

Contents

Preface	xxi
1 Introduction	1
<i>Alan E Gelfand, Montserrat Fuentes, Jennifer Hoeting, and Richard L. Smith</i>	
I Methodology for Statistical Analysis of Environmental Processes	7
2 Modeling for environmental and ecological processes	9
<i>Alan E. Gelfand</i>	
2.1 Introduction	10
2.2 Stochastic modeling	10
2.3 Basics of Bayesian inference	13
2.3.1 Priors	14
2.3.2 Posterior inference	15
2.3.3 Bayesian computation	15
2.4 Hierarchical modeling	16
2.4.1 Introducing uncertainty	17
2.4.2 Random effects and missing data	18
2.5 Latent variables	19
2.6 Mixture models	20
2.7 Random effects	21
2.8 Dynamic models	22
2.9 Model adequacy	23
2.10 Model comparison	25
2.10.1 Bayesian model comparison	25
2.10.2 Model comparison in predictive space	27
2.11 Summary	28
3 Time series methodology	33
<i>Peter F. Craigmile</i>	
3.1 Introduction	33
3.2 Time series processes	35
3.3 Stationary processes	35
3.3.1 Filtering preserves stationarity	36
3.3.2 Classes of stationary processes	36
3.3.2.1 IID noise and white noise	37
3.3.2.2 Linear processes	37
3.3.2.3 Autoregressive moving average processes	37
3.4 Statistical inference for stationary series	39
3.4.1 Estimating the process mean	39

3.4.2	Estimating the ACVF and ACF	40
3.4.3	Prediction and forecasting	41
3.4.4	Using measures of correlation for ARMA model identification . .	42
3.4.5	Parameter estimation	43
3.4.6	Model assessment and comparison	45
3.4.7	Statistical inference for the Canadian lynx series	46
3.5	Nonstationary time series	48
3.5.1	A classical decomposition for nonstationary processes	48
3.5.2	Stochastic representations of nonstationarity	49
3.6	Long memory processes	50
3.7	Changepoint methods	50
3.8	Discussion and conclusions	51
4	Dynamic models	57
	<i>Alexandra M. Schmidt and Hedibert F. Lopes</i>	
4.1	Introduction	57
4.2	Univariate Normal Dynamic Linear Models (NDLM)	58
4.2.1	Forward learning: the Kalman filter	59
4.2.2	Backward learning: the Kalman smoother	60
4.2.3	Integrated likelihood	62
4.2.4	Some properties of NDLMs	62
4.2.5	Dynamic generalized linear models (DGLM)	63
4.3	Multivariate Dynamic Linear Models	66
4.3.1	Multivariate NDLMs	66
4.3.2	Multivariate common-component NDLMs	66
4.3.3	Matrix-variate NDLMs	67
4.3.4	Hierarchical dynamic linear models (HDLM)	67
4.3.5	Spatio-temporal models	68
4.4	Further aspects of spatio-temporal modeling	73
4.4.1	Process convolution based approaches	73
4.4.2	Models based on stochastic partial differential equations	74
4.4.3	Models based on integro-difference equations	75
5	Geostatistical Modeling for Environmental Processes	81
	<i>Sudipto Banerjee</i>	
5.1	Introduction	81
5.2	Elements of point-referenced modeling	82
5.2.1	Spatial processes, covariance functions, stationarity and isotropy .	82
5.2.2	Anisotropy and nonstationarity	86
5.2.3	Variograms	87
5.3	Spatial interpolation and kriging	91
5.4	Summary	94
6	Spatial and spatio-temporal point processes in ecological applications	97
	<i>Janine B Illian</i>	
6.1	Introduction – relevance of spatial point processes to ecology	98
6.2	Point processes as mathematical objects	100
6.3	Basic definitions	100
6.4	Exploratory analysis – summary characteristics	101
6.4.1	The Poisson process—a null model	101
6.4.2	Descriptive methods	102

