ICON

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

ICON-NWP physics: General overview

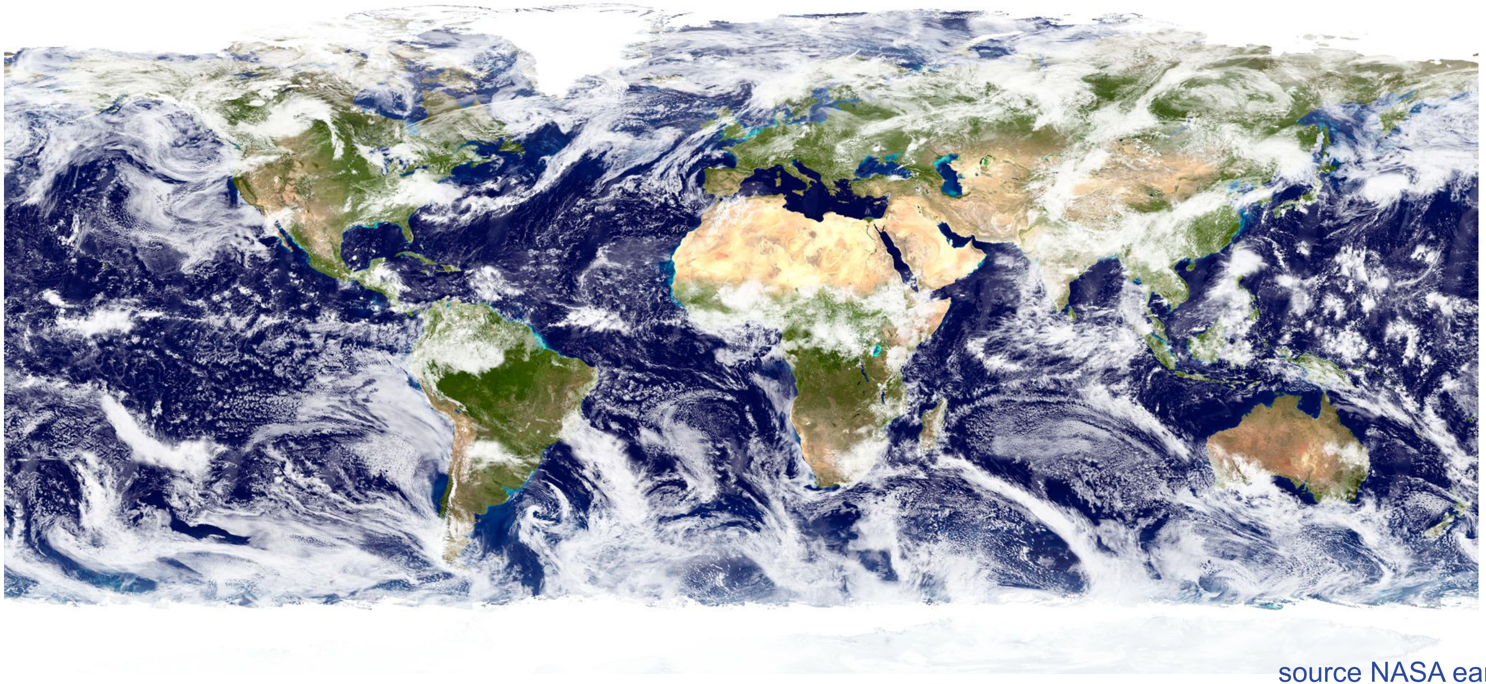
Martin Köhler | Academic ICON Training | July 2025

Based on material by Linda Schlemmer and Daniel Klocke

Overview

- What is a physical parameterization?
- The ICON (NWP) physics interface and physics time stepping
- Primer on physics packages of ICON (NWP)

The Problem



source NASA earth observatory

Compressible non-hydrostatic equations (Navier-Stokes equation)

$$\partial_t v_n + (\zeta + f)\, v_t + \partial_n K + w\,\partial_z v_n = -\, c_{pd}\theta_v \partial_n \pi$$ **Normal wind speed**

$$\partial_t w + \vec{v}_h \cdot \nabla w + w\,\partial_z w = -\, c_{pd}\theta_v \partial_z \pi - g$$ **Vertical wind speed**

$$\partial_t \rho + \nabla \cdot (\vec{v}\rho) = 0$$ **continuity equation**

$$\partial_t (\rho\theta_v) + \nabla \cdot (\vec{v}\rho\theta_v) = 0$$ **Virtuell potential temperature**

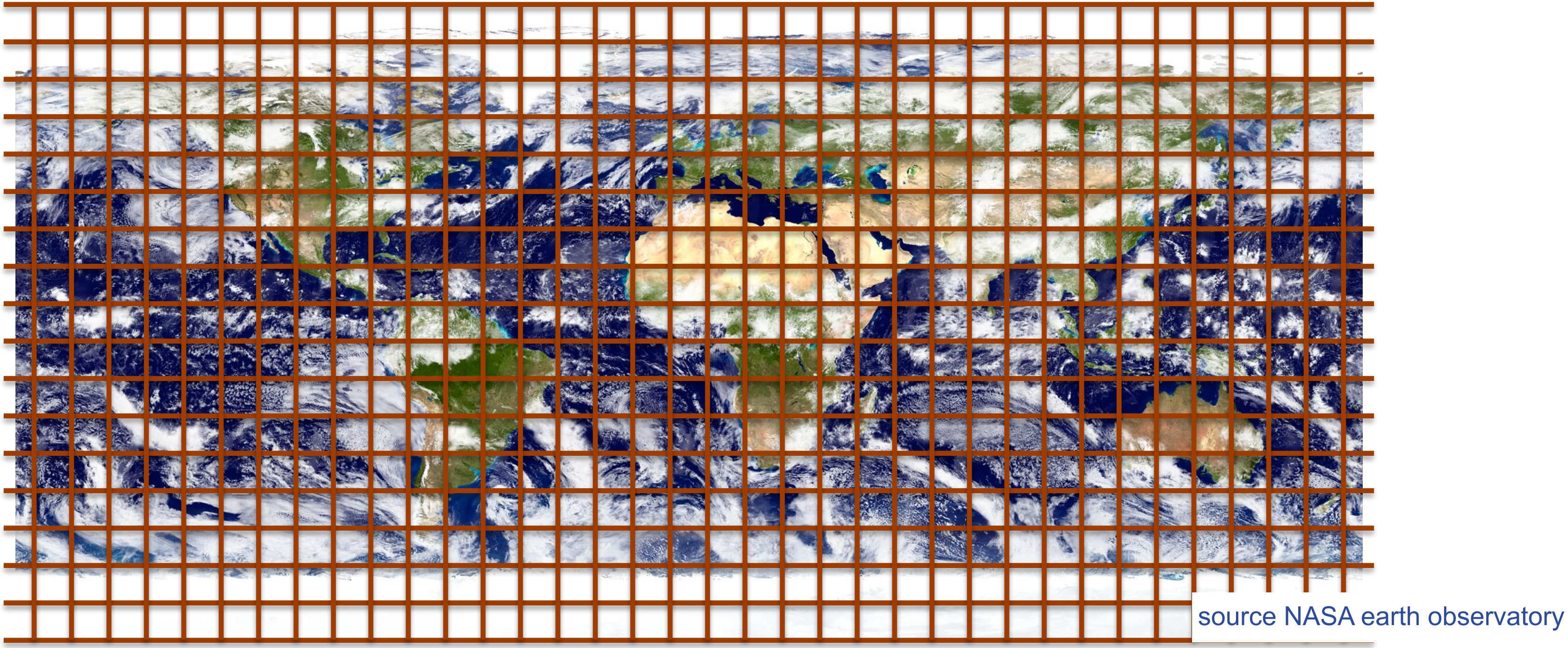
($v_n,\ w,\ \rho,\ \theta_v$: prognostic variables)

Also prognostic equations for water vapour, cloud liquid, ice, rain and snow and TKE.

- **Solvers:**

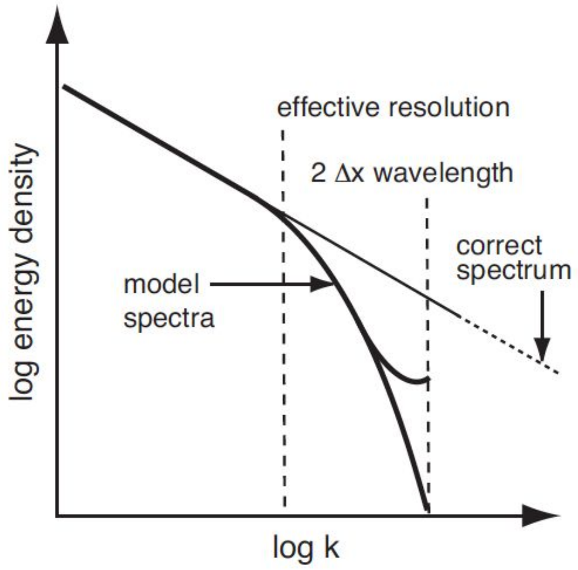
- Reynolds averaging: $\psi = \overline{\psi} + \psi'$ with average value and statistical deviations
- Finite Volume / finite differences discretization (mostly 2. order)
- Time integration: Two time level predictor-corrector scheme
- Vertical implicit (vertical sound propagation)
- Mass conserving (dry air and tracer)
- Computing time: ~50 minutes for a 7-day forecast (13km including 6.5km over Europe) with 32 Vector Engines (each with 8 cores) on NEC Aurora

Model grid -> resolution



Grid cell defines the smallest resolvable scale.
Many important phenomena and related processes are sub-grid.

Effective resolution



Skamarock, 2004

The effective resolution is estimated using total kinetic energy spectra.

Generally it is in the range of 4-10 · Δx.

