Page numbers followed by "f" indicates figures, "t" indicates tables and "n" indicates footnotes.

A	Air–sea interactions, 5
A-grid model, 294, 296f	ALADIN model, see Aire Limitée
Absolute velocity, 42, 43	Adaptation dynamique
Abyssal circulation, 677–681	Développement InterNational model
Abyssal layer, 658	Albedo, 628, 640
Accuracy, 118, 119	Algebraic Reynolds-stress models, 453
and errors, 120–125	Aliasing, 33–35, 329–330
Acoustic Doppler current profilers, 18	Alternating direction implicit (ADI)
Adams–Bashforth method, 66, 67f	methods, 156
Adaptive time-stepping, 125	Amphidromic points, 308, 381
Adiabatic conservation law, 350	Amplification factor, 145, 146, 150
Adiabatic lapse rate, 351	Angular frequency, 773
Adjoint method, 745f	Anticyclones, 20, 601, 609f
Adjoint model, 747	of midlatitude weather, 565
Adriatic	Anticyclonic vorticity, 490
density profile, 13	Arakawa, Akio, 295, 315
seiches, 278, 381	Arakawa Jacobian, 545
Advection, 193f, 194f, 768	Arakawa's grids, 289f, 296
1D, 191, 192 <i>f</i>	A-grid model, 294, 296f
2D, 186–187, 190 <i>f</i>	C-grid, 295, 297f
and diffusion, 163–167	Coriolis force, 291, 292, 300
multidimensional approach,	numerical models, 289
186–196	second-order method, 290
relative importance of, 167–168	staggered grid, 291, 293
with TVD scheme, 195f	Artificial diffusion, see Numerical diffusion
Advection schemes	Asselin filter, 334
centered, 169-176	Atlantic Ocean, 27
numerical, 187	Atmosphere, 715
standard test for, 175	length, velocity and time scales, 15t
upwind, 176–183, 177f, 178f	motion in, 14–17
Advection-diffusion	processes and structures in, 16f
equation, 163	Atmospheric boundary layer, 257, 462
properties of, 165	Atmospheric circulation models, 637–642
with sources and sinks, 183–186	Atmospheric convection, 463–465
Advective instability, 418	parameterization, 355, 643
AGCMs, see Atmospheric General	Atmospheric frontogenesis, 490-502,
Circulation Models	491 <i>f</i> –493 <i>f</i> , 499 <i>f</i> , 500 <i>f</i>
Ageostrophic motion, 280, 524-525, 529,	physical processes in, 492
532, 537, 601	temperature gradient, 494
Aire Limitée Adaptation dynamique	Atmospheric General Circulations Models
Développement InterNational	(AGCMs), 19, 638–639
(ALADIN) model, 639	Atmospheric stratification, 349–354

(816) Index

Automatic Sequence Controlled Calculator (ASCC), 22	BLUE, see Best Linear Unbiased Estimation
Available potential energy, 382, 530–532,	Boundary conditions, 109–112, 110 <i>f</i>
611–612	dynamic conditions, 114–116, 116 <i>f</i>
011-012	heat flux, 116–117
В	kinematic conditions, 112–114, 113 <i>f</i> ,
Backward-difference approximation, 29	114 <i>f</i>
Backward scheme, 63	numerical implementation of, 117–120,
Baltic Sea, 55, 56f	118 <i>f</i> , 119 <i>f</i>
Banded matrix, 152	salt flux, 117
Baroclinic mode, 377, 379 <i>f</i> , 535	
Baroclinic instability, 553–554, 600,	on streamfunction in ocean model, 223f
694	tracer, 117 Boundary layer, 115, 244, 251
interval for two-layer, 571f	atmospheric, 257
linear theory of, 566–574	
mechanism, 561–566	equations, 248
Baroclinic planetary wave, 536, 538 <i>f</i>	Boundedness, property of, 167
· •	Boussinesq, Joseph Valentin, 96
Barotropic flow, 210, 318	Boussinesq approximation, 83–87,
Barotropic instability, 317f, 600	106–107, 428
mechanism, 327, 328	Brunt, David, 363
Barotropic mode, 377, 379f Barotropic waves, 535	Brunt–Väisälä frequency, 349, 352, 398
•	Bryan, Kirk, 699
Arakawa's grids, 291f	Buffer layer, 242
inertia-gravity waves, 276–278	Bulk criteria, 576–579
Kelvin wave, 273–276	Buoyancy, 348
linear wave dynamics, 271–273	buoyancy force, 85, 348, 351, 425 <i>f</i> , 462
planetary waves, 278–283	556f
tides and storm surges, 309	buoyancy production, 444, 445
amphidromic point, 308	Burger number, 360, 528, 532, 539, 574
drag coefficient, 302 equilibrium tide, 307	C
shallow-water equations, 300, 301	Cartesian coordinates, 693
tidal force, 304, 308	Cartesian Coordinates, 693 Cartesian framework of reference, 53, 54 <i>f</i>
tidal potential, 307	
*	Cascade of energy, 133, 137, 438–440, 451
topographic waves, 283–287 Basis functions, 258	Catastrophic instability, 554
	Cauchy condition, 116
Beam–Warming schemes, 180–181, 508, 512 <i>f</i>	Cell-averaged concentrations, 169, 170
	Centered schemes, 169–176
Bergeron process, 643 Bernoulli function, 390, 666–667	Centrifugal force, 6, 592, 594, 602
Bessel functions, 541	unimportance of, 44–46, 45 <i>f</i> , 46 <i>f</i>
Best Linear Unbiased Estimation (BLUE),	CFD, see Computational fluid dynamics
743	CFL condition, 177, 178
	CFL parameter, see Courant number
Beta parameter, 279	CFT, see Cosine Fourier transforms
Beta plane, 279	Chaotic trajectories, 727, 727f
equatorial, 701–702 Beta spiral, 664–666	Characteristic line, 172, 173 <i>f</i>
Biharmonic diffusion, 197, 332, 613	Charney, Jule Gregory, 22, 161, 521, 550,
	565, 576, 586, 622, 760
Biharmonic filter, 332	Checker-board mode, 295f
Bjerknes, Vilhelm Frimann Koren, 20, 83,	Chemical species, 164
97, 269, 363, 490	Cholesky decomposition, 230
Black body, 628	Climate, 627
Blocking, 597	Cloud parameterizations, 642–644

