ABSTRACT

The objective of this research is the development and verification of a regional scale numerical weather prediction model for use in forecasting air pollution concentrations. The scope includes verification of meteorological forecasts of flow fields, boundary layer structure and precipitation using three hourly rawinsonde data in the central and eastern United States.

A prototype regional numerical weather forecast system has been developed. This system includes codes to read in the first guess data and observational data needed to initialize the prediction model. Other codes use these data to perform an isentropic analysis of the wind, temperature and pressure fields and analysis of the humidity field using optimal interpolation. Subsequent codes transform these analyses to the prediction grid and adjust the wind field to remove the vertically integrated mass convergence. The output from that code is the input to the fine mesh prediction model that uses a 140 km grid size and makes a 24 h forecast. Fine mesh model output is used to initialize the
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mesoscale model and provide time dependent lateral boundary tendencies to the mesoscale model. The mesoscale model is on a 35 km grid and normally makes a 12 h forecast during some portion of the 24 h fine mesh forecast period. Additional codes generate a condensed history tape for future diagnostic studies of the forecast, processor codes that use the condensed history to generate a variety of forms of graphical output, and verification codes that use the history tape to verify the forecasts against rawinsonde observations and against analyses at future times.

This system of codes has been run on four cases but the small scale forecast was on a 70 km grid in place of the 35 km grid that is intended. Verification studies on these four cases have revealed that the forecast system is particularly successful in predicting organized precipitation systems including both stable precipitation and convective precipitation. The verification also revealed weaknesses in the analysis code in the atmospheric boundary layer.

The present status of the forecast system is that the codes require some streamlining and obvious weaknesses need to be removed. Systematic documentation of the system of codes is underway at the present time. We believe that the structure of the codes and the results of preliminary forecasts on these four storms justifies the conclusion that this is the most flexible and powerful numerical weather forecast system for making small scale weather forecasts (35 km grid spacing).
1. Introduction

This is intended primarily as a management report rather than a scientific report. Most of the information has been published in Lutz & Kreitzberg (1977) or Kreitzberg (1977). Exceptions are the work by Pinkerton (1977) and the more complete up-to-date tabulation of verification statistics contained in Section 2 of this report. The implications of this research to the Department of Energy (DOE) are contained in Section 3 of this report.

The primary effort during the 15 month period covered by this report has been the development, testing and verification of the regional scale numerical prediction model. The research specifically directed at prediction of flows over a regular terrain for use in air pollution forecasting is contained in the paper by Lutz & Kreitzberg (1977). This paper introduces the terrain flowing coordinate system which is in sigma-z coordinates with the lowest level following the terrain of the earth and the levels above the middle troposphere being horizontal. Examples are shown of predictions using idealized conditions of standard atmosphere temperatures and uniform flow from the west of 5 m s\(^{-1}\) over the Alleghenies and 20 m s\(^{-1}\) over the Rockies. The Allegheny test was on a 35 km grid and showed that under these conditions pollution transport from the Ohio River Valley power plants to the East Coast of the United States would be deflected northward at the lowest levels traveling into Connecticut without reaching New Jersey or New York City. At higher levels, about 1 km above the terrain, the flow would travel from west to east across the mountains. Therefore, to travel from the Ohio River Valley power plants to New Jersey, the pollution would have to mix upward to 1 km west of the mountains, pass over the mountains, and then mix back down to the surface along the East Coast. The low level winds on the East Coast were from the southwest and would carry the pollution
northeastward along the coast once it has mixed down to the surface levels.

The Rocky Mountain tests were conducted on grids of 280 km, 140 km, and 70 km. The conclusion of this simple test, again with standard atmosphere temperatures and uniform 20 m s$^{-1}$ flow from the west initially, was that reasonable changes occurred in the forecast going from the coarser mesh down to the finer mesh. More specifically the finer meshes had larger amplitude deflections introduced by the orography and larger amplitude vertical motions. The locations of the ridges and the troughs in the wind flow pattern were fairly consistent from case to case in the large features while some smaller features did appear on the 70 km mesh that did not exist on the larger meshes. The amplitude of the vertical velocities increased substantially between the 140 km and the 70 km grid. For example the intense subsidence east of the Rockies in Colorado was $-31$ cm s$^{-1}$ on the 70 km grid and $-23$ cm s$^{-1}$ on the 140 km grid.

Since we see a very systematic and consistent progression of changes as we go from the coarsest mesh to the finest mesh in the Rockies we conclude that the dynamics of the primitive equations are stable and consistent enough that significant improvement in forecasting the wind flow structure over the Rockies can be achieved using a hydrostatic model down to grid sizes of at least 70 km and most probably 35 km. We ourselves do not propose to do further studies on orographic flows in the Rocky Mountains, but we could do so if the need arises; for example, in conjunction with pollution transport studies in Washington and Idaho.
The Ph.D. dissertation by John Pinkerton entitled "Numerical Experiments on Boundary Layer Effects on Frontal Structure" has recently been completed and defended but not retyped and printed. The abstract and summary and conclusions sections have been reproduced as Appendix A to this report. Briefly this work utilized a two dimensional (x,y) grid with a 20 km horizontal spacing and a 0.5 km vertical spacing to study the effects in a frontal zone of variations in surface roughness and surface heating. The unique aspect of the numerical formulation of this model is the use of a nested grid of 10 additional levels to better resolve the vertical fluxes in the boundary layer without greatly increasing the computer time. Computational savings are achieved by not computing the horizontal advection effects at the nested levels but rather interpolating the effects of horizontal advection from the standard levels at 0.5 km intervals. An implicit differencing scheme is used to compute the vertical fluxes so that these computations are only required every six time steps of the primitive equation computations.

The results show the effects of surface friction and surface heating are largely confined to the planetary boundary layer below 2 km. The features of the frontal structure which are affected by surface friction and surface heating include the slope and movement of the frontal zone, the maximum horizontal temperature gradient and vorticity in the frontal zone and the low level convergence/divergence patterns in the vicinity of the frontal zone. Results obtained by other researchers using analytic, synoptic and numerical modeling techniques are consistent with and in broad qualitative agreement with the results of this model. We intend to adapt this nested grid technique to improve our predictions in the boundary layer. We expect this improved vertical resolution to be particularly important when we include the vegetated ground layer.
Other Ph.D. dissertations that have been supported by this project that are nearing completion include those of Daniel Doyle and Leon Ettinger. These students are no longer being supported by the project and they should complete their dissertation within the next few months. The thesis titles are: Daniel Doyle, "Boundary conditions in limited-area models of flow over irregular terrain" and Leon Ettinger, "Numerical simulation of flow at the interface between the land and ocean boundary layers."

Recent progress and problems in regional numerical weather predictions are contained in Kreitzberg (1977). A copy of this paper has been provided to the technical contract monitor and will be included as Appendix B to this report. Very briefly, a new scale of numerical weather prediction model has been developed into a system of codes that include data preparation analysis, forecasts and verification codes. This regional scale forecast system includes a forecast on 140 km grid that is used to help initialize a mesoscale forecast on a 35 km grid. The principal gains from this new system are expected to be in the accuracy and detail of precipitation forecasts and cloudiness forecasts including the effects of terrain and parameterized cumulus convection. The finer mesh grid permits incorporation of a smaller scale depiction of the surface trajectories in the atmospheric boundary layer for pollution transport studies. It is this system of codes that we propose to install at BNL and use to demonstrate the capability of near real time forecasting during the next research period.

Interactions with other ERDA laboratories have been primarily with Brookhaven National Laboratory. Mr. Leon Ettinger has been located at BNL from February 1977 through mid-August 1977. Mr. Leach will be located at BNL beginning in September 1977 and he will continue on at BNL if the proposal for continuing this research is accepted.
Professor Kreitzberg has been in contact with personnel in the Atmospheric Sciences Division, BNL, in the development of plans for the trans Allegheny pollution transport study (TRAPS) to be included as part of MAP3S. He gave a seminar at BNL on July 19, 1977 at which time plans to transfer the complete regional forecast system to the BNL computer were discussed.

Professor Kreitzberg also presented a seminar on this research work at Lawrence Livermore Laboratories and discussed the implications and possible future applications of this forecast system to the accidental release advisory capability (ARAC). It was agreed that there is no duplication of effort between the Drexel and LLL efforts. Inclusion of the regional scale forecast system within the ARAC program will become feasible when LLL obtains a CRAY-1 computer. Software for this system developed at the National Center for Atmospheric Research (NCAR) CRAY-1 facility can be transferred to LLL.

Over the years we have been in touch with Pacific Northwest Laboratories (PNL) regarding trajectory calculations from the output of our forecast model. In the spring we sent to PNL a history tape from one of our forecasts for them to use to evaluate the usefulness of some such information in real time or post analysis research applications.

A complete list of publications on our modelling work appear within the list of references at the end of this report. Those which resulted primarily from support under this project are marked with an *. The major publications resulting from work this past year are those of Lutz & Kreitzberg (1977) and Kreitzberg (1977).
2. Summary of verification statistics.

Some of these statistics have been reported in the preprint volume of the Third Conference on Numerical Weather Prediction, April 1977, Omaha, Nebraska. These papers include Chang and Kreitzberg (1977), Lutz and Kreitzberg (1977), and Kreitzberg and Rasmussen (1977). We have since prepared statistics from additional forecasts and all these statistics computed to date are reproduced here for convenient comparisons. These statistics are on four different storms and on two different grid sizes, 140 km and 70 km.

The first three storms, February, 1971, April, 1975 and May, 1975, all contain severe weather but were of rather different synoptic structure. The February, 1971 case reported on by Perkey (1976) is a large midlatitude cyclone moving northwest from Texas into the Mississippi Valley with squall line and severe weather breaking out in the Gulf Coast states. The April, 1975 case had weak large scale forcing in a generally slow zonal current across the central United States; this is the Neosho tornado storm. The third case, May 1975, was a case of strong large scale forcing with a low in South Dakota and a well defined cold front along which the Omaha tornado developed. The April and May 1975 cases were discussed by Chang and Kreitzberg (1977).

The final case, April 1974, is the AVE-II case (Hill & Turner, 1977) for which rawinsonde data are available over the central and eastern United States at 3 hourly intervals. This case is being used most extensively for the ERDA studies because of the availability of frequent rawinsonde data over the Appalachians that can be used to verify predictions of wind fields over irregular terrain and the temporal evolution of the surface mixing layer depth and wind profile. Statistics will be shown for a 24 h forecast on a 140 km mesh and a 9 h forecast starting 3 hours after the start of the other forecast and extending for 9 hours.
Verification data are averages over layers extending from the midpoint of the layer below the level to the midpoint of the layer above the level. Thus the layers range in depth from about 350 m near the surface to about 2 km in the stratosphere. Even with this vertical averaging, the rawinsonde data still contains time fluctuations on scales smaller than predicted by the model. All heights in the verification figures and tables are in terrain coordinates h given by \( h = (z - E)H/(H - E) \) where \( z \) is height above sea level, \( E \) is terrain elevation and \( H \) is 5.25 km. That is, \( h \) is elevation above the terrain scaled to coincide with elevation above sea level at all heights above 5.25 km.

An additional form of verification is the comparison of the model forecast with the analysis at grid points. These analyses are performed on the 190 km half-NMC grid and interpolated to model grid points. The differenc values at grid points compare the model prediction against the large scale analyzed observed conditions.

In comparing the relative quality of forecasts of wind, temperature and humidity, we are comparing apples with oranges. We do so by comparing each quantity with its measurement accuracy, say 2 m s\(^{-1}\) "equals" 1 K "equals" 10%. To judge relative quality of forecasts in relation to user needs would make the discussion user dependent. To judge relative quality of forecasts in relation to dynamical significance would make the discussion scale dependent. As long as it is recognized that our comparisons are based on the 2 m s\(^{-1}\), 1 K, 10% relationship, these discussions can be understood.

