UNIFIED PROGRAM FOR THE SPECIFICATION OF HURRICANE BOUNDARY LAYER WINDS OVER SURFACES OF SPECIFIED ROUGHNESS

by

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The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.
A method is developed to specify the surface stress and the wind speed and direction in the planetary boundary layer of a tropical cyclone from meteorological storm parameters available for historical hurricanes. The method is based upon a numerical primitive-equation model of the planetary boundary layer in a moving tropical cyclone. The complete time history of the evolution of the surface wind field is described from a series of characteristic wind field states calculated at discrete times in a storm's history by the steady-state model.

A surface drag formulation, based upon a contemporary similarity model (Arya 1977), coupled with a roughness parameter specification for a water surface consistent with Cardone's (1969) law, is incorporated into the numerical model and found to produce a consistent description of the integrated planetary boundary layer wind, the surface stress and its direction, and the wind speed and direction at anemometer level. The surface winds calculated in several recent hurricanes are found to be in excellent agreement with available, representative surface wind measurements made from offshore platforms and data buoys.
13. (Concluded).

Transformations based upon an equilibrium planetary-boundary-layer similarity model are developed to specify the surface wind over terrain of specified roughness, including lake surfaces, from the over-water wind-field solution. Calculated over-land and over-lake winds are compared to the limited measurements available for several recent storms. Agreement is generally good.

The method is incorporated in a computer program, which provides surface winds on a variable-resolution rectangular grid. This report includes program documentation and sample grid results for a test simulation performed on Hurricane Betsy (1965).
PREFACE

This report describes the methods incorporated in a computer program developed to provide hurricane surface wind fields. The wind fields can be used in wave and surge modeling activities. The report also serves to document the computer program delivered as part of the study.

The work described in this report was originally performed under Work Unit No. 12114, "Wave Information Studies," Coastal Field Data Collection Program. Publication of the report is funded by Work Unit No. 32683, "Wind Estimation for Coastal Modeling," Coastal Research Program. Both programs are sponsored by Headquarters, US Army Corps of Engineers (HQUSACE). Messrs. John H. Lockhart, Jr., and John G. Housley were the HQUSACE Technical Monitors. Ms. Carolyn M. Holmes of the Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES), was Program Manager. Drs. Jon M. Hubertz and Edward F. Thompson were the Principal Investigators of Work Unit Nos. 12114 and 32683, respectively.

This study was conducted under Contract No. DACW39-78-C-0100 by Oceanweather, Inc., Cos Cob, Connecticut, and provided to CERC on October 31, 1979. This report is the original contract report provided to CERC. It is being published as a CERC Contract Report at this time because CERC has used and continues to use the study results extensively to estimate wave growth in hurricanes. This report provides an important historical basis for present CERC practice. The hurricane wind model described in this report has recently been modified under Work Unit No. 32683 and included in CERC's Coastal Modeling System (Instruction Report CERC-91-1). Both work units are under the direct supervision of Dr. Martin C. Miller, Chief, Coastal Oceanography Branch, and Mr. H. Lee Butler, Chief, Research Division, and under the general supervision of Mr. Charles C. Calhoun, Jr., Assistant Director, CERC, and Dr. James R. Houston, Director, CERC.

The authors express their appreciation to the technical contract monitor at the time the work was performed, Dr. Robert W. Whalin, and to the late Dr. Charles E. Abel, both of WES, for their support, assistance and patience throughout the course of the work. The authors also acknowledge the role of the late Dr. John Wanstrath, who recognized the critical need for improved wind field models in hurricane surge modelling, and whose intense interest
stimulated the initiation of this research study.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.
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Non-SI units of measurement can be converted to SI (metric) units as follows:

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A UNIFIED PROGRAM FOR THE SPECIFICATION OF HURRICANE BOUNDARY LAYER WINDS OVER SURFACES OF SPECIFIED ROUGHNESS

PART I: INTRODUCTION

Statement of Problem

1. Specification of the wind velocity and vector wind stress near the sea surface in tropical cyclones is required for the description of ocean surface phenomena (such as ocean currents, the storm surge, and surface gravity waves) related to such cyclones. Dynamical-numerical computer-based models to describe such phenomena continue to be developed: for example, the work of Jelesnianski (1970) and Wanstrath et al. (1976) on the open coast surge, Forristall (1974) on currents, Cardone et al. (1976) on waves, and Wanstrath (1978) on the surge, including coastal flooding.

2. In most studies very simple descriptions of the hurricane wind field have been used to drive very complicated ocean response models. This disparity has hindered further refinement and validation of ocean response models and has limited the defensibility of climatological series, design criteria, and like results based upon the application of such models. The lack of near-surface wind measurements in hurricanes serves as an excuse for applying simple wind models: in fact, the most widely applied empirical model, discussed below, of surface marine wind distribution in hurricanes is calibrated against wind measurements made in a lake during the passage of a single storm.

3. In recent years, however, great progress has been made in our understanding of the basic physical and dynamical characteristics of tropical cyclones, including the part of such storms relevant to this discussion: the planetary boundary layer (PBL). Further, a series of measurement programs, both public and private, employing offshore oil and gas production platforms, automated data buoys, and low-flying aircraft, have made available a wealth of data on wind structure in the PBL in
tropical cyclones.

4. Cardone et al. (1976), exploiting this recent progress, developed a method for specifying the surface wind field in hurricanes over the ocean by applying a dynamical-numerical model of the PBL in hurricanes. The method, requiring as input only a description of the surface pressure field and specification of storm motion and latitude, has been used to model the surface wind field in nearly every major hurricane to affect the Gulf of Mexico or the East coast of the United States in the past decade (Camille, 1969; Delia, 1973; Eloise, 1975; Belle, 1976). At least one representative series of wind measurements over water was available in each of those storms to validate the method for the intended environment (open water) and the intended parameter (time-averaged winds at a specific height). Those studies confirm that the model is able to give a convincing numerical representation of how friction, latitude, storm motion, and the shape and intensity of the sea-level pressure pattern in a severe storm interact to produce an asymmetrical vertically integrated flow in the PBL. The model, however, includes an empirically based scaling law to relate the integrated boundary layer wind to the effective 19.5 meter level wind. Further, the surface stress distribution in the numerical solution has not been validated.

5. The purpose of the study reported here is to generalize the method so that it can be applied to specify surface wind and wind stress in hurricanes in a self-consistent way not only over the open sea but over waters typical of the near-shore environment, over inland bodies of water (lakes), and over terrain of varying roughness in general (e.g. open marshland, dense forest, cities). Such a capability is required for the application of surge models which treat the open-coast storm tide and inland flooding of coastal areas (e.g. the Mississippi delta and Lake Pontchartrain area) or those applied to surge studies of large inland bodies of water (e.g. Lake Okeechobee).

6. The goal of this study was the development of an efficient algorithm, implemented as a computer program free from proprietary constraints, that can be used to specify hurricane-generated surface winds and wind stresses, in historical storms or hypothetical storms, from the
kind of meteorological information available for historical storms.

**Review of Prior Methods**

7. Considered theoretically, the problem of surface wind specification in tropical cyclones is to solve the basic equations of hurricane-scale circulation, subject to appropriate initial and boundary conditions. As a part of the system of equations, consider the primitive equations of motion in cylindrical coordinates \( r, \lambda, z \), with origin at the center of the cyclone, for \( u \) and \( v \), the (horizontal) tangential and radial components of the wind:

\[
\rho \left\{ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + v \frac{\partial u}{\partial \lambda} + \omega \frac{\partial u}{\partial z} - fu - \frac{v^2}{r} \right\}
= \frac{\partial p}{\partial r} + \frac{\partial e_r}{\partial s} + \left\{ \frac{\partial \tau_{rr}}{\partial r} + \frac{1}{r} \frac{\partial \tau_{\lambda r}}{\partial \lambda} + \frac{\tau_{rr}-\tau_{\lambda \lambda}}{r} \right\}
\]

(1a)

\[
\rho \left\{ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial r} + v \frac{\partial v}{\partial \lambda} + \omega \frac{\partial v}{\partial z} + fu + \frac{w}{r} \right\}
= \frac{1}{r} \frac{\partial p}{\partial \lambda} + \frac{\partial e_\lambda}{\partial s} + \left\{ \frac{\partial \tau_{r\lambda}}{\partial r} + \frac{1}{r} \frac{\partial \tau_{\lambda \lambda}}{\partial \lambda} + \frac{\tau_{r\lambda}}{r} \right\}
\]

(1b)

where \( \omega \) is the vertical component of the wind and the \( \tau \)'s are the radial, tangential, and vertical eddy stresses of the tangential and radial velocity components.

8. Lack of knowledge how to solve equations (1), in particular lack of knowledge how to specify the eddy stresses, has until rather recently prevented a straightforward application of the primitive equations to the study of tropical cyclones. Practical demands, however, dictated the development of surface wind models as early as the late 1940's and the early 1950's. Even today the most widely applied method for wind specification derives from a procedure first published in a se-
ries of reports of the U.S. Weather Bureau, Hydrometeorological Section, during the 1950's. This method, hereafter referred to as the HP (Hydrometeorological-Parametric) method, may be considered a three-parameter method: it requires knowledge of only three quantities related to a storm's structure, to specify the entire areal distribution of surface wind.

9. The basic steps involved in the HP method are the following:

a. Assume that the sea-level pressure distribution in a tropical cyclone is symmetric; specify pressure as a function of radius \( r \),

\[
p(r) = p_o + \Delta p e^{-R/r},
\]

where \( p_o \) is the central pressure (at the eye), \( \Delta p \) is a storm pressure anomaly, and \( R \) is a scale radius related to the radius of maximum wind.

b. Compute the profile of gradient wind as a function of radius: this step basically solves the \( u \) equation of motion for the steady-state, frictionless, locally horizontally homogenous solution:

\[
\frac{u^2}{gr} + \frac{\Delta p}{gr} = \frac{1}{\rho_f} \frac{\partial p}{\partial r}.
\]

c. Attempt to compensate for neglect of all other terms by reducing the gradient wind to the equivalent wind over water at 10 meters, using a reduction of the form

\[
u_{10}/u_{gr} = F(r/R)
\]

where \( F \) varies from .865 at the radius of maximum wind to about .60 at the periphery of the storm.

d. Add asymmetry to the storm by vectorially adding 50% of the storm's forward motion \( V_f \) to the right side of the storm and subtracting 50% from the left side.

e. Partition the reduced winds into tangential and radial components by specifying an inflow angle that is a function of \( r/R \) alone; in effect, this step attempts to compensate for the neglect of all physical effects contained in the \( v \) equation of motion.

10. The function \( F \) was derived from pressure and wind measurements made in and around Lake Okeechobee, Florida, during the passage of two hurricanes in 1949 and 1950; in fact, the constant .865 was chosen
from measurements in that single storm deemed more representative.

11. An attempt to solve by graphical means a less simplified version of equations (1), proposed by Myers and Malkin (1961), was applied to the determination of the wind field in hurricane Helene, 1958, by Schauss (1962). The study of Myers and Malkin (1961) was the first to demonstrate the dynamical inconsistencies in the HP method, especially the fallacy that superposition of storm motion on a circularly symmetric wind field can produce the right/left asymmetry observed in hurricanes. Schauss (1962) represented the eddy stresses in terms of friction coefficients which in turn were estimated indirectly from sea-level pressure analyses and ships' wind observations in hurricane Helene. An important element of Schauss' study was the realization that the pressure field about tropical cyclones is not axisymmetric. Schauss varied $\Delta p$ and $R$ by quadrant; he found that he could reliably estimate the quadrantal variation from conventional coastal measurements and marine pressure data, even though Helene remained offshore, east of the East coast of the United States.

12. The method of Myers and Malkin and Schauss is not, to our knowledge, in use today; the HP method, however, is in widespread use in design studies, climatological studies, and real-time forecast systems. Variants of the HP method are described by Patterson (1972) and Bretschneider (1976); the latest version is documented in Memorandum HUR?120, Hydrometeorology Branch, Office of Hydrology, NOAA.

Relevant Recent Research

13. Much of our current basic knowledge of the structure, dynamics, and energetics of tropical cyclones has been generated only within the past 10 or 15 years. This progress is a result of two factors: first, an extensive data base has been created as a result of the program of reconnaissance by NOAA research aircraft begun in the late 1950's; second, models of the tropical cyclone, based upon numerical integration of the primitive equations, have provided new insight into the basic dynamical and thermodynamic processes operative in tropical cyclones.
14. As a result of analysis of the reconnaissance data, the general distribution of pressure, wind, and temperature throughout the free atmosphere above the friction layer in the inner core of hurricanes has been revealed. Shea and Gray (1973), for example, composited all aircraft data obtained between 1957 and 1969, and derived the distribution of the mean tangential and radial components of actual winds at various levels including the 900 mb level, the level closest to the boundary layer. Their analysis suggested that at that level, the asymmetry in the tangential component exceeds the forward motion of the storm, and that the radial (inflow) component is not symmetrically distributed about the storm axis, as is assumed in the HP model.

15. In the area of numerical modelling, at least a dozen distinct prognostic models have been developed since 1964. Anthes (1974) summarized numerical models down to about 1972, several of which continue to be further developed today. Changes have been mainly in the use of increased horizontal and vertical resolution and in parametrizing the effects of cumulus convection.

16. Models of the prognostic type are designed to study the dynamics and energetics of tropical cyclones, to expose the mechanisms of hurricane formation from incipient tropical disturbances, to study the sensitivity of the tropical cyclone to boundary conditions at the lower boundary (in particular sea surface temperature), and to assess the prospective influence of various proposed schemes for artificially modifying such cyclones (e.g. cloud seeding near the eye wall). Such models typically can not be used directly to specify the distribution of surface wind or wind stress in hurricanes, because the models suffer from relatively low horizontal resolution, crude parametrization of the boundary layer, and time-dependent integration schemes: in fact, the models were designed not as diagnostic tools, but rather to describe the evolution of the circulation from an arbitrary set of initial conditions.

17. Recently there has been greater emphasis on the boundary layer of tropical cyclones in hurricane research: this is because the boundary layer is an important dynamical component of the total circulation in cyclones; additionally, much of the new knowledge gained within
the past decade about the structure of the surface and planetary boundary layers of the atmosphere over the sea can be profitably applied to the boundary layer in hurricanes. Elsberry et al. (1974) obtained realistic solutions for the temperature and moisture distribution within the boundary layer of an axisymmetric storm by applying the marine PBL model of Cardone (1969), originally developed for application to the extratropical atmosphere. More recently, Moss and Rosenthal (1975) estimated the vertical exchange rates of momentum, heat, and cloud mass in the boundary layer of hurricanes by combining the boundary layer model of Deardoff (1975) with the roughness parameter formulation of Cardone (1969). Anthes and Chang (1978) used a new parameterization of the planetary boundary layer in an axisymmetric numerical hurricane model to study the response of a hurricane boundary layer to changes of sea surface temperature.

18. In this study, a diagnostic model of the hurricane PBL, developed originally by Chow (1971) and applied later by Cardone et al. (1976), is modified to produce a consistent description of the vertically integrated wind in the PBL, the surface drag and the wind speed and direction at anemometer height in a moving hurricane with asymmetric horizontal wind distribution over water. Equilibrium PBL theory is used to extend the surface wind description to terrain of specified roughness. The wind model is incorporated in a computer program to provide a grid-ded temporal and spatial history of the surface wind for use in surge models.
PART II: THE HURRICANE PBL MODEL

Review of Chow's (1971) Vortex Model

19. As time dependent numerical hurricane models have been extended to three dimensions, it has become necessary to find efficient numerical schemes of solving the primitive equations on the high resolution grids required and to give more emphasis to the asymmetry of planetary boundary layer flow. The latter is important because frictionally induced convergence in the boundary layer (Ekman pumping) is an important mechanism in organizing moist convection and triggering the instability responsible for the development of tropical cyclones. Those requirements served as the principal motivation for Chow's study.

20. Chow's model concerned the planetary boundary layer (PBL) only and sought the solution for the wind field and horizontal convergence in the PBL of a moving tropical cyclone from the equations of motion. The pressure field in the boundary layer was prescribed and fixed, so that there would be no gravity waves excited in the numerical solution. This facilitated the use of a nested grid system, which allowed grid spacings as small as 5 km near the hurricane inner region without sacrifice of overall computational efficiency.

21. The model is based upon the equation of horizontal motion, vertically averaged through the depth of the PBL, written in coordinates fixed to the earth as

\[
\frac{d\hat{V}}{dt} + f|x| \times \hat{V} = -\frac{1}{\rho} \nabla p + \nabla \cdot (\kappa_H \nabla \hat{V}) - \frac{C_D}{h} |\nabla| V^2
\]

where

\[
\frac{d}{dt} = \frac{\partial}{\partial t} + \nabla \cdot V;
\]

\(\frac{\partial}{\partial t}\) is the time change local to the fixed coordinates; \(V\) the two-dimensional del operator; \(\hat{V}\) the vertically averaged horizontal velocity; \(f\) the Coriolis parameter; \(|k|\) the unit vector in the vertical direction; \(\rho\) the mean air density; \(\nabla\cdot p\) the pressure; \(\kappa_H\) the horizontal eddy viscosity coefficient; \(C_D\) the drag coefficient; \(h\) the
depth of the planetary boundary layer. It is assumed that the vertical advection of momentum is small compared to the horizontal advection and can be neglected and that the shearing stress vanishes at the top of the PBL.

22. The pressure is prescribed as the sum of $p_c$ and $\bar{P}$,

$$ p = p_c + \bar{P} $$

where $p_c$, not necessarily axisymmetric, is the pressure field representing the tropical cyclone and assumed to translate with the storm at a specified speed $\mathbf{v}_c$; and $\bar{P}$ is a large scale pressure field which may be specified by the corresponding constant geostrophic flow, $\mathbf{v}_g$, as

$$ f|\mathbf{K} \times \mathbf{v}_g| = -\frac{1}{\rho} \nabla \cdot \mathbf{p} $$

With this pressure specification, equation (2) may be written:

$$ \frac{d\mathbf{v}}{dt} + f|\mathbf{K} \times (\mathbf{v} - \mathbf{v}_g)| = -\frac{1}{\rho} \nabla \cdot \mathbf{P}_c + \nabla \cdot (\mathbf{K}_h \mathbf{v}_c) - \frac{C_d}{h} |\mathbf{v}_c| (\mathbf{v} + \mathbf{v}_c) $$

With respect to a moving Cartesian coordinate system $(x, y)$ whose origin is located at the moving low center of $p_c$, equation (4) is transformed into

$$ \frac{d\mathbf{v}}{dt} + f|\mathbf{K} \times (\mathbf{v} - \mathbf{v}_g)| = -\frac{1}{\rho} \nabla \cdot \mathbf{P}_c + \nabla \cdot (\mathbf{K}_h \mathbf{v}_c) - \frac{C_d}{h} |\mathbf{v}_c| (\mathbf{v} + \mathbf{v}_c) $$

where

$$ \frac{d}{dt} = (\frac{3}{\delta t})_c + \hat{\mathbf{v}} \cdot \mathbf{v} $$

$$ (\frac{3}{\delta t})_c = \frac{3}{\delta t} + \hat{\mathbf{v}}_c \cdot \mathbf{v} $$

$$ \hat{\mathbf{v}} = \mathbf{v} - \mathbf{v}_c $$

$$ \hat{\mathbf{v}}_g = \mathbf{v}_g - \mathbf{v}_c $$

13
$\mathbf{v}$ is now the horizontal wind relative to the low center; $\mathbf{V}$ the effective geostrophic flow relative to the low center; and $\left(\frac{\partial}{\partial t}\right)^c_c$ the time change local to the moving coordinates.

23. Chow solves equation (5) in component form

$$\frac{\partial u}{\partial t} = f v - A u - P v + H u - F v$$  \hspace{1cm} (5a)$$

$$\frac{\partial v}{\partial t} = -f u - A v - P v + H v - F v$$  \hspace{1cm} (5b)$$

where

$$A u = u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}$$

$$A v = u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y}$$

$$P u = f v + \frac{1}{\rho} \frac{\partial P_c}{\partial x}$$

$$P v = -f u + \frac{1}{\rho} \frac{\partial P_c}{\partial y}$$

$$H u = \frac{1}{\rho} \left( K_H \frac{\partial u}{\partial x} + \frac{\partial}{\partial y} \left( K_H \frac{\partial u}{\partial y} \right) \right)$$

$$H v = \frac{1}{\rho} \left( K_H \frac{\partial v}{\partial x} + \frac{\partial}{\partial y} \left( K_H \frac{\partial v}{\partial y} \right) \right)$$

$$F u = \frac{C_D}{h} \left[ (u + u_c)^2 + (v + v_c)^2 \right] \frac{1}{2} (u + u_c)$$  \hspace{1cm} (6a)$$

$$F v = \frac{C_D}{h} \left[ (u + u_c)^2 + (v + v_c)^2 \right] \frac{1}{2} (v + v_c)$$  \hspace{1cm} (6b)$$
24. The general formulation is completed with the specification of the form of $C_D$, $K_H$ and the boundary condition at the outermost boundary of the grid. Following Smagorinsky (1963)

$$K_H = 2\kappa^2 \left( \frac{\Delta}{Z} \right)^2 |\text{Def}|$$

where $|\text{Def}|$ is the total deformation, $\Delta$ is the mesh size and $\kappa$ is a non-dimensional constant ($\kappa = .4$ is assumed). The drag coefficient was assumed to increase linearly with wind speed

$$C_D = (0.5 + 0.6 |\vec{V}|) \times 10^{-3} \quad (\vec{V} \text{ in m/sec}) \quad (7)$$

At the outermost boundary of the grid, the acceleration and the horizontal diffusion of momentum are neglected, implying a balance between Coriolis force, pressure gradient force and the surface frictional force

$$f|K \times (\vec{V} - \vec{V}_g) = -\frac{1}{\rho} v_{p_c} - \frac{C_D}{h} |\vec{V} + \vec{V}_c| (\vec{V} + \vec{V}_c)$$

25. The computational grid is a rectangular nested grid system consisting of five nests, within each of which the mesh is constant. Figure 1 shows the inner three nests in one quadrant of the grid system; if the mesh size of the innermost nest is say 5 km, the second through fifth mesh sizes are 10, 20, 40, and 80 km respectively, and the entire grid covers an area of $(1600 \text{ km})^2$.

26. The details of the finite difference formulation and of the computational scheme are given by Chow (1971) and will not be repeated in detail here. Basically, a combination of diagonal and ordinary upstream differencing is used for spatial derivatives in order to reduce computational errors in the calculation of the advection terms and at the intermesh boundaries. The computation starts with an initial guess field consisting of the gradient wind components ($\text{computed from } P_{c}$). At each grid point, the equations (5) are integrated forward in time until the acceleration $(\partial \vec{V}/\partial t)_c$ is tolerably small. For an innermost grid mesh of size 5 km, the time step is 60 sec. Chow found that 800
iterations (equivalent to 13 hours 20 min) were sufficient to achieve a steady state solution.

27. Chow studied the accuracy of the numerical scheme by obtaining numerical solutions for a frictionless \((X_H, C_D = 0)\) stationary \(V_c = 0\) vortex in gradient balance. The pressure field was axisymmetric and defined by the well known exponential pressure law

\[
P_c = P_o + \Delta p e^{-R_p/r}
\]

where \(P_o\) is storm central pressure, \(\Delta p\) is the storm pressure anomaly, \(R_p\) is the scale radius and \(r\) is the radial distance from the eye.

For the test storm \((\Delta p = 50 \text{ mb}, R = 40 \text{ km})\), the truncation error decreased with the spacing of the inner nest mesh size. For a spacing of 5 km, the numerical solution for the radial and tangential components is compared to the analytical gradient-wind solution, which of course contains only a tangential component, in Figure 2. It is seen that the truncation error appears only in the radial component and serves to introduce a small inward-directed radial component.

28. Figure 3 shows the integrated boundary layer wind solution found by Chow for the same test storm but with friction, storm motion (10 m/sec) and a steering gradient of 10 m/sec aligned with the motion. The pattern is remarkably realistic, at least qualitatively, and displays considerable asymmetry in both speed and direction. In several sensitivity experiments Chow deduced that, at least for the test storm, friction and storm motion effects combine non-linearly to produce a strongly asymmetric inflow pattern. Storm motion is primarily responsible for front-back asymmetry in wind speed, while the asymmetric pressure field in the steering-flow case is mainly responsible for the left-right asymmetry in wind speed. These characteristics of the hurricane PBL wind field were proposed much earlier by Myers and Malkin (1961) on the basis of graphical integration of a vector equation of motion similar to equation (2), without lateral friction, but including both tangential and normal vertical friction forces.
A Consistent Surface Stress Parameterization

The model of Cardone et al. (1976)

29. Cardone et al. (1976) adapted Chow's model in order to specify hurricane surface winds in historical storms. While Chow's model provided a good qualitative description of the PBL wind field, Cardone et al. found it necessary to modify the model in several ways in order to attain good quantitative agreement between the modelled winds in real hurricanes and the limited amount of measured wind data available.

30. The model calibration rested mostly on the wind record measured on an oil rig directly in the path of Camille, 1969; at the time, this wind trace was believed to be the only existing accurate wind record representative of the surface boundary layer over open sea in a well-documented extreme hurricane.

31. The first modification made was to generalize the storm input parameter specification scheme adopted by Chow. The 3-parameter scheme, requiring only $A_P$, $R$, and $\vec{V}_C$, was retained; as was the 4-parameter scheme, which adds an ambient geostrophic ($\vec{V}_g$) pressure gradient directed normal to the storm track, a so-called steering flow. A 5-parameter scheme allowed the angle between the storm track and the ambient gradient to be varied. Finally the option to specify $A_p$ and $R$ in equation 8 by storm quadrant was added, providing up to an 11-parameter scheme. The motion and pressure parameters, along with storm latitude, completely defined the integrated boundary-layer wind solution for a given storm.

32. The calibration against Camille data, and to a lesser extent Carla wind direction information, involved two major modifications to the model. First, it was necessary to modify the boundary layer depth formulation. Chow had assumed a constant depth of 1 km. In the modified version, the depth was allowed to increase toward the storm center from a minimum depth of 1 km at the storm periphery to nearly 2 km in the vicinity of the eye wall of intense storms. This modification primarily affected the directional properties of the integrated boundary-layer wind solution.
33. Second, since the model was needed to drive a wave prediction model which required wind data at 20 meter elevation, the wind speed calibration incorporated a scaling law to reduce the integrated boundary-layer wind to 20 meters. The law was found to be dependent on wind speed, with low winds reduced only slightly and winds of 50 m/sec reduced by about 60%.

