
Contents

Introduction	1
Part A Does Land Surface Matter in Climate and Weather?	5
A.1 Introduction	7
A.2 The Climate near the Ground	9
A.2.1 Introduction	9
A.2.2 The Surface Energy Balance	9
A.2.3 The Surface Water Balance	14
A.2.4 Observing the Surface	16
A.3 The Regional Climate	21
A.3.1 Fundamental Mechanism in Land-Atmosphere Interactions	21
A.3.2 Atmospheric Response to Heterogenous Land Forcing	22
A.3.2.1 Microscale Impact	22
A.3.2.2 Mesoscale Impact	24
A.3.3 Regional Teleconnections	28
A.3.4 Discussion	31
A.4 The Global Climate	33
A.4.1 Feedbacks, Synergisms, Multiple Equilibria and Teleconnections	33
A.4.1.1 Feedbacks	33
A.4.1.2 Synergisms	36
A.4.1.3 Multiple Equilibria	37
A.4.1.4 Teleconnections	39
A.4.2 Palaeoclimate	40
A.4.2.1 Feedbacks in the Arctic Climate System	40
A.4.2.2 The Sahara	42
A.4.2.3 Historical Land-cover Change	44
A.4.3 Sensitivity to Decadal Biogeochemical Feedbacks	45
A.4.3.1 The Land Surface and Climate Change	45
A.4.3.2 Biogeochemical Feedbacks	46
A.4.3.3 Transient Experiments	48
A.4.4 Seasonal Variability	48
A.4.5 Impact of Land Surface on Weather	52
A.4.5.1 Brief Literature Survey	52
A.4.5.2 European Centre for Medium-range Weather Forecast (ECMWF) Examples	53
A.5 The Sahelian Climate	59
A.5.1 Introduction	59
A.5.1.1 Background	59
A.5.1.2 Climate Anomalies and Climate Change in the Sahel	60
A.5.1.3 The Complex Processes of Land-use Change in the Sahel	62

A.5.2	Observational Studies of Sahelian Land-surface/Atmosphere Interactions	63
A.5.2.1	The Sahelian Energy Balance Experiment (SEBEX)	63
A.5.2.2	The Hydrological and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel)	64
A.5.2.3	Coupling Tropical Atmosphere and Hydrological Cycle (CATCH)	65
A.5.2.4	Savannas at the Long Term (SALT)	65
A.5.2.5	Satellite Data	66
A.5.3	Coupled Modelling of Sahelian Land-Atmosphere Interactions	66
A.5.3.1	Brief Overview	66
A.5.3.2	Large Scale Force-Response Studies of the Sahelian Climate Anomaly: The Relative Importance of Land-surface Processes and Sea-surface Temperatures	68
A.5.3.3	Mesoscale Interactions between Sahelian Precipitation and Land-surface Patterns	71
A.5.3.4	Climate System Interactions in the Sahel	71
A.5.4	Understanding Mechanisms	73
A.5.5	Conclusion	75
A.6	The Amazonian Climate	79
A.6.1	Introduction	79
A.6.2	Future Climates in Amazonia	81
A.6.3	Observations of Land-Surface/Atmosphere Interactions	82
A.6.4	The General Characteristics and Variability of Water and Energy Balances in the Amazon Basin	85
A.6.4.1	Introduction	85
A.6.4.2	Water Balance	86
A.6.4.3	Energy Balance	87
A.6.5	Deforestation and Climate	88
A.7	The Boreal Climate	93
A.7.1	The Boreal Ecosystem, Boreal Climate and High-latitude Climate Change and Variability	93
A.7.1.1	Climate and Boreal Vegetation	94
A.7.1.2	Effects of Fire and Insects on Vegetation and Land Cover	95
A.7.1.3	High-latitude Climate Change	96
A.7.1.4	Changes in Snow Extent, Depth and Duration	96
A.7.2	Energy Dissipation and Transport by the Boreal Landscape	101
A.7.2.1	Effect of Soil Type on Surface Energy Partitioning	102
A.7.2.2	Effect of Land-cover Type on Seasonal Variation in Relative Humidity	103
A.7.2.3	Role of Stomatal Control	103
A.7.2.4	Role of Latitudinal Gradient	104
A.7.2.5	Role of Moss	106
