20030225140

UNCLASSIFIED

(2)

AD-A253 630

REPORT DOCUMENTATION PAGE

JUL 31 1992

S C D

1b. RESTRICTIVE MARKINGS	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
3. DISTRIBUTION/AVAILABILITY OF REPORT	Approved for public release; Distribution unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	
5. MONITORING ORGANIZATION REPORT NUMBER(S)	AFOSR-TR- 92 0730
6a. NAME OF PERFORMING ORGANIZATION	Colorado State University
6b. OFFICE SYMBOL (If applicable)	
7a. NAME OF MONITORING ORGANIZATION	AFOSR/NC NL
6c. ADDRESS (City, State, and ZIP Code)	Engineering Research Center, Room B315, Fort Collins, CO 80523
7b. ADDRESS (City, State, and ZIP Code)	Building 410, Bolling AFB, DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	AFOSR
8b. OFFICE SYMBOL (If applicable)	NC NL
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	F49620-89-C-0036
8c. ADDRESS (City, State, and ZIP Code)	Building 410, Bolling AFB, D.C. 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
61102F	2310	CS	

11. TITLE (Include Security Classification)
Mesoscale Severe Weather Development Under Orographic Influences - Unclassified

12. PERSONAL AUTHOR(S)
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13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final Report	FROM 2/1/89 TO 3/31/92	1992, June 30	35

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Mesoscale Weather Prediction
Hybrid Modeling
Nowcsting, Object-Oriented

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
Research summarized in this report addresses the lack of response of centralized weather services to specific user needs. Distributed weather prediction on tactical workstations can overcome most of the current barriers. Such a forecasting system, running on a 486/33 PC, has been developed and tested extensively in Colorado snowstorm and blizzard conditions. The system incorporates a mesoscale numerical prediction model, a detailed geographical database, and a graphics user interface based on Microsoft Windows 3.1. Through this user interface the user can assimilate local observations with simple mouse point-and-click actions. The system can make use of observational data and heuristic rules. A prototype, customized for Colorado, has been tested under real-time and operational conditions. Concepts of object-oriented nowcasting, using artificial intelligence tools, such as "fuzzy logic" have been developed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
Lt.Col. James G. Stobie	(202)767-4960	NC

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

JUL 1992

Colorado State University, Department of Civil Engineering

Mesoscale Severe Weather Development Under Orographic Influences

Final Report, Grant AFOSR F49620-89-C-0036,
for the Period 1 February 1989 to 31 March, 1992
Date: 30 June, 1992

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Table of Contents

1. Executive Summary

In this Final Report we depart from the customary presentation of project results in highly condensed, chronological fashion. Instead, Chapter 2 provides a critical view of the state of the art of (numerical) weather prediction, with emphasis on military applications. This view is based on experiences gained during our ongoing efforts under funding by the U.S. Air Force, the National Research Council (NRC) - Strategic Highway Research Program (SHRP), the Colorado Department of Transportation (CDOT), and matching funding by WELS Research Corporation. These experiences pertain to the application of artificial intelligence tools to meteorological forecasting requirements. In particular, we address the current lack of response by centralized weather services to specific user needs. We propose state of the art technologies developed in the course of our research to overcome this lack of response. With only minor modifications, such technologies can easily be implemented under battlefield conditions.

We discuss the merits of centralized versus distributed weather prediction. Since the user in the field usually has direct access to observational information to verify or discredit a forecast (often not available to a centralized weather service), he should be provided with the means of generating such forecasts himself. Technology now exists to allow distributed weather prediction.

Model output statistics (MOS) tend to be of little use in tactical planning since they only provide statistical probabilities of certain weather phenomena based upon past occurrences of similar patterns. More appropriate are applications of "fuzzy logic" which provide updates of the confidence that a certain phenomenon will or will not occur, based upon the collection of positive or negative evidence.

Hybrid modeling combines the skills of numerical weather prediction with those of object-oriented, computerized nowcasting. Meteorological phenomena (e.g. a thunderstorm, blizzard, etc.) are defined as objects which have certain characteristics (location, timing, intensity, etc.) and follow certain rules of behavior. These rules can be formulated in terms of algorithms relying on numerical model output, and/or from heuristics. An object can be "presumed" to exist for "what if" exercises. Once its existence is ascertained by evidence, application of the behavioral rules provide predictive skills, even though the original numerical model may not be capable of identifying such objects. A user-interactive capability to change behavioral constraints serves to correct forecasts "on the fly" without having to rerun a numerical model. Under such technology numerical models no longer need to be **accurate**; they only need to be **adequate** to provide reasonably good first guesses in the specification of behavioral rules for the objects under consideration. User interaction with an object-oriented nowcasting model is capable of four-dimensional data assimilation, even of information which does not fit into the parameter space required by a numerical model.

In Chapter 3 we list the original Project Objectives. Chapter 4 outlines the Project History which extends over almost 10 years, and ranges from field experiments in the Rocky Mountains, the Gobi Desert and Tibet, to numerical model developments, and to object-oriented nowcasting approaches. Theoretical approaches taken during the present project are briefly summarized in Chapter 5, mainly in terms of literature references.

Chapter 6 summarizes our experiences in modeling Colorado snowstorms and blizzards. A final Outlook (Chapter 7) indicates the steps that need to be taken to bring the newly developed technologies to battlefield applications as tactical decision aids on small tactical terminals. Since funding for this project has been terminated, it is unlikely that such applications will be implemented in the near future.

2. Weather Forecasting for Tactical Decisions

During the past several years our research team has gained enough experience in the diagnosis, analysis, and prediction of severe weather systems to voice some critical judgment on the state of short-term weather prediction in support of tactical decisions involving weather-sensitive operations. Meteorological decision support, especially that intended to aid the battlefield commander, suffers from several severe shortcomings which shall be described in this chapter. A good part of our research efforts under the current project was geared to address these problems.

