Note: Page numbers followed by f indicate figures, and t indicate tables.

A	ARMA (autoregressive moving average)	Bernoulli trial, 81, 83-84, 117, 209, 211-212,
Acceptance-rejection method for random	model, 513, 515–517, 538	217, 220–221
variates, 135-136	Artificial neural network, 290-293	Beta-binomial distribution, 218–220
Accuracy, 166-168, 235, 241, 294-295, 298,	Artificial skill, 265, 526–528	Beta distribution, 43, 111–113, 211–212,
300–301, 313, 324, 325 <i>f</i> , 372–373,	Asymptotic equitability, 383	217–219, 342, 593
376–378, 732	Attractor, 315–318, 315f, 317f	mode, 217–218
AC. See Anomaly correlation (AC)	Attributes diagram, 408–410, 409f	Beta-Pascal distribution, 220–221
Activation function, 291-292	Autocorrelation, 61–62, 156, 158–160,	Between-groups covariance matrix, 704–706,
Additive law of probability, 12	180–181, 190, 397–398, 470, 491, 493,	726
Affine kernel dressing, 343	503, 511–513, 598, 643, 649–650	BHF representation, 383–384
Agglomerative methods, 722–725, 732–734	Autocorrelation function, 62–63, 158, 487,	Bias, 65–66, 189–190, 192, 268–270,
Akaike Information Criterion, 277,	494 <i>f</i> , 502, 506–508, 507 <i>f</i> , 511, 513,	298–300, 299f, 308, 327–328,
498–499	517, 539f	330–331, 338–339, 348, 350, 352, 354,
Aliasing, 534–537	Autocovariance function, 63, 485, 661-662,	372, 378, 387–389, 396–398, 403–404,
Alternative hypothesis, 144, 146-151, 153,	664	406–407, 434–435, 543, 589, 646, 660,
165, 168–170, 499	Autoregression, 157–158, 500–504, 598–599,	733
Amplitude, 452, 462, 519–525, 527–531,	608	Bias ratio, 378, 382–384, 385f, 387
533-536, 540-546, 572, 626-627, 638,	Autoregressive model, 500–501, 504, 506,	Binary variable, 129, 254–255, 259, 425, 514
662–663	508f, 509, 514, 516, 537–540, 599	Binned spread-error diagram, 438–439,
definition of, 519	forecasting with, 516	438–439f
element of PCA, 626-627	order selection among, 509	Binomial distribution, 79–87, 89, 148–149,
Amplitude error, 452, 462–463	spectra of, 537–540	197, 209–211, 220, 471, 488, 490–491
Analysis equation, 525, 630, 672	statistical simulation with, 514	Bi-normal model, 416
Analysis of deviance, 276	Autoregressive-moving average model, 513,	Biplot, 666–667
Analysis formula, 619-620, 623-628,	598	Bivariate autoregression, 599
639–640	Average-linkage clustering, 723	Bivariate normal distribution, 97-100, 252,
Analysis of variance (ANOVA), 199-206	Average-rank histogram, 442-443	352, 587–588, 595
one-way, 199-201	Axioms of probability, 9	Biweight kernel, 36t
two-way, 202–205	_	Block maximum data, 113-118
in regression, 178, 180	В	Blue noise, 538, 538 <i>f</i>
Angular frequency, 519, 530, 535	Backward elimination, 262-263, 691	Bonferroni method, 201, 473–475, 477, 544,
Annual maximum data, 113, 117-118	Bagging, 290, 718	609–611
Anomaly, 50, 96–97, 232, 486, 504, 597, 660,	Band-depth rank histogram (BDH), 442	Bootstrap
692	Base rate, 376, 379, 383–385, 410	approximations to sampling distributions,
Anomaly correlation (AC), 452-455, 722	Bayesian Information Criterion (BIC), 277,	650
centered, 452-455	498–499, 509–510	circular block, 192
uncentered, 452-455	Bayesian interpretation of probability, 9-11,	confidence intervals, 148-151
Anomaly matrix, 577, 659-660	17–18, 125, 235, 305, 709	moving-blocks, 191-192, 191f, 479-480,
Anscombe's quartet, 54, 54f	Bayesian model averaging (BMA),	650
AR(1) model, 500, 501f, 502–507, 509–510,	338–343	nearest-neighbor, 191, 282-283, 713
513-517, 537-538, 538f, 544, 598,	Bayes' Theorem, 17-18, 209-213, 215-218,	for verification statistic, 479-480
600f, 608	225, 344, 709	Box-Cox transformation, 44-45, 47-50
AR(2) model, 504–510, 507f, 514, 516–517,	BC _a confidence interval, 189	Box-Jenkins model, 500, 513
539–540, 539–540 <i>f</i> , 663	Bernoulli distribution, 81, 275, 405, 490–491,	Box-Muller method for Gaussian variates,
Area under ROC curve, 413, 473-475	498–499	136–137

Boxplot. See Box-and-whisker plot	Classical statistical forecasting, 294-296	Consistent scoring rule, 417
Box-and-whisker plot, 30-31, 363	Classification and regression trees (CART),	Contingency table, 374–383, 470–473
Breeding method, 322	716–717	Continuity correction, 149-150, 180
Brier score (BS), 401–410, 416–419, 467,	Clayton skill score (CSS), 381, 467–468	Continuous distributions, 91–122
475–476	Cluster analysis	beta distributions, 111–113
Brier skill score (BSS), 402–403, 408–410,	vs. discriminant analysis, 721	distribution functions and expected values
421–422, 458, 467, 469, 475–476	hierarchical clustering, 722–732	91–93
Broken stick model, 642	agglomerative methods using distance	extreme-value distributions, 113–118
Brushing, 71–72	matrix, 722–725	gamma distributions, 104–111
Buell patterns, 638	dendrogram, or tree diagram, 725–726	evaluating gamma distribution
BUGS (Bayesian inference using Gibbs	divisive methods, 732	probabilities, 107
sampling), 232–233	number of clusters, 726–732	gamma distribution in operational
Burn-in, 228, 232	Ward's minimum variance method, 725	climatology, 108
6	nonhierarchical clustering, 732–734	Gaussian distributions, 93–100
C	clustering using mixture distributions,	bivariate normal distribution and
Calibration, 372, 435	734	conditional probability, 97–100
Calibration function, 405-408, 406f, 410, 476	K-means method, 732–733	evaluating Gaussian probabilities, 96
Calibration-refinement factorization,	nucleated agglomerative clustering,	mixture distributions, 119–122
370–373, 375–376, 383–386, 398–399,	733–734	vs. discrete distributions, 78–79
400t, 402, 404–405, 411, 422	Coefficient of determination (R ²), 242,	Continuous random variable, 78–79, 92–93,
Calibration simplex, 422–424	244–245, 254, 256	161, 487, 501
Canandaigua temperature data, 100, 156,	Coefficient profile graph, 272–274, 273f	Continuous ranked probability score (CRPS)
244–245, 285, 595, 599, 620, 673, 674 <i>t</i>	Cohen's kappa, 380	330–333, 335, 425–427, 426 <i>f</i> , 469
Canonical correlation analysis (CCA),	Co-inertia analysis, 689	Contrast, 24, 49–50, 75, 78, 91, 107, 158–160
670–687	Column binding, 554	209, 265, 300–301, 316–317, 322–324
applied to fields, 676–678	Countries 1 PCA (22) (78)	346, 373, 459, 553, 613–614, 635, 732
canonical variates, canonical vectors, and	Combined PCA, 632, 678	Copula, 353–358
canonical correlations, 669–670	Complements, 11–13	Correct rejection, 375, 544
computational considerations, 683–687	Complete-linkage clustering, 727–729	Correlation (1.62.156.159.169.169.199.265
operational forecast system, 680	Computational form, 56–59, 62, 90, 238–240	auto-, 61-63, 156, 158-160, 168, 190, 267
properties of, 670–676	correlation coefficient, 57, 59–60, 68–69,	397–398, 470, 478, 487, 491–493,
Canonical pattern, 677	238	494 <i>f</i> , 502, 504, 506–507, 508 <i>f</i> ,
Canonical variate, 670–676, 679–682	regression coefficient, 243–245, 262	511–513, 537–538, 539f, 643, 649–650
Canonical vector, 670–676, 679, 682 <i>f</i> ,	skewness coefficient, 57–58	heterogeneous, 672, 675, 677, 688–689
683–687, 690	standard deviation, 26–27, 50–51, 159–160 Concordant, 60	Kendall's τ , 59–61
Censored Gaussian distribution, 101–103		Lagged, 61–62, 513, 608, 661
Central credible interval (CCI), 213–214,	Conditional bias, 348, 372, 396–398, 403–407, 436	Pearson product-moment, 54–55, 59, 61, 69 398, 453
306–307, 431–432	Conditional climatology, 16, 294	Spearman rank, 59–61, 354–355
Central Limit Theorem, 94, 113–114, 119,	Conditional distribution, 98f, 99–100, 100f,	Correlation maps, 72–74, 677 <i>f</i> , 689 <i>f</i>
149, 151, 226, 243, 470, 541, 587, 591,	232, 238–239, 294, 344–345, 370–372,	Correlation matrix, 68–70, 72–73, 270, 555,
683, 700	378, 399, 401, 403, 405, 591–593,	565–567, 619, 623–626, 630–632,
multivariate, 601–602	711–712	632 <i>f</i> , 636, 644, 660, 669, 673–674, 700
univariate, 98	Conditional probability, 13–15, 14 <i>f</i> , 18,	Cosine function, 517–518
Centroid clustering, 723–724	53–54, 99, 346–347, 370–371, 386,	wave, 519
Certainty equivalent, 308–310	401, 405, 488, 490–491, 496, 701	Cost/loss ratio, 463–468
Chain-dependent process, 494–495	Conditional quantile plot, 398–399, 399f	Counting norm statistic, 193
Chaining, 724–725, 729, 730 <i>f</i> Chaos, 5, 313	Conditioning event, 13–15	Covariance, 54–56, 131, 485, 555, 558, 565,
Characteristic value, 571	Confidence interval, 148–151, 160, 172, 186,	571, 578–580, 610–611, 631–632, 660
	188–189, 201, 243, 251–253, 470–475,	663–664, 673–674, 690
Characteristic vector, 571. See also Eigenvector	477, 516 <i>f</i> , 541–542, 608–610, 612	Covariance matrix, 318, 429–430, 445, 555,
Chartjunk, 63–64	regression, 251	561, 565, 571–572, 576–581, 587–591
Check function, 286, 431	and ROC diagram, 473-475	597, 602–604, 606–607, 618, 620,
Chi-square (χ^2) distribution, 110, 478, 543	simultaneous joint, 473–474	625 <i>t</i> , 628, 647, 657–659, 664, 676,
Chi-square (χ^2) test, 161–162, 166,	Conjugate distribution, 216–227	691, 697, 700
478–479	Consecutive integers	eigenvalues and eigenvectors of, 570–574
Cholesky decomposition, 574–575, 684	mean of, 172	for linear combinations, 580–582
City-block distance, 722	variance of, 172	for regression parameters, 567, 665-666
Classical nonparametric tests, 171–177	Consensus forecasting, 309	vs. correlation matrix, 623–626
Classical horiparametric tests, 1/1 1//	<u> </u>	·