34. The modified vortex model has been applied to the specification of the time history of surface winds in many historical storms (Ward et al., 1979) and in many recent storms which have affected the U.S. coast (Cardone and Ross, 1977; Ross and Cardone, 1977; Cardone and Ross, 1978). Since most hurricanes are not strictly in steady state (though the calibration storm Camille was remarkably so), a wind time history in a given storm is interpolated from several characteristic states computed from the vortex model, on the implicit assumption that there is a rapid mutual adjustment between the wind field and pressure field in hurricanes. The simulated storms all included some direct PBL wind data measured from offshore platforms, data buoys or aircraft. The model appears to provide a good surface wind description for a fairly wide range of storm types.

Shortcomings

35. Recent theoretical and field studies of the structure of the PBL in hurricanes have revealed several shortcomings in the modified model described above. First, with regard to the depth of the PBL, the evidence now suggests a much lower height than 1-2 km as assumed above. Moss (1978) studied the PBL turbulence structure from aircraft measurements for a peripheral portion of Eloise, 1975; the data support a PBL height of about 650 meters.

36. Moss and Rosenthal (1978) estimated PBL variables in two intense storms by applying Deardoff's (1972) PBL parameterization scheme to bulk data to compute the surface exchange coefficients. Cardone's (1969) relation for the roughness length was used and found to provide drag coefficients in reasonable agreement with previous estimates. The calculation included the estimation of the PBL depth under the assumption that the top of the PBL coincides with the cloud base, which was
taken as the lifting condensation level of surface air. Figure 4 shows the PBL depth calculated for the storms studied. A depth of 600-700 meters characterized both storms except near the eye wall where the depth lowers to about 500 meters. Finally, Chang (1977) added a PBL parametrization of contemporary formulation to a time dependent multilevel primitive equation model and derived the radial distribution of the PBL height in both steady and unsteady cyclones. Figure 5 shows that in the steady-state hurricane the depth varies between 380 and 450 m with the PBL height lifted slightly near the eye wall. The PBL height was not found to exceed these heights significantly in the several unsteady cases studied.

37. Another inconsistency in the model results from the retention of the drag law, equation (7), used by Chow. That law is actually intended for use with marine wind data at standard height (10 m). Since the drag coefficient decreases with increasing height in the PBL, the use of (7) with vertically integrated winds implies overestimation of the surface drag. In addition, new evidence (Figure 6) for the behavior of the 10 m drag coefficient $C_{10}$, at sea reported by Garratt (1977) supports a Charnock-type roughness law

$$z_o = \frac{a u_*^2}{g}$$

where $z_o$ is the roughness parameter, $u_*$ is friction velocity and $g$ is the gravitational constant. The Charnock constant $a$ proposed was 0.0144 though the value is sensitive to the value assumed for the Kármán constant in the PBL model applied.

38. The scaling law adopted by Cardone et al. (1976) apparently compensates for the shortcomings noted above, at least insofar as the specification of the 20 meter wind speed in concerned. However, the computed surface wind is not consistent with the surface drag, which itself is likely to be incorrect. The integrated boundary-layer wind therefore is also likely to be in error in a given storm and is not suitable for the extension of the model solution to surfaces of arbitrarily specified roughness as required in this study.
39. In the next section, a revised PBL parameterization is adopted and shown to provide an accurate and consistent PBL wind and stress representation within the vortex model.

The revised PBL parameterization.

40. A new framework for parameterization of the fluxes of momentum, heat and moisture in the PBL has been developed within the past decade, beginning mainly with the work of Blackadar and Tennekes (1968) and Zilitinkevich (1969). The parametric relations result from the matching of mean profiles of wind, temperature, and moisture predicted by surface and outer-layer similarity theories for a PBL in which the flow is assumed to be horizontally homogeneous and quasi-stationary.

41. A particularly convenient form of the parameterization, first proposed by Deardoff (1972), expresses the PBL fluxes in terms of layer-averaged mean PBL properties. Deardoff's parameterization, combined with Cardone's roughness parameterization, was found by Moss and Rosenthal (1977) to provide reasonable results for hurricanes. The parameterization adapted here is taken from Arya's (1977) update of Deardoff's scheme.

42. The general form of the parametric relations may be written

\[
\frac{ku}{u_\kappa} = - (\ln \hat{z}_o + A_m) \tag{10a}
\]

\[
\frac{k\nu}{u_\kappa} = - B_m \text{sign} f \tag{10b}
\]

\[
k(\theta_v - \theta_o) / \theta_\kappa = - (\ln \hat{z}_o + C_m) \tag{10c}
\]

\[
k(q - q_o) / q_\kappa = - (\ln \hat{z}_o + D_m) \tag{10d}
\]

where \(u\) and \(v\) are the vertically integrated (as in equation 5) horizontal wind components (in the direction of the surface shear and perpendicular to it, respectively), \(\theta_v\) and \(q\) are the mean layer virtual potential temperature and specific humidity, respectively, \(\hat{z}_o\) is the roughness parameter normalized by the PBL height \((z_o/h)\), \(k\) is von Kármán's constant, \(\theta_\kappa\) is a potential temperature scale expressed in
terms of the heat flux $H$, $q_*$ is a specific humidity scale involving the moisture flux, and $A_m, B_m, C_m, D_m$ are universal functions of dimensionless similarity parameters.

43. The Monin-Obukov length $L$ may be expressed in terms of $\theta_*$ and $u_*$ since

$$L = \frac{-U_*^3 \delta v pc}{kgH} = \frac{-U_*^2 \delta v}{g \theta_*} \tag{11}$$

44. There exist two competing theories for the form of universal functions. In one theory, known as Rossby-number similarity theory, the boundary layer height is uniquely determined by $u_*/f$ and $L$. For the near neutral hurricane PBL, that theory predicts the PBL to increase as the ratio $u_*/f$ increases toward the center of storms, in apparent contradiction to observation.

45. In the generalized theory, the depth of the PBL, $h$, is specified as an independent variable. Arya (1977) presents updated expressions for the similarity functions in terms of this generalized theory as follows:

$$A_m = \ln(-\frac{h}{L}) + \ln \frac{fh}{u_*} + 1.5$$

$$B_m = 1.8 \frac{fh}{u_*} e^{0.2h/L} \quad \frac{h}{L} \leq -2 \tag{12}$$

$$C_m = \ln(-\frac{h}{L}) + 3.7 \quad \text{(unstable)}$$

$$A_m = -.96(h/L) + 2.5 \quad \frac{h}{L} \geq +2 \tag{13}$$

$$B_m = .80(h/L) + 1.1 \quad \text{(stable)}$$

$$C_m = -2.0(h/L) + 4.7$$

For near-neutral conditions, $-2 < h/L < 2$, $A_m, B_m, C_m$ are assumed to be given by linear interpolation between the above computed values at $h/L = \pm 2$.

46. In terms of the similarity relations (10), the drag coeffi-
cient with respect to the integrated PBL wind is

$$C_d = \frac{k^2}{[(\ln z_o + A_m)^2 + B_m^2]}$$

(14)

while the angle $\beta$, between the surface wind and the integrated PBL wind is

$$\beta = \tan^{-1}(v/u)$$

(15)

47. To incorporate the similarity theory in the hurricane model, two cases were considered:

a. Land. In a PBL over land, the following parameters are prescribed: $f, z_o, h, \theta_v - \theta_o$. The parametric relations then define the following functions

$$C_d = F_1(|\mathbf{v}|)_{f, z_o, h, \theta_v - \theta_o}$$

(16)

$$\beta = F_2(|\mathbf{v}|)_{f, z_o, h, \theta_v - \theta_o}$$

(17)

b. Water. Over water, the roughness parameter is not known but can be expressed in terms of $u^*$ through a Charnock-type relation (equation 9) or the form proposed by Cardone (1969). The parametric relations can then be solved for

$$C_d = F_3(|\mathbf{v}|)_{f, h, \theta_v - \theta_o}$$

(18)

$$\beta = F_4(|\mathbf{v}|)_{f, h, \theta_v - \theta_o}$$

(19)

48. Arya (1977) gives solutions graphically only for the condition $fh/u^* = I$, in which case $C_d$ and $\beta$ can be expressed, for a given latitude, in terms of $z_o$ and a bulk Richardson number. In this form, the theory is an updated version of Deardoff's scheme, which did not include dependence of $A_m, B_m, C_m, D_m$ on $fh/u^*$. In general, however, $fh/u^*$ or $z_o$ are not known a priori; equations (10-15) are solved by iteration starting from an initial guess on $u^*$.

49. In order to avoid the prohibitive computational expense of solving equations 10-15 iteratively at each grid point within the numerical vortex model, the assumptions are made that over water the air-sea
temperature difference and boundary layer height can be considered to be invariant over the domain of the storm. In view of the preceding discussion on $h$, this appears to be a reasonable approximation. Except for hurricanes crossing major ocean-current boundaries, the assumption of horizontal homogeneity of $\theta_v - \theta_o$ also seems reasonable, especially for Gulf of Mexico and lower U.S. East Coast hurricanes. Little is known about the characteristics of the PBL in hurricanes over land. However, given the high level of turbulent mixing there in hurricanes, it is reasonable to assume that an adiabatic lapse rate is established and that at least in the near-coastal zone, the boundary layer depth is close to that assumed for the over-water case.

Given the above conditions, the parametric relations $F_1$, $F_2$, $F_3$, $F_4$ can be found once for a given storm by iteration, and expressed in terms of tables. In practice, the upwind and crosswind drag coefficients, the ratio $u_\!/|\vec{V}|$ and the angle, $\beta$, between the surface wind and the integrated wind are computed for $|\vec{V}| = 0.8(0.8)80$ m/s and tabulated. Values for intermediate wind speeds are found by linear interpolation.

**Test results for the general parameterization**

The behavior of the over water drag coefficient for typical hurricane conditions ($\theta_v - \theta_o = -2^\circ C$, $h = 650$ m, $f = 10^{-4}$) according to the general parameterization is shown in Figure 7. The over water cases are computed for two separate values of the Charnock constant: .0144 and .035. The former value was recommended by Garratt (1977). However, in this model, $k = .35$, to be consistent with the Arya formulation, and $a = .035$ provides a better fit to the 10 meter drag coefficient measurements analyzed by Garratt. The drag coefficient for the land case is for a roughness parameter of .08 m, a boundary layer depth of 650 m and neutral stability. For comparison, Figure 7 also includes the form adopted by Chow.

While it is reasonable to expect the new theory to yield drag coefficients lower than equation (7), the magnitude of the decrease and the form of the wind dependence seen was surprising. The revised parameterization was tested in the numerical vortex model with the Camille
inputs used in the study of Cardone et al. (1976). The revised solution was referred to 20 meters by solving

\[ V_{20} = \frac{u^*}{k} \ln \left( \frac{20}{z_o} \right) \]

where \( u^* \) and \( z_o \) are determined by the numerical model, since for typical hurricane conditions, stability effects can be neglected in the surface layer.

Figure 8 compares the new solution and that derived by Cardone et al. Clearly, the general parameterization is underestimating the surface stress and therefore the surface wind. The difficulty with the general Arya formulation was traced to the dominating influence of the scale-height ratio \( fh/u^* \) on the similarity variables. This parameter was added by Arya mainly to describe the relative influence of the Coriolis force in an Ekman-type layer over a wide range of latitudes. In a hurricane, however, the parameter varies over two orders of magnitude because of the variation of \( u^* \) over an extreme range (typically 0-200 cm/sec) over a short distance. Considering the highly curved nature and spatial inhomogeneity of the flow in the hurricane PBL, that parameter is apparently irrelevant. Its influence was controlled therefore by restricting the solution to \( fh/u^* = 1 \).

The results of restricting the scale-height ratio to unity were dramatic. The revised dependence of drag coefficient on wind speed is shown in Figure 7 and the revised 20-meter wind profiles in Camille, for two boundary layer heights (\( h = 650, 325 \) m) are shown in Figure 8. The comparisons of modelled and measured wind speeds at Rig 50 in Camille for three PBL heights are shown in Figure 9. In the range of \( h = 325-650 \) m, the new theoretical calculation fits the measurements as well as the calibrated solution of Cardone et al. (1976).

Properties of the over-water solution

The final PBL parameterization chosen for the over-water case consists of the Arya (1977) parameterization, with the scale height ratio restricted \( (fh/u^* = 1) \) and with the crosswind drag term retained both in the calculation of the surface stress in the numerical solu-
tion and in the derivation of surface-layer wind direction from the integrated boundary-layer wind direction. The Charnock constant, \( a \), is assignable as is the value of \( k \). However, since a value of \( k \) of .35 is consistent with Arya’s model, an \( a \) of .035 provides a better fit to Garratt’s (Figure 6) drag coefficient data than the value suggested by Garratt.

56. The properties of the new over-water hurricane wind model solution are most directly seen in the relatively simple case of a stationary, symmetric vortex. The solution may then be compared more readily to the gradient wind. This is done in Figure 10 for a stationary symmetric vortex with the scale radius \((R_p = 12 \text{ n.mi})^2 \) and pressure anomaly \((\Delta p = 105 \text{ mb})\) of Camille. Note that the comparisons are only made at and outside the radius of maximum wind, since inside that radius, truncation errors remain fairly large for a small storm such as Camille.

57. The vortex model predicts integrated PBL winds which are supergradient within a radius of about \( 3 \times R_p \). The 20-meter winds, however, vary from 75 to 85% of the gradient wind. The surface inflow reaches a maximum of 25\(^\circ\) at a radius of about \( 5 \times R_p \) and decreases sharply at the eye wall. These features are entirely consistent with those deduced by Shea and Gray (1973) from composited low level aircraft data in hurricanes. Comparisons of modelled and measured winds over water in several recent storms will be presented in a later section.

**Numerical Experiments over Mixed Terrain**

58. The similarity PBL theory as modified above may be easily applied to the specification of \( C_D \) and \( \beta \) in the hurricane PBL over land. For a neutral PBL, the revised theory predicts that \( C_D \) and \( \beta \) are functions only of \( z_o \). For \( h \) of 500 m, some typical values of \( C_D (\beta) \) are \( 1.78 \times 10^{-3} \) \((13.6^\circ)\) for \( z_o = .04 \text{ m} \) and \( 2.54 \times 10^{-3} \) \((16.3^\circ)\) for \( z_o = .16 \text{ m} \).

59. The revised theory was tested in two ways. First, the numerical model was solved for the steady state wind field in a stationary

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.
symmetric intense hurricane situated entirely over homogeneous terrain. While this case is unrealistic, it was intended to provide an indication of the sensitivity of the numerical solution to a greatly increased drag. Second, the solution was sought for the more realistic case of an intense hurricane situated at the coast with terrain of homogeneous roughness under the northern half of the storm and open sea beneath the southern half. The storm was stationary since only in such a case is the numerical model, formed in a moving coordinate system, rigorous.

60. Solutions typical of both cases are shown in Table 1 where they are compared to the open-sea solution discussed above. The cases were run with symmetric stationary Camille inputs. The all-land case returned a symmetric solution as expected. The case shown is for $z_0 = 0.08$ m, which is typical of open, level, countryside with low vegetation. Within about 200 km of the eye, the integrated PBL wind is found to be larger than the open-sea case, though surface winds are slightly lower. The inflow angle is about 50% greater than the open-sea solution. In effect, the increased surface drag results in a more intense vortex for a given pressure field, reflecting the well known dual role of friction in tropical cyclones. In nature, decreased evaporation is largely responsible for hurricane decay over land, and rapid decrease in PBL winds.

61. Two typical examples of the mixed land/sea solution are shown in Table 1. The solutions in these cases were quite asymmetrical. In general, the solution over-land matched quite closely the solutions found in strictly over land cases for comparable $z_0$. However, over-water, the solution departed significantly from the reference over-water case. In particular, for all values of land roughness attempted, the PBL winds over water downwind of land increased to values above the all-water case, thus causing the formation of a distinct wind maximum in the left rear quadrant (with respect to north) of the storm.

62. In Table 1, the vertically integrated winds over sea in the mixed land/sea solution are taken along a radial extending south from the storm center. For a land $z_0$ of .04 m the maximum wind over water
Table 1

Comparison of over water, over land, and mixed terrain radial wind speed profiles in vortex model numerical solutions for a stationary, symmetric storm with pressure profile parameters $\Delta p = 105$ mb, $R_p = 12$ n.mi., and modified $(fh/U_a^* = 1)$ Arya (1977) similarity PBL parameterization.

<table>
<thead>
<tr>
<th>$R$</th>
<th>$V_g$</th>
<th>$V_20$</th>
<th>$V_{sea}$</th>
<th>$V_{land}$</th>
<th>$V_{sea}$</th>
<th>$V_{land}$</th>
<th>$V_{sea}$</th>
<th>$V_{land}$</th>
</tr>
</thead>
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<tr>
<td>800</td>
<td>6.9</td>
<td>7.2</td>
<td>7.2</td>
<td>7.3</td>
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<td>20.2</td>
<td>19.7</td>
<td>18.6</td>
<td>13.0</td>
<td>20.3</td>
<td>19.0</td>
<td>20.3</td>
</tr>
<tr>
<td>200</td>
<td>42.3</td>
<td>41.2</td>
<td>34.9</td>
<td>37.9</td>
<td>26.5</td>
<td>41.5</td>
<td>38.7</td>
<td>41.8</td>
</tr>
<tr>
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<td>67.0</td>
<td>53.5</td>
<td>64.5</td>
<td>45.1</td>
<td>69.0</td>
<td>64.7</td>
<td>70.4</td>
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<td>100.2</td>
<td>91.7</td>
<td>104.9</td>
</tr>
<tr>
<td>40</td>
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<td>102.4</td>
<td>78.3</td>
<td>108.1</td>
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<td>112.5</td>
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<td>81.8</td>
<td>116.9</td>
<td>109.6</td>
<td>133.9</td>
</tr>
</tbody>
</table>

Explanation of table:

- $R$: radial distance from hurricane center (km)
- $V_g$: magnitude of the gradient wind
- $|V|$: integrated boundary layer wind speed
- $V_{20}$: 20 meter wind speed
- $|V|_{sea}$: in mixed terrain solution, the over-sea values are taken from radial over sea extending out from eye (at coast) normal to coastline.
- $|V|_{land}$: as above except radial extended over land

All wind speeds are expressed in knots.
is increased about 5% over the all-water case, and about 15% for a land \( z_0 \) of .32 m. Even greater increases were found in the left rear quadrant. A similar experiment for actual Camille inputs (not shown) led to comparable results, showing an unrealistic speed maximum in the left rear quadrant, whereas the nominal over-water Camille solution displayed a maximum in the right hand quadrant.

63. It is difficult to explain the precise cause of the anomalous model behavior in the mixed-terrain case. Test cases were run with modified over-land drag laws derived from Rossby-number similarity theory but no change in the basic structure of the solution was noted. The solution was verified to be steady-state in trial integrations carried out for 1600 rather than 800 iterations of the vortex model. Indeed, the behavior might be attributed to the basic model formulation, which forces a steady state solution unrealistically. However, in an experiment with a three-level, three-dimensional nested-grid numerical model, reported by Moss and Jones (1978), behavior similar to that found here has been seen in a simulation of an intense hurricane approaching the coastline. In their integration, it was noted that as the hurricane approached the coastline, even though the sea-level pressure in the storm began to rise, a transient wind-speed maximum greater than found in the all-water control case was established over water on the landward side of the vortex and extending to the left side of the circulation (looking down the track toward land).

64. Moss and Jones attribute the anomalous behavior of the wind field near landfall to changes in the pressure field induced by greatly increased inflow in the part of the wind field over land. In our simulation, however, the anomalous behavior is present even though the pressure field is fixed. More likely, the behavior is caused by the simplified treatment of the PBL vertical structure and the neglect of boundary-layer-adjustment processes which occur on vertical scales of the order of the depth of the PBL and on horizontal scales of the order of the grid spacing.

65. Basic knowledge of the behavior of the PBL flow across discontinuities in roughness is in a remarkably inchoate state.
The theories fall into two classes: (1) those which treat surface boundary layers only (e.g. Elliott, 1958); (2) those which treat the Ekman layer as a whole. Nearly all the available field data are restricted to the former case: there is considerable evidence that upon crossing a change in surface roughness, the wind profile is modified from below as a new (internal) boundary layer grows in thickness at a rate which depends upon stability and roughness. As a crude rule, the new boundary layer is established to a height given by one tenth the distance to the upwind change in roughness. If we were to extend this rule to the hurricane PBL, whose height is typically 500 m, we would expect the flow to adjust within 5 km. However, the more general Ekman-layer adjustment theories (e.g. Taylor, 1969) suggest a more complicated process, in which the wind-speed profile near the surface adjusts rapidly as in the surface-layer theories, but in which the surface stress, the turbulence structure and the wind direction take much longer (by nearly an order of magnitude) to attain equilibrium with the new surface. The theory and scant available data (Jensen, 1978) suggest also that the process is not symmetrical with respect to roughness transitions with the adjustment from rough to smooth conditions taking place at a slower rate than from smooth to rough. It appears therefore that the basic process of PBL adjustment in hurricanes needs to be better understood before the simulation of PBL flow across discontinuities within numerical hurricane models can be improved.

**Equilibrium Theory Terrain Transformations**

**Empirical Evidence**

66. The numerical experiments described above indicated that the numerical model could not of itself provide reliable wind fields over terrain of arbitrary roughness. This raised three questions:

(a) are fetch effects near roughness discontinuities important enough to be accounted for empirically in the specification of surface winds in hurricanes?

(b) can over-land PBL winds be prescribed from the over water numerical solution?
are winds over lakes such as Pontchartrain and Okeechobee different from winds over open water, apart from fetch effects, other factors being equal?

67. Extensive empirical studies of the effect of fetch on winds over water downwind of the coastline have been reported by Richards et al. (1966) and Phillips and Irbe (1976), who processed large data sets obtained around and in the Great Lakes. Both studies employed the same analytical method. Extensive series of simultaneous surface wind measurements from coastal land stations and downwind ships and buoys were paired and stratified by wind speed, fetch, and stability. Both studies employed the same fetch and stability classes. The stability was parametrized by the temperature difference (land air minus lake water).

68. The problem of concern here is the adjustment of the surface wind over a shallow inland lake of the dimensions of lakes Pontchartrain and Okeechobee (fetch < 40 n.mi) in hurricane conditions. The latter are characterized by winds > 8 m/sec and near-neutral stability. The data of Phillips and Irbe, and Richards et al., in those wind-speed and stability categories are plotted in Figure 11. Clearly, up to a fetch of at least 40 n. mi., no significant trend with fetch is evident in the wind-speed ratio (over-land / over-water). The ratio tends to be slightly larger for the more recent study, because the over-water winds in the recent study were measured at 3 meter height while in the study of Richards et al. the anemometer height was 10 meters. Since the first fetch class covered the range 0-5 n.mi., the implication is that the wind speed over the lake in the indicated classes and at heights up to 10 m attained equilibrium with the lake surface within the first few miles of the coast. This behavior is consistent with the height-to-fetch ratio of 1:10 noted above for surface layer adjustment.

69. It should be noted that, in both of the studies cited, a dependence of the wind ratio on fetch is proposed. The dependence however appears mainly in data from low wind speed (< 8 m/sec) classes and very stable or unstable stability classes. The fetch dependence therefore probably is caused by an adjustment of the turbulence in the PBL due to changes in stability rather than in surface roughness and is therefore
not likely to be important in the hurricane environment.

70. An interesting corroborative piece of evidence has been provided recently by remote sensing data. The Seasat mission has proved that the marine surface wind speed as might be measured at 10 m height from say a data buoy, can be measured by a radar scatterometer to an accuracy of 1 m/s or better. The radar backscatter cross-section of the sea surface (σ₀) therefore appears to be mainly dependent on surface stress and wind speed (Jones et al. 1978). Ross and Jones (1978) reported several aircraft experiments in which a scatterometer was flown directly downwind off the U.S. East Coast in moderately strong offshore wind conditions. The σ₀ measurements were plotted versus fetch (Figure 12), beginning within 1 km of the shoreline. There was found to be no fetch dependence at least to 40 km offshore, which suggests that the surface stress, the friction velocity, and the surface wind speed adjusted quickly to the surface roughness.

71. The above studies all suggest strongly that the adjustment scale for near-surface wind speed in strong-wind, near-neutral conditions is a few kilometers at most, which is a small distance compared to the dimensions of lakes Okeechobee and Pontchartrain. A dependence of wind speed on fetch may therefore be omitted. The situation with regard to wind direction is not as clear. There are no comparable field data for the adjustment of PBL wind direction across a roughness discontinuity. The available theories suggest a much longer adjustment scale. In the adopted scheme, no fetch-dependent adjustment for wind direction is incorporated; however, the case is allowed whereby the wind speed adjusts to the lake roughness immediately while throughout the lake, the wind direction is computed in accordance with the roughness of the terrain surrounding the lake (subroutine BREEZE/SPECIAL). This is correct if the adjustment scale for wind direction in the PBL is larger than the lake dimension. Field measurements are required to test this hypothesis.

72. Apart from fetch considerations, the surface winds over a large lake in hurricanes might be different from equivalent over-ocean winds because of differences in the surface roughness between a lake and
open sea. That is, the drag coefficient over a lake might be different from the drag coefficient over open sea, particularly for uniformly shallow lakes in which the surface wave structure can be expected to differ significantly for a given wind from deep-water surface waves. Unfortunately, the correct drag formulation for a shallow lake is much less certain than for the sea. Whitaker, Reid and Vastano (1973) have inferred a drag law for Lake Okeechobee which is quite different from the form proposed by Garratt. The scheme adopted below therefore includes the allowance for the specification of over-lake winds relative to an altered lake specification of surface roughness.

The Transformation Model

73. In this section a simple model is proposed to derive the surface wind and stress over terrain of arbitrary roughness from the numerical wind-field solution computed exclusively from the revised over-water drag formulation. The approach is to employ equilibrium PBL theory to relate the over-water integrated PBL wind to the flow at the top of the PBL and then to employ a consistent equilibrium model to compute the surface wind stress from the wind at the top of the PBL for terrain (including lakes) of arbitrarily specified roughness. The model proposed assumes that the PBL over land or inland lakes in a hurricane is neutrally stratified.

74. The transformations are derived quite simply from consideration of the alternate forms of the similarity PBL theory adapted in this study. To parameterize the surface drag in the numerical vortex model we applied equations 10a and 10b which relate the stress to the integrated PBL wind. Alternatively (Arya, 1977), the surface drag may be referenced to the wind at the top of the PBL \( u_h, v_h \):

\[
\frac{k u_h}{u_*} = - (\ln \hat{z}_o + A) \quad (20a)
\]

\[
\frac{k v_h}{u_*} = - B \text{ sign } f \quad (20b)
\]

or to the surface geostrophic wind components.
As noted by Arya, $A_0$ and $B_0$ may be expected to differ from $A$ and $B$ due to the presence of baroclinicity and also in very low latitudes where winds are strongly geostrophic. In hurricanes, baroclinicity in the PBL may be ignored, but the flow at the top of the PBL is more nearly in gradient balance. The effects of curvature on $A$, $B$ have not been studied, but the success achieved with the similarity PBL theory in the over water case suggests that such effects are not large. In this model, differences between $A$, $B$ and $A_0$, $B_0$ are ignored.

