An Introduction to Clouds

From the Microscale to Climate

Clouds, in their various forms, are a vital part of our lives. Their effects on the Earth's energy budget and the hydrological cycle depend on processes on the microphysical scale, encompassing the formation of cloud droplets, ice crystals and precipitation. Cloud formation, in turn, depends on the large-scale environment as well as the characteristics and availability of aerosol particles. An integrated approach drawing on information from all these scales is essential to gain a complete picture of the behavior of clouds in the atmosphere.

An Introduction to Clouds provides a fundamental understanding of clouds, ranging from cloud microphysics to the large-scale impacts of clouds on climate. On the microscale, phase changes and ice nucleation are covered comprehensively, including aerosol particles and the thermodynamics relevant for the formation of clouds and precipitation. At larger scales, cloud dynamics, mid-latitude storms and tropical cyclones are discussed, leading to the role of clouds in the hydrological cycle and their effect on climate.

Each chapter ends with problem sets and multiple-choice questions that can be completed online; important equations are highlighted in boxes for ease of reference. Combining mathematical formulations with qualitative explanations of the underlying concepts, this accessible book requires relatively little previous knowledge, making it ideal for advanced undergraduate and graduate students in atmospheric science, environmental sciences and related disciplines.

Ulrike Lohmann is a professor at the Institute for Atmospheric and Climate Science, ETH Zurich. She obtained her Ph.D. in climate modeling and her research now focuses on the role of clouds and aerosol particles in the climate system, with an emphasis on clouds containing ice. Professor Lohmann has published more than 200 peer-reviewed articles and several book chapters, and was a lead author of the Fourth and Fifth IPCC Assessment Reports. She was awarded the Canada Research Chair in 2002 and was the recipient of the AMS Henry G. Houghton Award in 2007. She is a fellow of the American Geophysical Union and the German Academy of Sciences, Leopoldina. Ulrike Lohmann has been teaching classes in cloud microphysics and cloud dynamics for almost 20 years at both undergraduate and graduate levels.

Felix Lüönd is a researcher at the Swiss Federal Institute of Metrology, METAS. He obtained his Ph.D. in atmospheric ice nucleation, for which he was awarded the ETH medal. His experimental work focused on cloud microphysics. He specialized in the development of dedicated instrumentation to study the aerosol-induced freezing of cloud droplets and the interpretation of the resulting experimental data in the framework of nucleation theory and its advancements. Currently, Dr. Lüönd's research activities are concentrated on aerosol metrology, particularly in the generation of ambient-like aerosols dedicated to establish traceability in measurements of ambient particulate matter and particle number concentration.

Fabian Mahrt is a Ph.D. student at the Institute for Atmospheric and Climate Science, ETH Zurich. He obtained a Master's degree in Atmospheric and Climate Sciences from ETH. Early in his career he developed a passion for cloud microphysics. He is particularly interested in aerosol particles and their role in cloud droplets and ice crystal formation. Fabian Mahrt's work is experimental in nature, measuring and understanding aerosol–cloud interactions in both the laboratory and the field.

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An Introduction to Clouds

From the Microscale to Climate

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To our families
Kassiem, Stefanie, Claudia, Jana and Rainer

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Preface

Clouds, in their various forms, are a vital part of our lives. They are a crucial part of the global hydrological cycle, redistributing water to Earth's surface in the form of precipitation. In addition, they are a key element for the global energy budget since they interact with both shortwave (solar) and longwave (terrestrial) radiation. These so-called cloud–radiation interactions depend strongly on the type of cloud. Clearly clouds affect the global climate and thus understanding clouds is an important factor for future climate projections. The effects on Earth's energy budget and on the hydrological cycle both depend on processes on the microphysical scale, encompassing the formation of cloud droplets, ice crystals, raindrops, snowflakes, graupel and hailstones.

Establishing an understanding of clouds and precipitation requires a knowledge of the environment in which they form, i.e. the atmosphere, with all the gases and airborne particles present there. The latter are usually referred to as aerosol particles and encompass a wide range of solid and liquid particles suspended in air. Some aerosol particles can act as nuclei to form cloud droplets or ice crystals and thus initiate the formation of clouds or change their phase from liquid to solid. Thus they influence the microphysical properties of clouds. In turn aerosol particles are removed from the atmosphere when clouds precipitate. In order to gain a complete picture of the behavior of clouds in the atmosphere, the strong interplay between aerosol particles and clouds requires one to tackle the subject in an integrated approach.

