Prediction of clouds and precipitation in atmospheric models

Cumulus congestus. Sønderjylland, 2002. Foto: Flemming Byg.

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outline

- Basic definitions and characteristics of clouds and precipitation
- Scales of occurrence for clouds and precipitation
- Some basics about the atmospheric cloud formation process
- Basic modelling concepts
- Challenges related to modelling including aerosols
- Clouds in different types of models
- Known challenges and deficiences related to clouds and precipitation in NWP-models
- International research (the GCSS collaboration)
- Conclusions and outlook

Definition of atmospheric cloud and precipitation

1) **CLOUD**

→**A cloud is a volume of atmospheric air containing a certain amount of condensate as water or ice**

alternatively

→**an atmospheric air mass with visible water or ice particles**

2) **PRECIPITATION**

→ **Precipitation represents a detectable flux of falling water species (rain drops, snow particles, hail, graupel, sleet) formed by microphysical processes, e.g. vapor diffusion, collission and/or coalescense of cloud drops, freezing and melting.**

Absolute amount of water substance

Amount of condensed matter $q_c \in [10^{-5}, 10^{-3}]\mathrm{Kg} \cdot \mathrm{Kg}^{-1}$

Droplet concentration 100 – 1000 drops cm^{-3}

Droplet size (typical) $2\mu\mathrm{m} - 20\mu\mathrm{m}$

Cloud mass (typical) 0.1% of total mass of air

Volume of cloud drops (typically) one part out of 10^6

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Scales of occurrence (clouds)

→ horizontal dimension of order 100 m (e.g. for shallow cumulus clouds) to 100 km for large stratiform cloud sheets.

→ Cloud variables, e.g. cloud water inside clouds, often exhibit considrable variability inside clouds down to the smallest scales ~100m. (See, e.g. for cumulus clouds Rogers and Yau, 1996, - for stratocumulus in the context of ASTEX , Albrecht et al., 1995)

→ Time scales: The shortest scales are associatet with individual shallow cumulus clouds (minutes) to large stratiform cloud sheets (many hours)

Scales of occurrence (precipitation-1)

Many studies, e.g. using data from weather radar and rain gauges have show that precipitation exhibits very significant small structures in space and time , e.g.

→ Orographical influence, not only from high mountains, but also for small hills with a height of less than 50 m, e.g. Tor Bergeron in Uppsala report No. 6 (1968): ”Unexpectedly , small orographic features are reflected in the fine structure of rainfall distribution”. – Only a 20m-30m plateau is needed in the Upsala field to produce approximately a 20 % precipitation increase.

Mesoscale structure of rain has been noted by many, e.g. Austin and Houze (J. Appl.Meteor., 925-935 ,1972):

→ Different scales can be identified, from a ’synoptic scale’, (100km * 100km) down to mesoscales (3km *3km). The associated time scales vary from typically 24 hours to 0.5 hours, respectively.

Scales of occurrence (precipitation-2)

→ The associated peak precipitation rate is increased as the spatial scale is reduced.

→ Heavy rain is observed in both stratiform and in showery conditions.

→ Very fine scale structures have also been measured using rain gauges, e.g. in Denmark . A variability of intensity, using 9 rain gauges of the same design, was detected over a 500m*500m flat field (could be up to 20 % - 30 %)

The process of cloud formation in the atmosphere:

Not trivial at all !

The details of droplet or ice crystal formation very complex:

In the atmosphere there is not ` bulk water´, and water droplets/ice crystals do not automatically form –

A more refined thermodynamics is needed to understand droplet formation. This includes surface tension (σ) and the drop radius of curvature (r)

[for details see Pruppacher and Klett:
Microphysics of clouds and precipitation, Chapters 4 -6, Kluwer Academic Publishers, 1997]

Saturation inside clouds

Inside a cloud the specific humidity is as a first approximation saturated with respect to bulk water or ice:

Clausius Clapeyron equation:

$$e_s(T) = e_{s0} \cdot exp(\frac{L}{R_v}(T_0^{-1} - T^{-1}))$$

vapor pressure at $0°C$
$e_{s0} = 611\mathrm{Pa}$

water vapor gas constant
$R_v = 461.5\mathrm{J} \cdot \mathrm{Kg}^{-1} \cdot \mathrm{K}$

Latent heat of fusion
$L = 2.50 \cdot 10^6 \mathrm{J} \cdot \mathrm{Kg}^{-1}$

Freezing point
$T_0 = 273.16\mathrm{K}$

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The details of droplet or ice crystal formation very complex:

Theory predicts very large supersaturations compared to the bulk formula before droplet formation/ice crystals would occur !
(formula already derived in 1870 by Lord Kelvin)

In reality the presence of aerosols (cloud condensation nuclei (CCN) , with diametres typically < 0.2 μm) having an affinity for water is the reason for generation of droplets at saturation vapor pressures which may be either lower or somewhat higher than the `bulk water pressures´

When a socalled critical radius of the droplet containing the dissolved CCN is reached the droplet continues to grow in the supersaturated field towards large cloud droplets which may start the precipitation process by colliding with other droplets.

Saturation pressure over a droplet

("curvature"effect versus "solution" effect)

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Saturation pressure over a droplet of radius r:

$$e_s^{'}(r) = e_\infty \cdot (1 + \frac{a}{r} - \frac{b}{r^3})$$

e_∞ = bulk saturation

$a = 3.3 \cdot 10^{-5} \cdot \mathrm{T}^{-1} (\mathrm{cm})$

$b = 4.3 \cdot \mathrm{i} \cdot \mathrm{M} \cdot \mathrm{m}_s^{-1} (\mathrm{cm}^3)$

i : dissociation, M : solution mass , m_s : molecular weight of solute

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Basic modelling concepts (1)

- A model's forecast prognostic variables must be predicted in time and space.

- Conventional weather models use prediction variables such as

  U,V → horizontal wind components

  T → temperature

  P → pressure

  Q → specific humidity

  Qc → specific cloud water

  Qi → specific cloud ice

- The potential of future models (e.g. Enviro-HIRLAM) will be to incorporate

  → more hydrometeors

  → prognostic aerosole parameters

  → prognostic chemical species

Basic modelling concepts(2)

1) It is postulated that the time evolution of the model's forecast variables
   can be described by mathemathical-physical equations
   (partial differential equations with non-linear terms making analytical solutions impossible to derive)

2) As a consequence of (1) mumerical methods are used.

