Fantastic clouds and where to find them

Steven Böing, Univ. of Leeds

From Luke Howard's sketchbook

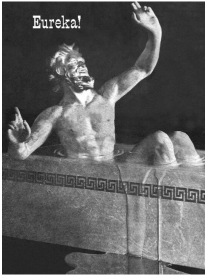
Time-lapse from DCMEX campaign

Ancient history

Studying clouds
- Cloud depictions on artworks (e.g. Chalcatzingo, around 1000BCE; della Francesca's baptism).
- Aristotle: meteorology

Since water is generated from air, and air from water, why are clouds not formed in the upper air? They ought to form there the more, the further from the earth and the colder that region is.

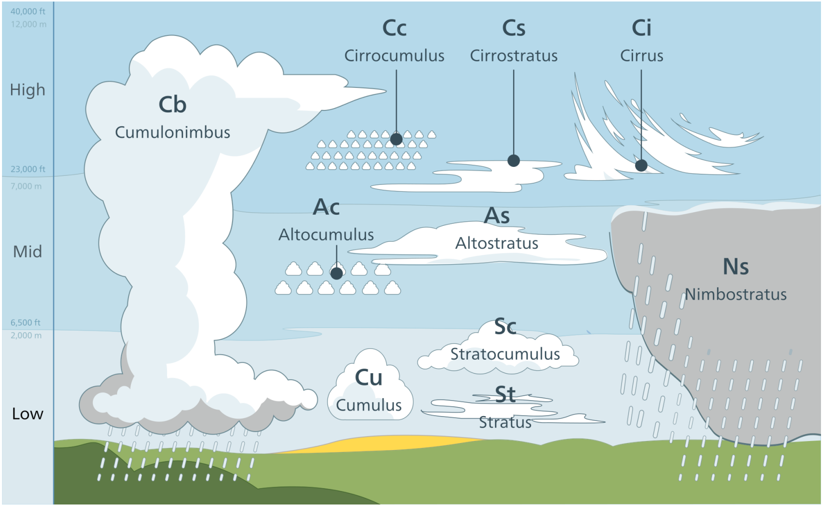
- Archimedes: buoyancy.



History: age of enlightenment

- Robert Hooke (1660s): *there are soe many that many of them want proper names*.
- Jean-Baptiste Lamarck, 1802: *hazy clouds (en forme de voile), massed clouds (attroupés), dappled clouds (pommelés), broomlike clouds (en balayeurs), and grouped clouds (groupés)*.
- Luke Howard: Latin names (which can combine), 1803.

Cloud types



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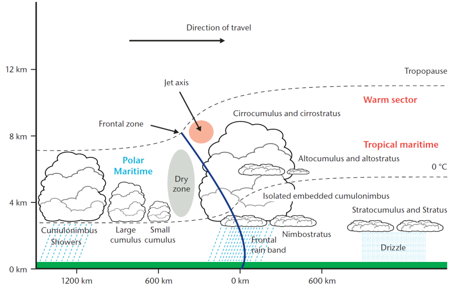
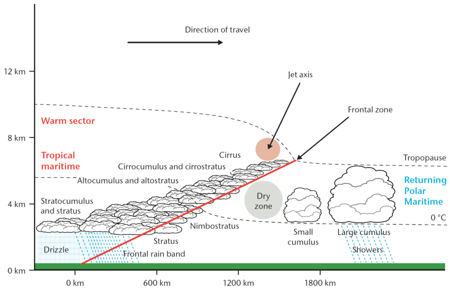
Midlatitude: relation to synoptics