Index (817)

Coastal upwelling, 15, 482f	Coriolis, Gaspard Gustave de, 75
development of, 482f	Coriolis acceleration, 44
finite-amplitude upwelling, 486–489,	Coriolis effect, 49, 478
488f, 489f	Coriolis force, 6, 291, 292, 300, 474, 476,
formation of, 489f	521, 592
model of, 484–486	centrifugal force, 44–46, 45f, 46f
outcomes of, 488f	in geophysical flows, 105
process of, 482–484, 483f, 484f	Rossby number, 108
simple model of, 484–486	Coriolis parameter, 47, 55, 205, 208, 213,
types of, 484	240, 245, 272, 273, 278–279, 283,
upwelling front, variability of, 489–490,	318, 538, 591, 599, 701
491 <i>f</i>	Corner Transport Upstream (CTU) scheme,
Cold front, 490, 492 <i>f</i>	188, 189 <i>f</i> , 190 <i>f</i>
Collocation methods, 258	Cosine Fourier transforms (CFT), 791
Complete vertical mixing, 426	Cost function, 744
Compressible fluid, 349	Coupled model, ENSO, 715–716, 717 <i>f</i>
Computational fluid dynamics (CFD), 39,	Courant Institute, 201, 202, 759
113	Courant number, 172, 182 <i>n</i> , 190, 506, 510
Computational mode, 174	Courant, Richard, 22, 174, 201
Computational speed, increase, 24f	Covariance matrix, 736
Conjugate gradient methods, 227, 229, 230,	model-error, 740
747	reduced rank, 752
Conservation of momentum, 78, 426, 765	Crank-Nicholson scheme, see
Conservative formulation, 87	Semi-implicit scheme
Continental shelf waves, 286	Crest, 594, 774, 776f
Continuity equation, 77, 764	Critical level, 323
Continuous stratification, 531	Cumulus clouds, 643
Contour dynamics, 334–340	Cutoff frequency, 34
contour surgery, 339	Cyclogenesis, 601
two-dimensional problem, replacing of,	Cyclones, 20, 22, 601, 609f, see also
339	Anticyclones
uniform vorticity simulated with, 338	of midlatitude weather, 565
velocity determination, 337	Cyclostrophic balance, 602
Contour surgery, 339	Cylindrical coordinates, equations in,
Control parameters, 747	768–769
Convection, 349, 353, 463–465	D
Convection parameterizations, atmospheric,	D
355	Damped modes, 751
Convective schemes, 354–355	Data acquisition, 17–19
Convergence of meridians, 639	measurement, vertical velocity and
Convergence–divergence pattern, 538	pressure, 18
Convergent method, 63	sampling frequencies, 18
Conveyor belt, 657, 658 <i>f</i> , 678	Data assimilation, 725–730, 727f, 728f,
Coordinate surface, 686	732 <i>f</i>
Coordinate systems, 692–693	implementation of, 750
cylindrical coordinates, 768–769	procedure of, 743–744
discrete equations, 686, 687f	Dead waters, 7–8, 8 <i>f</i> , 395
hybrid-grid models, 686	Decorrelation, 737n4
hydrostatic consistency, 691	Density gradient horizontal 473, 474, 4744
pressure-gradient problem, 689	Density gradient, horizontal, 473–474, 474 <i>j</i> DFT, <i>see</i> Discrete Fourier transform
sigma coordinate system, 689, 690 <i>f</i>	
spherical coordinates, 660, 678,	Diagnostic variables 110

Diffusion, 163–167	Eigenfunctions, 261-262, 263, 320, 404,
Diffusivity, 138, 154	406, 410, 534
Dimensionless numbers, 107–109	Eigenvalues, 261–263, 320, 404, 405, 409
Direct cells, see Hadley cell	432, 534
Direct convective cells and indirect	EKF, see Extended Kalman Filter
convective cells, 631	Ekman, Vagn Walfrid, 8, 251, 269
Ferrel cell, 636 <i>f</i> , 637, 637 <i>f</i>	Ekman depth, 247, 249, 252, 255–256
Hadley cell, 632–633, 636 <i>f</i>	Ekman drift, 255, 475, 482–483, 486, 489
indirect cells, 633	Ekman layer, 239f, 482, 566, 660
zonal averages, 634	bottom, 245–247, 249
Direct insertion, 731	velocity spiral in, 247, 253
Direct model, 747	definition, 244
Dirichlet condition, 116, 222	in real geophysical flows, 254-257
Discrete equations, 686, 687f	surface, 251–254
Discrete Fourier transform (DFT), 647,	over uneven terrain, 250–251
787–792	Ekman number, 108–109, 243–244, 522
Discretization	Ekman pumping, 249, 251, 254, 267, 663,
methods, 89–90, 90f	666, 669–670
variable, 25	subduction, 673, 675, 676, 677
Discretization errors, 120-121	Ekman transport, 253, 713
estimates, 121–125	El Niño, 703, 708, 709
Dispersion	occurrence, 710
turbulent dispersion, 102, 137	prediction of, 716, 718, 719f
numerical dispersion, 180-181, 182,	El Niño – Southern Oscillation (ENSO), 5
196, 389	707–711, 711 <i>f</i> , 717 <i>f</i>
wave dispersion, 146, 315, 418, 776f	forecasting, 716–720
Dissipation rate, 438, 441	model of
Divergence theorem, 87	conceptual, 710, 712f
Domain decomposition, 127	coupled, 715–716
Donor cell scheme, see Upwind scheme	empirical predictive, 719
Double diffusion, 86	Electronic Discrete Variable Calculator
Drag coefficient, 115	(EDVAC), 22
Drag force, 415, 416	Electronic Numerical Integrator and
Dynamic conditions, 114–116, 116f	Computer (ENIAC), 22
Dynamic pressure, 87	Elliptic equation, 217–218, 221, 222, 225
_	two-dimensional, discretization of,
E	218f
Earth simulators, 641	Emergence of coherent structures, 612
Earth–Sun orientation, 11	Energy budget, 80-82, 382, 444, 449,
Eastward jet, 599f, 600	452–453, 464–465, 480–481,
curvature and beta effects on, 596, 596f	530–532
meandering of, 594, 594 <i>f</i>	Energy cascade, 133, 137, 438-440, 451
ECMWF, see European Centre for	Energy conservation, 80, 381–383
Medium-Range Weather Forecasts	Energy dissipation, 133, 135
Eddy coefficients, 101–102	Energy method, 177–178
Eddy diffusivity, 86, 102, 117, 131	Energy propagation, 778–780
formulation, 447	Energy spectrum
Eddy viscosity, 101–102, 125, 242–243,	internal waves, 418
436	turbulence, 135-137, 440
formulation of, 441–442, 446, 450, 453,	English Channel, 275, 276f
454	ENO methods, see Essentially
profile, 268	nonoscillatory methods
value, 108, 255, 744	Ensemble forecast approach, 752, 753