This book is intended to offer a fundamental understanding of clouds in the atmosphere. It is primarily written for students at an advanced undergraduate level who are new to the field of atmospheric sciences. The content of this book evolved from the atmospheric physics lectures held at ETH Zurich. This book is intended to serve students with a multidisciplinary background as an introduction to cloud physics, assuming that most readers will have a basic understanding of physics.

The book is organized into 12 chapters, each focusing on a particular topic. Chapter 1 introduces the major cloud types found in the atmosphere and discusses them from a macroscopic point of view. Chapters 2–4 focus on the meteorological conditions and atmospheric dynamics needed for cloud formation and the thermodynamic principles needed to describe atmospheric processes, including phase transitions.

Chapter 5 treats atmospheric aerosol particles and their physical characteristics. The sources and sinks of aerosol particles are discussed at the process level as well as in terms of their global distributions and lifetimes.

Chapters 6–8 cover cloud microphysics. Chapter 6 discusses the fundamental equations that describe the formation of cloud droplets. Chapter 7 introduces the processes which ultimately lead to the formation of rain drops. Ice formation and other microphysical processes occurring in cold clouds are presented in Chapter 8.

Chapter 9 combines the macroscopic view of Chapter 1 with the microscopic view needed to understand the physics of precipitation as well as the differences between stratiform and convective precipitation. Also, the change in precipitation since pre-industrial times and projections into the future are included.

To understand convective clouds, knowledge about cloud dynamics is needed. This is provided in Chapter 10, where convective clouds at all scales, from isolated thunderstorms with lightning and thunder to multicells, supercells and mesoscale convective systems, including tropical cyclones, are discussed.

Finally, Chapters 11 and 12 bring the reader to the global scale. Chapter 11 outlines the physical principles of the global energy budget and discusses the effects of clouds on it. On the basis of the information in Chapter 11 the impact of aerosols and clouds on the climate since pre-industrial times and in future climate projections is considered in Chapter 12.

To strengthen concepts and test the reader's understanding, qualitative exercises and mathematical problems are provided at the end of each chapter. This allows the reader to apply directly the material of the text and provides an opportunity for further learning. To this end, online solutions are provided and can be accessed at www.cambridge.org/clouds. For some of the problem sets the usage of a tephigram will be helpful. This, along with some other material can be accessed from: www.cambridge.org/clouds. Some useful online information about atmospheric science includes the following links:

- Glossary of Meteorology: http://glossary.ametsoc.org/wiki
- Encyclopedia of Atmospheric Sciences:
  http://app.knovel.com/web/toc.v/cid:kpEASV0002/viewerType:toc/root_slug:encyclopedia-atmospheric/url_slug:encyclopedia-atmospheric/?
- NOAA glossary: http://w1.weather.gov/glossary/
- Fifth Assessment Report of the Intergovernmental Panel on Climate Change:
  http://www.climatechange2013.org

Throughout the book, important equations are underlaid in gray. All quantities are given in SI units unless stated otherwise. However, as we often refer to processes occurring above or below 0 °C, we will use degrees celsius whenever convenient, keeping in mind that temperatures need to be in kelvins in the equations given (if not noted otherwise).

The outline of the book follows a similar structure to the classic book *A Short Course in Cloud Physics* by Rogers and Yau (1989), which served the present authors not only for their own studies but also for over a decade of teaching at undergraduate level in the atmospheric physics course. Inspired by the straightforwardness of Rogers and Yau (1989) in explaining complex concepts of cloud physics and their style of imparting knowledge to readers new to the atmospheric sciences, paired with the enormous developments in this field over recent years, the authors decided to come up with this new introductory textbook, which places a stronger focus on ice clouds, cloud dynamics and climate change.

We felt that, although there are many excellent textbooks at the graduate level, a textbook introducing the physics of clouds, aerosols and precipitation in an integrated manner combining quantitative discussions at the undergraduate level was lacking. We believe that this book fills this niche in giving intuitive interpretations of the physical processes discussed. Through this approach we hope to present the fascination of clouds that has captured us and thus to stimulate the interest of the readers in this diverse field. The book provides a fundamental understanding, which can be deepened by the excellent further literature that is available.

