PARAMETERIZATION SCHEMES

Keys to Understanding Numerical Weather Prediction Models

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Preface

Numerical weather prediction models are playing an ever increasing role in meteorology. Not only are numerical models the foundation of short- and medium-range forecasting efforts, they are key components in studies of global climate change. Gaining insight into the physical processes behind many atmospheric phenomena often rests upon studying the output from numerical models, since observations of sufficient density or quality are not available. This ubiquitous use of numerical models suggests that all aspects of numerical models need to be understood very well by those who use the models or examine their output. However, it is my belief that the meteorological community has stressed an understanding of computational fluid dynamics above an understanding of the subgrid-scale parameterization schemes that play a significant role in determining model behavior. While some may argue in defense that parameterization schemes are fluid and changing all the time, implying that studying them is fruitless, closer inspection reveals that many basic assumptions used in the parameterization of specific processes have changed little over the past decades. The study of parameterization schemes also opens a window that allows one to examine our most fundamental ideas about how these important physical processes function and explore how they behave. Thus, the study of parameterization is a vital and necessary component in the study of numerical weather prediction and deserves far greater attention.

There are two main goals of this book. First, to provide the reader with sufficient background to be able to read and scrutinize the literature on the major model physical process parameterization schemes. While your personal list of the major parameterization schemes may differ from those in the text, the schemes selected for examination are used in a large majority of the numerical models available today. The second goal is to develop a deeper understanding of the various physical processes that are parameterized in numerical models and why their parameterization is necessary.

Each chapter begins with an overview that summarizes why this particular physical process is important to represent in a numerical model. Most chapters also contain a review of the theory behind the physical process being parameterized or highlight the observations upon which the parameterization is built. Several different parameterization schemes for this physical process are then presented and compared. Unfortunately, it is impossible to present all the parameterization schemes available and so choices had to be made. The parameterization schemes presented are intended to represent the spectrum of schemes available in commonly used numerical models, but are in no respect an exhaustive list. Each chapter also contains a discussion section in which concerns that have been raised regarding the parameterization are highlighted and future areas of research outlined. Questions are available at the end of each chapter that allow one to delve deeper into the various schemes and to gain an appreciation of their sensitivities. I encourage everyone to answer these questions and to ponder their implications. It is my fervent hope that this book will help those who use models in their research, and those who use model output in making forecasts, to understand both these tools and the atmosphere better.

My interest in parameterization schemes arose during my Ph.D. studies at The Pennsylvania State University when I first began using a numerical weather prediction model (The Pennsylvania State University – National Center for Atmospheric Research Mesoscale Model). While exploring the simulation of a mesoscale convective system in a weakly forced large-scale environment, sensitivities to small changes in the convective parameterization were seen. As the model matured over the following years and began to include a greater number of parameterization scheme options, the sensitivities of a given simulation to changes in the parameterizations selected became readily apparent in nearly all the simulations I studied. These sensitivities may not be seen in all models, due to the limited variety of parameterization schemes available for use in some models, but they are significant and raise a number of important issues regarding the way we view and use numerical weather prediction models. Thus, a graduate-level course in parameterization schemes was born.

This book began as a set of handwritten notes for a graduate course I taught within the School of Meteorology at the University of Oklahoma (OU) in 1994. The class has since been offered every 2 years, allowing every graduate student at OU the opportunity to take it if they so choose. Over the years the students asked for copies of my notes and in response I slowly put them into an electronic format. Once the notes were finalized, the transition to a book format was manageable if not easy. However, I could not have completed this book without the support of Jeff Kimpel and David Rust of the National Severe Storms Laboratory (NSSL) and Fred Carr of OU. Jeff and Dave have supported both my regular teaching stints at OU and the time it has taken to complete this book. Fred has graciously allowed me to teach this rather unusual course within the School of Meteorology all these years as an adjunct faculty member, entrusting many of the School's students to my care each time I teach. Other faculty members have encouraged their students to take my class, and I am thankful for their support and encouragement. Since teaching and dealing with university regulations is not my regular job, I greatly appreciate the support and kindness of everyone in the School of Meteorology office. I also want to recognize and thank Bob Maddox for first inspiring me to teach this course at OU and for supporting my teaching during his tenure at NSSL.

