Cloudy with a chance of snow: The life of a snowflake in a cloud microphysics model

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Special thanks and credits to my colleague: Anna Jaruga, Caltech

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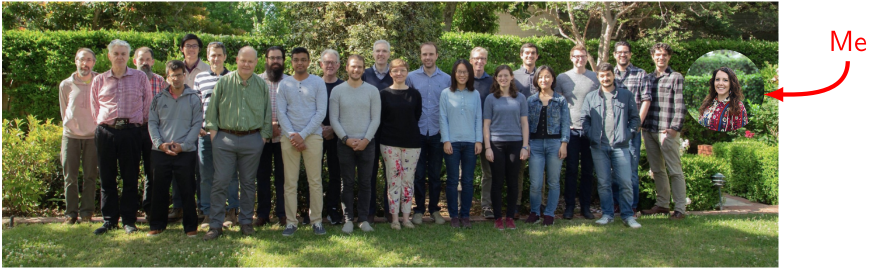
Outline

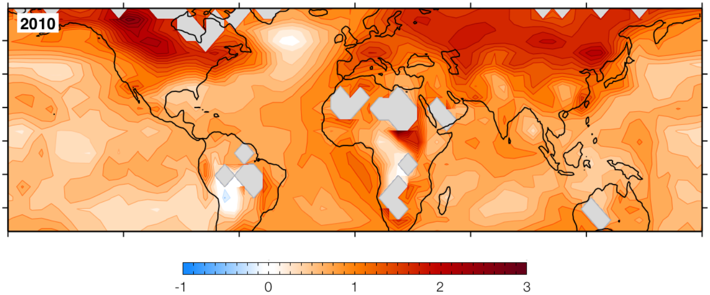
Context / Motivation

The Climate Modeling Alliance (CliMA)
is a coalition of scientists, engineers, and applied mathematicians from **Caltech**, **MIT**, and the **NASA Jet Propulsion Laboratory**.
We are building the first Earth System Model (ESM) that automatically learns from diverse data sources to produce more accurate climate predictions with quantified uncertainties.



What do we do?

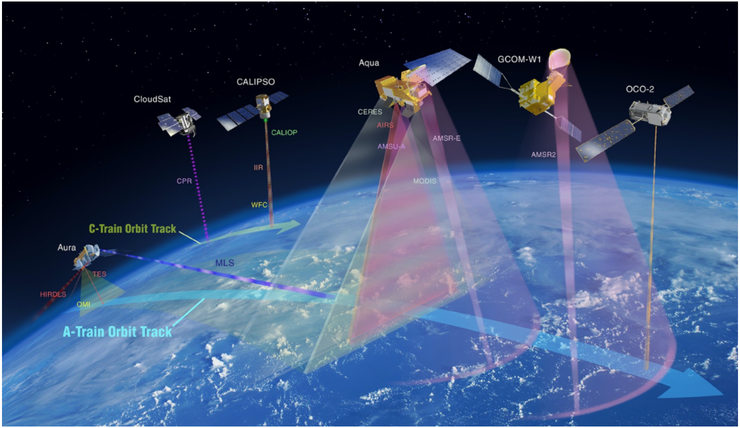
Temperatures have risen over the past 150 years



Temperature change (°C) from 1850s through 2010s.

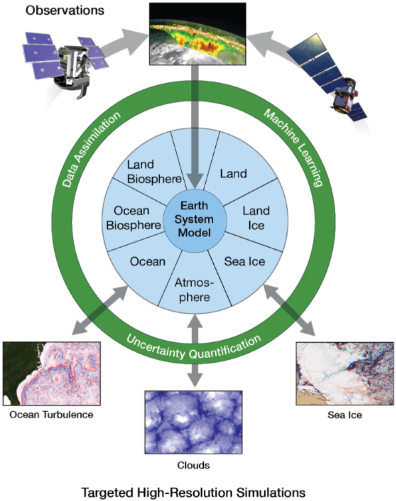
Source: Schneider & Held, J. Climate, 2011; update: https://climate-dynamics.org/videos/

How do we do it?



Source: NASA - The Afternoon Constellation

ESM

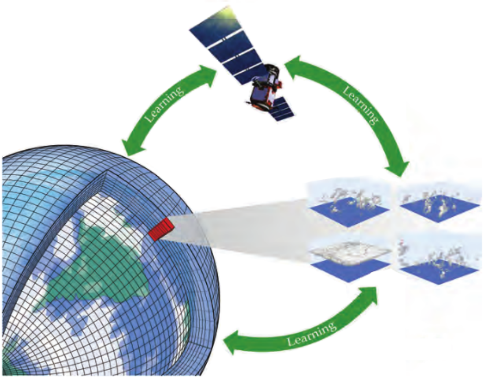


Source: courtesy of Tapio Schneider

An Earth System Model (ESM) couples several separate components (Atmosphere, Ocean, Land, etc).
In addition to this, we use Data Assimilation and Machine Learning to inform these models with more accurate parametrizations for subgrid scale phenomena.

Different Scales

For instance, a limited-area simulation can be nested in a global model and can, in turn, inform the global model.

