

Index

- 3D-Var, 562
- 4D-Var, 563–567
- accuracy, 5
- activation function, 176
 - hyperbolic tangent function (\tanh), 177–178, 183
 - logistic function, 176–178, 183
 - rectified linear unit (ReLU), 177–178, 496
 - softplus function, 177–178, 496
 - swish function, 177–178, 496
- active remote sensing, 208
- adjoint, 562
- Advanced Very High Resolution Radiometer (AVHRR), 209
- aerosols, 209
- AI winters, 2
- air quality, 213
- Akaike information criterion (AIC), 275–278
- Akaike information criterion corrected (AIC_c), 277–278
- aliasing, 382–384
- alternative hypothesis, 101
- altimeter, 211
- analysis (in NWP), 562
- analysis of variance (ANOVA), 149–151
- Anderson–Darling test, 120–121, 123
- anomaly, 25
- Antarctic Oscillation (AAO), 313
- architecture-constrained NN (ACnet), 558–559
- Arctic Oscillation (AO), 171, 313
- $\arg \min$, 451
- artificial intelligence (AI), 2–4, 570
- artificial neural network (ANN)
 - (*see* neural network (NN))
- atmospheric radiation, 550–551
- attention U-net, 510
- attribute, 15
- augmented data matrix, 406
- auto-covariance, 387
- auto-regressive (AR) process, 37, 410–413
- auto-regressive integrated moving average (ARIMA) model, 415
- auto-regressive moving average (ARMA) model, 414–415
- autocorrelation, 36–38, 107–109, 405
- autoencoder, 347–362, 546
 - sparse, 349
 - denoising, 348
 - dimensionality reduction, 347–362
 - variational, 348
- automatic differentiation, 557
- automatic relevance determination (ARD), 467
- autospectrum, 379–387
- averaging in time, 404–405
- axon, 175
- back-propagation, 180, 221–225
- backward optimization, 280
- bagging (bootstrap aggregating), 214, 263, 266, 269, 482
 - confidence interval, 263
 - out-of-bag (OOB), 263
 - prediction interval, 263
- Bartlett method, 384
- base rate, 519
- batch learning, 27, 154, 224
- batch normalization, 497
- Bayes factor, 272
- Bayes theorem, 21, 49–53
- Bayes, Thomas, 21
- Bayesian, 49, 51

- Bayesian information criterion (BIC), 273–275
- Bayesian model averaging (BMA), 278–280
- Bayesian model selection, 272–273
- Bayesian neural network (BNN), 260
- Beijing, 79
- beluga whale, 498
- Bernoulli distribution, 66
- Bessel
 - Friedrich, 25
- best linear unbiased estimator (BLUE), 147, 561
- beta distribution, 80–82
- BFGS method, 233–234
 - limited memory, 234
- bias
 - frequency bias, 520
 - bias error, 250–251, 264–266
 - bias parameter, 175
- Big data, 570
- bike sharing system, 493
- binomial distribution, 66–68
- bits, 58
- bivariate Gaussian distribution, 76
- biweight midcorrelation, 40–41
- black box, 4
- boosting, 473, 487–492
 - AdaBoost, 488
 - CatBoost, 488
 - gradient, 488–492
 - LightBoost, 488
 - XGBoost, 491–492
- bootstrapping, 126–131, 133–134, 214, 263, 269, 482
- block, 131
- confidence interval (CI), 126–131, 263
 - basic method, 128–129
 - BCa method, 129
 - percentile method, 128–129
- field significance, 133–134
- moving block, 131
- prediction interval, 263
- serial correlation, 131
- bottleneck, 347
- Box–Cox transformation, 94
- Box–Jenkins models, 414–415
- boxplot, 45–46
- breakdown point, 30
- Brent’s method, 231
- Brier score (BS), 528
 - multiple classes, 531
- Brier skill score (BSS), 528
- Burgers’ equation, 556–557
- canonical correlation analysis (CCA), 320–327
 - pre-filter with PCA, 324–326
- canonical correlation coordinates, 321
- canonical variate, 321, 365
- CART (*see* classification and regression tree)
- categorical data, 6, 19, 156–158
- central limit theorem, 7–8, 72, 404
- centroid, 55
- channel, 501
- cherry-picking, 537
- chi-squared distribution, 97–98, 385
- chlorophyll, 209
- circular data, 156–157
- circular statistics, 82
- city-block distance, 332
- class imbalance, 436–438
- classical mechanics, 5
- classification, 6, 15–16, 50–54, 418–439
 - binary, 15
 - multi-class, 15, 461–462
- classification and regression tree (CART), 474–481
 - relative importance of predictors, 479–481
 - surrogate split, 480–481
- climate downscaling, 543–547
- climate extremes, 8, 405
- climate of extreme weather events (*see* climate extremes)
- climatological seasonal cycle, 396
- climatology forecast, 524, 533–534
- cloud, 209–210, 508, 516
- cloud cover, 80–82
- cloud resolving model (CRM), 551
- CloudSat, 517
- cluster analysis (*see* clustering)
- clustering, 16, 54–56, 330–343, 453
 - Calinski–Harabasz index, 333
 - external evaluation, 335–337
 - gap statistic, 333–334
 - Gaussian mixture model, 339
 - hierarchical, 339–343

