Physical Processes in Clouds and Cloud Modeling

This book presents the most comprehensive and systematic description currently available of both classical and novel theories of cloud processes, providing a much-needed link between cloud theory, observation, experimental results, and cloud modeling. The book shows why and how modern models serve as a major tool of investigation of cloud processes responsible for atmospheric phenomena, including climate change. It systematically describes classical as well as recent advancements in cloud physics, including cloud-aerosol interaction; collisions of particles in turbulent clouds; and the formation of multiphase cloud particles. As the first of its kind to serve as a practical guide for using state-of-the-art numerical cloud models, major emphasis is placed on explaining how microphysical processes are treated in modern numerical cloud-resolving models. The book will be a valuable resource for advanced students, researchers, and numerical model designers in cloud physics, atmospheric science, meteorology, and environmental science.

Dr. Alexander P. Khain is Professor in the Institute of Earth Sciences at the Hebrew University of Jerusalem. He is a renowned leading expert in developing cloud and cloud-resolving models with precise microphysics in order to investigate the physics of clouds and precipitation. He has participated in several American, European, and Asian international research projects where his advanced microphysical schemes were widely used to investigate natural and anthropogenic aerosol effects and relations between microphysics and atmospheric dynamics. He has published two books on tropical cyclones and their interaction with the ocean, and approximately 200 academic papers on cloud physics, cloud-aerosol interaction, and numerical modeling of clouds, storms, and hurricanes.

Dr. Mark Pinsky is Professor in the Institute of Earth Sciences at the Hebrew University of Jerusalem. He is a leading expert in the investigation and modeling of drop condensation/evaporation and turbulence impact on collision processes in clouds. The cloud models he has developed have enabled us – for the first time – to explain the impact of turbulence on precipitation formation as well as drizzle formation. Dr. Pinsky has participated in several joint European and American research projects in the fields of cloud physics, precipitation enhancement, and satellite and radar meteorology. He has published more than 100 academic papers on cloud physics, cloud modeling, radar meteorology, and estimation of symmetry measure in chemistry.

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Physical Processes in Clouds and Cloud Modeling

ALEXANDER P. KHAIN
Hebrew University of Jerusalem

MARK PINSKY
Hebrew University of Jerusalem

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Preface

Clouds, to a great extent, govern the radiation balance and energy fluxes reaching Earth and have a strong impact on the hydrological cycle and freshwater distribution over the globe. Latent heat release in clouds is the energy source for atmospheric phenomena from the scale of a separate cloud to global circulation. Clouds are also a major component of hazardous atmospheric phenomena such as hurricanes, storms, and hailstorms. Changes in cloud microphysical and radiative properties are the main factors leading to climate change. All of these determine the vital impact that clouds exert on all forms of life on the planet, human life included.

Studies of clouds and cloud-related phenomena are an integral part of modern meteorology, providing data to be directly applied in weather forecasting, agriculture, environment control, air traffic control, and many other spheres of human activity.

One of the major methods of investigating clouds and cloud-related phenomena is numerical modeling. Numerical cloud models solve coupled dynamic and microphysical equations for different processes occurring in clouds. The microphysical processes characterizing transformation of cloud particles are typically accompanied by phase transitions and latent heat release determine, to a large extent, the type, dynamics, and structure of clouds.

There are several classic books on cloud physics and cloud microphysical processes, among them are the following (see the References in Chapter 1 for details): *A Short Course in Cloud Physics* by Rogers and Yau (1996); the fundamental book *Cloud Microphysics and Precipitation* by Pruppacher and Klett (1997); *Cloud and Precipitation Microphysics* by Straka (2009), describing simplified expressions for rates of microphysical processes used in bulk-parameterization; and *Thermodynamics, Kinetics, and Microphysics of Clouds* by Khvorostyanov and Curry (2014), dedicated to theoretical analysis of specific microphysical processes. These books, however, do not discuss the issues of numerical cloud model design. In the absence of detailed information, many scientists (especially students) use cloud models as "black boxes." Inevitably, analysis of model results in this case is rough and often conjectural and descriptive.