Tropics/subtropics: Hadley Cell

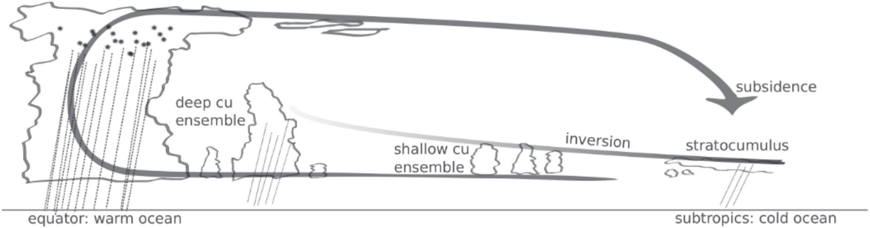
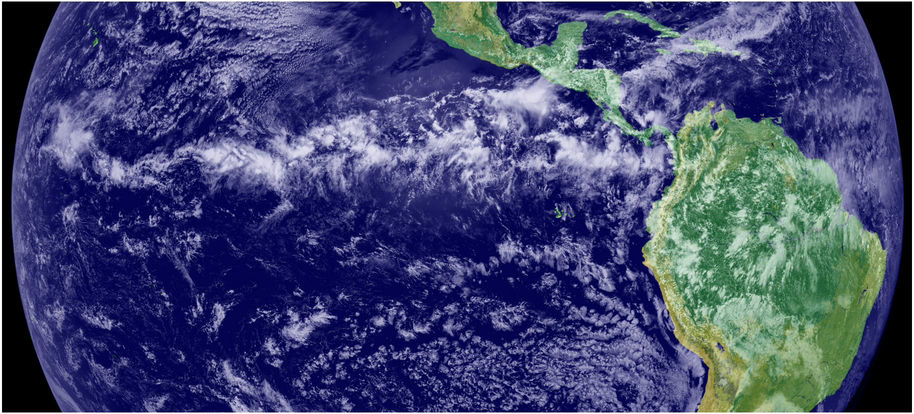


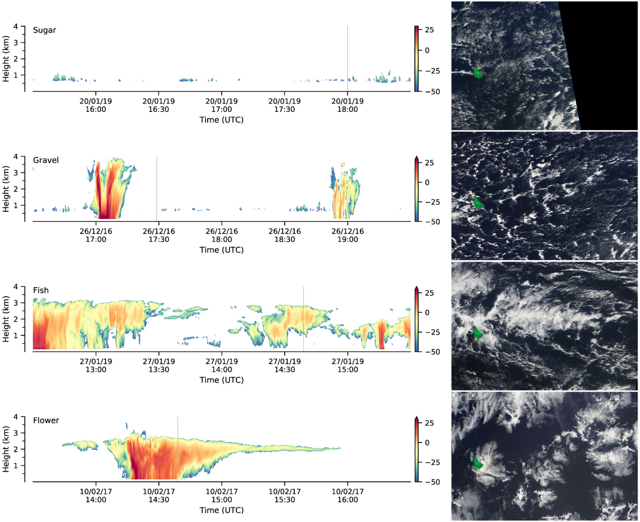
Fig. 1.1: Different cloud types and their location within the Hadley circulation (after e.g. Arakawa, 1975 and Stevens, 2005).

Inter-tropical convergence zone



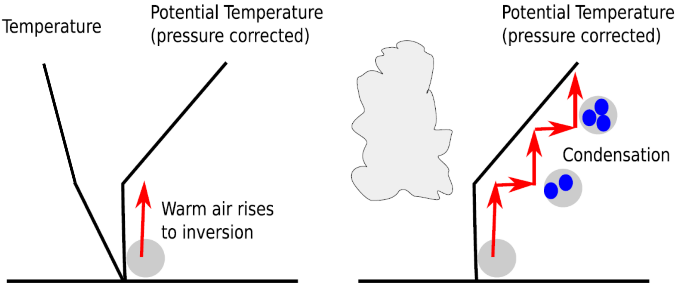
Public domain, NASA

Meso-scale organisation of low clouds



Vertical structure of the atmosphere

- Stratification above the mixed layer
- Specific humidity rapidly decreases in the vertical, as 'actual' temperature decreases as well.