Index

615

- internal evaluation, 332–334
- model evaluation, 332–337
- non-hierarchical, 337–339
- co-kriging, 467
- code (*see* bottleneck)
- coefficient of determination, 148
- collinearity, 159, 163, 172
- Columbus, 4
- committee, 262
- complementary cumulative distribution function (CCDF), 23, 103
- computational intelligence, 2, 570
- condition number of a matrix, 163
- conditional density network (CDN), 199–200, 544
- conditional distribution, 21–23
- conditional entropy, 59–61
- conditional Gaussian distribution, 77
- conditional probability, 21–22, 50
- conditional probability density, 23
- conditional probability distribution, 199–204
- confidence interval (CI), 115–119
 - bagging, 263
 - bootstrapping, 126–131
 - correlation, 118–119
 - joint confidence region, 152
 - multiple linear regression, 151–153
 - population mean, 116–118
 - simple linear regression, 141–145
 - spectrum, 385
- confidence level, 116
- congruence, 317
- conjugate gradient method, 229–233
- contingency table, 519
- continuous data, 19
- continuous ranked probability score (CRPS), 535
- continuous-time Fourier transform (CTFT), 375
- convolution, 377
 - discrete, 499–502
 - missing data, 509
 - partial, 509
 - theorem, 391
- convolutional layer, 496
- convolutional LSTM (ConvLSTM) network, 512–513
- convolutional neural network (CNN), 497, 499–510
- fully (FCN), 508
- temporal (TCN), 513–514
- correlation, 33
 - a pair of correlations, 110–111, 119
 - confidence interval, 119
 - significance test, 110–111
- biweight midcorrelation, 40–41
- confidence interval, 118–119
- Kendall, 39–40, 125
- multiple correlation, 148
- Pearson, 33–36
- rank correlation, 38–40
- relation to MSE, 533
- sample correlation, 33
- serial, 36–38, 67–68, 107–110
- significance test, 109–111
- Spearman, 38–39
- cosine taper, 379
- cost function, 173, 181
- covariance, 26–27
 - auto-covariance, 387
 - cross-covariance, 394
 - online algorithm, 28
- covariance matrix, 26–27, 75, 155, 285, 300
- covariate, 15, 137
- critical success index (CSI), 520
- cross-entropy, 60, 432–434, 477
- cross-spectrum, 393–394
- cross-validation, 164, 255–258, 477, 537–538
- cumulative distribution function (CDF), 23, 71
- curse of dimensionality, 17–18, 185, 430, 442, 450
- cyclonic, 388
- Daniell method, 384
- dark energy, 5
- dark matter, 5
- dark universe, 5
- Dartmouth Summer Research Project, 2
- data
 - categorical, 6, 12–15, 19
 - continuous, 6, 12–13, 19
 - discrete, 6, 12–15, 19
 - nominal, 19
 - ordinal, 6, 19
 - structured, 497

- test, 6
- training, 6
- types, 19
- validation, 11
- data assimilation, 560–567
 - 3D-Var, 562
 - 4D-Var, 563–567
 - ensemble Kalman filter, 567
 - variational, 560–567
- data augmentation, 506
- data driven, 3, 570
- data mining, 3, 570
- data science, 3–5, 570
- decibel (dB), 378
- decile, 31
- decision boundary, 52, 179
- decision region, 52
- decision surface, 52
- decision tree, 473–481
 - C4.5, 478
 - C5.0, 478
 - classification and regression tree (CART), 474–481
- decoder, 347
- deep belief network, 494
- deep learning (DL), 494–517
- deep neural network (DNN), 494–517
- DeepLabv3, 510
- degrees of freedom, 97
- delay coordinate space, 406
- dendrite, 175
- denoising, 348
- dense layer, 503
- densely connected convolutional networks (DenseNet), 505
- density estimation, 65
- dependent variable, 15
- depth
 - of a NN model, 501
 - of a layer, 501
- design matrix, 146
- deterministic optimization, 236
- detrend, 382
- deviance, 477
- DFP method, 233
- Differential evolution (DE), 241–244
- dimensionality reduction
 - autoencoder, 347–362
 - non-linear, 347–364
- principal component analysis (PCA), 300–301
- direct numerical simulation (DNS), 553
- directional statistics, 82
- discrete data, 19
- discrete Fourier transform (DFT), 374–375
- discrete-time Fourier transform (DTFT), 376
- discriminant analysis
 - Fisher, 421–423
 - linear (LDA), 419–423
 - quadratic (QDA), 419
 - regularized, 419
- discriminant function, 53–54, 419
- dissolved organic carbon (DOC), 82
- distance, 331–332
 - city-block, 332
 - Euclidean, 331
 - Hamming, 332
 - Minkowski, 332
- distribution, 12–15
 - beta, 80–82
 - chi-squared, 97–98
 - conditional, 199–204
 - exponential, 78
 - Fréchet, 84
 - gamma, 78–80, 98, 200
 - Gaussian, 7, 9, 13–15, 69–72, 75–77, 98
 - generalized extreme value (GEV), 84–86
 - Gumbel, 84
 - multivariate Gaussian, 75–76
 - Pearson type III, 78
 - Student *t*, 95–97
 - von Mises, 82–83
 - Weibull, 13, 84
- downsampling, 502–503
- downscaling, 543–547
 - climate, 543–547
 - climate of extremes, 544–545
 - dynamical, 543
 - expanded, 547
 - inflation, 546
 - precipitation, 544–545
 - quantile mapping, 546
 - randomization, 546
 - statistical, 543
 - streamflow, 546

