Session 5 Numerical modelling of the atmosphere - 2

Last session → numerical methods to solve the primitive equations.

But some processes are not properly described by equations so they cannot be resolved
→ **parameterization**

We will cover today:

1. What is a parameterization?
2. Parameterization of atm processes
3. Parameterization of surface processes
4. Ensemble methods

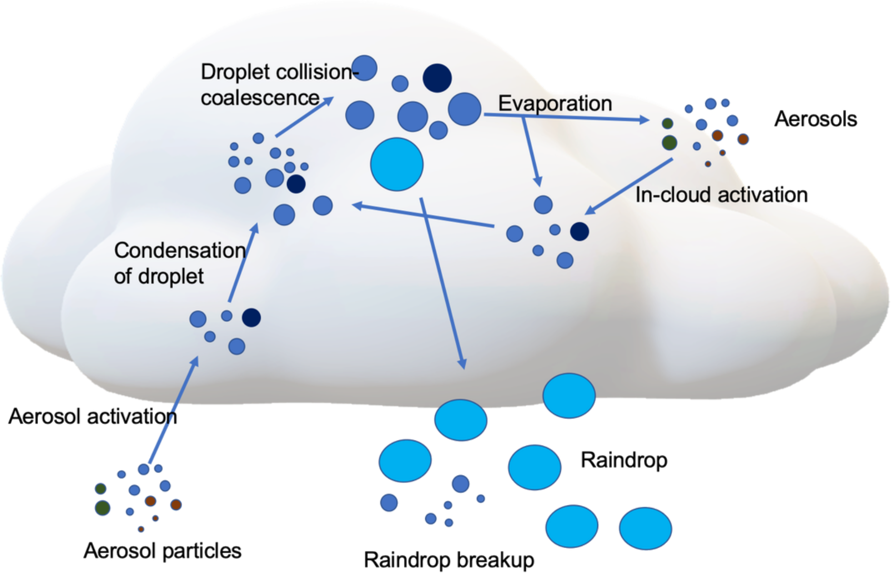
Book:
Warner, “Numerical weather and climate prediction”, 2011 → *W2011*
Stensrud, “Parameterization schemes: keys to understanding numerical weather prediction models”, 2007

1. Parameterization

What is a parameterization?

Some processes active in the atm are either:

- Happening at scales too small for the model resolution.
- The equations describing them are too complex to be properly resolved at reasonable cost.
- Not sufficiently understood to have equations properly describing them.



https://sisichenclouds.weebly.com/research.html

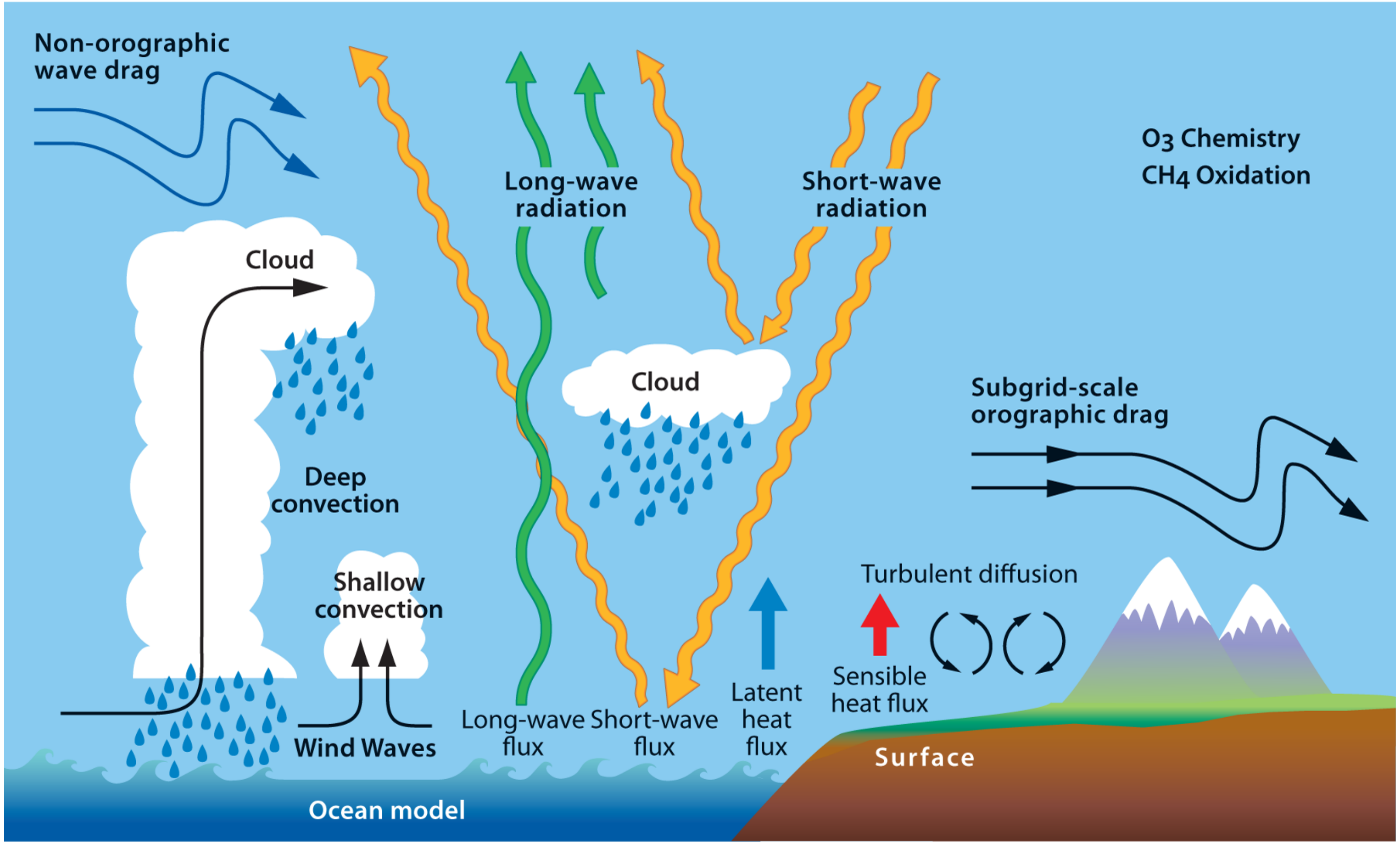
Those processes must be parameterized → linked to variables explicitly resolved by the model

1. Parameterization

What processes need to be parameterized in an atm model?

Atm processes:
Microphysics, turbulence / boundary layer, convection, radiation...

Surface processes:
All surf-atm water and energy fluxes, orography...



https://www.ecmwf.int/en/research/modelling-and-prediction/atmospheric-physics

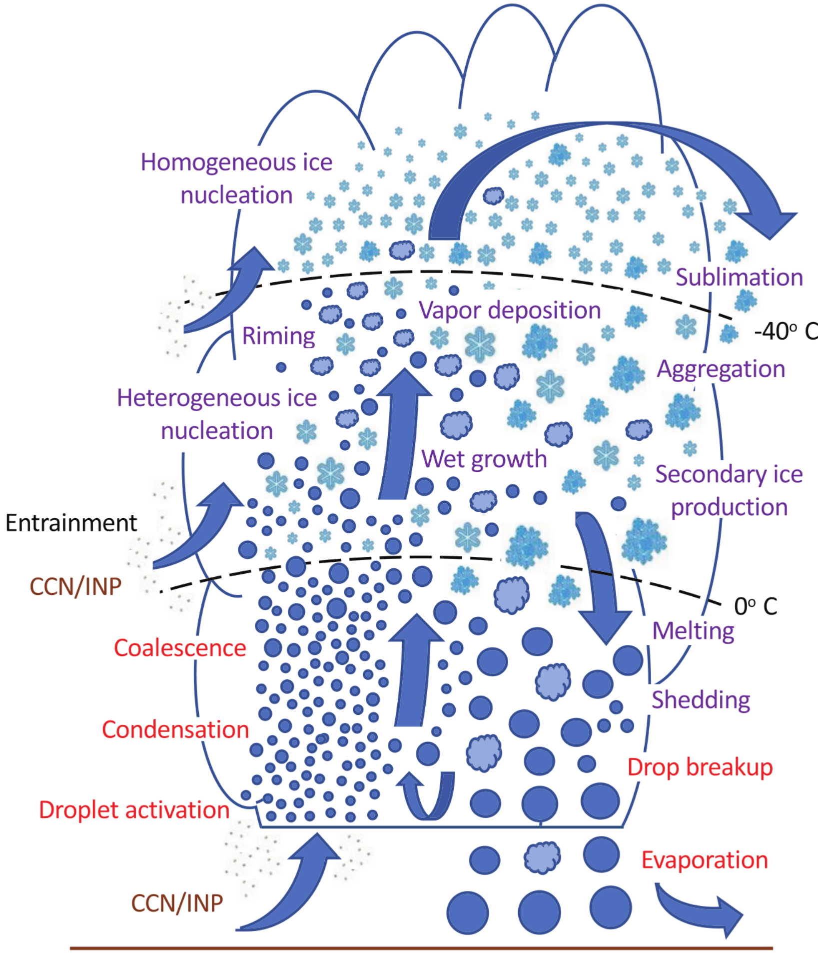
2. Parameterization of atm processes

a. Cloud and precipitation processes

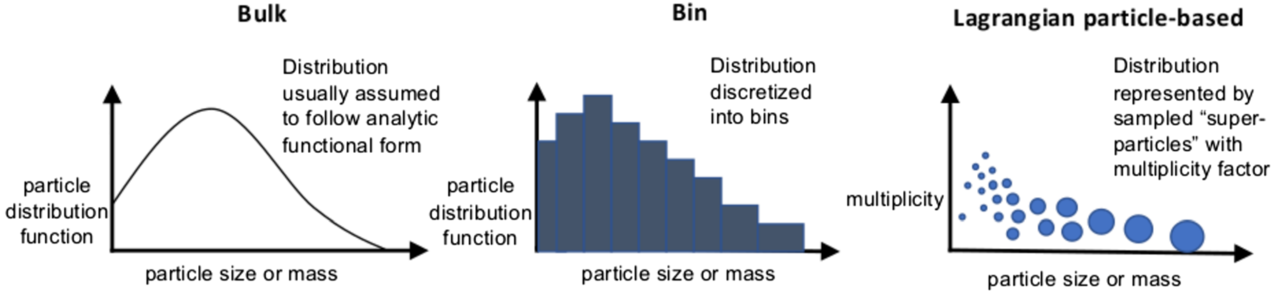
Cloud and precipitation microphysics is crucial to properly describe the phase changes of water

But takes place at scales << model resolution
→ microphysics parameterization

“Microphysics parameterization schemes in atm models attempt to represent the behavior of cloud and precipitation particle populations and their effects on weather and climate.” Morrison 2020.



