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This report outlines progress made during the second quarter of the project on new wind energy site selection methodology. Major emphasis during this quarter was on the coding and testing of a 3-D version of the mesoscale computer program SIGMET and on the acquisition of mesoscale field data for validation comparisons. Several auxiliary studies have also been made of topics contributing to increased computational efficiency. In Section 2 the work on field data acquisition is summarized. The mesoscale code development is reported in Section 3. Section 4 describes shorter studies of methods for improving the accuracy and speed of mesoscale calculations.

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1. INTRODUCTION

The following report constitutes the second quarterly report by the contractor, Science Applications, Inc., (SAI) on the National Science Foundation (NSF) contract entitled "A New Wind Energy Site Selection Methodology," NSF-C1006 (AER-75-00834). The reporting period is June 17, 1975, to September 16, 1975.

Major emphasis during this quarter has been on the coding and testing of a 3-D version of the mesoscale computer program SIGMET and on the acquisition of mesoscale field data for validation comparisons. Several auxiliary studies have also been made of topics contributing to increased computational efficiency.

In the following sections the status of the work is reported in greater detail. In Section 2 the work on field data acquisition is summarized. The mesoscale code development is reported in Section 3. In Section 4 we describe shorter studies of methods for improving the accuracy and speed of mesoscale calculations.

2. FIELD DATA ACQUISITION

Contacts with sources of meteorological data which may be suitable for model validation were reported in the first SAI quarterly report (Freeman, 1975). During the second quarter, additional contacts have been made and arrangements for obtaining reports and data have been concluded. During the third quarter it is planned to collect additional data, select the best cases for numerical simulation, and to perform comparisons between the data and calculations for validation of the SIGMET code.

During the quarter the following information was obtained:

Mr. Morris McCutchan of the Forest Fire Laboratory (FFL), Riverside, California, has indicated the availability of data from the FFL meteorological network located in the San Bernardino Mountains. A paper describing the network has been obtained and arrangements for acquiring short-period data from the 12-station network in Devil's Canyon are being concluded.

Mr. H. McGinness of the Jet Propulsion Laboratory (JPL) was contacted regarding anemometer data at six sites at the Goldstone Tracking Station (Mojave Desert, California). We have received maps showing terrain height and site locations, reports analyzing site data, and hour-by-hour data for two periods of one week. These can be supplemented with data from several military stations nearby.

Mr. William Olmstede of the Atmospheric Sciences Laboratory of White Sands Missile Range has agreed to supply data from field measurements conducted in the Tularosa Basin, New Mexico. These data, corresponding to several days for which data reduction has been completed, represent an extensive set of pibal ascents covering the region adjacent to the San Andres mountains.

Mr. Arnold Court has provided us with computerized data from Mt. Gibbons, California. These data, collected for Southern California Edison Company (SCE), consist of four years of wind speed data on the western slope of the Sierra Nevada mountains. A report from a study performed by North American Weather Consultants for SCE for the Lucerne Valley, California, has also been obtained. These data are relevant to more isolated mountains in high desert terrain.

Mr. David Barber of Oregon State University has arranged to send meteorological data for two locations on the Columbia River and for Yaquina Head on the Oregon coast. These data can be obtained at hourly intervals and can be supplemented with upper air data from Portland and Salem.

Inquiries regarding the availability of data have been made of a number of additional sources. We expect to continue our survey of site data in order to assure that the comparisons with calculations are as relevant as feasible.

3. MESOSCALE MODEL DEVELOPMENT

As indicated in the first quarterly report, a 3-D version of the SIGMET computer code is required for application to mesoscale simulations of regional climatology. The formulation and testing of this code constitutes one of the major activities of the second quarter. During this period the 3-D SIGMET code was formulated, coded, and preliminary versions are being tested.

Clearly, the 3-D mesoscale computer code is a large and expensive tool. It uses computer storage comparable to that available on the largest computers, and each calculation could require a substantial number of minutes on the fastest computers. Consequently, the mesoscale calculations are expected to be costly, especially so when large numbers of calculations are involved. In view of the anticipated expense of these calculations, the formulation of the 3-D SIGMET code was considered from the point of view of efficiency, as well as of accuracy and ease in coding. Two additional topics relating to accuracy and efficiency are considered in Section 4; in this section we describe those topics which were incorporated into the current version of 3-D SIGMET.

