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FEASIBILITY OF AN OPERATIONAL TROPICAL CYCLONE PREDICTION MODEL FOR THE WESTERN NORTH PACIFIC AREA

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Recent developments in numerical simulation of tropical cyclones and in limited-area, fine-mesh modeling of non-tropical systems are reviewed. Feasibility of developing an operational model for the western North Pacific Ocean region is discussed in terms of a nested grid model. Boundary conditions, numerical techniques, initialization and representation of the physical processes are considered. It is recommended that several Navy agencies cooperate in the development of an operational model to improve meteorological and oceanographic support in the western Pacific region.

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1. INTRODUCTION

Concurrent developments in tropical meteorology, in particular the numerical simulation of tropical cyclones, fine-mesh modeling of extratropical systems and computer technology have made it feasible to consider a fully dynamic treatment of tropical cyclone motion and development. The purpose of this paper is to review these developments and discuss the feasibility of developing such a model for the western Pacific Ocean region. Development of an operational model for predicting landfall and dissipation of hurricanes over the Atlantic coast regions of the United States is proceeding at the Regional Modeling Branch of the National Meteorological Center.

A small grid size is necessary to resolve the intense wind field and precipitation regimes near the center of typhoons. However, there seems to be evidence that the finest scales of motion may not have to be resolved to get an acceptable forecast of tropical cyclone movement. It seems unlikely that the dynamic model will be able to improve on the short-term (less than 24 h) movement forecast techniques now in existence. This is primarily due to the inherent limitations in determining characteristics of each storm with present reconnaissance techniques. The dynamic model may be expected to be most useful in the cases in which the tropical cyclone is affected by extratropical flow. An example is the period of recurvature of the storm into the mid-latitude westerlies, which presents one of the most severe problems for the typhoon forecaster. Consequently a dynamic model is likely to be advantageous in the 48-h to 72-h range. A possible exception to this may be the application of a dynamical model for sea and swell forecasts in the open ocean, and for storm surge forecasts in coastal regions. Because the intense wind regions are highly concentrated, the inclusion of the atmospheric forcing to these models may require the space and time scales achievable only with a dynamical model.

An operational numerical model capable of simulating the important features of tropical cyclones must have a much finer resolution than that required for extratropical cyclone prediction. As it is not presently feasible, or necessary, to maintain the same grid size far from the tropical cyclone, the general use of a grid(s) of finer resolution nested within the normal scale numerical weather prediction models is suggested. In the following sections, the status of nested-grid models and the problems involved in fine-mesh modeling will be reviewed. After a general discussion of the status of hurricane models, some consideration will be given to the feasibility of an operational model for the western Pacific Ocean. Such a developmental effort will require satisfaction of several interrelated tasks. These tasks will be described and alternative paths for attaining the objective will be suggested.

2. STATUS OF NESTED GRID MODELS

The need for finer scale models for tropical cyclone prediction has been described above. An awareness of the desirability of improved resolution in extratropical regions has also led to the development of regional models. In some cases, national needs may dictate a finer resolution than the usual 380 km resolution of a hemispheric model. Examples may be found in the efforts of several European countries to develop regional models suitable for their forecasting requirements.

More recently this has led to formation of a multi-national group to develop a fine-scale, regional model for the European area.

There are both computational and physical reasons for developing these models. One may generally state that a mesh of 8-10 points is required to resolve adequately a meteorological feature, such as a travelling short wave. With fewer points, the phase speed will be decreased significantly and the amplitude of the feature may not be well-represented. This is particularly important in forecasting rapidly moving meteorological waves and the associated weather. The physical processes associated with small-synoptic scale and mesoscale atmospheric motions may also dictate a finer resolution. Although large-scale forcing associated with development of an extratropical cyclone leads to frontogenesis, the scale of motion of the front and its associated weather cannot be fully resolved on a synoptic-scale grid. Likewise, squall line development is triggered by larger scale features, but the processes involved in the generation and movement of the squall line are not represented by the normal governing equations for large-scale flow. In this regard the short-synoptic scale and mesoscale features present similar difficulties for numerical prediction as does the tropical cyclone. As these smaller scale forecast problems are common, the efforts of many groups have been brought to bear on the problems and have contributed additional expertise for solving the tropical cyclone prediction problem.

The primary feature which distinguishes nested grid models is the nature of the interaction between the grid scales. That is, how the information passes between two grids of different scales. A common technique, called one-way interaction, by Phillips and Shukla (1974), is to first run the coarse-grid model saving the information on the boundaries of the fine mesh. Then the fine-grid model is run using the coarse-mesh forecast as boundary conditions. It should be recalled that decreasing the grid size requires an associated decrease in time step. Thus, a space and time interpolation of the coarse-mesh values is required to provide the proper boundary conditions at some of the points along the fine mesh perimeter. It is clear that this process of reducing the grid size can be repeated until the desired resolution is achieved. Since the model is run independently for each grid size, and the same model code is normally used for each scale, this technique is easy to program and requires only the additional storage necessary to save the fine-mesh boundary values.

There are two key limitations to this method. The inherent assumption in the one-way interaction models is that the larger scale motion determines the small scale motion, without significantly being affected by the processes occurring within the fine-mesh grid. Thus, the essential purpose of the finer resolution is to provide a better representation within a region from a purely computational viewpoint. An example is to decrease the phase error of small-synoptic scale waves. Another example of the technique is its use to provide synoptic-scale forcing for very fine resolution air-quality models, because the air-quality model is passive with respect to the synoptic-scale model. Thus the effect of different synoptic-scale regimes can be imposed on the air-quality models, without the need for a feedback from the area with finer resolution. There is strong evidence that tropical cyclones, short-synoptic and mesoscale features are not passive relative to the synoptic scales. These features trigger redistribution of energy and momentum that feeds back to the larger scale flow. Consequently it may be possible to forecast the initiation of these events with a one-way interaction model, but forecasting the active phase of interaction with the larger scale is prohibited. In one-way interaction models the boundaries of the fine mesh must necessarily be far removed from active development regions.

There is also a computational limitation which is common to all models of varying grid sizes, but it is particularly obvious for one-way interaction models. The accuracy of finite-difference equations is dependent on the grid size and time interval. With a discrete change in grid size between two points, the solutions of the finite-difference equations will not be consistent. A wave that is well resolved on the fine-mesh grid, but not on the coarse grid, will have a different phase and amplitude as it progresses across a region. Consequently the boundary value provided by the coarse grid integration in a one-way interaction model must be incorrect. This is true for all inertio-gravity modes as well as for the meteorological modes that are being predicted. The result of the inconsistent boundary conditions is a generation of spurious waves at all outflow points of the fine-mesh grid. Since the proper mass, momentum and energy fluxes are not permitted at the boundary, the reflected waves will propagate into the interior and eventually destroy the solution. It might be noted that this would occur even if it were possible to provide the analytical solution to equations on the boundaries, as this would still be inconsistent with the solutions based on finite-difference equations. At any rate, some technique must be found to specify the outflow boundary conditions to prevent the reflection of the waves at the boundary. As will be described later, this is possible for some simple linear sets of equations, but is generally not possible for all the wave modes permitted in the normal meteorological equations.

The two-way interaction models require a simultaneous integration on all grids. As the coarse grid integration provides the time-dependent values for the fine grid, and conversely the predicted fine-mesh values are a continually updated subset of coarse mesh, the solutions on the two grids are not permitted to develop separately. Because the coarse grid solution is influenced by the fine grid solution, the inevitable differences at boundaries are controlled, without the heavy smoothing required in one-way interaction models. The need for simultaneous integration does require a more complex program than the one-way interaction technique, as the time step is different for each grid. With multiple reductions in grid size, and provisions for movement of the grids, a sufficiently fine resolution can be achieved. If the region of large gradients is relatively small, the horizontal array size in each grid does not have to be large. Because only the arrays for a single grid must be in the central core at a time, the code is efficient for a computer with a rapid transfer to external mass storage. This, in principle, is equivalent to solving the equations over only segments of the region.

In summary, the one-way interaction technique can be used in situations in which the interior motions are passive relative to the large-scale forcing, or when the boundaries of the fine mesh are well-removed from the regions of redistribution of energy and momentum between the scales. A two-way interaction model is required where interaction between the different scales of motion occurs. If this region is localized, as in the tropical cyclone case, a movable fine grid with simultaneous integration should be used to properly resolve the scale interaction. Because an eightfold increase in computer time is required to increase the horizontal resolution by a factor of two, it is essential that the fine mesh region be kept as small as possible.

One alternative to the discrete variation of grid size discussed above is the use of a continuously variable grid interval. Thus no abrupt change in phase and amplitude occurs across boundaries as in the discrete case. A variable resolution grid has been used in many (stationary) hurricane models to resolve adequately the inner region without having to compute at superfluous points in the outer region (e.g., Kurihara and Tuleya, 1974). By specifying the functional dependence of grid size with radius, the equations may be transformed to an equivalent regular grid. The accuracy of the transformed equations varies with grid size. Furthermore the time step is that required for the smallest grid interval. However, the primary shortcoming of this type of model for operational use is the complexity for handling moving storms. As the center of the storm moves, the grid must also be moved to keep the large gradient region within the finest grid resolution. In practice, the grid may have to be moved nearly every time step, thus requiring interpolation in space and time of new boundary values around the perimeter of the region. Whether a realistic interaction between the hurricane circulation and the large-scale flow would occur through this interpolation has not been answered.