Index

617

- wind speed, 545–546
- dropout, 269–271, 497
- dual Lagrangian, 457
- dual solution, 444
- dual variable, 443
- Durbin–Watson statistic, 144–145
- early stopping, 224, 254–255, 263, 266
- effective sample size, 37–38, 46, 106, 108–109, 126
- efficiency
 - Legates–McCabe, 534
 - Nash–Sutcliffe, 534
- Ekman spiral, 319
- El Niño, 106, 113–114, 135, 290–295
- El Niño–Southern Oscillation (ENSO), 60, 121, 171, 213–214, 280, 290–295, 354–358, 366–367, 390–392, 401, 407–408, 498, 507, 513, 554–555
- empirical orthogonal function (EOF), 283, 289, 298
 - extended (EEOF), 408
- emulation, 550
- encoder, 347
- encoder–decoder network, 507–510
 - attention U-net, 510
 - DeepLabv3, 510
 - U-net, 508–510, 546
 - UNet 3+, 510
 - UNet++, 510, 546
- ensemble, 261–269
 - unequal weights, 266–269
- ensemble Kalman filter, 567
- entropy, 56–62
 - conditional, 59–61
 - cross, 60
 - joint, 59
 - relative, 60
- entropy impurity, 477
- environmental data science, 6–9
- environmental science (ES), 6
- EOF (*see* empirical orthogonal function)
- epoch, 224
- equitable threat score (ETS), 526
- error function, 173, 181
 - ϵ -insensitive, 463
- Euclidean distance, 331
- evolutionary algorithm (EA), 236–244
- evolutionary computation, 237
- expectation, 24
- expectation–maximization (EM) algorithm, 90–91, 339
- expert systems, 2
- explanatory variable, 137
- exploratory data analysis (EDA), 41–46
- exponential distribution, 78
- extended empirical orthogonal function (EEOF), 408
- extra trees (ET), 487
- extrapolation, 6–7, 12, 538–541
- extreme learning machine (ELM), 189–194, 196–199
 - classifier, 430–432
 - online sequential (OSELM), 193–194
- extreme values, 83–86
- extremely randomized trees (extra trees, ET), 487
- F* distribution, 124
- F*-measure, 522
- F*-test, 124
- factor analysis (FA), 311–312
- false alarm rate (F), 521
- false alarm ratio (FAR), 521
- fast Fourier transform (FFT), 386
- feature, 6, 15, 52, 137, 471
- feature selection (*see* predictor selection)
- feature space, 52, 442, 460
- feed-forward neural network (FFNN), 174, 180
- field significance, 131–134
 - bootstrap method, 133–134
 - false discovery rate (FDR) method, 134
- filter, 395–403
 - 1-2-1 filter, 402–403
 - 3-point triangular, 402–403
 - finite impulse response (FIR), 398
 - moving average (MA), 402–403
 - periodic signal, 396
 - response function, 397
 - symmetric, 399
 - tidal, 396
 - windowing method, 399–401
- Fisher transformation, 110, 118–119

- Fisher–Snedecor distribution (*see F distribution*)
- Fletcher–Reeves method, 231
- folding frequency (*see Nyquist frequency*)
- forecast lead time, 518
- forecast rate, 520
- forecast verification, 518–535
 - binary classes, 519–526
 - multiple classes, 527–528
 - probabilistic binary classes, 528–530
 - probabilistic multiple classes, 531–532
- forest, 209, 420
- Fourier analysis, 372–376
- Fourier series, 373–374
 - discrete Fourier transform, 374–375
- Fourier transform, 375–376
 - continuous-time, 375
 - discrete, 374–375
 - discrete-time, 376
- fraction correct, 520
- Fréchet distribution, 84
- frequentist, 49, 51
- fully convolutional network (FCN), 508
- fundamental frequency, 382
- gamma distribution, 78–80, 98, 200
 - generalized, 78
- gamma function, 78, 97
- Gauss–Markov theorem, 147
- Gauss–Newton method, 235
- Gaussian distribution, 7, 9, 13–15, 42, 43, 69–72, 75–77, 98
 - bivariate, 76
 - conditional, 77
 - marginal, 77
 - multivariate, 75–76
 - sample mean, 72
 - standard, 71
- Gaussian kernel, 93
- Gaussian mixture model, 86–91, 201, 339
- Gaussian process (GP), 440, 442, 463–469
- general circulation model (GCM), 212, 367–369, 543
- general linear model, 153–154
- generalization error, 251
- generalized cross-validation, 258
- generalized extreme value (GEV) distribution, 84–86, 200
- generalized gamma distribution, 78
- generalized least squares (GLS), 168–170
- generative adversarial network (GAN), 514–517
 - conditional (CGAN), 516–517
- generative topographic mapping (GTM), 345
- genetic algorithm (GA), 237, 239–241
- geopotential height, 312
 - 500 hPa (Z500), 367–369
- Geostationary Operational Environmental Satellites (GOES), 210
- Gilbert skill score (GSS), 526
- Gini impurity index, 477
- Glacier, BC, 129
- global climate model (GCM) (*see general circulation model (GCM)*)
- global minimum, 461
- goodness-of-fit test, 119–123
 - two-sample, 121–123
- Google Trends, 3, 569
- gradient boosting machine (GBM), 488–492
 - CatBoost, 488
 - LightBoost, 488
 - XGBoost, 491–492
- gradient descent method, 221, 225–227, 233, 236
- gradient tree boosting (*see gradient boosting machine*)
- Gram matrix, 443
- greedy algorithm, 238
- grid search, 260
- Grouse Mountain, BC, 113, 126, 135, 172, 282
- Gumbel distribution, 84
- hail, 213, 521
- Hamming distance, 332
- Hamming window, 379
- Hann window, 379
- harmonic analysis, 396
- Heaviside step function, 175, 178
- Heidke skill score (HSS), 525
- Hessian matrix, 217
- heteroscedastic, 169, 486
- hidden layer, 180, 186
- hidden neuron (*see neuron, hidden*)
- hidden node (*see neuron, hidden*)

