

A NEW PARADIGM FOR PARAMETERIZATIONS IN NUMERICAL WEATHER PREDICTION AND OTHER ATMOSPHERIC MODELS

Roger A. Pielke Sr.

Cooperative Institute for Research in Environmental Sciences and
Department of Atmospheric and Oceanic Sciences
University of Colorado at Boulder
Boulder, Colorado

Toshihisa Matsui and Giovanni Leoncini

Atmospheric Science Department
Colorado State University
Fort Collins, Colorado

Timothy Nobis

United States Air Force
Air Force Weather Agency
Offutt AFB, Nebraska

Udaysankar S. Nair

NSSTC, University of Alabama at Huntsville
Huntsville, Alabama

Er Lu

Agronomy Department
Iowa State University
Ames, Iowa

Joseph Eastman, Sujay Kumar,

Christa D. Peters-Lidard, and Yudong Tian
GEST/UMBC, Hydrological Services Branch
GSFC/NASA
Greenbelt, Maryland

Robert L. Walko

Department of Civil and Environmental Engineering
Duke University
Durham, North Carolina

Abstract

The use of look-up-tables (LUTs) to represent parameterizations within numerical weather prediction and other atmospheric models is presented. We discuss several approaches as to how the use of LUTs can be optimized in order to retain the physical representation of the parameterization, yet be much more computationally efficient than the parent parameterization from which they are derived.

1. Introduction

All atmospheric models are composed of a dynamical core, which represents advection, the pressure gradient force, and gravitational acceleration; and of a set of parameterizations that represent all other physical processes in the model. Only the dynamical core is based on fundamental physical concepts. For example, the pressure gradient force does not involve tunable coefficients. In con-

trast, parameterizations, although partly based on fundamental concepts of physics, involve tunable coefficients and empirical functions. In atmospheric models, parameterizations are constructed, for example, for deep cumulus convection, stratiform cloud and precipitation processes, subgrid-scale mixing, short- and longwave radiative fluxes, and land-surface interactions (see Pielke 2002, Appendix B for summaries of the parameterizations used by a variety of numerical weather prediction and other atmospheric models).

The computational costs of the parameterizations, however, are becoming much greater than for the dynamical core of a model, as parameterizations introduce greater complexity. Majewski et al. (2002) report the computational cost of different components of high-resolution global operational numerical weather prediction models. They show that parameterizations occupy 46.8% of the total when the radiation code was updated every 2 hours. If the radiation code (which represents 57.5% of the total parameterization cost) is updated on a more realistic

time scale, e.g., 10 minutes, this parameterization by itself would cost about 85% of the total computational time! In this paper, we outline a procedure to very significantly reduce this computational cost. Earlier discussions of this subject are available from Matsui et al. (2004) and Chevallier et al. (1998).

2. Methodology

The goal of a parameterization is to mimic the physical process that it is designed to represent without requiring a detailed, comprehensive, high spatial and temporal resolution model. Since the parameterization itself is an engineering module (i.e., it consists of empirical equations with tunable coefficients derived from observations and/or from a higher resolution model), the goal is to accurately represent the physics it is designed to simulate at a minimum of computational cost. The parameterization concept can be written as:

$$\text{Output}(\mathbf{x}) = T[\text{Input}(\mathbf{x}), \mathbf{y}] \quad (1)$$

where the dependent variables that need to be computed (the *Output* \mathbf{x}), are obtained from the *Input* values \mathbf{x} and the prescribed constants, \mathbf{y} of the parameterization, through the transfer function, T , which is the parameterization. The constants \mathbf{y} are obtained from observations and/or a higher resolution model when the parameterization was created (such as through a fit to the observed data as a function of observed values of \mathbf{x}). T can provide an instantaneous change (i.e., over a time step) or be inserted over a period of time, such as performed with the Fritsch-Chappell (1980) deep cumulus parameterization. This approach is also common in the remote-sensing community (e.g., Jin et al. 2004). Pielke (1984; pages 263-265) proposed this approach to parameterize the response of cumulus clouds to the larger-scale environment.

The current paradigm is to exercise the parameterization, T , within the atmospheric model for each gridpoint during the period of model integration.