THE STATE OF THE S	
ENSO, <i>see</i> El Niño – Southern Oscillation Enstrophy, 611–612	Finite-amplitude development, 328, 579–583
Entrainment, 384	Finite-amplitude upwelling, 486–489, 488f,
during convection, 644	489f
in thermocline, 673, 675	Finite-difference approximation, relative
Epilimnion, 379	error, 29, 30 <i>f</i> , 31 <i>f</i>
Equation of state, 79–80	Finite-difference representation, 263
Equatorial beta plane, 701–702	Finite differences, 23–28
Equatorial currents, 671	Finite elements, 261
Equatorial inertial time, 702	Finite-volume approach, 257
Equatorial radius of deformation, 702f	Finite-volume discretization, 88–92, 89f,
Equatorial radius of earth, 45	91 <i>f</i> , 92 <i>f</i>
Equatorial upwelling, 484, 520	Finite-volume technique, 153, 153f,
Equatorial waves, 424, 703f	169–170, 180
equatorial Kelvin wave, 704, 706, 709	2D advection, 186–187
equatorial planetary waves, 704,	one-dimensional, 170f
706–707, 708 <i>f</i>	First law of thermodynamics, 80
equatorial mixed wave, 706	First-order accurate, 57
Equilibrium tide, 307	First-order upwind scheme, 508
Equipotential surface, 46	Fluid-flow model, 739
Error-covariance matrix, 736, 737, 742,	Fluid layer, density, 10
743f	Fluid mechanics, budgets on infinitesimal
Error estimate, 123–124	volumes, 763–768
Error variance, 733	Fluid motions, rotations in, 10–12
Error vector, 737	Fluid parcels, vertical stretching and
Essential boundary condition, 260	squeezing of, 561, 562f
Essentially nonoscillatory (ENO) methods, 507	Fluid transverse transport, calculations of, 247
Euler method, 55-57, 63, 172	Flux, 137
Euler scheme, 111, 142, 146, 176	Flux-corrected transport (FCT), 507
diffusion, 184	Flux formulation and conservative form,
Eulerian approach, 387, 767, 768	87–88, 88 <i>f</i>
Eulerian vorticity evolution, 339	Flux-limiter methods, 507, 509
European Centre for Medium-Range	Forecast error, 735–736, 740
Weather Forecasts (ECMWF), 368,	Forecasting, 18–20, 23
734 <i>n</i> 3	Formal stability definition, 61
Explicit schemes, 58, 154	Forward-difference approximation, 28
Extended Kalman Filter (EKF), 740,	Forward scheme, 63
741 <i>f</i>	4D-Var method, 746, 749, 751
External radius of deformation, 373,	Fourier coefficient, 788, 790
377–378, 536, 546	Fourier law, 81
F	Fourier-mode formalism, 173
F	Fourth-order discretization, 119–120
Fast Fourier transform (FFT), 230, 616, 789–794	Fourth-order finite-difference approximation, 32, 785
FCT, see Flux-corrected transport	Fourth-order method, 66
Ferrel cell, 636 <i>f</i> , 637, 637 <i>f</i>	Fractional steps, see Operator splitting
FFT, see Fast Fourier transform	methods
Field estimation, 725	Free surface, 112, 113, 533
Filtering, 153, 280, 331–334	Frequency, 773, 776–778
Asselin filter, 334	Friction, 561
biharmonic filter, 332	velocity, 240, 458
Kalman filtering, 739–743	Frontal meanders, 599f

