Environmental multiphase flow – A new frontier

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GTP Workshop: Multiphase Turbulent Flows in the Atmosphere and Ocean

Boulder, Colorado

Outline

- **What is a multiphase flow?**
- **What is an environmental multiphase flow?**
- **Several Examples**
  - Characteristics of environmental multiphase flows
  - Open questions
  - Scientific challenges
  - Impact or environmental implications
- **Comments on research methods and approach**

Multiphase flows

- Simultaneous flow of materials with:
  - different states or phases (i.e. gas, liquid or solid)
  - different chemical properties but in the same state or phase (i.e. liquid-liquid systems such as oil droplets in water)
- The primary and secondary phases:
  - One of the phases is continuous (primary) while the other(s) (secondary) are dispersed within the continuous phase
  - The dispersed phase may be described by:

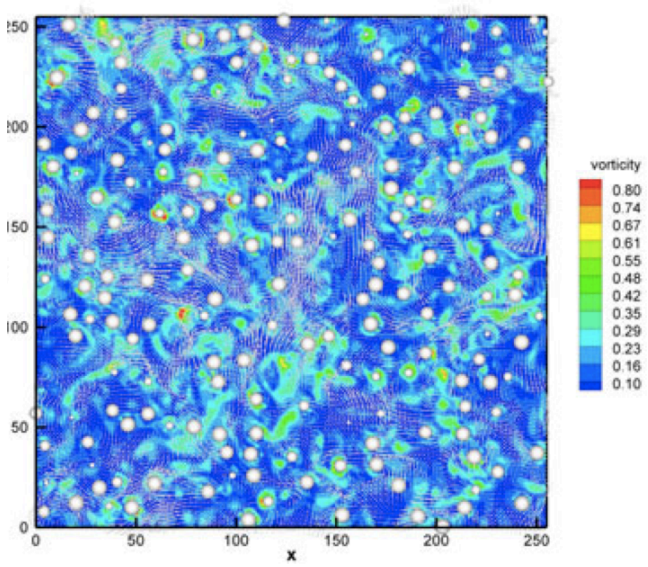
    a particle size distribution

    different chemical compositions

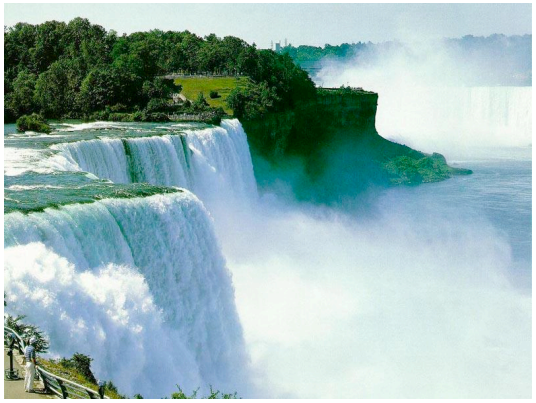
    viscous drag, latent heat, reaction rate, etc.

Multiphase flow regimes (unbounded)

- Bubbly flow: discrete gaseous bubbles in a continuous liquid
- Droplet-laden or particle-laden flow: discrete liquid droplets or solid particles in a continuous fluid
- Stratified and free-surface flow: immiscible fluids separated by a clearly-defined interface

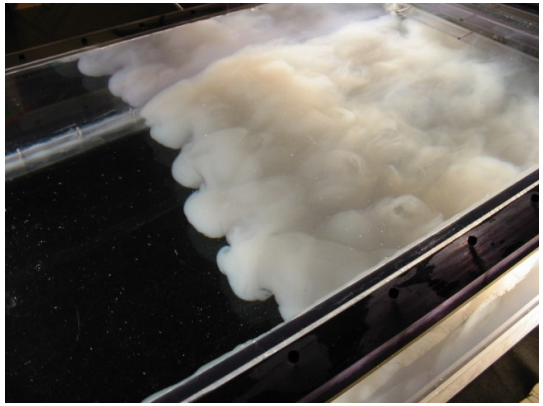


particle-laden flow



free-surface flow

bubbly flow



Stratified flow

Elemental definitions and governing parameters

- Dilute versus dense phase:

  Refers to the volume fraction of the dispersed phase Φ_V

$$\frac{\text{Volume of the phase in a cell/domain}}{\text{Volume of the cell/domain}}$$

- Phase couplings

  momentum, mass loading $\Phi_m=\Phi_V \times \rho_p/\rho_f$

  mass transfer due to reaction / condensation / evaporation

  energy coupling due to sensible heat and latent heat transfer

- For turbulent particle-laden flow

  particle size relative to flow length scale: D / η

  particle sedimentation / bubble rising: W / V_K

Equation of motion for small particles (a < η)

$$m_p \frac{d\vec{V}(t)}{dt} = \left(m_p - m_f\right)\vec{g} + m_f \left.\frac{D\vec{U}}{Dt}\right|_{\vec{Y}(t)} + \frac{1}{2} m_f \frac{d}{dt}\left(\vec{U} + \frac{1}{10} a^2 \nabla^2 \vec{U}\Big|_{\vec{Y}(t)} - \vec{V}(t)\right) + 6\pi a\mu\left(U + \frac{1}{6} a^2 \nabla^2 \vec{U}\Big|_{\vec{Y}(t)} - V\right)$$

$$+ \; 6a^2\sqrt{\pi\rho_f\mu}\int_0^\tau \frac{d/d\tau\left(U + \frac{1}{6} a^2 \nabla^2 \vec{U}\Big|_{\vec{Y}(t)} - V\right)}{\sqrt{(t-\tau)}} + \text{lift} + \text{others} \qquad \textit{for} \;\; \mathrm{Re}_p << 1$$

$$m_p \frac{d\vec{V}(t)}{dt} = \left(m_p - m_f\right)\vec{g} + 6\pi a\mu\left(U - V\right)\phi(\mathrm{Re}_p) + m_f \left.\frac{D\vec{U}}{Dt}\right|_{\vec{Y}(t)} + m_f C_M\left(\frac{D}{Dt}\vec{U} - \frac{d}{dt}\vec{V}(t)\right) +$$

$$+ \; 6a^2\sqrt{\pi\rho_f\mu}\int_0^\tau K(t,\tau)\frac{d}{d\tau}\left(\vec{U} - \vec{V}\right) + \text{lift} + \text{others} \qquad \text{finite } \mathrm{Re}_p$$

Heavy particles : $\rho_p >> \rho_f$

$$\frac{d\vec{V}(t)}{dt} = -\frac{\vec{V}(t) - U(\vec{Y}(t),t)}{\tau_p} - \vec{g}$$

$$\frac{d\vec{Y}(t)}{dt} = \vec{V}(t)$$

$$\tau_p = 2\rho_p a^2/(9\mu), \quad \mathrm{W} = \tau_p g$$

Microbubbles : $\rho_p << \rho_f$

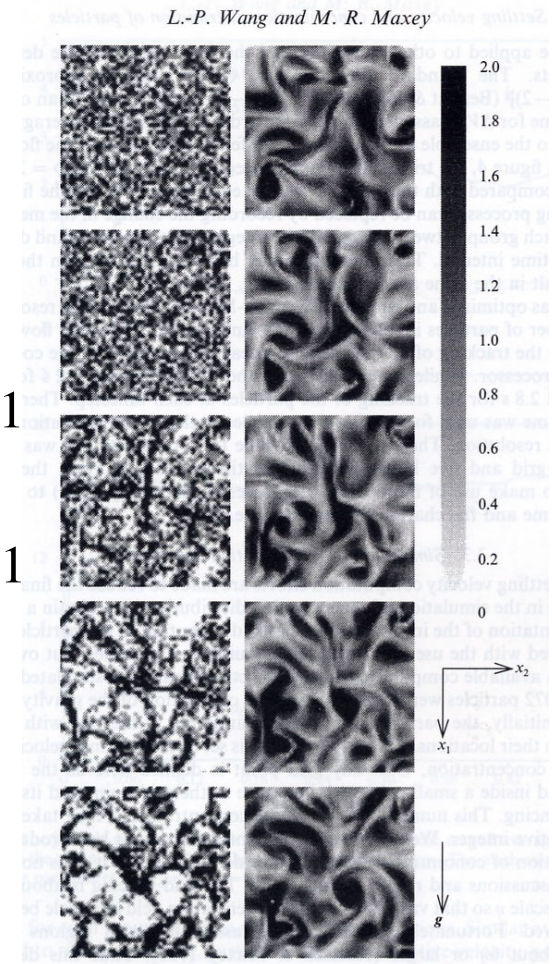
$$\frac{d\vec{V}(t)}{dt} = -\frac{\vec{V}(t) - \vec{U}(\vec{Y}(t),t) - \vec{W}}{\tau_B} + 3\frac{D\vec{U}}{Dt}$$

$$\frac{d\vec{Y}(t)}{dt} = \vec{V}(t)$$

$$\tau_p = a^2/(9\nu), \quad \vec{\mathrm{W}} = -2\tau_B\vec{g}$$

Maxey & Riley (1983), Balachandar and Eaton (2010)

Interactions with flow eddies:
Dynamics significant different from tracers



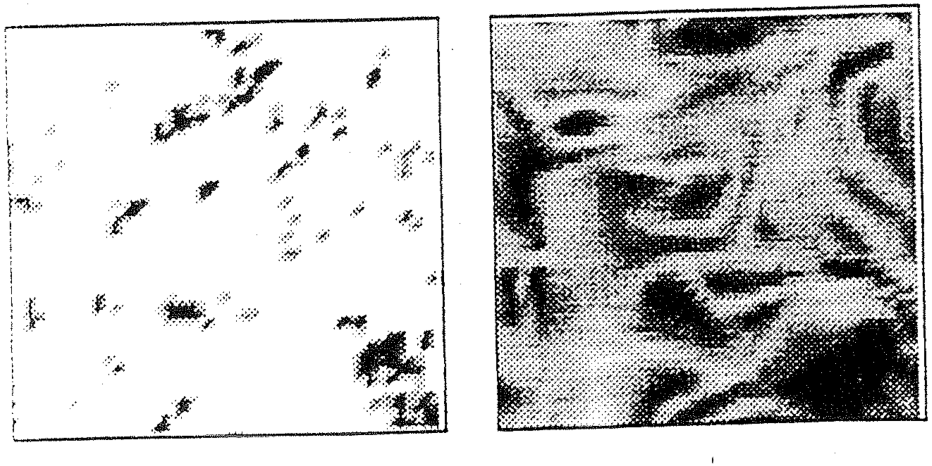
$$\frac{\tau_p}{\tau_K} = 1$$

$$\frac{W}{v_K} = 1$$

Particle concentration

Flow vorticity

$$\frac{\tau_b}{\tau_K} = 1, \qquad \frac{W}{v_K} = 1$$



Bubble concentration

Flow vorticity

Wang & Maxey, J. Fluid Mech., **256**:27-68, 1993.
Wang & Maxey, Applied Sci. Res., **51:**291-296, 1993.

Environmental multiphase flow

Multiphase flows occurring in the environment

An important topic of environmental fluid mechanics

Flows in the atmosphere and on Earth, including weather systems, oceanic circulation, coastal processes, overland flows, river, lake and estuary dynamics, groundwater flow, and geophysical fluid dynamics.

Multiple scales ranging from molecular diffusion, to droplet formation, to the spectrum of vortical structures, to the size of the planet (e.g. weather systems, tides and oceanic circulation).

Alistair et al., Current trends in engineering mechanics, Proceedings of the Institution of Civil Engineers, Engineering and Computational Mechanics,161 (2008) 43–49.