A.7.2.6	Role of Albedo of Forests, Wetlands and Lakes	106
A.7.2.7	Role of Fire-induced Atmospheric Aerosols	107
A.7.2.8	Role of Surface Hydrology	107
A.7.2.9	Scaling Energy and Water Flux from the Plot to the Region	108
A.7.3	Biospheric Carbon Exchange: Carbon Dioxide and Methane	109
A.7.3.1	Measurement Methods	109
A.7.3.2	Controlling Factors (above and below Ground)	110
A.7.3.3	Geographic Variations in Carbon Flux	110
A.7.3.4	Seasonal and Interannual Variations in Carbon Flux	111
A.7.3.5	Methane	112

A.7.3.6	The Effect of Landscape Patterns, Disturbance and Succession on Carbon Cycling	112
A.7.4	Sensitivity Experiments	113
A.7.4.1	Snow Albedo and Climate Feedback	113
A.7.4.2	Carbon Sequestration and Radiative Feedbacks	113
A.7.4.3	Effects of Climate Change on Land Cover	114
A.7.4.4	Hydrological Feedbacks	114
A.8	The Asian Monsoon Climate	115
A.8.1	Introduction	115
A.8.2	Role of Human-induced Large-scale Land-use/cover Change on the Water Cycle and Climate in Monsoon Asia	115
A.8.2.1	Atmospheric Water Cycle over Monsoon Asia	115
A.8.2.2	Is Monsoon Rainfall Decreasing? The Impact of Deforestation in Thailand on the Water Cycle	116
A.8.2.3	Do Water-fed Rice Paddy Fields Increase Rainfall in Monsoon Asia?	118
A.8.2.4	Conclusions	120
A.8.3	Can Human-induced Large-scale Land-cover Changes Modify the East Asian Monsoon?	120
A.8.3.1	History of Land-cover/Land-use Changes over East Asia	121
A.8.3.2	Design of the Numerical Experiments	121
A.8.3.3	Changes of Surface Dynamic Parameters under Two Vegetation Coverages	123
A.8.3.4	Changes of the East Asia Monsoon by Human-induced Land-cover Changes	123
A.8.4	Summary	127
A.9	Summary, Conclusion and Perspective	129
	References	137
Part B	How Measurable is the Earth System?	155
B.1	Introduction	157
B.1.1	The Need for Integrated Experiments	157
B.1.2	The Experimental Design	157
B.1.3	Guide to Part B	158
B.2	The Energy Balance Closure Problem	159
B.2.1	Examples of Energy Balance Closure in Field Experiments	159
B.2.2	Reasons for Poor Closure	161
B.2.3	Experiment Design	163
B.2.4	Calculation and Analysis Errors	163
B.2.5	Overall Accuracy – What Can Be Expected	164
B.2.6	Pushing Eddy Covariance past Its Limits	165
B.2.7	Coping with Poor Energy Balance Closure When Modelling	166
B.2.8	Summary and Conclusions	166
B.3	Radiation Measurements in Integrated Terrestrial Experiments	167
B.3.1	Introduction	167
B.3.2	Radiometry in Integrated Terrestrial Experiments	167
B.3.3	Available Radiometer Designs	169
B.3.4	Overview of Radiometry in the Last Two Decades	170
B.3.5	Summary	171

B.4	Surface Turbulent Fluxes	173
B.4.1	Where Are We Now?	173
B.4.2	How Did We Get Here?	173
B.4.3	The Main Micrometeorological Methods	174
B.4.3.1	The Aerodynamic Gradient Method	174
B.4.3.2	The Bowen Ratio (or Energy Balance) Method	176
B.4.3.3	The Eddy Covariance (or Correlation) Method	176
B.4.3.4	Flux Footprint	180
B.4.3.5	The Nocturnal “CO ₂ Loss” Problem	181
B.4.4	The Future for Surface Fluxes	182
B.5	Accuracy and Utility of Aircraft Flux Measurements	183
B.5.1	Introduction	183
B.5.2	Technology of Airborne Flux Measurement	184
B.5.3	Accuracy of Airborne Measurements	185
B.5.4	Utility of Airborne Flux Measurement	186
B.5.5	Conclusions	187
B.6	Boundary Layer Budgeting	189
B.6.1	Introduction	189