Frontogenesis	Gravitational force, 45-46
atmospheric, see Atmospheric	Gravitational instability, 553
frontogenesis	Great Red Spot in Jupiter's atmosphere, 9,
physical processes in, 492	35, 320, 542, 613, 620
temperature gradient, 494	Greenhouse effect, 630
Fronts	Greenhouse gases, 5–6
cold, 490, 492 <i>f</i>	Grid nodes, 503–505, 504f
definition, 589	Grid Peclet number, 179
origin and scales, 589–592	Grid spacing, 27–28
warm, 490, 492 <i>f</i>	Group velocity, 282, 282f, 780-782
Froude number, 356–358, 360, 417, 591	Growth rate, 320
Full upwelling, 486	Gulf Stream, 14, 17, 659, 672, 673
Fully implicit scheme, 150	
_	Н
G	Hadley cell, 632–633, 636f
Galerkin method, 260	Hadley, George, 632
Garrett–Munk spectrum, 418, 419f	Heat budget, 92, 464, 576, 627-631, 644,
Gaussian elimination, 151	685, 713
Gaussian grid, 649	Heat capacity, 80
Gauss-Seidel method, 155, 156, 225, 580,	Heat flux, 15, 116-117, 350
582	Heat transport, 574–576
Gelbstoff, 735	Helium, 164
General Circulation Models (GCMs), 19	Hermite polynomials, 706
Generalized inverse model, 748	Hessian matrix, 749, 750f
Gent-McWilliams parameterization, 694	Heun method, 65
Geoid, 46	High Reynolds-number flows, 439
Geopotential, 46	Higher-order approximations, 28–33
Georges Bank, 591	Higher-order schemes, 65-69, 66f-69f
Geostrophic adjustment, 475–480, 476f,	Highly advective situations, 168-169
479 <i>f</i>	Homogeneous fluids, rigidity, 6, 7f
energetics of, 480–482	Homogeneous geostrophic flows, 205-208
examples of, 479f	206f, 208–210
Geostrophic balance, 521	Horizontal density gradient, 473-474
Geostrophic component, 524	Horizontal eddy diffusivity, 452
Geostrophic contours, 209	Horizontal eddy viscosity, 102
Geostrophic coordinate, 497	Horizontal geostrophic interior flow, 250
Geostrophic equilibrium, 524	Horizontal momentum equations, 108
Geostrophic momentum, 556n	Howard, Louis Norberg, 343, 434
Geostrophic turbulence, 134, 539, 611-613	Howard semicircle theorem, 323, 435
simulations of, 613-618	Hurricane Frances, 9
Geostrophic velocity component, 537	computer prediction of path, $4f-5f$
Geostrophy, 207, 264, 483	Hurricanes, 602, 610
Ghil, Michael, 759	Hybrid-grid models, 686
Gibb's phenomena, 649	Hydrological cycle, 630, 631 <i>f</i> , 644
Gill, Adrian Edmund, 424, 623	Hydrostatic balance, 105-106
Glaciation cycles, 17	Hydrostatic consistency, 691
Global climate models, 641	Hydrostatic equation, 105, 109, 351
Global conservation, 92, 92f	Hypolimnion, 379
Godunov theorem, 182, 508	_
Governing equations, 522–527, 523f	I
summary of, 83	Implicit Euler scheme, 63
Gradient-wind balance, 601	Implicit scheme, 58
Gram-Schmidt orthogonalization process,	damping rate of, 150 , $151f$
228–229	Incompressible fluid, 213, 348

Index (821

Indirect cells, 633	Isotropic and homogeneous turbulence,
Indonesia's Sumatra Island, earthquake, 4	131–132
Inertia, 672	eddy length versus velocity scale in,
Inertia-gravity waves, 276–278	132–135, 132 <i>f</i>
Inertial instability, 553–561, 558 <i>f</i> –560 <i>f</i>	energy spectrum of, 135-137
Inertial oscillation, 48, 55	ITCZ, see Intertropical convergence zone
Inertial period, 48	Iteration errors, 120
Inertial (Poincaré) waves, 404	Iterative method, 503
Innovation vector, 735	Iterative solvers, 155, 224
Instability, 331	
advective, 418	J
baroclinic, 553–554, 600	Jacobi method, 155, 224
barotropic, 317 <i>f</i> , 600	Jacobian, 787
catastrophic, 554	Jacobian operator, 525, 542-543
gravitational, 553	grid notation for, 543f
inertial, 553–561, 558 <i>f</i> –560 <i>f</i>	Jet
Kelvin-Helmholtz, 427, 428	curvature and beta effects on, 596, 596f
mixed barotropic-baroclinic, 554, 579,	eastward and westward, 599f
600	instabilities, 600
types of, 553–554, 554 <i>t</i>	meandering, 592–597
Integrated models, 641	multiple equilibria, 597
Interface, 369	origin and scales, 589–592
Interference patterns, 779, 780	shear and orbital vorticity of, 593f, 594f
Interior cyclonic motion, 249	stretching and topographic effects,
Internal radius of deformation, 360, 373,	597–600
378, 406, 528, 536, 541, 590–591	Jupiter
Internal solitary wave, 418	equatorial circumference, 69
Internal waves	Great Red Spot, 3, 9, 320, 542, 613
amplitudes, 416	southern hemisphere, 9f
•	southern nemisphere, 9j
in atmosphere, 396 <i>f</i> nonlinear effects, 416–419	K
structure of, 399–401, 400f	$k - kl_m \mod 1,450$
surface manifestation of oceanic, 396f	k model, 437, 446
from surface to, 395–397	Kalman filter, 739–743, 748, 749
theory, 397–399	approach, 744 <i>f</i>
vertical modes, 401–404	Extended Kalman filter, 740, 741 <i>f</i>
bounds on frequency, 404–405	operation, 743
constant N^2 , 405–407	Kalman filtering, 739–743
numerical decomposition, 407–410	Kalman gain matrix, 738
vertical eigenvalue problem, 404	Kalman smoother, 749
waves concentration at pycnocline,	Kalnay, Eugenia, 760
410–412	Kelvin, Lord, 97, 274, 314
Intertropical convergence zone (ITCZ), 709	Kelvin wave
Inverse barometric response, 307	coastal, 273–276, 277, 286, 532, 704
Inverse methods, 743–750, 744 <i>f</i> , 745 <i>f</i> ,	equatorial, 704, 706, 707–708, 709, 718
747 <i>f</i>	internal, 406, 489
generalized, 749f	Kelvin–Helmholtz instability, 427–431,
Inversion, 462	554, 577
Inviscid fluid, 429	Kelvin's theorem, 214
Isobaric flow, 206, 207	Killworth, Peter Douglas, 623
Isobars, 206	Kinematic conditions, 112–114, 113f, 114f
Isobaths, 209, 215	Kinematic viscosity, 85
Isopycnal diffusion, 384	Kinetic energy, 481, 611–612
Isopycnal surface, 365	and stratification, 12