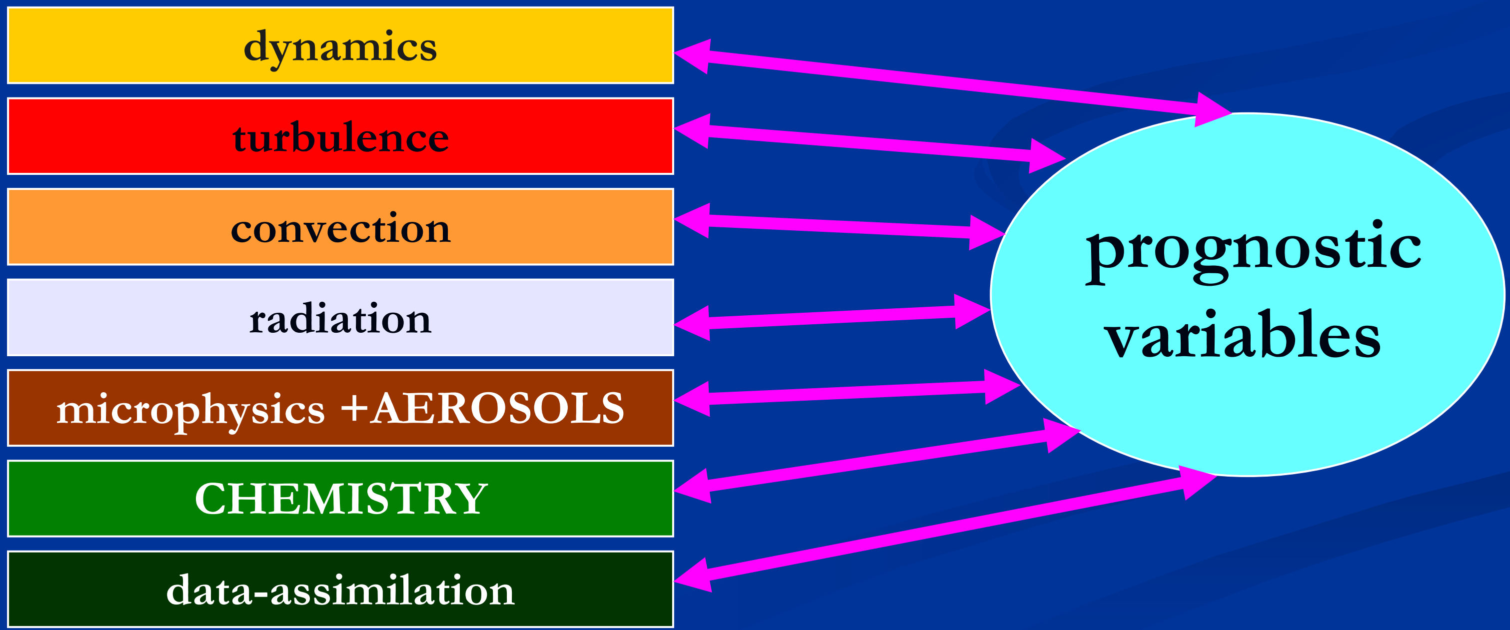
3) It is sometimes of vital importance to use accurate numerical methods, e.g. in the context of treating advection of trace gases or chemical species (accurate advection schemes)

Basic modelling concepts(3)

The concept of parameterization:

The evolution of meteorological variables are governed by relevant physical processes which are numerical counterparts of a governing equation or *parameterized*, that is, described in terms of the model variables:

Process: (treatment of aerosols and chemistry is new in 'weather models')



Modelling challenges (1)

Common to atmospheric models which involve real time predictions clouds and precipitation:

→Advanced cloud physics cannot alone make good predictions of clouds and precipitation ! The model must start from a realistic atmospheric state including a realistic dynamial forcing, e.g. the divergent wind field. This is because of a strong link between convergence or advection and the evolution of supersaturation and related condensation.

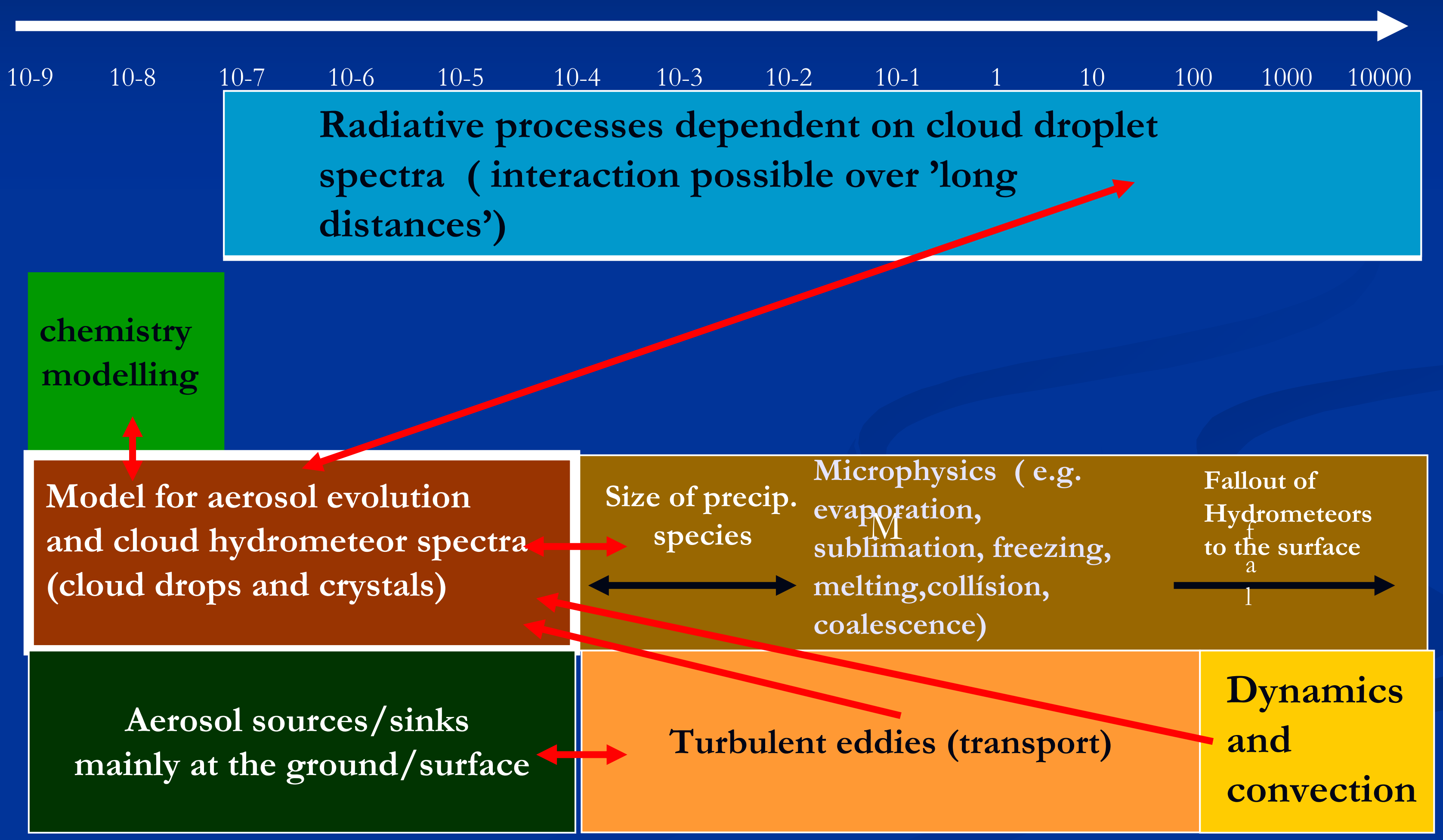
Modelling challenges (2)