B.6.2	Characteristic Structure of the Boundary Layer	189
B.6.3	Budget Relations	190
B.6.4	More Recent Budget Studies Conducted over Land	191
B.6.5	Conclusions and Suggestions for Ongoing Work	196
B.7	Vegetation Structure, Dynamics and Physiology	199
B.7.1	Introduction	199
B.7.2	Measurement of Vegetation Structure, Dynamics and Physiology	199
B.7.3	Vegetation Measurements in the Integrated Terrestrial Experiment	202
B.7.4	Synergy of Vegetation Measurements with Other Measurement Programmes in the Integrated Terrestrial Experiment	204
B.7.5	Summary	204
B.8	Remote Sensing and Land-surface Experiments	207
B.8.1	Introduction	207
B.8.2	Remote Sensing Input to the Experiments	208
B.8.3	Impact of Field Experiments on Remote Sensing of the Land Surface	208
B.8.4	The Future	212
B.9	The Water Balance Concept – How Useful Is It as a Guiding Principle for the Design of Land-Atmosphere Field Experiments?	213
B.9.1	Background	213
B.9.2	The Water Balance Concept	213
B.9.2.1	Snow-free Land Surface	213
B.9.2.2	Snowpack Water Balance	214
B.9.2.3	Atmospheric Water Balance	214
B.9.3	Application of the Water Balance Concept	214
B.9.3.1	Intensive Field Campaigns	214
B.9.3.2	GEWEX Continental Scale Experiments	218
B.9.4	Assessment and Recommendations	219
B.10	Use of Field Experiments in Improving the Land-surface Description in Atmospheric Models: Calibration, Aggregation and Scaling	221
B.10.1	Introduction	221

B.10.2	Benefit of Datasets from Integrated Terrestrial Experiments for Surface Modelling in Atmospheric and Hydrological Models	221
B.10.3	A Modelling Strategy for Upscaling from the Plot Scale to the Size of a GCM Grid Box	222
B.10.4	Use of a Macroscale Hydrological Model to Investigate Aggregation of Hydrological Processes	225
B.10.5	Concluding Remarks	227
B.11	Further Insight from Large-scale Observational Studies of Land/Atmosphere Interactions	229
B.11.1	Introduction	229
B.11.2	International Co-operation	229
B.11.3	The Use of Land-surface Data to Validate Global Models	229
B.11.4	Surface Flux Measurements	230
B.11.5	Hydrological Catchment Measurements	232
B.11.6	Aggregation and Models	233
B.11.7	Future for Large-scale Integrated Experiments	233
B.11.8	Concluding Remarks	233
	References	235
Part C	The Value of Land-surface Data Consolidation	245
C.1	Motivation for Data Consolidation	247
C.1.1	The Volume of Data	248
C.1.2	The Breadth of Data	250
C.1.3	The Trend toward Interdisciplinary Science	251
C.1.4	Who Needs Consolidated Data?	251
C.1.5	What Is Consolidation?	252
C.2	Existing Degrees of Consolidation	255
C.2.1	Project-specific Data Collections	255
C.2.2	Subject-specific Archives	258
C.2.3	Broad Data Archives	259
C.2.4	Co-registration	261
C.2.5	Tools and Data	264
C.3	Achieving Full Data Consolidation	267
C.3.1	Necessary Elements	267
C.3.2	Tools	268
C.3.3	Data Maintenance	270
C.3.4	Motivating Data Providers	271
C.4	Terrestrial Data Assimilation	273
C.4.1	Topographic Coherence of Weather – The Role of Statistical Assimilation	275
C.4.1.1	Stochastic Weather Models for Scenario Generation	275
C.4.1.2	Scheme for Generating Stochastic Weather Scenarios	276
C.4.1.3	Stochastic Models	277
C.4.1.4	Topographic Dependent Interpolation of Weather Model Parameters	278