6.4.3	Usage in ecology	104
6.5	Point process models	105
6.5.1	Modelling environmental heterogeneity – inhomogeneous Poisson processes and Cox processes	106
6.5.2	Modelling clustering – Neyman Scott processes	107
6.5.3	Modelling inter-individual interaction – Gibbs processes	109
6.5.4	Model fitting – approaches and software	110
6.5.4.1	Approaches	110
6.5.4.2	Relevant software packages	111
6.6	Point processes in ecological applications	111
6.7	Marked point processes – complex data structures	112
6.7.1	Different roles of marks in point patterns	113
6.7.2	Complex models – dependence between marks and patterns	114
6.7.3	Marked point pattern models reflecting the sampling process	115
6.8	Modelling partially observed point patterns	116
6.8.1	Point patterns observed in small subareas	117
6.8.2	Distance sampling	119
6.9	Discussion	120
6.9.1	Spatial point processes and geo-referenced data	120
6.9.2	Spatial point process modeling and statistical ecology	121
6.9.3	Other data structures	122
6.9.3.1	Telemetry data	122
6.9.3.2	Spatio-temporal patterns	123
6.9.4	Conclusion	124
6.10	Acknowledgments	125
7	Data assimilation	133
	<i>Veronica J. Berrocal</i>	
7.1	Introduction	133
7.2	Algorithms for data assimilation	134
7.2.1	Optimal interpolation	136
7.2.2	Variational approaches	137
7.2.3	Sequential approaches: the Kalman filter	139
7.3	Statistical approaches to data assimilation	141
7.3.1	Joint modeling approaches	141
7.3.2	Regression-based approaches	144
8	Univariate and Multivariate Extremes for the Environmental Sciences	153
	<i>Daniel Cooley, Brett D. Hunter, and Richard L. Smith</i>	
8.1	Extremes and Environmental Studies	153
8.2	Univariate Extremes	154
8.2.1	Theoretical underpinnings	154
8.2.2	Modeling Block Maxima	155
8.2.3	Threshold exceedances	156
8.2.4	Regression models for extremes	158
8.2.5	Application: Fitting a time-varying GEV model to climate model output	159
8.2.5.1	Analysis of individual ensembles and all data	160
8.2.5.2	Borrowing strength across locations	161
8.3	Multivariate Extremes	165
8.3.1	Multivariate EVDs and componentwise block maxima	165

8.3.2	Multivariate threshold exceedances	167
8.3.3	Application: Santa Ana winds and dryness	169
8.3.3.1	Assessing tail dependence	171
8.3.3.2	Risk region occurrence probability estimation	174
8.4	Conclusions	176
9	Environmental Sampling Design	181
	<i>Dale L. Zimmerman and Stephen T. Buckland</i>	
9.1	Introduction	181
9.2	Sampling Design for Environmental Monitoring	182
9.2.1	Design framework	182
9.2.2	Model-based design	183
9.2.2.1	Covariance estimation-based criteria	183
9.2.2.2	Prediction-based criteria	184
9.2.2.3	Mean estimation-based criteria	186
9.2.2.4	Multi-objective and entropy-based criteria	187
9.2.3	Probability-based spatial design	188
9.2.3.1	Simple random sampling	188
9.2.3.2	Systematic random sampling	189
9.2.3.3	Stratified random sampling	189
9.2.3.4	Variable probability sampling	190
9.2.4	Space-filling designs	190
9.2.5	Design for multivariate data and stream networks	193
9.2.6	Space-time designs	195
9.2.7	Discussion	198
9.3	Sampling for Estimation of Abundance	198
9.3.1	Distance sampling	199
9.3.1.1	Standard probability-based designs	199
9.3.1.2	Adaptive distance sampling designs	201
9.3.1.3	Designed distance sampling experiments	203
9.3.2	Capture-recapture	205
9.3.2.1	Standard capture-recapture	205
9.3.2.2	Spatial capture-recapture	205
9.3.3	Discussion	206
10	Accommodating so many zeros: univariate and multivariate data	211
	<i>James S. Clark and Alan E. Gelfand</i>	
10.1	Introduction	212
10.2	Basic univariate modeling ideas	215
10.2.1	Zeros and ones	215
10.2.2	Zero-inflated count data	216
10.2.2.1	The k-ZIG	217
10.2.2.2	Properties of the k -ZIG model	218
10.2.2.3	Incorporating the covariates	219
10.2.2.4	Model fitting and inference	219
10.2.2.5	Hurdle models	220
10.2.3	Zeros with continuous density $G(y)$	220
10.3	Multinomial trials	221
10.3.1	Ordinal categorical data	222
10.3.2	Nominal categorical data	223
10.4	Spatial and spatio-temporal versions	224

