parameter values) $C, C', D$ and $D'$ remain non-zero. Therefore, it follows from Eq. (4) that $\theta$ will diverge at the poles and pass outside the physical domain (0 to 1) at polar latitudes, a result that cannot be avoided by increasing the accuracy to which $\xi$ is estimated. Paltridge's calculations did not extend beyond 64°N and 64°S, and so did not meet this limitation. Hence, the assumption of maximum vertical heat flux cannot be applied in the polar regions, for to retain it would require that $(D'C - C'D) \to 0$ at the poles which would involve additional assumptions about high latitude atmospheric radiation processes. The assumption is also inapplicable if $(g - d)$ is small.

**Reference**


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**By Greg J. Holland**

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(Received 29 April 1980)

Johns and Anwar Ali (JA) have presented a detailed numerical simulation of storm surges generated by tropical cyclones in the Bay of Bengal, an area which history has shown to be particularly sensitive to such events. However, JA's surge analyses may be to a substantial degree negated by incorrect interpretations of the pressure (and hence wind) distribution in their idealized cyclone.

JA use a pressure distribution given by (their equation 23)

$$p = p_a - \Delta p \exp(-r/R)$$

where $p$ is pressure at radius $r$, $p_a$ the ambient pressure, $\Delta p$ the difference between the ambient and central pressures and $R$ a constant. JA describe $R$ as the c-folding radius of the cyclone (strictly of the pressure distribution) which they seem to incorrectly interpret as being 350 km. As shown below, $R$ is better described as the radius to maximum winds (RMW).

Since typical Rossby numbers for tropical cyclones are of order $10^{-2}$, especially in the strongest wind region, we may assume that the tangential winds are in approximate cyclostrophic balance and hence

$$V_c = (r/\rho) \partial p/\partial r$$

where $V_c$ is the cyclostrophic tangential wind and $\rho$ the air density. After substituting (1) for $p$ we have:

$$V_c = (r \Delta p \exp(-r/R)/\rho R)$$

The characteristic shape of this curve is a rapid increase in winds with radius from the origin to a single maximum followed by a gradual decrease and tangential approach to zero at infinite radius. We can therefore determine the RMW by differentiating (3) with respect to radius and setting the result equal to zero.

$$\partial V_c/\partial r = \frac{1}{4}(r \Delta p \exp(-r/R)/\rho R)^{1/2}(1 - r/R) \Delta p \exp(-r/R)/\rho R.$$  \hspace{1cm} (4)

The non-trivial solution is at $r = R$, hence $R$ is the RMW.

A typical RMW is 35 km with variations from 5 to 80 km possible (Shea and Gray 1973). Hence, for a typical cyclone JA's use of $R = 350$ km is wrong by an order of magnitude. To illus-
Figure 1. Radial distributions of gradient winds: A using (5) with $R = 350\, \text{km}$, B using (5) with $R = 35\, \text{km}$, and C using winds derived from (6).

To illustrate this, gradient wind distributions using $R = 35\, \text{km}$ and $R = 350\, \text{km}$ are shown in Fig. 1, where from (1) using the standard gradient relation

$$V_g = (r\Delta p \exp(-r/R)/\rho R + f^2 r^2/4)^{1/2} - fr/2$$  \hspace{1cm} (5)$$

$V_g$ is the gradient wind, $f$ the Coriolis force. Set $\Delta p = 50\, \text{mb}$, $\rho = 1.2\, \text{kg}\, \text{m}^{-3}$ and $f = 5 \times 10^{-5}\, \text{s}^{-1}$. Clearly using $R = 350\, \text{km}$ gives a tangential gradient wind distribution which is uncharacteristic of tropical cyclones, while $R = 35\, \text{km}$ is more realistic. (The maximum gradient wind setting $R = 350\, \text{km}$ is at about 280\, \text{km} because the $-fr/2$ term becomes important at these large radii.)

This incorrect interpretation of the pressure and wind distribution appears to substantially weaken the credibility of the accompanying surge analyses and discussion. In particular, the large wavelength from surge peak to trough of about 700\, km is far too large. As indicated by JA on p. 10, setting $R = 40\, \text{km}$ substantially reduces the wavelength and presumably gives better results (analyses not presented).

