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Initialization of a modeled convective storm using Doppler radar-derived fields

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INITIALIZATION OF A MODELED CONVECTIVE STORM USING DOPPLER RADAR-DERIVED FIELDS

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

(Asterisk (*) denotes prognostic variables in the model)

Symbols	*Description*
c	Parameter in eddy mixing coefficient (= 0.25 here)
c_p	Specific heat of air at constant pressure (1004 J deg^{-1} kg^{-1})
D	Deformation of wind field ($D^2 = D_H^2 + D_V^2$)
D_H	Horizontal part of the deformation
D_V	Vertical part of the deformation
f	Coriolis parameter
g	Acceleration of gravity (9.81 s^{-2})
H	Height of the model domain
H_R	Height of the bottom of the Rayleigh friction layer
K_D	Damping coefficient in 4th order horizontal damping term
K_h	Eddy mixing coefficient for heat and water substances
K_m	Momentum eddy mixing coefficient
ℓ	Turbulent length scale (= $(\Delta x \Delta y \Delta z)^{1/3}$)
L_x	x-dimension of the model domain
L_y	y-dimension of the model domain
L_v	Latent heat of vaporization at 0°C (2.5×10^6 J kg^{-1})
N	Brunt-Väisälä frequency in unsaturated air
N_m	Moist Brunt-Väisälä frequency
N_0	Marshall-Palmer distribution intercept parameter for rain water (10^7 m^{-4})
p	Pressure
p_0	Reference pressure (10^5Pa)
q_c	Cloud water mixing ratio (kg kg^{-1})
$*q_r$	Rain water mixing ratio (kg kg^{-1})
$*q_T$	Total water mixing ratio (kg kg^{-1})
q_v	Water vapor mixing ratio (kg kg^{-1})
q_{vs}	Saturation mixing ratio over plane water surface
R	Gas constant for dry air (287 J deg^{-1} kg^{-1})
R_v	Gas constant for water vapor (461 J deg^{-1} kg^{-1})
Ri	Richardson number
$S(\ )$	Source and sink terms in the thermodynamic and water substance conservation equations
$SM(\phi)$	4th order horizontal damping term

T	Temperature
$TURB(\ )$	Turbulence terms in model equations
Δt_L	Long time step
Δt_S	Short time step
$*\ u$	x-component of air motion
$*\ v$	y-component of air motion
$\mathbf{V}$	Three-dimensional wind vector
V_r	Mass-weighted terminal velocity of rain water
$*\ w$	z-component of air motion
x	East-west coordinate
y	North-South coordinate
z	Vertical coordinate
Δx	Grid size in x direction
Δy	Grid size in y direction
Δz	Grid size in z direction
ϵ	R/R_v (0.622)
κ	R/c_p (0.286)
θ	Potential temperature
$\bar{\theta}$	Base state potential temperature
$*\ \theta_\ell$	Liquid-water potential temperature
θ_v	Virtual potential temperature
$\bar{\theta}_v$	Base state virtual potential temperature
π	Exner function($=c_p(p/p_0)^\kappa$)
$\bar{\pi}$	Base state Exner function
$*\ \pi'$	Deviation of Exner function from the base state
$\bar{\rho}$	Base state air density
τ	Rayleigh dissipation time scale

ABSTRACT

A method is developed to initialize convective storm simulations with Doppler radar-derived fields. Input fields for initialization include velocity, rain water derived from radar reflectivity, and pressure and temperature fields obtained through thermodynamic retrieval. A procedure has been developed to fill in missing wind data, followed by a variational adjustment to the filled wind field to minimize "shocks" that would otherwise cause the simulated fields to deteriorate rapidly.

A series of experiments using data from a simulated storm establishes the feasibility of the initialization method. Multiple Doppler radar observations from the 20 May 1977 Del City tornadic storm are used for the initialization experiments. Simulation results initialized from observations taken at two different stages of storm development are shown and compared to observations taken at later times. A simulation initialized from one of the observation times showed good agreement with subsequent observations, though the simulated storm appeared to be evolving much faster than observed. Possible mechanisms for error growth are discussed.

CHAPTER 1
INTRODUCTION

1.1. The Problem

The rapid scientific and technological advances since World War II have made the concept of numerical weather prediction (Richardson, 1922) a reality. Numerical prediction models are now an important operational tool in global- and synoptic-scale forecasting. The development of numerical models applicable to the scale of individual storms has been much slower. Up to now, numerical models on the convective scale have been used mainly as a research tool, not for practical forecasting.

Lilly (1990) and Droegemeier (1990) discussed a number of difficulties in convective-scale numerical prediction, namely the unavailability of routine observational data of a space and time scale fine enough to be used for model initialization, the lack of sufficient computer power to resolve complicated convective scale events, lack of understanding of predictability of these events, the need for better parameterization of physical processes particularly important at the storm-scale, and the need for methods to initialize convective models with observational data.

