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978-0-521-51389-0 - Numerical Weather and Climate Prediction
Thomas Tomkins Warner
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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

Numerical Weather and Climate Prediction

THOMAS TOMKINS WARNER
National Center for Atmospheric Research, Boulder, Colorado
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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copyright permissions, and technical assistance with manuscript preparation was provided by Carol Makowski. Leslie Forehand and Judy Litsey of the library of the National Center for Atmospheric Research assisted with reference material. And, John Cahir offered useful comments on the organization of the chapters, which led to a more logical presentation. Lastly, valuable assistance in many forms was provided by Matt Lloyd, Editor; Laura Clark, Assistant Editor; and Abigail Jones, Production Editor, of Cambridge University Press.

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

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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

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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 TELemetry
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

$\mathbf{A}$	covariance matrix of the analysis errors
B	Planck's function
$\mathbf{B}$	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
$\mathbf{H}$	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

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$\mathbf{K}$	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
$\mathbf{M}$	model dynamic operator
P	wave period
	rate of water input through precipitation
$\mathbf{P}$	error covariance matrix
Q	direct-solar radiation intensity
Q_v	rates of gain or loss of water vapor through phase changes
$\mathbf{Q}$	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
$\mathbf{R}$	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
$\mathbf{X}$	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

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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