The characteristics of limited-area on regional models can generally be grouped into four topics: (1) boundary conditions used for one-way or two-way interaction; (2) numerical considerations, including lattice arrangement of the variables and the time difference scheme; (3) initialization procedure, and (4) the representation of physical processes. A discussion of these topics with respect to a number of operational and research-oriented regional models is presented in the Appendix. These considerations will also form the basis of the discussion of three-dimensional tropical cyclone models in the next section.

3. STATUS OF NUMERICAL TROPICAL CYCLONE MODELS

Two-dimensional models. There exists an extensive literature regarding the simulation of the symmetrical circulation in a hurricane. The motivation for these models is to simulate the important mechanisms that are involved in producing the intense winds near the center. The coupling between boundary layer convergence and associated latent heat release in deep convective towers near the center was shown to be an important aspect of hurricane development. A number of numerical problems, including the formulation of stable integration schemes, were examined in the process of developing these models. Although these two-dimensional models are not appropriate for real-time prediction, they continue to have great utility in testing new representations of physical processes, numerical methods, or the initialization of three-dimensional models (Anthes, 1974). It will be useful to review briefly the results of the two-dimensional models before proceeding to the three-dimensional models.

The various simulations of hurricane development may be generally grouped into three phases--(a) organizational period, (b) rapid development, and (c) a quasi-steady state. The organizational period is necessary since the symmetrical models are started from a weak cyclonic system to avoid prejudicing the final state. Typically the maximum wind of 10 m/sec is located at several hundred km from the center. Because the flow is cyclonic, the boundary layer flow is directed toward the center. This leads to a boundary layer pumping as the air must ascend before reaching the center. The horizontal convergence of moisture flux plus the air-sea exchange would eventually lead to saturation of the boundary layer air, in the absence of convective fluxes through the top of the boundary layer. An upward flux of moist air occurs within the clouds and drier air subsides in the environment. One of the important results of the symmetrical models is that convective release of latent heat occurring within the radius of maximum wind (RMW) tends to displace the RMW inward. Thus in the organizational stage the convective heat release increases the pressure gradient within the RMW by preferential heating of the columns near the center. As the pressure gradient is increased, the maximum wind increases. With a stronger cyclonic flow, the inward boundary layer flux strengthens. This provides additional fuel for convective heat release near the center, and the process continues. It is then clear that the rate of kinetic energy generation by the air flowing toward lower pressure must lead to development of a more intense system, unless the frictional dissipation is quite large.

A rapid development phase occurs in all the symmetric models as the RMW approaches the center. Not only is the boundary layer inflow increasing as the cyclonic forcing increases, but the upward flux is occurring over a progressively smaller domain within the RMW. Very large heating of this narrow vertical column occurs, which rapidly deepens the central pressure, and increases the pressure gradient and wind speeds. The process of feedback between the convective heat release and the large-scale flow, which forces the boundary layer flow, is called Conditional Instability of the Second Kind (CISK). Thus, CISK guarantees development in these models (with realistic friction); however, the direct extension to nature may not be assumed since less than half of all potential disturbances develop into severe tropical cyclones.

After the heating near the center brings the column to a moist adiabatic state, further deepening of the central pressure by convective heat release is halted. Non-convective heating continues due to the larger scale ascent, but this simply maintains moist adiabatic ascent and does not warm the column. Thus the minimum surface pressure is attained and the heating moves outward into regions that remain convectively unstable. If the model was run for sufficiently long periods the entire central region would become moist adiabatic, but the minimum pressure of the storm would remain in quasi-steady state.

The importance of various initial conditions has been tested with symmetrical models (Rosenthal, 1971). A more moist initial state will shorten the organizational phase, but does not change the ultimate intensity of the storm. A more intense initial vortex will also enhance the development process in these models. The importance of latent and sensible heat has also been studied. Addition of heat and moisture from the ocean is crucial in raising the equivalent potential temperature of the inflowing air, which enhances the latent heat release that drives the storm. This is demonstrated in nature as hurricanes crossing over land lose this supply of moisture and eventually decrease in intensity when the primary moisture supply is only due to advection from outer regions that remain over water. As suggested above, the frictionally-induced inflow plays an important role in tropical cyclone development. Slight increases in the drag coefficient enhance the boundary layer pumping, and thus the convective heat release, and the development time is shortened. However, the maximum intensity of the storm in the quasi-steady state is reduced by a larger drag coefficient, because the frictional dissipation is increased. In many of these respects, the symmetrical models provided guidance for the development of three-dimensional models that will be necessary for intensity and movement forecasts of actual storms. It should be emphasized that the two-dimensional models very realistically simulate the symmetrical aspects of intense hurricanes. The complex wind and temperature variations near the center are well-modeled, and thus one has some confidence that the mechanisms contained within these models are capable of reproducing these features in asymmetric models. However, the necessary resolution appears to be 10 km, if the intense wind region is to be resolved. This is crucial for three-dimensional models and leads to development of variable resolution, or nested-grid, models.

Three-dimensional models. The first successful three-dimensional simulation of hurricane movement and development from real data was achieved by Miller (1969). This model was in many respects similar to that of Krishnamurti (1973), which has also been used to study non-developing tropical disturbances. Furthermore, a nested version of Krishnamurti's model has been developed by Mathur (1974), and used with real data to simulate hurricane development. The ability of this type of model to forecast developing and non-developing tropical disturbances represents an important achievement. Therefore it seems likely that this model contains enough of the essential physics to begin real-time forecasts, if the data and numerical problems can be overcome. The above models were initialized from hand-drawn charts and required extensive computer resources. Miller is continuing to develop a real-time forecast model (independent of the work at the Regional Modeling Group under J. Hovermale) using the NMC wind analyses from 850 to 100 mb as input to the model.

The first fine-mesh (30 km) hurricane simulation capable of resolving the internal structure was described by Anthes, Rosenthal and Trout (1971).

Much of the physics of this model was also similar to the above models that used real data. Subsequent model development has continued under Rosenthal and R. Jones with the ultimate task of "simulating the track, intensity and inner core structure of tropical cyclones." In addition, "the model must also have the capability to provide rigorous simulation of various cloud seeding tactics associated with modification strategies proposed by Project Stormfury for hurricane moderation" (Rosenthal, Hurricane Research Progress Report #73, Nov. 1974). Finally, the fourth effort within NOAA to simulate hurricane development has recently been described by Kurihara and Tuleya (1974). This model incorporates a variable mesh grid ranging between 20 and 100 km resolution and includes an improved representation of physical processes. An important aspect of the improved physical aspects is that the model seems capable of simulating both the symmetrical component and the spiral bands. Because the vortex does not interact with a mean flow, this model is not capable of forecasting movement or development of actual storms.

In this section the general characteristics of selected three-dimensional tropical cyclone models (see Table 1) will be described in the same manner as for the regional models discussed in the Appendix. As this material is primarily based on published articles, the information is somewhat dated. Nevertheless the general characteristics of the established models listed in Table 1 are probably not changing. The Regional Modeling Group (NOAA) model is currently being developed for real-time forecasts and is more subject to change.

Boundary conditions. Results from the symmetrical models (e.g. Rosenthal, 1971) indicated that the boundaries should be well removed from the center of the hurricane to prevent contamination. Some recent

TABLE 1. Characteristics of selected three-dimensional tropical cyclone models.

Principal Investigator(s) Group	Nested?	*Boundary Conditions	Number of grids	Grid Size(s) (km)	#Time Differencing	**Space Differencing	Vertical Coordinate	Layers
Miller NHC-NOAA	No	C	1	75	LF	A	P	7
Anthes & Rosenthal NHRL-NOAA	No	0	1	30	EB	A	σ	3
Jones & Rosenthal NHRL-NOAA	Yes	2	3	10/30/90	EB	B	σ	3
Harrison NPS	Yes	2	3	25/50/100	LF	A	P	3
Mathur FSU	Yes	2	2	37/74	QL	A	P	3
Madala FSU	Yes	2	3	20/60/180	SI	C	Z	3
Kurihara GFDL-NOAA	No	C	1	20/100	EB	A	σ	11
Hovermale RMG-NOAA	Yes	1	2	60/380	LF	A	σ	10

* 1 = one-way; 2 = two-way; CY = cyclic; 0 = open; C = closed

\# LF = leap-frog; LW = Lax-Wendroff; SI = semi-implicit; EB = Euler-backward

**See text and Fig. 1

analytic results by Koss (Hurricane Research Progress Report #73, Nov. 1974) show that the solutions are strongly dependent on lateral boundary conditions when a small domain is used. Koss suggests that a domain in excess of 3000 km may be necessary, based on his model solutions. However, calculations with a fine mesh over such a large domain would require enormous computer resources. In order to proceed with actual forecasts, a much smaller domain has been used. Thus the lateral boundary conditions assume considerable importance, not only in representing the proper solution within the domain, but also for suppressing spurious computational modes.