(822) Index

Kinetic-energy	Leapfrog time discretization, 219, 222
loss in, 426	Lee waves, 412–414
spectrum, 439, 440	Legendre functions, 645, 648
Kolmogorov, Andrey Nikolaevich, 160	Leibniz rule, 506
Kolmogorov scale, 134	Limited area models (LAMs), see Regional
Kolmogorov turbulent cascade theory, 132,	models
133, 137, 441, 451	Limiter, 182–183
Kuroshio paths, 597, 598f	Linear dispersion approximation, 171
L	Linear discretization operator, 171
-	Linear observation operator, 735 Linear theory, of baroclinic instability,
La Niña, 708, 711, 716, 720	566–574
Lagrangian 248 287 200 506 760 770	
approach, 348, 387–390, 506, 769, 770 multipliers, 482, 745, 746	Linear wave dynamics, 271–273
Laminar flow, 131	theory, 703–707, 703 <i>f</i> , 705 <i>f</i> , 708 <i>f</i>
	Local conservation, 92, 92 <i>f</i>
Laplace, Pierre Simon Marquis de, 74 Laplacian inversion, 224–231	Logarithmic profile, 240–242
Laplacian inversion, 224–231 Laplacian operator, 81, 280, 525, 564	Long-wave disturbances, 326
•	Long-wave disturbances, 320 Long-wave radiation, 628f, 630, 638
Large gradients, numerical handling of, 502–507, 504 <i>f</i>	Lorenz, Edward Norton, 20, 654
Large-scale atmospheric flow, 7	Lorenz equations, 726–728, 728f
Large-scale motions, 3	Lower-upper decomposition, see Gaussian
Large-scale ocean dynamics, 660	elimination
Bernoulli function, 666–667	Lyapunov equation, 739–740
potential vorticity, 667–669	Eyapanov equation, 755 740
Sverdrup relation, 662–663	M
Sverdrup transport, 663–664	MacCormack scheme, second-order, 181
thermal wind and beta spiral, 664–666	Macro scales, 438
Lateral heterogeneities, 478	Malkus, Willem, 343, 519
Lax, Peter, 202, 759	Marginal ice zone, 483, 484f
Lax-Richtmyer theorem, 60, 62, 63, 148	Margules relation, 474, 475 <i>f</i>
Lax-Wendroff schemes, 180, 182, 183,	Mass budget, 77
196 <i>f</i> , 508, 511, 512 <i>f</i> , 651	Mass conservation, 77
second-order, 181f, 183	equation, one-dimensional, 766
Layered models	Material derivative, 78, 768, 769
from depth to density, 365–369	MATLAB TM programs, 34, 763
energy conservation, 381–383	Matrix decomposition, 151, 230, 785f
interface, 369	Matrix method, 148
Lagrangian approach, 387–390	Max-min property, 167
numerical, 383–387	McWilliams, James Cyrus, 238, 613, 694
potential vorticity, 374	Meanders, 592–597, 599f
radius of deformation, 373	meander scale, 595
reduced-gravity model, 371, 372f, 372t,	Mechanical-energy budget, 530
374	Mellor, George Lincoln, 470
rigid-lid approximation, 370	Mellor-Yamada model, 450
shallow-water reduced-gravity model,	Mercator ocean model, 734n3
374	Meshless spectral method, 613
two-layer models, 374–379	Mesoscale, 479
wind-induced seiches, lakes, 379-381	Meteorological Office, 39
Lead time, 725	Micro scales, 439
Leapfrog scheme, 66, 67 <i>f</i> , 174–176, 176 <i>f</i> ,	Midpoint method, 65
508	•
	Mixed barotropic-baroclinic instability,
amplification factor of, 152 numerical dependence of, 175 <i>f</i>	•

Index (823)

Mixing length, 86, 243, 270, 441–442, 446, 449 <i>f</i>	Nonlinear motions, quasi-geostrophic equation for, 526
Mode splitting, 386	Nonlinear numerical instability, 330
Model-error covariance matrix, 740	Nonlinear systems, 727
Modeling errors, 120	discretization error in, 122
Modon, 541	Nonlinearities, in barotropic instability,
Modular Ocean Model (MOM), 681	328–331
Moisture budgets, 82	Nonmonotonic behavior, 331-334
Molecular viscosity, 134	Nonuniform currents, generalization to,
MOM, see Modular Ocean Model	247–249
Momentum budget, 78–79	Nonzero perturbations, 326
Momentum equations, 769	North America, weather forecasting skill
Monin-Obukhov length, 459, 461, 465	23 <i>f</i>
Monotonic scheme, 167	Nudging, 730-731, 743, 750
Monotonicity preserving scheme, see	Numerical convergence, and stability,
Monotonic scheme	59–63, 62 <i>f</i>
Montgomery, Raymond Braislin, 369, 393	Numerical diffusion, 179
Montgomery potential, 367–371, 601, 604,	Numerical discretization, 544
666–667, 669, 690	Numerical grids, 651
Moore's Law, 28	of global atmospheric models, 644f
Motions	Numerical instability, 143, 153
parameterization of, 28	Numerical methods, 644
scales of, 8–10	Numerical models, 289
length and velocity, 11, 12t	layered, 383-387
Mountain ridges, 14	Numerical scheme
Mountain wave, structure of, 415f, 417f	multi-dimensional, 154-157
Moving boundary problem, 113	one-dimensional, 140-144, 150-154
Multidimensional approach, 186–196	stability analysis of, 144-150
Multigrid methods, 230, 231	stability condition of, 146-148
Multiple equilibria, 597	Numerical simulations, fluid motions,
Multistage methods, 65	19–23
Multistep methods, 65	Numerical stability, 174
Multivariate approach, 732	Numerical stencil, 32
Munk, Walter Heinrich, 418, 423	Nyquist frequency, 34
N	0
Nansen, Fridtjof, 8, 36, 251, 253, 269	O'Brien, James Joseph, 394
Natural fluid motions, 4	Ocean General Circulation Model
Neumann boundary condition, 116, 141,	(OGCM), 681
260	Oceanic circulation, 657–660
Neumann problem, 217	models
Neumann stability analysis, 173, 184	coastlines, 684
Newton's law, 44, 47, 301 <i>f</i> , 303	MOM, 681
second law, 78, 348, 557, 764, 767	pole problem, 682
Non-amplifying wave, 326	subgrid-scale processes, 693–695
Non-atmospheric system, 640	turbulence-closure schemes, 686
Nondiffusive fluid, 429	Oceanic flows, 7
Nondispersive wave, 778	Oceanic General Circulation Models
Nongeostrophic flows, 210–212	(OGCMs), 19
Nonhydrostaticity, 398	Oceans, see also Atmosphere
Nonlinear advection, 438	dynamics, 711–712
schemes, 507–512, 512 <i>f</i> , 513 <i>f</i>	heat budget, 713–715
Nonlinear effects, 539–542	length, velocity and time scales, 15t
Nonlinear instability, 331	motion in, 14–17

