Welcome to the Advanced Regional Prediction System!

We at the National Science Foundation's Science and Technology Center for Analysis and Prediction of Storms take great pleasure in welcoming you as a user of version 4 of our storm- and meso-scale prediction model, the Advanced Regional Prediction System (ARPS). This numerical model, data assimilation and data processing system, which is envisioned as a prototype for regional-scale operational prediction, has been developed primarily with the user in mind. Whether you are an expert in numerical modeling or if you've never before used a numerical model, we believe you'll find this self-contained, extensively documented code easy to learn, apply, and adapt to a variety of computer platforms. As ARPS continues to evolve, we welcome your advice and comments, for only through your input can we hope to perfect this tool. Happy computing!

Kelvin K. Droegemeier, Director

1 September 1995

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Important Message Concerning Library Software Not Supplied by CAPS

ARPS model and related codes are entirely self-contained (see Chapter 2) and do not *require* special mathematics, graphics, or other libraries. However, in order to utilize the full capability of our model system, we recommend that you obtain the *ZXPLOT graphics package* executable code from CAPS (see Chapter 12). CAPS can install this software for you if an executable version compatible with your particular machine is not available on our anonymous ftp server (see Chapter 12).

The software listed below will enhance your ability to view and process output produced by ARPS. They are *not* supported by CAPS, but can be obtained from the sources listed below.

- HDF history format option. Install the NCSA HDF software, which is available free of charge via anonymous ftp from *ftp.ncsa.uiuc.edu*.

- NetCDF history format option. Install NetCDF software, available from the UCAR Unidata Program Center, P. O. Box 3000, Boulder, Colorado, USA 80307. Tel: (303) 497-8644, Internet: *support@unidata.ucar.edu*

- NCAR Graphics for interfacing with ZXPLOT to produce CGM graphics metafiles. Install the NCAR Graphics package. For further information, call the National Center for Atmospheric Research at 303-497-1000.

- Savi3D history dump and visualization options. Install Savi3D, which is a commercial software package available from: SSESCO, 511 11th Ave. S., Box 212, Minneapolis, MN, 55415. Tel. (612) 342 0003, E-mail: *info@ ssesco.com*

- GrADS history dump and the graphic display options. GrADS was written by Brian Doty, University of Maryland (*doty@cola.umd.edu*, Tel: 310-405-5356).

- gzip, gunzip GNU Free Software Foundation software obtainable from GNU Internet site at *prep.ai.mit.edu* or from other mirror sites. They compress or decompress files to reduce their sizes.

Required Acknowledgment When Using CAPS Software and Related Resources

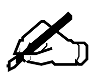
The following statement regarding the use of CAPS software must be included in the acknowledgments section of any written material, including non-archive journal publications:

"The simulations/predictions (or other items as appropriate) were made using the Advanced Regional Prediction (ARPS) developed by the Center for Analysis and Prediction of Storms (CAPS), University of Oklahoma. CAPS is supported by the National Science Foundation and the Federal Aviation Administration through combined grant ATM92-20009."

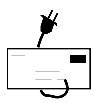
Typographical Conventions Used in this Guide

- **Bold** typeface is used for commands
- *Italic* characters or strings are used for variables, parameters and filenames
- `Courier` font is used for program listings
- Only times, symbol (σψμβολ), `courier` and helvetica fonts are used in this document

Several symbols appear in the margins of this Guide for your convenience:



Address



E-mail address

Phone number

Acknowledgments

The Center for Analysis and Prediction of Storms is supported by the National Science Foundation and Federal Aviation Administration through combined Grant and Cooperative Agreement ATM92-20009. A special acknowledgment is in order for our colleagues who contributed in various ways to the development and testing of the Advanced Regional Prediction System (ARPS). We would like to thank Paula Reid, Joe Bradley, and Robert Lindsey for their efforts at the beginning of this project, and more recently Mr. and Ms. Hao Jin, Dan Weber, Xiaoguang Song, Yuhe Liu, Adwait Sathye, Norman Lin, David Jahn, Min Zou, Limin Zhao, Steve Lazarus, Steve Weygandt, Dr. Gene Bassett, Dr. Donghai Wang, Dr. David Zhi Wang, Dr. Richard Carpenter, Yvette Richardson, Jian Zhang, Jason Levit, Scott Ellis, Yifeng Tang, Kenneth Nixon, Seon-Ki Park, Liping Sun, J. Nicolas Watson and Delano Barnes. Dan Weber, Yuhe Liu and Adwait Sathye also contributed to the preparation of this Guide.