A number of other people also have my sincere thanks and heartfelt gratitude. The students who were brave enough to take this course over the past 12 years contributed greatly to the evolution of this book by the questions they asked and their enthusiasm for meteorology. I have enjoyed teaching all of you! I also have a long list of chapter reviewers who helped me to improve the material presented. Thus, my deepest thanks go to Jeff Anderson, Jian-Wen Bao, Stan Benjamin, Toby Carlson, Fei Chen, Brad Ferrier, Matt Gilmore, Jack Kain, Young-Joon Kim, Brian Mapes, Bob Rabin, Chris Snyder, Roland Stull, Steve Weiss, Lou Wicker, Bob Zamora, and Conrad Ziegler for providing very helpful and professional reviews. The roots for Chapter 2 are in my notes from a course in bioclimatology taught by Toby Carlson at Penn State, and I am grateful to Toby for his wonderful teaching ability and his encouragement. I also want to recognize Bob Davies-Jones, John Locatelli, Chris Godfrey, and Tadashi Fujita for their assistance with specific aspects of the book. Joan O'Bannon drafted several of the more complex figures and her assistance is greatly appreciated. Working with Matt Lloyd, Lindsay Barnes, Louise Staples and Dawn Preston at Cambridge University Press was very easy and I appreciate their support and assistance.

As with all human endeavors, mistakes are guaranteed. I hope that my mistakes will not hamper your reading and understanding of the material. Choosing the notation for many parts of this book was particularly challenging, and so several variables have different meanings in different chapters. While this is not the best situation, the only other alternative was to depart from the notation commonly used in the literature for certain parameterizations. I decided to stay as close as possible to the conventional notation and accept the consequences. If you find any mistakes, I would be grateful if you would let me know via email to David.Stensrud@noaa.gov so that I may correct them. Finally, my admiration goes out to all those scientists who develop the parameterization schemes that help make numerical weather prediction models the success they are today.

David J. Stensrud

List of principal symbols and abbreviations

a	Albedo (0 to 1), various constants
b	Cloud cover fraction (0 to 1), various constants
c_g	Soil heat capacity
c_p	Specific heat at constant pressure ($1004\,\mathrm{J\,K^{-1}\,kg^{-1}}$)
d	Distance from sun to the Earth, displacement depth for the log wind profile
$\bar{d}$	Mean distance from sun to the Earth ($1.50 \times 10^{11}\,\mathrm{m}$)
e	Vapor pressure
$\bar{e}$	Turbulent kinetic energy
$e_s(T)$	Saturated vapor pressure at temperature T
f	Coriolis parameter
g	Acceleration due to gravity at the surface of the Earth ($9.81\,\mathrm{m\,s^{-2}}$)
h	Local hour of the sun
k	von Karman's constant (~ 0.4)
k_e	Entrainment coefficient (<1)
k_g	Thermal molecular conductivity
k_v	Plant resistance factor
k_ν	Absorption coefficient for radiation
k_w	Hydraulic conductivity
l	Mixing-length
l^2	Scorer parameter
n_o	Intercept parameter for drop distributions
p	Pressure
q	Specific humidity
q_c	Cloud water mixing ratio
q_i	Cloud ice mixing ratio
q_r	Rain water mixing ratio

q_s	Snow mixing ratio
q_v	Water vapor mixing ratio
$q_s(T)$	Saturation specific humidity at temperature T
r	Drop radius (cloud droplets, raindrops)
r_a	Resistance in atmospheric surface layer
r_b	Resistance of the interfacial sublayer to sensible heat flux
r_{bv}	Resistance of the interfacial sublayer to latent heat flux
r_c	Canopy resistance
r_H	Resistance to sensible heat flux
r_M	Resistance to momentum flux
r_V	Resistance to latent heat flux
u	East–west component of velocity
u_*	Friction velocity
v	North–south component of velocity
w	Vertical component of velocity
w^*	Free convection scaling velocity
w_p	Total column precipitable water
z	Height
z_{eff}	Effective height
z_0	Roughness length for momentum
z_{0h}	Roughness length for sensible heat flux
z_{0v}	Roughness length for latent heat flux
A_c	Cloud fractional area
API	Antecedent precipitation index
B_ν	Planck function
$CAPE$	Convective available potential energy
CIN	Convective inhibition
CWP	Cloud water path
D_v	Water vapor diffusivity
D_w	Soil water diffusivity
E	Collection efficiency (0 to 1)
E_p	Potential evaporation
EL	Equilibrium level
F_D	Downward directed radiative flux
F_U	Upward directed radiative flux
Fr	Inverse Froude number
I	Radiance, or intensity
K	Mixing coefficient used in K-theory
K_e	Kersten number