75. The relationship between $A_0$, $B_0$ and $A_m$, $B_m$ is given by Arya (1977) as derived from the equations of mean motion for a barotropic atmosphere in which the momentum flux is assumed to vanish at $z = h$:

\[
A_m = A_0 \quad (21a)
\]

\[
B_m = B_0 - k (fh/u_*)^{-1} \quad (21b)
\]

For the restricted case of $fh/u_* = 1$, which we have adopted only for the purposes of attaining a workable parameterization, it can be shown simply from equations 10, 20 and 21 that the flow at the top of the PBL, $z = h$, is related to the vertically integrated flow through

\[
u_h = \nu - u_* \quad (22b)
\]

In the coordinate system adopted (see Figure 13), $v_m$ is negative, $u_*$ is always positive so the wind speed at the top of the PBL is always larger than and turned clockwise (in the Northern Hemisphere) with respect to the mean layer wind $\nu$.
76. Given the wind at the level \( h \), the consistent similarity theory defined by equations 20a and 20b may be solved for the surface stress and surface layer wind in a neutral PBL over terrain of specified roughness \( z_0 \). For a neutrally stratified PBL, \( A_0 \) and \( B_0 \) are reduced simply to constants (1.39, 1.95 + \( k \), respectively). If \( z_0 \) is a constant, as say over a homogeneous land surface, \( u^* \) may be obtained directly from equations 20a and 20b. However since over a lake, the roughness probably depends on \( u^* \), \( z_0 \) may in general be prescribed in terms of \( u^* \) using the general form proposed by Cardone (1969).

\[
    z_0 = C_1 u^* + C_2 u^* + C_3
\]

(23)

where \( C_1 \), \( C_2 \), \( C_3 \) are constants to be chosen to impose a desired drag law. (For example, for a Charnock law, \( C_1 = C_3 = 0 \), \( C_2 = a/g \); for land, \( C_1 = C_2 = 0 \), \( C_3 \) is the roughness parameter for the terrain type).

77. The implementation of the above model in the specification of hurricane surface wind fields over terrain of arbitrary roughness or lakes is coded as subroutine UPDOWN, which allows for the calculation of transformations for up to six terrain categories, for each of which roughness constants \( C_1 \), \( C_2 \), \( C_3 \) have been specified. The procedure followed is:

a. Given the integrated boundary layer wind \( u, v \) and the conditions of a given hurricane over water
   \((h, \theta_a - \theta_0, f, k, a)\) compute \( u^* \) from the revised over water similarity parameterization.

b. From equations 22a, 22b, compute the wind speed and direction at level \( h \), the top of the PBL.

c. For each terrain roughness, specified in terms of equation 23, use the neutral similarity model (20a, 20b) to compute the friction velocity appropriate to the terrain roughness, \( u^*_t \), the ratio \( u^*_t / |\vec{\nu}| \), and the angle between the surface stress and the integrated wind. The ratio and the turning angle are computed for \( |\vec{\nu}| = 0.8(0.8)80.0 \text{ m/sec} \), for each roughness category and stored for use in the specification of surface winds in a given simulation over a grid covering different terrain types.
78. The overall behavior of the transformations is exemplified in Figure 14, which shows the ratio of surface wind speeds at 20 meters (over-land + over-sea) and the difference between the over-land and over-sea inflow angle for two terrain roughnesses: .04m, .32m. For comparison, Figure 14 shows the results for the wind-speed ratio derived from numerical mixed-terrain and over-water solutions for a symmetric stationary vortex (radius and pressure drop as in Camille). To arrive at the indicated quantities, the surface wind speed and direction along a radial extending north of the eye over land in the mixed terrain case was referenced to the (symmetrical) solution along the radial for open ocean. It should be recalled that in the mixed-terrain solution, the wind field over land looked quite reasonable. Apparently, that solution can be retrieved quite simply from the over-water solution using the equilibrium model described above. It is also interesting to note that the form of the dependence shown in Figure 14 conforms quite closely to the empirical wind-speed ratio derived from measurements in hurricanes in and around Lake Okeechobee (U.S. Weather Bureau, Hydrometeorological Section, 1954).

Results for Test Storms

79. In this section, the results of calculations of the entire history of the surface wind field in selected hurricanes are checked at measurement locations at which representative surface wind measurements are available. Indeed, the storms were chosen because over-water wind measurements and, in some cases, representative over-land wind measurements were available, and because extensive analyses of storm pressure and track characteristics had been performed in previous studies. Results are presented for hurricanes Camille, 1969; Betsy, 1965; Delia, 1973; Belle, 1976; Anita, 1977; and the Lake Okeechobee (LO) storm of 1949. Comparisons against over water winds are made in Camille, Delia, Belle, and Anita. A limited evaluation of over-land and over-lake winds in Camille and the LO storm is made. Finally, sample results for Betsy are presented without comparison against measurements, as no represen-
tative measured winds over land or lake are available in that storm.

**Camille**

80. Hurricane Camille played a crucial role in the calibration of the method developed by Cardone et al. (1976), because at that time, the wind trace in Camille from Rig 50 was deemed to be the only extant representative over-water wind trace in an intense hurricane. Indeed, the empirical law developed by Cardone et al. to scale integrated boundary layer winds to standard anemometer height was based largely on that wind trace. In the present scheme, the assignable model parameters are physical quantities related to fundamental properties of the planetary boundary layer model (PBL height, stability, roughness parameter formulation). Also, the method provides the wind speed as might be measured at any height in the constant-stress surface boundary layer, which in hurricanes may extend to a height of at least 50 meters.

81. The comparison of measured and modelled wind speed at Rig 50 at measurement height in Camille is shown in Figure 15. The agreement is at least as good as that achieved by Cardone et al. (1976). Results for two boundary-layer heights are shown. The numerical solutions differ little, except near the eye, where the lower height \( h = 500 \, \text{m} \) matches the peak measured wind better. This may reflect the fact that near the eye of intense hurricanes, the PBL height lowers slightly. Since the solutions differ little outside the eye, it is perhaps prudent to use a PBL height of 500 m in simulations of strong storms in the Gulf of Mexico.

82. To generate modelled surface-wind time histories at land sites requires knowledge of the roughness parameter representative of the terrain. Typical \( z_0 \) values for various terrain types have been given by several workers (e.g. Figure 16 after ESDU 72026, 1972). The roughness parameter is very sensitive to the terrain type within a few kilometers of a given measurement site, and therefore often varies significantly with wind direction at a site. For the sites at which winds have been measured in the selected hurricanes, the roughness parameter has not been determined experimentally. We therefore depict modelled time histories covering a reasonable range of roughness parameters at
also land sites. Also, with the exception of the lakefront comparison in Camille, comparisons are restricted to only those measurement sites at which the anemometer was recorded on strip chart, from which 30-minute-average wind speed and direction could be extracted.

83. Figure 17 compares measured and modelled winds at Keesler Air Force Base, Biloxi, Mississippi. The anemometer at Keesler is mounted 16 feet above the runway surrounded by fairly level terrain but with the coast less than a block away to the southeast. The anemometer measured winds up to the time of eye landfall at 0000 CDT. Measured wind directions support an over land trajectory up to about 2300 CDT and an over water trajectory thereafter. The modelled wind history for \( z_0 \) of 0.16 m, compares favorably with the measurements up to 2300 CDT; after which, the measurements agree better with an equivalent over-water history (also shown in Figure 17). Modeled wind direction is generally within ±0° of that measured.

84. The anemometer at Burwood CGS, Southwest Pass, is in a complex environment, with at least some influence of land to be expected, especially for wind directions between northwest and northeast. The wind comparisons in Figures 18 and 19 show better agreement in wind direction for an assumed over-water exposure. For wind speed, however, over-land histories agree better, but the effect of a shift in wind direction to an off-water direction (1800-2000 CDT) can clearly be seen in the measured wind speed.

85. Since fetch effects are not built into the present model, the Burwood and Keesler comparisons present worst-case examples of limitations of the present scheme. Nevertheless, the results appear accurate enough for specification of over-land winds in the coastal zone.

86. An important function of the present model is to specify winds over Lake Pontchartrain in hurricanes. The scheme adopted includes the provision for the specification of winds over the lake different from winds over open water in two ways. First, surface wind speeds may be computed relative to a \( z_0 \) specified for lakes which differs from the Charnock law assumed over water. Second, the program accommodates the condition, discussed earlier, whereby the surface layer
wind speed and stress are assumed to adjust to the lake roughness on length scales small compared to the lake width, but the PBL wind direction is governed by the roughness of that terrain upwind of the lake.

87. There is virtually no data on the roughness properties of Lake Pontchartrain. Whitaker, Reid and Vastano (1973) have deduced a drag law for Lake Okeechobee which differs substantially in level and wind dependence from equation 9. Their form was fit to equation 23, and was used to provide test wind histories at measurement sites around and in the lakes in the test simulations. (The form of equation 23 does not provide a particularly accurate fit to the odd form proposed by Whitaker et al., but is within about 20% over the range 10-50 m/s.)

88. The model was used to specify surface wind speed at the location and measurement height of Lakefront Airport, New Orleans, in Camille, for both water and lake roughness laws (Figure 20). The wind direction was computed for the water $z_o$ and for the special case described above, assuming an upwind terrain roughness of 1 m. Observed 1-minute hourly surface winds from the airport station are also plotted. Quantitative comparison of wind speeds is not warranted because the measurement is poorly averaged and the measurement site may not be representative of over-lake conditions. The reported wind directions should be more representative; the comparisons there suggest that there may indeed be a larger inflow angle for winds over Lake Pontchartrain in hurricanes than returned by the nominal over-water or over-lake transformation. Higher quality measurements in the lake in storm conditions are required to verify this possibility.

89. Figure 20 also shows the wind speed over downtown New Orleans, at 85 feet, calculated with a $z_o$ of 1 m. Time-averaged measured winds are not available for comparison.

Delia

90. Forristall et al. (1977), using the method of Cardone et al. (1976), ran a simulation of hurricane Delia in order to produce a wind field as accurate as possible, permitting the simulation of the surface wind and current at Buccaneer tower, offshore of Galveston, Texas. Thus
the storm parameters and track were adjusted, within their range of uncertainty, to produce best agreement between measured and modelled winds at the tower. Those storm parameters and track were used, without alteration, as input data to the present scheme and the wind field was computed. The boundary layer height was specified as 500 m.

91. The comparison of measured and modelled wind speed and direction in this storm is shown in Figures 21 and 22. The agreement in wind speed and direction is generally excellent, except for about an 10-20\(^\circ\) excess of inflow in the modelled wind directions. Slight alteration of the input parameters and track of this poorly organized highly erratic storm would probably have provided even better agreement.

Belle

92. The wind and wave fields in hurricane Belle have been modelled by Cardone and Ross (1979), using both the methods of Cardone et al. and simpler parametric schemes. Belle moved rapidly up along the east coast. As it did so, the central pressure rose sharply and the eye diameter increased. This storm, therefore, provides a critical test of the present method, which simulates such time changes in terms of a series of steady-state numerical solutions.

93. The center of Belle passed directly over two NOAA data buoys, one EB15 located offshore South Carolina; the other, EB41, located east of New Jersey. As for the Delia simulation, the storm input parameters and storm track determined by Cardone and Ross (1979) was used without alteration to drive the present model. Four steady-state solutions were utilized to attempt to accommodate the rapid changes in storm intensity, shape and speed.

94. The modelled and measured time histories are compared at sensor height at EB15 and EB41, in Figures 23, and 24. Agreement is generally excellent. The departure between modelled and measured wind direction early in the EB41 history is related to the presence of a frontal trough of low pressure which was located off the New Jersey coast and which distorted the pattern of isobars in the forward quadrants of the storm.
Lake Okeechobee Storm of 1949

95. The Lake Okeechobee storm of 1949 has been the subject of much past study. It is particularly important because winds were measured over the lake with calibrated anemometers mounted at 10 meters height. The wind data had been reduced to 10-minute averages by the Hydrometeorological Section, U.S. Weather Bureau. For the comparisons shown in this study, the data were reduced further to 30-minute averages, to be more consistent with the implied averaging interval of modelled winds.

96. Storm input parameters were specified as objectively as possible from the data published on this storm. While there is considerable storm data from the lake stations, there remains some uncertainty in the precise storm track; particularly east of the Florida coast and as the storm recurved northwest of the lake. There is also some uncertainty in the filling rate. In our simulation, no filling is applied until just after the eye of the hurricane has crossed the lake. Storm pressure input parameters \( p_0 = 954 \text{ mb}, R = 22 \text{ n.mi.} \) prior to the filling stage were taken directly from Graham and Hudson (1960), while the steering flow was estimated from historical Northern Hemisphere Surface Analyses. The four-parameter \( (A_p, R, V_c, V_g) \) pressure initialization scheme was adopted since the storm appeared to translate in the direction of the steering flow. There did not appear to be sufficient data in this storm to estimate \( A_p \) and \( R \) by quadrant. Storm track was taken from published track charts, though it is not clear whether the track relates to the pressure center or the center of surface wind circulation.

97. Surface winds were measured reliably at two locations within the lake, stations 14 and 16, shown in Figure 25. The same figure shows the path of the storm schematically. Surface winds were computed for two roughness categories: (1) the over-water Charnock law; (2) the roughness specification, equation 23, with constants consistent with the Lake Okeechobee drag law of Whitaker et al. (1973).

98. Measured and modelled winds at the lake stations are shown in Figures 27 and 28. The histories cover the period from about 8 hours before the occurrence of maximum wind on the lake, at which time the
storm center was between Nassau, Bahamas and West Palm Beach, Florida, and the 8-10 hour period after the occurrence of maximum winds, when the storm was filling rapidly and recurving northward over central Florida.

99. The wind speed comparisons show that in general the lake roughness histories compare better with the measurements than the over-water specification. There is one serious discrepancy between modelled and measured wind speeds: this occurs over a two-hour period just after the occurrence of maximum winds, when the modelled winds show a significant drop before rejoining the measurement history. The measurements also show a drop but to a much lesser degree. The double maximum suggests that the stations "entered" the eye briefly on the western side of the hurricane and that this affect was accentuated in the simulation perhaps because the offset between the wind circulation center and the pressure center was larger in the numerical model than actually occurred. Another possibility is that the pressure field in this storm was simply more complex than could be described by three parameters.

100. The modelled wind directions agree well with measurements at Station 14 in the forward quadrant of the storm and at Station 16 in the rear quadrant of the storm; otherwise systematic departures of 20-40° are evident. The sense of the discrepancy is that there is less inflow than modelled in the forward quadrants and more inflow than modelled in the rear quadrants, over the lake. Frictional effects associated with the presence of roughness boundaries are not as likely to be the cause of systematic effects of this nature as are differences between the actual large scale pressure field in this storm and the one simply modelled.

Betsy

101. Hurricane Betsy served to test the complete history program, including the specification of surface wind fields over a rectangular high resolution grid, each hour, throughout a 24-hour history run. Input data and sample output fields are included in Appendix C.

102. As a part of the test, surface wind histories were calculated at several locations around Lake Pontchartrain. Figure 28 displays sample wind histories for Lake Pontchartrain at Lakefront (open water
roughness), Lake Pontchartrain at Lakefront (Whitaker et al. lake roughness), New Orleans Moisant Airport \((z_0 = 0.16 \text{ m})\) and the U.S. Weather Bureau Office city office, New Orleans \((z_0 = 1 \text{ m})\). No attempt is made to compare these calculated histories to measurements.

**Anita**

103. Hurricane Anita was one of the most intense hurricanes of historical record to cross the Gulf of Mexico. The storm formed in the east central Gulf of Mexico on August 28, 1977 and moved west-southwestward into Mexico on September 02, 1977, sparing populated areas from its fury. Anita passed about 50 n.mi. north of NOAA buoy EB04 on the 30th as a poorly organized but deepening tropical storm and about 10 n.mi. south of EB71 early on September 01. As the storm moved past EB71, it was much better organized and undergoing explosive development. The general path of the storm and the time history of central pressure are shown in Figure 29.

104. Four steady-state solutions were generated for Anita, corresponding to the storms' parameters at the times indicated in Figure 29. The radius to maximum wind in Anita contracted from 30 n.mi. at the time of the first solution to 15 n.mi. at the last solution. The four solutions were used to interpolate winds in space to the buoy locations over a 48 hour period.

105. The modelled wind series at the locations of the buoys are compared to the winds measured at 20 meter height in Figures 30 and 31. At EB04, the agreement is surprisingly good considering the poorly organized nature of the storm during the period shown. Agreement is generally very good also at EB71. As suggested by the Belle test, the steady-state model provides reasonably good simulations even when applied to storms undergoing rapid changes in intensity and structure.
PART III: THE COMPUTER PROGRAM

Program Description

The program task which produces tropical storm wind histories at specified locations is divided into two main programs. The first, SNAP, produces snapshot wind fields on a nested grid and writes them onto an output data file from which the second program, HIST, obtains nested-grid wind fields for each hour of the storm's history, using linear interpolation if necessary. HIST then gets and prints the wind history at each measurement station specified, and, if requested, writes the wind history for a different grid onto an output data file.

The programs were written in Fortran V and were run on a UNIVAC 1108 computer. Each snapshot takes approximately 6 minutes of computer time, and execution of program HIST usually takes less than 3 minutes. Some mass storage is required, the amount varying with the number of snapshots, the number of interpolations between snapshots, the length of the history, and whether or not winds are to be interpolated to an output grid; 250,000 words is sufficient for most storms. Substitution of tapes for mass storage is possible, but efficiency would be decreased.

Program SNAP is composed of:

MAIN - Together with its subprograms, produces one or more snapshot wind fields on a nested grid according to card input specifications. It prints the computed winds and writes them onto an output file, and it optionally prints corresponding pressure fields and initial guess winds. MAIN itself reads all input cards, calls subroutine CCROSS which sets up tables, calls BLOWUQ which controls computation of the winds, and writes the final snapshot wind fields onto the output file.

SUBROUTINE AANGEL - Converts grid components (UN, VN) of integrated wind to speed (VTN) and direction (ANG) for all points of the $21 \times 21 \times 5$ wind grid. In addition, if
the switch variable I20 ≠ 0, AANGEL reduces the speed (VTN) to a height of 19.5 m; TWIST, the necessary correction to ANG, is computed by interpolating the array TURN; u* is computed by interpolating the array UXV containing u*/Vm; anemometer wind is computed from u* (called UXX in the code) by the usual logarithmic profile.
Arguments: input, typing implicit
I20: Flag, if non-zero winds are reduced to 19.5 meters.

SUBROUTINE ABCC - Computes Arya's $A_m$, $B_m$, $C_m$ (called $A_M$, $B_M$, $C_M$ in the FORTRAN program) and $UV$, the square of the integrated wind speed, all as functions of the friction velocity $u_*$. This is passed in common from CCROSS at location UX(K123), where $K123 = 1$, 2, or 3 at various stages of the iteration. The code is slightly more general than needed in the hurricane model, catering for unstable, neutral, and stable wind profiles (indexed by the sign of HL). In computing $A_m$ and $B_m$, the ratio $fh/u_*$ is taken equal to unity.

SUBROUTINE BLOWUQ - Controls computation and printing of all output on the nested grid. It is called once for each snapshot wind field.

SUBROUTINE CCROSS - Computes the upwind and crosswind drag coefficients, the ratio $u_*/V_m$, and the angle between surface wind and integrated wind, for all $V_m = 0.8(0.8)80.0$. Values for intermediate $V_m$ are linearly interpolated when required (lines 72–83 of COMQUT; lines 27–37 of AANGEL). The computation implements Arya's theory. The numerical method is an initial guess at $u_*$, followed by an iterative series of corrections by inverse interpolation. The iterations proper, and the computation of Arya's $A_m$, $B_m$, $C_m$, take place in subroutine ABCC.

SUBROUTINE COMQUT - Solves equations which determine the final wind fields on the nested grid. For each snapshot, COMQUT is called as many times as specified in input NAME3. At each calling a grid level is specified, and computation is done on that level.
and all finer-meshed levels only, so
that wind computation on the innermost
nest only is computed $NH$ times.
Arguments: input, typing implicit
LEVEL: Input $1 \leq \text{LEVEL} \leq 5$.
Grid distance is doubled at
each increase of LEVEL. Compu-
tation is done on all grid
levels $\leq \text{LEVEL}$.

SUBROUTINE GRAD - Computes the radial and tangential gra-
dients $\partial P/\partial r$ and $r^{-1} \partial P/\partial \theta$ of an
exponential pressure field and converts
them to rectangular gradients $\partial P/\partial x$
and $\partial P/\partial y$.

Mathematical Method:
1. Compute polar coordinates
   $(r, \cos \theta, \sin \theta)$ of the
   $21 \times 21 \times 5$ grid points.
2. Convert direction of track to
   radians.
3. Convert forward speed to meters
   per second.
4. Compute $x$- and $y$- components of
   forward speed. The method here
divides into two cases: circularly
   symmetric pressure field ($JA(6) = 0$)
   and quadrantal pressure field
   ($JA(6) \neq 0$).
   A: Circularly symmetric pressure
      field.
The governing equation
   \[ P = P_0 + \Delta P \exp \left(-\frac{R}{r}\right) \] 
   yields on differentiation
   \[ \frac{\partial P}{\partial r} = \frac{\Delta P r}{r^2} \exp \left(-\frac{R}{r}\right) . \]
5. Convert $R$ to kilometers.
6. Compute $P$.
7. Compute $\partial P/\partial r$, $\partial P/\partial x$, $\partial P/\partial y$.

B: Quadrantal pressure field.
$\Delta P$, prescribed in four quadrants,
is expanded as the trigonometric polynomial
\[ a_0 + a_1 \cos \theta + a_2 \sin \theta \]
\[ + [a_3 \cos 2\theta] \]
and then smoothed by removing the
bracketed term. \( R \) is similarly expanded and smoothed. Substituting these trigonometric polynomials in (*) yields

\[
P = P_0 + (a_0 + a_1 \cos \theta \\
+ a_2 \sin \theta) \exp (-[b_0 + b_1 \cos \theta \\
+ b_2 \sin \theta]/r)
\]

and the radial and tangential gradients

\[
\frac{\partial P}{\partial r} = (a_0 + a_1 \cos \theta \\
+ a_2 \sin \theta)(b_0 + b_1 \cos \theta \\
+ b_2 \sin \theta) r^{-2} \times \exp (-[b_0 \\
+ b_1 \cos \theta + b_2 \sin \theta]/r)
\]

\[
r^{-1} \frac{\partial P}{\partial \theta} = [r^{-1}(-a_1 \sin \theta \\
+ a_2 \cos \theta) + r^2(b_1 \sin \theta \\
- b_2 \cos \theta)] \times \exp (-[b_0 \\
+ b_1 \cos \theta + b_2 \sin \theta]/r)
\]

8. Convert \( R \) to kilometers in each quadrant.
9. Compute \( \Delta P \) to millibars in each quadrant.
10. Compute the coefficients in trigonometric polynomials.
11. Compute \( \partial P/\partial r \) and \( r^{-1} \partial P/\partial \theta \).
12. Compute \( \partial P/\partial x \) and \( \partial P/\partial y \).

Arguments: none

Variables (not in common):

- AD,\( \partial P/\partial r, r^{-1} \partial P/\partial \theta, \partial P/\partial x, \partial P/\partial y \)
- AE,AF,AG,AH Temporary storage
- AP, CR, CD Coefficients in trigonometric polynomials
- AT,CT Direction cosines of motion of storm
- BA,BC JA, floated and converted to metric units
- BP Temporary storage
- DEG Radian measure of 1 deg.
SUBROUTINE OUTBY1 - Sets outer boundary winds for the next time level. It is called once for each cycle of wind computation and grid level if the grid level is not the outermost computed at that time.
Arguments: typing implicit
NEST: Input - grid level at which boundary to be set.

SUBROUTINE OUTBY2 - Sets outer boundary winds for the same time level. It is called once for each cycle of wind computation for the coarsest meshed grid level being computed at that time unless that grid level is the outermost in the entire grid.
Arguments: typing implicit
NEST: Input - grid level at which boundary to be set.

SUBROUTINE OUTFLO - Operates on the entire field of 21 x 21 x 5 wind vectors, rotating every vector clockwise (in the northern hemisphere) by 80°. Extensive numerical experiment with earlier versions of the hurricane wind model has indicated that the finite difference scheme used leads to excessive inflow; the 80° rotation approximately removes that bias.

SUBROUTINE OUTQUT - Controls printing of winds on nested grid.
Arguments: input, typing implicit
I20: Passed on to subroutine AANGEL.
If I20 ≠ 0, wind speed will be adjusted to 19.5 meters.
NAME: 4-character name of storm
IDENT: 4-character identification of type of field (INIT or SNAP)
NSEQ: Snapshot sequence number.

SUBROUTINE PXYM - Receives the pressure gradients computed in GRAD, divides them by the density, and rearranges them in the order demanded by BLOWUQ. It then computes the gradient wind from the radial pres-
sure gradient to provide initial values for COMQUT.

Mathematical Method:
The gradient wind is given by Hess (1959, p. 183) as

\[ C = \frac{1}{r} \left( \frac{\partial p}{\partial r} \right) + \left( \left( \frac{1}{r} \right)^2 + \frac{\partial^2 p}{\partial r^2} \right)^{1/2} \] (*)

For large \( r \), (*) expresses \( C \) as the difference of two nearly equal terms, so it is advisable to compute the equivalent expression

\[ C = \left( \frac{\rho^{-1} \frac{\partial p}{\partial r}}{1/r} \right) + \left( \left( \frac{1}{r} \right)^2 + \frac{\partial^2 p}{\partial r^2} \right)^{1/2} \]

where \( f \) is the Coriolis acceleration and \( \rho \) is the density of the atmosphere.

1. Coriolis, computed in SNAP, is passed in \( C_1 \). Note that the latitude is taken as a constant throughout the cyclone; this approximation is inappropriate between \( \pm 5^\circ \) of latitude.

2. Divide \( \frac{\partial p}{\partial x} \) and \( \frac{\partial p}{\partial y} \) by \( \rho \). 1.15 \times 10^{-3} \) is the density; \( 1 \times 10^{-4} \) is a conversion factor from mb/km to newtons/m³.

3. Compute gradient wind. BC contains \( r \) in km, and the factor 1000 converts \( r \) to meters.

4. Resolve gradient wind into x- and y- components.

5. If steering flow is used, add \( (W_c x F) \) to the vector \( \rho^{-1} A P \).

Arguments: none
Variables (not in common):

- AG, AH, AI: Temporary storage
- I: Index variable for X
- J, MJ: Index variable for Y
- NEST: Index variable for nest (counted from inside out)
- FADE: Attenuation factor for steering flow
SUBROUTINE SHORE - Sets the land/sea table for the nested grid. It is currently set to 'sea' throughout.