However, there is another approach that can significantly reduce the cost. The concept is to integrate the parameterization *offline* for the universe of \mathbf{x} , where the number of values of \mathbf{x} that is needed depends on the graining that is chosen. This approach can be described as a look-up-table (LUT). The LUT, expressed as a multi-dimensional array or fitting function, provides the needed value of T .

There has been an impediment to the use of the LUT technique. The universe of permutations of \mathbf{x} that are needed produce an enormous number of values. Such large data arrays cannot be accommodated within the available CPU memory of any existing computer. The choice of the modeling community, therefore, has been to include the parameterizations within the atmospheric models and exercise them as the model integration proceeds.

As an alternate approach, we propose the solution of Eq. (1) offline in order to construct a LUT (or its functional interpolation). The LUT is then applied in lieu of actually running the parent parameterization as the atmospheric model is integrated in time and space. There are several items that permit the feasibility of this approach:

- *Existing parameterizations are exercised in 1-D vertical columns with the input values of \mathbf{x} obtained from just one x - y gridpoint.* This simplifies significantly the number of calculations that must be performed in creating the LUT.
- *Existing parameterizations include mathematical complexity which is not justified by the skill that it has in defining T .* In other words, the dimensionality (i.e., as represented by its degrees of freedom) of the parameterization is much greater than warranted. This means the number of separate values of T can be much less than provided by the parent parameterization. The term *graining* can be used to describe the number of separate values.
- *The success of LUTs highly depends on the availability of a large repository of the pre-computed values, and more critically, on fast, targeted retrieval of this information.* Fortunately, those commercial search engines, such as Google and Yahoo, have already demonstrated the feasibility of such an approach. For example, Google presently can search an index database of over 8 billion web pages in under a second for most user queries. Our proposed approach has the added advantage that the total information stored is much more compact, well structured, and much easier to index.

3. Discussion

The LUT-based approach is overviewed in the following text. We segment the discussion into data storage and retrieval, methods to reduce the dimensionality of the approach, and the relationship between the original parameterization and the LUT-based approach.

a) Data storage and retrieval

To use the LUT-based approach to reproduce essentially all of its values requires the organization and search for the correct LUT from perhaps billions of the available LUT values. To address the limitation of existing computer memory, the minimum size (one case of input and output values) of binary LUT can be stored in files on the hard disk. To efficiently search the LUT for the required value of T for each situation, a set of the input variables is converted into directory and file names, and then the machine operating system (e.g., UNIX) can read the binary LUT nearly instantaneously with the given directory and file name. This hard-disk, input-output approach is the type of procedure used by the business community to access specific values within vast data sets.

There are many ways to store the LUT in order to enable fast retrievals such as hashing, distributed I/O storage, and distributed data bases. The hashing technique enables the mapping of a unique key to the LUT entry. Examples of methods of data retrievals that can be employed are parallel, asynchronous retrievals, a hard-disk, input-output approach, and a multi-nonlinear fitting approach usually called a neural network.

An example of possible LUT storage and retrieval schemes is the hash table based data structure. A hash table (Corman et al. 1990) maps every LUT entry to a

unique integer, or an index, by using a hash function. The indexes are often used as the memory address of the stored LUT data, therefore the search efficiency is greatly increased to the order of $O(1)$. Hashing techniques are known to be fast lookup techniques compared to other common approaches such as binary or tertiary tree structures. Improvements to the hash table implementation of the LUT can be achieved by the use of a relational database. For example, in a specific simulation, if certain entries of the LUT are accessed repeatedly, this information can be used to weigh the LUT lookup, enabling faster turnaround times. Conceptually, this is similar to how the web search engines weighs and caches frequently accessed pages.

When the storage space required for the LUT becomes too large to be handled on a single processor, the use of distributed I/O storage or distributed databases can be employed. A distributed I/O system with large, scalable storage space can be created by taking advantage of easily available and inexpensive commodity resources instead of using large, expensive, centralized storage systems. The large storage space available on a distributed I/O system can be used to create a fault-tolerant, fail-safe LUT storage by the use of multiple data servers and data replication. Parallel, asynchronous LUT retrievals can also be used to improve the performance of the LUT approach.

