

CONTENTS

Preface		xi
<hr/>		
Part I: Earth's Climate System		1
<hr/>		
CHAPTER 1	An Introduction to the Climate System	3
CHAPTER 2	The Observed Climatology: An Atlas	7
	2.1 The Atmosphere	8
	2.2 The Oceans	25
	2.3 The Hydrosphere	36
	2.4 The Cryosphere	44
	2.5 The Biosphere	47
	2.6 Data Sources and References	49
	2.7 Exercises	50
CHAPTER 3	Natural Climate Variability	51
	3.1 Diurnal and Seasonal Climate Variations	52
	3.2 Intraseasonal Climate Variability	54
	3.3 Interannual Climate Variability	54
	3.4 Decadal Climate Variability	60
	3.5 Climate Variations on Century to Billion-Year Time Scales	63
	3.6 Data Sources	64
<hr/>		
Part II: Climate System Processes		65
<hr/>		
CHAPTER 4	Radiative Processes in the Climate System	67
	4.1 Blackbody Theory	67
	4.2 Application of Blackbody Theory to the Earth System	68
	4.3 How Constant Is the Solar Constant?	70
	4.4 Solar and Terrestrial Spectra	71
	4.5 The Greenhouse Effect	77
	4.6 The Equation of Transfer	82
	4.7 Radiative Effects of Clouds	84
	4.8 Data Sources	86
	4.9 Exercises	87



CHAPTER 5	Thermodynamics and the Flow of Heat through the Climate System	89
5.1	Equations of State	89
5.2	The First Law of Thermodynamics	91
5.3	Heat Balance Equations	93
5.4	Observed Heat Fluxes	98
5.5	Data Sources	108
5.6	Exercises	108
CHAPTER 6	Dynamics: The Forces That Drive Atmospheric and Ocean Circulations	111
6.1	Equations of Motion	111
6.2	The Coriolis Force	112
6.3	The Pressure Gradient Force	119
6.4	Gravitation and Hydrostatic Balance	120
6.5	Geostrophic Balance	123
6.6	Friction	125
6.7	The Momentum Equations	126
6.8	Conservation of Mass	126
6.9	Exercises	128
CHAPTER 7	Atmospheric Circulations	131
7.1	Thermally Direct Circulations	131
7.2	Midlatitude Circulation Systems	140
7.3	High-Latitude Circulation Systems	141
7.4	Data Sources and References	143
7.5	Exercises	143
CHAPTER 8	Ocean Circulation Systems	145
8.1	The Wind-Driven Circulation: Ekman Dynamics	145
8.2	The Density-Driven Circulation: Thermohaline Circulation	149
8.3	Vertical Mixing Processes	151
8.4	Data Sources	154
8.5	Exercises	155
CHAPTER 9	The Hydrologic Cycle	157
9.1	Atmospheric Moisture	157
9.2	Atmospheric Water Balance	159
9.3	Precipitation Processes	162
9.4	Land Surface Water Balance	163
9.5	Exercises	164
CHAPTER 10	Cryospheric Processes	165
10.1	Sea Ice	165
10.2	Glaciers and Ice Sheets	167