Writing this book would not have been possible without the knowledge we received from many pioneers of the field of atmospheric sciences; these are named in the appropriate context throughout the book. Equally important, the development of this book relied on the help and support from many colleagues and we are very grateful for help in different aspects. We owe a great debt to Anina Gilgen for her invaluable contribution in putting together the exercises. Chief among those who provided excellent support are the members of our research group, who discussed drafts of different chapters and were a great source of ideas.

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Symbols and acronyms

Symbols		
Symbol	Value/unit	Description
A, B		Different substances in Raoult's law
A_i, B_i		Empirical constants for the saturation vapor pressure over ice
A_w, B_w		Empirical constants for the saturation vapor pressure over water
A	m^2	Area
a	m	Coefficient of the curvature term in the Köhler equation
a_w		Water activity
B		Buoyancy term
B_λ	W m^{-2}	Black body source function
b	m^3	Coefficient of the solution term in the Köhler equation
b		Coefficient in the Hatch–Choate equation
C	cm^3	CCN concentration at 1% supersaturation
C	F/m	Capacitance for ice crystals
C_c		Cunningham correction factor
C_D		Drag coefficient
CKE	J	Collision kinetic energy
C_R		Constant for radar reflectivity
c_l	4219.9 J kg^{-1} K^{-1}	Specific heat capacity of liquid water
c_i	J kg^{-1} K^{-1}	Specific heat capacity of ice
c_p	1005 J kg^{-1} K^{-1}	Specific heat capacity of dry air at constant pressure
c_{pv}	1884.4 J kg^{-1} K^{-1}	Specific heat capacity of water vapor at constant pressure
c_v	718 J kg^{-1} K^{-1}	Specific heat capacity of dry air at constant volume
c_{vv}	1418.4 J kg^{-1} K^{-1}	Specific heat capacity of water vapor at constant volume
D_a, D_v	m^2 s^{-1}	Diffusivities of aerosol particles or water vapor in air
E, $\tilde{E}$, $\hat{E}$		Collision, collection, coalescence or coagulation efficiencies
E_{coal}	J	Total energy of coalescence
e	Pa	Partial pressure of water vapor
e_{mix}, e'_{mix}	Pa	Mean water vapor pressure of isobarically mixed air before and after condensation
$e_{s,i}$, $e_{s,w}$	Pa	Saturation vapor pressures with respect to ice or water
e_{s0}	611.2 Pa	Saturation vapor pressure at T_0 = 273.15 K
$e*$		Equilibrium vapor pressure over a solution
F	J	Helmholtz free energy
$\vec{F}$	N	Force vector

F_B	m s^{-2}	Buoyancy force per unit mass
$\vec{F}_C$	m s^{-2}	Coriolis force per unit mass
F_d	s m^{-2}	Vapor diffusion term in droplet radius growth equation
F_d^i, F_d^l	m s kg^{-1}	Vapor diffusion terms in the mass growth equations for ice crystals and cloud droplets
F_D	kg m s^{-2}	Drag force
$\vec{F}_F$	m s^{-2}	Dissipation term for momentum, per unit mass, i.e. friction
F_g	kg m s^{-2}	Gravity force
F_k	s m^{-2}	Thermodynamic term in droplet radius growth equation
F_k^i, F_k^l	m s kg^{-1}	Thermodynamic terms in the mass growth equations for ice crystals and cloud droplets
F_{LW}, F_{LW}^{cs}	W m^{-2}	Net longwave radiative fluxes at the TOA in all-sky and clear-sky conditions
$F_{LW}^{\uparrow}$, $F_{LW}^{\downarrow}$	W m^{-2}	Upward- and downward-directed longwave radiative fluxes
F_{Sun}	3.85×10^{26} W	Radiation emitted by the Sun
F_{SW}, F_{SW}^{cs}	W m^{-2}	Net shortwave radiative fluxes at the TOA in all-sky and clear-sky conditions
$F_{SW}^{\downarrow}$	W m^{-2}	Downward-directed shortwave radiative fluxes
$\vec{F}_{PG}$	m s^{-2}	Pressure gradient force per unit mass
f	s^{-1}	Coriolis parameter, i.e. planetary vorticity
f		Compatibility parameter for heterogeneous nucleation
f_{act}, f_f		Activation and frozen fractions
$\bar{f}_v$		Mean ventilation coefficient
G	J	Gibbs free energy
$G_{s,hom}$, $G_{v,hom}$, $G_{v,het}$	J	Surface and volume terms of the Gibbs free energy for a pure liquid droplet and for a solution droplet
$G_{ex}(n)$	J	Excess Gibbs free energy due to cluster formation
$G(n)$	J	Total Gibbs free energy of the cluster
g	9.81 m s^{-2}	Acceleration due to gravity
g, g_v, g_l	J kg^{-1}	Specific Gibbs free energy in general and in the vapor or liquid phases
H	J	Enthalpy
H	W m^{-2}	Heat flux into the ocean
H	m^2 s^{-2}	Helicity
h	m	Height above Earth's surface, vertical distance
I_λ	W m^{-2}	Wavelength-dependent intensity of radiation
I, I_0	W m^{-2}	Intensity of radiation in general and at TOA
i		Van 't Hoff factor
J, J_i, J_w	cm^{-3} s^{-1}	General nucleation rate and nucleation rates for ice in vapor and water in vapor
K	cm^{-3} s^{-1}	Kinetic prefactor for the nucleation rate
K	J m^{-1} s^{-1} K^{-1}	Coefficient of thermal conductivity in air
K	m^3 s^{-1}	Collision or collection kernel