The above mentioned hard-disk, input-output approach, for example, enables the delta-four-stream Fu-Liou radiation code (Fu and Liou 1992) (30 vertical layer, 140 input, and 33 output) to run 443 times faster than the original code in the Sun-Blade-1000 workstation (Dual CPU: 900 MHz frequency and 8 mb cash size) (Matsui et al. 2004). With this magnitude of speedup, the computational cost of the parameterization becomes negligible in comparison with that of the dynamic core.

A multi-nonlinear fitting approach, usually called Neural Network, also enables the dramatic saving of computational time for longwave radiation codes (Chevallier et al. 1998). The Neural-network-based radiation code was constructed from a line by line radiation model, achieves a speed that is 22 times faster, and yet, is a more accurate radiation code than the conventional band model (Chevallier et al. 1998).

b) Methods to reduce the dimensionality of the approach

With a parameterization, however, we do not require billions of data points in a LUT in order to realistically reproduce a parameterization of a specific process with the accuracy needed for use in an atmospheric model. To illustrate this point, the hyperspace of a transfer function T , and how slices through it can be applied to establish the needed resolution of a parameterization [the Louis surface flux parameterization (Louis 1979)] is discussed here (Lu 2004). The Louis surface flux scheme, although a simple parameterization, still requires considerable storage if used as an LUT. The surface heat flux, as calculated from the Louis surface flux parameterization, is a function of the wind (u) and the potential temperature (θ) at a height (z), the surface potential temperature (θ_{s0}), and the roughness length (z_0). Figure 1 shows one slice through hyperspace where the surface heat flux

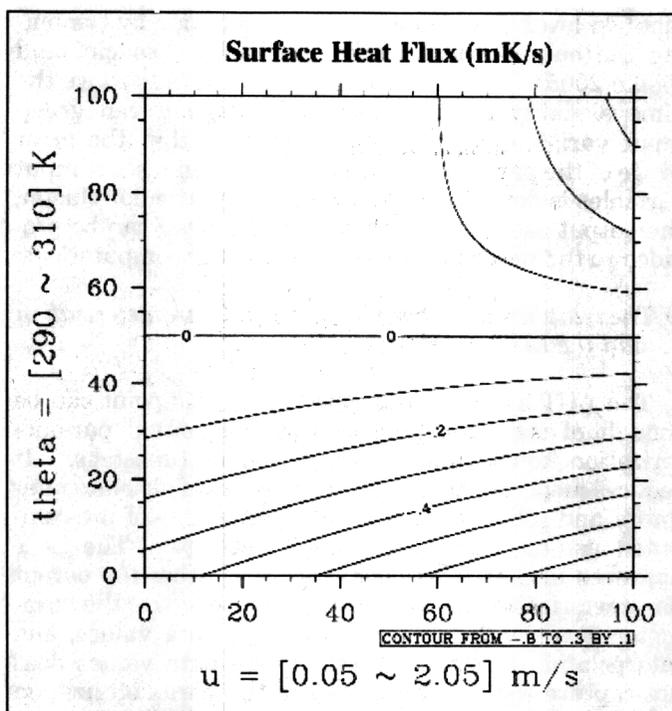


Fig. 1. Surface heat flux calculated from wind (u , $m s^{-1}$) and potential temperature (θ , $^{\circ}K$) at $z = 1.0$ m. The u is in domain of 0.05 to 2.05 $m s^{-1}$ with an interval of 0.02 . The domain of θ is 290 – 310 $^{\circ}K$ and the interval is 0.2 $^{\circ}K$. The surface potential temperature $\theta_{s0} = 300$ $^{\circ}K$ and the roughness length $z_0 = 0.1$ m (from Lu 2004).

varies with u and θ , while the other variables are fixed ($z = 1.0$ m, $\theta_{s0} = 300$ $^{\circ}K$, $z_0 = 0.1$ m). The domain of u is set from 0.05 to 2.05 $m s^{-1}$ with an interval of 0.02 $m s^{-1}$, and the domain of θ is from 290 to 310 $^{\circ}K$ with an interval of 0.2 $^{\circ}K$. This graining of the parameterization (with 100 by 100 data points) indicates that this resolution is sufficient to capture the physically important variations that are represented by the parameterization for the variable space used in this example. Even extending the domains to more realistic ranges (e.g., 250 – 320 $^{\circ}K$, and 0.05 – 50 $m s^{-1}$) with the same graining, the total number of calculations or data points would still be manageable ($875,000$ for the above ranges)

In the context of a general parameterization, we do not need billions of data points in an LUT in order to realistically parameterize a process for use in an atmospheric model.