Mechanisms for cloud formation and maintenance

- Buoyant ascent (surface fluxes)
- Elevated heating over mountains
- Forced lifting: convergence, topography
- Ascent by e.g. gravity waves
- Cooling by radiation

Wikimedia

Role of mountains

Moist Orographic Convection: Physical Mechanisms and Links to Surface-Exchange Processes

by Daniel J. Kirshbaum [1,*], Bianca Adler [2], Norbert Kalthoff [2], Christian Barthlott [3] and Stefano Serafin [4]

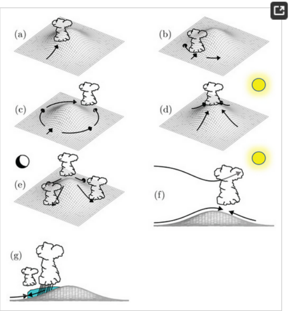


Figure 6. Schematic of basic mechanisms of convective initiation over mountains: (**a**) forced ascent, (**b**) upstream blocking, (**c**) lee-side convergence, (**d**) thermally forced anabatic flow and convection over the crest, (**e**) nocturnal katabatic flow and convection near the mountain base, (**f**) lee-side thermally driven upslope flow and gravity-wave ascent aloft, (**g**) quasi-stationary cold pool beneath precipitating convection.

The Role of Density Currents and Gravity Waves in the Offshore Propagation of Convection over Sumatra

SIMON C. PEATMAN,[a] CATHRYN E. BIRCH,[a] JULIANE SCHWENDIKE,[a] JOHN H. MARSHAM,[a] CHRIS DEARDEN,[b] STUART WEBSTER,[c] RYAN R. NEELY III,[a,d] AND ADRIAN J. MATTHEWS[e]

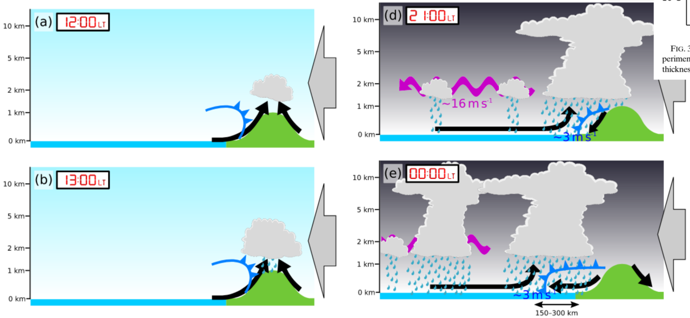


FIG. 14. Schematic diagram showing a day with an offshore prevailing wind and nocturnal offshore propagation of convection. The large gray arrow shows the prevailing wind direction and black arrows indicate density currents. Pink sinusoidal arrows represent gravity waves. Blue pointed lines are cold fronts, caused here by boundary layer density currents. The heights on the vertical axis, the horizontal length scale, and the local times on the clock are representative only. The timing of the convection and its propagation may vary by several hours from day to day.

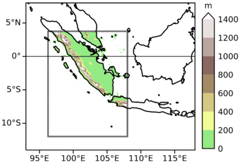


FIG. 3. Model orography for the convection-permitting MetUM experiment. The gray rectangle is the edge of the model domain and its thickness indicates the width of the lateral boundary forcing region.

Phase changes

$$\frac{D\theta}{Dt} = \frac{L_v(T)}{c_p\Pi}(C - E) + F_{\theta,rad}$$

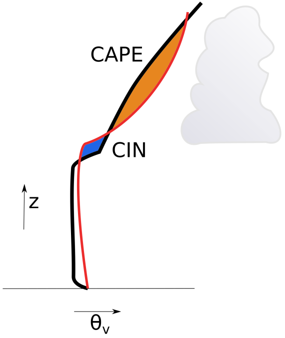
Most 'conserved variables' involve some approximation. Crude version of conserved temperature:

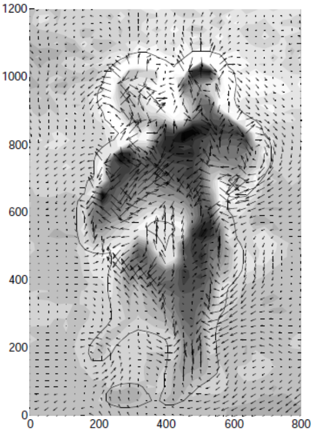
$$\frac{D\theta_l}{Dt} = F_{\theta,rad}$$

Where $\theta_l = \theta - \frac{L_v}{c_p\Pi} q_c$
Other 'conserved' variable $q_t = q_v + q_c$

More effects of phase changes

- Convective Available Potential Energy and Convective Inhibition.
- Cloud shell.

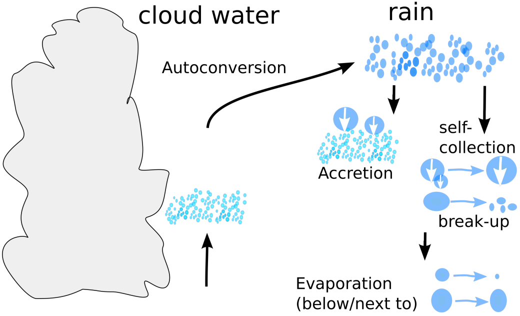




Heus et al., JAS, 2008

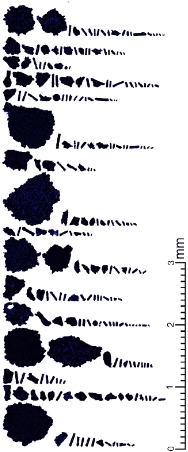
Rainfall (warm microphysics)

- Approximate balance between drag force exerted on rain drop and gravity.
- Effects: think about re-evaporation! If this is absent in upper cloud layer: potential intensification.
- Aerosols important for droplet size! Not all nuclei may be activated.
- Role of turbulence?



Ice processes

- Additional latent heat.
- Not reversible: homogeneous freezing not until -40 °C
- Ice nuclei key to determining when freezing takes place (including biogenic ones).
- Ice habits.



HALO-HOLO ice imaging

Microphysics and aerosols: modelling approaches.

- Bulk: predict a number of moments, e.g. droplet Number and volume.
- Bin: predict a full pdf of drop sizes.
- Superdroplets: stochastic simulation of 'representative drops'. Lagrangian (flow-following).
- Ice habits often discrete. Recent work includes a prognostic riming fraction.
- Prognostic aerosols: often multiple size modes included.

Journal of Advances in Modeling Earth Systems

Confronting the Challenge of Modeling Cloud and Precipitation Microphysics

Hugh Morrison[1], Marcus van Lier-Walqui[2], Ann M. Fridlind[3], Wojciech W. Grabowski[1], Jerry Y. Harrington[4], Corinna Hoose[5], Alexei Korolev[6], Matthew R. Kumjian[4], Jason A. Milbrandt[7], Hanna Pawlowska[8], Derek J. Posselt[9], Olivier P. Prat[10], Karly J. Reimel[4], Shin-Ichiro Shima[11], Bastiaan van Diedenhoven[2], and Lulin Xue[1]

