where $\bar{\eta}$ is the relative vorticity of the mean monthly zonal 1000 hPa wind and $\bar{u}_2$, $\bar{u}_{10}$ are the mean monthly zonal components of the winds at 200 hPa and 1000 hPa respectively. Values of I obtained in this way were found to be about one order of magnitude smaller than those obtained for individual disturbances (Ward 1971) in the main cyclone development area. I was taken to be zero in any five-degree square where 1000 hPa relative vorticity was zero or positive (i.e. anticyclonic). Details are contained in Ward (1973).

Prediction of hurricane index, H*, for individual disturbances

Similar principles to those for calculating seasonal values of intensification potential, I, are used for calculating the intensification potential, I*, for individual disturbances. I* is calculated for the mid-point of each five-degree latitude-longitude square in the tropical area 0°–25°S, 150°E–150°W, using grid-point values of the zonal component of the 1000 hPa wind 2.5 degrees north and south of the square centre to obtain the zonal component of the relative vorticity of the 1000 hPa wind, and mean values of the zonal 1000 and 200 hPa wind for each square to obtain the vertical shear (Fig. 1). The intensification potential for each five-degree square is then given by:

$$I^* = \frac{2\Delta u_{10}}{|S_z|} \times 10^{-2} \qquad \ldots 4$$

where Δu_{10} is the horizontal shear of the zonal wind per five degrees of latitude (or ~500 km) at 1000 hPa and $|S_z|$ is the magnitude of the vertical shear of the mean wind between 1000 hPa and 200 hPa (or ~per 10 km). I* thus works out as a dimensionless quantity. In practice the 250 hPa winds are used in preference to those at the 200 hPa level as analysed data are more readily available at the former level. Also the total (resultant) winds at 1000 hPa and 250 hPa are used in calculating $|S_z|$. (The mean meridional component of the 250 hPa wind is often at least as great as the zonal component in individual disturbances.)

The transition from I for interannual cases to I* for individual cases needs further clarification. For interannual studies meridional components of vertical wind shear can be ignored as they are generally small compared with the zonal components and average out. However, for individual studies, since meridional components of the wind at 200 hPa above developing systems can be significant, both zonal and meridional components have to be included, and the magnitude of the shear between the mean resultant wind at 200 hPa and that at 1000 hPa, $|S_z|$, is calculated.

As in interannual studies, only the $\partial u_{10}/\partial y$ term (Δu_{10}) of relative vorticity at 1000 hPa is calculated for individual cases. The magnitude of the $\partial v_{10}/\partial x$ term is approximately the same as the $\partial u_{10}/\partial y$ term in symmetrical systems, and therefore sufficient information is contained in the Δu_{10} term for the calculation of a hurricane index. In the case of convergence zones (generally orientated east-west), $\partial v_{10}/\partial x$ is small and most of the relative vorticity is contained in the $\partial u_{10}/\partial y$ term (Δu_{10}).

Since I* is about one order of magnitude greater than I, the expression for hurricane index, H*, for individual systems or day-to-day data has been adapted from Eqn 2 as:

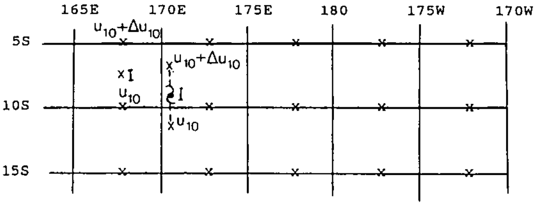
$$H^* = 2(T - 27.6)I^* \qquad \ldots 5$$

Thus $H^* \approx H \times 10^{-1}$ and it follows from Eqn 1 that H* for individual systems may also be written

$$H^* = V^2 \times 10^{-4} \qquad \ldots 6$$

where V gives some indication of the strength in

Fig. 1 Grid used to calculate intensification potential, I.



knots of the maximum sustained wind likely to be ultimately attained by the system.

If a definite circulation has already been identified, two grid-points, 2.5 degrees north and 2.5 degrees south of the estimated centre of the circulation, are used to obtain values of Δu_{10} for the circulation (Fig. 1). For reasons given earlier, grid-points 2.5 degrees east and 2.5 degrees west of the estimated centre are not used in calculating Δu_{10}. However, these are used (as additional points) in estimating the mean winds at 1000 hPa and 200 hPa, in the five-degree square centred on the disturbance, required to calculate $|S_Z|$. As before, I* is then calculated using Eqn 4.

Typical values of Δu_{10} and $|S_z|$ in a tropical convergence zone or trough are about 30 knots/5 degrees latitude and 30 knots/800 hPa respectively. This gives a typical value of 2×10^{-2} for I*. In the case of a developing tropical cyclone, typical values of Δu_{10} are about 50 knots/5 degrees latitude (for example 20 knot westerlies 2.5 degrees north of the estimated centre, and 30 knot easterlies 2.5 degrees south of the estimated centre) with typical values of $|S_z|$ around 10 knots. This leads to a typical value of $I^* = 10 \times 10^{-2}$ for a developing tropical cyclone.