10.3	Ice Shelves	169
10.4	Permafrost	170
10.5	Data Source	171
10.6	Exercises	171

Part III: Contemporary Climate Change		173
--	--	------------

CHAPTER 11	Radiative Forcing of Climate Change	175
11.1	The Atmosphere's Changing Chemical Composition	175
11.2	Direct Radiative Effects of Human Activity	189
11.3	Atmospheric Aerosols and Their Radiative Forcing	193
11.4	Data Sources and References	195
11.5	Exercises	196
CHAPTER 12	Climate Sensitivity and Feedbacks	197
12.1	Climate Sensitivity	197
12.2	Climate Feedback Processes	199
12.3	Extreme Events: Intensification of the Hydrologic Cycle	203
12.4	Abrupt Climate Change: Tipping Points	204
12.5	Exercises	205
CHAPTER 13	Earth's Changing Climate	207
13.1	Global Warming: A Planet in Disequilibrium	207
13.2	Temperature Trends	209
13.3	Hydrologic Trends	215
13.4	Tropical Storms, Hurricanes, and Tornadoes	218
13.5	Trends in the Ocean	220
13.6	Cryospheric Trends	225
13.7	Data Sources and References	230
13.8	Exercises	231
CHAPTER 14	Climate Change Prediction	233
14.1	Paleoclimate Analogs	233
14.2	Simple Climate Models	235
14.3	General Circulation Models	238
14.4	Regional and Convective-Permitting Climate Models	243
14.5	Earth System Models	243
14.6	Climate Model Projections and Uncertainty	244
14.7	Data Sources and References	247
Appendix A	Units, Constants, and Conversions	249
Appendix B	Coordinate Systems	251
Appendix C	Lagrangian and Eulerian Derivatives	257
Index		259

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

An aerial photograph of a river delta, showing a complex network of water channels and land. The water is a deep blue, and the land is a mix of green and brown. A teal and green rectangular box is overlaid on the top half of the image, containing the text 'PART I' and 'EARTH'S CLIMATE SYSTEM'.

PART I
EARTH'S CLIMATE SYSTEM

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

1

AN INTRODUCTION TO THE CLIMATE SYSTEM

Climate dynamics is the scientific study of how and why climate changes. The intent is not to understand day-to-day changes in weather but to explain average conditions over many years. Climate processes are typically associated with multidecadal time scales and continental to global space scales, but one can certainly refer to the climate of a particular city.

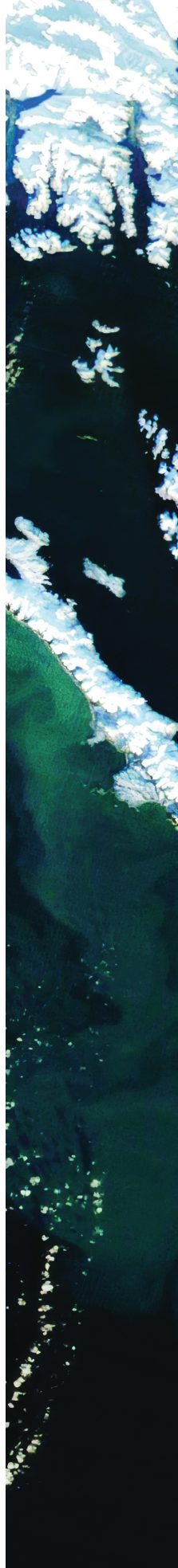
Climate dynamics is a rapidly developing field of study, motivated by the realization that human activity is changing climate. It is necessary to understand the natural, or unperturbed, climate system and the processes of human-induced change to be able to forecast climate so that individuals and governments can make informed decisions about energy use, agricultural practice, water resources, development, and environmental protection.

Climate has been defined as “the slowly varying aspects of the atmosphere–hydrosphere–land surface system.”¹ Other definitions of climate might also explicitly include the biosphere as part of the climate system, since life on the planet plays a well-documented role in determining climate. Anthropogenic climate change is one example, but there are others, such as the influence of life on the chemical composition of the atmosphere throughout most of Earth’s 4.5-billion-year life span.

The word *climate* is derived from the Greek word *klima*, which refers to the angle of incidence of the sun. This is a fitting origin because solar radiation is the ultimate energy source for the climate system. But to understand climate we need to consider much more than solar heating. Processes within the Earth system convert incoming solar radiation to other forms of energy and redistribute it over the globe from pole to pole and throughout the vertical expanses of the atmosphere and ocean. This energy not only warms the atmosphere and oceans but also fuels winds and ocean currents, activates phase changes of water, drives chemical transformations, and supports biological activity. Many interacting processes create the variety of climates found on Earth.