$\lvert K\rvert^2$		Modulus squared of the complex index of refraction
k	1.38×10^{-23} J K^{-1}	Boltzmann constant
k		Slope of the $CCN-S$ relationship
$k_{\lambda,abs} = k_{abs}$	m^{-1}	Wavelength-dependent absorption coefficient for greenhous gases, aerosol particles and cloud hydrometeors
$k_{\lambda,ext} = k_{ext}$	m^{-1}	Wavelength-dependent extinction coefficient for greenhous gases, aerosol particles and cloud hydrometeors
$k_{\lambda,scat} = k_{scat}$	m^{-1}	Wavelength-dependent scattering coefficient for greenhous gases, aerosol particles and cloud hydrometeors
L	m	Characteristic length scale for geostrophic flow
$L_{2,1}$	J kg^{-1}	Latent heat for the phase change from phase 1 to phase 2
L_f	J kg^{-1}	Latent heat of fusion
$L_{f0} = L_f(T_0)$	0.333×10^6 J kg^{-1}	Latent heat of fusion at T_0 = 273.15 K
L_s		Latent heat of sublimation
$L_{s0} = L_s(T_0)$	2.834×10^6 J kg^{-1}	Latent heat of sublimation at T_0 = 273.15 K
L_v	J kg^{-1}	Latent heat of vaporization
$L_{v0} = L_v(T_0)$	2.501×10^6 J kg^{-1}	Latent heat of vaporization at T_0 = 273.15 K
M	m s^{-1}	Absolute momentum
MF	kg s^{-1}	Mass flux
M_d	28.96 g mol^{-1}	Molecular weight of dry air
M_l	kg m^{-3}	Cloud liquid water content in units of mass per unit volume
M_m	g mol^{-1}	Molecular weight of moist air
M_s	g mol^{-1}	Molecular weight of a solute
M_w	18 g mol^{-1}	Molecular weight of water
MF$_d$, MF$_u$	kg s^{-1}	Downward and upward mass fluxes
m, m_w, m_s	kg	Masses of air parcel, bulk water and solute
m_d, m_m, m_v	kg	Masses of dry air, moist air and water vapor
m_0	kg	Masses of one water molecule
m_i, m_l, m_R, $m(r)$	kg	Masses of an ice crystal, cloud droplet and collector drop and of hydrometeors in general
m_a, m_{tot}	kg	Total mass of aerosol particles and of the solution droplet
N	s^{-1}	Brunt–Väisälä frequency
N		Number of molecules
N_A	6.022×10^{23} mol^{-1}	Avogadro's constant
N_0	cm^{-4}	Intercept parameter for hydrometeor size distributions
N, N_a, N_{CCN}, N_c, N_d, N_i, N_r	cm^{-3}	Number concentrations in general and of aerosol particles, CCN, cloud droplets, drizzle drops, ice crystals and raindrops
N_j		Number of particles of type j