To detect local departures of forecast from observations that might be related to particular weather or terrain features, the differences between forecasts and observations at rawinsonde sites are mapped out for each level. Some examples of these maps are shown in Fig. 1.
These diagrams in Fig. 1 show the errors at each site and the statistics of the errors on the chart. The station model is shown below the chart, to the left of the statistics. That is, the first line of numbers are RH(%) and T(°K); the second line are v, u (m s⁻¹) and the third line are speed (m s⁻¹) and rawinsonde station number. The standard deviation and mean errors are shown in the same order beneath the charts on the right.

Fig. 1a is at the initial time so the errors are simply the departure of the analysis from the observed layer mean rawinsonde data. The largest humidity error is 6% at station 250 (Brownsville, TX) and one of the largest is at station 393 (Vandenberg, AFB, CA). The largest wind errors are at stations 451 and 562 (Dodge City, KA and North Platte, NE). Actually, the analysis fits the observations very closely on a site by site basis as well as in terms of standard deviations. Mean errors are truly negligible for this case.

Fig. 1b shows errors 12 h into the forecast at the same level (0.025 km) as Fig. 1a. The temperature errors are particularly large and negative at the higher elevations (Colorado and Wyoming) due, we believe, to lack of consideration of precipitable water or station elevation in our solar radiation formulation. This is what we mean by an obvious weakness that needs to be rectified. The eastern half of the United States has very good temperatures but, for some reason, Southern California has a poor temperature forecast in this case. Relative humidity errors are large where temperature errors are large and generally of opposite sign as would be expected. The largest wind error is in Alabama.
Fig. lc and ld show 12 h forecast errors at 0.750 km and 4.5 km, respectively. The humidity errors show a systematic positive bias which is under investigation. The large negative temperature errors over the Rockies at 0.025 km show up again at 0.075 km but not at 4.5 km. The wind errors have some consistancy, e.g. positive v and negative u around Ohio, but a vector plot of predicted and observed velocities may be necessary to reveal patterns. (Tables 8, 9 and 10 give the statistics at all levels in this AVE-II, 140 km case and are discussed later.)

Table 1 shows the statistics from the 12 h forecast of the storm discussed by Perkey (1976) but with terrain included in the model. The statistics are standard deviations \( (S', T_v', RH') \) and mean values of the errors. The mean errors are generally small indicating little conclusive evidence of systematic bias.

The standard deviations show that wind speed errors increase with height, just as the speed itself does. It may be worthwhile to compute the percent error in wind speed and it may be worthwhile to compute the vector error, i.e. \( (u'^2 + v'^2)^{1/2} \), in the future as well as a measure of wind direction error as a function of wind speed. The temperature errors are twice as large in the boundary layer as in the middle troposphere. Charts like Fig. 1b and 1c show that the forecast was too cold over the Rockies in this case too, presumably due to our treatment of solar radiation with no correction for station elevation. The relative humidity errors are disappointingly large and there is a suggestion in this case of a bias toward too much vertical transfer of moisture giving positive mean errors aloft and negative values in the boundary layer. Humidity above 9 km is not considered significant enough to verify; specific humidity is small and observational errors are large.

Tables 2, 3, 4 refer to the Neosho storm. Table 2 includes statistics at the initial time to verify the analysis system. It is clear that a serious bias exists in the boundary layer wind speed that needs to be rectified.
This problem does not appear in later cases we have run (Table 8) but it will be investigated further. Table 3 shows that after 12 h of forecast the boundary layer wind speed bias is small. All the errors in Table 3 are rather small but then this forecast is on a 70 km grid that does not include the Rocky Mountains or the West Coast (see Chang and Kreitzberg, 1977).

Table 4 shows the errors between the forecast and the analysis at the 70 km grid points for the same case and time as Table 3. The last column shows the RMS error in isobaric heights that correspond to the RMS errors in pressure on height charts from the preceding column. It can be seen that pressure forecasts are remarkably accurate in this case.

Tables 5 and 6 are for the Omaha tornado case. These values are rather similar to those in the Neosho case, Tables 3 and 4, even though this is for a strong synoptic system while the former was for a weak system. Boundary layer speed errors are on the order of 5 m s$^{-1}$.

The wind and humidity statistics at rawinsonde sites are very similar to the statistics on the grid after analysis, while errors in temperature after analysis are significantly smaller. Notice that the RMS values should be compared with the square root of the sum of the squares of the standard deviations and the mean errors. This suggests that small spatial variations in temperature contribute to degradation of the verification at sites but this problem is not noticeable in the wind and humidity statistics.

We had expected the opposite results. That is, we expected sub-grid scale wind and humidity variations would be more "troublesome" than sub-grid scale temperature variations. These statistics can be reconciled with our preconception only if we conclude that wind and humidity errors are so large compared to temperature errors that the sub-grid scale contribution to the wind and humidity statistics are lost in the noise. Clearly, these data in Tables 4 and 6 are inadequate and further cases are needed.
Table 7 is for the AVE-II forecast for 9 h on a 70 km grid east of the Rocky Mountains reported by Lutz and Kreitzberg (1977). The wind errors are unusually large compared with the Omaha case, Table 5, and the boundary layer humidity bias is too large. We believe the problem is in the initial analysis over a limited domain that can be corrected as shown in Fig. 1a and Table 8. We expect to repeat the AVE-II 70 km forecast in the near future and significantly improve upon the results in Table 7.

Tables 8, 9, 10 are for the same storm as Table 7 but for the whole United States and for a 140 km grid forecast. These tables show the decay in accuracy with time from 0 h to 12 h to 24 h. Table 8 shows that at the initial time the errors are very small except for the wind speed in the stratosphere. This means the bivariate isentropic analysis scheme on the 190 km, half-NMC grid works well. Even after the analysis is transformed to latitude/longitude terrain coordinates, the vertically integrated mass divergence is removed, and the data are interpolated to rawinsonde sites, the model data and observed data still agree closely.

Tables 9 and 10 show that the 12 h forecast is considerably better than the 24 h forecast, the latter errors being about 30% larger than the former. The notable exception is the boundary layer temperature mean error. After 24 h there is very little mean error in the low level temperature. This fact is remarkable because the model does not have long wave radiation cooling which one would think to be necessary to balance the short wave heating that the model does have.

The 24 h forecast in the upper troposphere has large wind and temperature standard deviations in this case. Examination of the detailed isobaric charts shows that the movement of the upper trough slowed down in the second 12 h in the
forecast but not in reality. We believe this error can be removed with a 70 km grid forecast. We hope that a 24 h, 70 km forecast will verify substantially better, improving greatly upon values in Table 10.

Evidence from these experiments suggests that the eastern United States forecasts are measurably better than western United States forecasts, particularly in the lowest kilometer. We want to verify these regions separately as well as jointly in the future.

Verification of the clouds and precipitation forecasts to date have primarily been on the basis of pattern comparisons in the qualitative sense. For example, Fig. 2 shows the total 12 h precipitation predicted and observed at 00 GMT February 21, 1971. The main problem is the observed maximum in northern Alabama was held back into Arkansas in the forecast. However, comparison with the radar summary chart valid at that time, indicates that the position and therefore the timing of this 12 h forecast is rather good in the vicinity of the squall line through Mississippi. This forecast was made using 140 km grid and including orography in contrast to the forecast of Perkey (1976) which used the same grid but which did not include orography.

Fig. 3 shows the predicted and observed 12 h accumulation of precipitation ending at 00 GMT April 25, 1975. This forecast was made using a moisture field modified to include indications of moisture from radar observations 12 hours earlier. The patterns agree rather well and the maximum precipitation was predicted to be 31.7 mm and was observed to be 34.0 mm when the observed data are analyzed onto a grid comparable to that of the forecast model.

Fig. 4 shows the convective precipitation rate predicted in the Omaha case at 21 GMT on May 6, 1975. This is a 9 h forecast made using a 70 km grid. Also shown in that figure is the area in which stratiform cloudiness
is predicted at some level in the vertical. These forecasts can be compared with the satellite picture taken at the same time as shown in Fig. 5. It can be seen that the convective precipitation lines up well with the observed line of thunderstorms from the satellite picture. The cloudiness over Missouri was predicted in the cloud water prediction but there is no indication in the forecast of precipitation from that cloud mass.

Fig. 6 shows the 18 h prediction of precipitation on the 140 km grid in the AVE-II case, ending at 06 GMT 5/12/74. The forecast can only be compared against the 24 h observation of precipitation ending at the same time as obtained from the daily weather map series and shown in Fig. 7. We have ordered more appropriate verification data, but little of the precipitation included in Fig. 7 can be expected to have fallen prior to the period covered by Fig. 6. Because of the complexity of the pattern and sparsity of data in Fig. 7, the values are shown but not analysed. There really does seem to be good agreement except for some extreme values observed on the Gulf Coast and the station in southeast Ohio.

It can be seen from the preceding diagrams on precipitation rates, precipitation accumulation, and cloudiness that we are having rather remarkable success in these types of forecasts on both the 140 km and 70 km grids. While we have shown the verification of cloudiness and precipitation in every case we have predicted, I have emphasized those features which verified particularly have been emphasized.
The aspect of cloudiness and precipitation that we are most weak in is that which occurs in the first 6 hours of the forecast before the model is able to generate cloudiness and precipitation from the initial water vapor fields. We have not yet developed satisfactory techniques for including cloud water concentration in the initial data fields. It takes the model a few hours to develop the clouds and, therefore, there is a lag in the initial timing of precipitation early in the forecast. Another aspect of our precipitation prediction that has not yet been adequately analyzed is the heights of our convective clouds compared with the heights observed by radar. Spot checks have indicated that our convective cloud tops do not penetrate the stratosphere even in the severe weather cases where the observed tops do so. To overcome this weakness, we would have to reduce the cloud water loading in the updraft calculation in our cumulus field. This change can be made, but care must be taken that it does not cause overshooting of more modest convective clouds. Also, we will need more resolution in the lower stratosphere if we are to adequately depict the ability of convection to penetrate those levels. At the present our model has 1.5 km to 2 km deep layers in the lower stratosphere.

The preceding summary of verification statistics has clearly shown the usefulness of such an analysis in locating weaknesses and quantifying improvements that arise from model changes. Several suggestions have been made as to additional verification statistics that are needed, particularly lapse rate and wind direction errors. Numerical experiments and verification studies to date have been piecemeal as we develop the system. The goal in the future is for careful definition of series experiments and verification measures beforehand to increase the objectivity of the analysis.
3. Implications of this research to Department of Energy (DOE).

This research has provided DOE with the world's most detailed numerical weather forecast system that can be run in near real-time and explicitly predicts cloud water and precipitation concentrations, including stable and convective processes. With a CDC-7600 class computer, the system can be run on a substantial number of cases of different types and verified against meteorological observations. The system can be run in support of pollution transport field projects during post-observation research or adapted for near real time use during the field project.

The system can also be adapted to run in emergency situations, be they threatened or actual nuclear releases, air pollution episodes or ocean oil spills. It would take a year to harden the system so it could be relied upon to operate in an emergency with minimum possibility of hanging up.

Clarification is required of the meaning of the term "near real time." We mean the model can be driven from data routinely available to predict meteorological conditions before they occur. Presuming a 140 km grid forecast has been run first to provide a first guess of initial conditions and time dependent lateral boundary conditions, a 35 km grid forecast can be begun an hour after the latest observations that are to be included as initial data. The forecast will predict four hours per hour of CDC-7600. Thus the model can get ahead of nature but it is not suitable for routine 24 h forecasts to be rerun several times per day as in an operational forecast setting. With computers now becoming available, the forecast can be run about four times faster and will be operationally feasible on the faster computers.
The primary near term questions remaining are how good are the forecasts and how can the system be optimized. We have begun to answer these questions and have proposed to concentrate the major effort on these questions next year. Certainly there are critical long term problems to get started on even as we concentrate on these near term problems.