Our book is aimed at filling in this gap. Major focus is put on explaining how cloud microphysical processes are treated in modern numerical cloud models. We stress the relationship between the physics of the cloud processes and the mathematical description of these processes in cloud models. Cloud hydrometeors of different types such as liquid drops, low density ice particles such as snowflakes, and high-density particles such as hail are active participants in condensation, collision, sedimentation, and other phase-transition processes. These processes unfold in different ways (and, accordingly, are differently represented in the models) depending on specific conditions and hydrometeors. Therefore, the two largest chapters in this book are dedicated to description and modeling of warm microphysical processes occurring at positive temperatures, and mixed-phase microphysical processes (in particular, ice processes) occurring at negative temperatures.

Considerable attention is paid to the two main approaches used for description of microphysical processes in models. The bin approach focuses on the evolution of size distributions of hydrometeors. The bulk parameterization is less time-consuming, while treating only changes of several moments of these distributions. In this book, we systematically describe how cloud microphysical processes are treated in modern bin and bulk cloud models.

Along with the classic studies, we analyze numerous modern research contributions made over the past two decades that have greatly improved understanding of the cloud microphysical processes. We present the state-of-the-art view of liquid precipitation and ice precipitation formation. This book also outlines the recent progress in modeling techniques, which enabled an increase in the number of the microphysical processes described by models and also improved the representation of these processes in models of both bin and bulk types. Comparison of model results obtained by both approaches and analysis of their importance for atmospheric and cloud physics is also a distinctive feature of this book.

To make the content accessible for a wide reading audience, we included extensive background material

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that is intended as the reference source on a vast variety of cloud-related phenomena. Large numbers of illustrations, figures, and tables are provided to facilitate better understanding of this material. We hope that the approach undertaken in this book, which combines the theory of cloud microphysical processes and their numerical realizations in models, will prove to be helpful for students, researchers, and cloud-model designers in the fields of cloud physics, atmospheric science, and meteorology.

Work on this book took several years. We express our sincere gratitude to Dr. Elena Negnevitsky, who took over the hard work of editing. She can rightfully be considered a coauthor of this book.

We thank our former and current students Igor Sednev, Yaron Segal, Nir Benmoshe, Leehi Magaritz-Ronen, Eyal Ilotoviz, Jacob Shpund, and others for their help with model development and for performing numerical experiments. We express our deep gratitude to colleagues from different countries: Profs. Daniel Rosenfeld, Hans Pruppacher, Vaughan Phillips, Isaac Ginis, Alexei Korolev, Ilia Mazin, Klaus Beheng, Alexander Ryzhkov; Drs. Axel Seifert, Thara Prabhakaran, Mikhail Ovchinnikov, Jiwen Fan, Barry Lynn and many others for their fruitful collaboration, exchange of ideas and work in the framework of joint grants. This book would have never appeared without this invaluable collaboration. We remember with gratitude our late colleague Dr. Andrei Pokrovsky, who made an enormous contribution to the development of the Hebrew University Cloud Model.

We express our gratitude to the U.S.-Israel Binational Science Foundation, the Israel Science Foundation, the U.S. Department of Energy, the Ministry of Science, Technology and Space of Israel, and to the Hebrew University of Jerusalem for support of our scientific work.

