A	circulation, 341-349
Absolute angular momentum, 342, 343	oscillations, 17–18
Absolute coordinate system, 96	zonal mean, 345–349
Absolute momentum, 151, 292	Annular modes, 364
Absolute vorticity, 100, 101, 109, 112, 116,	Anomaly correlation, 485, 485f
119f, 213	Antibaric flow, 77
advection of, 465	Anticyclonic flow, 73, 74
conservation of, 119, 396	APE. See Available potential energy
of flow, 151	Arbitrary vector, 33
geostrophic, 185	Asian monsoon, 386–387, 388f
Acceleration	Asymmetric atmospheric circulations,
centripetal, 10–11, 10 <i>f</i>	389
eddy-driven mean flow, 340	Atmosphere. See also Middle atmosphere
gradient tangential, 74	barotropic and baroclinic, 84
inertial, 127, 261	data, standard, 507–508
net mean flow, 439f, 444	structure of static, 18–23
wave-driven mean-flow, 433	turbulence, 256–258
Acoustic waves, 131, 136-139	Atmosphere-ocean coupling, 391
Adiabatic cooling, 56, 331, 337, 365,	Atmospheric equatorial wave propagation,
398–400	401
Adiabatic lapse rate, dry, 54	Atmospheric general circulation models
Adiabatic method, 53, 85, 87, 228	(AGCMs)
Adiabatic speed of sound, 139	development of, 367
Advection, temperature, 32, 196, 284	formulation of, 368
vorticity, 183	physical processes and
Aerodynamic formula, 316	parameterizations, 369–370
African wave disturbances, 384–386	Atmospheric motions, principles of, 31
AGCMs. See Atmospheric general	Atmospheric tracers, motion of, 446
circulation models	Available potential energy (APE), 227–229
Ageostrophic circulation, 201–203, 203f,	
289 <i>f</i>	В
cross-frontal, 287–290	Backing wind, 83, 83f
Ageostrophic wind, 43, 85, 181–185	Balanced flow, 69-77
Air parcel and particle, 4	Balance equation, nonlinear, 397
Lagrangian motion of, 418-420	Baric flow, 77
Air-sea interaction, 319	Baroclinic atmospheres, 84
Along-front velocity in geostrophic	Baroclinic disturbance, model of, 100f, 177,
balance, 286, 287	204–206
Amplification, 246	Baroclinic instability, 177, 213-251
Angular momentum	continuous stratified atmosphere and,
absolute, 342, 343	234–245

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

Baroclinic instability (continued)	frame, 46
neutral modes, growth and propagation	system, 37, 200
of, 245–251	Cartesian geometry, 401
normal mode, 215–226	CAT. See Clear air turbulence
Rayleigh theorem, 237–241	Centered differences, 456, 457–458
symmetric, 290–294	Centrifugal force, 10-11, 14, 15, 318
Baroclinic (Ertel) potential vorticity	Coriolis force and, 72–73, 313
equation, 120-122	Centripetal acceleration, 10-11, 10f
Baroclinic Rossby wave, 180f, 219	CFL stability criterion. See Courant-
Baroclinic waves, 177, 328, 355, 361	Friedrichs-Levy stability criterion
energetics of, 227–234	Chaos, 364
energy equations for two-layer model,	Chaotic system, 482
229–234	Charney–DeVore model, 363f, 364
potential energy, 227–229	Charney, J. G., 454
vertical motion in, 223–226, 225 <i>f</i>	Chemical timescale, 447–448
Barometer, 33	Chemical tracers, 447–448
Barotropic atmospheres, 84	Circulation. See also Mesoscale circulation
Barotropic fluids, vorticity and, 118–120	Tropical circulation
Barotropic instability, 214, 240	ageostrophic, 201–203, 289f
Barotropic potential vorticity, 118–120	cross-frontal, 287–290
Barotropic Rossby waves, 161–163	diabatic, 325
Barotropic vorticity equation, 119	extratropical, structure of, 171–178
in finite difference, 455, 464–467	Hadley, 326, 332
in spherical coordinates, 468–470	secondary, 270–275, 284, 313
Bayes's theorem, 511	theorem, 95–99
Bjerknes circulation theorem, 98	Walker, 389–390
Blocking patterns, 361–362	zonal-mean circulation of middle
Body forces, 4	atmosphere, 417–426
Boundary condition, 89, 403	Circulation, general, 325
Dirichlet, 190	angular momentum, 341–349
Neumann, 190	climate regimes, 362–364
no-slip, 255	conventional Eulerian mean, 330–337
for pressure tendency, 195	dynamical formulation, 368
Robin, 190	jet stream and storm tracks, 359–361
in two-layer model, 237	Lorenz energy cycle, 349–355
Boundary value problem, 367	low-frequency variability, 325, 361–366
Boussinesq approximation, 57–58,	monsoonal, 325
146, 178, 181, 184, 255,	nature of, 326–328
285, 288	numerical simulation of, 367–370
β-plane, 160, 179, 206, 401, 464	quasi-stationary, 325
Brunt–Väisälä frequency, 56 <i>n</i>	* · · · · · · · · · · · · · · · · · · ·
Bulk aerodynamic formula, 262	stationary waves, 356–359 transformed Eulerian mean, 337–339
Buoyancy frequency, 56	
Buoyancy oscillations, 55, 144, 294	zonally averaged, 328–341
Buoyancy waves. See Gravity waves	Clausius–Clapeyron equation, 59, 503
	Clear air turbulence (CAT), 145
Burger number, 187, 188	Climate feedbacks, 370–373
C	Climate models, 368, 371, 372
•	Climate variability, 1
CAPE. See Convective available potential	Component equations in spherical
energy	coordinates, 37–41
Cartesian coordinate	Computational instability, 459, 460
directions, 7	Computational mode, 463
form and vorticity equation, 104–106	Computational stability, 458–460

Index (521)