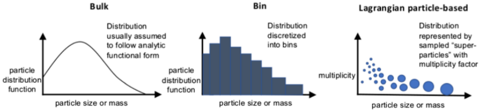
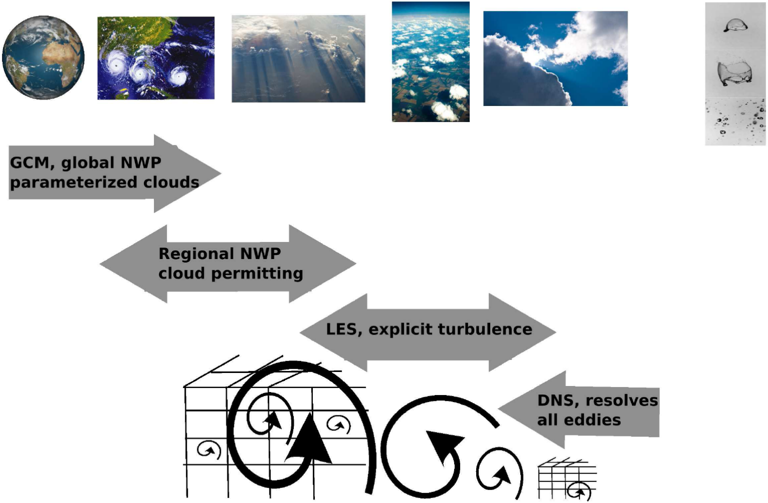


Figure 3. Representation of cloud and precipitation particle distributions in the three main types of microphysics schemes: Bulk (left), bin (center), and particle-based Lagrangian (right). The horizontal axes show particle diameter or mass, and the vertical axes show the number density distribution for the bulk and bin diagrams and "multiplicity" for the Lagrangian particle-based diagram, which is the actual number of particles that each super-particle represents. The size of the blue super-particles in this diagram represents the size or mass of a super-particle. Note that almost all current bulk schemes represent particle distributions using analytic functions, although some earlier schemes did not make any assumptions about the cloud particle distribution and only considered bulk cloud water content.

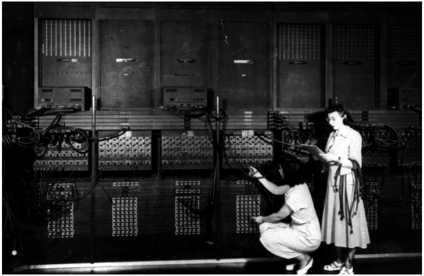
Models of the atmosphere

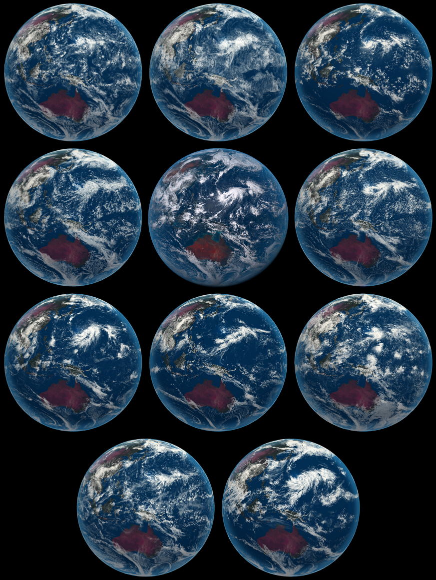


Droplets: Villermaux and Bossa, Nature Phys.

History: cloud computing

- From computing weather to computing clouds
- First Numerical Weather Forecasts: Richardson (1920s), Charney/UKMO/Rossby (1950s)
- Deardorff (1970s): Large-Eddy Simulation (32x32x32 points)
- Nowadays: global modelling at cloud-resolving scales, 10x10x10m LES on large domains.



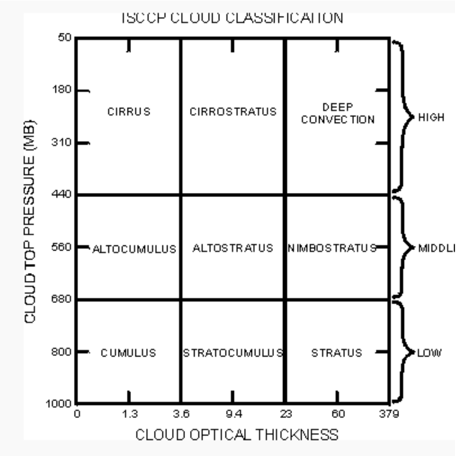


Stevens, B., Satoh, M., et al. (2019). DYAMOND: The DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. Progress in Earth and Planetary Science, Vol. 6: 61.