Length, velocity, and time scales (from Cushman-Roisin, 2006)

	Horizontal Length Scale L	Vertical Length Scale H	Velocity Scale U	Time scale T
Processes:				
Microturbulence	1–10 cm	1–10 cm	1–10 cm/s	few seconds
Shear turbulence	0.1–10 m	0.1–10 m	0.1–1 m/s	few minutes
Water waves	0.1–10 m	1–100 cm	1–10 m/s	seconds to minutes
Convection	10–1000 m	1–1000 m	0.1–1 m/s	hours, days or seasons
Atmospheric systems:				
Urban airshed	1–10 km	100–1000 m	1–10 m/s	hours
Sea breeze	1–10 km	100–1000 m	1–10 m/s	hours
Thunderstorms	1–10 km	100–5000 m	1–10 m/s	hours
Mountain waves	10–100 km	10–1000 m	1–10 m/s	days
Tornado	10–100 m	100–1000 m	100 m/s	minutes to hours
Hurricane	100–1000 km	10 km	100 m/s	days to weeks
Weather patterns	100–1000 km	10 km	1–10 m/s	days to weeks
Climatic variations	global	50 km	1–10 m/s	decades and beyond
Water systems:				
Aquifers	1–1000 km	10–100 m	1–10 mm/s	seasons to decades
Wetlands	10–100 m	10–1000 m	0.1–10 cm/s	days to seasons
Small stream	1–10 m	0.1–1 m	10–100 cm/s	seconds to minutes
Major river	10–1000 m	1–10 m	1–100 cm/s	minutes to hours
Lakes	1–100 km	10–1000 m	1–10 m/s	days to seasons
Ocean tides	basin scale	basin depth	0.1–10 m/s	hours
Estuaries	1–10 km	1–10 m	0.1–1 m/s	hours to days
Coastal ocean	1–100 km	10-1000 m	0.1–1 m/s	few days
Deep ocean	basin scale	basin depth	0.01–1 m/s	weeks to decades

Scientific methods

- Field observation
- Laboratory experimentation
- Theory (conservation laws, thermodynamics, chemistry, …)
- Computer simulations

In 1922, Lewis F. Richardson has envisioned computer simulation of weather.

Description for the turbulent carrier phase (e.g., atmospheric convection, ocean circulation)

Turbulence transport, buoyancy, thermal / density stratification, rotation, …

An example: moist turbulence

Air turbulence

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} = -\frac{\nabla P}{\rho_0} - \mathbf{g}\left[\frac{T'}{T_0} + 0.608 q_v' - q_c'\right] + \nu \nabla^2 \mathbf{U}$$

Temperature

$$\frac{\partial T}{\partial t} = -\nabla \cdot (\mathbf{U} T) - W \Gamma_d + \frac{L}{c_p} C_d + \kappa_a \nabla^2 T$$

cooling heating

Water vapor mixing ratio

$$\frac{\partial q_v}{\partial t} = -\nabla \cdot (\mathbf{U} q_v) - C_d + D_v \nabla^2 q_v$$

W = vertical draft
Γ_d = dry adiabatic lapse rate
C_d = condensation rate per unit mass
c_p = specific heat of dry air

Vaillancourt et al. (2001) J. Atmos. Sci. 58: 1945 - 1964.

Description for the dispersed phase

(i.e., aerosols, dust particles, droplets, ice particles, bubbles, phytoplankton, ….)

- Depending on Stokes number and d_p / η
- Particles are usually not resolved
- Eulerian approaches
  - Dusty gas or pseudo-fluid with modified properties (density, viscosity)
  - Equilibrium Eulerian
  - Two-fluids (i.e., dispersed phase as a second fluid)
  - Method of moments (concentration, mass, reflectivity)
  - Particle size distribution and general population dynamics
    Discrete bin microphysics
- Lagrangian approaches
  Discrete element method
  motion of individual particles
  super-droplets or pseudo-particles
- Particle-resolved simulation

Balachandar and Eaton, 2010, Annu Rev Fluid Mech 42:111-33.

The global climate system

- ✧ Heating by the incoming solar radiation
- ✧ Cooling by the outgoing long-wave (infrared) radiation
- ✧ Factors that disturb these (i.e., radiative forcing)

  External: changes in incident solar flux, Earth orbit variation

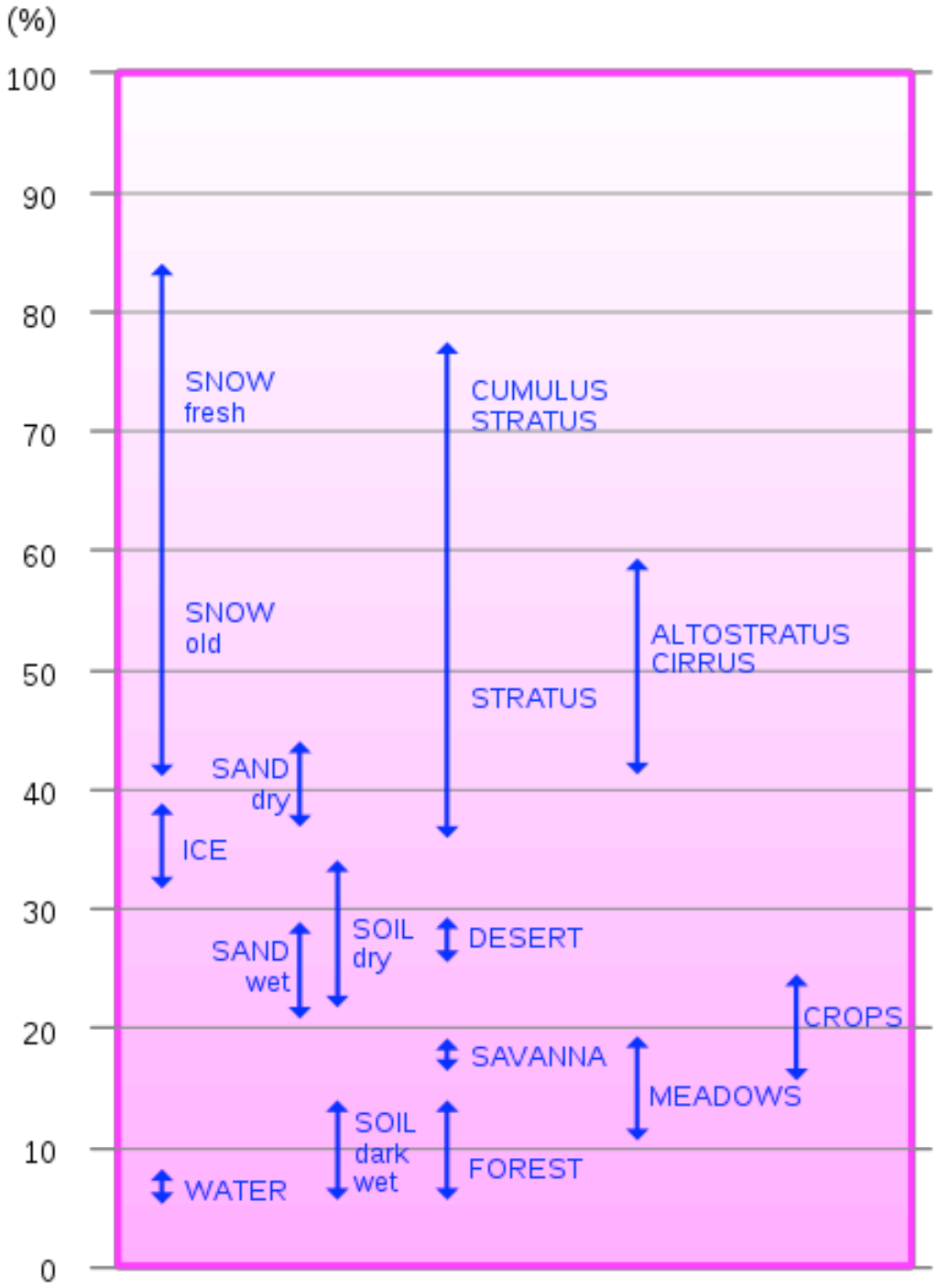
  Internal:

  Volcanic activity and wild fires

  Changes in the composition of the atmospheric constituents

  green house gases (CO_2 – warming by ~1 C in last 100 yrs)

  aerosols, dusts (natural or anthropogenic), droplets, ice particles

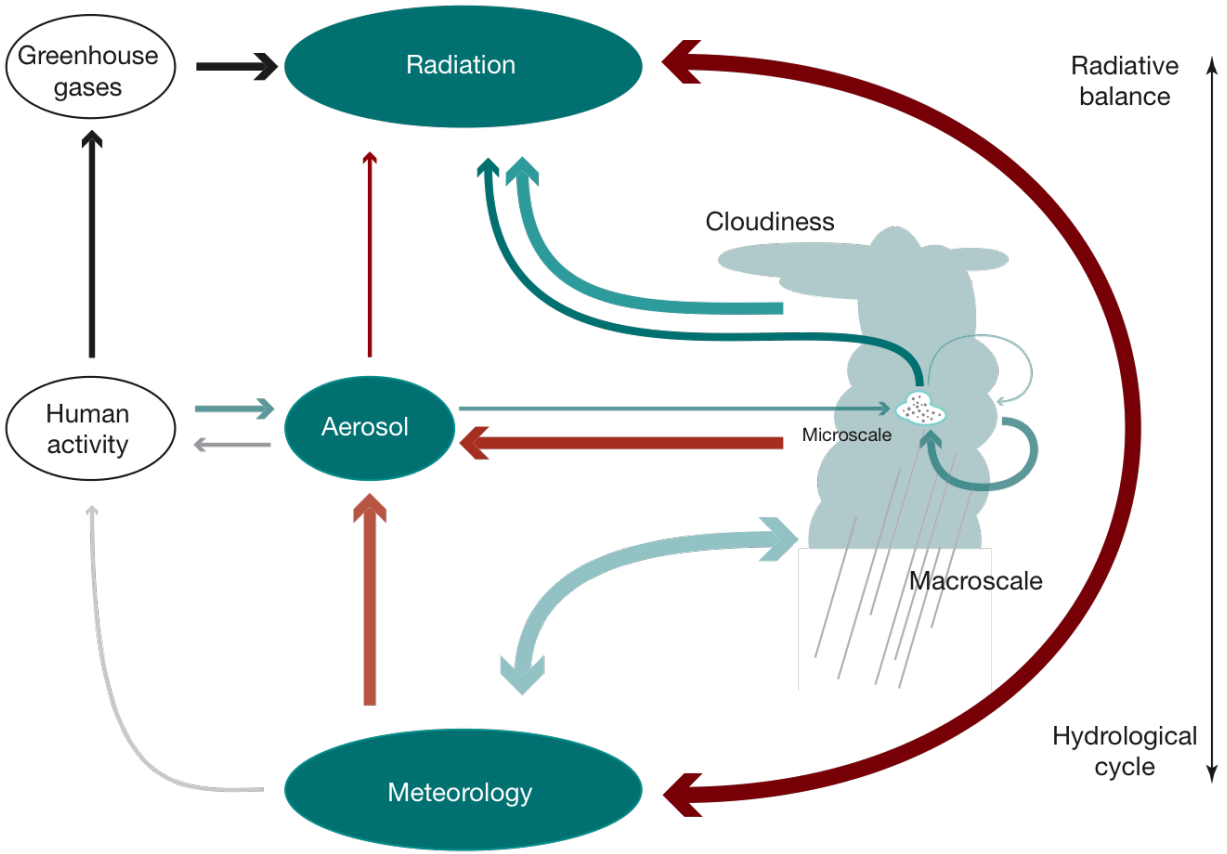


Albedo

Percentage of diffusely reflected sun light in relation to various surface conditions of the Earth

wikipedia.org

Aerosol-cloud-precipitation-climate interactions



Cloud albedo: How much incoming solar radiation is reflected back / how much is transmitted

Precipitation - The water cycle

Cloud lifetime, cloud coverage

Autoconversion rate? A factor of 10 uncertainty!