Areas of application of these forecasts to DOE problems, once the system is verified and optimized, are rather direct. Air pollution transport and washout on interstate, 24 h scales could be predicted for guidance in fuel use tactics. If pollution levels are expected to become dangerous, cleaner fuels or less consumption may have to be scheduled. During a severe episode, the forecast could be used to anticipate relaxation of emergency restrictions that have been imposed.

Good prediction of surface temperature and cloudiness is essential for optimal day to day natural gas shipments and solar energy system operation. Severe weather forecasts are necessary to anticipate requirements monitoring emergency controls and scheduling repair crews. Specific lightning strikes and wind damage events will never be predicted explicitly hours in advance but the probability of a given number of events in a given time window could be predicted.

As work progresses on development of gas and oil fields off the New Jersey coast it will become more important to have the best possible meteorological forecasts for that region. This research should indicate how good numerical weather prediction could be in the early 1980's. This system could be implemented on an advanced computer for routine operational forecasts for off-shore oil fields in the early 1980's.

As energy supplies and pollution problems become more critical, the contribution of the highest quality meteorological information possible becomes that much more.
worthwhile. As we push numerical weather prediction to the limit, that is, implement the most powerful system on a demonstration basis, we can really see the limits of our skill and the areas in most need of further development.

Clearly there is need to develop the models, software and communication systems to take meteorological predictions as input and produce air pollution, oil spill drift, power load and emergency crew staffing plans as output. It is just as clear that these follow-on efforts are beyond the scope of this project but we look forward to collaborating with other groups to insure a successful interface.
References


*Papers reflecting work supported primarily by this project.*
Table 1. Verification statistics at sites, 12 h forecast on 140 km grid, 2/22/71, 00 GMT.

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<td>RH (%)</td>
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Table 2. Verification statistics at sites, Neosho case, initial time, 4/24/75, 12 GMT.
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<th>$\overline{T}_V$ (°K)</th>
<th>RH' (%)</th>
<th>$\overline{RH}$ (%)</th>
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Table 3. Verification statistics at sites, Neosho, 70 km grid, 12 h forecast, 4/25/75, 00 GMT.
Table 4. Verification statistics on the forecast model grid, Neosho, 70 km grid, 12 h forecast, 4/25/75, 00 GMT.
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<th>$\bar{T}_v$ (°K)</th>
<th>RH' (%)</th>
<th>RH (%)</th>
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Table 5. Verification statistics at sites, Omaha, 70 km grid, 12 h forecast, 5/7/75, 00 GMT.
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<th>S (m s(^{-1}))</th>
<th>(T_v) (^°C)</th>
<th>RH (%)</th>
<th>p (mb)</th>
<th>z (m)</th>
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Table 6. Verification statistics on the forecast model grid, Omaha, 70 km grid 12 h forecast, 5/7/75, 00 GMT.
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<th>$S$ (m s$^{-1}$)</th>
<th>$T'_v$ (°K)</th>
<th>$T_{v}$ (°K)</th>
<th>RH' (%)</th>
<th>RH (%)</th>
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Table 7. Verification statistics at sites, AVE-II, 70 km grid, 9 h forecast, 5/12/74, 00 GMT.
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Table 8. Verification statistics at sites, AVE-II, initial time, 5/11/74, 12 GMT.
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<th>( T_v ) (°K)</th>
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<th>RH (%)</th>
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<td>21.4</td>
<td>20.2</td>
</tr>
<tr>
<td>.750</td>
<td>4.9</td>
<td>1.9</td>
<td>3.9</td>
<td>--2.3</td>
<td>19.9</td>
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<td>4.6</td>
<td>--5</td>
<td>4.8</td>
<td>--3.0</td>
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<td>3.9</td>
<td>--7</td>
<td>5.3</td>
<td>--2.6</td>
<td>21.7</td>
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<td>--4.0</td>
<td>5.4</td>
<td>--3.7</td>
<td>21.3</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Table 9. Verification statistics at sites, AVE-II, 140 km grid, 12 h forecast, 5/12/74, 00 GMT.
Figure 1. Maps of errors at sites for AVE-II forecast on 140 km grid: (a) .025 km level, initial time, 5/11/74, 12 GMT; (b) .025 km level, 12 h forecast, 5/12/74, 00 GMT; (c) .750 km level, 12 h forecast, 5/12/74, 00 GMT; (d) 4.50 km level, 12 h forecast, 5/12/74, 00 GMT.

<table>
<thead>
<tr>
<th>Level</th>
<th>Mean Error</th>
</tr>
</thead>
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</tr>
<tr>
<td>025</td>
<td>4.3 -1.8</td>
</tr>
</tbody>
</table>
Figure 2. Twelve hour total precipitation (mm) ending at 00 GMT, 2/22/71: (a) predicted; (b) observed.
Figure 3. Twelve hour total precipitation (mm), Neosho case, ending at 00 GMT, 4/25/75: (a) predicted; (b) observed.

Figure 4. Forecast on 70 km grid for 5/6/75, 21 GMT: (a) convective precipitation rate (mm/10^4 s); (b) area with stratiform clouds is stippled on this chart of vertically integrated cloud water content (mm).
LIQUID PRECIP WATER
2100 GMT (mm)
FIELD RANGES FROM 0.0 to 1.14
INTERVAL: 0.5 (mm)

Figure 4 (b)
Figure 5. Satellite cloud picture with surface data at 5/6/75, 21 GMT.
Figure 6. Total precipitation (mm) predicted for AVE-II on a 140 km grid for 18 h ending 5/12/74 at 06 GMT.

Figure 7. Total precipitation (mm) observed for AVE-II for 24 h ending 5/12/74 at 06 GMT.
Appendix A

"Numerical Experiments on Boundary Layer Effects on Frontal Structure"

John E. Pinkerton

Abstract

A two-dimensional numerical model is developed to study the effects of surface friction and daytime surface heating on a developing cold frontal zone. Horizontal wind and temperature are predicted with a hydrostatic primitive equation set in a plane normal to the frontal zone. Moisture, radiation and terrain are not considered. The prediction equations are numerically solved with a semi-implicit combination of the Crank-Nicolson and leapfrog techniques on a grid with 23 vertical levels and 49 horizontal grid points. The horizontal grid spacing is a constant 20 km while the vertical grid spacing in the lowest 2 km increases from 17 m to 500 m and then remains 500 m to the upper boundary at 5550 m. Turbulent vertical fluxes of heat and momentum in the planetary boundary layer, as well as the planetary boundary layer height, are explicitly calculated using specific values of surface heat flux and surface roughness at the bottom of a 50 m thick surface flux layer and K-theory. Initial conditions are specified analytically to simulate a realistic cold frontal zone at a time shortly after sunrise.

The roles which surface friction and daytime surface heating play in the development of the frontal zone structure and the transverse circulation in the plane normal to the frontal zone are identified in a series of numerical experiments performed with the model. Various specifications of surface roughness and upward sensible surface heat flux are used in determining the relative importance of these parameters to frontal zone structure and the attendant transverse circulation. The results show that the effects
of surface friction and surface heating are largely confined to the plan-
tary boundary layer. The features of frontal structure which are affected
by surface friction and surface heating include the slope and movement of
the frontal zone, the maximum horizontal temperature gradient and vorticity
in the frontal zone and the low-level convergence-divergence patterns in
the vicinity of the frontal zone. The transverse circulation location and
strength are also markedly influenced. The model results indicate that
both frontal structure and the transverse circulation are much more sensi-
tive to horizontal variations in the surface heat flux magnitude than to
horizontal variations in surface roughness. Surface heat flux may act
either in a frontogenetic or frontolytic manner depending upon its speci-
fied horizontal variation.

Overall the model results demonstrate the complexity of frontal zone
development in the planetary boundary layer and the substantial interplay
of various physical mechanisms. Results obtained by other researchers
using analytic, synoptic and numerical modeling techniques are consistent with
and in broad qualitative agreement with the results presented here.
V. Summary and Conclusions

A. Review of Model

The study of mesoscale systems through the use of numerical models has become quite widespread in the past few years. Similarly, numerical models have also been employed in the study of atmospheric boundary layer phenomena. More recently, these two types of models have been melded in the study of mesoscale systems such as the sea breeze and the urban heat island. A melded model approach has not yet been applied to the investigation of low level frontal zone structure, although the diagnostic study by Rao (1971), while utilizing certain idealized assumptions about fronts, does use a boundary layer parameterization scheme.

In this thesis, a mesoscale numerical model with a relatively detailed treatment of the planetary boundary is developed so that the effects of surface roughness and daytime surface heating on an intensifying cold frontal zone can be studied. This type of numerical modeling approach is necessitated by the complexities of interactions that occur at low levels in the vicinity of the frontal zone, which make synoptic or observational or analytic studies very difficult to carry out. By use of this numerical model, the structure of an idealized cold frontal zone is investigated to identify the roles which friction and surface heating play in the evolution of the frontal zone's structure and attendant transverse circulation.

Because of many complex mechanisms which can influence frontal zone structure, the model has been designed to only include certain fundamental processes. It is recognized that a more complete treatment is required to fully understand the development and resultant structure of actual atmospheric frontal zones. However at this early stage it is desirable to keep the numerical model...
relatively simple to facilitate the interpretation of the numerical results and identify the relative importance of the processes under consideration.

The numerical model itself is a two dimensional $(x, z)$ cross section model with the cross section normal to a north-south frontal zone. Moisture, radiation, and terrain are not included. A hydrostatic compressible primitive equation set is used to predict the two wind components $u$ and $v$ and the temperature. Pressure, density and vertical velocity are diagnosed. Gradients normal to the cross section are considered to be zero, except that there is a $\partial p/\partial y$ which corresponds to the geostrophic wind $u_g$ and a $\partial v/\partial y$ which is determined such that the geostrophic divergence is zero in the cross section.

With regard to the planetary boundary layer in the model, the PBL heights are determined from a prognostic equation which includes the effects of specified upward surface sensible heat fluxes, vertical velocities at the top of the boundary layer, and horizontal advection. In the boundary layer the turbulent vertical fluxes of momentum and heat are parameterized through the use of $K$-theory. The eddy coefficients are determined with an interpolating polynomial and depend on the values of $K$ and $\partial K/\partial z$ at the top of a 50 m thick surface flux layer (SFL). In the SFL, Monin-Obukhov similarity theory is used to calculate wind and temperature and vertical gradients of these quantities based on the specified values of $z_0$ and upward sensible heat flux from the surface.

The prognostic equations for $u$, $v$ and $T$ are solved on an array of grid points which contains 49 grid points in the $x$-direction and 23 grid points in the $z$-direction. The horizontal grid spacing is 20 km whilst the vertical grid spacing is 0.5 km except in the lowest 1.5 km where an expanding grid with many additional levels near the surface is employed. The uppermost
model level is at a height of 5.5 km. The prognostic equations are solved with a "semi-implicit" technique whereby terms involving vertical derivatives are handled with an implicit Crank-Nicolson scheme and the remaining terms are handled by an explicit leap-frog technique. Boundary conditions for the prognostic equations include the lower boundary conditions of fluxes of heat and momentum calculated at the top of the surface flux layer through the SFL equations, the upper boundary conditions of specified pressure tendencies and a constant geostrophic wind in the x-direction, the use of porous sponge lateral boundary conditions, and a longitudinal boundary condition that results in no geostrophic divergence.