Index 619

- hill climbing, 238–239
 - random mutation, 238
 - steepest ascent, 238
- Hinton, Geoffrey, 4, 16
- histogram, 41–42, 59, 61
- hit rate, 520
- Hotelling T^2 test, 105
- Huber function, 204–206, 250
- humidity, 34, 43, 45, 144, 149, 160
- hurricane, 67
- hybrid coupled model, 554–555
- hydrology, 212
- hyperbolic tangent function (\tanh), 177–178, 183
- hyperparameter, 237, 252, 448
 - Bayesian approach, 260–261
 - grid search, 260
 - random search, 260
 - tuning, 258–261
- hyperplane, 54, 454–455
- hypothesis testing, 101–111
 - field significance, 131–134
- i.i.d. (independent and identically distributed), 72
- ignorance score, 528–529, 535
 - multiple classes, 531
- ill-conditioned matrix, 163, 198
- impurity, 477
- imputation, 304–305, 358, 509–510
- inconsistency index, 359, 362
- independent and identically distributed (i.i.d.), 72
- independent variable, 15
- index of agreement, 534
- indicator function, 435
- infiltration, 212
- informatics, 2, 570
- information criterion, 273–278, 360
 - Akaike (AIC), 275–278
 - Akaike, corrected (AIC_c), 277–278
 - Bayesian (BIC), 273–275
- information theory, 56–62
- infrared, 209–210
- Intergovernmental Panel on Climate Change (IPCC), 262
- interpretability, 5
- interpretable AI, 280–281
- interpretable ML, 280–281
- interquartile range (IQR), 31
- inverse modelling, 560
- isomap, 363
- Jacobian, 562
- Johnson transformation, 95
- joint confidence region, 152
- joint entropy, 59
- joint probability, 20–22
- joint probability density, 23
- K*-means clustering, 55, 89, 197, 337–338, 344, 453
 - K*-means++, 55
- K*-nearest neighbours (KNN), 18, 61, 428–430
- Karush–Kuhn–Tucker (KKT) conditions, 456, 457, 459, 571
- Kendall’s tau, 39–40, 125
- kernel, 201, 444–448, 469
 - automatic relevance determination, 467
 - Gaussian, 447, 460
 - Matérn, 467
 - polynomial, 447
 - radial basis function (RBF), 447, 460
 - ridge regression, 448–449
- kernel density estimation (KDE), 61, 91–93
- kernel function, 445, 460
- kernel matrix, 446
- kernel method, 440–471
- kernel principal component analysis, 451, 469–471
- kernel trick, 445, 450, 460
- Kolmogorov–Smirnov (KS) test, 119–123, 136
- kriging, 463
 - co-kriging, 467
- Kronecker delta function, 49, 75, 416, 465
- Kullback–Leibler (KL) divergence, 60, 275
- kurtosis, 32
- L-moment, 32
- L_1 norm, 165
- L_2 norm, 165
- La Niña, 113–114, 135, 290–295
- Lagrange function (Lagrangian), 457, 570

Lagrange multiplier, 164, 165, 286, 321, 456, 569–572
 Landsat, 209
 lasso, 165–166
 latent variable, 87–88
 layerwise relevance propagation (LRP), 280–281
 lead time, 518
 leaf angle, 81
 learning, 224
 batch, 27
 online, 27–28
 learning rate, 222, 260
 least squares, 198
 generalized (GLS), 168–170
 ordinary (OLS), 138, 145–147, 168
 leave-one-out cross-validation, 257–258
 Legates–McCabe efficiency, 534
 Levenberg–Marquardt method, 236
 Lighthill report, 2
 likelihood, 50–51, 73–74, 200, 246
 Lilliefors test, 121
 line search, 231
 linear discriminant analysis (LDA), 54, 419–423
 linear least squares, 138, 145–147
 recursive, 154–156
 linear regression (*see* regression)
 linearly separable, 179
 loading, 289
 locally-linear embedding (LLE), 363
 log odds, 419
 logarithmic score, 528–529
 logistic function, 176–178, 183, 424, 436
 logistic regression, 424–427
 multiclass, 425–427
 multinomial, 425–427
 long short-term memory (LSTM) network, 510–513
 longwave radiation (LWR), 550
 loss function, 167–168, 173, 181
 Lotka–Volterra equations, 568
 L_p norm, 165