n		Number of moles or molecules
n_i, n_v	m^{-3}	Number concentrations of gas molecules and of water vapor molecules
$n_m^e(r)$	g cm^{-3}	Mass concentration of hydrometeors
$n_N(r)$	cm^{-3} μm^{-1}	Number concentration of aerosol particles per micrometer size
$n_N(r)$	m^{-3} mm^{-1} or m^{-3} m^{-1}	Number concentration of hydrometeors per unit length
$n_N^e(r)$	cm^{-3}	Number concentration of aerosol particles on a logarithmic scale
n_s, n_w		Numbers of solute and water molecules
$n_S(r)$	μm^2 cm^{-3} μm^{-1}	Surface concentration of aerosol particles per micrometer size
$n_S^e(r)$	μm^2 cm^{-3}	Surface concentration of aerosol particles on a logarithmic scale
$n_V(r)$	μm^3 cm^{-3} μm^{-1}	Volume concentration of aerosol particles per micrometer size
$n_V^e(r)$	μm^3 cm^{-3}	Volume concentration of aerosol particles on a logarithmic scale
P		Probability
$\overline{P}_R$	W	Power received at a radar antenna
p	Pa	Atmospheric pressure
p_0	1000 hPa	Reference pressure
p_c	Pa	Pressure of the lifting condensation level
p_i, p_A, p_B	Pa	Partial pressure of particle type i and of substances A and B
p_n	Pa	Pressure within a cluster
p_s	Pa	Saturation vapor pressure
p_{tot}	Pa	Total vapor pressure of a solution
Q	J	Heat energy
Q		Generic quantity in thermodynamics
Q_1	m^{-1}	Thermodynamic variable in supersaturation equation
Q_2		Thermodynamic variable in supersaturation equation
$Q_{\lambda,ext}$		Extinction efficiency
q	J kg^{-1}	Specific heat energy
q_i	kg kg^{-1}	Cloud ice mass mixing ratio
q_l	kg kg^{-1}	Cloud liquid water mass mixing ratio
q_s, $q_{s,i}$	kg kg^{-1}	Saturation specific humidity with respect to water and ice
q_v	kg kg^{-1}	Specific humidity: mass of water vapor per unit mass of moist air
$q_{v,cl}$	kg kg^{-1}	Specific humidity in a cloudy air parcel
$q_{v,env}$	kg kg^{-1}	Specific humidity in the environment
$q_{v,mix}$	kg kg^{-1}	Mean specific humidity in well-mixed air
q_x	kg kg^{-1}	Condensate mixing ratio: mass of condensate per unit mass of dry air
R	m	Radius of a collector drop
R	mm h^{-1}	Precipitation or rain rate
R_d	287 J kg^{-1} K^{-1}	Gas constant of dry air
R_i	m	Melted radius of a snowflake

R_m	J kg^{-1} K^{-1}	Gas constant of moist air
R_{Sun}	6.98×10^8 m	Radius of the Sun
R_v	461.5 J kg^{-1} K^{-1}	Gas constant of water vapor
R^*	8.314 J mol^{-1} K^{-1}	Universal gas constant
R_{50}	m	Radius at which 50% of aerosol particles are activated
Re		Reynolds number
RH, RH$_i$	%	Relative humidities with respect to water and ice
Ro		Rossby number
r	m	Radius, distance in spherical coordinates
r_{act}	m	Critical radius for activation
r_c	m	Critical radius
r_d, r_h, r_i, r_r	m	Radii of a droplet, hydrometeor, ice particle and raindrop
$\bar{r}_d$	m	Mean volume radius
r_{eq}	m	Equivalent radius for a raindrop or for the drop that is formed when a snowflake melts
r_{dry}	m	Dry radius of an aerosol particle
r_{Earth}	6.371×10^9 m	Radius of the Earth
r_{max}	m	Maximum raindrop radius
$r_{Sun-Earth}$	1.5×10^{11} m	Sun–Earth distance
S	J K^{-1}	Entropy
S	m^2	Surface area
$S = S_w, S_i$		Ambient saturation ratios with respect to water and ice
S_a	µm^2 cm^{-3}	Total aerosol surface area concentration
S_{act}		Activation saturation ratio
S_c	J	Surface energy
S_{cry}		Crystallization saturation ratio
S_{del}		Deliquesence saturation ratio
S_{max}		Maximum supersaturation reached in a cloud
$S(r)$		Size-dependent saturation ratio of a solution droplet with radius r
S_0	1360 W m^{-2}	Solar constant
Sc		Schmidt number
s	J kg^{-1} K^{-1}	Specific entropy
s	m	Path length
s, s_{cl}, s_{env}	J kg^{-1}	Moist static energies in general and for cloudy or environmental air
s	%	Supersaturation
s_{act}	%	Supersaturation required for activation
T	K	Temperature of an air parcel
T	m s^{-1}	Characteristic time scale for geostrophic flow
T_0	273.15 K	Melting point temperature (0 °C)
T_{atm}	K	Average temperature of the atmosphere
T_{cl}	K	Temperature of a cloudy air parcel
T_{env}	K	Temperature of the environment
T_c	K	Isentropic condensation temperature
T_d	K	Dew point temperature
T_e	K	Effective temperature
T_e, T_{es}	K	Equivalent and saturation equivalent temperature