The initial conditions for the model are specified analytically to simulate an idealized cold frontal zone. A horizontal temperature gradient pattern and a basic wind field are specified so that the horizontal deformation in the basic wind field will force frontogenesis. Also included in the initial horizontal wind field is an ageostrophic component which results in an initial thermally direct transverse circulation in the plane normal to the frontal zone. An additional ageostrophic component in the initial wind field is determined from an Ekman balance. Essentially the same initial conditions are used for all model experiments.
B. Review of Results

The influence that surface friction and daytime surface heating exert upon the development and resultant structure of an idealized cold frontal zone and its attendant transverse circulation has been studied with the use of a two dimensional primitive equation model. A series of numerical experiments was performed in which the specifications for surface roughness lengths and daytime upward sensible heat fluxes from the surface were varied. The sequence of five numerical experiments was designed so that progressively more complicated physical situations were considered, i.e. the effects of surface friction and surface heating were ignored in Experiment I; horizontally uniform surface roughnesses and surface heating were introduced in Experiment II; horizontal variations in surface roughness, but not surface heating, were included in Experiment III; Experiment IV considered horizontally non-uniform surface heating with constant surface roughness; and horizontal variations in both surface roughness and surface heat flux were included in Experiment V. For all experiments the same analytically specified initial conditions, applicable to a time shortly after sunrise, were utilized to obtain a 512 min forecast. By comparing the results of the various model integrations, the roles that surface friction and surface heating play in the dynamics of frontal zone development were identified. The relative importance of horizontal variations across the frontal zone of surface roughness and surface heat flux was also evaluated by comparing the results of the model integrations.
The first experiment, in which there was no surface heating and surface friction was ignored, served as a control experiment to illuminate the basic dynamical mechanisms operating in the model without the complicating effects of an active planetary boundary layer. In Experiment I, it was found that the initially specified frontal zone, as identified by the horizontal temperature gradient $\partial T/\partial x$, moved eastward at an approximate speed of 6 m s$^{-1}$ while maintaining its initial slope of 1:50 and its symmetry about this sloping axis. The largest values of temperature gradient, vorticity and horizontal convergence were found to occur at the surface, indicating substantial frontogenesis at low levels. The frontogenesis in the model is forced by the basic steady state horizontal deformation field. During the integration, the maximum $\partial T/\partial x$ value increased from 1.6 to 4.3°C ($10^2$ km)$^{-1}$ and the maximum vorticity value increased from 7 to 18 m s$^{-1}$ ($10^2$ km)$^{-1}$. The observed trends in $\partial T/\partial x$ and $\zeta$ indicated that the frontal zone was becoming very sharp near the surface at the end of the forecast period. The horizontal variation of the wind normal to the frontal zone, i.e. the u component, was playing a crucial role in the development of the $\partial T/\partial x$, $\partial u_{ag}/\partial x$, and $\zeta$ fields. At low levels the significant differences in horizontal advection across the frontal zone contributed to the sharpening of the frontal properties and the eastward movement of the frontal zone.

Above the surface, the frontogenetic horizontal deformation mechanism is balanced in varying degrees by the effects of vertical motion. The low level horizontal convergence in and ahead of the frontal zone must result in upward vertical motion and similarly the divergence in
the post-frontal region results in descent. This thermally direct transverse circulation in the plane normal to the frontal zone has a frontolytic effect on horizontal temperature gradients since the warm pre-frontal air is rising and cooling adiabatically while the colder post-frontal air is warming adiabatically as it descends. In Experiment I, the basic deformation leads to increases in \( \frac{\partial T}{\partial x} \) which diminish with height as the frontolytic effect of differential vertical advection becomes more important with height.

During the first half of the integration the vertical motions in the transverse circulation increased somewhat in strength but then decreased slightly over the remainder of the forecast. It was also noted that the geostrophic wind shears in the along front direction were roughly in balance with the actual wind shears, which implied that there was little tendency for changes in the transverse circulation strength. Therefore the rapid development of the frontal zone near the surface was not accompanied by a concomitant increase in the transverse circulation strength. The rapid frontogenesis was confined to a shallow near surface layer and thus had little effect on the wind shear and vertical motion over a much deeper layer.

In Experiment II, an active planetary boundary layer (PBL) was introduced. A horizontally uniform surface roughness length \( z_0 \) of 1 cm was specified and a horizontally uniform upward surface sensible heat flux with a sinusoidal temporal variation was included. The specified surface heat flux had a half period of 10 hr. The upward heat flux resulted in a PBL whose depth increased with time. In the PBL, the turbulent fluxes of momentum and heat altered the dynamics of the frontal zone from those
observed in Experiment I and thus resulted in a somewhat different frontal zone structure and transverse circulation. However, the basic deformation mechanism present in the model still exerted a substantial degree of control over the development of the frontal zone.

The results of Experiment II showed that the effects of surface friction and surface heating on the frontal zone were confined to the lower 2 km or so, the nominal afternoon height of the PBL in this experiment. Above the PBL, the development of the frontal zone was little affected and was substantially similar to that observed in Experiment I. Now in the PBL, the net effects of adding surface friction and surface heating were a reduction in speed of frontal movement near the surface, a reduction in the maximum \( \partial T/\partial x \) at the surface, a significant reduction in the vorticity in the frontal zone, an increase in the slope of the frontal zone from 1:50 to near vertical, and a significant increase in the transverse circulation strength with the maximum vertical velocities occurring near the top of the PBL. As a consequence of friction, winds in the PBL were turned towards low pressure and reduced in magnitude, which led to a reduction of momentum, vorticity, and temperature advections in the plane normal to the frontal zone and contributed to the slower frontal zone movement. The lower values of \( \partial T/\partial x \) near the surface were the result of the decreased advection of temperature in combination with the frontolytic effect of surface heating across the frontal zone — smaller temperature increases ahead of the frontal zone because of the greater PBL depth. The lower values of \( \tau \) near the surface were not only the result of decreased vorticity advection but also the result of frictional destruction of cyclonic vorticity.
in the frontal zone. The near vertical slope of the frontal zone in the PBL in Experiment II was associated with slower movement of the frontal zone near the surface and vertically well-mixed properties of the neutral PBL.

The increased strength of the transverse circulation in Experiment II was brought about by the frictional reduction of the front-parallel winds at low levels. As the horizontal temperature gradients in the PBL increased and the vertical shear in the front-parallel geostrophic winds increased, the actual wind shear did not increase as rapidly and a large negative ageostrophic shear developed over the depth of the PBL which increased development of the horizontal branches of the direct transverse circulation. Furthermore the effectiveness of the self-limiting mechanism of differential vertical advection of temperature was somewhat curtailed by the near neutral lapse rates in the PBL. The continued development of the direct transverse circulation of Experiment II, as opposed to the gradually weakening one at the end of Experiment I, was favored by the increasing imbalance of the geostrophic and actual wind shears parallel to the frontal zone.

In Experiment III various specifications of surface roughness lengths were introduced, including horizontal variations across the frontal zone in which the frontal zone moved from a smooth to a relatively rough region and also from a relatively rough to a smooth region. The numerical results for these experiments showed that surface roughness differences result in only minor perturbations of frontal zone structure and transverse circulation strengths from those observed in Experiment II.
with a uniformly smooth surface. It was concluded that surface roughness effects are "second-order" effects in the model.

In Experiment IV, the surface roughness was a uniform 1 cm but the values specified for surface heat flux varied in magnitude across the frontal zone. When the magnitude of the upward heat flux in the warmer pre-frontal region was four times as great as that in the colder post-frontal air, the temperature gradients in the frontal zone were substantially increased in the PBL over those observed in Experiment II. The enhanced horizontal temperature gradients in the PBL led to an increase in the transverse circulation strength because the front-parallel geostrophic wind shear was also increased. As in Experiment II the actual wind shear did not increase nearly as rapidly and the transverse circulation was enhanced by the imbalance. The large contrast in PBL heights across the frontal zone also strengthened the horizontal temperature gradient since surface heating extended to relatively large depths in the warm air with no heating at corresponding levels in the post-frontal region. In fact the axis of maximum $\partial T/\partial x$ in the PBL was actually tilted slightly towards the warm air rather than the cold air. Similar but more pronounced effects were observed when the surface heat flux in the warm air was specified to be eight times as great as that in the cold air.

When an opposite horizontal variation in surface heat flux magnitude was specified, viz. the surface heat flux in the warm air being four times less than that in cold air, the temperature gradients in the frontal zone were observed to markedly decrease in the PBL. As a result of this temperature gradient decrease the transverse circulation strength was weakened. The vertical branches of the circulation were not well organized.
tude eight times less than that in the cold air, the frontal zone in the PBL ceased to exist and the transverse circulation became ill defined.

Thus horizontal gradients of upward surface heat flux were found to exert a considerable influence on the development of the cold frontal zone's structure in the PBL and its attendant transverse circulation. Dramatic strengthening of frontogenesis and significant transverse circulation increases were associated with larger upward heat fluxes in the warm air and small heat fluxes in the cold air. When the gradient of surface heat fluxes was in the opposite direction, frontolysis and a poorly organized transverse circulation were observed. When horizontal variations of surface roughness in addition to variations in surface heat flux were considered in Experiment V, little difference was observed from the results obtained in Experiment IV.

In this series of numerical experiments it has been shown that surface friction and daytime surface heating exert a significant influence on the development and resultant structure of a cold frontal zone in the PBL. Although horizontal variations in surface roughness are of minor importance, horizontal variations in upward surface heat flux across the frontal zone can substantially alter the horizontal temperature gradients in the frontal zone. When the surface heat flux acts to increase temperature gradients in the PBL, the direct transverse circulation in the plane normal to the frontal zone is enhanced, with an opposite effect when the surface heat flux decreases \( \partial T/\partial x \) in the PBL. The relationship among changes in \( \partial T/\partial x \), \( \partial v/\partial z \), \( \partial v_{g}/\partial z \) and the vertical and horizontal branches of the transverse circulation was found to be quite complex and very much
dependent in the PBL upon the effects of surface friction and surface heating.

The model results have also been examined with respect to theoretical developments, observational studies and other numerical model results. The relationships exhibited in the model among the horizontal temperature gradient, the geostrophic and actual vertical wind shears in the front parallel direction, and the transverse circulation strength are in broad agreement with the theoretical discussions in Palmen and Newton (1969) and the analytic results of Kreitzberg (1972). The strong development of frontal characteristics near the surface shown in the model results have also been found in observational studies, e.g. Sanders (1955), and other numerical model results, e.g. Williams (1974). The characteristics of the model frontal zone fall into Sansom's (1951) anafront category and qualitatively agree with his observations. Reasonably good qualitative agreement was observed between the model results of Experiment IV-A and results obtained by Rao (1971) with a different numerical model as applied to a synoptic case study. In general, the frontal characteristics in the PBL found in the model calculations - steep frontal slope, reduced frontal movement, destruction of vorticity, intense convergence - divergence patterns, maximum vertical velocities near the top of the PBL, and the frontogenic / frontolytic effect of horizontal variations of surface heat flux - have also been identified in observational studies, analytic models, and other numerical models of cold frontal zones. However, the series of numerical experiments performed in this thesis has systematically identified the role that surface friction and daytime surface heating play in the development of all of these frontal characteristics.
C. Suggestions for Future Research

The numerical model developed in this thesis to study the influence of surface friction and surface heating upon the development and structure of a cold frontal zone represents an initial attempt to define the roles that surface heating and surface friction play in the development of a frontal zone and its associated transverse circulation. In order to isolate and identify the importance of surface heating and surface friction, an idealized two dimensional frontal zone was considered and complicating factors such as moisture, radiation and terrain were neglected. Relatively simple parameterization schemes, i.e. "K-theory", were used to obtain fluxes of heat and momentum in the PBL. In nature, frontal zones are rarely in conformance with the idealized situations envisaged in the model. Since ultimately the model should be tested with actual data, the model should be expanded so that less idealistic frontal zones, which compose the majority of atmospheric frontal zones, could be treated.