K_m	Eddy viscosity
L	Monin–Obukhov length, empirical length scale
LAI	Leaf area index
L_f	Latent heat of fusion ($3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$ at 273.16 K)
L_v	Latent heat of vaporization ($2.500 \times 10^6\,\mathrm{J\,kg^{-1}}$ at 273.16 K)
LCL	Lifting condensation level
LFC	Level of free convection
M	Moisture availability (0 to 1)
M_c	Convective mass flux
N	Brunt-Väisälä frequency
$NDVI$	Normalized difference vegetation index
PAR	Photosynthetically active radiation
Q_1	Apparent heat source
Q_2	Apparent moisture source
Q_S	Incoming solar radiation
Q_{Lu}	Upwelling longwave radiation
Q_{Ld}	Downwelling longwave radiation
Q_H	Sensible heat flux
Q_E	Latent heat flux
Q_{EB}	Bare soil evaporation
Q_{EV}	Vegetation transpiration
Q_{EW}	Canopy evaporation
Q_G	Ground heat flux
Q_R	Heating rate due to radiation
R_d	Individual gas constant for dry air ($287\,\mathrm{J\,K^{-1}\,kg^{-1}}$)
R_{NET}	Total radiation from both shortwave and longwave components
R_v	Individual gas constant for water vapor ($461\,\mathrm{J\,K^{-1}\,kg^{-1}}$)
R_r	Roughness Reynolds number
Re	Reynolds number
Re^*	Roughness Reynolds number
Ri	Richardson number
RH	Relative humidity
S	Solar irradiance, supersaturation, maximum intercepted canopy water
T	Temperature
T_c	Temperature at cloud base
T_g	Ground temperature
T_{SST}	Sea surface temperature
V_r	Fall speed of precipitation particles
W_c	Intercepted canopy liquid water content

α_c	Charnock's constant
δ	Solar declination angle
δ_i	Unit vector
δ_{nm}	Kronecker delta
ε_a	Atmospheric emissivity
ε_{ijk}	Alternating unit tensor
ε_g	Ground surface emissivity
ζ	Solar zenith angle
θ	Potential temperature
θ_v	Virtual potential temperature
κ	Thermal diffusivity of the air
κ_m	Molecular thermal diffusivity of air ($0.18 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$)
κ_{soil}	Soil hydraulic conductivity
κ_w	Soil water thermal conductivity
λ	Entrainment coefficient, slope parameter
ν	Kinematic viscosity
ν_g	Soil thermal diffusivity
π	Exner function
ρ, ρ_a	Air density
ρ_w	Water density ($1000\,\mathrm{kg\,m^{-3}}$ at 273.16 K)
σ	Stefan–Boltzmann constant ($5.6767 \times 10^{\ 8}\,\mathrm{W\,m^{-2}\,K^{-4}}$)
σ_f	Vegetation fraction (0 to 1)
τ	Momentum flux or Reynolds stress, optical thickness
τ_s	Transmissivity
τ_ν	Transmission function
φ	Latitude
ψ_g	Gravitational potential
ψ_m	Correction to log wind profile for non-neutral conditions
ψ_m	Matric potential
ψ_o	Osmotic potential
ψ_p	Plant potential
ψ_s	Saturation matric potential
ψ_{soil}	Soil potential
ω	Vertical velocity in pressure coordinates
$\overline{\Delta}$	Change in saturation vapor pressure with respect to temperature
Θ	Volumetric water content
Θ_{fc}	Volumetric water content at field capacity
Θ_S	Soil porosity
Θ_w	Wilting point

1

Why study parameterization schemes?