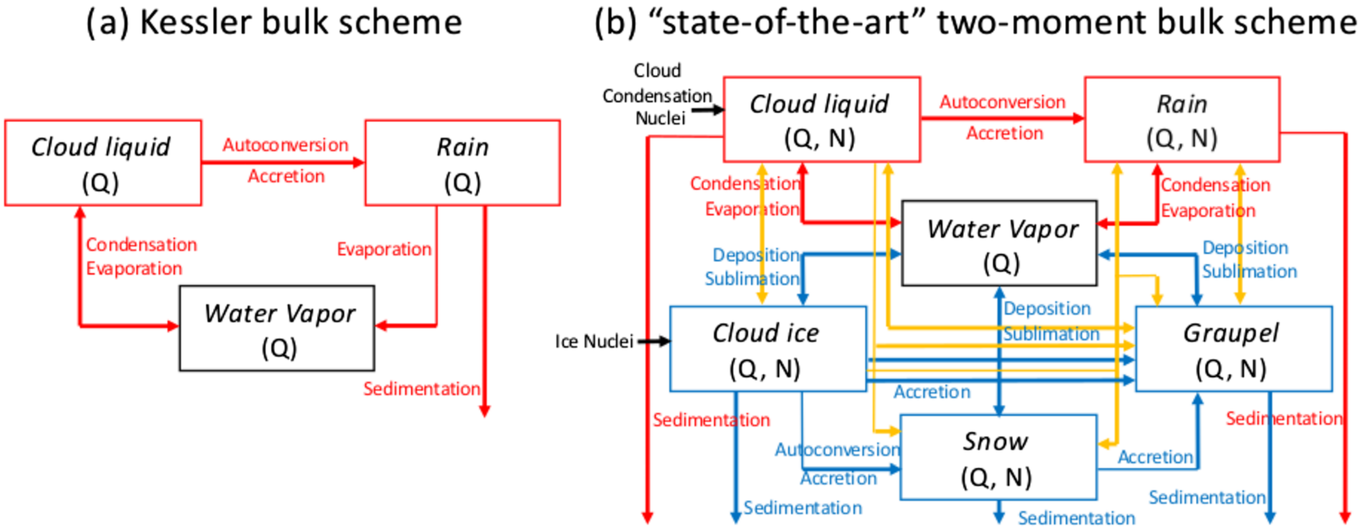
3 main types: bulk, binned, Lagrangian



Morrison JAMES 2020

2. Parameterization of atm processes

Typical schemes



Morrison JAMES 2020

The exchanges between those boxes can be described by PDEs:

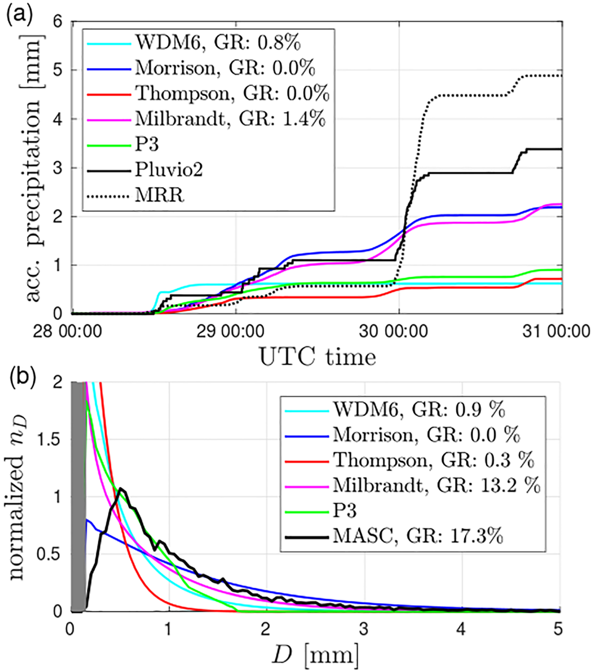
$$\frac{\partial q_s}{\partial t} = -u_i \frac{\partial q_s}{\partial x_i} - \frac{1}{\rho_0} \frac{\partial}{\partial x_i} \overline{u_i' q_s'} - V_{ts} \frac{\partial q_s}{\partial z} - S_\alpha$$

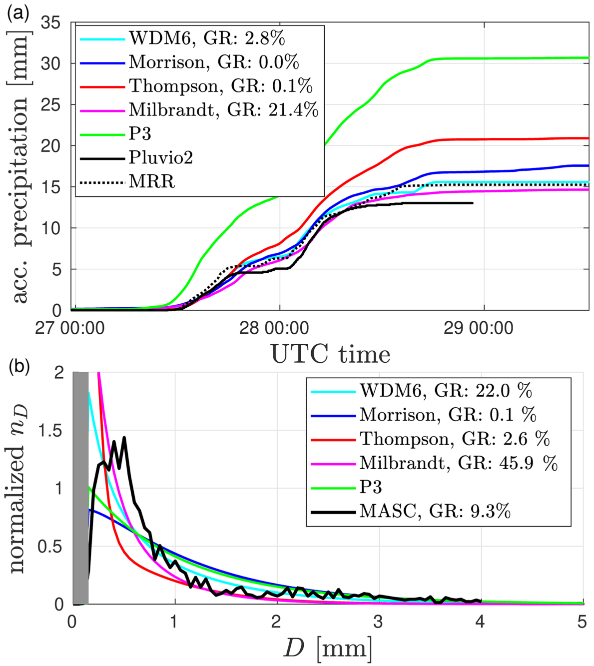
q_s	water species (and aerosol more generally)
u_i	velocity component (Cartesian)
V_{ts}	terminal vel. (significant for rain and snow)
S_α	source (and sink) terms, process specific

Microphysics parameterizations in those terms S_α: evolution of population of particles

Examples

Evaluation of snowfall simulated by WRF and different microphysical schemes at DDU





Vignon JGR 2019

Microphysical parameterizations/schemes have a large impact!

2. Parameterization of atm processes

b. Turbulence in boundary layer

Two main sources of turbulence in the BL:

1. Buoyancy/convection (mostly during daytime)

2. Wind shear (main/only source during night time)

These turbulence sources shape the BL and the fluxes within and outside the BL.

Laminar sublayer: thin layer just at the interface with ground, laminar because 0-velocity boundary.

Surface layer: 50 – 100 m above ground, in which turbulent fluxes are ~constant (with height)

Mixed layer: 100 – 1000s m, mixed by convection.

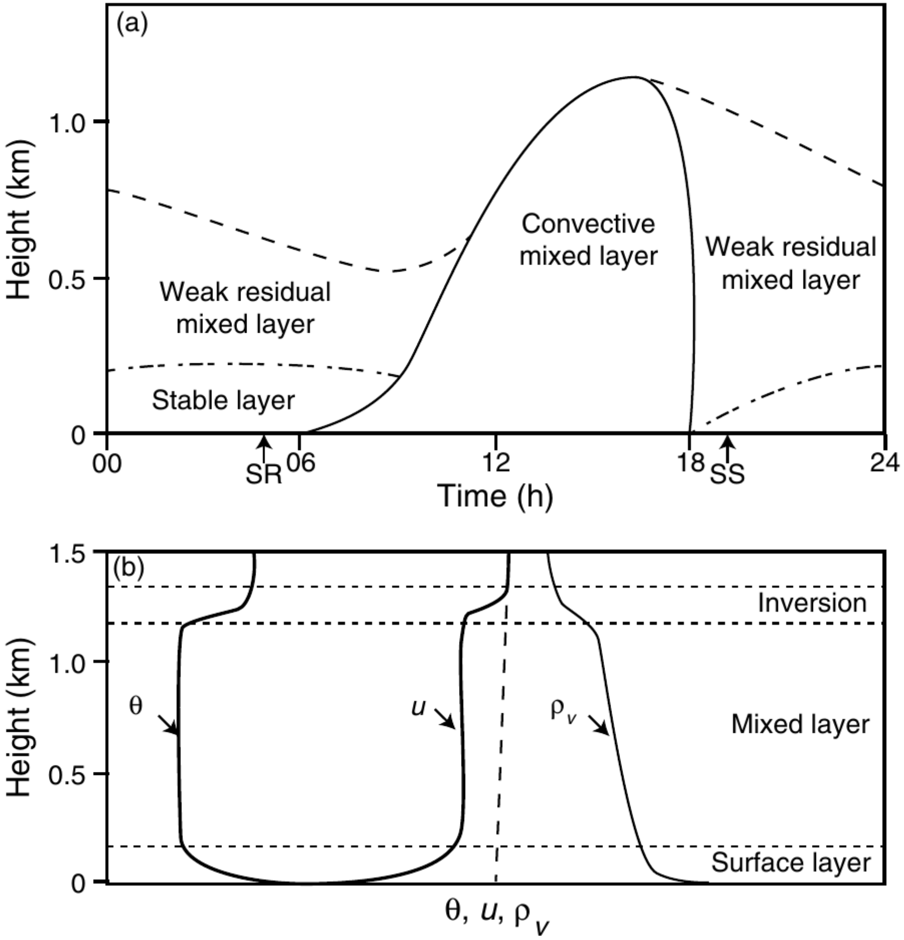


Fig. 4.12 Schematics of (a) the typical diurnal variation of the boundary-layer structure and (b) typical vertical profiles within the daytime boundary layer of potential temperature (θ), horizontal wind speed (u), and water-vapor density (ρ_v). The times of sunrise (SR) and sunset (SS) are shown in (a). The dashed line in (b) represents the wind speed that would exist without friction between the atmosphere and ground. Adapted from Oke (1987).