2.1. Centralized Versus Distributed Weather Prediction

2.1.1. Present State of the Art

All national and military meteorological services of the industrialized nations provide centralized forecasts, the products of which are accessible to users in various alpha-numeric (weather bulletins) and/or graphical (weather maps, satellite, radar pictures) displays. These services rely on data from a plethora of observation platforms. Data are centrally collected, decoded, quality controlled, analyzed, and used as input into numerical prediction models. In essence, one can state that numerical weather forecasting has become the backbone of all technologically advanced prediction systems.

Improvements in observational technologies, data communication networks, and numerical modeling approaches have led to significant advances in the skill of meteorological prediction out to a range of approximately one week. However, there is a bit of legerdemain in these claims of improved forecast accuracies: They pertain mainly to the anticipated behavior of large-scale weather patterns, and should be taken with a grain of salt when it comes to the prediction of specific weather effects on sensitive operations. As an example, in the recent 30th Anniversary Symposium of the Department of Atmospheric Science at Colorado State University Prof. Mike Fritch (Pennsylvania State University) showed a trend diagram with root-mean-squared errors in the prediction of 500-hPa steadily decreasing during the past two decades. Similar trends have frequently been exhibited in the literature and at scientific meetings.

Without trying to belittle this progress, one cannot help noticing that the 500-hPa surface analyzed with more than a hundred km grid resolution is of little consequence to the field commander when planning a tank assault over rain-soaked "desert" terrain, or attempting a helicopter mission in a blinding dust storm. The national weather services are not yet doing well in predicting the arrival times and duration of winter storms at specific locations, the amounts and forms of precipitation to expect as functions of time and space, and the effects of these storms on the conduct of society's affairs (Kocin and Uccellini, 1990). Neither can present weather forecasts boast great success in providing sufficient warning time with local focus for flash floods and other severe weather disasters beyond the short span covered by "nowcasting" extrapolations of already present weather phenomena.

Mesoscale numerical modeling research is vigorously addressing these issues, but results are slow in alleviating problems at the consumer end of weather prediction.

2.1.2. Statistical "Games"

Forecasts of weather phenomena (e.g. thunderstorms or snowstorms) of interest to consumers are often caged in terms of Model Output Statistics (MOS; see Glahn and Lowry, 1972), taking the typical form:

> "There is a 30 percent chance of snow between 1 and 5 inches tonight along the foothills and in the central mountains...".

For the forecaster, this is a "win-win" situation: If it snows he can claim: "We predicted it". If it does not snow, he can shrug: "We only gave it a small chance." During the past winter, under funding from the National Research Council, Strategic Highway Research Program (NRC-SHRP) and the Colorado Department of Transportation (CDOT), we worked closely with highway maintenance engineers in charge of snow and ice control operations on federal and state highways. They find such predictions next to useless as tactical decision aids. We expect that the battlefield commander would not be thrilled with them either.

First of all, real life does not revolve around statistical probabilities derived from past scenarios. Decisions have to cope with **now** and **here**. Will the terrain turn to mud within a given time frame and at a certain location, or can it hold tracked vehicles, how many and for how long?

Our team has made ground-breaking efforts in introducing the concepts of "fuzzy logic" into weather prediction: Instead of accepting a single-value probability derived in binary, Aristotelian "Yes/No" logic that a certain event will or will not occur, we adopt the "theory of possibility" (Zadeh, 1965, 1975, 1978; Buchanan and Shortliffe, 1985) that an event could or could not occur **based on accumulating positive or negative evidence** (Reiter, 1991). Instead of handling weather prediction as though it were a one-time roll of the dice, it is treated as a tool with steadily increasing precision based on evidence and its reliability as Zero-Hour approaches. There is nothing "fuzzy" about "fuzzy logic". It received its ill-chosen name from the fact that "truth" values, or **certainty factors** (CF) are not considered to be binary, either 0 or 1, but can assume the full range of possibilities in between, from 0 = "absolutely not", to 0.2 = "possible, but not likely", to 0.8 = "probably yes", to 1.0 = "absolutely yes". (CFs can also be defined to range between -1 for "absolutely not" to +1 for "absolutely yes".)

"Fuzzy logic" has been successfully employed in artificial intelligence (AI)-based expert systems for medical diagnosis where successive tests will support certain diagnostic conclusions and eliminate others (Buchanan and Shortliffe, 1985, Townsend, 1987). More recently, fuzzy logic-based computer chips have been acclaimed in Japan as energy-saving solutions in control mechanisms for trains, air conditioning systems, etc.

The introduction of fuzzy logic into short-range forecasting and nowcasting was proposed by Reiter (1991) in view of the facts that:

> Numerical weather prediction results, even those from sophisticated mesoscale models, are never 100 percent accurate.
>
> The local forecaster usually has access to supporting or refuting evidence that certain weather phenomena will, or will not, occur. Such evidence may be difficult, if not impossible, to transmit to a central weather service with the request to re-run the prediction model.
>
> Even if such evidence could be transmitted, the re-running of a numerical forecasting model may be out-paced by the course of events to be predicted.
>
> Certainty factors by which to judge the significance and validity of accumulating evidence are better assessed on location than in a basement in Suitland, Omaha, or Traben-Trarbach.

The example given by Reiter (1991) pertains to the prediction of a flash flood in mountainous terrain and illustrates the use of arithmetic developed by the MYCIN Project (Buchanan and Shortliffe, 1985), based on "personal", i.e. subjective, certainty factor assessments by a forecaster. With access to observational systems, such as weather radar, lightning strike sensors, etc., a number of certainty assessment steps can be objectivized and automated, relieving the forecaster under decision pressures from making (perhaps erroneous) subjective judgments.

One of the major barriers standing in the way of generating objective forecasts with continually improving local precision lies in the organizational structure of centralized weather services:

- Weather services produce their forecasts centrally on super-computers and ship their products to the consumer on a "take it or leave it" basis. Interaction with users and their immediate requirements is limited at best.