10.5	Multivariate models with zeros	225
10.5.1	Multivariate Gaussian models	226
10.5.2	Joint species distribution models	227
10.5.3	A general framework for zero-dominated multivariate data	227
10.5.3.1	Model elements	228
10.5.3.2	Specific data types	228
10.6	Joint Attribute Modeling Application	230
10.6.1	Host state and its microbiome composition	230
10.6.2	Forest traits	230
10.7	Summary and Challenges	234
11	Gradient Analysis of Ecological Communities (Ordination)	241
	<i>Michael W. Palmer</i>	
11.1	Introduction	242
11.2	History of ordination methods	242
11.3	Theory and background	243
11.3.1	Properties of community data	243
11.3.2	Coenospace	243
11.3.3	Alpha, beta, gamma diversity	247
11.3.4	Ecological similarity and distance	248
11.4	Why ordination?	249
11.5	Exploratory analysis and hypothesis testing	249
11.6	Ordination vs. Factor Analysis	250
11.7	A classification of ordination	251
11.8	Informal techniques	251
11.9	Distance-based techniques	251
11.9.1	Polar ordination	252
11.9.1.1	Interpretation of ordination scatter plots	253
11.9.2	Principal coordinates analysis	254
11.9.3	Nonmetric Multidimensional Scaling	254
11.10	Eigenanalysis-based indirect gradient analysis	255
11.10.1	Principal Components Analysis	256
11.10.2	Correspondence Analysis	258
11.10.3	Detrended Correspondence Analysis	259
11.10.4	Contrast between DCA and NMDS	262
11.11	Direct gradient analysis	263
11.11.1	Canonical Correspondence Analysis	263
11.11.2	Environmental variables in CCA	267
11.11.3	Hypothesis testing	269
11.11.4	Redundancy Analysis	269
11.12	Extensions of direct ordination	270
11.13	Conclusions	271
II	Topics in Ecological Processes	275
12	Species distribution models	277
	<i>Otso Ovaskainen</i>	
12.1	Aims of species distribution modelling	277
12.2	Example data used in this chapter	279
12.3	Single species distribution models	279
12.4	Joint species distribution models	284

12.4.1	Shared responses to environmental covariates	285
12.4.2	Statistical co-occurrence	290
12.5	Prior distributions	293
12.6	Acknowledgments	295
13	Capture-Recapture and distance sampling to estimate population sizes	299
	<i>Richard J. Barker</i>	
13.1	Basic ideas	299
13.2	Inference for closed populations	300
13.2.1	Censuses and finite population sampling	301
13.2.2	The problem of imperfect detection	301
13.2.3	Capture-recapture on closed populations	302
13.2.4	Distance sampling methods on closed populations	304
13.2.5	N-mixture models for closed populations	308
13.2.6	Count regression	309
13.3	Inference for open populations	309
13.3.1	Crosbie-Manly-Schwarz-Arnason model	310
13.3.2	Cormack-Jolly-Seber model and tag-recovery models	311
13.3.3	Pollock's robust design	313
13.3.4	Capture recapture models for population growth rate	313
13.3.5	Capture recapture models in terms of latent variable	314
13.4	Combining observation and process models	315
13.5	Software and model fitting	316
14	Animal Movement Models	321
	<i>Mevin Hooten and Devin Johnson</i>	
14.1	Introduction	321
14.2	Data Models	322
14.3	Point Process Models	324
14.4	Discrete-Time Models	326
14.5	Continuous-Time Models	329
14.6	Conclusion	335
15	Population Demography for Ecology	341
	<i>Ken Newman</i>	
15.1	Introduction	342
15.2	Components of demography	344
15.2.1	Multiple subpopulations	344
15.2.2	Multiple processes	345
15.2.3	Stochasticity	345
15.2.4	Density dependence	346
15.2.5	Competitors, predators, and prey	346
15.2.6	Human manipulation of dynamics	346
15.2.7	Uncertainty in abundances	346
15.3	General mathematical features of PDMs	347
15.3.1	Multiple subpopulations	347
15.3.2	Multiple processes	347
15.3.3	Stochasticity	349
15.3.4	Density dependence	350
15.3.5	Inclusion of covariates	351
15.3.6	Remarks: Estimability and Data Collection.	351

