

Numerical Weather and Climate Prediction

This textbook provides a comprehensive, yet accessible, treatment of weather and climate prediction, for graduate students, researchers, and professionals. It teaches the strengths, weaknesses, and best practices for the use of atmospheric models, and is ideal for the many scientists who use such models across a wide variety of applications. The book describes different numerical methods, data assimilation, ensemble methods, predictability, land-surface modeling, climate modeling and downscaling, computational fluid-dynamics models, experimental designs in model-based research, verification methods, operational prediction, and special applications such as air-quality modeling and flood prediction. The book is based on a course that the author has taught for over 30 years at the Pennsylvania State University and the University of Colorado, Boulder, and also benefits from his wide practical modeling experience at the US National Center for Atmospheric Research.

This volume will satisfy everyone who needs to know about atmospheric modeling for use in research or operations. It is ideal both as a textbook for a course on weather and climate prediction and as a reference text for researchers and professionals from a range of backgrounds: atmospheric science, meteorology, climatology, environmental science, geography, and geophysical fluid mechanics/dynamics.

Tom Warner was a Professor in the Department of Meteorology at the Pennsylvania State University before accepting his current joint appointment with the National Center for Atmospheric Research and the University of Colorado at Boulder. His career has involved teaching and research in numerical weather prediction and mesoscale meteorological processes. He has published on these and other subjects in numerous professional journals. His recent research and teaching has focussed on atmospheric processes, operational weather prediction, and arid-land meteorology. He is the author of *Desert Meteorology* (2004), also published by Cambridge University Press.

“Numerical Weather and Climate Prediction is an excellent book for those who want a comprehensive introduction to numerical modeling of the atmosphere and Earth system, whether their interest is in weather forecasting, climate modeling, or many other applications of numerical models. The book is comprehensive, well written, and contains clear and informative illustrations.”

Dr. Richard A. Anthes, President,
University Corporation for Atmospheric Research, Boulder

“Tom Warner’s book is a rich, effectively written and comprehensive detailed summary of the field of atmospheric modeling from local to global scales. It should be in the library of all meteorologists, climate researchers, and other scientists who are interested in the capabilities, strengths and weaknesses of modeling.”

Professor Roger A. Pielke, Sr.,
Department of Atmospheric Science, Colorado State University, Fort Collins

“Tom Warner has taught Numerical Weather and Climate Prediction courses for over thirty years at Pennsylvania State University and the University of Colorado at Boulder. He also has been one of the principle developers of numerical models widely used in the atmospheric science community, and has a long history of applying such codes. This extensive background gives Professor Warner a unique insight into how models work, how to use them, where their problems lie, and how to explain all of this to students. His book assumes students have a basic understanding of atmospheric science. It covers all aspects of modeling one might expect, such as numerical techniques, but also some that might be unexpected such as ensemble modeling, initialization, and error growth. Today most students have become model users instead of model developers. Fewer and fewer peer into the models they use beyond the narrow regions that may directly interest them. With hundreds of thousands of lines of code, and groups of developers working on individual parts of the code, very few can say they truly understand all the parts of a model. Professor Warner's textbook should help both the student and the more advanced user of codes better appreciate and understand the numerical models that have come to dominate atmospheric science.”

Professor Brian Toon, Chair,
Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder

“Tom’s new book covers an impressive range of need-to-know material spanning traditional and cutting-edge atmospheric modeling topics. It should be required reading for all model users and aspiring model developers, and it will be a required text for my NWP students.”

Professor David R. Stauffer,
Department of Meteorology, The Pennsylvania State University

“The book addresses many practical issues in modern numerical weather prediction. It is particularly suitable for the students and scientists who use numerical models for their research and applications. While there have already been a few excellent textbooks that provide fundamental theory of NWP, this book offers complementary materials, which is useful for understanding of key components of operational numerical weather forecasting.”