T_{in}, T_{out}	K	Input and output temperature of the Carnot cycle
T_{mix}, T'_{mix}	K	Mean temperature in isobarically mixed air before and after condensation
T_p	K	Temperature of the air parcel
T_{p0}, T_{tropo}	K	Temperatures at 1000 hPa and at the tropopause
T_{r_d}	K	Temperature at a droplet's surface
T_s	K	Annual global mean temperature at the Earth's surface
T_{Sun}	5769.56 K	Temperature of the Sun
T_v, $T_{v,env}$	K	Virtual temperature in general and of the environment
T_w	K	Wet-bulb temperature
t	s	Time
U	J	Internal energy
U	m s^{-1}	Characteristic velocity scale for geostrophic flow
u	J kg^{-1}	Specific internal energy
u, v	m s^{-1}	Horizontal velocity components in x- and y- directions
u_g, v_g	m s^{-1}	Geostrophic wind components in x- and y- directions
V, V_n	m^3	Volume in general and of the cluster
V_a	μm^3 cm^{-3}	Total aerosol volume concentration
V_{sweep}	m^3	Sweep-out volume
$\vec{v}$	m s^{-1}	Three-dimensional velocity vector
$\vec{v_h}$	m s^{-1}	Horizontal velocity vector
v, v_i, v_w	m^3 kg^{-1}	Specific volume in general and of ice and water
v_0	m^3	Volume of an individual molecule
v_D	m s^{-1}	Doppler velocity
v_h	m s^{-1}	Fall velocity of hydrometeors
v_r	m s^{-1}	Relative velocity of two falling hydrometeors
v_T, $v_{T,snow}$	m s^{-1}	Terminal velocity in general and for snow
W	J	Work
w	J kg^{-1}	Specific external work
w, w_{cl}	m s^{-1}	Vertical velocity in general and for a cloudy air parcel
w_j		mass fraction
w_l	kg kg^{-1}	Adiabatic cloud liquid water mixing ratio
w_s	kg kg^{-1}	Saturation water vapor mixing ratio
w_v	kg kg^{-1}	Water vapor mixing ratio: mass of water vapor per unit mass of dry air
x		Dimensionless size parameter for scattering
x_0	m	Impact parameter within which a collision is certain to occur
Z	mm^6 m^{-3}	Radar reflectivity factor
Z_e	mm^6 m^{-3}	Equivalent radar reflectivity factor
z	m	Height
α, α_i, α_l, α_v	m^3 kg^{-1}	Specific volumes of air, ice, liquid water and water vapor
α_m		Accommodation coefficient for ice crystal growth
α_c		Cloud albedo
α_p		Planetary albedo
β	m^{-1} s^{-1}	Meridional gradient of Coriolis parameter f
γ, Γ	K m^{-1}	Lapse rates of the ambient air and of an air parcel
γ		Radii ratio of collector drop to smaller droplet