15.4	Matrix Projection Models, MPMs	351
15.4.1	Analysis of MPMs	352
15.4.2	Limiting behavior of density independent, time invariate MPMs .	352
15.4.3	Stochasticity	353
15.4.4	Building block approach to matrix construction	354
15.4.5	Determining the elements of projection matrices	355
15.4.6	Density dependent MPMs	355
15.5	Integral Projection Models, IPMs	355
15.5.1	Kernel structure of IPMs.	356
15.5.2	Implementation of an IPM	357
15.5.3	Estimation of kernel components	357
15.5.4	Application, use and analysis of IPMs	358
15.6	Individual Based Models, IBMs	358
15.6.1	Statistical designs for and analysis of IBMs	359
15.6.2	Comparison with population models	359
15.6.3	Applications of IBMs	360
15.6.4	Data needs and structure	360
15.6.5	Relationship with IPMs	361
15.7	State-Space Models, SSMs	361
15.7.1	Normal dynamic linear models	362
15.7.2	Non-normal, nonlinear SSMs	362
15.7.3	Hierarchical and continuous time SSMs	363
15.8	Concluding Remarks	363
15.8.1	Omissions and sparse coverage	363
15.8.2	Recommended literature	364
15.8.3	Speculations on future developments	364
16	Statistical Methods for Modeling Traits	371
	<i>Matthew Aiello-Lammens and John A. Silander, Jr.</i>	
16.1	Introduction	371
16.1.1	What Are We Modeling?	373
16.1.2	Traits Versus “Functional Traits”	373
16.2	Overview of Data for Trait Modeling	374
16.2.1	Example data sets	375
16.3	Exploratory Data Analysis	376
16.3.1	Dimension Reduction of Trait Data	376
16.4	Trait Modeling - Algorithmic	378
16.4.1	Redundancy Analysis on Individual-Level Trait Data	379
16.4.2	Community Aggregated Trait Metrics	382
16.4.2.1	CWM-RDA	382
16.4.2.2	CWM Randomization Approaches	383
16.4.2.3	Concerns with CWM approaches	385
16.4.3	Fourth-corner Methods	386
16.4.3.1	Fourth-corner Problem	386
16.4.3.2	RLQ Analysis	388
16.4.3.3	Maximum Entropy	391
16.5	Trait Modeling - Statistical Model-Based	391
16.6	Conclusion	392
16.7	Acknowledgments	393

17 Statistical models of vegetation fires: Spatial and temporal patterns	401
<i>J.M.C. Pereira and K.F. Turkman</i>	
17.1 Introduction	401
17.1.1 The global relevance of vegetation fires	401
17.1.2 Fire likelihood, intensity, and effects	402
17.1.3 Acquisition of fire data from Earth observation satellites	403
17.1.4 Research overview	405
17.2 Statistical methods and models for vegetation fire studies	406
17.2.1 Spatio-temporal point patterns of vegetation fires	407
17.2.2 Models for fire sizes	408
17.2.3 Models for fire incidence and fire frequency data	409
17.2.4 Measures of risk for vegetation fires and fire risk maps	411
17.2.5 Post-fire vegetation recovery	412
17.2.6 Weekly cycles of vegetation burning as anthropogenic fingerprint	413
18 Spatial Statistical Models for Stream Networks	421
<i>Jay M. Ver Hoef, Erin E. Peterson, and Daniel J. Isaak</i>	
18.1 Introduction	421
18.1.1 Motivating Example	422
18.1.2 Why Stream Network Models?	425
18.2 Preliminaries	428
18.2.1 Notation	428
18.2.2 Computing Distance in a Branching Network	430
18.3 Moving Average Construction for Spatial Error Process	431
18.3.1 Tail-up models	432
18.3.2 Tail-down models	434
18.3.3 Spatial Linear Mixed Models	435
18.4 Example	436
18.4.1 Estimation	436
18.4.2 Torgegram	437
18.4.3 Prediction	438
18.4.4 Software	440
18.5 Summary	440
III Topics in Environmental Exposure	445
19 Statistical methods for exposure assessment	447
<i>Montse Fuentes, Brian J Reich, and Yen-Ning Huang</i>	
19.1 Defining Exposure	447
19.2 Spatiotemporal Mapping of Monitoring Data	449
19.2.1 K -Nearest Neighbor (KNN) interpolation	449
19.2.2 Inverse Distance Weighting (IDW)	450
19.2.3 Kriging	450
19.2.4 Bayesian Interpolation	452
19.2.5 Comparison of methods	453
19.2.6 Case study: PM _{2.5} data in the Eastern US	453
19.3 Spatiotemporal extensions	455
19.4 Data Fusion	458
19.4.1 Calibration of Computer Models	458
19.4.2 Spatial Downscaler	459
19.4.3 Spatial Bayesian Melding	459