Miller's (1969) attempt to forecast hurricane development with constant geopotential values on the lateral boundaries resulted in unrealistic gradients of vorticity near the boundary. More recently Miller et al (1972) hold the u and v components of the wind constant on the two outer rows during the forecast cycle. After each step these two rows are adjusted so the area means of divergence and vorticity for the entire grid are equal to those within the dynamically active regions. To constrain further the amplification of spurious waves near the boundaries, a large value of lateral viscosity is applied at the third and fourth rows in from the boundary. Open boundary conditions were essential for the small domain size (435 km radius) used by Anthes et al (1971) for simulation of hurricane development. Boundary conditions similar to those employed in symmetric models were used. Constant pressure and temperature values were specified around the boundary, and the horizontal velocity components were extrapolated to the boundary such that the horizontal divergence and relative vorticity tended to vanish at the boundary. Kurihara and Tuleya (1974) were able to use a 4000-km square domain because of the variable resolution grid. Consequently a closed boundary condition prohibiting any normal flux across the boundary was realistic. The normal component of the pressure gradient force was obtained from the geostrophic balance relation with the wind tangent to the wall.

The only nested tropical cyclone model with one-way interaction listed in Table 1 is that of the RMG-NOAA. In the early stages of development, it was anticipated that this model would use boundary conditions similar to those of the limited fine-mesh (LFM) model at NOAA. That is, values along the boundary would be stored from the earlier run of the operational forecast model. If the storm was within the LFM domain the coarse grid size would be about 190 km at 60 N; otherwise the baroclinic primitive-equation model with resolution of 381 km at 60 N would be used. The stored values would be used to update the boundary values of the hurricane model, with perhaps some smoothing near the boundaries to damp the spurious modes. More recently this group has been testing two-way interaction models of the type to be described below.

One-way interaction boundary conditions must also be specified for the coarse-mesh grid (CMG) of the nested models. Mathur (1974) held the initially analyzed variables constant throughout the forecast period, and applied a nine-point smoother on the grid points within three rows from the boundary. The particular situation that Mathur considered included little interaction between the developing hurricane and the surroundings. In cases with stronger interaction, the constant boundary conditions would have been inappropriate. As Harrison (1973) used analytical initial conditions, the CMG boundary conditions were chosen appropriate for a channel flow with cyclic conditions at the east-west boundaries. Allowing no flow across the northern and southern walls tends to emphasize the westerly movement of the disturbance. Madala (1973) also used a channel flow for the coarse grid, but he used upstream differencing to obtain the necessary boundary values.

The key aspect of the nested grid integrations is the two-way interaction across each discrete change in grid size. Harrison (1973) adapted the one-dimensional method of Harrison and Elsberry (1972) for specifying the variables on a two-dimensional FMG from the computed CMG tendencies along the interface. This method was successful in simulating the intensification of a weak tropical circulation, and in particular, allowed the transfer of mass and energy through the interfaces as the system developed. However, the method has not been tested with the more intense stages. Jones and Rosenthal (personal communication) have used the Harrison method in successful simulations of hurricane development. Mathur (1974) also used the tendencies at CMG points on the interface common to both the FMG and CMG in calculating the pressure gradients and nine-point, quasi-Lagrangian advection terms. Rather than interpolating the CMG tendencies in space to the non-coincident FMG grid points along the interface, as in Harrison (1973), the variables were assumed to have continuity in the second-order derivatives calculated at the adjacent CMG points. The latter step tends to smooth the values along the interface between grids. However, since all variables are interpolated in this manner, the variables are not necessarily in dynamic balance at the intermediate points.

In the semi-implicit model of Madala (1973), a governing Helmholtz equation for the geopotential field must be solved for each grid (see Appendix). Madala simultaneously solved the Helmholtz equations for the three grids. Furthermore, new boundary conditions for the inner grids were calculated (from the coarse-grid solution using quasi-Lagrangian advection) after each iteration of the relaxation process. Presumably the solution would have converged more rapidly if the coarse-grid solution would have been calculated, and boundary conditions set only once for each successively smaller grid. After the finer mesh solution is obtained, the coincident points in the interior of the CMG would be replaced by an average of the surrounding points in the FMG. This would produce an interaction directed from the FMG to the CMG comparable to the explicit solution method of Harrison (1973). Interaction between the different grids occurs in every iteration of the Helmholtz equation solution in Madala's case, rather than during each time step as in Harrison's method. This highly interactive solution method may account for Madala having to reduce the time step by a factor of more than 10 during the course of the integration. It is not clear whether the method suggested above with interaction only during a time step would give a comparable solution. If so, this procedure would be more economical, as a longer time step could be utilized in each grid interval.

In summary, the boundary conditions for a model capable of resolving the inner features of a tropical cyclone must provide for two-way interaction in a nested-type model. This allows mass, momentum and energy transfer and reduces computer requirements compared with a uniform fine-mesh region over the entire domain.

Numerical considerations. The time differencing schemes for the models listed in Table 1 are as varied as in the fine-mesh, mid-latitude models (see Appendix). Leapfrog differences are used for simplicity in the Miller et al (1972) and Harrison (1973) models. The NHRL and

GFDL models use Euler-backward differencing to damp the high-frequency modes. Mathur (1974) has used the quasi-Lagrangian scheme for evaluating the substantial derivatives. This scheme has advantages in minimizing phase errors over the normal centered-space and time technique. The importance of this advantage is not obvious since the reason for using a nested grid is to provide adequate resolution for the short waves. On the other hand, the grid size may not have to be reduced as much to obtain the same phase error properties if the quasi-Lagrangian scheme was incorporated. Furthermore, use of the quasi-Lagrangian (or higher order space differencing) would be useful in the coarse-mesh grid to provide optimum handling of the phase of the large scale waves.

An efficient, semi-implicit time differencing scheme has been developed by Madala (1973). The pressure gradient and divergence terms are treated implicitly, because these terms control the high-speed gravity waves. If the time necessary to solve the Helmholtz equation could be further reduced by newly developed techniques, the advantages of the semi-implicit technique could be exploited. In some cases these new techniques have constraints on the number of grid intervals, although this should have little impact on the development of a new model.

A majority of the nested tropical cyclone models listed in Table 1 carry all variables at each gridpoint (Scheme A in Fig. 1). Although convenient, this scheme is inefficient and results in noise generation as the solutions on different lattice points tend to separate (Gerrity and McPherson, 1970). Madala (1973) used Scheme C, which Arakawa et al (1974) suggest has favorable properties both for geostrophic adjustment and for simulating the slowly changing quasi-geostrophic modes. Madala notes that this scheme is also very desirable in formulating the Helmholtz equation that arises with semi-implicit time differencing. Elvius and Sundstrom (1973) showed that an even more compact form which required fewer Helmholtz equation solutions was possible. Thus, the interrelation between optimum space and time differencing should be considered in planning a fine-mesh tropical cyclone model.

For open-ocean forecasting of tropical cyclones, it would seem appropriate, as well as convenient, to use a pressure-coordinate model. However, forecasting landfall and the subsequent filling stages of tropical cyclones may require the sigma coordinate system. This is probably most important if a prime consideration is for precipitation forecasts as the storm moves over mountainous terrain. Furthermore, if the hurricane model boundary conditions are to be derived from a hemispheric model in sigma (σ) coordinates, it seems essential that the hurricane model be cast in σ coordinates. Thus the use of vertical height (Z) coordinates by Madala can be viewed as a disadvantage for initialization and for operational, nested-grid forecasts over terrain. A σ coordinate version of Madala's model would appear to be most favorable for tropical cyclone forecasting.

Initialization. The discussion of initialization for fine-mesh, mid-latitude models (see Appendix) is also applicable to the tropical cyclone problem. Certainly the emphasis must be upon an accurate specification of the wind field. However, the scarcity of data, particularly on the scale of intense wind regions, will require an optimum use of all available data. It remains to be seen if useful information can be obtained from satellite data. The tropical storm is typically covered by a thick overcast so that sensors in the carbon dioxide bands cannot be used to determine the vertical temperature profiles. Another difficulty with polar-orbiting satellites is that the data are asynoptic and methods must be developed to blend this information to produce an initial field. If sensors (or processing techniques) could be perfected that would permit inference of the profiles on the desired scale, say 20-30 km, the temperature errors on these scales may well be of the same order as the gradients. Even in the most optimum case, one must correctly specify the wind field that is consistent with the deduced mass field. For once the integration is begun, the mass field will tend to adjust to the specified wind field.

Given the need for accurate wind information within and surrounding the tropical cyclone, maintaining the existing reconnaissance is an absolute minimum. The technology for rapid transmission of this reconnaissance data to the operational centers must be pursued. However, aircraft can only provide information within 150 km of the center at one or two levels. Perhaps extensive exploitation of satellite-derived cloud motions will provide low-level and upper-level wind information to mesh with the aircraft-sensed region. This near-environment wind regime will be essential for proper short-term steering of the model storm. Aircraft reports play an important role in tropical wind field analysis, but these tend to be concentrated near 250 mb. Between this layer and the surface, where ship reports tend to improve the coverage, there are few wind reports.