1.1 Introduction

The weather forecasts depicted in brilliant colors on television, in the newspapers, and on the Internet are providing ever greater details about how the atmosphere is going to evolve over the coming days and even the coming seasons. Both these details and the length of these predictions are due in large part to the increasing processing power of computers and the improving numerical weather prediction models that run on them. Numerical weather prediction models are computer software programs based upon the mathematical equations of motion describing the flow of fluids. Given the present state of the atmosphere, as estimated from weather observations across the globe, these models are able to move the atmosphere forward in time using a sequence of small steps and thereby predict a future state. Not only are these models a critical component in making weather forecasts for the coming week and season, but versions of these models are used to examine how increasing greenhouse gases influence future global climate. Thus, numerical models are important in making decisions not only about daily human activities but about how to be good stewards of planet Earth.

The initial models used for numerical weather prediction (NWP) were simplified versions of the complete equations of motion and were applied over relatively small portions of the globe. In 1949, Charney, Fjørtoft, and von Neumann produced the first one-day weather forecast using a one-layer barotropic model (Charney *et al.* 1950). Another 5 years passed before a barotropic model was used to produce routine forecasts of the 500 hPa flow patterns out to 3 days in an operational forecast center (Shuman 1989; Kalnay 2003; Persson 2005a, b, c). A number of problems still had to be overcome before a multi-vertical-layer quasi-geostrophic model became operational in 1962, with the acquisition of a faster computer system being an important enabling factor (Shuman 1989). A six-vertical-layer primitive equation model became operational in 1966 (Shuman and Hovermale 1968). Each of these models had to be able to compete with or improve upon the manual human-generated forecasts available at the time and each new model needed to be more skillful than its predecessor. Under these constraints, over a short time span of 17 years numerical weather prediction evolved from a simplified model forecast of a single atmospheric layer to a multi-layer primitive equation model capable of predicting cyclone development.

Numerical models also were being developed and used by the research community for a variety of purposes. Non-hydrostatic cloud-scale numerical models to study thunderstorms, hydrostatic mesoscale models to examine the details of cyclogenesis, and hydrostatic general circulation models to study climate all appeared in the late 1970s and slowly started to develop their own user communities. While the simulations often required days of computer time on supercomputers at national research centers, these models were developed to provide an improved understanding of atmospheric processes and so the computer time required to complete the simulation was not a significant factor. As more and more researchers began using these models, the model developers responded by making the models more user friendly, more computer efficient, and began providing documentation on how to use the models.

While both the models used in operations and in research continued to advance throughout the ensuing years, arguably the next major advancement in operational weather prediction was the arrival in 1980 of models that made predictions for the entire globe (Sela 1980). In the early 1990s local computer resources became sufficient for numerical model forecasts to be produced at universities and smaller research laboratories (Warner and Seaman 1990; Cotton *et al.* 1994). These local modeling activities have only increased over the years and have provided many unique opportunities for public education and public service (Mass and Kuo 1998; Mass *et al.* 2003). Improved computer capabilities also led to the operational implementation of the first mesoscale model in the United States in 1995 (Black 1994). Since the 1990s, numerical models have continued to develop along with even greater improvements and affordability in the needed computational resources. Thus, the complexity and sophistication of numerical weather prediction models has increased tremendously since the first forecast in 1949, thanks to both model improvements and the continued availability of ever larger and faster computers.

The evolution towards increasing numerical model complexity has both positive and negative aspects. The positive aspects of this evolution are that the model forecasts are more accurate, more skillful, and produce features that often very closely resemble what actually occurs in the atmosphere. The improvement in model skill has contributed greatly to the improved forecasts that are delivered to the public and influence numerous weather-sensitive industries across the world. The negative aspects of this evolution are that the model behaviors are more difficult to understand, and that errors in the model can be much more difficult to find and correct.

In tandem with the improvement in numerical models came the realization that the atmosphere is sensitive to slight changes in initial conditions (Lorenz 1963). Even the tiniest of errors in the atmospheric initial state is capable of growing quickly and eventually overwhelming the numerical forecast. By introducing very small differences into a model's initial condition, and comparing the forecasts generated from this perturbed initial condition to the forecast from the original unperturbed initial condition, one finds that the differences grow with time. After about two weeks the differences are large enough that the two forecasts are as different as two forecasts started from initial conditions on the same day but from different years (Lorenz 1969). Thus, instead of producing a single (deterministic) forecast, Epstein (1969) and Leith (1974) suggested producing an ensemble of forecasts in order to provide information on forecast uncertainty.