Condensation heating, 398–400	Coriolis acceleration, 36
vorticity equation in, 396	Coriolis force, 5, 9, 14-17, 16f, 43-44, 284,
Conditional instability, 62–64, 319, 321	318, 326, 331, 333, 335, 338
Conditional instability of the second kind	causes of, 336–337
(CISK), 319	and centrifugal force, 72-73, 313
Conditional probability, 511–512	role in supercell dynamics, 306
Confluent flow, 283	Coriolis parameter, 16, 42, 105, 118, 160,
Conservation laws	179, 206, 401, 406
Boussinesq approximation, 57-58	β -plane approximation, 160
component equations in spherical	f-plane approximation, 179
coordinates, 37–41	variation of, 422
continuity equation, 45-49	Cost function, 477, 481f
control volume, 31	Coupled climate models, 367
momentum equation in rotating	Coupled model intercomparison project
coordinates, 35–37	(CMIP), 367
scale analysis of momentum equations,	Courant-Friedrichs-Levy (CFL) stability
41–42	criterion, 459–460
thermodynamic energy equation, 50-53	Courant number, 458
thermodynamics of dry atmosphere,	Covariance, 257, 479
53–57	Critical level, 222, 299
thermodynamics of moist atmosphere,	Critical surface, 429
58–64	Cross-frontal circulation, 287–290
total differentiation, 31–35	Cumulus cells, 383
Conservation of energy, 50–53	Cumulus convection, 302–305, 319
Conservation of mass, 45–49	Curvature
Continuity equation, 407	effect, 14–17
Eulerian derivation, 46–47	radius of, 70, 72–73
in isobaric coordinate system, 68–69, 207	of streamlines and trajectories, 78, 80 terms, 40
Lagrangian derivation, 47–48	vorticity, 103, 104
scale analysis of, 48–49	Cyclogenesis, 205–206, 213, 214, 215f
Continuum, approximation, 3–4	Cyclones
Control volume, 31	extratropical, 177, 180f, 250
Convection, cumulus, 302–305, 319	surface, development of, 177, 180f,
Convective adjustment, 475	243–244
Convective available potential energy	tropical, 312–321
(CAPE), 302–303	Cyclonic flow, 73, 74
Convective heating, 379	Cyclostrophic flow, 73–74
Convective storms, 306–312	force balance in, 75f
Conventional Eulerian mean, 330–337,	Cyclostrophic wind, 73–74
418–420	5
Coordinates	D
Cartesian, 500	Dalton's Law, 59
cylindrical, 500	Darwin-Tahiti pressure difference, 390, 391
generalized, 22–23	Data assimilation, 478–481
geostrophic, 287n	for many variables, 479–481
inertial, 13	for single variable, 476–478
isentropic, 120–121	Deflecting forces, 15
isobaric, 21, 206	Deformation, radius of, 157, 243
log-pressure, 235–237	Delayed oscillator model, 391
natural, 70–71	Derivative, total and local, 31–33
sigma, 343–345	Diabatic circulation, 339
spherical, 37–41, 501	Diabatic cooling, 420, 450

Diabatic heating, 56, 57, 401, 417, 420, 450	Ekman, V.W., 267
in equatorial regions, 389	Eliassen-Palm (EP) flux, 338, 338f, 339
monsoons, 388	convergence, 416, 424
in tropics, 377	in wave activity, 433
Diagnostic relationship, 42–43	Elliptical polarization, 150
Dimensional homogeneity, 2	Elliptic boundary value problem, 289, 294
Dirichlet condition, 190	El Niño-Southern Oscillation (ENSO),
Discretization error, 463	390–392
Dispersion, 131–132	Energetics of baroclinic waves, 227-234
Disturbance vorticity, 224	Energy
Divergence, 8, 24f, 25	CAPE, 302-303
equation, quasi-geostrophic, 186	conservation of, 50–53
theorem, 499	equations for two-layer model, 229-234
Doppler shifting, 139, 429, 444	equation, thermodynamic, 215, 216, 24
Downgradient diffusion, 8	flow in amplifying baroclinic wave, 235
Downslope windstorms, 299–302	Lorenz energy cycle, 349–355
Downward control, 422	potential, 227–229
Drag coefficient, 262	transfer, 280
Dry air, 321	turbulent kinetic, 259-261
Dry static energy, 61	EnKF. See Ensemble Kalman filter
Dynamical instability, role of, 213	Ensemble forecasting, 481–486
Dynamical timescale, 447–448	Ensemble Kalman filter (EnKF), 480
Dynamical tracers, 446–447	Ensemble spread, 486
Dynamic meteorology, 1–4	Enstrophy, 466, 467
_ , g,,	Entrainment, 303–305
E	Entropy form of first law of
Eady stability model, 235, 242, 243	thermodynamics, 53, 54
Eady stability problem, 241–245	EP flux. See Eliassen-Palm flux
Eady wave, properties of, 244f	Equations of motion, scale analysis of,
Earth system models (ESMs), 367	41–45
Eastward-propagating waves, 445	Equatorial β -plane, 401
ECMWF. See European Centre for	Equatorial intraseasonal oscillation, 392
Medium-Range Weather Forecasts	Equatorial Kelvin waves, 404–406, 405 <i>f</i> ,
Eddies, 328, 329	406 <i>f</i>
diabatic process, 354	Equatorial motions, steady forced, 406–409
geostrophic streamfunction, 363	Equatorial stratosphere, waves in, 435–440
stress, 343	Equatorial stratosphere, waves in, 435–440 Equatorial wave disturbances, 381–384
	observed, 438–440
viscosity, 264 vorticity, 114	
Eddy flux, 333 <i>f</i>	schematic model for, 381, 382 <i>f</i> theory, 401–406
heat, 330, 335–336	•
	Equivalent barotropic model, 454 Equivalent potential temperature, 59–61,
momentum, 330, 334 <i>f</i> , 335–337, 335 <i>f</i> , 336 <i>f</i>	294, 304, 503–504
3	Equivalent static stability, 398
potential vorticity, 329	Ertel potential vorticity, 120–122, 175,
Eddy kinetic energy, 352, 353, 388	¥
Eddy motions, 347, 417	289
Eddy potential energy, 387–388	conservation law, 184
Eddy stress, 262n	theorem, 111, 112, 114
Eddy transport, 425	Eulerian control volume, 31
Eddy viscosity coefficient, 264	continuity equation, 45, 46f
e-folding time scale, 272	Eulerian derivation, 46–47
Ekman layer, 266–268, 267 <i>n</i> , 390	Eulerian mean
modified, 269–270	conventional, 330–337, 418–420