The fascination with super-computers is spawned by the desire to achieve ultimate accuracy in forecast products, no matter what their final destination or purpose may be. Since it is difficult to imagine a Cray or Cyber being carried in a backpack or even on a HMMWV (High Mobility Multi-Purpose Wheeled Vehicle), the supreme reign of centralized weather prediction remains unchallenged. Only forecast products and data displays are "piped" to users in the field. With the acceptance of this reign comes the penalty of overloaded communication links which, when interrupted, leave the user with severely restricted forecasting options. Inaccurate forecasts are discarded and operations proceed as though there were no predictions available.

Reiter (1991) suggested that forecasts need not necessarily have to be **accurate** to be of use. However, they need to be **adequate** in providing first indications that a certain weather phenomenon might, or might not, happen within a certain time frame and at a certain location. These first assessments, coming from a less-than-perfect numerical prediction model, can then be parlayed into perfect, location-specific forecasts as locally supplied evidence begins to accumulate. We have proven that "adequate" numerical forecasts can be obtained operationally, in real time, using high-end PCs (perhaps even in laptop configurations), as will be pointed out in Chapter 6 (see also Reiter and Teixeira, 1992a, b; Reiter et al., 1992a, b).

To bring a PC-based weather prediction technology to field applications one has to set up all facets of "distributed" (versus centralized) weather prediction. Under support from SHRP and WELS Research Corporation we have done so. These facets include:

- Reception of raw upper-air and surface data from synoptic observation times. On the civilian market, such data are available from value-adding vendors tied into the National Weather Service (NWS). To initialize a limited-area forecasting model (LFM), raw observational data are needed only for continent-wide regions. With proper data packaging (not yet implemented by NWS) transmission times required to deliver these data to the field will be a fraction of the time needed to send forecast products.

- Data quality control procedures will have to operate centrally before data transmission to the field or will have to be enacted in the field by expert meteorologists.
- Automatic data decoding and analysis software will have to be installed on PCs in forecasting field locations.

Distributed weather prediction, with its focus on mesoscale and regional weather developments, is not envisioned to **displace**, but to **augment** centralized weather prediction. There always will be a need for a "global" view on weather. However, there also must be a recognition that a local user in the field knows better when a forecast begins to derail than a Cray operator thousands of miles away.

Having made the case for distributed weather prediction, the demand for **interactive** prediction capabilities is a logical next step. As the local user recognizes that his forecast is going off track, he must be given tools to correct such misbehavior. "Fuzzy logic" approaches leading to compounded certainty factors are but one such tool in a PC-based environment. Their effectiveness is fully realized in the implementation of "hybrid modeling" (Reiter, 1991).

2.2. Hybrid Modeling

2.2.1. A Challenge to the Monopoly of Numerical Modeling

As the synoptic meteorologist of yore has become an endangered species, much of meteorology has given way to applied mathematics: "What we can't express with a set of simultaneous differential equations, we cannot claim to understand fully." This statement may be true to a certain extent. However, since we cannot measure everything everywhere all the time (without disturbing the environment, to paraphrase Heisenberg), we will never be able to predict precisely, even if a complete system of equations existed, aided by unlimited computer power waiting for completely specified initial and boundary conditions.

If one accepts the premise that a forecast needs to be **adequate**, but not necessarily **accurate**, provided one has tools to upgrade its precision, the futility of the statement given above becomes less frustrating. How can computerized forecasts be upgraded?

The current rave in the numerical modeling community flies under the heading of "four-dimensional data assimilation." Observational data received before a certain deadline after model initialization are carefully "nudged" into the model at the appropriate time and place, whereupon the model is restarted. Such procedures achieved good results in medium-range forecasting (Bengtsson and Palmer, 1989; Hollingsworth, 1987; Hollingsworth and Loennberg, 1989; Takano et al., 1987) where there is still plenty of time left in the remainder of the forecast period. We have also seen successful attempts of three-hourly upgrades with surface network observations of a mesoscale isentropic model developed at NOAA-ERL (Tracey L.Smith, 1992, oral communication), giving predictions of standard meteorological parameters on isentropic surfaces. There is cause for optimism in future improvements of such data assimilation techniques.

However, there still remain major drawbacks in relying exclusively on approaches calling for rerunning a numerical model after appropriate data assimilation:

- Realistic battlefield scenarios cannot promise access to dense observational networks from which data can be called at will to be introduced into a mesoscale model.
- Feeding and rerunning a numerical model requires considerable time, the luxury of which may not be available in the prediction of short-lived, local phenomena -- especially of phenomena which may be beyond the resolution capability of the model no matter how it is initialized.
- Readily available observations may not conform to the parameter space of numerical modeling which is restricted to pressure (or geopotential height) temperature, humidity and wind. What would be accomplished by rerunning a forecast that provided "a 30 percent chance for afternoon showers" to satisfy a request such as: "Target acquisition by laser guided missile in this heavy downpour is impossible. When can we expect it to quit?"

Under present circumstances, questions such as the one above are strictly relegated to the domain of "nowcasting": If observations from local radar or ground "spotters" are available, one finds out how the weather system of concern behaved during the immediate past and hopes that it will not change its behavior within the immediate future. Linear extrapolation will be the name of the game leaving little, if any, room for tactical planning. NEXRAD currently has embedded algorithms taking advantage of such extrapolation by plotting arrows over severe thunderstorm cells. These arrows indicate the anticipated movement of such cells derived from comparisons between past and present positions of the cells on the computer screen.

We think that better ways of addressing the data assimilation and nowcasting problems are offered by object-oriented approaches. It appears that Reiter (1991) was the first to point out meteorological applications of object-oriented computing concepts.

2.2.2. Object-Oriented Forecasting

Object-oriented computing is a well-proven concept, albeit not in the FORTRAN-steeped world of meteorological modeling. Smalltalk-80, developed by the Xerox Corporation, was one of the first object-oriented languages. Other languages, such as PROLOG and C++, followed suit.. PC-based environments, such as Microsoft Windows provide graphical user interfaces (GUIs) in which windows, text boxes, buttons, scroll bars, etc. are objects which can be manipulated with user-friendly mouse point-and-click actions. Parent-child relationships with appropriate inheritance characteristics can be defined by which certain child-windows and their contents "belong" to specified "parent" objects (e.g. a window and its menus) from which they can be called (Petzold, 1990).

