

# Climate System Modeling

*Edited by*

**KEVIN E. TRENBERTH**



# Climate System Modeling

Edited by  
**Kevin E. Trenberth**

285/3540 INSTITUT  
FÜR METEOROLOGIE U. KLIMATOLOGIE  
UNIVERSITÄT HANNOVER  
HERRENHAUSER STR. 2 3000 HANNOVER 41



**CAMBRIDGE**  
UNIVERSITY PRESS

# Contents

|                    |        |
|--------------------|--------|
| Preface            | xvii   |
| Acknowledgments    | xxi    |
| The authors        | xxiii  |
| Acronyms           | xxvi   |
| Notation           | xxviii |
| Physical constants | xxix   |

## PART 1 INTRODUCTION

|   |           |
|---|-----------|
| <b>1 Introduction to climate modeling</b>             | <b>3</b>  |
| <i>Stephen H. Schneider</i>                           |           |
| 1.1 Context of global climate change                  | 3         |
| 1.2 Mechanisms of climate change                      | 6         |
| 1.2.1 The climate system                              | 6         |
| 1.2.2 Radiation balance and greenhouse effect         | 8         |
| 1.2.3 Climate models of the radiation balance         | 12        |
| 1.2.4 Climatic feedback mechanisms                    | 13        |
| 1.2.5 Transient response                              | 15        |
| 1.2.6 Hierarchy of models                             | 16        |
| 1.3 Climate predictions                               | 17        |
| 1.3.1 Empirical statistical versus “first principles” | 17        |
| 1.3.2 Grids and parameterization                      | 18        |
| 1.3.3 Climate sensitivity and scenarios               | 19        |
| 1.3.4 Theoretical issues                              | 19        |
| 1.3.5 Scale transition                                | 21        |
| 1.4 Validation  | 23        |
| <b>2 Human components of the climate system</b>       | <b>27</b> |
| <i>Michael H. Glantz and Jerryold H. Krenz</i>        |           |
| 2.1 Introduction                                      | 27        |
| 2.2 Greenhouse gases emissions                        | 28        |
| 2.2.1 Carbon dioxide (CO <sub>2</sub> )               | 29        |
| 2.2.2 Nitrous oxide (N <sub>2</sub> O)                | 32        |
| 2.2.3 Methane (CH <sub>4</sub> )                      | 32        |
| 2.2.4 Chlorofluorocarbons (CFCs)                      | 33        |

## Contents

|  |    |
|--|----|
| 2.2.5 Estimating future greenhouse gas concentrations                | 33 |
| 2.3 Deforestation  | 34 |
| 2.4 Desertification  | 37 |
| 2.5 Changes in human activities that led to changes in GHG emissions | 40 |
| 2.5.1 The energy crisis of the 1970s                                 | 40 |
| 2.5.2 The spray can ban in the mid-1970s                             | 45 |
| 2.5.3 The Vienna Convention and the Montreal Protocol                | 47 |
| 2.5.4 Deforestation of the Brazilian Amazon                          | 47 |
| 2.6 Conclusions  | 48 |