Professor Zhaoxia Pu,
Department of Atmospheric Sciences, University of Utah

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Numerical Weather and Climate Prediction

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and

University of Colorado, Boulder



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**Lewis Fry Richardson is arguably the father of numerical weather prediction.
In addition to his great interest in methods for modeling the atmosphere,
he was equally passionate about developing mathematical equations
that could predict wars, with the hope that they could thus be avoided.
Let us all, in small or large ways, follow LFR's passions.**

**With gratitude
to
John Hovermale,
who wanted to write this book**

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Preface

This textbook provides a general introduction to atmospheric modeling for those using models for either operational forecasting or research. It is motivated by the fact that all those who use such models should be aware of their strengths and limitations. Unlike the many other books that specialize in particular aspects of atmospheric modeling, the aim here is to offer a general treatment of the subject that can be used for self study or in conjunction with a course on the subject. Even though there is considerable space devoted here to numerical methods, this is not intended to be the major focus. As the reader will see, there are many other subjects associated with the modeling process that must be understood well in order for models to be used effectively for research or operations. For those who need more information on particular topics, each chapter includes references to specialized resources. It is assumed that the reader has a Bachelors Degree in atmospheric sciences, with mathematics through differential equations.

Abbreviations or acronyms, as well as symbols, will be defined in the text the first time that they appear, and for future reference they are also defined in the lists that appear before Chapter 1. Even though the student should focus on concepts rather than jargon, a technical vocabulary is still necessary in order to discuss these subjects. Thus, commonly used, important terms will appear in italics the first time, in order to identify them as worth remembering.

There has been no attempt to provide an exhaustive list of references for any particular topic. The reader should refer to the more-recent references, or one of the review papers recommended at the end of the chapters, for a thorough list of historical references. Because World Wide Web addresses tend to change frequently, none are provided here. Instead, the reader should use an available search engine to access current information about model specifications or data sources.

Many colleagues provided tangible and moral support during the production of this book. Cindy Halley-Gotway skillfully and patiently produced the graphic art for the figures and for the cover. Gregory Roux ran model experiments that served as the basis for plots of shallow-fluid-model solutions, and also generated graphical displays of some of the functions in Chapter 3. Many individuals shared their time by engaging in very helpful technical discussions, where special thanks go to George Bryan, Gregory Byrd, Janice Coen, Joshua Hacker, Yubao Liu, Rebecca Morss, Daran Rife, Dorita Rostkier-Edelstein, Robert Sharman, Piotr Smolarkiewicz, Wei Wang, and Andrzej Wyszogrodzki. Those who donated their time and skills by reading and editing chapters include Fei Chen, Luca Della Monache, Joshua Hacker, Andrea Hahmann, Thomas Hopson, Jason Knievel, Yubao Liu, Yuwei Liu, Linlin Pan, Daran Rife, Robert Sharman, David Stensrud, Wei Wang, Jeffrey Weil, and Yongxin Zhang. Christina Brown efficiently managed the process of obtaining

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Acronyms and abbreviations

| | |
|--------|--|
| 3DVAR | Three-Dimensional VARiational data assimilation |
| 4DVAR | Four-Dimensional VARiational data assimilation |
| AC | Anomaly Correlation |
| AGCM | Atmospheric General Circulation Model |
| AGL | Above Ground Level |
| ALADIN | European NWP project |
| AOGCM | Atmosphere-Ocean General Circulation Model |
| AR4 | Assessment Report number 4 |
| ARPEGE | Action de Recherche Petite Echelle Grande Echelle (Research Project on Small and Large Scales) |
| ARPS | Advanced Regional Prediction System |
| ARW | Advanced Research WRF model |
| ASL | Above Sea Level |
| BB-LB | Big-Brother–Little-Brother experiment |
| BS | Brier Score |
| BSS | Brier Skill Score |
| CAM | Community Atmospheric Model, of NCAR |
| CAPE | Convective Available Potential Energy |
| CCA | Canonical Correlation Analysis |
| CCM | Community Climate Model, of NCAR |
| CCN | Cloud Condensation Nucleus |
| CCSM | Community Climate System Model |
| CFD | Computational Fluid Dynamics |
| CFL | Courant–Friedrichs–Lewy numerical stability criterion, which requires that $U\Delta t/\Delta x \leq 1$ |
| CFS | Climate Forecast System of the US NCEP |
| CIN | Convective INhibition |
| CMAP | CPC Merged Analysis of Precipitation |
| CMC | Canadian Meteorological Centre |
| CMIP | Climate Model Intercomparison Project |
| COAMPS | Coupled Ocean–Atmosphere Mesoscale Prediction System, of the US Navy |
| COLA | Center for Ocean–Land–Atmosphere studies, USA |