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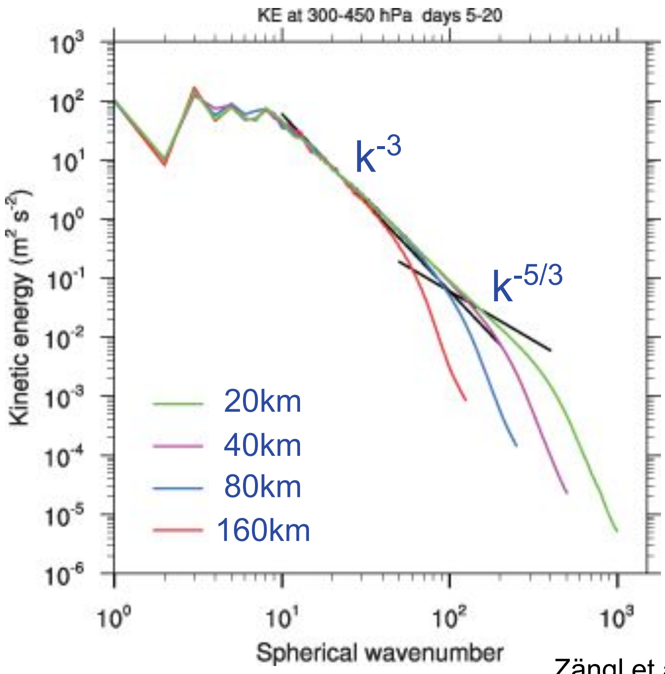
Effective resolution



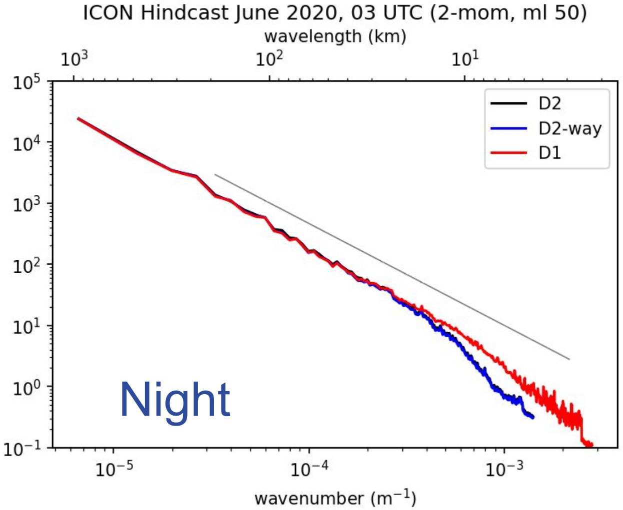
Zängl et al. 2014

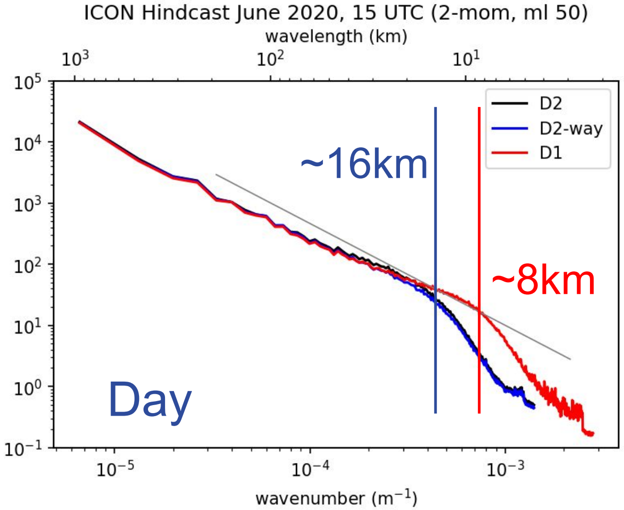
The effective resolution is estimated using total kinetic energy spectra.

Generally it is in the range of 4-10 · Δx.

Effective resolution

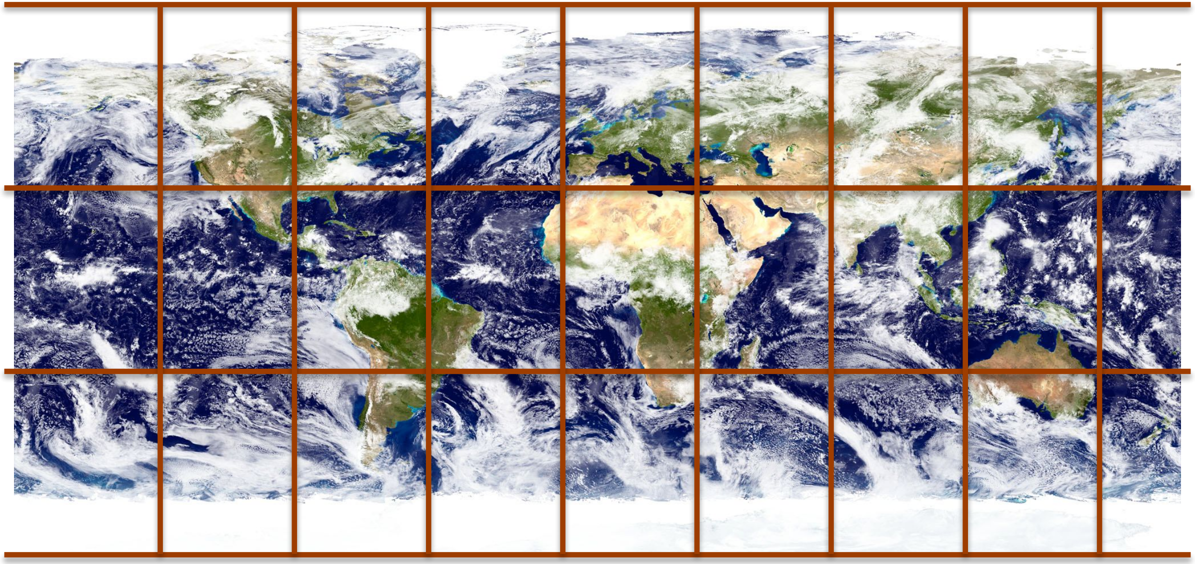
- Energy spectra for ICON D2 (~ 2km grid spacing) and D1 (~ 1km)
- averaged spectra over 1 month at 03 and 15 UTC and one model level are shown





Philipp Zschenderlein,
Alberto de Lozar,
Günther Zängl

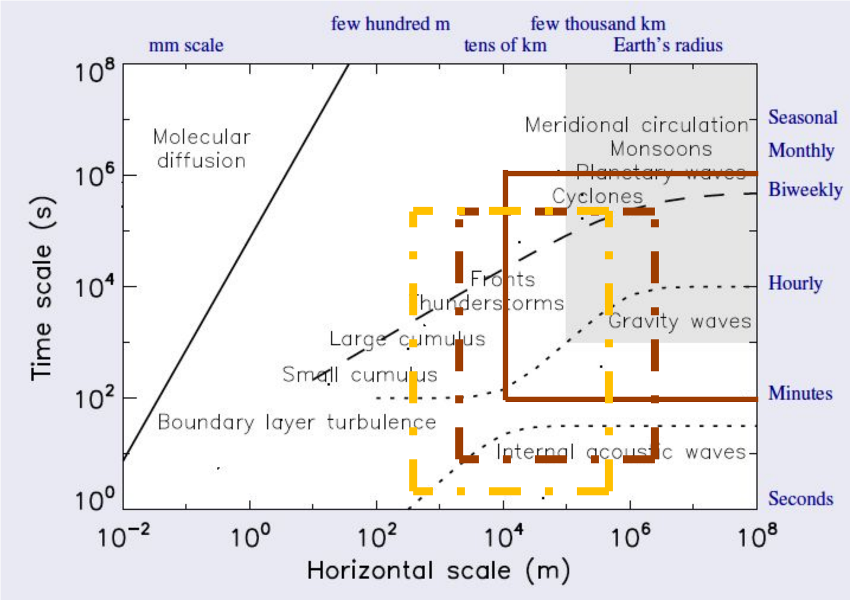
Model grid -> effective resolution



source NASA earth observatory

Phenomena and processes properly resolved on this scale.

Characteristic scales

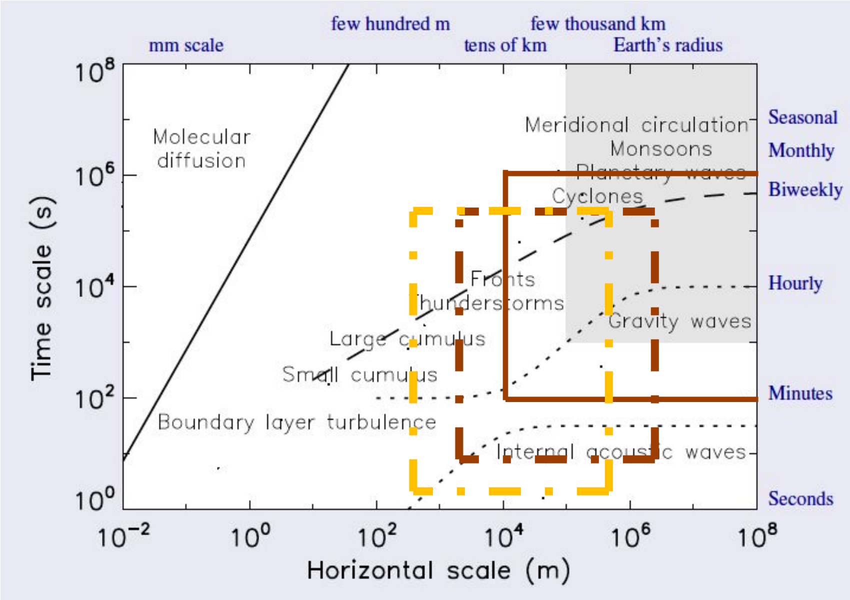


Resolved scales:

- ICON global
- ICON-D2
- ICON-D05

10^4km: large scale circulations (Asian summer monsoon).
10^4km: Rossby waves (called planetary waves)
10^3km: cyclones and anticyclones
10km: fronts with widths of a few tens of km