W2011, fig4.12

Turbulence / boundary layer parameterization closure

When Reynolds averaging is applied to Navier–Stokes equations → there are more unknowns than equations.

Closure = approximations of some unknowns (as functions of prognostic variables)

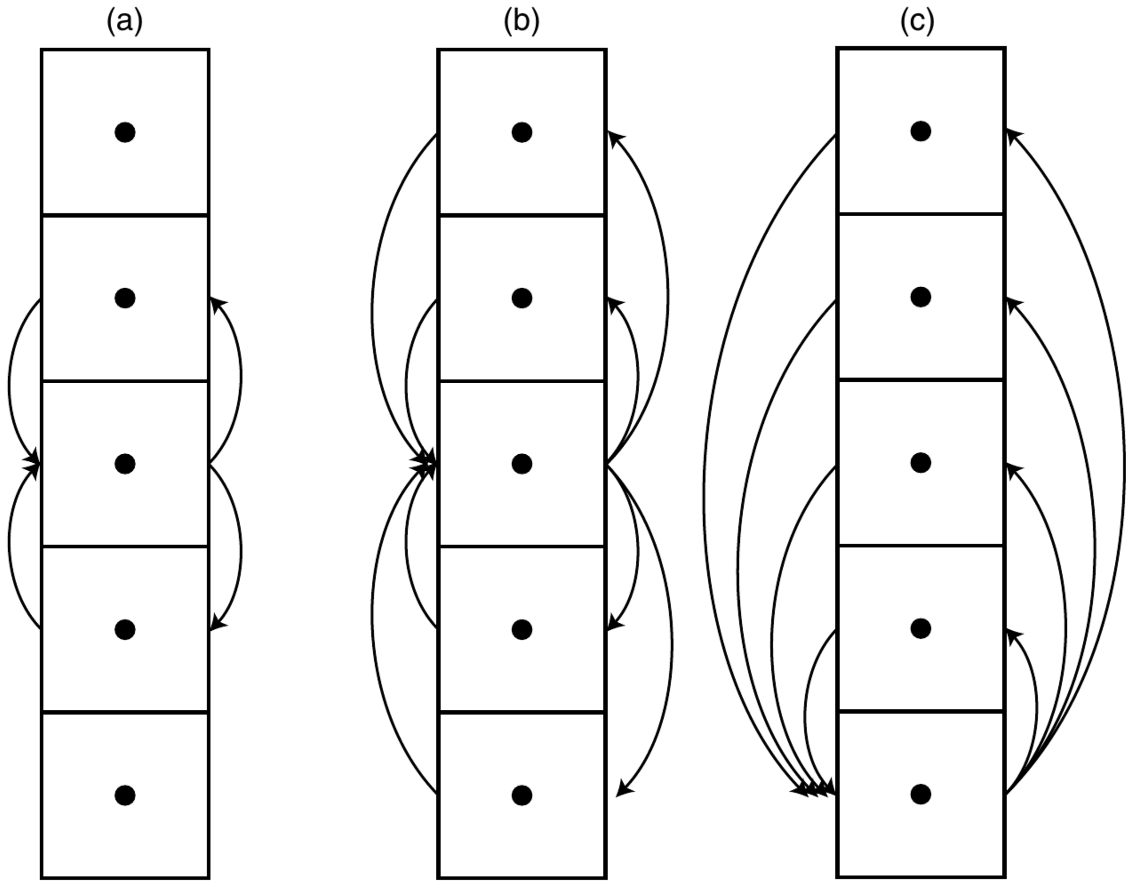
Local closure schemes:

- Unknown quantity parameterized by values and/or gradients of known quantities at the same point.
- Ex: K-theory closure encompassing the 1st-order, TKE and K-profiles schemes.
- As turbulent fluxes are defined by local conditions, work best for small eddies locally generated.

Non-local closure schemes:

- Unknown quantity parameterized by values and/or gradients of known quantities at many points in space.
- Ex: non-local K-profile, eddy-diffusion mass-flux (EDMF) parameterizations
- More adapted when eddies are large (~size of BL) so not driven by local conditions.

Turbulence / boundary layer parameterization closure



W2011, fig4.15

Questions

1. What is a parameterization?

2. What do the microphysics parameterizations describe?

3. What is the difference between local and non-local closure for turbulence parameterizations?

c. Radiation

- Sun radiation is the external source of energy of the Earth system, driving atm circulation (global circulation, tropical and extra tropical cyclones…) and surface energy budget.

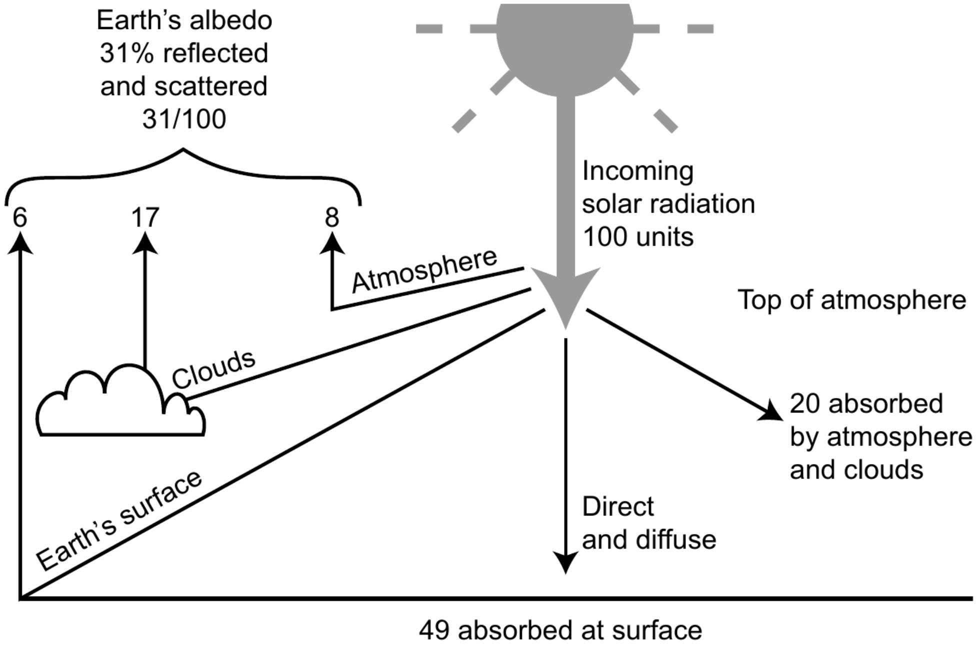
- A small change in mean radiation arriving on the Earth may have large impacts.

- But radiation is computationally expensive to compute.

→ Radiation parameterizations are needed to (rapidly) derive accurate radiative fluxes everywhere in the atmosphere.

Energy exchanges - 1

Typical relative radiative budget in the atmosphere (global annual average)



W2011, fig4.17

Of 100% incoming solar radiation at TOA

- 31% reflected back to space (clouds, atm gas/aerosols, Earth's surface).
- 20% absorbed by atm (gas/aerosols, clouds).
- 49% absorbed by Earth's surface (land-surface model).

Session 5 2. Parameterization of atm processes

Energy exchanges - 2

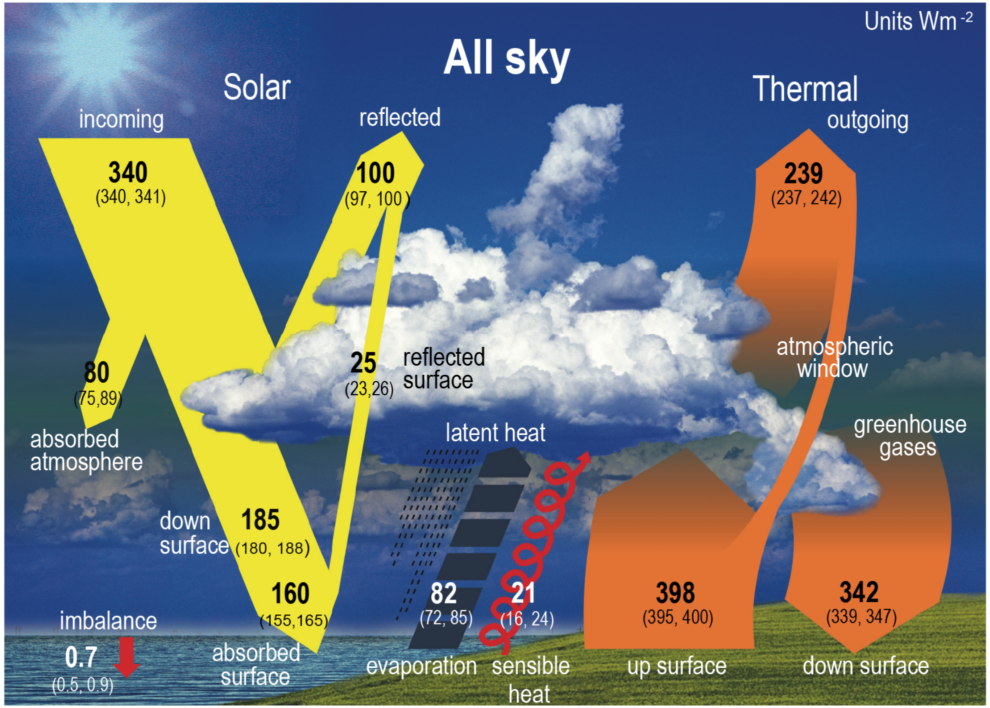
Typical absolute radiative budget
(global annual average)

Top of the atm incoming radiation ~ 340 Wm^{-2}

Balance at surface: received = emitted

Atm processes: absorption and reflection from clouds, aerosols, gas + water phase changes

Surface processes: absorption, reflection and evaporation by land/ocean.



IPCC AR6, fig.7.2

2. Parameterization of atm processes

Heading rate

The temperature of layer of atm will evolve according to $\frac{\partial T}{\partial t} = \frac{1}{\rho c_P} \frac{\partial}{\partial z} (F_D - F_U)$

c_P specific heat of air [J K^{-1} kg^{-1}]

F_D downward radiative flux [W m^{-2}]

F_U upward radiative flux [W m^{-2}]

In models, those fluxes must be computed with enough accuracy and efficiency.