a	D: 06.00	5
Covariance stationarity, 485	Poisson, 86–88	Dominant variance selection rules, 651
Credible interval forecast	vs. continuous, 78–79	Dotplot, 34f, 35, 37
central, 306–307	Discrete Fourier transform, 529–530, 531 <i>t</i> ,	Dot product, 560–561, 563–564, 571, 573,
fixed-width, 306–307 operational, 307	534, 542 Discrete random variable, 78–79, 88–89,	620–622, 630, 666, 674–675, 697, 699 Double penalty problem, 455–456
Critical region, 146, 165	92–93, 161, 487–488	Drop-size distribution, 109
Critical success index (CSI), 377	Discriminant analysis, 695–696, 699–700,	Dummy variable, 240–241, 254–255, 274–275
Critical value, 146, 150–151, 163–168, 249f,	703–718, 721, 727	Durbin-Watson test, 248–250
478 <i>t</i> , 595–596, 640, 643	Discriminant coordinates, 705	Dyadic product, 564
Cross-validation, 38–39, 265–268, 734	Discriminant function, 695–698, 699f, 704,	Dyadic product, 504
CRPS (continuous ranked probability score),	710–711	E
330–333, 335, 425–427, 426 <i>f</i> , 469	Discriminant space, 698, 705–708	
CSI (critical success index), 377	Discrimination, 372, 379, 410–412, 695	Economic value
CSS (Clayton skill score), 381, 467–468	Discrimination and classification	value score, 466–467
Cumulative distribution function, 43–44, 85,	alternatives to classical discriminant	verification based on, 463–468
163, 165–166, 330	analysis, 711–714	connections with other verification
Cumulative frequency distribution, 40–44, 42 <i>f</i>	discrimination vs. classification, 695	statistics, 467–468
Cumulative probability, 40–44, 83 <i>f</i> , 85, 92, 97,	forecasting with discriminant analysis,	optimal decision making and cost/loss
107, 111, 117, 124, 165, 248, 309, 328,	710–711	ratio problem, 463–466
337, 346–347, 430, 432, 588–591,	multiple discriminant analysis (MDA),	EDA (exploratory data analysis), 23–75, 721
595–596, 607	704–710	Eddy covariance, 54–55
Cyclostationarity, 486	Fisher's procedure for more than two	Effective multiplet, 647–648, 650, 652, 657
Cyclostationality, 100	groups, 704–708	Effective sample size, 157–160, 476, 511–513
D	minimizing expected cost of	643, 649–650
	misclassification, 708	Eigendecomposition, 684–687, 705–708
Data matrix, 554, 567, 631–632, 655,	probabilistic classification, 709–710	Eigenspace, 571
659–660, 666, 721	separating two populations, 695–703	Eigenvalue
David-Sebastiani score, 428–430	equal covariance structure, Fisher's linear	of (2×2) symmetric matrix, 573
Deciles, 25, 337–338 Declustering, 119	discriminant, 695–700	of covariance matrix, 572
Degrees of freedom, 110, 152, 161–162,	Fisher's linear discriminant for	direct extraction of, from sample covariance
	multivariate normal data, 700	matrix, 658–659
169–171, 200–201, 203–205, 276, 371, 391, 478, 492–493, 496, 543, 588–591,	minimizing expected cost of	rules based on size of last retained, 641–642 sampling properties of, 645–650
594–596, 602–603	misclassification, 701–702	of square matrix, 570–574
Delay window, 661, 662 <i>f</i> , 663, 665	unequal covariances, quadratic	Eigenvalue spectrum, 640, 642, 651
Democratic voting method, 328	discrimination, 702–703	Eigenvector, 570–574
DeMorgan's Laws, 13	Discrimination diagram, 410-412	of (2×2) symmetric matrix, 573
Dendrogram, 725–726	Discrimination distance, 411, 411f	of covariance matrix, 573
Dependence template, 354–355	Dispersion, 25–26, 44, 46, 120, 183–185, 286,	direct extraction of, from sample covariance
Dependent sample, 258	321, 323–324, 326–329, 339, 354,	matrix, 658–659
Dependent variable, 15–16, 236	360-362, 370-371, 407, 557, 582-584,	PCA, 627–628, 632–634
Derived predictor variables, 254–256	588–591, 602, 622, 700	rotation of, 650–658
Descriptive statistics, 3–4	Dispersion matrix, 555, 639, 642, 722	sampling properties of, 645–650
Developmental sample, 258, 260, 264, 267,	Distance	Eigenvector scaling, 627–628, 627 <i>t</i>
298	city-block, 722	sensitivity of orthogonal rotation to initial,
Deviance, 169, 276	Euclidean, 428, 444-445, 556-557,	655–657
Diagnostic verification, 370–371, 384–385, 399	582-583, 705, 721-722	Eighth, 25
Diagonal matrix, 562, 565–567, 571–572,	Karl-Pearson, 722, 727, 729, 733	El Niño, 35, 52, 67–68, 119, 232, 327, 680,
574–575, 577, 619, 656–657, 659–660,	Mahalanobis, 557-558, 582-584, 587-588,	713, 713 <i>f</i>
670–671, 685–688, 692	592, 595–596, 596 <i>f</i> , 602–603,	Embedding dimension, 661, 663–665
Dichotomous event, 82, 274–275, 308,	608–609, 611 <i>f</i> , 628, 697, 722	EM (expectation-maximization) algorithm,
363–364, 400–402, 400 <i>t</i> , 410, 413,	Minkowski, 722	120, 128–131, 130 <i>t</i> , 339, 734
416–417, 427, 435–436, 465–466,	Distance matrix, 721–722	Empirical copula, 353–356, 358
490–491	Distribution-free tests, 144	Empirical copula coupling (ECC), 354, 356,
Diebold–Mariano test, 158–160, 511–513	Distribution parameters, 77–78, 85–86, 89t,	357 <i>f</i>
Diffuse prior, 215, 222–223, 225	93, 95, 114, 117–118, 125, 127, 130,	Empirical cumulative distribution function,
Discordant, 60	143, 163–164, 166–168, 335, 425, 734	40, 85, 165–166
Discrete distributions, 79–88	Distributions-oriented verification, 371	Empirical distributions
binomial, 79–82	Divisive clustering, 732	exploratory techniques for paired data,
geometric, 82–83	Domain expertise, 259	52–63
negative binomial, 83–86	Domain size effects, 638	autocorrelation function, 62–63
U		