The successful hurricane forecasts with real data (Miller et al, 1972; Mathur, 1974) have used hand-analyzed wind fields. This has the advantage that the analysts subjectively interpolated into data gap regions to provide a realistic analysis. An important point is that

Mathur (1974) analyzed on the fine mesh scale throughout the region and discarded the unnecessary points within the coarse grid. Miller (1969) also had initial data on the fine scale. The alternative, interpolation of large-scale data to smaller scales, has not been tested with real data cases. Clearly some additional information must be provided for an accurate representation near the center, but the amount and distribution are not obvious. It should also be noted that Mathur's and Miller's data were analyzed at each vertical level, and presumably were carefully checked for vertical consistency. As indicated above, the available data sources tend to be concentrated at upper levels and the surface. Some attention must be given to producing objective analyses that are vertically consistent between these levels.

As Anthes (1974) points out, because the local forcing is so strong in a tropical cyclone, there is hope that the initial data need not be of high resolution over the entire horizontal and vertical extent of the domain. Anthes used a symmetric model of a nearly steady-state hurricane to determine the variables that are most important in providing an adequate initial state. The low- and middle-level observations were most useful in reducing the initial errors in Anthes' experiment. As would be expected, observations in the region of highest winds were crucial. If only observations from the surroundings were utilized, the capability of the model to reproduce the control state was rather poor. Note that these variables may not be the same as in the situation in which the development of the hurricane is to be simulated, rather than the duplication of an existing intense hurricane. That is, a more (or less) stringent specification of initial conditions may be applicable depending on the purpose of the forecast.

Miller et al (1972) normally start their model with wind fields. The height fields can be determined from a version of the divergence equation, and temperatures can be computed from the thickness fields using the hydrostatic equation. Vertical motions are diagnosed from an omega equation and the divergent component of the wind field is derived. The temperatures and winds are then forecast. After a short period, the rotational component of the forecast wind fields is retained as initial data, and the initialization cycle is repeated to obtain a new mass, temperature and divergent wind component fields. This diagnostic-prognostic cycle is repeated four or five times until the heights and vertical motions are relatively stable. Mathur (1974) followed a similar procedure, but did not repeat the initialization cycle. Mathur used a balance equation and a quasi-geostrophic ω equation that are subsets of the complete divergence and ω equations of Miller et al. Most of the models listed in Table 1 were started from a weak vortex that was in gradient balance, and the initialization phase was of little interest.

Because the amount of data available within the tropical cyclone region will normally be insufficient, some method is necessary to introduce, or bogus, data on the proper scales. For example, the actual values of maximum wind and the eyewall radius available from satellite or reconnaissance data are insufficient, but one may be able to construct a model that is consistent with these storm parameters. At the RMG, a two-dimensional version of the complete model will be run to produce initial conditions that are consistent with the environmental sounding. Such a symmetrical model would require little computer time to achieve steady conditions, and the symmetrical component of the storm can then be used as bogus data during the initialization phase. In a four-dimensional assimilation scheme, the complete model equations are integrated from a prior (say 12-h old) time. During this initialization integration, a correction will be added at each time step to "nudge" the predicted gridpoint value toward the "observations." The weighting factor for the correction term may be a variable which "decreases with observation error, increasing horizontal and vertical distance separation, and increasing time separation" (Anthes, 1974). The advantage of this system is that the observations never replace the forecast variables and are never added impulsively. In some experiments with a constant weighting factor, Anthes showed that only a few selected points of data were sufficient to dynamically initialize a symmetrical hurricane model.

It may also be possible to bogus data derived from empirical models of the symmetric component in mature tropical cyclones. For example, Riehl (1963), LaSeur (1966), Shea and Gray (1973), and Gray and Shea (1973) summarize observations of the two-dimensional structure of hurricanes. Given only a few characteristics of the actual storm, one could specify an inner structure that is consistent with these observational models. Elsberry, Pearson and Corgnati (1974) have used such a quasi-empirical model to determine the boundary layer characteristics and the maximum intensity of the model storm for different sea-surface temperatures. This type of model could be used to specify the symmetric wind and thermal structure that would be consistent with actual observations. Selected data from the model could then be used to enhance the data coverage for statically or dynamically initialized models.

As indicated in the discussion of initialization for regional models (see Appendix), the variational approach of Sasaki (1958) can make use of several different types of data, and blend the information into a form that is dynamically consistent with the model equations. These are desirable properties for an operational tropical cyclone model, as such a method would reduce the computer time necessary for dynamic initialization techniques. As the final state is not completely in agreement with the dynamical equations (or the observations), an adjustment will occur during the early stages. The effects of this adjustment can be reduced by properly specifying the weighting factors on the dynamical terms.

Representation of the physical processes. The primary process required in a simulation of tropical cyclone development is the latent heat release, which is related to the convergence of moisture within the boundary layer. Some crude representations of this highly complicated interaction have been used to demonstrate the role of latent heat release. Nested grid models by Harrison (1973) and Madala (1973) simply specified the distribution of latent heat release in the vertical as a function of boundary layer convergence. These models were not intended to duplicate observed cases of hurricane development, but this representation was sufficient to demonstrate that nested grid models could properly handle cases of energy redistribution from the fine mesh to the coarse mesh. Progressively more complex representations are available for latent heat release and planetary boundary layer effects. Miller et al (1972), Mathur (1974) and Anthes et al (1971) have used modified versions of the Kuo (1965) parameterization of convective latent heat release. Kuo related the amount of heating to the ratio of the moisture supply to the moisture required to saturate the atmospheric column and bring it to the temperature of the moist adiabat passing through the base of the cloud. The supply of moisture to the clouds was related to the net convergence of moisture into the column by the large-scale flow. In a tropical cyclone this convergence is primarily due to boundary layer convergence plus evaporation. The second key element in any convective parameterization scheme is the specification of the vertical distribution of the heat release. Kuo related the heating to the temperature difference between the environment and the moist adiabat, which leads to a maximum heating rate in the upper troposphere, as is observed in actual storms. This representation of convective heat release seems to contain the necessary ingredients for hurricane development forecasts in both two- and three-dimensional models. The ultimate intensity of the model storm is the dependent on the moist adiabat near the center, because the Kuo heating function is self-limiting for a moist adiabatic environment. Continued maintenance of the storm requires a non-convective heat release proportional to the large-scale ascent rate. It is well-known that unconditional heat release will result in grid scale overturning, so this process must be controlled by smoothing (Miller et al, 1972).

The most sophisticated representation of physical processes is found in the recent model of Kurihara and Tuleya (1974). Several aspects of the model are similar to the Geophysical Fluid Dynamics Laboratory general circulation model, although radiative effects are neglected. Subgrid-scale vertical diffusion processes include an air-sea interaction within a Monin-Obukhov framework, free dry convection and mechanical turbulence above the surface layer. Free moist convection is included if the vertical change of temperature in a rising cloud element is greater than the lapse rate of the cloud environment. The fractional entrainment rate for the cloud elements is assumed to be inversely proportional to the radius of the cloud (only one size is permitted). A key assumption appears to be a specification of the efficiency of the convective transport by an empirical coefficient. The parameterization scheme is similar to that of Ooyama (1971), in that an arbitrary factor determines the importance of each cloud size. A closed solution to the parameterization problem has been proposed by Arakawa and Schubert (1974). This new scheme will be tested by Jones and Rosenthal (Hurricane Research Progress Report, No. 73), since the tests of Project Stormfury hypotheses will be more convincing if some of the arbitrariness of the convective heat release rates is removed. Schubert (personal communication) also will test the new parameterization scheme for prediction of various tropical weather systems.

The progress made in representing the cumulus heat release, and the previous applications to hurricane development simulation, indicate that methods for representing these physical processes are sufficient for an operational model. The degree of sophistication necessary, of course, depends on the purpose of the model. In the initial stages of model development, the Kuo scheme would seem adequate, as considerable experience has been gained with this method of parameterization. A comparison with more sophisticated parameterization schemes would be appropriate at a later stage.

4. PROPOSAL FOR A TROPICAL CYCLONE MODEL DEVELOPMENT

As noted in the above review, there is active research in the area of tropical cyclone simulation. We propose development of an operational, fine-mesh tropical cyclone model suitable for Navy needs in the western Pacific Ocean. The considerable progress toward solution of the numerical aspects of this problem puts this research in the category of research applied to Navy needs. It is recommended that this effort make maximum use of concurrent efforts among government (and non-government) agencies. Whereas the problems associated with the development of such a model are similar, and the basic model will have many common aspects, the required resolution, initial data and forecast interval will be determined by the different tasks. Exchanges of information with the various government agencies active in tropical cyclone prediction would assist in the development of a Navy model for WESTPAC (see Table 2). It seems essential that the proposed development be closely coordinated between the Environmental Prediction Research Facility, Fleet Numerical Weather Central and the Naval Research Laboratory. Furthermore, the sustained interest, and operational data inputs of the Fleet Weather Central/Joint Typhoon Warning Center will be necessary throughout the developmental period. The timing of this development effort, and the eventual operational application, will depend on the resources available to each group. In many cases the efforts dedicated to the tropical cyclone problem will be transferable to other regional, or global models; for example, any improvement in numerical techniques or representation of the physical processes. Exploiting the commonality then requires an awareness of the similar problems, which can be achieved through good communication, rather than a redirection of effort.

