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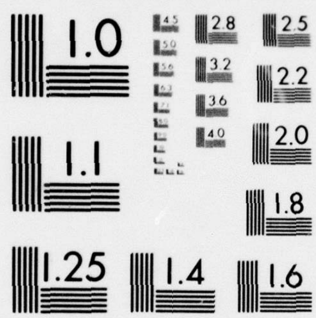


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# Acoustically Relevant Eddy Effects and Ocean Surface Height.

by

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## ABSTRACT

Underwater sound transmissions are significantly affected by the presence of mesoscale eddies, because large sound-speed variations and rotational currents are associated with these phenomena. Using an earlier axisymmetric eddy model, equations and graphs of the ocean surface are found above an eddy. The surface is elevated above an anticyclonic eddy and depressed in the cyclonic case (northern hemisphere). This behavior may be used to detect and partially classify an ocean eddy. With an appropriate eddy model, satellite altimeter data may be used to approximate acoustically-relevant effects.

## INTRODUCTION

The effects of an ocean eddy on underwater sound transmissions can be dramatic. In particular, major acoustical influences occur through large sound-speed variations and relatively large currents. Several eddy-acoustics studies have been presented at Acoustical Society meetings, while others have appeared as published papers or technical reports. Although most investigations have emphasized eddy effects on sound propagation, others have been concerned with the inverse problem of using acoustics to detect eddies and predict their properties. Examples of some of these studies are Refs. 1-6.

Recently, three of the authors of this Letter used an analytical approach to obtain an approximate solution for deep-ocean eddies, and used the solution in the development of a model relating acoustically-relevant quantities to eddy parameters.[7] The model was intended to provide a basis for analytical sound-transmission studies. Subsequently, we considered the use of limited observational data and analytical eddy models in approximating acoustically-important environmental effects.[8]

Because of the strong interrelationships between underwater acoustics and ocean eddies, it is important to know when an eddy lies in a sound-transmission path, or when its trajectory appears to ultimately intersect such a path. It is important also to know the characteristics of such an eddy. A possible procedure for determining such information is to investigate one or more of the ways in which an eddy expresses itself on the ocean surface. For example, an eddy will affect surface height, its maximum rotational current should occur near the surface, and a cold or warm surface temperature pattern may sometimes be present.

In this Letter, we are concerned with two aspects of surface height above an eddy. First, using the model of Ref. 7, we examine surface height in terms of eddy parameters and location within the eddy. Second, we consider the possible prediction of eddy parameters from surface behavior, emphasizing the utilization of satellite altimetry data.

## II. SURFACE HEIGHT

Although mesoscale eddies are complex and varied ocean formations, they can be divided into two distinct types: Cyclonic eddies consist of a cold-water mass circulating in the counter-clockwise direction (in the northern hemisphere); anticyclonic eddies have a warm core and rotate clockwise. A number of actual eddies of either type can be satisfactorily described by the model of Ref. 7. In this study axisymmetry was taken, so that each horizontal section of the eddy is circular. The vanishing of eddy-induced effects beyond a radius $r_0$, and below a depth $z_0$, was assumed.

If r is dimensional radial distance from the vertical eddy axis and z is dimensional depth from the ocean surface in the absence of the eddy, then the dimensional pressure within the eddy is given by Ref. 7 as

$$P(r,z) = P_A + \rho_0 g\{(1+gDA/c_0^2)z + gz^2/2c_0^2 - (gD^2A/c_0^2B)\ln(1+Bz/D) - U_0 r_0 K[J_0(\alpha r/r_0) - J_0(\alpha)][F^{(1)}(z) - F^{(1)}(z_0)]\} \quad . \tag{1}$$

In Eq. (1),

$$K = \pm\, 2\Omega g^{-1}(\sin\phi)\{\alpha m[1-F^{(1)}(z_0)]\}^{-1} \quad , \tag{2a}$$

$$F^{(1)}(z) = (1+Bz/D)^{-1/2}\{\cos\,[(\gamma/2)\ell n(1+Bz/D) + (1/\gamma)\sin[(\gamma/2)\ell n(1+Bz/D)]\} \ , \tag{2b}$$

and

$$\gamma = 2\pi[\ell n(1+Bz_0/D)]^{-1} \ . \tag{2c}$$

In the above equations $P_A$ is atmospheric pressure, $\rho_0$ and $c_0$ are the density and sound speed at $z = 0$, $g = 9.81$ m/sec$^2$ is the gravitational constant, and D is unperturbed ocean depth. The symbols A and B are constants depending on the mean ocean state, chosen here as 0.3064 and 11.56, $U_0$ is the maximum rotational surface speed, $\ell n$ is the natural logarithm, and $J_0$ is the Bessel function of order zero. The constant $\Omega = 7.27 \times 10^{-5}$ rad sec$^{-1}$ is the magnitude of the earth's angular velocity, $\phi$ is latitude which we will take subsequently to be $35^o$, $m = 0.582$, and $\alpha = 3.83$. The plus (minus) sign in Eq. (2a) corresponds to a cyclonic (anticyclonic) eddy.