## PART 2 THE SCIENCE: SUBSYSTEMS AND PROCESSES

|  |           |
|--|-----------|
| <b>3 The atmosphere</b>                                  | <b>53</b> |
| <i>Murry L. Salby</i>                                    |           |
| 3.1 Introduction   | 53        |
| 3.1.1 Composition and structure                          | 54        |
| 3.1.2 Radiative equilibrium of the planet                | 65        |
| 3.1.3 The global energy budget                           | 65        |
| 3.1.4 The general circulation                            | 67        |
| 3.2 Atmospheric thermodynamics                           | 71        |
| 3.2.1 The first law                                      | 72        |
| 3.2.2 Adiabatic processes                                | 72        |
| 3.2.3 The second law                                     | 73        |
| 3.2.4 Heterogeneous systems                              | 74        |
| 3.2.5 Moist air  | 76        |
| 3.2.6 Vertical displacements                             | 78        |
| 3.3 Hydrostatic equilibrium                              | 80        |
| 3.3.1 Hydrostatic balance                                | 83        |
| 3.3.2 Vertical displacements                             | 83        |
| 3.3.3 Hydrostatic stability                              | 84        |
| 3.3.4 Buoyancy reactions                                 | 87        |
| 3.3.5 Vertical motions                                   | 87        |
| 3.4 Radiative transfer                                   | 88        |
| 3.4.1 Radiative equilibrium                              | 91        |
| 3.4.2 Thermal dissipation                                | 93        |
| 3.4.3 The greenhouse effect                              | 93        |
| 3.5 Clouds   | 94        |
| 3.5.1 Cloud formation                                    | 95        |
| 3.5.2 Radiative processes in clouds                      | 96        |
| 3.6 Atmospheric dynamics                                 | 98        |
| 3.6.1 Equations of motion in an inertial reference frame | 99        |
| 3.6.2 Equations of motion in a rotating reference frame  | 100       |
| 3.7 Classes of motion                                    | 102       |
| 3.7.1 Scales of motion                                   | 102       |
| 3.7.2 Geostrophic motion                                 | 102       |
| 3.7.3 Frictional geostrophic motion                      | 105       |
| 3.7.4 Vertical shear                                     | 105       |
| 3.8 Atmospheric waves                                    | 107       |
| 3.8.1 Gravity waves                                      | 107       |
| 3.8.2 Planetary waves                                    | 108       |

|  |            |
|--|------------|
| 3.9 The general circulation  | 110        |
| 3.10 The upper atmosphere  | 112        |
| <b>4 The ocean circulation</b>   | <b>117</b> |
| <i>Pearn P. Niiler</i>   |            |
| 4.1 Introduction   | 117        |
| 4.2 Basic concepts   | 117        |
| 4.3 Upper ocean circulation observations   | 120        |
| 4.4 Forces which maintain the surface currents                                     | 125        |
| 4.5 Thermocline circulation and western boundary currents                          | 128        |
| 4.6 How oceans exchange heat with the atmosphere                                   | 131        |
| 4.7 Deep circulation patterns  | 136        |
| 4.8 Heat transport by ocean circulation patterns                                   | 144        |
| <b>5 Land surface</b>  | <b>149</b> |
| <i>Robert E. Dickinson</i>   |            |
| 5.1 Role of the land surface in the climate system                                 | 149        |
| 5.2 Observational elements of land climate   | 150        |
| 5.2.1 Precipitation  | 151        |
| 5.2.2 Solar radiation  | 153        |
| 5.2.3 Surface temperatures, humidities, and winds                                  | 156        |
| 5.3 Surface albedo   | 158        |
| 5.4 Idealized canopies   | 163        |
| 5.5 Role of soil and its hydrology   | 166        |
| 5.6 Geographic data needed for land processes                                      | 168        |
| <b>6 Terrestrial ecosystems</b>  | <b>173</b> |
| <i>John D. Aber</i>  |            |
| 6.1 Introduction   | 173        |
| 6.2 Climate- and human-driven changes in ecosystem structure                       | 175        |
| 6.2.1 Importance of the vegetated surface  | 175        |
| 6.2.2 Potential global changes in the vegetated surface                            | 175        |
| 6.2.3 Land use and alteration of the vegetated surface                             | 180        |
| 6.3 Climate- and human-driven changes in carbon balances of terrestrial ecosystems | 181        |
| 6.3.1 Importance of terrestrial ecosystem carbon balances                          | 181        |
| 6.3.2 The carbon and nutrient cycles of terrestrial ecosystems                     | 182        |
| 6.3.3 Models of carbon-nutrient-climate interactions                               | 186        |
| 6.3.4 Role of land use in production and nutrient cycling                          | 188        |
| 6.4 Interactions between climate and fluxes of methane and nitrous oxide           | 193        |
| 6.4.1 Importance of net terrestrial fluxes of trace gases                          | 193        |
| 6.4.2 Factors controlling fluxes of methane  | 193        |
| 6.4.3 Factors controlling fluxes of nitrous oxide                                  | 196        |
| 6.4.4 Models and regional estimates of fluxes                                      | 198        |
| 6.5 Methods of direct measurement at the regional scale                            | 198        |
| 6.6 Summary  | 199        |
| <b>7 Atmospheric chemistry</b>   | <b>201</b> |
| <i>Richard P. Turco</i>  |            |
| 7.1 Introduction   | 201        |
| 7.2 Coupling of chemistry to climate   | 201        |