C.4.1.5	Spatial Structure and Topographic Dependencies of Weather Anomalies	278
C.4.2	Terrestrial Model Prediction	279

C.4.3	Terrestrial Observations	280
C.4.4	Data Assimilation Concepts and Methods	281
C.4.5	Current Projects	283
C.4.6	Future Opportunities	286
C.4.6.1	Terrestrial Observation	286
C.4.6.2	Terrestrial Simulation	286
C.4.6.3	Terrestrial Data Assimilation	287
C.5	Conclusions	289
	References	291
Part D The Integrity of River and Drainage Basin Systems: Challenges from Environmental Change		
D.1	Introduction	299
D.2	Responses of Hydrological Processes to Environmental Change at Small Catchment Scales	301
D.2.1	Introduction	301
D.2.2	Terrestrial Hydrological Processes – Overview, Definitions, Classification	301
D.2.2.1	Fundamental Hydrological Processes	301
D.2.2.2	Spatial Differentiation of Vertical Hydrological Processes	302
D.2.2.3	Runoff Generation and Runoff Components	305
D.2.2.4	Time Behaviour of Runoff Components	307
D.2.2.5	Unresolved Understanding of Processes of Subsurface Flow and Limitations in Assessing the Controlling Subsurface Characteristics and Parameters	308
D.2.3	The Unsaturated Zone and Its Interaction with the Atmosphere through the Biosphere	310
D.2.3.1	The Role of Soil Moisture in Coupled Land-surface/Atmosphere Modelling	310
D.2.3.2	Soil Water Flow and Root Water Uptake at the Field Scale	311
D.2.3.3	Effects of Frozen Soil Moisture	312
D.2.3.4	Representation of Available Soil and Root Information in Land-surface Models	313
D.2.3.5	Conclusions	316
D.2.4	Overland Flow, Erosion and Associated Sediment and Biogeochemical Transports	317
D.2.4.1	Impact of Climate Change	317
D.2.4.2	Impact of Land-use Change	319
D.2.5	Subsurface Stormflow and Lateral Flow Processes	322
D.2.5.1	Rapid, Shallow Subsurface Stormflow Processes	322
D.2.5.2	Separating Event Water and Subsurface Stormflow in the Storm Hydrograph	324
D.2.5.3	Modelling Lateral Flow at the Catchment Scale	326
D.2.5.4	Subsurface Flow and Catchment-scale Nutrient Dynamics	326
D.2.5.5	Conclusions	328
D.2.6	Integrated Ecohydrological Modelling Considering Nutrient Dynamics in River Catchments	328
D.2.6.1	General issues	328
D.2.6.2	Structure of Integrated Ecohydrological Models	329
D.2.6.3	Assessment of Land-surface Heterogeneity in Modelling	330
D.2.6.4	GIS-based Estimation of Land-surface Characteristics and Related Model Parameters	331

D.2.6.5	Calibration and Verification of Component Models (Modules) within Integrated Models	332
D.2.6.6	Examples of Integrated Ecohydrological Models: SWIM and ACURU	332
D.2.7	Conclusions	337
D.3	River Basin Responses to Global Change and Anthropogenic Impacts	339
D.3.1	Introducing the River Basin Scale and Its Response to Anthropogenic Change	339
D.3.2	Natural Landscape Processes at the River Basin Scale	341
D.3.2.1	Introduction	341
D.3.2.2	Natural Watercourses and Aquatic Ecosystems	341
D.3.2.3	Evaporation and Transmission Losses from Riverine Systems	343
D.3.2.4	Wetlands	345
D.3.3	Anthropogenic Modifications of the River Basin Landscape	347
D.3.3.1	Land-use Change and Its Impacts on Hydrological Responses	347
D.3.3.2	Plantation Afforestation Effects	349
D.3.3.3	Urban Influences on Hydrological Responses	352
D.3.3.4	Water Quality Degradation Resulting from Agricultural Pollution by Nitrogen and Phosphorus	354