 M5 model tree, 479
 machine learning (ML), 1–5, 570
 Madden–Julian oscillation (MJO), 362
 Mahalanobis distance, 47–49, 75–76
 Mann–Kendall trend test, 125–126

Mann–Whitney *U*-test (*see* Wilcoxon–Mann–Whitney test)
 Mann–Whitney–Wilcoxon test, 136
 marginal distribution, 20–23
 marginal Gaussian distribution, 77
 marginal likelihood, 272
 marginal probability, 20–22
 marginal probability density, 23
 Markov chain Monte Carlo method, 464, 467
 matrix
 Hermitian, 288
 orthonormal, 302
 positive semi-definite, 288
 max pooling, 502
 maximum covariance analysis (MCA), 320, 326–327
 maximum likelihood, 78, 200, 245–247
 maximum likelihood estimation, 73–74
 maximum margin classifier, 454–462
 maximum norm (max-norm) constraint, 271–272
 McCulloch and Pitts model, 174–175
 mean, 24
 conditional, 248
 online algorithm, 27–28
 population mean, 24
 sample mean, 24
 mean absolute error (MAE), 247, 532
 mean error (ME), 532
 mean squared error (MSE), 10–11, 181, 245–247, 532–534
 mean squared error skill score (MSE SS), 533–534
 median, 29–30, 40, 41, 167–168
 conditional, 250
 median absolute deviation (MAD), 30, 41
 Medium Resolution Imaging Spectrometer (MERIS), 209
 memory-based model, 428
 Mercer’s theorem, 446
 MeteoNet, 517
 method of moments, 70
 mini-batch, 229, 232, 270
 Minkowski distance, 332
 misclassification rate, 477
 missing data, 304–305, 509–510
 mixing coefficient, 86, 201

Index

621

- mixture density network (MDN), 201–204
- mixture model, 86–87, 201–204
- MLP (see multi-layer perceptron), 180
- mode (of a distribution), 70
- model evidence, 272
- model output statistics (MOS), 542–543
 - updatable MOS (UMOS), 543
- model tree, 479
- model validation, 11
- Moderate-Resolution Imaging Spectroradiometer (MODIS), 517
- momentum, 227
- monotonic MLP (MonMLP), 187–189, 204
- Monte Carlo method, 108
- Moore–Penrose inverse, 146, 153, 190, 198
- moving average (MA) filter, 384, 402–403
- moving average (MA) process, 414
- multi-class classification, 461–462
- multi-layer perceptron (MLP), 3, 174, 180–186, 198, 365
 - classifier, 434–436
 - monotonic, 187–189
- multi-model ensemble, 267
- multichannel singular spectrum analysis (MSSA), 407–408
- multinomial distribution, 68–69
- multiple correlation coefficient, 148
- multiple linear regression (*see* regression)
- multivariate Gaussian distribution, 75–76
- multivariate linear regression (*see* regression)
- mutual information, 61–62
- naive Bayes classifier, 427–428
- Nash–Sutcliffe efficiency, 534
- nats, 58
- Navier–Stokes equation, 557–558
- neural network (NN), 3, 5, 12, 173–214
 - Bayesian, 260
 - confidence interval, 263
 - deep (DNN), 494–517
 - prediction interval, 263, 266
 - randomized, 189–195
 - recurrent, 180, 210
- neuron, 173, 174, 176
 - hidden, 180, 186–187
- Newton’s method, 220, 232
- Niño 1+2 region, 63, 291
- Niño 3 region, 291
- Niño 3.4 region, 63, 121, 136, 171, 215, 291
- Niño 4 region, 291
- node, 176
- nominal data, 19, 531
- non-linear canonical correlation analysis (NLCCA), 365–369
 - robust, 366
- non-linear complex principal component analysis, 358
- non-linear dimensionality reduction, 347–364
- non-linear least squares, 234–236
- non-linear principal component analysis (NLPCA), 349–362, 507, 509
 - closed curve, 360–362
 - complex variables, 358
 - hierarchical, 353–354
 - missing data imputation, 358
 - open curve, 350–360
 - overfitting, 358–360
- non-linear singular spectrum analysis (NLSSA), 408–410
- non-parametric distribution, 65
- non-parametric models, 428
- non-parametric statistics, 111–115
- non-stationary data, 395
- normal distribution (*see* Gaussian distribution)
- normal equations, 138, 146, 235
- North Atlantic Oscillation (NAO), 171, 313
- nowcasting, 508, 513
- null hypothesis, 101–105
- numerical weather prediction (NWP), 2, 541
- Nyquist frequency, 382
- objective function, 162, 173, 181, 247–250
- oblique rotation, 305
- observation operator, 562
- ocean colour, 209
- ocean heat content, 213
- odds ratio, 524

