The Advanced Regional Prediction System (ARPS) and Its Applications

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1. INTRODUCTION

In 1989, the Center for Analysis and Prediction of Storms (CAPS) was established at the University of Oklahoma as one of the National Science Foundation's first 11 Science and Technology (S&T) Centers. Its formal mission is to *demonstrate the practicability of storm-scale numerical weather prediction and to develop, test, and validate a regional forecast system appropriate for operational, commercial, and research applications*. Its ultimate vision is to make available a fully functioning storm-scale NWP system around the turn of the century (Lilly 1990; Droegemeier 1990).

Central to achieving this goal is an entirely new three-dimensional, nonhydrostatic model *system* known as the Advanced Regional Prediction System (ARPS). It includes a data ingest, quality control, and objective analysis package, a single-Doppler radar parameter retrieval and assimilation system, the prediction model itself, and a post-processing package. These components are illustrated in Fig. 1.

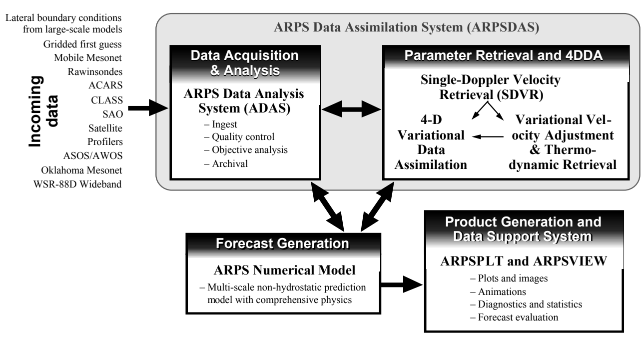


Figure 1. Principal components of the ARPS.

The numerical prediction component of the ARPS is a three-dimensional, nonhydrostatic compressible model formulated in generalized terrain-following coordinates. It is designed from the beginning to run on computing platforms ranging from single-processor scalar workstations to massively parallel scalar or vector processors. Guided by modern software engineering theories and practices, the entire system is written in a consistent style and is easy to use, extend and maintain. The code is also extensively documented and has served as an effective educational tool for many applications. The present version (Version 4.5.0) of ARPS contains a comprehensive physics package and has been applied successfully during the past few years to real-time operational prediction of storm-scale weather over several regions (Xue et al. 1996; Carpenter et al. 1999).

An early version (4.0) of the ARPS is described in Xue et al (1995), a comprehensive user's guide to the system. More recent development and model verifications are described in Xue et al (2000a; 2000b). In this paper, we briefly describe the current capabilities of ARPS and present some recent results of timing on parallel platforms and of a case study.

2. CURRENT STATUS AND FUTURE PLAN OF ARPS

ARPS Version 4.0 was officially released in mid-1995. Since then, many improvements have been made to the system and many sub-releases were made available on the CAPS anonymous FTP server (ftp://ftp.caps.ou.edu/ARPS). Significant improvements include:

- A completely new real-time data ingest and analysis system (ADAS) capable of handling a variety of data sources, including raw and retrieved Doppler radar and satellite data.
- A cloud analysis component in ADAS that creates three-dimensional fields of cloud, rainwater and improved fields of humidity and temperature;
- An integrated package for single-Doppler velocity and thermodynamic retrievals together with the associated variational adjustment procedures;
- A long and short-wave radiation package based on that of the NASA Goddard Space Flight Center;
- The Skamarock adaptive grid refinement that supports multiple level two-way interactive grid nesting;
- Kain-Fritsch cumulus parameterization;
- A non-local PBL parameterization based on 1.5-order TKE scheme;
- Schultz simplified ice microphysics;
- Inclusion of snow cover in the land surface-vegetation model;
- High resolution (~1km) terrain, land-user and land-cover data base and the option to use multiple soil types in each grid cells;
- An ensemble prediction component using Scaled Lagged Averaged Forecasting (SLAF) method for initial perturbations;

- Flux-corrected transport (FCT) monotonic advection option plus the choice of an efficient positive-definite advection scheme based on leapfrog centered scheme;
- A radiation top-boundary condition with a relaxed limitation on the lateral boundaries;
- Map factor in dynamic equations and provision for stretching in horizontal directions;
- Support of data sets from NCEP models (e.g., RUC, ETA and AVN) as analysis background and boundary condition;
- Streamlined support for MPP platforms (Cray T3E, SGI Origin 2000; IBM SP-2 and network of workstations including PC Linux clusters) via message-passing libraries;
- Significant code optimization, including that achieved by removing differencing opeartors;
- Soil model initialization procedure using antecedent precipitation index (API) or NCEP model fields;
- A perl-based fully automated procedure for real time analysis and prediction;
- Significantly enhanced graphics post-analysis program;
- Support of several new data formats (e.g., Vis5D, GRIB and GrADS) and data visualization tools;
- Conversion of the entire system to a new ARPS coding standard based on Fortran-90.