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Abbreviations

2DC	A Two-Dimensional Cloud probe
2DP	A Two-Dimensional Precipitation probe
ACE	Aerosol Characterization Experiment
ACTOS	Airborne Cloud Turbulence Observation System
ADI	Alternating-Direction Implicit method
AF	Adiabatic Fraction
AP	Aerosol Particle
ARM	Atmospheric Radiation Measurement
ARW	Advanced Research WRF solver
ASASP	Active-Scattering Aerosol Spectrometer Probe
ASTEX	Atlantic Stratocumulus Transition Experiment
ATSR	Along Track Scanning Radiometer
BB	Bright Band
BBC	Baltex Bridge Campaign
BIMGQ	Bin Integral Method with Gauss Quadrature
BL	Boundary Layer
BM	Bin Microphysics
BRM	Berry and Reinhardt Method
CAIAPEEX	Cloud-Aerosol Interaction and Precipitation Enhancement Experiment
CAPE	Convective Available Potential Energy
CaPE	Convection and Precipitation/ Electrification experiment
CASP	Canadian Atlantic Storms Program
CCN	Cloud Condensation Nuclei
CCOPE	Cooperative Convective Precipitation Experiment
CFAD	Contoured Frequency Altitude Diagram
CFDC	Continuous Flow Diffusion Chamber
CFL	Courant–Friedrichs–Lewy condition
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies model
CKE	Collision Kinetic Energy
CN	Condensational Nuclei
COPE	Convective Precipitation Experiment
COPE-MED	Convective Precipitation Experiment - Microphysical and Entrainment Dependencies
COSMO	Consortium for Small-Scale Modeling
CPI	Cloud Particle Imager
CRM	Cloud Resolving Model
CRYSTAL-FACE	NASA Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment
CWC	Cloud Water Content
DHARMA	Distributed Hydrodynamic Aerosol and Radiative Modeling Application
DHF	Deliquescent-Heterogeneous Freezing
DNS	Direct Numerical Simulation
DSD	Drop Size Distribution
DYCOMS	Dynamics and Chemistry of Marine Stratocumulus field study
EARLINET	European Aerosol Research Lidar Network
EC	Elemental Carbon
ECHAM	Atmospheric general circulation Model
EL	Equilibrium Level
EMPM	Explicit Mixing Parcel Model
ETEM	Entity-Type Entrainment Mixing process
EUCREX	European Cloud-Radiation Experiment
FATE	First ATSR Tropical Experiment
FD	Freeing Drops
FFT	Fast Fourier Transform
FIRE	First ISCCP Regional Experiment
FSSP	Forward Scattering Spectrometer Probe
GATE	Global Atlantic Tropical Experiment
GCCN	Giant Cloud Condensation Nuclei

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GCE	Goddard Cumulus Ensemble model
GCM	General (Global) Circulation Model
GT	Glaciation Time
HDI	Hydrodynamic Drop Interaction
HMT	Hydrometeorology Testbed project
HUCM	Hebrew University Cloud Model