offset parameter, 175
 oil spill, 212
 Old Faithful geyser, 171
 one-hot encoding, 157, 430, 434, 521
 one-of-*C* encoding (*see* one-hot encoding)
 one-tailed test, 103, 105, 108–109
 one-versus-one classification, 461
 one-versus-the-rest classification, 461
 online learning, 27–28, 154–156, 193–194, 229, 543
 online training, 224
 operation count, 147
 optimal fingerprinting, 170
 ordinal data, 6, 19, 528, 531
 ordinary least squares (OLS), 138, 145–147, 168
 orthonormal matrix, 302
 orthonormal rotation, 305–315
 out-of-bag (OOB) data, 263
 outlier, 6–7, 29, 247
 overfit, 3, 9–12, 158, 172, 224, 245, 249, 358
 ozone concentration, 172

p-value, 103
 Pacific-North American (PNA) pattern, 171, 215, 313, 367
 pairwise classification, 461
 parametric density estimation, 92
 parametric distribution, 65
 parametric models, 428
 passive remote sensing, 208
 Pearson type III distribution, 78
 Peirce skill score (PSS), 526
 percentile, 30, 31, 71
 perceptron, 175–180
 perfect prog, 542–543
 periodogram, 380
 persistence, 36
 persistence forecast, 524, 533–534
 physics-informed machine learning (PIML), 556–559
 physics-informed neural network (PINN), 556–559
 hard constraint, 558–559
 soft constraint, 556–558
 phytoplankton, 209
 PM_{2.5} concentration, 7, 78, 514
 Poisson distribution, 68

Polak–Ribiere method, 231
 polynomial, 9, 18, 185
 pooling, 502–503
 positive semi-definite, 446
 post-processing, 541–543
 power (of statistical test), 102–103, 120
 pre-image, 451–453
 precipitation, 16, 78, 96, 210, 508, 510, 513, 517
 Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PER-SIANN), 508
 precision, 522
 predictand, 15, 137
 prediction interval (PI)
 bagging, 263
 Gaussian process, 467
 multiple linear regression, 151–153
 neural network, 266
 random forest, 485–486
 simple linear regression, 143–145
 predictor, 6, 15, 137, 148–149
 selection, 5, 62, 158–160
 standardized, 148–149
 pressure, 34, 43, 89, 149, 160
 primal solution, 444
 principal component (PC), 286, 289
 principal component analysis (PCA), 16, 47–49, 75–76, 283–301
 2-dimensional vectors, 317–319
 kernel PCA, 469–471
 amplitudes, 289
 Buell patterns, 315
 combined PCA, 288, 318
 complex variables, 288, 318, 358
 correlation, 288
 degenerate eigenvalues, 299
 dimensionality reduction, 300–301
 eigenvalues, 288
 eigenvectors, 289
 Hotelling scaling, 298
 Kaiser test, 301
 latitudinal scaling, 290
 loadings, 289
 Lorenz scaling, 298
 missing data, 304–305
 Monte Carlo test, 301
 non-linear, 349–362

Index 623

- number of modes to retain, 300–301
- orthogonality relations, 289–290
- principal components, 289
- removing temporal or spatial mean, 302
- rotated, 305–317
- rotated A-frame, 311–315
- rotated E-frame, 308–310
- Rule N, 301
- scaling, 298–299
- scores, 289
- scree graph, 301
- smaller covariance matrix, 299–300
- space–time PCA, 407–408
- principal vector, 289
- probabilistic forecast
 - binary classes, 528–530
 - continuous variable, 535
 - multiple classes, 531–532
- probability, 1–2, 19–22
 - p*-value, 103
 - a posteriori*, 50
 - a priori*, 50
 - Bayesian, 49, 51
 - complementary cumulative, 23, 103
 - conditional, 21–22, 50
 - cumulative, 23
 - density, 22–23
 - frequentist, 49, 51
 - joint, 20–22
 - marginal, 20–22
 - posterior, 50, 88
 - prior, 50, 88
 - tail, 23, 103
- probability density function (PDF), 23
- probability distribution (*see* distribution)
- probability of detection (POD), 520
- probability of false detection (POFD), 521
- proportion correct, 520
- QR decomposition, 147
- quadratic discriminant analysis (QDA), 419
- quadratic programming, 165, 456
- quadrature, 408
- quantile, 30–31, 71–72, 167–168
- quantile regression, 167–168, 188, 485–486
- neural network (QRNN), 204–207, 544
- quantile regression forest, 485–486
- quantile–quantile (Q–Q) plot, 42–45
- quantization error (QE), 344
- quantum mechanics, 5
- quartile, 31, 45
- quasi-biennial oscillation (QBO), 362
- quasi-Newton method, 232–234
 - BFGS method, 233–234
 - DFP method, 233
 - limited memory, 234
- quasi-Newton methods, 236
- quintile, 31
- radar, 208, 211, 213
- radial basis functions (RBF), 195–199
 - normalized, 196
- radiometer, 208
- rainfall, 439
- random forecast, 524
- random forest (RF), 5, 473, 482–487
 - prediction interval, 485–486
 - quantile regression, 485–486
 - relative importance of predictors, 483–485
- random vector functional link (RVFL), 194–195
- randomized neural network, 189–195
- ranked probability score (RPS), 531–532
- re-expressing data, 93–95
- reanalysis, 404, 560
- recall, 522
- rectified linear unit (ReLU), 177–178, 496
- recurrent neural network (RNN), 180, 210, 510–513
- recursive least squares, 154–156
- regional climate model (RCM), 543
- regressand, 137
- regression, 6, 15–16
 - analysis of variance (ANOVA), 149–151
 - dual solution, 442–444
 - general linear model, 153–154
 - lasso, 165–166
 - linear, 137–172