An ensemble is simply a group of forecasts valid over the same time period. A common method of generating an ensemble is to create a number of different model initial conditions, that all lie within the range of analysis uncertainty, and to use each of these initial conditions to produce a separate model forecast. More recently the use of different models in the ensemble has been shown to provide additional value. Ensembles have been used in medium-range forecasting since the early 1990s (see Kalnay 2003) and for short-range forecasting since 2001. The use of an ensemble alters the way in which model guidance is used from a deterministic perspective to a probabilistic perspective that provides richer information for the end users of weather information. The computational cost of ensembles is high, however, since each additional member requires a separate forecast to be produced. While ensembles have been found to be very beneficial, the basic tool – the numerical model – is the same. Only the way in which this numerical tool is applied has been changed when using ensembles instead of single model forecasts.

1.2 Model improvements

Most of the improvements in numerical models that occurred over the past 50 years can be categorized as either improved numerical techniques, improved model resolution, or improved model physical process parameterization schemes. In addition to model improvements, data assimilation methods that judiciously incorporate the wide variety of available observations into numerical model initial conditions also have been very important in increasing forecast skill and their importance should not be underestimated. Daley (1991) discusses many of the advancements and remaining challenges in data assimilation.

Numerical techniques are the methods by which the equations of motion are stepped forward in time. The equations of motion that govern fluid flow are called partial differential equations and are common in mathematical models of many different physical, chemical, and biological phenomena. The partial differential equations that govern fluid flow cannot be solved analytically and so numerical techniques are needed to convert the continuous partial differential equations into a set of algebraic equations that can be solved using a computer (Durran 1999). The numerical techniques differ in the strategies used for representing the original continuous equations by a finite data set that can be stored on a computer and in the computation of derivatives. The basic approaches used are grid point methods, series expansions, and finite-element methods (Haltiner and Williams 1980; Durran 1999; Kalnay 2003).

Model resolution refers to the horizontal and vertical scales that can be resolved or reproduced by the numerical model. Since each algebraic operation used to step the numerical model forward in time requires computer processor time, memory, and disk storage, the number of computations that can be completed in a given time period or for a given memory and disk size is limited even for the fastest computers. This means that the atmosphere cannot be represented perfectly by the numerical model and instead is approximated by a finite data set. Regardless of the type of model, at some point in the computation the atmosphere is represented by a three-dimensional set of points, called a grid, that covers the region of interest (e.g., country, continent, or globe). These points often are regularly spaced horizontally and represent the state of the atmosphere at the point in question (Fig. 1.1). It is easily seen that the number of discrete grid points determines how well the atmospheric structures are represented by the model. As the number of discrete grid points increases, the structures in the atmosphere are represented (or resolved) with increasing accuracy (Fig. 1.1b). However, for a given number of grid points there are always structures small enough that they cannot be captured. When looking at the horizontal distribution of grid points, the grid created often resembles a chessboard when viewed from above with the value of the variables at each grid point representing the conditions within the surrounding grid cell, or the rectangular area for which the grid point is the center point (Fig. 1.2).

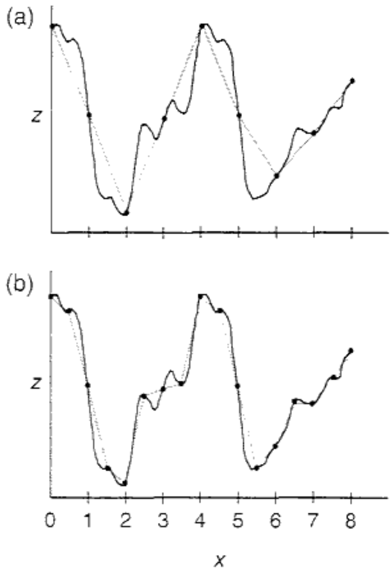

Figure 1.1. Idealized grid point approximation (gray) of a function z (black) plotted on the interval [0, 8]. Grid points every 1 in (a) and every 0.5 in (b) are indicated by black circles. Note how the idealized grid point approximation follows the function more closely in (b), although some wave structures are still not captured as clearly seen between the interval [2.5, 3.5].