This study will focus on the last difficulty mentioned above, the initialization of convective models with three dimensional fields derived from observations. The problem mainly involves providing a complete, consistent set of three dimensional kinematic, thermodynamic and water fields, since on the convective scale there is much interdependency among these fields. In addition, even when available, observational data usually do not cover the entire model domain, so we need to find a way to fill the voids in the observed fields.

1.2. Existing Convective Initialization Methods

Since the first three-dimensional cloud models were developed (Steiner, 1973; Schlesinger, 1975; Klemp and Wilhelmson, 1978), there has been significant advancement in the study of severe convective storms using numerical cloud models. For example, Wilhelmson and Klemp (1978) showed that an idealized environment with strong thermal instability and vertical wind shear can produce long-lived cells that display characteristics of "supercell" thunderstorms (Browning, 1964). Using observed profiles of wind, temperature and moisture obtained in an environment that produced tornadic storms, Klemp *et al.* (1981) produced a simulated storm that bore a striking similarity to the observed storm. By initializing a high-resolution model with interpolated fields taken from the central portion of the simulated storm in Klemp *et al.* (1981), Klemp and Rotunno (1983) simulated the tornadic phase of this storm.

The initial fields for convective models are generally specified by horizontally homogeneous wind, temperature and moisture profiles obtained from an observed or hypothetical rawinsonde sounding that contains positive convective energy. Then an initial perturbation is introduced to initiate the convection process. There are several types of initial perturbations, as discussed below.

The first type is an artificial thermal perturbation in the form of either a subcloud heating source or sink that is turned on for a limited amount of time to induce convection (Miller and Pearce, 1974, Thorpe *et al.*, 1980), or a warm or moist region near the surface. For example, Schlesinger (1975) used a cylindrical shaped buoyant region with a maximum potential temperature excess of 1°C; Klemp and Wilhelmson (1978) used a ellipsoid with a maximum potential temperature excess of 1.5°C; Rotunno *et al.* (1988) used a 2°C line thermal to initiate their squall line simulation. Though simulations using this type of initial condition often produce storms that compare well with observations, these thermal perturbations often contain considerable amounts of energy and lead to unrealistic features in the simulated storms (Clark, 1979, Tripoli and Cotton, 1980).

The second type of initial perturbations provides more realistic, and more complicated initial perturbations. Tripoli and Cotton (1980) used a horizontally homogeneous field of initial vertical motion to simulate the effect of larger scale convergence which leads to convection. Smolarkiewicz and Clark (1985) used surface layer forcing calculated from mesonet data. Johnson *et al.* (1989) used differential surface heating produced by a radiation model.

All of the above initialization methods start the simulation from a relatively calm, horizontally homogeneous model domain, not from three-dimensional fields based on observations. As most convective events are much more complicated than the idealized cases, and their initial states cannot be adequately described by artificially specified initial perturbations, the convective models of today are used only as a research tool to study various types of "typical" convective behavior, not for actual forecasting. Also, since numerical model results invariably deteriorate with time, for a convective model to be useful as a forecasting tool, it must be able to start from the observations of a developing storm, rather than just from a calm initial environment.

1.3. Availability of Observational Data on the Convective Scale

The numerical forecasting of convective scale events relies on the availability of detailed three dimensional information on wind, pressure, temperature and water substance fields. Currently, large scale operational models rely on the rawinsonde network to provide wind, temperature and humidity data as input. Although a rawinsonde provides data at many levels during its ascent through the atmosphere, the average horizontal spacing between rawinsonde stations in the U.S. is over 300 km, and rawinsonde data are taken every 12 hours. In contrast, the characteristic convective length scale is 10-20 km, with a time scale of a few hours. Therefore rawinsonde data are only useful as a base state in convective initialization.

Since the mid 1960's, rapidly improving computer technology has helped to foster remarkable progress in Doppler radar observations of convective storms. It is now possible to obtain detailed wind data in small scale convective systems from dual Doppler radar observations (Armijo, 1969, Ray *et al.*, 1975) and multiple (three or more) Doppler radar observations (Ray *et al.*, 1978 and Ray *et al.*, 1980) made during special field projects.

Although there is yet no way to measure directly the three dimensional structure of pressure and temperature fields in a storm, a number of researchers have developed indirect methods to derive these fields from Doppler radar wind observations using the momentum equations (Gal-Chen, 1978; Hane and Scott, 1978; Bonesteel and Lin, 1978; and Leise, 1978). Since then the technique has been used by many to obtain insights on thermodynamic structures of various observed storms (*e.g.*, Brandes, 1984a, Hane and Ray, 1985, Parsons *et al.*, 1987).