A schematic overview of the global climate system is provided in Figure 1.1. This diagram represents the climate system as being composed of five subsystems: the atmosphere, the hydrosphere, the biosphere, the cryosphere, and the land surface. It also

1. From the Glossary of Meteorology, published online by the American Meteorological Society.



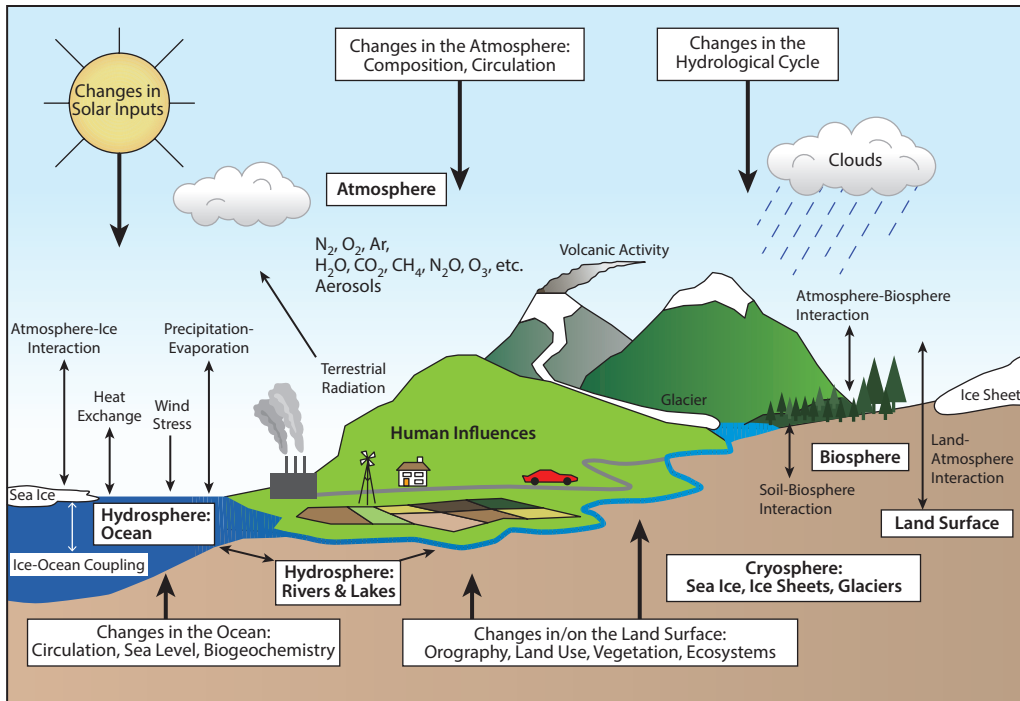


Figure 1.1: Schematic overview of the climate system, with some of the interactions among its subsystems indicated by arrows. From “Climate Change 2001: The Scientific Basis.” Intergovernmental Panel on Climate Change.

depicts some of the processes that are important for determining climate, such as the exchange of heat, momentum, and water among the subsystems, and it identifies some of the agents of climate change.

Figure 1.1 provides a rough overview of the climate system, and it is useful as a first-order, nontechnical description of the system. At the other end of the spectrum is the *Bretherton diagram*, shown in Figure 1.2. This detailed, perhaps a bit overwhelming, schematic was constructed to characterize the full complexity of climate. It is a remarkable and rich representation of the system, illustrating the many processes that influence climate on all time scales. It coalesces historically separate fields of scientific inquiry, demonstrating that not only atmospheric science and oceanography are relevant to climate science, but that various subdisciplines of geology, biology, physics, and chemistry—as well as the social sciences—are all integral to an understanding of climate.

This is a very exciting and critical time in the field of climate dynamics. There is reliable information that past climates were very different from today’s climate, so we know the system is capable of significant change. We also understand that it is possible for the system to change quickly. The chemical composition of the atmosphere is changing before our eyes, and satellite- and Earth-based observing networks allow us to monitor changes in climate fairly accurately.