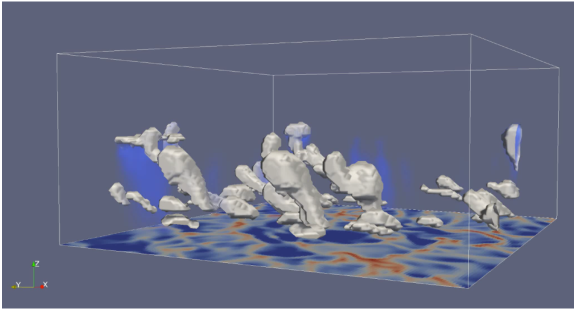


Source: Physics Today - June 2021, pg. 44-51

Thousands of high-resolution large-eddy simulations (LES) can be embedded in a global circulation model (GCM) in a massively parallel computing environment (HPC clusters or cloud services), and the global model can learn from them.

Different Scales

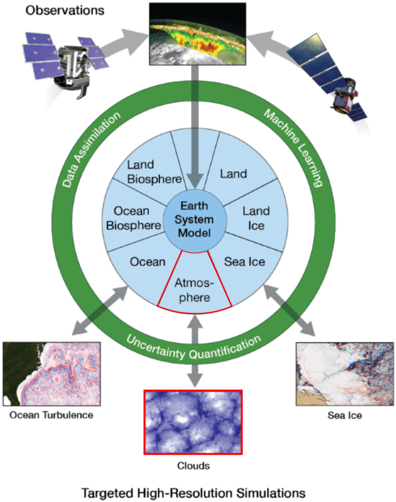
We can simulate some processes (e.g., clouds) faithfully, albeit only in limited areas.



Large-eddy simulation of tropical cumulus.

Source: Simulation with PyCLES (Pressel et al. 2015)

Clouds in the Atmosphere



Source: courtesy of Tapio Schneider

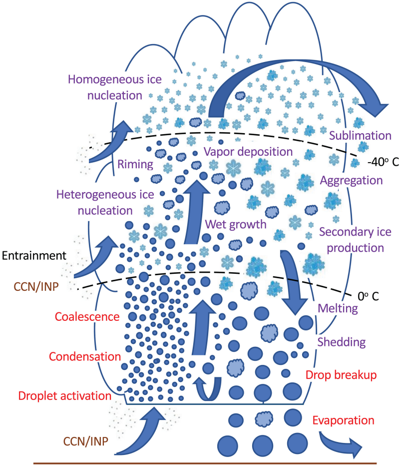
Of the Earth System Model (ESM) we are going to focus on the cloud processes that happen in the atmosphere.

Clouds are one of the greatest sources of uncertainty in climate forecasts.

What is cloud microphysics?

It is that area of research that studies:

- Liquid & solid particles suspended in the atmosphere.
- Physics that govern how they interact with each other and the surrounding environment.



Source: Morrison et al. JAMES 2020

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How to model clouds?

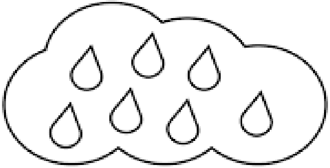
There are different approaches to model clouds. The main goal is to track a *distribution* of particles.

Three main approaches:

1. **Bulk / method of moments**: looks at cumulative quantities; uses a semiempirical description of particle size distributions based on particle mass.
2. **Method of bins / spectral**: does not assume particle size distributions, but computes them (typically numercially, using a finite differerences scheme).
3. **Particle-based methods**: track single particles, or super-particles (clusters), their collisions, coalescence, break-up.

Method of moments

For the camp, we will use the *method of moments* or *bulk method*.



A cloud with rain drops

This is a model that treats the cloud as a continuum and tries to predict cumulative quantities, such as the total mass of rain or snow produced in a cloud.

Governing equations

We consider different tracers/particles to be governed by a conservation law:

$$\frac{\partial Q}{\partial t} = \nabla \cdot (\boldsymbol{u} Q) + S(Q) \tag{1}$$

where $Q = \rho_a q$ is the tracer density (a scalar field), q denotes tracer concentration per unit mass, ρ_a the air density, $\boldsymbol{u}$ is the advective velocity, and $S(Q)$ is a source/sink term representing the creation/destruction rate of the field inside a given volume.

For the Camp, we will consider $\boldsymbol{u} = 0$ and focus only on modeling the source/sink term $S(Q)$.

Governing equations (cont'd)

We will consider different tracers/particle species:

`q_tot` : total water specific humidity,
`q_liq` : cloud liquid water specific humidity,
`q_vap` : water vapor specific humidity,
`q_rai` : rain specific humidity,
`q_ice` : ice specific humidity,
`q_sno` : snow specific humidity.

We define q_r, q_c, and q_{tot} to be:

$$
\begin{aligned}
q_r &= \frac{\text{mass of rain water}}{\text{mass of air}} = \\
&= \frac{\text{mass of rain water}}{\text{dry air mass} + \text{water vapor} + \text{liquid water} + \text{ice}}
\end{aligned}
$$

$$
q_c = q_{\mathrm{liq}} + q_{\mathrm{ice}}, \qquad q_{\mathrm{tot}} = q_c + q_{\mathrm{vap}}
$$

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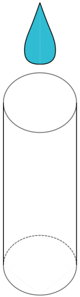
Modeling falling particles

We want to start our modeling by estimating the amount of cloud water collected by the falling rain drops.