SUBROUTINE TVEL - Prints the contents of arrays VTN and ANG on the grid level indicated as well as on the next coarser grid level.
Arguments: Input, typing implicit
  VTN: The top number in each pair of numbers printed is taken from this array. It is printed with the decimal moved one place to the right.
  ANG: The bottom number in each pair of numbers printed is taken from this array.
  NBASE: 4-character heading information
  IDENT: 4-character heading information
  KSEQ: Header information, 4-digit integer number.
  LV: Finer-meshed (lower numbered) grid level to be printed at this call to TVEL.
  I20: Flag, controlling printing of the legends "reduced" and "not reduced".

Note heading:

[NBASE] [IDENT] [KSEQ] LEVEL LV+1..
Program HIST is composed of:

**MAIN**

- Produces winds at specified measurement stations for each hour of a storm's history. If requested, it will also interpolate winds to a grid. After card input has been read and tables have been set up, it writes all unique nested-grid winds (i.e. all snapshots plus all interpolated fields) on a temporary file in the order needed. It next loops through the list of stations and, using the temporary file just written, finds and prints the winds for each station throughout the storm's history. Then, if requested, it interpolates winds to another grid for each hour of the storm's history, prints the winds on the grid for any hours indicated, and writes the fields onto an output file.

**SUBROUTINE ABCCC**

- (called by UXXV) Operates exactly the same algorithm as ABCC (called by CCROSS). The only difference in coding is that ABCCCC references the common block /C57/, defined in program HIST.

**SUBROUTINE BREEZE**

- Given LA0, L00, R0T, LA1, L01, DX, SHT, and LANSEA in common block D1, BREEZE determines the wind at point LA1, L01 at height SHT on the nested grid wind field in array XX in common block D2 and returns the wind data in W1, TH1, D, AL, and UST of common block D1.

**Mathematical Method:**

Let \( a, b, c \) be the sides of a spherical triangle, and \( \alpha, \beta, \gamma \) the angles opposite; define \( s = \frac{1}{2}(a + b + c) \).

Then

\[
\hav c = \hav (a - b) + \sin a \sin b \hav \gamma;
\]

\[
\tan^2 \frac{1}{2} \alpha = \frac{\cos (s - b) \cos (s - c)}{\sin (s - a) \sin s};
\]

1. Compute distance and bearing. If \( c \) is very small, \( (s - a) \) and \( (s - b) \) are nearly zero, and eq. (*) is unsuitable for computation; the bearing can then be computed without sen-
sible error by solving a plane tri-
angle.
2. Reduce bearing to rectangular grid.
3. Reduce distance to kilometers.
4. Compute rectangular coordinates.
5. Search for the smallest rectangular
grid in whose interior the point
lies. If point lies without fifth
nest, no wind has been computed; set
wind to zero.
6. Interpolate components of wind, us-
ing bivariate linear interpolation:
\[ \phi(x + f_1 \Delta x, y + f_2 \Delta y) = (1 - f_1)(1 - f_2) \phi(x,y) + (1 - f_1) f_2 \phi(x,y + \Delta y) + f_1(1 - f_2) \phi(x + \Delta x,y) + f_1 f_2 \phi(x + \Delta x, y + \Delta y) \]
7. Compute wind speed and reduce to
anemometer height. The factor
3600/1852 converts from m/sec
to knots; the MIN function as-
sures that the anemometer wind is
never greater than the integrated
wind.
8. Compute wind direction and reduce to
ture south.

Arguments: none

Variables: All variables except
temporary storage are annotated in
the program listing.

SUBROUTINE INVJD - Is the inverse of the function JULIAN.
Given the Julian date, it returns the
month, day, and year.
Arguments:
J: Input-Julian date, type integer
M: Output-Month, type integer
D: Output-Day, type integer
Y: Output-Year, type integer

FUNCTION JULIAN - Returns the Julian date.
Arguments:
MO: Month, type integer  
DA: Day, type integer  
YR: Year, type integer

SUBROUTINE PRLAKE - Is a grid-dependent subroutine and must be changed or replaced if the output grid is changed. It prints winds for each grid point, with speed on top, direction in the middle, and terrain code on the bottom.

Arguments: Input, typing implicit

NBASE: 4-character name of storm;
KHR: Integer sequence number of hour of storm;
ISTART: First hour of storm, corresponds to KHR = 1. Format is YYMMDDHH;
IZONE: 3-character time zone of ISTART;
WIND: As on output file 20;
LSTAB: Terrain code table for output grid;
MAXI: Number of longitudes in output grid;
MAXJ: Number of latitudes in output grid.

Note: The grid currently used uses unequally spaced meridians and parallels; printed map is distorted.

SUBROUTINE RDGRID - Is a grid-dependent subroutine and must be replaced or altered if the output grid is changed. Its function is to read latitude, longitude, and terrain code for each grid point and store them in arrays ZLA, ZLØ, and LSTAB respectively. It is called only if winds are to be interpolated to an output grid.

Arguments: typing implicit

ZLA: Output - latitudes in radians ordered south to north.
ZLØ: Output - west longitudes in radians, ordered west to east.
LSTAB: Output - terrain codes for all grid points; the first subscript increases eastward, the second increases northward.
MAXI: Input - number of longitudes in grid.
MAXJ : Input - number of latitudes in grid

SUBROUTINE UPDOWN - Computes the ratio $u_a/V_m$ and the angle between surface wind and integrated wind, all for $V_m = 0.8(0.8)80.0$, for terrains other than open ocean. The program consists of two parts: "UP" (lines 8-19) and "DOWN" (the rest of the code). UP computes $U_M$ and $V_{TOP}$ (components of wind at the top of the boundary layer), $VW2$ (squared wind speed at top), and $TARN$ (tan of angle between integrated wind and wind at top). The computation in UP uses quantities computed in UXXV (open ocean) and is consistent with Arya's theory. The assumption is now made that wind at the top of the boundary layer in a hurricane does not "see" the terrain below, so that the surface wind over any terrain can be computed by working UP and then DOWN. DOWN follows a logic similar to UXXV: Arya's $A_0$ and $B_0$ are constants (neutral wind profile); the roughness length is computed as $Z_o = A_Z/u_a + B_Z u_a + C_Z$.

SUBROUTINE UXXV - Computes the ratio $u_a/V_m$, the angle between surface wind and integrated wind and the cosine and sine of this angle, all for $V_m = 0.8(0.8)80.0$. Values for intermediate $V_m$ are linearly interpolated when required (line 73-82 of BREEZE). The computation implements Arya's theory. The numerical method is an initial guess at $u_a$, followed by an iterative series of corrections by inverse interpolation. The iteration proper, and the computation of Arya's $A_m$, $B_m$, $C_m$, take place in subroutine ABCCC. UXXV works the part of the algorithm of CCROSS (called from SNAP) pertaining to sea, i.e. $LS = 2$. The computations in UXXV are valid for open ocean only; all other terrains are treated in subroutine UPDOWN.
Remarks

In all arrays dimensioned $21 \times 21 \times N$, where $N$ is a multiple of 5, the 1st dimension increases eastward, the 2nd dimension increases northward, and the 3rd dimension, grid nest, increases with grid spacing. Grid spacing doubles with each increasing nest level.

Logical unit numbers for the card reader and printer are 5 and 6, respectively, on the system under which these programs were run. These unit numbers are set by a DATA statement into variables LR and LP in programs HIST and SNAP, and the printer unit is set into LU in subroutines GRAD and TVEL.

Equivalences between snapshot input parameters and array JA in COMMON block C2 of program SNAP:

<table>
<thead>
<tr>
<th>JA</th>
<th>NAME</th>
<th>TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ITRACK</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>EYELAT</td>
<td>R</td>
</tr>
<tr>
<td>3</td>
<td>EYLONG</td>
<td>R</td>
</tr>
<tr>
<td>4</td>
<td>DIREC</td>
<td>R</td>
</tr>
<tr>
<td>5</td>
<td>SPEED</td>
<td>R</td>
</tr>
<tr>
<td>6</td>
<td>IQUAD</td>
<td>I</td>
</tr>
<tr>
<td>7</td>
<td>EYPRES</td>
<td>R</td>
</tr>
<tr>
<td>8</td>
<td>RADIUS(1)</td>
<td>R</td>
</tr>
<tr>
<td>9</td>
<td>RADIUS(2)</td>
<td>R</td>
</tr>
<tr>
<td>10</td>
<td>RADIUS(3)</td>
<td>R</td>
</tr>
<tr>
<td>11</td>
<td>RADIUS(4)</td>
<td>R</td>
</tr>
<tr>
<td>12</td>
<td>PFAR(1)</td>
<td>R</td>
</tr>
<tr>
<td>13</td>
<td>PFAR(2)</td>
<td>R</td>
</tr>
<tr>
<td>14</td>
<td>PFAR(3)</td>
<td>R</td>
</tr>
<tr>
<td>15</td>
<td>PFAR(4)</td>
<td>R</td>
</tr>
</tbody>
</table>
Explanation of program organization charts:

Rectangular box - program element
Cut-off corner - punched card image
Diamond - printer
Barrel - mass storage
Rounded ends - program stop
### Table 2

**Files**

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit Number</th>
<th>Size</th>
<th>Program SNAP</th>
<th>Program HIST</th>
<th>Save</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card Reader</td>
<td>5</td>
<td>Input</td>
<td>Input</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Printer</td>
<td>6</td>
<td>Output</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snapshot Wind</td>
<td>13</td>
<td>4436 Words each</td>
<td>Output</td>
<td>Input</td>
<td>✓</td>
</tr>
<tr>
<td>Fields on Nested Grid</td>
<td></td>
<td>Record (Snapshot)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordered Unique Wind Fields on Nested Grid</td>
<td>10</td>
<td>4411 Words each</td>
<td>Work</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Record (Wind Field)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hourly Wind Fields on Output Grid</td>
<td>20</td>
<td>Grid-dependent, 3855 Words each</td>
<td>Output</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Record (Hour) for Test Grid</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Records in files 10, 13, and 20 are written with Fortran unformatted WRITE statements. There are file marks after the last data records in output files 13 and 20.
<table>
<thead>
<tr>
<th>Program</th>
<th>Seq. Number</th>
<th>Name*</th>
<th>Number/Remarks</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNAP</td>
<td>1</td>
<td>NAME1</td>
<td>1</td>
<td>Processing control</td>
</tr>
<tr>
<td>SNAP</td>
<td>2</td>
<td>NAME2</td>
<td>1</td>
<td>Parameters in roughness law (usually constant)</td>
</tr>
<tr>
<td>SNAP</td>
<td>3</td>
<td>NAME3</td>
<td>1 for each wind snapshot</td>
<td>Parameters describing wind field</td>
</tr>
<tr>
<td>HIST</td>
<td>1</td>
<td>NAME4</td>
<td>1</td>
<td>Storm identification, also grid parameters if winds are to be interpolated to an output grid</td>
</tr>
<tr>
<td>HIST</td>
<td>2</td>
<td>NAME5</td>
<td>1</td>
<td>Terrain coefficients and number of types of terrain other than open ocean</td>
</tr>
<tr>
<td>HIST (RDGRID)</td>
<td>3</td>
<td>Only if grid conversion</td>
<td>Longitudes and latitudes of grid points. Card count, format and ordering of data must agree with subroutine RDGRID.</td>
<td></td>
</tr>
<tr>
<td>HIST (RDGRID)</td>
<td>4</td>
<td>Only if grid conversion</td>
<td>Code for type of terrain at each grid point. Card count, format, and ordering of data must agree with subroutine RDGRID.</td>
<td></td>
</tr>
</tbody>
</table>

* Namelist is not a construction recognized by the current FORTRAN standard (ANSI X3.9-1978). Appendix A contains an account of Namelist as used in this program.
<table>
<thead>
<tr>
<th>Program</th>
<th>Seq. Number</th>
<th>Name (If Namelist)</th>
<th>Number/Remarks</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIST 5(or 3)</td>
<td>One card for each station where wind history is needed, terminated by end-of-file</td>
<td>Station location and height at which measurements taken.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIST 6(or 4)</td>
<td>One card for each hour of storm history, terminated by end-of-file</td>
<td>Location of eye of storm, snapshot identification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Namelist Name</td>
<td>Variable Name</td>
<td>Size in Words</td>
<td>Units</td>
<td>Type</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>NAME1</td>
<td>IB</td>
<td>1</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>NZ</td>
<td>1</td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>NAME2</td>
<td>DTH</td>
<td>2</td>
<td>°K</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>HH</td>
<td>1</td>
<td>m</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>ZOLAND</td>
<td>1</td>
<td></td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>GARR</td>
<td>1</td>
<td></td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>PTH</td>
<td>1</td>
<td>°K</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>K35</td>
<td>1</td>
<td></td>
<td>R</td>
</tr>
<tr>
<td>Namelist Name</td>
<td>Variable Name</td>
<td>Size in Words</td>
<td>Units</td>
<td>Type</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>NAME3</td>
<td>SGW</td>
<td>1</td>
<td>m/sec</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>ANI</td>
<td>1</td>
<td>deg</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>NAME</td>
<td>1</td>
<td>H</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EYELAT</td>
<td>1</td>
<td>deg</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>EYLONG</td>
<td>1</td>
<td>deg</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>DIREC</td>
<td>1</td>
<td></td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>SPEED</td>
<td>1</td>
<td>kn</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>EXPRES</td>
<td>1</td>
<td>mb</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>RADIUS</td>
<td>4</td>
<td>nm</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>PFAR</td>
<td>4</td>
<td>mb</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>NN</td>
<td>1</td>
<td>I</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>DX</td>
<td>1</td>
<td>km</td>
<td>R</td>
</tr>
<tr>
<td></td>
<td>ST12</td>
<td>1</td>
<td>km</td>
<td>R</td>
</tr>
</tbody>
</table>

(continued)
Table 4 (concluded)

<table>
<thead>
<tr>
<th>Namelist Name</th>
<th>Variable Name</th>
<th>Size in Words</th>
<th>Units</th>
<th>Type</th>
<th>Default Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAME3</td>
<td>ITRACK</td>
<td>1</td>
<td></td>
<td>I</td>
<td>0</td>
<td>If 0, DIREC in degrees; if 1, DIREC in points of 11.25 degrees</td>
</tr>
<tr>
<td></td>
<td>IQUAD</td>
<td>1</td>
<td></td>
<td>I</td>
<td>0</td>
<td>Indicator for quadrants of pressure field: 0, circularly symmetric pressure field; 1, 1st quadrant is right front; 2, 1st quadrant if forward</td>
</tr>
<tr>
<td>Namelist Name</td>
<td>Variable Name</td>
<td>Size in Words</td>
<td>Type</td>
<td>Description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>---------------</td>
<td>---------------</td>
<td>------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAME3</td>
<td>NBASE</td>
<td>1</td>
<td>H</td>
<td>4-character name of storm - must be same as 1st SNAP namelist NAME3, item NAME</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ISTART</td>
<td>1</td>
<td>I</td>
<td>Starting time of storm, format YYMDDHH</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IZONE</td>
<td>1</td>
<td>H</td>
<td>3-character time zone of ISTART</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICNVRT</td>
<td>1</td>
<td>I</td>
<td>Flag: if non-zero, winds will be interpolated to an output grid, and grid data must be input</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NPRT</td>
<td>1</td>
<td>I</td>
<td>Interval in hours at which to print winds on output grid. If zero, winds will be printed only for hours so flagged in the history table</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAME5</td>
<td>LAKE</td>
<td>1</td>
<td>I</td>
<td>Number of types of terrain in addition to open ocean. 0 ≤ LAKE ≤ 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ZCOEFF</td>
<td>15</td>
<td>R</td>
<td>3 coefficients in formula relating $Z_o$ to $U^*$ for all terrains except open ocean. Dimensioned (3,5).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6

Program HIST Fixed Format Card Input

1) Station location and data: One card for each measurement station, format (5I4,F6.1,1X,I3)

1. Degrees of north latitude
2. Minutes of latitude
3. Degrees of west longitude
4. Minutes of longitude
5. Terrain code, same codes as grid terrain code table
6. Station height in meters
7. Station number (for identification only)

2) History: One card for each hour, format (6I4,F8.4,2I4)

1. Degrees of north latitude of eye of storm
2. Minutes of latitude of eye
3. Degrees of west longitude of eye
4. Minutes of longitude of eye
5. Sequence number of 1st snapshot wind field to be used for this hour
6. Sequence number of 2nd snapshot wind field to be used for this hour (blank if no interpolation this hour)
7. Interpolation distance between 1st and 2nd snapshots (blank if (6) is blank)
8. Clockwise rotation of snapshot in degrees
9. Flag: non-zero if output grid wind field is to be printed
Table 7

Input Cards with Data Defining Program HIST Test Output Grid

1) 5 cards with 62 west longitudes in the form DDMM and progressing from west to east. Each card, except the last has 15 longitudes and a sequence number in format 16I5. The last card is blank filled between the last data field and the sequence number.

2) 3 cards with 31 latitudes progressing from south to north. Form and format are the same as those of the longitude cards.

3) 31 cards of terrain code. Each card is for one latitude, and cards are ordered from south to north. The format is 2I3, for degrees and minutes of latitude, then 2X,62II, where the 62II's are one-digit numeric terrain codes for each longitude and progress from west to east. As used in the test grid for Lake Pontchartrain, the codes are as follows -
   1: open ocean
   2: lake
   3: marsh
   4: plains
   5: woods
   6: cities
<table>
<thead>
<tr>
<th>Block Name</th>
<th>Variable Name</th>
<th>Size in Words</th>
<th>Units</th>
<th>Source</th>
<th>Disposition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>NAME</td>
<td>1</td>
<td></td>
<td>Input</td>
<td>Snapshot wind data file</td>
<td>4-character name of storm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NAME3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSNAP</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Sequence number of wind snapshot</td>
</tr>
<tr>
<td>DX</td>
<td></td>
<td>1</td>
<td>km</td>
<td>Input</td>
<td>Snapshot wind data file</td>
<td>Grid spacing of innermost nest</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NAME3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT</td>
<td></td>
<td>1</td>
<td>sec</td>
<td></td>
<td></td>
<td>Time increment for computation of winds in innermost nest</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Coriolis force</td>
</tr>
<tr>
<td>SGW</td>
<td></td>
<td>1</td>
<td>m/sec</td>
<td>Input</td>
<td>Snapshot wind data file</td>
<td>Surface geostrophic wind of ambient flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NAME3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AN1</td>
<td></td>
<td>1</td>
<td>deg</td>
<td>Input</td>
<td>Snapshot wind data file</td>
<td>Direction of SGW counterclockwise from snapshot x-axis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NAME3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UC</td>
<td></td>
<td>1</td>
<td>m/sec</td>
<td></td>
<td></td>
<td>X-component of velocity of storm movement</td>
</tr>
<tr>
<td>VC</td>
<td></td>
<td>1</td>
<td>m/sec</td>
<td></td>
<td></td>
<td>Y-component of velocity of storm movement</td>
</tr>
<tr>
<td>UG</td>
<td></td>
<td>1</td>
<td>m/sec</td>
<td></td>
<td></td>
<td>X-component of surface geostrophic wind</td>
</tr>
<tr>
<td>VG</td>
<td></td>
<td>1</td>
<td>m/sec</td>
<td></td>
<td></td>
<td>Y-component of surface geostrophic wind</td>
</tr>
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<td>Number of times to cycle wind computation in innermost grid nest</td>
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<td>Flag: if zero, do not print pressure field or initial wind</td>
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<td>Distance from axis to ( \frac{1}{2} ) magnitude of SGW</td>
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<tr>
<td>C2</td>
<td>JA</td>
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<td>Snapshot wind data file</td>
<td>See program SNAP output data file record description, page . Also note equivalence list in remarks, page .</td>
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<td>NAME3</td>
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<td>Work array, 1st third, ( \partial p/\partial x ); 2nd third, ( \partial p/\partial y ); last third, ( \partial p/\partial r )</td>
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<td>AB</td>
<td></td>
<td>6615</td>
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<td>Dimensioned ( 21 \times 7 \times 21 ). Location in grid defined by 1st and 3rd subscripts. If 2nd subscript, N, is 1, value is cosine of angle of grid point; if 2, value is sine of angle of grid point; is 3-7, value is radius in meters of point in nest N-2.</td>
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<tr>
<td>AC</td>
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<td>Work array, ( x )-component of boundary layer wind</td>
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<td>Work array, ( y )-component of boundary layer wind</td>
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<td>m/sec</td>
<td></td>
<td>Snapshot wind data file</td>
<td>X-component of boundary layer wind</td>
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<td>Y-component of boundary layer wind</td>
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<td>Work array, ( \partial p/\partial x )</td>
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<td>VTN</td>
<td>2205</td>
<td>kn</td>
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<td>Work array, holds wind speeds to be printed</td>
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<td>ANG</td>
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<td>deg</td>
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Table 8 (continued)

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<td>(C3)</td>
<td>LW</td>
<td>2205</td>
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<td>Land/sea table: 1 for land, 2 for sea</td>
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<td>C4</td>
<td>CDR</td>
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<td>Work array, dimensioned 100 x 2 x 2. Drag coefficients: CDR(I,1,1) is upwind component of drag coefficients over land, when integrated wind speed is (.8xI) m/sec. CDR(I,2,1) is crosswind component over land. CDR(I,1,2) is upwind component over ocean. CDR(I,2,2) is crosswind component over ocean.</td>
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<td>UXV</td>
<td>200</td>
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<td></td>
<td>Work array, dimensioned 100 x 2. UXV(I,1) is ( \frac{U_m}{V_m} ) over land, when ( V_m = (0.8xI) ) m/sec. UXV(I,2) is the same over ocean.</td>
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<tr>
<td></td>
<td>TURN</td>
<td>200</td>
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<td></td>
<td></td>
<td>Work array, dimensioned 100 x 2. TURN(I,1) is the angle between surface wind and integrated wind, over land, when integrated wind speed is (.8xI) m/sec. TURN(I,2) is the same over ocean.</td>
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<tr>
<td>C5</td>
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<td>Coriolis force</td>
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<td>( ^{\circ}K )</td>
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<td>Input Snapshot wind data file</td>
<td>(1) Air-land temperature difference (2) Air-sea temperature difference</td>
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<td>NAME2</td>
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<tr>
<td>VV</td>
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<td>m/sec</td>
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<td></td>
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<td>Vertically integrated wind speeds. VV(I) at point I = .8m/sec × I</td>
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<tr>
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<td>Latest 3 values of U* in an iterative loop</td>
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<td>Latest 3 values of integrated wind speed corresponding to U*</td>
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<td>Interpolated value of wind speed squared minus desired value squared</td>
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<td>Snapshot wind data file</td>
<td>Karman's constant, type real</td>
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<td>K35^2, type real</td>
</tr>
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<td>Acceleration of gravity = 9.806 m/sec^2</td>
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<tr>
<td>GA</td>
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<td>sec^2/m</td>
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<td>Charnock's constant divided by G</td>
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<tr>
<td>DEN</td>
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<td></td>
<td></td>
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<td>m^2/sec^2</td>
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<td>VV(I)^2 for current I</td>
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<tr>
<td>HL</td>
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<td>HH/stability length</td>
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<tr>
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<td>Roughness length</td>
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(continued)
### Table 8 (continued)

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<th>Units</th>
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<td>Constant in Arya's logarithmic scale law</td>
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<td>Constant in Arya's logarithmic scale law</td>
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<td>Coriolis parameter. Retained for consistency with other versions of CCROSS; not used in this program.</td>
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<td>C57</td>
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<td>Air-sea temperature difference</td>
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<tr>
<td></td>
<td>HH</td>
<td>1 m</td>
<td></td>
<td>Snapshot wind data file</td>
<td>Boundary layer height over water</td>
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<td>ZCOEFF</td>
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<td>Input NAME5</td>
<td>3 coefficients in formula relating Z₀ to Uₘ for all terrains except open ocean, where Garratt's formula is used</td>
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<tr>
<td></td>
<td>VV</td>
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<td>Latest 3 values of Uₘ in an iterative loop</td>
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<td>Kₚ², type real</td>
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<td>G</td>
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<td>Uₜ/VV for each I, terrain type</td>
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<td>West longitude of point of which wind is wanted, type real</td>
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<tr>
<td></td>
<td>IPI</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td>Flag: non-zero if listing of winds on output wanted</td>
</tr>
<tr>
<td></td>
<td>NHT</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Number of hours in storm history</td>
</tr>
<tr>
<td></td>
<td>INTVN</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Not used</td>
</tr>
<tr>
<td></td>
<td>INTVI</td>
<td>1</td>
<td>hours</td>
<td></td>
<td></td>
<td>Interval at which to print winds on output grid</td>
</tr>
<tr>
<td>LGRID*</td>
<td>ILAT</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>List of output grid latitudes, south to north, in the format DDMM</td>
</tr>
<tr>
<td></td>
<td>ILONG</td>
<td>62</td>
<td></td>
<td></td>
<td></td>
<td>List of output grid west longitudes, west to east, in the format DDMM</td>
</tr>
</tbody>
</table>

*Not in main program, in subroutines RDGRID and PRLAKE only.
Table 9

Description of Program HIST arrays not in COMMON

Station data arrays - all dimensioned 100

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>Location, from card input - degrees of north latitude</td>
</tr>
<tr>
<td>NAM</td>
<td>Location, from card input - minutes of latitude</td>
</tr>
<tr>
<td>MMOD</td>
<td>Location, from card input - degrees of west longitude</td>
</tr>
<tr>
<td>MMM</td>
<td>Location, from card input - minutes of longitude</td>
</tr>
<tr>
<td>LLAKE</td>
<td>Terrain code, from card input</td>
</tr>
<tr>
<td>STAHT</td>
<td>Height in meters, from card input</td>
</tr>
<tr>
<td>KSTA</td>
<td>Station number (identification), from card input</td>
</tr>
<tr>
<td>YLA</td>
<td>Latitude in radians</td>
</tr>
<tr>
<td>YLO</td>
<td>Longitude in radians</td>
</tr>
</tbody>
</table>

History table arrays - all dimensioned 100

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAD</td>
<td>Location of eye of storm, from card input - degrees of north latitude</td>
</tr>
<tr>
<td>NAM</td>
<td>Location of eye of storm, from card input - minutes of latitude</td>
</tr>
<tr>
<td>NOD</td>
<td>Location of eye of storm, from card input - degrees of west longitude</td>
</tr>
<tr>
<td>NOM</td>
<td>Location of eye of storm, from card input - minutes of longitude</td>
</tr>
<tr>
<td>IROT</td>
<td>Grid rotation angles, from card input</td>
</tr>
<tr>
<td>KDATE</td>
<td>Date in form YYMMDD</td>
</tr>
<tr>
<td>KTIME</td>
<td>Hour of KDATE</td>
</tr>
<tr>
<td>JSEQ</td>
<td>Sequence numbers of nested grid winds on work file</td>
</tr>
</tbody>
</table>

Output grid data arrays as used with test grid

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZLA</td>
<td>List of latitudes of grid points, south to north, in radians</td>
</tr>
<tr>
<td>ZLO</td>
<td>List of west longitudes of grid points, west to east, in radians</td>
</tr>
</tbody>
</table>

73
Table 9 (concluded)

ZANG Deviation between true north and grid north for each grid point – zero throughout test grid

LSTAB List of terrain codes of grid points.