The rather complicated Windows language, based on "C" and often dubbed a "programmer's nightmare", now offers resource tools which allow the design and construction of user interfaces by graphical means, automatically generating appropriate computer code (see e.g., Borland, 1991). More user-friendly object-oriented languages, such as MacroScope (also based on C) have recently become available which handle an even wider variety of tasks than Windows (Objective, 1992).

The real power of object-oriented programming approaches is revealed in animated computer graphics. Relying on the concepts of "teleological (goal-oriented) modeling", graphical shapes on the computer screen are treated as a "objects" which have to follow certain rules of behavior until they reach a certain goal (e.g. a pterodactyl "flying" until it exits the computer screen, or a ball bouncing until it comes to rest). The rules of behavior of such objects usually are anchored in the laws of physics. Object-oriented approaches have vastly increased the efficiency by which computer animation can be achieved and made to look realistic. The old "kinematic" approach, by which the movement of each surface element of each shape on the computer screen had to be prescribed in detail, required enormous code which was slow in execution, even on super-computers.

In the meteorological analogy discussed by Reiter (1991) certain meteorological phenomena, e.g. a severe thunderstorm or a blizzard, can be defined as "objects" which

- have certain characteristics of time, location, size, intensity, etc.;
- follow certain rules of behavior which are defined either by the laws of physics or by heuristics (experience gained from past encounters), or by a combination of both. (E.g. an object "thunderstorm" will move with an integrated wind field, will intensify depending on stability, available moisture, etc.);
- are subject to constraints dictated by the environment in which they occur. These constraints serve to initialize the aforementioned rules and can be time- and space-dependent. (E.g. an object "thunderstorm", once its presence in the environment is ascertained by visual, radar, or lightning strike observations, will move and intensify according to observed and predicted wind fields, stability and moisture distributions.). Constraints can be specified from

    output of numerical prediction models (even from models that are adequate but not completely accurate), observations obtained locally,

climatologically or heuristically determined default values.

- can be depicted uniquely and recognizable on the computer screen as "icons". (E.g. in the presence of several thunderstorms, each one should be represented individually, and its behavior should be predicted to gauge its potential effect on specific locations at specific times, such as on "Runway 24 thirty minutes from now". No longer shall we be satisfied with general statements such as "a 30 percent chance of thunderstorms in the afternoon, mainly along the foothills".)

It should be obvious from this discussion that certain objects can be made predictable, even if they are essentially unpredictable by a numerical model because they are of sub-grid scale and of fleeting duration. The model only needs to recognize the constraints under which such an object can potentially exist. Such a "potential existence" may have a low certainty factor (CF) of perhaps 0.2 (= "possible, but not likely) automatically assigned to itself.

It now behooves the user in the field to find supporting or refuting evidence for the actual existence of said object. E.g. the first Cb buildup, lightning strike, significant radar reflectivity pattern, etc., should prompt the user to click on the computer screen an appropriate icon at the proper forecast time and coordinate location. From the numerical forecast output (and, if necessary, from climatological or heuristic rule bases) that icon should now be forced to follow teleological modeling concepts, i.e. to move, change color or size according to changing intensity, until either the limits of the forecast space and time domains are reached, or until the object is expected to decay.

Because this approach combines object-oriented as well as numerical modeling components, we chose to call it "hybrid modeling". We have proven that the hybrid modeling concept performs with great efficiency and operationally, in real time, on a high-end PC with Windows 3.0 or 3.1.

2.2.3. Object-Oriented Data Assimilation

Behavior and constraint specifications for an object "thunderstorm", incorporating "fuzzy logic" CFs, can be depicted in the form of "inverted bull's eyes" (Fig. 2.1): An icon placed at the time and location of initial existence confirmation projects its movement (e.g. for the first hour) into concentric areas, the largest of which carries a high CF ("the object will be very likely within this area"), the smallest one carrying a low CF ("the object should be in this precise location, but our confidence in such precision is low"). Such information should carry more weight in tactical decisions than a MOS-inspired statement of "a 30 percent chance of thunderstorms this afternoon along the foothills".

If the underlying numerical model gave correct predictions of the wind field dictating the behavior of the object (and if the rules for such behavior had been specified correctly) a forecast such as the one schematically shown in Fig. 21 should provide reliable results. However, such luck can hardly be expected in view of several potential error sources:

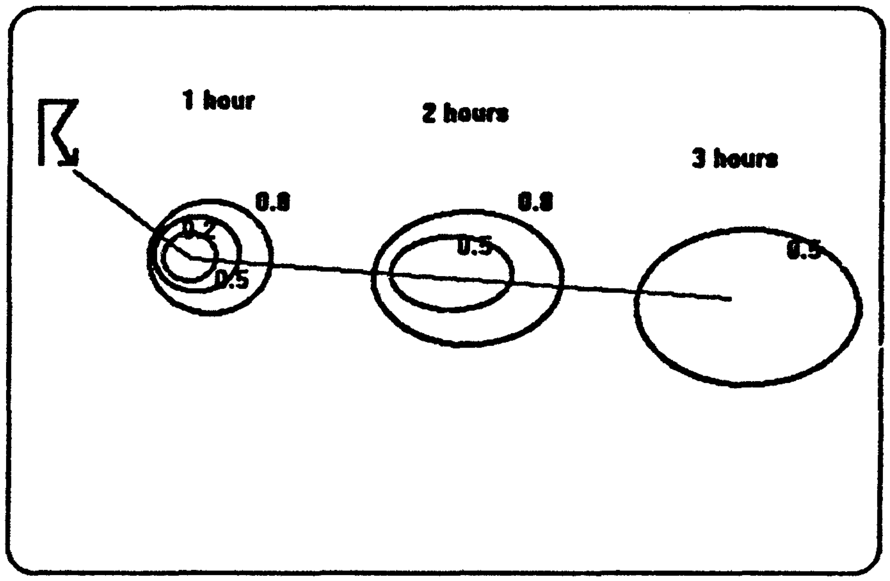

Fig. 2.1: Schematic diagram of screen representation of "fuzzy logic" thunderstorm prediction. Certainty factors (CFs) increase with increasing target area; they decrease with increasing prediction time. (They would increase again, the smaller any required forecast adjustments.)