The dimensionality of the input space of the T operator can be further reduced from the number obtained by simply combining the number of variables with the number of discretization intervals. Such a large number of combinations results in a large number of physically meaningless inputs that result from the mathematical formulation used to construct a parameterization, rather than based on the data used to construct the parameterization. *No parameterization can justify a dimensionality in the billions.*

We are applying the technique of Empirical Orthogonal Functions (EOF) to the parameterizations as one method to reduce the dimensionality to a physically

justified level. The values for T are obtained by combining the output of the individual EOFs (Leoncini and Pielke 2005). A second technique that could reduce the dimensionality is cluster analysis, since it can group input variables that provide outputs within the error range of the parameterization. Thus, when a set of input variables is determined to belong to a particular cluster, the output associated with the cluster itself can be provided to the parent model without further computations.

c) The relationship between the original parameterization and the LUT-based approach.

The LUT approach described up to this point can be thought of as the complement of carrying out all parameterization computations during model timesteps. It reduces model runtime computations to an absolute minimum and relies instead on efficient access of pre-computed values from a very large database. The LUT approach also sacrifices some accuracy from the parent parameterization because it must approximate the parameter space with a finite number of data values, and interpolation methods between these data values does not capture the full complexity of the parameterization (which may or may not have physical realism).

However, there are levels of compromise between these two extremes that may provide an optimal combination of accuracy and efficiency between the full LUT and the full parameterization method.

One form of compromise is possible for parameterizations of low dimensionality, such as the Louis surface layer parameterization, where parameter space can be adequately covered with relatively few data values (e.g., less than 1 million). Such a small LUT may be computed at model initialization time and stored in model arrays where access of table values is faster than from a disk.

A more important compromise that is often possible is a hybrid approach where LUTs are constructed for subsets of a full parameterization, particularly those that consume the most time. For example, LUTs have been used for years to store pre-computed rates of hydrometeor collisions, melting, and nucleation in the RAMS microphysics parameterization (Walko et al. 1995), while the overall parameterization is computed in the conventional way. Schultz (1995) developed an explicit cloud physics parameterization for use in operational models which encompasses the hybrid LUT concept. These LUTs have only 2 or 3 dimensions and are thus easy to fill at high density for good accuracy. The speed of the overall scheme was increased several fold to the point where it consumes much less time than the model dynamics. While this speed does not match what might be obtained by constructing an LUT of the full microphysics parameterization, the accuracy is improved and the complexity of the LUT is reduced to the point that the hybrid approach is probably the most attractive.

The hybrid LUT approach may be particularly attractive for a parameterization of very high dimensionality, such as a radiative transfer model representing, possibly, 50 vertical levels. For example, it is probably an impossible task to pre-compute all possible combinations of moist and dry model levels that may occur. Thus, the full LUT

approach will be prone to incorrect heating and cooling rates at some model levels for a subset of situations if the LUT does not have fine enough graining of the range of combinations. A hybrid LUT approach could be designed to replace only certain time consuming calculations in the parameterization while keeping the computations involved in the specific vertical atmospheric profile within the realm of the parameterization.

There is an additional approach that can be applied once either a hybrid or complete LUT is constructed. Since the LUT is a parameterization itself, if new observations (or higher resolution model simulations) are obtained that would warrant the updating of the parent parameterization, that parameterization might be bypassed and the LUT itself adjusted. This will be a particularly straightforward approach to use when a functional interpolation is applied to represent the LUT.