## Contents

|  |     |
|--|-----|
| 7.2.1 Photochemical kinetics and tracer modeling           | 203 |
| 7.2.2 Radiative processes                                  | 207 |
| 7.2.3 Effects on the hydrological cycle                    | 210 |
| 7.2.4 Biological feedback processes                        | 210 |
| 7.3 Atmospheric chemistry of climatologically active gases | 211 |
| 7.3.1 Water vapor ( $H_2O$ )                               | 211 |
| 7.3.2 Carbon dioxide ( $CO_2$ )                            | 215 |
| 7.3.3 Ozone ( $O_3$ )                                      | 219 |
| 7.3.4 Methane ( $CH_4$ )                                   | 223 |
| 7.3.5 Nitrous oxide ( $N_2O$ )                             | 226 |
| 7.3.6 Chlorofluorocarbons                                  | 228 |
| 7.3.7 Other greenhouse gases                               | 231 |
| 7.4 Atmospheric chemistry of aerosols                      | 233 |
| 7.4.1 Sources and distributions                            | 233 |
| 7.4.2 Aerosol chemistry                                    | 237 |
| 7.4.3 Aerosol microphysics                                 | 238 |
| 7.5 Future developments                                    | 239 |

## 8 Marine biogeochemistry

*Raymond G. Najjar*

**241**

|   |     |
|---|-----|
| 8.1 Introduction  | 241 |
| 8.2 Air-sea gas exchange                                  | 242 |
| 8.2.1 Air-sea interface                                   | 242 |
| 8.2.2 Bubbles   | 245 |
| 8.2.3 Formulations of the piston velocity                 | 246 |
| 8.2.4 Equilibration time in the surface ocean mixed layer | 247 |
| 8.3 The carbon cycle                                      | 247 |
| 8.3.1 The inorganic chemistry of carbon dioxide           | 248 |
| 8.3.2 The cycle of organic matter                         | 254 |
| 8.3.3 The cycle of calcium carbonate                      | 266 |
| 8.3.4 Air-sea gas exchange of carbon dioxide              | 271 |
| 8.3.5 Relative strengths of the carbon pump               | 273 |
| 8.3.6 Oceanic buffers of atmospheric $CO_2$               | 274 |
| 8.4 Dimethyl sulfide                                      | 275 |
| 8.5 Nitrous oxide   | 277 |

## PART 3 MODELING AND PARAMETERIZATION

### 9 Climate system simulation: basic numerical & computational concepts

*James J. Hack*

**283**

|  |     |
|--|-----|
| 9.1 Introduction   | 283 |
| 9.1.1 Development of atmospheric simulation capabilities | 284 |
| 9.1.2 Development of computational capabilities          | 287 |
| 9.2 Numerical methods used in global climate models      | 290 |
| 9.2.1 Numerical approximation concepts                   | 290 |
| 9.2.2 Horizontal and vertical coordinate systems         | 301 |
| 9.2.3 Representation of parameterized physics            | 307 |
| 9.3 Computational requirements and constraints           | 308 |
| 9.3.1 Basic concepts in computer systems architecture    | 309 |