We have benefited tremendously from collaborations and discussions with numerous scientists around the world, including: Dr. Kenneth Johnson, Dr. Dennis Duke, Tom Green, Jeff Bauer, Gregory Riccardi and Randy Langley of the Supercomputer Computations Research Institute at Florida State University; Dr. Paul R. Woodward, Dr. Matt O'Keefe, Olivier Meirhaeghe, and Tom Varghese of the University of Minnesota's Army High Performance Computing Research Center; Dr. Kim Mills, Dr. Geoffrey Fox, and Dr. Nancy McCracken of the Northeast Parallel Architecture Center; Dr. Gary Sabot of Sabot Associates, Inc.; Dr. Skef Wholey of Sun Microsystems, Inc.; Neil Lincoln and Dr. Dennis Moon of SSESCO; Drs. W. Skamarock, A. Crook and J. Dudhia of National Center for Atmospheric Research, Dr. G. Tripolli of University of Wisconsin at Madison, Dr. Craig Mattocks of NOAA's Atlantic Oceanographic and Marine Laboratory; Dr. Sandrine Anquetin of INRIA/France; Dr. Francois LeDimet from Grenoble University, France; Dr. Wei-Kuo Tao of the NASA Goddard Space Flight Center; Don Crow and Mike Tuttle of Cray Research, Inc.; Dr. Lance Leslie of the University of New South Wales; Dr. Patrice Mestayer of the French National Scientific Research Center; Drs. Ge Peng and Christopher N.K. Mooers of the University of Miami; Dr. Ron Cresswell of Monash University; Milton Speer of the Bureau of Meteorology, Sydney, Australia; Dr. Burton Freeman of Maxwell Laboratories; and Dr. Robert Lee of the Lawrence Livermore National Laboratory. Our special thanks go to Dr. W.-K. Tao for providing the original ice microphysics parameterization code from the Goddard cumulus ensemble model, to Dr. W. Skamarock for collaborative work on the adaptive grid refinement interface, and to Dr. Craig Mattocks for developing ARPS GRIB data reader.

CAPS wishes to acknowledge the National Center for Atmospheric Research, which is sponsored by the National Science Foundation, for supplying the digital terrain data. The surface characteristics database is taken from the Global Ecosystems Database and Experimental Calibrated Global Vegetation Index, both produced by the National Geophysical Data Center.

Finally, we extend our appreciation to Sue Weygandt and Eileen Hasselwander for their expert assistance with the preparation of this User's Guide. We express our special thanks to Dr. Burton Freemen, whose thorough review of the draft significantly improved the readability of this Guide.

1 Overview of CAPS and ARPS Project

1.1. Purpose of this Document

This document provides a complete and self-contained description of the Advanced Regional Prediction System, ARPS, and related components as of the official release date of Version 4.0. The document contains information about accessing the code, a tutorial, a reference guide, theoretical and numerical formulations, code structure charts and performance statistics, descriptions of pre-processing tools and a self-contained graphics post-processing package for viewing model output, results from validation experiments, and solutions against which the model can be validated when moved across platforms. Extensive documentation can also be found within the codes that supplement this guide.

The authors of this User’s Guide recognize that typographical and other errors may be present, and your assistance in correcting them and patience in dealing with them are greatly appreciated. Comments on how the documentation might be altered to better suit your needs are welcome, and you may direct such information to (e-mail is preferred):

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e-mail: arpsuser@uoknor.edu

For additional information about CAPS, please consult our Mosaic home page at URL address *http://wwwcaps.uoknor.edu*.

1.2. The Mission, Goals, and Structure of CAPS

In December, 1988, the National Science Foundation established 11 Science and Technology Centers in response to concerns that the U. S. was losing its competitive edge in scientific pursuits that have important technological consequences, particularly with respect to potentially marketable products. Through relatively stable, long-term funding, these centers were designed to investigate problems that have considerable societal impact, require collaboration among disciplines, are too broad for the single-investigator mode of research, and have long-term objectives that cannot be reasonably met using the traditional mode of 1 to 3 year grants. It was hoped that these centers, based at universities, would establish broad collaborations with private sector and government agencies and, as a result, substantially reduce the time between basic discovery and practical utilization.

The Center for Analysis and Prediction of Storms (CAPS), located at the University of Oklahoma and one of the first 11 of 25 S&T centers now in operation, has as its mission the development of techniques for the numerical prediction of small-scale weather, with a principal emphasis on increasing substantially the accuracy and reliability of warnings of hazardous events associated with thunderstorms on time scales of one to several hours over spatial domains of several hundred to a few thousand kilometers on a side. Expansion of this research to wintertime events is now being undertaken. CAPS postulates that the location (to within a few miles) and intensity of new thunderstorms and their associated severe weather (hail, strong winds, heavy rain) can be predicted up to 4 hours in advance, while the detailed evolution of existing storms can be foreseen for periods of up to 12 hours.

