### 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.

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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

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Preface

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

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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	
Α	$m^2$	Area	
а	m	Coefficient of the curvature term in the Köhler equation	
$a_w$		Water activity	
В		Buoyancy term	
$B_{\lambda}$	$\mathrm{W}\mathrm{m}^{-2}$	Black body source function	
b	m <sup>3</sup>	Coefficient of the solution term in the Köhler equation	
b		Coefficient in the Hatch–Choate equation	
С	cm <sup>3</sup>	CCN concentration at 1% supersaturation	
С	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 <sup><math>-1</math></sup> K <sup><math>-1</math></sup>	Specific heat capacity of liquid water	
ci	$J kg^{-1} K^{-1}$	Specific heat capacity of ice	
$c_p$	$1005 \mathrm{J  kg^{-1}  K^{-1}}$	Specific heat capacity of dry air at constant pressure	
$c_{pv}$	$1884.4 \text{ J kg}^{-1} \text{ K}^{-1}$	Specific heat capacity of water vapor at constant pressure	
$c_{v}$	$718 \mathrm{Jkg^{-1}\ K^{-1}}$	Specific heat capacity of dry air at constant volume	
$c_{VV}$	$1418.4 \text{ J kg}^{-1} \text{ K}^{-1}$	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	Ра	Partial pressure of water vapor	
$e_{mix}, e'_{mix}$	Ра	Mean water vapor pressure of isobarically mixed air before	
		and after condensation	
$e_{s,i}, e_{s,w}$	Ра	Saturation vapor pressures with respect to ice or water	
$e_{s0}$	611.2 Pa	Saturation vapor pressure at $T_0 = 273.15$ K	
<i>e</i> *		Equilibrium vapor pressure over a solution	
F	J	Helmholtz free energy	
F	Ν	Force vector	

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xvii	Symbols and acronyms			
	En	$m s^{-2}$	Buoyancy force per unit mass	
	$\vec{F}_{C}$	$m s^{-2}$	Coriolis force per unit mass	
	F <sub>4</sub>	$sm^{-2}$	Vapor diffusion term in droplet radius growth	
	- u	5	equation	
	$F^{i}_{l}, F^{l}_{l}$	$m s kg^{-1}$	Vapor diffusion terms in the mass growth equations	
	d' d	6	for ice crystals and cloud droplets	
	$F_D$	$kg m s^{-2}$	Drag force	
	$\vec{F}_F$	m s <sup>-2</sup>	Dissipation term for momentum, per unit mass, i.e.	
			friction	
	$F_g$	$kg m s^{-2}$	Gravity force	
	$F_k$	s m <sup>-2</sup>	Thermodynamic term in droplet radius growth equation	
	$F_{i}^{l}$ , $F_{i}^{l}$	m s kg <sup>-1</sup>	Thermodynamic terms in the mass growth equations	
	- k' - k	in o ng	for ice crystals and cloud droplets	
	$F_{IW}, F_{IW}^{CS}$	$\mathrm{W}\mathrm{m}^{-2}$	Net longwave radiative fluxes at the TOA in all-sky	
	±, Lw		and clear-sky conditions	
	$F_{LW}^+, F_{LW}^+$	$W m^{-2}$	Upward- and downward-directed longwave radiative	
	_		fluxes	
	$F_{Sun}$	$3.85 \times 10^{20} \text{ W}$	Radiation emitted by the Sun	
	$F_{SW}, F_{SW}^{cs}$	W m <sup>-2</sup>	Net shortwave radiative fluxes at the TOA in all-sky and clear-sky conditions	
	$F_{SW}^{\downarrow}$	$\mathrm{W}\mathrm{m}^{-2}$	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	
	$f_{\mathcal{V}}$		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	
	<b>G</b> ( )	T	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 = -2	Total Gibbs free energy of the cluster	
	g a a ai	$5.61 \text{ m s}^{-1}$	Specific Gibbs free energy in general and in the	
	$g, g_{v}, g_{l}$	JKg	specific Globs free energy in general and in the	
	Н	T	Forthalov	
	H	$W m^{-2}$	Heat flux into the ocean	
	H	$m^2 s^{-2}$	Helicity	
	h	m	Height above Earth's surface, vertical distance	
	$I_{\lambda}$	$\mathrm{W}\mathrm{m}^{-2}$	Wavelength-dependent intensity of radiation	
	<i>I</i> , <i>I</i> <sub>0</sub>	${ m W}{ m m}^{-2}$	Intensity of radiation in general and at TOA	
	i		Van 't Hoff factor	
	$J, J_i, J_w$	${\rm cm}^{-3} {\rm s}^{-1}$	General nucleation rate and nucleation rates for ice	
			in vapor and water in vapor	
	Κ	$cm^{-3} s^{-1}$	Kinetic prefactor for the nucleation rate	
	Κ	$J m^{-1} s^{-1} K^{-1}$	Coefficient of thermal conductivity in air	
	K	$m^{3} s^{-1}$	Collision or collection kernel	