- Considering Levin's and Cotton's book (2009)
  "Aerosol Pollution Impact on Precipitation" on page 273-274
  the conclusions on aerosol effects are along the same direction:

"Evaluation of aerosol effects on clouds and precipitation must be considered in a dynamical/meteorological context. Aerosol-cloud interactions occur in a tightly coupled system, and it is important that models couple dynamics, microphysics, radiation, chemistry and surface characteristics "

Spatial scales of process interaction (m)

affecting cloud and precipitation over a time evolution of hours to days

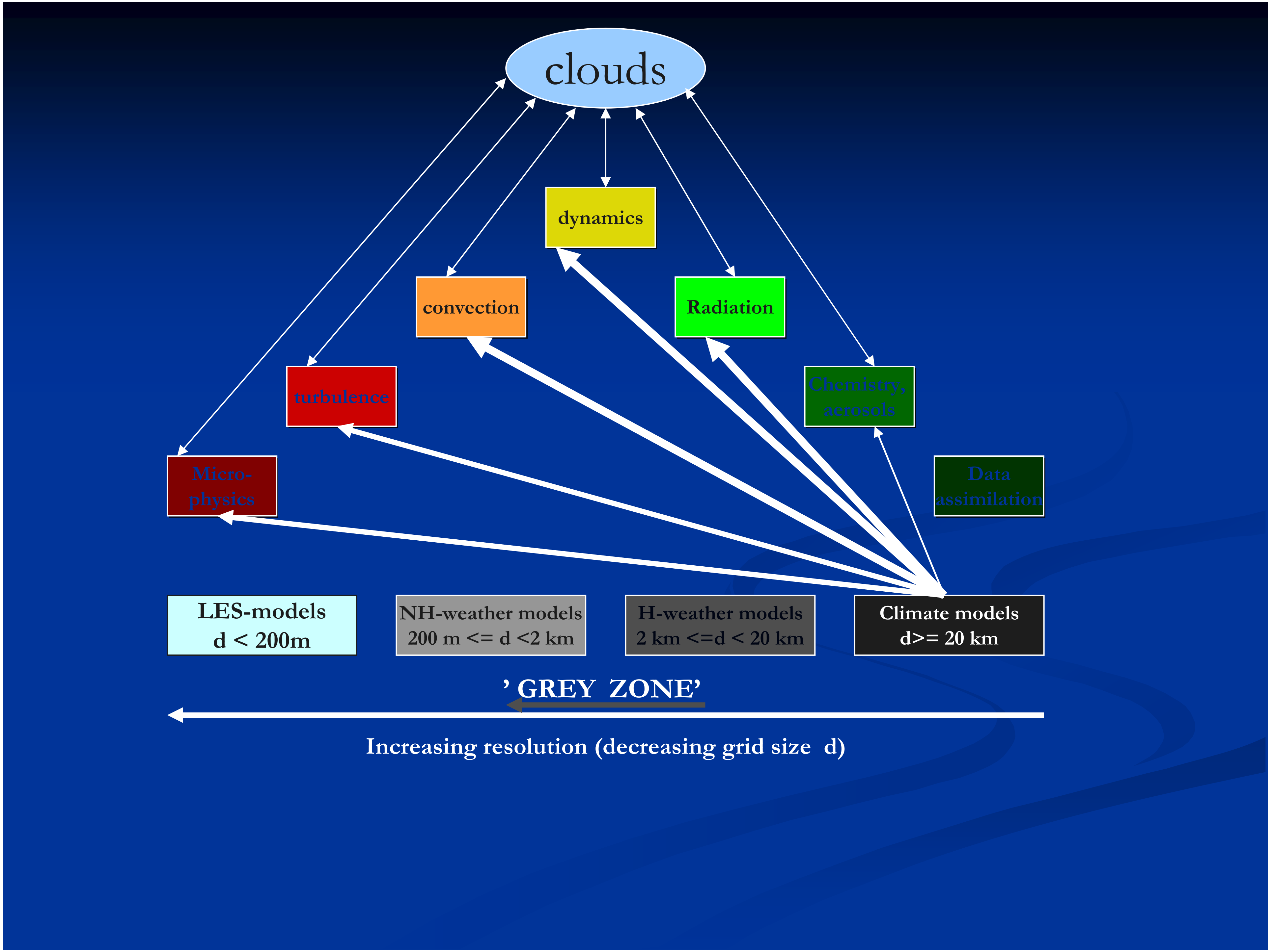


Potential of aerosol aerosol modelling

The new aerosol-modelling including information on cloud- and ice-particle spectra is interesting becausse of the interaction with both

- Chemistry
- Aerosol sources and sinks (mainly at the surface/ground) transported via turbulence
- Convection and dynamics
- Microphysics including precipitation
- Radiation

From a modelling point of view (hydrostatic and non-hydrostatic forecast models) it will be an interesting challenge to develop new parameterizations which can make use of new variables from the aerosol module !