The addition of moisture to the model would represent a significant step towards increasing the capability of the model to handle more realistic frontal zones. Inclusion of a moisture variable such as specific humidity would permit an assessment of the moisture distribution in the vicinity of the frontal zone and in the warm and cold air masses on either side of the frontal zone. However, the introduction of additional variables to the model would require more computer memory and the model presently requires virtually all of the "live" memory of NCAR's CDC 6600 or 7600 computer system. Thus significant coding changes or a computer with a larger memory would be necessary.
Inclusion of moisture in the model would also permit an evaluation of the effects of latent heat release upon the frontal zone. As reported by Palmen and Newton (1969), Eliassen found that the latent heat release in the pre-frontal warm air aided in the frontogenetic process and Sawyer concluded that latent heat release on the warm air side of a frontal zone significantly increased the transverse circulation in the plane normal to the frontal zone. These findings suggest that latent heat release can be important and moisture should be considered in the model.

If moisture were to be included in the model, it would then be possible to identify the locations of saturation and relate this to cloud cover. A distribution of cloud cover could also be used in calculating a surface energy balance since both long and short wave radiation components are affected by cloudiness. A boundary layer model developed by Long and Schaffer (1975) utilizes cloud cover information in the calculation of a surface energy balance. Moisture information could also be utilized for input into cumulus parameterization schemes as has been done by Kreitzberg et al (1974).

A surface energy balance appears to be a desirable feature to include in the model. It would be more realistic than the upward sensible heat flux values currently specified in the model. However, information on cloud cover, soil heat flux and latent heat flux would be required for a surface energy balance calculation. A relatively economic surface energy balance scheme has already been proposed by Schaffer and Long (1975), and this
scheme could be incorporated into the present model without undue complications. A surface energy balance would represent an initial step towards the treatment of nocturnal situations. Also needed for nocturnal modeling would be a variably thick surface layer, since the surface flux layer can be much smaller than 50 m at nighttime.

Another feature of the present model which needs improvement is the use of "K-theory" to parameterize the turbulent vertical fluxes of momentum and heat; K-theory is an obvious oversimplification of physical reality. Unfortunately the alternatives to K-theory, e.g. second-order closure methods, require considerably more computer time and memory. Also many of the alternatives to K-theory are still in the development stage. For the time being it appears that K-theory will continue to be used in mesoscale models until alternative schemes are better developed.

The present model could be made more general by expanding it from two dimensions to three dimensions, introducing a terrain following coordinate system so that topographic effects could be examined, and specifying time dependent upper and lateral boundary conditions, perhaps from a larger scale numerical model. All of these enhancements for mesoscale models in general are being developed by Kreitzberg et al (1974, 1976). The present numerical model was initially conceived as a portion of this overall mesoscale numerical modeling capability for a wide variety of mesoscale circulations.

Once the model is made more general, it is felt that model should be tested with actual data, using data both for initial conditions and for verification purposes. A rather detailed set of observational data would be
necessary, including surface observations, meteorological tower data, instrumented aircraft observations and standard rawinsonde observations. The most likely sources of such data would be St. Louis area MESOMEX experiments or the NSSL mesonet observational network in the Oklahoma area. Even with observational data, verification of predicted vertical motion patterns would be difficult since vertical velocities are not directly observed.

In summary, the present model is only capable of treating highly idealized two dimensional frontal zones over flat terrain during daytime conditions. Expansion of the model to three dimensions and the inclusion of moisture, radiation, surface energy balance, and terrain would make the model capable of handling more general situations and would also permit the use of actual data for initialization and verification purposes. It is suggested that future research efforts be directed towards expanding the model's capabilities so that a more complete understanding of frontal zones can be gained. Verification of model predictions with observational data would enhance such understanding.
Appendix B

Progress and Problems in Regional Numerical Weather Prediction

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PROGRESS AND PROBLEMS IN REGIONAL NUMERICAL WEATHER PREDICTION

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ABSTRACT. The status of research and development on numerical weather prediction at a new (smaller) scale is reviewed. This regional scale uses a horizontal mesh size of about 35 km over a horizontal domain size of about 1700 km squared. The model forecasts weather, including clouds and stratiform (steady) and cumulus (showery) precipitation out to 24 h beyond the latest observation time. Technological developments permitted this research to begin in 1970 and a prototype system for operational weather forecasting will be completed in 1980. The principal gains are expected to be in the accuracy and detail of precipitation forecasts and cloudiness forecasts, including the effects of terrain and (paramaterized) cumulus convection.

The principal problem area is the development of techniques to incorporate into the preceding forecast, more recent, detailed observations from surface-based and satellite observations. Other problems include parameterization of small scale physical processes, particularly those associated with cloudiness and topography, such that these processes properly interact with the dynamics of scales resolved by the model. Statistical treatment of model output, expression of predictions in statistical terms, and meaningful verification measures are all very important to an effective forecast system. The optimization of the entire system is important to both the quality and the cost of an operational system.

1. INTRODUCTION AND SUMMARY

A new scale of numerical weather prediction (NWP), the regional scale with a grid mesh size of about 35 km and a domain size of 1700 km square is being developed during this decade. In 1970 operational numerical weather prediction used a mesh size of 380 km and the domain included most of the Northern Hemisphere (Shuman and Hovermale, 1968). In 1980, the regional models will be ready for operational implementation and should provide much more detailed and accurate weather forecasts for the time period 6 to 24 h in advance of the latest observations used to make the forecasts.

This paper will summarize the progress to date and the primary problems to be overcome in development of this new numerical forecast system. That this system was impossible in 1970 and will be feasible in 1980 is the result of technological developments in computers, communications and satellites.
Realization of this system in a prototype mode by 1980 is dependent upon the concerted effort of dynamists, modelers and system analysts in the remaining 24 years. Routine operational implementation could occur early in the 1980's but the timing will depend on the skill demonstrated by the research models and prototype systems for producing highly useful products (Shuman, 1977).

As explained later, regional models require computation with 1.5 million words every 1 or 2 min throughout the duration of the forecast. This fact, in view of computer power, limits the duration of the forecast, the detail of the resolution and the domain size to the values defined above for the regional model. Computers that allowed work to begin on such models have only been available since 1970; computers adequate to perform the extensive testing needed to develop a reasonably efficient prototype system have just now become available at a few locations. The domain size limitation means that these regional dynamic models require time varying lateral boundary conditions from a larger scale coarser grid model (Perkey and Kreitzberg, 1976).

The physical mechanisms important in producing atmospheric variations on the smallest scales treated in regional models include several processes beyond those important to the larger scales. Therefore additional "physics" must be added when converting large-scale models to regional models.

The conventional meteorological observing system that directly provides input to numerical prediction models is the rawinsonde network that has a characteristic spacing of 300 km in the United States. Therefore, regional models must look to additional observing systems for more detailed initial conditions if they are to be efficient in providing forecasts commensurate with their 35 km grid size.

These three features, limited domains, smaller scale physics and more detailed observations are the key elements needed to extend NWP to smaller scales and will be discussed in some detail after the basic equation set has been outlined. We will conclude that the most severe problem is the deduction of a comprehensive and consistent initial data set from which the forecast can be made. The practical problem becomes one of establishing a system which includes: communications, data processing, data ingestion, dynamical numerical prediction, statistical expression of forecast information and dissemination of the results in a timely and understandable way.

The researcher must be careful to interact with the system development process so as to be effective. Effectiveness in this context means the development of new knowledge and techniques that are useful to the system, which, in large part, may be based on utilization of information produced by the
system. To develop new knowledge beyond that arising directly from the system, the researcher must remain an intelligent critic of the system and not a captive of the system (Gillman, 1977).

2. THE EQUATIONS

The independent variables are time \( t \) and coordinate distances east \( x \), north \( y \), and up \( h \). Most symbols are defined as they are introduced but all are listed in the appendix. The distance \( h \) is measured vertically from the earth's surface \( E(x, y) \). This vertical distance is compressed relative to physical distance \( z \) by the factor \( o(x, y) \) so that \( h \)-surfaces are parallel to the terrain at \( h = 0 \) and become horizontal and coincide with \( z \)-surfaces above some level \( H \). This level \( H \) is about half-way up in the atmosphere in terms of mass, i.e., about half the mass of the atmosphere is above \( H \) and half is below \( H \). This terrain coordinate system in an east-west cross section is depicted in Fig. 1 along with the definitions of the compression and slope factors, \( a, \beta \). The top of the model domain is at level \( z_p \), which is about 26 km and above which less than 10% of the mass of the atmosphere is located.

\[
\begin{align*}
\frac{h - E}{H - E} &= h, \\
\frac{o(x)}{\beta} &= o, \\
\frac{z}{h} &= z/\alpha.
\end{align*}
\]

Figure 1. Terrain coordinate system.

The regional numerical weather prediction model uses the hydrostatic equations (primitive equations) with the weight of condensed moisture as well as water vapor included in the hydrostatic pressure. Non-hydrostatic cumulus clouds are treated as a sub-grid process, the net effect of which is incorporated by a parameterization discussed later.

The prognostic equations for east and north wind velocity \( u, v \), virtual potential temperature \( \Theta \), water vapor \( q \), cloud water (or ice) concentration \( c \), \( r(z) \) are of the form...
\[
\frac{\partial \psi}{\partial t} = -\nabla \cdot \nabla (\psi) + \frac{D\psi}{Dt} + \left( \frac{\partial \psi}{\partial t} \right)_g
\]

where \( \psi \) is any of the prognostic variables. The local, advective, material and sub-grid scale changes are \( \partial \psi/\partial t, -\nabla \cdot \nabla (\psi), D\psi/Dt \) and \( (\partial \psi/\partial t)_g \), respectively.

The material derivations are expressible in terms of the basic variables using physical laws of conservation of momentum:

\[
\frac{Du}{Dt} = f v - \phi \frac{\partial \psi}{\partial x} - g \beta \frac{\partial E}{\partial x} + u \nu \tan \frac{\hat{a}}{E} + \left( \frac{\partial u}{\partial t} \right)_g
\]

\[
\frac{Dv}{Dt} = -f u - \phi \frac{\partial \psi}{\partial y} - g \beta \frac{\partial E}{\partial y} - u \nu \frac{\tan \frac{\hat{a}}{E}}{E} + \left( \frac{\partial v}{\partial t} \right)_g
\]

conservation of energy:

\[
\frac{D\psi}{Dt} = \frac{\partial \psi}{\partial t}
\]

conservation of moisture:

\[
\frac{Dc}{Dt} = \frac{E_c}{E_r} + \frac{E_r}{E_r} - C_d
\]

\[
\frac{Dc}{Dt} = C_d + E_c - C_v - C_l
\]

\[
\frac{Dr}{Dt} = C_v + C_l - E_r - D_r
\]

and an upper boundary condition,

\[
\frac{D}{DE} = (\varepsilon_t) = 0.
\]

The diagnostic equations (no time derivatives) for vertical velocity \( \hat{h} \) and pressure (scaled) \( \pi \) are

\[
\frac{\partial^2 \pi}{\partial \hat{h}^2} + \frac{\beta}{E-E_r} \delta
\]

where \( \delta = 1 \) for \( \hat{h} < \varepsilon \) and \( \delta = 0 \) for \( \hat{h} \geq \varepsilon \), and

\[
\frac{\partial \pi}{\partial \hat{h}} = -\alpha \frac{\delta}{\hat{h}} \left( 1 + c + r \right).
\]
The relations between thermodynamic variables \((T, \theta)\) and the usual pressure \((p, T)\) are

\[
\begin{align*}
\pi &= c_p \left( \frac{p}{p_0} \right) \frac{R}{c_p} \; T^2; \\
\theta &= T_v \left( \frac{p}{p_0} \right) \frac{R}{c_p}; \\
\pi \theta &= c_p \; T_v
\end{align*}
\]  

The virtual temperature \(T_v\) includes the effect of water vapor on the gas constants \(c_p\) and \(R\) so that constants for dry air can be used throughout with little error:

\[
T_v = (1 + 0.61 q) \; T. 
\]  

The right-hand-side (R.H.S.) terms in Eqs. (1), (2) are Coriolis' acceleration, pressure gradient acceleration, terrain component of pressure gradient term, first-order effect of earth's curvature and the sub-grid scale term, respectively. Coriolis and the two pressure terms tend to balance so each are an order of magnitude larger than their total. The earth's curvature term is of minor importance except when the model is run on a large domain to obtain lateral boundary tendencies for the regional domain. The sub-grid scale accelerations include the effect of eddy viscosity in the boundary layer and parameterized cumulus momentum transport in regions with convective storms (like thunderstorms).