Other arrays

XY Dimensioned $21 \times 21 \times 10$. Contains 2nd snapshot wind field when needed
### Table 10

#### Program Stops

<table>
<thead>
<tr>
<th>Program</th>
<th>Stop Number</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNAP</td>
<td>999*</td>
<td>Normal completion of run</td>
</tr>
<tr>
<td>HIST</td>
<td>999*</td>
<td>Normal completion of run</td>
</tr>
<tr>
<td>HIST</td>
<td>5</td>
<td>Error in reading station or history input card</td>
</tr>
<tr>
<td>HIST</td>
<td>146</td>
<td>Error in reading mass storage work file of wind fields on nested grid</td>
</tr>
<tr>
<td>HIST</td>
<td>444</td>
<td>Snapshot interpolation distance out of range ( &lt; 0 or &gt; 1 ).</td>
</tr>
<tr>
<td>HIST</td>
<td>515</td>
<td>Input card and snapshot data file storm identifications are different</td>
</tr>
<tr>
<td>HIST</td>
<td>516</td>
<td>Too many station input cards ( &gt; 100 )</td>
</tr>
<tr>
<td>HIST</td>
<td>517</td>
<td>Too many history input cards ( &gt; 100 )</td>
</tr>
<tr>
<td>HIST</td>
<td>21</td>
<td>Error in reading grid longitude card</td>
</tr>
<tr>
<td>(RDGRID)</td>
<td></td>
<td>Error in reading grid terrain code card</td>
</tr>
<tr>
<td>HIST</td>
<td>23</td>
<td>Error in reading grid latitude card</td>
</tr>
<tr>
<td>(RDGRID)</td>
<td></td>
<td>Error in reading grid terrain code card</td>
</tr>
</tbody>
</table>

* If running a FORTRAN that requires STOP number to be octal, substitute 777.
### Table 11

**Output Data File Record Description**

**Snapshot wind field record from program SNAP**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>(Dimension)</th>
<th>Size</th>
<th>Accumulated Word Count</th>
<th>Units</th>
<th>Applicable Format*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN</td>
<td>(21,21,5)</td>
<td>2205</td>
<td>2205</td>
<td>m/sec</td>
<td>F4.1</td>
<td>X-component of boundary layer wind 1st dimension increases with increasing x</td>
</tr>
<tr>
<td>VN</td>
<td>(21,21,5)</td>
<td>2205</td>
<td>4410</td>
<td>m/sec</td>
<td>F4.1</td>
<td>Y-component of boundary layer wind 2nd dimension increases with increasing y 3rd dimension (grid nest) increases with grid spacing</td>
</tr>
<tr>
<td>NAME</td>
<td>1</td>
<td></td>
<td>4411</td>
<td></td>
<td>A4</td>
<td>4-character name of storm</td>
</tr>
<tr>
<td>DX</td>
<td>1</td>
<td></td>
<td>4412</td>
<td>km</td>
<td>F3.0</td>
<td>Grid spacing of innermost nest</td>
</tr>
</tbody>
</table>
| JA            | (15)        | 15   | 4427                    | I1    |                    | 1: Indicator for coding of (4)
  If 0, (4) in degrees; if 1, (4) in points of 11.25 degrees. 2: North latitude of eye of storm |
|               |             |      |                         |       |                    | 3: West longitude of eye of storm 4: Direction of track of storm, clockwise from north |
|               |             |      |                         |       |                    | see JA(1) |
|               |             |      |                         |       | F4.0               | 5: Forward speed of storm |
|               |             |      |                         |       | F5.1               | 6: Indicator for quadrants of pressure field |

* Format appropriate for printing this variable or array.
<table>
<thead>
<tr>
<th>Variable Name</th>
<th>(Dimension)</th>
<th>Size</th>
<th>Accumulated Word Count</th>
<th>Units</th>
<th>Applicable Format</th>
<th>Description</th>
</tr>
</thead>
</table>
| [JA]          |             |      |                         |       |                  | 0 - circularly symmetric pressure field  
|               |             |      |                         |       |                  | 1 - 1st quadrant is right front  
|               |             |      |                         |       |                  | 2 - 1st quadrant is forward  
|               |             |      |                         | mb    | F6.1             | 7: Pressure at eye of storm  
|               |             |      |                         | nm    | F4.0             | 8-11: Exponential pressure profile scale radius in four quadrants. If JA(6) is zero, JA(9) - JA(11) may not contain valid data  
|               |             |      |                         | mb    | F5.0             | 12-15: Far field pressure in four quadrants. If JA(6) is zero, JA(13) - JA(15) may not contain valid data  
| SGW           | 1           | 4428 | m/sec                   | F3.0  |                  | Surface geostrophic wind of ambient flow  
| AN1           | 1           | 4429 | deg                     | F4.0  |                  | Direction of SGW counterclockwise from snapshot x-axis  
| ST12          | 1           | 4430 | km                      | F5.1  |                  | Distance from axis to \( \alpha \) magnitude of SGW  
| DTH           | 2           | 4432 | o_K                     |       |                  | (1) Air-land temperature difference  
|               |             |      |                         |       |                  | (2) Air-sea temperature difference  
| HH            | 1           | 4433 | m                       |       |                  | Boundary layer height over water  
| GARR          | 1           | 4434 |                         |       |                  | Charnock's constant  
| PTH           | 1           | 4435 | o_K                     |       |                  | Potential temperature  
| K35           | 1           | 4436 |                         |       |                  | Karman's constant, type real  

(continued)
### Table 11 (concluded)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Dimension</th>
<th>Size</th>
<th>Accumulated Word Count</th>
<th>Units</th>
<th>Applicable Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBASE</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>A4</td>
<td>4-character name of storm</td>
</tr>
<tr>
<td>KHR</td>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
<td>I3</td>
<td>Sequence number of hour of storm</td>
</tr>
<tr>
<td>ISTART</td>
<td></td>
<td>1</td>
<td>3</td>
<td></td>
<td>I8</td>
<td>Starting time of storm in format YYYYMMDDHH (Time at which KHR=1)</td>
</tr>
<tr>
<td>IZONE</td>
<td></td>
<td>1</td>
<td>4</td>
<td></td>
<td>A3</td>
<td>Time zone of ISTART</td>
</tr>
<tr>
<td>IMAX</td>
<td></td>
<td>1</td>
<td>5</td>
<td></td>
<td>I2</td>
<td>Longitudinal dimension of output grid</td>
</tr>
<tr>
<td>JMAX</td>
<td></td>
<td>1</td>
<td>6</td>
<td></td>
<td>I2</td>
<td>Latitudinal dimension of output grid</td>
</tr>
<tr>
<td>GRIDHT</td>
<td></td>
<td>1</td>
<td>7</td>
<td>m</td>
<td>F6.1</td>
<td>Height to which wind speeds are scaled</td>
</tr>
<tr>
<td>NAD</td>
<td></td>
<td>1</td>
<td>8</td>
<td></td>
<td>I3</td>
<td>Location of eye of storm - degrees of north latitude</td>
</tr>
<tr>
<td>NAM</td>
<td></td>
<td>1</td>
<td>9</td>
<td></td>
<td>I2</td>
<td>Location of eye of storm - minutes of latitude</td>
</tr>
<tr>
<td>NOD</td>
<td></td>
<td>1</td>
<td>10</td>
<td></td>
<td>I4</td>
<td>Location of eye of storm - degrees of west longitude</td>
</tr>
<tr>
<td>NOM</td>
<td></td>
<td>1</td>
<td>11</td>
<td></td>
<td>I2</td>
<td>Location of eye of storm - minutes of longitude</td>
</tr>
<tr>
<td>WIND</td>
<td>(2,MAXI,MAXJ)</td>
<td>11+2×MAXI×MAXJ</td>
<td>(3844 for test grid)</td>
<td>(3855 for test grid)</td>
<td></td>
<td>Wind at specified height on wave grid. If 1st subscript is 1, value is wind speed in knots. If 1st subscript is 2, value is direction in degrees toward which wind blows counterclockwise from north</td>
</tr>
</tbody>
</table>
Printed Output

Program SNAP initially prints card input data and finally prints an end-of-job message. For each snapshot it prints card input data pertinent to that snapshot, a pressure field and an initial guess wind field if requested, and a final snapshot wind field on the nested grid. Snapshot wind speeds are printed in tenths of knots, directions are meteorological, and west is at the top of the page. Each snapshot is printed both with wind speeds as computed and with wind speeds scaled to 19.5 meters.

Program HIST prints card input data, the wind history at each requested station, wind fields on the output grid for hours requested, and an end-of-job message. Output grid wind speeds are in knots and directions are meteorological. Terrain types are indicated by blank for type 1, '*' for 2, '=' for 3, '-' for 4, '+' for 5 and 'S' for 6.
Table 12

Program Changes Needed for a New Output Grid

1) Subroutine RDGRID
2) Subroutine PRLAKE
3) COMMON block LGRID (used in RDGRID and PRLAKE only)
4) In program Hist:
   a) Parameters MAXI, MAXJ, and IGRDHT, where MAXI is the longitudinal dimension of the grid, MAXJ is the latitudinal dimension, and IGRDHT is its height in tenths of meters.
   b) ZLA, ZLO become two-dimensional if rows and columns do not fall on latitude, longitude lines, and the settings of LA1 and LO1 in the DO 111 and DO 110 loops will be affected
   c) Array ZANG, the angle between true meridian and grid meridian, may become non-zero.
PART IV: CONCLUSIONS AND RECOMMENDATIONS

A method is developed to specify the surface stress and the wind speed and direction in the planetary boundary layer of a tropical cyclone from meteorological storm parameters available for historical hurricanes. The method is based upon a numerical primitive-equation model of the planetary boundary layer in a moving tropical cyclone. The complete time history of the evolution of the surface wind field is described from a series of characteristic wind field states calculated at discrete times in a storm's history by the steady-state model.

A surface drag formulation, based upon a contemporary similarity model (Arya, 1977) coupled with a roughness parameter specification for a water surface consistent with Cardone's (1969) law, is incorporated into the numerical model. As a result, the model was found to produce a consistent description of the integrated planetary boundary layer wind, the magnitude and direction of the surface stress, and the wind speed and direction at anemometer level, without recourse to arbitrary, empirical calibration schemes. The surface winds calculated in several recent hurricanes are found to be in excellent agreement with available, representative surface wind measurements made from offshore platforms and data buoys.

Transformations based upon an equilibrium planetary-boundary-layer similarity model are developed to specify the surface wind over terrain of specified roughness, including lake surfaces, from the over-water wind-field solution. Calculated over-land and over-lake winds are compared to the limited measurements available for several recent storms. Agreement is generally good.

The principal limitation of the model is the neglect of fetch effects in the adjustment of the PBL across roughness discontinuities. Adjustments in near-surface wind speed, however, are believed to occur sufficiently rapidly that accuracy over homogeneous terrain and lakes the size of Pontchartrain and Okeechobee should not be significantly limited. The adjustment scale for wind direction, however, might be much larger.
The principal obstacle to further development and evaluation of the method developed here is the lack of high-quality measurements of surface winds over the lakes of interest in well documented storms. As part of an intensive field program conducted in Lake Pontchartrain by the U.S. Army Corps of Engineers during the past year, wind data was apparently collected at several points in the lake during the passage of two hurricanes (Bob and Frederick, 1979). Even though only the peripheral parts of those storms were sampled, it is strongly recommended that those measurements be carefully processed and that the method developed in this study be applied to those storms.
LITERATURE CITED


Whitaker, R.E., R.O. Reid, A.C. Vastano. 1973. Drag coefficient at hurricane wind speeds as deduced from numerical simulation of dynamic water level changes in Lake Okeechobee. Ref. 73-13-T, Dept. of Oceanography, Texas A&M University, College Station, Texas.

Figure 1. Grid points of the inner three grids in one quadrant of the nested grid system. The center of the grid system is indicated by 0 (from Chow 1971).
Figure 2. Radial distribution of tangential velocity ($V_\theta$) and radial velocity ($V_r$) for a frictionless, symmetrical, stationary storm given by $\Delta p = 50$ mb and $R = 40$ km, computed from Chow's numerical model. Analytical (gradient wind solution) solution ($V_{\theta g}$) for specified pressure field is shown (from Chow 1971).
Figure 3. Streamlines (solid lines) and isotachs (dashed lines) of the steady-state solution for the vertically integrated boundary layer wind in a mature tropical cyclone moving westward at 10 m/sec, in a westerly steering flow (10 m/sec), from the model of Chow (1971)
Figure 4. Computed depth of the planetary boundary layer versus radial distance from the eye for Hurricanes Daisy (1958) and Inez (1966) (from Moss and Rosenthal 1975)
Figure 5. Computed depth of the planetary boundary layer in a mature, steady-state tropical cyclone (from Chang 1977)
Figure 6. Garratt's (1977) collection of mean values of the drag coefficient as a function of wind speed at the 10-m height for 5-m/sec intervals, based on individual data from hurricane studies (O), wind flume experiments (*), and vorticity/mass budget analysis (A). Vertical bars refer to the standard deviation of individual data for each mean, with the number of data used in each mean shown below each mean value immediately above the abscissa scale. The dashed curve represents the variation of the 10-m neutral drag coefficient $C_{DN}$ with wind speed based on

$$z_{o} = \frac{a u_{*}^{2}}{g}$$

with $a = 0.0144$ and a value of the barrier constant $k$ of 0.41. The solid curve represents the variation with $a = 0.035$ and $k = 0.35$. 
Figure 7. Drag coefficient with respect to the vertically integrated planetary boundary layer wind versus integrated boundary layer wind from Arya's model for alternate air-sea temperature and roughness parameter specifications and/or the case of restricted scale/height ratio. The form used by Chow (1971) is shown for comparison.
Figure 8. Predictions of 20-m wind speed versus radial distance to eye in Camille from the model of Cardone et al. (1976) and from the model with revised PBL stress law.
Figure 9. Comparison of modelled and measured surface wind speed at Rig 50 in Camille for vortex model with modified similarity model drag law and alternate boundary layer heights.
Figure 10. Radial profile of gradient wind speed, integrated PBL wind speed, 20-m wind speed, inflow angle of integrated and surface wind for a severe, stationary, symmetric hurricane.
Figure 11. Ratio of overland/over-water wind speed versus fetch for near neutral moderate-high wind speed data of Richards et al. (1966) and Phillips and Irbe (1977)
Figure 12. Radar scattering cross section $\sigma_0$ as a function of fetch at an incidence angle of 40°. Surface wind speeds were 9.0 m s$^{-1}$. 

Radar scattering cross section $\sigma_0$ as a function of fetch at an incidence angle of 53°. Surface wind speeds were 13.0 m s$^{-1}$. 

Radar scattering cross section $\sigma_0$ as a function of fetch at an incidence angle of 40° for wind speeds of 9.0 m/sec (above) and an incidence angle of 53° for wind speeds of 13.0 m/sec (below)
Figure 13. Coordinate system and relationship of wind stress components in the equilibrium model PBL over rough and smooth (sea) terrain.
From equilibrium model

From vortex model

Lake Okeechobee empirical transformation

Figure 14. Ratio of the surface wind speed at the 20-m height overland to oversea (above) and the difference between the overland and over-sea inflow angle (below) from the equilibrium PBL model for two terrain roughnesses, from the numerical vortex model and the empirical wind speed ratio derived from measurements in hurricanes at Lake Okeechobee.
Figure 15. Comparison of measured and modelled wind speed at Rig 50 at measurement height in Camille.
$z_o$ Values for Typical Terrain Types (After ESDU 72026, 1972)

Terrain description of area within several kilometres upwind of site

<table>
<thead>
<tr>
<th>$z_o$ (m$^{-1}$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>Many hedges</td>
</tr>
<tr>
<td></td>
<td>Few trees, summer time</td>
</tr>
<tr>
<td></td>
<td>Isolated trees</td>
</tr>
<tr>
<td></td>
<td>Uncut grass</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>Few trees, winter time</td>
</tr>
<tr>
<td></td>
<td>Cut grass ($\leq 3$ cm)</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>Many trees, hedges, few buildings</td>
</tr>
<tr>
<td></td>
<td>Centres of cities with very tall buildings</td>
</tr>
<tr>
<td></td>
<td>Very hilly or mountainous areas</td>
</tr>
<tr>
<td></td>
<td>Centres of large towns, cities</td>
</tr>
<tr>
<td></td>
<td>Forest</td>
</tr>
<tr>
<td></td>
<td>Centres of small towns</td>
</tr>
<tr>
<td></td>
<td>Fairly level wooded country</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>Outskirts of towns</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>Many trees</td>
</tr>
<tr>
<td></td>
<td>Natural snow surface (framland)</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>Off-sea wind in coastal areas</td>
</tr>
<tr>
<td></td>
<td>Desert (flat)</td>
</tr>
<tr>
<td></td>
<td>Large expanses of water</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>Calm open sea</td>
</tr>
<tr>
<td></td>
<td>Snow-covered flat or rolling ground</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>Ice, mud flats</td>
</tr>
</tbody>
</table>

Figure 16. Roughness parameter values for typical terrain types (after ESDU 72026, 1972)
Figure 17. Comparison of measured and modelled winds at Keesler Air Force Base, Biloxi, MS, in Camille
Figure 18. Comparison of measured and modelled wind direction at Burwood, LA, in Camille
Figure 19. Comparison of measured and modelled wind speed at Burwood, LA, in Camille.
Figure 20. Comparison of measured and modelled wind speed (above) and wind direction (below) at New Orleans Lakefront Airport in Camille. Modelled wind at New Orleans for roughness parameter of 1 m shown.
Figure 23. Comparison of measured and modelled wind speed and direction at buoy EB15 in Belle
Figure 24. Comparison of measured and modelled wind direction at buoy EB41 in Belle
Figure 25. Location of measurement stations in Lake Okeechobee and path of the 1949 Lake Okeechobee hurricane.
Figure 26. Comparison of measured and modelled wind speed and direction at station 14 in the 1949 Lake Okeechobee hurricane
Figure 27. Comparison of measured and modelled wind speed and direction at station 15 in the 1949 Lake Okeechobee hurricane.
Figure 28. Modelled wind speed and direction for various terrain roughnesses in Hurricane Betsy
Figure 30. Comparison of measured and modelled wind speed and direction at buoy EB04 in Hurricane Anita
Figure 31. Comparison of measured and modelled wind speed and direction at buoy EB71 in Hurricane Anita
1. **Source.** The material below is abridged from §6.4 of "Sperry Univac Series 1100, FORTRAN V Level 4 R1, programmer reference", edition of April 1979.

2. The nonexecutable NAMELIST statement and the associated forms of the formatted input/output statements provide a simplified means of transmitting an annotated list of data to and from peripheral units. The input/output statements take the form

```
READ (unit, x)
```

and

```
WRITE (unit, x)
```

where `x` is a namelist name. The list of items in the namelist is used on input to specify those items which may have their values defined in the records to be read. Not all items of the namelist list need be used in the input records nor must the input fields be in the same order as the list items. On output, each list item of the designated namelist is formatted in a standard fashion for output in the order specified by the list.

3. **Namelist Statement.** The general form of the statement is

```
NAMELIST /X/A,B,....,C/Y/D,E,....,F/Z/G,H,....,I
```

where `X, Y, Z,....` are namelist names and `A, B, C, D,....` are simple variables, subscripted variables, or array names. An array must be dimensioned before appearing in a namelist. The following rules apply to defining and using a namelist:

- **a.** A namelist name consists of from one to six alphanumeric characters, the first of which must be alphabetic.

- **b.** Within a NAMELIST statement, a namelist name is enclosed in slashes. The list of variables associated with a namelist name ends when a new namelist name enclosed in slashes is encountered or with the end of the NAMELIST statement.

- **c.** A namelist name may be defined only once in a routine by its appearance in a NAMELIST statement. In the routine in which it is defined, a namelist name may appear only in
input/output statements and in the defining NAMELIST statement.

d. A namelist name must not be the same as any other name in the routine in which it appears.

e. A variable name, array element name, or an array name may be assigned to one or more namelist names. Array names must have been previously declared.

f. The subscript(s) of an array element must consist of constants.

4. Namelist Input. The READ (i,X) statement causes the records that contain the input data for the variables and arrays that belong to the namelist name X to be read from input unit i. For READ (i,X), the first character in each data record to be read is always ignored. The second character of the first record of a group of data records to be read must be a $ immediately followed by the namelist name and a blank. The remainder of the first record and following records may contain any combination of the legal data items which are separated by commas (a comma after the last data group is ignored). The last input record is terminated by a blank followed by $END.

5. The forms the data items may take are:

a. Variable Name= Constant. Variable name is a simple variable name.

b. Subscripted Variable=Constant. The array element appears in the NAMELIST statement. The subscripts in the input record must be constants.

c. Array Name=Set of Constants. The set is represented by constants separated by commas, or k*constant may represent k constants (k is an unsigned integer). The number of constants must be less than or equal to the number of elements in the array.

6. Constants used in the data items may take any of the following forms:

a. Integer constants.

b. Real constants. These are written with a decimal point, and, optionally, they are written with an exponent consisting of E, +, or -, or a combination of E and sign (for example, E+2, E2, +2).

c. Hollerith constants. These are written as nHhhh....h where hh....h is a string of n alphanumeric characters, including blanks. Six characters can be stored in one
location. If less than six characters remain they are stored left-justified with the rest of the computer word filled out with blanks.

7. Hollerith constants may only be associated with integer or real variables. The data items that appear on the input records need not appear in the same order as the corresponding variable or array names in the namelist. All variable or array names of the namelist need not have a corresponding data item in the input records; if none appears, the contents of the variable or array are unchanged. Names that are equivalenced to these names may not be used in the input records unless they are part of the namelist. Blanks must not be embedded in a constant or a repeat constant field, but may be used freely elsewhere in a data record. The name of an array and the value of its first elements must appear on the same record. The last item on each record that contains data items must be a constant followed by a comma. The comma is optional in the record that contains or precedes the $END sentinel.

8. Namelist Output. The WRITE (i,X) statement causes all names of variables and arrays (as well as their values) that belong to the namelist name X to be written on the output unit i. In the WRITE (i,X) statement, all variables and arrays, and their values belonging to the namelist name, are written out according to their types. The output data is written such that:

a. The name of a variable and its value are written on one line.

b. The name of an array is written, with the values of the elements of the array written in a convenient number of columns, in the order of the array in main storage, that is, with the left dimension [varying fastest].

c. The data fields are large enough to contain all the significant digits.

d. The output can be read by an input statement referencing the namelist name.
910 IF (KPP .GE. 100) GO TO 920
UXX = VTN(I,J,NEST)*(1.-SPP)*UXV(KPP,LS)+SPP*UXV(KPP+1,LS)
TWIST = (1.-SPP)*TURN(KPP,LS)+SPP*TURN(KPP+1,LS)
GO TO 930
920 UXX = VTN(I,J,NEST)*UXV(100,LS)
TWIST = TURN(100,LS)
930 Z20 = 19.5/Z0LAND
IF (LS EQ 2) Z20 = 19.5/(6A+UXX*2)
VTN(I,J,NEST) = (3600./1852.)*AMIN1
$ (UXX/K35+ALOG(Z20),VTN(I,J,NEST))
ANG(I,J,NEST) = ANG(I,J,NEST)+57.29578*TWIST
IF (ANG(I,J,NEST).LT. 0.) ANG(I,J,NEST) = ANG(I,J,NEST)+360.
1000 CONTINUE
RETURN
END
SUBROUTINE ABCC
COMMON
/C4/ CDR(100,2,2),UXV(100,2),TURN(100,2)
/C5/ FLAT,PTH,OTH(2),HH,ZOLANG,LS,VV(100),UX(3),UV(3)
$ DUV(3),K35,K2,G,GA,DEN,VV2,HL,K123,ZO,ZLOG,AM,BM,CM,FF
REAL K35,K2
IF (LS .EQ. 1) GO TO 53
Z0 = GA*UX(K123)**2/HH
ZLOG = ALOG(Z0)
53 HL = -HH*DEN/(UX(K123)**2*PTH*(ZLOG+CM))
IF (HL+2.) 54,55,56
54 HLOG = ALOG(-HL)
AM = AMIN1(HLOG+1.5,-.875*ZLOG)
BM = 1.8*EXP(.2*HL)
CM = AMIN1(HLOG+3.7,-.875*ZLOG)
GO TO 60
55 AM = 2.1931472
BM = 1.2065761
CM = 4.3931472
GO TO 60
IF (HL=2.) 57, 58, 59
AM = 1.3865736-4032868*HL
BM = 1.953288*.3733598*HL
CM = 2.5465736-9232868
GO TO 60
AM = .58
BM = 2.70
CM = .7
GO TO 60
YLOG = 2LOG+4.7
HL = .25*(YLOG*SQR((YLOG*2.8*HH*DEN/(UX(K123)*2*PTH))))
AM = AMAX1(2.5-.96*HL, 99.)
BM = AMIN1(1.1+.8*HL, 99.)
CM = 4.7-2*HL
UV(K123) = UX(K123)*2/K2*((2LOG+AM)**2+BM**2)
DUV(K123) = UV(K123)-VV2
RETURN
END
SUBROUTINE ABCCC
COMMON /C57/ PTH, DTH, HH, ZCOEFF(3,5), LAKE, VV(100), UX(3), UV(3), $ DUV(3), K35, K2, G, 6A, DEN, VV2, HL, K123, Z0, ZLOG, AM, BM, CM, UXV(100, 6), $ TURN(100, 6), COST(100), SINT(100)
REAL K2, K35
Z0 = 6A*UX(K123)**2/HH
ZLOG = ALOG(Z0)
53 HL = -HH*DEN/(UX(K123)**2*PTH*(ZLOG+CM))
IF (HL+2.) 54, 55, 56
54 HLOG = ALOG(-HL)
AM = AMIN1(HLOG+1.5, -875*ZLOG)
BM = 1.8*EXP(.2*HL)
CM = AMIN1(HLOG+3.7, -875*ZLOG)
GO TO 60
55 AM = 2.1931472
BM = 1.2065761
CM = 4.3931472
GO TO 60
56 IF (HL-2.) 57, 58, 59
57 AM = 1.8665736-.4032868*HL
BM = 1.953288+.3733598*HL
CM = 2.5465736-HL-.9232868
GO TO 60
58 AM = .58
BM = 2.70
CM = .7
GO TO 60
59 YLOG = ZLOG+4.7
HL = .25*(YLOG+SORT(YLOG**2+8.*HH*DEN/(UX(K123)**2*PTH)))
AM = AMAX1(2.5-.96*HL, .99)
BM = AMIN1(1.1+.8*HL, .99)
CM = .7-.2*HL
60 UV(K123) = UX(K123)**2/K2*(ZLOG+AM)**2+BM**2
DUV(K123) = UV(K123)-VV2
RETURN
END
SUBROUTINE BLOWUP