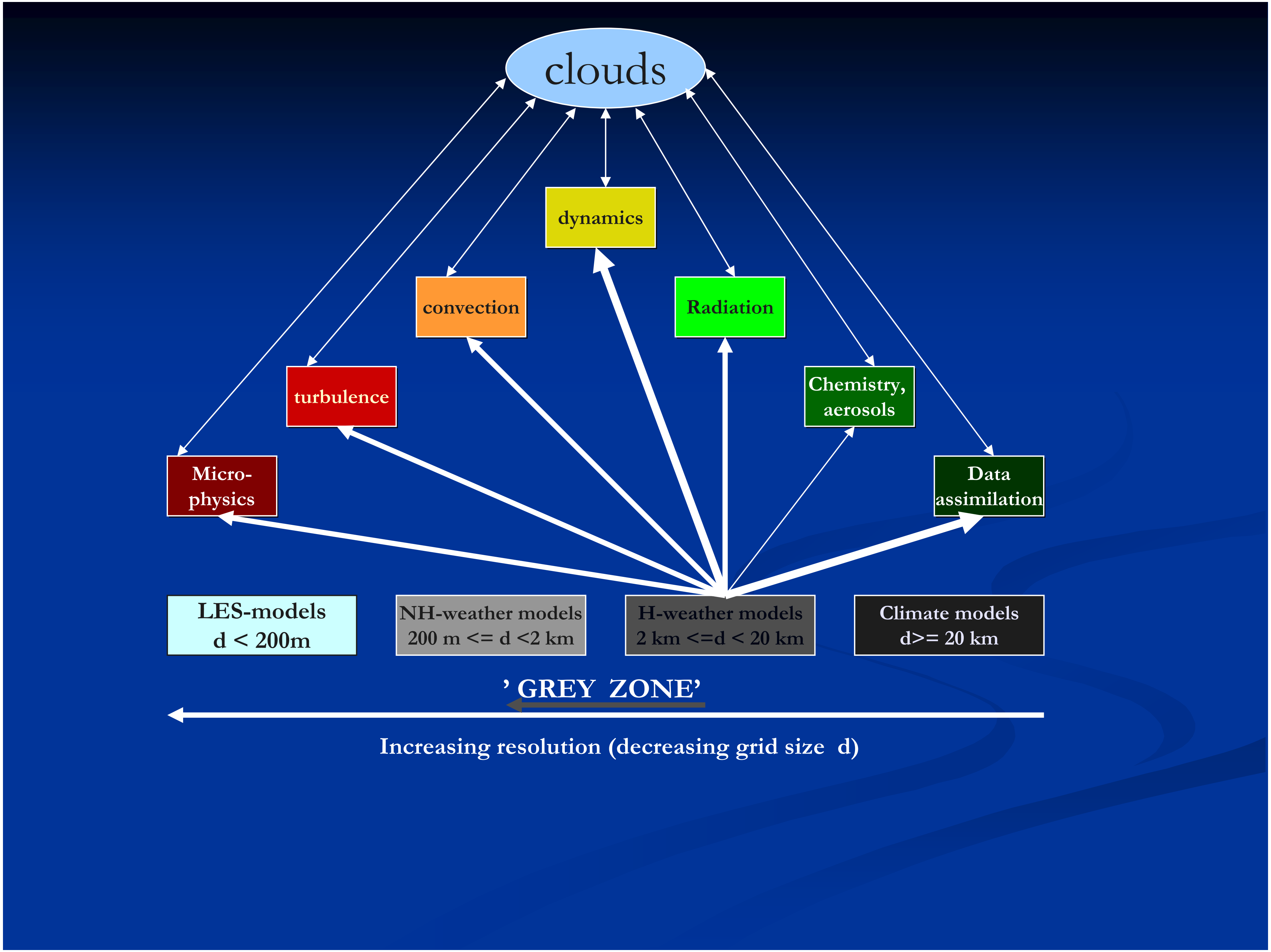


clouds
dynamics
convection
Radiation
turbulence
Chemistry, aerosols
Micro-physics
Data assimilation
LES-models d < 200m
NH-weather models 200 m <= d <2 km
H-weather models 2 km <=d < 20 km
Climate models d>= 20 km
' GREY ZONE'
Increasing resolution (decreasing grid size d)

Characteristics of the different models (1)

Climate models: (time prediction range : months to years)

- Coarse mesh with the risk that accuracy is insufficient: The fact that many subgrid scales need to be parameterized creates a big challenge !
- Convection needs parameterization, also mesoscale large convective complexes (if possible)
- Other physics (turbulence, radiation, microphysics need to be fairly realistic if feasible , but precipitation may be assumed to fall to the ground in one time step)
- Data-assimilation is not an issue apart from the initial state of the run
- Chemistry and aerosols are rather new in climate models and are difficult due to sources and sinks !



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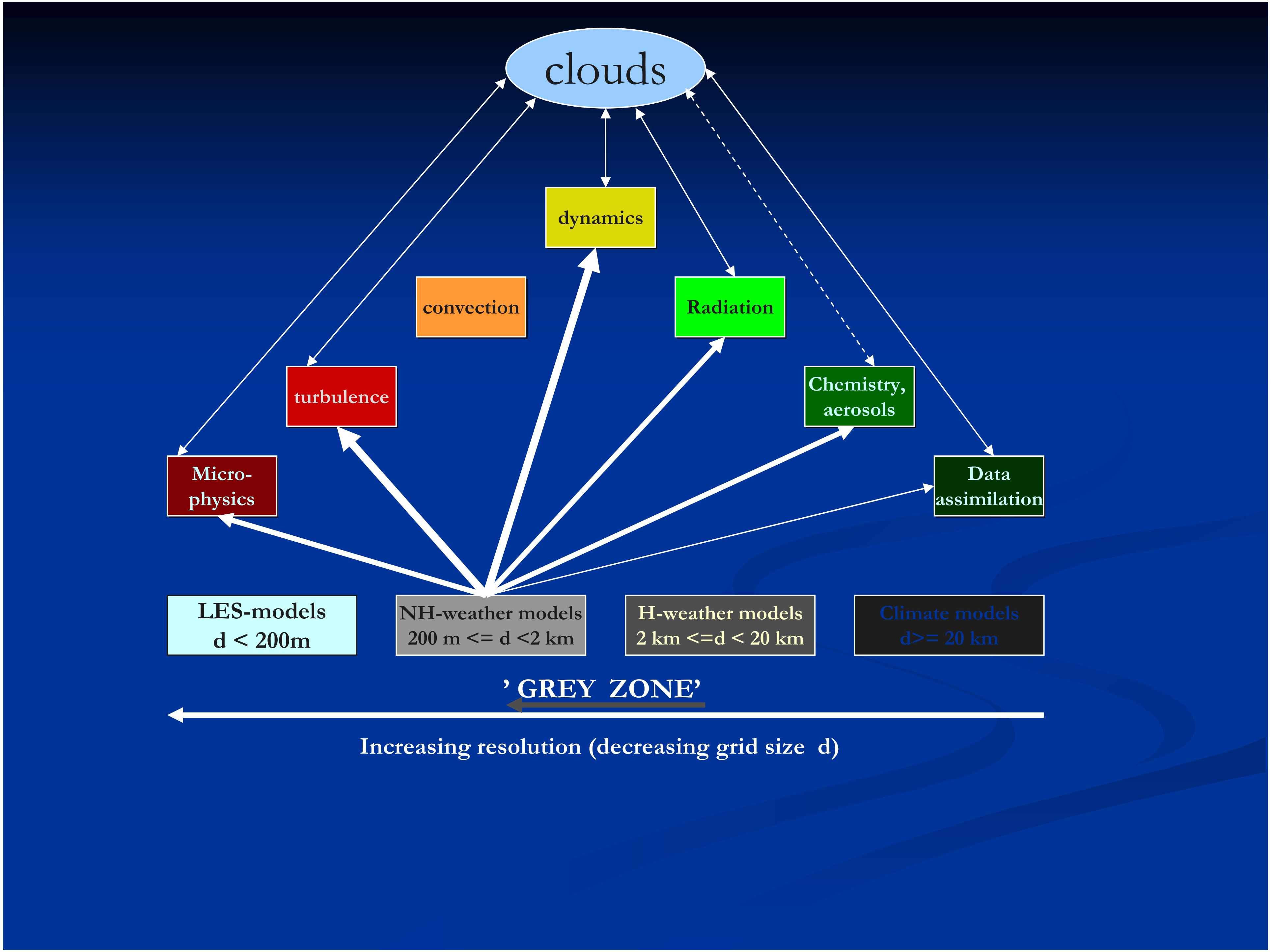
Characteristics of the different models (2)

H (hydrostatic) weather model: (time range: now-casting to days or weeks)