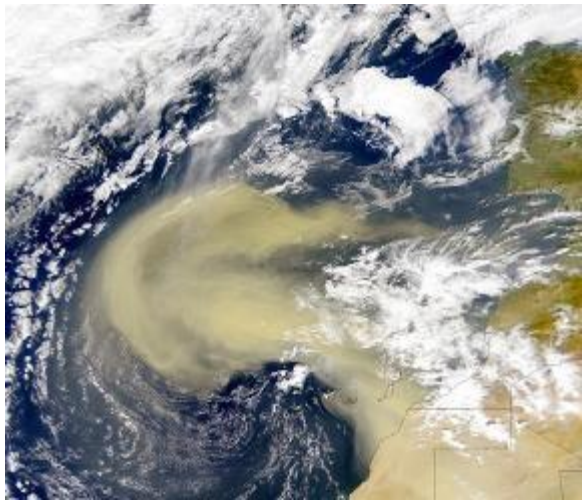
Stevens and Feingold, 2009, Nature, 461, doi:10.1038.

Example 1

Dust particle transport

Dust particle transport

Saharan dust and soil dust transport in the atmosphere – particles



Satellite photo of a large Saharan sandstorm showing a dust cloud over the Atlantic Ocean. This is a crop of a photo taken by NASA 26 February 2000. This cloud had reached the northeast coast of South America by 4 March 2000.

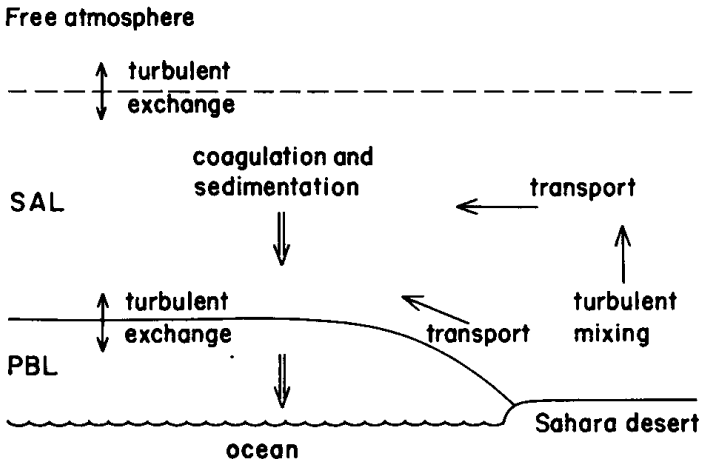


FIG. 1. Schematic illustration of Saharan dust transport and removal processes.

From: Lee, J.Climate & Applied Meteorology 22

Storms entrain sand particles (0.5-120 micron size range) to heights of 6,000 metres in the dry, hot Saharan Air Layer (SAL) that overlays the cooler, moist PBL over the ocean

From Maxey's Dresden (2008) talk

Phoenix Dust Storm (July 21, 2012)

…… a wall of dust almost 1 1/2 miles high and 100 miles wide that deposited an estimated 40,000 tons of sand and dust in just two hours.

….. more deadly traffic accidents, more harmful pollution and more health problems for people breathing in the irritating dust particles.

www.usatoday.com

Questions in modeling dust particle transport

- **What factors affect dust particle transport?**
  - wind intensity: i.e., surface dust flux ~ [surface wind]^3
  - vegetated cover (leaf area index below a certain level)
  - soil moisture (below a certain threshold)
  - Also from volcanic dust, sea salt, natural sulphate, forest fires

Current source flux model is very crude: estimated surface dust fluxes by different models may differ by a factor of > 10

How do changes in vegetation cover affect dust entrainment?

How to include seasonal changes in potential source regions?

How to couple the dust phase with atmospheric convection?

What is the wet deposition rate (i.e., deposition due to rain)?

Many open questions in production, transport, and removal

- **What are the implications of dust particle transport**
  - the global climate (i.e., radiative forcing, micronutrients to the ocean)

e.g., estimated radiative forcing of dust, -2 to $+0.5$ Wm^{-2} (compared to ~ $+1.5$ Wm^{-2} for CO_2)

  - visibility (optical depth, affecting driver safety)
  - Health impact (size distribution; e.g., desert fever fungus carried by soil particles)

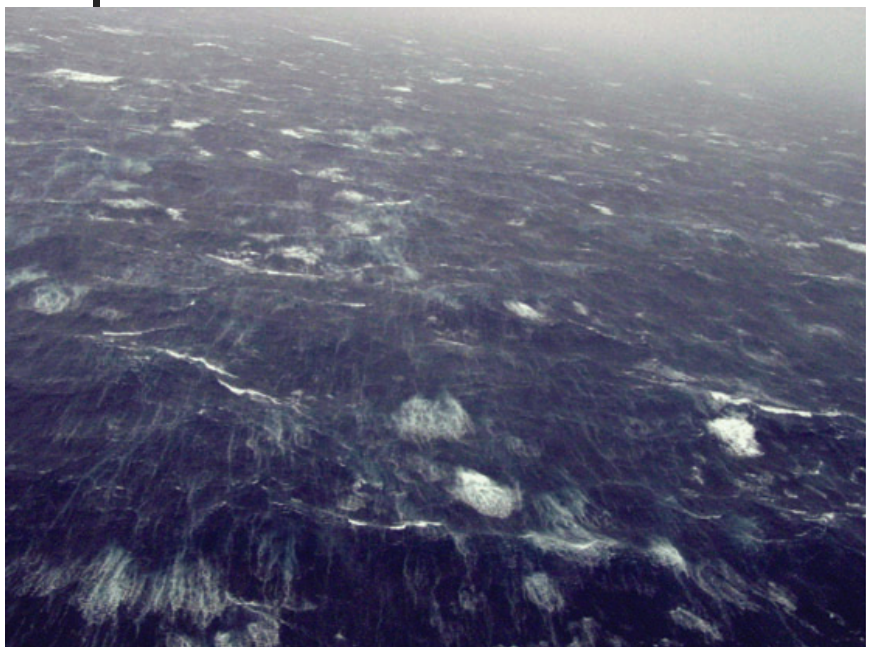
How to model the radiative properties of dust particles?

N. Mahowald, J. Geophys. Res. 104, 1999; Satheesh & Moorthy, Atmos. Env. 39, 2005.

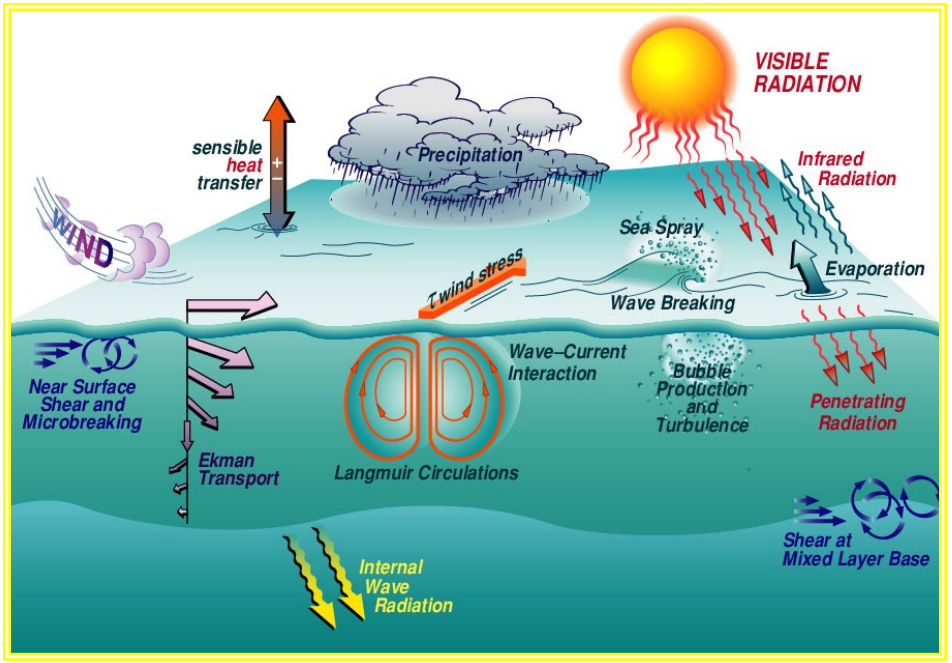
Example 2

Air-sea interaction

Air-sea interaction

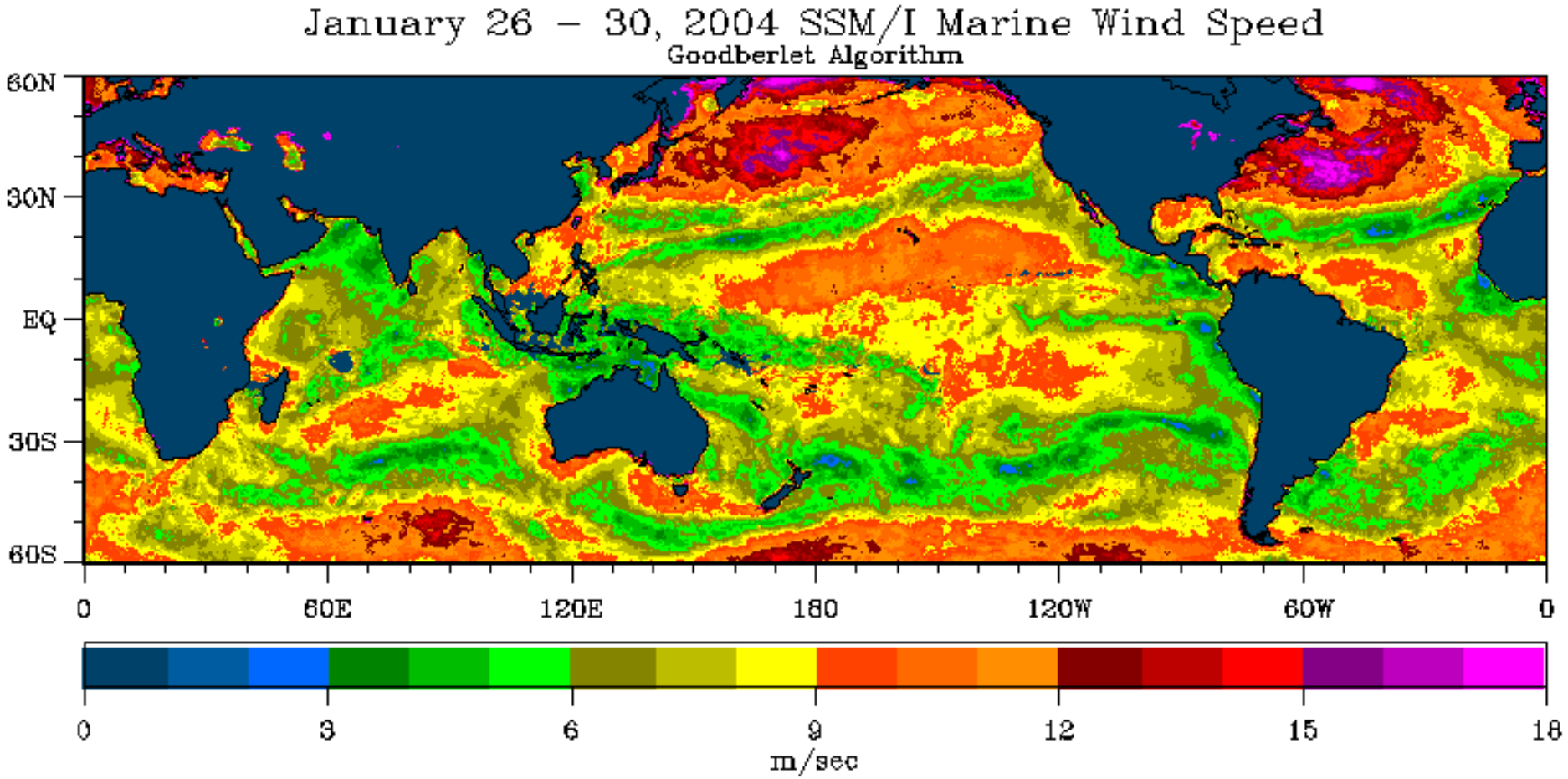


Sea surface and breaking waves in Hurricane Isabel



Questions:
Wind-driven waves versus wave-driven winds?
How do sea sprays affect the drag coefficient within the atmospheric boundary layer?
How do air bubbles affect mixing and gas transport?