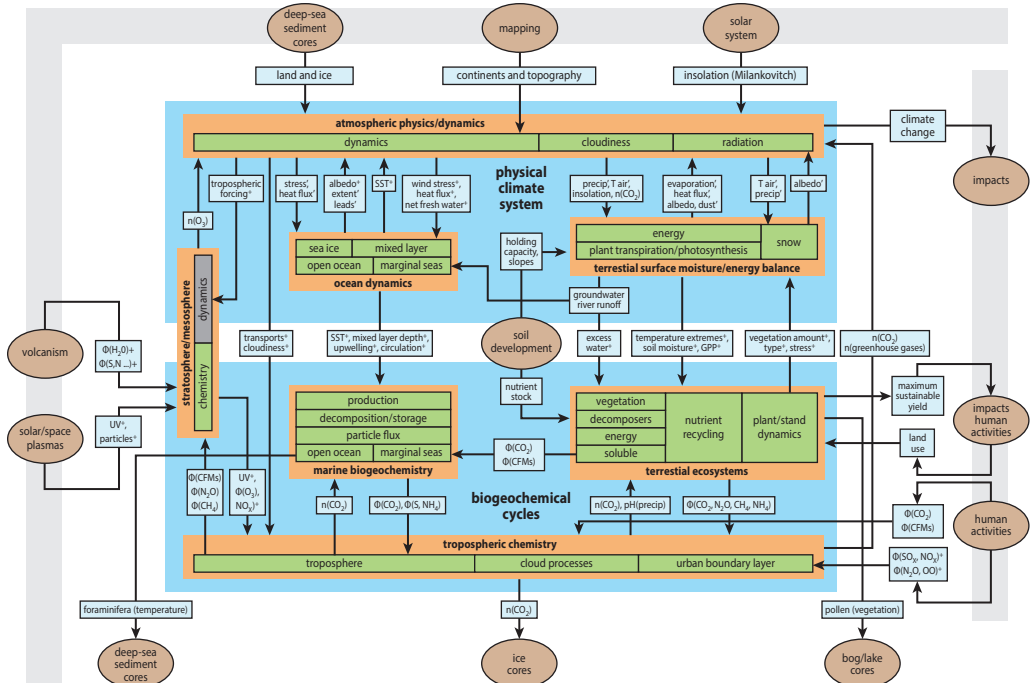


Figure 1.2: The Bretherton diagram, illustrating the components of the climate system and the interactions among them. (' = on time scale of hours to days; + = on time scale of months to seasons; Φ = flux; n = concentration; SST is sea surface temperature.)

Clearly, this one text on climate dynamics cannot cover the full breadth of this wide-ranging and rapidly developing field of study, but it provides the reader with the fundamentals—the background needed for a basic understanding of climate and climate change, and a launchpad for reading the scientific literature and, it is hoped, contributing to the profound challenge facing us of managing climate change and avoiding its worst impacts. With this fundamental understanding, science can address the questions, needs, and constraints of humanity in a reasonable and useful way, and offer informed answers to guide society's behavior.

INDEX

- Absolute frame of reference, 112
Absorption spectrum, 76–77
Absorptivity (a), 68, 79
Adiabatic conditions, 92, 121
Adiabatic lapse rate, 121, 162
Aerosols, 63, 193, 211; climate feedback, 202;
 indirect effect, 194; precursor species, 194;
 radiative forcing, 193–195; sources and sinks,
 193–194; tipping point, 204; types, 194
African easterly jet, 137
African wave disturbances, 218
Albedo (α), 70; climate feedback, 199–200,
 236–237; cloud, 84–85, 202; planetary, 70,
 100–103, 197–198, 200, 236–237; surface,
 93–94, 97, 103, 237, 241
Amazon monsoon, 53; tipping point, 205
Angular momentum, 112–115; conservation,
 115
Antarctic bottom water (AABW), 34, 150–151
Antarctic ice sheet, 227; trends 227–229
Antarctic Oscillation, 62
Arctic amplification, 211–213
Arctic Oscillation, 61
Astronomical theory of climate change, 63–64
Atlantic meridional overturning circulation
 (AMOC), 149; tipping point, 204; predictions,
 246; trends, 224
Atlantic Multidecadal Oscillation (AMO), 61
Atmospheric general circulation model (AGCM),
 238–240
Atmospheric windows, 75–76
Antarctic bottom water, 34
Antarctic circumpolar current, 33
Anticyclonic flow, 25