- Resolution is not sufficient to skip any parameterization of the main processes
- Assumptions related to convection and precipitation release (if released during a single time step) become questionable at high model resolution (a claimed `grey zone issue´)
- Approximations and simplicity of schemes may be acceptable for nowcasting purposes in view of the demands for fast production of products !
- Data-assimilation is essential in NWP (for clouds: radar data, Nowcasting SAF, other satellite data, GPS data and other data for humidity information)
- Inclusion of chemical/aerosol effects is rather new but in progress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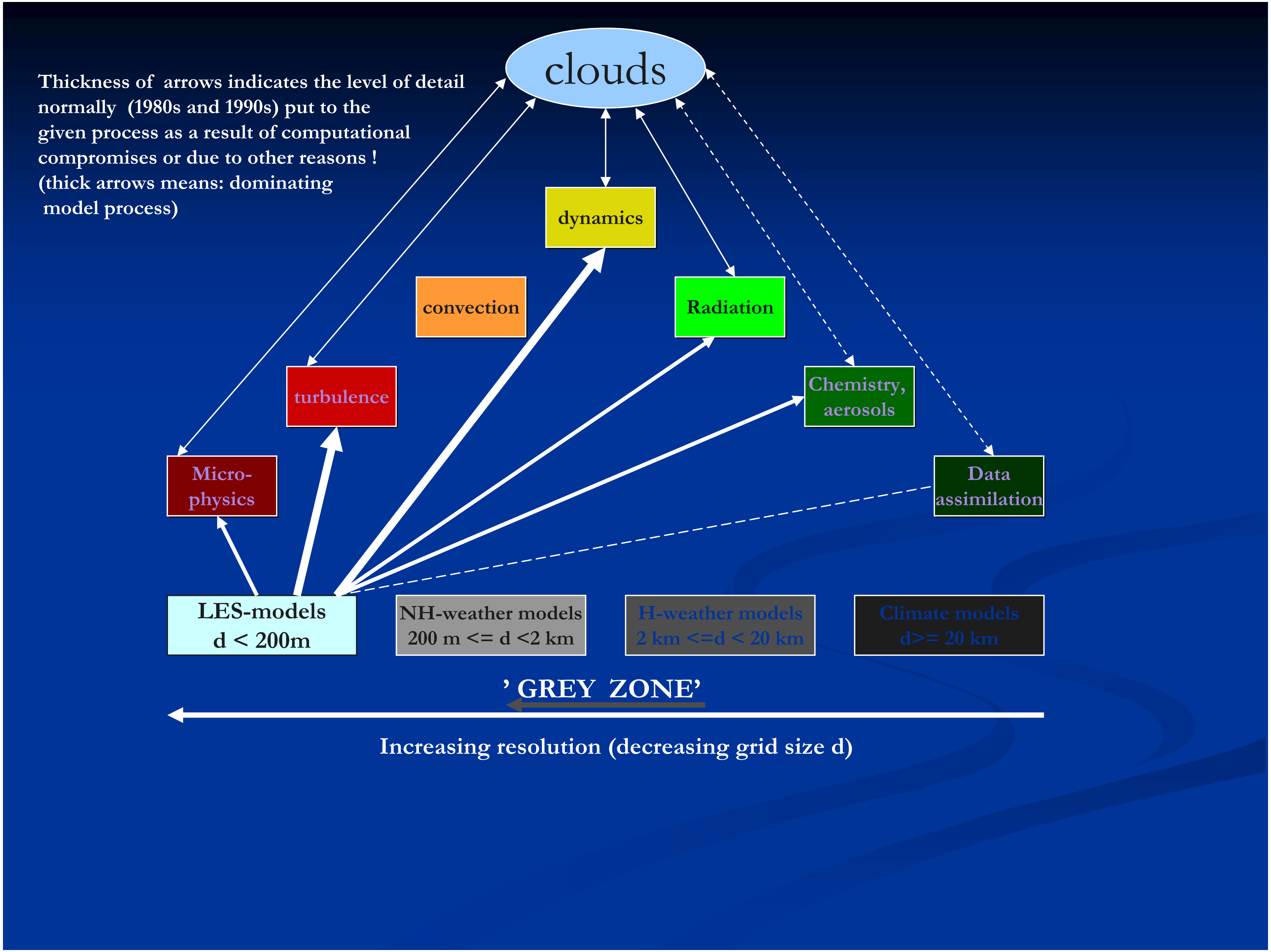
Characteristics of the different models (3)

NH-weather model: (time range: now-casting to few days)

- Resolution sometimes sufficient to skip convective parameterization (special schemes combining turbulence and aspects of convection is under development , e.g. EDMF , 'Eddy-Diffusion-Mass-Flux' schemes)
- The NH model dynamics is typically computationally expensive: Different type of schemes are available: ´split-explicit' (`WRF´), semi-implicit ( `ALADIN´)
- Approximations and simplicity of schemes may be acceptable for nowcasting purposes in view of the demands for fast production of products !
- Data-assimilation essential in NWP but is less developed (so far) for very high resolution weather prediction (for clouds: radar data, Nowcasting SAF, other satellite data, GPS data and other data for humidity information)
- Inclusion of chemical/aerosol effects is new and computationally demanding.



Thickness of arrows indicates the level of detail normally (1980s and 1990s) put to the given process as a result of computational compromises or due to other reasons ! (thick arrows means: dominating model process)
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Increasing resolution (decreasing grid size d)

Characteristics of the different models (4)

LES: large eddy simulation method is based on Navier-Stokes equations. The LES model concept has been used since the 1970s. A variety of different \`flavours´ and applications of LES exist. – from engineering fluid dynamic problems to meteorological research models.

In meteorology:

- normally Reynolds-averaged Navier-Stokes equations,
- incompressibility and Boussinesq aproximations widely used.
- no convection scheme needed !
- in research the microphysics and radiation is often simplified, in real forecasts using LES this is not desirable.
- Initialization/data-assimilation is very difficult which has been seen in many studies (partly linked to boundary conditions, research ongoing)
- Relevant for very detailed air pollution studies and also forecasts (if feasible)
- LES are very expensive to run on large model areas due to small time steps

Known model challenges related to clouds and precipitation (1)

→to analyse properly the atmospheric initial state using data-assimilation

→to describe subgride scale physics properly, especially convective transports described by convection schemes in models using grid sizes larger than about 1 km

→Some models assume that the model precipitation falls to the surface in a single time step of the model which is unrealistic in high resolution models.

→ Lack of knowledge on actual number density and the properties of the cloud condensation nuclei – and a lack of proper model physics to take into account the effects of CCNs.