19.4.4	Case Study: Statistical downscale of PM _{2.5}	460
20	Alternative models for estimating air pollution exposures – Land Use Regression and Stochastic Human Exposure and Dose Simulation for particulate matter (SHEDS-PM)	465
	<i>Joshua L. Warren and Michelle L. Bell</i>	
20.1	Introduction	465
20.2	Land Use Regression Modeling	466
20.2.1	Background	466
20.2.2	Land Use Regression Methods	467
20.2.3	Examples of Land Use Regression	470
20.2.4	Limitations to Land Use Regression	471
20.3	Population Exposure Modeling	472
20.3.1	Background	472
20.3.2	Stochastic Human Exposure and Dose Simulation for particulate matter (SHEDS-PM)	473
20.3.3	Examples of SHEDS-PM Use	476
20.3.4	Limitations to SHEDS-PM	477
20.4	Conclusions	478
21	Preferential sampling of exposure levels	485
	<i>Peter J Diggle and Emanuele Giorgi</i>	
21.1	Introduction	485
21.2	Geostatistical sampling designs	486
21.2.1	Definitions	486
21.3	Preferential sampling methodology	487
21.3.1	Non-uniform designs need not be preferential	488
21.3.2	Adaptive designs need not be strongly preferential	488
21.3.3	The Diggle, Menezes and Su model	489
21.3.4	The Pati, Reich and Dunson model	489
21.3.4.1	Monte Carlo maximum likelihood using stochastic partial differential equations	490
21.4	Application: lead pollution monitoring	492
21.5	Discussion	494
22	Monitoring network design	499
	<i>James V. Zidek and Dale L. Zimmerman</i>	
22.1	Introduction	499
22.2	Monitoring environmental processes	501
22.3	Design objectives	502
22.4	Design paradigms	503
22.5	Probability-based designs	504
22.6	Model based designs	506
22.6.1	Estimation of covariance parameters	506
22.6.2	Estimation of mean parameters: The regression model approach	508
22.6.3	Spatial prediction	509
22.6.4	Prediction and process model inference	510
22.6.5	Entropy-based design	511
22.7	From ambient monitors to personal exposures	515
22.8	New directions	516
22.9	Concluding remarks	517

23 Statistical methods for source apportionment	523
<i>Jenna R. Krall and Howard H. Chang</i>	
23.1 Introduction	523
23.1.1 Source apportionment	524
23.1.2 Example	525
23.2 Methods when source profiles are known	525
23.2.1 Ordinary least squares approaches	527
23.2.2 Chemical Mass Balance (CMB)	527
23.3 Methods when source profiles are unknown	528
23.3.1 Principal component analysis (PCA)	528
23.3.2 Absolute principal component analysis (APCA)	529
23.3.3 Unmix	529
23.3.4 Factor analytic methods	530
23.3.5 Positive matrix factorization	530
23.3.6 Bayesian approaches	531
23.3.7 Ensemble approaches	532
23.4 Comparison of source apportionment methods	533
23.5 Challenges in source apportionment	534
23.5.1 Number of sources	535
23.5.2 Incorporating uncertainty	537
23.5.3 Measurement error	538
23.5.4 Temporal variation	538
23.5.5 Evaluation of source apportionment results	539
23.5.6 Multiple site data	539
23.6 Estimating source-specific health effects	540
23.7 Conclusions	541
24 Statistical Methods for Environmental Epidemiology	547
<i>Francesca Dominici and Ander Wilson</i>	
24.1 Introduction	547
24.1.1 Data Characteristics	548
24.1.2 Sources of Confounding Bias	549
24.2 Epidemiological Designs	550
24.2.1 Multi-Site Time Series Studies	551
24.2.1.1 Distributed Lag Models	552
24.2.2 Cohort Studies	553
24.2.3 Intervention Studies	554
24.2.4 Spatial Misalignment	556
24.2.5 Exposure Prediction Modeling	558
24.3 Estimating the Exposure-Response Relationship	559
24.3.1 Generalized Linear Models	559
24.3.2 Semi-Parametric Approaches	560
24.3.3 Model Uncertainty in the Shape of the Exposure-Response	560
24.4 Confounding Adjustment	561
24.4.1 Bayesian Adjustment for Confounding	562
24.4.2 Relation to BMA	564
24.4.3 Air Pollution Example	564
24.4.4 Concluding Remarks	565
24.5 Estimation of Health Effects From Simultaneous Exposure to Multiple Pollutants	567
24.5.1 Multi-Pollutant Profile Clustering and Effect Estimation	568