in log-pressure coordinates, 349	Forecasting. See Numerical modeling and
meridional streamfunction, 331f, 333f	prediction
model, 355	Form drag, 363
by poleward heat fluxes, 334	Four-dimensional data assimilation
transformed, 337–339, 420–424	(4DVAR), 480
European Centre for Medium-Range	Fourier
Weather Forecasts (ECMWF), 480	coefficients, 131
Exner function, 121	component, 131
Explicit time differencing, 457–458	modes, 297
Extratropical circulation, structure of,	series, 130–131
171–178	f-plane approximation, 179
Extratropical cyclones, 250	Free atmosphere, 255
Eyewall, 313	Free transverse oscillations, 294
г	Frequency, intrinsic, 148
F	Friction, planetary boundary layer,
Ferrel cell, 335, 336	263
Field variables, 3–4	Friction velocity, 268
Finite difference approximations, horizontal	Frontal circulation, 280
divergence using, 86	Frontogenesis, 280–290
Finite difference method, 455–456	Fronts, 172, 280–290
barotropic vorticity equation, 455,	gust, 306, 310
464–467, 465 <i>f</i>	Froude number, 300, 301
centered, 456, 457–458	6
computational stability, 458–460	G
explicit time differencing, 457–458	Gas constant, 18
implicit time differencing, 460–461	Gaussian functions, 406
Finite Fourier series expansion, 455	Geocentric reference frame, 9
First law of thermodynamics. See	Geopotential
Thermodynamic energy equation	constant, 11–12
Flow	height, 19, 507t, 508t
balanced, 69–77	perturbation, 220–221
baric, 77	tendency equation, 200
cyclostrophic, 73–74	Geostrophic approximation, 42-44
geostrophic, 71–72	Geostrophic balance, 42, 43
gradient, 74–77	adjustment to, 156–159
inertial, 72–73	along-front velocity in, 286, 287
time-averaged, 356–361	Geostrophic coordinates, 287n
Fluid instabilities, 213	Geostrophic equilibrium, balance of forces
Flux. See also Eddy flux	for, 72, 72 <i>f</i>
gradient theory, 264	Geostrophic flow, 71–72
Richardson number, 260–261	Geostrophic momentum approximation,
turbulent momentum, 261, 262 <i>n</i>	287
Forces	Geostrophic motion, 71, 284
balance, 75, 76 <i>f</i>	Geostrophic streamfunction, 215
body, 4	Geostrophic vorticity, 215, 220
centrifugal, 11	Geostrophic wind, 42-43, 181, 206, 215,
Coriolis. See Coriolis force	286
deflecting, 15	vertical shear of, 81, 81f
gravity, 8–9, 11–13, 12 <i>f</i>	Gradient flow, 74–77
hydrostatic equilibrium, 19f	Gradient tangential acceleration, 74
pressure gradient, 5–7, 7f	Gradient wind approximation, 74-77
surface, 4	Gravitational constant, 8
viscous, 6–8	Gravitational force, 8–9

Gravitational potential energy, 227	Incompressible fluid, 49
Gravity, 11–13, 12 <i>f</i>	Induced flow, 188–193
Gravity waves	Inertia circle, 73
inertia, 152–156	Inertia gravity waves, 141, 152–156, 152 <i>f</i> ,
internal, 145–150	171
modified by rotation, 150–156	Inertial flow, 72–73
shallow water, 139–144	Inertial instability, 151, 213
topographic, 163–165	Inertial motion, 9, 73
Grid point models, 473	Inertial oscillation, 73, 150–151
Group velocity, 132–133, 132 <i>f</i>	Inertial reference frame, 33, 34
Gust front, 306, 310	law of motion (second) in, 35–37
	Inflow of mass, 46, 47
Н	Initial value approach, 214
Hadley circulation (cell), 326, 332, 333 <i>f</i> ,	Initial value problems, 367, 455
343, 378, 381	Instability
Hadley, George, 326	baroclinic, 177, 213-251, 290-294
Heat	barotropic, 214, 240
latent, 313, 319	computational, 459, 460
specific, 52, 53	conditional, 62–64, 321
Heating, condensation, 398–400	conditional of the second kind (CISK),
Height tendency equation, 194–197, 207	319
Helmholtz theorem, 396	dynamical, 213
Hermite polynomial, 403	fluid, 213
High-index state, 362	hydrodynamic, 213–215
Horizontal divergence, using finite	inertial, 151, 213
difference approximations, 86	Kelvin–Helmholtz, 280
Horizontal momentum equation, 67–68,	parcel, 213
236, 286	symmetric, 213–214
approximate, 43	wave, 214
in natural coordinate system, 71	Intergovernmental Panel on Climate
scale analysis of, 42, 42t	Change (IPCC), 367
Horizontal shearing deformation, 281, 282f	Internal gravity waves, 144–150, 425
Horizontal stretching deformation, 281, 282f	Intertropical convergence zone (ITCZ),
Horizontal velocity	378–381
field, 43, 44, 48	Intrinsic frequency, 148
vector, 67	Inversion, potential vorticity, 188–189
Hot towers, 378–379, 383–384	Isentropic coordinates
Hurricanes, 312	momentum equation in, 120
development, 318–321	system, 65
dynamics of, 314–318	Isentropic vorticity, 121–122
Hydrodynamic instability, 213–215	Isobaric coordinates, 67–69
Hydrostatic approximation, 44–45	QG equations in, 206
Hydrostatic balance, 18, 44, 55, 182, 206,	Isobaric coordinate system, 21, 106–107
313	continuity equation in, 207
Hydrostatic equation, 18–20, 21, 115, 120,	equations of motion in, 120–121
236	hydrostatic equation, 18–20, 21
Hydrostatic equilibrium, 19f, 44–45	potential vorticity equation, 121
Hydrostatic thermodynamic energy	scale analysis and, 179
equation, 215	vorticity and, 106–107
I	Isobaric coordinate system, basic
	equations
Ideal gas law, 54, 55, 58–59, 82	continuity equation, 68–69
Implicit time differencing, 460–461	geostrophic wind using, 67–68

Index (525)

horizontal momentum equation, 67–68	Linearized equations, 136
thermodynamic energy equation, 69	Linear perturbation analysis, 217-223
Isolated ridges, flow over, 297-298	Linear stability theory, 318
	Liouville equation, 482, 483f
J	Local derivative, 31–33
Jet streak, 192, 193 <i>f</i> , 202	Logarithmic wind profile, 269
Jet stream, 172, 175, 359–361	Log-pressure coordinates, 235–237, 328–329
K Kalman gain matrix, 479	Longitudinal dependence of unit vector, 35 <i>f</i> , 38, 39 <i>f</i>
Kelvin-Helmholtz instability, 280	Longitudinally dependent time-averaged flow, 356–361
Kelvin's circulation theorem, 97, 110	Longitudinal waves, 136-139
Kelvin's theorem, 110	Long-lived tracers, 448, 449
Kelvin waves, 404–406, 405f, 406f	Long-wave stabilization, 221
in observational data, 438–440	Lorenz energy cycle, 349–355
vertically propagating, 436–437 Kinematics, 23–25	Lower-level cyclonic vorticity, 215f
of frontogenesis, 281–285	Low-frequency variability, 325, 361–366
method, 85–86	
Kinematic viscosity coefficient, 7	M
Kinetic energy, 159, 228–229, 291, 303,	Madden–Julian oscillation (MJO), 392,
327, 355	393 <i>f</i>
See also Potential energy	Marginal stability, 222
eddy, 352, 353, 388	Mass, conservation of, 45–49, 115
perturbation, 231, 233	Mass flux, 49
power spectrum of, 74f	Material derivative, 31
in thermodynamic energy, 50	Maxwell relations, 314
turbulent, 259–261	Mean energy cycle, 354f
Kronecker delta, 198	Mean zonal wind, 328
K theory, 264	Measurements, SI (Systéme International) units of, 2–3
L	Mechanical energy, 52
Lagrangian control volume, 31, 50	Mechanical energy equation, 52
as result of fluid motion, 48, 48f	Meridional circulation
in thermodynamic system, 50	Eulerian mean, 330–337
Lagrangian derivation, 47–48	residual, 337
Lagrangian motion of air parcels, 418–420	transformed Eulerian mean, 337–339
La Niña, 390	Meridional force balance for Kelvin mode,
Lapse rate of temperature, 54	406
pseudoadiabatic, 504–505	Meridional wind, statistical analysis of,
Latitude dependence of unit vector, 38, 39f	177, 178 <i>f</i>
Law of gravitation, 8	Mesopause, 413
Law of motion	Mesoscale circulation
Newton's first, 14	convective storms, 306–312
Newton's second, 14, 33, 35-37	cross-frontal circulation, 287-290
Lax equivalence theorem, 463	cumulus convection, 302-305, 319
Leapfrog differencing method, 458	energy sources for, 279-280
Lee wave, 298–299	fronts and frontogenesis, 280-290
Level of free convection (LFC), 60	hurricanes, 312–321
Lifting condensation level (LCL), 60	mountain waves, 294-302
Likelihood, 511–512	symmetric baroclinic instability,
Linear interpolation, 224	290–294