In a similar way to the monthly/seasonal values of intensification potential, I, individual values, I*, are taken to be zero in any five-degree square where 1000 hPa relative vorticity is zero or positive (i.e. anticyclonic). Measured values of the vertical shear term, $|S_z|$, found to be less than five knots are inserted as five knots in the calculations for H*. (Otherwise values of H* would approach infinity as vertical shear goes to zero!)

It is interesting to note from Eqn 4 that intensification is directly proportional to low-level, horizontal, cyclonic wind shear and inversely proportional to deep-layer vertical wind shear. Horizontal and vertical shear thus oppose one another in the development process. Equation 5 indicates that sea-surface temperature (SST) must exceed 27.6°C for major cyclone development. Thus $H^* = 0$ for SST equal to or below 27.6°C. Overall, Eqn 5 states that hurricane index, H* (or the potential for major cyclone development), is directly proportional to low-level, horizontal, cyclonic shear and excess of sea-surface temperature above a threshold value of 27.6°C, and inversely proportional to deep-layer vertical shear.

Day-to-day observations of synoptic data in the tropical southwest Pacific during the period 1990–1993 showed that typical values of H* for sea-surface temperature excesses of 2.5°C above the threshold value of 27.6°C (i.e. SST about 30°C) were about $10 \times 10^{-2}\text{kn}^2$ for a tropical convergence zone or trough and $50 \times 10^{-2}\text{kn}^2$ for a major tropical cyclone in its developing stage. These observations showed that mean values of $H^* \geqslant 24 \times 10^{-2}\text{kn}^2$ observed over a period of at least 48 consecutive hours for a tropical system usually lead to the development of a cyclone. According to Eqn 6 this corresponds to values of $V \geqslant 50$ knots, that is for values of H* on or above the threshold value of $24 \times 10^{-2}\text{kn}^2$ the maximum sustained wind likely to be ultimately attained by the system is 50 knots or greater.

Case studies of the prediction of individual cyclone development

The purpose of these studies and later ones of composite samples was to test the hypothesis that cyclone development normally occurs only when values of H* equal or exceed 24 (units $\times 10^{-2}\text{kn}^2$ omitted) for a period of at least 48 hours preceding the development.

The area of study was the tropical southwest Pacific between longitudes 150°E and 150°W during the 1991/92 and 1992/93 cyclone seasons. As there was a good source of synoptic data available for tropical cyclone *Sina* (November 1990), this cyclone was included as a case study, but not in the later composite samples since it did not belong to either the 1991/92 or 1992/93 cyclone seasons.

Tropical cyclone *Sina*, 24–30 November 1990

The first indication of possible development came at 1200 UTC on 20 November 1990 when a value of $H^* = 29$ (five above the threshold value of $H^* = 24$) was obtained within the South Pacific covergence zone (SPCZ), in the area just west of Wallis Island (Fig. 2). At that stage SST in the area was about 30°C with low-level horizontal wind shear around 15 knots and deep-layer vertical wind shear five knots (Table 1).

Fig. 2 **Hurricane index, H* for 1200 UTC 20 November 1990 during development stage of *Sina*.**

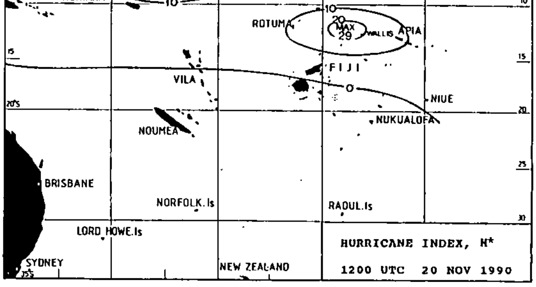


Table 1. Environmental parameters during development and mature stages of tropical cyclone *Sina*.

Date/time	*T(°C)*	$\Delta u_{10}(kn)$	$\lvert S_z \rvert (kn)$	$H^*(\times 10^{-2} kn^2)$	*V(kn)*
20 Nov 1990 1200 UTC	30.0	15	5	29	10
21 Nov 1990 1200 UTC	30.0	15	5	29	15
22 Nov 1990 1200 UTC	30.0	20	5	39	10
23 Nov 1990 1200 UTC	30.0	30	5	58	15
24 Nov 1990 1200 UTC	30.0	40	10	40	30
25 Nov 1990 1200 UTC	30.0	45	15	30	45
26 Nov 1990 1200 UTC	29.0	65	15	26	75
27 Nov 1990 1200 UTC	28.0	65	20	6	75
28 Nov 1990 1200 UTC	27.0	60	30	0	65
29 Nov 1990 1200 UTC	26.0	60	50	0	55

Note: V is estimated strength of the maximum sustained wind associated with the disturbance at the times shown.