The tasks to be undertaken to develop an operational model are listed in Table 3. For convenience, the developmental progress is grouped into four phases, although there inevitably will be some overlapping. Time sequences have not yet been established, because the level of funding is uncertain (a fully committed effort, which would include adequate computer resources for developmental and quasi-operational phases, perhaps would

TABLE 2. Possible coordination with other government agencies.[*]

Group	
NHC-NOAA	Exchange of data/model comparison
RMG-NOAA	Exchange of data, model development and initialization techniques
NHRL-NOAA	Model development comparison/parameterization techniques
NRL	Model development for semi-implicit technique
FWC/JTWC	Data collection/evaluation
	Possible coordinated EPRF, FNWC and NPS endeavors
EPRF	Development of semi-implicit version with efficient Helmholtz equation solution. Initialization with variational techniques. Evaluation of possible satellite data input for WPAC. Parameterization of latent heat release development/evaluation.
FNWC	Latent heat release parameterization package from global model-evaluation. Planetary boundary layer package from global model. Sigma coordinate model Objective analysis package Initialization with variational techniques
NPS	Consideration of numerical aspects including time and space-differencing schemes. Evaluation of use of model data for bogusing. Evaluation of data and model requirements. Dynamical initialization experiments.

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[*] Coordination with university or non-U.S. groups might also be considered. Groups at Colorado State University and Pennsylvania State University are active in fine-mesh modeling of tropical disturbances, and the Japanese Meteorological Agency has developed an operational, nested grid model.

TABLE 3. Proposed plan for development of an operational tropical cyclone model for the western Pacific region.

Task	Feasibility phase	Development Phase I	Development Phase II	Quasi-operational testing phase
Initialization	Hand-analyzed wind data from WPAC typhoons.	Hand-analyzed fine mesh data variational analysis technique.	Objective analysis data tests.	Improvement of objective analysis.
	Test inclusion of divergent component.	Bogus with dynamic/empirical model data.	Comparison of dynamic and variational techniques.	Evaluation of bogusing techniques.
		Interchange of data with other groups	Satellite data input.	
Numerical aspects	Averaged pressure-gradient to reduce time.	Staggered grid to reduce core requirements.	Increase number of layers.	Reduction in grid size to 20/60/180 km.
	Triply nested model with grid sizes 55/110/220 km.	Semi-implicit time differencing. σ coordinate.	Mesh with FNWC global model.	
Physical processes	Simplified heating/BL package.	Modified Kuo heating package.	Improved heating package including radiation.	Relate to oceanographic products.
		Improved BL representation.		
Goals	Demonstrate feasibility for 36-h motion forecast of tropical cyclones.	Extend movement forecast to 48h for tropical cyclones.	Extend movement forecasts to 72h for tropical cyclones.	Evaluate intensity and movement forecasts to 72h.
	Development of test model.	Improve efficiency of test model.	Evaluate model forecasts for tropical disturbances.	Near real-time forecasts in support of Project Stormfury and comparison with NHRL model.
	Collect sample of test cases.	Evaluate data and model requirements through interchange of test cases.		

require a three-year period to fully accomplish the goals listed at the bottom of the table).

The first phase may be thought of as a preliminary effort to demonstrate the feasibility of using a currently available model (Harrison, 1973) to forecast typhoon movement. Data for one experiment have been prepared by FWC (GUAM) JTWC personnel. The meteorological situation is a late-season typhoon (IRMA), that did not recurve as expected. Such a potential recurvature situation is considerably more difficult than the case of Mathur (1974). As in Mathur's case, the initialization will be from the wind field. One purpose of this phase is to evaluate the adequacy of the data sources in the Western Pacific Ocean for specifying the environmental conditions surrounding a typhoon. As the case has been subjectively analyzed by an experienced forecaster, one might consider that this is an optimum analysis, at least compared to an objective analysis case. A second purpose will be to test the role of a fine-mesh analysis (or lack thereof) in forecasting movement. A procedure for establishing the initial center location within the grid will be required. A final goal is to establish a test model and procedure as a reference base for evaluting future improvements or modifications. The basic model of Harrison (1973) will be modified by time averaging of the pressure-gradient term (Brown and Campana, NMC technical note). This should permit a doubling of the time step, and thus allow more cases to be efficiently run.

Based on Mathur's one case, and the work of Miller et al (1972) with a non-nested model, it is expected that the first phase will indicate the potential of a dynamic model forecast. One cannot satisfactorily demonstrate feasibility with a single case. Nor are we anticipating that the Harrison model will be adequate as an operational model, since more efficient time and space differencing schemes are now available. Furthermore, the model includes minimal physical effects.

The primary efforts in developmental phase I should be directed toward initialization and numerical aspects of the model. Certainly additional cases should be prepared by FWC/JTWC personnel. However, it is quite expensive to prepare even a single case, and a parallel effort should be made to establish a data exchange with other interested groups. As these groups have predominately used Atlantic cases, it might be beneficial for them to have access to additional cases from the Pacific. This exchange should also assist in comparisons of initialization techniques, and of the individual models. A considerable effort should be made to develop initialization techniques that are appropriate to the tropical cyclone case. The developing expertise in both variational and dynamical initialization methods should be utilized. It may occur that these more complicated techniques will not be required for satisfactory movement forecasts, although the intensity forecasts will likely require a superior initialization technique. The second emphasis in phase I should be the improvement of the model by exploiting recent developments in numerical techniques. Here we hope to make use of the experience gained by various active groups. For example, the NHRL group under Jones and Rosenthal are tasked with developing a model in support of the Project Stormfury experiment scheduled for the western Pacific area during 1977-78. As their primary goal will be to test typhoon modification hypotheses, it would be an advantage to them to have a comparable numerical model for 48- to 72-h forecasts of typhoon movement and intensity. This would greatly aid in their operational planning, and would provide a reference to evaluate the seeded versus non-seeded experiments. A number of other possibilities for coordination with other groups are suggested in Table 2. By the end of the development phase I, enough test cases should be run to demonstrate the possibilities for an operational model-both in terms of data and an efficient model code.

During development phase II the main objective may be described as a refinement of all aspects of the planned model. Evaluation of the initialization task should include a comparison of an objective analysis versus a subjective analysis.* Within this time frame the potential use of satellite data over the western Pacific region should be pursued. The refinement of the model should be directed toward making it compatible with the operational FNWC system, so far as is possible considering the different goals of the tropical cyclone system. An increase in computer resources should be planned for this period as the number of levels is increased and the representation of physical processes is improved. Furthermore, the goal of extending the movement forecasts to 72 h will require additional computer time.

Movement to a quasi-operational phase will primarily be dependent on new computer resources. The additional goal of forecasting intensity as well as movement will require a finer resolution. Essentially another order of magnitude in computer power will be required for the planned reduction in grid increment. Without the additional resources, one might still opt for movement forecasts, and perhaps some definition of the

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*This is not to say that a project designed to compare objective and subjective analyses could not be initiated during phase I as a number of test cases become available.

envelope of gale-force winds. It might be noted that a reduction of grid size would likely improve the movement forecasts as well. To obtain the full benefit of the dynamic model for fleet use, the output should also be tailored to the FNWC oceanographic products. Because of the United States Navy meteorological and oceanographic needs in the western Pacific area, it is hoped that the Navy community will give full support toward development of an operational, tropical cyclone forecast model.

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APPENDIX

PROBLEMS IN FINE-MESH MODELING

Boundary conditions. The general problem of selecting boundary conditions for a regional model has been studied for many systems of meteorological equations (e.g. see summary in Harrison and Elsberry, 1972; and recent work by Elvius and Sundstrom, 1973). For nested models, the selection of a one-way or a two-way interaction model is dependent on the meteorological parameters to be forecast. If one develops a regional model independent of a hemispheric or global model, the boundary values must be generated from the internal flow or be held fixed. The early version of the limited fine mesh (LFM) model of the National Meteorological Center used constant boundary values (Howcroft, personal communication). Platzman (1954) showed that constant boundary values permit a computationally stable interior solution, but the noise generated at the outflow points propagates into the field and the solution is useless after a relatively short time. Heavy smoothing is normally required near the boundaries to keep the predicted solution consistent with the constant boundary values. Krishnamurti (1973) uses constant boundary values after a 24 h adjustment period, during which a condition for controlling the horizontal divergence is applied at the first interior gridpoints. Thus the normal (meridional) component at the northern wall (J=M) may be written from the horizontal divergence expression

$$v(I,M) = \eta[v(I,M-2) - \frac{\Delta y}{\Delta x}\left\{ u(I+1,M-1) - u(I-1,M-1)\right\}]$$

where $\eta = \frac{24-t}{24}$ for $t \leq 24$ h and $\eta = 0$ for $t > 24$ h. A similar expression is used for the meridional component along the southern wall.

