

Contents

Acknowledgements	ix
Preface	xiii
1 Introduction to Spatio-Temporal Statistics	1
1.1 Why Should Spatio-Temporal Models Be <i>Statistical</i> ?	6
1.2 Goals of Spatio-Temporal Statistics	7
1.2.1 The Two Ds of Spatio-Temporal Statistical Modeling	7
1.2.2 Descriptive Modeling	8
1.2.3 Dynamic Modeling	9
1.3 Hierarchical Statistical Models	10
1.4 Structure of the Book	14
2 Exploring Spatio-Temporal Data	17
2.1 Spatio-Temporal Data	17
2.2 Representation of Spatio-Temporal Data in R	22
2.3 Visualization of Spatio-Temporal Data	24
2.3.1 Spatial Plots	25
2.3.2 Time-Series Plots	26
2.3.3 Hovmöller Plots	28
2.3.4 Interactive Plots	28
2.3.5 Animations	29
2.3.6 Trelliscope: Visualizing Large Spatio-Temporal Data Sets	29
2.3.7 Visualizing Uncertainty	31
2.4 Exploratory Analysis of Spatio-Temporal Data	32
2.4.1 Empirical Spatial Means and Covariances	33
2.4.2 Spatio-Temporal Covariograms and Semivariograms	36
2.4.3 Empirical Orthogonal Functions (EOFs)	39
2.4.4 Spatio-Temporal Canonical Correlation Analysis	47
2.5 Chapter 2 Wrap-Up	50
Lab 2.1: Data Wrangling	51

Lab 2.2: Visualization	60
Lab 2.3: Exploratory Data Analysis	67
3 Spatio-Temporal Statistical Models	77
3.1 Spatio-Temporal Prediction	78
3.2 Regression (Trend-Surface) Estimation	84
3.2.1 Model Diagnostics: Dependent Errors	88
3.2.2 Parameter Inference for Spatio-Temporal Data	93
3.2.3 Variable Selection	96
3.3 Spatio-Temporal Forecasting	99
3.4 Non-Gaussian Errors	100
3.4.1 Generalized Linear Models and Generalized Additive Models	101
3.5 Hierarchical Spatio-Temporal Statistical Models	104
3.6 Chapter 3 Wrap-Up	105
Lab 3.1: Deterministic Prediction Methods	106
Lab 3.2: Trend Prediction	112
Lab 3.3: Regression Models for Forecasting	125
Lab 3.4: Generalized Linear Spatio-Temporal Regression	130
4 Descriptive Spatio-Temporal Statistical Models	137
4.1 Additive Measurement Error and Process Models	138
4.2 Prediction for Gaussian Data and Processes	139
4.2.1 Spatio-Temporal Covariance Functions	143
4.2.2 Spatio-Temporal Semivariograms	150
4.2.3 Gaussian Spatio-Temporal Model Estimation	151
4.3 Random-Effects Parameterizations	154
4.4 Basis-Function Representations	157
4.4.1 Random Effects with Spatio-Temporal Basis Functions	158
4.4.2 Random Effects with Spatial Basis Functions	161
4.4.3 Random Effects with Temporal Basis Functions	162
4.4.4 Confounding of Fixed Effects and Random Effects	164
4.5 Non-Gaussian Data Models with Latent Gaussian Processes	165
4.5.1 Generalized Additive Models (GAMs)	166
4.5.2 Inference for Spatio-Temporal Hierarchical Models	167
4.6 Chapter 4 Wrap-Up	170
Lab 4.1: Spatio-Temporal Kriging with gstat	172
Lab 4.2: Spatio-Temporal Basis Functions with FRK	175
Lab 4.3: Temporal Basis Functions with SpatioTemporal	180
Lab 4.4: Non-Gaussian Spatio-Temporal GAMs with mgcv	189
Lab 4.5: Non-Gaussian Spatio-Temporal Models with INLA	192

5	Dynamic Spatio-Temporal Models	205
5.1	General Dynamic Spatio-Temporal Models	206
5.1.1	Data Model	207
5.1.2	Process Model	207
5.1.3	Parameters	209
5.2	Latent Linear Gaussian DSTMs	209
5.2.1	Linear Data Model with Additive Gaussian Error	209
5.2.2	Non-Gaussian and Nonlinear Data Model	212
5.2.3	Process Model	213
5.3	Process and Parameter Dimension Reduction	218
5.3.1	Parameter Dimension Reduction	218
5.3.2	Dimension Reduction in the Process Model	222
5.4	Nonlinear DSTMs	224
5.5	Chapter 5 Wrap-Up	228
	Lab 5.1: Implementing an IDE Model in One-Dimensional Space	229
	Lab 5.2: Spatio-Temporal Inference using the IDE Model	234
	Lab 5.3: Spatio-Temporal Inference with Unknown Evolution Operator	244
6	Evaluating Spatio-Temporal Statistical Models	253
6.1	Comparing Model Output to Data: What Do We Compare?	254
6.1.1	Comparison to a Simulated “True” Process	255
6.1.2	Predictive Distributions of the Data	256
6.1.3	Validation and Cross-Validation	258
6.2	Model Checking	260
6.2.1	Extensions of Regression Diagnostics	260
6.2.2	Graphical Diagnostics	262
6.2.3	Sensitivity Analysis	266
6.3	Model Validation	268
6.3.1	Predictive Model Validation	268
6.3.2	Spatio-Temporal Validation Statistics	269
6.3.3	Spatio-Temporal Cross-Validation Measures	272
6.3.4	Scoring Rules	273
6.3.5	Field Comparison	278
6.4	Model Selection	281
6.4.1	Model Averaging	282
6.4.2	Model Comparison via Bayes Factors	283
6.4.3	Model Comparison via Validation	283
6.4.4	Information Criteria	284
6.5	Chapter 6 Wrap-Up	287
	Lab 6.1: Spatio-Temporal Model Validation	289

Pergimus (Epilogue)	303
Appendices	307
A Some Useful Matrix-Algebra Definitions and Properties	307
B General Smoothing Kernels	311
C Estimation and Prediction for Dynamic Spatio-Temporal Models	312
C.1 Estimation in Vector Autoregressive Spatio-Temporal Models via the Method of Moments	312
C.2 Prediction and Estimation in Fully Parameterized Linear DSTMs .	313
C.3 Estimation for Non-Gaussian and Nonlinear DSTMs	318
D Mechanistically Motivated Dynamic Spatio-Temporal Models	318
D.1 Example of a Process Model Motivated by a PDE: Finite Differences	318
D.2 Example of a Process Model Motivated by a PDE: Spectral	320
D.3 Example of a Process Model Motivated by an IDE	321
E Case Study: Physical-Statistical Bayesian Hierarchical Model for Predict- ing Mediterranean Surface Winds	323
F Case Study: Quadratic Echo State Networks for Sea Surface Temperature Long-Lead Prediction	340
List of R Packages	351
References	355
Subject Index	367
Author Index	373
R Function Index	377