D.3.3.5	Salinisation	357
D.3.4	Water and River Engineered Landscape	362
D.3.4.1	River Channel Modification	362
D.3.4.2	Dams and Their Impacts	363
D.3.5	The Road Ahead 1: Integrated Water Resources Management (IWRM)	365
D.3.5.1	Integrated Water Resources Management as a Response to an Inheritance of Damaged River Basins	365
D.3.5.2	What Is Integrated Water Resources Management (IWRM)?	367
D.3.5.3	The River Basin as the Fundamental Unit for IWRM	369
D.3.5.4	At What Space and Time Scales Should IWRM Be Carried Out?	370
D.3.5.5	Differences in IWRM between Developing Countries and Developed Countries	371
D.3.5.6	Conditions for the Success of IWRM	372
D.3.5.7	Conclusions	372
D.3.6	The Road Ahead 2: Restoration of Riverine Ecosystems	373
D.3.7	Conclusions	374
D.4	Responses of Continental Aquatic Systems at the Global Scale: New Paradigms, New Methods	375
D.4.1	Introduction	375
D.4.2	Terms of Reference	376
D.4.2.1	Relevant Time and Space Scales Associated with Global Change and Continental Aquatic Systems	376
D.4.2.2	Emerging Techniques for Analysing Continental Aquatic Systems and Global Change	377
D.4.3	Changes in River Connectivity and Basin Characteristics: Palaeo to Present	377
D.4.3.1	A Global Classification System for Flow Connectivity in River Systems	377
D.4.3.2	Major Earth System Processes Controlling Land-to-Ocean Coupling: Glaciation/De-glaciation, Climate Variability and Recent Tectonics	381

D.4.4	Human Conditioning of Continental Runoff	385
D.4.4.1	A Focus on Reservoirs	386
D.4.4.2	Impacts of Land-cover Change on Water Budgets	390
D.4.5	Global Sediment Flux	390
D.4.5.1	The Continuum of Fluxes from Field Erosion to River Mouth Export	391
D.4.5.2	Approaches toward Estimating Basin Fluxes	391
D.4.5.3	Additional Temporal Complexities	396
D.4.5.4	Globally, What Is the Net Change in Riverborne Sediment Flux due to Humans?	397
D.4.6	Global River Transfer of Carbon and Its Alteration and Storage	397
D.4.6.1	Sources, Sinks and Re-cycling	397
D.4.6.2	Estimates of Riverborne Carbon Flux to the Oceans	399
D.4.7	Global Riverine Nutrient Flux to the Oceans	402
D.4.7.1	Inventory Methods	402
D.4.7.2	New Regression and Multiple Regression Models	405
D.4.7.3	“Hot Spots” at the Global Scale	407
D.4.7.4	Stoichiometric Changes of N:P:Si	408
D.4.8	Future Trends	409
D.4.8.1	Pressure on Inland Water Systems	409
D.4.8.2	The Future State of Riverine Carbon Loads	411
D.4.8.3	The Future State of Inorganic Nitrogen Loads in Rivers	411
D.4.9	Future Research	412
D.5	Case Study 1: Integrated Analysis of a Humid Tropical Region – The Amazon Basin	415
D.5.1	Towards an Integrated Analysis of the Amazon Basin	415
D.5.2	Coupling Hydrology, Organic Matter and Nutrient Dynamics in Large River Basins	415
D.5.3	The Amazon Basin: Vargem Grande to Óbidos	417
D.5.4	Hydrology of the Amazon River System: A Mainstem Perspective	419
D.5.4.1	Patterns of Rainfall	419
D.5.4.2	Mainstem and Tributary Hydrographs	419
D.5.4.3	Models of Amazon Water Movement	421
D.5.5	River Chemistry	422
D.5.5.1	A Synoptic View of Chemical Profiles	422
D.5.5.2	In-river Dynamics	424
D.5.5.3	Organic Geochemical Signatures	425
D.5.5.4	Dynamics of Floodplains	425
D.5.6	Potential Impact of Anthropogenic Change on the River System	427