A falling drop will collect a cylinder volume of air $V = Ah$.

Particles are assumed (semi-empirically) to follow power-law relationships for:

- $m(r)$: mass, $m(r) = m_0 \left(\frac{r}{r_0}\right)^{m_e}$
- $a(r)$: cross sectional area, $a(r) = a_0 \left(\frac{r}{r_0}\right)^{a_e}$
- $v_{term}(r)$: terminal velocity, $v(r) = v_0 \left(\frac{r}{r_0}\right)^{v_e}$



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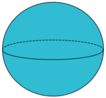
Spherical rain drop

The simplest model considers rain drops to be spherical in shape.
Hence their cross-sectional area and mass are simple:

- $m(r) = \frac{4}{3}\pi\rho_w r^3$
- $a(r) = \pi r^2$



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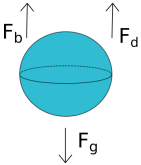


What about its terminal velocity?
It is found by the balance of forces: $\sum_i \boldsymbol{F}_i = m\boldsymbol{a}$, when $\boldsymbol{a} = 0 \Rightarrow \boldsymbol{F}_g = \boldsymbol{F}_b + \boldsymbol{F}_d$.
With $\boldsymbol{F}_g$ the gravitational body force, $\boldsymbol{F}_b$ buoyancy force, and $\boldsymbol{F}_d$ the drag force.

Spherical rain drop (cont'd)

We will see that the drag force $\boldsymbol{F}_d$ can be modeled in different ways. The "kinetic" way:

$$\boldsymbol{F}_d = \frac{1}{2} C_d \rho_a a(r) v_{term}^2 \tag{2}$$

which gives

$$v_{term}(r) = \left[\frac{8g}{3C_d} \left(\frac{\rho_w}{\rho_a} - 1 \right) \right]^{1/2} r^{1/2}. \tag{3}$$

Accretion

Accretion defines the rates of conversion between different particle categories due to collisions between particles.
For the case of collisions between cloud water (liquid water or ice) and precipitation (rain or snow) the rain specific humidity, q_r, will define a source of cloud rain, given by the following relationship:

$$\frac{dq_r}{dt} = \int_0^\infty n(r) \underbrace{a(r) v_{term}(r)}_{\sim \text{ volume V in time}} q_c E_{cp} dr, \tag{4}$$

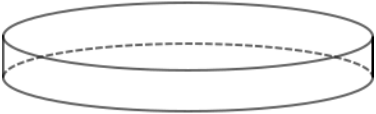
with E_{cp} the collision efficiency ($E_{cp} \in [0, 1]$), and $n(r)$ a size distribution of the particles.

How to model snow?

How can we change/extend this model to account for snow particles?

Snow flakes come in different shapes and sizes. We can start by defining a very idealized snow flake in a disc shape.

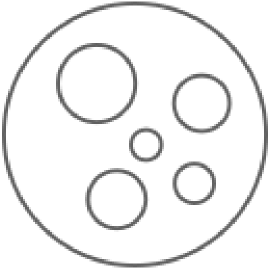
- $m(r) = ?$
- $a(r) = ?$
- $v_{term}(r) = ?$



How to model snow? (cont'd)

What if, instead of a flat compact disc, the snow flake is modeled as a disc with holes?

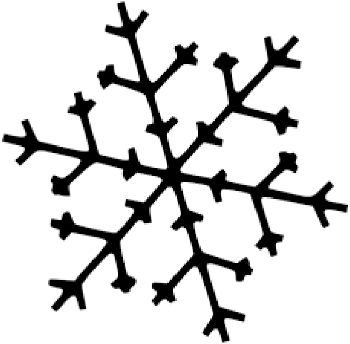
- $m(r) = ?$
- $a(r) = ?$
- $v_{term}(r) = ?$



More realistic snow flakes

What if, we consider that snow flakes are not really lines or discs, but have a fractal dimension (i.e., a non-integer dimension between 1 and 2)?

- $m(r) = ?$
- $a(r) = ?$
- $v_{term}(r) = ?$



Outlook and challenges:

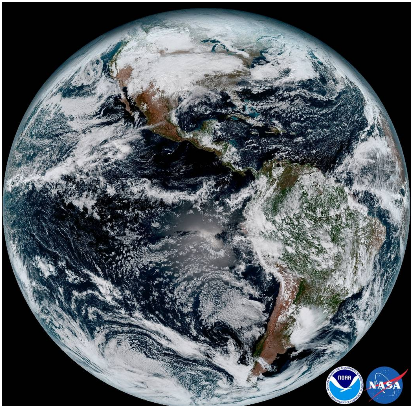


photo credit: NASA

Choose this problem if:

- You care about a problem with a direct societal impact (saving our planet and life on it)
- You like challenging problems that involve some numerical solutions [preferably in Julia ← code prototype provided!]

What to expect:

- Expect some mess!

Questions?

Thank you!

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