HVPS	High Volume Precipitation Spectrometer
ICE	International Cirrus Experiment
ICE-L	Ice in Clouds Experiment – Layer clouds
ICE-T	Ice in Clouds Experiment–Tropical
IN	Ice Nuclei
INCA	Interaction with Chemistry and Aerosols model
INSPECT-1	First Ice Nuclei Spectroscopy study
INSPECTRO	Influence of clouds on the Spectral actinic flux density in the lower troposphere field campaigns
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
ISDAC	Indirect and Semi-Direct Aerosol Campaign
ISF	Ice Sponge Front
ITCZ	Inter-tropical Convergence Zone
IWC	Ice Water Content
IWP	Ice Water Pass
JMA-NHM	Japan Meteorological Agency Non-Hydrostatic Model
LAM	Limited Area Model
LBA-SMOCC	Large-Scale Biosphere Atmosphere Experiment in Amazonia -Smoke Aerosols, Clouds, Rainfall, and Climate: Climate Campaign
LCL	Lifting Condensation Level
LCM	Lagrangian Cloud Model
LDM	Linear Discrete Method
LE	Large Eddies
LEM	Lagrangian-Eulerian Model
LES	Large-Eddy Simulation
LFC	Level of Free Convection
LFM	Linear Flux Method
LMDzT	Laboratoire de Meteorologie Dynamique general circulation model
LSM	Land-Surface Model
LST	Local Standard Time
LWC	Liquid Water Content
LWF	Liquid Water Fraction
LWP	Liquid Water Pass
MCS	Mesoscale Convective System
MD	Mass Distribution
MM5	Fifth-Generation Penn State/NCAR Mesoscale Model
MMM	Microphysical Method of Moments
M-PACE	Mixed-Phase Arctic Cloud Experiment
MPL	Maximum Parcel Level
NASA	National Aeronautics and Space Administration
NASA FIRE	NASA FIRE Arctic Cloud Experiment
ACE	Atmospheric Chemistry Experiment
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
OAP	Optical Array Probe
PBAP	Primary Biological Aerosols Particles
PBE	Positive Buoyant Energy
PCASP	Passive Cavity Aerosol Spectrometer Probe
PDF	Probability Distribution Function
PMS	Particle Measuring System
PRE-STORM	Preliminary Regional Experiment for Storm-scale Operational and Research Meteorology
PSD	Particle Size Distribution
PVM	Particulate Volume Monitor
RACORO	Routine AAF CLOWD Optical Radiative Observations
RAMS	Regional Atmospheric Modeling System
RDF	Radial Distribution Function
RF	Research Flight
RH	Relative Humidity
RICO	Rain in Cumulus over the Ocean field program
RK2	Runge-Kutta 2 step method
RK3	Runge-Kutta 3 step method
RMS	Root Mean Square
RSD	Raindrop Size Distribution
RWC	Rain Water Content
SAM	System for Atmospheric Modeling
SBE	Stochastic Breakup Equation
SBM	Spectral Bin Microphysics
SCE	Stochastic Collection Equation
SCMS	Small Cumulus Microphysics Study
SLL	Schumann–Ludlam Limit