4. Relevance to Superparameterizations

It has been proposed (Grabowski 2001, Randall et al. 2003) to embed a cloud-resolving model within a larger-scale model in order to improve the accuracy of simulating cloud interactions with the larger-scale model. This has been called a "superparameterization". Superparameterization refers to using a 2-D or 3-D cloud-resolving model to simulate a process in place of a very simplified parameterization that has been commonly used in weather and climate models in order to keep the computational cost low. Superparameterization embedded, Multi-Modeling Frameworks (MMF) are recently under development at several institutions, and there are plans to create global cloud libraries which includes detailed mass and energy output from cloud resolving models. With the LUT-based approach, the superparameterization approach could be used much more efficiently since the simulations (e.g., the 3-D cloud model) are integrated offline, and the results are archived in a database for future retrieval. Column parameterizations, which are what is exclusively used now in atmospheric models, only consider vertical processes in the parameterization. By using the LUT-based approach, the realism of the superparameterization is retained but without its enormous computational cost. Moreover, as long as data libraries are organized, the LUT approach can always be mapped back to the original parameterization; therefore, the LUT approach is not a "black box" in that the reason for a particular output can be described from the original.

An advantage of the superparameterization approach, in contrast with the column parameterizations, is that it can dynamically more directly interact with the parent model at each time step. However, there is an alternate method. Once T is selected from the suite of available off-line cloud-resolving simulations, its values can be fed into the vertical profiles at the GCM gridpoint as they are produced (i.e., after each time step) for the lifetime of the cloud system for that particular value of T . This lifetime is determined for each specific set of GCM input variables from the lifetime that comes out of running the off-line cloud field model that is used to construct T .

This approach of inserting the cumulus cloud effect over time is adopted from the procedure used by Fritsch and Chappell (1980). Comparisons of the much more computationally efficient LUT approach with the use of the superparameterization methodology should be made. With the LUT approach, it should be computationally possible to utilize higher-resolution, 3-D cloud-resolving models, instead of relying on coarser-resolution, 2-D cloud resolving models with a resultant possible improvement in realism of the parameterization. A key aspect of realism enabled by the LUT approach is the ability to represent the full spatial heterogeneity of the land surface, which is known to significantly impact the initiation, growth, and maintenance of convective clouds (e.g., Avissar and Liu, 1996).

5. Conclusions

This paper introduces a new procedure to accurately and efficiently parameterize physical processes in numerical weather prediction models, and in other types of atmospheric models. The method, which we refer to as the LUT approach, utilizes data access and retrieval procedures, and methods to reduce the dimensionality of the original parameterization to create this method of model improvement. A major advantage of the LUT approach, for example, includes the ability to create more realizations in the creation of ensemble forecasts. As shown by Mullen and Buizza (2002) and Bright and Mullen (2002), such ensemble forecasts provide a particularly valuable way to improve forecasting skill.

However, the LUT approach as a replacement for the standard form of model parameterizations requires development and application with a diversity of atmospheric models at many different organizations. The input-output datasets library, such as cloud libraries, must be established and made accessible for the LUT constructions.

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Authors

Professor Roger A. Pielke, Sr. received a B.A. in Mathematics from Towson State College in 1968, and an M.S. and Ph.D. in Meteorology from Pennsylvania State University in 1969 and 1973, respectively. Dr. Pielke has worked for NOAA's Experimental Meteorology Lab (1971-1974), the University of Virginia (1974-1981), and

Colorado State University (1981-present). Currently, he is a Senior Research Scientist in CIRES and ATOC at the University of Colorado in Boulder, Colorado and an Emeritus Professor in the Department of Atmospheric Science at Colorado State University in Fort Collins, Colorado. His research interests include land-atmosphere interactions, ocean-atmosphere interactions, climate system dynamics, nonlinear mathematical study of atmospheric and climate processes, large eddy simulation (LES) modeling, and mesoscale modeling.

Toshihisa Matsui is currently a Ph.D. candidate in Atmospheric Science at Colorado State University, and is the CEAS fellow at NASA Goddard Space Flight Center. His research field is related to remote sensing and numerical hydrology-atmospheric modeling for better understanding of the regional energy and water cycles. [For more information you may contact him online at http://members.at.infoseek.co.jp/toshihisa_matsui/cv.htm].

Giovanni Leoncini received a "Laurea" in Physics (~M.S.) from the University of Bologna, Italy in 1996, and a Health Physics Diploma, also from the University of Bologna in 1998. He worked as junior researcher at the Regional Weather Service in Bologna, and as a private environmental consultant (1996-1999). He obtained a M.S. in Meteorology from San Jose State University in 2002. He is currently a Ph.D. student at the Department of Atmospheric Science at Colorado State University under the supervision of Professor R.A. Pielke, Sr. His research interests include mesoscale dynamics, scale interaction, and model development.