xviii	Symbols and acronyms			
	<i>K</i>   <sup>2</sup>		Modulus squared of the complex index of refraction	
	k	$1.38 \times 10^{-23} \text{ J K}^{-1}$	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	
	N,Setti Setti		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	
	2,1	U	1 to phase 2	
	$L_{f}$	$J kg^{-1}$	Latent heat of fusion	
	$L_{f0}^{J} = L_{f}(T_{0})$	$0.333 \times 10^{6} \mathrm{J  kg^{-1}}$	Latent heat of fusion at $T_0 = 273.15$ K	
	$L_{S}$	C	Latent heat of sublimation	
	$L_{s0} = L_s(T_0)$	$2.834 \times 10^{6} \mathrm{J  kg^{-1}}$	Latent heat of sublimation at $T_0 = 273.15$ K	
	$L_{v}$	J kg <sup>-1</sup>	Latent heat of vaporization	
	$L_{v0} = L_v(T_0)$	$2.501 \times 10^{6} \mathrm{J  kg^{-1}}$	Latent heat of vaporization at $T_0 = 273.15$ K	
	Μ	m s <sup>-1</sup>	Absolute momentum	
	MF	kg s <sup>−1</sup>	Mass flux	
	$M_d$	$28.96 \text{ g mol}^{-1}$	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 <sup>-1</sup>	Molecular weight of moist air	
	$M_{s}$	g mol <sup>-1</sup>	Molecular weight of a solute	
	$M_W$	$18 \text{ g mol}^{-1}$	Molecular weight of water	
	$MF_d, MF_u$	kg s <sup>-1</sup>	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	
		1	solution droplet	
	Ν	s <sup>-1</sup>	Brunt–Väisälä frequency	
	N	· · · · · · · · · · · · · · · · · · ·	Number of molecules	
	NA	$6.022 \times 10^{23} \text{ mol}^{-1}$	Avogadro's constant	
	N <sub>0</sub>	cm <sup>-4</sup>	Intercept parameter for hydrometeor size distributions	
	$N, N_a, N_{CCN}, N_c,$	$cm^{-3}$	Number concentrations in general and of	
	$N_d, N_i, N_r$		aerosol particles, CCN, cloud droplets,	
			drizzle drops, ice crystals and raindrops	
	Nj		Number of particles of type <i>j</i>	

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	-	,
n		Number of moles or molecules
$n_i, n_v$	$m^{-3}$	Number concentrations of gas molecules and of water
., ,		vapor molecules
$n_m^e(r)$	$\rm g~cm^{-3}$	Mass concentration of hydrometeors
$n_N(r)$	$cm^{-3} \mu m^{-1}$	Number concentration of aerosol particles per
11(()	•	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
IV V		logarithmic scale
$n_s, n_w$		Numbers of solute and water molecules
$n_{\rm S}(r)$	$\mu m^2 cm^{-3} \mu m^{-1}$	Surface concentration of aerosol particles per
5.7		micrometer size
$n_{c}^{e}(r)$	$\mu$ m <sup>2</sup> cm <sup>-3</sup>	Surface concentration of aerosol particles on a
3.7	•	logarithmic scale
$n_V(r)$	$\mu m^3 cm^{-3} \mu m^{-1}$	Volume concentration of aerosol particles per
• • • •		micrometer size
$n_{V}^{e}(r)$	$\mu$ m <sup>3</sup> cm <sup>-3</sup>	Volume concentration of aerosol particles on a
V	•	logarithmic scale
Р		Probability
$\overline{P}_R$	W	Power received at a radar antenna
p	Ра	Atmospheric pressure
$p_0$	1000 hPa	Reference pressure
$p_c$	Ра	Pressure of the lifting condensation level
$p_i, p_A, p_B$	Ра	Partial pressure of particle type <i>i</i> and of substances A
		and <i>B</i>
$p_n$	Pa	Pressure within a cluster
$p_s$	Pa	Saturation vapor pressure
<i>p</i> 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 <sup>-1</sup>	Cloud ice mass mixing ratio
$q_l$	$kg kg^{-1}$	Cloud liquid water mass mixing ratio
$q_s, q_{s,i}$	kg kg <sup>-1</sup>	Saturation specific humidity with respect to water and
		ice
$q_{v}$	kg kg <sup>-1</sup>	Specific humidity: mass of water vapor per unit mass
		of moist air
$q_{v,cl}$	kg kg <sup>-1</sup>	Specific humidity in a cloudy air parcel
$q_{v,env}$	kg kg <sup>-1</sup>	Specific humidity in the environment
$q_{v,mix}$	kg kg <sup>-1</sup>	Mean specific humidity in well-mixed air
$q_X$	kg kg <sup>-1</sup>	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
$R_d$	$287 \text{ J kg}^{-1} \text{ K}^{-1}$	Gas constant of dry air
$R_i$	m	Melted radius of a snowflake