The Fortran-90 Version of ARPS will be released in earlier 2000, after additional structure changes are made that exploit new Fortran-90 features such as dynamic memory allocation. The primary focus of development for the next few years will be the development of a new three-dimensional variational (3DVAR) system that performs radar data retrievals and the analysis of all other data types in one single variational framework. This effort will also be part of a collaborative project with NCEP, NCAR and FSL to develop the next generation US weather research and prediction (WRF) model. The new 3DVAR system will be a natural successor to the current ADAS. There are also plans to continue improving the model physics, including those for precipitation and land surface processes. We also plan to implement a new two-way nesting capability that will run on distributed memory parallel platforms. Information on all aspects of the ARPS system can be found at http://www.caps.ou.edu/ARPS. Questions and comments can be addressed to arpssupport@ou.edu.

3. PARALLEL IMPLEMENTATION OF ARPS

The ARPS was developed from the beginning to run on both shared and distributed memory platforms. The distributed memory implementation is based on the Message Passing Interface (MPI). A single version of source code is maintained (Sathye et al. 1996). In the following, we present some recent timing results of ARPS.

Figure 2 shows the timings of ARPS running at 3-km spatial resolution on various distributed-memory platforms. The computational domain was decomposed into cubes of 19 x 19 x 53 grid points per processor. Individual processor domains were held constant and the number of processors increased to evaluate machine and code performance. Simulations were extended to 594 seconds and include 1 radiation time step, full surface physics, and ice microphysics for the standard May 20, 1977 Del City sounding. Note the excellent scaling as the number of processors is increased.

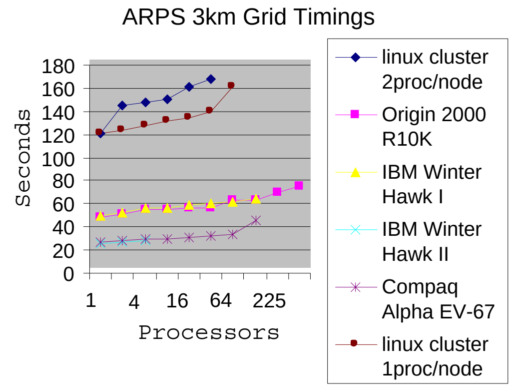


Figure 2. Timings for the ARPS on a variety of computing platforms for a fixed per-node domain size of 19 x 19 x 53 points.

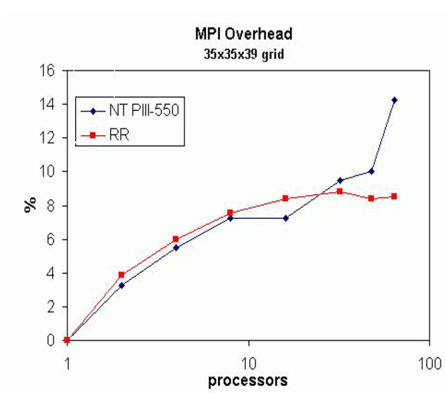


Figure 3. Message passing overhead as a function of the number of processors for dual Pentium-II based PC clusters. The MPI overhead is computed by dividing the MPI time by the time of a corresponding single processor run.

A research version of ARPS has also been tested on dual Pentium-II based PC clusters with Windows NT and Linux operating systems. Figure 3 shows the MPI overhead as a function of the number of processors. Note that the time attributed to message passing is less than 15% for both types of clusters and compares favorably, despite a slower network, to the more sophisticated Origin 2000 and Cray T3E parallel platforms. These favorable results may be due in part to the slower processor speed of the Pentium-II based clusters, which would tend to weight the model calculations more than for the Origin class machines.

In summary, the ARPS has been run with good efficiency on essentially all computer platforms currently available. In general, only a very small amount of effort is needed to move the system to a completely new platform.