|   |            |
|---|------------|
| 9.3.2 Algorithmic implications                                  | 315        |
| 9.4 Modularization and coupling                                 | 317        |
| <b>10 Atmospheric general circulation modeling</b>              | <b>319</b> |
| <i>Jeffrey T. Kiehl</i>   |            |
| 10.1 Introduction   | 319        |
| 10.1.1 Historical review  | 319        |
| 10.1.2 Hierarchy of atmospheric models                          | 320        |
| 10.2 Simple models of the atmosphere                            | 323        |
| 10.2.1 Zero-dimensional models                                  | 323        |
| 10.2.2 One-dimensional models                                   | 326        |
| 10.2.3 Two-dimensional climate models                           | 333        |
| 10.3 Atmospheric general circulation models (AGCMs)             | 334        |
| 10.3.1 Parameterization of atmospheric radiation                | 337        |
| 10.3.2 Convective processes in atmospheric models               | 347        |
| 10.3.3 Planetary boundary layer and surface processes           | 355        |
| 10.3.4 Cloud prediction schemes for atmospheric models          | 359        |
| 10.3.5 Mechanical dissipation mechanisms in the free atmosphere | 360        |
| 10.4 Simulation and validation of AGCMs                         | 361        |
| 10.5 Future improvements for AGCMs                              | 368        |
| <b>11 Ocean general circulation modeling</b>                    | <b>371</b> |
| <i>Dale B. Haidvogel and Frank O. Bryan</i>                     |            |
| 11.1 Introduction   | 371        |
| 11.2 Equations of motion  | 373        |
| 11.2.1 The hydrostatic primitive equations                      | 373        |
| 11.2.2 Turbulent friction and the closure “problem”             | 374        |
| 11.2.3 Surface, lateral, and bottom boundary conditions         | 377        |
| 11.2.4 The surface mixed layer                                  | 380        |
| 11.3 Solving the equations of motion                            | 383        |
| 11.3.1 Horizontal discretization                                | 383        |
| 11.3.2 Vertical coordinates                                     | 383        |
| 11.3.3 Conservation and positivity properties                   | 384        |
| 11.4 Simple models of the ocean circulation                     | 385        |
| 11.4.1 The wind-driven ocean                                    | 385        |
| 11.4.2 Box models of the thermohaline circulation               | 388        |
| 11.4.3 Two-dimensional meridional plane models                  | 391        |
| 11.5 Ocean general circulation models                           | 394        |
| 11.5.1 Idealized geometry models                                | 394        |
| 11.5.2 Basin-scale models                                       | 400        |
| 11.5.3 Global models  | 404        |
| 11.6 Future directions  | 408        |
| 11.6.1 Simplifying the equations of motion                      | 409        |
| 11.6.2 What about those eddies?                                 | 410        |
| 11.6.3 Numerical algorithms                                     | 411        |
| 11.6.4 Optimal combination of models and data                   | 411        |
| <b>12 Sea ice models</b>  | <b>413</b> |
| <i>William D. Hibler, III and Gregory M. Flato</i>              |            |
| 12.1 Introduction   | 413        |
| 12.2 Sea ice dynamics   | 415        |