The diabatic heating \(\dot{Q}\) in the thermodynamic energy equation (3) is due to radiation eddy heat flux in the boundary layer, stable or convective scale latent heat release during condensation and cooling during evaporation of clouds and rain (or snow). Radiational heating at solar wavelengths is important at the earth's surface, primarily. Radiation from the atmosphere, clouds and earth is at relatively long wavelengths (3 - 20 \(\mu m\)). Long wave heating and cooling is very important at night near the earth's surface. All radiation calculations are sensitive to the cloudiness and provide an important response to the initial cloud water (or ice) concentration field \(c\).

Conservation of moisture equations, (4), (5), (6), include evaporation of clouds \(E_c\) and precipitation \(E_p\) as well as condensation (or sublimation) \(C\). The relative humidity in the presence of clouds is kept at 100% with respect to water down to \(-15^\circ C\) and with respect to ice at colder temperatures. Conversion \(C\) and collection \(C\) are two processes for transfer from cloud water \(c\) to rain water \(r\). Rain water falls out rapidly and large scale models often assume instantaneous rainout. We carry this quantity explicitly to better predict its effect on cloud water and thence on radiation. Of less importance to regional scales is the effect of \(r\) on the pressure (Eq. 9). The divergence of rain \(D_p\) during fallout is most important at the melting level where slowly falling snow is located just above rapidly falling rain.

We will go no further into the cloud microphysics treatment but equations...
for $E_\rho$, $Cd$, $C_l$, $C_v$, $D_n$ and precipitation terminal velocity are given in Perkey (1976a, 1976b). In summary, there are a variety of cloud microphysics processes of some importance to regional NWP in some situations. The principal impact is through latent heating and cooling and the next most important impact of cloudiness is through radiation.

The upper boundary condition (Eq. 7) is only one of several that can be used. Work is continuing on evaluation of the implications and suitability of different upper boundary conditions. This point is discussed further in Section 3.2.

The vertical velocity equation (8) is a form of the mass continuity equation appropriate for hydrostatic models; the first and second r.h.s. terms dominate. Hydrostatic models use pressure from Eq. (9) to force $(u, v)$ in Eq. (1), (2) which then determine $w$ through Eq. (8). By disregarding non-hydrostatic pressure, vertically propagating sound waves are impossible so larger time-steps are permitted in the computations. As long as horizontal scales are much larger than vertical scales, this approximation is valid. This class of model is adequate for a very broad class of physical phenomena in the atmosphere. However, numerical problems can introduce scales which won't be treated in a physically realistic manner so numerical methods must be devised to avoid or properly handle numerically induced disturbances.

The use of $(\pi, \theta)$ in place of the $(p, T_v)$ formulation in Perkey (1976a, 1976b) has several advantages. The equations are simpler, particularly the energy and vertical-motion equations, so that computing time is reduced. Smoothing on h-surfaces is required to avoid the numerical problems that would arise from waves shorter than 4 times the horizontal grid spacing (Grotjahn and O'Brien, 1976). We believe smoothing of the $\theta$ on h-surfaces is better than smoothing $T_v$ on h-surfaces, because there is less natural variation in the case of $\theta$ on h-surfaces. Finally we expect to be able to devise a better upper boundary condition in $(\pi, \theta)$ than $(p, T_v)$ but this remains to be seen. Vertical eddy diffusion requires use of $\theta$ instead of $T_v$ so $\theta$ is more convenient in the boundary layer, below about 1.5 km.

3. BOUNDARY CONDITIONS.

3.1 LATERAL BOUNDARY CONDITIONS.

This set of equations permits a variety of responses (gravity waves, inertial waves, Rossby waves) to a variety of forcing mechanisms (orography, convection, radiation, boundary layer processes). A significant amount of the forcing comes about within the model domain but lateral boundary conditions must provide for at least large scale forcing from outside the domain. The conditions also must permit internally excited waves to pass out of the domain without abnormal reflection back into the domain.
We use parasitic nesting with the small domain, as shown in the southeastern United States in Fig. 2, embedded within a larger "national" region. Typically, a 36 h forecast is made on the national grid with 140 km spacing using porous sponge lateral boundary conditions. Then the regional forecast is begun at some time during between 6 h and 18 h and run for 18 h on a 35 km grid using time-dependent sponge boundary conditions (Perkey and Kreitzberg, 1976).

The porous sponge conditions are applied to the tendencies after linear extrapolation to the boundary from tendencies at the two interior points. The tendencies at the three outermost rows are then multiplied by 0.4 (outermost row), 0.7 (first interior row), and 0.9 (second interior row), respectively. Thus, the national boundaries can change with time in response to interior developments but they need no information from a still larger scale model.

The national scale forecast is used to deduce boundary tendencies at
the four outermost rows of the regional grid. The regional model also produces tendencies at all but the boundary row. The two sets of boundary tendencies are then combined weighting the large scale values by 1.0, 0.6, 0.3, 0.1 and the regional scale values by 0.0, 0.4, 0.7, 0.9, on rows progressing inward from the boundary. Thus, the regional domain changes in response to forcing from the national domain but not vice versa (hence, the term parasitic nesting).

As waves generated within the domain approach the boundary, their leading portions are slowed down by the truncation of the tendencies and the wavelength is shortened. A smoothing filter is then applied around the boundary (about 7 rows) selectively removing short wave variations. See Perkey and Kreitzberg (1976) for systematic experiments on the behavior of this scheme. The net effect of the sponge and the filter is that long waves can enter the regional domain and negligible reflection occurs as any waves exit the domain.

During special field programs (Hill and Turner, 1977), observations can be used to specify time-dependent changes on the lateral boundaries. These can then be used in place of a national forecast to provide time-dependent tendencies to the regional model for after the fact simulations (Chang and Kreitzberg, 1977), but not for forecasts of future events.

These lateral boundary conditions are engineering solutions and much room for improvement remains, particularly from a theoretical standpoint. Nevertheless, these do work satisfactorily in practice and progress can be made on other problems as work continues on improving lateral boundary conditions. The main problem with nesting different distinct grids is that only large scale features can enter the regional domain. Therefore, as time continues, the only detail in the upwind portion of the regional domain will be that which is generated internally, regardless of how detailed the initial conditions may have been within the regional domain.

3.2 UPPER BOUNDARY CONDITIONS.

The upper boundary condition was introduced earlier (Eq. 7), and it was mentioned that this is an arbitrary selection. The essence of the problem is to incorporate the effect of the atmosphere above the top of the model domain \( z_* \) on the flow within the domain. Clearly, the only effects that can be incorporated are those that constitute a response to disturbances from within the domain. When no information is retained above \( z_* \), no response can be transmitted horizontally above \( z_* \). Waves can be initiated on \( z_* \) at one location and propagated horizontally as external waves.

Typically then, upper boundary conditions are applied locally wherein the pressure tendency at \( z_* \) depends upon the vertical motion or the vertically-integrated mass divergence below \( z_* \) in that column. This limitation on types
of reactions means that more general physical situations can be treated only with deeper models. However, the deeper the domain, the more extensive will be the computations and the data required for initial conditions. Fortunately, less than 10% of the atmosphere lies above 15 km and the stratosphere (above about 12 km depending on season and latitude) is rather statically stable and vertical displacements are small.

Attempts to construct "radiative" upper boundary conditions that will not artificially reflect disturbances from below have been disappointing for models as complex as this regional model. Sponge-type upper boundaries using several layers of high artificial viscosity will work but these are computationally wasteful.

It can be hoped that for short period forecasts (less than 24 h), little damage is done at middle levels by reflection of waves that propagate upward, are reflected, and return. This hope may be justified for waves generated by orography of long horizontal scale. Disturbances generated by convection (thunderstorms) extending to 12 km or so above the surface do produce unrealistic disturbances above 10 km when the domain only extends to 16.5 km (Kreitzberg and Rasmussen, 1977). To alleviate this problem, we expect to have to extend the model to above 20 km if good results are required, to 16 km when deep convection occurs. Perhaps, the results will be satisfactory if only crude initial conditions are used above 16 km.

3.3 LOWER BOUNDARY CONDITIONS.

The surface kinematic boundary condition is trivial: the air blows parallel to the ground. Vertical flux of horizontal momentum (surface stress), heat and moisture (surface evaporation of condensation) can be much more complex. The complexity of surface flux specification used in NWP depends upon the phenomena one wishes to predict. Large scale models used for 1 or 2 day forecasts can get along with a single bulk coefficient formulation because little information on boundary layer structure is expected. Over most land areas, surface forcing varies on fairly short space scales and dominates the vertical structure in the lowest layers. Therefore large grid models are inadequate for providing detailed low-level forecasts (Barr and Kreitzberg, 1975).

In regional models, several physical regimes can be incorporated near the surface: a ground layer (uppermost meter of soil), a vegetation layer, a surface flux layer (about 50 m deep) and a mixing layer (varying from about 50 m at night to 2 km during a sunny day). The central problem is computation of the energy budget at the surface of the earth which determines its temperature and the fluxes of heat into the soil and the atmosphere, radiation exchange with the atmosphere and evaporation into the atmosphere.
The standard level of sophistication in boundary layer modeling in real data three-dimensional regional models is that of Shaffer and Long (1975), while Perkey (1976a, 1976b) used a similar but significantly less general formulation. Because neglect of vegetation can alter surface fluxes by a factor of 2, Deardorff (1977) has introduced an adequate and simple vegetated ground model. It will be close to a year before this formulation is fully tested in three dimensions with real data.

The profiles (vertical variation) of temperature, moisture and wind in the surface flux layer are usually specified from the surface fluxes using Monin-Obukhov similarity theory. Turbulent fluxes in the mixing layer are parameterized in terms of a specified vertical variation of the eddy mixing coefficient from values determined from similarity theory in the surface flux layer to near zero at the top of the mixing layer. The depth of the mixing layer is itself a predicted quantity (Deardorff, 1974). The dominance of surface fluxes in controlling conditions throughout the mixing layer, rather than using mixing layer stability, is a limitation on the generality of these models.

The vertical structure that can be retained in boundary layer models is a function of the vertical spacing. Generally this spacing decreases from about 50 m near the surface to 300 m by 2 km. Implicit or semi-implicit numerical schemes are often used for the eddy flux terms. A nested mesh used solely for the vertical terms has been developed and tested in two-dimensions (x, z) by Pinkerton but has not yet been implemented in three-dimensions (Chap. 6 in Kreitzberg, et al., 1974).

It can be seen that regional modelers are devoting considerable attention to the boundary layer processes. This fact arises from the many applications of a good boundary layer forecast and the role of these processes in cumulus convection starting within the mixing layer. The practical problem is that good general boundary layer forecasts need a good forecast of stable clouds and convective clouds throughout the atmosphere to obtain the correct radiation forcing. Thus, cloud microphysics as well as boundary layer physics must be treated simultaneously and initialization of the moisture fields $q$ and $c$ presents a substantial additional complication.