By 1200 UTC on 21 November the position of maximum H* had moved westwards towards Rotuma, maintaining a value of H* = 29, and was close to Rotuma at 1200 UTC on 22 November with H* increasing to 39 (Figs 3 and 4). Subsequently the disturbance moved slowly northwestwards as a shallow depression, with values of H* peaking around 58 at 1200 UTC on the 23rd (Fig. 5) as an upper-level outflow became established over the system, developing into tropical cyclone *Sina* (Prasad 1992) about 1800 UTC on 24 November in a position about 250 miles northwest of Rotuma. The first indications of possible cyclone development thus came about four days before the cyclone formed, and 48-hour mean values of H* (48-hour mean H* = 32 for the period up to and including 22 November) were predicting a cyclone two days before it developed. The maximum value of H* (H*max) occurred one day before the system was designated a cyclone (H* = 58 at 1200 UTC on the 23rd). It is also interesting to note that vertical shear was no more than five knots during the four days preceding the naming of the cyclone (Table 1).

Sina reached peak intensity around 1800 UTC on the 26th with maximum sustained winds estimated at 75 knots, as the cyclone passed close to the southwest coast of Viti Levu (Fiji) (Fig. 6). Thereafter, steadily decreasing SST and increasing vertical shear quickly reduced H* to zero with a corresponding weakening of the cyclone.

Tropical cyclone *Val*, 4–13 December 1991

A value of H* = 29 at 1200 UTC on 1 December 1991 in the intertropical convergence zone (ITCZ), in the area just north of the Tokelaus, warned of the possibility of cyclone development in that area (Fig. 7). At that stage SST in the area was about 30°C with low-level horizontal wind shear around 15 knots and deep-layer vertical wind shear five knots (Table 2). Succeeding values of H* = 40 at 1200 UTC on the 2nd and H* = 77

Fig. 3 Hurricane index, H* for 1200 UTC 21 November 1990 during development stage of *Sina*.

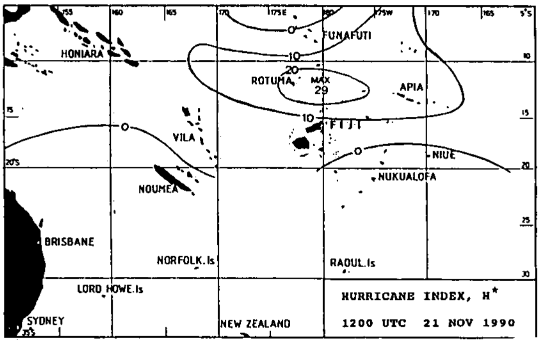
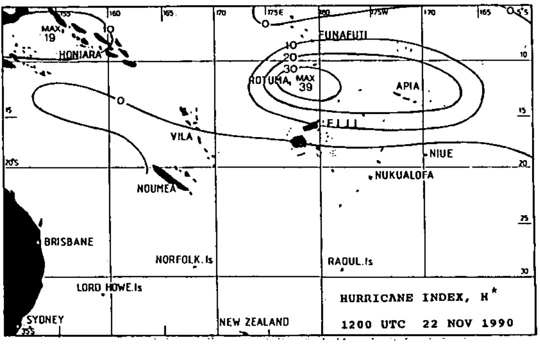
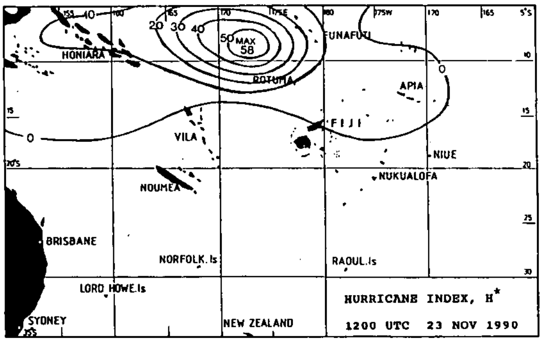


Fig. 4 Hurricane index, H* for 1200 UTC 22 November 1990 during development stage of *Sina*.



at 1200 UTC on the 3rd (Figs 8, 9) (48-hour mean H* = 49, 25 above threshold value, H* = 24), apparently confirmed that a cyclone was developing, as the disturbance moved steadily westwards within the ITCZ towards Rotuma on the 2nd and 3rd. During this initial phase the disturbance lay in a position close to the centre of an area of upper-level outflow. The potential cyclone development area moved towards Tuvalu as a small depression on the 4th, and a tropical cyclone finally developed around 0600 UTC on the 5th, between Tuvalu and the Tokelaus (Pandaram and Prasad 1992). This was nearly four days after the first value of H* ⩾ 24 was observed, nearly two days after the first 48-hour mean values of H*⩾24 were obtained, and nearly two days after the primary H*max occurred (H* = 77 at 1200 UTC on the 3rd).