D.5.7	Towards a Synthetic Model of Drainage Basins	427
D.6	Case Study 2: Integrated Ecohydrological Analysis of a Temperate Developed Region: The Elbe River Basin in Central Europe	429
D.6.1	General Outline of the Elbe River Basin	429
D.6.2	Integrated Analysis of Hydrological Processes and Nitrogen Dynamics	431
D.6.2.1	Comparison of Nitrogen Dynamics in the Lowland and Mountainous Sub-regions of the Elbe	431
D.6.2.2	Regional Nitrogen Dynamics across the German Part of the Elbe Basin	433
D.6.3	Agricultural Land-use Change and Its Impact on Water Resources	435
D.6.4	Climate Change Impacts on Hydrology and Crop Yields	437
D.6.5	Conclusions	439

D.7	Case Study 3: Modelling the Impacts of Land Use and Climate Change on Hydrological Responses in the Mixed Underdeveloped/Developed Mgeni Catchment, South Africa	441
D.7.1	Setting the Scene	441
D.7.2	Attributes of the Mgeni Catchment and Human Pressures	443
D.7.3	Configuration of the Mgeni System for Simulation Modelling	444
D.7.4	Verification of Simulated Hydrological Outputs	446
D.7.5	Modelling Impacts of Contrasting Land Uses on Streamflow Generation	446
D.7.6	Modelling Impacts of Land Uses on Water Quality Indicators	447
D.7.7	Scenario Studies on Impacts of Land Use on Water Quantity and Quality	450
D.7.7.1	Effects of Individual Land Uses on Runoff at the Management Catchment Level	450
D.7.7.2	Impacts of Subsistence Farming and Informal Settlements on Water Quality and Quantity	452
D.7.7.3	Impacts of Potential Climate Change on Streamflows	452
D.7.8	Conclusions	453
D.8	Conclusions: Scaling Relative Responses of Terrestrial Aquatic Systems to Global Changes	455
D.8.1	Terrestrial Aquatic Systems and the Earth System under Pressure	455
D.8.2	Spatial Organisation of Terrestrial Aquatic Systems and Their Responses to Anthropogenic Change	457
D.8.3	Spatial Scale of Drivers Operating on Terrestrial Aquatic Systems	459
D.8.3.1	Natural Drivers	459
D.8.3.2	Anthropogenic Drivers	460
D.8.3.3	Integrated Water Management and Governance	461
D.8.4	Time Scales of Responses of Continental Aquatic Systems (CAS) to Imposed Changes	461
D.8.5	Continental Aquatic Systems and Emergence of the Anthropocene	461
D.8.6	Continental Aquatic Systems Shared by Social Systems and the Biogeophysical Earth System: An Extension of the DPSIR Approach	463
	References	465
Part E	How to Evaluate Vulnerability in Changing Environmental Conditions?	481
E.1	Introduction	483
E.2	Predictability and Uncertainty	485
E.3	Contrast between Predictive and Vulnerability Approaches	491
E.3.1	Societal Needs	493
E.3.2	Quantifying Uncertainty Using a Bayesian Approach	494
E.4	The Scenario Approach	497
E.5	The Vulnerability Approach	499
E.5.1	Risk, Hazard and Vulnerability: Concepts	499
E.5.2	Anthropogenic Land-use and Land-cover Changes	502
E.5.3	Procedures to Assess the Effect of Environmental Conditions on Water Resources: Natural Landscape Changes	506
E.5.4	An Example of the Vulnerability Approach: Ecosystem Vulnerability	509

E.6	Case Studies	515
E.6.1	Population and Climate	515
E.6.2	Water Resources in the Lake Erhai Basin, China	523
E.6.3	Yellow River: Recent Trends	526
E.6.4	Examples of Hazard Determination and Risk Mitigation from South Africa	528
E.7	Conclusions	537
	References	539
	Index	545