P.P. Sullivan and J.C. McWilliams, 2010, *Annu Rev Fluid Mech* 2010: 42: 19-42.



Surface wind: ~ 1 m/s to 50 m/s

Ocean water: ~ 0.1 m/s or 1 m/s

Surface drag coefficient in a hurricane

$$\boldsymbol{\tau}_a = \rho_a C_d |\mathbf{U}_a| \mathbf{U}_a ,$$

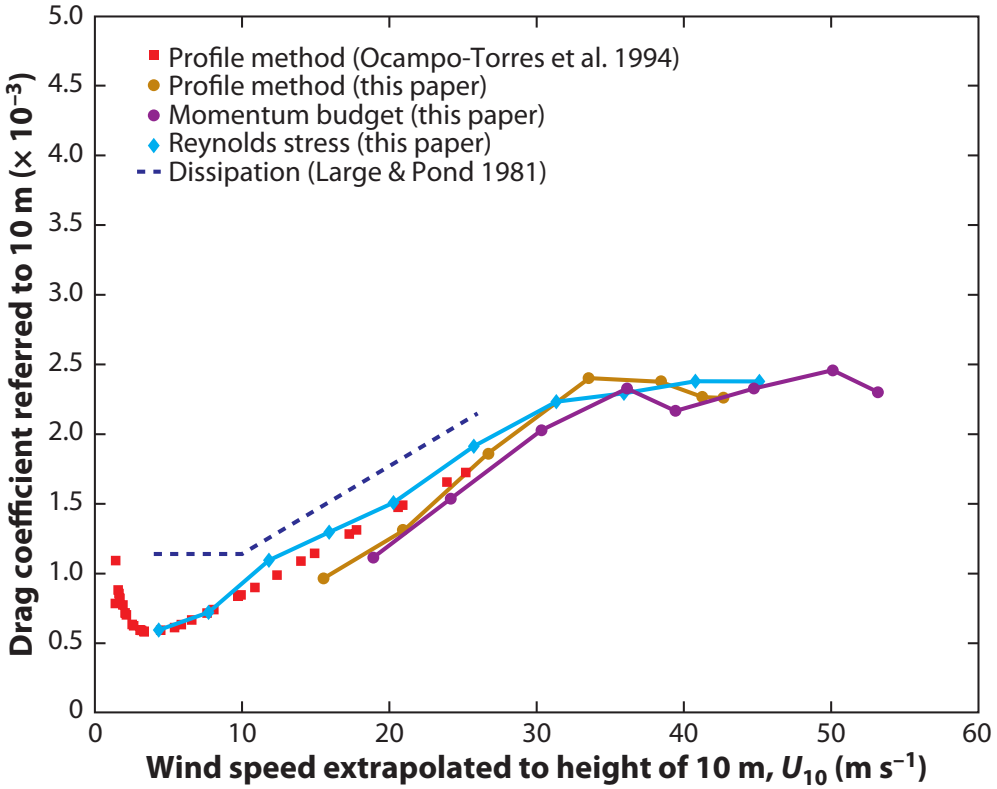


Figure 4

Variation of the neutral stability drag coefficient C_d with wind speed U_a derived from laboratory measurements using various methods from Donelan et al. (2004). The dotted line is the drag coefficient formula developed to fit the field measurements of Large & Pond (1981). Note the saturation at high wind speeds $U_a > 30$ m s^{-1}. Results provided by Mark Donelan, used by permission from the American Geophysical Union.

More questions related to the air-sea interactions

- **Factors affect air-sea interactions**
  - Surface wind speed
  - Bursting of air bubbles
  - Wave breaking and sea sprays

Particle mass flux may depend exponentially on the surface wind speed

Also non-sea salt particles originated from DMS (CH_3-S-CH_3) release from marine phytoplankton

What are the implications of air-sea interactions?

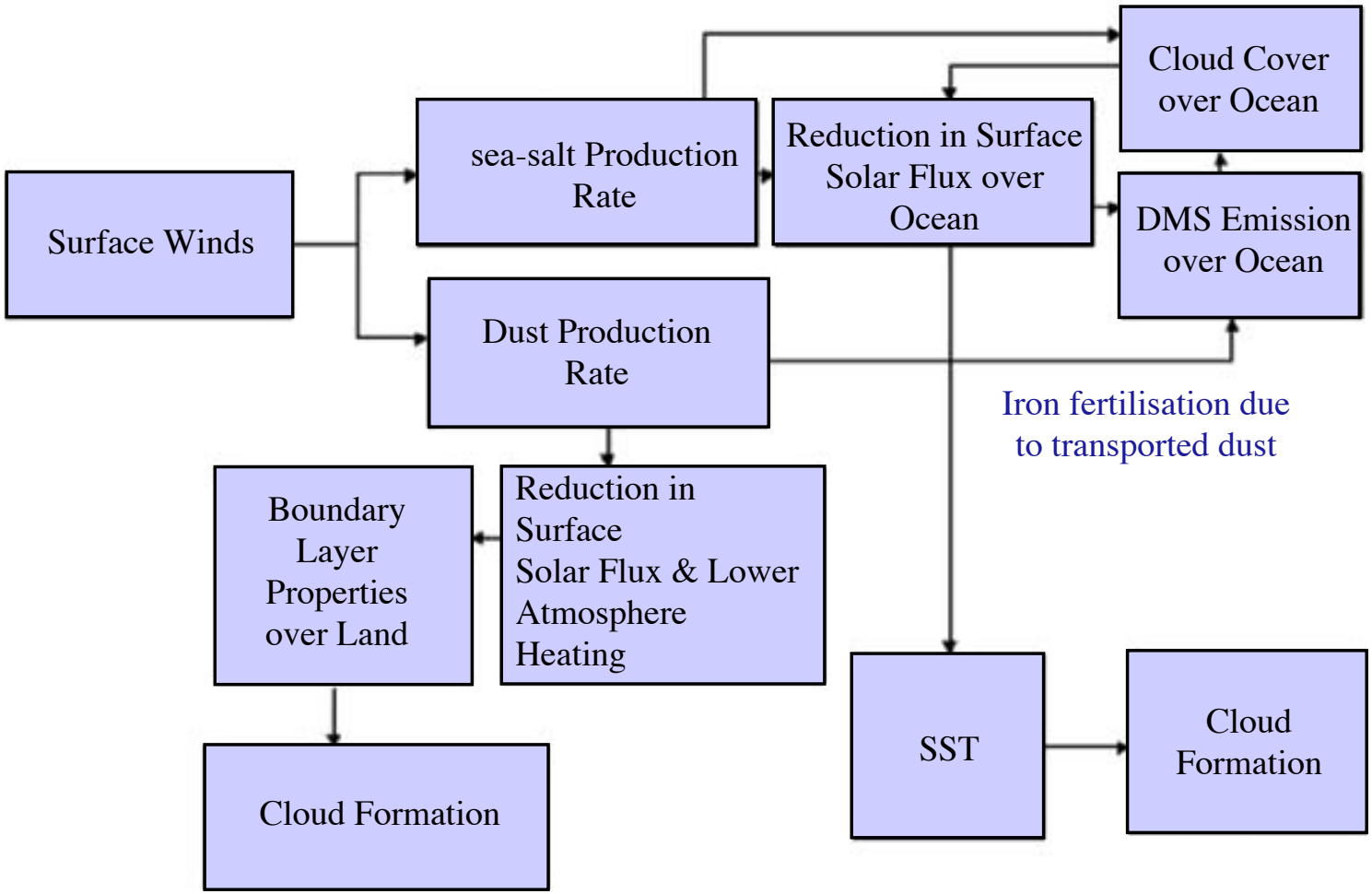
Generation of sea salt aerosol: more CCN, more cloud droplets, increased cloud albedo

How to reduce uncertainty in estimating sea-salt aerosol radiative forcing? e.g., estimated radiative forcing of sea-salt aerosols, -0.5 to -2 Wm^{-2} at low wind speeds; -1 to -6 Wm^{-2} at high wind speeds (compared to $\sim +1.5$ Wm^{-2} for CO_2)

How to make accurate measurements of aerosol flux and surface drag at high wind speeds?
How does transported soil dust affect marine life cycle?
How to model interactions of natural aerosols with anthropogenic aerosols?

Satheesh & Krishna Moorthy (2005)

Climate impact of natural aerosols



Satheesh & Moorthy, 2005, Atmos. Environ. 39.