Two major developments during the past few years provided the impetus for creating CAPS and for moving from a mode of storm simulation to one of prediction. The first is a national, multi-agency effort to place some 175 scanning Doppler radars around the U. S. (the WSR-88D Program, formerly known as NEXRAD) by the end of the decade, providing nearly continuous single-Doppler coverage of spatial and temporal scales relevant to storm prediction. The second development, stimulated by the first and now the centerpiece for making storm-scale prediction a reality, concerns techniques for retrieving unobserved quantities from single-Doppler radar data to yield a consistent set of mass and wind fields appropriate for initializing a storm-scale prediction model.

The CAPS program now comprises **six major thrusts**, the *first* of which involves the development and operational testing of a new prediction model (ARPS, or Advanced Regional Prediction System). ARPS employs strict coding and documentation practices and is thus easy to learn and use. Further, it is highly portable among a variety of computer architectures with emphasis on parallel and massively parallel systems, modular for ease of modification, growing in the sophistication of its physical and numerical formulations, and has, through the use of massively parallel computers, achieved problem sizes never before possible for a storm-scale model. ARPS was a finalist for the 1993 Gordon Bell Prize in high-performance computing, and is being used by over 100 scientists worldwide as both a research and educational tool. Collaborations with notable individuals and centers of high-performance computing and automated differentiation have played a key role in the success of ARPS as a tool for meeting the objectives of CAPS, and in it becoming a modern paradigm for large scientific code.

The *second research thrust* involves the development of a variety of techniques for assimilating data, principally from single Doppler radars, into ARPS or similar models. Many competing strategies are currently being evaluated in a multi-institutional “bake-off” to assess their overall effectiveness and sensitivity to particular weather scenarios, and to suggest improvements or methods for combining elements of each to arrive at a single technique that is best suited for CAPS' needs. The techniques being evaluated, most of which were developed at CAPS or with CAPS support, include a forward-variational method that represents an embellishment of earlier work at CAPS, a simple adjoint technique and its related variational methods, a full adjoint of a dry 3-D convective-scale model, and a new two-scalar approach that combines some elements of the aforementioned techniques.

Sensitivity of numerical storm-scale forecasts to errors in initial and boundary conditions, along with simulation studies of convective storms and the application of ensemble forecasting to the storm-scale, compose the *third thrust area* and seek to provide a better understanding of small-scale atmospheric predictability and its practical assessment in operational meteorology. In this context, CAPS is collaborating with Argonne National Laboratory to explore the use of forward-accumulation as well as backward (adjoint) differentiation techniques as a means for evaluating model sensitivity to control parameters, though within the constraint of linear departures about a particular nonlinear forecast. A principal goal of this work is to determine whether such an approach, compared to the more traditional and expensive "brute force" method using multiple forecasts from a nonlinear model, is viable for deep convection where the linear approximation may be valid only for relatively short periods of time. Sensitivity studies are also being performed using real-data to provide useful information for improving existing and developing new four-dimensional data assimilation schemes and mesoscale observing systems/strategies.

The *fourth and newest thrust area* involves close collaboration with the NOAA Forecast Systems Laboratory to develop an Oklahoma-area version of the Local Analysis and Prediction System (LAPS). The new so-called OLAPS (Oklahoma LAPS), now running at 10 km horizontal resolution on the CAPS cluster of IBM RISC workstations, is designed to provide background fields for *assimilating* WSR-88D data into ARPS model. OLAPS improves significantly the surface analysis by using data from the 111-station Oklahoma Mesonet, and is designed to utilize data from profilers, mobile mesonets, fixed and mobile balloon soundings, the operational NWS stream, WSR-88D and research radars, satellite sounding and imagery, and the DOE ARM-CART suite of instruments. The OLAPS is the prototype for relocatable regional analysis systems that are a necessary component of regional storm-scale data assimilation and numerical prediction.

The *fifth* involves the operational evaluation of all CAPS components in collaboration with the Experimental Forecast Facility (EFF) at the Norman National Weather Service Forecast Office and, eventually, with the NOAA Storm Prediction Center. A preliminary test with ARPS during May, 1993 sought to provide CAPS and the EFF with experience using, and evaluating the logistics of integrating, a realtime nonhydrostatic model into an operational environment as a preface to subsequent evaluations using the more complete data assimilation and model frameworks now under development. The results of this test were very encouraging, and the program was expanded as part of the VORTEX tornado field experiment during the spring storm seasons of 1994 and 1995.

The *sixth* area involves the transfer of CAPS' intellectual property and technology to the private sector. This is accomplished through the OU Center for Computational Geosciences (CCG), a non-profit element of the OU Research Corporation directed by Kenneth Nixon, CAPS' Industrial Liaison. The CAPS commercialization strategy has several different yet interrelated elements or goals, including exploiting the uniqueness of ARPS for application to problems outside the severe storms arena, *e.g.*, fog prediction, aviation weather, air and water quality, fire weather, and emergency response. A number of projects along these lines have already been funded, and CAPS is actively seeking additional collaborations that will enhance ARPS and broaden its scope of application..