Fig. 5 Hurricane index, H* for 1200 UTC 23 November 1990 during development stage of *Sina*.



Val reached peak intensity just before making landfall on Savaii (Western Samoa) around 1800 UTC on the 7th, with maximum sustained winds of about 90 knots (Fig. 10).

Again, it is interesting to note that vertical wind shear was no more than five knots for three of the four days preceding the naming of the cyclone (Table 2). However, $|S_z|$ increased temporarily to 25 knots on the 4th but dropped to 10 knots on the 5th and 6th as a strong new upper-level outflow pattern quickly became established above the centre of the surface disturbance. This lead to a secondary H*max (= 64) on the 6th which appears to have preceded a period of 'explosive' development in the next 24 hours (maximum sustained winds increasing from 55 knots to 90 knots).

Fig. 6 Track of tropical cyclone *Sina* 24–30 November 1990.

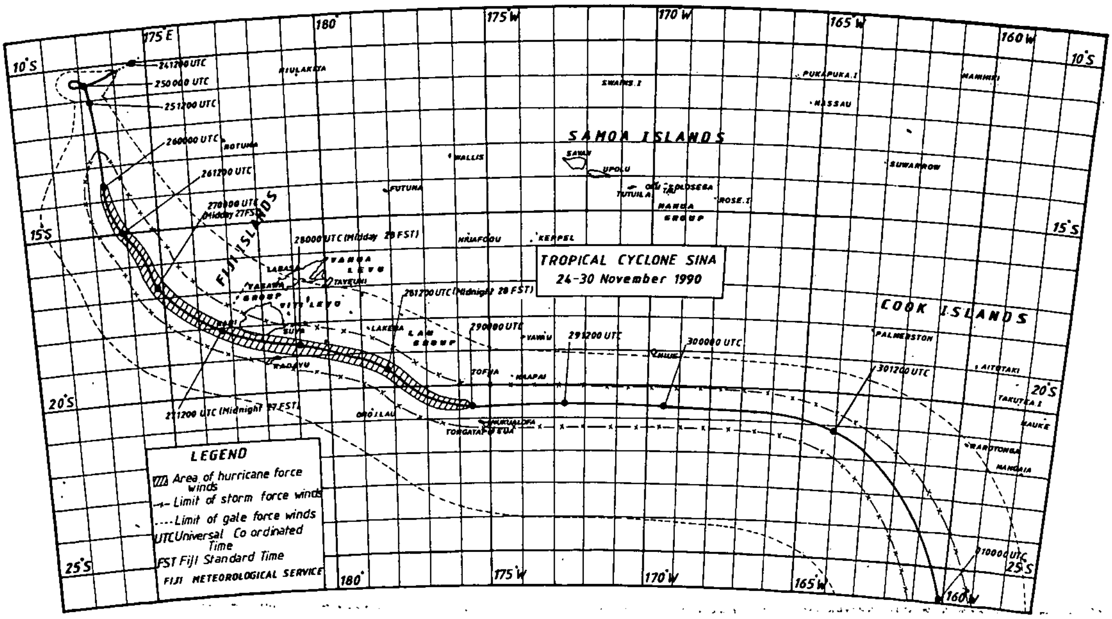


Fig. 7 **Hurricane index, H* for 1200 UTC 1 December 1991 during development stage of *Val*.**

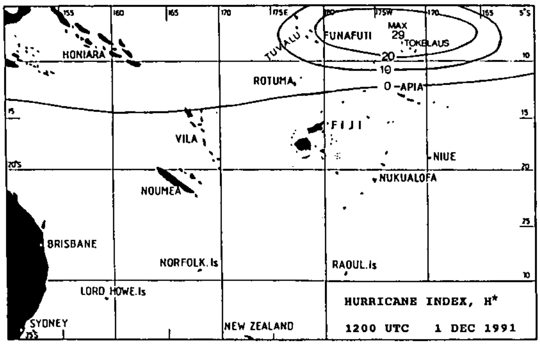


Fig. 8 **Hurricane index, H* for 1200 UTC 2 December 1991 during development stage of *Val*.**