Characteristic scales

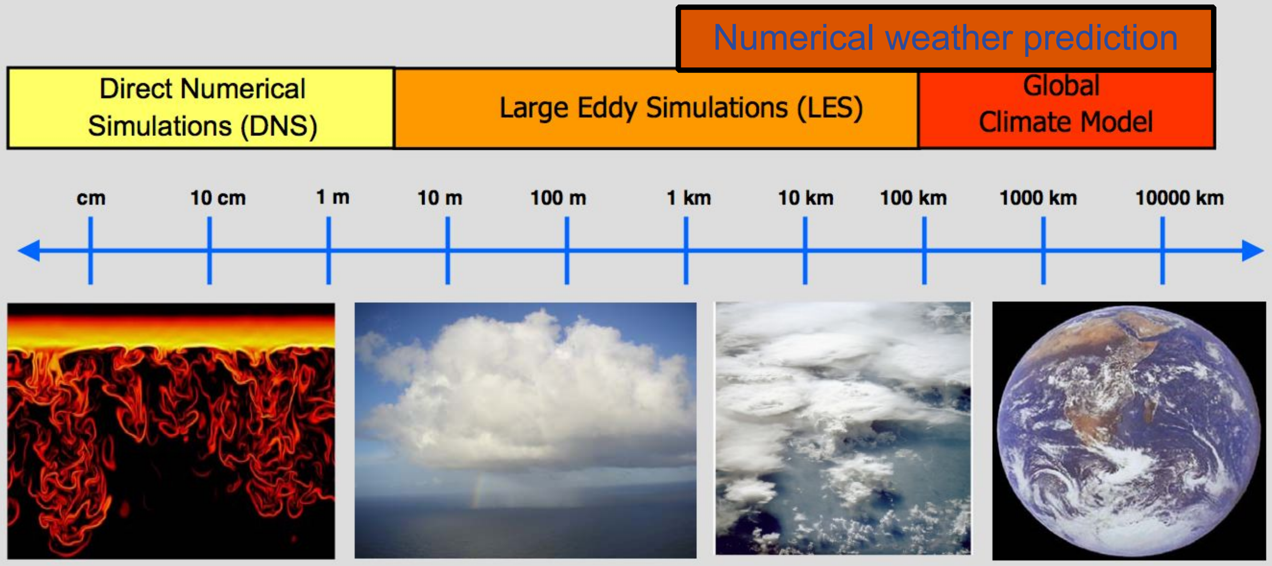


Resolved scales:

- ICON global
- ICON-D2
- ICON-D05

10^3km - 100m: convection can be organized on a huge range of different scales
10m - 1mm: turbulent eddies in boundary layer; range in scale from few hundred m's down to mm scale at which molecular diffusion becomes significant.

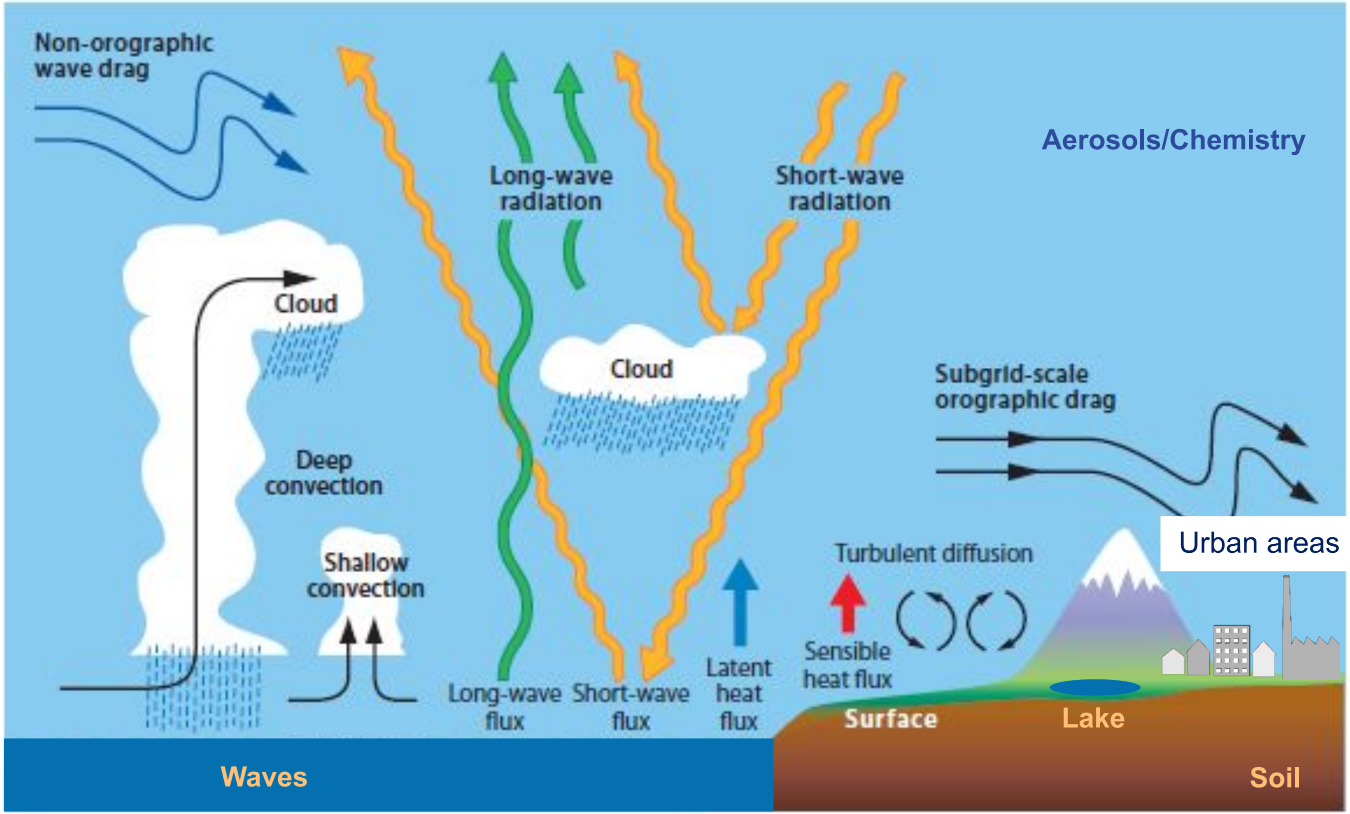
Models and their scales



courtesy of Pier Siebesma

The system

Physical Parametrization in an NWP Model



ecmwf.int

Basic Requirements of the Parameterizations

- Accommodate different applications (global and limited-area numerical weather prediction, environmental forecasts, climate projections and research).
- Work on a wide range of scales (horizontal, vertical and time).
  - Kilometer-scale modeling: ICON-D2 and ICON-D05
  - global (13km) and high resolution European nest (6.5km) at DWD
  - ensemble forecasts (26km)
  - seasonal predictions to decadal scales (→ ICON seamless).
- The numerics need to be efficient and robust, especially for time critical numerical weather prediction.
- Interactions between processes are important and should be considered in the design of schemes and the physics-dynamics coupling.

Parameterizations - Physical Processes

General

- Tendencies from sub-grid processes are substantial and contribute to the evolution of the atmosphere even in the short range.
- Diabatic processes drive the general circulation.

Synoptic development

- Diabatic heating and friction influence synoptic development (upscale growth)

Weather parameters

- Diurnal cycle
- Clouds, precipitation, fog
- Wind, gusts, temperature and humidity at 2m level.

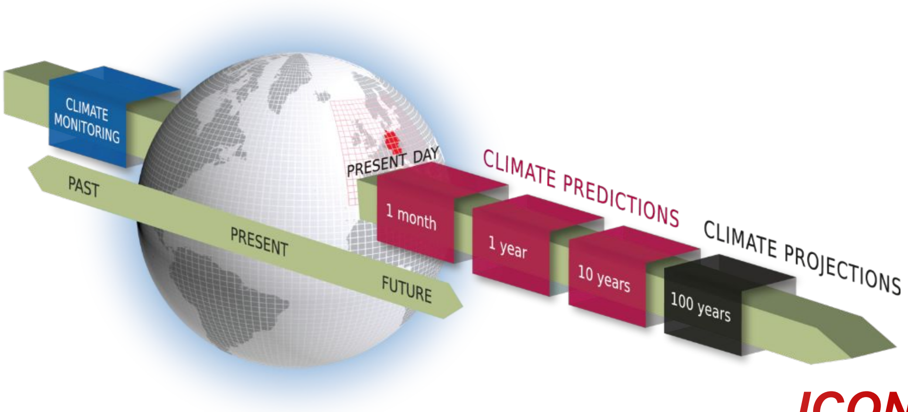
Data assimilation

- Forward operators are needed for observations.

ICON seamless

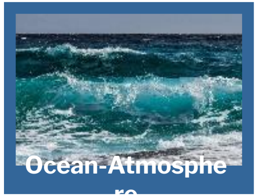
Forecasting system for

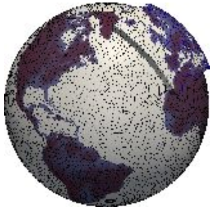
- NWP: 0-10 days
- Seasonal Predictions
- Decadal Predictions