Γ_d	9.8 K km^{-1}	Dry adiabatic lapse rate
Γ_s	K km^{-1}	Pseudoadiabatic lapse rate
ΔF = RF	W m^{-2}	Radiative forcing
ΔF_{LW}, ΔF_{SW}	W m^{-2}	Changes in F_{LW} and F_{SW} at the TOA
ΔH	W m^{-2}	Heat uptake by the ocean
ΔG	J	Change in Gibbs free energy
ΔG^*, ΔG^*_{het}	J	Gibbs free energy barrier in general and for heterogeneous nucleation
ΔG_s, ΔG_v	J	Surface and volume terms of the change in Gibbs free energy
$\Delta G_{s,hom}$, $\Delta G_{s,sol}$	J	Surface terms of the change in Gibbs free energy in pure water and in a solution
$\Delta G_{v,hom}$, $\Delta G_{v,sol}$	J	Volume terms of the change in Gibbs free energy in pure water and in a solution
$\Delta G_{w,v}$, $\Delta G_{i,w}$, $\Delta G_{i,v}$	J	Changes in Gibbs free energy between water and vapor, ice and water, and ice and vapor
ΔR	W m^{-2}	Net radiative imbalance at the TOA
ΔT_s	K	Change in global mean surface temperature
δ		infinitesimal change
ϵ, ϵ_λ		Emissivity in general and wavelength-dependent emissivity
ϵ		Entrainment
ϵ	0.622	Ratio $R_d/R_v = m_w/m_d$
ζ	s^{-1}	z-component of the relative vorticity
η	s^{-1}	x-component of the relative vorticity
η		Thermodynamic efficiency of the Carnot process
θ		Contact angle
θ	K	Potential temperature
θ_e, θ_{es}	K	Equivalent and saturation equivalent potential temperatures
θ_{mix}	K	Mean potential temperature in well-mixed air
θ_w	K	Wet-bulb potential temperature
κ	0.286	Ratio R_d/c_p
κ		Hygroscopicity parameter
Λ	m^{-1}	Entrainment rate
Λ	cm^{-1}	Slope of hydrometeor size distributions
Λ_B	s^{-1}	Scavenging coefficient
λ	m	Wavelength
λ	W m^{-2} K^{-1}	Climate sensitivity parameter
λ_0	W m^{-2} K^{-1}	Null climate sensitivity parameter
μ		Shape parameter of hydrometeor size distributions
μ	kg m^{-1} s^{-1}	Dynamic viscosity of air
μ	J s^{-1}	Chemical potential

μ, μ_S, μ_V, μ_m	m	Number mean radius and arithmetic means of the surface, volume and mass radii
μ_g, $\mu_{g,S}$, $\mu_{g,V}$, $\mu_{g,m}$	m	Geometric means of the number, surface, volume and mass distributions of aerosol particles
$\widetilde{\mu}$, $\overline{\mu}$	m	Number mode radius and radius of average mass
ν	$m^2\ s^{-1}$	Kinematic viscocity
ξ	s^{-1}	*y*-component of the relative vorticity
ρ_a	$kg\ m^{-3}$	Density of an aerosol particle
ρ_d	$kg\ m^{-3}$	Density of dry air
ρ_{env}	$kg\ m^{-3}$	Density of ambient air
ρ_l, ρ_i, ρ_s	$kg\ m^{-3}$	Densities of liquid water, ice and a solution droplet
ρ, ρ_m	$kg\ m^{-3}$	Density in general and of moist air
ρ_v, ρ_{v,r_d}, ρ_{vs}	$kg\ m^{-3}$	Ambient water vapor density, water vapor density at a droplet's surface and saturation water vapor density
σ		Arithmetic standard deviation
σ	$5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$	Stefan–Boltzmann constant
σ	$N\ m^{-1}$	Surface tension
$\sigma_{i,a}$, $\sigma_{i,v}$	$N\ m^{-1}$	Surface tension of ice in air or vapor
$\sigma_{w,a} = \sigma_w$	$N\ m^{-1}$	Surface tension of water in air
$\sigma_{w,v}$	$0.0756\ N\ m^{-1}$	Surface tension of water in water vapor at 273.15 K
$\sigma_{i,w}$	$N\ m^{-1}$	Surface tension between ice and water
$\sigma_{INP,i}$, $\sigma_{INP,v}$, $\sigma_{INP,w}$	$N\ m^{-1}$	Surface tensions between an INP and ice, vapor or water
σ, σ_i	m	Standard deviations of the aerosol size distribution in mode *i*
σ_g		Geometric standard deviation of the aerosol size distribution
τ		Optical depth
τ_{AP}		Aerosol optical depth
ϕ	°, degrees	Latitude
$\varphi(V_n)$	J	Gibbs free energy of the interface between a cluster and the parent phase
Ω	$7.29 \times 10^{-5}\ s^{-1}$	Earth's rotation
ω	$Pa\ s^{-1}$	Vertical velocity in the *p*-system
$\vec{\omega}$	s^{-1}	Three-dimensional vorticity vector
$\vec{\omega}_h$	s^{-1}	Horizontal vorticity vector