824) Index

Oceans (continued)	Plume, 164, 164 <i>f</i>
oceanic interior, 658, 660, 669, 672,	Poincaré waves, see Inertia-gravity waves
673f, 692	Poisson equation, 222, 545, 614
processes and structures in, 16	inversion of discrete, 224-231
volume conservation, 712–713	Polar-front jet stream, 589
OGCM, see Ocean General Circulation	Pole-to-equator temperature difference, 7
Model	Potential density, 352
OI, see Optimal interpolation	Potential-energy, 480-481, 530-532
One D finite-difference schemes, 785	barrier, 434
One-dimensional tracer equation, 505	and stratification, 12-13
One-equation turbulence model, 446	Potential temperature, 81, 352, 353f
One-layer reduced-gravity model, 703	Potential vorticity, 487, 542, 667-669
One-point closure model, 440	conservation principle, 477, 481
One-point closure schemes, 450	definition, 214
Open boundary, 115, 116f	equation for, 526
Operational models, 750–753	expression, 287, 289, 527–528
Operator splitting methods, 190	layered models, 374
Optimal interpolation (OI), 731–738, 750	Power spectrum, of turbulence, 135, 136f
formulation of, 739	Prandtl, Ludwig, 96, 244, 270, 441–442
Orbital vorticity, 593f, 594f	Prandtl frequency, 433, 451
Orders of magnitude, 8	Prandtl model/closure, 451, 452, 453
Oscillatory motions, numerical approach to,	Predictability
55–59	behavior, 729f
Outcrop line, 676	gradual loss of, 728
Overreflection, 328	inherent problem of, 729
Over-relaxation, 224f, 545, 580	limit, 727
• • •	Predictor-corrector methods, 63–65, 64f, 181
P	Predictors, 718
Padding, 794	Pressure-gradient
Parameterization	anomaly, 712
cloud, 642-644	problem, 689
of shorter scale motions, 28	Primitive equations, 22, 107
subgrid-scale, 101, 616, 685	Probability density function, 738–739
Partial-derivatives finite differences, 789	Progressive vector diagram, 55, 56f
Patankar-type discretizations, 455–458	Prototypical vortex, 601
Peclet number, 167–168	Pseudo-compressible approach, 194, 195 <i>f</i>
Pedlosky, Joseph, 586	Pseudo dissipation, 444n
Penetrative convection, 461–466	Pseudospectral methods, 265
Perigee, 51	Pycnocline, waves concentration at,
Perturbation, 7	410–412
equations, 436	
growth rate, 323	O
wavelength of, 327	Quasi-equilibrium versions, 454
Phase lines, 774, 774 <i>f</i>	Quasi-geostrophic dynamics, 542
Phase speed, 277, 285, 323, 432, 777	energetics, 530–532, 531 <i>f</i>
of topographic waves, 286	length and timescale, 527–529
Philander, George, 723	simplifying assumption, 521–522
Physical advection, 179–180	Quasi-geostrophic equation, 522, 539, 577
Physical molecular diffusion, 332	for nonlinear motions, 526
Planetary heat budget, 627–631	Quasi-geostrophic formalism, 523, 529,
Planetary number, 279	530
Planetary waves, 278–283, 536	Quasi-geostrophic ocean modeling,
in stratified fluid, 532–539, 535 <i>f</i>	542–545

Index (825)

Quasi-geostrophic structure, 529	Rizzoli, Paola Malanotte, 724
Quasi-geostrophic theory, 573	Robin condition, 116
n	Robinson, Allan Richard, 551
R	Root-mean-square (RMS) error, 726
Radiating energy, 481	Rossby, Carl-Gustaf Arvid, 129, 280, 393
Radiating waves, 414–415	Rossby number, 108, 214, 215, 356–358,
Radiation law, 631	360, 521, 522, 573, 591, 602
Radius of deformation	temporal Rossby number, 108, 280f, 522
equatorial, 702	Rossby radius of deformation, 275
external, 373, 377–378, 536, 546	Rossby waves, see Planetary waves
internal, 360, 373, 378, 406, 528, 536,	Rotating fluids, 401
541, 590–591	Rotating framework, of reference, 41–44,
Random walk, 389	42f
Rayleigh equation, 319, 432	Rotating homogenous fluids, 204, 205
Rayleigh, Lord, 314	Rotating plane, free motion on, 47–50, 48f,
Rayleigh number, 462, 463, 465	49 <i>f</i>
Rayleigh-Ritz inequalities, 408, 421	Rotation, 10–12, 43, 45, 48
Recapitulation of equations, 106–107	Rotation effect, 521
Reciprocal Coriolis parameter, 55	Roughness height, 242
Red-black method, 225–226, 226f	Rounding errors, 120
Reduced-gravity model, 371, 372f, 372t,	Runge–Kutta methods, 65, 66f
374, 385, 476–477, 484–485, 713	
framework of, 712	S
Reduced rank	Salinity, 79, 82
approximations, 753	Salt budget, 82
covariance matrix, 752	Salt flux, 117
effect of, 752	Saturated adiabatic lapse rate, 354
Regional models, 639	Scale analysis, 23–28, 103–106
Relative error, finite-difference	Scales of motion, 8–10, 103–106, 103 <i>t</i> , 522
approximation, 29, 30 <i>f</i> , 31 <i>f</i>	Schmidt number, 446n
Relative velocity, 42, 43	Sea surface temperature (SST), 709, 716,
Relative vorticity, 527–528	719 <i>f</i>
Representer method, 749	Seasonal thermocline, 658
Reynolds, Osborne, 96, 100, 128, 160	Second-moment closure, 437
Reynolds-averaged equations, 99-101	Second-order approximation, 33
Reynolds averages, 436	Second-order closure, 437
Reynolds number, 109, 134–135, 137	Second-order convergence, 29
Reynolds stress, 100, 415, 416, 435, 436	Second-order difference, design of, 29
Reynolds stress tensor, 445	Second-order differential equation, 478
Rhines, Peter Broomell, 587	Second-order partial differential equations,
Rhomboidal truncation, 647f	111
Rhône River waters, 163–164, 164 <i>f</i>	Second-order truncation error, 29
Richardson extrapolation, 123	Seiches, 278, 379–380
Richardson, Lewis Fry, 20–22, 161, 363,	in the Adriatic Sea, 381
434, 438, 469, 550	Self-amplifying wave, 330
Richardson number, 109, 433–434, 453,	Semi-implicit scheme, 59, 182
461	Semi-Lagrangian methods, 649-652
Richardson's model, 20–22	Semicircle theorem, 435
Rigid-lid approximation, 113, 215-216,	Semidiscrete numerical scheme, 142
370–371, 385	SFT, see Sine Fourier transforms
Rigid-lid pressure equation, numerical	Shadow zones, 676
solution of, 217–221	Shallow flows, numerical simulation of,
Rigidity, homogeneous fluids, 6, 7f	257–258