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SMOCC	Smoke Aerosols, Clouds, Rainfall and Climate program
SST	Sea-Surface Temperature
STD	STandard Deviation
STEPS	Severe Thunderstorm Electrification and Precipitation Study
SUCCESS	Subsonic Aircraft: Contrail and Cloud Effect Special Study
TARA	Transportable Atmospheric Radar
TAU	Tel-Aviv University model
TC	Tropical Cyclone
TEM	Trajectory Ensemble Model
TKE	Turbulent Kinetic Energy
TLS	Tethered Lifting System
TOGA	Tropical Ocean Global Atmosphere program
TOGA COARE	TOGA Coupled Ocean-Atmosphere Response Experiment
TOM	Total Organic Matter
UHSAS	Ultra-High Sensitivity Aerosol Spectrometer
UT	Universal Time
UTC	Coordinated Universal Time
UWNMS	The University of Wisconsin Non-Hydrostatic Model
WBF	Wegener–Bergeron–Findeisen process
WDM6	WRF Double-Moment 6-class Microphysics scheme
WINSIC	Water Insoluble Inorganic Carbon
WINSOC	Water Insoluble Organic Compounds
WRF	Weather Research and Forecasting model
WSF	WRF Software Framework
WSOC	Water Soluble Organic Compounds

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Symbols

Symbol	Description	Units
$\mathbf{A}$, A_i	Lagrangian acceleration of the air	ms^{-2}
B_{ll}	Longitudinal correlation function of turbulent velocity	m^2s^{-2}
B_{nn}	Lateral correlation function of turbulent velocity	m^2s^{-2}
c_p	Specific heat capacity at constant pressure	$J\ kg^{-1}\ K^{-1}$
c_v	Specific heat capacity at constant volume	$J\ kg^{-1}\ K^{-1}$
c_w	Specific heat of water	$J\ kg^{-1}\ K^{-1}$
C_0	Courant number	–
C_{0_cr}	Critical Courant number	–
C_d	Drag coefficient	–
C_{ph}	Phase speed	m/s
d, D	Diameter or width of particle	m
D	Diffusivity of water vapor in air	m^2s^{-1}
Da	Damköhler number	–
e	Water vapor pressure	Nm^{-2}
e_w	Saturation vapor pressure over water	Nm^{-2}
e_i	- over ice	Nm^{-2}
E	Turbulent kinetic energy per unit mass	m^2s^{-2}
E_l	- on subgrid scale	m^2s^{-2}
$E(r_1, r_2)$	Collision efficiency	–
E_{coal}	Coalescence efficiency	–
E_T	Total coalescence energy	J
f	Coriolis parameter	–
f_w	Liquid water fraction	–
$f(m)$	Size distribution of water drops as a function of mass	$kg^{-1}m^{-3}$
$f_r(r)$	- as a function of radius	m^{-4}
$f_i(m)$	Size distribution of ice particles or ice crystals	$kg^{-1}m^{-3}$
$f_g(m)$	- of graupel	$kg^{-1}m^{-3}$
$f_h(m)$	- of hail	$kg^{-1}m^{-3}$
$f_s(m)$	- of snow	$kg^{-1}m^{-3}$
F_v	Ventilation coefficient	–
$F(k)$	Spectrum of turbulent kinetic energy	m^3s^{-2}
Fl	Flatness of velocity gradient	–
g, $\mathbf{g}$	Acceleration of gravity	ms^{-2}
$g(m)$	Mass distribution of drops	m^{-3}
h	Planck constant	J s
h	Thickness or length of particle	m
h	static energy of dry air	m^2s^{-2}
h_l	- of moist air	m^2s^{-2}
k	Boltzmann constant	JK^{-1}
κ	Heat conductivity	$W\ K^{-1}m^{-1}$
k_a	- of air	$W\ K^{-1}m^{-1}$
k_i	- of ice	$W\ K^{-1}m^{-1}$
k_w	- of water	$W\ K^{-1}m^{-1}$
k	Wave number	m^{-1}
K	Turbulent coefficient	m^2s^{-1}
$K(r_1, r_2)$	Collision kernel	m^3s^{-1}
K_{g_col}	Collection kernel	m^3s^{-1}
K_{num}	Coefficient of numerical viscosity	m^2s^{-1}
Kn	Knudsen number	–
l	Spatial scale, mixing length	m
L	External turbulent scale	m
L_w	Latent heat of water evaporation	$J\ kg^{-1}$
L_i	- of ice sublimation	$J\ kg^{-1}$
L_m	- of ice melting/freezing	$J\ kg^{-1}$
m	Mass of cloud particle, or drop	kg
m_i	- of ice particle	kg
m_N	- of aerosol particle	kg
m_{is}	Wettability parameter	–
M	Mass content	$kg\ m^{-3}$
M_w	Molecular weight of water	$kg\ mol^{-1}$
M_N	- of aerosol salt	$kg\ mol^{-1}$
M^k	The moment of particle size distribution of order k	
N	Concentration of cloud particles or drops	m^{-3}

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(cont.)