XX			Symbols and acronyms
	$R_m$	$J kg^{-1} K^{-1}$	Gas constant of moist air
	R <sub>Sun</sub>	$6.98 \times 10^8 \text{ m}$	Radius of the Sun
	$R_v$	$461.5 \text{ J kg}^{-1} \text{ K}^{-1}$	Gas constant of water vapor
	$R^*$	$8.314 \text{ J mol}^{-1} \text{ K}^{-1}$	Universal gas constant
	$R_{50}$	m	Radius at which 50% of aerosol particles are activated
	Re		Reynolds number
	RH, RH <sub>i</sub>	%	Relative humidities with respect to water and ice
	Ro		Rossby number
	r	m	Radius, distance in spherical coordinates
	r <sub>act</sub>	m	Critical radius for activation
	r <sub>c</sub>	m	Critical radius
	$r_d, r_h, r_i, r_r$	m	Radii of a droplet, hydrometeor, ice particle and raindrop
	$\overline{r}_d$	m	Mean volume radius
	r <sub>eq</sub>	m	Equivalent radius for a raindrop or for the drop that is
	· ·		formed when a snowflake melts
	<i>r</i> <sub>dry</sub>	m	Dry radius of an aerosol particle
	r <sub>Earth</sub>	$6.371 \times 10^9 \text{ m}$	Radius of the Earth
	<i>r<sub>max</sub></i>	m	Maximum raindrop radius
	r <sub>Sun-Earth</sub>	$1.5 \times 10^{11} \text{ m}$	Sun–Earth distance
	S	$J K^{-1}$	Entropy
	S	m <sup>2</sup>	Surface area
	$S = S_w, S_i$		Ambient saturation ratios with respect to water and ice
	$S_a$	$\mu$ m <sup>2</sup> cm <sup>-3</sup>	Total aerosol surface area concentration
	Sact		Activation saturation ratio
	$S_c$	J	Surface energy
	Scry		Crystallization saturation ratio
	$S_{del}$		Deliquesence saturation ratio
	S <sub>max</sub>		Maximum supersaturation reached in a cloud
	S(r)		Size-dependent saturation ratio of a solution droplet with
		2	radius r
	$S_0$	$1360 \text{ W m}^{-2}$	Solar constant
	Sc	. 1 1	Schmidt number
	S	$J kg^{-1} K^{-1}$	Specific entropy
	S	m	Path length
	$s, s_{cl}, s_{env}$	J kg <sup>-1</sup>	Moist static energies in general and for cloudy or
		~	environmental air
	S	%	Supersaturation
	Sact	%	Supersaturation required for activation
	T	K _1	Temperature of an air parcel
	T	m s <sup>1</sup>	Characteristic time scale for geostrophic flow
	$I_0$	2/3.15 K	Melting point temperature (0 °C)
	I <sub>atm</sub>	K	Average temperature of the atmosphere
	I <sub>cl</sub>	K	Temperature of a cloudy air parcel
	T <sub>env</sub>	K V	International and an action to the environment
		K V	Dev point temperature
	$T_d$	K V	Effective temperature
		K V	Encouve temperature
	$1_e, 1_{es}$	N	Equivalent and saturation equivalent temperature