Timothy Nobis is a Major in the United States Air Force where he works towards transitioning space environmental research efforts from research into current forecast operations. He continues to work towards a Ph.D. in Meteorology (research area is urban boundary layers) at Colorado State University. He received a B.S. in Meteorology from Lyndon State College, VT in 1990, and his M.S. in Meteorology (research area urban ozone) from Texas A&M University in 1998. His interests range from land/atmosphere interactions right up through solar wind interaction with the earth's magnetosphere.

Udaysankar S. Nair received a Bachelor of Technology in Mechanical Engineering from the University of Kerala, Thiruvananthapuram, India in 1988, M.S. in Meteorology from South Dakota School of Mines and Technology in 1991, and his Ph.D. in Atmospheric Science from Colorado State University in 2002. Dr. Nair is currently a Research Scientist at the Earth Science System Center, National Space Science Technology Center, University of Alabama in Huntsville. He is also an adjunct Assistant Professor at the Department of Atmospheric Science in University of Alabama in Huntsville. His research interests include land-atmosphere interaction, remote sensing of surface energetics, remote sensing of clouds, biogeographical mapping of cloud forests, numerical modeling of dust and smoke transport, cloud field organization and behavior, data mining, and orographic processes.

Er Lu received B.S. and M.S. degrees in meteorology from Nanjing University, Nanjing, China in 1984 and 1987, respectively, and a Ph.D. from the

Department of Atmospheric Science, University of Arizona in 2006. He is currently employed at the Department of Agronomy at Iowa State University. His research interests include monsoon, atmospheric circulation, water vapor, and precipitation.

Joseph Eastman received a B.A. in Physics from the University of Minnesota in 1987, an M.S. in Atmospheric Science from Colorado State University in 1994, and a Ph.D. from the Graduate Degree Program in Ecology from Colorado State University in 1999. He has been working with numerical models for the past 17 years. His expertise is in modeling land-surface and land-use change and their feedback on regional climate. He has also been active in hurricane, dispersion, and biophysical modeling. He is currently working on high-resolution simulation of moist processes.

Sujay Kumar received a Bachelor of Technology in Civil Engineering from the Indian Institute of Technology, Bombay in 1996, and a M.S. in Environmental Engineering and a Ph.D. in Computer-Aided Engineering from North Carolina State University, Raleigh, North Carolina, in 1998 and 2002, respectively. Dr. Kumar is currently an Assistant Research Scientist at the University of Maryland at Baltimore County (UMBC), Goddard Earth Sciences and Technology Center (GEST) at the NASA Goddard Space Flight Center. His research interests include land-atmosphere interactions, high performance computing, decision support systems, and mathematical optimization.

Dr. Christa D. Peters-Lidard received a B.S. in Geophysics from Virginia Polytechnic Institute and State University (Virginia Tech) in 1991, and an M.A. and Ph.D. from the Water Resources Program in the Department of Civil Engineering and Operations Research at Princeton University in 1993 and 1997, respectively. Dr. Peters-Lidard has worked for Georgia Institute of Technology (1997-2001), and NASA's Goddard Space Flight Center (NASA/GSFC) from 2001 to the present. Currently, she is a Physical Scientist at NASA/GSFC. Her research interests include land-atmosphere interactions, soil moisture measurement and modeling, and the application of high performance computing and communications technologies in earth system modeling.

Dr. Yudong Tian received a Ph.D. in Atmospheric Sciences in 1999 from UCLA, where he conducted research in climate dynamics and geophysical fluid dynamics. He has been working on GSFC's Land Information System since early 2002, building a high-performance computing platform for real-time land-surface simulation and data assimilation.

Dr. Robert Walko has been a Senior Research Scientist in the Department of Civil and Environmental Engineering at Duke University since 2001. He is developing and testing a comprehensive numerical modeling system known as the Ocean-Land-Atmosphere Model, or OLAM. This model is partly based on the Regional Atmospheric Modeling System (RAMS) which he helped to develop over a 13-year period at Colorado State University. Dr. Walko's research has focused primarily on atmospheric phenomena from micro-scale to global scale, but he works

very closely with scientists in diverse fields including hydrology and biosciences. Dr. Walko received B.S. in Physics, and an M.S. and Ph.D. in Atmospheric Sciences from the University of Arizona in 1977, 1979, and 1983, respectively. He was a Postdoc and Research Scientist at the University of Oklahoma from 1984 to 1987, a Research Scientist at Colorado State University from 1987 to 2000, and a Research Professor at Rutgers University from 2000 to 2001. He has also worked as a consultant for Aster, Inc., Mission Research Corp., and ATMET LLC, all in Colorado.