526) Index

atmosphere Meteorology applications of, 33 instabilities in, 214 Metric terms, 15 Middle atmosphere, 413 conventional Eulerian mean, 418–420 layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MIO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Mormal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Northern Hemisphere troposphere, 172 Northern Hemisphere troposphere, 172 Northern Hemisphere troposphere, 435, 464–467 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in fini	Mesosphere, 413. See also Middle	Ν
worticity in, 102–104 Neumann boundary condition, 190 Neutral curve, 221, 222f Neutral modes downstream development, 250–251 growth and propagation of, 245–250 Neutral stability, 242 curve, 222f Neutral modes downstream development, 250–251 growth and propagation of, 245–250 Neutral stability, 242 curve, 222f Neutral waves, transient growth of, 247–250 Newtonian relaxation rate, 421 Newtonian relaxation rate, 426 Nondimensional geostrophic valuations, 407 Nonlinear balance equa	*	
applications of, 33 instabilities in, 214 Metric terms, 15 Middle atmosphere, 413 conventional Eulerian mean, 418–420 layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratosphere, 435–440 zonal-mean transport, 424–426 midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture development, 250–250 Newtoni's laws of gravitation, 8 of motion (first)	*	•
instabilities in, 214 Metric terms, 15 Middle atmosphere, 413 conventional Eulerian mean, 418–420 layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden-Julian oscillation Moist static energy, 61 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Neutral curve, 221, 222f Neutral modes downstream development, 250–251 growth and propagation of, 245–250 Neutral stability, 242 curve, 222f Neutral stability, 242 curve, 22f Neutral stability, 242 curve, 22f Neutral	<i>C.</i>	
Metric terms, 15 Middle atmosphere, 413 conventional Eulerian mean, 418–420 layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratosphere, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26f tropical, 392–398 Neutral modes downstream development, 250–251 growth and propagation of, 245–250 Neutral stability, 242 curve, 222f Newton is laws of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nondinear balance equation, 89 Nondinear balance equation, 397 Nonlinear partial differential equations, 41 baroclinic instability, 215–226 Northern Hemisphere, 430 Northe	**	· · · · · · · · · · · · · · · · · · ·
Middle atmosphere, 413 conventional Eulerian mean, 418–420 layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratosphere, 435–440 waves in equatorial stratosphere, 435–440 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist trace convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26f tropical, 392–398 downstream development, 250–251 growth and propagation of, 245–250 Neutral stability, 242 curve, 222f Neutral stability, 215 verve, 222f Noancecleration theorem, 433 sondinnean relaxation rate, 421 vervioa, 247–250 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equa		•
conventional Eulerian mean, 418–420 layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Nonlinear partial differential equations, 4170 See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 growth and propagation of, 245–250 Neutral stability, 242 curve, 222f Neutral stability, 215 veroins, 431 sof motion (first), 40 fmotion (second), 4, 9, 10, 14, 33, 35–37 Nonacceleration theorem, 433 Nonlinear partial differential equations, 41 horizontal, 41 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 horizontal dispe		
layers of, 413 quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 Miosture convergence, low-level, 401 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Neutral stability, 242 curve, 222f Neutral waves, transient growth of, 247–250 Newtonian relaxation rate, 421 Newtonian relaxation rate, 421 Newton's laws of gravitation, 8 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nonacceleration theorem, 433 Nondimensional geostrophic wind, 187, Nonlinear balance equations, 497 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 242 curve, 222f Neutral waves, transient growth of, 247–250 Newtonian relaxation rate, 421 Newton's laws of gravitation, 8 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nonacceleration theorem, 433 Nondimensional geostrophic wind, 187, Nonlinear balance equations, 497 Nonlinear balance equation, 397 Nonlinear balance equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470		
quasi-biennial oscillation, 440–445 structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 sonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Nonlinear partial differential equations, 410 sisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's laws of gravitation, 8 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nondinear balance equation, 397 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 incretial simulation of general circulation, 367–370 observed equatorial waves, 438–440		
structure and circulation of, 413–417 trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Wotton on the definition of general circulation, 392–398 Wotton's first law of, 9 scales of, 26t tropical, 392–398 Neutral waves, transient growth of, 247–250 Newton's laws of gravitation rate, 421 Newton's laws of gravitation, 8 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nonacceleration theorem, 433 Nonalinear balance equation, 497 Nonlinear partial differential equations. 41 horolinear partial differential equations. 41 horolinear partial differential equations, 42 horolinear partial differential equations, 41 horolinear partial differential equations, 41 horolinear partial differential		• •
trace constituent transport, 446–450 transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden-Julian oscillation Moist tatic energy, 61 Moisture variables, 503–505 Molecular diffusion, 255 molecular diffusion in sability, 215–226 mortion (approximation of motion equations, 455–464 barotropic vorticity equation in spherical coo		· ·
transformed Eulerian mean, 420–424 vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 sonal-mean transport, 424–426 midlatitude β-plane approximation, 160, 179 Nonlinear partial differential equations, 35–37 Nonacceleration theorem, 433 Nondimensional geostrophic wind, 1877 Nonlinear partial differential equations, 417 Nonlinear partial differential equations, 418 baroclinic instability, 215–226 Northern Hemisphere, 430 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26f tropical, 392–398 Observed equatorial waves, 438–440		
vertically propagating planetary waves, 426–430 warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 Mixing ratio, 59, 61, 503 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's laws of gravitation, 8 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nonacceleration theorem, 433 Nondimensional geostrophic wind, 187/ Nonlinear balance equation, 397 Nonlinear partial differential equations, 41 baroclinic instability, 215–226 Northern Hemisphere, 430 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 214 baroclinic instability, 215–226 Northern Hemisphere, 430 baroclinic instability, 215–226 baroclinic instability,		
warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β -plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nonlinear balance equation, 397 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Norlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical dispersion, 464 Numerical modelling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Oobserved equatorial waves, 438–440		
warmings, sudden stratospheric, 430–435 waves in equatorial stratosphere, 435–440 zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MIO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 of motion (first), 4 of motion (second), 4, 9, 10, 14, 33, 35–37 Nonacceleration theorem, 433 Nondimensional geostrophic wind, 1877 Nonlinear balance equation, 397 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Oobservation operator, 479 Observed equatorial waves, 438–440		
$\begin{array}{c} 430-435\\ \text{waves in equatorial stratosphere,}\\ 435-440\\ \text{zonal-mean circulation of, } 417-426\\ \text{zonal-mean transport, } 424-426\\ \text{Midlatitude } \beta\text{-plane approximation, } 160,\\ 179\\ \text{Mixing length hypothesis, } 264-266\\ \text{Mixing ratio, } 59, 61, 503\\ \text{MiO. } See \text{ Madden-Julian oscillation}\\ \text{Moisture convergence, low-level, } 401\\ \text{Moisture variables, } 503-505\\ \text{Molecular diffusion, } 255\\ \text{Molecular diffusion, } 255\\ \text{Momentum equations, } 407\\ \text{horizontal, } 67-68\\ \text{isentropic coordinates and, } 120\\ \text{planetary boundary layer, } 261-270\\ \text{quasi-geostrophic, } 186, 207\\ \text{in rotating coordinates, } 37-41\\ \text{transformation of, } 33\\ \text{Monsoons, } 325, 386-389\\ \text{Montgomery streamfunction, } 120\\ \text{Motion}\\ \text{and the Coriolis force, } 16f\\ \text{equations of, } 455-464\\ \text{geostrophic, } 71\\ \text{inertial, } 9\\ \text{Newton's first law of, } 9\\ \text{scales of, } 26t\\ \text{tropical, } 392-398\\ \end{array}$		•
waves in equatorial stratosphere,		