BLOWUP PRODUCE THE WIND FIELD FOR MOVING VORTEX IN THE PLANETARY
BOUNDARY LAYER. ITS U(EASTWARD) AND V(NORTHWARD) COMPONENTS
ARE IN ARRAYS UN, VN RESPECTIVELY UPON EXIT.
SGW IS MAGNITUDE OF SURFACE GEOSTROPHIC WIND
AN1 IS ANGLE BETWEEN SGW AND EAST, COUNTERCLOCKWISE FROM EAST
ST12 IS DISTANCE IN KM FROM AXIS OF STORM TO HALF MAGNITUDE OF SGW
(UG, VG) IS THE SFC GEOSTROPHIC WIND.
CS IS SPEED OF STORM MOVEMENT.
COMMON/C1/NAME, NSNAP, D1(2), F, SGW, AN1, UC, VC, UG, VG, CS, NM, IB
, ST12
COMMON /C3/ U(21, 21, 5), V(21, 21, 5), UN(21, 21, 5), VN(21, 21, 5)
1 PX(21, 21, 5), PY(21, 21, 5), VTN(21, 21, 5), ANG(21, 21, 5)
2 LW(21, 21, 5)
COMMON
$/C4/ CDR(100, 2, 2), UXV(100, 2), TURN(100, 2)
$/C5/ FLAT, PTH, DTH(2), HH, Z0LAND, LS, VX(100), UX(3), UV(3),
$ DUV(3), K35, K2, GA, DEN, VX2, HL, K123, Z0, ZLOG, AM, BM, CM, FF
REAL K35, K2
DIMENSION LEVEL(16)
REAL CDH2(2)
DATA LEVEL/155, 1, 2, 1, 3, 1, 2, 1, 4, 1, 2, 1, 1, 2/
DEGG = AN1/57.29578
UG = SGW*COS(DEGG)
VG = SGW*SIN(DEGG)
CALL SHORE
CALL PXYH
IF (IB.NE.0) CALL OUTOUT(0, NAME, 4HINIT, NSNAP)
SPF = 1.25*SGW
KPP = SPF
SPP = SPF-KPP
DO 1020 LS = 1, 2
   CDH2(LS) = (((1.-SPP)*UXV(KPP, LS)+SPP*UXV(KPP+1, LS))**2/HH)**2
1020 CONTINUE
CS = SQRT(UC**2+VC**2)
DG 1026 I = 1, 21
DO 1026 J = 1,21
IF (I .EQ. 1) GO TO 1025
IF (I .EQ. 21) GO TO 1025
IF (J .EQ. 1) GO TO 1025
IF (J .EQ. 21) GO TO 1025
GO TO 1026
1025 CONTINUE
LS = LW(I,J,5)
AA = CDH2(LS)*(PX(I,J,5)**2+PY(I,J,5)**2)
F2=F**2/2.0
SK=AA/(F2+SQR(T(F2**2+2*AA))
BK=SQR(T(SK)
V(I,J,5)=(F*PX(I,J,5)-BK*PY(I,J,5))/(F**2+SK)
U(I,J,5)=-PY(I,J,5)/F-V(I,J,5)*BK/F
V(I,J,5)=V(I,J,5)-VC
U(I,J,5)=U(I,J,5)-UC
1026 CONTINUE
DO 1028 I = 1,21
DO 1028 J = 1,21
UN(I,J,5)=U(I,J,5)
VN(I,J,5)=V(I,J,5)
1028 CONTINUE
DO 1030 IEST = 1,5
DO 1030 I = 1,21
DO 1030 J = 1,21
PX(I,J,NEST)=PX(I,J,NEST)-F*VC
1030 PY(I,J,NEST)=PY(I,J,NEST)+F*UC
C DO 1430 K=1,NM
KCK = MOD(K,16)
CALL COMOUT (LEVEL(KCK+1))
1430 CONTINUE
CALL OUTFLO
C SOLUTION OF WIND FIELD ON COORDINATE SYSTEM MOVING
C WITH STORM IS NOW COMPLETE.
C  COMPUTE SOLUTION WITH RESPECT TO SEA SURFACE.
      DO 1450 NEST=1,5
      DO 1450 I=1,21
      DO 1450 J=1,21
         UN(I,J,NEST)=UN(I,J,NEST)+UC
         VN(I,J,NEST)=VN(I,J,NEST)+VC
      1450 CONTINUE
      CALL OUTPUT(1,NAME,4HSNAP,NSNAP)
      CALL OUTPUT(0,NAME,4HSNAP,NSNAP)
      RETURN
      END
SUBROUTINE BREEZE
REAL LA0,LA1,LO0,LO1,LB,LL
COMMON /C57/ PTH,DTH,H2,COEFF(3,5),LAKE,VV(100),UX(3),UV(3),
$ DUV(3),K35,K2,GA,DE,VLX,K123,20,ZLOG,AM,BM,CM,UXV(100,6),
$ TURN(100,6),COST(100),SINT(100)
REAL K2,K35
COMMON /D1/LA0,LO0,ROT,LA1,LO1,DX,STHT,LANSEA,W1,TH1,D,AL,U1ST
COMMON /D2/ XX(21,21,10)
EQUIVALENCE (U1,XY), (V1,XY(2)), (UXX,U1ST)
C
LA0,LO0 ARE LAT, LON OF EYE (PTO) INPUT (RADIANS)
C
LA1,LO1 ARE LAT, LON OF POINT AT WHICH WIND IS WANTED (PT1) - INPUT (RAD)
C
LONGITUDE IS POSITIVE WEST
C
DX IS GRID SPACING OF INNERMOST NEST - INPUT (KILOMETERS)
C
W1 IS WIND SPEED AT PT1, 20 METERS - OUTPUT (KNOTS)
C
D IS DISTANCE BETWEEN PT0 AND PT1 OUTPUT (KM)
C
ROT IS ANGLE FROM TRUE NORTH TO Y-AXIS OF NESTED RECTANGULAR
C
GRID WIND FIELD (CLOCKWISE, DEGREES)
C
TH1 IS DIRECTION TO WHICH WIND BLOWS, CLOCKWISE FROM SOUTH (DEG)
C
AL IS BEARING OF POINT 1 FROM POINT 0, CLOCKWISE FROM NORTH (DEG)
C
LANSEA IS TERRAIN CODE AT POINT 1
C
1 IS OCEAN, 2 TO 6 ARE VARIOUS GROUNDS AND LAKES
DIMENSION XY(2)
NAMELIST/DBG2/L,J,F1,F2,XY,SPP,LANSEA,UXX,TWIST,STHT,GA,K35
HAV(X) = (SIN(5*X))**2
AHAV(X) = 2.0*ASIN(SQRT(X))
SQRU(X) = SQRT(ABS(X))
5
LL = LA0+LA1
LB = LA0-LA1
R = AHAV(HAV(LB)*COS(LA0)*COS(LA1)*HAV(LO0-LO1))
IF (R.00.04) GO TO 16
IF (R.LT.1E-4) AB = ATAN2((LO0-LO1)*COS(.5*LL),-LB)
AB = AB**.5
IF (R.GE.1E-4) AB = ATAN2(SQRU(COS(.5*(LL+R)))*SIN(.5*(R+LB)),
1 SQRU(COS(.5*(LL-R))*SIN(.5*(R-LB))))
IF (LO0.6G.00) AB = -AB
AL = 2.0*57.29578*AB
IF (AL .LT. 0.) AL = AL+360.
DE = (AL-ROT)/57.29578
D = R*1.052*3437.7468
AA = 10.0*D
I2 = 1
XY(1) = D*SIN(DE)
XY(2) = D*COS(DE)
AB = AMAX1(ABS(XY(1)),ABS(XY(2)))
10 IF (AB .LT. AA) GO TO 11
AA = AA+AA
I2 = I2+1
GO TO 10
11 IF (I2 .LE. 5) GO TO 12
U1 = 0.
V1 = 0.
W1 = 0.
110 TH1 = 0.
RETURN
12 DO 13 IA = 1,2
13 XY(IA) = (AA+XY(IA))*10./AA
I = XY(1)
J = XY(2)
F1 = XY(1)-I
F2 = XY(2)-J
G11 = (1.-F1)*(1.-F2)
G12 = (1.-F1)*F2
G21 = F1*(1.-F2)
G22 = F1*F2
DO 14 IA = 1,2
1B = 5.*IA+I2-5
14 XY(IA) = G11*XX(I+1,J+1,I2)+G12*XX(I+1,J+2,1B)+G21*XX(I+2,J+1,1B)
15 W1 = U1+U1+V1+V1
IF (W1.EQ.0.) GO TO 110
W1 = SORT(W1)
C REDUCE W1 TO STATION HEIGHT
900 SPP = 1.25*W1
   KPP = SPP
   SPP = SPP-KPP
   IF (KPP .NE. 0) GO TO 910
   UX = W1*UXV(1,LANSEA)
   TWIST = TURN(1,LANSEA)
   GO TO 930
910 IF (KPP .GE. 100) GO TO 920
   UX = W1*((1.-SPP)*UXV(KPP,LANSEA)+SPP*UXV(KPP+1,LANSEA))
   TWIST = (1.-SPP)*TURN(KPP,LANSEA)+SPP*TURN(KPP+1,LANSEA)
   GO TO 930
920 UX = W1*UXV(100,LANSEA)
   TWIST = TURN(100,LANSEA)
930 IF (LANSEA .EQ. 1) Z0 = GA*UST**2
   IF (LANSEA .NE. 1) Z0 = ZCOEFF(1,LANSEA-1)/UST+
   $ ZCOEFF(2,LANSEA-1)*UST**2+ZCOEFF(3,LANSEA-1)
   Z20 = STHT/Z0

C WRITE(6,DBG2)
16 W1 = (3600.*/1852.*)*AMIN1
   $ (UX/35*ALOG(Z20),W1)
   TH1 = (ATAN2(-U1,-V1)+TWIST)*57.29578*ROT
   IF (TH1 .LT. 0.) TH1 = TH1+360.
   RETURN
   U1=XX(11,11,1)
   V1=XX(11,11,6)
   D=0.
   AL=0.
   GO TO 15
END
SUBROUTINE BREEZE

***** THIS VERSION OF BREEZE USES TURNING FROM TERRAIN TYPE 6 *****
***** FOR TERRAIN TYPE 2 *****

REAL LAO,LA1,LO0,LO1,LB,LL
COMMON /C57/ PTH,DTH,HH,2COORD(3,5),LAKE,UV(100),UX(3),UV(3),
$ DUU(3),K35,K2,G,GA,DEU,VV2,HL,K123,Z0,ZLOG,AM,AN,CM,UXV(100,6),
$ TURN(100,6),COST(100),SINT(100)
REAL K2,K35
COMMON /D1/LAO,LO0,ROT,LA1,LO1,OX,STHT,LANZ,IN1,TH1,D,AL,UST
COMMON /D2/ XX(21,21,10)
EQUIVALENCE (U1,XY), (V1,XY(2)), (UXX,UST)
LA0,LO0 ARE LAT, LON OF SIGHT (PTD) INPUT (RADIANS)
LA1,LO1 ARE LAT, LON OF POINT AT WHICH WIND IS WANTED (PT1) INPUT (RAD)
LONGITUDE IS POSITIVE WEST
OX IS GRID SPACING OF INNERMOST NEST INPUT (KILOMETERS)
W1 IS WIND SPEED AT PT1,20 METERS OUTPUT (KNOTS)
D IS DISTANCE BETWEEN PT0 AND PT1 OUTPUT (KMS)
ROT IS ANGLE FROM TRUE NORTH TO Y-AXIS OF NESTED RECTANGULAR
GRID WIND FIELD (CLOCKWISE, DEGREES).
TH1 IS DIRECTION TO WHICH WIND BLOWS, CLOCKWISE FROM SOUTH (DEG)
AL IS BEARING OF POINT 1 FROM POINT C, CLOCKWISE FROM NORTH (DEG)
LANZ IS TERRAIN CODE AT PTN 1
1 IS OCEAN, 2 TO 6 ARE VARIOUS GROUNDS AND LAKES
DIMENSION XY(2)
NAMELIST/DBG2/I,J,F1,F2,XY,SP,LANZ,UX,STW,STHT,GK35
HAV(X) = (SIN(0.5*X))**2
AHAV(X) = 2.0*ASIN(SQRT(X))
SURU(X) = SQRT(ABS(X))

LL = LAO*LA1
LD = LAO*LA1
R = AHAV(HAV(LB)+COS(LA0)*COS(LA1)+HAY(LD0-LO1))
IF(R.EQ.0.0) GO TO 16
IF (R.LT.1.E-4) AB = ATAN2((LO0-LO1)*COS(0.5+LL),-LB)
AB = AB+.5
IF(R.GE.1.E-4) AB = ATAN2(SQRU(COS(.5*(LL+R))*SIN(.5*(R+LB))))
1 SQRU(COS(.5*(LL-R))*SIN(.5*(R-LD))))
IF (LEI .GT. LOO) AB = -AB
AL = 2. * 57.29578 * AB
IF (AL .LT. 0.) AL = AL + 360.
DE = (AL - ROT) / 57.29578
D = R * 1.8523437 * 1.968
AA = 10. * D * DX
IZ = 1
XY(1) = 0 * SIN(DE)
XY(2) = 0 * COS(DE)
AB = AMAX1(ABS(XY(1)) * ABS(XY(2)))
10 IF (AB .LT. AA) GO TO 11
AA = AA + AA
IZ = IZ + 1
GO TO 10
11 IF (IZ .LE. 5) GO TO 12
U1 = 0.
V1 = 0.
W1 = 0.
110 TH1 = 0.
RETURN
12 DO 13 IA = 1,2
13 XY(IA) = (AA + XY(IA)) * 10. / AA
I = XY(1)
J = XY(2)
F1 = XY(1) - I
F2 = XY(2) - J
G11 = (1.-F1)*(1.-F2)
G12 = (1.-F1)*F2
G21 = F1*(1.-F2)
G22 = F1*F2
DO 14 IA = 1,2
   IB = 5*IA+1Z-5
   XY(IA) = G11*XX(I+1,J+1,IB)+G12*XX(I+1,J+2,IB)+G21*
         *XX(I+2,J+1,IB)+G22*XX(I+2,J+2,IB)
14   W1 = U1*U1+V1*V1
   IF (W1.EQ.0.) GO TO 110
      W1 = SQRT(W1)
C REDUCE W1 TO STATION HEIGHT
900  SPP = 1.25*W1
   KPP = SPP
   SPP = SPP-KPP
   LSSUB=LANSEA
   IF (LSSUB.EQ.2) LSSUB=6
   IF (KPP .NE. 0) GO TO 910
   UXX = W1*UXV1,LANSEA)
   TWIST = TURN1,LSSUB)
   GO TO 930
910  IF (KPP .GE. 100) GO TO 920
      UXX = W1*(1.-SPP)*UXV(KPP,LANSEA)+SPP*UXV(KPP+1,LANSEA))
      TWIST = (1.-SPP)*TURN(KPP,LSSUB)+SPP*TURN(KPP+1,LSSUB)
      GO TO 930
920  UXX = W1*UXV100,LANSEA)
      TWIST = TURN100,LSSUB)
930  IF (LANSEA .EQ. 1) ZG = 6A*UST**2
      IF (LANSEA .NE. 1) ZG = ZCOEFF1,LANSEA-1)/UST+
         $ ZCOEFF2,LANSEA-1)*UST**2+ZCOEFF3,LANSEA-1)
      Z20 = STHT/Z0
C  WRITE(6,6BG2)
   W1 = (3600./1852.)*AMIN1
   $  (UXX/K35*ALOG(Z20),W1)
   TH1 = (ATAN2(-U1,-V1)*TWIST)*57.29578*ROT
   IF (TH1 .LT. 0.) TH1 = TH1+360.
   RETURN
16  U1=XX(11,11,1)
    V1=XX(11,11,6)
    D=0.
    AL=0.
    GO TO 15
END
SUBROUTINE C CROSS
COMMON
$\text{C4} / \text{COR}(100,2,2), \text{UXV}(100,2), \text{TURF}(100,2)$
$\text{C5} / \text{FLAT}, \text{PTH}, \text{DTH}(2), \text{HH}, \text{ZOLAND}, \text{LS}, \text{VV}(100), \text{UX}(3), \text{UV}(3),$
$\text{DUV}(3), \text{K35}, \text{K2}, \text{G}, \text{GA}, \text{DEN}, \text{VV2}, 113, \text{K123}, 20, \text{ZLOG}, \text{AM}, \text{BM}, \text{CM}, \text{FF}$
REAL K35, K2
FF = AMAX1(ABS(FLAT), 1.832E-6)
DO 10 IA = 1, 100
  VV(IA) = 0.8 * FLOAT(IA)
10 CONTINUE
DO 40 LS = 1, 2
  DEN = G * K2 * DTH(LS)
  DO 40 IA = 1, 100
    IB = 101 - IA
    VV2 = VV(IB)**2
    IF (IA .NE. 1) GO TO 20
    CM = 2.55
    K123 = 1
    UX(1) = 2.74
    IF (LS .EQ. 1) UX(1) = 3.38
20    ZD = ZOLAND/HH
    ZLOG = ALOG(ZD)
    CALL ABCC
    K123 = 2
    UX(2) = UX(1)*80./SQR(T(UV(1)))
    GO TO 30
30    UX(1) = UX(3)
    UV(1) = UV(3)
    DUV(1) = UV(1) - VV2
    K123 = 2
    UX(2) = UX(1)*VV(IB)/VV(IB+1)
    CALL ABCC
    KSTOP = 0
    K123 = 3
IF (DUV(1) .EQ. DUV(2)) GO TO 32
UX(3) = AMAX1(5. * AMIN1(UX(1), UX(2))),
$ \quad AMIN1(2. * AMAX1(UX(1), UX(2))),
$ \quad (UX(1) * DUV(2) - UX(2) * DUV(1)) / (DUV(2) - DUV(1)))
CALL ABCC
IF (KSTOP .NE. 0) GO TO 32
IF (ABS(DUV(3)) .LT. .1E-4 * VV2) KSTOP = 1
UX(1) = UX(2)
UX(2) = UX(3)
DUV(1) = DUV(2)
DUV(2) = DUV(3)
GO TO 31
32
AB = SQRT((ZLOG*AM)**2 + BH**2)
UXV(IB, LS) = K35 / AB
AB = UXV(IB, LS)**2 / AB
CDR(IB, LS, 1) = (ZLOG*AM) * AB
CDR(IB, LS, 2) = BH * AB
TURN(IB, LS) = ATAN(BM / (ZLOG*AM))
40
CONTINUE
41
CONTINUE
RETURN
END
SUBROUTINE COMPUT (LEVEL)
COMMON/C1/DM1(2),DX,DT,F,DM2(2),UC,VC,DM3(5)
**ST12
COMMON/C3/U(21,21,5),V(21,21,5),UN(21,21,5),VN(21,21,5)
1 PX(21,21,5),PY(21,21,5),VTN(21,21,5),ANG(21,21,5)
2 LW(21,21,5)
COMMON
$/C4/ CDR(100,2,2),UXV(100,2),TURN(100,2)
$/C5/ FLAT,DTH(2),HH,ZOLAND,LS,VV(100),UX(3),UV(3),
KUV(3),K35,K26,GADEN,SVV2,HLSK123,ZD,ZLOG,AM,BM,CH,FF
DIMENSION HKL(21,21),DRAG(2)
DATA E1,E2/0.5,0.5/
DATA VONK/0.4/
C SQQ IS APPROXIMATION TO SORT OF SUM OF SQUARES
SQQ(A,B) = (ABS(A)+ABS(B))/2.51 + (ABS(A+B)+ABS(A-B))/2.51
DO 800 NC = 1,LEVEL
NEST = LEVEL-NC+1
DO 720 I = 1,21
DO 720 J = 1,21
U(I,J,NEST) = UN(I,J,NEST)
V(I,J,NEST) = VN(I,J,NEST)
720 CONTINUE
IF(NEST .NE. LEVEL) GO TO 721
IF(NEST .NE. 5) CALL OUTBY2(NEST)
GO TO 722
721 CALL OUTBY1(NEST)
722 CONTINUE
DXL = 2.0***(NEST-1)*DX*1000.0
DXL2 = DXL**2
DTL = 2.0***(NEST-1)*DT
FTL = F*DTL
FTL1 = FTL**2+1.0
FCL = 2.0*VONK**2*(DXL/2.0)**2
C INNER BOUNDARY
IF(NEST .EQ. 1) GO TO 730
DO 724 J=1,10
U(7,J+6,NEST)=UN(3,2+J+1,NEST-1)
V(7,J+6,NEST)=VN(3,2+J+1,NEST-1)
V(15,J+6,NEST)=VN(19,2+J+1,NEST-1)
U(15,J+6,NEST)=U(19,2+J+1,NEST-1)

724 CONTINUE
DO 726 I=1,10
U(I+6,7,NEST)=UN(2*I+1,3,NEST-1)
V(I+6,7,NEST)=VN(2*I+1,3,NEST-1)
U(I+6,15,NEST)=UN(2*I+1,19,NEST-1)
V(I+6,15,NEST)=VN(2*I+1,19,NEST-1)

726 CONTINUE

C COMPUTATION OF INTERIOR POINT

730 DO 734 J=1,20
    IF (NEST .EQ. 1) GO TO 733
    IF (I .LE. 6 .OR. J .GE. 15) GO TO 733
    IF (J .LE. 6 .OR. J .GE. 15) GO TO 733
    HKL(I,J)=0.0
    GO TO 734

733 D1=0.5*(U(I+1,J,NEST)-U(I,J,NEST)+U(I+1,J+1,NEST)-U(I+1,J,NEST))
    -V(I+1,J,NEST)+V(I+1,J+1,NEST)-V(I+1,J,NEST))/DXL
    D2=0.5*(V(I+1,J,NEST)-V(I,J,NEST)+V(I+1,J+1,NEST)-V(I+1,J,NEST))
    +U(I+1,J,NEST)-U(I,J,NEST)+U(I+1,J+1,NEST)-U(I+1,J,NEST))/DXL
    HKL(I,J)=FCL*SQRT(D1*D2)

734 CONTINUE
DO 775 I=2,20
    IF (NEST .EQ. 1) GO TO 736
    IF (I .LE. 6 .OR. I .GE. 16) GO TO 736
    IF (J .LE. 6 .OR. J .GE. 16) GO TO 736
UN(I,J,NEST)=U(I,J,NEST)
VN(I,J,NEST)=V(I,J,NEST)
    GO TO 775

736 UI=U(I,J,NEST)+UC
    V1=V(I,J,NEST)+VC
C DRAG(1) IS TANGENTIAL DRAG CORRECTION TERM
C DRAG(2) IS NORMAL DRAG CORRECTION TERM
LS = LW(I, J, NEST)
SPP = SQRT(U1*V1)
SPP1 = A MAX1(1., AMIN1(99.99, 1.25*SPP))
KPP = SPP1
SPP1 = SPP1 - KPP
SPH = SPP / HH
DO 737 IA = 1, 2
   DRAG(I) = SPH* (CDR(KPP, LS, IA) +
               SPP1* (CDR(KPP + 1, LS, IA) - CDR(KPP, LS, IA)))
737 CONTINUE
IF (NEST .NE. 5) GO TO 741
IF (I .NE. 2 .AND. J .NE. 20) GO TO 741
IF (I - 2) 738, 739, 740
738 IF (U(I, J, NEST)) 739, 739, 741
739 UKX = 0.0
   VKX = 0.0
   GO TO 742
740 IF (U(I, J, NEST)) 741, 739, 739
741 UKX = 0.5* ((HKL(I-1, J) + HKL(I, J)) * (U(I+1, J, NEST) - U(I, J, NEST))
            - (HKL(I-1, J) + HKL(I, J)) * (U(I, J, NEST) - U(I-1, J, NEST))) / DXL2
   VKX = 0.5* ((HKL(I, J-1) + HKL(I, J)) * (V(I+1, J, NEST) - V(I, J, NEST))
            - (HKL(I-1, J) + HKL(I, J)) * (V(I, J, NEST) - V(I-1, J, NEST))) / DXL2
IF (NEST .NE. 5) GO TO 746
742 IF (J .NE. 2 .AND. J .NE. 20) GO TO 746
IF (J - 2) 743, 743, 745
743 IF (V(I, J, NEST)) 744, 744, 746
744 UKY = 0.0
   VKY = 0.0
   GO TO 747
745 IF (V(I, J, NEST)) 746, 744, 746
746 UKY = 0.5* ((HKL(I-1, J) + HKL(I, J)) * (U(I, J+1, NEST) - U(I, J, NEST))
            - (HKL(I-1, J) + HKL(I, J)) * (U(I, J, NEST) - U(I-1, J, NEST))) / DXL2
   VKY = 0.5* ((HKL(I-1, J) + HKL(I, J)) * (V(I, J+1, NEST) - V(I, J, NEST))
            - (HKL(I-1, J) + HKL(I, J)) * (V(I, J, NEST) - V(I-1, J, NEST))) / DXL2
747 IF(U(I,J,NEST)) 748 750 750
748 UX=-U(I,J,NEST)*U(I,J,NEST)-U(I+1,J,NEST))/DXL
VX=-U(I,J,NEST)*(V(I,J,NEST)-V(I+1,J,NEST))/DXL
GO TO 752
750 UX= U(I,J,NEST)*U(I,J,NEST)-U(I-1,J,NEST))/DXL
VX= U(I,J,NEST)*(V(I,J,NEST)-V(I-1,J,NEST))/DXL
752 IF(V(I,J,NEST)) 754 756 756
754 UY=-V(I,J,NEST)*U(I,J,NEST)-U(I,J+1,NEST))/DXL
VY=-V(I,J,NEST)*(V(I,J,NEST)-V(I,J+1,NEST))/DXL
GO TO 758
756 UY= V(I,J,NEST)*U(I,J,NEST)-U(I,J-1,NEST))/DXL
VY= V(I,J,NEST)*(V(I,J,NEST)-V(I,J-1,NEST))/DXL
758 UR=0.5*(U(I,J,NEST)+V(I,J,NEST))
VR=0.5*(-U(I,J,NEST)+V(I,J,NEST))
IF(UR) 760 762 762
760 UX= -UR*(U(I,J,NEST)-U(I+1,J+1,NEST))/DXL
VX= -UR*(V(I,J,NEST)-V(I+1,J+1,NEST))/DXL
GO TO 764
762 UX= UR*(U(I,J,NEST)-U(I-1,J-1,NEST))/DXL
VX= UR*(V(I,J,NEST)-V(I-1,J-1,NEST))/DXL
764 IF(VR) 766 768 768
766 UY= -VR*(U(I,J,NEST)-U(I-1,J+1,NEST))/DXL
VY= -VR*(V(I,J,NEST)-V(I-1,J+1,NEST))/DXL
GO TO 770
768 UY= VR*(U(I,J,NEST)-U(I+1,J-1,NEST))/DXL
VY= VR*(V(I,J,NEST)-V(I+1,J-1,NEST))/DXL
770 UXY=E1*(UX+UY)+E2*(UX1+UY1)
VXY=E1*(VX+VY)+E2*(VX1+VY1)
B1 = U(I, J, NEST) + DTL *
$ (UKX + UKY - PX(I, J, NEST) - UXY + U1 + DRAG(1) + V1 + DRAG(2))$
B2 = V(I, J, NEST) + DTL *
$ (VKX + VKY - PY(I, J, NEST) - VXY + V1 + DRAG(1) - U1 + DRAG(2))$
UN(I, J, NEST) = (B1 + FTL * B2) / FTL1
VN(I, J, NEST) = (B2 - FTL * B1) / FTL1