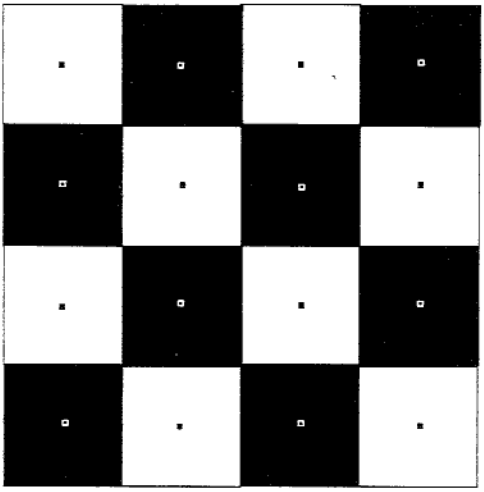

Figure 1.2. Each white or black square represents a grid cell or grid box, whose properties are represented by the grid point value in the middle of the box. In a numerical model, these grid cells are approximately cube-like in shape with an additional dimension in the vertical direction.

Since there are many small-scale phenomena in the atmosphere that are very important to human activities, such as sea breezes, thunderstorms, and snow bands to name just a few, one of the consistent improvements to numerical models has been to increase the ability of the model to resolve smaller and smaller features. This also is important because small-scale features can influence the larger-scale circulations through upscale growth (Thompson 1957; Tribbia and Baumhefner 2004), and so the better these observed small-scale features are captured the more accurate the resulting forecast. The difficulty, of course, is that many small-scale features are not observed with the present observational network and so cannot be included in the model initial conditions. Regardless, the original numerical models in the 1950s had grid points every few hundred kilometers in the horizontal, whereas today models with grid points approximately every 10 km are used in operations and models used in research may have grid points every 50 m. In parallel with the changes in horizontal resolution are changes in vertical resolution, such that models today often have between 50 and 100 vertical layers. It is important to note that a factor of 2 decrease in model grid spacing requires eight times as many grid points on a three-dimensional grid, and the time step generally also must be reduced by a factor of 2, thereby requiring 16 times more computer time! This simple analysis further highlights the important role that increases in computer processor speed play in numerical modeling.

There are always physical processes and scales of motion that cannot be represented by a numerical model, regardless of the resolution. Unfortunately, these unresolved processes may be very important in producing an accurate and useful weather forecast. Parameterization is the process by which the important physical processes that cannot be resolved directly by a numerical model are represented. The transfer of radiation through the atmosphere, which strongly influences surface temperatures, occurs on the molecular scale and so is not resolved by any numerical model. Similarly, the formation of cloud droplets, that may grow and fall to the surface as raindrops, occurs on the molecular scale and so is not resolved by any numerical model. Yet high and low temperatures and precipitation are arguably the most important forecast concerns of people on daily, seasonal, and climate timescales. Thus, processes at the molecular scale are important to represent in numerical models, even though they cannot be resolved directly by the model.

A quick look out of the window may provide another simple illustration of the need for parameterization. Cumulus clouds often form on a sunny afternoon (Fig. 1.3). These clouds are a few hundred meters across, and likely have a similar depth. Most operational forecast models in use in 2005 have horizontal grid spacings of 10 km or larger, roughly 10 to 20 times the size of the

Figure 1.3. A small cumulus cloud developing on a sunny afternoon.

cumulus clouds. When examined from above, it becomes clear that these cumulus clouds cannot be represented explicitly even using 5 km horizontal grid spacing (Fig. 1.4). Since it takes eight or more grid points to represent to some (undefined) level of accuracy any wave-like feature (Haltiner and Williams 1980; Walters 2000), a grid spacing of perhaps 25 m is needed to resolve small cumulus clouds well. Since the grid box is larger than the feature of interest – the cumulus cloud – cloud development and evolution is therefore a subgrid process. If the effects of cumulus clouds are to be included in the evolution of the model variables, then a parameterization that represents the effects of cumulus clouds is needed in the numerical model. If the effects of cumulus clouds are not parameterized, then the model never knows that a cloud formed.

