Introducing libmpdata++ and libcloudph++: reusable software components for atmospheric modelling

Sylwester Arabas[1],
Wojciech W. Grabowski[2], Anna Jaruga[1], Dorota Jarecka[2,1],
Hanna Pawłowska[1], Piotr K. Smolarkiewicz[3], Maciej Waruszewski[1]

1: University of Warsaw, 2: NCAR, 3: ECMWF

6th GCRM & 3rd NHM @ RIKEN AICS, Kobe, Sep. 25th 2014

aerosol-cloud interactions

aerosol-cloud interactions: a conceptual picture

background image: vitsly.ru / Hokusai

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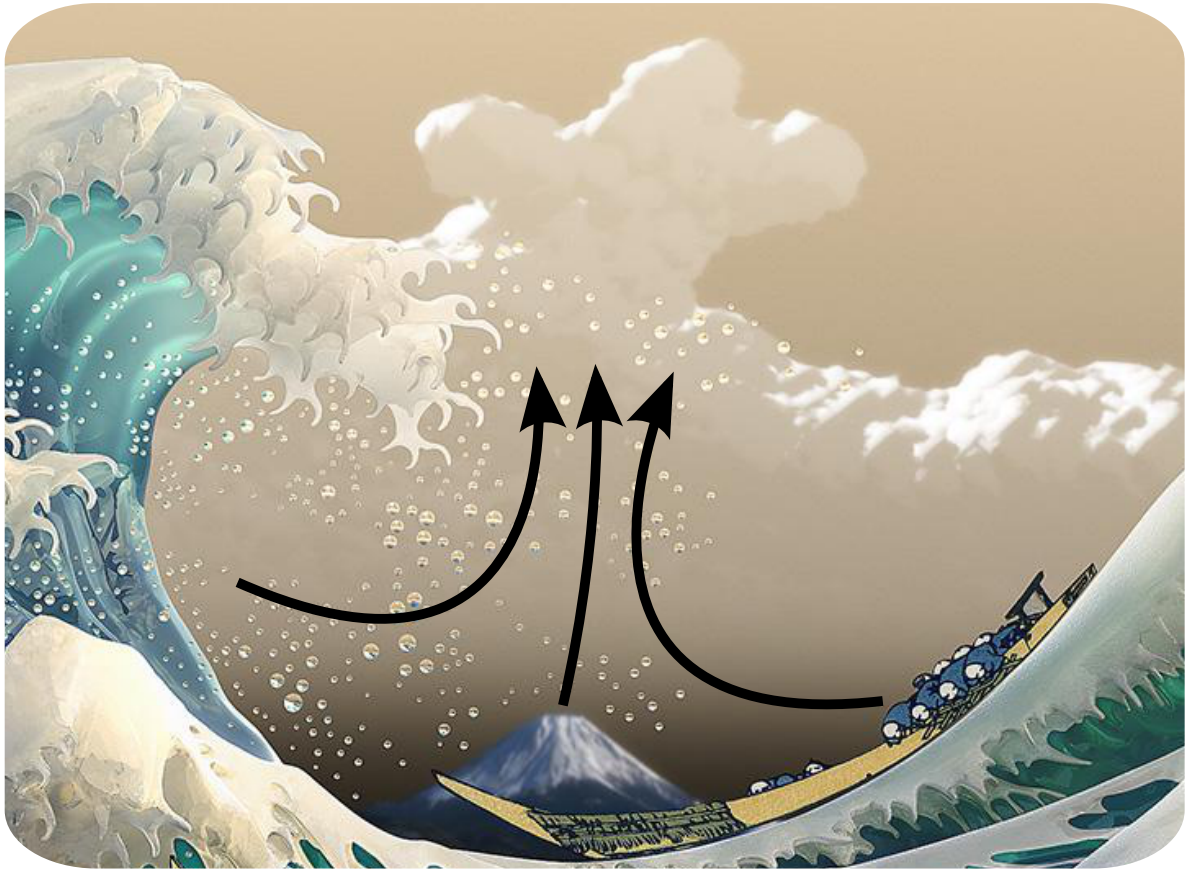

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two-way interactions:
- aerosol characteristics influence cloud microstructure
- cloud processes influence aerosol size and composition

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- result reproducibility (open source, easy to use)

free & open-source C++ libraries developed at our group

libmpdata++ / arXiv:1407.1309 / submitted to GMD

libmpdata++ 0.1: a library of parallel MPDATA solvers for systems of generalised transport equations

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libmpdata++: 1D advection / hello world

$$\partial_t(G\psi) + \nabla \cdot (G\vec{u}\psi) = GR$$

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Smolarkiewicz's MPDATA scheme

- sign-preserving
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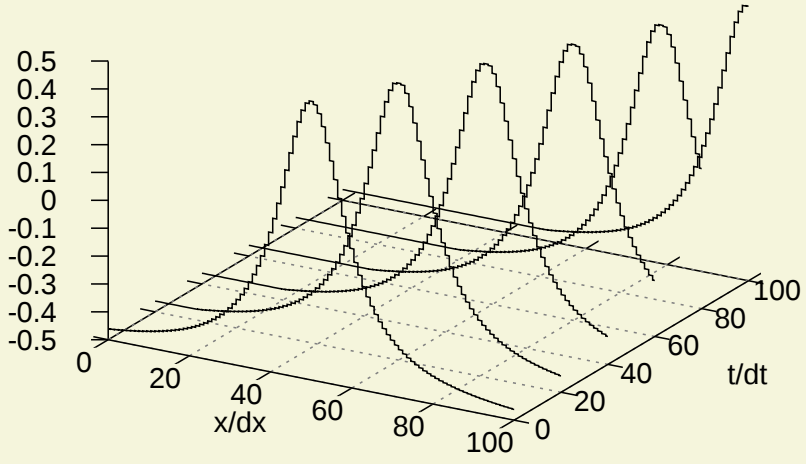

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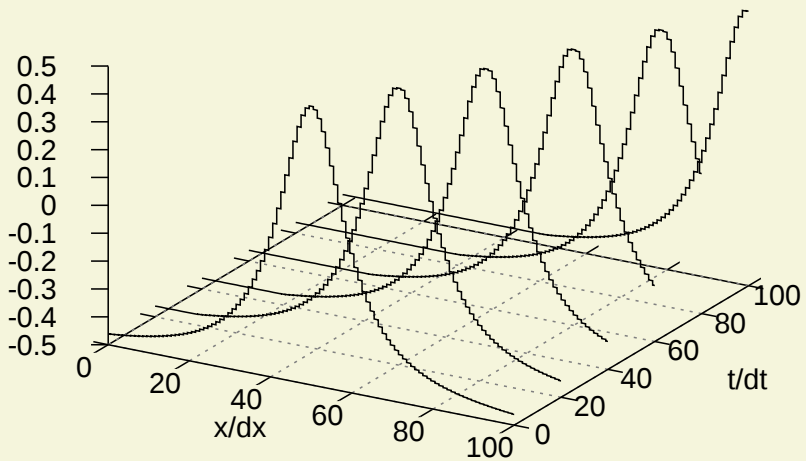
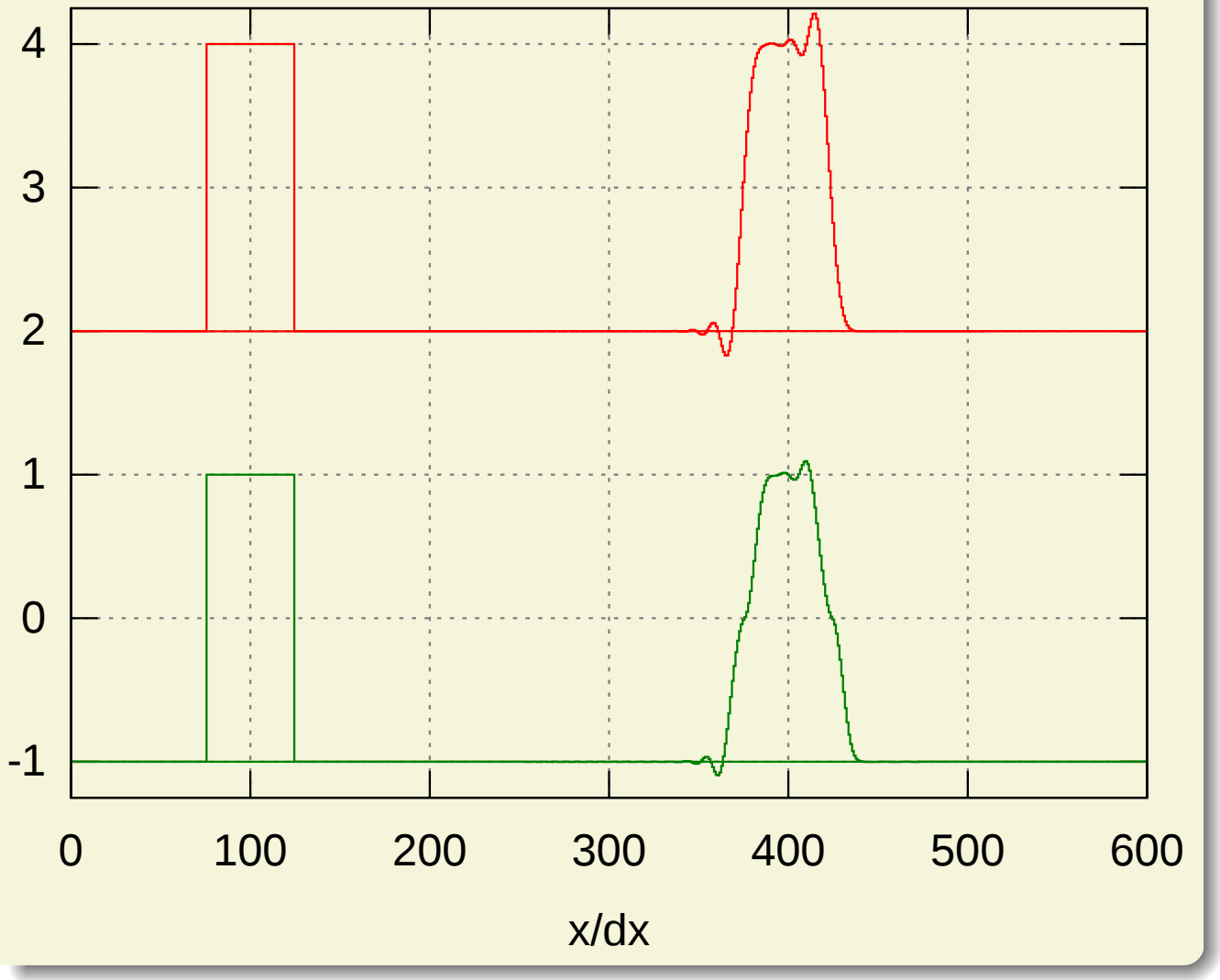


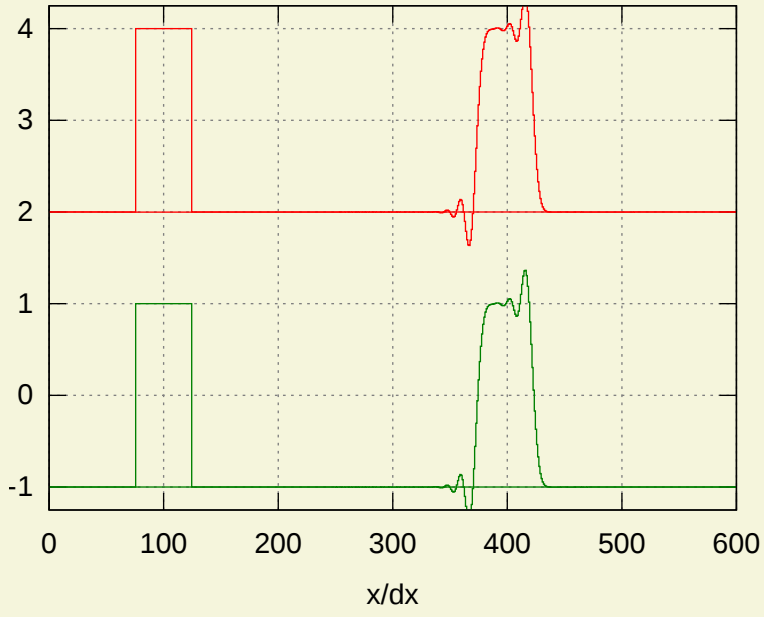

```
 1 #include <libmpdata++/solvers/mpdata.hpp>
 2 #include <libmpdata++/concurr/serial.hpp>
 3 #include <libmpdata++/output/gnuplot.hpp>
 4
 5 using namespace libmpdataxx;
 6 using namespace blitz::tensor;
 7
 8 int main()
 9 {
10   // compile-time parameters
11   struct ct_params_t : ct_params_default_t
12   {
13     using real_t = double;
14     enum { n_dims = 1 };
15     enum { n_eqns = 1 };
16   };
17
18   // solver choice
19   using slv_t = solvers::mpdata<ct_params_t>;
20
21   // output choice
22   using slv_out_t = output::gnuplot<slv_t>;
23
24   // concurency choice + boundary conditions
25   using run_t = concurr::serial<slv_out_t,
26     bcond::open, bcond::open>;
27
28   // run-time parameters
29   typename slv_out_t::rt_params_t p;
30   int nx = 101, nt = 100;
31   ct_params_t::real_t dx = 0.1;
32   p.grid_size = { nx };
33   p.outfreq = 20;
34
35   run_t run(p);                  // instantiation
36   run.advectee() =               // initial cond.
37     -.5 + 1 / (pow(dx*(i - (nx-1)/2.), 2) + 1);
38   run.advector() = .5;           // Courant number
39   run.advance(nt);               // integration
40 }
```

libmpdata++: implemented MPDATA flavours

basic 2-pass MPDATA + “abs” trick for var-sign signals



infinite-gauge option ("iga")



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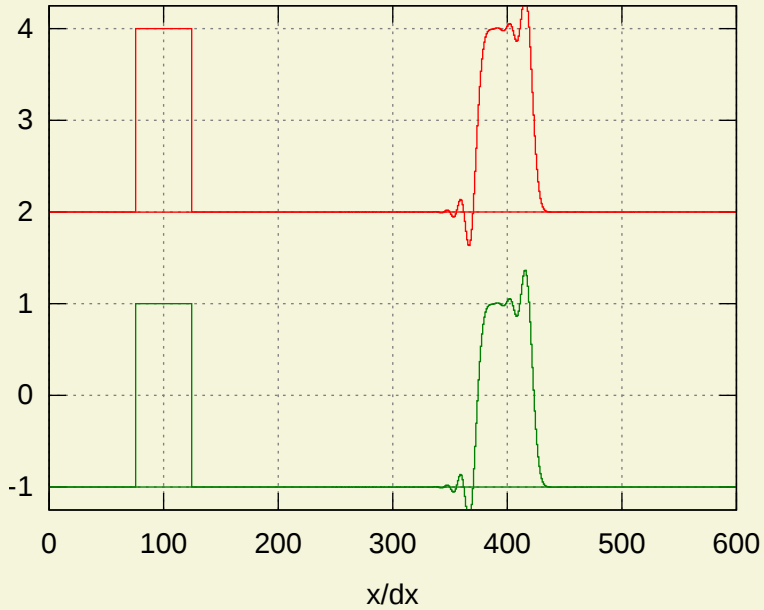
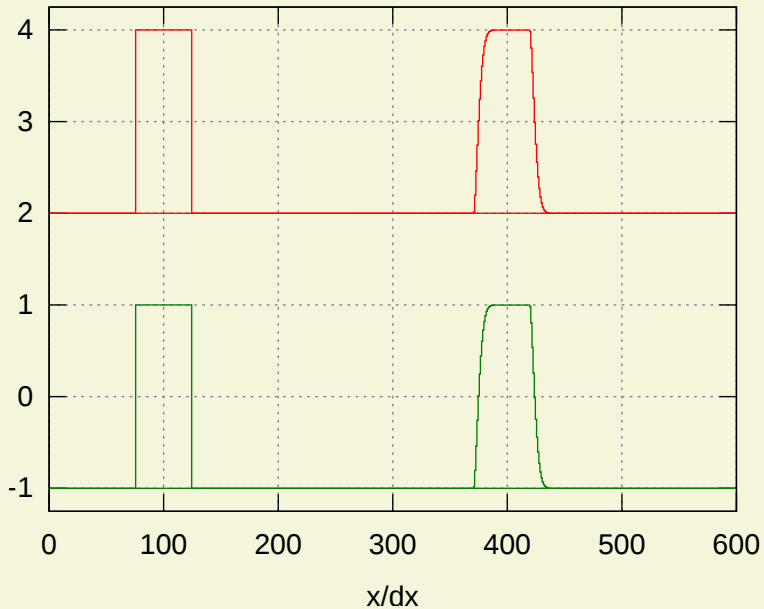


iga + non-oscillatory option ("fct")



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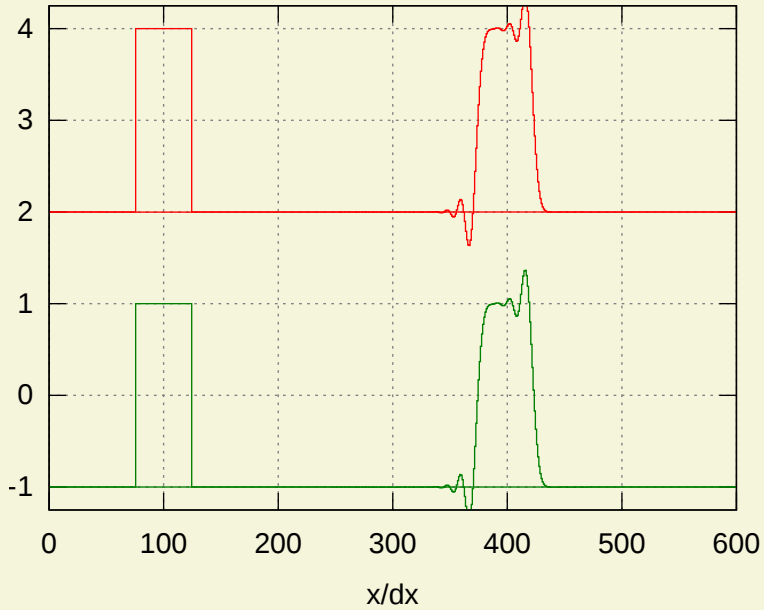
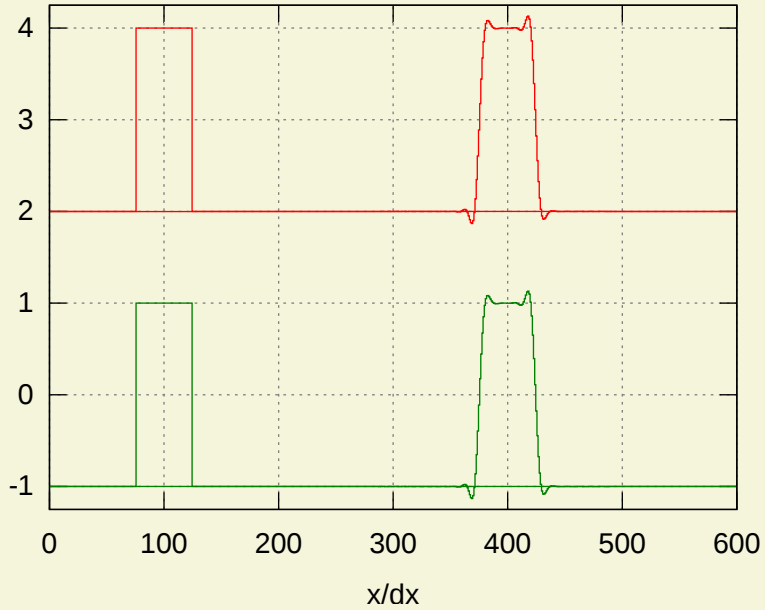


iga + 3rd-order-accurate variant ("tot")



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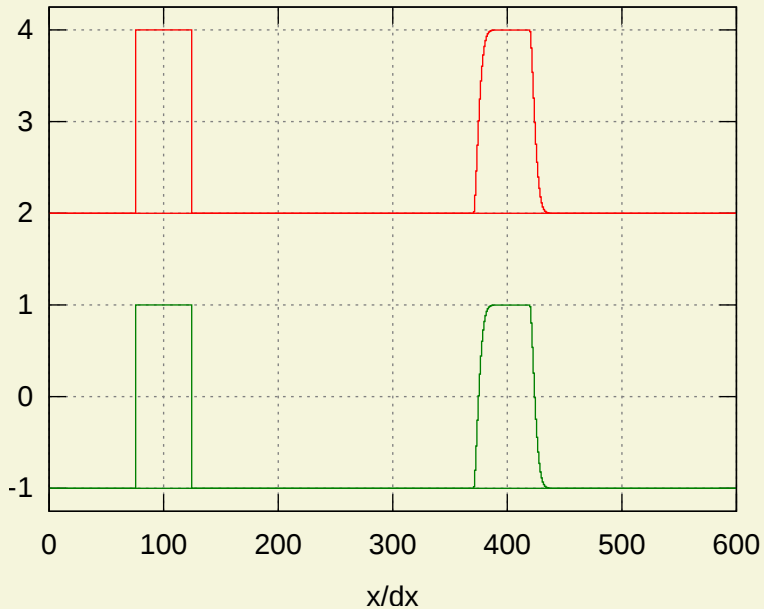

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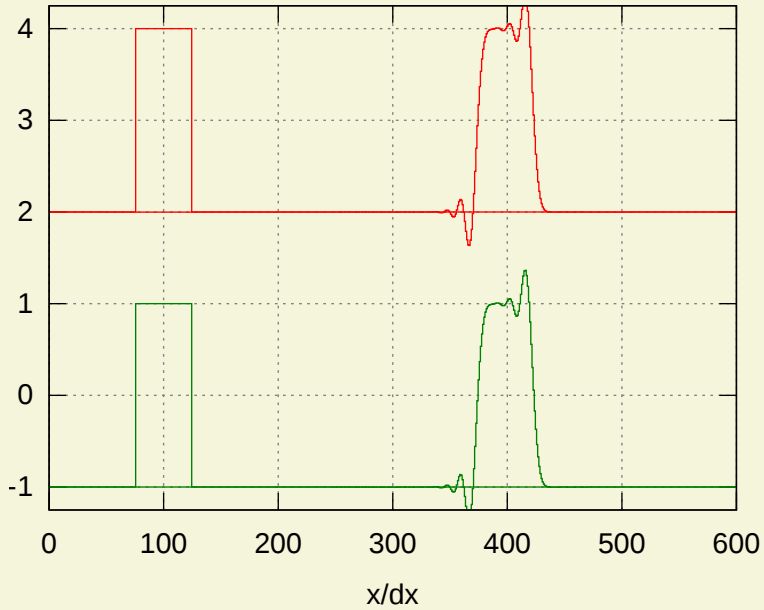

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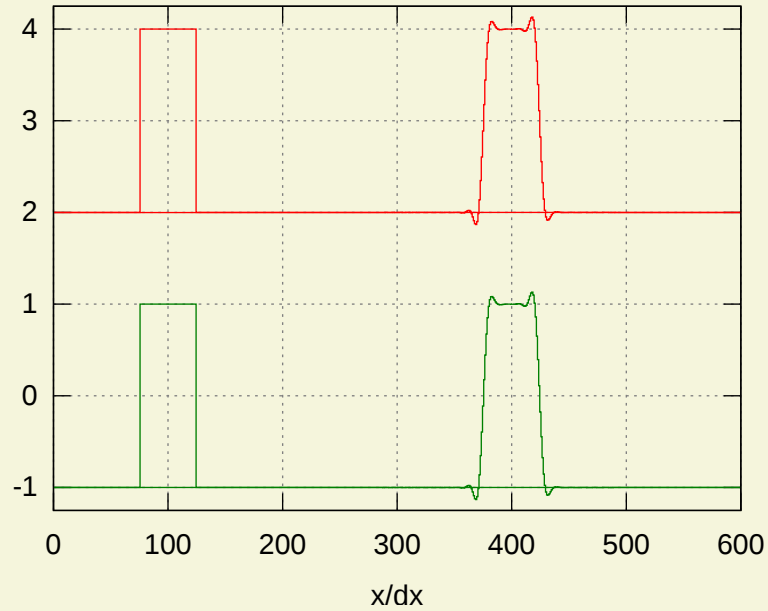