Radiation parameterization = parameterization of F_D and F_U

Challenges:

- Radiation can influence atm dynamics in multiple ways → difficult to select one set of approximations valid for all situations.
- Complex non-linear coupled interactions between atm dynamics, radiation, latent and sensible heat (ex: diabatic heating) → difficult to approximate.

Radiation in the atmosphere

Sun (Earth's surface) ~black body at 6000(300) K→ radiation described by Stefan-Boltzmann and Planck's laws

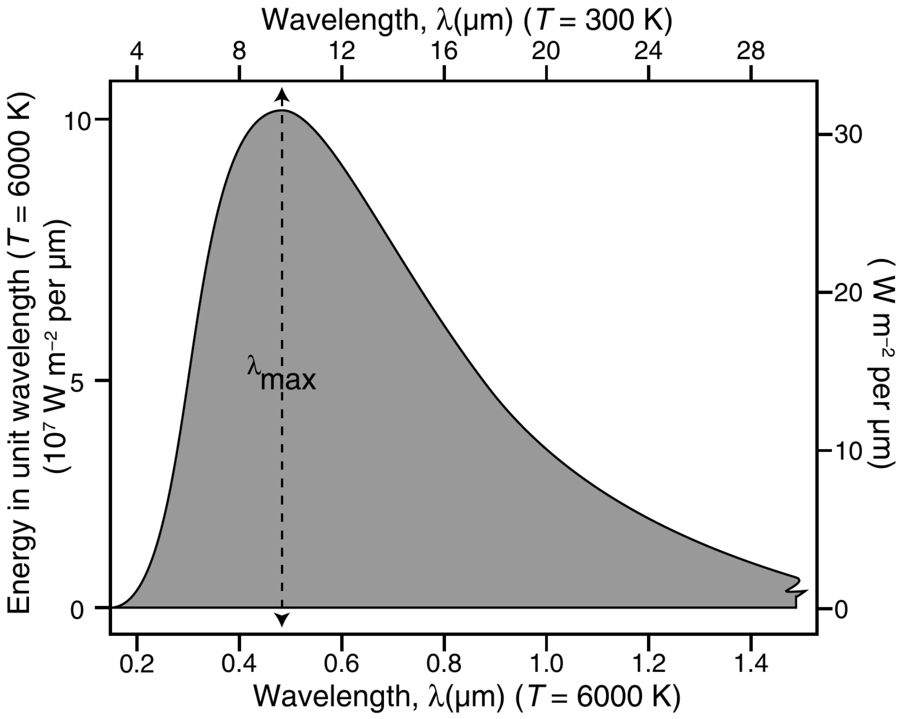


Fig. 4.19 The spectral distribution of radiant energy emitted from a black body at (a) 6000 K, left vertical and lower horizontal axes and (b) 300 K, right vertical and upper horizontal axes. The λ_{max} is the wavelength at which the energy output per unit wavelength is a maximum. Approximately 10% of the energy is emitted at wavelengths longer than those shown. Adapted from Monteith and Unsworth (1990).

W2011, fig4.19

- Most solar radiation is in UV, visible and near IR
- Most Earth emitted radiation is in thermal IR

→ Shortwave radiation in [0.15 , 3 μm]

→ Longwave radiation in [3, 100 μm]

Parameterization of longwave fluxes - 1

Challenge: in the longwave radiation, the atmosphere both emits and absorbs simultaneously.

Empirical approaches (only at ground surface)

Unsworth and Monthey (1975): $F_{LD} = c + d\sigma T_a^4$

c -119 +/- 16 [W m^{-2}]
d 1.06 +/- 0.04 [-]
σ Stefan-Boltzmann constant
T_a air temperature at 2 m [K]

Anthes (1987): $F_{Lnet} = \epsilon_g \epsilon_a \sigma T_a^4 - \epsilon_g \sigma T_g^4$

$$\epsilon_a = 0.725 + 0.17 \log_{10} w_p$$

ϵ_g ground lw emissivity [-]
ϵ_a air (+40 hPa) lw emissivity [-]
T_g ground surface temperature [K]
w_p total atm precipitable water [cm]

Pros: easy and inexpensive to compute.
Cons: fluxes only at ground level + no interactions within the atm...

Parameterization of longwave fluxes - 2

Radiative transfer equation

$$F_D(z) = \int_0^{\infty}\int_z^{\infty} \pi B_\nu(z')\frac{d\tau_\nu^f}{dz'}(z,z')\,dz'd\nu$$

B_ν	Planck's function
τ_ν^f	diffuse transmission function
ν	frequency [Hz]

$$F_U(z) = \int_0^{\infty} B_\nu(z=0)\tau_\nu^f(z,z=0)\,d\nu + \int_0^{\infty}\int_0^{z} \pi B_\nu(z')\frac{d\tau_\nu^f}{dz'}(z,z')\,dz'd\nu$$

τ_ν^f is a (integral) function of absorption coef and concentration in atm gas along path.

Parameterizations to simplify these equations (transmittivity function, absorption lines...)
Ex: two-stream, narrow-band, wide-band methods.

Pros: more accurate + longwave radiative fluxes at all altitudes.
Cons: more computationally expensive...

Parameterization of shortwave fluxes - 1

No emission at sw in atm, but absorption and scattering due to gas, aerosol, clouds and precip

Empirical approaches (fluxes at ground surface)

F_{SD} absorbed by ground (Anthes, 1987): $H_s = S_0(1-\alpha)\tau\cos\zeta$

S_0	solar constant
α	surface albedo [-]
τ	sw transmissivity [-]
ζ	solar zenith angle [rad]

Transmissivity τ from Benjamin (1978), taking into account multiple scattering.

Pros: easy and inexpensive to compute.
Cons: fluxes only at ground level + no interactions within the atm...

Parameterization of shortwave fluxes - 2

Radiative equation for shortwaves (i.e. < 3 µm) must include:

- Absorption (similar to longwave) → function of transmissivity
- Scattering: single + multiple.
- No emission from atm at shortwave (contrarily to longwave).
- Different methods have been developed, based on diff approx of diff terms of the radiative equation: two-stream, Eddington, Delta-Eddington methods.

Pros: more accurate + shortwave radiative fluxes at all altitudes.
Cons: more computationally expensive...

d. Convection

Convection, deep or shallow, has important effects on the atm:
- Upward heat transport, moisture redistribution + precipitation (→ stabilization of the atm)
- Outflow jets and mid-level vortices → it influences larger scale atm circulation (if large enough convective areas).

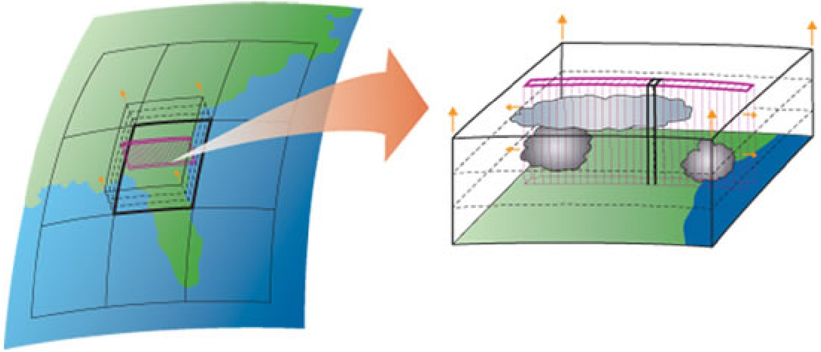
But typical convective scales are from a few 100s to 1000s of m, so well below typical grid increments in atm model (in particular global ones).

→ parameterization of subgrid convection is needed.

Tasks of the convective parameterization:
- What triggers convection in a grid column?
- How convection, when present, modifies the vertical structure in the grid column?
- How convection and grid-scale dynamics affect each other?