| | |
|---------|---|
| CPC | Climate Prediction Center |
| CRMSE | Centered Root-Mean-Square Error |
| CSI | Critical Success Index |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation, Australia |
| DCISL | Departure Cell-Integrated Semi-Lagrangian finite-volume method |
| DEMETER | Development of a European Multimodel Ensemble system for seasonal to inTERannual prediction |
| DMO | Direct Model Output |
| DNS | Direct Numerical Simulation |
| DSS | Decision Support System |
| ECHAM | Global climate model developed by the Max Planck Institute for meteorology |
| ECMWF | European Centre for Medium-range Weather Forecasts |
| ECPC | Experimental Climate Prediction Center, US Scripps Institution of Oceanography |
| EKF | Extended Kalman Filter |
| EL | Equilibrium Level |
| EML | Elevated Mixed Layer |
| EnKF | Ensemble Kalman Filter |
| ENSO | El Niño - Southern Oscillation |
| EOF | Empirical Orthogonal Function |
| ERA | ECMWF global reanalysis |
| EROS | Earth Resources Observing System, of the US Geological Survey |
| ESA | European Space Agency |
| ETKF | Ensemble Transform Kalman Filter |
| ETS | Equitable Threat Score |
| F | False-alarm rate |
| FAR | False-Alarm Ratio |
| FASTEX | Fronts and Atlantic Storm Tracks EXperiment |
| FDDA | Four-Dimensional Data Assimilation |
| FFSL | Flux-Form Semi-Lagrangian finite-volume method |
| FIM | Flow-following finite-volume Icosahedral Model, of the US NOAA |
| GABLS | Global Energy and Water-cycle EXperiment (GEWEX) Atmospheric Boundary-Layer Study |
| GCM | General Circulation Model |
| GEM | Global Environmental Multiscale model of the Meteorological Service of Canada |
| GEOS | Goddard Earth Observing System, of NASA |
| GFS | Global Forecasting System, of the US NCEP |
| GLDAS | Global Land Data Assimilation System, of the US NOAA and NASA |
| GME | Global model of the German Weather Service |

| | |
|--------|---|
| GOES | Geostationary Operational Environmental Satellite |
| GPI | GOES Precipitation Index |
| GPS | Global Positioning System |
| GSS | Gilbert Skill Score |
| H | Hit rate |
| HIRLAM | HIgh-Resolution Limited Area Model |
| HRLDAS | High-Resolution Land Data Assimilation System, part of the WRF system |
| HSS | Heidke Skill Score |
| IC | Initial Conditions |
| IN | Ice Nucleus |
| IPCC | Intergovernmental Panel on Climate Change |
| IRI | International Research Institute for Climate and Society |
| KE | Kinetic Energy |
| KF | Kalman Filter |
| LAM | Limited-Area Model |
| LBC | Lateral-Boundary Condition |
| LCL | Lifting Condensation Level |
| LDAS | Land Data-Assimilation System |
| LES | Large-Eddy Simulation |
| LFC | Level of Free Convection |
| LM | Lokal Modell, of the German Weather Service |
| LSM | Land-Surface Model |
| MADS | Model-Assimilated Data Set |
| MAE | Mean Absolute Error |
| ME | Mean Error |
| MERRA | Modern Era Retrospective-analysis for Research and Applications, of NASA |
| MET | Model Evaluation Toolkit |
| MICE | Modeling the Impact of Climate Extremes |
| MM4 | Penn State University–NCAR Mesoscale Model Version 4 |
| MODIS | MODerate-resolution Imaging Spectroradiometer |
| MOS | Model Output Statistics |
| MRF | Medium-Range Forecast model, of the US NWS |
| MSC | Meteorological Service of Canada |
| MSE | Mean-Square Error |
| NAM | North American mesoscale Model, of the US NCEP |
| NAO | North Atlantic Oscillation |
| NARR | North American Regional Reanalysis |
| NASA | National Aeronautics and Space Administration, of the USA |
| NCAR | National Center for Atmospheric Research, of the USA |
| NCDC | National Climatic Data Center, of NOAA |