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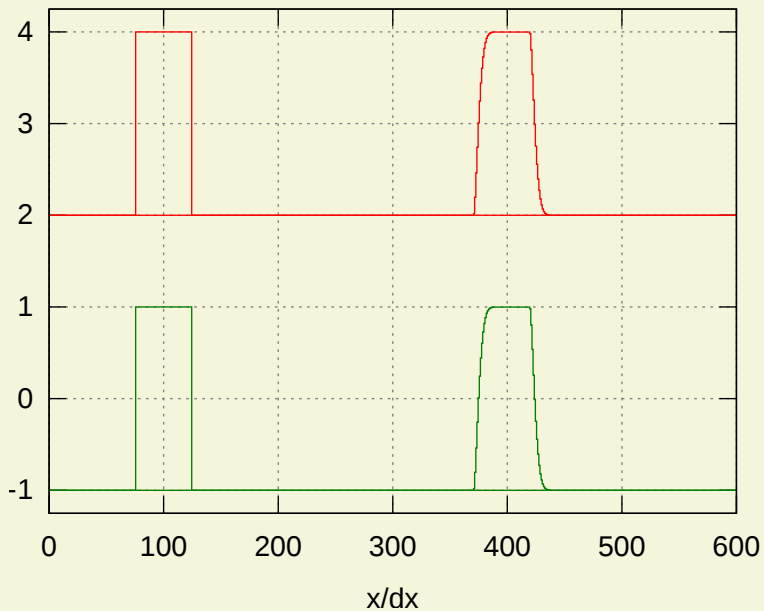

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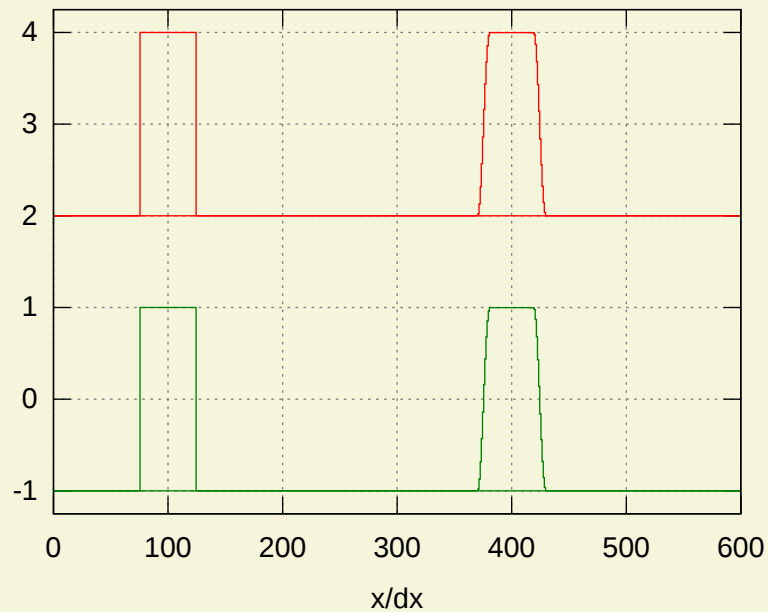
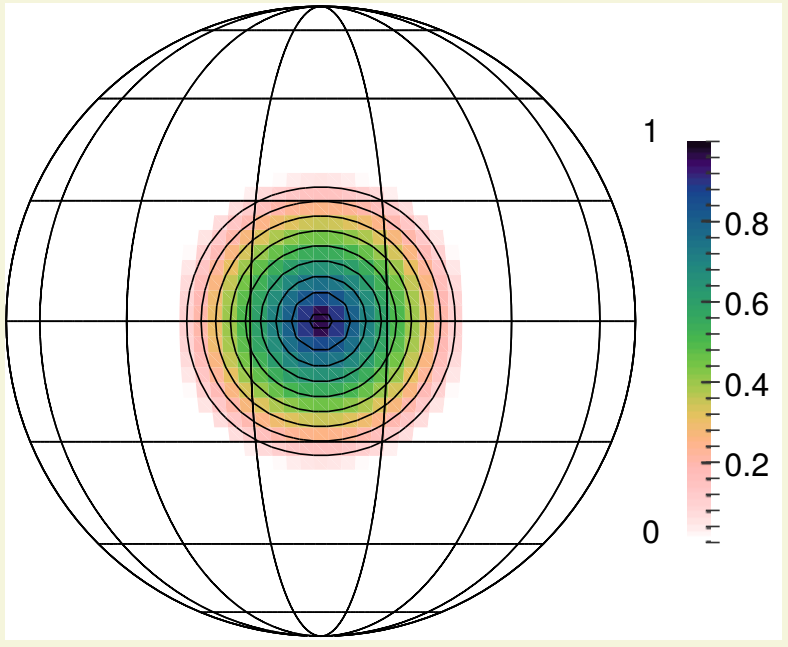
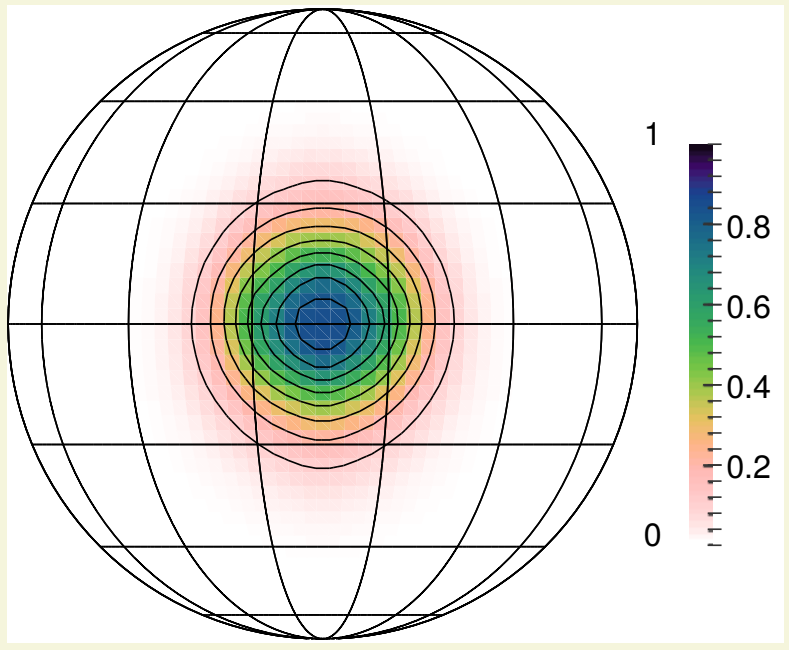


libmpdata++: 2D advection on a sphere

$t = 0$
cone-shaped signal (128×64)
over-the-pole advection



$t/\Delta t = 5120$ (one revolution)
3-pass FCT MPDATA
with third-order terms



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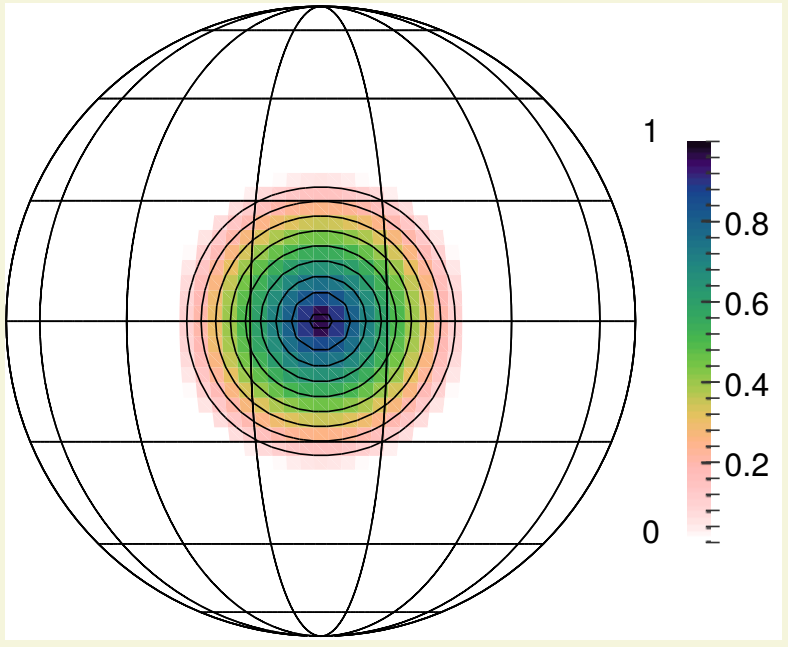

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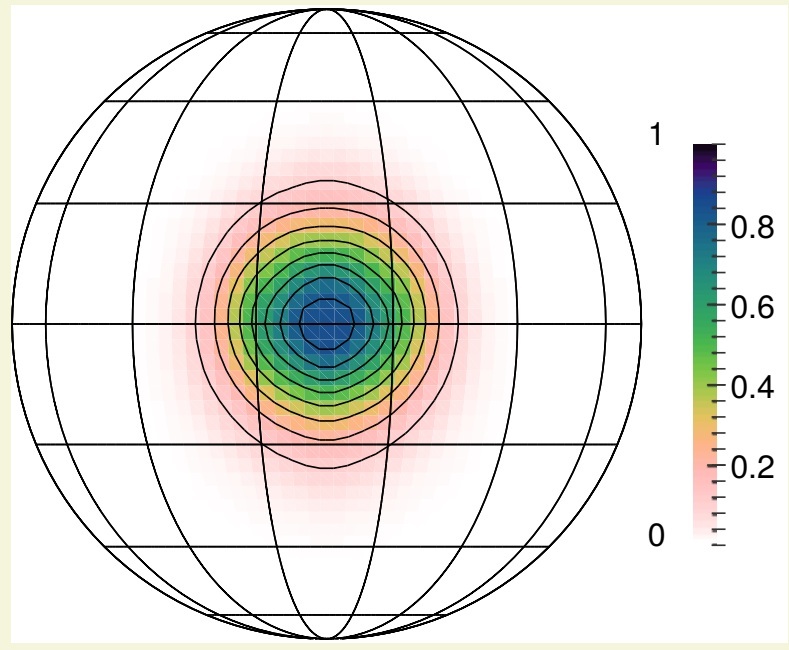

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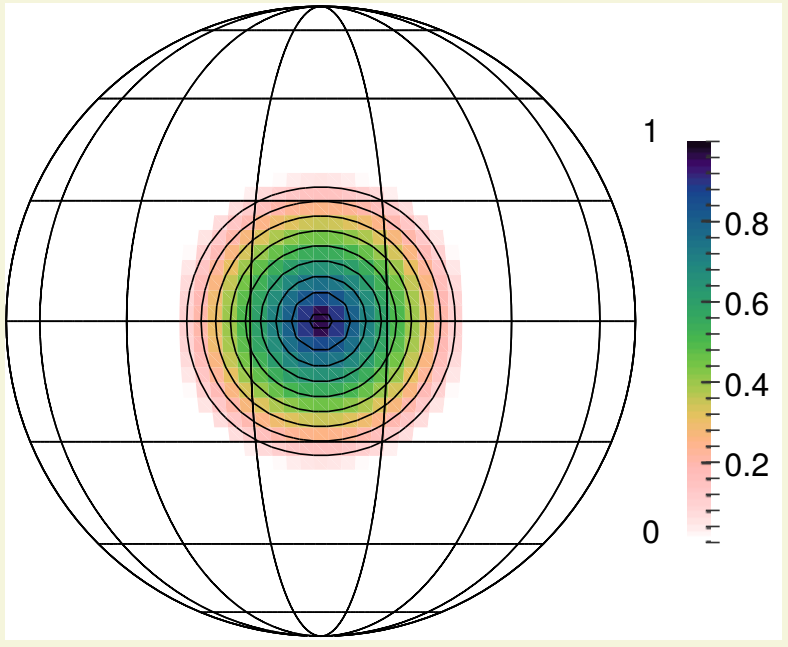

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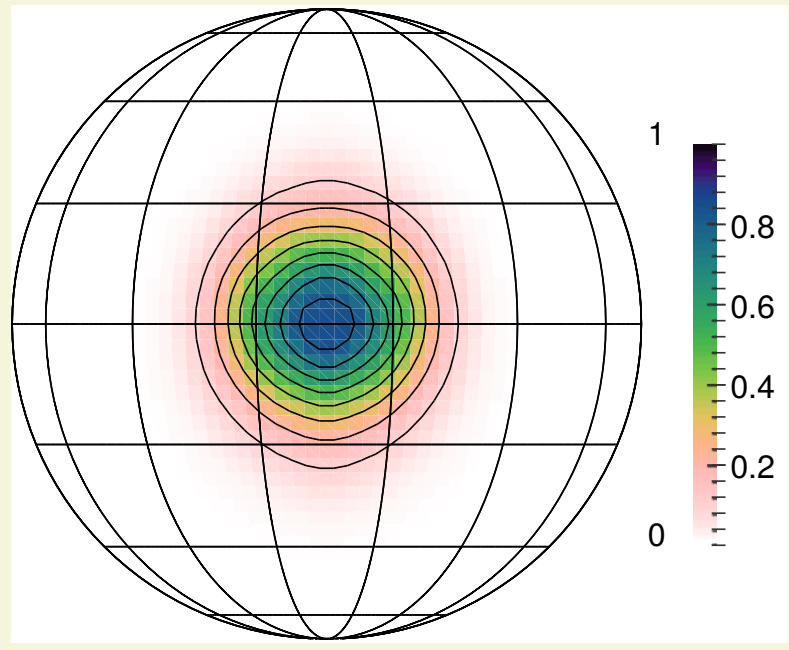

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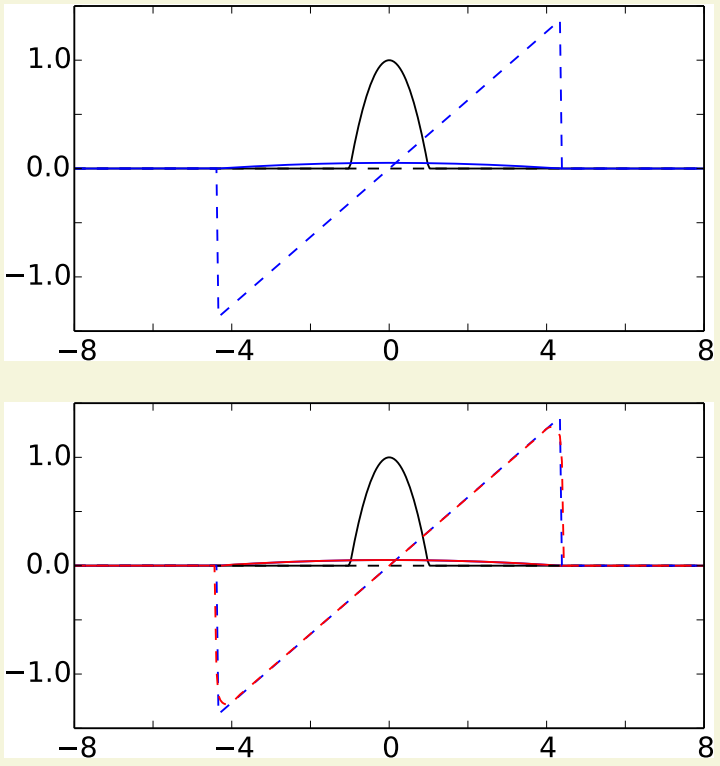
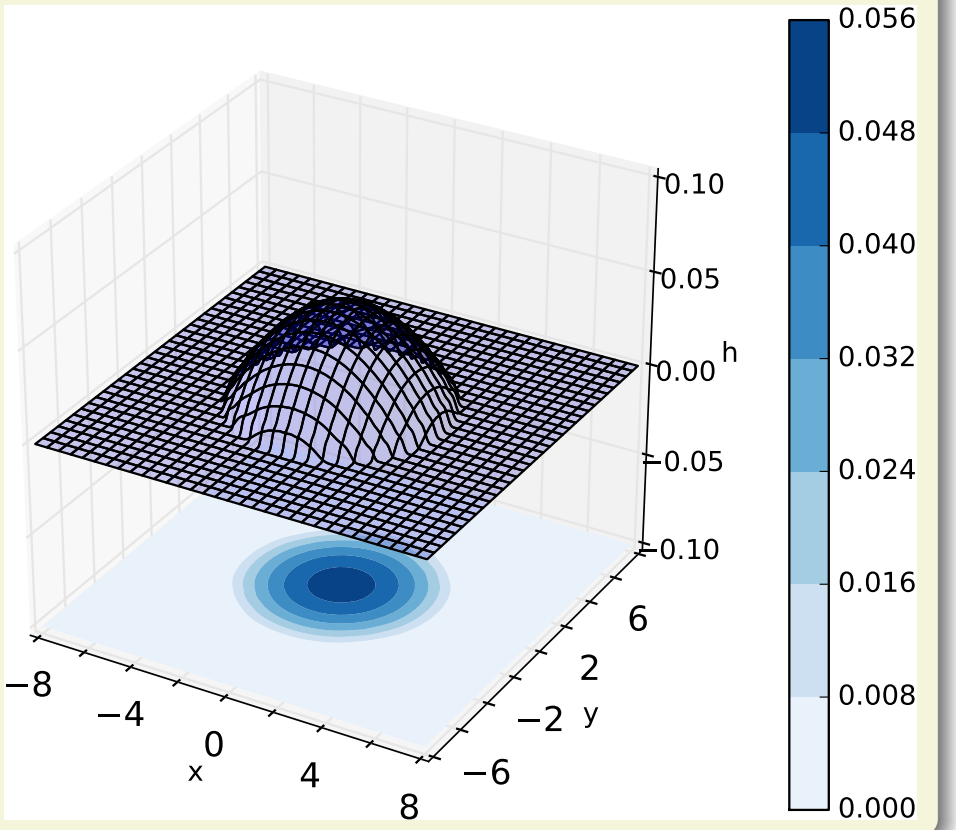
black: initial; blue: analytic; red: MPDATA



initial condition



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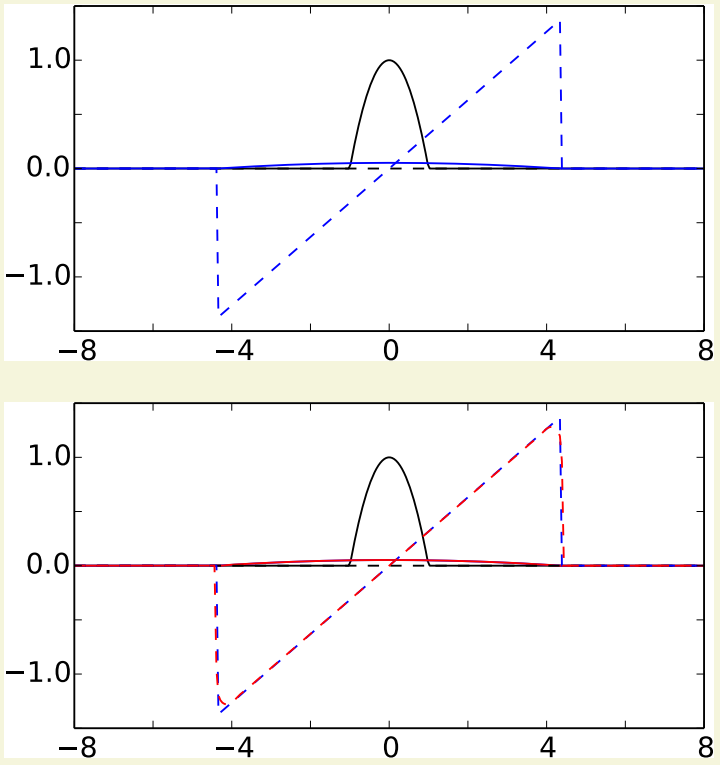

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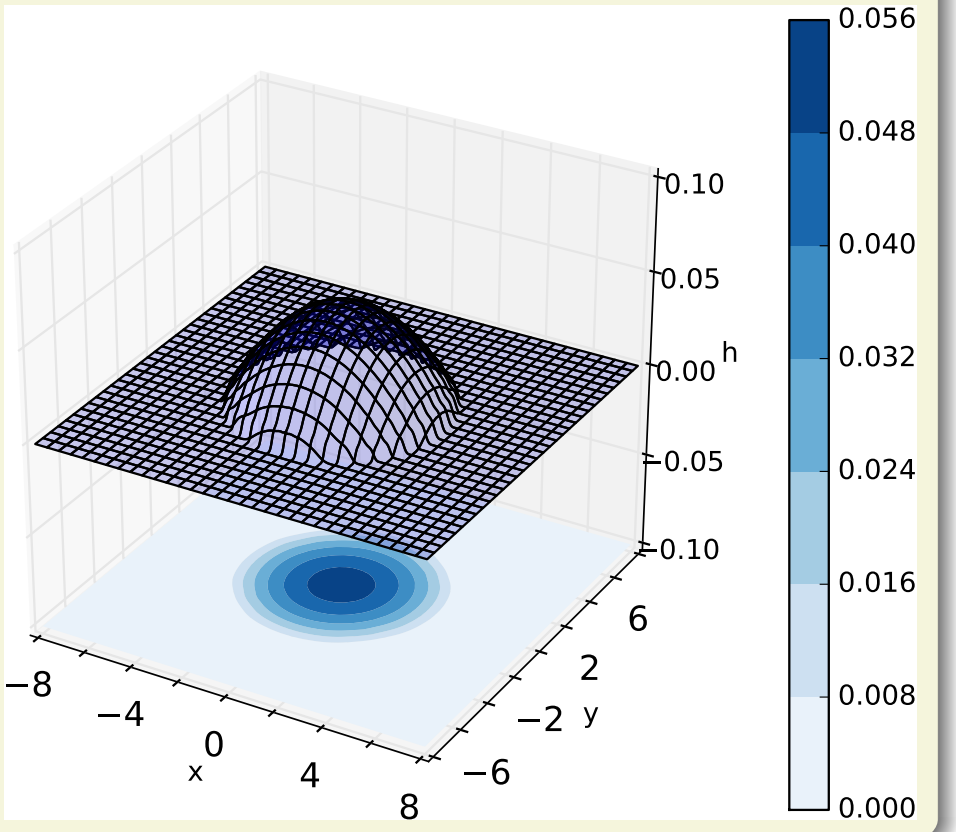

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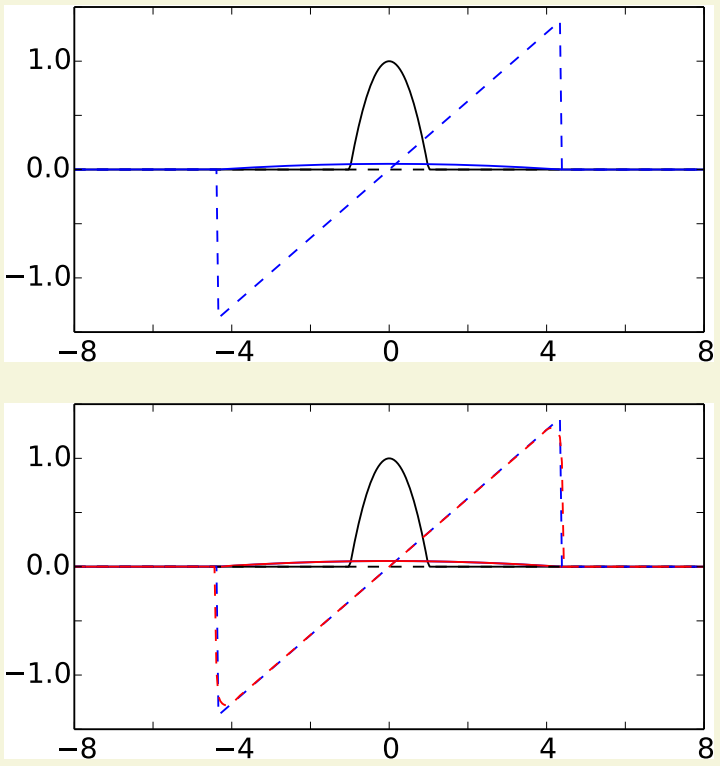