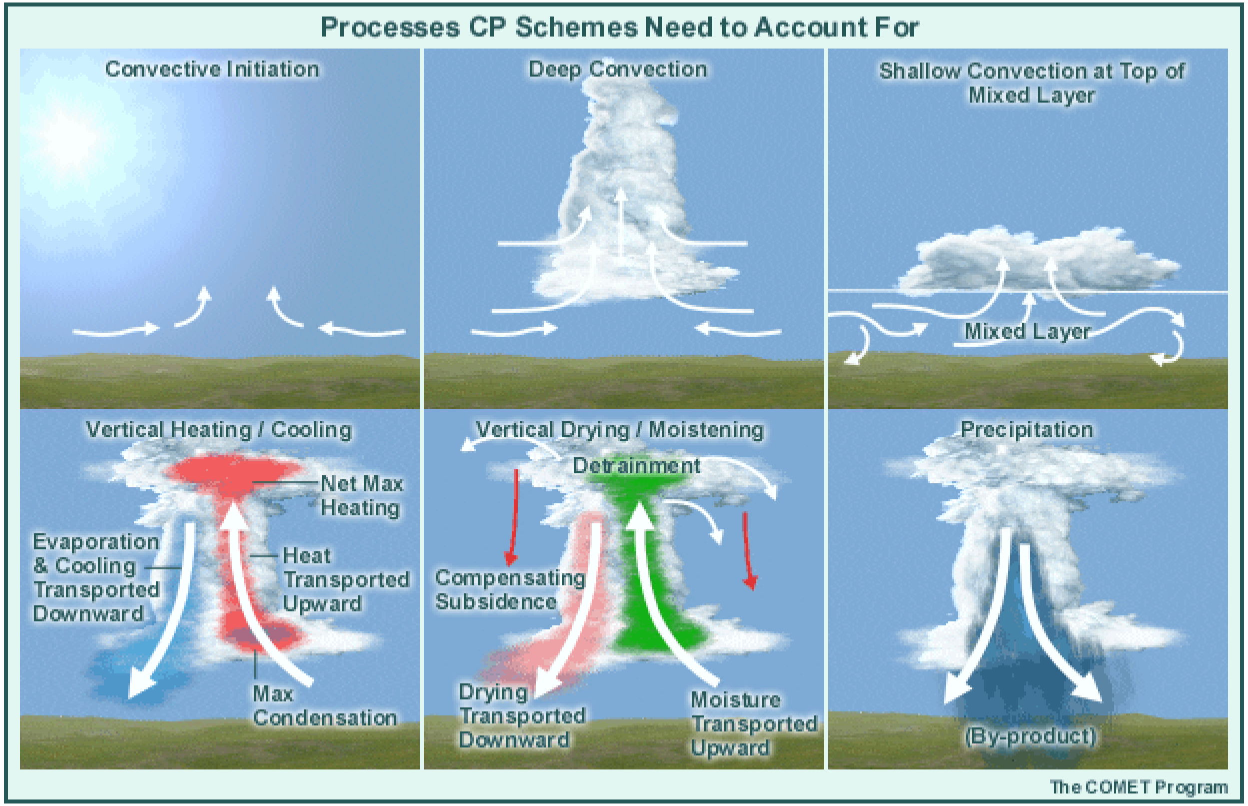
Convection parameterizations

Principle



http://www.jeremymcgibbon.com/

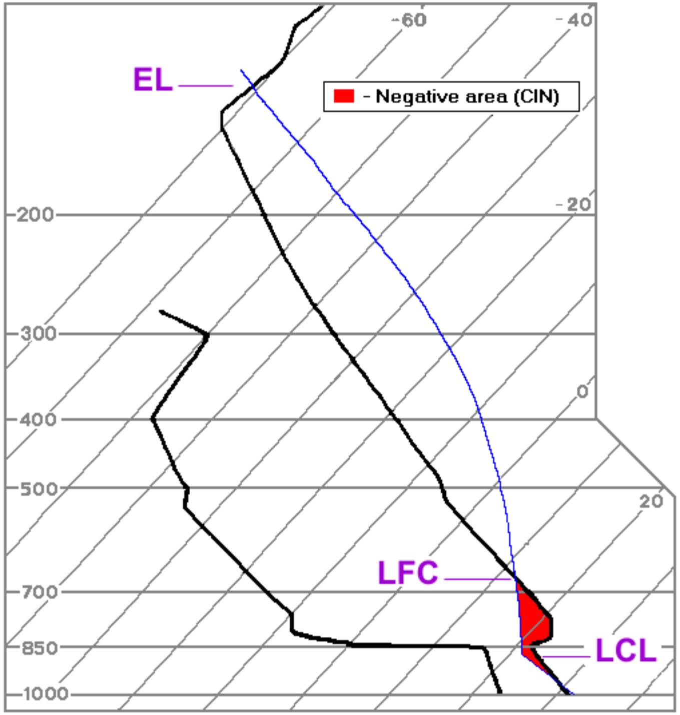
Tasks



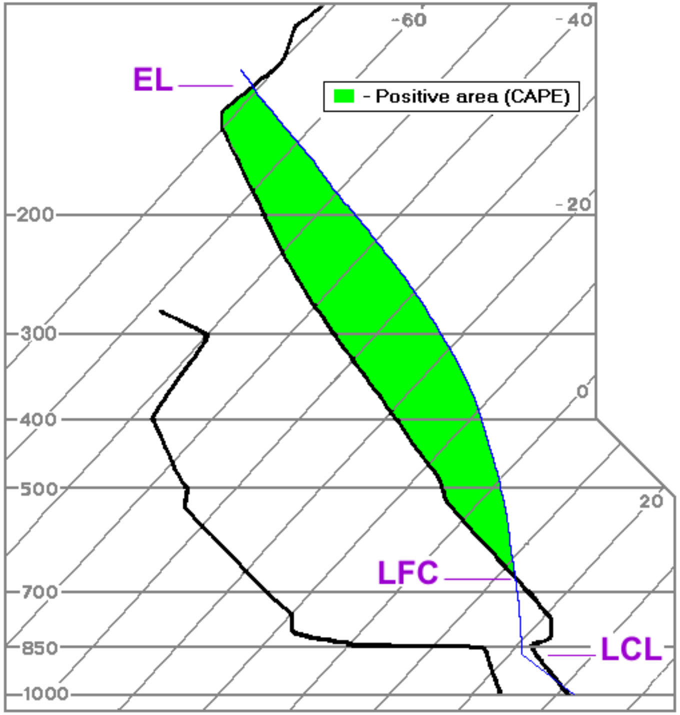
http://stream1.cmatc.cn/pub/comet/numerical/HowModelsProducePrecipitationandCloudsversion2/comet/nwp/model_precipandclouds/navmenu.php_tab_1_page_3.1.0.htm

CIN and CAPE

CIN = Convection inhibition



CAPE = Convective available potential energy



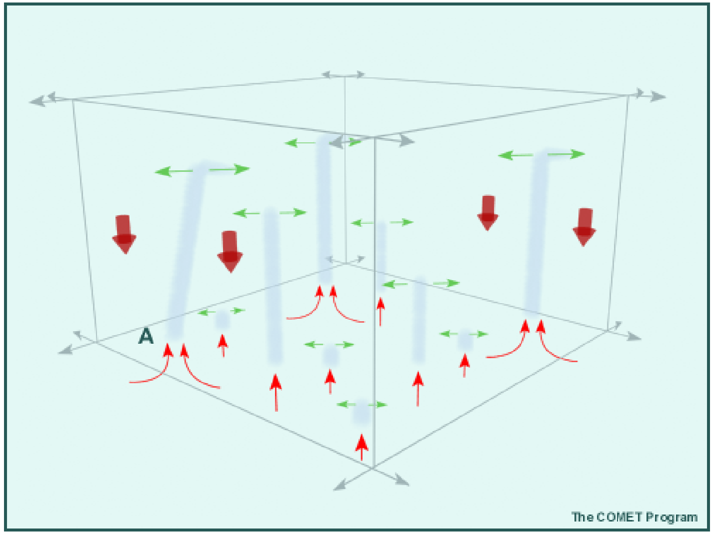
https://learningweather.psu.edu/node/87

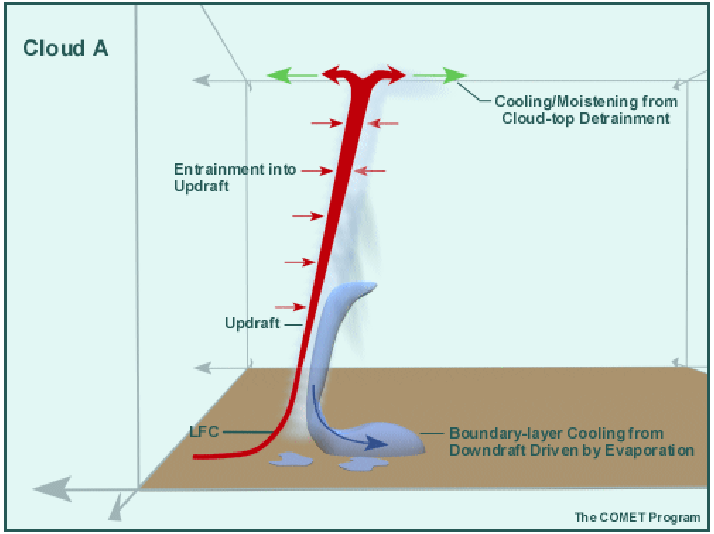
Many parameterizations are based on CAPE and CIN.

Examples of convective parameterization schemes - 1

Various approaches and parameterizations have been proposed, we will only see 2...

Arakawa-Schubert (1974): effects of moisture detrainment from convective clouds, warming from environmental subsidence, and convective stabilization in balance with the large-scale destabilization rate. Complex (and computationally expensive) scheme.



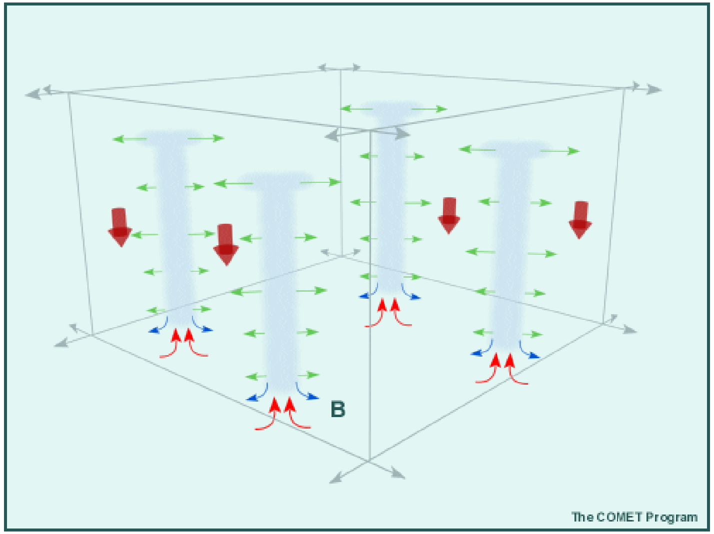


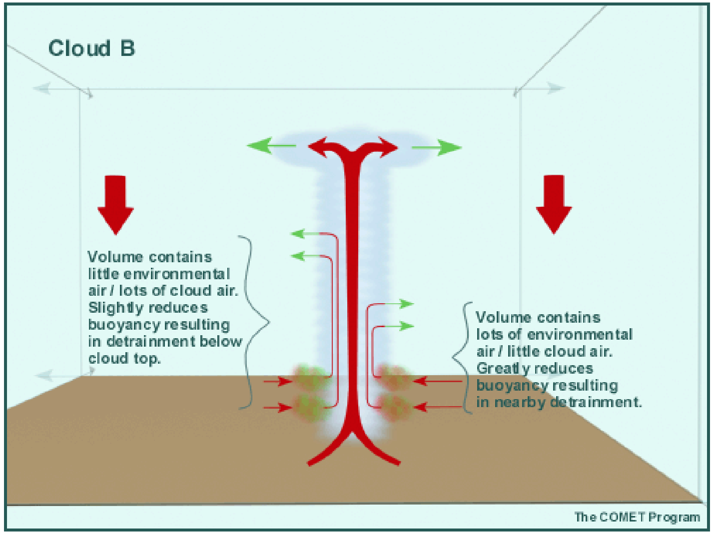
http://stream1.cmatc.cn/pub/comet/numerical/HowModelsProducePrecipitationandCloudsversion2/comet/nwp/model_precipandclouds/navmenu.php_tab_1_page_3.5.2.htm

Examples of convective parameterization schemes - 2

Kain-Fritsch (1993): complex scheme designed to rearrange mass in a column so that CAPE is consumed. Both low-level (LCL forcing) and deep-layer (CAPE) control.