Shallow-water equations, 300, 301	State variables, 110
Shallow-water model, 212, 729	State vector, 730, 732, 738, 739
momentum equations of, 216	Static stability, fluid in, 348–349
reduced-gravity model, 374	Steepest descent method, 226
Shallow-water system, deformation radius	Stefan–Boltzmann law, 628, 630
in, 406	Stern, Melvin Ernest, 622
Shear flow	Stokes theorem, 223, 334
finite-amplitude development of, 328	Stommel, Henry Melson, 660, 672, 698
idealized shear flow profile, 325	Storm surge, 303
in homogeneous fluid, 317f	Strang splitting method, 192, 195 <i>f</i>
in stratified fluid, 426, 429f	Stratification, 7, 10, 347, 348, 429, 431,
velocity shear, 239	442, 459
waves on, 318–321	atmospheric, 349–354 combination of rotation and, 358–360
Shear production, 444	
Shear production, 444	continuous, 531
Shear turbulence, 239–240	dynamical, 12–14
eddy viscosity, 242–243	Froude numbers, 356–358, 360
logarithmic profile, 240–242	Stratification frequency, see Brunt–Väisälä
Shear vorticity, 593 <i>f</i> –595 <i>f</i> Sherman-Morisson formula, 752	frequency
Short-wave radiation, 628, 628 <i>f</i> , 638	Stratified fluids, 347
Short-wave radiation, 628, 628 <i>f</i> , 638 Shortest wave, 34 <i>f</i>	instability of, 429–435
Sidereal day, 10	mixing of, 425–429 planetary waves in, 532–539, 535 <i>f</i>
•	with velocity shear, 426
Sigma coordinate system, 689, 690 <i>f</i>	•
Signal, aliasing, 33–35 Sine Fourier transforms (SFT), 791	Stratus-type clouds, 643 Streamfunction, 187, 530, 532, 533,
	539–541, 614
Smagorinski formulation, 102, 139, 451 Smagorinsky, Joseph, 655	,
SOI, see Southern Oscillation Index	distributions, 537 equation, numerical solution of,
	221–224
Solar radiation in atmosphere, 14–15 Southern hemisphere of Jupiter, 9 <i>f</i>	scale, 529
Southern Oscillation, 710	Strict stability, 61
Southern Oscillation Index (SOI), 710, 711 <i>f</i>	Stripes, 320
Specific humidity, 80	Subduction, 673–676
Spectral coefficients, see Time-dependent	Subgrid-scale parameterization, 101, 616,
coefficients	685
Spectral methods, 262, 644–649	Subgrid-scale processes, 693–695
Spectral space, 614	Successive over-relaxation (SOR), 225, 545
Spherical	Sulfuric acid in atmosphere, 164
coordinates, 660, 678, 769–770	Sumatra Island, 4, 311
geometry, 45, 77	Superbee scheme, 511, 512 <i>f</i>
Spherical harmonics, 645, 647f, 649	Surface Ekman layer, 251–254
orthogonality of, 646	structure of, 253
Splitting method, 191, 192 <i>f</i>	Surface waves, 395
Spurious mode, 152, 174	Sverdrup
SST, see Sea surface temperature	dynamics, 660f
Stability criterion, choice of, 61–63, 62 <i>f</i>	Harald Ulrik Sverdrup, 660
Stability functions, 453, 454	interior, 671
Stability parameters, 453	relation, 662–663
Staggered grid, 219, 291, 293	transport, 663–664, 671
Standard linear differential equation, 60	unit, 660
Standard microturbulent (eddy) diffusion,	Symmetric instability, 554
333	Synchronization, 21

Index (827)