| | |
|----------|---|
| NCEP | National Centers for Environmental Prediction, of NOAA |
| NESDIS | National Environmental Satellite, Data, and Information Service, of NOAA |
| NetCDF | Network Common Data Format |
| NMC | National Meteorological Center, predecessor of NCEP |
| NNMI | Nonlinear Normal-Mode Initialization |
| NNRP | NCEP-NCAR Reanalysis Project |
| NOAA | National Oceanic and Atmospheric Administration, of the USA |
| NOGAPS | Navy Operational Global Atmospheric Prediction System, of the USA |
| NSIP | NASA Seasonal-Interannual Prediction Project |
| NWP | Numerical Weather Prediction |
| NWS | National Weather Service, of the USA |
| OI | Optimal Interpolation |
| OLAM | Ocean–Land–Atmosphere Model |
| OLR | Outgoing Longwave Radiation |
| OMEGA | Operational Multiscale Environment Model with Grid Adaptivity |
| OSE | Observing-System Experiment, Observation Sensitivity Experiment |
| OSSE | Observing-System Simulation Experiment |
| PC | Proportion Correct |
| PCA | Principal Component Analysis |
| PCMDI | Program for Climate Model Diagnosis and Intercomparison |
| PDF | Probability Distribution (or Density) Function |
| PILPS | Project for Intercomparison of Land-surface Parameterization Schemes |
| POD | Probability Of Detection |
| PP | Perfect-Prognosis |
| PRUDENCE | Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects |
| PV | Potential Vorticity |
| QA | Quality Assurance |
| QC | Quality Control |
| QPF | Quantitative Precipitation Forecast |
| RAMS | Regional Atmospheric Modeling System, of Colorado State University |
| RANS | Reynolds-Averaged Navier–Stokes equations |
| RASS | Radio Acoustic Sounding System |
| RCM | Regional Climate Model |
| RFE | Regional Finite Element model, of Canada |
| RH | Relative Humidity |
| RMS | Root-Mean-Square, error or difference |
| RMSE | Root-Mean-Square Error |
| ROC | Relative Operating Characteristic |
| RPS | Rank Probability Score |

| | |
|---------|---|
| RPSS | Rank Probability Skill Score |
| RSM | Regional Spectral Model, of NCEP |
| RTG | Real-Time Global analysis, of the Marine Modeling and Analysis Branch of NCEP |
| RUC | Rapid Update Cycle model, of the US NCEP |
| RUC-2 | RUC, version 2 |
| SC | Successive Correction |
| SCIPUFF | Second-order Closure Integrated PUFF model |
| SEVIRI | Spinning Enhanced Visible and InfraRed Imager |
| SFS | SubFilter Scale |
| SGMIP | Stretched-Grid Model Intercomparison Project |
| SL | Starting Level |
| SLP | Sea-Level Pressure |
| SNOTEL | SNOw TELelemetry |
| SOM | Self-Organizing Map |
| SREF | Short-Range Ensemble Forecasting |
| SS | Skill Score |
| SSM/I | Special Sensor Microwave Imager |
| SST | Sea-Surface Temperature |
| STARDEX | STATistical and Regional dynamical Downscaling of EXtremes |
| STATSGO | State Soil Geographic data base |
| SVD | Singular Value Decomposition |
| TKE | Turbulent Kinetic Energy |
| TOMS | Total Ozone Mapping Spectrometer |
| TRMM | Tropical Rainfall Measurement Mission satellite |
| TS | Threat Score |
| UCM | Urban Canopy Model |
| UKMO | United Kingdom Meteorological Office |
| UMOS | Updatable MOS |
| WRF | Weather Research and Forecasting model |
| WSR-88D | Weather Service Radar, 1988, Doppler |

Principal symbols

Roman capital letters

| | |
|----------------|---|
| A | covariance matrix of the analysis errors |
| B | Planck's function |
| B | background covariance matrix |
| C | phase speed |
| | cloud fraction |
| | thermal capacity, or heat capacity |
| | economic cost of protecting against a weather event |
| C_G | group speed |
| C_P | phase speed |
| C_R | real part of a phase speed |
| D | rate of water loss through drainage within the substrate |
| D_Θ | soil-water diffusivity |
| E | evaporation rate |
| ET | evapotranspiration rate |
| F | all terms on the right side of a prognostic equation |
| | flux |
| Fr_x | frictional acceleration in the x direction |
| G | sensible heat flux between the surface and subsurface |
| H | rate of gain or loss of heat |
| | sensible heat flux between the surface and the atmosphere |
| | mean depth of a fluid |
| | scale height |
| H | forward operator, observation operator |
| H_S | heat flux within the substrate |
| I | longwave radiation intensity |
| I_\downarrow | downward-directed longwave radiation intensity |
| I_\uparrow | upward-directed longwave radiation intensity |
| J | cost function |
| K | highest permitted wavenumber |
| | transfer coefficient |