TABLE 4. Characteristics of selected limited-area models.

Principal Investigator Group	Nested?	*Boundary Conditions	Number of grids	Grid Size(s) (km)	#Time Differencing	**Space Differencing	Vertical Coordinate	Layers
Howcroft NMC-NOAA	Yes	1	2	190/380	LF	A	σ	5
Jones Great Britain	Yes	1	2	100/380	LW	D	P	9
Okamura Japan	Yes	1	2	?	?	?	P	5
Williamson/Browning NCAR	Yes	1	2	70/265	LW	A	Z	V
Chen/Miyakoda GFDL-NOAA	Yes	1	2	270/540	SI	C	P	1
Bleck/Shapiro NCAR	No	CY	1	350	LF	C	θ	20
Kreitzberg/Perkey Drexel	Yes	1	3	35/140/280	LF	A	Z	11
Kaplan/Paine AFGWC/Cornell	No	1	1	42	EB	A	P	9
Krishnamurti FSU	No	CY	1	200	QL	A	P	5

* 1 = one-way; 2 = two-way; CY = cyclic; 0 = open; C = closed

\# LF = leap-frog; LW = Lax-Wendroff; SI = semi-implicit; EB = Euler-backward

**See text and Fig. 1.

The remaining variables along the walls are held fixed at the initially analyzed values. Since the Krishnamurti (1973) model was developed for short-term prediction in the tropics, the east-west boundary condition was made cyclic by inserting a buffer region across which the eastern and western boundary values are matched. Krishnamurti has used the foregoing boundary conditions to allow for propagation of inertio-gravity oscillations at the boundaries during the 24 h adjustment phase. After 24 h the interior flow has adjusted to the presence of the walls.

If the boundary values along the perimeter of the fine mesh are available from a coarse-grid model, the interior solution will not be consistent with the boundary values. One may think of the problem as an over-specification of the fine-mesh boundary values, which leads to a spurious computational solution. Charney (1962) has shown that for a barotropic equation set, the normal velocity component should be specified at all boundaries, and the potential vorticity at the inflow points. At outflow points, the vorticity may be extrapolated from the interior. For the nonlinear barotropic model (shallow-water equations), both Elvius and Sundstrom (1973) and Chen and Miyakoda (1974) propose specifying the normal velocity at all points and the tangential velocity at the inflow points. The remaining required variables at the outflow points are determined from the governing interior equations using one-sided differences, or by a method of characteristics (Chen and Miyakoda). These boundary conditions have been shown to be stable for the shallow water equations, but will be ill conditioned with a baroclinic model using the hydrostatic approximation (Oliger, personal communication). Thus in most cases of one-way interaction boundary conditions, an over-specification is used and various artifices are employed to control the resulting computational modes. In the British model (Jones, 1974) the height changes (and other variables) on the fine mesh are saved from the earlier octagon model run. However, the normal velocity changes on the boundary are replaced by geostrophically calculated values. Strong diffusion is applied to the three rings within the boundary. Williamson and Browning (1973) describe boundary conditions for a limited area model (LAM), which may be located at any point within the National Center for Atmospheric Research (NCAR) general circulation model. If the wind computed by the global model (stored on tape) is directed into the LAM, the variables from the global model are used on the LAM boundaries. If the global wind is outward, an extrapolation scheme from within the LAM is used to determine the LAM boundary values. The extrapolation technique follows Shapiro and O'Brien (1970) in that a path, or space-time line, is calculated to determine the interior properties that will arrive at a boundary point during the time step. That is, the global winds are used to advect the LAM variables to the boundary grid point. Another technique to melt the interior solution to the external solution is to use so-called "spongy boundary conditions" (see Kesel and Winninghoff, 1972). For example, Kreitzberg et al (1974) applied these conditions to the predicted tendencies of the property A,

$$\frac{\partial A(B-n)}{\partial t} = \gamma(n) \frac{\partial A(B-n)}{\partial t}$$

where $\gamma(n) = 0.3$, 0.7 and 0.9 at $n = 0$, 1, and 2 points from the boundary point (B). These conditions are designed to control reflections at the boundary by permitting only a slow rate of change near the boundary. Nevertheless, Kreitzberg et al (1974) found it necessary to apply a smoother-desmoother to the variables near the boundaries as frequently as every 5 time steps. The "sponge" can also be used to provide a smooth transition between two scales by the relation

$$A_{adj}(B-n) = \gamma(n)\ A_{fine}(B-n) + [1-\gamma(n)]\ A_{coarse}(B-n)$$

to all the variables.

In summary, a number of techniques are available for using coarse-mesh values at fine-mesh boundary points in one-way interaction type models. In every case the spurious computational models generated near the boundaries must be controlled or the interior solution will be contaminated. The smoothing, or filtering, must be carefully applied to avoid destroying the meteorological modes as well. If the coarse-mesh grid (CMG) is sufficiently large relative to the tropical cyclone, the CMG may be a subset of the hemispheric/global model, and one-way interaction boundary conditions of the type described above will be useful.

In a two-way interaction model the time change at the outflow (and inflow) boundary points is calculated from the numerical solution at the corresponding CMG point. Consider the cyclic grid network depicted in Fig. 2 which changes spatial increment at the points $j = 4$ and $j = 10$. The ratio of the spatial increment in the CMG to that of the FMG is two, so the even numbered gridpoints for $4 \leq j \leq 10$ are also coarse mesh gridpoints. Thus a centered space difference across point 4 will involve points 3 and 6, although the solution at 6 is calculated on the FMG. The adjacent interior point $j = 5$ then uses the value at $j = 4$ calculated from the CMG solution as a boundary value in the centered space difference on the FMG. Two-way interactions specify CMG values as boundary conditions as in the one-way type, but the CMG solution is simultaneously calculated and interacts with the FMG through use of the interior values $j = 6$ and $j = 8$. Because the time step for the FMG is half that of the CMG, the time sequence of the two solutions must be maintained with two steps in the FMG for every CMG time step. In some cases the same time step has been used in both grids, and although convenient for programming, this procedure is quite wasteful if more than two nested grids are used. Extension of the above procedure to two dimensions may be examined with the aid of Fig. 3, which illustrates a multiple reduction of grid scales. Again the ratio of grid interval between successive grids is a factor of two (for staggered grids, the ratio is normally three). If each of the three grids shown contained the same number of gridpoints, the medium-mesh grid (MMG) would cover 1/4 of the CMG area, and the FMG only 1/16 of the CMG area. Thus the advantage of the nested grid is obvious if the important features to be forecast are contained within a small region, as in the case of a tropical cyclone.

Numerical considerations. One of the common problems of every operational forecast center is the need to generate the best forecast in the shortest time possible. Because each reduction of grid interval by a factor of two requires an eight-fold increase in computing time, the use of fine-mesh grid models has promoted extensive research into increasing the maximum time interval for a given grid size (the reader is referred to numerical weather prediction texts, e.g. Haltiner 1971, for discussion of the criteria for various time-differencing schemes). Several of the models listed in Table 4 use the standard, centered time difference, or leapfrog (LF) scheme. In other cases, Lax-Wendroff (LW) or Euler-backward (EB) schemes are used to take advantage of the selective dampening of high frequency modes by these schemes. Although these schemes may be expected to reduce the noise generated at the mesh interface, they require a doubling of computer time. It is therefore essential that the mesh interface be carefully handled to minimize, or control, the noise near the interface and avoid using these expensive time-differencing schemes. If the noise does not seriously contaminate the larger scale solution, filtering before output will adequately remove the short-wave components.

The above discussion has primarily been concerned with the handling of the inertio-gravity and computational modes inherent in limited-area, primitive equation models. The use of primitive-equation models is most essential for phenomena in which the Rossby number may approach unity. Several groups active in fine-mesh modeling have been testing an implicit treatment of the gravity waves present in these models which will permit an increase in the time step. The semi-implicit time differencing, after Robert (1969), implicitly treats both the spatial gradient of geopotential height in the equations of motion, and the divergence term in the continuity equation that is multiplied by the mean geopotential height. As this requires a simultaneous solution for the geopotential and horizontal velocity components, the equations may be combined to form a Helmholtz equation (usually in ϕ), which may be solved by standard techniques. Solution of the Helmholtz equation requires additional computer time, but the implicit treatment of the gravity modes permits a much longer time step. Several semi-implicit treatments of barotropic models (e.g. Chen and Miyakoda, 1974) have documented a savings of a factor of about five over explicit treatments. In the baroclinic case a set of coupled Helmholtz equations results, which requires special treatment (Robert et al, 1972; Sela and Scolnik, 1972). In particular, the convective heat release schemes may be troublesome in semi-implicit models. Because of these difficulties, and the reduction in phase speed of gravity modes that are the primary characteristic of the primitive equation set, some groups have reexamined the use of filtered equation models (e.g. Environmental Prediction Research Facility; Bengtsson, 1974).