Methods have also been developed to obtain microphysical fields in a storm from Doppler wind and reflectivity observations either by using kinematic cloud models to find microphysical fields consistent with the dynamic fields (Ziegler, 1985), or by seeking solutions to the continuity equation of total water mixing ratio (Hauser and Amayenc, 1986).

1.4. Scope of This Research

As discussed in Section 1.1, numerical prediction of storms is a complex problem that involves a number of unresolved issues. We shall limit this study to the development of a method to initialize convective models with dynamical, thermodynamical and microphysical fields derived from multiple Doppler radar observations.

Chapter 2 describes the numerical model and the thermodynamic and microphysical retrieval methods used in this study, develops a method to fill in voids in the observed wind field, and outlines the model initialization method. Chapter 3 uses an idealized axisymmetric storm to test the filling, retrieval and initialization methods. In Chapter 4 we first test the initialization method with output from a model simulation initialized with a sounding for a tornadic storm (20 May 1977, Del City, Oklahoma) and a thermal bubble. Then we conduct initialization experiments using multiple Doppler radar wind observations of the Del City storm taken at two different times. Chapter 5 contains summary, discussions and recommendations for future work.

CHAPTER 2

METHODOLOGY

2.1. The Numerical Model

The numerical model used in this study is the Colorado State University Regional Atmospheric Modeling System (RAMS, version 2A), described by Tripoli and Cotton (1982), Cotton *et al.*, (1982), and Tripoli and Cotton (1986). RAMS is a modular system that contains many physical and numerical options. In this study the model solves seven prognostic equations for the three wind components (u, v and w), perturbation Exner function (π'), liquid water potential temperature (θ_ℓ, which is conserved during condensation/evaporation), total water mixing ratio (q_T) and rain water mixing ratio (q_r)*. A time-split leapfrog scheme (Klemp and Wilhelmson, 1978) is used for iteration, where the "acoustic" terms (those that participate in acoustic wave generation) in the momentum and pressure equations are solved over a short time step and the rest of the terms are solved over a long time step. Detailed descriptions of the model variables and model equations are given in Appendix A.

2.2. Thermodynamic Retrieval Method

"Thermodynamic retrieval" refers to the derivation of pressure and temperature fields that are in balance with a given wind field. The thermodynamic retrieval method used in this study follows that by Hane and Ray (1985), which is based

* Although the storms studied here are likely to contain ice, and RAMS is capable of simulating ice microphysical processes, we choose to use the simple "warm" (no ice) microphysical parameterizations here in order to concentrate on the problems of initialization.

on Gal-Chen (1978), Hane and Scott (1978), and Hane *et al.*, (1981). A brief description of the method is given below.

The horizontal momentum equations in Appendix A can be rewritten as

$$\frac{\partial \pi'}{\partial x} = \frac{1}{\bar{\theta}_v}\Big[TURB(u) - \frac{\partial u}{\partial t} - \mathbf{V}\cdot\nabla u + fv\Big] = F, \tag{2.1}$$

and

$$\frac{\partial \pi'}{\partial y} = \frac{1}{\bar{\theta}_v}\Big[TURB(v) - \frac{\partial v}{\partial t} - \mathbf{V}\cdot\nabla v - fu\Big] = G, \tag{2.2}$$

where π' is the perturbation Exner function (the Exner function is defined as $\pi = c_p(p/p_0)^\kappa$). The parameterization of the turbulence terms is given in Appendix A.

As a set of differential equations for π', (2.1) and (2.2) are over-determined and will have a solution only if

$$\frac{\partial F}{\partial y} = \frac{\partial G}{\partial x}. \tag{2.3}$$

Since the observations are not error free and the turbulence parameterization is not exact, (2.3) is generally not satisfied and (2.1) and (2.2) generally do not have a solution. Nevertheless they can be solved in the least squares sense by seeking a function π' that minimizes

$$\int\!\!\int \Big[\big(\frac{\partial \pi'}{\partial x} - F\big)^2 + \big(\frac{\partial \pi'}{\partial y} - G\big)^2\Big]dxdy \tag{2.4}$$

on each horizontal level. The Euler equation for this variational problem is

$$\frac{\partial^2 \pi'}{\partial x^2} + \frac{\partial^2 \pi'}{\partial y^2} = \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y}, \tag{2.5}$$

with the Neumann boundary conditions

$$\frac{\partial \pi'}{\partial x}n_x + \frac{\partial \pi'}{\partial y}n_y = Fn_x + Gn_y, \tag{2.6}$$

where n_x and n_y are the directional cosines of the normal to the boundary.