24.5.2	High-Dimensional Exposure-Response Function Estimation	569
24.5.3	Confounding Adjustment in Multiple Pollutant Models	569
25	Connecting Exposure to Outcome: Exposure Assessment	587
<i>Adam A. Szpiro</i>		
25.1	Background and overview of this chapter	587
25.2	Spatial statistics for exposure assessment	589
25.2.1	Land-Use Regression and Universal Kriging	589
25.2.2	Example 1: Stepwise Variable Selection in LUR	590
25.2.3	Example 2: Distance Decay Variable Selection (ADDRESS) in LUR	591
25.2.4	Example 3: Lasso Followed by Exhaustive Search Variable Selection in LUR and UK	591
25.2.5	Example 4: Accurate exposure prediction does not necessarily improve health effect estimation	592
25.3	Measurement error for spatially misaligned data	593
25.3.1	Correctly specified LUR or UK exposure model	593
25.3.2	Incorrectly specified LUR or regression spline exposure model . .	595
25.4	Optimizing exposure modeling for health effect estimation rather than prediction accuracy	598
26	Environmental epidemiology study designs	603
<i>Lianne Sheppard</i>		
26.1	Introduction	603
26.2	Studies that focus on short-term variation of exposures and acute effects .	605
26.2.1	Ecologic time series studies	605
26.2.2	Case-crossover studies	606
26.2.3	Panel studies	609
26.3	Studies that focus on long-term average exposures and chronic health effects	610
26.3.1	Cohort studies	610
26.3.2	Case-control and cross-sectional studies	611
26.4	Summary and Discussion	612
IV	Topics in Climatology	617
27	Modeling and assessing climatic trends	619
<i>Peter F. Craigmile and Peter Guttorp</i>		
27.1	Introduction	619
27.2	Two motivating examples	620
27.2.1	US average temperature anomaly	620
27.2.2	Global temperature series	621
27.3	Time series approaches	621
27.3.1	Candidate models for the noise	622
27.3.2	Linear trends	623
27.3.3	Nonlinear and nonparametric trends	625
27.3.4	Smoothing and filtering to estimate the trend	627
27.3.5	Removing or simplifying trend by differencing	627
27.3.6	Hierarchical and dynamic linear model decompositions for trend .	628
27.4	Two case studies	628
27.4.1	US annual temperatures	628
27.4.2	Global annual mean temperature	630