For additional information about CAPS, please consult our World Wide Web home page at *http://wwwcaps.uoknor.edu*.

1.3. Project History and Model Overview

The model development project began in July, 1990 with ARPS Version 1.0, which was designed as a tool for evaluating computational design strategies, developing communication links between our professional programming and scientific staff, and establishing collaborations with external groups. Intended as a "disposable code" and based upon dry, compressible dynamics, Version 1.0 was completed in October, 1990 and was replaced by Version 2 shortly thereafter, the latter based upon a fully 3-D transformed coordinate framework. At Version 2.5 (Spring, 1992), the model project underwent substantial personnel changes, resulting in the adoption of slightly different theoretical and vastly different code frameworks. This next version, 3.0, was the first formal release of ARPS to the national community, and distribution began on 23 September 1992.

The present release, Version 4.0, is significantly enhanced from the previous official release, Version 3.0, and has the following features:

- non-hydrostatic, compressible dynamics in a terrain-following vertical coordinate;
- global terrain database and configuration software with 30 second terrain resolution for most of the US and one degree terrain coverage for the world;
- 1-D, 2-D, and 3-D Cartesian geometry;
- user-specified vertical grid-stretching option;
- Smagorinsky, 1.5 order TKE, and Germano subgrid-scale turbulence models;
- 2nd and 4th order advection options;
- leapfrog time differencing and split-explicit treatment of gravity and acoustic modes; vertically implicit option;
- warm-rain and 3 category ice (total 6 water phase) microphysics,
- cloud water, rain water, cloud ice, snow, and hail/graupel;
- surface energy and moisture budgets with USDA surface characteristics data and associated pre-processing software;
- stability-dependent surface fluxes;
- two-layer soil model;
- forward-variational data assimilation system designed for incorporating spherical coordinate Doppler radar and other data;
- automated domain translation and storm-tracking capability;
- adaptive mesh refinement (dynamic grid nesting);

- solution validation suite;
- multiple data formats for history and restart dumps;
- ARPSplot post-processing and graphics package;
- ARPStools diagnostic analysis package that includes Skew-T diagram plotting program.
- Kuo cumulus parameterization scheme

ARPS 4.0 runs on both conventional scalar (*e.g*. IBM RS/6000 workstation) and vector machines (*e.g*. Cray C-90), as well as on MPP machines (*e.g*. Cray T3D, CM-5) and workstation clusters using PVM message passing library. A data parallel version for Cray T3D will be available.

1.4. Project Objectives

The principal objective of the Model Development Project is the creation of a meso-to-storm scale prediction system capable of meeting the scientific and educational objectives of the Center for Analysis and Prediction of Storms (CAPS). With regard to the former, the model, known as the CAPS Advanced Regional Prediction System (ARPS), must be able to accommodate, through various assimilation strategies, data from the WSR-88D radars and serve as a tool for evaluating the predictability of storm-scale motions. As an educational tool, the model is being developed as a framework for application in meteorology classes such as numerical weather prediction, mesoscale meteorology, and computational fluid dynamics, as well as in computer science and engineering disciplines for testing computational strategies and numerical techniques. A set of model-based exercises for college-level classes is being developed and will be made available to the national community.

1.5. Project Personnel and Their Responsibilities

The senior scientific and support personnel, along with their principal responsibilities as of 15 August 1995, are listed below:

- **Dr. Ming Xue (mxue@uoknor.edu) —** Project Director and Senior Research Scientist, responsible for overall project coordination and planning, model dynamics, code construction and testing, module integration, User's Guide, and vector graphics.

- **Dr. Kelvin Droegemeier (kdroege@uoknor.edu) —** Center Director and Associate Professor of Meteorology, responsible for parallel processing, automatic adjoint generation, model availability, documentation design, educational outreach, and operational testing and evaluation.

- **Dr. Vince Wong (vwong@uoknor.edu) —** Senior research scientist responsible for physics parameterizations.

- **Dr. Alan Shapiro (ashapiro@uoknor.edu) —** Senior research scientist responsible for model validation and testing, coordination of ARPS User's Group, and development of the forward-variational data assimilation system and single-Doppler retrieval algorithms.

- **Mr. Keith Brewster (kbrewster@uoknor.edu) —** Doctoral candidate responsible for the development and integration of the Oklahoma Local Analysis and Prediction System (OLAPS) as well as realtime prediction testing.

- **Dr. David Zhi Wang (dwang@uoknor.edu) —** Research scientist, responsible for the development and implementation of adjoint data assimilation techniques for ARPS.

- **Dr. Gene Bassett (gbassett@uoknor.edu) —** Post-doctoral fellow, responsible for parallel computing research and graphics support.

- **Dr. Richard Carpenter (rcarpenter@uoknor.edu) —** Research scientist at the OU Center for Computational Geosciences, responsible for physics testing and model application.