C 1 470	T 1 (1 (470
Synoptic scale, 479	Transcendental equation, 478
Synopticity errors, 729	Transform grid, see Gaussian grid
T	Transform method, 616
TAO, see Tropical Atmosphere Ocean	Trapezoidal scheme, 63, 182
Taylor, Geoffrey Ingram, 6, 237	second-order, 183
Taylor columns, 209, 277, 215, 358, 360,	Trapezoidal time discretization, 171
401	Trapped waves, 275, 286, 416, 424, 705
Taylor curtains, 7	Triangular truncation, 646, 647f
Taylor expansion, 57, 179, 556	Tridiagonal system solver, 783–785
•	Tritium, 164
Taylor series, 26, 28–30, 32, 59, 149, 279 Taylor–Goldstein equation, 432	Tropical Atmosphere Ocean (TAO), 717
Taylor–Goldstein equation, 432 Taylor–Proudman theorem, 206, 231	Trough, 774
Temporal Rossby number, 108	Truncation error, 27, 29, 32, 57, 121–122
Thermal wind, 473–475, 474 <i>f</i> , 475 <i>f</i> , 561,	Tsunami, 5, 278, 311, 753
664–666	Turbulence closure, 435 <i>f</i> , 686
	closure problem, 437
Thermal-wind balance, 495, 555, 561, 565, 590	eddy viscosity and, 436, 441, 448
Thermals, 354, 463–465, 643	high Reynolds-number flows, 439
Thermals, 354, 403–403, 043 Thermocline	second-order closure, 437
along equator, 703	turbulent kinetic energy model, 443
definition, 379	zero-equation turbulence model, 443
main / permanent, 369, 551, 586, 658,	Turbulence-enhanced mixing, 437 Turbulent diffusion, 137–140
660, 661 <i>f</i> , 673	Turbulent diffusion coefficient, 138
movement of, 379, 707, 709, 717	Turbulent dissipation, 527
scaling, 677	Turbulent eddies, 133
seasonal, 658, 660, 669, 675	Turbulent energy cascade, 133, 133 <i>f</i>
subduction into, 673, 675	Turbulent flow, 131, 132, 134
ventilated thermocline, 676	Turbulent kinetic energy model, 443, 446
Thermodynamics, first law of, 80	Turbulent velocity, 240
Thermohaline circulation	Turning point, 410
subduction, 673–676	TV, see Total Variation
thermocline, scaling of, 677	TVD, see Total Variation Diminishing
ventilated thermocline theory, 676	Two-equation models, 450
Thomas algorithm, 783	Two-equation turbulence model, 450
3D-Var method, 738, 751	Two-layer models, 374–379, 568, 580
Three-dimensional rotating planet,	Two-layer quasi-geostrophic model, 22
acceleration on, 52–55, 54 <i>f</i> , 56 <i>f</i>	Two-layer stratification, 530–531, 531 <i>f</i>
Tidal force, 304, 308	Two-point methods, 64
Tidal potential, 307	F
Tides, 303	U
Time-dependent coefficients, 614	Upwelling
Time-dependent function, 731	coastal, see Coastal upwelling
Time scales of relaxation, 730	finite-amplitude, 486–489
Time-stepping algorithms, 57, 58, 786	front, variability of, 489–490, 491f
Time-varying models, 747	full, 486
Timescale analysis, 25f	process, 482–484, 483f, 484f
Topographic waves, 283–287	Upwelling-favorable winds, 484
Total Variation Diminishing (TVD) scheme,	Upwind scheme, 176–183, 177 <i>f</i> , 178 <i>f</i>
183, 188, 507, 508, 510–512	
Total Variation (TV), 508	V
Trade winds, 273, 483, 632, 636, 637, 657,	Väisälä, Vilho, 364
672, 709 <i>f</i>	Velocity equation, 219, 221

828) Index

	1.7.0.45.406.2054
Velocity profile, 239	internal, 7–8, 15, 106, 395 <i>f</i>
Velocity shear, 239	Kelvin, 273f, 314, 406, 489, 704, 706,
Ventilated thermocline theory, 676	709, 719
Veronis, George, 519	lee / mountain, 412f
Vertical density stratification, 431	nondispersive, 274, 277, 704
Vertical eddy diffusivity, 102	phase speed, 277, 281, 285, 320,
Vertical modes, 401–404	322–324, 400, 418, 432, 536, 705,
decomposition into, 407f	776–777
Vertical-momentum equation, 85, 431	planetary (Rossby), 16, 129, 278f,
Vertical stretching, 527–528	287–288, 324, 532 <i>f</i> , 541–542, 569,
Vertical velocity, determination of, 250	596, 706–707
Vertical-velocity scale, 104	unstable, 145, 322, 326, 428, 571-572
Viscous sink, 439	Wave propagation, 708f, 718
Volume-conservation equation,	Wavelength, 398, 401, 413, 417, 773–775
transformation of, 688	Wavenumbers, 135, 398–401, 773–775
Volume-transport streamfunction, 221	unresolved short wave transformation,
von Helmholtz, Hermann, 97, 314, 474	329
von Kármán constant, 241, 442, 459	Weak constraint, 748
von Neumann, John Louis, 22, 144, 161,	Weather
202, 550	versus climate, 627
von Neumann method, 173, 177, 184	forecasting, 642
Vortex semi-major axis, 9 Vortex semi-minor axis, 9	prediction by numerical simulations, 19,
	20
Vortices, 334, 339	Weather Prediction by Numerical Process
anomalous layer volume due to, 605	(Richardson), 20–21
emergence of isolated, 618f	Wedge instability, 561
gradients in, 607	Weighted-residual equations, 259
prototypical, 601	Weighted-residual method, 260
secondary drift of, 609, 610f	Westerlies, 658
Vorticity	Western boundary currents, 669–673
distribution, 334	Western North Atlantic, currents in, 7
dynamics, 212–215	Westward intensification, 672
and rotation, 770–771	Westward jets, 599f, 600
347	Westward velocity, 324
W	Wind
Walker circulation, 710, 715, 717	impulse, 486–489
Walsh Cottage, 41	mixing, 459–461
Warm front, 490, 492 <i>f</i>	stress, 459
Warning system, 4	thermal, 473–475, 474f
Waves	upwelling-favorable, 484
amplitude, 275, 416, 773	Wind-driven horizontal transport, 252
continental shelf, 286	Wind-induced seiches, lakes, 379–381
dispersion, 780	Wind-stress anomaly, 712, 714
dispersion relation, 173–175, 276, 280,	•
285, 297–298, 326, 398, 404, 405,	Υ
414, 534, 705, 780	Yoshida, Kozo, 520
equatorial, 703f	•
group velocity, 282, 394, 400, 414–415,	Z
536, 781–782	Zabusky, Norman Julius, 334, 344
inertia-gravity (Poincaré), 276f, 286,	Zero-equation turbulence model, 443
289, 315, 401, 486, 704–706	Zonal velocity, 712, 713
,	