435–440Nonacceleration theorem, 433zonal-mean circulation of, 417–426Nondimensional geostrophic wind, 187rzonal-mean transport, 424–426Nonlinear balance equation, 397Midlatitude $β$ -plane approximation, 160, 179Nonlinear balance equation, 397Mixing length hypothesis, 264–266Nonlinear partial differential equations, 41Mixing ratio, 59, 61, 503Nonlinear partial differential equations, 41Mixing ratio, 59, 61, 503Normal mode method, 214Moisture convergence, low-level, 401baroclinic instability, 215–226Moisture variables, 503–505Northern Hemisphere, 430Monetum equations, 407Northern Hemisphere troposphere, 172horizontal, 67–68Northern Hemisphere troposphere, 172isentropic coordinates and, 120Northern Hemisphere troposphere, 172planetary boundary layer, 261–270Darotropic vorticity equation in finite difference, 455, 464–467quasi-geostrophic, 186, 207barotropic vorticity equation in spherical coordinates, 35–37scale analysis of, 41–42barotropic vorticity equation in spherical coordinates, 468–470data assimilation, 475–481finite difference, 455, 464–467barotropic vorticity equation models, 472–475primitive equation models, 472–475Motionpurpose of, 453and the Coriolis force, 16fpurpose of, 455equations of, 455–464peostrophic, 71inertial, 9Newton's first law of, 9Newton's first law of, 9Observation operator, 479Observed equatorial waves, 438–440		
zonal-mean circulation of, 417–426 zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MiO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Nondimensional geostrophic wind, 187 Nonlinear balance equation, 397 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical instability, 215–226 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 O Observation operator, 479 Observed equatorial waves, 438–440		
zonal-mean transport, 424–426 Midlatitude β-plane approximation, 160, 179 Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MiO. See Madden-Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Nonlinear balance equation, 397 Nonlinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Nos-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 41 Northern Hemisphere troposphere, 172 Nos-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440	zonal-mean circulation of, 417–426	
Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Norslinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Norslinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Norslinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Norslinear partial differential equations, 41 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Norslinear partial difference, 430 Northern Hemisphere troposphere, 172 Numerical dispersion, 464 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
Mixing length hypothesis, 264–266 Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Mormal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Northern Hemisphe	Midlatitude β -plane approximation, 160,	Nonlinearity, 455
Mixing ratio, 59, 61, 503 MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Normal mode method, 214 baroclinic instability, 215–226 Northern Hemisphere troposphere, 172 Numerical dispersion, 464 Numerical dispersion, 464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468	179	Nonlinear partial differential equations,
MJO. See Madden–Julian oscillation Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Morstore Madden–Julian oscillation Northern Hemisphere, 430 Northern Hemisphere troposphere, 172 Nos-slip boundary condition, 255 Numerical dispersion, 464 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in finite difference, 455, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observation operator, 479 Observed equatorial waves, 438–440	Mixing length hypothesis, 264–266	41
Moist static energy, 61 Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion Motion Motion Motion And the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Northern Hemisphere, 430 Northern Hemisphere troposphere, 172 Numerical dispersion, 464 Numerical dispersion, 464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in finite difference, 455, 464–470 data assimilation, 475–481 finite difference, 455, 464 barotropic vorticity equation in fini	Mixing ratio, 59, 61, 503	Normal mode method, 214
Moisture convergence, low-level, 401 Moisture variables, 503–505 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Northern Hemisphere troposphere, 172 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical dispersion, 464 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440	MJO. See Madden-Julian oscillation	baroclinic instability, 215-226
Moisture variables, 503–505 Molecular diffusion, 255 Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 No-slip boundary condition, 255 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in finite difference, 455, 464–467 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 purpose of, 453 spectral method, 467–472 Numerical isimulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440	Moist static energy, 61	Northern Hemisphere, 430
Molecular diffusion, 255 Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Numerical dispersion, 464 Numerical dispersion, 464 Numerical dispersion, 464 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440	Moisture convergence, low-level, 401	
Momentum equations, 407 horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Numerical modeling and prediction approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440	Moisture variables, 503–505	•
horizontal, 67–68 isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 approximation of motion equations, 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
isentropic coordinates and, 120 planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 455–464 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
planetary boundary layer, 261–270 quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
quasi-geostrophic, 186, 207 in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440	•	
in rotating coordinates, 35–37 scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 barotropic vorticity equation in spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
scale analysis of, 41–42 in spherical coordinates, 37–41 transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 spherical coordinates, 468–470 data assimilation, 475–481 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 spectral method, 467–472 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
in spherical coordinates, 37–41 transformation of, 33 finite differences, 455–456 Monsoons, 325, 386–389 historical background, 453–455 Montgomery streamfunction, 120 primitive equation models, 472–475 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 data assimilation, 475–481 finite differences, 455–466 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
transformation of, 33 Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 finite differences, 455–456 historical background, 453–455 primitive equation models, 472–475 primitive equation models, 472–475 primitive equation models, 472–475 Numerical simulation of general circulation, 367–370 Observation operator, 479 Observed equatorial waves, 438–440		
Monsoons, 325, 386–389 Montgomery streamfunction, 120 Motion and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 historical background, 453–455 primitive equation models, 472–475 spectral method, 467–472 Numerical simulation of general circulation, 367–370 O Observation operator, 479 Observed equatorial waves, 438–440		
Montgomery streamfunction, 120 primitive equation models, 472–475 Motion purpose of, 453 and the Coriolis force, 16f spectral method, 467–472 equations of, 455–464 Numerical simulation of general circulation, 367–370 inertial, 9 Newton's first law of, 9 scales of, 26t Observation operator, 479 tropical, 392–398 Observed equatorial waves, 438–440		
Motion purpose of, 453 and the Coriolis force, 16f spectral method, 467–472 equations of, 455–464 Numerical simulation of general geostrophic, 71 circulation, 367–370 inertial, 9 Newton's first law of, 9 scales of, 26t Observation operator, 479 tropical, 392–398 Observed equatorial waves, 438–440		
and the Coriolis force, 16f equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 spectral method, 467–472 Numerical simulation of general circulation, 367–370 O O O Servation operator, 479 Observed equatorial waves, 438–440		
equations of, 455–464 geostrophic, 71 inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 Numerical simulation of general circulation, 367–370 O O Observation operator, 479 Observed equatorial waves, 438–440		
geostrophic, 71 circulation, 367–370 inertial, 9 Newton's first law of, 9 scales of, 26t Observation operator, 479 tropical, 392–398 Observed equatorial waves, 438–440		
inertial, 9 Newton's first law of, 9 scales of, 26t tropical, 392–398 O Observation operator, 479 Observed equatorial waves, 438–440	=	
Newton's first law of, 9 scales of, 26t tropical, 392–398 Observation operator, 479 Observed equatorial waves, 438–440	• •	circulation, 307–370
scales of, 26 <i>t</i> tropical, 392–398 Observation operator, 479 Observed equatorial waves, 438–440		O
tropical, 392–398 Observed equatorial waves, 438–440		•
Country of the countr		
Mountain lee waves, 145, 298–299 401		
Mountain waves, 294–302 Omega equation, 87, 171, 198–200		
Multicell storms, 306 two-level model, 223		