- **Mr. Adwait Sathye (asathye@uoknor.edu) —** Senior scientific programmer and IBM RS6000 workstation cluster manager, responsible for code optimization, parallel computing research, and model I/O and graphics support.

- **Mr. Yuhe Liu (yuhe@uoknor.edu) —** Scientific programmer, responsible for code integration, maintenance and user support, physics module development and testing.

- **Dr. Donghai Wang (dhwang@uoknor.edu) —** Visiting research scientist, responsible for general code development and testing.

- **Ms. Limin Zhao (lzhao@uoknor.edu) —** Assistance with single-Doppler retrieval system development and cumulus parameterization implementation.

A number of students and support staff are also involved with the model development effort, including:

- **Edwin Adlerman (eadler@uoknor.edu)** (masters student) — Application of adaptive mesh refinement techniques; studies of cyclic mesocyclogenesis.

- **Delano Barnes (dbarnes@uoknor.edu)** (undergraduate fellow) — ARPS code testing.

- **Scott Ellis (sellis@uoknor.edu)** (masters student) — Development of hole-filling techniques in Doppler assimilation.

- **David Jahn (djahn@uoknor.edu)** (Center Assistant Director) — Numerical technique development; study of buoyancy and shear effects on deep convection.

- **Steven Lazarus (slazarus@uoknor.edu)** (doctoral student) — Development of ARPS forward-variational data assimilation system.

- **Jason Levit (jlevit@uoknor.edu)** (undergraduate student) — Predictability and model field adjustment studies.

- **Seon Ki Park (spark@uoknor.edu)** (doctoral candidate) — Adjoint sensitivity analyses of deep convection.

- **Yvette Richardson (yrichard@uoknor.edu)** (doctoral student) — Dynamics of organization and transition in rotating convective storms.

- **Xiaoguang Song (xsong@uoknor.edu)** (doctoral student) — Support for physics development, including subgrid scale turbulence parameterization.

- **J. Nicolas Watson (nwatson@uoknor.edu)** (undergraduate fellow) — ARPS code testing.

- **Daniel Weber (dweber@uoknor.edu)** (doctoral student) — Development of terrain database/management system; study of surface heating effects on terrain-induced flows.

- **Michael B. K. Wee (mwee@uoknor.edu)** (system administration assistant) — Assisting the management of CAPS IBM workstation cluster.

- **Stephen Weygandt (sweygan@uoknor.edu)** (doctoral candidate) — Development of ARPS forward-variational data assimilation system.

- **Sue Weygandt (swey@geoadm.gcn.uoknor.edu)** — Publications Design Specialist responsible for documentation and user support information.
- **Jian Zhang (jzhang@uoknor.edu)** (doctoral student) — Real-data mesoscale predictions using OLAPS data.
- **Jinxing Zong (jzong@uoknor.edu)** (doctoral student) — Real-data mesoscale simulations with Doppler radar data.
- **Min Zou (mzou@uoknor.edu)** (masters student) — Graphics and OLAPS support; mesoscale analysis techniques.

1.6. Model Design Philosophy and Rationale

Current numerical prediction models run by the National Weather Service operate at grid spacings down to about 30 km for periods out to 48 hours on a national scale. Consequently, they lack the spatial resolution required to capture small-scale, short-duration events such as individual thunderstorms, snow bands, and downslope windstorms. The numerical model developed by CAPS has been designed to predict just these sorts of weather events, with general prediction goals as follows:

Mesoscale Phenomena (Δx = 5 to 15 km)

- 0 to 12 hours
- Location of events to within 50 km
- Timing of events to within 1 hr
- $\Delta V \pm 5$ m/s, $\Delta T \pm 3$ degrees Kelvin, precip rate ± 5 mm/hr

Stormscale Phenomena (Δx = 1 to 3 km)

- 0 to 6 hours
- Location of events to within 10 km
- Timing of events to within 15 min
- $\Delta V \pm 5$ m/s, $\Delta T \pm 2$ degrees Kelvin, precip rate ± 5 mm/hr

Microscale Phenomena (Δx = 0.1 to 0.5 km)

- 0 to 1 hour
- Location of events to within 1 km
- Timing of events to within 5 min
- $\Delta V \pm 2$ m/s, $\Delta T \pm 2$ degrees Kelvin, precip rate ± 2 mm/hr

After an extensive survey of existing hydrostatic and nonhydrostatic models, CAPS chose to develop an entirely new prediction model to ensure sufficient adaptability to new data assimilation strategies, ease of use, and suitability for a variety of computing platforms, especially scalable parallel processors.