## Contents

|   |            |
|---|------------|
| 12.3 Ice thickness distribution models                          | 422        |
| 12.4 Sea ice thermodynamic models                               | 427        |
| 12.5 Summary  | 436        |
| <b>13 Land ice and climate</b>                                  | <b>437</b> |
| <i>Cornelis J. van der Veen</i>                                 |            |
| 13.1 Introduction   | 437        |
| 13.2 Ice sheets and climate                                     | 440        |
| 13.3 Modeling glacier flow                                      | 442        |
| 13.4 Modeling the surface mass balance                          | 444        |
| 13.5 Response of mountain glaciers to climate changes           | 445        |
| 13.6 Response of the polar ice sheets to climate changes        | 446        |
| 13.7 Possible instability of the West Antarctic ice sheet       | 449        |
| 13.8 Concluding remarks   | 449        |
| <b>14 Biophysical models of land surface processes</b>          | <b>451</b> |
| <i>Piers J. Sellers</i>   |            |
| 14.1 Introduction   | 451        |
| 14.2 The development and shortcomings of early models           | 454        |
| 14.2.1 Basic concepts   | 454        |
| 14.2.2 History of model development and implementation          | 457        |
| 14.2.3 Shortcomings of the early modeling approaches            | 460        |
| 14.3 The development of biophysical models                      | 461        |
| 14.3.1 Radiative transfer                                       | 461        |
| 14.3.2 Turbulent transfer                                       | 465        |
| 14.3.3 Transport of heat and water vapor                        | 471        |
| 14.3.4 Model assembly and operation                             | 478        |
| 14.3.5 Model testing and validation                             | 481        |
| 14.4 The future of biophysical models                           | 487        |
| 14.4.1 Simpler models for forecast applications                 | 487        |
| 14.4.2 More complex models for climate and carbon cycle studies | 488        |
| 14.4.3 Links to biogeochemistry and terrestrial ecology         | 489        |
| 14.5 Summary  | 490        |
| <b>15 Chemistry–transport models</b>                            | <b>491</b> |
| <i>Guy P. Brasseur and Sasha Madronich</i>                      |            |
| 15.1 Introduction   | 491        |
| 15.2 Components of chemistry–transport models                   | 492        |
| 15.3 Hierarchy of chemistry–transport models                    | 495        |
| 15.3.1 Zero-dimensional models                                  | 495        |
| 15.3.2 One-dimensional models                                   | 498        |
| 15.3.3 Two-dimensional models                                   | 499        |
| 15.3.4 Three-dimensional models                                 | 502        |
| 15.4 Chemical systems   | 505        |
| 15.4.1 Formulation of chemical equations                        | 505        |
| 15.4.2 Time integration   | 505        |
| 15.5 Tracer transport   | 509        |
| 15.5.1 Advection schemes  | 509        |
| 15.5.2 Diffusion schemes  | 515        |
| 15.5.3 Final remarks  | 517        |

|   |            |
|---|------------|
| <b>16 Biogeochemical ocean models</b>                             | <b>519</b> |
| <i>Jorge L. Sarmiento</i>   |            |
| 16.1 Introduction   | 519        |
| 16.2 Basic concepts   | 521        |
| 16.2.1 Two-box model  | 522        |
| 16.2.2 High latitude outcrop three-box model                      | 524        |
| 16.2.3 Three-box vertical model                                   | 526        |
| 16.3 Three-dimensional simulations of the natural carbon cycle    | 529        |
| 16.3.1 Simulation of new production and regeneration              | 531        |
| 16.3.2 Euphotic zone food web model                               | 535        |
| 16.4 Simulation of anthropogenic CO <sub>2</sub> uptake           | 542        |
| 16.5 Future directions  | 549        |
| 16.5.1 Anthropogenic CO <sub>2</sub> uptake                       | 549        |
| 16.5.2 The natural carbon cycle and other chemicals               | 549        |
| <b>PART 4</b>   |            |
| <b>COUPLINGS AND INTERACTIONS</b>                                 |            |
| <b>17 Global coupled models: atmosphere, ocean, sea ice</b>       | <b>555</b> |
| <i>Gerald A. Meehl</i>  |            |
| 17.1 Introduction   | 555        |
| 17.2 Hierarchy of global coupled models                           | 556        |
| 17.2.1 Swamp ocean  | 556        |
| 17.2.2 Mixed-layer ocean  | 558        |
| 17.2.3 Dynamical ocean GCM  | 559        |
| 17.3 Coupling strategies  | 561        |
| 17.3.1 Coupling interface   | 561        |
| 17.3.2 Atmosphere communicates with ocean and sea ice             | 562        |
| 17.3.3 Ocean and sea ice communicate with atmosphere              | 563        |
| 17.3.4 The problem of frequency of communication                  | 564        |
| 17.3.5 Spin-up problem  | 570        |
| 17.4 Climate drift in the coupled simulation                      | 572        |
| 17.5 Products of coupled interaction                              | 577        |
| 17.5.1 El Niño-Southern Oscillation                               | 577        |
| 17.5.2 Low-frequency variability and the thermohaline circulation | 579        |
| <b>18 Tropical Pacific ENSO models:</b>                           |            |
| <b>ENSO as a mode of the coupled system</b>                       | <b>583</b> |
| <i>Mark A. Cane</i>   |            |
| 18.1 Introduction   | 583        |
| 18.2 Our understanding of the mechanisms of ENSO: Pt I            | 587        |
| 18.3 Our understanding of the mechanisms of ENSO: Pt II           | 590        |
| 18.4 Modeling ENSO as a coupled system                            | 593        |
| 18.4.1 The atmosphere model                                       | 594        |
| 18.4.2 The ocean model  | 596        |
| 18.4.3 Coupled model results                                      | 598        |
| 18.4.4 Other models   | 604        |
| 18.5 Model verification and ENSO prediction                       | 604        |
| 18.6 Coupled GCMs   | 608        |
| 18.7 Discussion   | 613        |