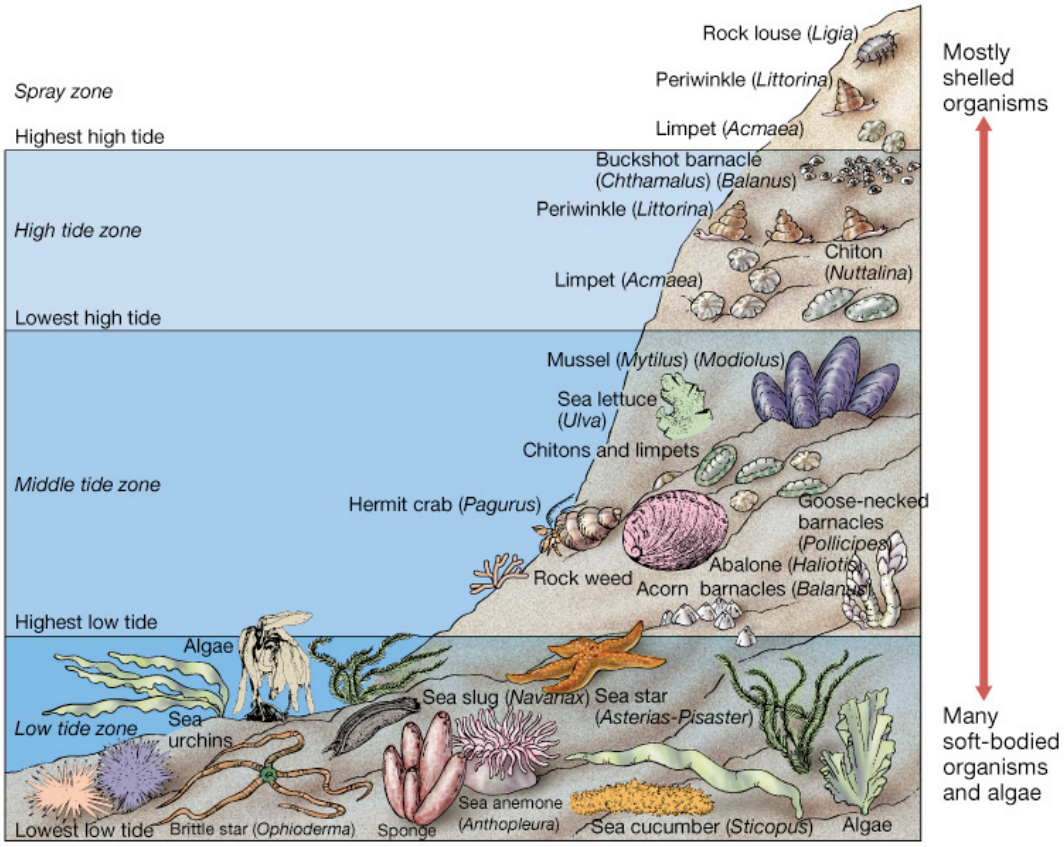
DMS =dimethyl sulphide $(CH_3)_2S$ from the oceanic phytoplankton

Example 3

Benthic organism – flow interactions: physical-biological coupling

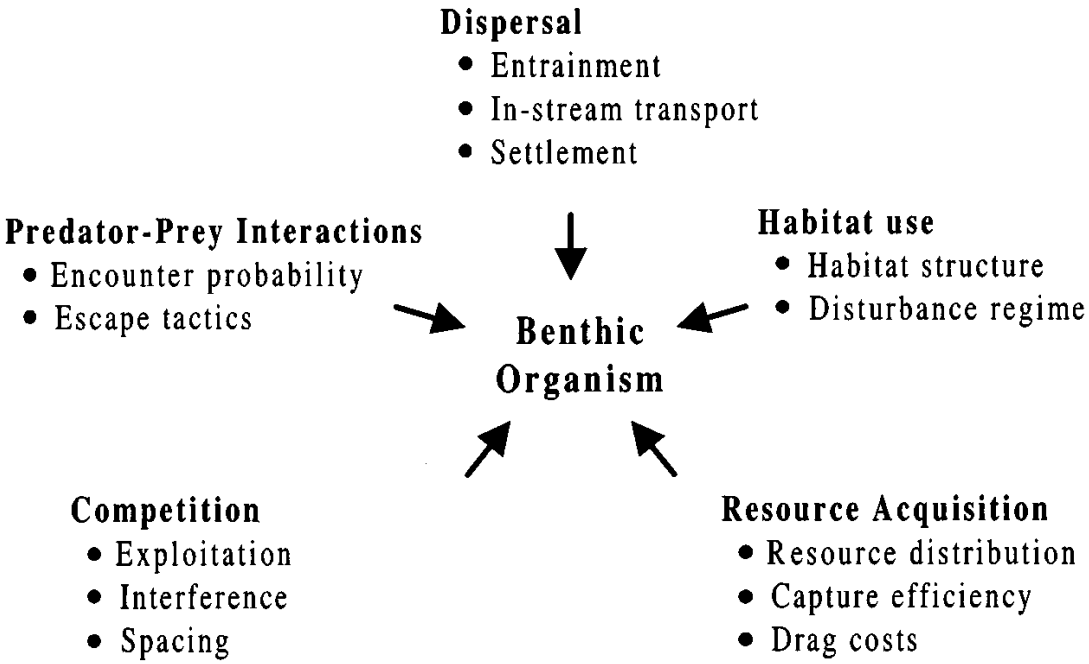
Benthic organism – flow interactions: physical-biological coupling

- Benthic organisms are those that live in or on the ocean / lake / river floor: e.g., corals, sea squirts, oysters, the mobile shellfish such as clams, snails, crabs, sea stars, worms and sea cucumbers
- More than 98% of known marine species are benthic
- The vast majority of benthic species live within the shallow continental shelf



H.V. Thurman & A.P. Trujillo, 2001, Essentials of Oceanography.

Ecological processes affected by flow



Organisms may be viewed as biologically active, flexible, finite-size, irregular particles

How do flow-induced drag and lift forces and mass transfer affect the growth and population of benthic organisms?

How do turbulent bursts lift and transport organisms?

How does turbulence affect their transport and settlement?

How does sediment transport affect the local living environment and food sources?

How does the physical-biological coupling at coarse scales is linked to fine-scale coupling?

D.H. Hart and C.M. Finelli, *Annu. Rev. Ecol. Syst.* 1999. 30:363–95

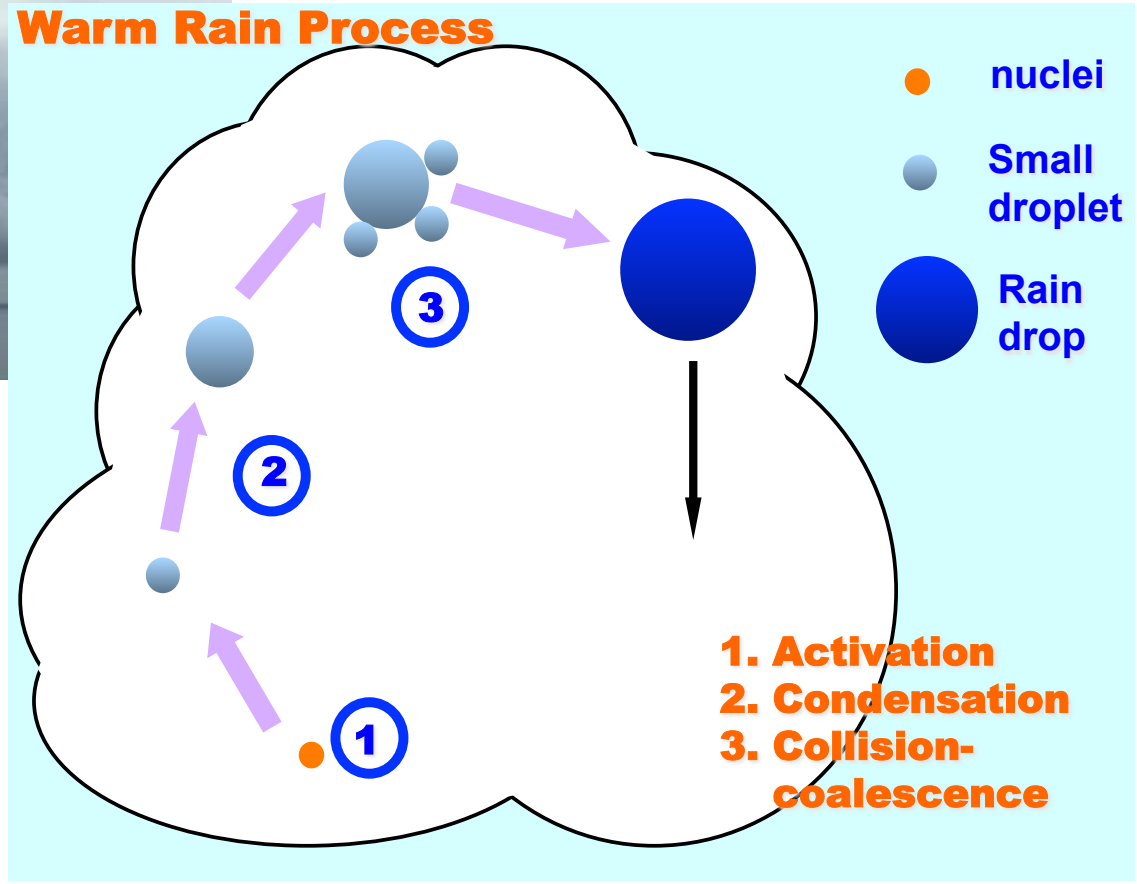
Example 4

Warm Rain Process and Cloud Microphysics

Warm Rain Process and Cloud Microphysics

(with Grabowski at NCAR; Aliseda at U. Washington, Chuang at UC Santa Cruz)

Growth of cloud droplets



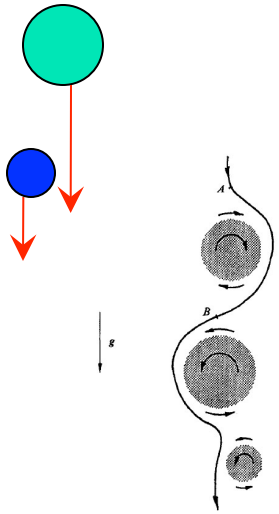
How does air turbulence affect the collision rates and collision efficiency of cloud droplets?

What is the impact on warm rain initiation?

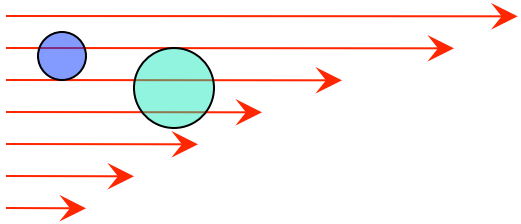
$$\frac{d\mathbf{V}}{dt} = -\frac{\mathbf{V} - [\mathbf{U}(\mathbf{Y}(t), t) + \mathbf{u}]}{\tau_p} + \mathbf{g}$$

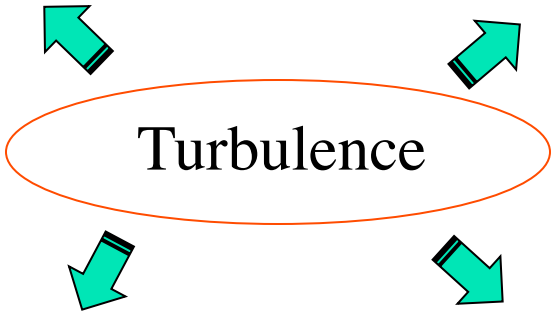
Mechanisms for geometric collision

Differential sedimentation

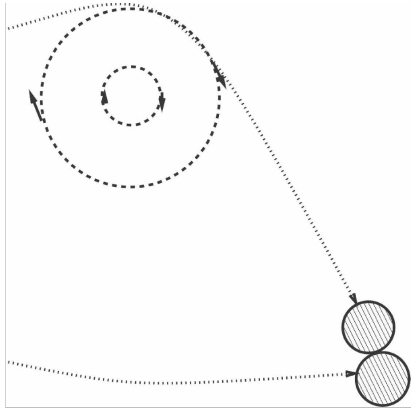


Local flow shear

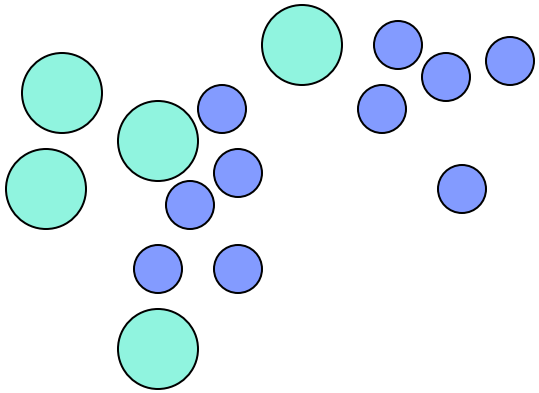




Inertial memory or sling effect



Droplet clustering



Cloud turbulence, scales, scale separation

Large scales

Large eddy size (integral length scale) $l \sim 100\ m$

rms fluctuation velocity $u' \sim 1\ \ m/s$

Large eddy time scale $T \sim \dfrac{l}{u'} \sim 100\ s$

Rate of volumetric energy input

$$\rho\varepsilon \sim \rho\frac{(u')^3}{l} \sim 0.01\ \ \frac{\mathrm{J}}{\mathrm{s}\cdot\mathrm{m}^3}$$

$$\frac{l}{\eta} \sim 120{,}000, \qquad \frac{T}{\tau_K} \sim 2{,}400, \qquad \frac{u'}{v_K} \sim 50$$