Baroclinic instability, 136
Bergeron process, 163
Blackbody, 67–68; spectra, 71–75
Bowen ratio, 100
Brightness temperature, 75, 87
Brine exclusion, 151, 165–166, 243
Bucket model, 241
Buoyancy force, 120, 132; for sea ice, 166–167; for
 ice shelves, 169

Cabbeling, 153–154
Carbon budget, 181–182

Carbon dioxide (CO_2), 75; direct radiative forc-
 ing, 191; effective radiative forcing, 192–193;
 global warming potential, 191–192; history,
 176; isotopes, 178; observed trend, 176–179;
 molecular absorption, 74–75; ocean uptake,
 181–183; preindustrial value, 178; role in car-
 bon budget, 171, 181–182; seasonal cycle, 176
Carbon emissions, 181–182
Carbon fixing, 183
Centrifugal acceleration, 116–118
Chlorofluorocarbons (CFCs), 189; direct radiative
 forcing, 191; effective radiative forcing, 192–
 193; global warming potential, 191–192
Clausius-Clapeyron relation, 158, 203, 216, 219
Climate feedback, 199–203; clouds, 199–202; feed-
 back loops, 199; ice albedo, 199–200, 212;
 water vapor, 199–200
Climate forcing, 51, 175, 197, 238
Climate models, 235–244; evaluating uncertainty,
 236–237; general circulation models (GCMs),
 238–240; model intercomparison projects
 (MIPs), 245; simulations, 236–237; surface
 heat balance, 237; zero dimensional, 235–236
Climate sensitivity, 197–199, 237; equilibrium, 245
Climate system, 3–5
Cloud condensation nuclei (CCN), 162–163, 194;
 climate feedback, 202
Cloud forcing, 86, 201
Clouds: climate feedbacks, 200–202; direct radi-
 ative effects, 84–86; formation, 162–163; ice,
 163; indirect radiative effects, 194, 202; semi-
 direct radiative effects, 202
Collision-coalescence, 163
Conservation of mass, 126–128; water, 159–162,
 238–239
Continental, 14, 142, 212
Continuity equation, 126–128, 133; divergence
 form, 128; flux form, 127
Convection, 131–132, 136; double-diffusion, 152–153;
 parameterization, 239, 243; role in climate
 feedback, 203; tipping points, 204
Convective-permitting (CP) models, 243
Convergence, 19–21, 125, 133–134; moisture, 159
Coordinate systems, 251–255
Coral, 244; bleaching, 224; proxy data, 233
Coriolis effect, 115
Coriolis force, 112–116, 123, 135, 137, 145–146, 218