| | |
|--------------|--|
| K | Kalman gain matrix Weight matrix of analysis |
| K_{Θ} | hydraulic conductivity |
| K_{Hs} | thermal diffusivity of a substrate |
| L | domain length latent heat of evaporation horizontal length scale economic loss from a weather event |
| L_R | length scale of the Rossby radius of deformation |
| M | model dynamic operator |
| P | wave period rate of water input through precipitation |
| P | error covariance matrix |
| Q | direct-solar radiation intensity |
| Q_v | rates of gain or loss of water vapor through phase changes |
| Q | covariance matrix of the model forecast errors |
| R | rhomboidal truncation gas constant for air Rossby radius of deformation net-radiation intensity rate of water loss through surface runoff radius of influence |
| R | covariance matrix of the observation errors |
| RH | relative humidity |
| S | source or sink of water substance |
| T | temperature turbulent, eddy, or Reynolds' stress triangular truncation |
| T_a | atmospheric temperature a short distance above the surface |
| T_g | temperature of the ground surface |
| T_s | temperature within the substrate |
| U | mean wind speed |
| V | value, economic value |
| \vec{V} | velocity vector |
| V_T | terminal velocity |
| X | vector of atmospheric state variables |

Roman small letters

| | |
|-----|-----------------|
| a | radius of Earth |
| c | specific heat |

| | |
|--------------|--|
| c_p | specific heat at constant pressure |
| e | Coriolis parameter base of natural logarithms |
| f | Coriolis parameter generic dependent variable |
| g | acceleration of gravity |
| h | depth of a fluid |
| i | $\sqrt{-1}$ |
| k | wavenumber kinetic energy von Karman constant weighting coefficient in statistical analysis |
| k_s | soil thermal conductivity |
| l | length scale of energy-containing turbulence |
| m | map-scale factor integer wavenumber |
| n | integer wavenumber |
| o | observation |
| p | pressure probability |
| p_s | pressure at the land or water surface |
| p_t | pressure at the top of a model |
| q | specific humidity diffuse solar radiation |
| q_s | saturation specific humidity |
| r | radius of Earth radial distance |
| t | time |
| u | east–west component of wind |
| u^* | friction velocity |
| v | north–south component of wind |
| w | vertical component of wind |
| x | east–west space coordinate general space coordinate |
| \mathbf{x} | state vector |
| y | north–south space coordinate |
| \mathbf{y} | observation vector |
| z | vertical space coordinate – distance above or below surface of substrate |
| z_o | roughness length |

Greek capital letters

| | |
|------------|--|
| Δ | change or difference in some quantity, operator spatial filter length scale |
| Δx | grid increment |
| Θ | volumetric soil-moisture content |
| Ω | rotational frequency of Earth |

Greek small letters

| | |
|---------------|--|
| α | albedo generic dependent variable |
| γ | vertical lapse rate of temperature |
| γ_d | dry adiabatic lapse rate of temperature |
| δ | Kronecker delta |
| ε | alternating unit tensor emissivity error |
| θ | potential temperature |
| λ | longitude amplification factor wavelength |
| μ | dynamic viscosity coefficient thermal admittance |
| π | pi |
| ρ | density |
| σ | Stefan–Boltzmann constant terrain-following vertical coordinate standard deviation |
| τ | momentum stress, or shearing stress relaxation coefficient |
| ϕ | latitude |
| ω | frequency of a wave |

Common subscripts and superscripts

| | |
|-----|----------------------------|
| E | applies on Earth's surface |
| G | applies on a grid |
| I | imaginary part of a number |

| | |
|--------|--|
| R | real part of a variable |
| T | transpose |
| a | analysis atmosphere |
| b | background |
| g | ground or substrate surface |
| i | grid-point index in x direction |
| j | grid-point index in y direction |
| k | grid-point index in z direction |
| m | wavenumber |
| o | observation |
| p | wavenumber applies at constant pressure |
| s | saturation surface substrate or soil |
| τ | point on the discrete time axis |