Index (527

Operational forecast centers, 453	Positive cyclonic vorticity, 117
Orography, 172	Positive eddy momentum flux, 348f
Oscillations	Potential energy, 158–159
angular momentum, 17–18	available, 227–229, 231, 233, 234, 291,
buoyancy, 55	302–303
equatorial intraseasonal, 392	eddy, 387–388
quasi-biennial, 440–445	gravitational, 227
southern, 390–392	for hurricanes, 319
transverse, 137	of mean flow, 227
D	perturbation, 232
P	total, 227
Parameterization, 399, 475	Potential intensity, 317
Parcel dynamics in moist atmosphere, 60	Potential temperature, 53–54, 446
Parcel instability, 213	advection of, 215f
Parcel method, 55, 59–60	definition of, 110
Parcel motions	equivalent, 294, 304, 503-504
for adiabatic planetary, 419, 419f	Potential vorticity (PV), 110–115, 143,
on meridional plane, 420, 420f	160f, 241
Pendulum day, 73	anomaly, 214, 215f
Perturbation method	barotropic, 118-120
geostrophic balance, adjustment to,	conservation, 194–197
156–159	equation, 121
linear, 217–223	Ertel, 111, 175, 289
purpose of, 127–128	evolution of, 242
waves, gravity, 145-150	gradient, 235, 240
waves, properties of, 128-136	inversion, 188-189
waves, types of, 136-144	piecewise inversion, 192
Perturbed observations, 481	quasi-geostrophic, 171, 183-186
Phase speed, 129, 132f, 219	thinking, 187–197
Piecewise potential vorticity inversion,	as a tracer, 447
188–193	zonal mean, 340-341
Planetary boundary layer, 255	Prandtl, L., 264
atmospheric turbulence, 256-258	Predictability, 481–486
depth of, 255–256	Predicting. See Numerical modeling and
Ekman layer, 266–268, 269–270	prediction
flux gradient theory, 264	Pressure, as a vertical coordinates, 20-21
friction, 263	Pressure change, measuring, 33
mixing length hypothesis, 264–266	Pressure gradient, 40
momentum equations, 261-270	Pressure gradient force, 5–7, 5f, 22f
pumping, 271–272	Pressure tendency
secondary circulation and spin down,	equation, quasi-geostrophic, 195
270–275	surface, 87–89
surface layer, 268–269	Primary circulation, 313
turbulent kinetic energy, 259-261	Primitive equation models, 472–475
well-mixed, 262–263	grid point models, 473
Planetary vorticity, 101, 109, 207	physical parameterizations, 474–475
entropy and momentum, 114f	spectral models, 473–474
Planetary wave. See Rossby waves	Prognostic equations, approximate, 43–44
Planetary wave number, 130	Propagating waves, 445
Poisson's equation, 54, 69, 345	Pseudoadiabatic ascent, 60, 61, 378, 504
Polar-frontal zone, 175	Pseudoadiabatic lapse rate, 61–62,
Polar stratosphere, warming of, 430,	504–505
431_432f	PV See Potential vorticity