Can be used in mesoscale models...





Volume contains little environmental air / lots of cloud air. Slightly reduces buoyancy resulting in detrainment below cloud top.

Volume contains lots of environmental air / little cloud air. Greatly reduces buoyancy resulting in nearby detrainment.

Limitations explained → http://stream1.cmatc.cn/pub/comet/numerical/HowModelsProducePrecipitationandCloudsversion2/comet/nwp/model_precipandclouds/navmenu.php_tab_1_page_3.6.2.htm

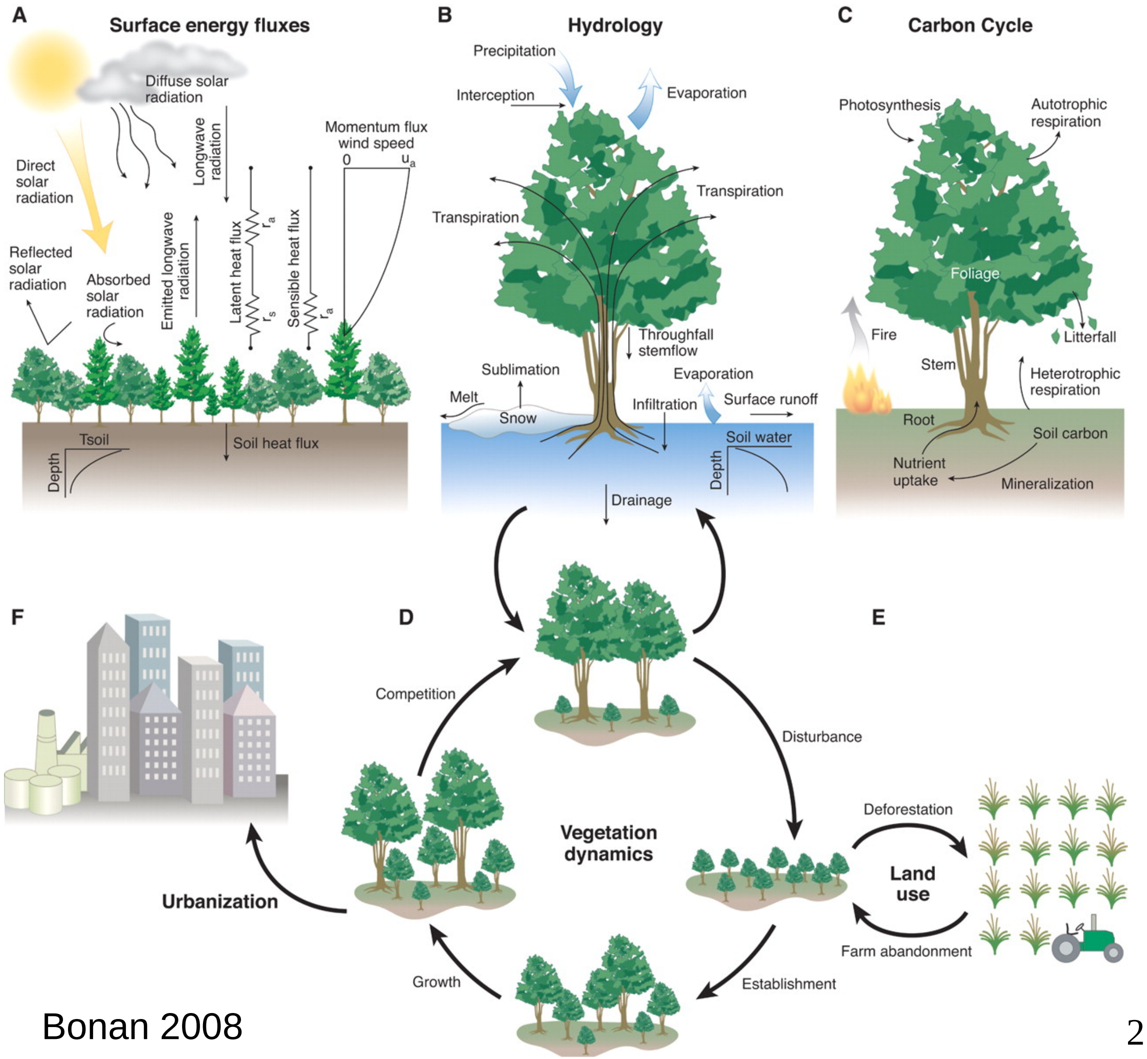
Session 5 3. Parameterization of surface processes

Land-surface processes

Processes driving fluxes of energy, water and carbon between land-surface and atm must be properly represented in the models.

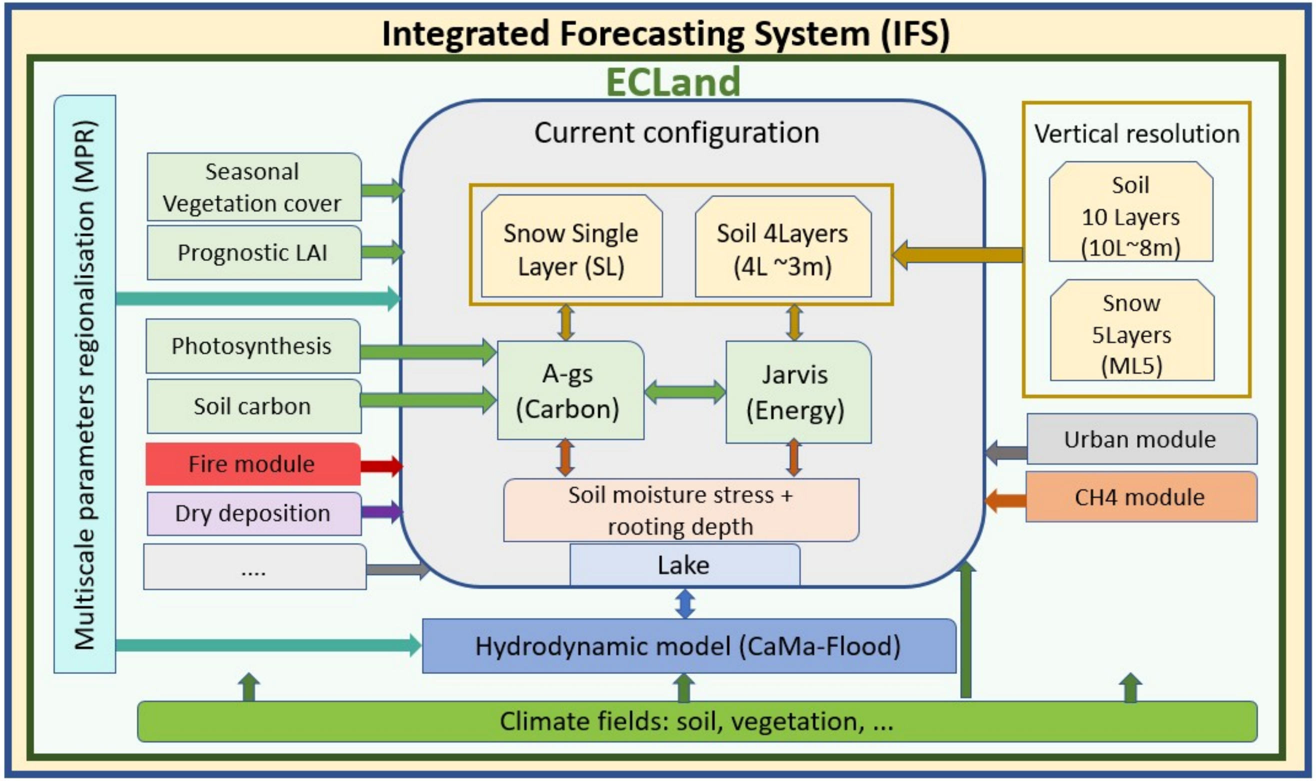
Complex non-linear problems + small-scale processes → parameterization

Depending on objectives, not all processes have to be represented.



Bonan 2008

Land-surface parameterization in IFS


Integrated Forecasting System (IFS)

ECLand

Multiscale parameters regionalisation (MPR)

Seasonal Vegetation cover

Prognostic LAI

Photosynthesis

Soil carbon

Fire module

Dry deposition

....