1.3 Motivation

Parameterization schemes are important because they strongly influence model forecasts and interact with each other indirectly through their changes to the model variables. A wet ground surface can lead to strong latent heat flux during the daytime and the development of a shallow and moist planetary boundary layer. The amount of radiation that reaches the ground, the latent heat flux from the ground, and the boundary layer evolution are all determined by parameterization schemes. Furthermore, at the top of the boundary layer cumulus clouds may form and a few of these could eventually grow into

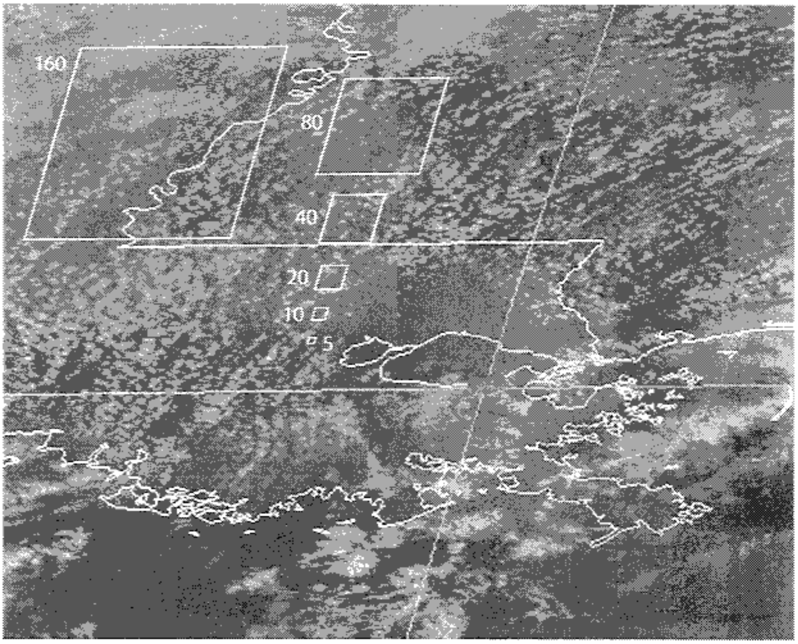

Figure 1.4. Satellite view of a field of cumulus clouds at 1 km resolution forming over Louisiana and Mississippi. Open white polygons represent different sizes of grid cell, varying from 160 km on a side down to 5 km. Even within the 5 km grid cell there are cumulus clouds smaller than the grid cell. Satellite image courtesy of the National Oceanic and Atmospheric Administration.

thunderstorms that produce rain. The development and evolution of these cloud processes also are determined by a parameterization scheme. When clouds are present in the atmosphere, they alter the amount of radiation that reaches the ground. Once the rain reaches the ground surface, it moistens the ground and feeds back to influence the partitioning of the sensible and latent heat fluxes. All of these physical processes from radiation to surface heat fluxes and from the boundary layer to cloud processes are parameterized in most numerical weather prediction models and are critical to the predicted evolution of the atmosphere. So many interactions occur within and between the parameterization schemes and the numerics of models that it is increasingly challenging to discern cause and effect.

Parameterizations almost always focus on the effects of the subgrid physical processes within the vertical column of each individual model grid cell, and only rarely examine what is happening at neighboring grid cells (Fig. 1.5). The vertical orientation of parameterization schemes is chosen since many of the physical processes naturally rearrange energy in this direction. Since

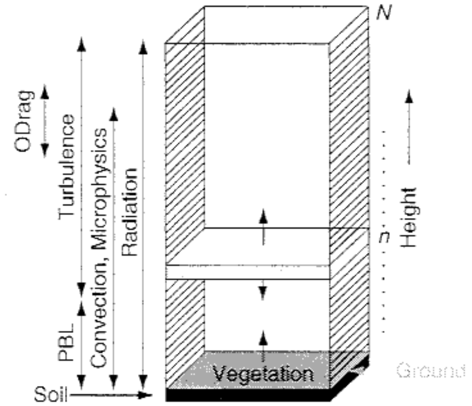

Figure 1.5. Idealized vertical column of model grid cell, with *N* vertical layers and vertical layer *n* highlighted. Soil layers are denoted by black shading. Vertical layers where radiation, convection, microphysics, planetary boundary layer (PBL), turbulence, orographic drag (ODrag), and vegetation (and/or bare soil and/or water) parameterizations are likely to affect the model variables are indicated. Vertical arrows emphasize that the parameterizations affect the vertical column only.