27.5	Spatial and spatio-temporal trends	632
27.6	Assessing climatic trends in other contexts	633
27.7	Discussion	633
28	Climate Modelling	641
	<i>David B. Stephenson</i>	
28.1	Aim	641
28.2	What is climate?	642
28.3	Climate modelling	643
28.3.1	Climate processes	643
28.3.2	Classes of climate model	644
28.3.2.1	General Circulation Model (GCM)	644
28.3.2.2	Regional Climate Model (RCM)	645
28.3.2.3	Earth System Model (ESM)	645
28.3.2.4	Low-order models	645
28.3.2.5	Stochastic Climate Models	646
28.4	Design of Experiments for Climate Change	646
28.4.1	Initial condition ensembles (ICE)	647
28.4.2	Perturbed Physics Ensembles (PPE)	647
28.4.3	Multi-Model Ensembles (MME)	647
28.4.4	Climate change projections	649
28.5	Real world inference from climate model data	650
28.5.1	Current practice	650
28.5.2	Imperfect climate model and observational data	650
28.5.3	Probabilistic inference	652
28.5.3.1	The truth-centered approach	652
28.5.3.2	The coexchangeable approach	652
28.5.4	Summary	652
28.6	Concluding remarks	653
29	Spatial Analysis in Climatology	657
	<i>Douglas Nychka and Christopher K. Wikle</i>	
29.1	Introduction	657
29.2	Exploratory/Descriptive Analysis	658
29.2.1	Moment-Based Methods	658
29.2.2	Spectral-Based Methods	659
29.2.3	Eigen-Decomposition-Based Methods	662
29.2.3.1	Empirical Orthogonal Functions (EOFs)	662
29.2.3.2	Spatio-Temporal Canonical Correlation Analysis (ST-CCA)	667
29.2.3.3	Empirical Principal Oscillation Patterns (POPs)/Empirical Normal Modes (ENMs)	667
29.3	Data Products	668
29.3.1	Data Assimilation	668
29.3.2	Spatial Prediction	671
29.3.3	Inference for spatial fields	674
29.3.3.1	Spatial and Spatio-Temporal Field Comparison	676
29.3.4	Spatio-Temporal Prediction	678
29.4	Conclusion	678
29.5	Acknowledgments	679
29.6	Figures	679

30 Assimilating Data into Models

687

Amarjit Budhiraja, Eric Friedlander, Colin Guider,, Christopher KRT Jones, and John Maclean

30.1	Introduction	688
30.1.1	The core of a DA scheme	689
30.1.2	Model and observations	689
30.1.3	Challenges of DA	690
30.1.4	Approaches to DA	691
30.1.4.1	Variational approach	691
30.1.4.2	Kalman gain approach	691
30.1.4.3	Probabilistic approach	692
30.1.5	Perspectives on DA	693
30.1.6	Chapter Overview	694
30.2	Variational Methods	694
30.2.1	3D-Var	695
30.2.1.1	Incremental Method for 3D-Var	695
30.2.2	4D-Var	696
30.2.2.1	Strong constraint 4D-Var	696
30.2.2.2	Incremental Method for 4D-Var	697
30.2.2.3	Weak Constraint 4D-Var	698
30.3	Bayesian formulation and sequential methods	699
30.3.1	Filtering	699
30.3.2	The Kalman Filter	700
30.3.2.1	Extensions	701
30.3.2.2	Equivalence of 4D-Var and KF	702
30.3.3	Particle Filters	703
30.3.3.1	A basic particle filter	703
30.3.3.2	Particle filter with resampling	704
30.3.3.3	Variance reduction: Deterministic allocation and residual resampling	704
30.3.3.4	Branching particle filter	704
30.3.3.5	Regularized particle filters	705
30.4	Implementation of DA methods	705
30.4.1	Common modifications for DA schemes	707
30.4.1.1	Localization	707
30.4.1.2	Inflation	707

31 Spatial Extremes

711

Anthony Davison, Raphaël Huser, and Emeric Thibaud

31.1	Introduction	711
31.2	Max-stable and related processes	713
31.2.1	Poisson process	713
31.2.2	Classical results	715
31.2.3	Spectral representation	716
31.2.4	Exceedances	719
31.3	Models	719
31.3.1	General	719
31.3.2	Brown–Resnick process	720
31.3.3	Extremal- <i>t</i> process	721
31.3.4	Other models	721
31.3.5	Asymptotic independence	722