528) Index

Q	Relative vorticity, 23, 100, 101, 109, 185,
Quadratic dispersion equation, 219	187
Quasi-biennial oscillation (QBO), 417, 440–445	Residual mean meridional streamfunction, 339
Quasi-geostrophic approximation, 185	Residual meridional circulation, 337, 338
Quasi-geostrophic divergence equation, 186	Residual vertical velocity, 337
Quasi-geostrophic energy cycle, 354	Reversible process in thermodynamic, 53,
Quasi-geostrophic (QG) equations, 171	54
derivation of, 178–183, 186	Reynolds averaging, 256–258
isobaric form, 206–208	Rhomboidal truncation, 474
potential vorticity derivation of,	Richardson, L. F., 453, 454, 455, 472
183–186	Richardson number
PV conservation, 194–197	flux, 260–261
Quasi-geostrophic height tendency	mean-flow, 293
equation, 194–197, 207	Right-moving storm, 310-312
Quasi-geostrophic mass continuity	Rossby adjustment problem, 157
equation, 185	Rossby critical velocity, 428
Quasi-geostrophic model, 327, 454	Rossby-gravity waves, 401-404, 442,
Quasi-geostrophic momentum, 359	444
equation, 186	in observational data, 438–440
Quasi-geostrophic perturbations, 233, 234	vertically propagating, 437–438
Quasi-geostrophic potential vorticity	Rossby-Haurwitz waves, 470
(QG PV), 171, 183–186	Rossby number, 43–44, 74, 77, 112, 181,
inversion, 189	188, 286, 395
scaling properties of, 187	Rossby radius of deformation, 157, 243
Quasi-geostrophic pressure tendency	Rossby waves, 141, 159–161, 171, 220 <i>n</i>
equation, 195	baroclinic, 219
Quasi-geostrophic scaling, 330	barotropic, 161–163
Quasi-geostrophic thermodynamic energy	equatorial, 401–404, 404 <i>f</i>
equation, 182, 185, 207	linear, 426–428
Quasi-geostrophic vertical motion equation,	propagation, 221
198	stationary, 356–359, 358f
Quasi-geostrophic vorticity equation,	theory, 366, 366 <i>f</i>
183–186, 207, 213, 215	topographic, 163–165
Quasi-Laplacian operator, 195, 198	vertical propagation, 426–430 wavebreaking, 428–430
Quasi-stationary circulation, 325	zonal-mean flow, 362
Quasi-stationary planetary waves in	Rotating coordinates
troposphere, 432 Q vector, 200–201, 202 <i>f</i> , 207–208,	momentum equation in, 35–37
223–225	total differentiation of vector in, 33–35
in frontogenetic confluence, 283 <i>f</i>	Rotation Street Rotation Rotation
in nontogenetic communice, 2033	circulation theorem, 95–99
R	macroscopic measure of, 95
Radiative cooling, 417, 418	in supercell thunderstorms, 306–310
Radiative heating, 56, 414, 417, 418	vorticity, 99–112
in tropical stratosphere, 424	Roughness length, 269
Radius of curvature, 70, 72–73	
Radius of deformation, 157, 243	S
Rayleigh theorem, 235, 237–241	Satellite cloud photos, 379, 380f
Reference frames	longitude sections of, 381, 382f
geocentric, 9–10	Saturation mixing ratio, 61, 503
inertial (absolute), 9	Saturation vapor pressure, 59
noninertial, 9–18	Sawyer–Eliassen equation, 288, 294

Scale analysis, 25–26	Squall lines, 306
of continuity equation, 48–49	Square root filters, 481
of momentum equations, 41–42	SST. See Sea surface temperature
isobaric coordinates and, 179	Stability
of thermodynamic energy equation,	computational, 458–460
56–57	Eady problem, 241–245
of tropical motion, 392–398	marginal, 222
of vorticity equation, 107–110	neutral, 242
Scorer parameter, 298, 299f	Stably stratified, 55
Sea breeze, 99	Standard atmosphere data, 507–508
Sea surface temperature (SST), 361,	Standard density, 44
364–366, 377, 390–391	Standard pressure, 44
Secondary circulation, 270–275, 313	State potential vorticity gradient, 240
associated with frontogenesis, 284	State vector, 479
Semigeostrophic equations, 287	Statically stable, 55
Semigeostrophic theory, 285–287	Static atmosphere, structure of, 18–23
Semi-Lagrangian integration method,	Static stability, 54–56
462–463	equivalent, 398
Shallow water	normal conditions of, 222
equations, 115–118	role of, 220
gravity waves, 139–144	Stationary waves, 356–359
Shallow water theory, 435	Steady circulations, dynamics of, 407
Shearing stress, 7	Steady forced equatorial motions,
Shear, vertical wind, 82	406–409
Shear vorticity, 103, 106	Steady-state motions, 78
Sigma coordinates, 342, 343–345, 347	Steady-state storm, potential intensity
Single cell storms, 306	formula for, 317
Sinking motion, 224	Steering level, 222
Sinusoidal topography, 294–297	Stokes's theorem, 499
SI (Systéme International) units of	relationship between vorticity and
measurement, 2–3	circulation, 102
Slantwise convection, 290	to solenoidal term, 106
Solar heating in ozone layer, 414	vorticity and circulation, 102
Solenoidal term	Storm tracks, 174, 359–361
in circulation theorem, 97, 106, 107	Stratopause, 413
synoptic-scale motions, 107	Stratosphere, 413, 414. See also Middle
in vorticity equation, 106	atmosphere
Solid curves, 484	Streamfunction, 119
Solitary waves, 362	geostrophic, 215
Sound waves, 136–139	Streamlines, 78–81
in equations of motion, 41	of meridional mass circulation, 422,
Southern oscillation, 390–392	423 <i>f</i>
Specific heat, 52, 53	Stretching deformation, 281, 282 <i>f</i>
of water vapor, 504	Stretching vorticity, 185
Spectral method, 467–472	Subcritical flow, 300
Spectral models, 473–474	Substantial derivative, 31
Spectral transform method, 471–472, 472 <i>f</i>	Sudden stratosperic warming, 430–435
Spherical coordinates	Supercell thunderstorms, 306–310
barotropic equation in, 468–470	Supercritical flow, 300
momentum equations in, 37–41	Surface cyclone, development of, 243–244
Spherical harmonics functions, 468, 469,	Surface forces, 4
469 <i>f</i>	Surface layer, 268–269
Spin-down, Ekman, 272–275	Surface pressure tendency, 87–89