Current configuration

Snow Single Layer (SL)

Soil 4Layers (4L ~3m)

A-gs (Carbon)

Jarvis (Energy)

Soil moisture stress + rooting depth

Lake

Vertical resolution

Soil 10 Layers (10L~8m)

Snow 5Layers (ML5)

Urban module

CH4 module

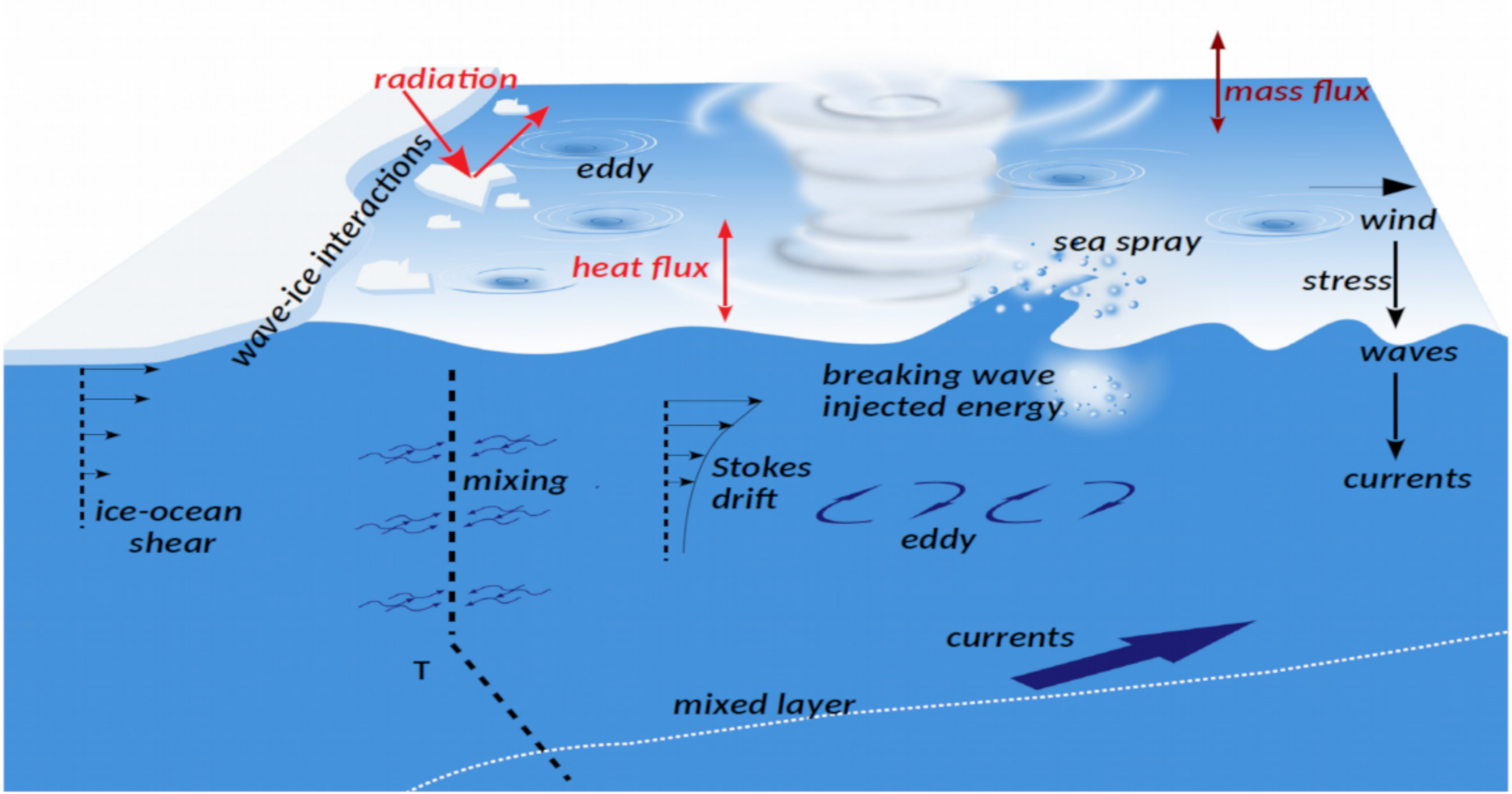
Hydrodynamic model (CaMa-Flood)

Climate fields: soil, vegetation, ...

Boussetta 2021

Ocean-surface processes

Similarly to land surface, fluxes of water and energy between ocean and atm must be accurate



https://www.mdpi.com/journal/jmse/special_issues/OWA_interaction

Parameterizations - summary

Overall message:

- Various parameterizations exist (for each “category”).
- Some more physical than others.
- Some more computationally costly than other.
- They all have their limitations and their selection depends on specific objectives.
- With decreasing grid increment size, convective parameterization is becoming less critical (because convection is resolved directly).

Questions

1. What are the fluxes to be estimated using a radiation parameterization?

2. Do all models need to parameterize convection?

3. Why does an atmospheric model need parameterizations for surface processes?

What are ensemble methods?

Various sources of error in numerical atm models: initial/boundary conditions, land/water surface conditions, numerical approximations and parameterizations.

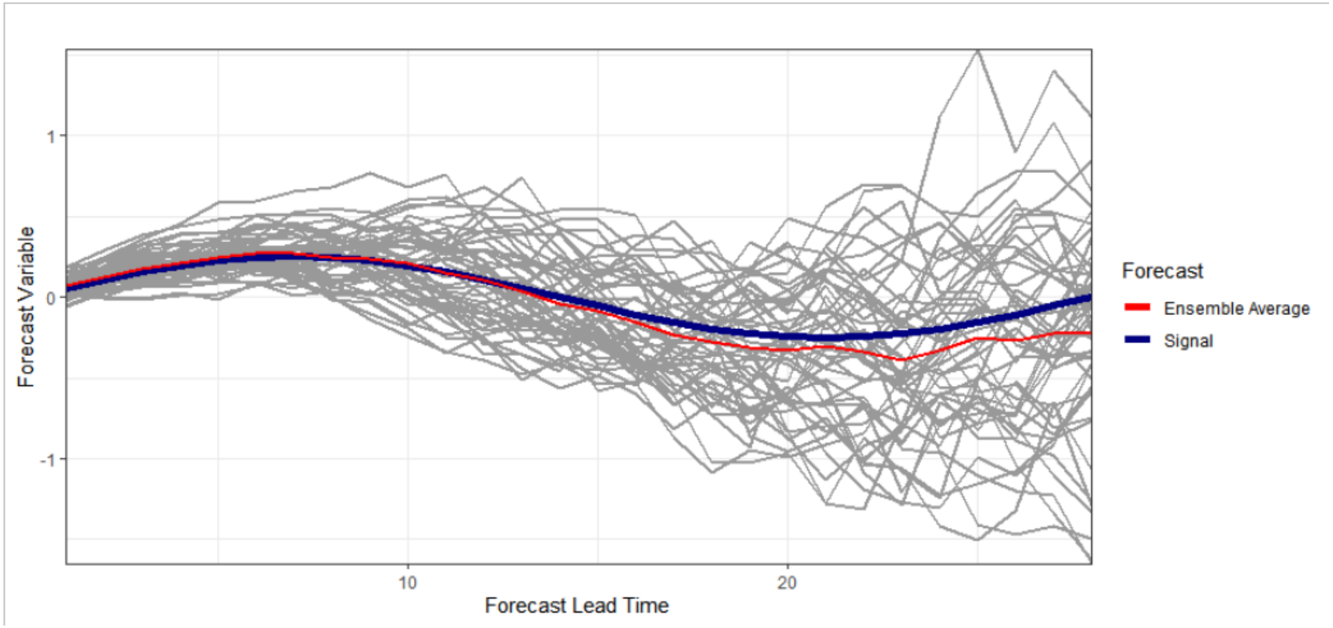
Ensemble methods:
- The goal is to generate an ensemble of output to qualify/quantify this uncertainty.
- Sample/explore the uncertainty space associated with the modelling process.

Ensemble of forecasts is more useful than a single one:
- Mean of ensemble of members more accurate than a single member.
- Spread between members is an indication of the uncertainty.
- PDF (if computed) provides info about extremes.
- Probabilistic info is useful for decision-support system.

Ensemble mean - 1

Ensemble mean = mean over all members of the ensemble.

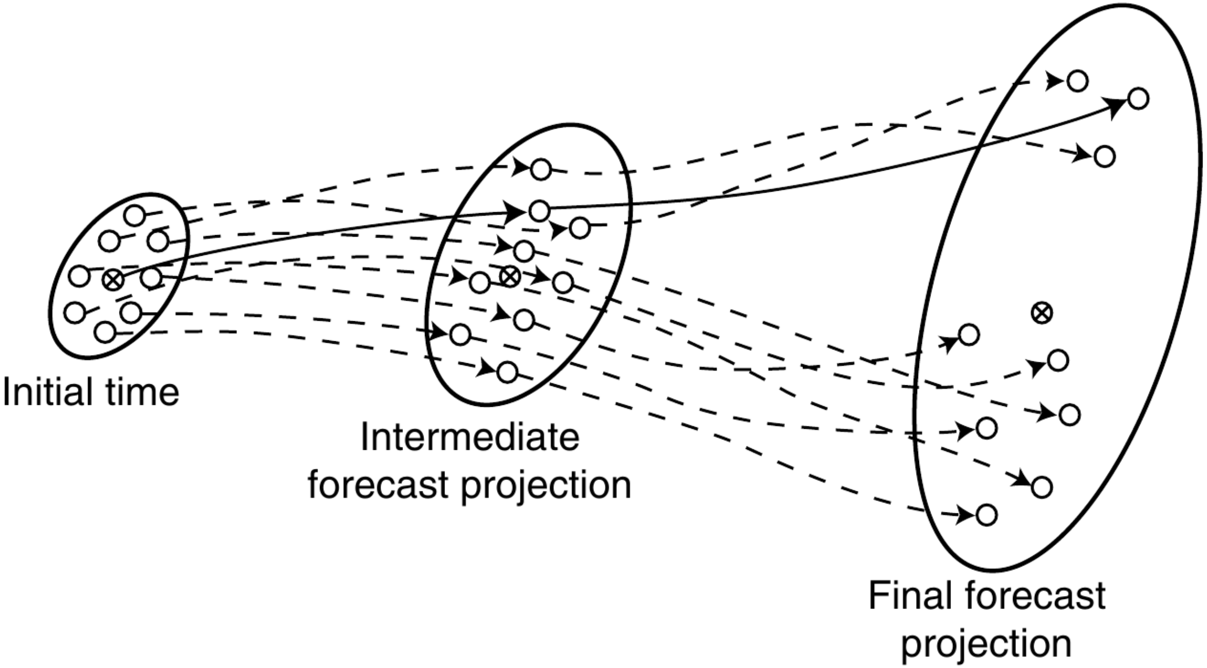
More accurate because filtering out random fluctuations while keeping features present in many individual members.



https://www.worldclimateservice.com/2021/10/12/difference-between-deterministic-and-ensemble-forecasts/

Ensemble mean - 2

But results in smoother fields at longer lead times and may not be representative if changes in meteorological regime.