31.4	Exploratory procedures	723
31.5	Inference	724
31.5.1	General	724
31.5.2	Likelihood inference for maxima	725
31.5.3	Likelihood inference for threshold exceedances	726
31.6	Examples	727
31.6.1	Saudi Arabian rainfall	727
31.6.2	Spanish temperatures	734
31.7	Discussion	737
31.8	Computing	738
32	Statistics in Oceanography	745
	<i>Christopher K. Wikle</i>	
32.1	Introduction	745
32.2	Descriptive Multivariate Methods	746
32.2.1	PCA and EOF Analysis	746
32.2.2	Spatio-Temporal Canonical Correlation Analysis (ST-CCA)	747
32.3	Time Series Methods	747
32.3.1	Time-Domain Methods	748
32.3.2	Frequency-Domain Methods	748
32.3.2.1	Univariate Spectral Analysis	749
32.3.2.2	Bivariate Spectral Analysis	750
32.3.2.3	Space-Time Spectral Analysis	753
32.4	Spatio-Temporal Methods	753
32.5	Methods for Data Assimilation	755
32.5.1	Assimilating Near Surface Ocean Winds	755
32.5.2	Assimilating Lower Trophic Ecosystem Components	756
32.6	Methods for Long-Lead Forecasting	757
32.6.1	Multivariate Methods	757
32.6.2	Autoregressive and State-Space Approaches	757
32.6.3	Alternative Approaches	758
32.6.4	Long-Lead Forecast Example: Pacific SST	758
32.6.4.1	SST Forecast Model	759
32.6.4.2	Results	759
32.7	Conclusion	761
32.8	Acknowledgments	761
33	Paleoclimate reconstruction: looking backwards to look forward	767
	<i>Peter F. Craigmile, Murali Haran, Bo Li, Elizabeth Mannshardt, Bala Rajaratnam, and Martin Tingley</i>	
33.1	Introduction	768
33.2	Paleoclimate reconstruction: looking backwards	769
33.2.1	A multiproxy, multforcing IR reconstruction	770
33.2.2	Statistical issues in paleoclimate reconstruction	771
33.2.2.1	Incorporating climate forcings in the HBM	771
33.2.2.2	Handling proxies separately	772
33.2.2.3	Modeling temporal dependence	772
33.2.2.4	Modeling spatial dependence and spatio-temporal reconstructions	773
33.2.2.5	Missing values and data augmentation	774
33.2.2.6	Temporal uncertainty	774

33.2.2.7	Non-Gaussian paleoclimate reconstruction	774
33.2.2.8	Multivariate reconstructions	775
33.2.3	Ideas and good practices	775
33.3	Climate models and paleoclimate	776
33.3.1	Climate model assessment using paleoclimate reconstructions . . .	776
33.3.2	Statistical issues	778
33.3.2.1	Considering and embracing the lack of independence . .	778
33.3.2.2	Refining model components	778
33.3.3	Research directions	779
33.3.3.1	Paleoclimate-based climate model calibration	779
33.3.3.2	Making climate projections using paleoclimate reconstructions	779
33.3.3.3	Paleoclimate reconstructions using climate models	779
33.4	Discussion: looking forward	780
34	Climate Change Detection and Attribution	789
	<i>Dorit Hammerling, Matthias Katzfuss, and Richard Smith</i>	
34.1	Introduction	789
34.2	Statistical model description	791
34.3	Methodological development	792
34.3.1	The beginning: Hasselmann’s method and its enhancements . . .	792
34.3.2	The method comes to maturity: Reformulation as a regression problem; random effects and total least squares	794
34.3.3	Accounting for noise in model-simulated responses: the total least squares algorithm	795
34.3.4	Combining multiple climate models	797
34.3.5	Recent advances	798
34.4	Attribution of extreme events	799
34.4.1	Introduction	799
34.4.2	Framing the question	800
34.4.3	Other “Framing” Issues	802
34.4.4	Statistical methods	805
34.4.5	Application to precipitation data from Hurricane Harvey	806
34.4.6	An example	808
34.4.7	Another approach	812
34.5	Summary and open questions	812
34.6	Acknowledgments	813
35	Health risks of climate variability and change	819
	<i>Kristie L. Ebi, David Hondula, Patrick Kinney, Andrew Monaghan, Cory W. Morin, Nick Ogden, and Marco Springmann</i>	
35.1	Introduction	820
35.2	Framework of the health risks of climate variability and change	821
35.3	Quantifying the associations between weather/climate and health	821
35.3.1	Cases of adverse health outcomes	822
35.3.2	Human sensitivity to disease risk	823
35.3.3	Exposure risk	823
35.3.4	Analyzing associations between exposures to weather/climate variability and adverse health outcomes	823
35.3.5	Spatial analyses	824
35.3.6	Vulnerability mapping	825

35.3.7 Cautions and considerations 826

35.4 Modeling future risks of climate-sensitive health outcomes 828

35.4.1 Spatiotemporal issues and other considerations when using climate
projections 829

35.4.2 Projections using statistical models 831

35.4.3 Projections using process-based models 832

35.4.4 Other considerations 833

35.4.5 Scenarios 834

35.5 Conclusions 841

Index