xxi			Symbols and acronyms
	Tin, Tout	К	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
	$T_{p_0}, T_{tropo}$	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 <sub>Sun</sub>	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	lime
	U	$J_{m e^{-1}}$	Characteristic valocity scale for geostrophic flow
	U	III s	Specific internal energy
		$m s^{-1}$	Horizontal velocity components in r- and v- directions
	u, v Ua, Va	$m s^{-1}$	Geostrophic wind components in x- and y- directions
	$V, V_n$	m <sup>3</sup>	Volume in general and of the cluster
	$V_a$	$\mu$ m <sup>3</sup> cm <sup>-3</sup>	Total aerosol volume concentration
	Vsweep	m <sup>3</sup>	Sweep-out volume
	$\vec{v}$	${ m m~s^{-1}}$	Three-dimensional velocity vector
	$\vec{v_h}$	${ m m~s^{-1}}$	Horizontal velocity vector
	$v, v_i, v_w$	$m^3 kg^{-1}$	Specific volume in general and of ice and water
	v <sub>0</sub>	m <sup>3</sup>	Volume of an individual molecule
	vD	$m s^{-1}$	Doppler velocity
	$v_h$	$m s^{-1}$	Fall velocity of hydrometeors
	$v_r$	$m s^{-1}$	Relative velocity of two failing hydrometeors
	VT, VT, snow	III S -	Work
	W	$I k \sigma^{-1}$	Specific external work
	W. Wal	$m s^{-1}$	Vertical velocity in general and for a cloudy air parcel
	Wi		mass fraction
	wi	$kg kg^{-1}$	Adiabatic cloud liquid water mixing ratio
	Ws	$kg kg^{-1}$	Saturation water vapor mixing ratio
	WV	$ m kgkg^{-1}$	Water vapor mixing ratio: mass of water vapor per unit
			mass of dry air
	x		Dimensionless size parameter for scattering
	<i>x</i> <sub>0</sub>	m	Impact parameter within which a collision is certain to
	7	6 -3	occur De la clicica fonda
	2 7	$mm^{\circ}m^{\circ}$	Fauitalant reder reflectivity factor
	$\Sigma_e$	m	Equivalent radar renectivity factor
	$\mathcal{A}$	$m^3 k \sigma^{-1}$	Specific volumes of air ice liquid water and water vapor
	$\alpha, \alpha_l, \alpha_l, \alpha_v$ $\alpha_m$	in kg	Accommodation coefficient for ice crystal growth
	$\alpha_c$		Cloud albedo
	$\alpha_p$		Planetary albedo
	β	$m^{-1} s^{-1}$	Meridional gradient of Coriolis parameter $f$
	γ, Γ	${ m K}~{ m m}^{-1}$	Lapse rates of the ambient air and of an air parcel
	γ		Radii ratio of collector drop to smaller droplet