530) Index

Surf zone, 450	Thermodynamics of dry atmosphere, 53-57
Symmetric baroclinic instability, 290–294	adiabatic lapse rate, 54
Symmetric instability, 213–214	potential temperature, 53–54
Synoptic-scale motion, 41, 85, 86	static stability, 54–56
baroclinic disturbance, model of, 204–206	Thermodynamics of moist atmosphere, 58–64
baroclinic instability, continuous	conditional instability, 62-64
stratified atmosphere and, 234-245	equivalent potential temperature, 58-64
baroclinic instability, normal mode,	pseudoadiabatic lapse rate, 61-62
215–226	Three-dimensional variational assimilation
continuity equation for, 48–49	(3DVAR), 480
energetics of baroclinic waves, 227–234	Three dimensions, wave properties in,
extratropical circulation, 171–178	133–135
hydrodynamic instability, 213–215	Thunderstorms, 306–310
hydrostatic approximation for, 44	Timescale, dynamical and chemical,
neutral modes, growth and propagation	447–448
of, 245–251	Topographically forced waves, 430 Topographic waves, 163–165
potential vorticity thinking, 187–197 quasi-geostrophic approximation,	Rossby waves, 159–161
178–183	Total derivative, 31–33
quasi-geostrophic vorticity equation,	Total differentiation, 31–33
183–186	of vector in rotating system, 33–35
solenoidal term in, 107, 108	Tracers
vertical motion analysis, 197-204	chemical, 447–448
Synoptic-scale pressure systems, 81	dynamical, 446–447
_	long-lived, 448, 449
T	Trajectories, 78–81
Taylor approximation, 7, 23	Transformed Eulerian mean (TEM),
Taylor series, 5, 456	337–339, 342, 355, 420–424
TEM. See Transformed Eulerian mean	Transient growth of neutral waves, 247–250
Temperature	Transient wave, schematic of, 434, 434f
advection, 32, 196, 284	Transport process in strategrhere, 448, 450
equivalent potential, 294, 304, 503–504 lapse rate of, 54	Transport process in stratosphere, 448–450 Transverse oscillations, 137
oscillation, 439	Trapezoidal implicit scheme, 460–461
potential, 53–54, 446	Triangular truncation, 474
pseudoadiabatic lapse rate, 504–505	Tropical circulation
sea surface, 361, 364–366, 377	African wave disturbances, 384–386
Thermal low, 387	condensation heating, 398–400
Thermally direct cell, 332	El Niño and southern oscillation,
Thermals, 302	390–392
Thermal wind, 33, 81-84, 280, 327, 330,	equatorial intraseasonal oscillation, 392
435	equatorial wave disturbances, 381-384
equation, 82, 314	equatorial wave theory, 401–406
Thermocline, 390, 391	intertropical convergence zone, 378–381
Thermodynamic energy equation, 50–53,	monsoons, 325, 386–389
216, 241	Walker circulation, 389–390
in condensation heating, 399	Tropical cyclones, 312–321
hydrostatic, 215	Tropical motion
in isobaric coordinate system, 69, 207	scale analysis of, 392–398
in log-pressure coordinates, 237 quasi-geostrophic, 182, 185	steady forced equatorial, 406–409 Tropopause, 1, 113, 114, 172
scale analysis of, 56–57	maps, 112–113
· · · · · · · · · · · · · · · · · · ·	r

Troposphere, 1, 172, 413, 414	advection, 220, 223, 224, 225
Truncation	barotropic fluids and, 118-120
error, 463–464	barotropic potential, 118-120
rhomboidal, 474	changes of, 220
triangular, 474	concentration of, 225, 226
Turbulence, atmospheric, 256–258	curvature, 103, 104
Turbulent kinetic energy, 259–261	definition of, 100
Two-layer model	generation, 105f
energy equations for, 229–234	geostrophic, 215
normal mode baroclinic instability,	lower-level cyclonic, 215f
215–226	natural coordinates and, 102-104
Typhoons, 312–321	planetary, 207
	potential. See Potential vorticity
U	relative, 100, 101, 185, 187
Upper-level anomaly, 214	shear, 103
• /	stretching, 185
V	tendencies, 224-225, 250
Vapor pressure, 503	Vorticity equation, 207, 216
Vector analysis, 499–501	baroclinic (Ertel) potential, 120-122
Vectorial momentum equation, 37	barotropic, 464-467
Velocity, 24f	barotropic potential, 118-120
absolute, 36	Cartesian coordinate form, 104-106
dispersion and group, 131–133	isentropic, 121–122
friction, 268	in isobaric coordinates, 106-107
Rossby critical, 428	quasi-geostrophic, 213, 215
vector, 32, 36	scale analysis of, 107-110
Vertical coordinates	zonal mean potential, 340-341
generalized, 22–23	***
isentropic, 120	W
isobaric, 21, 206	Walker circulation, 389-390, 406
log-pressure, 235–236	Walker, G. T, 389
pressure, 20–21	Warm-air advection, 195
sigma, 343–345	Warm core systems, 320f
Vertically propagating waves	Warming, sudden stratospheric, 430–435
Kelvin waves, 436–437	Water vapor in atmospheric dynamics, 58
planetary waves, 426-430	Wavebreaking, 428–430
Rossby-gravity waves, 437-438	Wave equation, 139
Vertical momentum equation, 45	Wave instabilities, 214
in Boussinesq approximation, 57	Wave number, 129
scale analysis of, 44, 44t	planetary, 130
Vertical motion, 84–87, 197	zonal, 130
ageostrophic circulation, 201–203,	Waves
203f	acoustic, 136-139
baroclinic waves and, 223–226, 225f	African wave disturbances, 384–386
omega equation, 198–200	baroclinic, 223-234, 328, 355, 361
Q -vector, 200–201, 202 <i>f</i>	dispersive and group, 131–133
Virtual temperature, 58	eddy heat fluxes, 332
Viscosity coefficient, kinematic, 7	equatorial Kelvin, 404–406, 405f, 406f
Viscosity, eddy, 264	in equatorial stratosphere, 435-440
Viscous force, 6–8	equatorial wave disturbances, 381-384
Von Karman's constant, 269	equatorial wave theory, 401-406
Vorticity, 23, 24f, 25. See also under type of	gravity, inertia, 152-156
absolute, 100, 101, 119f, 213	gravity, internal, 145-150

Waves (continued)	gradient approximation, 74-77
gravity, shallow water, 139-144	irrotational, 396
Kelvin, 404–406, 405f, 406f, 436–437	mean zonal, 328
longitudinal, 136–139	nondivergent, 396
mountain, 294–302	thermal, 81-84, 327, 330, 333, 335, 359,
mountain lee, 145, 298-299	361
neutral, transient growth of, 247-250	Wind-induced surface heat exchange
properties of, 128–136	(WISHE), 319
Rossby, 159–165, 356–359, 426–430	Wind profile, logarithmic, 269
Rossby-gravity, 401-404, 437-438	Windstorms
Rossby-Haurwitz, 470	downslope, 299-302
solitary, 362	hurricanes, 312–321
sound, 136–139	_
stationary, 356–359	Z
strategy, 135–136	Zonal force, 421
topographic, 163–165	in mesosphere, 424
types of, 136–144	Zonally averaged circulation, 328–341
Wave speed	Zonal mean angular momentum,
Rossby, 162	345–349
shallow water, 141	Zonal-mean circulation
two-layer, 219	analysis of, 339
Wave vector, 134, 134 <i>f</i>	maintenance of, 341
Weather forecasting, 455	of middle atmosphere, 417-426
Weather Prediction by Numerical Process	structure of, 325
(Richardson), 449	Zonal-mean flow, 213, 325-326
Well-mixed planetary boundary layer,	Rossby waves, 362
262–263, 263 <i>f</i>	Zonal mean potential vorticity equation,
Wind	340–341
ageostrophic, 85, 181, 185	Zonal-mean transport, 424–426
cyclostrophic, 73–74	zonal wave number, 130
geostrophic, 42-43, 181, 215	Zonal wind oscillations, 439