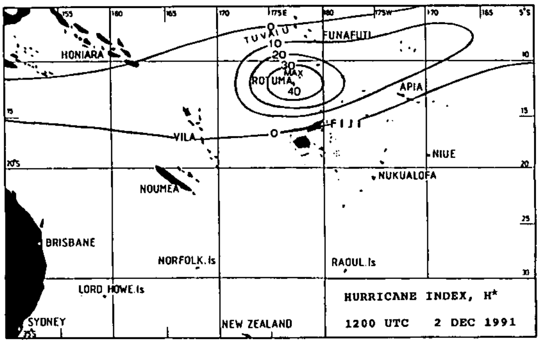
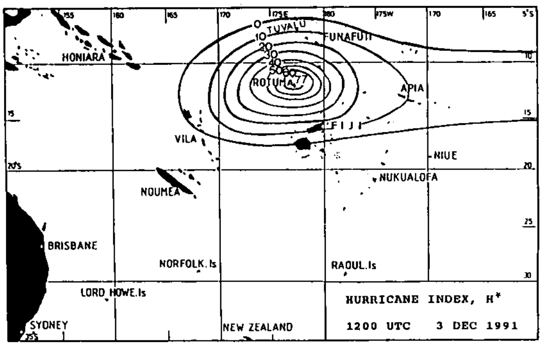


Fig. 9 **Hurricane index, H* for 1200 UTC 3 December 1991 during development stage of *Val*.**



Composite 'H*' and 'V' time-series for samples of developing and non-developing systems

Time-series were constructed using the composite data for eleven disturbances which developed into cyclones during the 1991/92 and 1992/93 seasons, together with those for 14 disturbances which failed to become cyclones during the same period.

Again, the study area was the tropical southwest Pacific between 150°E and 150°W. All calculations of H*-values for the disturbances were made on an operational basis as predictions at the times when the systems were in existence, using the synoptic data then available. An exception was tropical cyclone *Val* for the period after day −1 when the calculations were made after the event. In all cases of cyclone development values of H* above the threshold value of 24 were calculated *before* the systems became cyclones. Due to operational limitations values of H* were not obtained for all disturbances during the 1991/92 and 1992/93 cyclone seasons but there was no bias in the selection of those cases that were studied. In two of the cases of non-development (9–11 November 1992 and 24–26 November 1992) the data were doubtful or incomplete but considered to be adequate for inclusion in the composite analyses.

Composite values of H* and V, where V = strength in knots of the maximum sustained wind of each individual disturbance, were obtained for the eleven cyclones and the fourteen non-developing disturbances for each day preceding and following 'day 0', where 'day 0' corresponds to the day when H* reaches its maximum value (H*max). In most cases H*max is found to correspond closely with the time the system becomes a cyclone (winds 34 knots or above).

Figure 11 shows the variation of the composite H* values (thick line) for the eleven cyclones. Note that H* falls off rapidly following H*max even though the cyclone may still be intensifying. The decrease in H* is due to decreasing SST and/or increasing vertical wind shear. The former may result from upwelling of sea water due to stirring by the increasing winds, also from the poleward movement of the cyclone. Vertical wind shear is much influenced by the high-level outflow. When this is centred over the cyclone vertical shear is generally small. If the cyclone and centre of high-level outflow become separated, vertical shear usually increases. In all cases of cyclone development the individual values of H*max (48-hour mean) exceed the threshold value of 24 (see Table 3).

The thin line in Fig. 11 represents the variation of the composite H*-values for the fourteen non-developing disturbances. Note that the values of

Fig. 10 **Track of tropical cyclone *Val* 4–13 December 1991.**

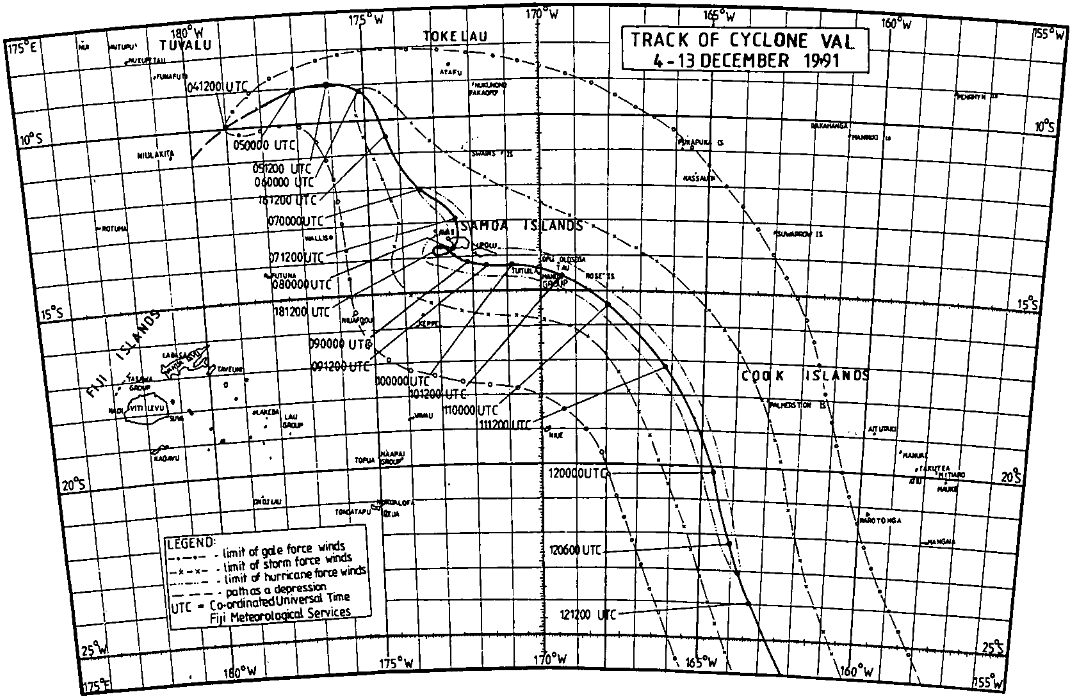


Table 2. Environmental parameters during development and mature stages of tropical cyclone *Val*.