810) Index

Empirical distributions (Continued) Pearson (ordinary) correlation, 54–59	Ensemble meteogram, 362–363, 365 <i>f</i> Ensemble MOS, 327–351	False rejection, 146, 197 Fast Fourier transform (FFT), 534
scatterplots, 53–54	Ensemble postprocessing, 327–359	Fences, 31–33, 32 <i>f</i>
serial correlation, 61–62	Ensemble ranked probability score, 420–422	Field forecasts, 445–451, 456, 459–462, 665
Spearman rank correlation and Kendall's	Entropy, 417, 436, 717	Field significance, 192–199
τ, 59–61	Epanechnikov kernel, 36t	Filliben test for normality, 166–168, 594
graphical summary techniques, 29–44	Error function, 95–96	Finley tornado forecasts, 381, 382t, 472–475
boxplots, 30–31	Equitability, 383, 391	First-order autoregression, 500–504
cumulative frequency distributions,	Equitable threat score (ETS), 381, 383	in choosing block length, 191–192
40–44	Equivalence of events, 377	in estimating effective sample size, 156
histograms, 34–35	Equivalent number of independent samples,	Fisher's linear discriminant function, 696–697
kernel density smoothing, 35–40	157. See also Effective sample size	Fisher-Tippett distribution. See Gumbel
other boxplot variants, 33–34	Erlang distribution, 109	distribution
schematic plots, 31–33	Error bars, 148, 150, 438 <i>f</i>	Fisher Z-transformation, 49
stem-and-leaf display, 29–30	Euclidean distance, 428, 444–445, 556–557,	Flat prior, 215
numerical summary measures, 25–29	557 <i>f</i> , 583, 705, 721–722	Folding frequency, 535–536
reexpression, 44–52		Forecasting
power transformations, 44–48	Euclidean norm, 560, 685	classical, 294–296
=	Euler exponential notation, 534	
standardized anomalies, 50–52	Euler's constant, 93t, 115	ensemble, 313–366
vs. parametric, 77–78	Event	MOS, 296–301, 327–328
visualization for higher-dimensional data,	compound event, 7–8	perfect prog, 296–301
63–75	elementary event, 7–8	subjective, 304–305
correlation maps, 72–74	Excess kurtosis, 28–29	with autoregressive model, 516
correlation matrix, 68–69	Exchangeability principle, 182–183, 185	with CCA, 676–678
glyph scatterplot, 65–66	Expansion coefficient, 626–627	with discriminant analysis, 710–711
rotating scatterplot, 67–68	Expected cost of misclassification, 701–702,	with MCA, 691
scatterplot matrix, 70–72	708	with RDA, 692
star plot, 64	Expected payoff, 308–309	Forecasting forecast skill, 324
Empirical orthogonal function (EOF) analysis,	Expected value, 88–93, 252, 386–387,	Forecast quality, 369, 372–373, 403–405, 424
617–667	469–470, 504–505, 514, 577–578,	427, 446–447, 466
Empirical orthogonal variable, 626–627	627–628	Forecast skill, 324, 331, 373–374, 410, 468,
Empirical orthogonal weights, 626	Experimental design	495, 692
Energy score, 426, 428, 444–445	completely randomized, 199–201	Forecast variance, 318
Ensemble average, 323–324, 342, 344–345,	randomized block, 202–205	Forecast verification
350, 437–438	Exploratory data analysis (EDA), 23–75, 721	nonprobabilistic forecasts of continuous
Ensemble consistency, 432–434, 437–438,	Exponential distribution, 104–105, 109,	predictands
440–441	120–122, 134, 137, 170, 494–495, 540,	conditional quantile plots, 398–399
Ensemble dressing, 338–343	544–545, 607	scalar accuracy measures, 394–397
Ensemble energy score, 444–445	Extended EOF (EEOF) analysis, 632, 634	skill scores, 397–398, 516
Ensemble forecasting	Extended logistic regression (XLR), 97,	nonprobabilistic forecasts of discrete
choosing initial ensemble members,	336–337	predictands, 374–394
321–323	Extremal dependence index (EDI), 379	2×2 contingency table, 374–376
effects of model errors, 325–327	Extremal Types Theorem, 113–114	conversion of probabilistic to
ensemble average and ensemble dispersion,	Extreme event, 113, 117, 322–323	nonprobabilistic forecasts, 386–388
323–324	Extreme-value distribution, 103, 113–119, 190	extensions for multicategory discrete
ensemble forecasts, 319-327	_	predictands, 388–394
graphical display of ensemble forecast	F	scalar attributes characterizing 2×2
information, 359–366	F distribution, 184–185, 602	contingency tables, 376–379
statistical postprocessing, ensemble MOS,	F-ratio, 264	skill scores for 2×2 contingency tables,
327–328	F-test, 184–185, 242–243	379–383
stochastic dynamical systems in phase	Factor analysis, 617	which score, 383–385
space, 313–317	Factorial function, 84. See also Gamma	nonprobabilistic forecasts of fields,
Ensemble forecasts, verification of, 432–445	function	445–463
minimum spanning tree (MST) histogram,	False alarm, 375, 377-379	anomaly correlation, 452–455
439–441	False alarm rate, 378–381, 383–384, 412–415,	field verification based on spatial
verification rank histogram, 433-437	470–475	structure, 455–463
Ensemble Kalman filter (EnKF), 322	False alarm ratio, 378, 382-384, 387-388,	general considerations for field forecasts
Ensemble members, 319–323, 320 <i>f</i> , 326–330,	470–471	445–447
335, 337–342, 345, 347–348, 432–434,	False discovery rate, 194-197	mean squared error, 448–452
440–441, 440 <i>f</i> , 731–732	False-positive fraction, 379	S1 score, 447–448

Index (811)

probability forecasts for continuous	Gandin-Murphy skill score (GMSS), 391-393	Harmonic predictors, 256, 529
predictands, 425–431	Gaussian approximation to the binomial,	Harmonics, higher, 524–527
probability forecasts of discrete predictands,	149–150, 150 <i>f</i> , 471, 474–475	Heatmap, 70
400–424	Gaussian copula, 358	Hedging, 418–419
algebraic decomposition of Brier score,	Gaussian distribution, 93–100	Heidke skill score (HSS), 380, 389–390
402–404	bivariate normal distribution and	Heterogeneous correlations, 672, 675, 677,
Brier score, 401–402	conditional probability, 97–100	688–689
discrimination diagram, 410–412	censored, 102–103	Heteroscedasticity, 245–247
hedging, and strictly proper scoring rules, 418–419	circular, 192	Hexbin plot, 65–66
	evaluating Gaussian probabilities, 96	H–F diagram, 384–385, 385f
joint distribution for dichotomous events,	lognormal, 101–102	Hierarchical clustering
400–401	truncated, 102	agglomerative methods using distance
probability forecasts for multiple- category events, 419–424	Gaussian ensemble dressing (GED), 342 Gaussian kernel, 36–38, 40, 233, 342	matrix, 722–725 dendrogram, or tree diagram, 725–726
reliability diagram, 404–410	Gauss-Markov theorem, 268–269	divisive methods, 732
ROC diagram, 412–416	Generalized extreme value (GEV)	number of clusters, 726–732
sampling and inference for verification	distribution, 103, 114, 333	Ward's minimum variance method, 725
statistics, 470–480	Type I (Gumbel), 114–115	Hierarchical models, 232–234
reliability diagram sampling	Type II (Frechet), 115	Higher harmonics, 517, 524–527
characteristics, 476–478	Type III (Weibull), 115–116	Highest posterior density (HPD) interval,
resampling verification statistics,	Generalized linear model, 274, 292	214
479–480	Generalized Pareto distribution, 118–119, 122,	Hinges, 25
ROC diagram sampling characteristics,	336	Hinkley d_{λ} statistic, 46–48, 49 f
473–475	Generalized variance, 588–591	Histogram
sampling characteristics of contingency	Geometric distribution, 82–83, 117, 220–221,	bivariate, 65–66, 399
table statistics, 470–473	491	minimum spanning tree (MST), 439–441
verification based on economic value,	Gerrity skill score, 391–393	superposition of PDFs onto, 123
463–468	Gibbs sampler, 231–234	verification rank, 346, 430–431, 433–437
verification of ensemble forecasts, 432–445	Gilbert score, 377	Hit, 377–378
minimum spanning tree (MST)	Gilbert skill score (GSS), 377, 381	Hit rate, 377, 379–384, 387–388, 412–415,
histogram, 439–441	Gini Index, 717	470–471, 473–474
verification rank histogram, 433–437	Global significance, 192	Homogeneous correlations, 671–672, 675,
Forward selection, 260–261, 263–264, 263 <i>f</i> ,	Glyph scatter plot, 65–66, 65 <i>f</i> , 399	677, 689–691
267, 271, 273–274, 296	Goodness-of-fit tests, 160–168	Homoscedasticity, 246–247
Fourier analysis, 548, 662–663	Chi-square, 161–162	Honest significant difference, 201
Fourier line spectrum, 529–533	Fillliben Q–Q correlation, 166–168	Hotelling T^2 , 602–608, 700
Fourth-spread, 26	Kolmogorov–Smirnov (K-S), 160–168	Hyperparameter, 213–214, 216–224, 232–234
Fractiles, 24	Lilliefors, 162–165	Hyperprior, 232–234
Fractions skill score (FSS), 457–458	Shapiro-Wilk, 166	Hypothesis test
Frechet distribution, 115	Graphical summary techinques, 29–44	Bonferroni method, 201, 473–475, 477,
Frequency domain analysis, 486–487,	boxplots, 30–31	544, 609–611
528–529	boxplot variants, 33–34	counting norm, 193
Frequency interpretation of probability, 10	cumulative frequency distributions, 40-44	false discovery rate (FDR), 194-197
Full enumeration, 182–183	histograms, 34–35	multiplicity problem for independent tests.
Full rank, 564, 574–575, 587	kernel density smoothing, 35–40	192–194
Fundamental frequency, 517, 519, 524, 531	schematic plots, 31–33	nonparametric tests, 171-192
	stem-and-leaf display, 29-30	bootstrap, 185–192
G	Gringorten's skill score (GSS), 380-381	classical nonparametric tests for location
Gamma distribution, 104–111	Gumbel distribution, 114-115, 168	171–177
algorithm for maximum likelihood		field significance given spatial
estimates of parameters, 127	Н	correlation, 197-199
evaluating gamma distribution		permutation tests, 182–185
probabilities, 107	Half-Brier score, 402	resampling tests, 181-182
gamma distribution in operational	Hanssen-Kuipers discriminant, 380–381	parametric tests, 151-171
climatology, 108	Harmonic analysis, 517–527	goodness-of-fit tests. (see Goodness-of-
generalized, 110–111	Harmonic function	fit tests)
mode, 223	representing simple time series with,	Hotelling T^2 , 602–608
Gamma function, 83–84, 84t, 114, 212, 223,	518–520	likelihood ratio test, 168–171
334–335, 588–591	as uncorrelated regression predictors, 528–529	one-sample t test, 151–153