Acronyms	
AEJ	African easterly jet
AEROCOM	Aerosol Intercomparison project
AERONET	Aerosol Robotic Network
AOD	Aerosol optical depth
AOGCM	Coupled atmosphere–ocean general circulation model
AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
aci	Aerosol–cloud interactions
ari	Aerosol–radiation interactions
a.u.	arbitrary units
BC	Black carbon
BWER	Bounded weak echo region
CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAPE	Convectively available potential energy (J kg^{-1})
CCB	Cold conveyor belt
CCL	Convective condensation level
CCN	Cloud condensation nuclei
CCNC	Cloud condensation nuclei counter
CERES	Capacité de Renseignement Electromagnétique Spatial
CIN	Convective inhibition
CKE	Collision kinetic energy
CNT	Classical nucleation theory
CRE	Cloud radiative effect
CRH	Crystallization relative humidity
CTP	Cloud top pressure
DCAPE	Downdraft convectively available potential energy (J kg^{-1})
DJF	December, January, February
DMS	Dimethyl sulfide
DRH	Deliquescence relative humidity
DU	Mineral dust particles
EC	Elemental carbon
ECA	Emission controlled area
ECHAM6 GCM	Global climate model from the Max Planck Institute for Meteorology in Hamburg, Germany
ECMWF	European Centre for Medium-Range Weather Forecast
ERA-interim	ECMWF Re-analysis interim
ERFaci	Effective radiative forcing due to aerosol–cloud interactions
ERFari	Effective radiative forcing due to aerosol–radiation interactions
ERFacitari	Effective radiative forcing due to aerosol–cloud and aerosol–radiation interactions
GCCN	Giant CCN
GCM	Global climate model
GeoMIP	Geoengineering Model Intercomparison Project
GHG	Greenhouse gases

GPCC	Global Precipitation Climatology Centre
HTI	Height–time indicator
INP	Ice nucleating particle
IPCC	Intergovernmental Panel on Climate Change
ISA	International standard atmosphere
ISCCP	International Satellite Cloud Climatology Project
ITCZ	Intertropical Convergence Zone
IWC	Ice water content
JJA	June, July, August
LAADS	Level-1 and Atmosphere Archive and Distribution System
LCRE	Longwave cloud radiative effect
LCL	Lifting condensation level
LFC	Level of free convection
LH	Latent heat flux
LNB	Level of neutral buoyancy
LW	Longwave
LWC	Liquid water content
MCC	Mesoscale convective complex
MCS	Mesoscale convective system
MEE	Mass extinction efficiency
MISR	Multi-angle imaging spectroradiometer
MODIS	Moderate resolution imaging spectroradiometer
NCFR	Narrow cold frontal rainband
NOAA	National Oceanic and Atmospheric Administration
OC	Organic carbon
OLR	Outgoing longwave radiation
PBL	Planetary boundary layer
POA	Primary organic aerosol
POM	Particulate organic matter
PPI	Plan position indicator
QLL	Quasi-liquid layer
Radar	Radio detection and ranging
RCP	Representative concentration pathway
RF	Radiative forcing
RFaci	Radiative forcing due to aerosol–cloud interactions
RFacitari	Radiative forcing due to aerosol–cloud and aerosol–radiation interactions
RFari	Radiative forcing due to aerosol–radiation interactions
RH	Relative humidity
SCE	Stochastic coalescence equation
SCRE	Shortwave cloud radiative effect
SH	Sensible heat flux
SOA	Secondary organic aerosols
SPCZ	South Pacific Convergence Zone
SRM	Solar radiation management
SST	Sea surface temperature
SS	Sea salt

SU	Sulfate
TC	Tropical cyclone
TDE	Thermodynamic equilibrium
TOA	Top of the atmosphere
WCB	Warm conveyor belt
WCFR	Wide cold frontal rainband
WFR	Warm frontal rainband
WMGHG	Well-mixed greenhouse gases
WMO	World Meteorological Organization