- Cyclone, 218
Cyclonic flow, 25, 218
- Data assimilation, 7
Denitrification, 187
Density: atmosphere, 89; seawater, 89–91
Deserts, 135, 136
Dew point, 162
Diabatic heating, 91–92, 239
Diffusion, 152
Direct radiative forcing, 189–191, 198, 199; in emissions scenarios, 245
Divergence, 20–21, 125, 133–134, 152; moisture, 159
Doldrums, 24
Downwelling, 36, 152
Drought, 203–204; trends, 217–218
Dynamic vegetation model (DVM), 241
- Earth's energy imbalance (EEI), 208–209
Earth system models (ESMs), 244–245
Eastern boundary currents, 33, 140, 148
Eddies, 136
Effective gravity, 116–117
Effective radiative forcing (ERF), 192–193
Ekman dynamics, 145–149; layer, 145; pumping, 152; spiral, 145; transport, 148, 152, 213; velocity, 146–148
El Niño, 54, 56
Emission scenarios, 245
Emissivity (ϵ), 67, 79
Ensemble simulation, 244
ENSO, 54, 56–60, 87, 139–140
Eocene climate optimum, 234–235
Equation of state: air, 89; seawater, 89–90
Equation of transfer, 82–84
Equatorial Countercurrent, 33–56
Equatorial trough, 10
Equatorial undercurrents, 149
Equilibrium climate sensitivity (ECS), 245
Equilibrium line altitude (ELA), 168
Eukaryotes, 48
Eulerian derivative, 257–258
Euphotic zone, 47, 183
Evaporation (E), 36, 40–41, 131, 136, 158–162; land surface water balance, 163–164, 241
Evapotranspiration, 40, 159
- Feedback loops, 199
Ferrell cell, 140
Fingerprint, 215
Friction, 125, 145–147
- Gaia hypothesis, 48–49, 202
General circulation model (GCM), 238–240; atmosphere, 238–240; coupled, 240–241; governing equations, 238–239; ocean, 240–241
Geopotential (Φ), 10, 122–125
Geopotential height (Z), 8–14, 22–25, 122; gradients, 131, 136–137
Geostrophic balance, 123–125
Geostrophic velocity, 123–125; in ocean, 148–149; intensification, 148; vertical shear, 124–125
Gigaton, 181
Glacial/interglacial periods, 63–64, 175; CO₂ variations, 178; methane variation, 183–185; temperature differences, 211, 247
Glacial isostatic adjustment (GIA), 220, 221–222
Glaciers, 44–45, 167–169; flow, 168–169; mass balance, 167–168; models, 241–242; terminus, 168
Global mean sea level (GMSL), 220
Global warming potential (GWP), 191
Gravitational potential energy, 10
Gravity, 9, 116, 120; for sea ice, 166–167
Gravity Recovery and Climate experiment (GRACE), 221, 225
Graybody, 67
Greenhouse effect, 77–82
Greenland ice sheet, 37, 44–45, 167, 178; sea level, 222; trends, 225–227
Grounding line, 169, 227
Gulf Stream, 31, 35, 108, 148, 149, 224; tipping point, 205
Gyres, 33
- Hadley circulation, 22, 132–136; seasonality 135–136
Harmattan wind, 136
Heat balance, 93–97; observed 99–108; surface, 93–98, 198, 237, 239; top of atmosphere, 68–70, 93, 207–208, 235
Heat capacity, 97–98, 136, 204, 210, 212
Heat waves, 214–215
Hectapascal (hPa), 8
Hovmöller diagram, 54
Hurricane, 218–219; Harvey, 219; Sandy, 219; trends, 219
Hydrochlorofluorocarbons (HCFCs), 189; direct radiative forcing, 191; effective radiative forcing, 92–193; global warming potential, 191–192
Hydrologic cycle, 36–37
Hydrostatic balance, 120–122, 128; for sea ice, 166–167
Hydroxyl radical (OH), 185, 188–189, 194
- Icebergs, 45, 169
Ice cores, 178, 180, 183, 211, 233
Ice sheets, 44–45, 167
Ice shelves, 45, 169; calving, 169; trends in Antarctica, 227–230
Ideal gas law, 89, 92, 121–122
Index cycle, 136–137