- Random errors may have been introduced in the original positioning of the icon (perhaps due to imprecise observational information).
- Inaccurate numerical model predictions may give rise to systematic errors (especially when strongly non-linear events are at work).
- Improper specification of the "rules" governing object behavior should cause systematic prediction errors.

Future observed object behavior will provide clues on the nature of such errors.

The next observation indicating a significant departure between the predicted and observed tracks of the object should prompt the user to "click" the icon at its appropriate "new" location. The discrepancy between the "old" predicted and the "new" observed locations should be evaluated automatically, and should result in an adjusted track prediction.

This step will be repeated with the next, discrepant observation. Random error sources, most likely, will give rise to seemingly inconsistent, non-converging requests for positive and negative track adjustments. The graphical forecast output should reflect the high uncertainty caused by random error sources in the form of relatively large target regions labeled with low CF values.

On the other hand, if systematic errors plague the forecast, a few iterative adjustments should converge rapidly towards acceptable agreement between observations and predictions. Such convergence should automatically give rise to the computation of more precisely defined target areas with high CF values.

None of these procedures require rerunning of the numerical prediction model. As a matter of fact, information used to great advantage by the above discussed, object-oriented approach (e.g. lightning strike data) may be unsuitable for numerical model input.

Our prototype developments indicate that object-oriented data assimilation to upgrade forecasts can be handle almost instantaneously by high-end PCs.

2.3. The Bottom Line

Presently centralized weather services (The U.S. Air Weather Service not excluded) will have to decide on possible redefinitions of their missions to satisfy certain user requirements which, under current operational settings, cannot be met. Our present involvement with state highway authorities clearly demonstrated the inadequacy of information provided by the NWS for tactical decisions on local snow and ice control on roadways. It is difficult to see how bigger and faster computers at a central facility can alleviate the problem of local weather outpacing data flow requirements. Instead of bringing the Mountain to Mohammed, it would seem more efficient and decidedly less expensive to bring Mohammed to the Mountain: Off the shelf technology is available to implement operational distributed weather prediction for limited-area forecasting domains. Let the local user reconcile forecasts with reality as an ongoing amelioration process, rather than by pondering over forecast products which may be "dead on arrival" from a central prediction facility.

Present weather prediction methodologies preponderantly based on numerical model output, perhaps garnished with MOS, are not conducive to increase the precision of forecasts targeted for specific weather phenomena and their potential effects on certain operations. In the absence of any precision, the tactical planner will either assume worst-case scenarios or ignore weather effect altogether. Either option can be misleading and should no longer be accepted under present technology. Object-oriented forecasting approaches point towards significant improvements in tactical decision support.

3. Project Objectives

Our original proposal envisioned a 3-year research program with a starting date of 7-1-88. The actual start of the project was postponed until 1 February, 1989. As has to be expected with research plans covering an extended time period, new findings determined changes in emphasis and new approaches which could not be anticipated at the beginning of the investigation.

Our anticipated program, proposed in February of 1988, listed the following objectives:

(1) A field measurements program to investigate mesoscale flow patterns at mountain peak levels in the Rocky Mountains during winter. This program was to serve as a continuation of ROMPEX, the Rocky Mountain Peaks Experiment started in the summer of 1985 (Reiter et al., 1987a; Reiter and Sheaffer, 1987), and continued with several modifications during subsequent summers (Bossert and Reiter, 1987; Reiter et al, 1987b, 1989; Sheaffer and Reiter, 1988; Bossert, et al., 1989). This proposal item for a winter project was dropped in negotiations with the U.S. Air Force, due to the unavailability of funding for equipment.

(2) Diagnostic analysis of data obtained from field experiments in the Rocky Mountains, Tibet and Kansas. Such analyses have been carried out, as summarized in the next section.

(3) Mesoscale prediction model development:

(i) Hardware tests to find desktop computers that can perform in real-time operational scenarios, such as in a battlefield environment. Such equipment has been identified in the form of 486/25 and 486/35 desktop computers. As a matter of fact, present technology would allow to fit our forecasting system into a laptop computer. System performance has been described in detail by Reiter, Doyle and Teixeira (1992a).

(ii) Additional test cases for severe summer convective conditions over mountainous terrain. Such cases have been reported by Tucker and Reiter (1988a,b, 1989), Tucker et al. (1989), Reiter and Tucker (1988), Reiter et al. (1988), Bossert (1990).

(iii) Preliminary tests of the model on winter snowstorm cases. This task provided the focal issue of our work during the third project year and will be covered in more detail in Chapter 6 (Reiter, Doyle and Teixeira, 1992a).

(iv) Computer modeling incorporating numerical as well as heuristic concepts, the latter employing techniques developed in the area of Artificial Intelligence (AI). The following target areas for a hybrid modeling approach were tentatively identified:

(a) "Jet streaks" to be identified as "features" that can be retained in, or reinserted into, numerical model integration to sharpen up wind field and vorticity patterns. Macdonald (1988) pursued this idea in Ph.D. dissertation research started after proposal submission, but completed before project funding arrived. This idea was no longer pursued during after Dr. Macdonald's initial work because the concept required too many subjective decisions to be of immediate usefulness.

(b) Terminal weather prediction for certain Air Force Bases in Colorado (Warren, Lowry, Peterson) with focus on snowstorms, snow drift, and high wind conditions. We anticipated to employ a neural network design developed under past DoE-sponsored research. Additional details of this effort will be provided in Chapter 6. The neural network idea was abandoned, as it would have required too large a number of cases for adequate model development than would have been feasible to consider under given budget and personnel constraints. Instead, we developed the concept of object-oriented nowcasting as a component of hybrid modeling (Reiter, 1991). The concept takes advantage of the latest computing technology (such as used in Microsoft Windows) and incorporates significant elements of Artificial Intelligence, such as those used in heuristic modeling.