Hypothesis test (Continued)	kernel density estimate, 37	prediction intervals, 250–253
test for differences of mean under serial	discrimination and classification using,	principal components, 619
dependence, 156-160	713–714	sampling distributions of regression
tests for differences of mean under	simulation from, 137-138	coefficients, 243-245
independence, 153-155	smoothing, 35-40	simple linear regression, 244
tests for differences of mean for paired	Kolmogorov-Smirnov (K-S) test, 162-165	Link function, 274, 279
samples, 155–156	Kuipers' performance index, 380–381	Loading, 626
PCA rules based on, 642–644	Kurtosis, 28–29	Locality, 424
, , , , , , , , , , , , , , , , , , , ,	,	Local test, 192–197, 198f
•	_	Location, 26, 171–177, 427t, 698t
I	L	Loess smoothing, 281
Ideal user, 467–468	L1 regularization, 272, 678	Logarithmic score, 416–418
Identity matrix, 561-562, 564	Lasso, 272–274	Logarithmic transformation, 45, 47–48, 49 <i>f</i> ,
Ignorance score, 331, 416–418, 424, 428–429,	L-moments, 114-117	167–168, 233, 248
444	L-scale, 183, 187	Log-eigenvalue (LEV) diagram, 640–641
Improper prior, 215, 222	Ladder of powers, 45	Logistic distribution, 103–104
Incomplete beta function, 113	Lag-1 autocorrelation, 61-62, 61f, 156,	Logistic function, 275–276, 291–292,
Incomplete gamma function, 107-109	158-160, 180-181, 267, 397-398, 476,	711–712
Independence, 14-16, 86-87, 153-160,	478, 491, 501–502, 544, 649–650	Logistic regression, 274–279, 336–338,
229–231, 279–281, 472–473, 476, 479,	Lagged correlation, 61-62, 513, 608, 661	340–341, 404, 711–712, 712 <i>f</i>
491–493, 610	Lagged covariance, 598–600	Logit function, 103–104
Independent tests, 192-194, 268	Latent value, 571	Logit transformation, 275
Independent variable, 125-126, 236, 284,	Latent vector, 571. See also Eigenvector	Log-hyperbolic sine transformation, 49
592–593	Law of cosines, 451	Log-likelihood, 46–47, 126–128, 130–131,
Indicator variable, 129-130, 254-255, 705	Law of large numbers, 10	169–170, 169 <i>t</i> , 276–278, 280–281,
Inferential statistics, 3-4	Law of total probability, 16-17, 406-407	331, 429–430, 498–499
Infinite monkeys theorem, 192-193	Least-absolute-deviation (LAD) regression,	Lognormal distribution, 101–102, 336
Information matrix, 131, 279	247–248, 286, 293	Log-odds, 49, 275, 336–337
Inner product, 560, 564	Least-squares regression, 178, 235-236, 236f,	Log-Pearson III distribution, 110–111
Innovation variance, 502	242–246, 270, 284–286, 295–296, 347,	Loss, 182, 300–301, 308–309, 386, 463–466
Interquartile range (IQR), 26, 32, 37-38,	350, 398, 408, 504, 620, 658	2033, 102, 300 301, 300 307, 300, 403 400
365f	Leave-one-out cross validation, 266-268, 710	M
Intersection, 12-14, 214, 377, 415, 564	Leptokurtic, 28–29	
Interval score, 432	Level of a test, 145–146	Madden–Julian oscillation, 634
Intrinsic EOFs, 635	Likelihood, 18, 47-49, 125, 169, 210-213,	Mahalanobis distance, 557–558, 582–584,
Invariance, 182	215–217, 219, 221, 225, 232–234, 276,	587, 595–596, 603, 611 <i>f</i> , 628, 697, 722
Inversion method for random variates,	305, 344, 346, 411–413, 702, 709–710	Mahalanobis transformation, 597, 628,
134–135	Likelihood-base rate factorization, 371, 376,	685–688
Inverting hypothesis tests, 148-151	380-381, 383-384, 400t, 404, 410	Mann–Kendall trend test, 178–181, 283–284
	Likelihood function, 125-127, 169, 227, 509,	Marginal distribution, 53–54, 98, 352,
1	734	354–356, 370–371, 375–376, 380–381,
J	Likelihood ratio test, 168-171, 180, 276, 278,	396, 403, 591, 594
Jaccard coefficient, 377	499	Marginal total, 375, 492
Jackknife, 189–190, 268	Lilliefors test, 162–165	Markov chain, 79–80, 227, 487–492, 494–499
JAGS (Just Another Gibbs Sampler), 232	Linear algebra, 69, 558	Markov chain Monte Carlo (MCMC),
January thaw, 51	Linear combinations, 153, 291, 322, 329, 564,	227–228
Joint distribution	580–582, 591, 596–597, 607, 612–614,	Markovian property, 487–488, 490–492, 497,
for dichotomous events, 400–401	617–618, 620–623, 628, 635, 662, 669,	502 Markov 222 403 501
of forecasts and observations, 370–371	674, 678, 688, 690, 692, 695–696, 702	Markov process, 83, 493, 501
multivariate normal, 587	Linear congruential generator, 132–134	Marshall–Palmer distribution, 109
Joint probability, 12–14, 375, 492, 609	Linear correlation, 54, 58	Matrices
Jordan decomposition, 571–572	Linear discriminant analysis, 699f, 703	addition of, 561–570
	Linear regression	computation of covariance and correlation
K	analysis of variance table, 240–241	matrices, 565
	derived predictor variables in multiple	correlation. (see Correlation matrix)
K-means clustering, 732–733	regression, 254–256	covariance. (see Covariance matrix)
Kaiser's rule, 641	distribution of residuals, 238–240	data. (see Data matrix)
Kalman filter, 301 Karl Pearson distance, 722, 727, 729	examining residuals, 245–250	determinant, 564
	goodness-of-fit measures, 241–243	diagonalization, 572
Kendall's τ , 59–61, 179–180, 283–284	multiple linear regression, 253–256	dimension, 561
	,	