The existence of direct-solvers of Poisson or Helmholtz equations (work in progress at EPRF and elsewhere) may also contribute to the time advantage of the semi-implicit scheme over explicit time-differencing. If it could be shown that no loss of accuracy occurs with the semi-implicit solution, the time advantage could be exploited to run fine-mesh models with existing computer systems. This is one of the most important reasons that tropical cyclone models may be feasible at the present time.

It might be noted that a savings of about one half can be achieved in explicit models by arrangement of the solution order to permit averaging the pressure gradient terms in the equations of motion (J. Brown and K. Campana, NMC technical note). That is, the thermodynamic and ϕ_{1000} (in pressure-coordinate models) equations are first solved to calculate the new geopotential field. Proper weighting of the pressure gradient terms at the past, present and future time steps will evidently permit a doubling of the time step. Although some additional storage is required, no Helmholtz equation must be solved, so the full time advantage is realized.

Arakawa et al (1974) have studied the effect of space-differencing on two computational problems that arise in simulating large-scale atmospheric motions with the primitive equations. The first problem is the proper simulation of geostrophic adjustment-the process by which the energy of locally excited inertio-gravity waves is dispersed away into the wider space. A second computational problem is the simulation of the slowly changing quasi-geostrophic motion after it has been established by geostrophic adjustment. The letters A-E for the space difference schemes listed in Table 4 refer to the five orientations of the dependent variables illustrated in Fig. 1. Arakawa et al (1974) suggest that schemes B and C have more satisfactory dispersive properties for inertio-gravity waves, and should simulate geostrophic adjustment for meteorological waves better than the other schemes. A careful treatment of the inertia terms in the momentum equation with the grid schemes B and C was shown by Arakawa et al (1974) to prevent a computational cascade for purely non-divergent flow. Thus this arrangement can be expected to provide a proper representation of the large scale, quasi-nondivergent atmospheric motions.

The majority of the models listed in Table 4 use scheme A, which carries geopotential and velocity values at every grid point. Scheme D, which has the u(v) velocity points between meridional (zonal) geopotential values, has similar properties as Scheme C for preventing cascade, but is less satisfactory in terms of geostrophic adjustment. The two research models by Chen and Miyakoda (1974) and Bleck and Shapiro (1974) do make use of the more favorable Scheme C. Chen and Miyakoda point out that Scheme C is also very convenient in terms of applying semi-implicit time differencing described above. Elvius and Sundstrom (1973) have also investigated the accuracy and stability of the shallow water equations using semi-implicit time differencing with Scheme C. In its most compact form, the u and v gridpoints alternate locations between odd and even time steps. In this case a single Helmholtz equation must be solved, rather than two disconnected Helmholtz equations if the velocity components do not alternate grid points with time steps (Elvius and Sundstrom, 1973). It thus appears that Scheme C with semi-implicit time differencing has a number of advantages for fine-mesh modeling.

Various coordinate systems may be used to represent the vertical structure of the atmosphere. Kasahara (1974) reviews the features of the primitive equations in various vertical coordinate systems. The pressure coordinate system, which is used in most of the models listed in Table 1, has certain computational limitations in the vicinity of mountains. Use of the vertical height (Z) coordinate was not common until the system was adopted by the NCAR general circulation group. The limited-area models by Williamson and Browning (1974) and by Kreitzberg et al (1974) use input from the NCAR GCM, and thus are cast in height coordinates. Phillips (1957) proposed a modified version of the pressure coordinate, the sigma system, to make the earth's surface a coordinate surface. This system is used by many operational numerical weather prediction centers, and is the coordinate system for the LFM. The use of potential temperature (θ) as a vertical coordinate has advantages for resolution of strong vertical gradients of wind. Shapiro and Hastings (1973) have shown that details of frontal structure can be resolved in θ coordinates using the synoptic-scale network over the United States. Furthermore, development of the high wind speed regions associated with frontogenesis seems to be better predicted in θ coordinate models than in pressure coordinate models (Bleck and Shapiro, 1974). However, the difficulty in handling the lower boundary condition in isentropic coordinates, and the lack of adequate resolution of rawinsonde stations over the oceans, will probably limit the usefulness of θ coordinate models to continental regions with good data coverage.

Initialization. The specification of initial conditions is one of the most important problems for integration of the primitive-equation models, because of the gravity waves that are excited if the mass and wind fields are not properly balanced. Although the geostrophic adjustment process will eventually disperse these waves, the associated divergence and pressure fluctuations may seriously contaminate the meteorological modes during the

the transition phase. The precise effect on the large-scale motion forecast, or on such derived quantities as precipitation amounts, has not been evaluated. These effects are probably model-dependent, especially with regard to processes that depend on the divergent portion of the motion. Recent developments relative to initialization of primitive-equation models are discussed by Haltiner and Williams (1974), including the developments in four-dimensional assimilation of data. Insertion of new data during the forecast also generates inertio-gravity waves in the model. Thus careful treatment of data prior to, or during, the integration is required to minimize adverse effects on the forecast.

Many of the fine-mesh models listed in Table 4 follow the practice of filtered models, in that the wind fields are derived from a solution of the balance equation with an objectively analyzed geopotential field. As shown by Phillips (1960), inertio-gravity waves will be generated in this case, unless an appropriate divergent wind component is included. The required form of the divergent wind component is far from clear, as several operational centers have found that the use of a ω-equation, which is seemingly appropriate to the balance equation, does not improve the initial adjustment phase in the model, or the forecast results. For fine-mesh models, and particularly for tropical applications, it seems rather clear that the traditional initialization methods are inappropriate. It can be shown that the mass field tends to adjust to the wind field as the scale of the motion is reduced. For mesoscale models the mass field immediately tends to adjust to the specified wind field, rather than vice versa (Anthes, 1974). Furthermore, as the distance between observations is decreased, the errors in determining the geopotential approach the magnitude of the gradient. Consequently, in mesoscale studies, as in the tropical cases, the analysis and initialization phase must consider both wind and mass fields.

One must question the mesoscale initialization technique described by Rao and Fishman (1974), because the wind field was forced to adjust to the mass field. This study does suggest that a staggered grid (Scheme D in Fig. 1) improved the convergence rate over the original Miyakoda and Moyer (1968) iterative technique. Likewise, Paine and Kaplan (1974) use operationally-analyzed height fields interpolated to a 42-km grid, and calculate goestrophic winds. The imbalance created by this technique leads to massive readjustment through large-amplitude, rapidly propagating gravity waves. It might be noted that the tropical model of Krishnamurti (1973) is initialized from the wind field, from which the geopotential field is derived. The divergent component is derived from an omega equation. Williamson and Browning (1973) initialized 2 1/2°, 1 1/4° and 5/8° versions of the NCAR LAM with data interpolated from a 5° global model. Even though the original mass and wind fields were dynamically consistent, the fields are not necessarily in balance after the interpolation process. Even more important is that no meteorologically significant features with scales less than 5° are included in the data. Normally a 5° grid, or at most a 2.5° grid, would be sufficient to forecast these larger scale features. One justification of forecasting with 1 1/4° and 5/8° grids would be the anticipated development of small-scale features. Even in this case, it would appear essential that the maximum amount of data is used in each grid, rather than simply interpolating from larger scale data.

Temperaton (1973) tested various methods that have been proposed for initializing primitive-equation models. Temperaton concludes that forcing the wind field to adjust to the mass field is "unnatural" for the small-scale components. Rather provision needs to be made for the mass field to adjust to the wind field, as well as vice versa. The best method of accomplishing the dynamic initialization appeared to be a cycle of averaging two forecasts integrated forward and backward in time from an initial state, alternately restoring ϕ or the wind components during each iteration. Temperaton demonstrated that it was not sufficient that the initialization method just reduce the root-mean square error for the geopotential field. Rather the principal test of the method must be in elimination of the unwanted gravity-wave modes during the integration phase. A suitable measure of these waves is the divergent component or vertical motion.

The difficulty in applying these dynamic initialization techniques is that the computer time required for the forward and backward integration of the model is more or less equivalent to that of the actual forecast. Consequently the variational approach originally developed by Sasaki (1958) and applied by Lewis (1972) for operational use may have considerable promise. With this approach the objectively analyzed wind and temperature fields are simultaneously modified, based on dynamical constraints. These constraints must be cast in the same form as in the prediction model, but the model itself is not integrated. The variational approach requires solution of a Helmholtz equation, but with the development of direct solvers for this type of equation, as mentioned above, the initialization phase need not consume a large fraction of the actual forecast time. Although arbitrary weighting factors must be specified to determine the relative importance of observations to dynamical constraints, these factors may be used to emphasize the wind field in the desired regions.