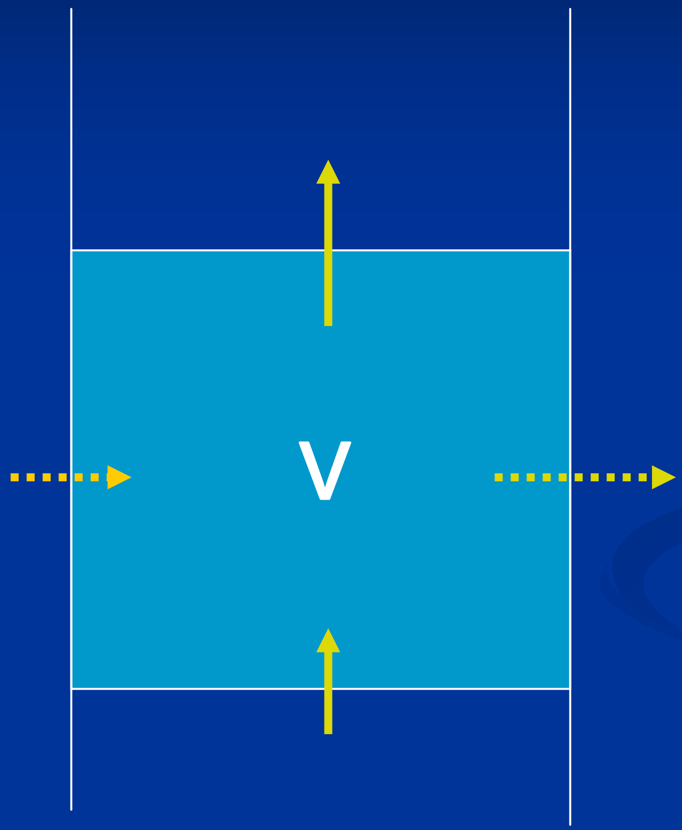
→Ice clouds is a special issue requiring `freezing nuclei´ which are sparse in the atmosphere and not well known.

Cloud physics in models:
Model physics computations are often done in
a vertical column even in high resolution models

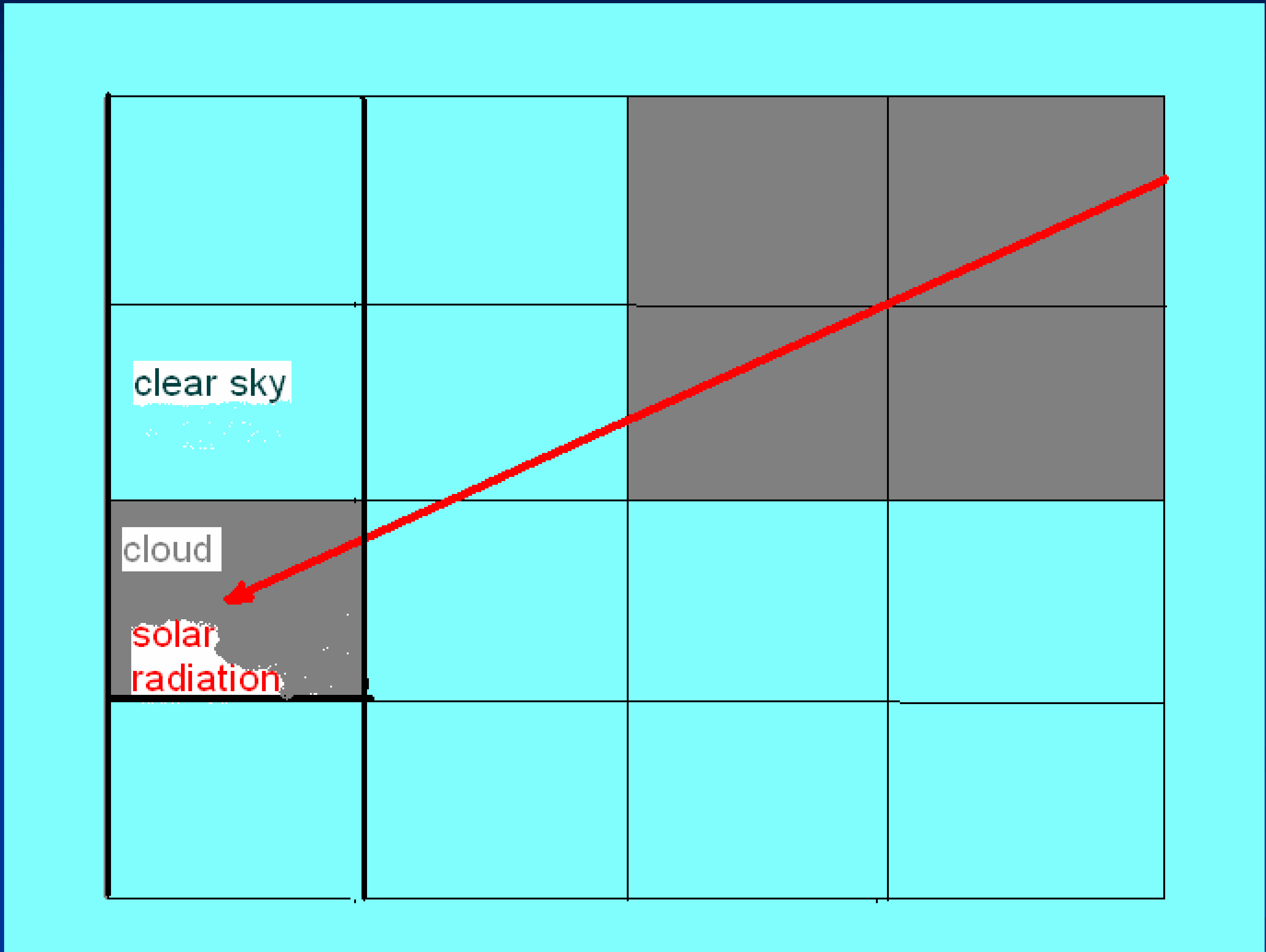
BUT

there are
limitations associated with the model grid
in case of `column´ physics !

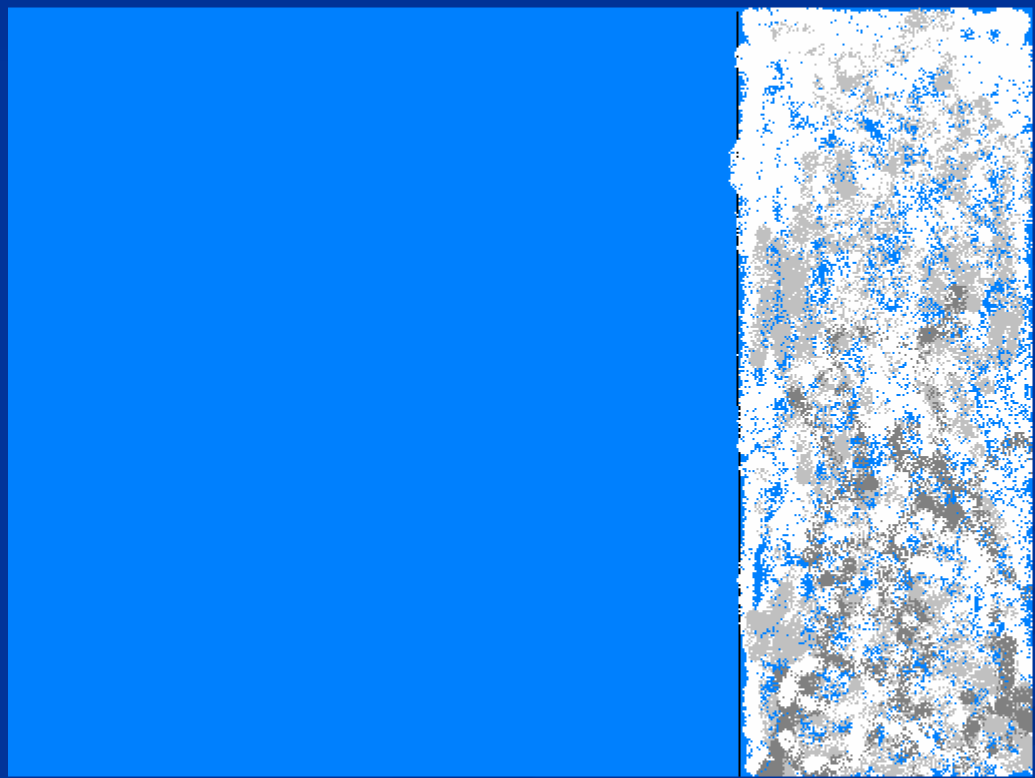
Temperature and humidity changes in a grid volume V is influenced by subgrid scale flux variations across the volume. The flux variations are often considered as varying in the vertical (`column physics´). The horizontal variation is not properly accounted for !