parameterizations represent subgrid physical processes for which the model has no direct information, parameterization schemes must relate the subgrid processes to known model variables. For example, the amount of solar radiation that passes through the atmosphere can be related to the cloud cover and water vapor in the vertical column. The formation of cloud droplets can be related to the relative humidity within the grid cell, and the formation of raindrops then can be related to the number of cloud droplets. The specified relationships between the subgrid processes and the known model variables define the parameterization scheme closure. While parameterizations are simplified and idealized representations of complex physical processes, it is common and useful for parameterizations to retain the essential behavior of the process they represent. It also is important to recognize that without parameterization model forecasts are not very interesting or helpful, since the parameterized processes are the most important factors in the forecasts of sensible weather that concern people. Thus, parameterization is a requirement if a model is to provide forecasts for use in weather prediction on any scale of motion.

Parameterization schemes by necessity distill only the essential aspects of the physical processes they represent. Only a limited amount of complexity is possible within a parameterization since it is difficult enough to correctly reproduce the basic behaviors of the physical process for a variety of environmental conditions. Thus, parameterization schemes are an idealized window through which one can gain an understanding of a number of complex atmospheric physical processes when reduced to their most fundamental form. Studying parameterization schemes can help one to understand weather and how weather affects climate.

The outputs from a given parameterization scheme are used to step the numerical model forward in time and often include the time tendencies ($\partial X/\partial t$, where X is a model variable) for most of the model variables, such as temperature, specific humidity, mixing ratios for microphysical particles, and the horizontal wind components at each grid point and vertical level. These time tendencies are added to the time tendencies due to advection, all the other forcing terms in the equations of motion, and all the other parameterization schemes to yield a total time tendency for each model variable. Some parameterization schemes are called at every time step in the model integration, while others may be called less frequently. The individual parameterization scheme time tendencies typically are held constant until the scheme is called again and the values of the time tendencies updated. The total time tendency calculated by the numerical model defines how the model variables change with time and so is very important to the evolution of the model forecasts. Parameterization schemes play a large role in determining this time tendency, further underscoring their importance to numerical weather prediction.

Finally, there are many challenges that increasingly better model forecasts provide to forecasters (Bosart 2003). With every model improvement it seems to become harder and harder for human forecasters to produce forecasts that disagree with the model, even when forecasters are faced with evidence that the model forecast may be incorrect. Bosart suggests that part of this inability to discard model forecasts may be due to the human forecasters losing their analysis skills in this age of enhanced automation, and part of it may be forecaster apathy. However, another contributing factor may be a lack of understanding of how models function, and in particular of how the physical process parameterization schemes behave. These schemes are the dominant players in deciding how the model develops features that are important to daily activities, such as high and low temperatures, rainfall, cloudiness, and winds. These schemes also are crucial to seasonal forecasts and climate assessments. Increased knowledge of model physical process schemes may provide enough understanding and confidence that forecasters are enabled to disagree with the models when presented with good evidence.

In the following chapters the main types of parameterization schemes for the land surface, vegetation, planetary boundary layer and turbulence, convection, microphysics, radiation in clear skies, cloud cover and radiation in cloudy skies, and orographic drag are explored. Many more parameterization schemes exist than can be realistically discussed in a single book. Thus, the intent is not to conduct a complete survey of the literature, but instead to provide the reader with sufficient background information and some reasonable appreciation for the breadth of the literature. It is hoped that by reading the material one can gain enough perspective and sufficient understanding of the parameterization process to read the available literature easily.

1.4 Question

1. Do an Internet search looking for information on operational and/or research numerical weather prediction models. Read over the outlines of what is available with regard to these systems. Based upon the information available on these web pages, list the positive and any negative aspects of each modeling system. Which one seems most complete and user friendly?