xxii	Symbols and acronyms		
	1		
	$\Gamma_d$	$9.8 \text{ K km}^{-1}$	Dry adiabatic lapse rate
	$\Gamma_s$	$\mathrm{K}~\mathrm{km}^{-1}$	Pseudoadiabatic lapse rate
	$\Delta F = RF$	${ m W}~{ m m}^{-2}$	Radiative forcing
	$\Delta F_{LW}, \Delta F_{SW}$	${ m W}~{ m m}^{-2}$	Changes in $F_{LW}$ and $F_{SW}$ at the TOA
	$\Delta H$	${ m W}~{ m m}^{-2}$	Heat uptake by the ocean
	$\Delta G$	J	Change in Gibbs free energy
	$\Delta G^*, \Delta G^*_{het}$	J	Gibbs free energy barrier in general and for heterogeneous nucleation
	$\Delta G_s, \Delta G_v$	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
	$\Delta G_{v,hom}, \Delta G_{v,sol}$	J	Volume terms of the change in Gibbs free
	$\Delta G_{w,v}, \Delta G_{i,w}, \Delta G_{i,v}$	J	changes in Gibbs free energy between water and vapor, ice and water, and ice and
	٨D	$Wm^{-2}$	Vapor
		VV III V	Change in global mean surface temperature
	$\Delta I_{S}$ $\delta$	K	infinitesimal change
	$\epsilon,\epsilon_\lambda$		Emissivity in general and wavelength-dependent emissivity
	$\epsilon$		Entrainment
	$\epsilon$	0.622	Ratio $R_d/R_v = m_w/m_d$
	ζ	$s^{-1}$	z-component of the relative vorticity
	η	$s^{-1}$	<i>x</i> -component of the relative vorticity
	η		Thermodynamic efficiency of the Carnot
	θ		Contact angle
	$\hat{\theta}$	К	Potential temperature
	$\theta_{a}, \theta_{as}$	K	Equivalent and saturation equivalent
			potential temperatures
	$\theta_{mix}$	Κ	Mean potential temperature in well-mixed air
	$\theta_w$	К	Wet-bulb potential temperature
	κ	0.286	Ratio $R_d/c_p$
	κ		Hygroscopicity parameter
	Λ	$m^{-1}$	Entrainment rate
	Λ	$\rm cm^{-1}$	Slope of hydrometeor size distributions
	$\Lambda_B$	$s^{-1}$	Scavenging coefficient
	λ	m	Wavelength
	λ	$W m^{-2} K^{-1}$	Climate sensitivity parameter
	λ <sub>0</sub>	$W m^{-2} K^{-1}$	Null climate sensitivity parameter
	μ		Shape parameter of hydrometeor size
			distributions
	μ	$kg m^{-1} s^{-1}$	Dynamic viscocity of air
	$\mu$	$J s^{-1}$	Chemical potential

xxiii	Symbols and acronyms		
	$\mu, \mu_S, \mu_V, \mu_m$	m	Number mean radius and arithmetric means
	$\mu_g, \mu_{g,S}, \mu_{g,V}, \mu_{g,m}$	m	Geometric means of the number, surface, volume and mass distributions of aerosol
	$\widetilde{\mu}, \overline{\mu}$	m	Number mode radius and radius of average
	ν	$m^2 s^{-1}$	Kinematic viscocity
	ξ	s <sup>-1</sup>	y-component of the relative vorticity
	$\rho_a$	$kg m^{-3}$	Density of an aerosol particle
	$\rho_d$	$kg m^{-3}$	Density of dry air
	ρ <sub>env</sub>	$kg m^{-3}$	Density of ambient air
	$\rho_l, \rho_i, \rho_s$	$kg m^{-3}$	Densities of liquid water, ice and a solution
		2	droplet
	$\rho, \rho_m$	kg m <sup>-3</sup>	Density in general and of moist air
	$\rho_{v}, \rho_{v,r_d}, \rho_{vs}$	$kg m^{-3}$	Ambient water vapor density, water vapor
			density at a droplet's surface and saturation
			water vapor density
	σ		Arithmetic standard deviation
	σ	$5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$	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
	$\sigma_{w,v}$	$0.0756 \text{ N m}^{-1}$	Surface tension of water in water vapor at 273.15 K
	$\sigma_{i,w}$	$ m 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
	$\sigma, \sigma_i$	m	Standard deviations of the aerosol size
			distribution in mode <i>i</i>
	$\sigma_g$		Geometric standard deviation of the aerosol
	_		Ontion donth
	1		A smooth antical denth
		9 dagmaas	Latitude
	$\varphi$	, degrees	Cibbs free energy of the interface between
	$\varphi(v_n)$	J	a cluster and the parent phase
	0	$7.29 \times 10^{-5} \text{ s}^{-1}$	Farth's rotation
	(1)	$P_{a} s^{-1}$	Vertical velocity in the n-system
	i i i i i i i i i i i i i i i i i i i	s-1	Three dimensional vorticity vector
	i i i i i i i i i i i i i i i i i i i	s s <sup>-1</sup>	Horizontal vorticity vector
	Wh	0	

xxiv	Symbols and acronyms				
		Acronyms			
	AEJ AEROCOM	African easterly jet Aerosol Intercomparison project			
	AERONET	Aerosol Robotic Network			
	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			
	CERES	Cioud condensation nuclei counter			
	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 $(J \text{ kg}^{-1})$			
	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 cloud and concell radiation			
	EKFacitan	interactions			
	GCCN	Giant CCN			
	GCM	Global climate model			
	GHG	Geoengineering Model Intercomparison Project Greenhouse gases			

XXV	Symbols and acronyms	
	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

ххvі	Symbols and acronyms		
	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	