Global models

- Grid spacing: typical 15-100 km in horizontal (NWP/climate)...nowadays approaching the size of larger clouds.
- Cloud parametrisation and convection parametrisation: parametrised convection, parametrised cloud, cloud in boundary-layer/turbulence parametrisation, sometimes also resolved cloud.
- Typical ingredients of convection parametrisation: cloud model, closure (determines mass-flux $M = \int \rho w \; dA$ at cloud base), trigger function
- For closure: many different approaches (CAPE/CIN/boundary layer).
- Need to suppress grid-scale storms.

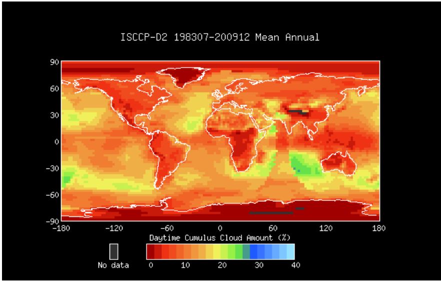
Validation: cloud types in satellite data.

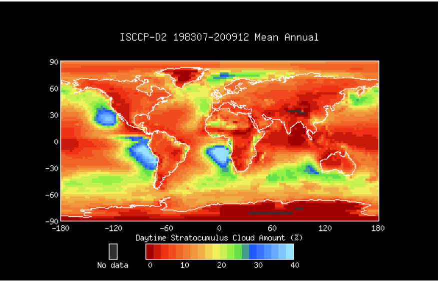


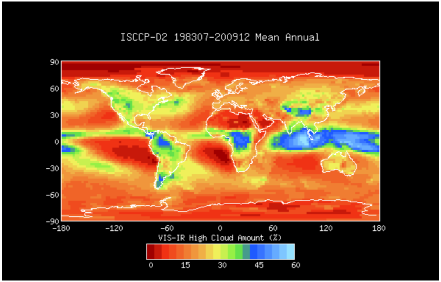
- Recent articles trying to use machine learning for classification.

Validation: where to find convection?

- Look at satellite-derived variables (e.g. ISCCP). Satellite simulators.







When to find convection?

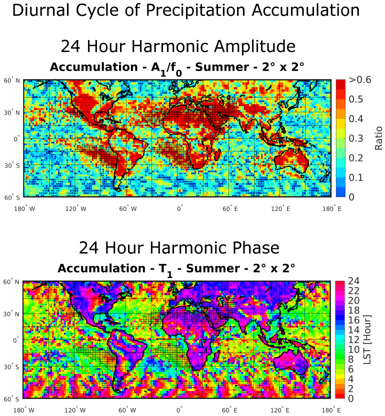
- Seasonal, subseasonal and diurnal modes.
- Parametrised convection often peaks too early in the day.

Article

The Summertime Diurnal Cycle of Precipitation Derived from IMERG

Daniel Watters [1] **and Alessandro Battaglia** [1,2,*]

[1] Earth Observation Science Group, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK
[2] National Centre for Earth Observation, University of Leicester, Leicester LE1 7RH, UK
[*] Correspondence: ab474@leicester.ac.uk



Regional models

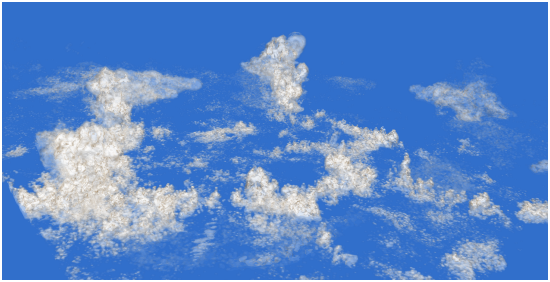
- Resolution mostly convection-permitting: below 10km.
- Weather and climate purposes