Symbol	Description	Units
N_i	- of ice particles	m^{-3}
N_N	- of aerosols	m^{-3}
N_{CCN}	- of cloud condensational nuclei	m^{-3}
N_{IN}	- of ice nuclei	m^{-3}
N_c	- of crystals	m^{-3}
N_r	- of raindrops	m^{-3}
N_B	Brunt–Väisälä frequency	Hz
p	Pressure of moist air	Pa
p_a	of dry air	Pa
P_r	Probability of spontaneous breakup	–
Pr	Prandtl number	–
q	Mixing ratio of water vapor	kg/kg
q_c	- of cloud droplets	kg/kg
q_l	- of liquid water	kg/kg
q_{iw}	- of ice water	kg/kg
q_r	- of rain water	kg/kg
q_S	- saturated	kg/kg
q_t	- total	kg/kg
q_v	Specific humidity	kg/kg
q_i	Ice water content (IWC)	kg m^{-3}
q_N	Aerosol mass content	kg m^{-3}
q_w	Liquid water content (LWC)	kg m^{-3}
Q	Integral of supersaturation	s
r	radius of wet particle, or liquid drop	m
r_N	- of dry aerosol particle	m
r_{cr}	- critical	m
r_d	- of water drop	m
r_i	- of ice particle	m
$\bar{r}$	Mean radius	m
r_v	Mean volume radius	m
r_{eff}	Effective radius	m
r_{mod}	Modal radius	m
R	Universal gas constant	J $K^{-1}mol^{-1}$
R	Specific gas constant of moist air	J $K^{-1}kg^{-1}$
R_a	- of dry air	J $K^{-1}kg^{-1}$
R_v	- of water vapor	J $K^{-1}kg^{-1}$
R	Potential evaporation parameter	–
Ra	Rayleigh number	–
Ra_{cr}	Critical Rayleigh number	–
Ra_t	Turbulent Rayleigh number	–
Re	Reynolds number	–
Re_{cr}	Critical Reynolds number	–
Re_λ	Taylor microscale Reynolds number	–
Re_t	Turbulent Reynolds number	–
Ri	Richardson number	–
Ri_{cr}	Critical Richardson number	–
s_N	Solubility of aerosol water solution	–
S_w	Supersaturation over water	–
S_i	- over ice	–
S_{qs}	- quasi-steady	–
S_{ij}	Velocity gradient tensor	s^{-1}
Sk	Skewness of velocity gradient	–
St	Stokes number	–
Sc	Schmidt number	–
T	Absolute temperature of air	K
T_C	Temperature of air in Celsius scale	°C
T_d	Dew point	°C
T_L	Lagrangian time scale	s
T_v	Virtual temperature	K
T_0	Triple point (273.15)	K
t	Time	s
t_f	- of freezing	s
t_{gl}	- glaciation time	s
$\mathbf{u}$, u_i	Air velocity, turbulent air velocity	ms^{-1}
V	air volume	m^3
$\mathbf{V}$, V_i	Particle velocity	ms^{-1}
V'_i	Particle velocity relative to the air	ms^{-1}
V_{imp}	Impact velocity	ms^{-1}
V_g	Sedimentation velocity of particles (terminal velocity)	ms^{-1}
V_{swept}	Swept volume	m^3s^{-1}
w	Vertical air velocity	ms^{-1}
We	Weber number	–
$\mathbf{x}$, x_i	Spatial coordinates	m
X	Best number (Davis number)	–
Z	Radar reflectivity	dBZ
β_{ext}	Optical extinction	m^{-1}
$\Gamma(p,T)$	Psychrometric correction	–
γ_a	Dry adiabatic lapse rate	Km^{-1}
γ_{ma}	Moist adiabatic lapse rate	Km^{-1}
γ_d	Aspect ratio of drop	–
γ_i	Aspect ratio of ice crystals	–
γ_F	Fourier number	–

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Symbol	Description	Units
δ_f	Dispersion of size distribution	–
δ_s	Soluble fraction of aerosol particle	–
δ_{ij}	Kronecker symbol	–
Δt	Time step	s
Δx, Δy, Δz	Grid space lengths	m
ε	Turbulent energy dissipation rate	m^2s^{-3}
ε_{ijk}	Levy–Civita tensor	–
Φ_s	Osmotic coefficient	–
λ	Taylor microscale	m^{-1}
λ	Entrainment parameter	m
μ	Dynamic viscosity of air	$kg\ m^{-1}s^{-1}$
μ	Chemical potential	–
μ	Cloud fraction	$Jmol^{-1}$
μ_k, l_k	Kolmogorov microscale	m
ν	Kinematic viscosity of air	m^2s^{-1}
ν_N	Number of dissociated ions per aerosol molecular	–
Π	Exner function	–
Π_0	Reference Exner function	–
π''	Deviation of Exner function	–
θ	Potential temperature	K
θ_e	Equivalent potential temperature	K
θ_{il}	Ice-water potential temperature	K
θ_l	Liquid potential temperature	K
ρ	Density of wet air	$kg\ m^{-3}$
ρ_a	- of dry air	$kg\ m^{-3}$
ρ_{bulk}	- bulk density of particle	$kg\ m^{-3}$
ρ_v	- of water vapor (absolute humidity)	$kg\ m^{-3}$
ρ_N	- of aerosol particle	$kg\ m^{-3}$
ρ_w	- of water	$kg\ m^{-3}$
ρ_i	- of ice	$kg\ m^{-3}$
σ_w	Surface tension of water-air interface	Nm^{-1}
σ_i	- of ice-air interface	Nm^{-1}
σ_{iw}	- of water-ice interface	Nm^{-1}
σ_f	RMS size distribution width	m
τ	Lifetime	s
τ_{mix}	Characteristic mixing time	s
τ_p, τ_d	Particle or drop relaxation time	s
τ_k	Kolmogorov time scale	s
τ_{pr}	Phase relaxation time	s

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