An equation for the surface may be obtained from Eq. (1) by setting the pressure equal to the constant atmospheric pressure $P_A$, giving

$$(1+gDA/c_0^2)z + gz^2/2c_0^2 - (gD^2A/c_0^2B)\ell n(1+Bz/D)$$

$$-U_0r_0K[J_0(\alpha r/r_0)-J_0(\alpha)][F^{(1)}(z)-F^{(1)}(z_0)] = 0 \ . \tag{3}$$

We observe that Ref. 7 assumes axisymmetric eddies and vanishing vertical velocity as a boundary condition near the surface, which together imply the vanishing of the velocity component normal to the surface.

## III. RESULTS

Although Eq. (3) is a proper surface expression, it is more convenient to be able to write z as an explicit function of r. Since $|z/D|$ is small at the surface, this can be accomplished approximately by expanding the left side of Eq. (3) in powers of z/D and retaining only linear terms. We obtain as a highly accurate approximation,

$$z = \pm\ (2\Omega\ \sin\ \phi/\alpha\ mg) U_0 r_0 [J_0(\alpha r/r_0) - J_0(\alpha)]\ . \qquad (4)$$

The extreme value of z occurs when $r = 0$, and is directly proportional to both eddy strength $U_0$ and radius $r_0$. In Eq. (4), choice of the plus (minus) sign corresponds to a cyclonic (anticyclonic) eddy. Thus, the surface is depressed ($z > 0$) above cyclonic eddies and is elevated ($z < 0$) in the anticyclonic case. By examining Eq. (4) in conjunction with Ref. 7, we make the important and physically-plausible observation that the approximate surface expression is independent of the functional form of the potential density, and consequently of the vertical mode structure.

Equation (4) can be written conveniently in terms of a dimensionless height $\bar{z}$:

$$\bar{z} = \pm(\alpha mg/2\Omega U_0 r_0 \sin\ \phi) z = J_0(\alpha r/r_0) - J_0(\alpha)\ . \qquad (5)$$

The graph of Eq. (5) is plotted in Fig. 1. It can be applied for any values of the fundamental parameters $U_0$ and $r_0$; it describes the magnitude of surface height in any radial direction from the eddy center. We observe that the height deviation from the static ocean is a maximum at the eddy center, and decreases steadily to zero on the eddy circumference.

Figures 2 and 3, obtained from Eq. (4) or (5) or Fig. 1, show specific surface profiles in a vertical cut through eddy centers. Figure 2 shows the surface for various eddy radii and $U_0$ = 1 m/sec. Figure 3 shows similar results for several peak currents and a fixed radius of 125 km. In both figures, the maximum height deviation at the eddy center is approximately 1 m.

## IV. USE OF ALTIMETRY DATA

Recent developments in satellite altimetry instrumentation permit reasonable accuracy in measuring ocean surface-height perturbations. If a satellite traverses an eddy during an orbit, the traversal will be nearly a linear path. Surface-height readings along the path, when compared with those predicted by a suitable eddy model, may predict some model parameters. For example, this might be accomplished by minimizing the sum of squares of the error between observed data and that predicted by Eq. (4) at a discrete number of points along the path. This procedure[8] was proposed previously for other types of eddy observations such as temperature and current. In particular, for the model of Ref. 7, $r_0$ and $U_0$ can be obtained uniquely. However, since height data are available only on an eddy chord (the linear trajectory), an ambiguity can be shown to exist in the position of the eddy center. Thus, either one of two eddies, whose centers are on opposite sides of the chord, could be responsible for the observed surface height. To locate the center uniquely, additional data, such as that along a second chord from another satellite traversal, would be required.