This task occupied the major portion of our research effort. As a consequence, several technological breakthroughs were achieved, resulting in a real-time, operational mesoscale prediction system that runs on a PC. The system incorporates numerical modeling procedures, geographic information system databases, and object-

oriented graphical user interface (GUI) designs in a truly hybrid modeling approach ready to be used in battlefield weather management as a weather tactical decision aid and a battlefield planning tool which can run on a small tactical terminal. The system is fully user interactive and permits local data assimilation to upgrade forecasts. Furthermore, it can handle the prediction of specific weather conditions, for instance as needed for snow and ice control.

(c) Route forecasting to address problems of clear air turbulence over mountainous terrain. In view of our heavy involvement in Task (b) above, the issue of in-flight weather was not addressed. It turns out, however, that the concepts developed under (c) are easily applicable to in-flight weather prediction, with only minor modifications of the present system setup.

4. Project History

The Principal Investigator's involvement with the US Air Force Office of Scientific Research started with a proposal submitted in 1981, and funded as of April 15, 1982 for a three-year project on the "Effects of Mountain Ranges on Mesoscale Systems Development". Research on the topic of mountain effects on severe weather has been going on uninterrupted since then, covering a variety of issues, until 31 March, 1992. Looking back on this long and fruitful period of almost ten years, a number of "firsts" can be credited to our work. (The following, brief review does not cite all publications credited to U.S. Air Force Support. Complete publication listings are contained in the Annual Project Reports issued over the years.)

(1) The P.I. was the first to become involved with Chinese scientists and their valuable databases to explore the effects of the Tibetan Plateau on local, regional, and global weather patterns. From the beginning of the project we became convinced that:

(a) available data on the interaction between the surface and the atmosphere do grave injustice to meteorological conditions prevailing over and near mountainous terrain, since existing databases are strongly biased towards population centers in valleys;

(b) if we wish to claim any understanding of mountain effects on mesoscale weather, we ought to be able to model such effects.

(2) Our initial concern was to establish large-scale mountain effects from existing, historic databases. Often-cited results of our studies on Asian and North American monsoons (Tang and Reiter, 1984; Reiter and Tang, 1984) spawned the idea of investigating "monsoonal" flow patterns at

peak levels in the Rocky Mountains. The P.I. and his team (in collaboration with the Los Alamos National Laboratories) were the first to instrument more than 20 high mountain peaks in the Colorado/New Mexico main range of the Rockies. This project, known as ROMPEX 85 (Reiter et al., 1987a) led to a number of follow-on studies exploring low level jet stream-like wind system newly discovered by us, that appeared with great regularity and sharply defined onset times in the evening and night hours (Reiter and Sheaffer, 1987; Bossert et al, 1989). Vertical shears and wind velocities were deemed of sufficient magnitude to endanger small aircraft and helicopter operations near mountain peak levels. According to our research, this wind system appears to be tied to the nocturnal cooling of the high mountain regions. This cooling cycle can, at times, be strongly enhanced by collapsing convective cloud systems with rain evaporating into the sub-cloud layer.

(3) Earlier indications of strong correlations between mesoscale terrain features and the climatology of pressure perturbations in the planetary boundary layer of Tibet (Reiter 1982), as well as results from a workshop organized by the P.I. in Beijing in 1982 (Reiter et al., 1983) gave rise to the idea of detailed surface energy budget measurements in high plateau regions. With U.S. Air Force support instrumentation was obtained to undertake such measurements. In April 1984 permission was received at long last from the People's Republic of China to erect a micro-meteorological station in the Gobi desert near Zhangye (western part of Gansu Province) at the foot of the northern edge of the Tibetan Plateau. To the best of the P.I.'s knowledge, this was the first such venture in post-revolution China. Valuable data were received from this station and used in comparison with data from the Rocky Mountains. The Gobi data indicated a much higher albedo in the near infrared spectrum than in the visible spectrum. It could also be shown that the Chinese method of measuring surface temperatures by large-bulb thermometers placed on the ground was more reliable than surface temperatures derived from radiation balance equations (as used in numerical models). (Smith, Reiter and Gao, 1986).

These early, successful field measurements culminated several years later in an international micro- and meso-meteorological measurement program at nearby locations, launched by Academia Sinica and supported financially by Japanese efforts.

(4) The successful conduction of the Gobi Experiment led to an invitation by Mr. Zou Jingmeng, the Director of the P.R.C's State Meteorological Administration in Beijing, to design and initiate a similar measurement experiment for the heartland of Tibet. The lure to follow this invitation came from the serious discrepancies between different estimates of the role of the Tibetan Plateau as an elevated heat source in the general circulation of the atmosphere (Chen, Reiter and Feng,1985; Feng et al., 1985), and from the potential effects of the Plateau on the general circulation of the atmosphere (Reiter and Ding, 1980/81; Reiter et al., 1984, 1986b). After two years of detailed planning, which also included

the organization of another workshop on the Tibetan Plateau and Mountain Meteorology (Science Press, 1986) the "green light" was given for spring of 1986. Two micrometeorological stations for detailed surface energy budget measurements were erected under enormous logistic difficulties, one near Lhasa (3635 m a.m.s.l.), the other near Nagqu (4500 m). Both stations were supported by a radiosonde capability. (Reiter et al., 1986a, 1987c; Shi et al., 1989). Again, the P.I. and his team were the first to launch such a cooperative effort between the U.S.A. and the P.R.C. Results from these measurements revealed striking differences between river valleys in which evaporation from the soil plays an important role, and high plateau regions where frequent rain, hail and snow are recycled to the atmosphere with little delay.