Courtesy Barbara Früh

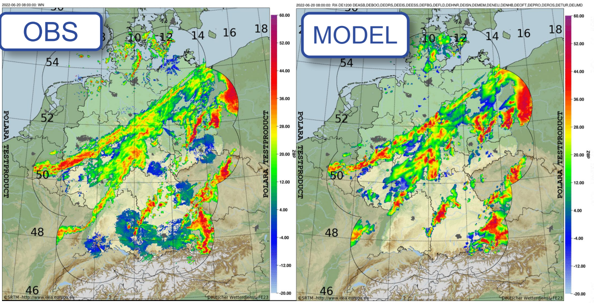
ICON-Seamless

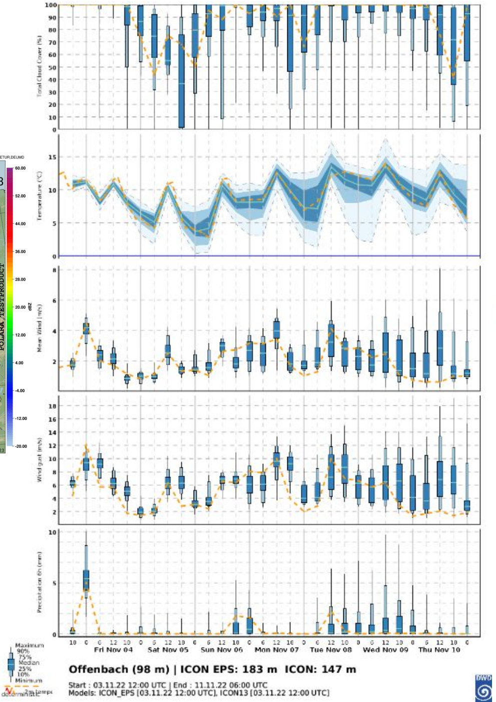


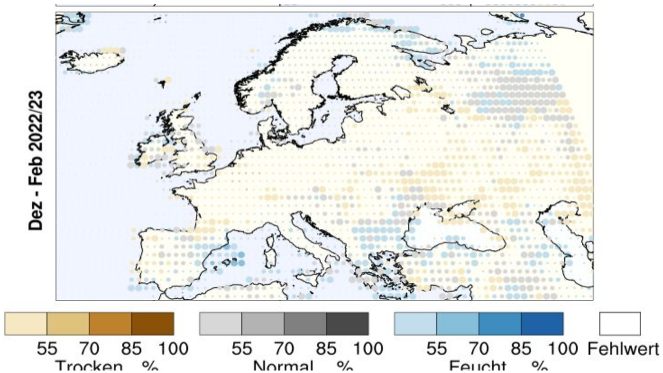


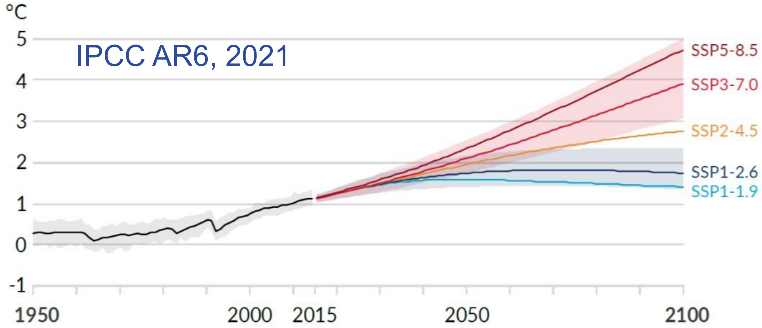
in collaboration with MPI-M, KIT, DKRZ, UHH, MPI-BGC, …

Seamless Prediction









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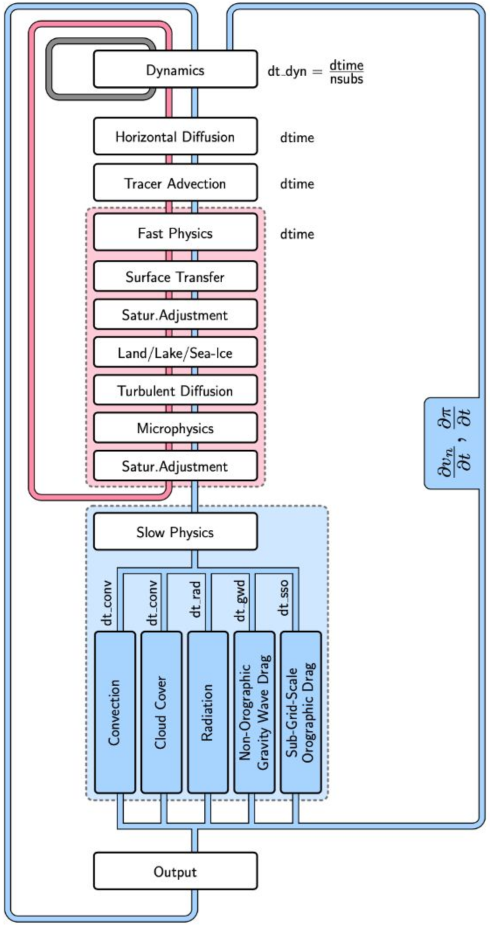
Process	Scheme	Settings
Radiation	~~RRTM (Rapid Radiative Transfer Model)~~ ~~Mlawer et al. (1997), Barker et al. (2003)~~	inwp_radiation=1
	ecRad Hogan and Bozzo (2018)	inwp_radiation=4
Non-orographic gravity wave drag	Wave dissipation at critical level Orr et al. (2010)	inwp_gwd=1
Sub-grid scale orographic drag	Lott and Miller scheme Lott and Miller (1997)	inwp_sso=1
Cloud cover	Diagnostic PDF *M. Köhler et al. (DWD)*	inwp_cldcover=1
	All-or-nothing scheme (grid-scale clouds)	inwp_cldcover=5
Microphysics	Single-moment scheme Doms et al. (2011), Seifert (2008)	inwp_gscp=1, 2
	Double-moment scheme Seifert and Beheng (2006)	inwp_gscp=4
	Warm Spectral Bin Microphysics (SBM) Khain and Sednev (1996), Khain et al. (2004)	inwp_gscp=8
Convection	Mass-flux shallow and deep Tiedtke (1989), Bechtold et al. (2008)	inwp_convection=1
Turbulent transfer	Prognostic TKE (COSMO) Raschendorfer (2001)	inwp_turb=1
	3D Smagorinsky diffusion (for LES) Smagorinsky (1963), Lilly (1962)	inwp_turb=5
Land	Tiled TERRA Schrodin and Heise (2001), Schulz et al. (2016)	inwp_surface=1
	Flake: Mironov (2008)	llake=.TRUE.
	Sea-ice: Mironov et al. (2012)	lseaice=.TRUE.

Operationally used

Rapid update cycle



Dynamics - Physics coupling

- The coupling is performed at constant density (volume)
  → heating rates have to be converted to temperature change using c_v.
- The physics parameterizations work on mass points.
  → Diagnose pressure and temperature, interpolate vn to u, v
- Conversion between the set of thermodynamical variables is reversible, but the interpolation between velocity points and mass points can introduce errors.
- After the atmospheric state was updated by the fast processes the atmospheric state has to be converted back to the ICON prognostic variables.

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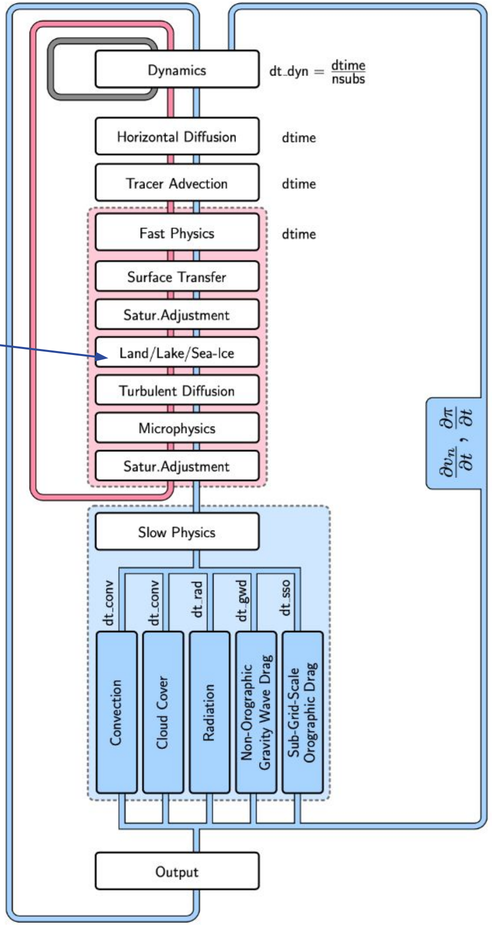
Fast physics:
- Called every time step
- Processes update atmospheric state sequentially



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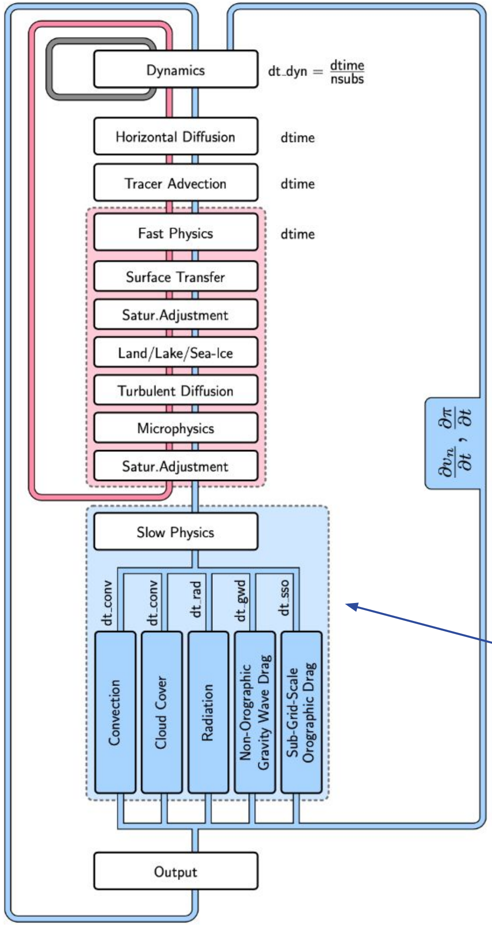
```
dt_rad      = 120.
dt_conv     = 360., 180.
dt_sso      = 720., 360.
dt_gwd      = 720., 360.
```

Parent domain

Child domain



Slow physics:
Called every k^th time step

- All processes computed on the same state
- Tendencies are passed to the dynamical core
- Parallel split