EXAMPLE: Column physics see a clear sky above cloud – `Correct´ physics see dense cloud giving no direct sunshine reaching the cloud !

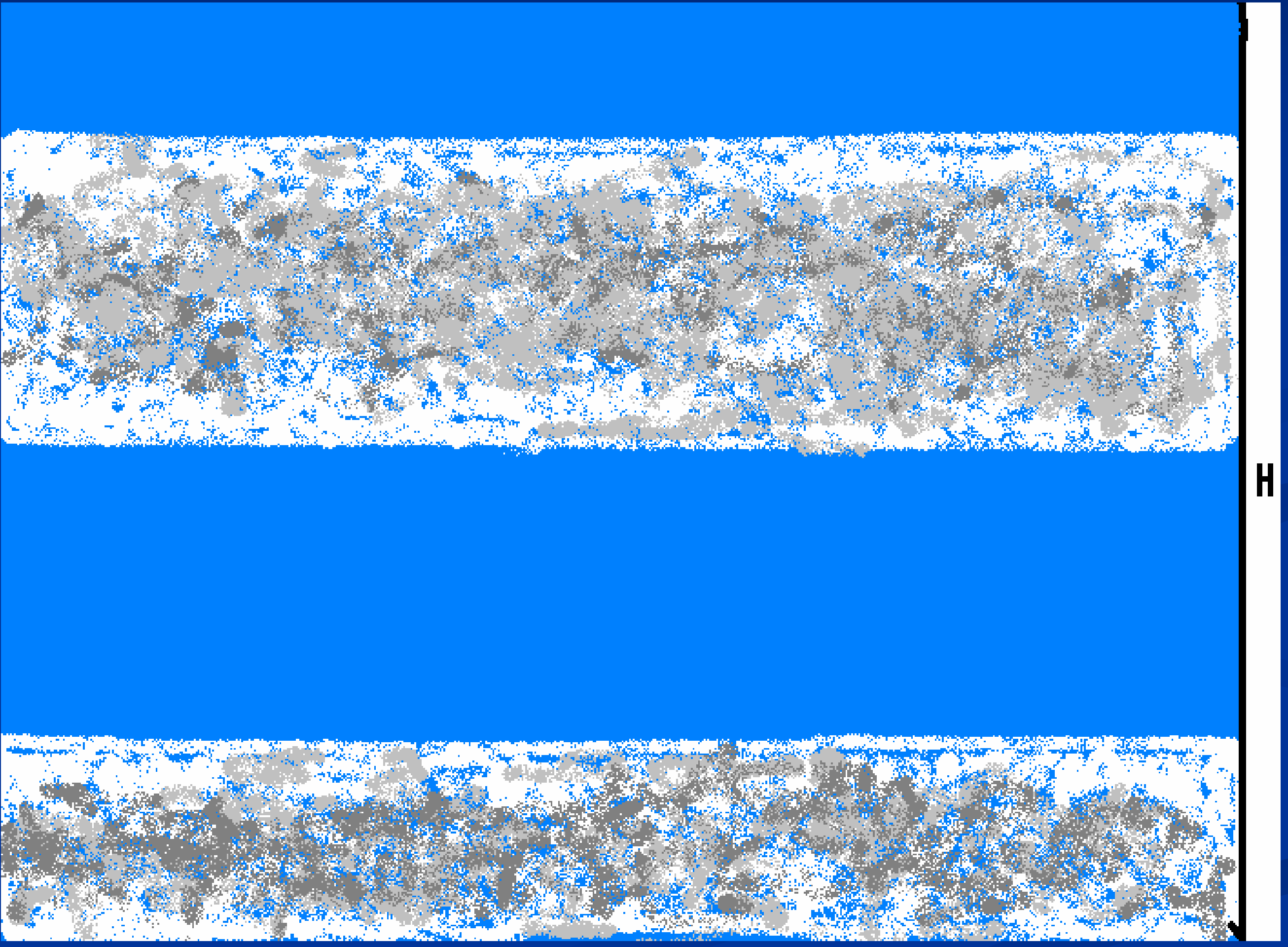


Model clouds are normally treated as fractional in horizontal and not in the vertical. This is reasonable to some extent because the horizontal grid size (e.g. 10 km) is larger than the vertical grid size (e.g. 100 m)