775 CONTINUE
800 CONTINUE
RETURN
END
SUBROUTINE GRAD
C
GRAD COMPUTES PRESSURE GRADIENT
COMPLEX CD,CT,CR
COMMON/C1/DM1(2),DX,DM2(4),UC,VC,DM3(4),IB
,ST12
COMMON/C2/IA1(15),AB(21,21,15),AC(21,7,21)
DIMENSION AD(21,4),AP(3,2),AT(2),BA(15),BC(4,2),BP(2,2)
EQUIVALENCE (CR,AP(2,1)),(CD,AP(2,2)),(CT,AT),(BC,BA(8))
C
IB IS SWITCH VARIABLE. IB = 0 TO SUPPRESS PRINTING.
C
ITRACK IS INDICATOR FOR CODING OF DIREC
C
EYELAT IS NORTH LATITUDE OF EYE IN DEGREES
(SOUTH LATITUDE MUST HAVE MINUS SIGN)
C
EYLONG IS EAST LONGITUDE OF EYE IN DEGREES
(WEST LONGITUDE MUST HAVE MINUS SIGN)
C
DIREC IS DIRECTION OF TRACK OF HURRICANE, CLOCKWISE FROM NORTH
ITRACK = 0, DIREC IN DEGREES
ITRACK = 1, DIREC IN POINTS OF 11.25 DEG
C
SPEED IS FORWARD SPEED OF HURRICANE IN KNOTS
C
IQUAD IS INDICATOR FOR QUADRANTS OF PRESSURE FIELD
IQUAD = 0, CIRCULARLY SYMMETRIC PRESSURE FIELD
IQUAD = 1, FIRST QUADRANT IS RIGHT FRONT
IQUAD = 2, FIRST QUADRANT IS FORWARD
C
QUADRANTS FOLLOW CLOCKWISE FROM FIRST
C
EYPRES IS PRESSURE AT EYE IN MILLIBARS
C
RADIUS(1,2,3,4) ARE IN FOUR QUADRANTS IN UNITS OF 1.0 NM
(1852 METERS)
C
PFAR(1,2,3,4) ARE FAR FIELD PRESSURE IN FOUR QUADRANTS,
IN MILLIBARS
C
IF IQUAD = 0, ENTER RADIUS(1) AND PFAR(1) ONLY
C
AB(I+11,J+11,K+1) IS DP/DX (EAST) IN MB/KM AT 5*I+2**K KM EAST OF EYE
AND 5*J+2**K KM SOUTH OF EYE
C
AB(I+11,J+11,K+6) IS DP/DY (NORTH) IN MB/KM AT SAME POINT
C
AB(I+11,J+11,K+11) IS DP/DR (OUTWARD) IN MB/KM AT SAME POINT
C
AC(I+11,1,J+11) IS COS OF ANGLE OF POINT I,J
(SAME FOR ALL GRID NESTS)
AC(I+11,2,J+11) IS SIN OF ANGLE OF POINT I,J
(SAME FOR ALL GRID NESTS)
AC(I+11,3...7,J+11) IS RADIUS OF POINT I,J IN NEST 1...5
RESPECTIVELY (METERS)
REAL RADIUS(4),PFAR(4)
EQUIVALENCE (ITRACK,JA),(EYELAT,JA(2)),(LYLONG,JA(3)),
$ (DIREC,JA(4)),(SPEED,JA(5)),(IQUAD,JA(6)),(EYPRES,JA(7)),
$ (RADIUS,JA(8)),(PFAR,JA(12))
DATA LU/6/
DATA DEG / .017453293/
DATA S45 / .70710678/
COMPUTE GRID ANGLES AND DISTANCES (FUNCTION OF DX ONLY)
DO 10 IG = 1,21
   10 AD(IG,1) = DX*FLOAT(IG-11)
   DO 12 IC = 1,21
       DO 12 ID = 1,21
       AE = AD(IC,1)**2+AD(ID,1)**2
       IF (AE.LE.0) GO TO 12
       AC(IC,5,ID) = SQRT(AE)
       AC(IC,1,ID) = AD(IC,1)/AC(IC,5,ID)
       AC(IC,2,ID) = -AD(ID,1)/AC(IC,5,ID)
   DO 11 IE = 1,7
       11 AC(IC,IE,1) = AC(IC,IE-1,1)+AC(IC,IE-1,1)
   12 CONTINUE
   HA(4) = DIREC*DEG
   IF (JA(1).NE. 0) BA(4) = BA(4)*11.25
   BA(5) = SPEED*(1852./3600.)
   IF (JA(6).EQ. 0) GO TO 280
   DO 21 IC = 1,4
       BA(IC+7) = RADIUS(IC)*1.852
       BA(IC+11) = PFAR(IC)*EYPRES
   21 CONTINUE
   DO 25 IC=1,2
   25 AP(1,IC) = .25*(BC(1,IC)+BC(2,IC)+BC(3,IC)+BC(4,IC))
   IF (JA(6).EQ. 2) GO TO 27
DO 26 IC = 1,2
AP(2,IC) = .5*SQRT(BC(1,IC)+BC(2,IC)-BC(3,IC)-BC(4,IC))
26 AP(3,IC) = .5*SQRT(BC(1,IC)-BC(2,IC)-BC(3,IC)+BC(4,IC))
GO TO 29
27 DO 28 IC = 1,2
AP(2,IC) = .5*(EC(2,IC)-BC(4,IC))
AP(3,IC) = .5*(BC(1,IC)-BC(3,IC))
28 CONTINUE
GO TO 29
280 CONTINUE
AP(1,1) = RADIUS(1)*1.052
AP(1,2) = PFAR(1)-EYPRES
29 CONTINUE
AT(1) = COS(BA(4))
AT(2) = -SIN(BA(4))
CR = CT*C
CD = CD*C
UC = AT(2)*BA(5)
VC = AT(1)*BA(5)
31 DO 40 IE = 1,5
DO 38 ID = 1,21
DO 35 IC = 1,21
IF (JA(6).EQ.0) GO TO 340
DO 32 IH = 1,2
BP(1,IH) = AP(1,IH)*AC(IC,1,ID)+AP(3,IH)*AC(IC,2,ID)
32 UP(2,IH) = -AP(2,IH)*AC(IC,2,ID)+AP(3,IH)*AC(IC,1,ID)
IF (AC(IC,3,ID).GT. 0) GO TO 33
AD(IC,1) = 0.
AD(IC,2) = 0.
GO TO 34
33 AE = EXP(-BP(1,1)/AC(IC,IE+2,ID))
AF = AE*BP(1,2)
C COMPUTE RADIAL PRESSURE GRADIENT
AD(IC,1) = AF*BP(1,1)/AC(IC,IE+2,ID)**2
AD(IC,2) = (AE*BP(2,2)*AF/AC(IC,IE+2,ID)*BP(2,1))/AC(IC,IE+2,ID)
C TANGENTIAL PRESSURE GRADIENT
34 $A_D(\text{IC}, 3) = A_D(\text{IC}, 1) \cdot AC(\text{IC}, 1, ID) - A_D(\text{IC}, 2) \cdot AC(\text{IC}, 2, ID)$

$A_D(\text{IC}, 4) = A_D(\text{IC}, 1) \cdot AC(\text{IC}, 2, ID) + A_D(\text{IC}, 2) \cdot AC(\text{IC}, 1, ID)$

GO TO 341

340 $A_D(\text{IC}, 2) = 0.$

CIRCULARLY SYMMETRIC PRESSURE FIELD: ZERO TANGENTIAL GRADIENT

$A_D(\text{IC}, 1) = \exp(-A_P(1, 1)/AC(\text{IC}, 1E+2, ID)) \cdot A_P(1, 2) \cdot A_P(1, 1) /$

$A_A(\text{IC}, 1E+2, ID) \cdot 2$

$A_D(\text{IC}, 3) = A_D(\text{IC}, 1) \cdot AC(\text{IC}, 1, ID)$

$A_D(\text{IC}, 4) = A_D(\text{IC}, 1) \cdot AC(\text{IC}, 2, ID)$

341 CONTINUE

$A_B(\text{IC}, ID, 1E+10) = A_D(\text{IC}, 1)$

$A_B(\text{IC}, ID, IE) = A_D(\text{IC}, 3)$

35 $A_B(\text{IC}, ID, 1E+5) = A_D(\text{IC}, 4)$

IF (IB .EQ. 0) GO TO 38

C IF NO PROGRAM CHANGES, NORTH IS PRINTED AT TOP

C OF PAGE, WEST AT LEFT, ETC.

WRITE (LU, 36) AD

36 FORMAT (*1X,1P21F6.2*)

38 CONTINUE

IF (IB .EQ. 0) GO TO 40

WRITE (LU, 39)

39 FORMAT (/////)

40 CONTINUE

RETURN

END
**** THIS IS MAIN PROGRAM HIST ****

A.C.E. PROGRAM TO FIND WINDS AT STATIONS

INPUT CARDS:
1. NAMELIST NAME4,NAME5
2. HINDCAST LOCATIONS REQUESTED: LAT-DEG,LAT-MIN,LON-DEG,
   LON-MIN, TERRAIN CODE, STA HT IN METERS,
   STATION IDENTIFICATION NUMBER,
   (S14,F6.1,14)
   WEST LONGITUDE IS POSITIVE.
   1 CARD PER LOCATION. TERMINATED BY EOF.
3. ONE CARD FOR EACH HOUR OF STORM
   LAT-DEG OF EYE, LAT-MIN OF EYE, LON-DEG OF
   EYE, LON-MIN OF EYE, SNAPSHOT 1 RECORD SEQUENCE
   NUMBER IN FILE SNAP 2 REC SEQ NBR,
   ROTATION ANGLE(DEG CLOCKWISE
   TO ROTATE WIND ON NESTED GRID),
   INDICATOR - IF NONZERO WIND ON WAVE GRID IS PRINTED.
   (S14,F8.4,214)
   WEST LONGITUDE IS POSITIVE. TERMINATED BY EOF.

INPUT FILES:
1. FILE 13(LSNAP): SNAPSHOTS FOR STORM (R,A,F,)

OUTPUT FILES:
1. FILE 20(LTHOUT): WIND DATA ON ICOSAHEDRAL GRID(R,A,F,)

TEMPORARY FILES
1. FILE 10(LTEMP) ALL SNAPSHOTS PLUS ALL INTERPOLATED WIND FIELDS

STANDARD UNITS: 5(LR) IS CARD READER, 6(LP) IS PRINTER.
TERRAIN CODE (LLAKE) 1-6, LAKE 0-5.

REAL LAO,LA1,LOO,LO1
PARAMETER MAXI=62, MAXJ=31, IGRDHT=100

C****
COMMON /C57/ PTH, DTH, HH, 2COEFF (3,5), LAKE, VV (100), UX (3), UV (3),
1 DUU (3), K35, K2, G/GA/DEN, VV2, HL, K123, ZQ, ZLOG, AM, BM, CM, UXV (100, 6),
2 TURN (100, 6), COST (100), SINT (100)
REAL K2, K35
INTEGER LLAKE (100)
COMMON /D1/ LAO, L00, ROTL, LA1, L01, DX, STHT, LAKH, W1, TH1, D, AL, UST
COMMON /D2/ XX (21, 21, 10)
COMMON /D3/ NSNAP1 (100), NSNAP2 (100), PCT (100),
1 IP1 (100), NHT, INTV, INTVi
DIMENSION MAD (100), NAM (100), nod (100), NOM (100), IROT (100)
DIMENSION MAD (100), NAM (100), MMOD (100), NOM (100), YLA (100), YLO (100)
DIMENSION JSEJ (100), KDE (100), KTIME (100)
DIMENSION WIND (2, MAXI, MAXJ)
C****
DIMENSION ZLA (MAXJ), ZLO (MAXI), ZANG (MAXI, MAXJ)
DIMENSION LSTAB (MAXI, MAXJ)
C****
DIMENSION XY (21, 21, 10)
DIMENSION STAHT (100), DTHI (2), KSTA (100)
DIMENSION JA (15)
EQUIVALENCE (ITRACK, JA), (FYELAT, JA (2)), (LYLONG, JA (3)),
1 (DIREC, JA (4)), (SPEED, JA (5)), (IQUAD, JA (6)), (EYPRES, JA (7)),
2 (RADIUS, JA (8)), (PFAR, JA (12))
EQUIVALENCE (XY, WIND)
C
DATA CON /57, 29578/
DATA LR, LP, LSNAK/5, 6, 13/
DATA LTEMP/10/
DATA LTROUT/20/
DATA KSNAP1, KSNAP2/2.0/
C
NAMELIST NAME4/NBASE, ISTART, IZONE, ICHVR, NPRT
NAMELIST NAME5/LAKE, 2COEFF
NAMELIST/NAMEP/DTH,HH,LAKE,G,ZCOEFF,GARR,PTH,K35
GRIDHT=FLOAT(IGROHT)/10.
IMAX=MAXI
JMAX=MAXJ
DO 5 J=1,MAXJ
DO 5 I=1,MAXI
LSTAB(I,J)=0
5 ZANG(I,J)=0.
DTH=-2.
HI=650.
LAKE=0
G=9.806
GARR=.035
PTH=300.
K35=.35
DO 10 J=1,5
DO 10 I=1,3
ZCOEFF(I,J)=0.
REWIND LSAP
REWIND LTMP
READ (LR+NAME4)
WRITE (LP+NAME4)
WRITE (LP+NAME5)
READ (LSAP) XX,NAME,DX,JA,SGW,AN1,ST12,DTHI,HH,GARR,PTH,K35
READ (LR+NAME5)
IF (CNVRT.NE.0) CALL RDGRID(ZLA,ZLO,LSTAB,MAXI,MAXJ)
DTH=DTHI12)
WRITE (LP+NAME P)
K2=K35**2
GA=GARR/G
QT=10.0*OK
CALL UXXV
CALL UPDOWN
IF (NBASE.NE.NAME) STOP 515
NBR=0
READ HINDCAST LOCATIONS INPUT CARDS

IF (NBR.EQ.100) STOP 516
READ (LR,165,ERR=145,END=20) MAD(NBR+1),NAM(NER+1),MMOD(NBR+1),MOM
1(NBR+1),LJAVA(NBR+1),STAHT(NBR+1),KSTA(NBR+1)
NBR=NBR+1
WRITE(LP,170) MAD(NBR),NAM(NBR),MMOD(NBR),MOM(NBR),
1 JAVA(NBR),STAHT(NER),KSTA(NBR)
XL=IABS(MAD(NBR))
YLA(NBR)=(XL+FLOAT(MAH(NER)))/60.0/CON
IF (MAH(NBR).LT.0) YLA(NBR)=-YLA(NBR)
XL=IABS(MMOD(NBR))
YLO(NBR)=(XL+FLOAT(MGM(NBR)))/60.0/CON
IF (MMGD(NBR).LT.0) YLO(NBR)=-YLO(NBR)
GO TO 15

CONTINUE
IF (NBR.NE.0) WRITE (LP,175)

READ HOURLY INPUT CARDS

NHT=6
READ (LR,180,ERR=145,END=30) NAD(NHT+1),NAM(NHT+1),NOD(NHT+1),NOM
1(NHT+1),NNSAP1(NHT+1),NNSAP2(NHT+1),PCT(NHT+1),IROT(NHT+1),
2 IPI(NHT+1)
NHT=NHT+1
IF (NHT. LT. 100) GO TO 25
STOP 517

CONTINUE
WRITE (LP,185)
KY=ISTART/10**6+1900
KM=MOD((ISTART/10**4),100)
KD=MOD((ISTART/100),100)
K TIME (1)=MOD(ISTART,100)
KJD=JULIAN(KM,KD,KY)
KDATE(1)=ISTART/100
JSEQ(1)=1
DO 35 J=2,NHT
JSEQ(J)=JSEQ(J-1)
IF(NSNAP1(J-1).NE.NSNAP1(J).OR.NSNAP2(J-1).NE.NSNAP2(J).OR.
PCT(J-1).NE.PCT(J)) JSEQ(J)=JSEQ(J)+1
KDATE(J)=KDATE(J-1)
KTIME(J)=KTIME(J-1)+1
IF (KTIME(J).LT.24) GO TO 35
KTIME(J)=0
KJD=KJD+1
CALL INVJD (KJD,KM,KD,KY)
KDATE(J)=(KY-1900)*10**4+KM*100+KD
35 CONTINUE
WRITE (LP,190) ISTART,IZONE,(J,NAD(J),NAM(J),NOD(J),NOM(J),NSNAP1(J),
NSNAP2(J),PCT(J),IROT(J),IPI(J),JSEQ(J),KDATE(J),KTIME(J)
2),J=1,NHT)
C
C LOOP TIME HISTORY OF STORM
C WRITE SNAPSHOTS ON LTEMP
C
DO 80 KHR=1,NHT
C
IF (KSNAP1.EQ.NSNAP1(KHR)) GO TO 50
KSNAP1=NSNAP1(KHR)
REWIND LSNAP
DO 45 I=1,KSNAP1
READ (LSNAP) XX,NAMEI
45 CONTINUE
50 IF (NSNAP2(KHR).EQ.0) GO TO 60
IF (NSNAP2(KHR).EQ.KSNAP2) GO TO 60
KSNAP2=NSNAP2(KHR)
REWIND LSNAP
DO 55 I=1,KSNAP2
55
READ (LSNAP) X, Y, NAMEI

55 CONTINUE
60 CONTINUE
IF (PCT(KHR).EQ.0.) GO TO 70
KSNAP1=0
IF (PCT(KHR).LT.0. OR PCT(KHR).GT.1.) STOP 444
DO 65 K=1,10
DO 65 J=1,21
DO 65 I=1,21
XX(I,J,K)=(1.-PCT(KHR))**XX(I,J,K)+PCT(KHR)**XY(I,J,K)
65 CONTINUE
70 CONTINUE

C
IF (KHR.EQ.1.) GO TO 75
IF (JSEQ(KHR).EQ.JSEQ(KHR-1)) GO TO 80
75 WRITE (LTEMP) XX,JSEQ(KHR)
80 CONTINUE
IF (NBR.EQ.0.) GO TO 106
C
COMPUTE WIND FOR EACH HINDCAST LOCATION AT THIS TIME STEP

C
DO 105 K=1,NBR
WRITE (LP,185)
LAI=YLAI(K)
LDL=YLDL(K)
STHT=STHT(K)
LANSEA=LLAKE(K)
105 CONTINUE
C
REWIND LTEMP
C
DO 100 KHR=1,NHT
IF (KHR.EQ.1.) GO TO 85
IF (JSEQ(KHR).EQ.JSEQ(KHR-1)) GO TO 90
85 READ (LTEMP,ERR=146) XX,KSLQ
XL=IBAS(NAD(KHR))
LAO=(XL+FLOAT(NAM(KHR)))/60.0)/CON
IF(NAD(KHR)*LT.0)LAO=-LAO
XL=IBAS(NOD(KHR))
LOO=(XL+FLOAT(NOM(KHR))/60.0)/CON
IF(NOD(KHR)*LT.0)LOO=-LOO
ROT=IRUT(KHR)
CALL BREEZE
UST=UST*100.
C
UST IN CM/SEC
WRITE (LP,155) NAME,KDATE(KHR),KTIME(KHR),W1,TH1,AL,UST,KSTA(K),NM,K,MMOD(K),NMH(K),NAD(KHR),NAM(KHR),NOD(KHR),NOM(KHR),LAKE(K),STAHT(K),KHR,KSEQ
CONTINUE
WRITE (LP,200)
CONTINUE

C
CONVERT WIND TO WAVE GRID FOR THIS TIME STEP
C
IF(INVRT.EQ.0) GO TO 135
C
REWIND LTEMP
REWIND LTROUT
STHT=GRUHT

U0 113 KHR=1,NHT
XL=IBAS(NAD(KHR))
LAO=(XL+FLOAT(NAM(KHR))/60.0)/CON
IF(NAD(KHR)*LT.0)LAO=-LAO
XL=IBAS(NOD(KHR))
LOO=(XL+FLOAT(NOM(KHR))/60.0)/CON
IF(NOD(KHR)*LT.0)LOO=-LOO
ROT=IRUT(KHR)
IF(KHR.EQ.1) GO TO 1065
IF(JSEQ(KHR1.EQ.JSEQ(KHR-1)) GO TO 107
1065 READ (LTEMP, EKH=146) XX, KSEQ
107 CONTINUE
   DO 111 J=1, MAXJ
C****
   LA1=ZLA(J)
C****
   DO 110 I=1, MAXI
C****
   LO1=ZLO(I)
C****
   LAMSE=LISTAB(I,J)
   CALL BREEZE
   WIND(1,1,J)=W1
   WIND(2,1,J)=TH1+ZANG(I,J)
110 CONTINUE
111 CONTINUE
   WRITE (LTHOUT) NBASE, KHR, ISTART, IZONE, IMAX, JMAX, GRIDHT, NAD(KHR),
   1 NAM(KHR), NOD(KHR), NOM(KHR), WIND
   IF (IPI(KHR).NE.0) GO TO 112
   IF (NPRT.EQ.0) GO TO 113
   IF (MOD(KHR-1,NPRT).NE.0) GO TO 113
112 CALL PRLAKE (NBASE, KHR, ISTART, IZONE, WIND, LISTAB, MAXI, MAXJ)
113 CONTINUE
   END FILE LTHOUT
C
135 WRITE (LP, 205)
   STOP 999
145 STOP 5
146 STOP 146
C
160 FORMAT (4X, A4, 4X, I8, A3)
165 FORMAT (5I4, F6.1, 1X, I3)
170 FORMAT (1X, 2(I4, 1X, J2), I3, F6.1, I3)
175 FORMAT 4(/)
180 FORMAT (6I4, F8.4, 2I4)
185 FORMAT (1H1)
194 FORMAT (1H1, //, T20, 'STORM HISTORY 1ST HOUR IS ', IB, 1X, A3, /, (1
1X, I4, 6I4, F8.4, I4, I8, J2))
1.1, * UST=*, F6.2, * STA=*, I3, 1X, J2, I4, 1X, J2,
2 * EYE=*, I3, 1X, J2, I4, 1X, J2, * TERR=*, I1,
3 * HT=*, F5.1, I4, J2)
200 FORMAT (/)
205 FORMAT (1H1, ' END OF HIST/MAIN')
END
COMPILER (XH=1), (EQUIV= chores)
SUBROUTINE INVJO (J, M, D, Y)
C REVERSE OF FUNCTION 'JULIAN'.
C COMPUTES INVERSE JULIAN DATE J FROM
C MONTH(M), DAY(D), AND YEAR(Y) INPUT.
INTEGER J, M, D, Y, TJ, TM, TD, TY, MTD
TJ=J-1721119
TY=(4*TJ-1)/146097
TJ=4*TJ-1-146097*TY
TD=TJ/4
MTD=4*TD+3
TJ=MTD/1461
TD=MTD-1461*TJ
TD=(TD+1)/4
MTD=5*TD+3
TM=MTD/153
TD=MTD-153*TM
D=(TD+5)/5
Y=100*TY+TJ
IF (TM *GE* 10) GO TO 2
1 M=TM+3
RETURN
2 M=TM-9
Y=Y+1
RETURN
END
COMPILER (XM=1), (EQUIV=CMN)
FUNCTION JULIAN(MO, DA, YR)
C REVERSE OF SUBROUTINE 'INVJD'.
C COMPUTES JULIAN DATE.
INTEGER D, Y, M, C, YA, MU, DA, YR
M = MO
D = DA
Y = YR
IF (M.LE.2) GO TO 2
1  M = M - 3
   GO TO 3
2  M = M + 9
   Y = Y - 1
3  C = Y/100
   YA = Y - 100*C
   JULIAN = (146097* C)/4 + (1461* YA)/4 + (153*M + 2)/5 + D + 1721119
END
SUBROUTINE OUTBY1(NEST)
C OUTER BOUNDARY ( NOT AT THE SAME TIME LEVEL)
COMMON /C3/ U(21,21,5),V(21,21,5),UN(21,21,5),VN(21,21,5)
1 PX(21,21,5),PY(21,21,5),VNP(21,21,5),ANP(21,21,5)
2 LW(21,21,5)
  UN(1,1,NEST)=0.5*(UN(6,6,NEST+1)+U(6,6,NEST+1))
  VN(1,1,NEST)=0.5*(VN(6,6,NEST+1)+V(6,6,NEST+1))
DO 780 J=1,10
  UN(1,2+J,NEST)=0.5*(UN(6,J+6,NEST+1)+U(6,J+6,NEST+1))
  VN(1,2+J,NEST)=0.5*(VN(6,J+6,NEST+1)+V(6,J+6,NEST+1))
  UN(21,2+J,NEST)=0.5*(UN(16,J+6,NEST+1)+U(16,J+6,NEST+1))
  VN(21,2+J,NEST)=0.5*(VN(16,J+6,NEST+1)+V(16,J+6,NEST+1))
  UN(1,2+J,NEST)=0.250*(UN(6,J+5,NEST+1)+UN(6,J+6,NEST+1)
    + U(6,J+5,NEST+1)+U(6,J+6,NEST+1))
  VN(1,2+J,NEST)=0.250*(VN(6,J+5,NEST+1)+VN(6,J+6,NEST+1)
    + V(6,J+5,NEST+1)+V(6,J+6,NEST+1))
  UN(21,2+J,NEST)=0.250*(UN(16,J+5,NEST+1)+UN(16,J+6,NEST+1)
    + U(16,J+5,NEST+1)+U(16,J+6,NEST+1))
  VN(21,2+J,NEST)=0.250*(VN(16,J+5,NEST+1)+VN(16,J+6,NEST+1)
    + V(16,J+5,NEST+1)+V(16,J+6,NEST+1))
780 CONTINUE
DO 790 I=1,10
  UN(2*I+1,1,NEST)=0.5*(UN(I+1,6,NEST+1)+U(I+6,6,NEST+1))
  VN(2*I+1,1,NEST)=0.5*(VN(I+1,6,NEST+1)+V(I+6,6,NEST+1))
  UN(2*I+1,21,NEST)=0.5*(UN(I+1,6,16,NEST+1)+U(I+6,16,NEST+1))
  VN(2*I+1,21,NEST)=0.5*(VN(I+1,6,16,NEST+1)+V(I+6,16,NEST+1))
  UN(2*I+1,NEST)=0.250*(UN(I+5,6,NEST+1)+UN(I+6,6,NEST+1)
    + U(I+5,6,NEST+1)+U(I+6,6,NEST+1))
  VN(2*I+1,NEST)=0.250*(VN(I+5,6,NEST+1)+VN(I+6,6,NEST+1)
    + V(I+5,6,NEST+1)+V(I+6,6,NEST+1))
  UN(2*I+21,NEST)=0.250*(UN(I+5,16,NEST+1)+UN(I+6,16,NEST+1)
    + U(I+5,16,NEST+1)+U(I+6,16,NEST+1))
  VN(2*I+21,NEST)=0.250*(VN(I+5,16,NEST+1)+VN(I+6,16,NEST+1)
    + V(I+5,16,NEST+1)+V(I+6,16,NEST+1))
790 CONTINUE
RETURN
END
SUBROUTINE OUTBY2(NEST)
C OUTER BOUNDARY (AT SAME TIME LEVEL)
COMMON /C3/ U(21, 21, 5), V(21, 21, 5), UN(21, 21, 5), VN(21, 21, 5)
1 , PX(21, 21, 5), PY(21, 21, 5), VTN(21, 21, 5), ANG(21, 21, 5)
2 , LW(21, 21, 5)
UN(1, 1, NEST) = UN(6, 6, NEST+1)
VN(1, 1, NEST) = VN(6, 6, NEST+1)
DO 20 J=1, 10
UN(1, 2*J+1, NEST) = UN(6, J+6, NEST+1)
VN(1, 2*J+1, NEST) = VN(6, J+6, NEST+1)
VN(21, 2*J+1, NEST) = VN(16, J+6, NEST+1)
20 CONTINUE
CONTINUE
DO 30 I=1, 10
UN(2*I+1, 1, NEST) = UN(I+6, 6, NEST+1)
VN(2*I+1, 1, NEST) = VN(I+6, 6, NEST+1)
VN(2*I+1, 21, NEST) = VN(I+6, 16, NEST+1)
UN(2*I+1, 21, NEST) = UN(I+6, 16, NEST+1)
UN(2*I+1, 21, NEST) = 0.5*(UN(I+5, 6, NEST+1) + UN(I+6, 6, NEST+1))
VN(2*I+1, 21, NEST) = UN(I+5, 6, NEST+1) + VN(I+6, 6, NEST+1))
VN(2*I+1, 21, NEST) = 0.5*(VN(I+5, 16, NEST+1) + VN(I+6, 16, NEST+1))
UN(2*I+1, 21, NEST) = 0.5*(UN(I+5, 16, NEST+1) + UN(I+6, 16, NEST+1))
30 CONTINUE
RETURN
END
SUBROUTINE OUTFLO
COMMON /C3/ U(21,21,5),V(21,21,5),UN(21,21,5),VN(21,21,5)
1 PX(21,21,5),PY(21,21,5),VTN(21,21,5),ANG(21,21,5)
2 LW(21,21,5)
DATA CO8,SI8/099026807,1391731/
DO 10 IA = 1,2205
  XX = UN(IA,1,1)*COR*V8(IA,1,1)*SIA
  VN(IA,1,1) = VN(IA,1,1)*CO8*UN(IA,1,1)*S18
  UN(IA,1,1) = XX
10 CONTINUE
RETURN
END
SUBROUTINE OUTPUT(I20,NAME,IDENT,NSEQ)