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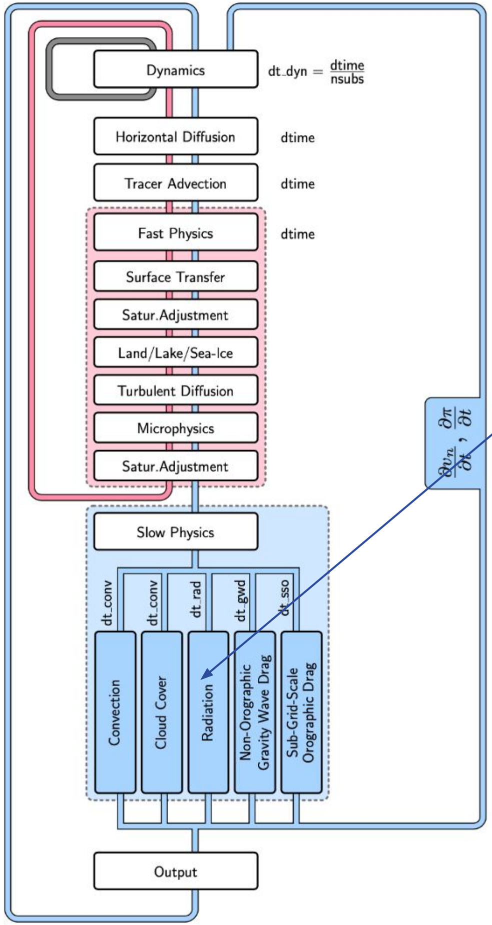
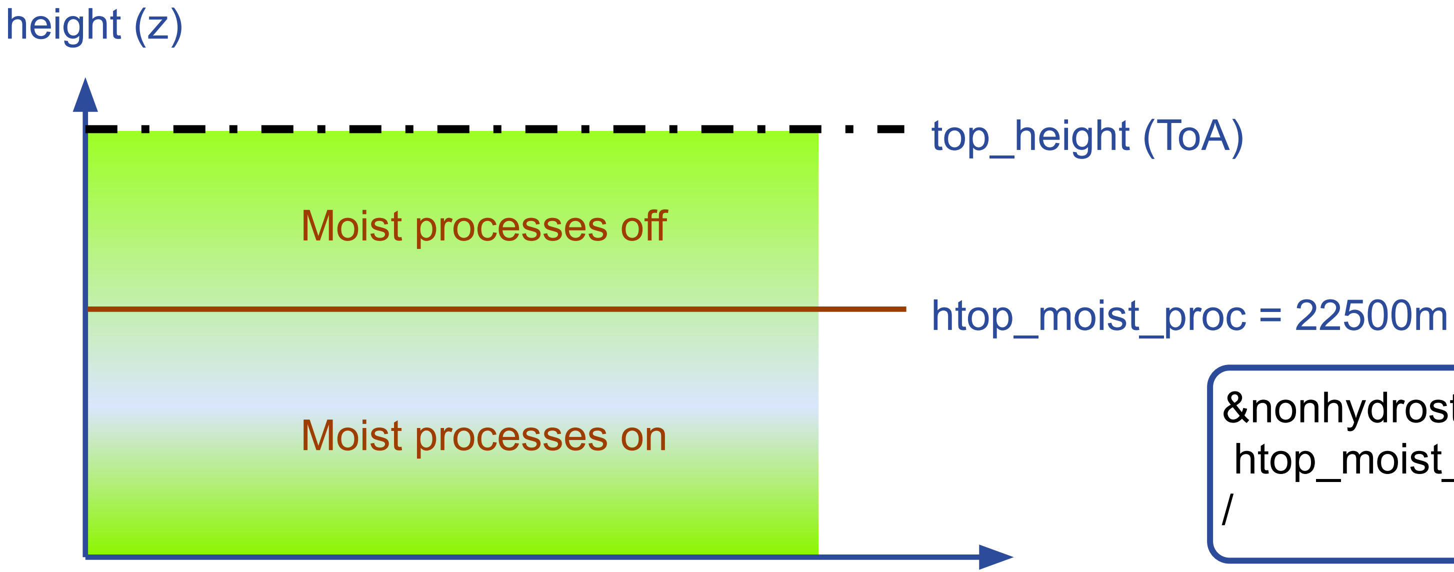


ICON also allows to sub-sample the radiation in space and calculate the radiation on a coarser grid.

Moist physics off in stratosphere



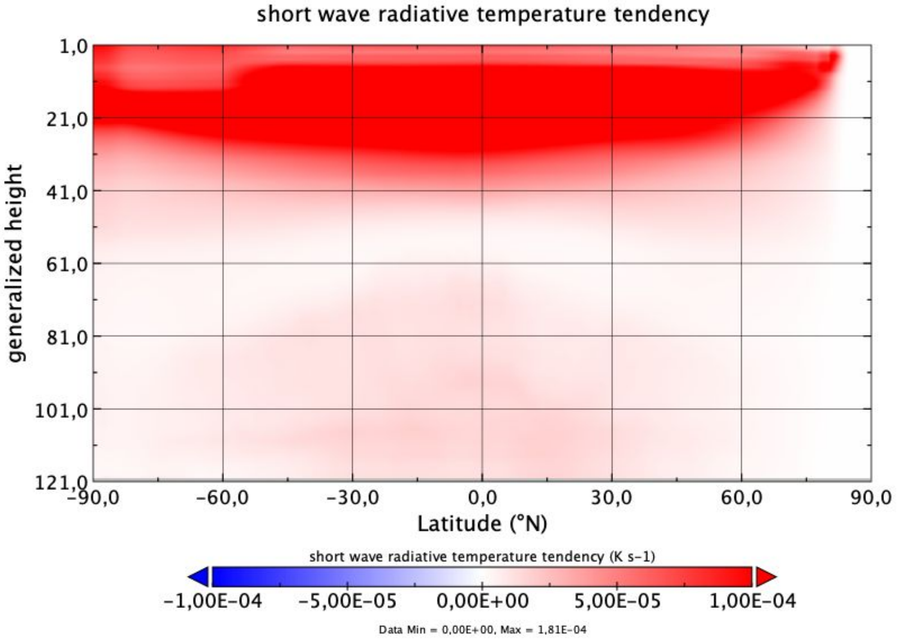

```
&nonhydrostatic_nml
 htop_moist_proc          =  22500
/
```

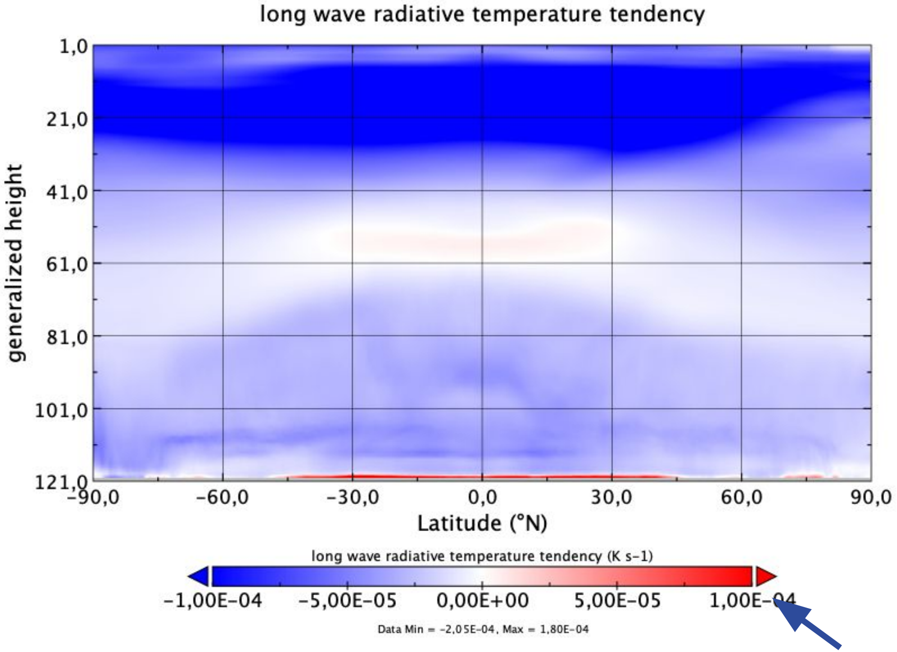
For efficiency reasons the moist physics can be switched off above a certain level, as well as transport of all water species but vapor.