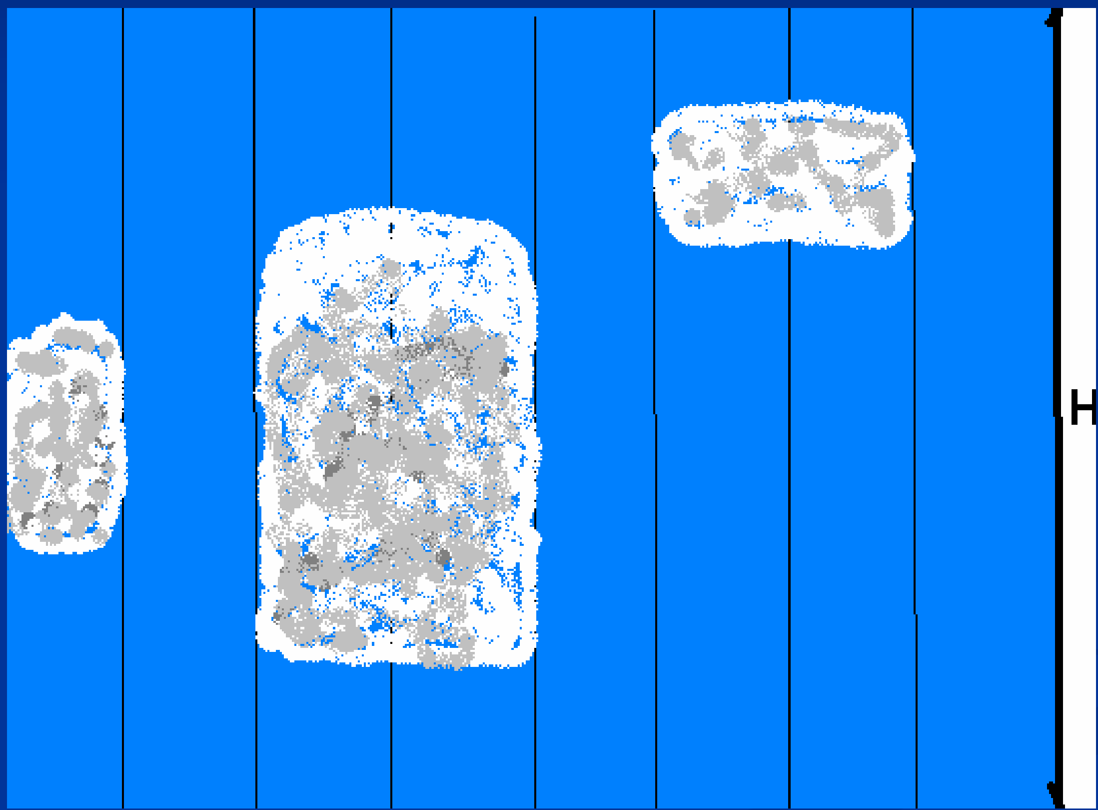


For small heigth to horizontal grid size ratio it seems more reasonable to treat cloud cover as fractional in the horizontal direction only

Real clouds may be fractional in the vertical (model grid height =H)



Real clouds may be fractional both in the horizontal and in the vertical



International collaboration :

GEWEX cloud system study (GCSS)

GEWEX is established under the World Climate Research Programme (WCRP)

- It is generally recognized that inadequate parameterization of clouds is one of the greatest sources of uncertainty in the prediction of weather and climate.
- Recent GCSS meeting (4th PAN-GCSS meeting) was held in Toulouse June 2008 (See the many relevant abstracts on www.knmi.nl/~siebesma/PNN-GCSS/)
- GCSS is developing better parameterizations of cloud systems for climate models by improving our understanding of the physical processes at work within the following types of cloud systems: (1) boundary layer, (2) cirrus, (3) extra tropical layer, (4) precipitating convective, and (5) polar. There are five GCSS working groups, one for each type of cloud system. Each of these working groups has adopted single-column modeling as a key research strategy, and each is also making use of cloud ensemble models.

GCSS working groups

The GCSS working groups are performing the following activities:

- Identifing and developing cloud-resolving and mesoscale models appropriate for each cloud system type.
- Specifing blueprints of minimum observational requirements for the development and validation of these models.
- Assembling, for particular cloud types, case-study data sets accessible to the community of (a) matched observations from satellites, surface and aircraft, and (b) model-derived synthetic data sets.
- Conducting workshops, including model intercomparisions using the above case study data sets.
- Using the data sets to derive a better understanding of the coupled processes within different types of cloud systems and to derive improved parameterization schemes for large-scale models.

GCSS –related work with HIRLAM

- Some GCSS related 1D cloud physics tests have been conducted .
- Initial and boundary conditions and dynamical forcing is specified in the case description.
- Model simulation results, e.g. fractional cloud cover, amount of cloud condensate etc. can be compared to the model results of LES. This type of experiments can be used for tests and developments of cloud parameterizations.

EXAMPLE :

The \`ASTEX stratocumulus´ case. It has been possible to verify, e.g. that the HIRLAM physics can produce a realistic \`cloud top entrainment´ for the experimental conditions of this case. The entrainment of dry air at the top implies that the whole cloud layer is 'lifted' during the simulation time.

Conclusions and outlook (1)

- Clouds are very important in relation to weather- and climate type of models
- The coming years will show to what extent new model developments related to aerosols (and chemistry) will show up in increased skills of NWP type of model predictions, but the chemistry and aerosol modules do provide forecasts of new variables and a better framework for predicting visibility, clouds and precipitation.
- As the model resolution increases new challenges imerge. It is important to understand the effect of various approximations (e.g. `column physics ')

Conclusions and outlook (2)

- Data-assimilation of new variables related to aerosol and air pollution/chemistry will be important to get maximum benefit
  of new model extensions related to air-quality.

- Data-assimilation at very high resolution requires more research and computer power. It seems important to do research in assimilation of moisture related data at very high resolution to provide optimal conditions for cloud prediction !

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Types of cloud parameterizations in atmospheric models

Types of cloud parameterization in models(1)

- Diagnostic cloud parameterizations verified

by mainly synop observations, satellite data, radar data:

Example: Slingo and Ritter in the ECMWF model (1985):

Formulation based on

- relative humidity,
- \`strength of inversion´ for stratocumulus type of clouds,
- function of convective precipitation rate

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Types of cloud parameterizations in models(2)

- Diagnostic cloud parameterizations developed

and verified by means of high resolution LES (idea started in 1980s -1990s):

Example: Xu and Randall (J. Atmos. Sci. 53, 3084 - 3102, - 1996): Diagnostic fomula as a function of

- Relative humidity
- Specific cloud condensate
- Saturation specific humidity

Types of cloud parameterizations (3)

- In recent years it is most common to express cloud cover from probablbility density functions (PDFs) descibing how the subgrid scale variability of prognostic variables occurs across the model grid
The PDFs may be more or less complicated (e.g. varying in time)
and asymmetric. The links to the rests of model formulation need to be consistent:

- Examples in litterature since 1980s
- An example from the HIRLAM model based on a PDF is given in the Appendix - A formula for convective cloud cover at a given level
is derived by solving 3 equations for , respectively, integral probability, total specific humidity and specific cloud condensate.

Special parameterization: The ’super-parameterization’.

In recent years David Randall has suggested
a multiscale model approach:

`Run a LES model inside every grid square of a coarse mesh model in order to produce subgrid scale output for the coarse mesh model´

Disadvantage:

- **It is extremely expensive to run LES model in an operational context in such a manner !**
- **The lateral boundary conditions impose potential problems for `imperfect´ interaction between the two models.**

Convection, condensation, precipitation in HIRLAM

Development issues of KF-RK and STRACO schemes:

→ Both schemes will in the future be able to use cloud water and cloud ice (and probably more variables in the future). For the STRACO scheme convective transports of extra tracer variables are currently being developed and tested.

→ In HIRLAM-model KF-RK has currently a reputation for predicting high precipitation amounts better than STRACO scheme but the reverse applies to small precipitation amounts.

→ New developments of the schemes (in CAM3 to be adopted for HIRLAM) and in STRACO seem to produce schemes with more similar behaviour than seen previously –
for STRACO some treatment of local CAPE is introduced while the CAPE closure of KF is becoming less extreme in forthcoming CAM3-version to be used in HIRLAM.