To specify eddy effects at all depths, Ref. 7 requires that $z_0$ also be specified. This parameter cannot be determined from surface-height information. Fortunately, however, vertical eddy structure is relatively insensitive to variations in $z_0$, so that it could be reasonably estimated from past study of the eddy or from knowledge of similar previously-studied eddy types. With all parameter values specified, acoustically-relevant quantities, including sound speed and current, could then be described throughout the eddy.[7]

## V. CONCLUSIONS

Since mesoscale eddies have a profound effect on underwater sound transmissions, their existence and properties must be known. Using a previously derived eddy model, equations are derived and discussed for the mean ocean surface above a class of axisymmetric eddies. In addition, it is indicated how satellite altimetry data might be used to estimate the sound-speed and current structures within an eddy.

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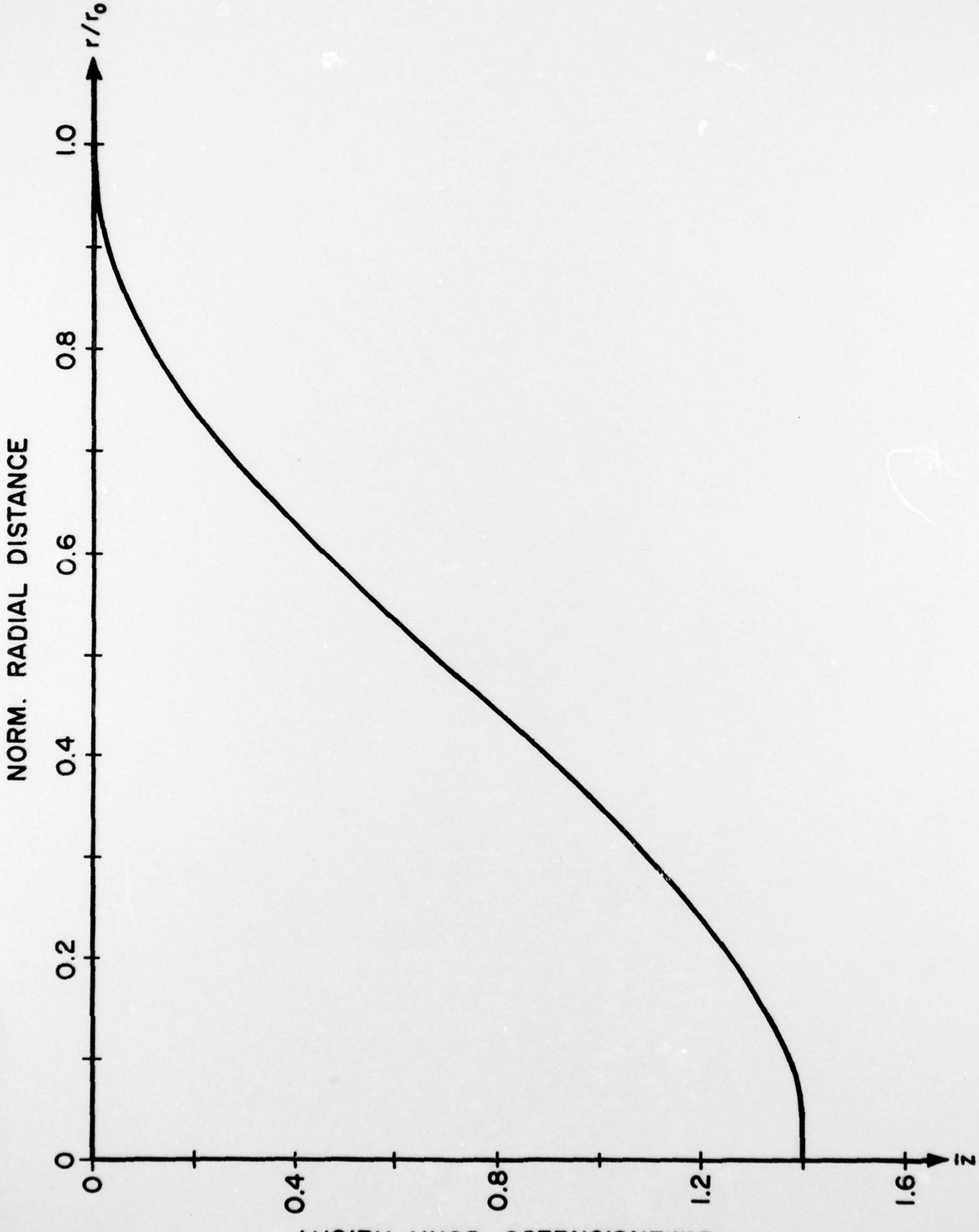
FIGURE LEGENDS

FIG. 1. Dimensionless surface height versus normalized radial distance, Eq. (5).

FIG. 2. Surface height versus radial distance for selected values of eddy radius $r_0$. Maximum surface speed $U_0$ = 1.0 m/sec, latitude $\phi = 35^o$.