4. ARPS PREDICTION OF THE JANUARY 21-23, 1999 ARKANSAS TORNADO OUTBREAK CASE

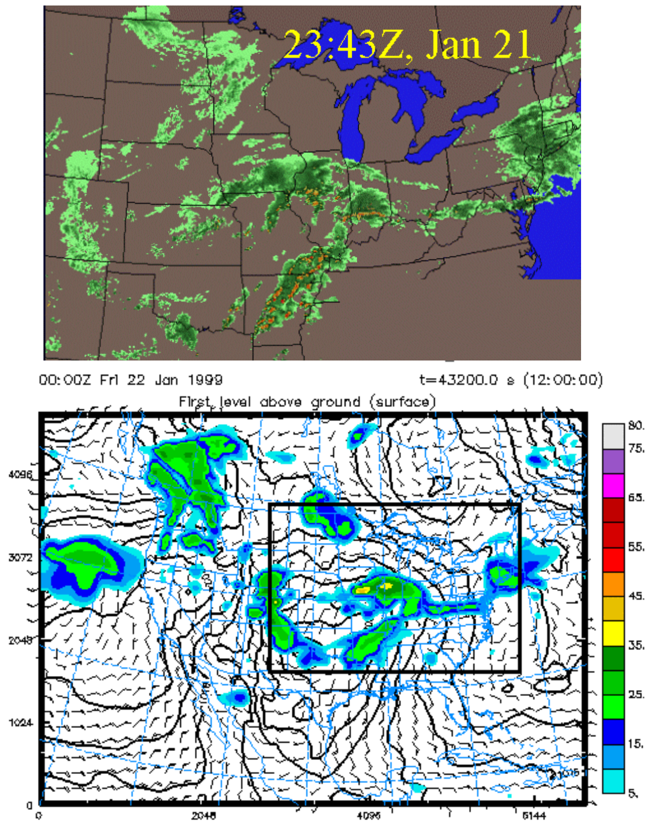


Figure 4. Observed radar reflectivity field (upper panel) and ARPS simulated (lower panel) surface winds, mean sea-level pressure (contours) and composite reflectivity field (shaded contours) at 00 UTC 22 on the 32 km grid, corresponding to 12 h of model simulation time. The upper panel corresponds to the area inside the box in lower panel.

An interesting case of 56-tornado outbreak in the state of Arkansas in central US occurred during the extended period of CAPS AMS-99 (1999 American Meteorological Society Annual Meetings) real-time forecasting experiment. Continued simulation study of this case has been made, with the goal of improving the longer range (48 hours) forecast and the understanding of the initiation of the tornadic thunderstorms in Arkansas, the later organization of convection into a mature and long-lived squall line, and the interaction among different scales. Best results are obtained when 32, 6 and 2 km resolution nested grids are used with each of them covering a rather large area. Hourly intermittent data assimilation for the first 24 hours of the 32 km grid simulation helped improving the development of the upper-level trough and the associated low-level cyclone to the lee of the Rockies, in particular in the first 12 hours of simulation. This improved prediction of large scalar flow ensured very realistic development and evolution of convective processes on the 6 and 2km grids, which did not include any data assimilation cycle.

Figure 4 shows the ARPS simulated fields at 00 UTC 22, January on the 32 km grid, corresponding to 12 h from the model start time. The observed reflectivity field is also shown. Compared with the radar observations, the spatial pattern of the precipitation in the observation domain is well reproduced by the model, so it the convection associated with the supercells across the SW-NE diagonal line of Arkansas.