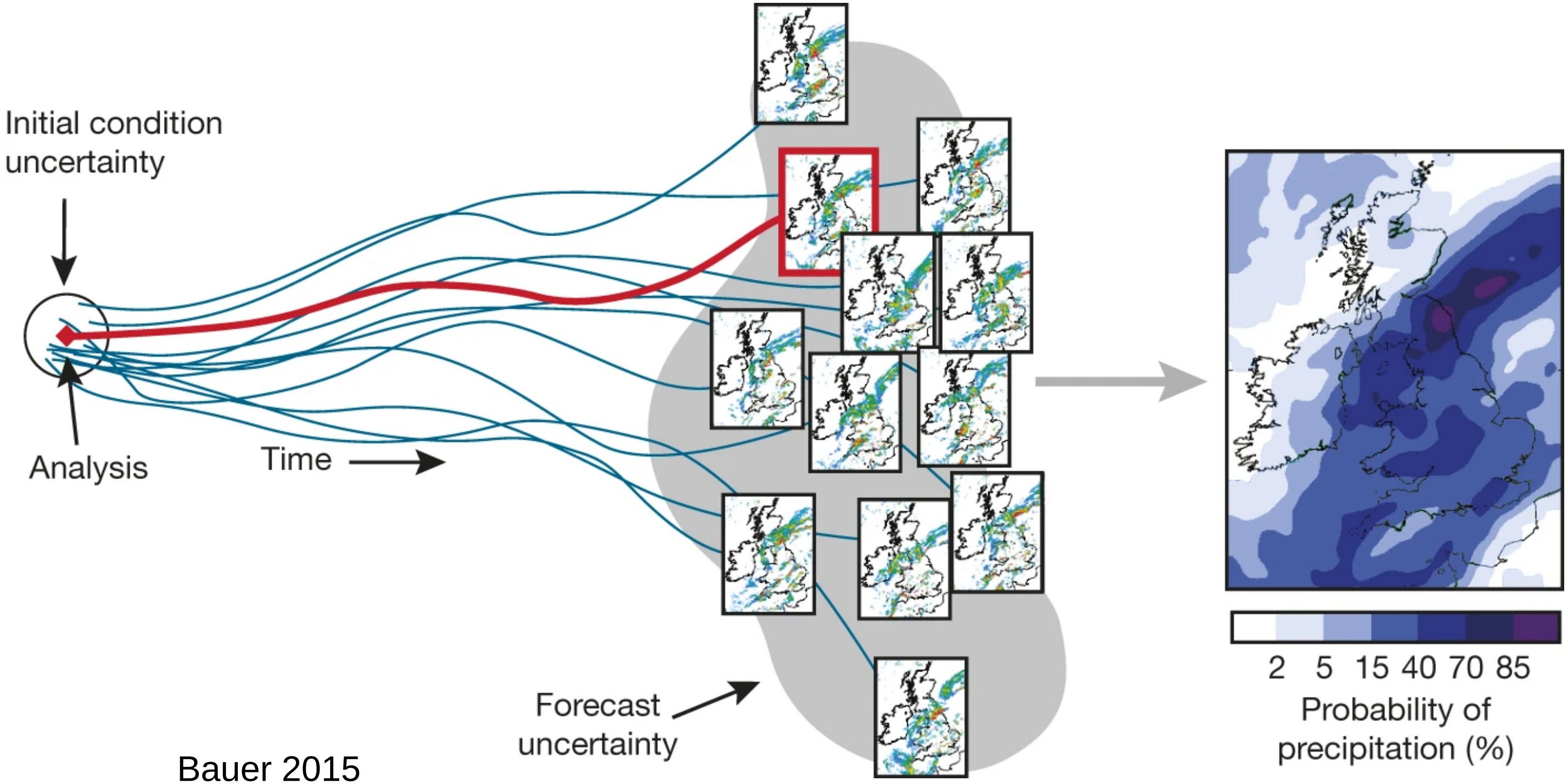


W2011, fig7.2

4. Ensemble methods

Ensemble spread

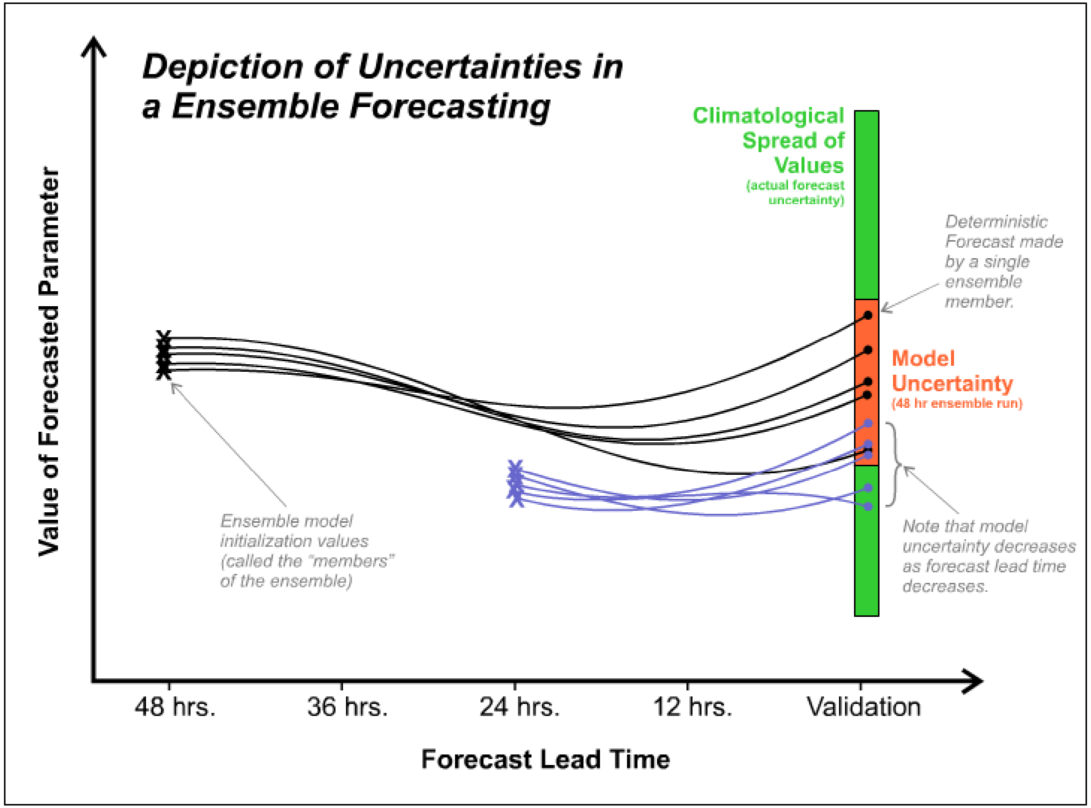
Spread of the members is indicative of the uncertainty associated with the forecast.



Bauer 2015

Ensemble spread

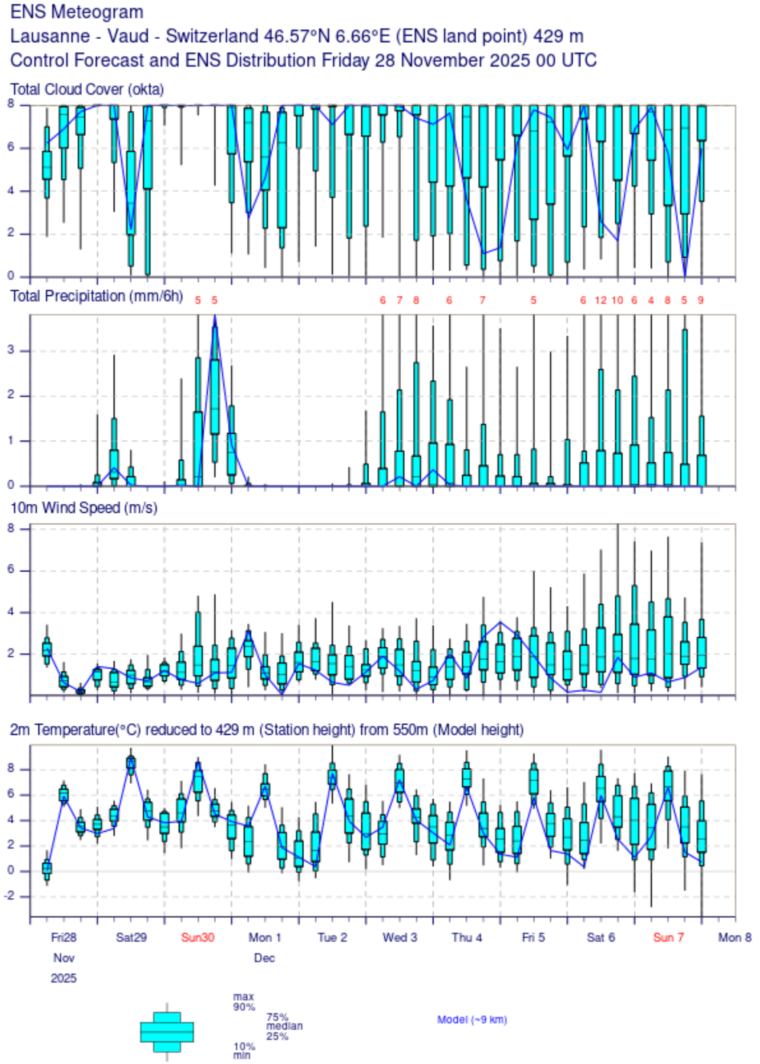
But the ensemble spread may underestimate this uncertainty...



https://www.e-education.psu.edu/meteo810/content/l4_p6.html

4. Ensemble methods

Ex of prediction based on ensembles



https://charts.ecmwf.int/products/opencharts_meteogram?base_time=202212020000&epsgram=classical_10d&lat=46.516&lon=6.63282&station_name=Lausanne

Questions

1. What is an ensemble prediction?

2. What feature of the ensemble can be used to derive information about the uncertainty?

Summary

Numerical modelling - 2

1. Parameterizations → To represent processes too small scales, too costly, not well known
   → Microphysics: evolution of hydrometeor populations of diff. types.
   → Turbulence: boundary layer turbulent eddies and fluxes.
   → Radiation: lw and sw up and down fluxes to compute heating rate.
   → Convection: subgrid convective circulation + precipitation.
   → Surface: land and ocean surface processes for fluxes from/to atm.

2. Ensemble meth. → To represent the various sources of uncertainty in model output.
   → To improve accuracy of forecast and quantify uncertainty.
   → May not be so accurate at long lead times...