∂T/ ∂t from radiation

Short-wave Long-wave

March 1st- March7th, 2023



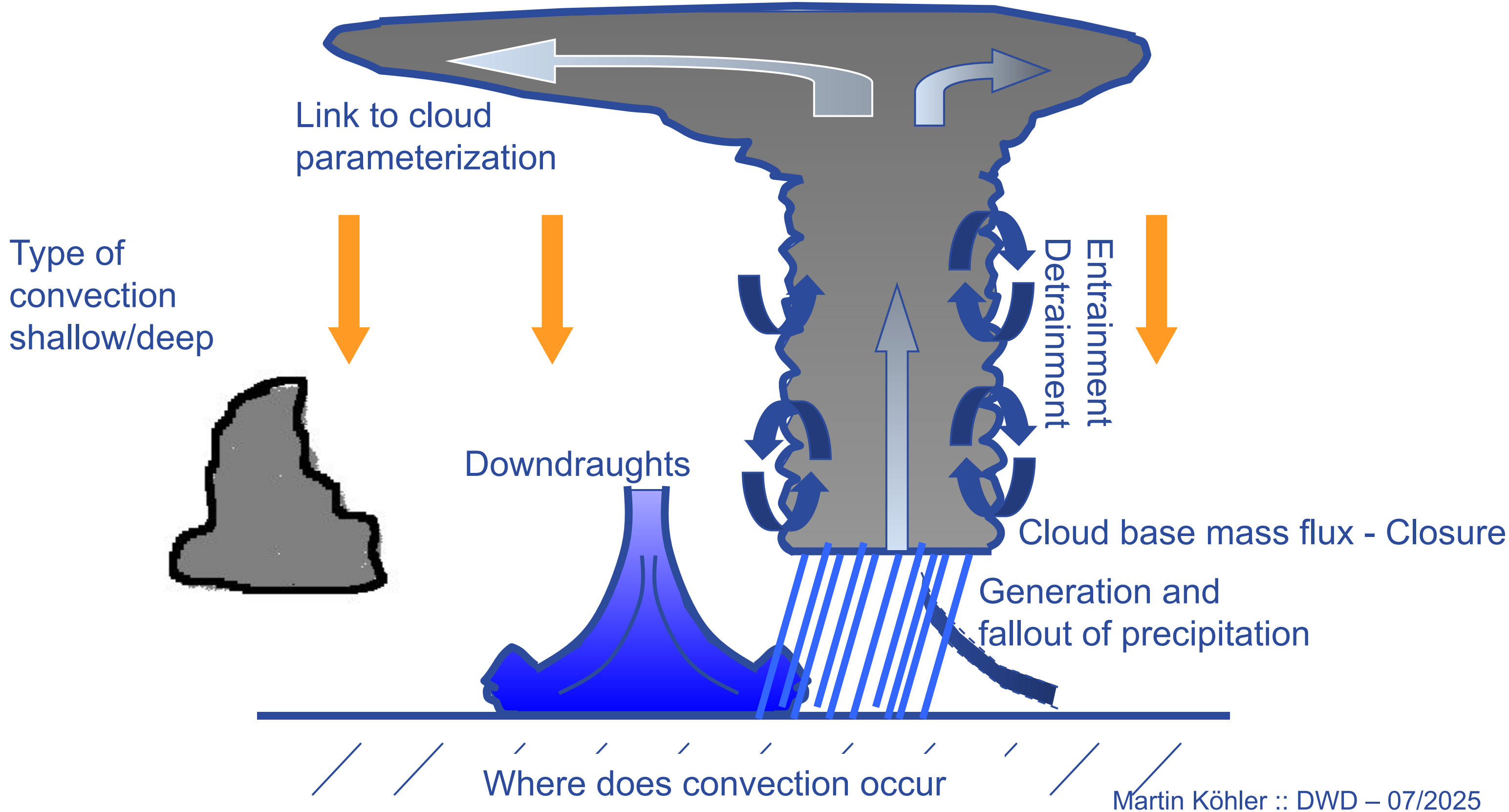


≙ 8.64 K/day

Convection

Source: https://learnweather.com/basic-weather/convective-cloud-types-mk/

Tiedtke/Bechtold bulk mass flux scheme



Tiedtke/Bechtold bulk mass flux scheme

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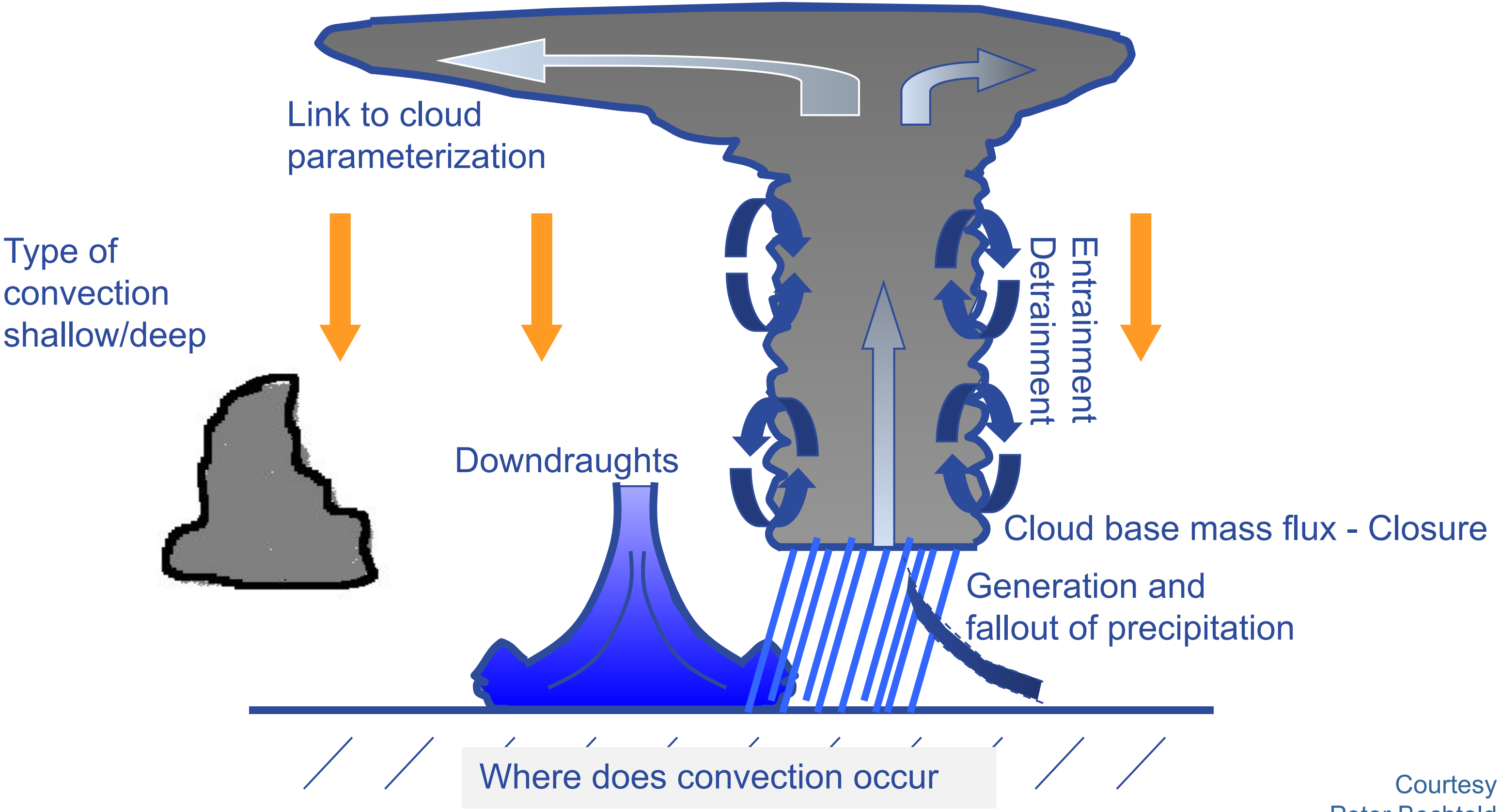
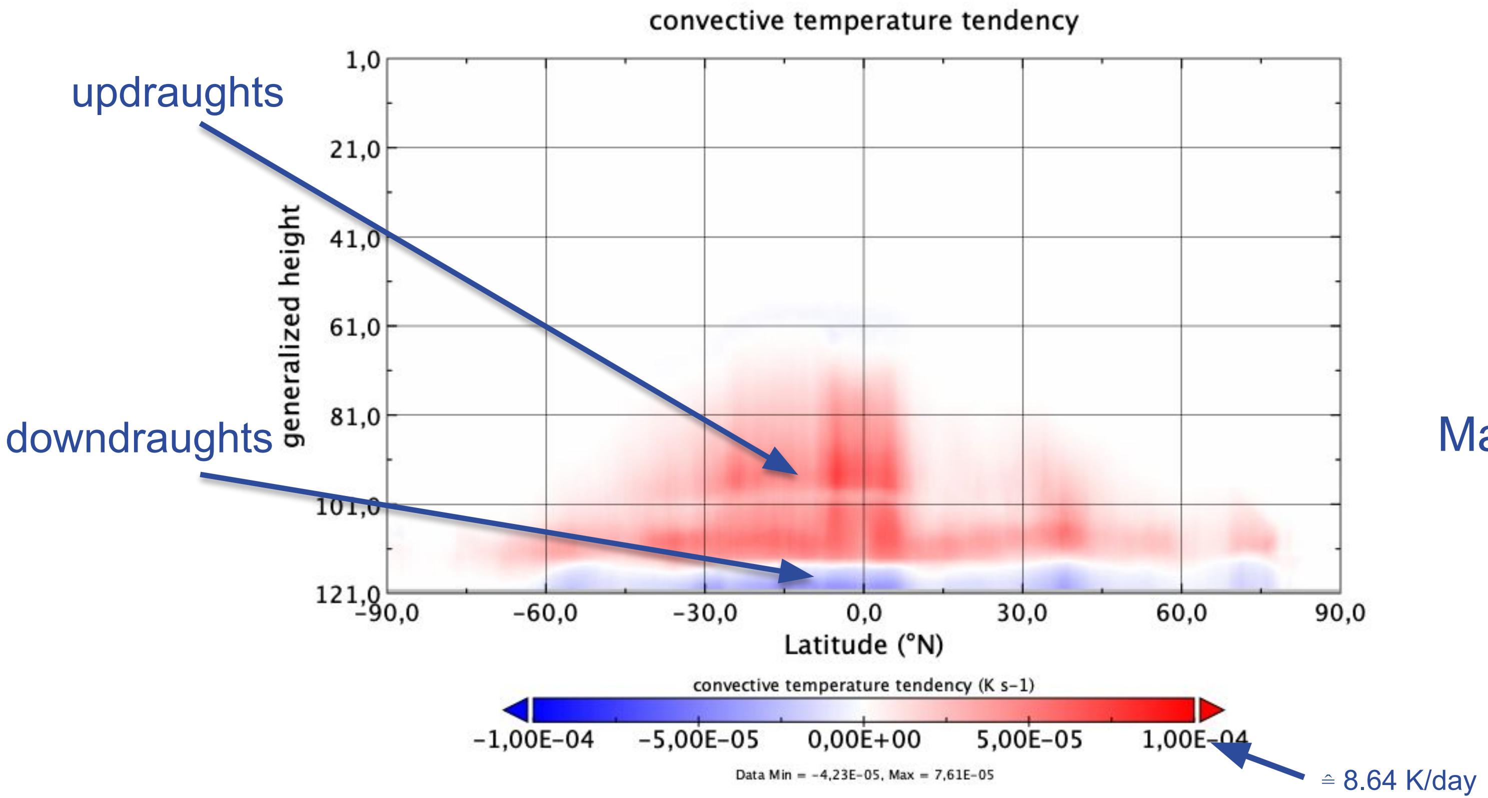