Date/time	*T(°C)*	*Δu_{10}(kn)*	*$\lvert S_z \rvert$(kn)*	*H^*($\times 10^{-2}$kn^2)*	*V(kn)*
1 Dec 1991 1200 UTC	30.0	15	5	29	10
2 Dec 1991 1200 UTC	30.0	20	5	40	20
3 Dec 1991 1200 UTC	30.0	40	5	77	25
4 Dec 1991 1200 UTC	30.0	30	25	12	35
5 Dec 1991 1200 UTC	29.5	40	10	38	45
6 Dec 1991 1200 UTC	29.5	80	10	64	55
7 Dec 1991 1200 UTC	29.0	70	15	28	90
8 Dec 1991 1200 UTC	28.5	70	15	19	90
9 Dec 1991 1200 UTC	28.0	80	10	16	85
10 Dec 1991 1200 UTC	28.0	80	20	8	80

Note: V is estimated strength of the maximum sustained wind associated with the disturbance at the times shown.

Table 3. Evironmental parameters (48-hour mean values) corresponding to the highest 48-hour mean value of H* observed during the history of each disturbance, H*max (48-hour mean). Vmax is the highest sustained wind attained during the history of each disturbance.

Tropical cyclones			*T(°C)*	*Δu_{10}(kn)*	*$\lvert S_z \rvert$(kn)*	*H^*max (48-hour mean) ($\times 10^{-2}$kn^2)*	*Vmax(kn)*
Val	4–13 Dec 1991	Samoa	30.0	25	5	49	90
Betsy	5–13 Jan 1992	Vanuatu	29.5	55	8	67	90
Esau	25 Feb–5 Mar 1992	Vanuatu	29.5	80	12	55	100
Fran	4–15 Mar 1992	N of Fiji/Vanuatu	29.5	80	13	47	100
Joni	6–13 Dec 1992	Fiji	29.5	65	12	48	80
Kina	26 Dec 1992–5 Jan 1993	Fiji	29.5	65	15	35	75
Lin	30 Jan 1992–5 Feb 1993	Samoa	30.0	45	8	67	65
Mick	5–9 Feb 1993	Tonga	30.0	40	17	26	45
Nisha	12–16 Feb 1993	Southern Cooks	29.0	40	13	27	50
Oli	15–18 Feb 1993	Fiji	30.0	45	17	28	40
Polly	25 Feb–2 Mar 1993	Coral Sea	28.5	65	8	39	85

Table 4. Environmental parameters (48-hour mean values) corresponding to the highest 48-hour mean value of H* observed during the history of each disturbance, H*max (48-hour mean).

Disturbances which failed to become tropical cyclones	*T(°C)*	*Δu_{10}(kn)*	*$\lvert S_z \rvert$(kn)*	*H*max (48-hour mean) ($\times 10^{-2}$ kn^2)*	*Vmax (kn)*
30 Oct–3 Nov 1992 initially near 5S 163E	30.0	40	15	29	30
9–11 Nov 1992 " " 9S 170W	28.5	25	13	9**	15
17–20 Nov 1992 " " 4S 174E	29.0	30	13	12	20
24–26 Nov 1992 " " 11S 163W	30.0	25	5	50**	20
27 Nov–3 Dec 1992 " " 10S 175W	30.0	45	13	31	25
28 Nov–3 Dec 1992 " " 6S 174E	30.0	40	17	28	30
11–17 Dec 1992 " " 8S 162W	30.0	25	22	12	20
13–15 Dec 1992 " " 3S 158E	30.0	25	8	38	20
17–19 Dec 1992 " " 9S 174W	30.0	30	23	13	20
19–22 Dec 1992 " " 7S 152E	30.0	20	8	32	10
29–30 Dec 1992 " " 9S 173W	30.5	20	10	20	15
6–8 Jan 1993 " " 11S 171W	29.5	20	10	18	15
11–13 Jan 1993 " " 12S 148W	29.0	45	10	29	35
18–23 Feb 1993 " " 10S 162E	30.5	20	10	25	20

**Data doubtful or incomplete

Fig. 11 Composite time-series for H* for 11 cyclones (*Val*, *Betsy*, *Esau*, *Fran*, *Joni*, *Kina*, *Lin*, *Mick*, *Nisha*, *Oli*, *Polly*) and fourteen non-developing disturbances (see Table 4 for details).