4. INITIAL CONDITIONS

The prognostic equations (1) to (7) constitute an initial value problem. The relative importance of initial conditions to surface induced conditions or to disturbances induced by cumulus convection will vary from case to case. With strong small scale forcing from the surface, convection or non-linear interaction, considerable small scale structure does develop from large scale initial fields by 6 h into the forecast. Nevertheless, the range of
application of regional models can be extended greatly with improved definition of small scales in the initial fields.

The large scale meteorological fields for NWP can be obtained every 12 h from the rawinsonde network with stations at above 300 km spacing. These observations use balloons to lift temperature, humidity and pressure sensor aloft to about 30 km. Data are radioed back to the ground station which tracks the balloon, thereby permitting calculation of horizontal wind velocity. The national model using a 140 km grid is initialized with these data. After 6 h or more of forecast, the national model has good information for first guess fields with which to initialize the 35 km regional model.

Figure 3. East Coast regional forecast grid. The domain is outlined and a sample of the regional grid (35 km spacing) appears off the Massachusetts coast. National scale (140 km) grid points also appear. Rawinsonde sites within and adjacent to the domain are indicated by the "stars".

The initialization problem can be seen by reference to the northeastern United States regional grid in Fig. 3. Rawinsonde observation sites are located at 21 points and the 140 km spaced grid points are shown for which national model forecast data are available. The 35 km regional model grid
points are shown for a small section off the coast. In all, 1985 of these 35 km grid points are carried in this regional model. The large scale initial fields for the regional model will come from the 140 km grid model and can be updated if the regional forecast is begun when rawinsonde observations are made, normally at 0000 GMT and 1200 GMT (Greenwich Mean Time). The rawinsonde data assimilation problem is to correct the phase or amplitude of the 140 km model forecast without destroying the dynamic balance it has achieved in the boundary layer in response to the geography on the 140 km grid.

The regional scale data assimilation problem is to refine the larger scale fields in view of surface observations with a spacing of 100 km, weather radar observations showing the location and general height of precipitation r, and satellite visible and infrared image data that show cloud locations and give an indication of their tops. Satellite sounder data giving information on the temperature and water vapor fields may be useful for regional models in a few years. See Kreitzberg (1976) and Kreitzberg and Rasmussen (1977) for further discussion of regional scale data assimilation.

For purposes of this paper, it is sufficient to recognize that data assimilation problems are probably the most serious limitation to a successful regional weather forecast system in the next few years. A variety of data types must be utilized very rapidly (1 h from observation to composite data analysis) to provide detailed information consistent with the regional model scale, geography and physics. Data collection with satellites is reasonably advanced with images provided every half-hour and communicated almost immediately. A new National Weather Service communication system called Automation of Field Operations and Services, AFOS, will link the United States with a network of minicomputers by 1980. AFOS includes data display terminals for viewing data in alpha-numeric and graphical form and for preparation of forecasts to be disseminated by the minicomputers (Klein, 1976, 1977).

More elaborate computer data analysis and display systems of particular value for treating satellite and radar data in real time have been developed at the University of Wisconsin (MCIDAS) and NASA's Goddard Space Flight Center (AOIPS). These data access systems, in conjunction with AFOS, satellites and the newer large computers now becoming available, are the essential technological ingredients to the regional forecast system. Development of techniques to combine these ingredients into an efficient, effective and reliable system is significant challenge in itself.

5. SYSTEM OF CODES

The software required for research, development and implementation of
the regional forecast system deserves careful consideration. Its cost is comparable to that of the hardware. For example, conversion of codes from one computer system to another recently cost the National Meteorological Center 50 man-years.

There are several segments of code in the system:

1. Data collection including error checking and consistency checks;
2. Composite data analysis and conversion to parameters used by the model;
3. Dynamic balancing or assimilation avoiding unreasonable departure from the model's numerical equations;
4. Large scale (140 km) forecast to provide first-guess and later time-dependent lateral boundary data for the regional model;
5. Regional scale dynamics forecast model;
6. Output processing to convert model forecasts to optimal forecasts tailored to user requirements.

Data communication is primarily by teletype and facsimile (graphics) circuits with different categories of users. The need and technology exists for a National Meteorological Data Satellite Communication System, but it will be early 1980 before this system could become a reality. Error checking and consistency checks are an essential feature of preliminary data processing and several organizations have developed such software to meet their requirements.

Composite data analysis is the extraction of a complete and consistent data field from a variety of types of data, each of which has strengths and weaknesses. Moisture analyses, including vapor, cloud condensate and precipitation fields require utilization of several types of meteorological satellite data plus surface and upper-air data, pilot reports and radar data. The Air Force Global Weather Central has the most advanced software (3-dimensional nephanalysis) for this purpose (Fye and Logan, 1977) and it will be extensively revised in the next year or two. Some form of optimal interpolation or variational analysis along with an interactive data access and graphics system is required for this complex task. Different organizations will have different needs but hopefully they will help each other in areas of mutual need. This methodology can be expected to evolve rapidly during the next five years. The parameters needed for regional MWPF will be a subset or derivable from the composite moisture analysis output.

Numerical models contain approximations and dynamical behavior that differ from reality. It should not be surprising that they have special requirements for data consistency and that the most accurate depiction of real conditions is not optimum for input to these models. Initial conditions for model forecasts must be obtained by assimilation of information from the previous model forecast with recent observations into an improved data set as consistent as possible with the numerical model's equations. This
procedure is very tedious and in some forms is called dynamic data assimilation (McPherson, 1975).

Since the time dependence of the lateral boundary conditions must be provided by a large-scale model, such a model must be run prior to or coincident with the regional forecast model. Two-way interaction can be achieved by a single run of a model with spatially varying grid density. Such nesting has many theoretical advantages but these may be offset by the computational burden of running such a big model soon enough to disseminate the regional-scale forecast in a timely manner. Large scale models cannot be run until data from the large area are received and processed. It may prove expedient for several years to use parasitic nesting, such as described in Section 3.1, whereby the large scale model is run at an earlier time using earlier data so that the regional model can be run alone immediately after incorporation of the latest observations. Such a system is particularly useful during development of techniques used in the regional model because many regional experiments can be run from a single run of the large scale model.

In parasitic nested models, the regional model need not use the same grid system, topography, numerics and physics as the large model, although any differences will require special attention to achieve adequate meshing of the models. For example, it may be most efficient to run the East Coast United States model (see Fig. 3) on a grid mesh that parallels the boundaries of the regional domain.

The output of any dynamical model will not be optimal for the ultimate user of weather forecasts. The user may need different quantities than those produced directly by a dynamic model. For example, confidence limits or probability estimates may be useful. Statistical techniques can be used to correct model biases or to account for stochastic aspects of weather and for local peculiarities of a site (Leith and Little, 1977).

The meteorological forecast may be just one step in forecasting a more complex process. For example, Kreitzberg, et al., (1977) use the history tape generated by the dynamical model to calculate air trajectories and the precipitation falling through (thereby cleansing) air parcels as they move through a storm. Atmospheric chemistry and diffusion processes related to air quality are best handled in a Lagrangian framework following the air over a period of time. In most cases the air chemistry does not influence the meteorological evolution significantly so separation of the models is justified and greatly reduces the complexity of the system.

Powerful new computers can perform calculations very rapidly, particularly if they can be treated in a vector or pipeline mode whereby a long stream of numbers can be run through the computer's functional units. The design of the data flow software becomes a critical aspect of large codes that require
computing with large volumes of data. A flow system that can handle a rather
general class of hydrodynamic model has been developed over several years at
the National Center for Atmospheric Research (NCAR) under the direction of
Daniel Anderson. Documentation will be available soon from NCAR's Computing

| 50 columns per slab |
| 50 slabs on disk |
| 5 slab in large core memory |
| 9 column stencil in small core memory |
| 15 levels in each column |
| 40 variables at each level |
| 1.5 x 10^5 values |

Figure 4. Organization of data in the FLOW code. The numbers are typical
of the data set used in a region forecast model.

This FLOW code is organized as sketched in Fig. 4. As applied to the
regional model, each column corresponds to a vertical column in the atmosphere
and includes 40 quantities defined at each of 15 levels in the vertical. Many
computations require data at these levels in a single column. Horizontal
derivatives utilize information from columns to the east, north, west and
south of the central columns and this information is contained in the 9 column
stencil that can reside in small (fast) core memory (5400 words). Upon comple­
tion of computations at one column, the data are shifted so that the stencil is
located one column to the east (right). When the stencil has reached the east
end of the slab, the southern slab is output to disk, a new slab is read from
disk into large (slow) core memory and the stencil is "moved" to the west end,
one slab further north.

Such a geometric organization of the FLOW data system makes the code easy
for the modeler to understand and work with. The instructions that move the
slabs and stencils are buried beneath simple special statements. Other
statements can be used to output any vertical or horizontal section of data
to a graphics subroutine, and thence, to printers, microfilm plots or cathode
ray display devices.

The regional forecast model is but a part of the system of codes, most of
which are in FORTRAN but which use the FLCTRN/IFTRAN and MACRO definition statements for compactness and simplicity. This preprocessor is a modification of IFTRAN and is portable to other computers that use FORTRAN. It is very fast because it is table driven.

The code is structured in a modular form using subroutines. Separate sections are devoted to:
1. grid and parameter initialization;
2. macro, global and common definitions;
3. definition of numerical operators;
4. model control logic;
5. save and restart codes;
6. history file generation code;
7. debug (including statistical) default options;
8. subroutines for different physical processes;
9. treatment of lateral boundary conditions.

This code structure combines simplicity with flexibility and yields a compact code that is relatively easy to document, read, follow, verify and modify.

Software development costs are substantial for such a system of codes but by retaining flexibility the codes can be used for many years by many users. Extensive use not only amortizes the cost but contributes to detection and elimination of errors and weaknesses in the system. It provides many researchers access to a complex system without undue preparatory efforts so that the system can benefit from their advances as they extend or improve the system. It is much easier for these researchers to communicate and collaborate with each other when they use the same code structure. Extensive use of a code justifies efforts required to optimize it. This code runs more efficiently, in general, than less flexible research codes developed by a single group that devotes less effort to optimization.

6. STATUS AND GOALS OF THIS RESEARCH

This regional NWP forecast system can now be run for any storm in the United States during recent years. We have run three-dimensional forecasts on several idealized situations and five real-data cases; the most recent results are summarized in Perkey (1976a, 1976b), Chang and Kreitzberg (1977), Lutz and Kreitzberg (1977) and Kreitzberg and Rasmussen (1977). The most spectacular success is in precipitation forecasting and the most prominent weakness is in initialization of the moisture fields. Of course, extensive development and systematic testing remains to be done; perhaps we are 25% of the way toward the goal to be reached before 1980.

An example of a forecast and verification is shown in Figs. (5) and (6). Fig. 5 is the result of a 9 h forecast with a 140 km grid mesh of the convec-
tive precipitation rate valid at 2100 GMT on 21 February 1971 (3 pm CST). The location of precipitation observed by several weather radars at this time is shown in Fig. 6. Certainly nature produces much more variability that can be resolved with the 140 km model but the forecast location and general form is excellent. This storm killed 117 people, injured 1600 and did more than 20 million dollars damage. The forecast in Fig. 5 was made with orography in the model but results of the forecast without orography are reported in some detail in Perkey (1976a, 1976b). Comparable success in severe weather prediction is reported in Chang and Kreitzberg (1977) for a different storm using a 70 km grid. Quantitative precipitation forecasts for 12 h accumulations are generally quite good in location and pattern and within ±50% in maximum intensity in heavy rain cases (also, see Shuman, 1977).

Figure 5. Forecast of convective precipitation rate, mm (10^4 a)^{-1}, at 2100 GMT, 21 February 1971.