distance, 721-722	Mean squared error (MSE)	Multiple-state Markov chains, 495-496
element, 561-570	to determine stopping criterion, 264	Multiplicative law of probability, 14, 16–17,
identity, 561-570	for non-probabilistic forecasts, 395	80-83, 387-388
inverse, 131, 565, 676	regression, 241	Multiplicity, 192-199, 242-243, 277, 498,
invertable, 591, 601, 679-681	Mean vector, 318, 352, 577–578, 581, 591,	544–545, 609
lower-triangular, 574	596-597, 600-614, 669, 679-681, 683,	Multivariate autoregression, 598-599
multiple linear regression expressed in	696–697, 700, 709	Multivariate central limit theorem, 587,
matrix notation, 567	Measures-oriented verification, 371	601–602
multiplication of, 562	Median, 25–27, 30–33, 39–40, 43–44, 46,	Multivariate distance, 556-558
nonsingular, 564	50, 107–108, 117, 181, 189,	Multivariate kurtosis, 594
orthogonal. (see Orthogonal, matrix)	230–231, 284, 286, 293, 309, 334,	Multivariate multiple regression, 303-304,
partitioned, 579, 669	395, 642	691
positive definite, 572, 584, 587	Median absolute deviation, 27	Multivariate normal (MVN) distribution
random vectors and, 577–584	Median-slope regression, 283–285	assessing multinormality, 593–596
(see also Random vectors and	Member-by-member postprocessing, 358	definition of, 587–590
matrices)	Mersenne twister, 133–134	four handy properties of, 591–593
	Metaverification, 383	Hotelling's T ² , 602–608
square, 561–562, 569 square root. (<i>see</i> Square-root matrix)	Method of maximum likelihood, 106, 114,	- · · · · · · · · · · · · · · · · · · ·
		inferences about multinormal mean vector, 601–614
subtraction of, 575	125, 168–169, 276	
symmetric, 573	Method of moments, 85–88, 95, 112, 114, 116,	interpretation of multivariate statistical
Toeplitz, 661–662, 664	350	significance, 611–614
trace, 564	Method of successive subdivision, 309	multivariate central limit theorem, 601–602
transpose, 562	Metropolis–Hastings algorithm, 228–231	probability ellipses, 588
triangular, 69, 135–136, 138, 506, 508, 574	Minimax linkage, 723, 726	simulation from multivariate normal
unitary, 569	Minimum-distance clustering, 723	distribution, 596–601
Matrix algebra	Minimum spanning tree (MST) histogram,	simultaneous confidence statements,
eigenvalues and eigenvectors of square	439–441	608–611
matrix, 570-574	Minimum volatility methods, 191–192	Multivariate outlier, 583–584, 594–596,
matrices. (see Matrices)	Minkowski metric, 722	628–629, 629 <i>f</i>
multivariate distance, 556-558	Misclassification, 701–702, 708, 728–729	Multivariate rank histogram, 441–443
random vectors and matrices, 577-584	Miss, 432	Multivariate skewness, 594
expectations and other extensions of	Mixed exponential distribution, 120-121, 137,	Multivariate time series, 597-601, 661
univariate concepts, 577-579	494–495	Mutually exclusive and collectively
linear combinations, 580-582	Mixture distributions, 119-122, 137-138,	exhaustive (MECE), 79-80, 86, 161,
Mahalanobis distance, 582-584	338–339, 343, 734	305–306, 374, 388, 401, 490, 695
partitioning vectors and matrices,	Mixture probability density, 119-122	
579-580	MODE, 459-461	N.I.
singular-value decomposition (SVD),	Model errors, 325–328	N
576–577	Model output statistics (MOS), 296-301, 386,	Nadaraya-Watson kernel-weighted average,
square roots of symmetric matrix,	399, 678–679	40
574–576	Modes of variation, 626	Nash-Sutcliffe efficiency, 398
vectors, 577-584	Monte-Carlo test, 181	Nearest-neighbor bootstrap, 191
Maximum covariance analysis (MCA), 577,	Moving-average process, 513	Negative binomial distribution, 83–86
687–691	Moving-blocks bootstrap, 191–192, 479–480,	Neural network, 716-718
Maximum-distance clustering, 723	650	Neural network classifier, 716–718
Maximum likelihood, 47–49, 102, 106–107,	Moving-blocks cross validation, 266–268	Newton-Raphson method, 127-128, 277-281
114, 116, 120, 125–131, 170, 213,	Multichannel SSA (MSSA), 665	Nominal predictand, 419
219–220, 276, 278 <i>f</i> , 331, 349	Multicollinearity, 665	Nonhierarchical clustering
Maximum likelihood estimator, 106, 161–162,	Multimodel ensemble, 326, 329–330	clustering using mixture distributions, 734
490, 589	Multinomial distribution, 86	K-means method, 732–733
Maximum margin classifier, 715–716	Multiple correlation, 270–271	nucleated agglomerative clustering,
Mean, 26	Multiple discriminant analysis (MDA)	733–734
test for differences of	Fisher's procedure for more than two	Nonhomogeneous Gaussian regression
	groups, 704–708	(NGR), 329–331
under independence, 153–155	minimizing expected cost of	Nonhomogeneous regression, 328–336
for paired samples, 155–156	misclassification, 708	censored, 334–336
multivariate (vector), 601–602 under serial dependence, 156–160	probabilistic classification, 709–710	Gaussian, 329-331
Mean absolute error (MAE), 394–395, 397	•	lognormal, 331–332
	Multiple linear regression, 236, 253–256, 274,	truncated, 333–334
Mean error (ME). See Bias	298, 567, 580, 665	Noninformative prior, 215

814) Index

X		
Nonlinear regression	O	likelihood function, 125–127
logistic regression, 274–279	Objective forecast, 235	method of moments, 85–88, 95, 105–106,
Poisson regression, 279–281	classical statistical forecasting, 294-296	111–112, 114–115, 125, 350
probit regression, 275–276	operational MOS forecasts, 301-304	Newton–Raphson method, 127–128,
Nonparametric regression	perfect prog and MOS, 296-301	279–281
local polynomial, 281–283	Oblique rotation, 655	Parameterization, 325–327
median-slope (Theil-Sen), 283–285	Observed Fisher information, 131, 589	Parameters vs. statistics, 78
quantile, 283–285	Odds ratio, 49, 276, 377-378, 381, 391,	Parametric bootstrap, 190
Nonparametric test, 171–192	471–473	Parametric distribution
bootstrap, 185–192	Odds ratio skill score (ORSS), 381, 385, 385f	continuous distributions, 91–122
classical nonparametric tests for location,	One-point correlation map, 72-74	beta distributions, 111–113
171–177	One-s.e. rule, 267f, 268, 271–274, 277–279	distribution functions and expected
permutation tests, 182–185	One-sample t test, 151–153, 185, 201, 244,	values, 91–93
vs. parametric tests, 143–144	472, 604	extreme-value distributions, 113–118
resampling tests, 181–182	One-sided test, 147, 165	gamma distributions. (see Gamma
Nonprobabilistic forecast	One-tailed test, 147, 153, 158-159	distribution)
of discrete predictands, 374–394	Optical flow, 462-463	Gaussian distributions. (see Gaussian
2×2 contingency table, 374–376	Optimal decision making, 463–466	distribution)
conditional quantile plots, 398–399	Orbit, 313–314	mixture distributions, 119–122
conversion of probabilistic to	Order selection criteria, 509-510	discrete distributions, 79–88
nonprobabilistic forecasts, 386–388	Order statistics, 24, 41-43, 195, 282	binomial distribution, 79–82
extensions for multicategory discrete	Ordinal predictand, 419-420	geometric distribution, 82–83
predictands, 388–394	Ordinary least squares (OLS), 236, 277, 285,	negative binomial distribution, 83–86
scalar accuracy measures, 394–397	293, 295–296, 347	parameter fitting using maximum
scalar attributes characterizing 2×2	Orthogonal	likelihood, 125–131
contingency tables, 376–379	matrix, 569-570, 618	EM algorithm, 128–130
scores, 383–385	rotation, 570f, 651–652, 655–657	likelihood function, 125–127
skill scores, 379–383, 397–398	transformation, 569-571	Newton–Raphson method, 127–128
of fields, 445–463	vectors, 571	sampling distribution of maximum-
anomaly correlation, 452–455	Orthogonality, 528, 571-572, 618-620, 630,	likelihood estimates, 130–131
field verification based on spatial	650–651, 654–656	Parametric tests, 143, 151–171
structure, 455–463	Orthonormal, 571, 576, 671, 687-688	goodness-of-fit tests, 160–168
general considerations for field forecasts,	Outer product, 564, 566-567, 572, 598, 676	comparing Gaussian and gamma
445–447	Outliers, 24, 26, 28, 53, 69, 176, 184, 247–248,	distribution fits using x^2 test, 161
mean squared error, 448–452	285-286, 395-396, 434, 583-584,	comparing Gaussian and gamma fits
S1 score, 447–448	594–596, 628–629, 629f, 722	using K-S test, 164
Nonuniform random number generation,	Overconfidence, 156, 308, 327, 407, 437	Filliben Q–Q correlation test or Gaussian
134–136	Overfitting, 258t, 259, 264, 266, 287–288,	distribution, 166
Normal distribution, 93–94, 97–100, 252,	509-510, 525-528, 710	Hotelling T ² test, 602–608
587–588, 596–601, 628–629, 700, 709	Overforecasting, 65-66, 378, 399, 405-407,	likelihood ratio test, 168–171
Normal equations, 237–238, 244, 568	434–436, 448	one-sample t test, $151-153$
Normalization transformation, 50	Overlap method, 154-155, 160	for paired samples, 155–156
Normal probability plot, 124–125		under serial dependence, 156–160
Normal quantile transform, 111, 189	P	tests for differences of mean under
North Atlantic Oscillation (NAO), 232	•	independence, 153–155
North et al. rule of thumb, 648–650	Pacific North America (PNA) pattern, 74,	vs. nonparametric tests, 143–144
Nowcasting, 294, 710	630–631, 653, 677, 677 <i>f</i>	Partial duration data, 118
Nucleated agglomerative clustering, 733–734	Paired data	Partial whitening, 693
Null distribution, 144–147, 149–150, 150 <i>f</i> ,	correlation matrix, 68–69	Partitioning vectors and matrices,
152, 155–156, 165, 170–173, 176–177,	glyph scatterplot, 65–66	579–580
180, 182–185, 184 <i>f</i> , 194, 203–205,	Pearson (ordinary) correlation, 54–59	Pascal distribution, 83
493–494, 596, 603	rotating scatterplot, 67–68	Pattern coefficients, 626
Null event, 8	scatterplot matrix, 70–72	Pattern correlation, 453
Null hypothesis, 144–154, 158–172, 193–194,	scatterplots, 53–54	Pattern significance, 192
199, 201, 203–204, 242–245, 472–475,	Spearman rank correlation and Kendall's t,	Pattern vector, 626
492, 543, 594, 612–613, 642, 644–645,	59–61	Peaks-over-threshold (POT), 118–119
678, 700	star plot, 64	Pearson correlation, 54–59, 69, 72–73, 100,
Numerical summary measures, 25–29	Paired t test, 604	238, 244–245, 254, 398, 528, 620
Nyquist frequency, 530–531, 533, 535–537,	Parameter fitting	Pearson III distribution, 103 <i>f</i> , 110, 168,
535–536 <i>f</i>	EM algorithm, 128–130	643–644