- Intergovernmental Panel on Climate Change (IPCC), 244–245
- Intertropical Convergence Zone (ITCZ), 24, 38, 41, 54, 104, 135, 162
- Isobar, 8
- Isopycnal, 90
- Isotope, 178, 183, 211, 233–234
- Katabatic winds, 151
- Keeling curve, 176
- Kirchhoff's law, 68, 79
- Kuroshio, 31, 108
- Lagrangian derivative, 257–258
- Land surface models (LSMs), 241–242
- La Niña, 57–58
- Lapse rate (Γ), 17, 84–85; adiabatic 121; climate feedback, 203, 212
- Latent heat flux (H_L), 93–97, 100, 105–107, 131–132
- Lifting condensation level, 162
- Little Ice Age, 63
- Local Cartesian coordinate system, 112, 126, 251–253
- Longwave radiation, 71, 99–100; longwave back radiation, 79, 99–100, 198, 237; role in surface heat balance, 93, 104–106
- Madden-Julian Oscillation (MJO), 54–55
- Main development region (MDR), 218, 219
- Marine biological pump, 47–48; 183
- Mauna Loa observatory, 176
- Mean meridional circulation, 133–134
- Meridional overturning circulation (MOC), 33
- Meridional wind (v), 19–21
- Mesoscale, 243
- Mesosphere, 15
- Methane (CH_4), 183–186; direct radiative forcing, 191; effective radiative forcing, 192–193; global warming potential, 191–192; in ice core records, 183; isotopes, 183; observed trend, 183–184; in permafrost, 171; pre-industrial, 185; radiative properties, 74–76; sources and sinks, 185–186
- Milankovitch cycles, 63–64, 71
- Mixing ratio, 89, 157
- Models. See *Climate models*
- Moisture flux, 160–161; convergence, 162
- Molecular absorption, 73–75; absorption coefficient, 82; attenuation of a beam, 82–84
- Momentum equations, 112, 126
- Monsoon depression, 136
- Monsoons, 24, 43–44, 53, 136–138; Asian, 136–137; South American, 53, 205; West African, 136–137
- Moulin, 186
- Niño 3.4 region, 58
- Nitrogen budget, 186–188
- Nitrogen fixation, 186
- Nitrous oxide (N_2O), 186–188; direct radiative forcing, 191; effective radiative forcing, 192–193; global warming potential, 191–192; observed trends, 186–187; preindustrial, 186; radiative properties, 74–76
- North Atlantic deep water formation (NADW), 34, 149–150; 213; tipping point, 204; trends, 224
- North Atlantic Oscillation (NAO), 62
- Northern Annular Mode (NAM), 61–61
- Ocean acidity, 222–224; buffering, 222–223; pH, 223; predictions, 246; trends, 223–224
- Ocean biological pump, 47–48; 183
- Ocean currents, 31–33, 146–148
- Ocean general circulation model (OGCM), 240–241
- Ocean heat content (OHC), 210
- Ocean mixed layer, 29–30, 148, 219
- Ocean Niño Index (ONI), 58–59
- Ocean water density, 29, 33, 89–91
- Opacity, 76, 83
- Optical depth, 83
- Outgoing longwave radiation (OLR), 75, 78–80, 87, 100, 102–103, 203
- Ozone (O_3), 15, 19, 62, 82, 99; molecular absorption, 74–76; sources and sinks, 188; trends, 188
- Pacific cold tongue, 26, 33, 137–139, 152, 218
- Pacific Decadal Oscillation (PDO), 60–61, 209
- Pacific warm pool, 25, 137, 162
- Paleoclimate, 63; analogs, 233–235; proxy data, 233–235
- Palmer drought severity index (PDSI), 204, 217
- Parameterization, 96
- Permafrost, 47, 170–171
- Peru current, 31, 152
- Photosphere, 72
- Phytoplankton, 48, 183, 202
- Planck curve, 68; for Earth, 71, 74–76; for the sun, 41–74
- Planck formula, 67–68
- Planetary albedo, 70
- Pliocene, 234
- Polar jet, 61, 141–142
- Polar vortex, 142
- Polynya, 151
- Potential temperature, 92, 121
- Precipitation (P), 37–40, 41, 135; column moisture budget, 159–162; formation processes, 162–163; land surface water balance, 163–164, 241; predictions, 246; trends, 215–217