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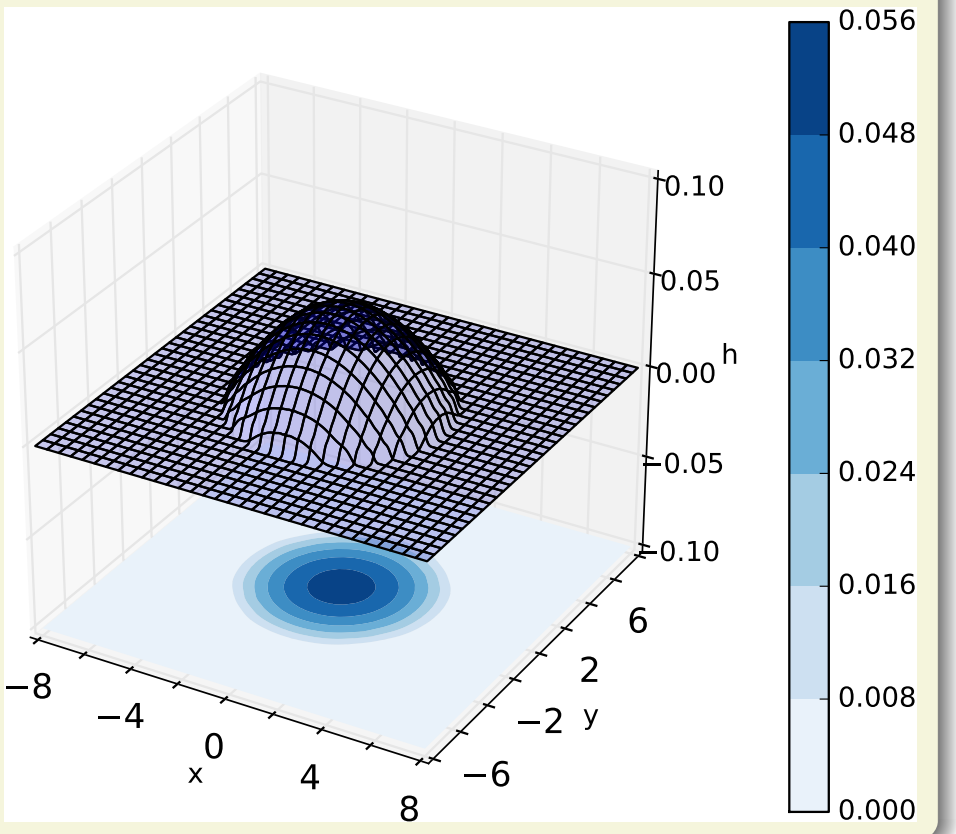

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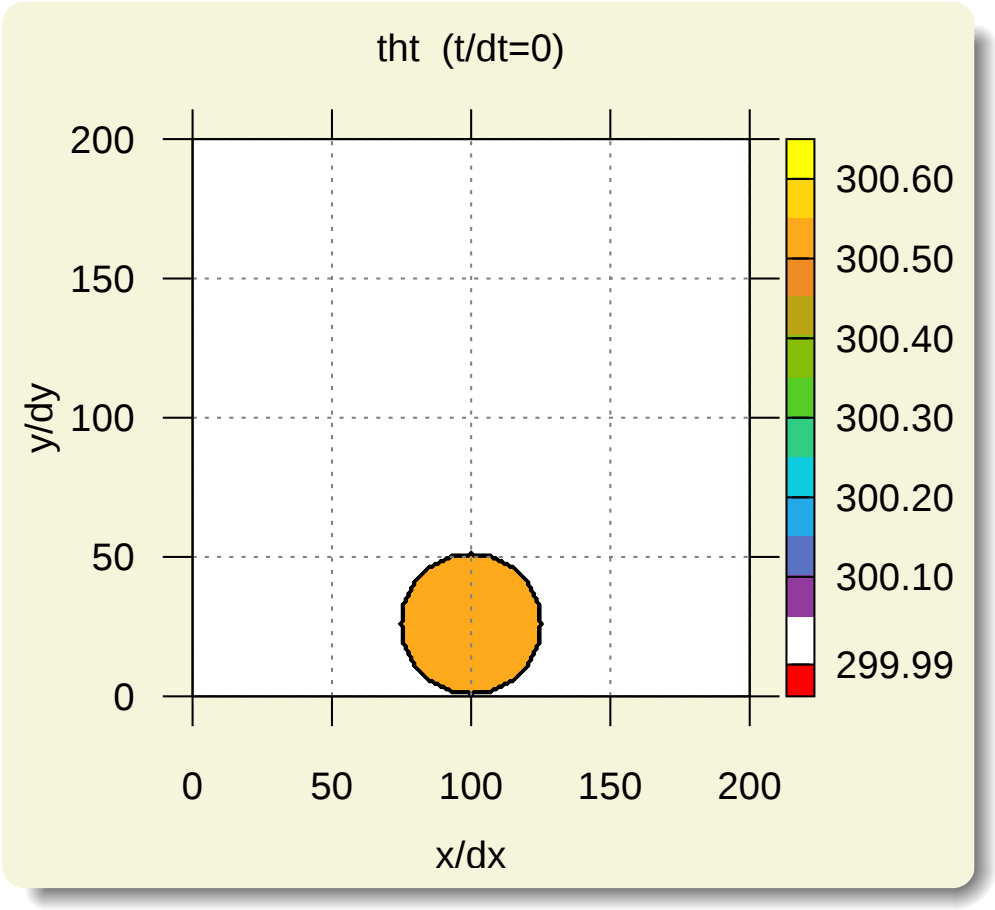

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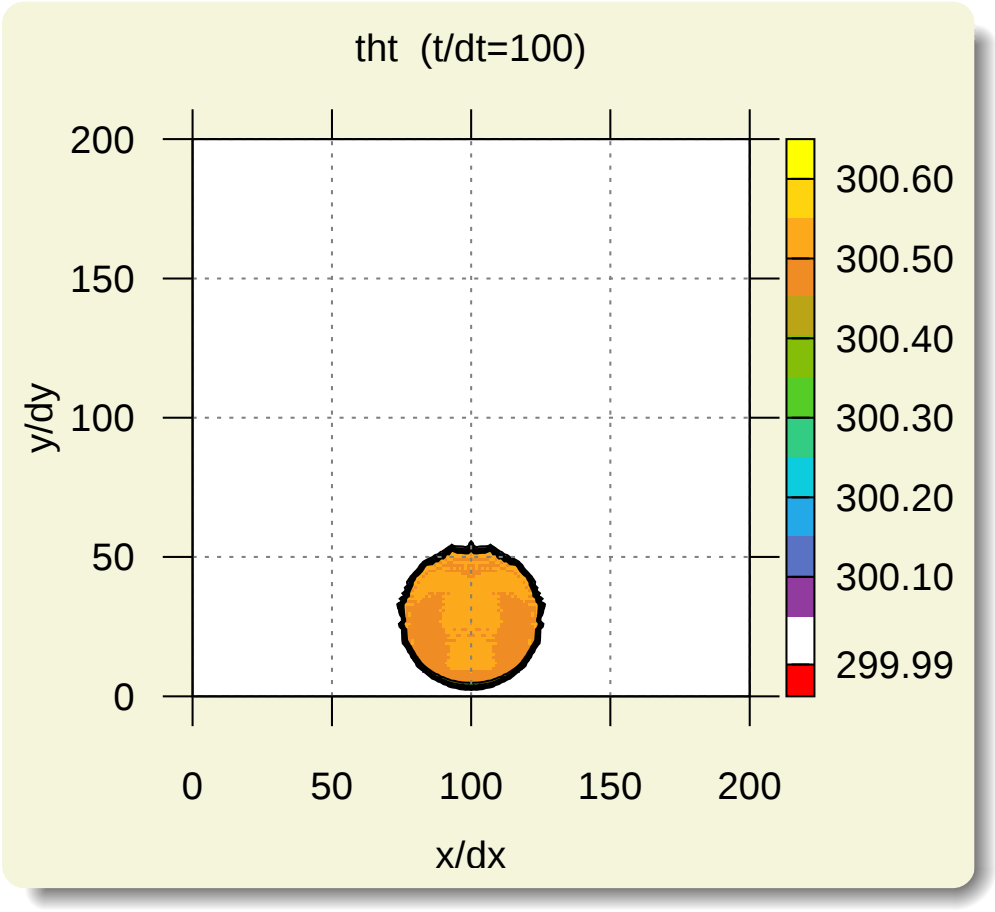

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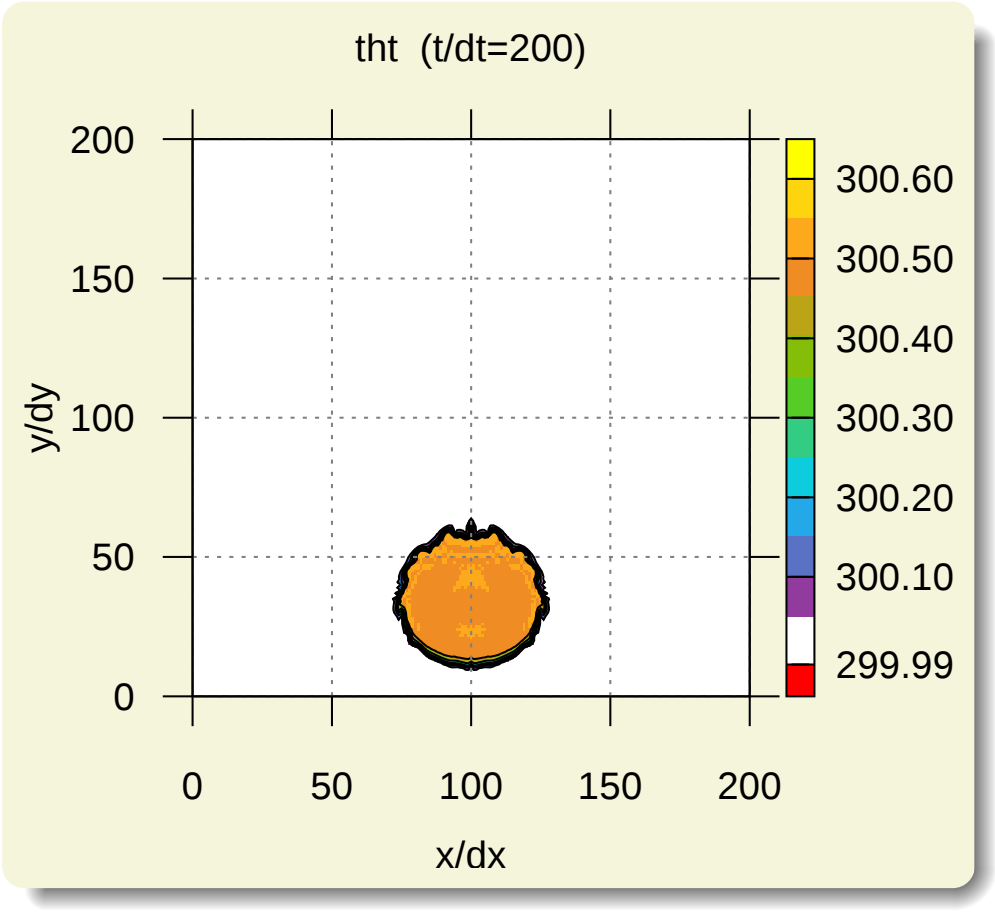

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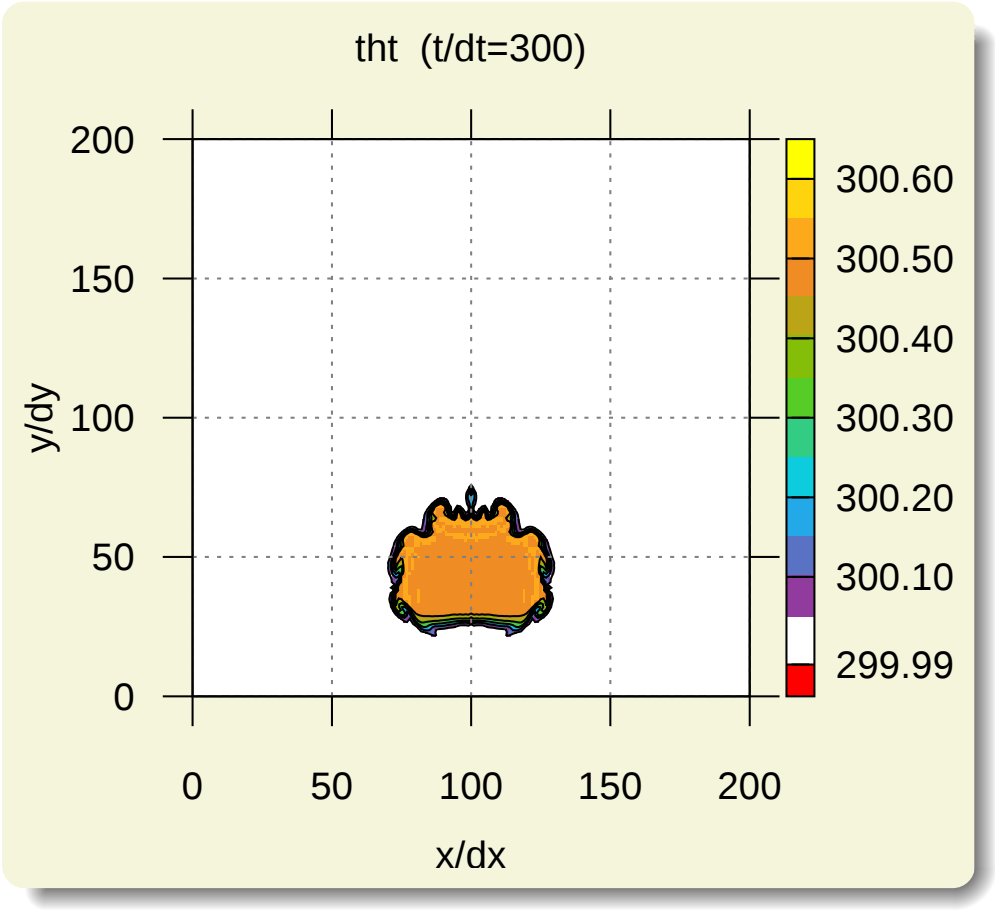

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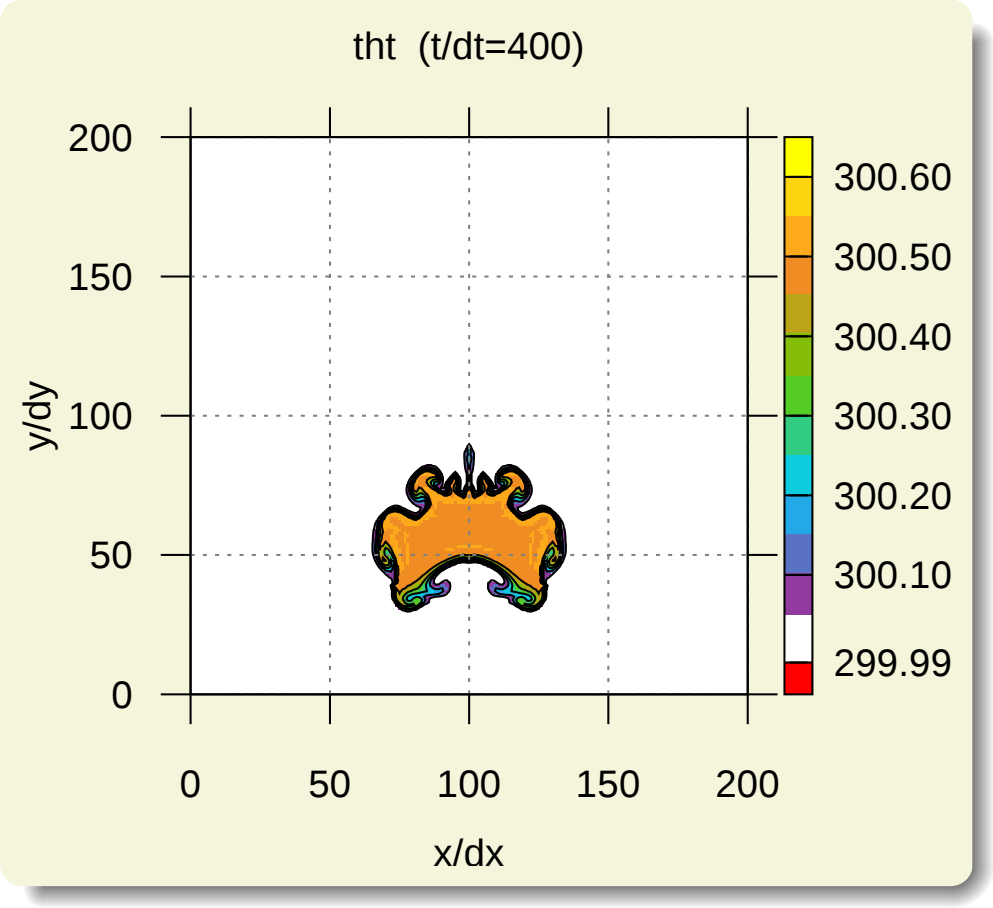

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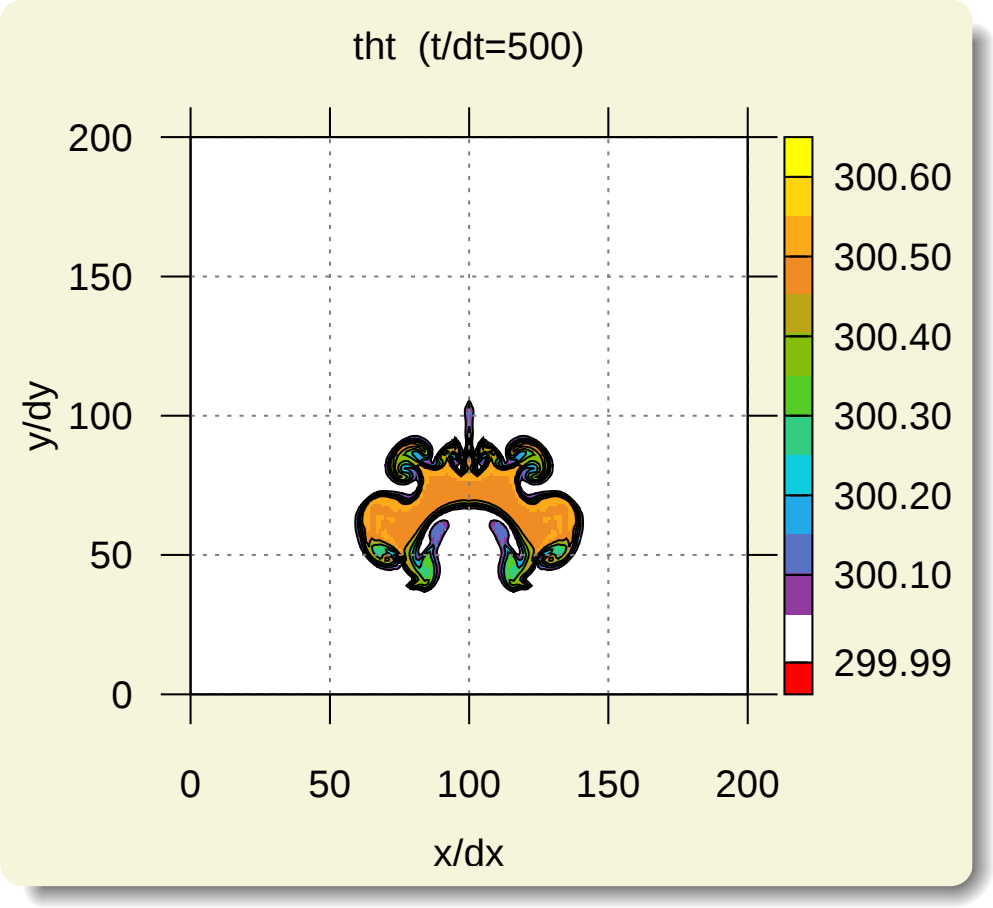

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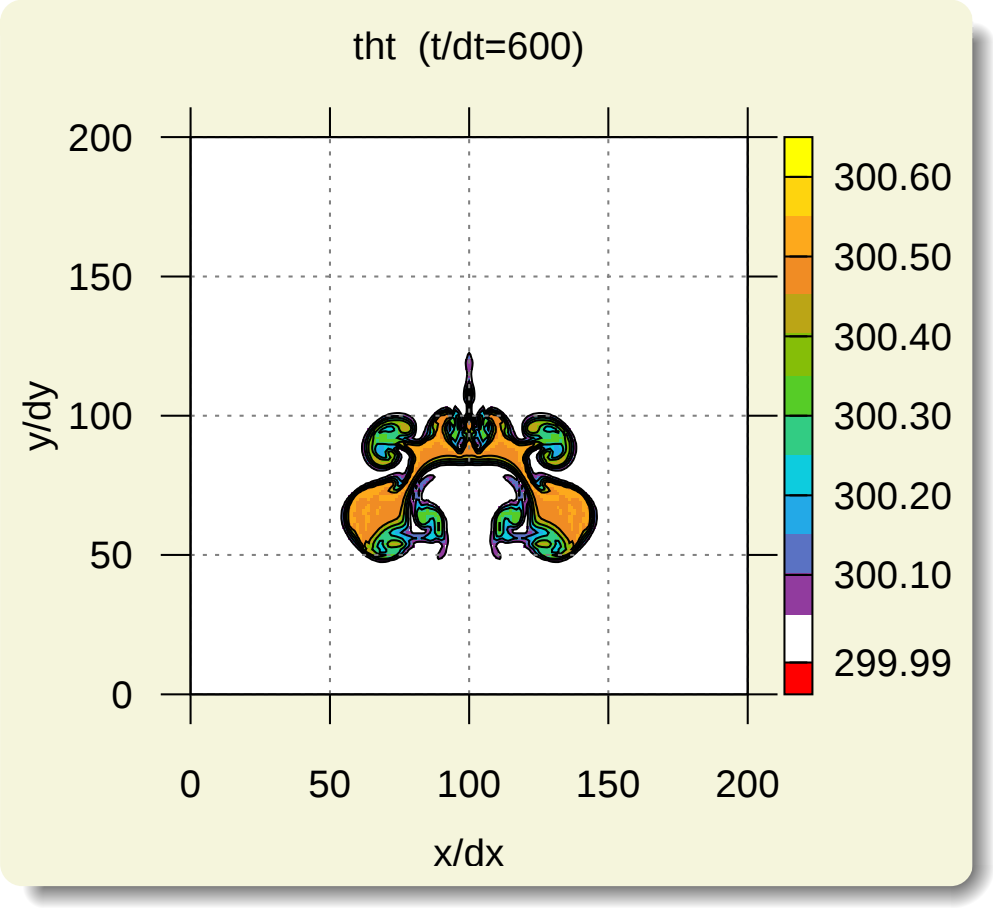

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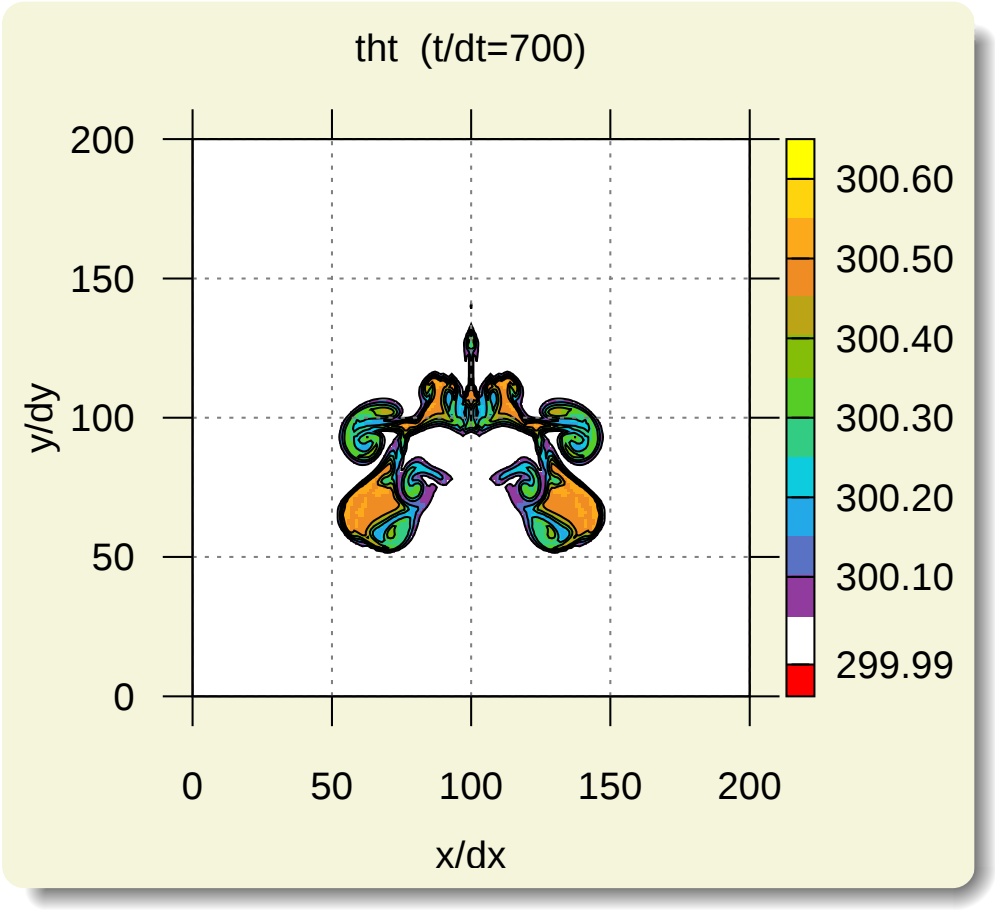