## Contents

### PART 5 SENSITIVITY EXPERIMENTS AND APPLICATIONS

|  |            |
|--|------------|
| <b>19 Climate variability simulated in GCMs</b>  | <b>617</b> |
| <i>Ngar-Cheung Lau</i>   |            |
| 19.1 Introduction  | 617        |
| 19.2 Variability on daily and monthly time scales  | 621        |
| 19.2.1 Phenomena with periods of several days  | 621        |
| 19.2.2 Phenomena with periods ranging from 10 days to a season                           | 624        |
| 19.3 Variability on time scales ranging from months to several years                     | 630        |
| 19.3.1 Phenomena associated with air-sea interaction in the tropics                      | 630        |
| 19.3.2 Phenomena associated with air-sea interaction in the extratropics                 | 633        |
| 19.3.3 Air-land interaction  | 635        |
| 19.4 Variability on decadal and centennial time scales                                   | 638        |
| 19.5 Outlook   | 642        |
| <b>20 Climate-model responses to increased CO<sub>2</sub> and other greenhouse gases</b> | <b>643</b> |
| <i>Warren M. Washington</i>  |            |
| 20.1 Introduction  | 643        |
| 20.2 Radiative effects of increased greenhouse gases                                     | 644        |
| 20.3 Water-vapor and cloud feedbacks   | 645        |
| 20.4 Snow-, sea, and land ice-albedo feedbacks   | 647        |
| 20.5 Energy balance climate-model estimates  | 647        |
| 20.6 Radiative-convective model estimates  | 648        |
| 20.7 Global coupled-model equilibrium estimates with simple oceans                       | 652        |
| 20.8 Global coupled-model estimates with dynamical oceans                                | 660        |
| 20.9 Future studies  | 667        |
| <b>21 Modeling large climatic changes of the past</b>                                    | <b>669</b> |
| <i>John E. Kutzbach</i>  |            |
| 21.1 Introduction  | 669        |
| 21.2 Climatic changes of the past several glacial-interglacial cycles                    | 672        |
| 21.3 Climatic changes of the past several hundred million years                          | 681        |
| 21.4 Climatic changes of early Earth history   | 686        |
| 21.5 Conclusions   | 687        |
| <b>22 Changes in land use</b>  | <b>689</b> |
| <i>Robert E. Dickinson</i>   |            |
| 22.1 General scaling arguments   | 689        |
| 22.2 Modeling sensitivity studies  | 690        |
| 22.3 Climate effects of tropical deforestation   | 696        |
| 22.4 Appropriate role of land use studies  | 700        |

### PART 6 FUTURE PROSPECTS

|   |            |
|---|------------|
| <b>23 Climate system modeling prospects</b> | <b>705</b> |
| <i>Lennart O. Bengtsson</i>                 |            |
| 23.1 Introduction and background            | 705        |

## *Contents*

|   |            |
|---|------------|
| 23.1.1 Atmospheric GCM development                                | 705        |
| 23.1.2 The rest of the climate system                             | 708        |
| 23.2 Climate models   | 708        |
| 23.3 Predictability   | 713        |
| 23.4 Improvements required  | 717        |
| 23.4.1 Long-range weather prediction/short-term climate forecasts | 718        |
| 23.4.2 Climate scenarios of order 100 years                       | 719        |
| 23.4.3 Climate scenarios of order 10,000 years                    | 721        |
| 23.5 Future prospects   | 722        |
| <b>References</b>   | <b>729</b> |
| <b>Index</b>  | <b>773</b> |