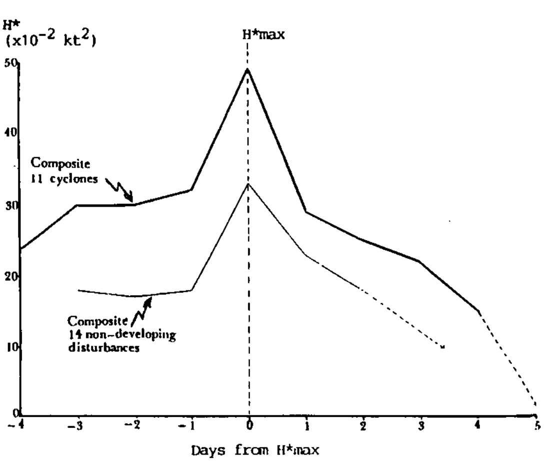
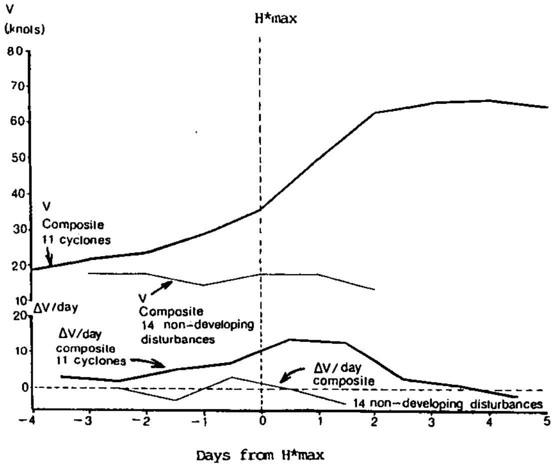


Fig. 12 Composite time-series for V for eleven cyclones (*Val*, *Betsy*, *Esau*, *Fran*, *Joni*, *Kina*, *Lin*, *Mick*, *Nisha*, *Oli*, *Polly*) and fourteen non-developing disturbances (see Table 4 for details).



H* are much lower than for the cyclones and are below 24 except for H*max. However, the general shape of the H*-curve is much the same for developing and non-developing disturbances alike. In eight cases of non-development the individual values of H*max (48-hour mean) exceeded the threshold value of 24 (see Table 4) and could have given rise to false alarms.

Figure 12 shows the variation of the composite V-value (thick line) for the eleven cyclones. Note that V steadily increases in the days leading up to H*max, reaching about 35 knots and becoming a cyclone about that time. Vmax (the highest composite value of V) is not reached until some three to four days after H*max. Possibly the time-lag between the release of latent heat of condensation and its eventual conversion into kinetic energy (manifested by strengthening winds) may account for the further intensification of the cyclone even though H* may be falling off rapidly following H*max. The reason for H*max occurring about the time a cyclone is named is not clear and needs further study. The rapid formation of a warm core about this time, perhaps leading to the formation of an 'eye', appears to be associated with a minimum value of vertical shear.

This, together with high values of SST (preceding significant sea water upwelling) and high values of Δu_{10}, produce the highest value of H* about that time.

The thin line in Fig. 12 shows the variation of the composite V-values for the fourteen non-developing disturbances. Note that V shows little variation throughout the life cycle of the non-developers.

Also shown in Fig. 12 is the daily increase/decrease in V for developers and non-developers. In the case of the developers, the most rapid intensification is in the 24 hours following H*max, that is in the day immediately after the system becomes a cyclone. Non-developers, on the other hand, exhibit zero intensification in the 24 hours following H*max.

The eleven developers were then further divided into those that developed into hurricanes (eight) and those that only reached storm or gale intensity (three) (Figs 13 and 14). Note that in the case of the hurricanes Vmax was not reached until some four to five days after H*max (or after the system became a cyclone), while in the case of the systems that reached only storm or gale intensity Vmax was reached by 'day +1'. After 'day −4'

Fig. 13 **Composite time-series for H* for eight hurricanes (*Val, Betsy, Esau, Fran, Joni, Kina, Lin, Polly*), and three cyclones that failed to reach hurricane intensity (*Mick, Nisha, Oli*).**