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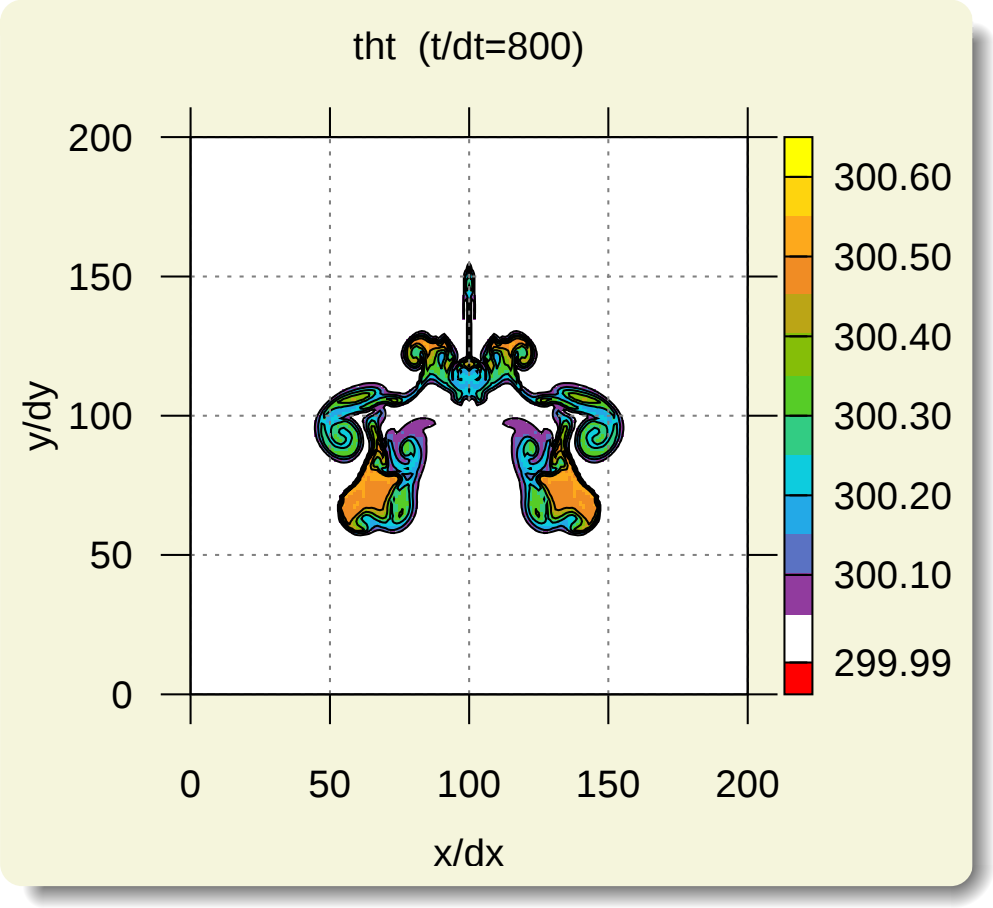

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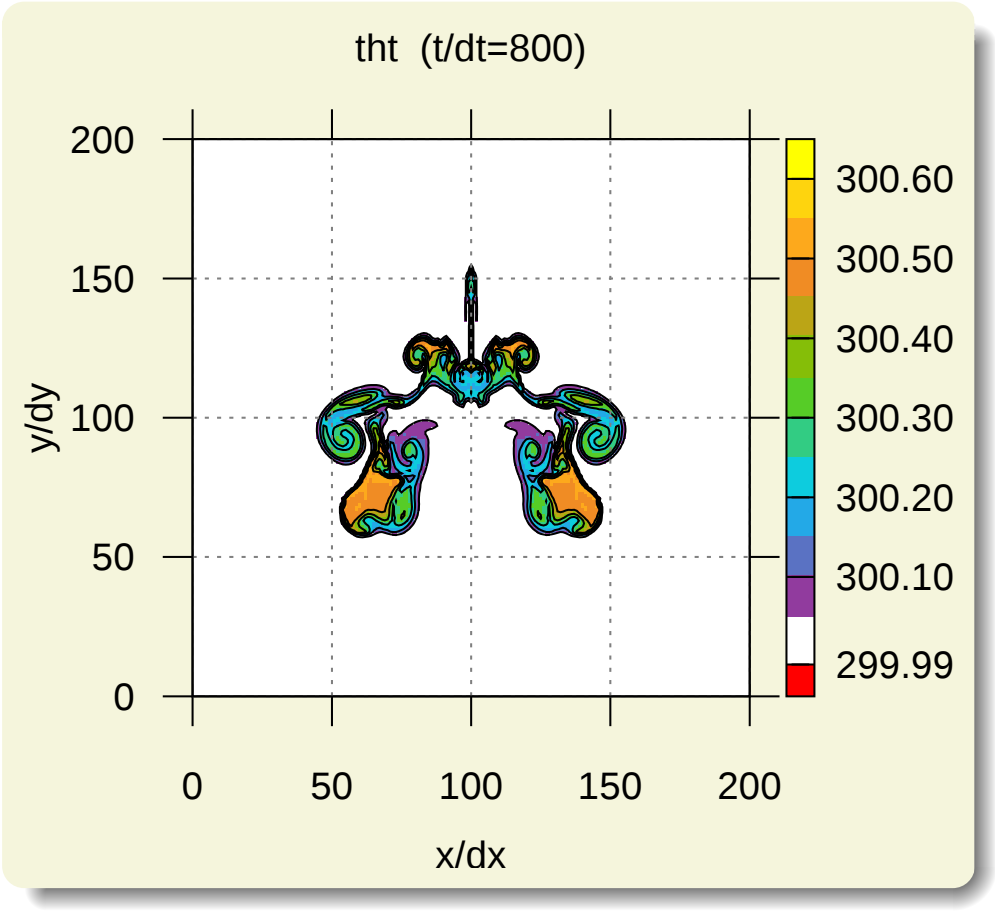

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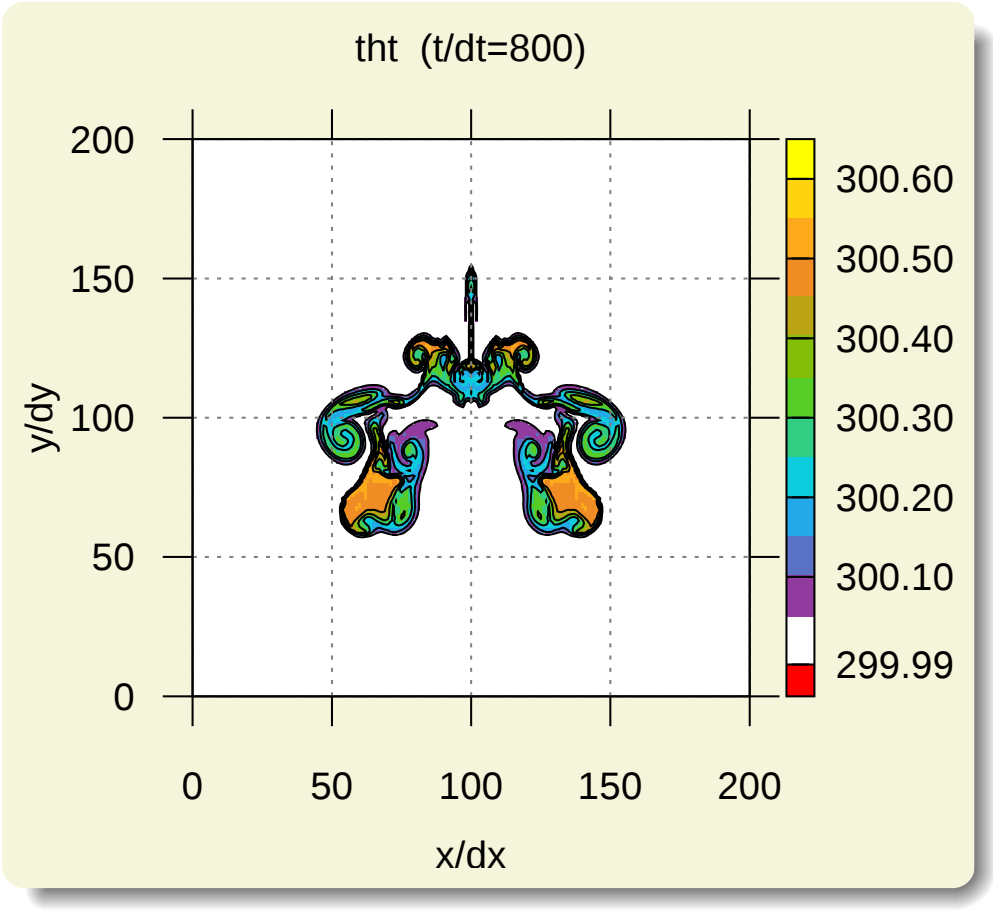

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libmpdata++: summary & some technicalities

free & open source C++ library of parallel MPDATA solvers

key features:

- reusable – API documented in the paper; out-of-tree setups
- rich set of MPDATA flavours (incl. FCT, infinite-gauge, . . .)
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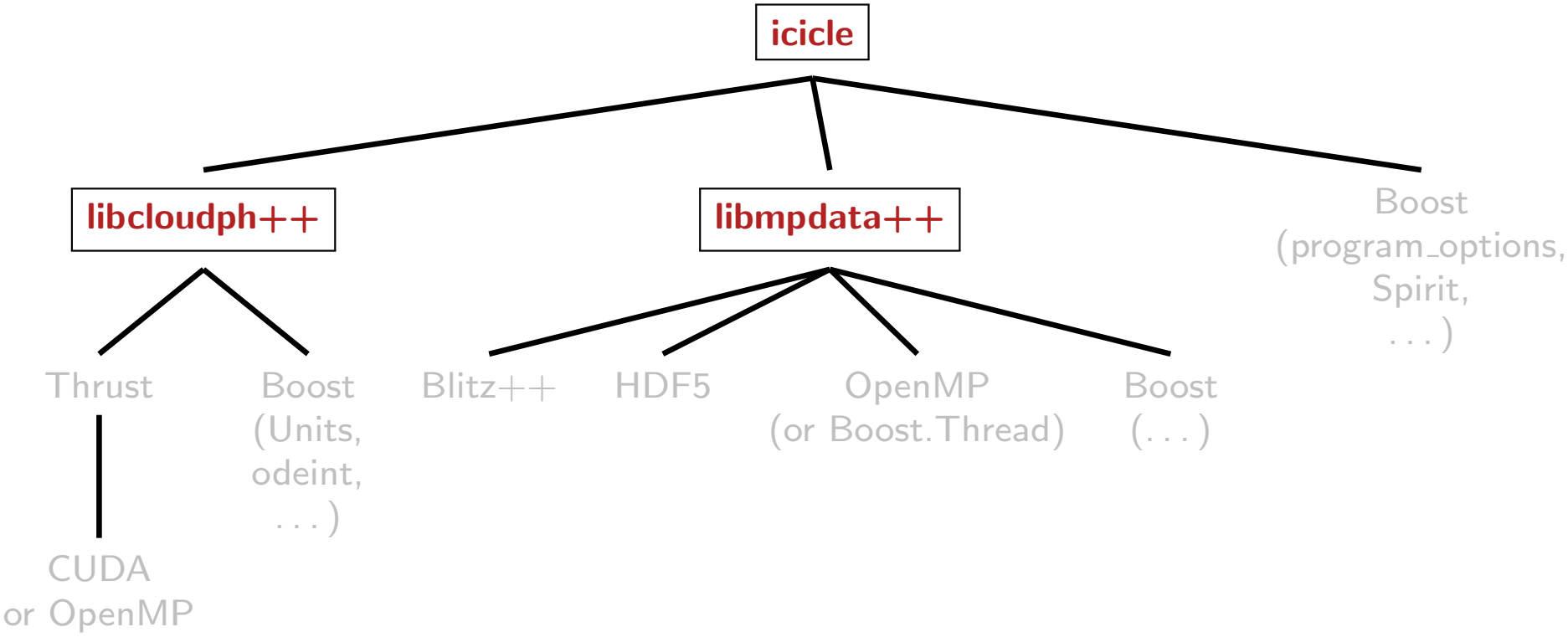

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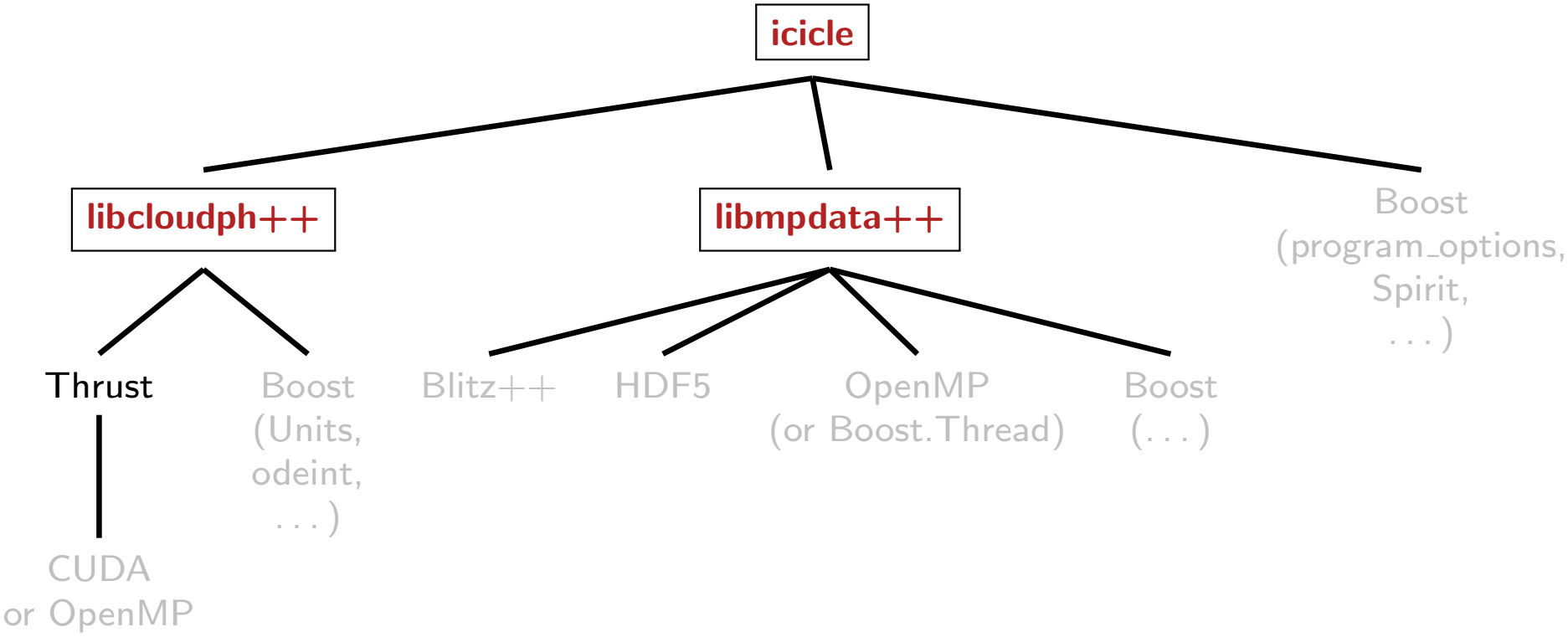

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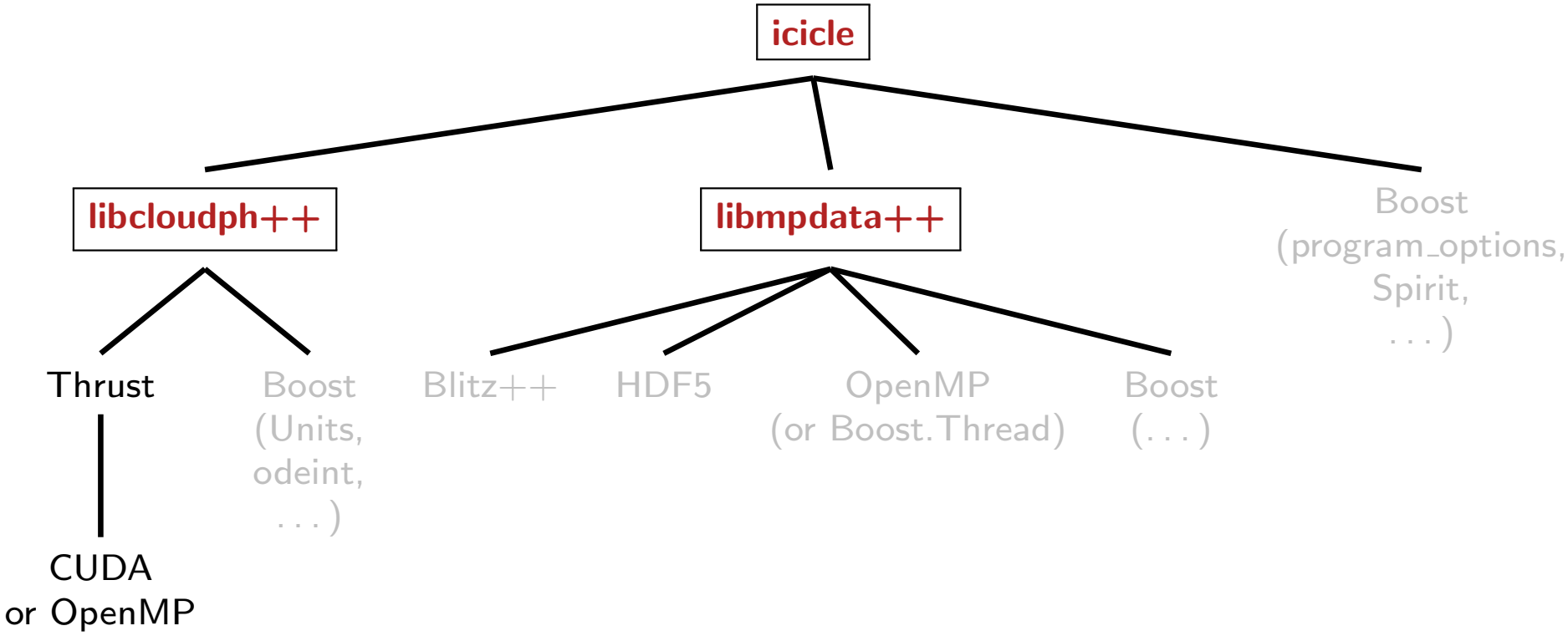

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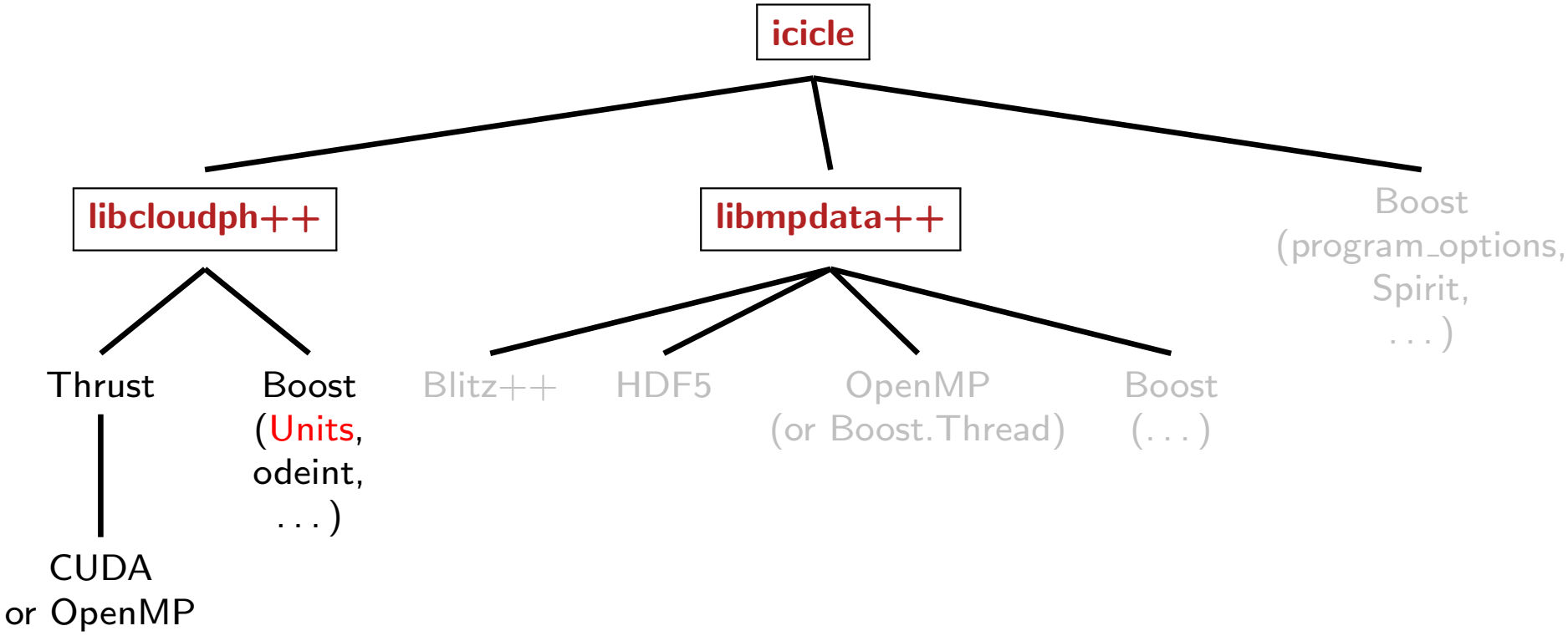

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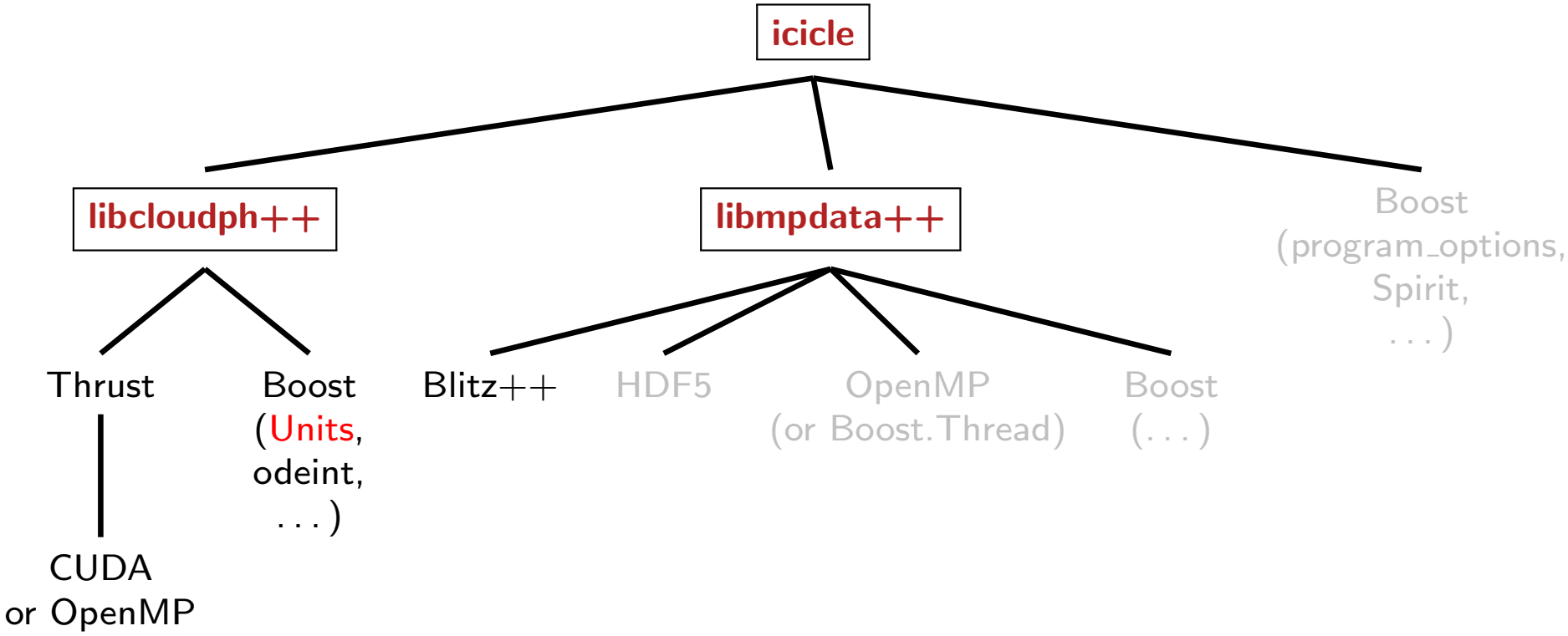