References

Avissar, R., and Y. Liu, 1996: Three-dimensional numerical study of shallow convective clouds and precipitation induced by land surface forcing. *J. Geophys. Res.*, *101*, 7499-7518.

Bright, D. A., and S. L. Mullen, 2002: Short-term ensemble forecasts of precipitation during the Southwest Monsoon. *Wea. Forecasting*, *17*, 1080-1100.

Chevallier, F., F. Chéruy, N. A. Scott, and A. Chédin, 1998: A neural network approach for a fast and accurate computation of a longwave radiative budget. *J. Appl. Meteor.*, *37*(11), 1385-1397.

Corman, T. H., C.E. Leiserson, and R. L. Rivest, 1990: *Introduction to Algorithms*. MIT Press, 1990, 768 pp.

Fritsch, J.M., and C.F. Chappell, 1980: Numerical prediction of convectively driven mesoscale pressure systems, Part I. Convective parameterization. *J. Atmos. Sci.*, *37*, 1722-1733.

Fu, Q., and K.N. Liou, 1992: On the correlated k-distribution method for radiative transfer nonhomogeneous atmospheres. *J. Atmos. Sci.*, *49*, 2139-2156.

Grabowski, W. W., 2001: Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP). *J. Atmos. Sci.*, *58*, 978-997.

Jin, Z., T. P. Charlock, W. L. Smith Jr., and K. Rutledge, 2004: A parameterization of ocean surface albedo. *Geophys. Res. Lett.* *31*, L22301, doi:10.1029/2004GL021180.

Leoncini, G., and R.A. Pielke, 2005: The use of EOFs to reduce the dimensionality of a radiation Look Up Table, in preparation.

Louis, J.F., 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Bound. Layer Meteor.*, *17*, 187-202.

Lu, E., 2004: Louis surface flux scheme and look-up table approach for parameterization. [Available online at: http://blue.atmos.colostate.edu/courses/ErLu_2.pdf].

Majewski, D., D. Liermann, P. Prohl, B. Ritter, M. Buchhold, T. Hanisch, G. Paul, W. Wergen, and J. Baumgardner, 2002: The Operational Global Icosahedral–Hexagonal Gridpoint Model GME: Description and high-resolution tests. *Mon. Wea. Rev.*, **130**(2), 319–338.

Matsui, T., G. Leoncini, R.A. Pielke Sr., and U.S. Nair, 2004: A new paradigm for parameterization in atmospheric models: Application to the new Fu-Liou radiation code. Atmospheric Science Paper No. 747, Colorado State University, Fort Collins, CO 80523, 32 pp.

Mullen, S. L., and R. Buizza, 2002: The impact of horizontal resolution and ensemble size on probabilistic precipitation forecasts by the ECMWF ensemble prediction system. *Wea. Forecasting*, **17**, 173–191.

Pielke, R.A., 1984: *Mesoscale Meteorological Modeling*, 1st ed., Academic Press, New York, NY, 612 pp.

Pielke, R.A., Sr., 2002: *Mesoscale Meteorological Modeling*, 2nd ed., Academic Press, San Diego, CA, 676 pp.

Randall, D. A., M. Khairoutdinov, A. Arakawa, and W. Grabowski, 2003: Breaking the cloud-parameterization deadlock. *Bull. Amer. Meteor. Soc.*, **84**, 1547–1564.

Schultz, P., 1995: An explicit cloud physics parameterization for operational numerical weather prediction. *Mon. Wea. Rev.*, **123**, 3331–3343.

Walko, R.L., C.J. Tremback, R.A. Pielke, and W.R. Cotton, 1995: An interactive nesting algorithm for stretched grids and variable nesting ratios. *J. Appl. Meteor.*, **34**, 994–999.