(5) A major effort in the understanding of mesoscale weather systems affected by high plateaus and mountains started with a modeling effort over Tibet and its surroundings (Shen et al., 1985, 1986a,b,c,d). Departures from the Anthes-Warner (1978) model became necessary, because of the structure of Chinese data sources which treated significant-point data as "classified" information. Nevertheless, the great density of the Chinese radiosonde network permitted more detailed analysis of upper-air flow patterns surrounding the mountains, than would be possible anywhere else (Reiter and Gao, 1982). Because the use of the NCAR Cray was expensive, and turn-around time was long, we embarked on the development of a mesoscale model which would run on small computers. First modeling attempts were made on an HP 9836 computer, and took more than three weeks of computer time for a 24-hour forecast. The next system of choice was an HP 9000/500 computer, which brought integration time down to one day. Steady model and computational procedure improvements helped eventually to decrease computer time on this machine to 4 hours for a 24-hour forecast. (Now we are able to run a 24-hour forecast for a region the size of the United States, with less than 100 km grid spacing, three-minute integration time steps, and a state-sized nested-grid area with 24-km grid resolution, in under one hour on a 486 PC.).

Early model applications (Shen et al., op. cit.) gave encouraging results for mesoscale system developments to the east of the Tibetan Plateau as a consequence of small precursor perturbations over the Tibetan Plateau. Subsequent applications over the Unites States, using improved modeling approaches, not only showed significant skill in the modeling of severe cyclones ("bombs") to the east of the Rockies (Macdonald, op. cit.), but also in "predicting" some major flash flood events, using historic databases (Bresch et al., 1986; Tucker and Reiter, 1986; Tucker et al., op.cit., Reiter et al., 1989).

(6) With better performing hardware and with optimization of model code a capability of running a mesoscale prediction model on a PC operationally and in real time appeared feasible. Such a capability would open up a wide field of applications as a battlefield planning tool, providing weather-related tactical decision aids, and running on a small

tactical terminal. Since funding under the present grant from the U.S. Air Force Office of Scientific Research only gave us the latitude to address basic research issues without involvement in field applications, we sought, and received, additional funding from the National Research Council, Strategic Highway Research Program (SHRP), the Colorado Department of Transportation (CDOT), and matching funding from WELS Research Corporation to explore operational applications. As a result of these additional efforts a fully functional, mesoscale prediction model in tactical support of snow and ice maintenance operations on Colorado's federal and state highways could be brought on line and tested operationally during the winter season 1991/92 (Reiter et al., 1992a). The model performed outstandingly, providing considerably more detail in the prediction of timing, location, and severity of snowstorms and blizzards than could be obtained from NWS and the news media. The CDOT plans to implement this prediction capability operationally for the next winter season, starting with the most troubled highway districts in the mountains and in the northeastern plains. To the best of our knowledge, this is the first, operational mesoscale prediction system that runs operationally on a PC.

(7) One cannot expect forecasts, even from the most sophisticated numerical prediction models, to be absolutely accurate. Incomplete specifications of initial and boundary conditions prohibit this dream to come true, even with "perfect" model physics. In mesoscale prediction models four-dimensional data assimilation has brought significant improvements to forecast quality. However, for short-term prediction (nowcasting) such data assimilation techniques tend to be of little benefit since rerunning of the model may require too much time under the pressure of tactical decisions to be made.

We have developed the concept of object oriented nowcasting to overcome these difficulties (Reiter, 1991). Again, SHRP, CDOT, and WELS helped to support the development and implementation of this concept: Meteorological phenomena, such as snowstorms, thunderstorms, etc., are defined as "objects" which exist in the real world. These objects have a number of defining characteristics, such as "location", "timing", "intensity", etc. by which they can be uniquely described. For each class of objects there exists a set of constraints, either in algorithmic form or in the form of heuristic rules, which define the behavior in space and time of each object within the class. As it turns out, many of these constraints can be defined by parameters which can be extracted from mesoscale numerical prediction, even if predictions cannot be made for individual objects of the class themselves. (For instance, a numerical forecast can prescribe rather well the environment in which a thunderstorm exists, moves, intensifies or dissipates, even though individual thunderstorm cells may escape the numerical prediction process.)

These objects in the real world are matched to "symbolic objects" on the computer screen (e.g. symbolized by icons) whose behavior mimics that of the real objects. Once a real object (e.g. a thunderstorm) has been ascertained to exist (by visual, radar, or lightning strike observations), its symbolic counterpart can be "clicked" to the computer screen at the proper time and place. Following the predetermined set of constraints, the symbolic object will provide a prediction of what the real object is expected to do for the remainder of the forecast period. If the predicted behavior departs from the observed one, the symbolic object can be manipulated to conformance by simple mouse point-and-click action. Instead of rerunning a numerical model (perhaps with scant input information), the corrective action taken on the symbolic object can be projected over the remainder of the forecast period. If there are systematic errors in the constraints that define the behavior of the particular object, a few iterative adjustments of the object on the computer screen should provide near-perfect nowcasts.

Rules of object behavior can be provided by laws of physics, but also by heuristic concepts, thus bringing to bear the tools of artificial intelligence.

The concept of symbolic object manipulation is not new in the field of computer graphics. However, we believe ours is the first such application in meteorology.

(8) Our involvement with artificial intelligence brought us in close contact with "fuzzy logic" (Reiter, 1991). The implementation of these logic concepts in meteorology should lead to much better assessments of forecast reliability than is currently possible with Model Output Statistics. Whereas MOS provides a "fixed" value of probability that a certain event will happen, "fuzzy logic" updates the certainty that such an event is likely (or not likely) to happen whenever new positive (or negative) evidence arrives. It would seem that fuzzy logic implementations in weather decision aids for battlefield applications would provide a decided advantage over present modes of operation. Again, to the best of our knowledge, we were the first to open this door for meteorology.

5. Theoretical Developments

5.1. Surface Energy Budgets

These studies relied on field data gathered by our team in the Rocky Mountains, in the Gobi Desert and in Tibet. The results of these studies, including suggestions on how to use them for parameterizations in numerical models, have been reported in the open literature cited earlier in this report.