Courtesy
Peter Bechtold

∂T/∂t from convection

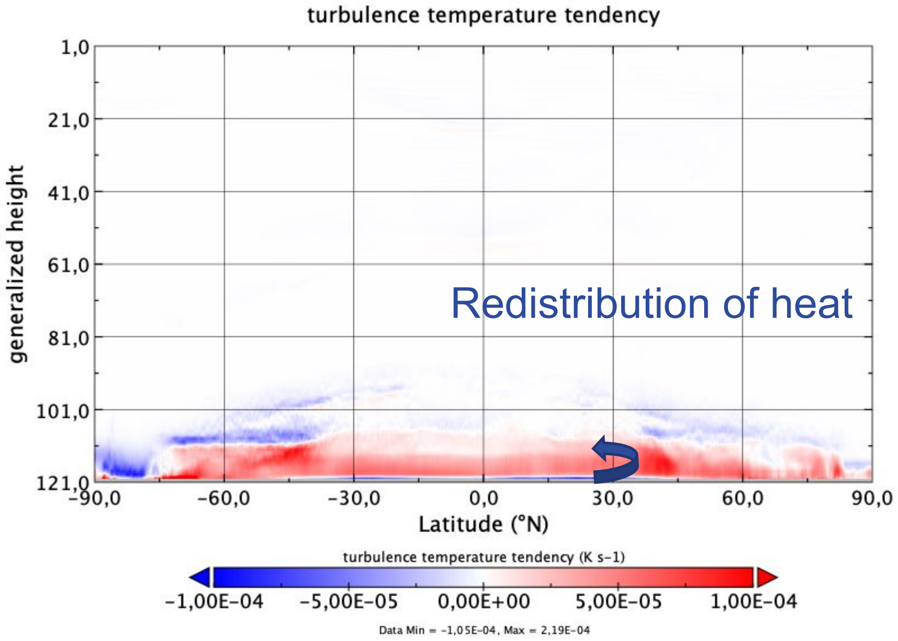


March 1st-
March7th, 2023

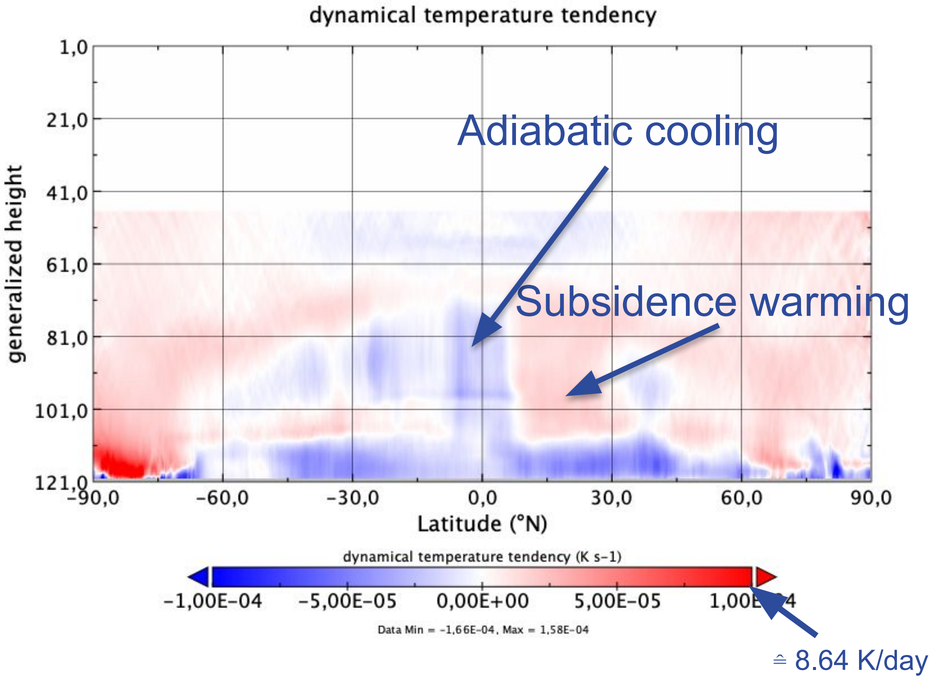
∂T/∂t turbulence and dynamics

March 1st- March7th, 2023

Turbulence



Dynamics



Subgrid-scale orography (SSO) and GWD

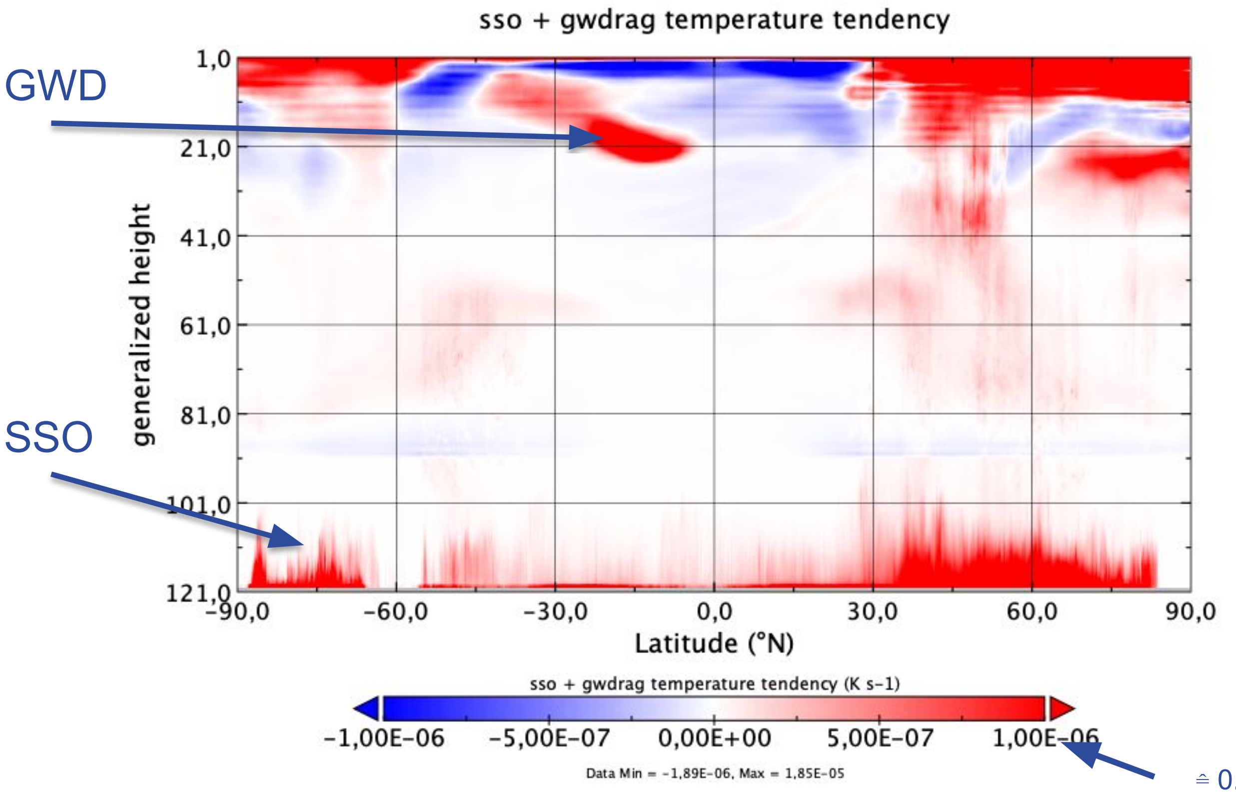
1. Sub-grid scale orography (Lott & Miller 1997):
   - unresolved orography: sink for momentum (drag).
   - stably stratified flows: effects of low-level blocking and reflection and/or absorption of vertically propagating gravity waves.

   →The sub-grid information of the orography is included in the external parameters.

2. Non-orographic gravity wave drag (Orr et al. 2010):
   - wave breaking effects
     - convection
     - shear zones, or frontal disturbances

   travel from the troposphere up and break in the middle atmosphere → drag on the flow.

∂T/∂t from SSO and GWD



≙ 0.0864 K/day

March 1st-
March7th, 2023

Cloud cover

- ICON predicts and advects grid-scale specific water quantities (qv, ql, qi, qr, qs, qg, qh) which are used by the micro-physics and radiation.
- The turbulence scheme calculates a temporary cloud cover for the use in the calculation of the buoyancy flux.
- The diagnosed clouds impact radiation + latent heat release.
- Distinction between stratiform and convective clouds.
- Cloud cover is diagnosed at dt_rad.

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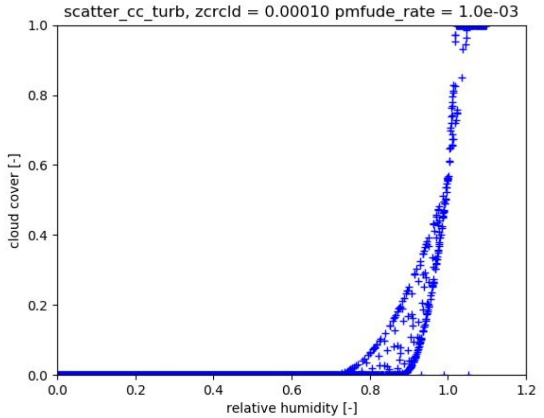
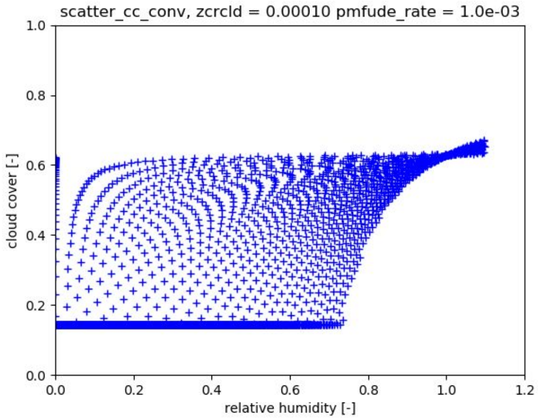
Cloud cover

stratiform part



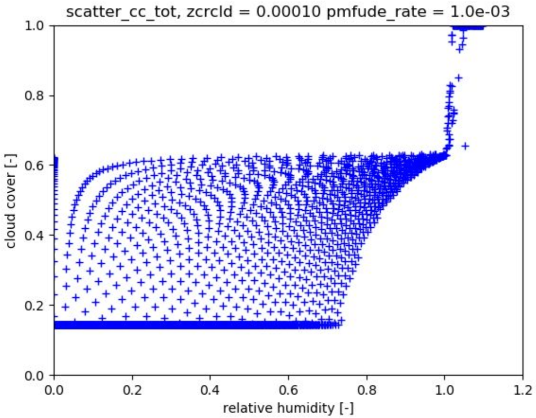
+

convective part



=

total



Function of std. dev. of saturation deficit σ_{dqs} (rcld)