Grey zones:
- Convection (deep/shallow)
- Boundary layer turbulence (for grid spacings below 1km)

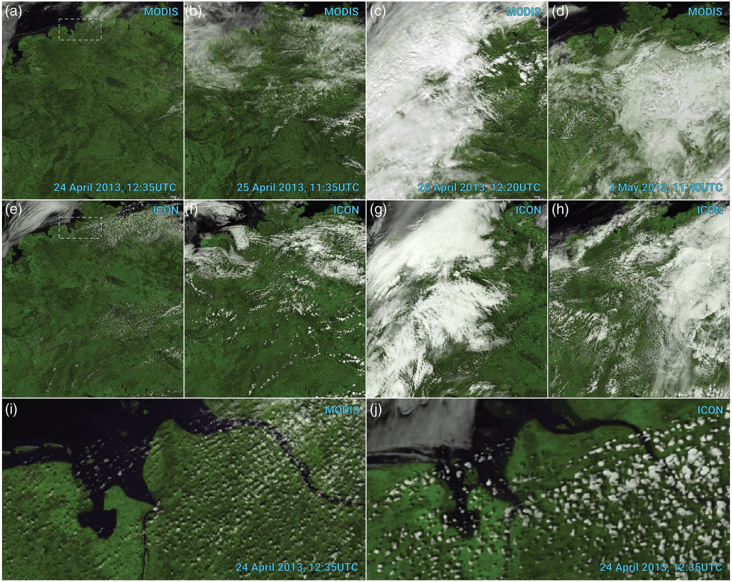
Anisotropic grid

Large-Eddy Simulation

- Ability to resolve most of the larger-turbulent eddies in boundary layer.
- Idealised case studies: idealised, doubly-periodic, simulations.
- Nowadays: real case studies with compressible models and LES-type turbulence closure.



Large-Eddy Simulation

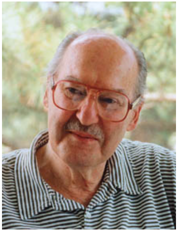


Heinze et al. 2017, QJRMS (125m over Germany)

Turbulence: Smagorinsky approach (rate-of-strain tensor)

$$\frac{\partial}{\partial t}\widetilde{\psi} = -\frac{1}{\rho_0}\frac{\partial}{\partial x_j}\rho_0\widetilde{\psi}\widetilde{u_j} + \frac{1}{\rho_0}\left(\frac{\partial}{\partial x_j}\rho_0 K_h \frac{\partial}{\partial x_j}\widetilde{\psi}\right) + \mathcal{S}_\psi$$

Eddy viscosities (K_m/K_h): obtain from diagnostic balance between shear and dissipation (Smagorinsky), length scale λ often related to grid-spacing (also: grid anisotropy, stability).

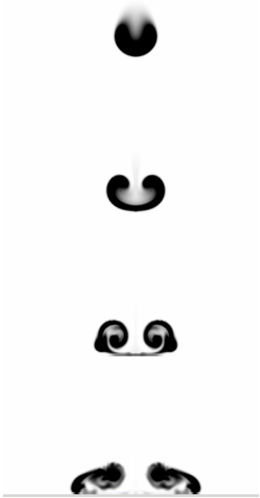


Alternatives: Prognostic TKE, Dynamic LES, Implicit LES, Higher order closure models.

Direct Numerical Simulation

Use an explicit viscosity. Resolve turbulence, but lower Reynolds number.

Use cases:
- Theoretical studies: plumes, gravity currents (laboratory like), cloud shell
- Stable boundary layer
- Droplet collisions on small scales: turbulence enhances rainfall!



Alternative: (almost fully) Lagrangian parcel approach.

- Advantage: resolution below grid, large time steps, simple parcel operations. Parcel concentrations can vary (on small scales).
- Needs explicit mixing formulation!
- Alternative to LES and DNS: still early days (runs on ARCHER2 supercomputer).