Considerable attention was given to the organization of the computer code from the point of view of the sequence of operations. The code is highly modular, being divided into subroutines in which different physical effects are evaluated. This modular organization of the code contributes substantially to its efficiency. An example in point is the evaluation of the advection terms. This calculation of the progress of quantities through the computational mesh due to the wind velocity relative to the mesh has been formulated in conservative form. By performing the calculation in the direction of the advection it is possible to avoid recalculation of many of these terms without introducing new storage arrays. This procedure has been applied to the vertical advection and both components of horizontal advection.

Timing investigations, measuring the amount of computation performed in each of the subroutines, were performed on the 2-D SIGMET version. These tests indicate which subroutines and which calculations are the most important consumers of time. It was found that, following the calculation of advection and pressure gradients, the terrestrial radiation calculation is the largest time consumer (accounting for approximately one-third of the total calculation time). The calculation of vertical turbulent diffusion was found to require a smaller, but not negligible, amount of time. Careful reprogramming of the terrestrial radiation subroutine has reduced its calculation time by approximately a factor of two. This calculation can be further reduced to a small fraction of the total by using a larger time interval for the radiation subroutines than for the remaining parts of the mesoscale calculation. Improvements in the calculational efficiency of the diffusion coefficients have also been made. However, as discussed below, alternative diffusion coefficients are being tested whose computational requirements have not yet been evaluated carefully.

A major consideration in the expense of the 3-D calculation is the time interval which can be employed in the time integration. This is currently smaller than required by accuracy considerations alone due to the requirements for numerical stability. In the preceding quarterly report two stability inequalities were identified as imposing time interval limitations: vertical diffusion, and gravity wave propagation. We return to the consideration of the gravity waves in the following section.

Strong turbulent diffusion across the small zones required to resolve the planetary boundary layer near the surface may, under some circumstances, limit the time interval to a few seconds if an explicit formulation is used. In order to remove this limitation we have implemented a new formulation of the vertical diffusion which is partially implicit. This method eliminates the time interval restriction associated with diffusion. As indicated by a linear stability analysis, it also markedly relaxes the stability inequality associated with vertical advection. It is not yet known whether the time interval limitations from other processes are similarly ameliorated. The partially implicit code contains simultaneous linear equations in each vertical column of zones. These equations are equivalent to a coefficient matrix of the unknown quantities which is tri-diagonal and is solved by a forward-backward substitution algorithm.

This vertical diffusion subroutine was incorporated into a reorganized 3-D SIGMET formulation, and the resulting code has been debugged and tested. Some loss of accuracy was experienced on the SAI DEC10 computer, where the code is being developed, due to the substraction of numbers of approximately equal size. This loss is especially acute in the pressure gradient calculation. The problem was overcome by use of a limited amount of double precision arithmetic and by algebraic reformulation to eliminate the most severe figure loss. Due to the larger word length of the CDC 7600 computer, the figure loss is not a problem for the "production" calculations at the Berkeley computation center.

Testing of the 3-D SIGMET is still in progress, and it is anticipated that additional improvements will be made. The basic computer code, however, seems to be performing satisfactorily.

4. IMPROVEMENTS IN ACCURACY AND EFFICIENCY

The modifications described in Section 3 have been incorporated into the 3-D SIGMET code. In addition, there are several investigations in progress which are not yet ready for operational use. These are: implicitization of gravity wave propagation, flux corrected transport, and evaluations of alternative boundary layer turbulence formulations.