Below are listed the principal computational/structural characteristics of ARPS model system, some of which are currently being implemented as discussed in subsequent sections:

- Modular code structure for the sequential introduction of improved physics and numerics;
- Scalable code structure to accommodate broad classes of parallel and massively parallel architecture of both the MIMD and SIMD class;
- Extensive internal and external documentation, including tutorials, as well as the use of new coding strategies based upon numerical differential operators, to facilitate ease of learning, use, and modification;
- Coupling to an interactive visualization system that also permits window/menu control of the model execution and examination of model results as they are being computed;
- Use of pure FORTRAN-77 constructs (except for NAMELISTS) to render the code portable among a wide variety of computer systems;
- Ability to handle multiple-scale phenomena through the use of adaptive mesh refinement;
- Rapidly optimizable for any chosen computer system.

1.7. Subroutine Design Conventions and Constraints

1.7.1. ARPS' discrete operator methodology

The development of complex hydrodynamic numerical models is an arduous task that typically consumes tens of thousands of person hours over periods of years or even decades. The proper maintenance and continued improvement of such codes are even more time consuming and challenging, due in part to a lack of knowledge by scientists of appropriate software development strategies typically known only to or understood by professional software engineers. Another contributing cause, however, is the fact that most computer languages used in the scientific and engineering communities (*e.g.*, FORTRAN, C) do not provide constructs directly analogous to the “native language” of a user, *e.g.*, derivatives, integrals, *etc*. As a result of these and other factors, many existing models require considerable investments of time to learn and use and are unable to be adapted to rapid advances in technology (*e.g.,* massively parallel computers) because their design is tied to prevailing standards, languages and architecture rather than more elemental and stable mathematical expressions.

In an effort to overcome some of these problems, and to establish a methodology for the rapid design and validation of complex models that are easily maintainable and operable across a variety of computer architecture, including those anticipated during the next 20 or so years, CAPS has developed a new strategy for solving differential equations based on the use of discrete numerical operators (Droegemeier *et al.*, 1995). By design, the operators preserve the formal algebraic structure of the hydrodynamic equations, producing a code that, upon visual inspection, resembles the equations themselves rather than unwieldy expressions involving multiple increments to array subscripts. As fundamental units of discrete computation, the operators preserve the fine granularity inherent in hydrodynamics computations (*e.g*., multiplication of two dependent variables, single and multiple derivatives), giving the user an ability to distribute this granularity and associated parallelism in a manner most appropriate for the target computer architecture. The simplicity of the operators facilitates code validation, maintainability, ease of modification, and ease of learning, and therefore greatly reduces the time required to develop and, most importantly, to debug and validate complex models.

The operator-based strategy is illustrated in detail for a scalar advection equation in Appendix A.

1.7.2. Rules and conventions used in ARPS subroutines

Subroutine layout:

SUBROUTINE SUBNAME (input_argument_list,
output_argument_list, work_arrays)

The following information, separated by a full line of “###” characters, is provided at the beginning of each subroutine:

Purpose
Author, date, and modification history
Input and output list and definitions
Variable declarations (the IMPLICIT NONE construct is always used)

Include files
Executable code
RETURN
END

Subroutine Conventions:

- The subroutine and its name are in CAPITAL letters.
- The ordering of subroutine arguments is as follows: input; output; and work arrays.
- Major comment blocks are separated by a full line of “###” characters.
- Comment lines start with a “c” and the text starts in the 7th column.
- The executable code in each routine begins immediately following the block of characters given below:

```
c
c@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
c
c     Beginning of executable code...
c
c@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
c
```

  This allows one to search for the beginning of executable code in each subroutine by simply searching for the string “@”.

- Key commands including IF, THEN, ELSE, ENDIF, DO, CONTINUE, RETURN, STOP, END, OPEN, CLOSE, CALL are given in CAPITAL letters.

- Statements inside IF and DO blocks are indented successively by 2 spaces.
- The “implicit none” construct is always enforced, **and thus all variables and constants must be explicitly declared.**
- All temporary work arrays (*e.g.*, tem1, tem2, *etc*.) are local to the routine in which they appear. They may be overwritten once the routine in which they are used is exited.
- A colon (:) is used as the continuation mark.
- Tabs are not used.

1.8. ARPS 4.0 Characteristics

1.8.1. ARPS 4.0 Features

Below are listed the basic functional features of ARPS 4. **Features added since the release of ARPS 3.0 are shown in italics**. **Those entries marked with an asterisk (*) are auxiliary features** that are part of the "system" of ARPS while those without are components of ARPS40 (prediction model itself) program. Please consult other chapters in this document for a detailed description of the model and related software.