COMMON /C3/ U(21,21,5), V(21,21,5), UN(21,21,5), VN(21,21,5)
1  *PX(21,21,5), FY(21,21,5), VTN(21,21,5), ANG(21,21,5)
2  *LW(21,21,5)
DATA LP/6/
WRITE (6,10)
10 FORMAT (1H1)
IF (IDENT.EQ.4HINIT) GO TO 190
DO 80 NEST = 1,4
DO 80 I=1,10
DO 80 J=1,10
UN(I+6,J+6,NEST+1)=UN(2*I+1,2*J+1,NEST)
VN(I+6,J+6,NEST+1)=VN(2*I+1,2*J+1,NEST)
80 CONTINUE
190 CALL AANGEL(I20)
CALL TVEL(VTN,ANG,NAME,IDENT,NSEG,4,120)
CALL TVEL(VTN,ANG,NAME,IDENT,NSEG,3,120)
CALL TVEL(VTN,ANG,NAME,IDENT,NSEG,1,120)
RETURN
END
SUBROUTINE PRLAKE(NBASE,KHR,ISTART,IZONE,WIND,LSTAB,MAX1,MAXJ)
COMMON /GRID/ ILAT(J1),ILONG(62)
DIMENSION WIND(2,MAX1,MAXJ),LSTAB(MAX1,MAXJ)
DIMENSION ILN(3),LLN(3),KODES(6)
DIMENSION LIST(24)
DATA ILN/1,20,39/
DATA LLN/24,43,62/
DATA KODES/3H,3H==,3H===,3H----,3H+++,
DEFIINE KODESP(N)=KODES(N)
DO 60 NPLAT=1,2
LLATSQ=(2-NPLAT)*14+1
ILATSQ=LLATSQ+16
DO 55 NPLONG=1,3
J1=ILN(NPLONG)
J2=LLN(NPLONG)
PRINT 20,NBASE,KHR,ISTART,IZONE,(ILONG(J),J=J1,J2)
FORMAT(1H1,2,STORM *A4,1
 1 'LAKE PONT WINDS AT HCUR*, I3,* 1ST HOUR IS*,
 2 110,A3,1/45X,2415,1/
DO 36 L=LLATSQ,ILATSQ
LAT=ILATSQ+LLATSQ-L
KOUNT=0
DO 22 I=J1,J2
KOUNT=KOUNT+1
LIST(KOUNT)=KODESP(LSTAB(I,LAT))
CONTINUE
PRINT 25,ILAT(LAT),(WIND(1,J,LAT),J=J1,J2),ILAT(LAT),
1 ILAT(LAT),(WIND(2,K,LAT),K=J1,J2),ILAT(LAT),LIST
25 FORMAT(1X,I4,24F5.1,15,/,1X,I4,24F5.0,15,/,7X,24(A3,2X))
30 CONTINUE
55 CONTINUE
60 CONTINUE
END
SUBROUTINE PXYM

PXYM CALLS SUBROUTINE GRAD TO GET PRESSURE GRADIENT;

THEN REARRANGES THE PRESSURE GRADIENT, THEN PRODUCES

INITIAL GRADIENT WIND FIELD.

COMMON /C1/ 21(2),DX,DT,F,SGW,AN1,Z2(2),UG,VG,Z3(3),ST12

COMMON/C2/ JA(15),BA(21,21,15),BC(21,7,21)

COMMON /C3/ U(21,21,5),V(21,21,5),UN(21,21,5),VN(21,21,5)

1  PX(21,21,5),PY(21,21,5),VTH(21,21,5),ANG(21,21,5)

2  LW(21,21,5)

DO 50 NEST = 1, 5

GO TO (10,30,30,30,30),NEST

10  CALL GRAD

AN2 = AN1*3.14159265/180.

IF (St12 .LE. 0) GO TO 30

DX2 = 5*DX/ST12

CO2 = COS(AN2)*DX2

SI2 = SIN(AN2)*DX2

DO 31 I = 1, 21

DO 31 J = 1, 21

M = 22-J

PX(I,J,NEST) = BA(I,M,NEST)*(1E-4/1.15E-3)

PY(I,J,NEST) = BA(I,M,NEST+5)*(1E-4/1.15E-3)

AG = BA(I,M,NEST+10)*(1L-4/1.15E-3)

AH = BC(I,M,NEST+2,MJ)*F*500.


IF (A1 .NE. 0.) A1 = A1/(AH+SQRT(AH*AH+A1))

U(I,J,NEST) = -A1*BC(I,1,MJ)

V(I,J,NEST) = A1*BC(I,1,MJ)

UH(I,J,NEST) = U(I,J,NEST)

VN(I,J,NEST) = V(I,J,NEST)

C  SGW NON-ZERO FOR STEERING FLOW.

32  IF (SGW .EQ. 0.) GO TO 50

AG = F*UG

AH = F*VG
SUBROUTINE HGRID (ZLA, ZLO, LSTAB, MAXI, MAYJ)
COMMON /GRID/ ILAT(31), ILOGN(62)
DIMENSION LSTAB(MAXI), MAXJ
DIMENSION ZLA(MAXI), ZLO(MAXI)
DO 25 J=1,4
  IL=(J-1)*15+1
  I2=11+14
  READ 15, (ILOGN(I), I=I1, I2), KSEQ
  FORMAT (16I5)
  IF(KSEQ.EQ.J) GO TO 25
  PRINT 20, KSEQ, J, (ILOGN(I), I=I1, I2)
  STOP 21
25 CONTINUE
  READ 30, ILOGN(I1), ILOGN(I2), KSEQ
  FORMAT (2I5, 65X, I5)
  IF(KSEQ.EQ.5) GO TO 35
  PRINT 20, KSEQ, ILOGN(I1), ILOGN(I2)
  STOP 21
35  READ 15, (ILAT(I), I=I1, I5), KSEQ
    IF(KSEQ.NE.1) GO TO 40
    READ 15, (ILAT(I), I=I6, I30), KSEQ
    IF(KSEQ.NE.2) GO TO 40
    READ 37, ILAT(31), KSEQ
    FORMAT (15, 70X, I5)
    IF(KSEQ.EQ.3) GO TO 45
30    PRINT 20, ILAT, KSEQ
    STOP 23
45 CONTINUE
  DO 55 J=1, MAXJ
    L=IABS(ILAT(J))/100
    M=IABS(MOD(ILAT(J), 100))
    ZLA(J)=(FLOAT(L)+FLOAT(M)/60.)*.0174532
    IF(ILAT(J), LT, 0.0) ZLA(J)=-ZLA(J)
    READ 50, (LSTAB(I,J), I=I1, I2), KSEQ
50 FORMAT (10X, 62I1, 6X, I2)
IF (SEQ(EU..II)) GO TO 55
PRINT 51, J, K, E Q (LSTAB(I,J), I=1,63)
FORMAT (* LS INPUT ERROR, 214, 2X, 64)
STOP 51
CONTINUE
DO 60 J=1, MAXI
L=IABS(MOD(I,100))/100
M=IABS(MOD(I,10))/100
ZL(I)=FLOAT(L)/FLOAT(M)/FLOAT(0.0174532)
IF (L/I, LT., 0.) ZL(I)=0
CONTINUE
END
**** THIS IS MAIN PROGRAM SNAP ****

MAIN PROGRAM FOR SNAPSHOT WINDS ON NESTED GRID.

INPUT IB IS SWITCH VARIABLE IB = 0 TO SUPPRESS PRINTING
OF PRESSURE FIELD
AND INITIAL WIND FIELD

NZ IS NUMBER OF WIND SNAPSHOTS TO PRODUCE.
FOR THE QUANTITIES EQUIVALENCED TO JA, SEE COMMENTS TO
SURROUNDS GRAD
NH IS NUMBER OF TIMES TO CYCLE WIND COMPUTATION IN
INNERMOST GRID NEST.
SGW IS MAGNITUDE OF SURFACE GEOSTROPHIC WIND (MTRS/SEC)
AN1 IS DIRECTION OF SGW, COUNTERCLOCKWISE FROM EAST (DEG)
ST12 IS DIST (KM) FROM AXIS TO 1/2 MAGNITUDE OF SGW
FROM AXIS TO 1
DX IS GRID DISTANCE OF INNERMOST NEST (KILOMETERS).
NAME IS SNAPSHOT NAME FORMAT YYL (YY=YEAR, L=1ST LETTER
OF HURRICANE NAME).

FOR ALL ARRAYS IN COMMON C3 :
1ST DIMENSION INCREASES FROM WEST TO EAST
2ND DIMENSION INCREASES FROM SOUTH TO NORTH
3RD DIMENSION (NEST NUMBER) INCREASES FROM
INNERMOST TO OUTERMOST

COMMON/C1/NAME, NSNAP, DX, DT, F, SGW, AN1, UC, VC, UG, VG, CS, NH, IB, ST12
COMMON/C2/JA(15), AB(21, 21, 15), AC(21, 7, 21)
COMMON/C3/ U(21, 21, 5), V(21, 21, 5), UN(21, 21, 5), VN(21, 21, 5)
1 PX(21, 21, 5), PY(21, 21, 5), VTN(21, 21, 5), ANG(21, 21, 5)
2 LW(21, 21, 5)

COMMON
/$C4/ CDR(100, 2, 2), UXV(100, 2), TURH(100, 2)
$/C5/ FLAT, PTH, DTH(2), HH, Z0LAND, LS, VV(100), UX(3), UV(3),
$ DUV(3), K35, K2, G6A, DNN, VV2, HL, K123, Z0, ZLOG, AM, BM, CM, FF
REAL RADIUS(4), PFAR(4)
EQUIVALENCE (ITRACK, JA), (EYELAT, JA(2)), (EYLONG, JA(3)),
$ (DIREC, JA(4)), (SPEED, JA(5)), (IQUAD, JA(6)), (EYRES, JA(7)),
$ (RADIUS, JA(8)), (PFAR, JA(12))
REAL K35,K2

C
DATA LR,LP,LSNAP,LSHORE/5,6,13,14/
DATA PTH/3000./
DATA HH/650./
DATA ZOLAND/006/
DATA K35/.35/
DATA G/9.805/
DATA GRAV/.0144/
DATA DTH/0.,-2./

C
NAMELIST/NAME1/IB,NZ
NAMELIST/NAME2/DTH,HH,ZOLAND,GARR,PTH,K35
NAMELIST/NAME3/SGW,AN1,NAME,
$ EYELAT,LYLON,DIREC,SPD,EYPRES,RADIUS,PFAR,
$ NM,DX,ST12,ITRACK,IQUAD

C
REWIND LSNAP
READ (LR,NAME1)
WRITE (LP,NAME1)
FORMAT (215)
READ (LR,NAME2)
WRITE (LP,NAME2)
K2=K35**2
GA = GARR/G

C
DO 20 NSNAP= 1,NZ
WRITE (LP,15)
NM = 800
DX = 5.
ST12 = 0.
ITRACK = 0
IQUAD = 0
READ (LR,NAME3)
WRITE (LP,NAME3)
DT = 10.0*DX

1 FORMAT (215)
   I1 = INT (ITRACK)
   I2 = INT (ST12)
   I3 = INT (NM)
   I4 = INT (DX)
   I5 = INT (DT)
PHI = 57.29578
C PHI IS LATITUDE IN RADIANS
F = 2*7.29 E-5*SIN(PHI)
C F IS CORIOLIS FORCE
FLAT = F
CALL CCRUSS
WRITE (LP,15)
15 FORMAT(1H1)
CALL BLOWUO
WRITE (LSNAP) UN, VN, NAME, DX, JA, SGW, AN1, ST12, 1
20 CONTINUE
C
WRITE (LP,25)
25 FORMAT(1 END OF SNAP/MAIN)
END FILE LSNAP
STOP 999
END
SUBROUTINE TVEL(VIN,ANG,ABASE,IDENT,KSEQ,LV,120)
C IF IN ARRAYS VIN,ANG 1ST DIMENSION INCREASES EASTWARD AND
C 2ND DIMENSION INCREASES NORTHWARD, SUBROUTINE TVEL PRINTS
C WEST AT TOP OF PAGE, NORTH AT RIGHT OF PAGE, ETC.
C NEST LV IS PRINTED AS INNER NEST, LV+1 AS OUTER NEST.
DIMENSION VIN(21,21,5),ANG(21,21,5)
DIMENSION KREDUC(2)/4/HNOST,1H/
DATA LU/6/
WRITE (LU,100)
100 FORMAT(1I1)
   LV=LV+1
   WRITE (LU,200)NBASE,IDENT,KSEQ,LVP,KREDUC(I20P)
200 FORMAT(1H0,20X,A4,5X,A4,1X,I4,* LEVEL",13,5X,A4,*REDUCED")
190 WRITE (LU,1200) (J,J=1,12)
1120 FORMAT(1H0,11X,12(12,8X))
   DO 1210 I=1,5
1210 WRITE (LU,1220) (I,(VIN(I,J,LVP),J=1,12),(ANG(I,J,LVP),J=1,12))
1220 FORMAT(1H0,6X,12,12(1PF5.0,5X)/9X,12(0PF5.0,5X),/1H0,/) 
   DO 1240 I=1,11
      IL=I+5
      IO=2*I-1
      IE=2*I
      IF(I-1)1242,1246,1246
1242 WRITE (LU,1244)IL,(VIN(IL,J,LVP),J=1,5),(VIN(IO,N,LV),N=1,13)
   1,(ANG(IL,J,LVP),J=1,5),(ANG(IO,N,LV),N=1,13)
   2,(VIN(IE,N,LV),N=1,13),(ANG(IE,N,LV),N=1,13)
1244 FORMAT(1H0,6X,12,5(1PF5.0,5X),13(1PF5.0)/9X,5(0PF5.0,5X),
       13(0PF5.0)/1H0,58X,13(1PF5.0)/59X,13(0PF5.0))
   GO TO 1248
1246 WRITE (LU,1247)IL,(VIN(IL,J,LVP),J=1,5),(VIN(IO,N,LV),N=1,13)
   1,(ANG(IL,J,LVP),J=1,5),(ANG(IO,N,LV),N=1,13)
1247 FORMAT(1H0,6X,12,5(1PF5.0,5X),13(1PF5.0)/9X,5(0PF5.0,5X),
       13(0PF5.0)/1H0,/) 
1248 CONTINUE
DO 1300 I=17,21
1300 WRITE (LU,1220) (I,(VTN(I,J,LVP),J=1,12),(ANG(I,J,LVP),J=1,12))
   WRITE (LU,1330)
1330 FORMAT (1H1,/&H0,15X)
   WRITE (LU,1340) (J,J=13,21)
1340 FORMAT(1H0,16X,9(12,8X))
   DO 1345 I=1,5
1345 WRITE (LU,1350) ((VTN(I,J,LVP),J=13,21),I,(ANG(I,J,LVP),J=13,21))
1350 FORMAT(1H0,13X,9(1PF5.0,5X),12/14X,9(0PF5.0,5X),/1H0,/)!
1370 DO 1378 I=1,11
   IL=I+5
   IO=2*I-1
   IE=2*I
   IF(I-11) 1372,1376,1376
1372 WRITE (LU,1374) (VTN(IO,N,LV),N=14,21),(VTN(IL,J,LVP),J=17,21),IL,
   1 (ANG(IO,N,LV),N=14,21), (ANG(IL,J,LVP),J=17,21),
   2 (VTN(IE,N,LV),N=14,21), (ANG(IE,N,LV),N=14,21)
1374 FORMAT(1H0,8X,8(1PF5.0,5X),5X,5(1PF5.0,5X),12/9X,8(0PF5.0,5X),5X,
   1 5(0PF5.0,5X)/1H0,8X, 8(1PF5.0)/9X, 8(0PF5.0))
   GO TO 1378
1376 WRITE (LU,1377) (VTN(IO,N,LV),N=14,21),(VTN(IL,J,LVP),J=17,21),IL,
   1 (ANG(IO,N,LV),N=14,21), (ANG(IL,J,LVP),J=17,21)
1377 FORMAT(1H0,8X,8(1PF5.0,5X),5X,5(1PF5.0,5X),12/9X,8(0PF5.0,5X),5,
   1 5(0PF5.0,5X)/1H0,/)!
1378 CONTINUE
   DO 1400 I=17,21
1400 WRITE (LU,1350) ((VTN(I,J,LVP),J=13,21),I,(ANG(I,J,LVP),J=13,21))
   RETURN
END
SUBROUTINE UPDOWN
COMMON /C57/ PTH*DTH*HH*ZCOEFF(3,5),LAKE,VV(100),UX(3),UV(3),
$DUV(3),K35,K2,GA,DEN,VV2,HL,K123,2D,ZLOG,AM,BM,CM,UXV(100,6),
$TURN(100,6),COST(100),SINT(100)
REAL K2,K35
REAL VW2(100),TOL(100),TARN(100)
IF (LAKE .EQ. 0) RETURN
BM = 1.95*K35
BM2 = BM**2
HLOG = 1.39-ALOG(HH)
DO 61 IA = 1,100
   UM = VV(IA)*COST(IA)
   VM = VV(IA)*SINT(IA)
   VPLUS = -VV(IA)*UXV(IA,1)
   VTOP = VM+VPLUS
   VW2(IA) = UM**2+VTOP**2
   TOL(IA) = 1E-4+VW2(IA)
   TARN(IA) = UM+VPLUS/(UM**2+VM+VTOP)
   CONTINUE
DO 70 INCH = 1,LAKE
   AZ = ZCOEFF(1,INCH)
   BZ = ZCOEFF(2,INCH)
   CZ = ZCOEFF(3,INCH)
   UX(1) = 1.
   IF (AZ+BZ .NE. 0.) UX(1) = CBRT(.5*AZ/BZ)
   ZLOG = HLOG+ALOG(AZ/UX(1)+BZ*UX(1)**2+CZ)
   DO 69 IA = 1,100
      UX(1) = K35*SORT(VW2(IA)/(ZLOG**2+BM2))
      ZLOG = HLOG+ALOG(AZ/UX(1)+BZ*UX(1)**2+CZ)
      UV(1) = UX(1)**2/K2*(ZLOG**2+BM2)
      DUV(1) = UV(1)-VW2(IA)
      UX(2) = K35*SORT(VW2(IA)/(ZLOG**2+BM2))
      UV(2) = UX(2)**2/K2*(ZLOG**2+BM2)
      DUV(2) = UV(2)-VW2(IA)
      KSTOP = 0
   70 CONTINUE
61 CONTINUE
69 CONTINUE

IF (DUV(1).EQ. DUV(2)) GO TO 63
UX(3) = (UX(1)*DUV(2)-UX(2)*DUV(1))/(DUV(2)-DUV(1))
ZLOG = HLOG+ALOG(AZ/UX(3)+BZ*UX(3)**2+CZ)
UV(3) = UX(3)**2/K2*(ZLOG**2+BH2)
DUV(3) = UV(3)-VW2(IA)
IF (KSTOP .NE. 0) GO TO 63
IF (ABS(DUV(3)).LT. TOL) KSTOP = 1
UX(1) = UX(2)
UX(2) = UX(3)
DUV(1) = DUV(2)
DUV(2) = DUV(3)
GO TO 62
63
UXV(IA,INCH+1) = K35*SQRT(VW2(IA)/(ZLOG**2+BH2))/VV(IA)
TURN(IA,INCH+1) = (BH-ZLOG*TARN(IA))/(ZLOG+BH*TARN(IA))
69
CONTINUE
70 CONTINUE
RETURN
END
SUBROUTINE UXV
COMMON /C57/ PTH, DTH, HH, ZCOEFF(3, 5), LAKE, VV(100), UX(3), UV(3),
$ DUV(3), K35, K2, G, GA, DEN, VV2, HL, K123, Z0, ZLOG, AM, BM, CM, UXV(100, 6),
$ TURN(100, 6), COST(100), SINT(100)
REAL K2, K35
DATA A125/1. 25/
DO 10 IA = 1,100
   VV(IA) = FLOAT(IA)/A125
10 CONTINUE
DEN = 6*K2*DTH
DO 40 IA = 1,160
   IB = 101-IA
   VV2 = VV(IB)**2
   TOL = 1E-4*VV2
   IF (IA .NE. 1) GO TO 20
   CH = 2.55
   K123 = 1
   UX(1) = 2.74
   CALL ABCC
   K123 = 2
   UX(2) = UX(1)*80./SQRT(UV(1))
   GO TO 30
20 UX(1) = UX(3)
   UV(1) = UV(3)
   DUV(1) = UV(1)-VV2
   K123 = 2
   UX(2) = UX(1)*VV(IB)/VV(IB+1)
30 CALL ABCC
   KSTOP = 0
   K123 = 3
   IF (DUV(1) .LE. 0. DUV(2)) GO TO 32
   UX(3) = AMAX1(1.5, AMIN1(UX(1), UX(2)),
   $ AMIN1(2., AMAX1(UX(1), UX(2))),
   $ (UX(1)*DUV(2)-UX(2)*DUV(1))/(DUV(2)-DUV(1)))
CALL AHCCC
IF (KSTOP .NE. 0) GO TO 32
IF (ABS(DUV(3)) .LT. TOL) KSTOP = 1
UX(1) = UX(2)
UX(2) = UX(3)
DUV(1) = DUV(2)
DUV(2) = DUV(3)
GO TO 31

32

32

32

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32

AB = SQRT((ZLOG+AM)**2+BM**2)
UXV(IB+1) = K35/AB
TURN(IB+1) = ATAN(BM/(ZLOG+AM))
COST(IB) = -(ZLOG+AM)/AB
SINT(IB) = BM/AB
CONTINUE
RETURN
END
APPENDIX C: PROGRAM HIST LISTING
OF TEST STORM (BETSY) INPUT
AND SAMPLE ANNOTATED OUTPUT
Sample listings of time history of surface wind field at individual stations

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>65B1</td>
<td>Storm identification</td>
</tr>
<tr>
<td>65091001</td>
<td>Year, month, day, hour</td>
</tr>
<tr>
<td>W1</td>
<td>Wind speed in knots</td>
</tr>
<tr>
<td>TH1</td>
<td>Wind direction (meteorological) in degrees</td>
</tr>
<tr>
<td>D</td>
<td>Distance of station from eye of hurricane (km)</td>
</tr>
<tr>
<td>AL</td>
<td>Bearing of station from eye (degrees)</td>
</tr>
<tr>
<td>UST</td>
<td>Friction velocity (cm/sec)</td>
</tr>
<tr>
<td>STA</td>
<td>Station number, latitude (deg, min) longitude (deg, min)</td>
</tr>
<tr>
<td>EYE</td>
<td>Eye latitude and longitude (deg, min)</td>
</tr>
<tr>
<td>TERR</td>
<td>Terrain roughness category</td>
</tr>
<tr>
<td>H</td>
<td>Anemometer height at station</td>
</tr>
</tbody>
</table>
Sample listing of surface wind speed direction on Wes grid:

Six pages of output are required to list the wind field at one time level. Grid points are identified on each page by latitude (deg, min), left side margin, and longitude (deg, min), top margin. At each grid point location are printed the wind speed at 10 meter height in knots (top), the wind direction in degrees (middle) and the terrain classification code of the grid points (bottom). The sample listing shown is for the 24th hour of the test Betsy simulation, for the rectangular grid system provided by WES.