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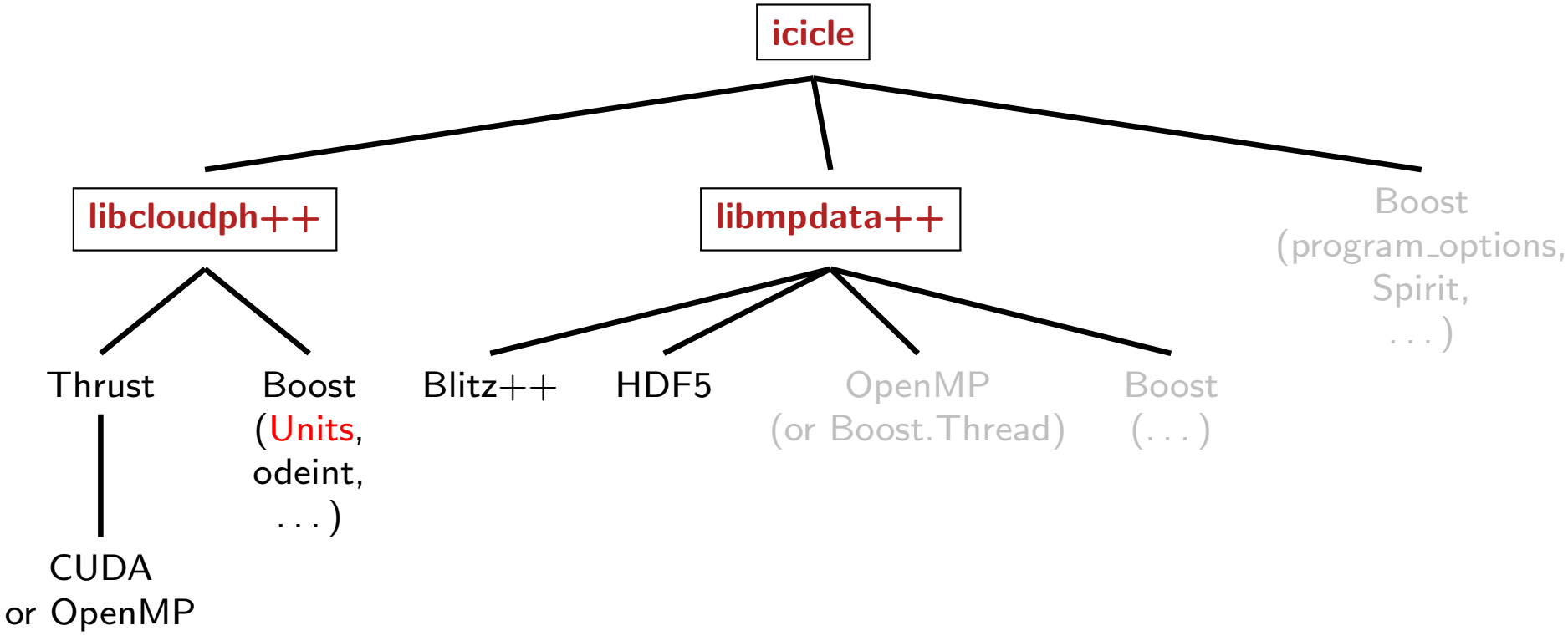

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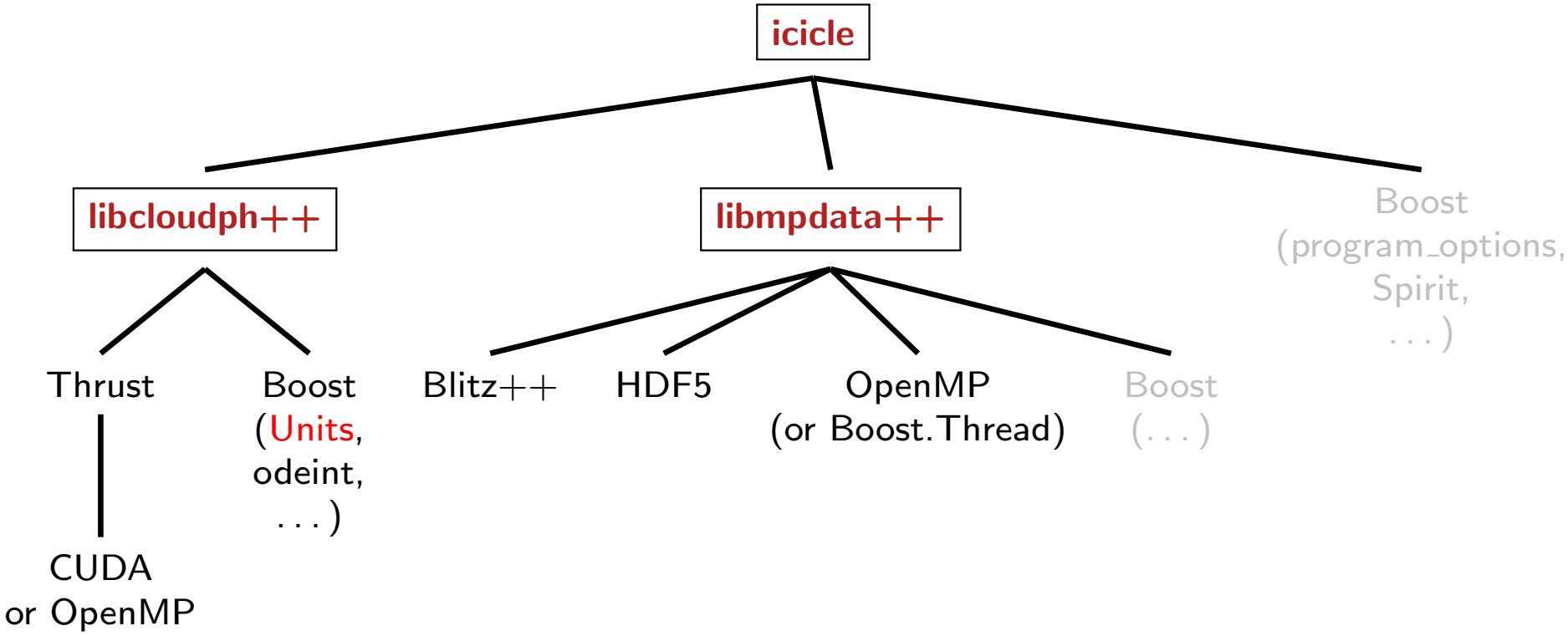

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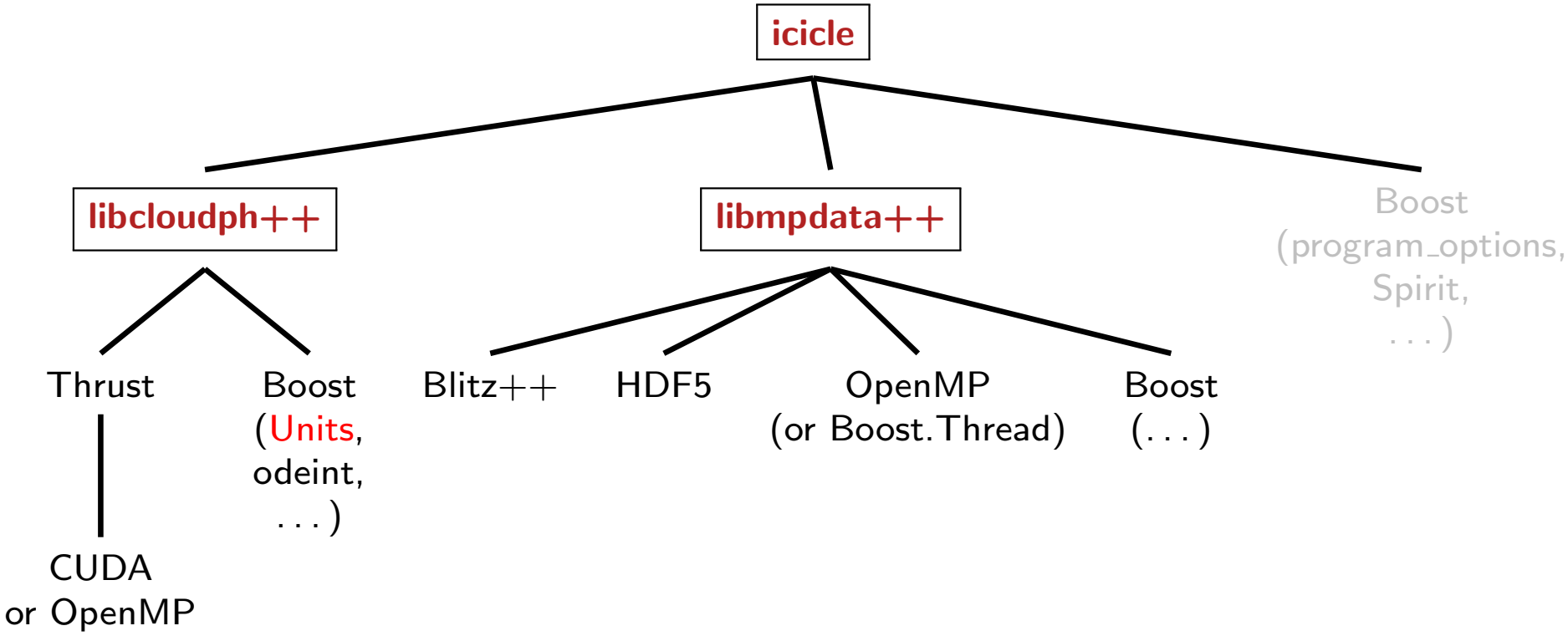

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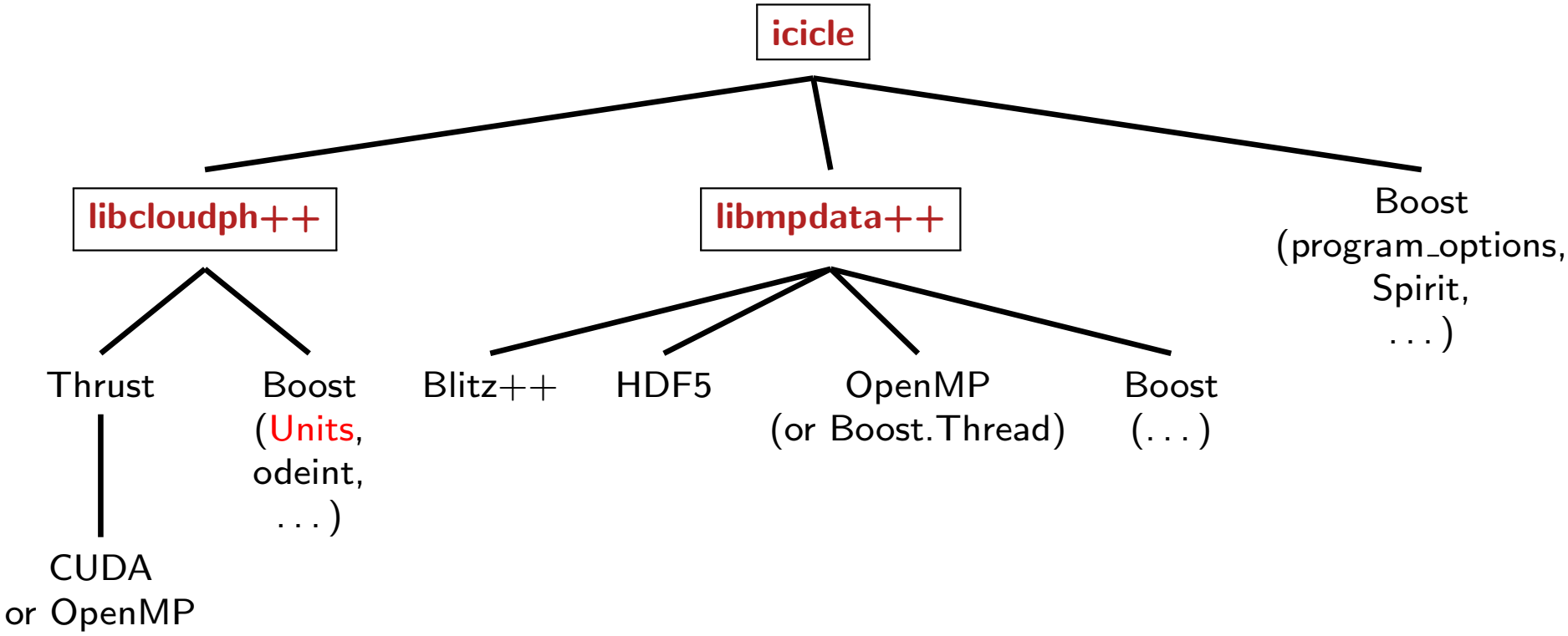
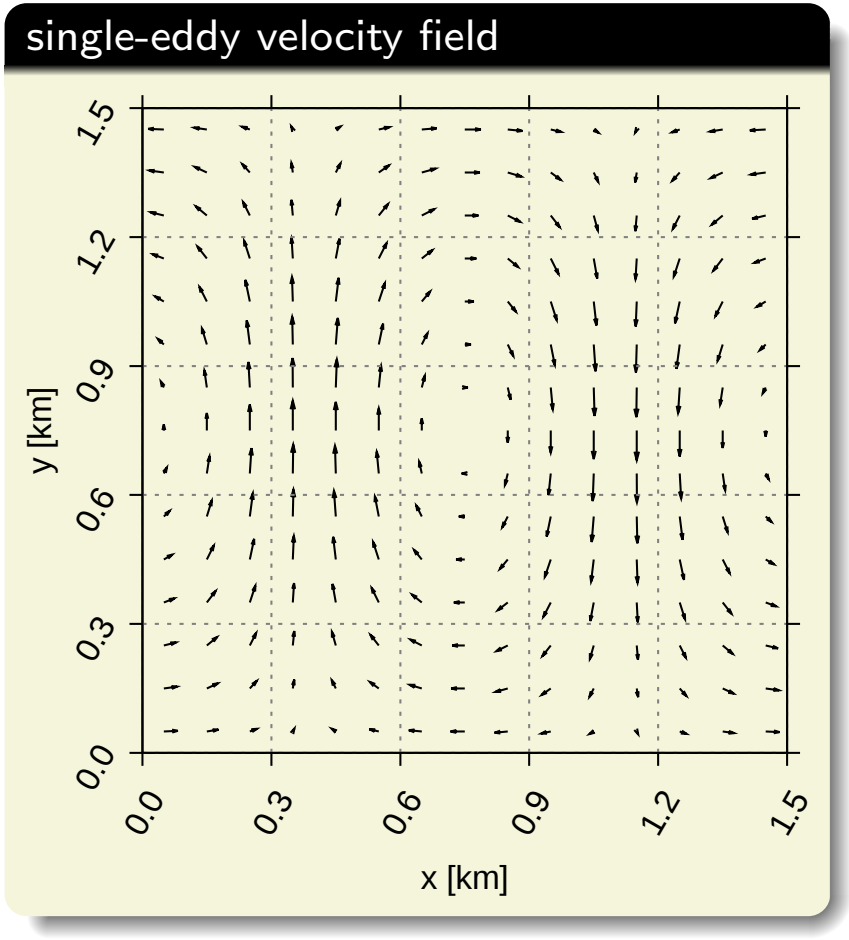
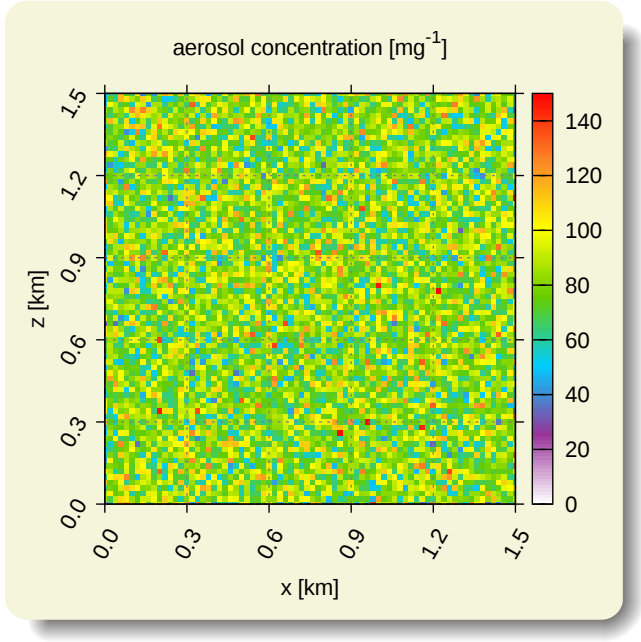


libcloudph++: VOCALS-inspired aerosol processing set-up





- set-up: Grabowski & Lebo (ICMW 2012)
- 2D prescribed flow
- advection: libmpdata++ (2-pass FCT)
- μ-physics: libcloudph++

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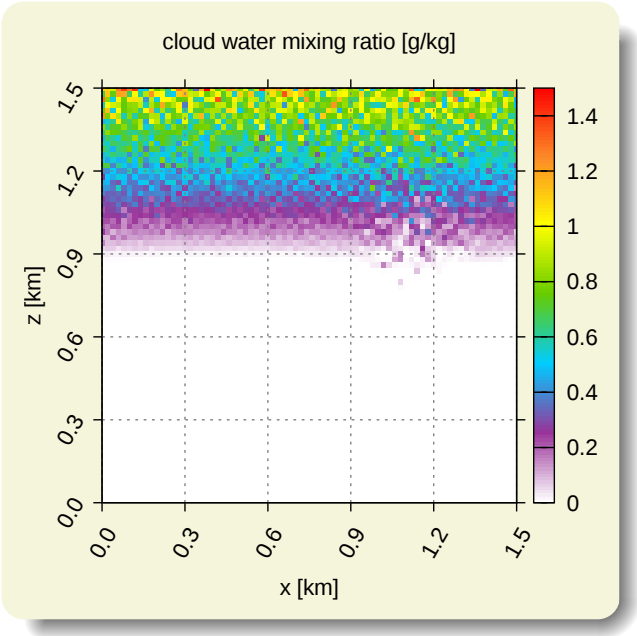

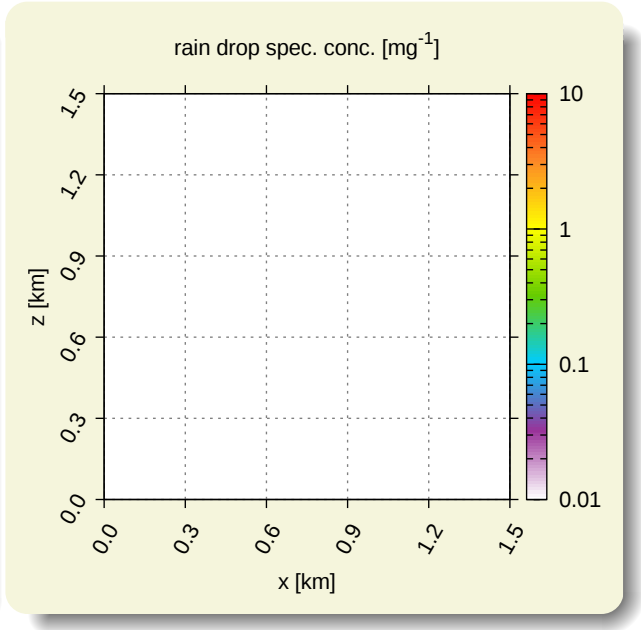

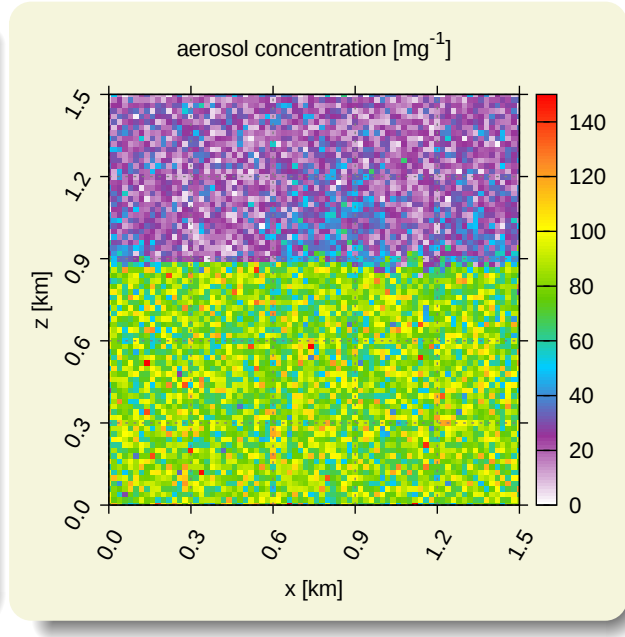

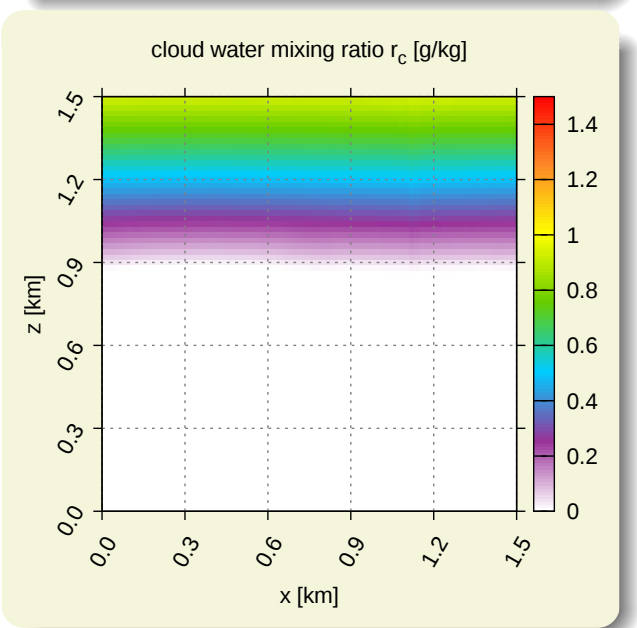

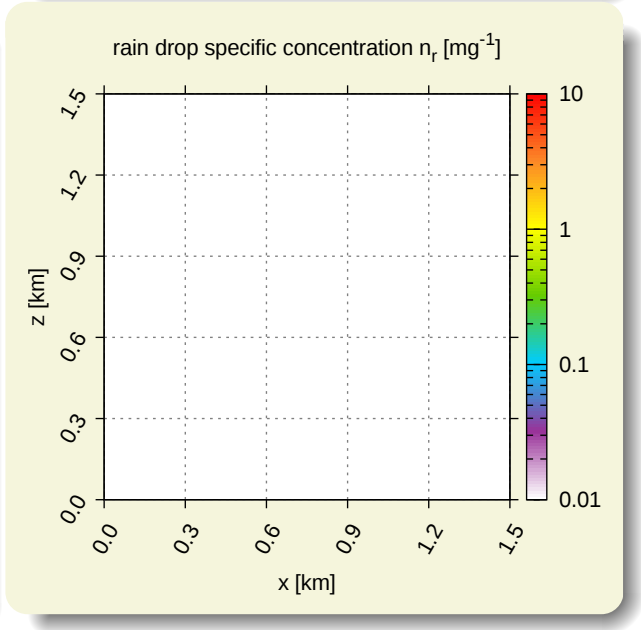

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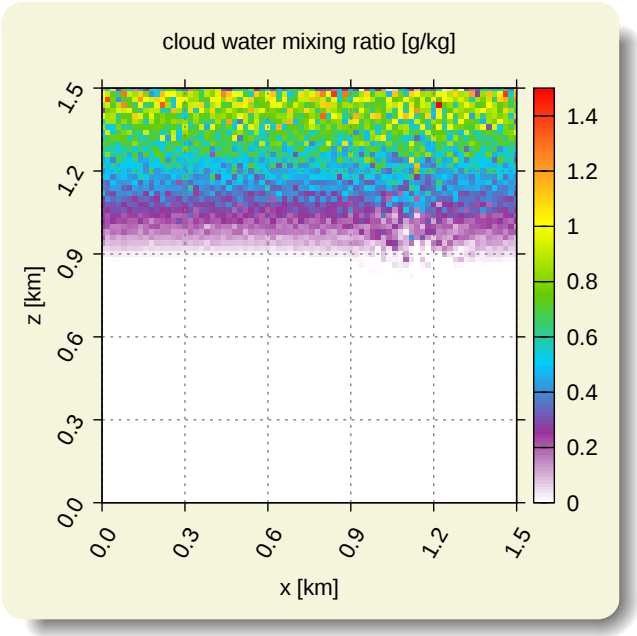