5.2. Numerical Modeling

Mesoscale modeling efforts started out to help in the understanding of terrain effects on severe weather leading to flash floods. Results have been reported in the open literature cited earlier(see also Reiter, 1988, 1989a,b)

5.3. Artificial Intelligence

Our investigation broke new ground in the application of artificial intelligence (AI) concepts in meteorology. The introduction of object-oriented nowcasting concepts provided the vehicle by which rule-based heuristics could be combined with numerical modeling into a "hybrid modeling" approach. Such an approach is of particular significance in operational, objective nowcasting, where time is of the essence and rerunning of numerical models may not be feasible because of restricted computer resources and observations that may not conform to the parameter space of a numerical model. The manipulation of symbolic objects by computer can be made fast and efficient, even on a PC, thus providing computerized forecasting capabilities as battlefield planning tools on small tactical terminals. Initial prototype developments have been reported in the literature cited earlier (see also Reiter and Teixeira, 1991a,b, 1992a,b).

We regret that termination of funding prevents further exploitation of this new technology in support of potential DoD applications.

6. Colorado Snowstorms

6.1. Summary of Results

The bulk of funding in support of operational weather prediction with our hybrid forecasting system came from the National Research Council, Strategic Highway Research Program, from the Colorado Department of Transportation, and from WELS Research Corporation. Operational, real-time predictions were made during the time period from the end of October 1991 until early April 1992. Aside from the fact, that our model, on the average, performed significantly better in predicting detailed timing, locations, and amounts of snowfall than the NWS forecasts distributed by the media and by Weather Brief (Reiter et al., 1992a,b, Reiter and Teixeira, 1992 a,b, Strategic Highway Research Program, 1992), we gained considerable insight into terrain effects on severe winter weather in mountainous terrain.

(1) Even small ranges of hills are reflected in significant variations in snow deposition. It is well known that the Monument Hill/Palmer Divide area between Denver and Colorado Springs (in the vicinity of the U.S. Air Force Academy) is frequently hit by snowstorms causing havoc to traffic on I-25. Curiously, we found that quite often a tongue of predicted snowfall extended from the Monument Hill area towards Akron in northeastern Colorado. We received confirmation of these predictions from the Colorado Department of Transportation whose engineers, by experience, have to cope with more than the usual amount of plowing in this snow corridor. A very low range of hills, hardly noticeable on a map of Colorado, and mainly indicated by the divergent pattern of usually dry creek beds, juts northeastward from Colorado Springs. Lowry and Peterson Air Force Bases are located on either side of this spine of hills,

whereas the Air Fore Academy sits more or less astride. The nicely forested surroundings of the Academy are an indication of more abundant precipitation in that area, not only during winter, but also in convective storms of summer.

(2) Under strong Chinook wind conditions, nicely predicted by our model, one can often observe light snow (aggravated by severe ground blizzard conditions causing pass road closures) over the Continental Divide. "Foehn wall" clouds with a rather limited vertical extent and a "fuzzy" appearance signal such snowfall, but also indicate rapid evaporation of clouds along the lee side of the mountains. Such precipitation from shallow "Foehn" clouds tended to elude our prediction model. On at least one occasion we found that the moisture leading to such snowfall over the Continental Divide was contained within a roughly 100 m deep layer topping the planetary boundary layer over Grand Junction.

In a hybrid modeling approach one has two options to catch such elusive snowfall episodes:

(a) One can increase the vertical resolution of the numerical model by introducing additional model levels, especially in the lower troposphere where most of the moisture resides. Doing so would extract a heavy penalty in model performance on a small tactical terminal, perhaps to the point where the model can no longer be used as a battlefield decision aid.

(b) One can define snowfall caused by abrupt orographic lifting as an "object" whose behavior is controlled by the rate of lifting (affected by low-level wind speed, wind direction and slope aspect), and by the amount of moisture available for condensation. The **potential** for the existence of such an object can be provided by automated scrutiny of upwind soundings. The behavioral constraints are elicited from the output of a numerical prediction model which need not be **accurate** enough to forecast the object itself, but **adequate** to feed reliable values into the constraint formulations. **Evidence** for the existence of the object comes from first cloud or precipitation observations and can be transmitted to the computer screen in the form of suitable icons. Snowfall amounts and blizzard severity now become predictable by subjecting the object under consideration to the time- and space-variability of its constraints as forecast by the numerical model. These procedures would require only seconds on a PC.

7. Outlook

Hybrid modeling, especially when incorporating object-oriented approaches, shows great promise as a battlefield planning tool utilizing small tactical terminals, perhaps more so than the exclusive reliance on numerical modeling.

Numerical model output often provides insufficient clues as to the present and future behavior of specific weather phenomena, such as dust storms, visibility restrictions in downpours, etc. The local forecaster will be hard pressed to provide adequate input into a field commander's decisions, especially if data-poor areas and alien surroundings have to be covered by reliable predictions.

Hybrid modeling still will utilize all the help it can get from numerical modeling. However, it need not rely exclusively on such input. In essence, it will address the field commander's concern that certain weather "objects" can exist at a specified time and place. The answer to this initial question can come from numerical model output, from climatology, G.I.S. databases, etc. If the answer is affirmative, it will have to be honed as quickly and as reliably as possible towards an estimate that the object will exist at the given time and place. Evidence collection for, or against, the existence of that object will make use of "fuzzy logic" and certainty factors as described earlier. The existence of the object can be postulated in a "what if" game to reveal possible effects of anticipated behavior, even if the object has not yet been verified. Once its existence is confirmed, its future behavior can be predicted through adequate constraint formulations, even though the object itself may elude a numerical prediction model.

To attack the subject of object-oriented nowcasting in an efficient manner, one will have to come up with a priority listing of meteorological phenomena of concern to battlefield planning in a host of seasonal and location scenarios. These phenomena need to be translated into "objects", and constraints need to be defined which car accurately describe what makes these objects "tick". The resulting constraint libraries then need to be matched against available data sources (numerical model output, climatology, observations from humans or sensors). Finally, each object and its constraints needs to be tested before its release for field applications. Obviously, these are not small tasks.

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