- Pressure (p), 8; at the surface, 9; as a vertical coordinate, 8, 123–124
Pressure gradient force, 119–122, 123, 131
Prokaryotes, 48
Proxy data, 63, 233–235
Pycnocline, 29
- Quai-biennial oscillation (QBO), 60
- Radiation surplus/deficit, 102–104
Radiative equilibrium, 68, 81
Radiative equilibrium temperature, 68–70, 78, 197–198, 200, 235
Radiative forcing, 175, 189–191
Reanalysis, 7, 49
Regional climate model (RCM), 243
Relative humidity, 158
Residence time, 176; carbon dioxide, 176–177
Return time, 218
- Saharan high, 137
Salinity (S), 30–31, 136
Salt fingering, 152
Scale height, 121–122
Scattering, 72–73, 99; by aerosols, 194; attenuation of a beam, 82–84; Mie scattering, 73; Rayleigh scattering, 73
Sea ice, 46–47; Antarctica, 46–47, 227; Arctic, 46–47, 219, 225; effects on salinity, 162–163; formation processes, 165; insulating effect, 166; models, 242–243; predictions, 246; trends, 225
Sea level, 220; eustatic, 220; global mean, 220; predictions, 246
Sea level rise, 220–222; satellite measurement, 220–221; sea ice effects, 167
Seasonality, 14; in precipitation, 39–40, 53; in temperature, 52
Sea surface temperature, 25–28
Sensible heat flux (H_s), 91, 93–97, 100, 105–107, 131–132
Shared Socioeconomic Pathways (SSPs), 245
Shortwave radiation, 71, 93, 99–101; role in surface heat balance, 104–105
Solar constant, 69–71, 197–198
Solar luminosity, 69
Solar radiation, 71, 93, 99–101; role in surface heat balance, 104–105
Solid body rotation, 113, 116
Somali jet, 136, 152
South Atlantic convergence zone, 39, 54
Southern Annular mode (SAM), 62
Southern Oscillation Index (SOI), 59–60, 139
South Indian convergence zone, 39
South Pacific convergence zone, 39, 54
Specific heat, 91–92, 97
Specific humidity, 41–44, 157, 160
Specific volume, 91
Spectral radiance, 68, 72; attenuation of a beam, 82–84
Spherical coordinates (Earth-centered), 253–254
Standardized Precipitation Index (SPI), 204, 217
Stefan-Boltzmann law, 67, 69
Stokes' stream function, 135–135
Stomata, 159, 234; stomatal resistance, 241
Storm tracks, 14
Stratopause, 15, 17
Stratosphere, 15, 17; temperature trends, 81–82, 215
Stream function, 133; Stokes', 134–135
Subsidence, 21, 132, 135
Subtropical high, 10, 205
Subtropical jets, 20, 135, 141
Sulfur hexafluoride (SF_6), 189
Sunspot cycle, 70–71
Sverdrup (Sv), 148
Synoptic scale, 141; system, 220
- Teleconnection, 62
Temperature, 13; dew point, 162; freezing, 90–91; glacial/interglacial periods, 211; inversions, 19, 212; ocean, 25–28; potential, 92; predictions, 246–247; profile, 14–15, 17–19; radiative equilibrium, 68–70, 78, 93, 208–209, 235; trends, 209–215; virtual, 89
Teragram, 187
Thermal equator, 14
Thermal low, 136
Thermally direction circulation, 131–140
Thermal wind equations, 124–125
Thermocline, 29
Thermodynamic equation, 91–92
Thermohaline circulation, 33–36, 149–151, 243; trends, 224
Thermosphere, 15
Thickness, 10, 122, 131
Thin atmosphere approximation, 113
Tide gauge, 220
Tipping points, 204–205
Tornadoes, 219–220; outbreaks, 220
Total solar irradiance (TSI), 70–71, 195
Trade winds, 23, 136, 140
Transient tracers, 150–151; dissolved oxygen, 150–151; tritium 150
Transpiration, 159
Tree rings, 233
Tritium, 150
Tropical easterly jet, 137
Tropical storms, 218–219; trends, 219
Tropopause, 15, 17–19
Troposphere, 14–15, 17, 137

- T-S plot, 89–90, 154, 165–166
- Turbulent heat flux, 93, 105
- Typhoon, 218

- Upwelling, 36, 152; equatorial 152

- Vapor pressure, 157; saturation, 157–159
- Vertical p-velocity (ω), 20, 138–139
- Volcanoes, 63, 162, 175; aerosols, 193; Eocene climate optimum, 234; radiative forcing, 194–195, 211, 215, 245

- Walker circulation, 138–140
- Water cycle, 157–158
- Water vapor mass flux, 160–161
- Western boundary currents, 31–33, 148
- Wien's displacement law, 68
- Wind shear, 20, 219
- Wind stress 147–148

- Zenith angle, 100
- Zonal mean, 8, 17, 133
- Zonal wind (u), 19–20