Small scales

ϵ ($\mathrm{cm^2\ s^{-3}}$)	τ_k (s)	η (cm)	υ_k ($\mathrm{cm\ s^{-1}}$)
10	0.1304	0.1488	1.142
100	0.0412	0.0837	2.031
400	0.0206	0.0592	2.872

Time evolution of real clouds

2 hours played in 47 seconds

1 s is 2.5 minutes in real time

Prof. Joe Zehnder
Department of Atmospheric Sciences
Creighton University

Deliverables after about ~10 years

Hybrid direct numerical simulation tool

Theoretical parameterization of turbulent collision kernel

Two review papers:

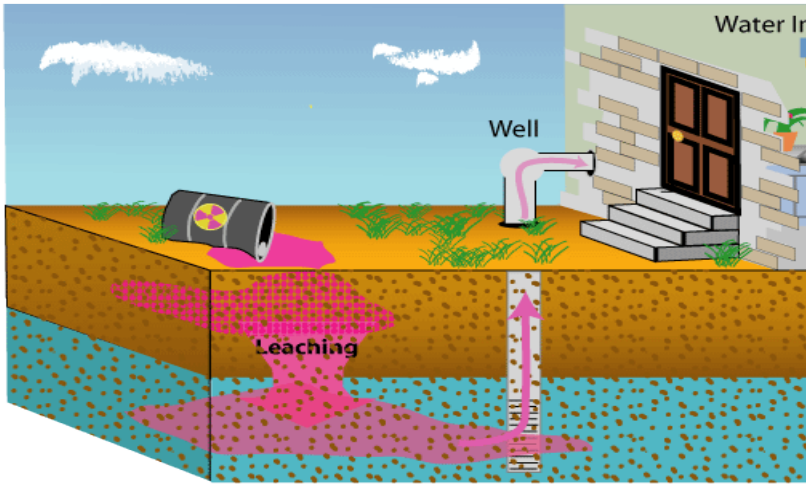
Devenish, Bartello, Brenguier, Collins, Grabowski, IJzermans, Malinowski, Reeks, Vassilicos, Wang, Warhaft, 2012, Droplet growth in warm turbulent clouds, *Q. J. R. Meteorol. Soc.*, DOI:10.1002/qj.1897

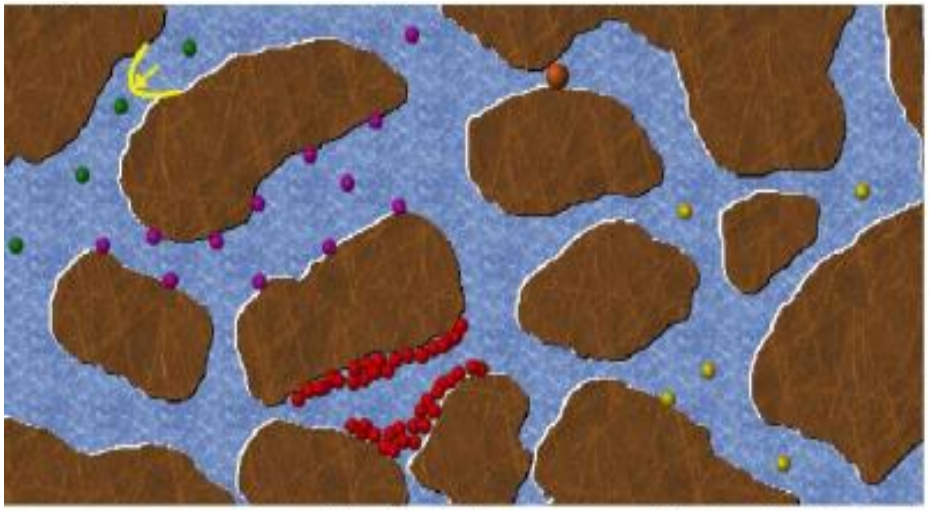
Grabowski and Wang, 2013, Growth of cloud droplets in a turbulent environment, *Annu. Rev. Fluid Mech.*, to appear.

Example 5

Colloid transport in soil

Colloid transport in saturated or unsaturated soil: groundwater contamination





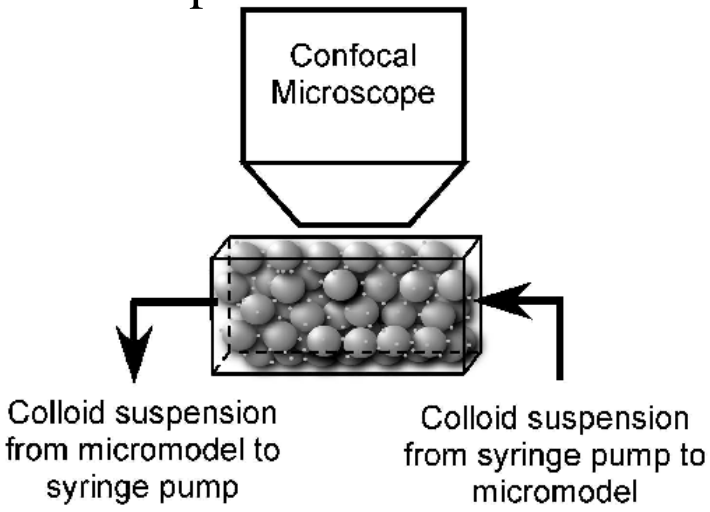
How far will contaminants (biocolloids, nanoparticles) be transported?

What are the relative role of fluid transport and physico-chemical interactions?

How to quantitatively model the transport process?

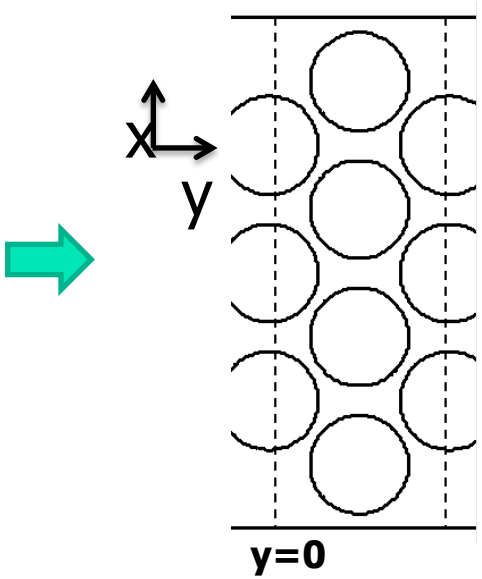
Experimental settings

3D pore-scale micromodel used for experimental observation

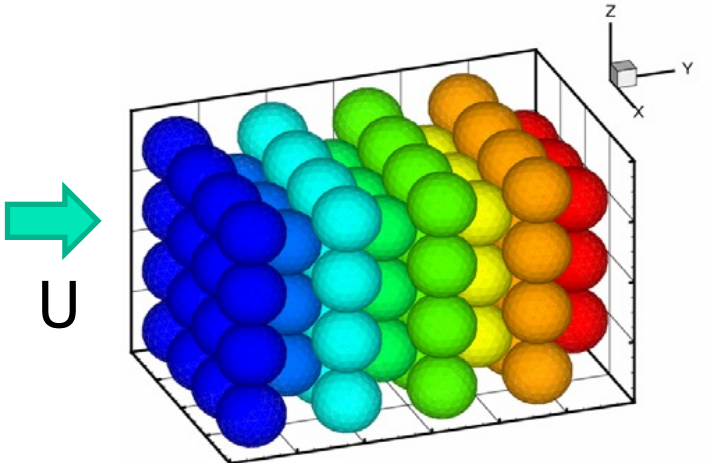


Jin's Group in Soil Science at UD

2D and 3D geometries for simulation



2D



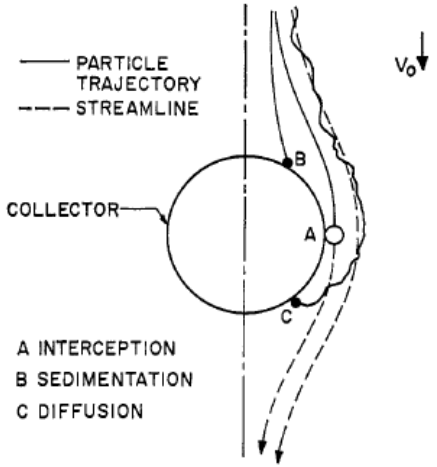
3D

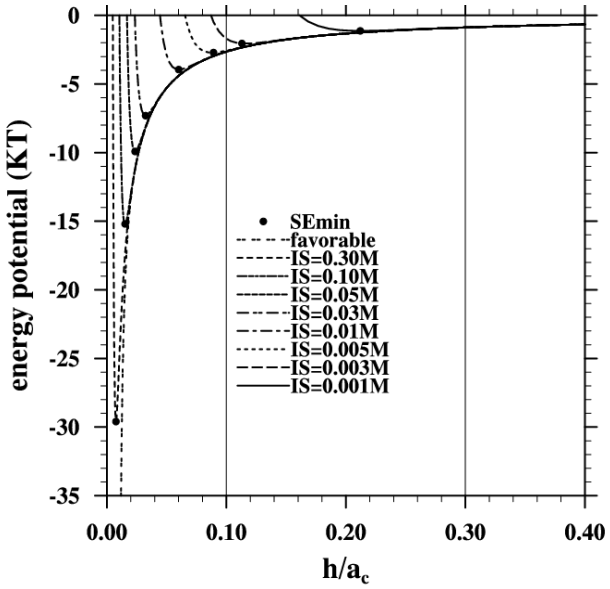
Pore-scale deposition mechanisms

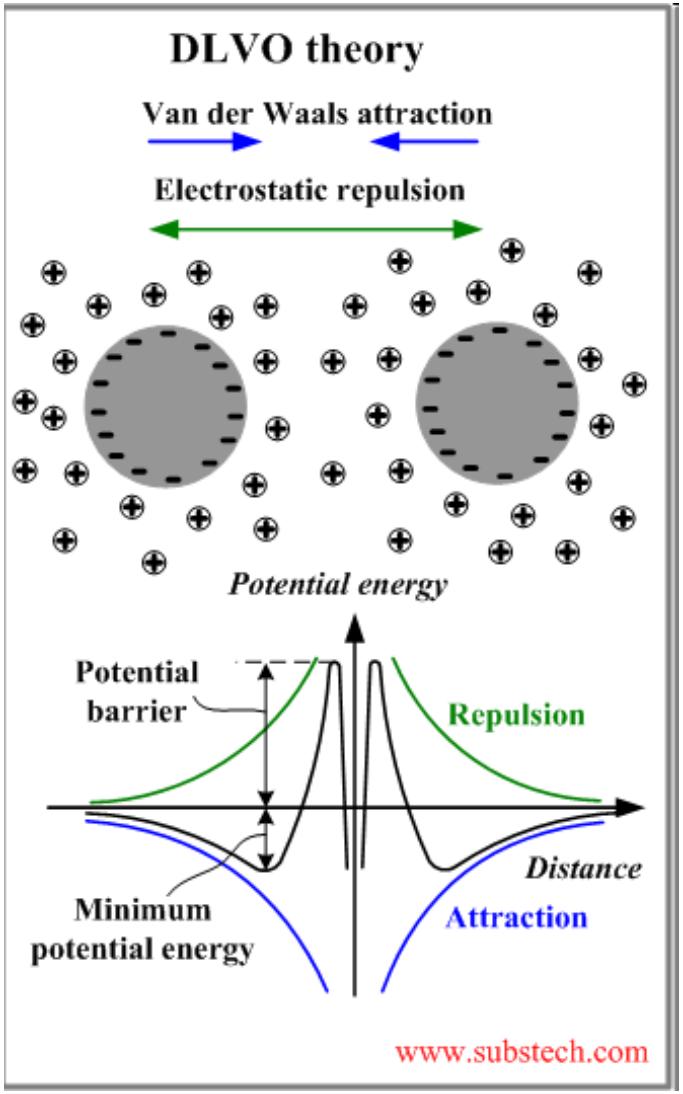
Interception: follow stream line
Sedimentation: gravity + buoyancy
Diffusion: Brownian motion
Colloid-collector interaction: DLVO forces etc