FIG. 3. Surface height versus radial distance for selected values of maximum surface speed $U_0$. Eddy radius $r_0$ = 125 km, latitude $\phi = 35^o$.



NORM. RADIAL DISTANCE
r/r₀
DIMENSIONLESS SURF. HEIGHT
z̃
0
0.2
0.4
0.6
0.8
1.0
1.2
1.6


FIGURE 1

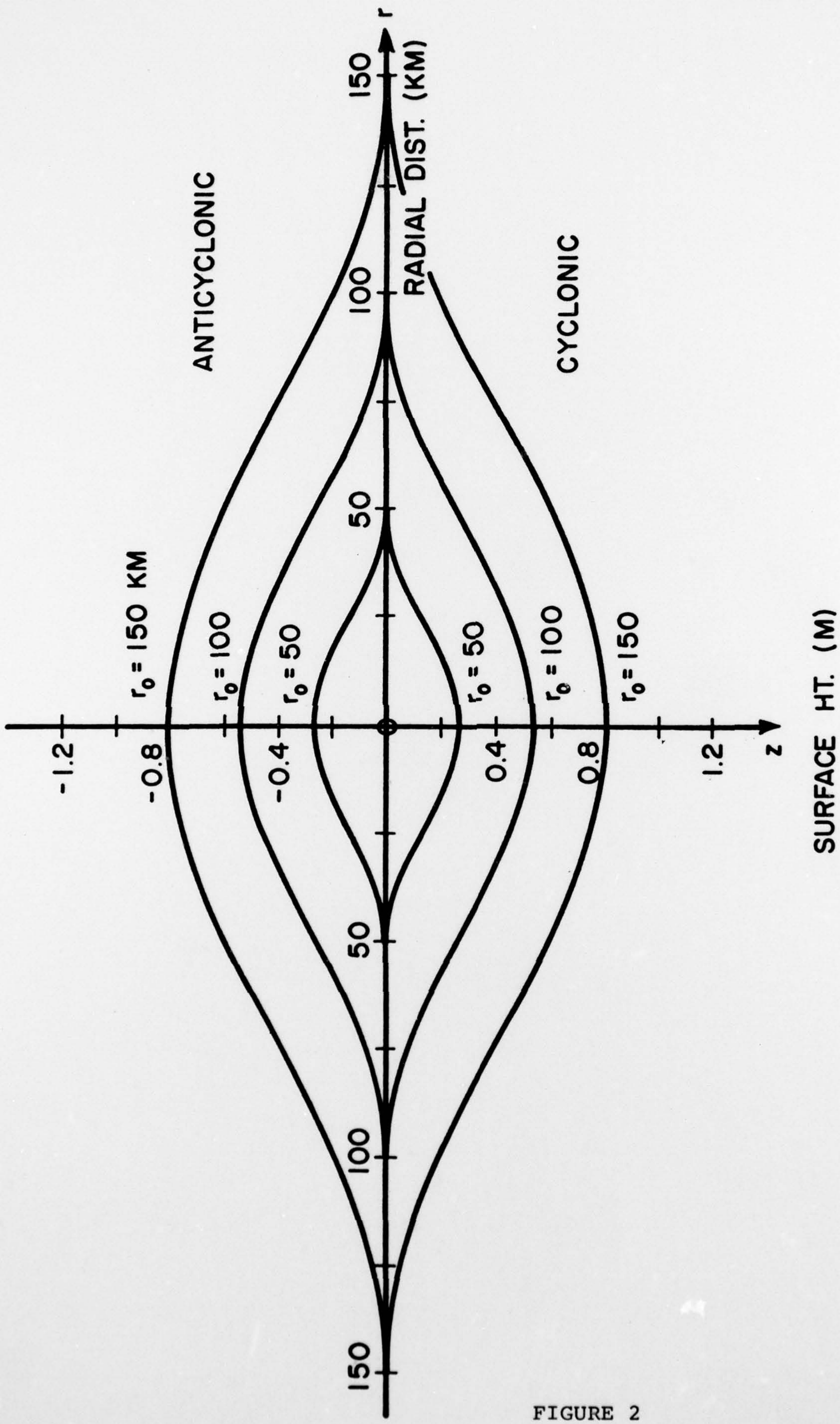
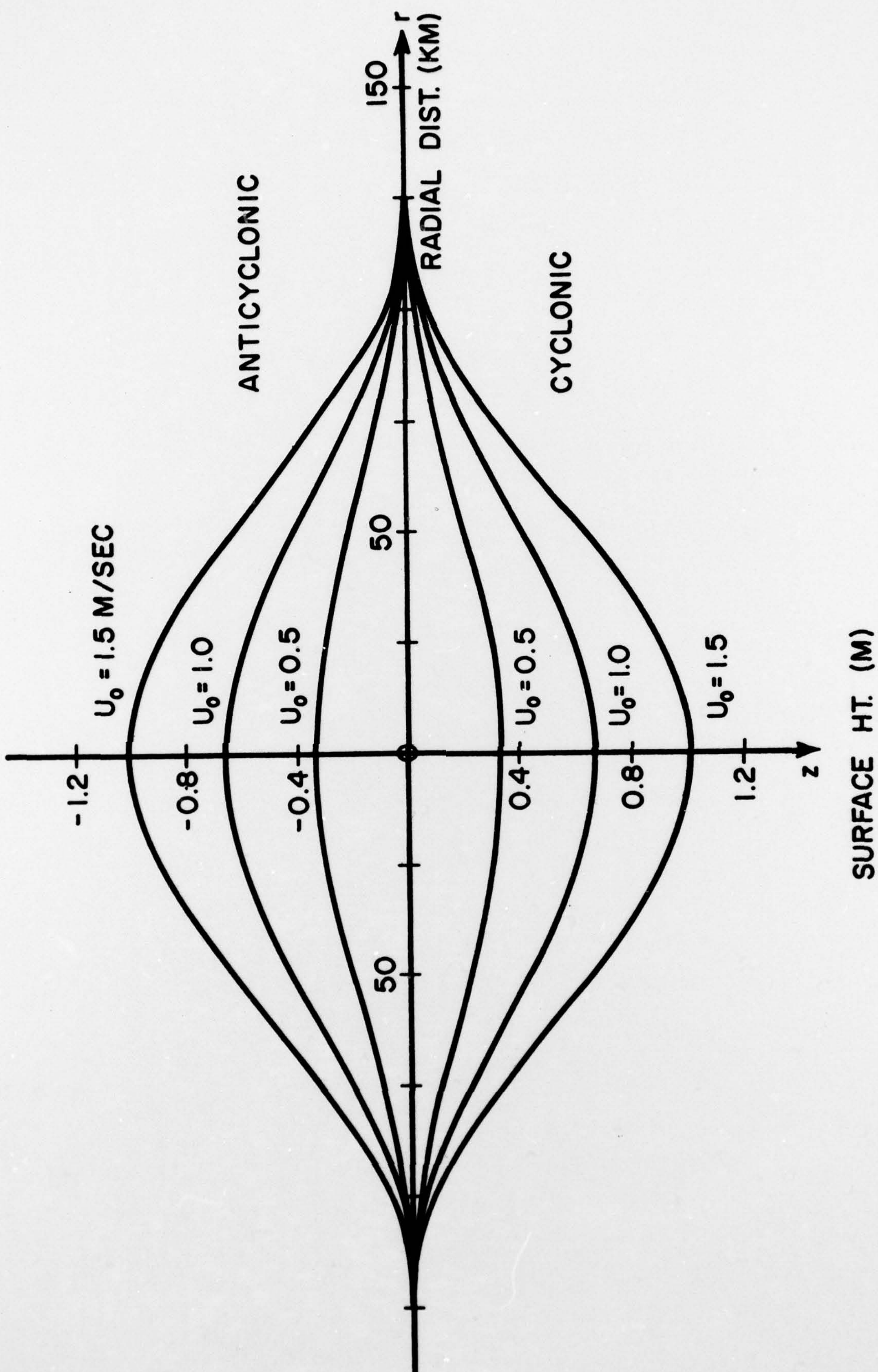

ANTICYCLONIC
CYCLONIC
RADIAL DIST. (KM)
r
SURFACE HT. (M)
z
$r_0$ = 150 KM
$r_0$ = 100
$r_0$ = 50
$r_0$ = 50
$r_0$ = 100
$r_0$ = 150
-1.2
-0.8
-0.4
0.4
0.8
1.2
150
100
50
50
100
150

FIGURE 2



r
RADIAL DIST. (KM)
150
50
50
150
ANTICYCLONIC
CYCLONIC
$U_0$ = 1.5 M/SEC
$U_0$ = 1.0
$U_0$ = 0.5
$U_0$ = 0.5
$U_0$ = 1.0
$U_0$ = 1.5
-1.2
-0.8
-0.4
0.4
0.8
1.2
z
SURFACE HT. (M)


FIGURE 3

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