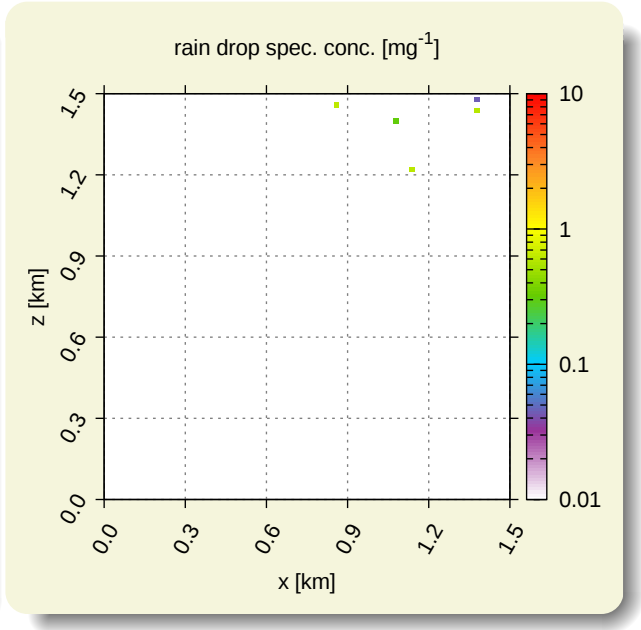

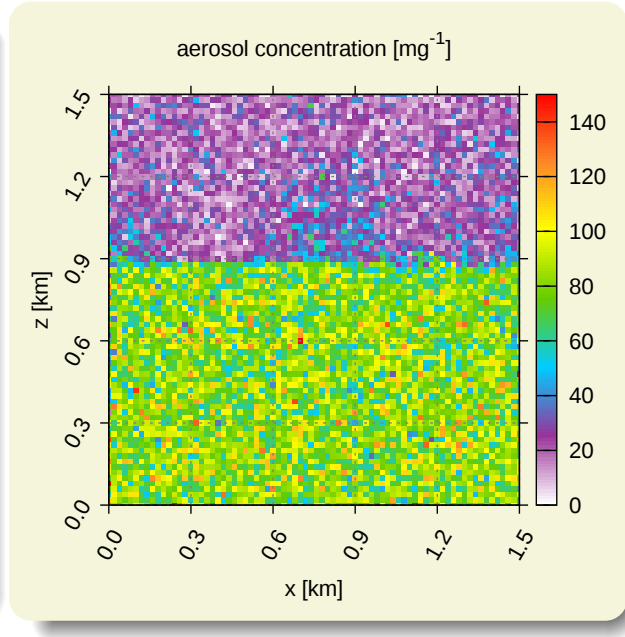

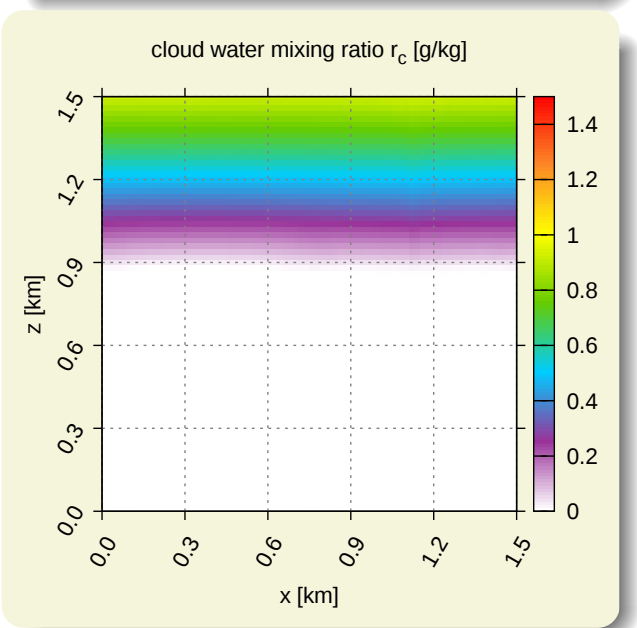

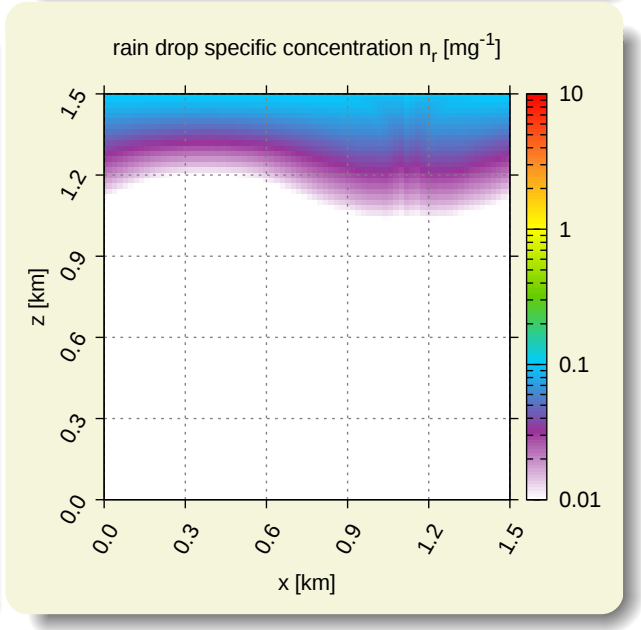

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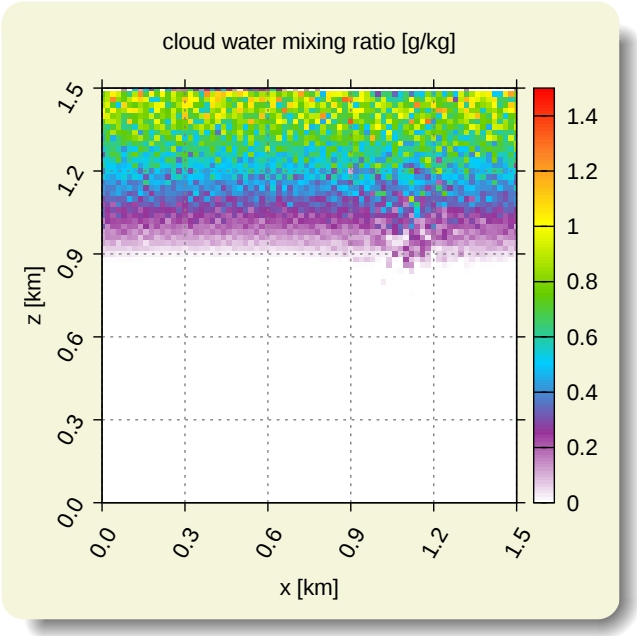

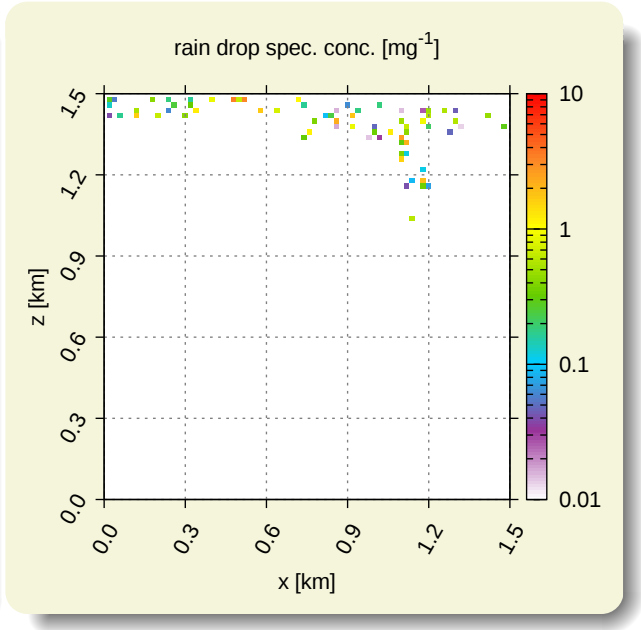

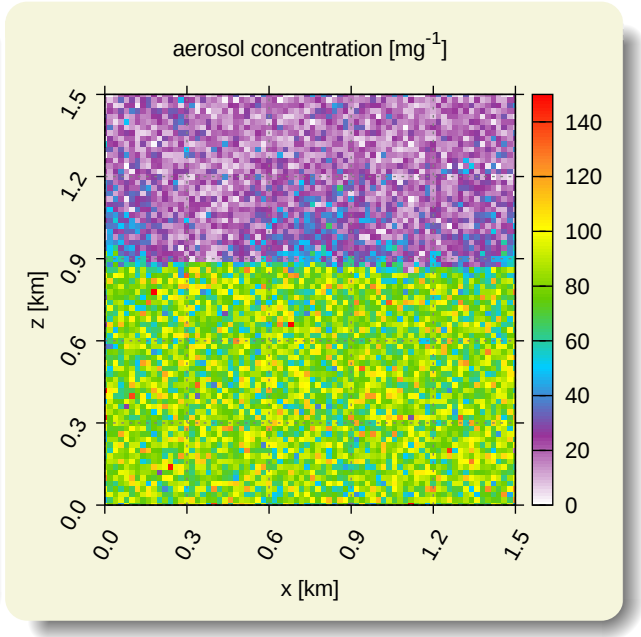

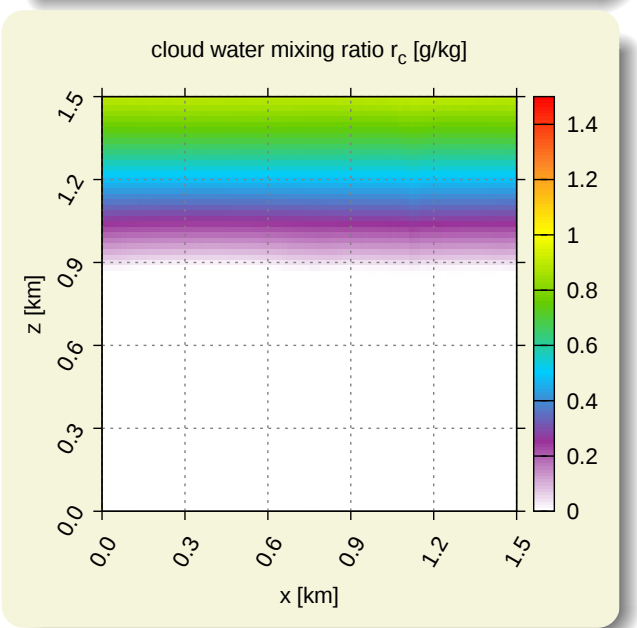

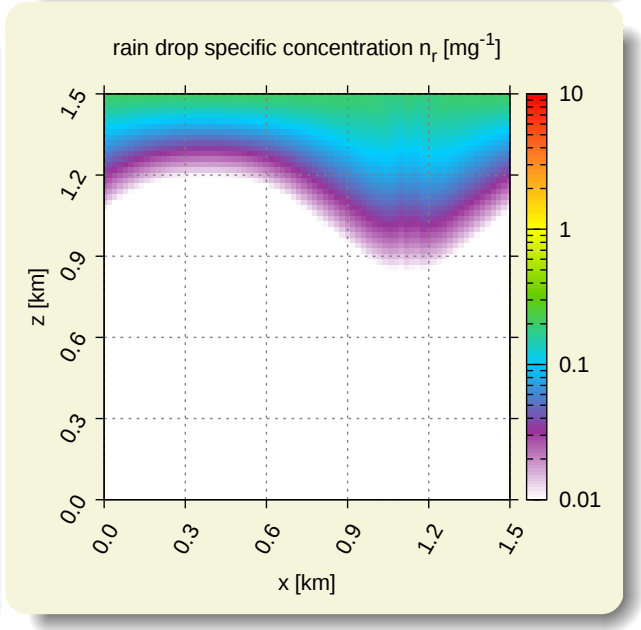

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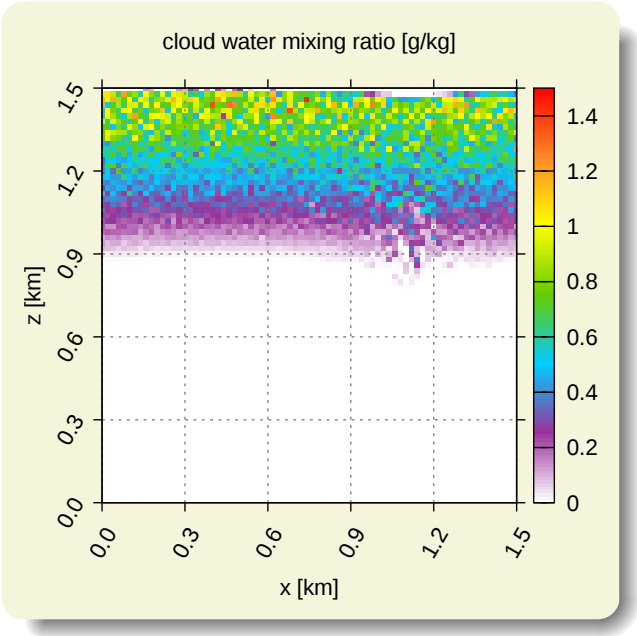

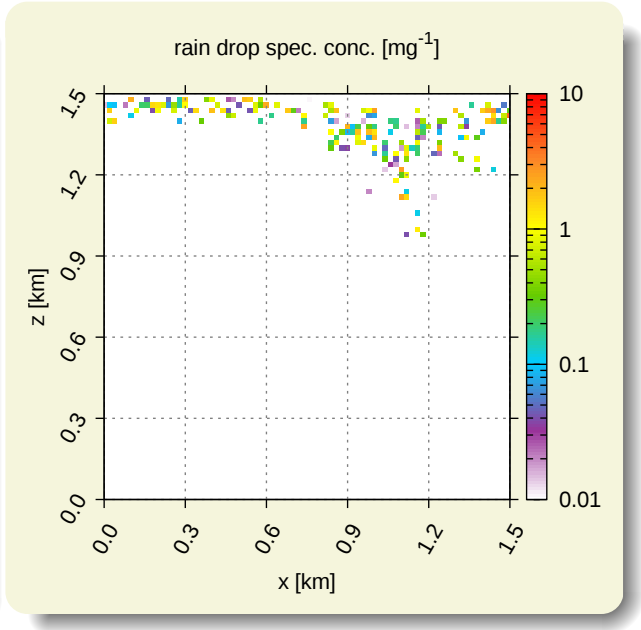

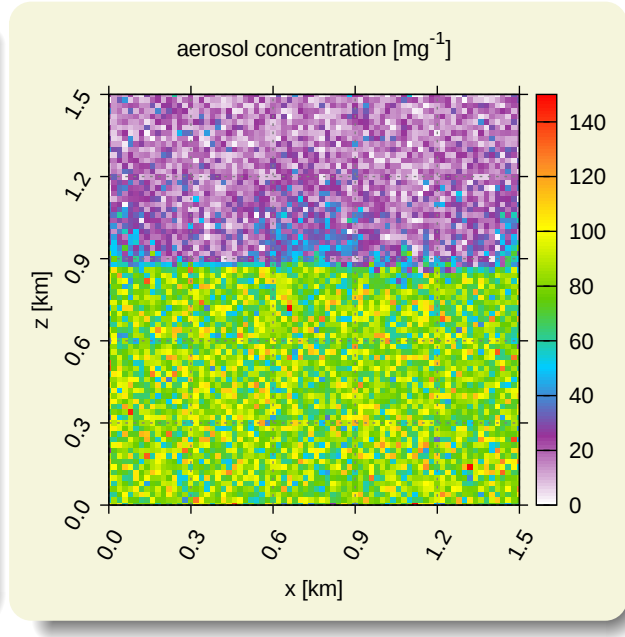

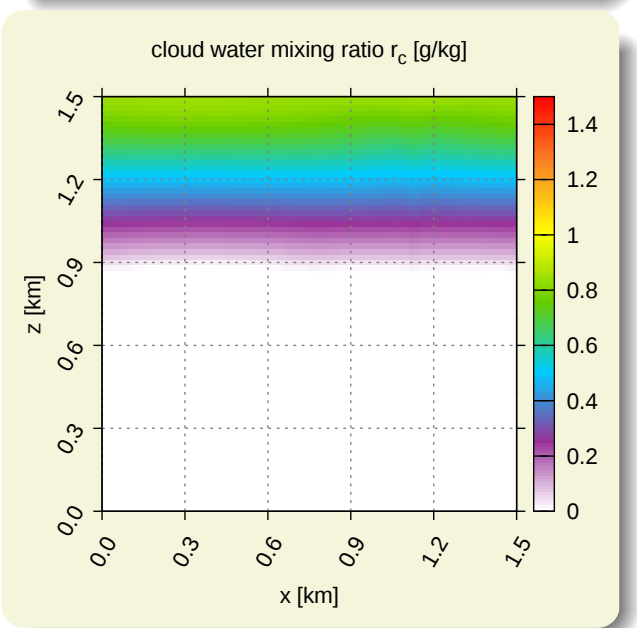

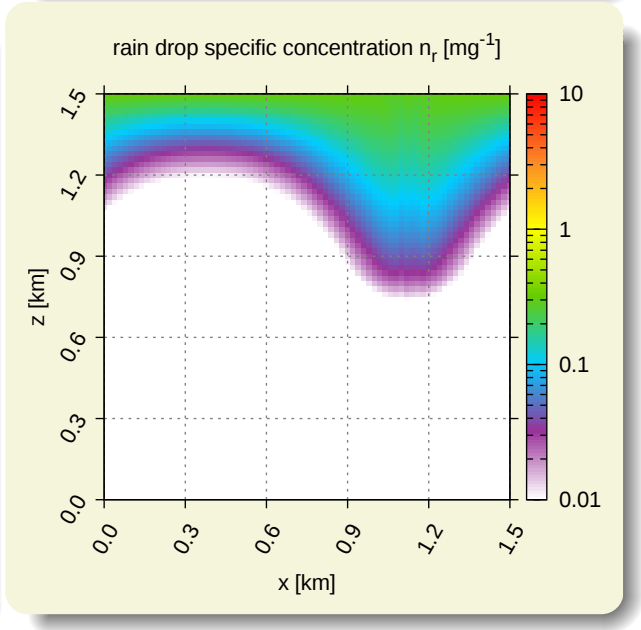

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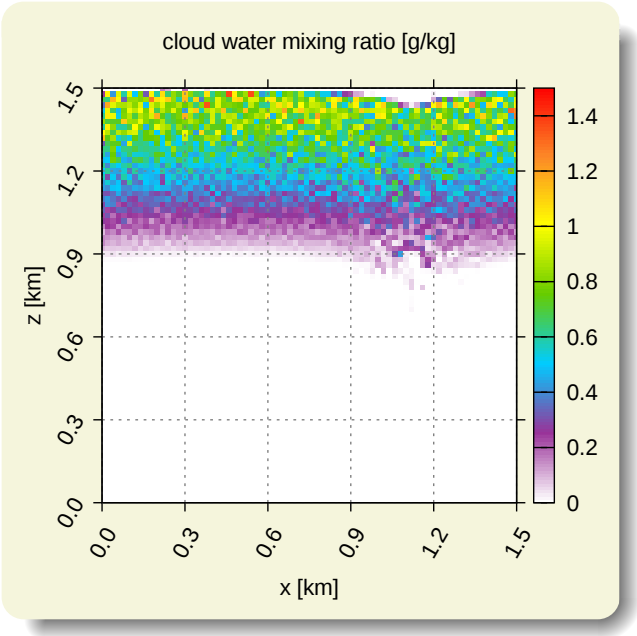

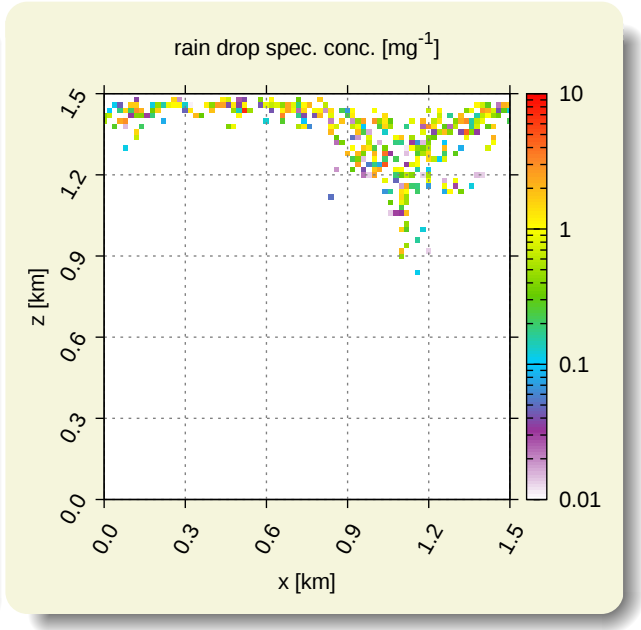

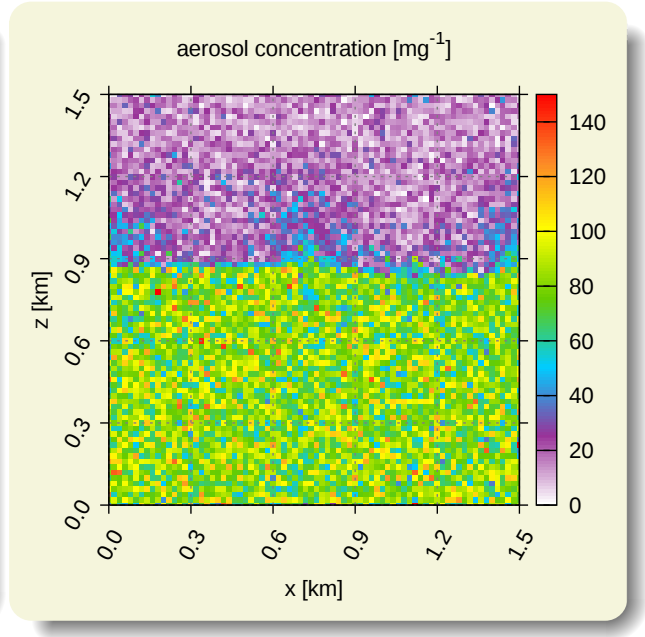

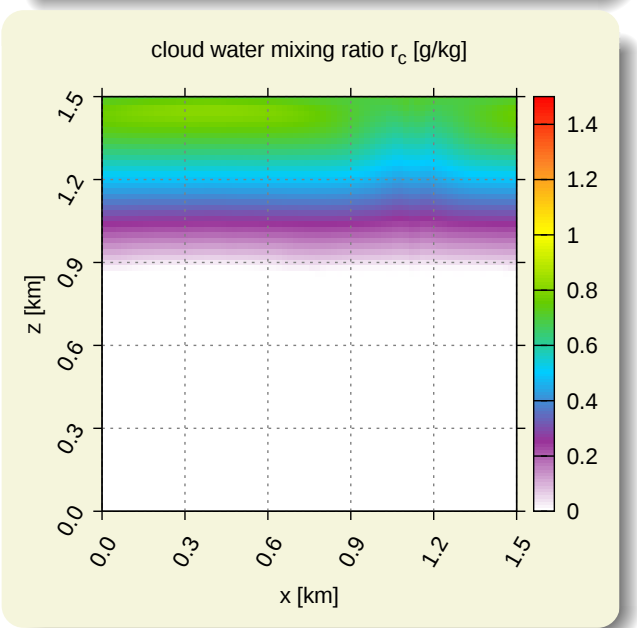

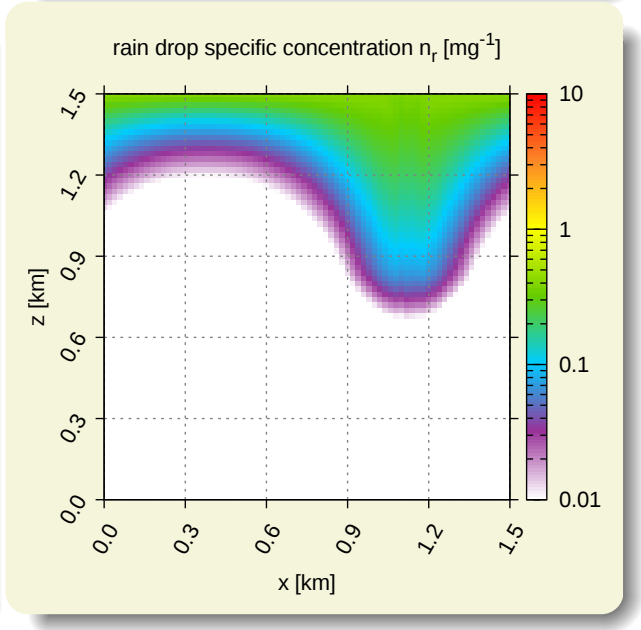

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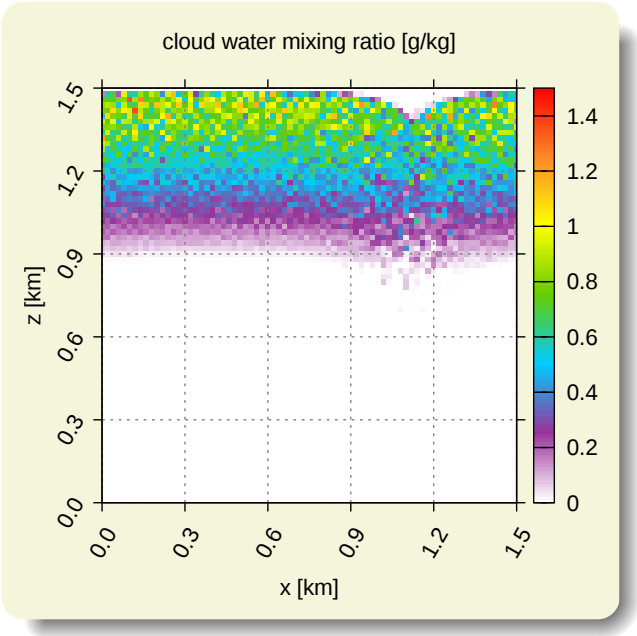