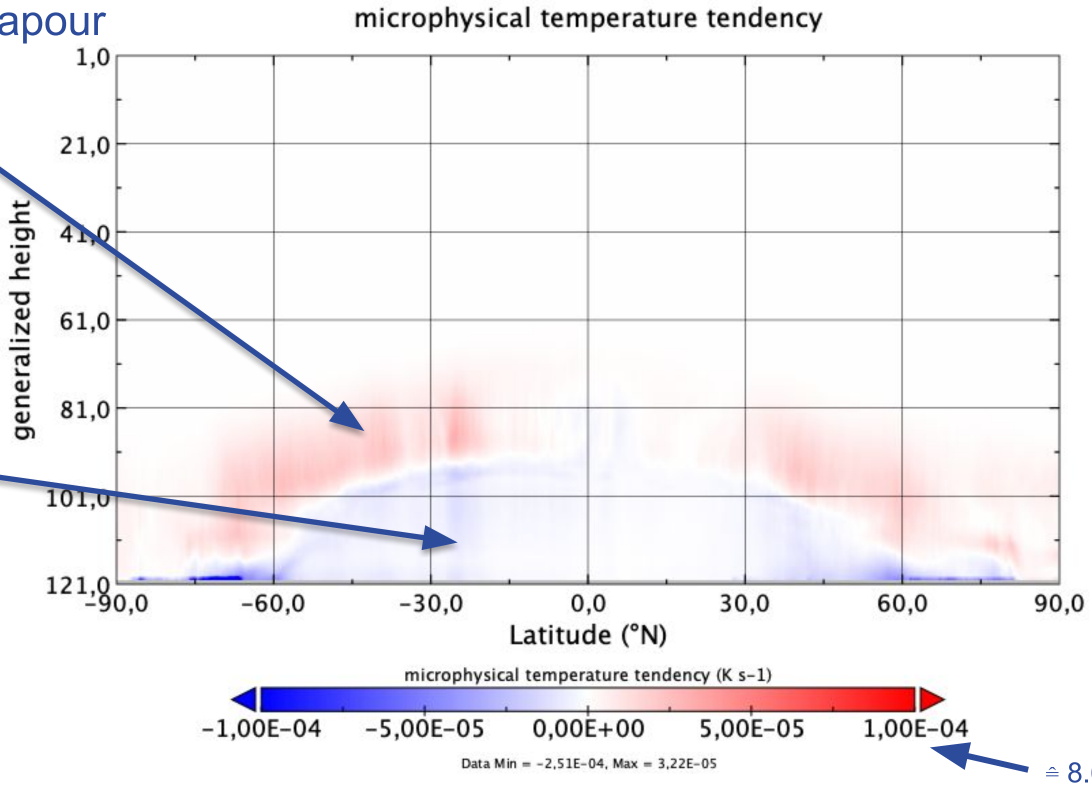
diagnostic anvil cloud cover that is a function of detrainment (convection scheme) and decay time-scale.

cc_tot = max(cc_turb, cc_conv)
qc_tot = max(qc_turb, qc_conv)
qi_tot = max(qi_turb, qi_conv)

∂T/∂t microphysics + saturation adjustment

Latent heating (vapour -> liquid)

Latent cooling (evaporation of precipitation)



≙ 8.64 K/day

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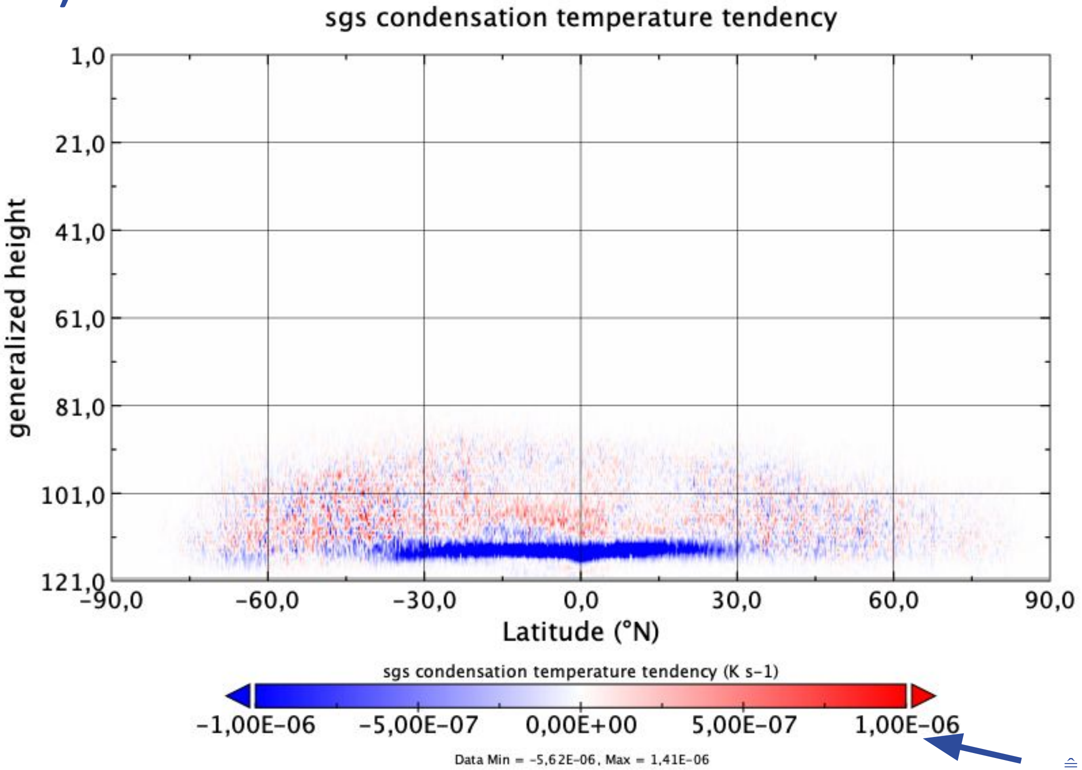
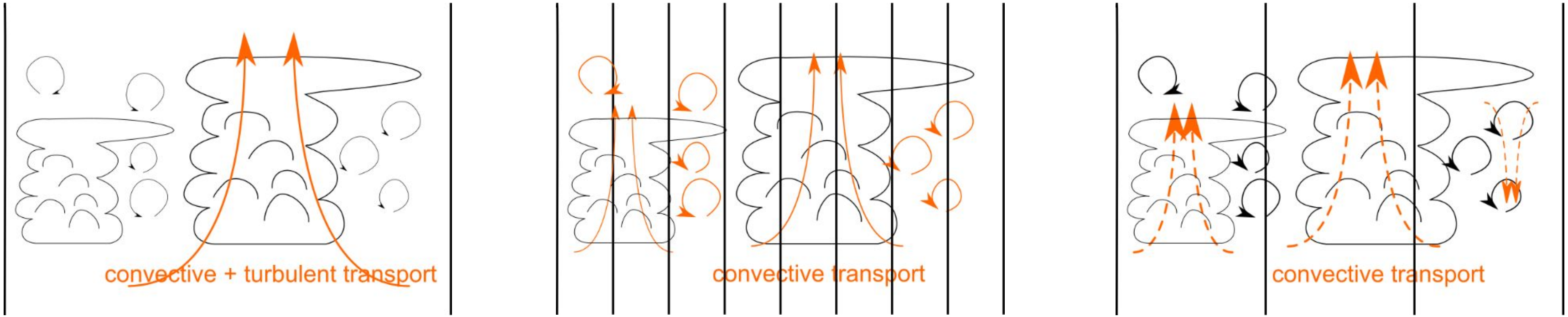
∂T/∂t from cloud cover (sgs latent heat release)



≙ 0.0864 K/day

March 1st-
March7th, 2023

„Grey-zone“ of physical parametrizations (terra incognita)



coarse model
$\Delta x > \sim 10km$
process parametrized

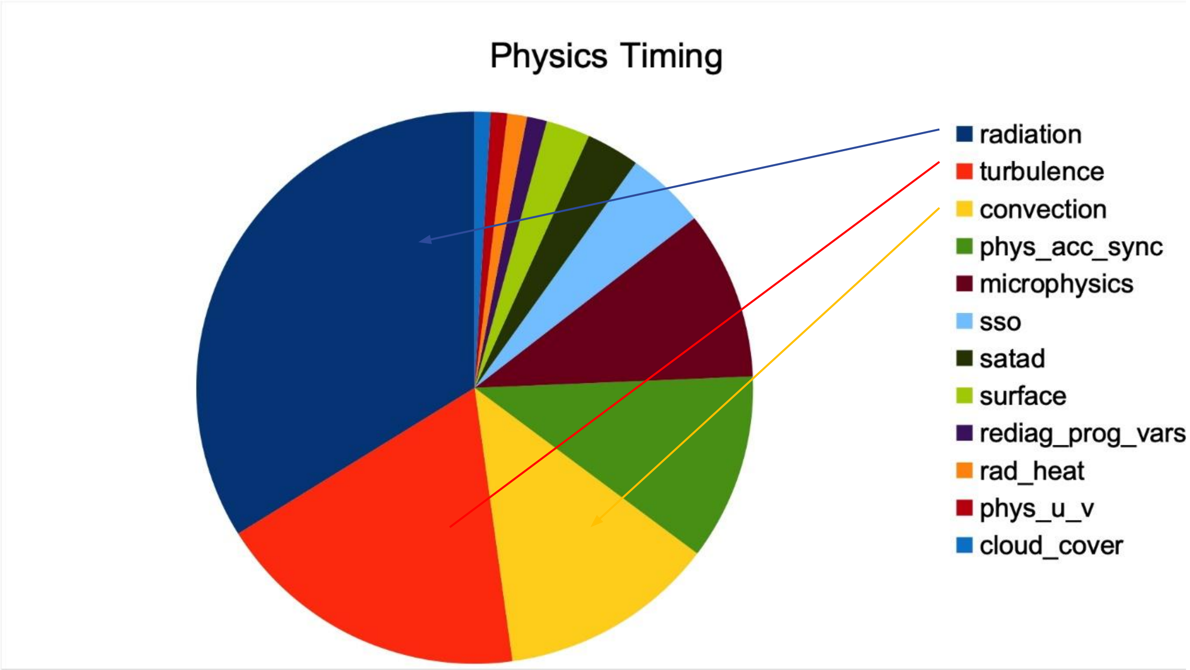
fine model
$\Delta x < \sim 100\ m$
process resolved

grey zone:
process partially resolved
and partially parametrized

Particularly affected: convection and turbulence scheme

Physics Timing

total	1512.791
sum	1509.505
radiation	511.137
turbulence	276.568
convection	189.923
phys_acc_sy	164.354
microphysics	149.066
sso	69.826
satad	46.94
surface	38.415
rediag_prog_	17.54
rad_heat	17.325
phys_u_v	14.568
cloud_cover	13.843



Summary

- There is a huge variety of physical processes in the atmosphere, acting on different temporal and spatial scales feeding back onto different scales
- Different approaches are followed to represent the different processes
- An in-depth introduction to some of the individual schemes used for numerical weather prediction in ICON at DWD will be given from tomorrow onward.

Questions?

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Quiz Time

- https://partici.fi/65152793

partici.fi/65152793

Quiz Time

- https://partici.fi/20151793

partici.fi/20151793