Peirce skill score (PSS), 380–381, 383–384, 386–387, 389–391, 472–473	importance of careful predictor selection, 257–260	Probability distribution function, 40, 80, 82–83, 83 <i>f</i> , 85–86, 89 <i>t</i> , 121, 123, 194,
Percentile, 24–25, 108, 109f, 147, 170, 186,	screening predictors, 260-263	210, 215–216, 220–221, 370, 491
187–188 <i>f</i> , 188–189, 244–245, 347,	stopping rules, 263–265	Probability of false detection (POFD), 379
461, 642	Predictor variable, 236, 239 <i>f</i> , 240, 244, 249 <i>f</i> ,	Probability forecasts
Percent (or proportion) correct, 377, 380, 382,	253–256, 260, 262–265, 270–271, 280,	for continuous predictands, 425–431
388–390	286, 288, 290, 293, 297, 347	for discrete predictands, 400–424
Perceptrons, 290-291	Pre-rank, 441–443	algebraic decomposition of Brier score,
Perfect prog, 297–301, 299f	Principal component, 64, 595-596, 617-667	402–404
Performance diagram, 384, 384f	Principal component analysis (PCA)	Brier score, 401–402
Period, 117, 132, 169–170, 487, 507, 518–519,	application of to geophysical fields,	discrimination diagram, 410–412
530–533, 663	629–638	joint distribution for dichotomous events,
Periodogram. See Fourier line spectrum	basics of principal component analysis,	400–401
Permutation test, 182–185, 187, 479–480	617–629	for multiple-category events, 419-424
Persistence, 61–62, 156–157, 295–296, 373,	connections to multivariate normal	reliability diagram, 404–410
397, 449, 453–455, 462, 488–489, 491,	distribution, 628-629	ROC diagram, 412–416
493, 495, 499–500, 515	definition of, 617–622	Probability integral transform (PIT)
Persistence parameter, 491, 493	scaling conventions in, 627–628	histogram, 134, 430
<i>p</i> -hacking, 145–146	varied terminology of, 626–627	Probability mass function, 80
Phase angle, 519–520, 520 <i>f</i> , 522–525, 529	CCA applied to fields, 676–678	Probability of precipitation (PoP) forecast, 15,
Phase association, 452	computational considerations, 658–661	18, 277, 305–306, 386, 387 <i>f</i> , 411, 481 <i>t</i>
Phase shift, 519–520	for multiple fields, 632–634	Probability plot, 85, 124–125
Phase space, 313–319, 321, 326, 432–433,	rotation of eigenvectors, 650–658	Probability tables, 99, 101
634	rotation mechanics, 651–655	Probability wheel, 308
PIT, 134	sensitivity of orthogonal rotation to initial	Probit function, 103–104
PIT histogram, 430–431	eigenvector scaling, 655–657	Probit regression, 275–276, 346–347
Pivotal statistics, 182	sampling properties of eigenvalues and	Projection of a vector, 687–688, 692, 697
Platykurtic, 28–29	eigenvectors, 658–659	Proper scoring rule, 418–419
Plotting position, 41–43, 42 <i>t</i> , 166, 417,	for single field, 629–632	Proper value, 571
595–596	S-mode, 631–632	Proper vector, 571. See also Eigenvector
Plug-in principle, 185–188	T-mode, 631–632	Proportional odds logistic regression, 337–338
Plume graph, 363, 366f	truncation of principal components,	Proportion correct, 377, 380, 382, 386–391
Poisson distribution, 86-88	639–645	Pseudoperiodicity, 664
Poisson process, 86–87	in two dimensions, 620	Pseudo-random-number generator, 131-132
Poisson regression, 233, 279-281	uses of, 661-667	p-value, 149, 159–160, 607
Polya distribution, 218-220	via SVD, 659-660	
Pooled estimate of variance, 154, 186-188,	Principal component selection rules, 640-641	Q
697–698, 700, 704–706, 709	Principal components regression, 665-666	Quadratic discrimination, 702–703
Posterior distribution, 210-211, 213-234, 322,	Prior distribution, 210-212, 214-215, 217,	Quadratic form, 583-584, 587
345	222, 226, 229–232, 344	Quadratic kernel, 36
Posterior predictive distribution, 215–216	Prior probability, 18, 217, 701	Quantile, 24-25, 45, 107-109, 115, 117-118,
Posterior probability, 18, 713–714	Probabilistic classification, 709–710	161–162, 188–190, 204–205, 213–214,
Positive predictive value, 378	Probability	222-223, 328, 394, 431-432, 610-611
Power function, 147, 150–151, 151f	axioms of, 7	Quantile function, 92, 97, 104, 109, 114, 116,
Power method, 660	definition of, 7	135–137, 166, 356, 593
Power spectrum, 529–530, 640	elements of, 7–9	Quantile mapping, 111
Power of a test, 146–147	frequency interpretation of, 10	Quantile-quantile (Q-Q) plot, 124-125
Power transformation, 44–48, 101, 110–111,	multiplicative law of, 14, 16–17	Quantile regression, 285–287
246–247, 593	properties of, 11–18	Quantile regression forests, 290
Predictand, 236–237, 239–242, 244–248, 248f,	Bayes' Theorem, 17–18	Quantile score, 431
250–253, 256, 259–264, 266–267, 271,	conditional probability, 13–14	Quartic kernel, 36, 38f, 138
274–275, 279, 285, 288, 292, 294,	DeMorgan's Laws, 13	Quartile, 25–26, 30, 31f, 32–33, 45, 309–310,
300–301, 331, 333, 337–338, 346–347,	domain, subsets, complements, and	463f
362–363, 369, 373, 397, 425, 468, 500,	unions, 11–13	Quintile, 25
679–680, 691, 710	independence, 14–16	_
Prediction interval, 250–253	Law of Total Probability, 16–17	R
Prediction markets, 309	Probability density function (PDF), 35–37, 91,	Randomization tests, 181
Predictive distribution, 215–216	93 <i>t</i> , 120 <i>f</i> , 146, 149–150, 181, 209–210,	Random forest, 288-290
Predictor selection	307f, 317–318, 340, 467, 557, 587 Probability of detection (POD), 370	Random matrix, 577
cross validation, 265–268	Probability of detection (POD), 379	