- **Equations** - Nonhydrostatic and fully compressible.
- **Coordinate System** - *Generalized terrain-following coordinate with* equal-spacing in x and y directions *and grid stretching in the vertical*. Map projection factor is included the pre-processing and post-processing programs but has yet to be included in the dynamic equations.
- **Geometry** - 1-D, 2-D, 3-D configurations.
- **Prognostic Variables** - Cartesian wind components, perturbation potential temperature and pressure, *subgrid-scale turbulent kinetic energy*, mixing ratios for water vapor, cloud water, rainwater, *cloud ice, snow and graupel/hail*.
- **Spatial Discretization** - Second-order quadratically-conservative and *fourth-order* quadratically-conservative finite differences for advection, and second-order differencing for other terms. Arakawa C-grid is used.
- **Temporal Discretization** - Second-order leapfrog scheme for large time steps with Asselin time filter option. First-order forward-backward explicit *with second-order centered implicit option* for small time steps.
- **Solution Technique** - Split-explicit (mode-splitting) with *vertically-implicit option.*
- **Initial State** - Horizontally-homogeneous initialization using a single sounding, using analytic functions, or using *three dimensional horizontally inhomogeneous data.*
- **Lateral Boundary Conditions** - Options for periodic, rigid, zero-gradient, wave-radiating, *externally-forced*, and user-specified conditions.

- **Top & Bottom Boundary Conditions** - Options for rigid, zero-gradient, periodic, and top radiation condition using a Rayleigh sponge layer.

- **Divergence Damping** - The model provides an option for divergence damping to control acoustic oscillations.

- **Reference Frame Rotation** - Options for various Coriolis formulations.

- ***Domain Translation** - Options for user-specified or automated (based on feature-tracking algorithms) translation of the computational domain.*

- ***Nesting** - Adaptive grid refinement interface for unlimited level of grid nesting at arbitrary locations and orientations to be placed at run time. One-way interactive self-nesting is also available.*

- **Subgrid Scale Turbulence** - Options include Smagorinsky-Lilly diagnostic first-order closure, *1.5-order turbulent kinetic energy formulation, and Germano dynamic closure*. *The model also provides options for isotropic and anisotropic turbulence treatments.*

- **Spatial Computational Mixing** - 2nd- and 4th-order options.

- **Cloud Microphysics** - Kessler warm-rain and *3-category ice (adapted from the NASA Goddard Cumulus Ensemble Model written by Dr. W.-K. Tao)* microphysics parameterizations.

- ***Cumulus Parameterization** - Kuo cumulus parameterization.* Kain-Fritsch cumulus parameterization scheme to be added.

- **Surface Layer Parameterizations** - Surface momentum, heat, and moisture fluxes from bulk aerodynamic drag laws as well as *stability-dependent formulations.*

- ***Soil Model** - Two-layer diffusive soil model with surface energy budget equations.*

- ***Longwave and Shortware Radiation** - A component that is related to the surface energy budget is included.* Direct radiation interaction with the cloudy atmosphere to be added.

- ***Surface Data** - USDA surface characteristics database and pre-processing software.*

- ***Terrain** — Terrain database and pre-processing software with 30 sec terrain for most of the US and 1 deg terrain for the world.*

- ***Objective Analysis**** - *Oklahoma Local Analysis and Prediction System (OLAPS) that can provide real-time analyses for model initialization.*

- ***Interface**** - Interface with NMC RUC model or Eta model is available.

- ***Data Assimilation*** - *Forward-variational four-dimensional data assimilation system, augmented by a single-Doppler velocity retrieval package. These systems may be used with ARPS or as stand-alone software.*

- **ARPS Adjoint*** - *The adjoint of the dry version of ARPS 4.0 has been completed.*

- **History Data** - ARPS supports the following history data dump formats: unformatted binary, formatted ASCII, packed binary, NCSA HDF, *NetCDF, packed NetCDF, GrADS,* and Savi3D (for visualization using the Savi3D software package). *GRIB format will be available at a later time.* These formats can be read by post-processing programs provided with the model (see below), or by user-created programs based on a template provided.

- **Restart Option** - Full restart capability at intervals selected by the user.

- **ZXPLOT*** - A vector graphics package, similar to NCAR Graphics, that performs a variety of graphics functions and supports X-windows, GKS, and postscript functionality. This package, which is the underpinning for ARPSPLT (see below), was developed by CAPS senior research scientist Dr. Ming Xue during his doctoral work at Reading University. The ZXPLOT object code (only) is currently available free of charge and is required for using ARPSPLT (see below).

- **ARPSPLT*** - A vector graphics post-processing package that allows the user to make contour plots, 3-D wire frame plots, and profiles of basic and derived fields using model-generated history data. The package supports overlays, color filling, user-specified contour intervals and annotation, and multiple picture formats. This package is based on ZXPLOT (see above).

- ***ARPSTools**** - *A combination of software packages supplied by both local and external users for use in analyzing output from ARPS. Capabilities include time-dependent trajectories, skew-T/log-P and hodographs, and various statistics.*

- **Validation** - A suite of validation tests is available. These range from basic advection and symmetry tests to 3-D storm simulations. A real data test case will be available later.