As mentioned in Section 3, numerical stability conditions limit the time interval of the mesoscale calculation; one of the most stringent is that for the propagation of gravity waves. In the SIGMET 2-D computer code, for example, the explicit formulation limits the time interval to

$$\Delta t \leq \frac{\Delta X}{2C},$$

where $C = \sqrt{gH}$ is the effective wave speed of the "external" gravity wave; i.e., that gravity wave motion in which the entire atmosphere participates. Slower waves propagate as internal waves, but these are less restrictive. Since the external wave speed is around 300 m/s, a 3 Km horizontal zone interval will limit the time interval to 5 seconds. In an effort to increase this time interval we are investigating partial implicitization of those terms of the equations which control gravity wave propagation. Two aspects of this problem have been studied: the reduction of the 3-D equations to a 2-D set, and the algorithm for the solution of the resulting 2-D equations.

The first approach is motivated by the recognition that the 3-D SIGMET equations can be reduced to a system closely resembling the one-level shallow water equations by integration vertically through the depth of the atmosphere. The resulting equation describes the dynamics of the external gravity wave. The same can be done for the three SIGMET difference equations, describing the two horizontal velocity components and the surface pressure, by performing a summation over zones in the vertical. The resulting equations do not contain vertical advection or diffusion, and the remaining horizontal terms not required to be implicit, such as diffusion, can be calculated explicitly. As soon as this set of equations has been solved implicitly it appears from cursory examination that velocities at intermediate altitudes can be obtained explicitly, even though they are at an advanced time. This formulation has not yet been coded or tested.

The solution of the implicit equations in two spatial dimensions, resulting from the reduction described above, has also been considered. We find that the matrix equations appropriate to the staggered-in-space spatial zoning of the 3-D SIGMET code do not contain the same coupled terms that are involved in an unstaggered mesh. Consequently, the coefficient matrix of the unknowns contains more terms, seeming to indicate that an iterative method of solution is required. Such an iterative method might substantially reduce the computational advantage that the implicit formulation was designed to achieve. When $\Delta x = \Delta y$ (equal spatial intervals in the horizontal directions), however, we find that the coefficient matrix is simplified in such a way that direct solution of the equations is feasible. It turns out that, under these circumstances, the coupling is along the two diagonal directions. A direct solution can be achieved by performing successive sweeps of the mesh in these two perpendicular diagonal directions. In order to test this method an experimental code solving the shallow water equations in 2-D has been written. This code incorporates the same spatial and temporal difference equations used in SIGMET. Comparisons are now being made between explicit and implicit solutions of simple test problems. It appears that this method of diagonal splitting is feasible; it is anticipated that the net gain in computational efficiency resulting from it will be determined during the next quarter through a series of additional test calculations.

Calculations with 2-D SIGMET have given results that, in the presence of sharp gradients, show strong fluctuations in space and time. These noisy solutions appear to be attributable to inaccuracies in the advection calculation of the leapfrog difference equations when strong gradients are encountered. In an effort to increase the accuracy of the advection calculation we are investigating the Flux Corrected Transport method (Book, et al., 1975). This procedure for enhancing the accuracy of numerical advection treatments has been applied by the authors to several difference equation schemes, among them the leapfrog method. The method consists of several correction steps which are applied to the results of the transport algorithm. First, an artificial diffusion operator is applied. This is followed by an antidiffusion step, in which the fluxes are also limited in such a way as to prevent local maxima or minima from being formed. Tests performed by the above authors indicate that when the artificial diffusion is appropriately chosen, striking improvements in the advection calculations for all of the methods are obtained. In order to apply the scheme to several spatial dimensions it appears to be necessary to use the splitting technique; this requires additional changes in SIGMET. We are currently incorporating the appropriate formulation in the 2-D SIGMET code, and code debugging and testing are in progress.

Turbulence models have been investigated further during the past quarter. Several of these were described in the first quarterly report. Programming has been finished to incorporate the generalized mixing length prescription (Yamada and Mellor, 1975) into the SIGMET code, where it can be readily shifted from the 2-D to the 3-D version. Test calculations with this prescription can now be made and are planned for the next quarter. Programming of the turbulence contribution due to rough terrain, also described in the first quarterly report, has been completed, but not yet in a form compatible with SIGMET. This scheme (MacCready, et al., 1974) incorporates a representation of LO-LOCAT turbulent intensity data into a prescription employing terrain height data, such as that required for the representation of the surface elevations in the SIGMET code.

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