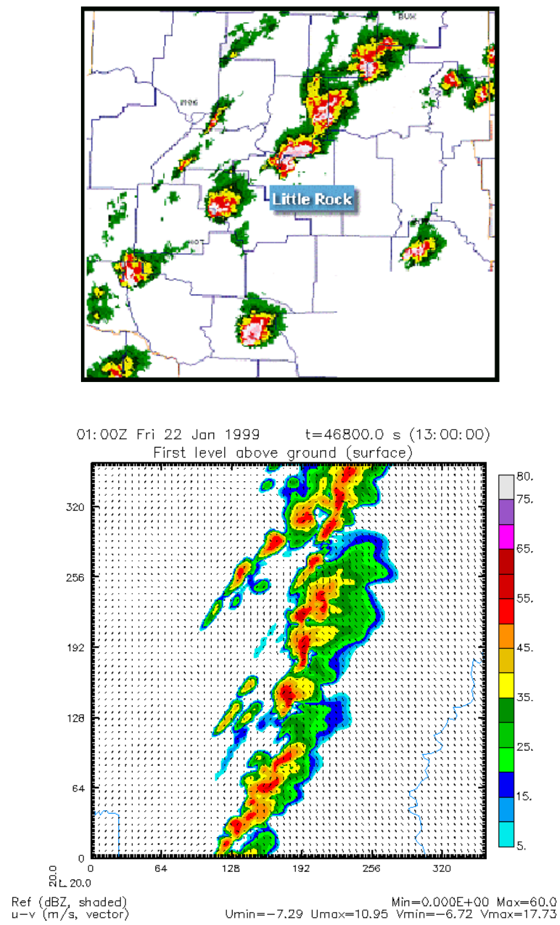
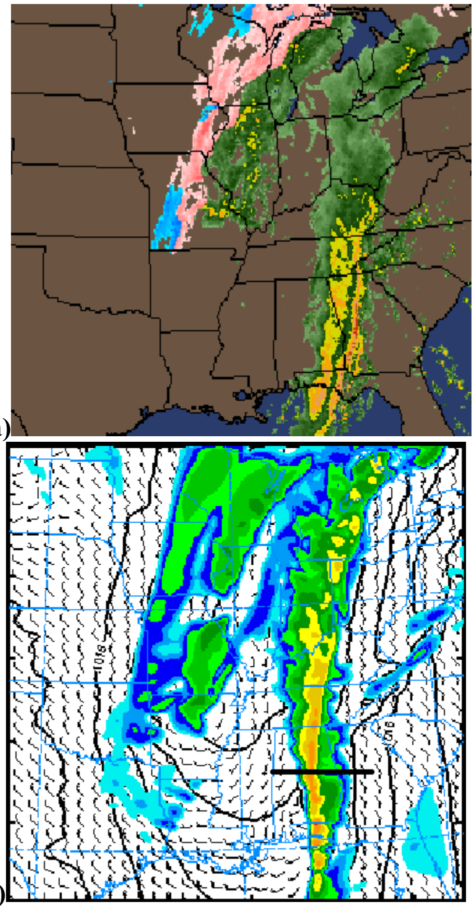


Fig. 5. Observed (upper) and ARPS predicted (lower) low-level reflectivity fields on 2 km grid, at 00 UTC January 22, the same time as Fig.4.

In Fig.5, the observed and 12 hour ARPS prediction of low-level reflectivity on the 2 km grid, valid at 00 UTC 22 January (the time of most tornadoes), are shown. The rotating supercell characteristics of the cells are correctly reproduced, as indicated the hook shape of the radar echoes. It is still difficult to compare the cells on a one to one basis, however.



(a) (b)

Figure 6. Observed reflectivity field (panel a) and color coded by precipitation estimated precipitation types) and ARPS 48 hour forecast on 6 km grid (panel b) of surface winds, mean sea-level pressure (contours) and total precipitation rate (shaded contours) at 12 UTC 23 January 1999. Note that the map project is slightly different.

At 12 UTC 23 January, corresponding to 48 hours of model prediction, the most interesting feature is an intense squall line stretching from the eastern Great Lakes region into the Gulf of Mexico. This is seen in both model and observations (Fig.6). The details of the squall line are reasonably captured on the 6 km grid, which used only explicit microphysics. The region of precipitation on the back (northwest) side of the surface cyclone is also well reproduced. The vertical cross-section (not shown) through the thick line across the squall line in Fig.6b shows that the vertical circulation associated with classic mature squall lines are all present. The intense updraft is seen tilting slight to the rear in the up-shear direction, and there is an overturning branch of updraft, a relatively weak mid-level rear to front inflow and a rotor circulation in the downdraft region. The cold pool is rather weak, suggesting the propagation of this squall line is not entirely driven by the cold pool.

Detailed diagnostic analyses are being performed. Preliminary analyses show that large-scale forcing provided the primary focusing in triggering the initial convection in Arkansas before the outbreak of tornadic thunderstorms. It is also found that the mesoscale circulation induced by the intense long-lived squall line at the later time, through vertical momentum transport and the geostrophic adjustment process, contributed significantly to the intensification and northward propagation of upper-level jet core, which in term influenced the evolution of surface cyclone and associated precipitation.

Acknowledgments

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