- ***User Interfaces*** - *ARPS and ARPSPLT utilize namelist input files which can be edited manually or configured using an X-windows interface that is particularly helpful to new users.*

- **Compilation** - *The compilations of all programs are handled by a single Unix shell script that invokes the Unix make command. The system dependencies are automatically handled by the script.*

- **Execution Mode** - Interactive (via *X-windows interface*) and batch execution are supported for ARPS and ARPSPLT.

- ***PVM version*** of ARPS together with automatic parallel code translation tools.

1.8.2. Separately-Available Features of ARPS 4.0

Certain features of ARPS are not included in the standard distribution package of ARPS 4.0 official release. Most of them are available as separate packages (consult relevant chapters) and a few of them can be obtained under special arrangement with CAPS. These features are listed in the following. Interested users please contact `arpsuser@uoknor.edu`.

- Oklahoma local analysis and prediction system (OLAPS);
- Adaptive grid refinement capability;
- Germano subgrid scale turbulence closure scheme;
- Forward variational data assimilation system;
- Doppler radar retrieval packages;
- Adjoint of ARPS;
- ZXPLOT library object code;
- X-window interface for ARPS and ARPSPLT;
- ARPStools;

1.9. ARPS Further Development Plans

The CAPS model development team has prepared a multi-year plan that describes incremental changes to ARPS model (see Figure 1.1, which also shows principal milestones for CAPS among all 6 thrust groups and anticipated interactions with the NOAA Storm Prediction Center).

Version 5 of ARPS will see further improvements in the numerical solution techniques, complete radiation physics, better cumulus parameterization schemes, an interface to the NMC operational Eta model, enhancements to the four-dimensional data assimilation system, and an adjoint with full-physics.

ARPS Version 6 will boast further refinements to the physics, numerics, and data assimilation systems.

Center for Analysis and Prediction of Storms, 1994 - 2001

Target Year	Model Develop-ment	Assimila-tion Devel-opment	Simulation/ Prediction Studies	Data Acquisition & Archival	Opera-tional Testing	Tech-nology Transfer	Storm Predict-ion Center
1994	• Further testing and shakedown • Improve code performance on MPP's	• Bakeoff complete • First-generation forward scheme • Begin hand-coded adjoint	• ADIFOR & 1-D Model • Begin VORTEX case studies • Begin QPF study • Continue ensemble experiments	• OLAPS I and T-OLAPS operational • R/T WSR-88D ingest testing	• CRAFT/ VORTEX • Begin daily ARPS runs on IBM Cluster	• Establish joint venture with UNISYS • Seek additional STTR/ SBIR contracts • Full marketing plan in place	• P. Botherell and G. Grice arrive • Begin discussion on collaboration
1995	• ARPS 4 released • Enhance time and space discretization • Improve physics • Add cumulus parameterization scheme	• ARPS 4 dry adjoint • Further testing of all schemes	• Begin winter case study • Apply ADIFOR to ARPS 4 • Continue storm dynamics studies • Continue ensemble experiments and begin MOS work • Begin convective initiation study	• OLAPS II (includes WSR-88D data) • Improve OBAN	• CRAFT/ VORTEX	• Establish formal relationship with metr. consulting firm	• Start construction of new building • CRAFT/ VORTEX collaboration
1996	• ARPS 5 released • Full production on MPPs and workstation clusters	• Second-generation forward scheme • ARPS 4 full adjoint	• VORTEX case studies	• Add resampled WSR-88D data (?) on Level II data	• 2-part CRAFT (EFF, airlines)	• $600 K revenue base	• Plan for ARPS testing in SPC
1997	• Shakedown and testing	• Testing/ comparison with real data	• Case studies • Sensitivity studies	• Local data archive • R/T 88D data available regionally	• 1-part CRAFT (EFF), local television	• $800 K revenue base	• 40-member SPC staff arrives
1998	• Testing and improvement	• Testing/ comparison with real data	• Case studies • Sensitivity studies	• Evaluation	• Daily R/T model runs	• Establish formal agree-ment for joint operations with NOAA/NSF	• SPC fully operational
1999	• ARPS 6 released	• Final operational scheme	• Final MOS and ensemble strategy	• Evaluation	• Daily R/T support of SPC via ARPS 6	• Continue con-sulting work • $1000 K revenue base	• ARPS 6 R/T testing
2000	• Final testing and documentation	• Testing of scheme at SPC	• Testing of MOS/ ensemble at SPC	• Final version tested at SPC	• Further evaluation	• Continue con-sulting work	• ARPS 6 R/T testing
2001	Formal STC designation ends. CAPS continues to operate, though at perhaps reduced levels via an NSF "group" grant and other support (*e.g.*, DoD, DoE, ARPA, private sector). CAPS becomes an R&D component of the SPC via a MOA with NOAA and makes available the "frozen" ARPS 6 for operational use.						

Figure 1.1. Milestone chart for CAPS from 1994 to 2001.