Lagrangian approach: a more direct approach for studying individual colloid transport and retention

$$m_p \frac{dV_p}{dt} = F^{drag} + F^{DLVO} + F^{Brownian} + F^{G}$$







Favorable condition: colloid and collector surface are oppositely-charged
Unfavorable condition: colloid and collector surface are like-charged

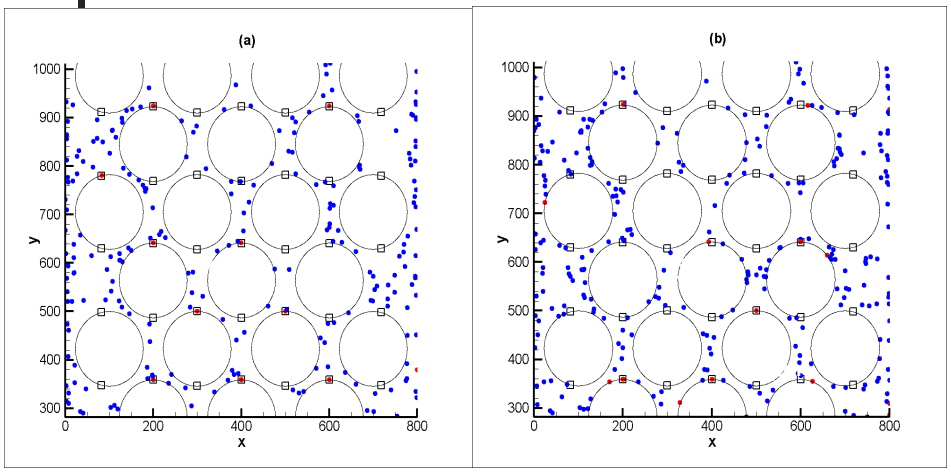
Comparison of colloid retention at different conditions

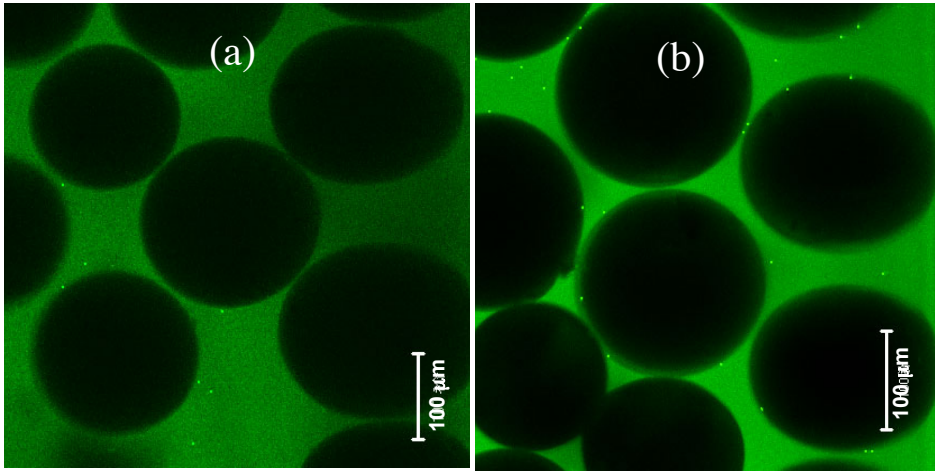
53m/d, 0.001M

5.3m/d, 0.001M

53m/d, 0.001M

5.3m/d, 0.001M



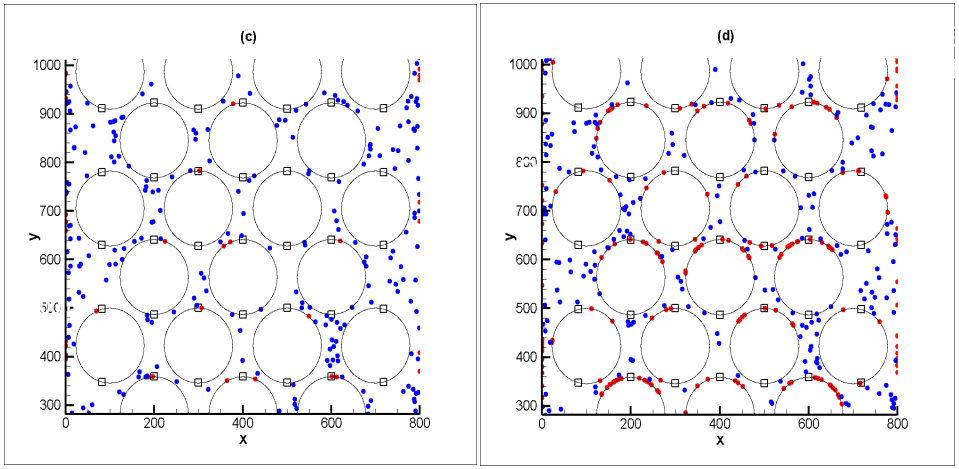


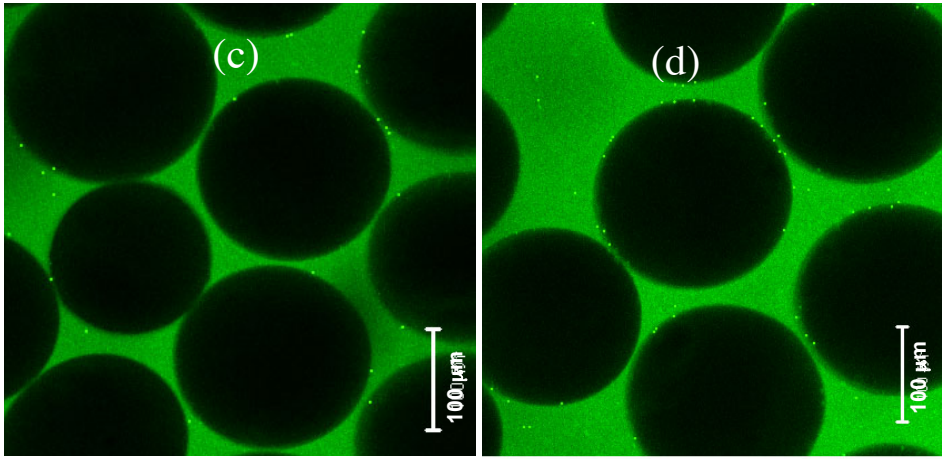
53m/d, 0.1M

5.3m/d, 0.1M

53m/d, 0.1M

5.3m/d, 0.1M



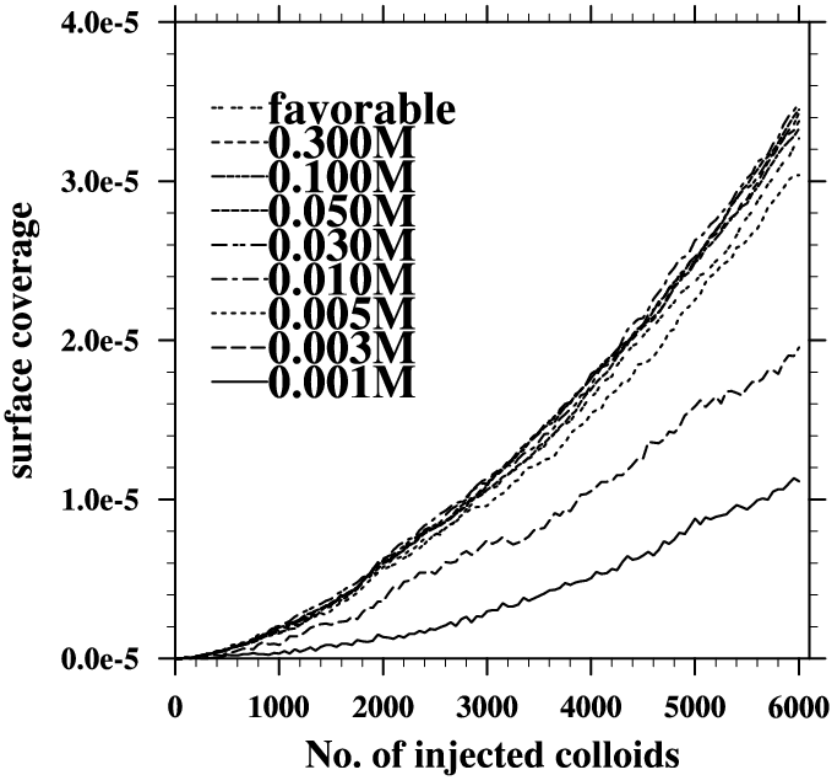


Simulations

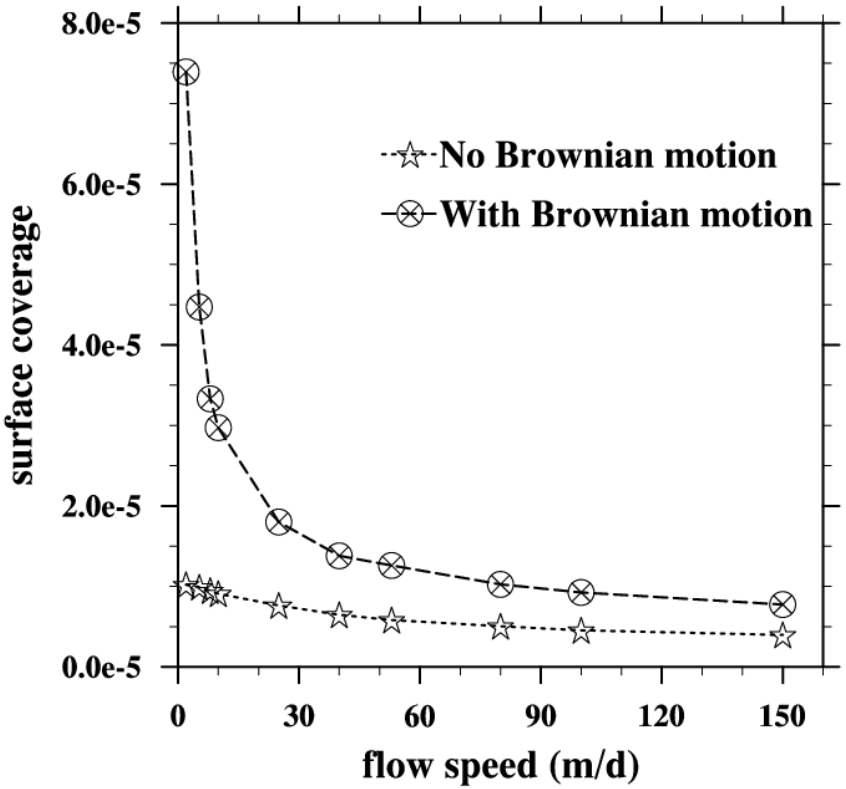
Experimental visualizations

Qiu CQ, Han J, Gao H, Wang L-P, Jin Y, *2012, Vadose Zone J.,* 11, DOI:10.2136/vzj2011.0071.