Random number generator, 131–134, 186, 599	Relative (or reduction of) ignorance, 424	Schematic plot, 31-33, 94-95
Random variable, 40, 78-80, 88-93, 95-96,	Relative operating characteristic (ROC),	SCoTLASS, 658
110-111, 124, 161, 238, 286, 430,	412–416	Scree graph, 640, 641f
487-488, 491, 501, 577, 580-581	Reliability, 372-373, 378, 398, 403-410, 436,	Screening regression, 260
Random vectors and matrices	476–478	Seed, for random-number generation, 132, 135
expectations and other extensions of	Reliability diagram, 404-410, 422, 436-437,	Selection rules, 640
univariate concepts, 577–579	476–478	Self-organizing maps, 734-738
linear combinations, 580–582	Reliability index, 436	Sensitive to distance, 391, 420, 424
Mahalanobis distance, 582–584	Replacement, 182–183, 185–188, 650	Sensitivity, 24, 26, 194–195, 197, 294, 313,
partitioning vectors and matrices, 579–580	Representativeness error, 468–469	319, 379, 429, 655–657
Rank correlation, 59–61	Re-randomization tests, 181	Serial correlation, 61–62, 119, 148, 156,
Ranked data, 24	Resampling test, 144, 171, 181–182, 479–480,	158–160, 172, 180–181, 191–192,
Ranked probability score	678	204 <i>t</i> , 228–229, 248–250, 256,
continuous (CRPS), 330, 425–427	Residual, 199, 236–240, 245–250	477–478, 488–489, 491, 493, 495,
discrete (RPS), 425	Residual plot, 245–248, 246 <i>f</i> , 254, 256	499–501, 503, 510, 607, 650
ensemble continuous (eCRPS), 444, 467	Residual variance, 239–240, 245–249, 502,	Serial dependence, 15–16, 156–160, 227,
Rank histogram, 433–437	509–510, 692	492–493, 608
Rank-sum test, 172–176	Resistance, 23–24, 306	Shannon information, 417
Ratio of success, 381	Resistant statistics, 26–27, 247–248	Shape parameter, 104–107, 109–110, 114,
Ratio of verification, 377–378	Resolution	118–119, 164, 170, 223, 345
Rayleigh distribution, 137	and Brier score, 403	Shapiro–Wilk test for normality, 166
Recalibration, 346, 410	definition of, 372	Sharpness, 370–371, 373, 417, 428–429, 437
Receiver operating characteristic (ROC),	Return period, 116–118	Shifted gamma distribution, 110
412–416	Ridge regression, 270–271	Shrinkage, 268–274
		Sieve bootstrap, 191
Rectangular distribution, 112	Ridge trace, 271–273, 272 <i>f</i> Robust statistic, 23–25	•
Red noise, 501, 537–538, 544–545	•	Signal detection theory, 412
Reduction of variance (RV), 398, 449–450	Root-mean-squared error (RMSE), 324,	Signed rank test, 171–172, 176–177, 178 <i>t</i>
Redundancy analysis, 692	395–397, 449, 451–452, 462–463	Significance testing. See Hypothesis test
Re-expression	Rotated principal components, 651, 654–657	Simple linear regression, 236–238, 253–254,
power transformations, 44–48	Rotating scatterplot, 67–68, 594–595	500, 679
standardized anomalies, 50–52	Row binding, 554	Simple structure, 651–652, 658
Reference forecast, 373–374, 390, 402, 418,	Rug plot, 53–54	Simultaneous confidence statements, 608–611
495	Rule N, 642–644	Sine function, 517–520
Refinement, 31, 373, 401, 403, 407	C	Single-linkage clustering, 724–725
Refinement distribution, 370–371, 375–376,	S	Singular spectrum analysis (SSA), 661–665
405, 407–409, 437	SAL (structure-amplitude-location), 461–462,	for AR(2) series, 663
Reforecasting, 301	463 <i>f</i>	multichannel SSA (MSSA), 665
Regression. See Linear regression; Logistic	S1 score, 447-448	Singular systems analysis (SSA), 661–665
regression; Poisson regression;	Sample climatological distribution, 371, 392,	Singular value decomposition (SVD),
Regression coefficients, sampling distribution,	401	576–577, 684–685, 688–690
243–245	Sample space, 80, 86-87, 305-306, 487, 490	calculating CCA through, 684-685
Regression constant, 253, 329	Sample statistics, 78, 95–96, 106, 130–131,	maximum covariance analysis, 687–691
Regression equation, 237, 239, 244–245, 251,	144, 148, 155, 190, 268, 376, 554–555,	PCA via, 659–660
254, 258–259, 259f, 261, 262f,	599, 608, 650	redundancy analysis, 692
263–264, 267, 276, 286, 293–295,	Sampling distribution	Singular values, 576–577, 659–660, 688
297–298, 398, 504, 521–522, 529	cumulative probability, 43	Singular vectors, 322, 576–577, 659, 688
Regression estimation of event probabilities	of maximum-likelihood estimates, 130-131	Skewness, 28, 47–50, 69, 94–95, 107–108,
(REEP), 275, 277	test statistic, 143-145, 147-150, 152-156,	189, 594
Regression parameters, 238, 243-246,	159, 161, 163, 165–166, 169–173, 177,	Skewness coefficient, 27-28, 57-58
251–253, 263, 270–272, 274, 276–277,	179, 181–183, 186–188, 204–205,	Skill, 373-374, 383-385, 444-445
279-282, 329-330, 333-334, 338-339,	249–250, 478, 492–493, 594, 606	Skill score, 379-383, 392, 397-398, 475-476
350, 568, 665	Scale parameter, 102, 104–105, 107, 110,	Slack variable, 714f, 715
Regression sum of squares, 240, 529	118–119, 333–335	Smirnov test, 162-165
Regression tree, 288–289	Scaling transformation, 566–567, 597, 623	Softmax function, 292
Regularization, 268–274	Scatterplot, 53–54	Southern oscillation index (SOI), 51–52, 665
Rejection level, 145	glyph, 65–66	Spaghetti plot, 360–362, 362f
Rejection method for random variates,	matrix, 70–72	Spatial correlation, 181, 192, 197–199, 204,
135–136	rotating, 67–68	358–359, 469, 479–480, 612–613
Rejection region, 146–147	Schaake shuffle 356–357	Spearman rank correlation, 59–61, 354–355

Index (817)