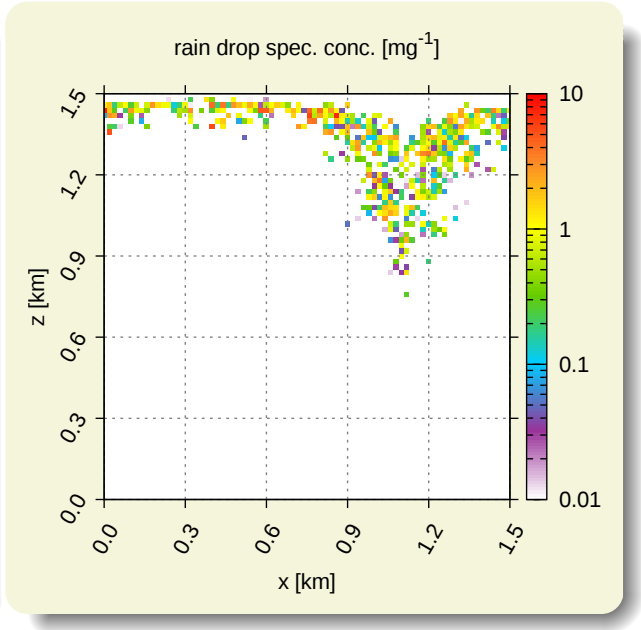

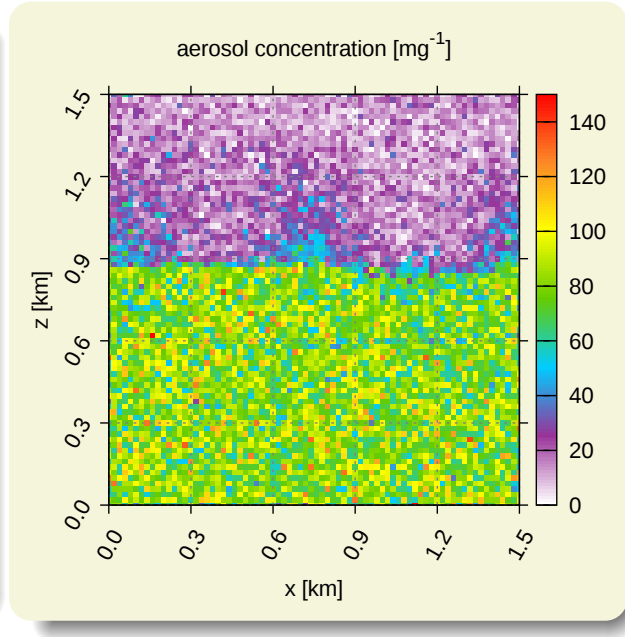

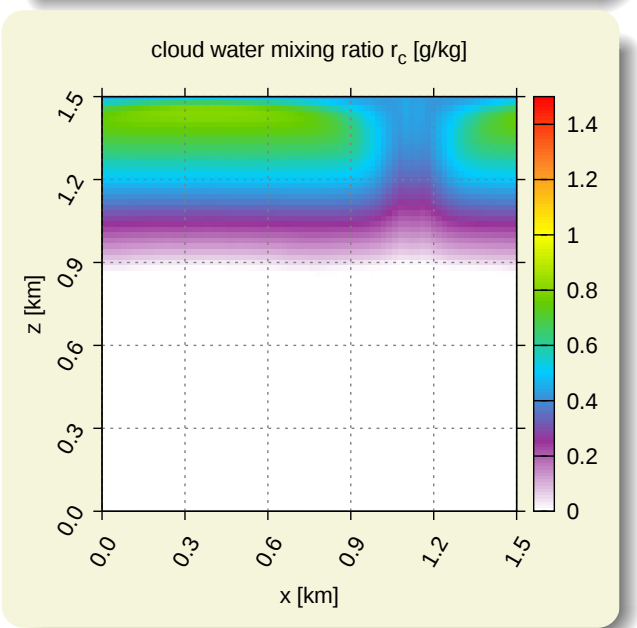

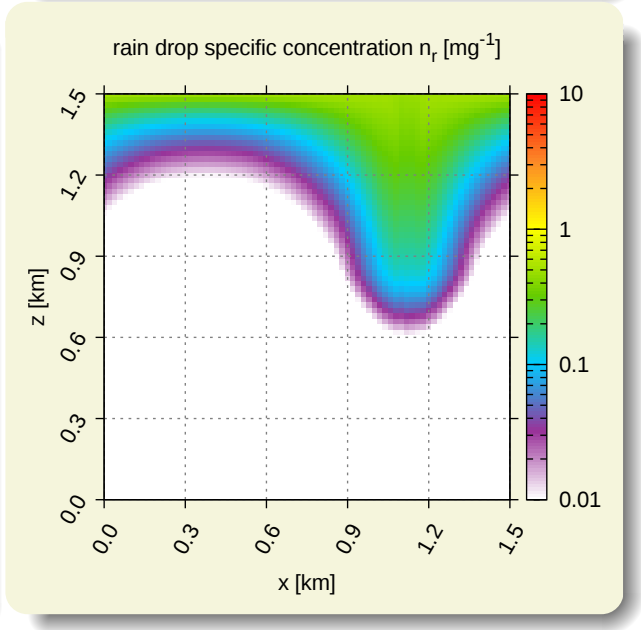

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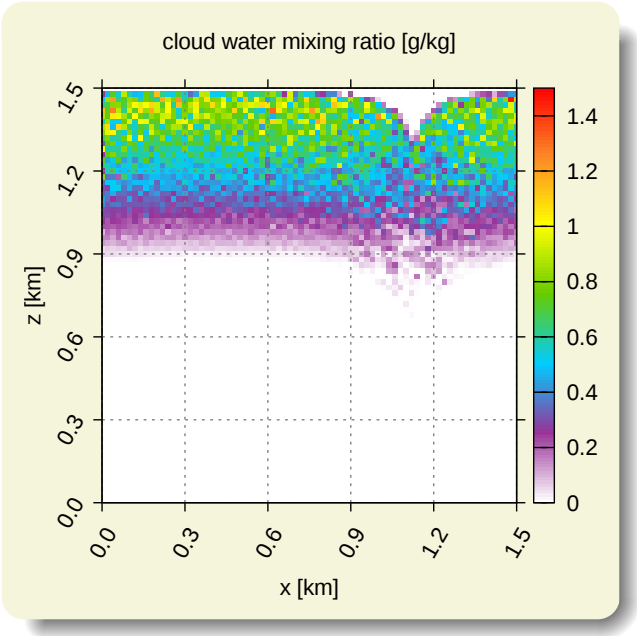

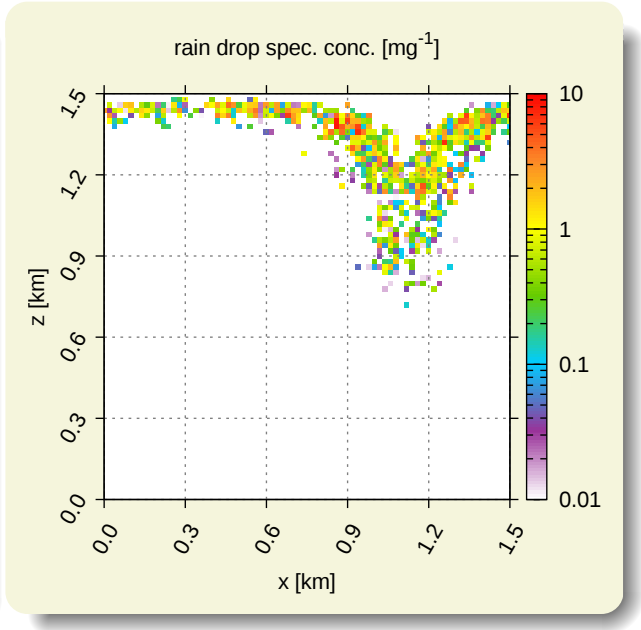

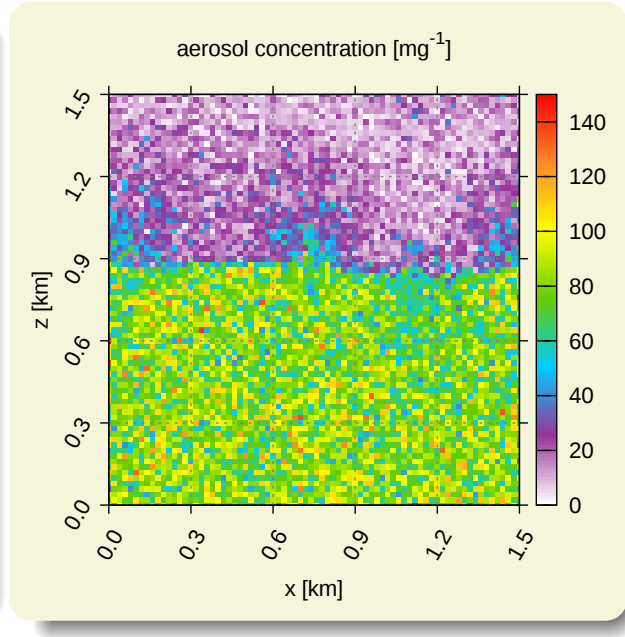

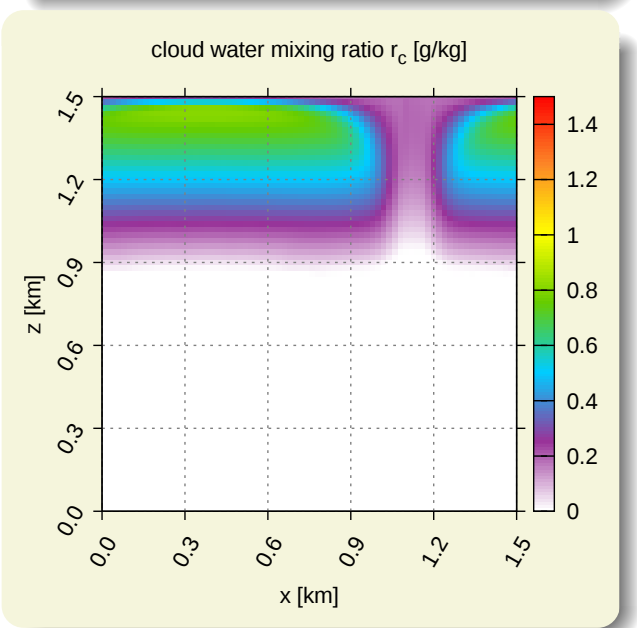

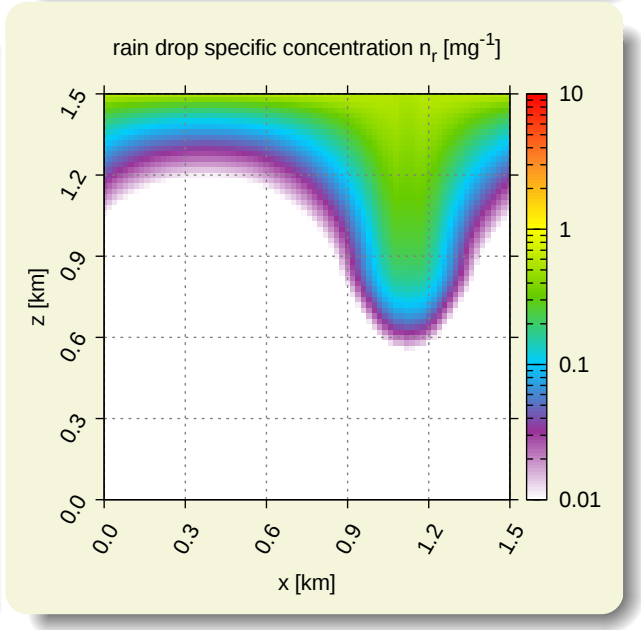

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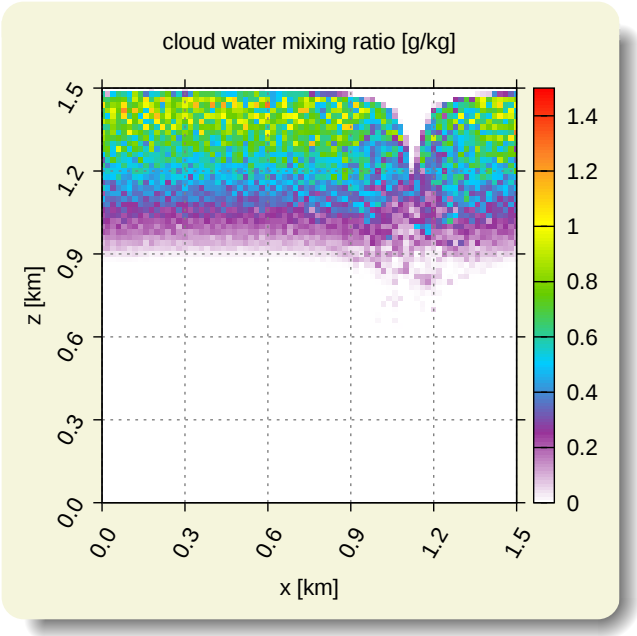

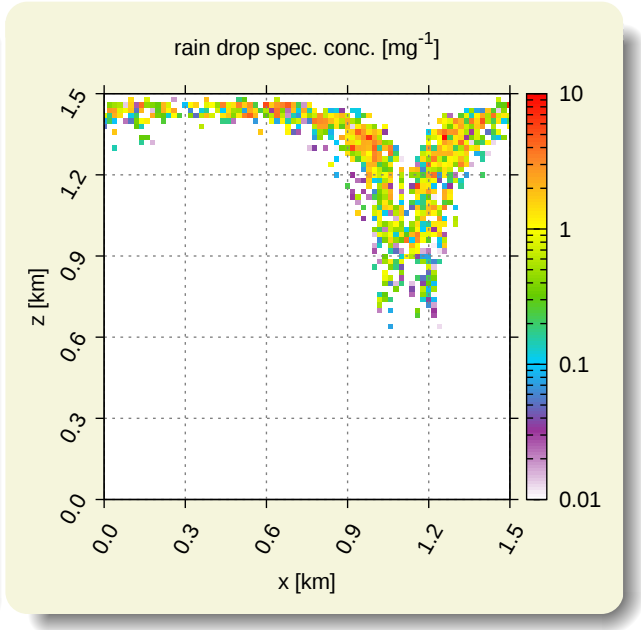

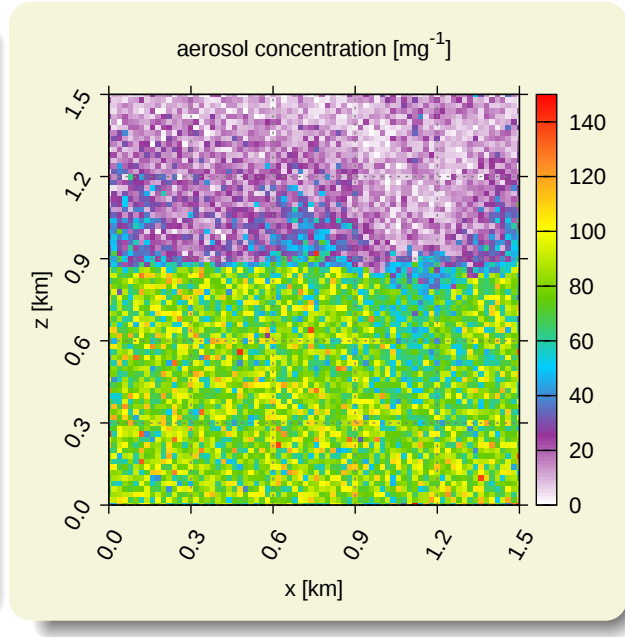

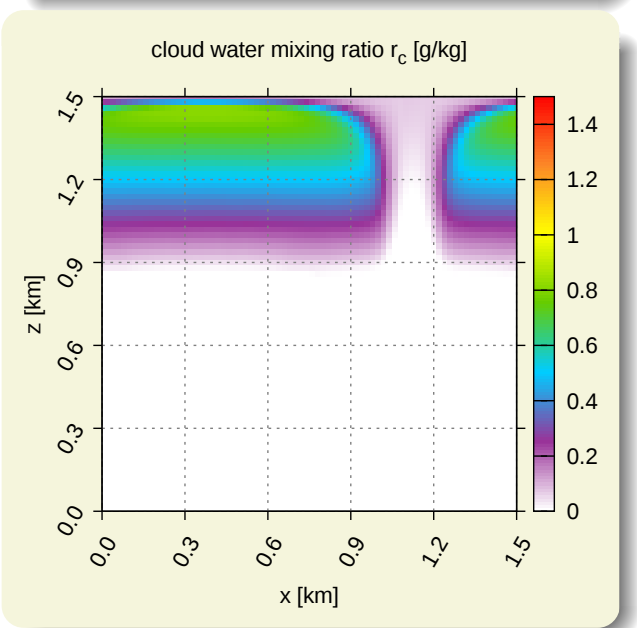

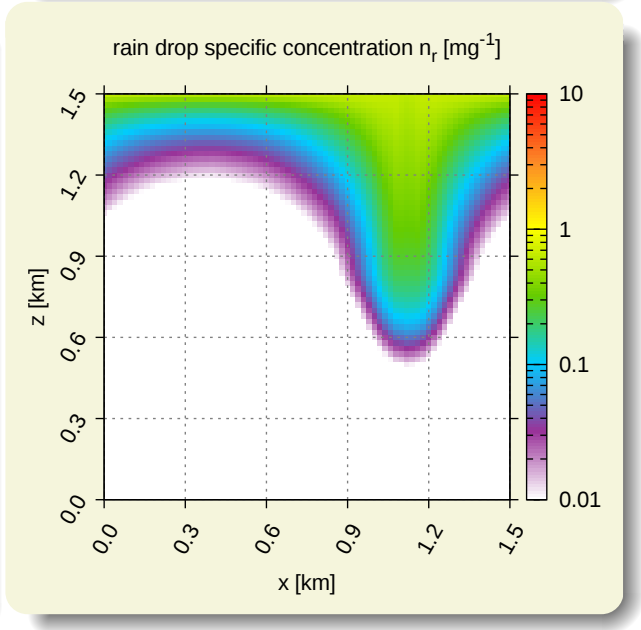

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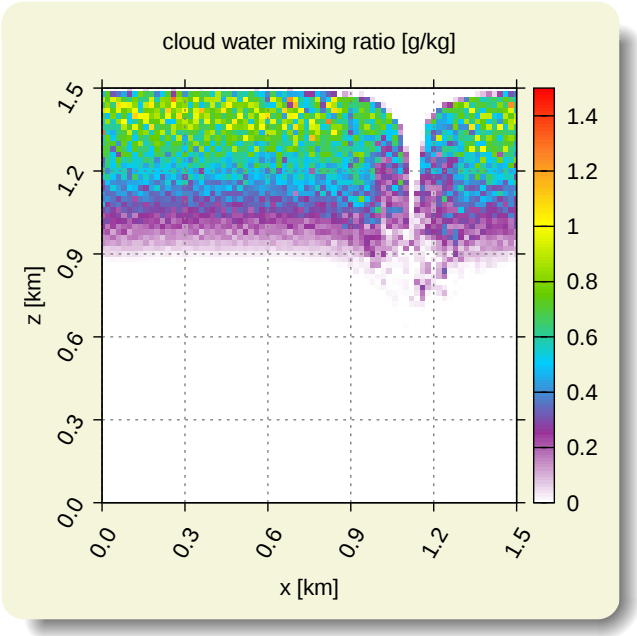