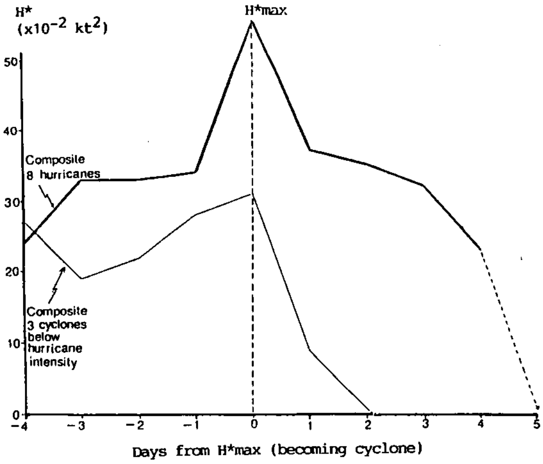


Fig. 14 **Composite time-series for V for eight hurricanes (*Val, Betsy, Esau, Fran, Joni, Kina, Lin, Polly*), and three cyclones that failed to reach hurricane intensity (*Mick, Nisha, Oli*).**

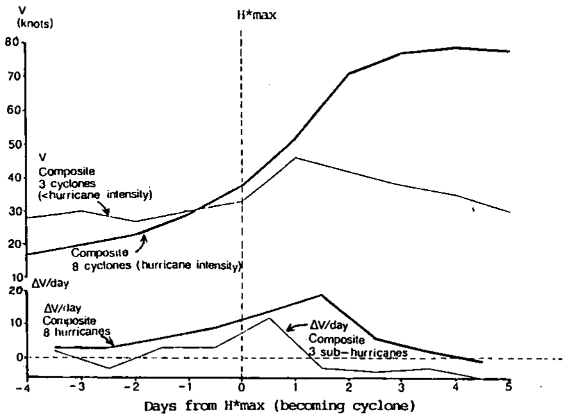


Fig. 15 **Time-series for H* for individual systems. (Note that H*-values for *Val* were not obtained operationally after day −1. Therefore subsequent values are shown by a dashed line.)**

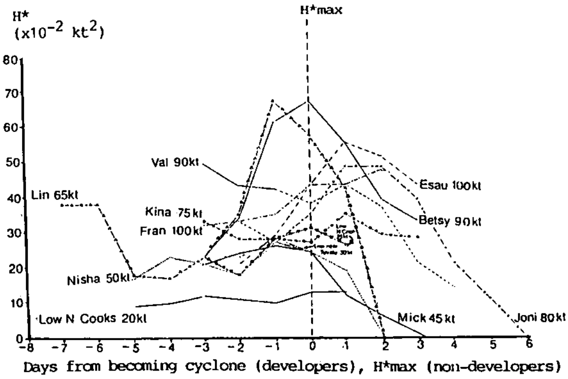
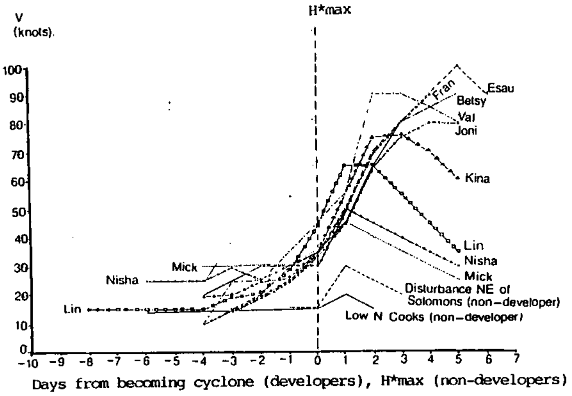


Fig. 16 **Time-series for V for individual systems.**



the composite values of H* were always larger for the systems that developed into hurricanes than for the systems that reached only storm or gale intensity.

Figures 15 and 16 display the variation of H* and V for individual systems. Since there is considerable noise in the individual values, H* has been smoothed by using 48-hour mean values, $\frac{1}{3}(H^*_{-1} + H^*_0 + H^*_{+1})$.

Conclusion

At least for the sample of disturbances studied, H*-values are shown to be a useful tool in predicting the formation and development of tropical cyclones. The potential for a small disturbance to develop into a tropical cyclone is usually revealed when average values of H* equal to or greater than 24 are observed for a period of at least 48 hours. This generally gives at least 24-hours warning before cyclone intensity is reached.

In addition, the potential for cyclone formation is often revealed by the H*-values several days before the typical cloud pattern associated with cyclone development is observed in the satellite imagery. It is thus a valuable addition to the satellite picture interpretations in predicting development. However, there is a problem with the non-developers, about half of which in the sample indicated 48-hour mean values of H*max above the threshold value of 24. Further investigation is needed to distinguish these cases from those where development occurred. Of the total of 19 disturbances which had H*max (48-hour mean) equal to or greater than 24, 58 per cent developed into cyclones. Of the total of six disturbances which had H*max (48-hour mean) below 24, all failed to develop into cyclones. It can thus be stated, for the total sample of 25 disturbances studied, a necessary but *not* sufficient condition for cyclone development is H*max (48-hour mean) $\geqslant 24$, and that development is unlikely for H*max (48-hour mean) < 24. The technique can thus be applied to cloud clusters observed in the satellite imagery to determine whether such systems are likely or not to develop into cyclones, using synoptic data that are normally readily available on an operational basis.

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