Even with a correct value of $R$, I have reservations about the use of (1) and (5) to model tropical cyclone wind and pressure distributions. As discussed in Holland (1980) there are many problems with analytically modelling these distributions, however reasonable accuracy may be obtained with a profile of the form

$$p = p_c + \Delta p \exp(-A/r^w)$$  \hspace{1cm} (6)$$

where $p_c$ is the central pressure and $A$, $B$ are empirical constants. Using empirical and physical arguments, $B$ was shown to be a function of central pressure which varied between 1 and 2.5, the parameter $A$ being then uniquely determined by the selected value of the RMW.

Further details may be found in Holland (1980), but for comparison the gradient wind distribu-
tion for the above idealized cyclone is plotted on Fig. 1 (here $B = 1.5$, $A = 207$). This profile (which is markedly different to (5) with $R = 35$ km) is for an isolated symmetrical cyclone and is strictly not valid beyond about 150–200 km where the effects of cyclone movement and imposed environmental fields will often be dominant.

ACKNOWLEDGMENTS

Many thanks to Professor W. M. Gray, G. Love, C. S. Lee for their helpful comments and to B. Brumit for typing the manuscript.

REFERENCES


REPLY

By B. Johns and Anwar Ali

Greg Holland raises an important point when commenting on our paper. His claim that our Eq. (23) implies a maximum gradient wind speed at a radial distance of about 250 km from the centre of our idealized cyclone is obviously correct and we recognize that this contradicts the generally accepted value of about 40 km. We base a justification of our choice of parameters on the following points. If, as mentioned in our paper, we select $R = 40$ km in Eq. (23) the surge response is much altered in character. In particular, the maximum surface elevation is about 1.5 m. This contrasts strongly with the 7 m estimated for the Chittagong region during the November 1970 surge. We attributed this unrealistically low model response to the fact that our Eq. (23) with $R = 40$ km yields insignificant winds at $r = 200$ km. This is evident from curve (B) in Holland’s Fig. (1). Our contention, therefore, is that wind stress forcing at such radial distances from the centre of a tropical cyclone must play an important part in generating the surge response. In view of the unacceptability of Eq. (23) with $R = 40$ km, we considered an empirical representation of the wind field suggested by Jelensianski (1965). This states that

\[
V = \begin{cases} 
V_{\text{max}} (r/R)^{1/4} & \text{for } 0 < r < R \\
V_{\text{max}} (R/r)^{1/4} & \text{for } r \geq R 
\end{cases}
\]

(1)

According to (1), the maximum wind speed $V_{\text{max}}$ occurs at $r = R$. Taking $R = 40$ km, with $V_{\text{max}} = 65$ m s$^{-1}$ (the estimated value for the mature stage of the 1970 cyclone), the wind speed for $r = 1000$ km is 13 m s$^{-1}$. The representation (1) therefore shows a similar concentrated peaking of the wind speed at $r = 40$ km as is apparent in curve (C) in Holland’s Fig. (1). However, the direct application of (1) in our model hardly seems appropriate because of the inability of our grid to resolve features having a length scale of less than 36 km. In other words, the resolution in our model does not permit an adequate representation of the detail of the wind-stress forcing beneath the inner core of the cyclone. We therefore decided to use our Eq. (23) with $\Delta p = 50$ mb and with $R = 350$ km. Taking $f = 5 \times 10^{-5}$ s$^{-1}$, the resulting gradient balance wind speed at $r = 250$ km is approximately 30 m s$^{-1}$. This compares with 26 m s$^{-1}$ from (1) when $R$ is 40 km and $V_{\text{max}} = 65$ m s$^{-1}$. At $r = 1000$ km, our Eq. (23) leads to a wind speed of about 10 m s$^{-1}$ which is comparable with the 13 m s$^{-1}$ obtained from (1).

As support for taking a representation having the form of (1) to model Bay of Bengal cyclones, we may refer to the Andhra Pradesh cyclone of 1977. This struck the Andhra coast of India and led to a well-authenticated surge response of about 4.5 m. The forcing cyclone led to estimated wind speeds of 50 m s$^{-1}$ at 35–40 km from its centre. Wind speeds in excess of 15 m s$^{-1}$ were estimated at about 500 km. The application of (1) with $V_{\text{max}} = 50$ m s$^{-1}$ and $R = 40$ km models this distribution fairly well.

Whilst we do not regard our simplistic representation of the cyclone to be ideal (or the only way of proceeding), we submit that the generation of a significant surge is predominantly controlled by wind-stress forcing over a distance of several hundred kilometres. Although, in this
region, the associated wind speeds are reduced well below the maximum at the perimeter of the core of the cyclone, we contend that the effect of the wind-stress forcing in this relatively small inner region is comparatively weak.

REFERENCE