Representation of physical processes. One of the prime motivations for fine-mesh modelling is a more accurate representation of the physical processes. These may involve flow over detailed orography, momentum and energy redistribution in convective systems, or the vertical flux of properties through the planetary boundary layer to the upper atmosphere. Methods of representing these processes are presently being actively researched. This is particularly true for the effects of convective-scale heat release on the larger scale flow and for boundary layer processes. As these processes occur on scales smaller than the grid size, their effect on the grid scale flow must be parameterized. The success of these parameterization schemes will be increased if the large scale processes are represented on the scale that triggers the exchange, and/or receives the primary feedback signal. This will require fine-mesh modeling as the triggering processes appear on scales no larger than the mesoscale.

Garstang and Betts (1974) has summarized the extensive research regarding representation of latent heat release in both prognostic and diagnostic studies. One of the key features is an improved understanding of how the large scale responds to the presence of a cloud, in particular through the subsidence heating in the environment in response to the buoyant ascent of cloud air. However, the vertical distribution of this heating is dependent on the entrainment/detrainment process, and the associated downdraft-production mechanism, which are not well understood. The very active research in this area, and the results of further studies based on GATE data obtained during 1974, promise an improved parameterization of the latent heat release. The basic framework for these schemes has been established by studies such as Ooyama (1971) and Arakawa and Schubert (1974). In these studies the two key model elements are the large scale forcing of the cumulus clouds and the feedback to the environment through a spectrum of cloud sizes. Arakawa and Schubert (1974) particularly emphasize the role of the boundary layer processes in determining the amount of mass ascent through clouds. An example of a fully coupled boundary layer and latent heat parameterization model has been described by Arakawa and Randall (1974). Kreitzberg et al (1974) also anticipate a dominant role for the planetary boundary layer model, with the coupling of the horizontal flow to the detailed vertical structure requiring a mesoscale rather than cyclonic scale resolution. Whereas Arakawa and Randall use a simple boundary layer model primarily to improve the vertical flux calculation at the lowest levels in the global model, Kreitzberg et al actually insert about 15 additional levels and calculate the vertical flux at each level.

In general the models described in Table 4 incorporate rather crude schemes for parameterization of latent heat release. Those derived from operational models use a form of convective adjustment to remove instability. Such schemes cannot be directly used in regions that are typically conditionally unstable--such as the tropics, in the warm sectors of extratropical cyclones, or in continental regions during the summer. If the convective adjustment scheme is not modified, the conditionally unstable regions will be completely eliminated, with a large overestimate of precipitation. One model that includes an extremely complex latent heat parameterization scheme is Kreitzberg et al (1974). The potential instability at each gridpoint is released by a detailed, one-dimensional cloud model that includes microphysical processes. This brute-force technique is extremely costly in terms of computer resources, but may be particularly useful if the simulation or modification of cloud processes is being studied. An intermediate example is the use of a modified Kuo parameterization scheme by Krishnamurti et al (1973). This scheme has been tested in various tropical systems and in some mid-latitude diagnostic studies.

It appears that the association of large-scale and boundary layer convergence of moisture with convective mass flux gives useful results. Even though the physical interpretation of the vertical heat distribution mechanism is questionable for the Kuo scheme, the utility of the scheme for short-term forecasts of convectively-active weather systems has been established.

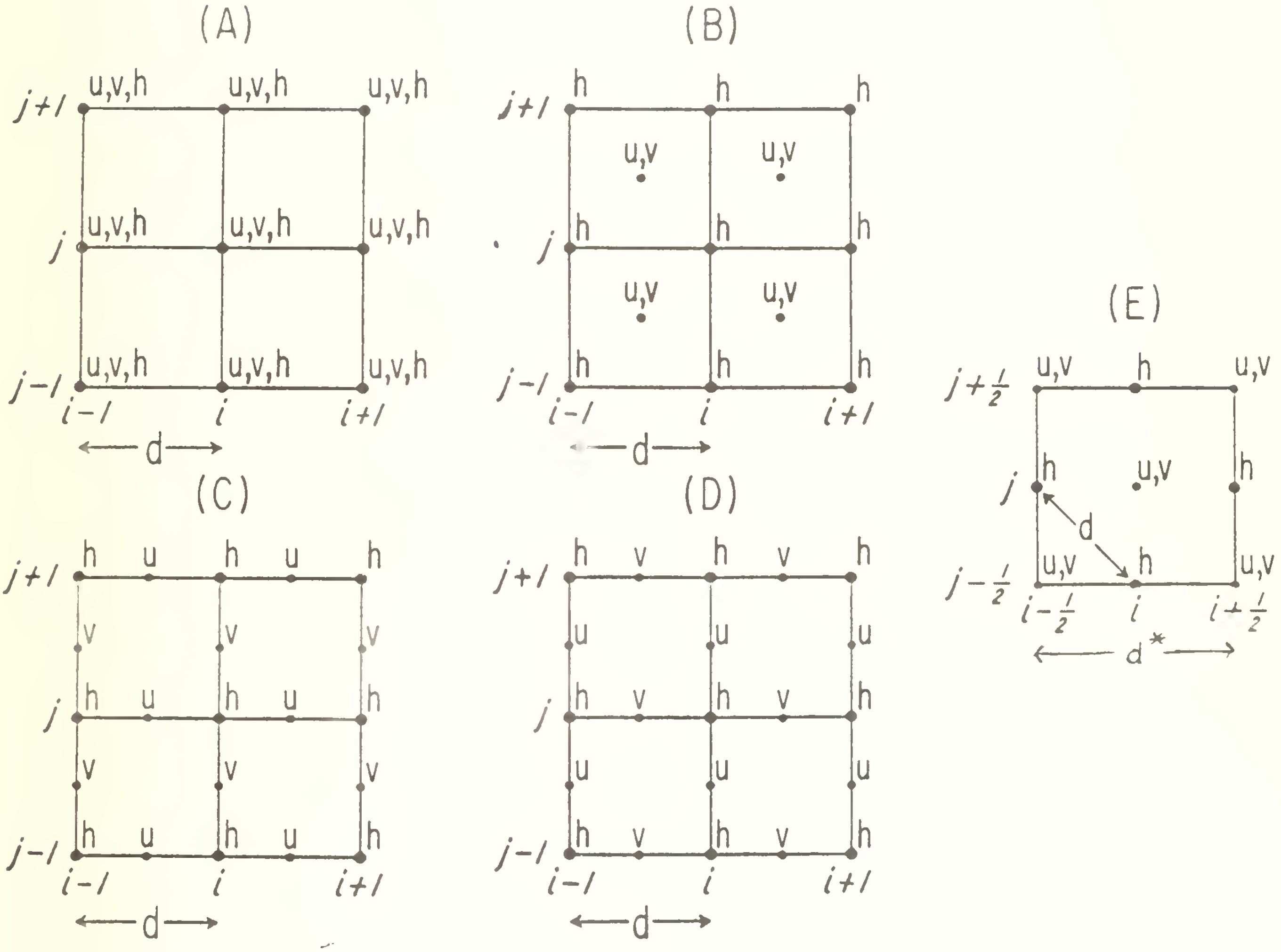

Fig. 1 Various spatial arrangements of variables suggested by Arakawa et al (1974), as described in the text and Tables 1 and 4.

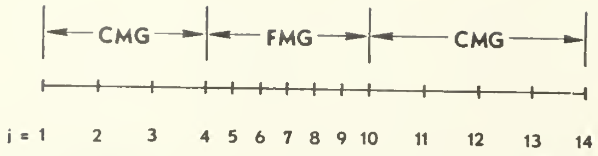

Fig. 2 An example of a meshed grid with a discrete change in resolution by a factor of two.

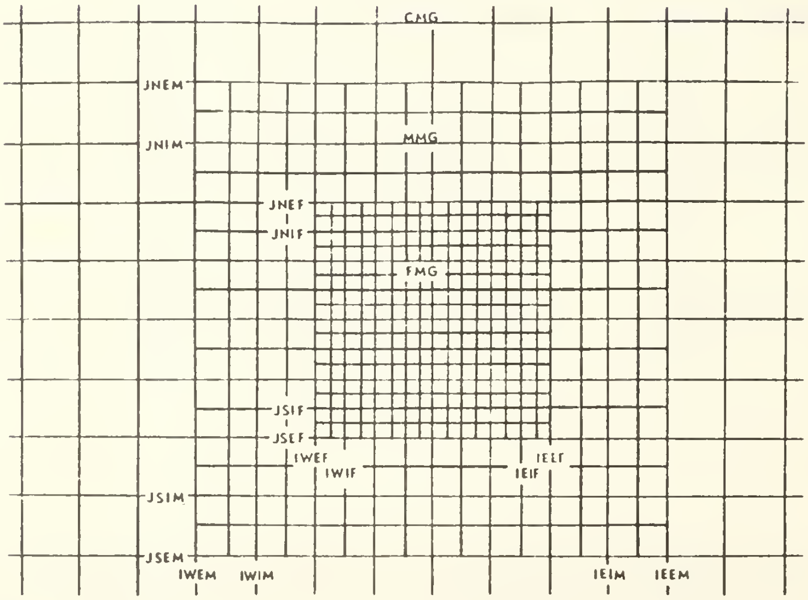

Fig. 3 An example of a triply nested grid arrangement (Harrison, 1973).

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