- multiple linear regression (MLR), 145–156
 - without intercept term, 146
- multivariate linear regression, 153–154
- online learning, 154–156
- partition of sums of squares, 139–141, 148
- quantile, 167–168
- relation with correlation, 139
- ridge, 161–165, 172, 252, 443, 448
- serial correlation, 144–145
- simple linear regression (SLR), 10, 137–145
 - stepwise, 158–160
- regressor, 137
- regularization, 158, 251–254
 - Tikhonov, 161
- regularized least squares, 161
- reinforced learning, 17
- relative efficiency, 113
- relative entropy, 60
- relative humidity, 80–82, 96
- relative operating characteristic (ROC), 521, 522
- reliability diagram, 529–530, 532
- remote sensing, 208–212
 - active, 208
 - infrared, 209–210
 - microwave, 210–212
 - passive, 208
 - visible light, 209
- resampling, 126
- residual neural network (ResNet), 505–506
- resistant, 29, 30, 34, 38, 247–250
- response variable, 6, 15, 137
- retroactive validation, 538
- return level, 85
- return period, 85
- Reynolds stress, 553
- ridge regression, 161–165, 172, 252, 443
- River Thames, 85
- robust, 29, 30, 34, 38, 247–250
- robust statistics, 29
- rogues wave, 85
- rotated principal component analysis (RPCA), 305–317
 - A-frame rotation, 311–315
 - E-frame rotation, 308–310
- oblique rotation, 305
- orthonormal rotation, 305–315
- promax rotation, 308
- S-mode decomposition, 315
- T-mode decomposition, 315
- varimax rotation, 308–315
- rotation
 - orthonormal, 305–315
- running mean (*see* moving average)
- runoff, 212
- saddle point, 218
- sample size, 3, 15
 - effective, 37–38, 145
- scatterometer, 211
- scatterplot, 33–34
- score, 289
- scree graph, 301
- sea level, 214
- sea level pressure (SLP), 366–367
- sea surface temperature (SST), 185, 211, 213–214, 291, 354–358, 366–369
- Sea-viewing Wide Field-of-view Sensor (SeaWiFS), 209
- self-organizing map (SOM), 343–347, 360
- semantic segmentation, 507–510
- sensitivity, 223
- sequential training, 224
- serial correlation, 36–38, 46, 67–68, 106–110, 113, 144–145, 257
- sgn function, 125
- Shapiro–Wilk test, 121
- shortwave radiation (SWR), 550
- shrinkage method, 159–166
- sigmoidal function, 176
- significance level, 103
- significance test, 101–104
- Silverman’s rule of thumb, 93
- Sinclair Pass, BC, 127
- singular spectrum analysis (SSA), 405–408
 - non-linear, 408–410
 - rotation, 408
- singular value, 302
- singular value decomposition (SVD), 147, 302–304, 326
- singular vector, 302, 327
- skewness, 32, 67
- skill score, 525