Effects of Ionic strength and flow speed on colloid retention



flow speed: 8m/d
colloid concentration: 5ppm



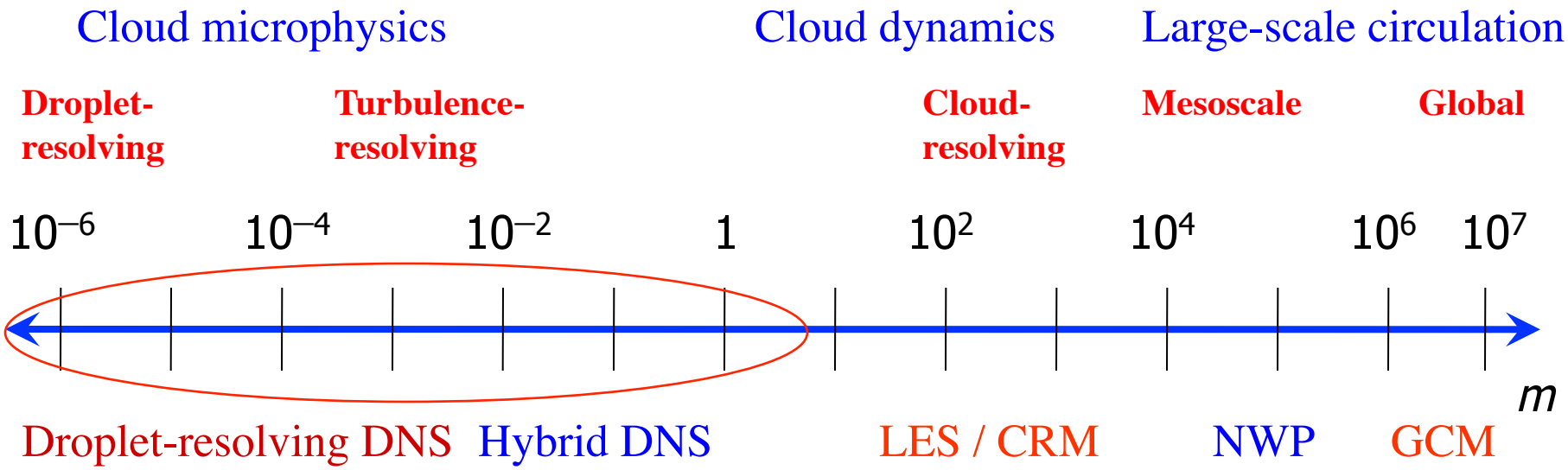
ionic strength: 0.1 M
colloid concentration: 5ppm

Qiu CQ, Han J, Gao H, Wang L-P, Jin Y, *2012, Vadose Zone J.,* 11, DOI:10.2136/vzj2011.0071.

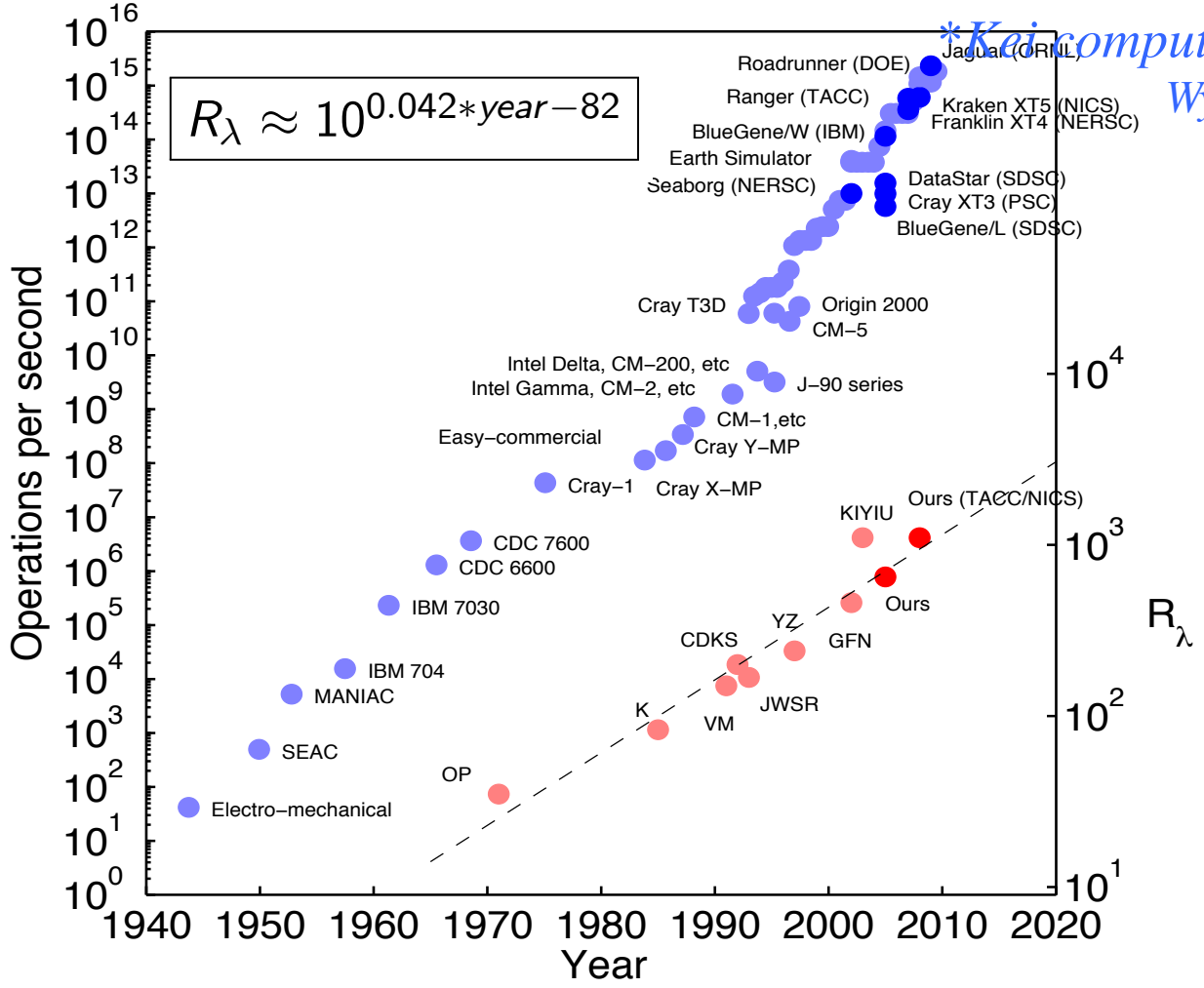
Extreme multi-scales

Cloud physics and atmospheric circulation:

A multi-scale problem down to droplet size and more



High-performance computing



*Kei computer (Kobe, Nov. 2012)

Wyoming

Computation is an independent research method.

After Donzis, 2010

Modeling atmospheric circulations (i.e., weather / climate)

Past (N~100)

GCM: $L \sim 10^7$ m, $\Delta x \sim 10^5$ m

NWP: $L \sim 10^6$ m, $\Delta x \sim 10^4$ m

CRM: $L \sim 10^6$ to 10^5 m, $\Delta x \sim 10^4$ m to 10^3 m

PBL LES: $L \sim 10^4$ m, $\Delta x \sim 10^2$ to 10 m

Near Future (N~10,000)

Global-scale CRM: $L \sim 10^7$ m, $\Delta x \sim 10^3$ m

Cloud-ensemble LES: $L \sim 10^4$ m, $\Delta x \sim 1$ m

Scaled-up hybrid DNS: $L \sim 10$ m, $\Delta x \sim 10^{-3}$ m

Significant overlaps in scales

Challenges:

- Better mathematical formulations and new algorithms
- **Scale-aware parameterization**
- Parallel implementation with significant data communication
- Data-intensive post processing (transferring data is a bottleneck)
- Theory: how to transform data to better parameterizations?
- ……

Better field data and laboratory experiments

- Fine-scale in-situ field observations
  - ACTOS (Siebert, Shaw et al.)
  - mountain-top facilities (Colorado, France, Switzerland, Germany)
  - Bodenschartz (mountain measurements)
- Controlled laboratory experiments
  - cloud chambers to look at ice and droplet microphysics
  - wave tanks to examine phenomena at the air-water interface
  - better instrumentation (fast camera, PIV, phase Doppler, etc.)
- Direct comparisons between field data / lab data /simulations

Why are research collaborations necessary?

- Understanding the application context and literature
  - May take years
  - Venture into a new community
  - Interactions among physicists, engineers, and geoscientists, ecologists, chemists, biologists, ….

- Need to combine theory, simulations, lab experiments, field observations to advance the field
  - A single approach cannot solve the whole problem

- Understanding various components of methodology
  - Flow simulation vs dispersed phase modeling
  - Incorporation of physics at various length scales
  - Incorporation physics (dynamics, thermodynamics), chemistry, biology
  - The same applies to experimental work (i.e., multiple instrumentation)

Some challenging problems to be addressed in the next decade

Climate variability on the ecosystem and civil infrastructure

Atmosphere-ocean coupling

Storms and freak waves (> 5m height)

Earthquakes, volcanic eruptions, and landslides

Coastal sediment transport, morphodynamic bed change

Floods and debris flows

The dispersion and fate of waterborne micro-organisms (safe drinking water)

Flow turbulence and marine life

Ice mechanics (related to climate change, offshore oil and gas industry)

Conversion of environmental flow energy to electricity

Crazy idea – geoengineering?

Geoengineering: restoring Earth's environment on a large scale to suit human needs and enhance habitability.

Inject sea salt particles into the low atmosphere to alter cloud coverage

Launch mirrors into orbit to shield Earth from the Sun

Reforesting the globe on a massive scale to absorb CO_2

Inject sulfate particles into stratosphere to block sunlight

Also **weather modification or weather engineering**

Why Environmental Multiphase Flow?

- **New scientific challenges**
  - ✧ Multi-scale: e.g., atmospheric circulation, from 10^{7} m to 10^{-6} m
  - ✧ Multidisciplinary: e.g., momentum, thermodynamics, chemistry, radiation, biology, etc.
- **Great motivations**
  - ✧ many unsolved questions (many crude parameterizations)
  - ✧ societal impact
- **Interdisciplinary (the reason why we have this workshop)**
  - ✧ breaking you own boundary
  - ✧ collaborations
  - ✧ rewarding adventure

Questions and discussions

Notes:

1. Try the projector or load your talks.
2. Leave a copy of your talk for others to review
3. Tuesday – Boulder walking mall
4. Thursday – more serous hiking!
5. Internet

Comparing to engineering multiphase flows

- Characteristics
  unbounded
  low average flow dissipation (clouds ~0.01 m2/s3, ocean)
  large flow Reynolds numbers

- Complications
  a huge range of scales

- Simplifications
  low volume fraction (10^{-6} in clouds)

Outcomes of this workshop

- learn a lot from other speakers / participants
  - a book on Environmental multiphase flow?
  - or a special journal issue?
  - ……
- **Some suggestions**
  - more discussions during your talk
  - …..