Specificity, 379	nonlinear regression, 274–281	Subjective interpretation of probability,
Spectral analysis, 528–545	objective forecasts using traditional	10–11, 271
Spectral decomposition of a matrix, 571–573,	statistical methods, 294-304	Subsample relative frequency, 403-404
576, 647–648, 659–660, 673–676	predictor selection, 257-268	Subset, 11-13, 62, 97, 257-259, 266, 315-316,
Spectral estimates, 530, 540-545	cross validation, 265-268	374, 409 <i>f</i> , 438, 553, 591–593, 651
Spectrum, 45, 529–533, 532 <i>f</i> , 536, 542–543,	importance of careful predictor selection,	Subspace, 554, 705-708
640, 661–665	257–260	Successive subdivision, 309
Spread, 25–27, 46–48, 102, 174, 226, 337,	screening predictors, 260–263	Sufficiency, 182, 370, 416
370–371, 622	stopping rules, 263–265	Support, 36–37, 91, 113, 125, 199, 229
Spread-skill relationship, 324, 337, 345	subjective probability forecasts, 304–310	Support vector regression, 293
Square-root matrix, 574–575, 597	assessing continuous distributions,	Support vector classifier, 714f, 715–716
Stamp map, 360, 361 <i>f</i>	309–310	Support vector machine, 714–716
Standard deviation, 26–27, 37–38, 50–52,		Survivorship bias, 192–199, 201
	assessing discrete probabilities, 308–309	•
54–55, 57, 59–60, 78, 95–96, 95 <i>f</i> ,	central credible interval forecasts,	Symmetric matrix, 561–562
98–101, 106, 120, 130, 150, 153–154,	306–307	eigenvalues and eigenvectors of, 573
159–160, 170–171, 182, 186, 187 <i>f</i> ,	nature of subjective forecasts, 304–305	square roots of, 574–576
188–189, 226, 231, 238, 244–245, 324,	subjective distribution, 305–306	Symmetry, 25–28, 44–48, 49f, 64f, 167–168,
340, 349, 360–362, 396, 398, 451, 471,	Statistical inference, 15, 110, 143–206	593–594, 675
486, 511–512, 557, 557 <i>f</i> , 582–583,	Statistical learning, 287–288	Synthesis equation, 524, 622, 630, 675–676
620, 671, 696, 727	Statistical postprocessing, 296–297, 342	Synthesis formula, 619–620, 623–625,
Standard gamma distribution, 107–109, 341	Statistical significance, 195–197, 470, 474,	639–640
Standard Gaussian distribution, 95–96,	492, 499, 502, 544, 607, 611–614	Synthetic weather generator, 598
103–104, 152, 154, 189, 330, 471,	Statistical simulation	Systematic bias, 299f, 372
593, 610	with autoregressive model, 514	_
Standardized anomaly, 50–52, 96–97	Box-Muller method for Gaussian random	T
Standardized precipitation index (SPI), 110	number generation, 136–137	t distribution, 152-154, 603, 609
Star plot, 64	multivariate, 596-601	t-ratio, 244, 262, 280–281
Stationarity	nonuniform random number generation by	t test, 151–153, 155–156, 158, 171–192, 244,
covariance, 485	inversion, 134-135	502, 603
strict, 485	nonuniform random number generation by	Talagrand diagram, 433–434
Stationary probability, 491, 494	rejection, 135-136	Taylor diagram, 396–397, 451–452, 452f
Statistical distance. See Mahalanobis distance	simulating from mixture distributions and	Teleconnection, 73–74, 653, 654 <i>f</i>
Statistical expectation, 88-91, 426, 467	kernel density estimates, 137-138	Teleconnectivity, 73, 74 <i>f</i> , 232
Statistical forecasting	uniform random number generators,	Temporal autocorrelation, 61, 73, 662
classical, 294–296	132–134	Tensor product, 564
ensemble forecasting	vector time series, 597-601	Tercile, 25, 336, 407, 408f
choosing initial ensemble members,	Statistics vs. parameters, 78	Ternary reliability diagram, 424
321–323	Stem-and-leaf display, 29–30	Test level, 145–146, 193, 264, 544–545
effects of model errors, 325-327	Stepwise regression, 260	Test statistic, 143–145, 147–150, 152–156,
ensemble mean and ensemble dispersion,	Stippling method, 194, 197–199	159, 161, 163, 165–166, 169–173, 177,
323–324	Stochastic dynamic prediction, 318	
ensemble forecasts, 319-327	Stochastic physics, 326–327	179, 181–183, 186–188, 204–205, 249–250, 478, 492–493, 594, 606
graphical display of ensemble forecast	Stochastic process, 79–80, 487, 489	
information, 359–366	Stopping criterion, 263–264, 288, 732	Thinning, 228, 232
statistical postprocessing, ensemble	Stopping rules	Theil-Sen regression, 285 Thom estimator, 106
MOS, 327–328	for clusters, 726–732	· · · · · · · · · · · · · · · · · · ·
stochastic dynamical systems in phase	for forward selection, 263	Threat score (TS), 377, 381–382, 387,
space, 313–317	Stratification, 295, 301, 721	387 <i>f</i>
linear regression, 235–253	Strictly proper scoring rule, 418–419, 427	Tikhonov regularization, 270
analysis of variance table, 240–241	Strict stationarity, 485	Time domain, 132, 486–487
		Time between effectively independent
derived predictor variables in multiple	Structure function, 445	samples, 158–160, 228
regression, 254–256	Student's t, 152	Time-frequency analysis, 545-549
distribution of residuals, 238–240	Subjective distribution, 229, 305–306, 307 <i>f</i> ,	Time lag, 294, 297, 678–679
examining residuals, 245–250	394	Time series
goodness-of-fit measures, 241–243	Subjective forecast	harmonic analysis, 517-527
multiple linear regression, 253–256	assessing continuous distributions, 309–310	cosine and sine functions, 517-518
prediction intervals, 250–253	assessing discrete probabilities, 308–309	estimation of amplitude and phase of
sampling distributions of regression	central credible interval forecasts, 306–307	single harmonic, 520-524
coefficients, 243–245	nature of subjective forecasts, 304–305	higher harmonics, 524-527
simple linear regression, 236–238	subjective distribution, 305–306	

818) Index

Time series (Continued)	Trimmed mean, 26	observation, 420
representing simple time series with	Trimmed variance, 27	outer product of, 564
harmonic function, 518-520	True positive fraction, 379	regression parameters, 568
spectral analysis, 528-545	True skill statistic (TSS), 380-381	row, 554, 559-560, 563
aliasing, 534-537	Truncated Gaussian distribution, 102	subtraction, 559
computing spectra, 533-534	Tukey's ladder, 45	Venn diagram, 8–9, 9f, 11, 12f, 13–14
harmonic functions as uncorrelated	Two-sample t test, 154–155, 158–159, 199,	Verification data, 259, 266, 369, 371,
regression predictors, 528-529	202, 204–205, 603	375–376, 379, 382, 386t, 394–395,
periodogram, or Fourier line spectrum,	Two-sided test, 147	438, 473, 481 <i>t</i> , 719 <i>t</i>
529–533	Two-tailed test, 147, 150	Verification rank histogram, 433-437
sampling properties of spectral estimates,	Type I error, 146–147	Violin plot, 39–40, 39f
540–545	Type II error, 146–147	Von Mises distribution, 427 <i>t</i>
theoretical spectra of autoregressive	31	, , , , , , , , , , , , , , , , , , , ,
models, 537–540	• •	347
time domain—discrete data, 487–499	U	W
deciding among alternative orders of	U-statistic, 173, 176, 373, 474	Waiting distribution, 83-85
Markov chains, 498–499	Uncertainty, 3-7, 99-100, 131, 155-156,	Walker test, 544
higher-order Markov chains, 497–498	209-211, 214-216, 218-219, 222-227,	Ward's minimum variance clustering, 725
Markov chains, 487–488	239-240, 250-251, 304, 306, 313, 319,	Wavelets, 459, 548-549
multiple-state Markov chains, 495–496	324, 327, 329, 342, 363, 404, 427,	Weak stationarity, 485
•	432-433, 469, 502-503, 515, 607, 647	Weather generator, 598
some applications of two-state Markov	Unconditional bias, 372, 396, 398, 434-435,	Weibull distribution, 115–116, 116f, 229–230
chains, 494–495	451, 453	Whitening transformation, 685–687, 693
test for independence vs. first-order serial	Unconditional distribution, 100, 100f, 239,	White noise, 469–470, 508–509, 538,
dependence, 492–493	241, 371, 373, 399 <i>f</i>	538f, 543
two-state, first-order Markov chains,	Underforecast, 378, 406–408, 435–436, 443 <i>f</i>	White-noise variance, 502–503, 506, 509–510,
488–492	Undersample, 192, 535	513, 516
time domain—continuous data, 500–517	Uniform distribution, 112–113, 132, 135, 168,	Wilcoxon-Mann-Whitney test, 171-172, 174,
AR(2) model, 505–509	217–218, 430, 434	182–183
autoregressive-moving average models,	Uniform random number generator, 132–134,	Wilcoxon signed-rank test, 171–172,
513	494	176–177, 178 <i>t</i>
first-order autoregression, 500–504	Union, 11–13, 146–147, 389	Windowed Fourier transform, 546–547
higher-order autoregressions, 504–505	cmon, 11 15, 110 117, 505	Wind power density, 226
order selection criteria, 509–510		Winkler's score, 432
simulation and forecasting with	V	Within-groups covariance matrix, 705, 726
continuous time-domain models,	Vague prior, 215, 233	William groups covariance matrix, 705, 720
513–517	Validity, 372, 645	**
variance of time average, 510–512	Value score, 466–467	X
Γ-M diagram, 385f	Variance, 27, 44, 54-55, 89, 119-120, 152,	X–y plot, 53
Toeplitz matrix, 661–662, 664	240-241, 502, 635-638	
Fraining data, 247, 269–272, 280, 282–283,	Variance-covariance matrix, 555	V
286–288, 290, 301, 330, 333–334,	Variance inflation factor (VIF), 158-160,	Y
338–339, 344, 347–348, 353 <i>f</i> , 467,	180-181, 228, 250, 252, 510-513	Youden's index, 380–381
524, 589, 680, 695, 699 <i>f</i> , 712 <i>f</i> , 715,	Variance reduction, 135	Yule–Kendall index, 28
721, 734	Variance-stabilizing transformation, 44	Yule's Q, 381
Fraining sample, 258–259, 330–331, 344, 691,	Variance of a time average, 156, 158,	Yule-Walker equations, 504-505, 509,
695–696, 710–711, 713, 715	510–512, 537	511–513, 599
Γrajectory, 313–314, 316–317	Varimax rotation, 651–652	
Fransition probability, 494, 496–498	Variogram score, 445	Z
Transpose (vector or matrix), 559, 562,	Vector, 559–561	
566–567, 569–570, 577	addition, 559	Z-scores, 557–558
Гree diagram. See Dendrogram	column, 559, 561	Z-transformation for the correlation
Triangular kernel, 37	forecast, 419–424, 439–441	coefficient, 49
Γricube kernel, 282	multiplication, 560	
	p	

Trimean, 26