Index 625

- binary classes, 524–526
- climatology as reference, 533–534
- continuous variable, 533–534
- equitable, 527–528
- equitable threat score, 526
- Gilbert, 526
- Hanssen and Kupers, 526
- Heidke, 525
- Legates–McCabe efficiency, 534
- multiple classes, 527–528
- Nash–Sutcliffe efficiency, 534
- Peirce, 526
- persistence as reference, 533–534
- skip connection, 194, 505–506, 508
- slack variable, 458
- Snedecor’s *F* distribution (*see F* distribution)
- snow, 210–211
- snow water equivalent (SWE), 113, 126, 129, 172, 212, 282
- soft computing, 2, 570
- softmax function, 201, 435–436
- softplus function, 177–178, 496, 539
- soil properties, 81
- Southern Oscillation, 295
- Southern Oscillation Index (SOI), 63, 295
- sparsity, 166, 458
- Special Sensor Microwave Imager (SSM/I), 210–211
- spectrum, 379–394
 - amplitude spectrum, 393
 - autospectrum, 379–387
 - band averaging, 384
 - Bartlett method, 384
 - co-spectrum, 393
 - coherence spectrum, 393
 - confidence interval, 385
 - cross-spectrum, 393–394
 - Daniell method, 384
 - ensemble averaging, 384
 - phase spectrum, 393
 - quadrature spectrum, 393
 - rotary, 387–390
 - smoothing, 384–385
 - Welch method, 384
- SSE (sum of squared errors), 138–140
- SSR (sum of squares, regression), 140
- SST (*see* sea surface temperature)
- SST (sum of squares), 140
- stacked generalization, 268–269
- stacking, 268–269
- standard deviation, 25
 - population standard deviation, 25
 - sample standard deviation, 25
- standard error, 72
- standard Gaussian distribution, 71
- standard score, 25, 71
- standardized anomaly, 25
- standardized variable, 25, 71, 183, 253
- stationary process, 395, 412
- statistical inference, 101–111
- statistics, 1–5
- Stave River, B.C., 79
- steepest descent method, 221, 225
- stepwise regression, 158–160
- stochastic gradient descent (SGD), 221, 227–229
- stochastic optimization, 236–244
- stochastic training, 224
- stream function, 557
- streamflow, 78, 85, 212, 511, 514
- stride, 501
- structured datasets, 497
- Student *t*-distribution (*see t*-distribution)
- Student *t*-test (*see t*-test)
- sub-grid processes, 517
- subsurface temperature, 214
- super-resolution, 510
- supervised learning, 15–17, 54, 173
- support vector, 455, 457, 460
- support vector machine (SVM), 440, 453–463
- support vector regression (SVR), 462–463
 - least squares, 448
- surface gravity wave, 555
- surface wind speed, 210
- suspended sediment, 209
- swish function, 177–178, 496
- Sydney airport, 438
- symmetric function, 445
- synapse, 175
- synthetic aperture radar (SAR), 211–212
- t*-distribution, 95–97, 109, 117
- t*-test, 104–110, 533
 - correlation, 109–110
 - cross-validated, 533

- dependent paired samples, 107–109
independent two-sampled, 105–109
one-sampled, 105
tail distribution, 23, 103
target, 15, 55, 176, 181
teleconnection, 171, 312–315, 367–369
temperature, 34, 38, 43, 45, 108–109,
117–118, 149, 160
temporal convolutional network (TCN),
513–514
tercile, 31
terminology
 trends, 3, 569
test data, 6, 11, 258
Thematic Mapper, 209
threat score (TS), 520
threshold parameter, 176
tidal harmonic analysis, 396
Tikhonov regularization, 161
time-averaging, 404–405
topographic error (TE), 345
tornado, 213
Toronto, Ontario, 44, 45, 171
total least squares (TLS), 170
training data, 6, 256
training error, 251
transfer learning, 498–499
transformation
 Box–Cox, 94
 Johnson, 95
 Yeo–Johnson, 94–95
transforming data, 93–95
tree (*see* decision tree)
trend removal, 382
trend test, 125–126
tropical cyclone, 213
Tropical Ocean Global Atmosphere (TOGA)
 program, 312
true skill statistics, 526
turbulent flux, 553–554
two-tailed test, 104–105, 108–109, 116
Type I error, 103
Type II error, 103

U-net, 508–510, 546
underfit, 11, 245
UNet 3+, 510
UNet++, 510, 546
unit (in neural network model), 176
universal approximator, 186, 187

unmanned aerial system (UAS), 487
unstructured datasets, 497
unsupervised learning, 15–17, 54, 173,
196
upsampling, 507
urban land cover, 209

validation, 11, 224, 253–255
 cross-validation, 255–258
 double cross-validation, 258
 generalized cross-validation, 258
 leave-one-out, 257–258
 retroactive, 538
validation data, 11, 164, 172, 191, 256
Vancouver, BC, 34, 38–39, 42, 45, 78,
82, 89, 96, 108–109, 117–118,
144, 149, 160, 168, 171
vanishing gradient problem, 494
variance, 25
 online algorithm, 28
 population variance, 25
 sample variance, 25
variance compensation factor, 381
variance error, 250–251, 264–266
variance matrix, 26–27
variational autoencoder, 348
variational data assimilation, 560–567
varimax rotation, 308–315
verification data, 258
Victoria, BC, 45, 108–109, 117–118
visibility, 144, 149, 160–162
von Mises distribution, 82–83
voting, 432

water wave, 85, 555
watershed, 212
wavelet, 390–392
weak learner, 262, 473
Weibull distribution, 13, 84
weight, 175, 222
weight penalty, 163, 251–254, 359–360,
459, 462, 477
Welch method, 384
Welford algorithm, 28
Western Pacific pattern, 313
whale, 498, 507
white noise, 410
Wilcoxon rank sum test (*see* Wilcoxon–
Mann–Whitney test)
Wilcoxon signed-rank test, 114–115

Index 627

- Wilcoxon–Mann–Whitney (WMW) test, 111–114
wind direction, 172, 211
wind speed, 34, 43, 45, 89, 96, 160, 168, 185, 211, 212
wind stress, 367
wind wave, 555–556
window, 376–381
 cosine-tapered, 379
 Hamming, 379
 Hann, 379
Winnipeg, Manitoba, 135
Woodbury matrix identity, 156
Yeo–Johnson transformation, 94–95
yin and yang, 4
Yule–Walker equations, 413
z-score, 25, 71, 118
zero-padding, 386
zonal, 362