Figure 6. Composite of weather radar precipitation echo areas, 2100 GMT, 21 February 1971.
The goal of this research is to establish the limit of accuracy of NWP using mesh sizes down to 35 km and observations that are routinely available now or that could be so in the near future at reasonable cost. The interim goal is to locate the primary obstacles to accuracy that can be overcome by 1980. We believe that it is necessary to determine the strengths and weaknesses of the most complete system in order to guide future research and development. Finally, systematic tests will be made to establish the relative gains achieved by using the more complex physical formulations and the smaller grids. This information will provide guidance in the design of future cost-effective operational systems.

It appears that regional models should be developed separately, by different research groups in close collaboration, for different regions of the United States. Each region has particular high priority problems. For example, an East Coast model would stress flash floods, air pollution transport, coastal meteorology and East Coast cyclogenesis. The Central States model would stress severe thunderstorms, blizzards and precipitation modification research. The Rocky Mountain model would stress orographic effects on windstorms, air pollution transport, forest fire meteorology, snowfall and research on snowfall augmentation. The Gulf Coast model would treat severe weather, flash floods, coastal meteorology, summertime convective precipitation in general, and tropical storms in particular. This region must deal with the problem of data sparsity over the source of the warm moist air, the Gulf of Mexico.

7. SURVEY OF PROMINENT PROBLEM AREAS

The principal problem facing regional weather prediction is that of systematic utilization of available observations. Information from former observations is carried forward in large part by the numerical weather forecast itself and the latest forecast of conditions at time \( t_0 \) is the first guess of initial conditions to extend the forecast. Some fields, like middle tropospheric layer-mean temperature, have a high ratio of predictability to observability so inclusion of recent observations does not change the first guess too much. Other quantities, like moisture fields and surface pressure and temperature, have a low ratio of predictability to observability so that incorporation of the latest observations is very important.

The problem is to modify the first guess from the earlier forecast to incorporate more recent but spatially scattered observations without losing information by degradation of resolution or by adding information that is unrepresentative of scales that are treated and retained in the model. For example, the forecast may include a storm of the correct structure but
observations show that its position or amplitude is incorrect. It is difficult to shift a pattern without disruption of the dynamics of the seven prognostic partial differential equations.

On the other hand, a simple timing error could be corrected by changing the clock time or even the clock speed. That is, conditions predicted to exist at hour 13 could be used to initialize a new forecast starting at hour 12. If the model systematically moves or develops a certain type of storm too fast, the best forecast time could be advanced at a faster rate than the model forecast time. However, systematic errors are not expected to be the most serious problem on the regional scale. Normally, the subjective judgment of a modeler or forecaster can begin to correct for repeated model errors well before enough evidence can be assembled for objective correction of these errors.

It has been the policy of the National Meteorological Center not to arbitrarily tune the dynamic model to remove all systematic errors but to remove these through use of model output statistics between NWP output and the output of actual forecasts to the users (Klein and Glahn, 1974). Then attempts can be made to upgrade the forecast model and reduce the biases on more "scientific" and permanent grounds. However, this does not mean that statistical modification of the forecast fields should not be done between the NWP output and its reuse as the first guess for the next forecast cycle.

We are not sure of the best method of incorporating some information that is currently available. Examples include surface observations from many stations in between rawinsonde stations and the divergent component of the wind from the previous forecast or from current observations at the surface and aloft.

The mathematical formalism exists to incorporate different types of data with different error statistics as well as constraints from appropriate physical laws into a single analysis. Optimal (least squares) interpolation and variational analysis are two such formalisms. The problem becomes one of devising methods that are least expensive to apply. Costs of evaluating and upgrading the forms and weights used in the analysis scheme must be included along with the cost of running the analysis each time. The analysis system must deal with spatial and temporal discontinuities in data density and any operational system must have fall-back positions in case one or more of the observing, communication or computation systems fail.

The "best" analysis system will remain elusive because observing systems remain in a state of flux (satellite systems change frequently). Furthermore, new numerical forecast models and model resolutions are always being considered and they may find a different analysis system to be optimal.
Of particular concern in regional modeling is the use of detailed information on terrain elevation with relatively sparse observation of wind fields. To a large extent, the dynamic model will adjust initially smooth wind fields to detailed orography in a few hours, but the adjustment is not complete. The seriousness and solution of this question remain a major research problem.

The consistency of analyses and models and the analysis of moisture fields have been discussed in Section 4. Further discussion will be omitted but these are major problems.

Parameterization of sub-grid scale processes has always been a major concern of numerical modelers. How can you incorporate the effects some processes have on resolvable scale motions when those physical processes occur on scales smaller than can be resolved? The extent to which parameterization is possible is open to question but necessity is the mother of invention and many schemes have been produced.

Figure 7. Schematic representation of the cumulus scale imbedded in the 35 km primitive equation mesh.

The problem of cumulus parameterization can be visualized from the sketch in Fig. 7. The cumulus cloud may have a 2 km radius and it certainly evolves from processes not explicitly treated in the hydrostatic primitive equations used in the 35 km mesh regional model. Yet the cumulus cloud transports heat and moisture in the vertical that must be approximated.
just to keep the regional model stable, not to mention accurate. The scheme we use is the sequential plume model that serves as a subroutine within the regional model (Kreitzberg and Perkey, 1976). This model "works" in all situations to keep the regional model stable and reasonable, but it has obvious limitations. The most serious limitation would seem to be the lack of provision for downdrafts on the cumulus scale that form in nature from evaporation of precipitation that falls into unsaturated air (Johnson, 1976). This phenomena is most frequent and serious when the horizontal wind changes rapidly from level to level in the vertical. Then, vertical transport and generation of horizontal motion is important in triggering additional updrafts.

A second sub-grid scale cloud problem is that of partly cloudy skies with clouds coexisting beside sub-saturated air. For example, the relative humidity averaged over the volume represented by the regional grid may be 90% while the average cloud water content is non-zero. This problem is not too serious for precipitation forecasts in regional models but it does pose a problem in calculating solar radiation that can reach the ground. Errors in the radiation lead to errors in surface temperature that can accumulate and produce errors in prediction of large cumulus clouds.

The parameterization of sub-grid scale surface fluxes has been discussed in Section 3.3. These flux calculations remain a serious problem in forecasting some important low-level phenomena, notably air pollution concentration and fog. However, advances during the past ten years have been substantial and current parameterization schemes are adequate for many purposes including determination of the effect that the surface has on the regional scale flow under most conditions.

Another class of statistical problems that impacts significantly on the regional forecast system development is that of verification measures. Some quantities can be verified rather directly, such as model wind, temperature and relative humidity against rawinsonde observations or accumulated precipitation against rain gauge observations. The only question is how to average the observations that are available to emphasize the scale corresponding to the prediction model scale. Other model variables, such as vertical velocity, cannot be measured directly but are rather directly coupled to observable quantities, cloudiness and precipitation in the case of vertical motion.

It is difficult but important to find verification measures for patterns as distinct from point values or simple averages. How well does the model predict the shape and temporal evolution of a convective rain shower band?
Then, how well does it predict the timing and maximum intensity or severity of the showers? A model that predicts the correct intensity but is slightly off in location and timing would be extremely valuable in anticipating the type of weather to look out for that day. Information on the exact location and timing could then be refined as the day progresses and the storm is seen to develop. Yet, this model would do poorly in a point by point root-mean-square measure and a better "score" would be achieved if the features were smoothed out in the forecast.

The user of the forecast may have very different utility criteria for verification than the modeler. The user is interested only in schemes that can be interpreted in terms of his requirements, just as the modeler is most interested in measures that clarify deficiencies within the model itself. Furthermore, model intercomparison studies are important but they are difficult unless common verification measures are used for the different models. Common measures are hard to agree on because each modeling group feels its model has unique strengths that should be emphasized during validation.

It is essential that both the utility and the realism of the forecast system be validated. If both are not validated in a meaningful way, research will be hampered by lack of funding support, pursuit of trivial refinements or by stagnation (rather than expansion) of broad long-lasting model capabilities. Verification measures may be selected on mathematical grounds but they take on the role of value statements that then guide future research and development. For this reason, care must be taken in their selection as caveats to their use are soon forgotten in practice.

Carefully designed systematic experiments are expensive and become suspect or obsolete if the model itself is changed. As the initial results are examined, it is tempting to change the model a little to improve its performance a little at the expense of having to repeat the initial experiments. The only solution is to do some validation throughout the period of model development and then occasionally stop development while more extensive and systematic tests are conducted.

It has been emphasized that regional forecasting involves a system of models and the dynamic numerical forecast model is only one part of the system. Routine operation of the completed system will be very expensive and it is critical that the whole system be examined and optimized. Usually, small changes can improve the system significantly while extensive computations may prove to be useless in view of the final product. Refinements that are justified during research and development might impose undo burdens that prevent implementation of the system.
Numerical techniques are particularly difficult to evaluate until the system is complete because their behavior or value may change markedly when new physical or statistical features are added. In general, we elect rather well tested robust and accurate schemes while the system is being developed and leave refinement and optimization for future consideration. It is not feasible, however, to ignore efficiency completely because reduction in computer running time can often be used to increase the number of useful experiments that can be conducted.

It is hoped that the preceding review will foster effective collaboration of numerical analysts and atmospheric modelers in development of an improved weather forecast system. They must appreciate the scope of the problem in order to judge what research methods will be effective. In any collaborative effort, the specialists must retain the strongest attributes of their specialty in order to contribute the most effective tools to advance the overall effort.

If collaborators contribute something to each other every few months, even if it is something minor, it will foster mutual respect and appreciation. In the same way, the group must contribute information of value to someone outside the modeling community if they are to retain the respect and support of other scientists and institutions.

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REFERENCES


APPENDIX

List of Symbols

a mean radius of the earth.
c cloud water (or ice) concentration, mass of condensate per unit mass of air.
Cd: condensation of water vapor into cloud water (or ice).
Cl: collection of cloud water (or ice) by rain (or snow).
$c_p$: specific heat constant for dry air.
Cv: conversion of cloud water (or ice) into rain (or snow).
Dr: divergence of falling rain (or snow) due to changes in its terminal velocity.
E: elevation of the earth's topography, above mean sea level (MSL).
Ec: evaporation of cloud water (or ice).
Ee: evaporation of rain (or snow).
$f$: Coriolis parameter, \(2 \Omega \sin \phi\), where \(\Omega\) is the earth's rotation rate.
g: acceleration of gravity.
h: vertical coordinate distance, compressed by the factor \(a\).
E: vertical velocity in terms of \(h\), namely \(\frac{Dh}{Dt}\).
H: height (MSL) above which \(h\)-surfaces coincide with \(z\)-surfaces.
p: atmospheric pressure.
p0: reference atmospheric pressure, normally \(10^5 \text{ N m}^{-2}\).
q: specific humidity, mass of water vapor per unit mass of air.
Q: diabatic (non-adiabatic) heating rate.
$r$: rain (or snow) concentration, mass per unit mass of air.
R: specific gas constant of dry air, ratio of universal gas constant to molecular weight.
t: time.
T: temperature.
Tv: virtual temperature.
$u, v, w$: velocity in \(x, y, z\) directions, namely, \(\frac{Dx}{Dt}, \frac{Dy}{Dt}, \frac{Dz}{Dt}\).
V: three-dimensional wind velocity vector.
x, y, z: coordinate distances in east, north and up directions, where \(z\)
is measured above MSL.
$z_e$: height (MSL) of the top of the model domain.
$\alpha$: terrain coordinate compression factor.
$\beta$: terrain coordinate slope factor.
$\delta$: delta function, 1 below \(H\) and 0 above \(H\).
$\phi$: gradient operator.
$\theta$: virtual potential temperature.
$\psi$: scaled pressure variable.
$\varphi$: earth latitude.
$j$: any of the predicted variables.
ADDITIONAL BIBLIOGRAPHY

A brief comprehensive review of large scale NWP with extensive citations —

A text book —

A simple discussion of the most frequently used numerical methods —

Seminar proceedings —