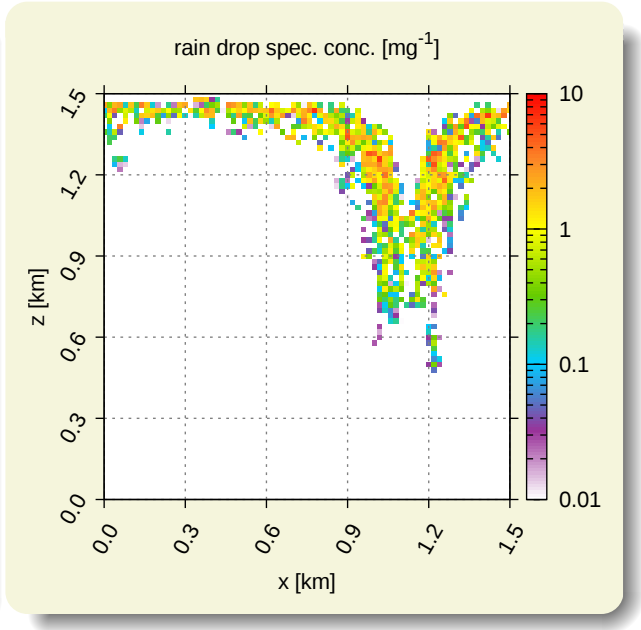

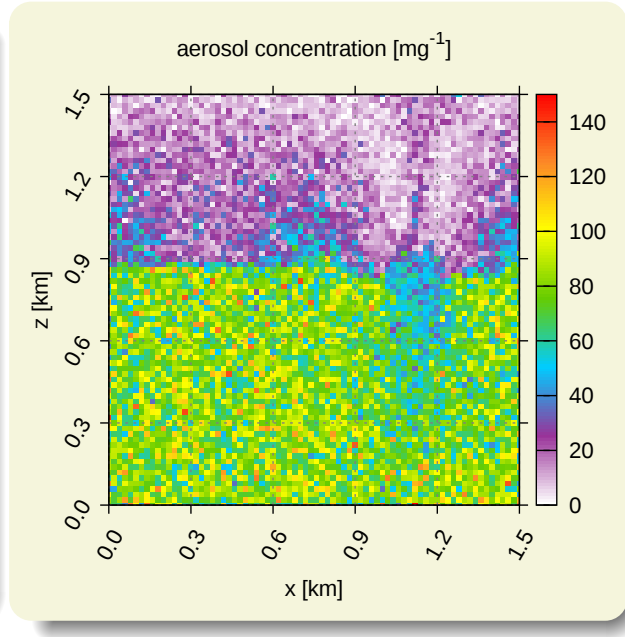

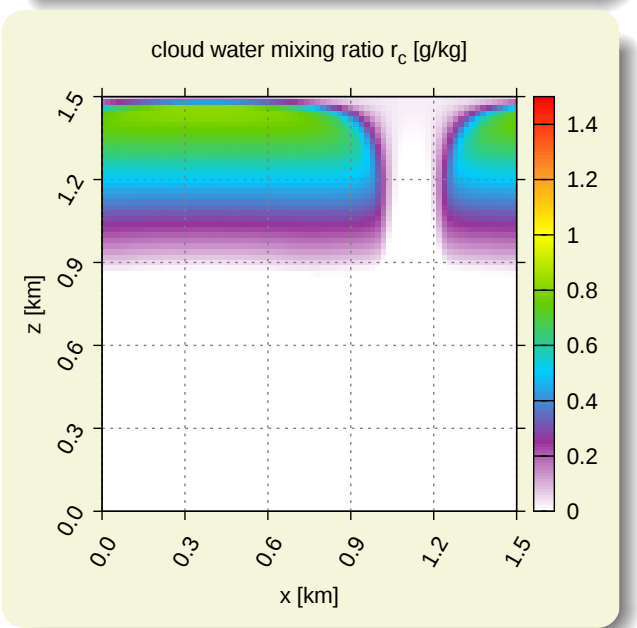

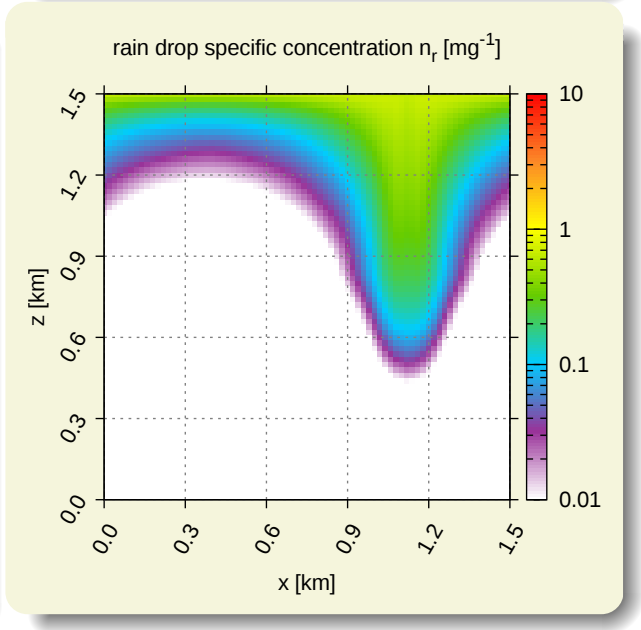

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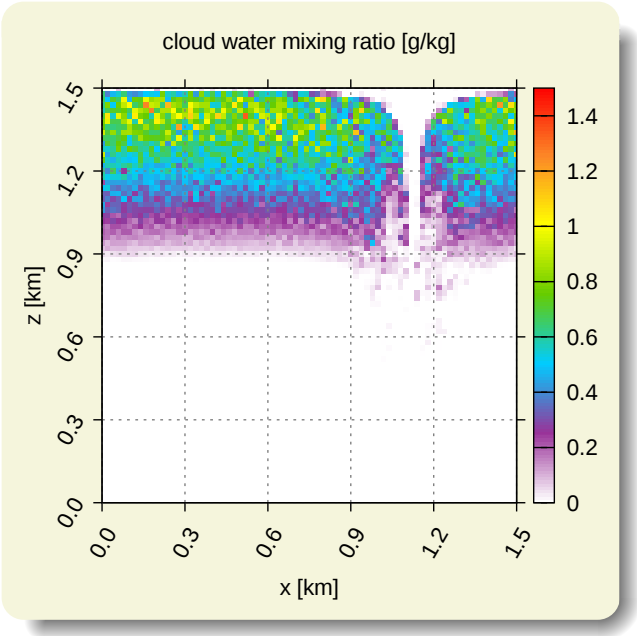

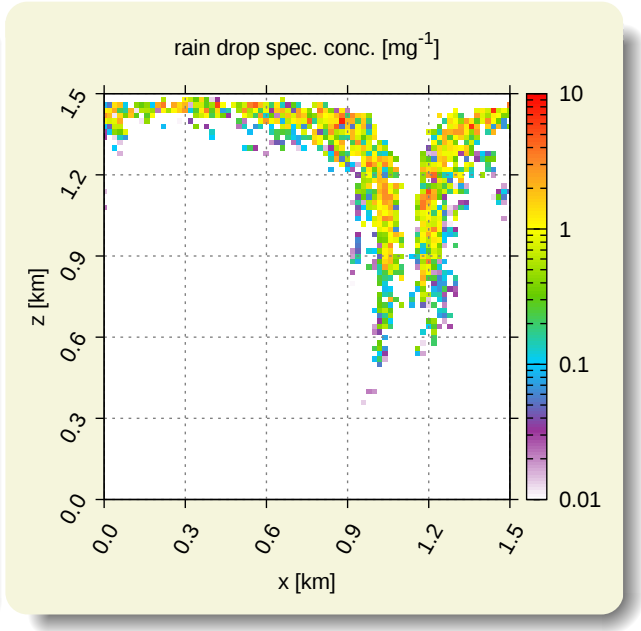

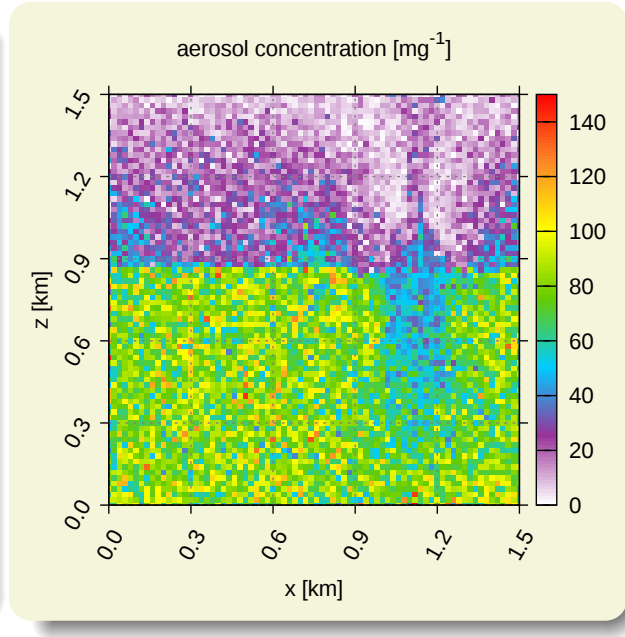

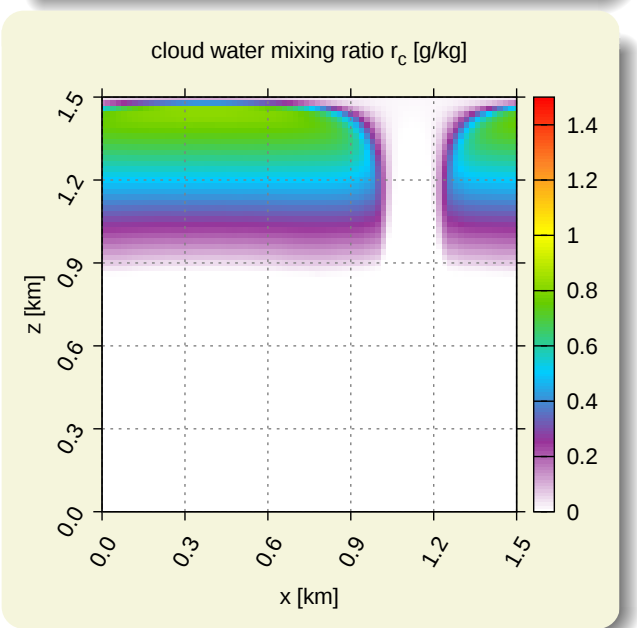

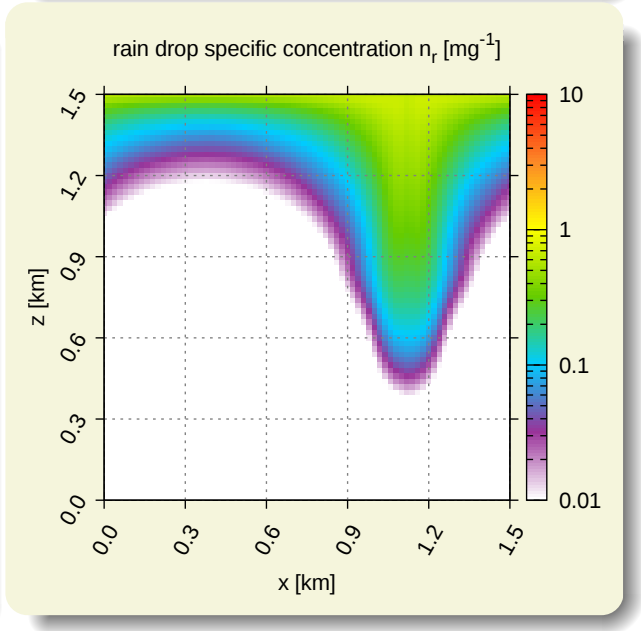

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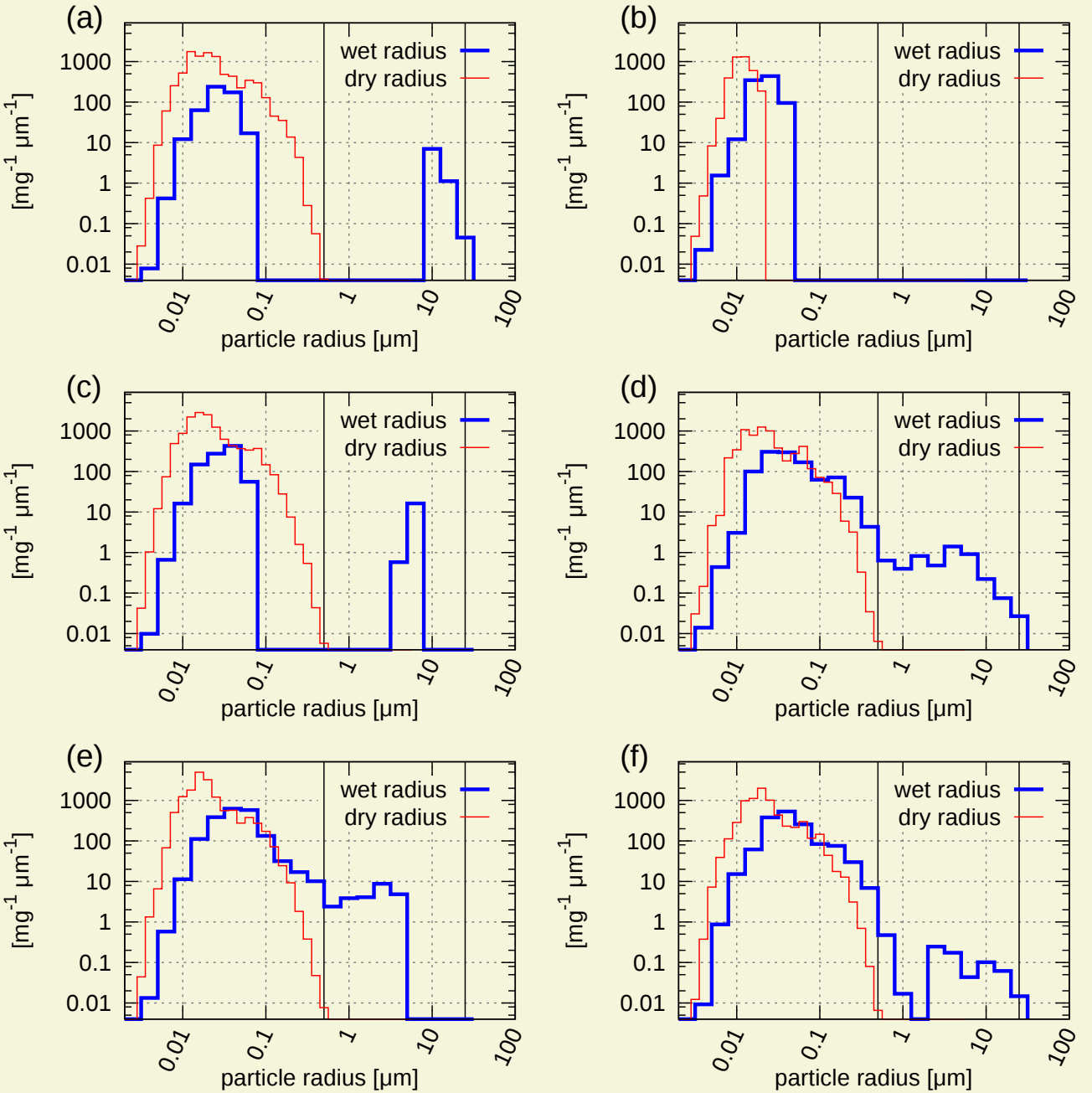
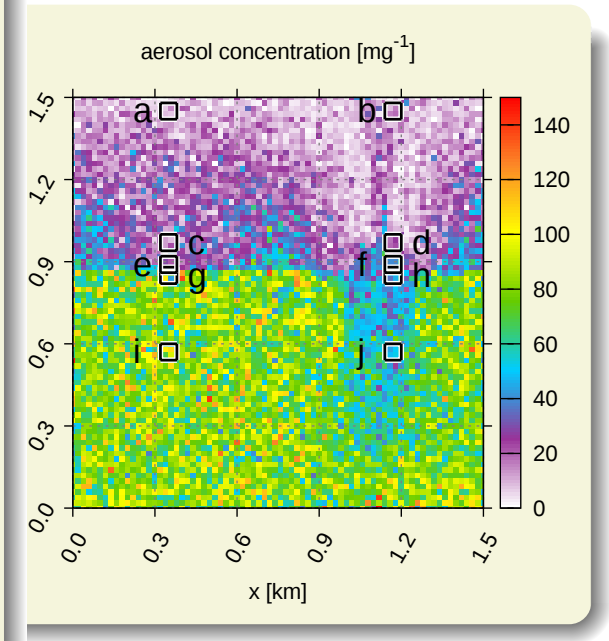
2×2 cell particle-derived spectra





libcloudph++: summary & some technicalities

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- written using Boost.units – compile-time dimensional analysis

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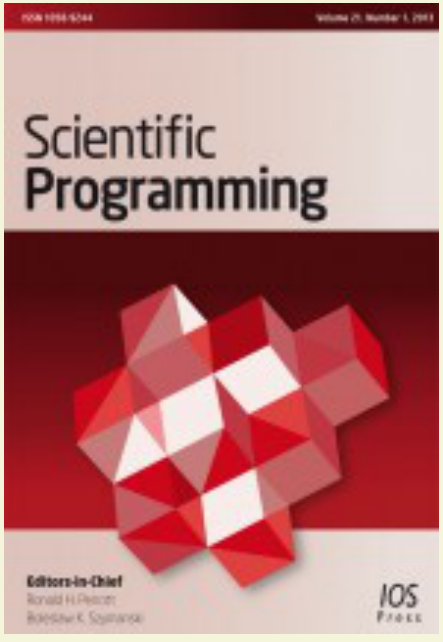
acknowledgements:

- Development of libmpdata++ and libcloudph++ have been supported by Poland's National Science Centre (decision no. 2012/06/M/ST10/00434)

MPDATA in C++, Fortran and Python



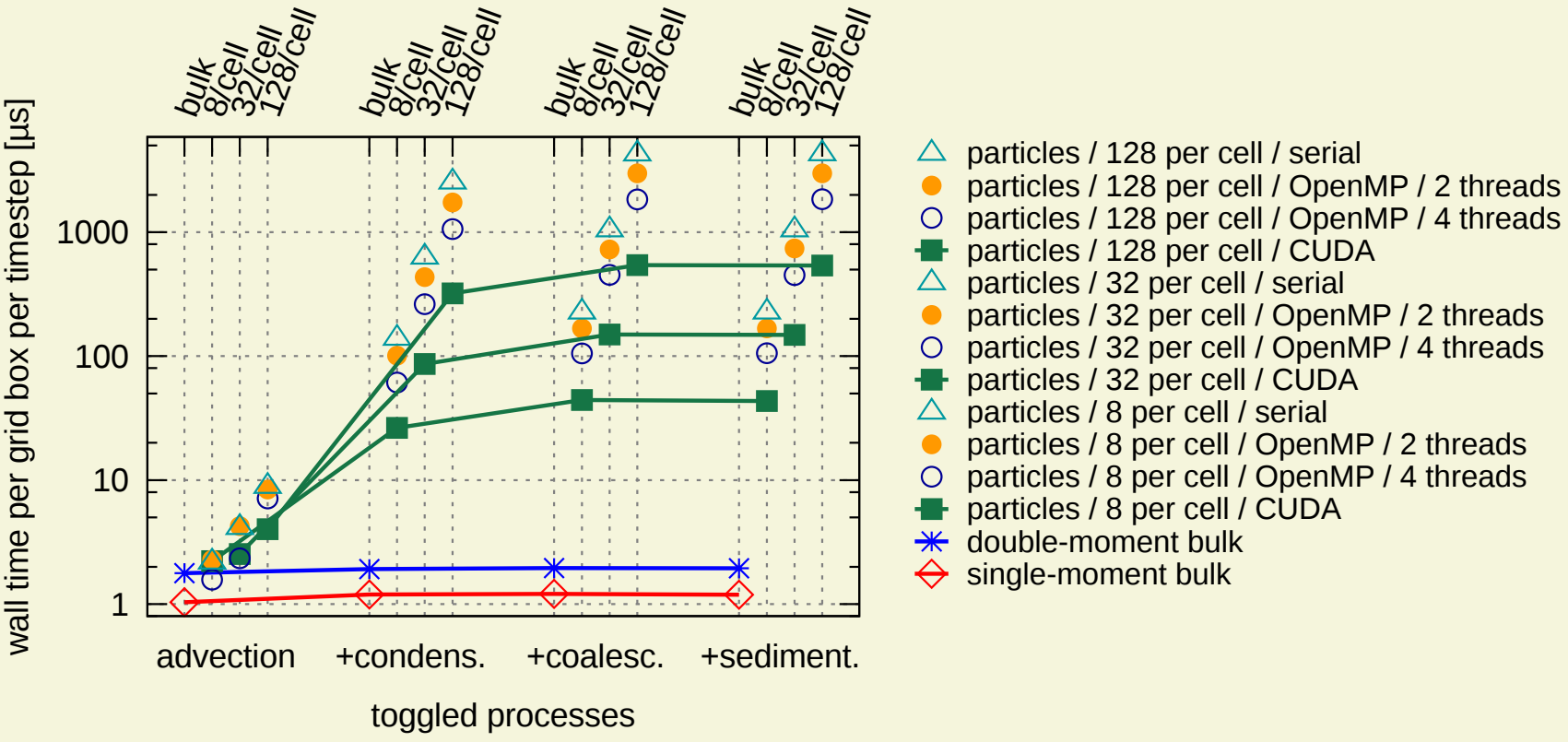
Formula translation in Blitz++, NumPy and modern Fortran: A case study of the language choice tradeoffs

Sylwester Arabas[1], Dorota Jarecka[1], Anna Jaruga[1], Maciej Fijałkowski[2]

[1]Institute of Geophysics, Faculty of Physics, University of Warsaw
[2]PyPy Team

Journal	Scientific Programming
DOI	10.3233/SPR-140379
Online Date	Monday, March 24, 2014

libcloudph++: GPU-resident option for Lagrangian scheme



implemented using Thrust: OpenMP/GPU choice with no code modif.

ongoing work

libmpdata++

libcloudph++

ongoing work

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- higher-order operators for subgrid-scale modelling
  (with Piotr Smolarkiewicz & Maciej Waruszewski / U. Warsaw)

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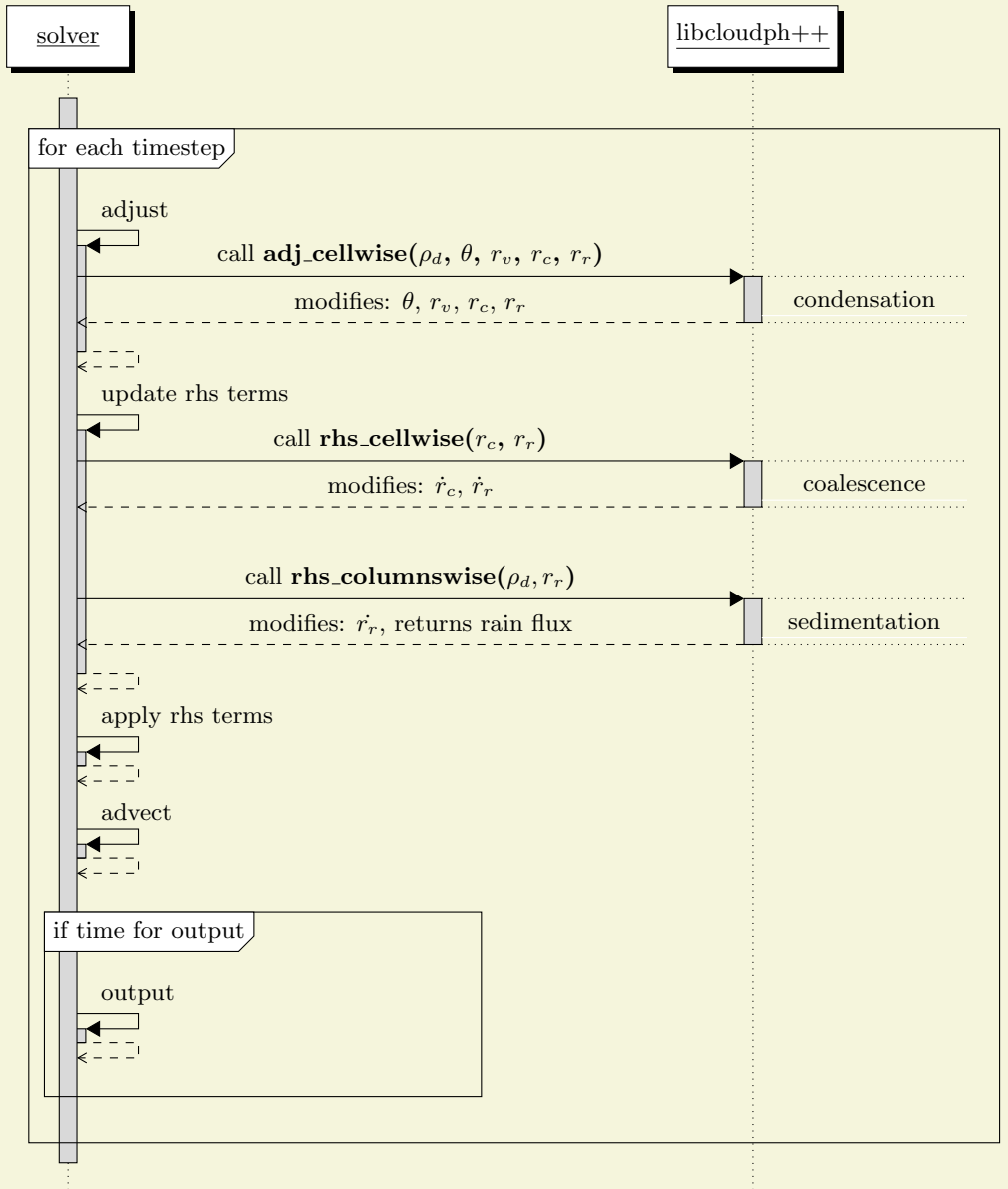
- DALES/libcloudph++ coupling
  (with Harm Jonker / TU Delft)

libcloudph++: reusable μ-physics

sequence diagram



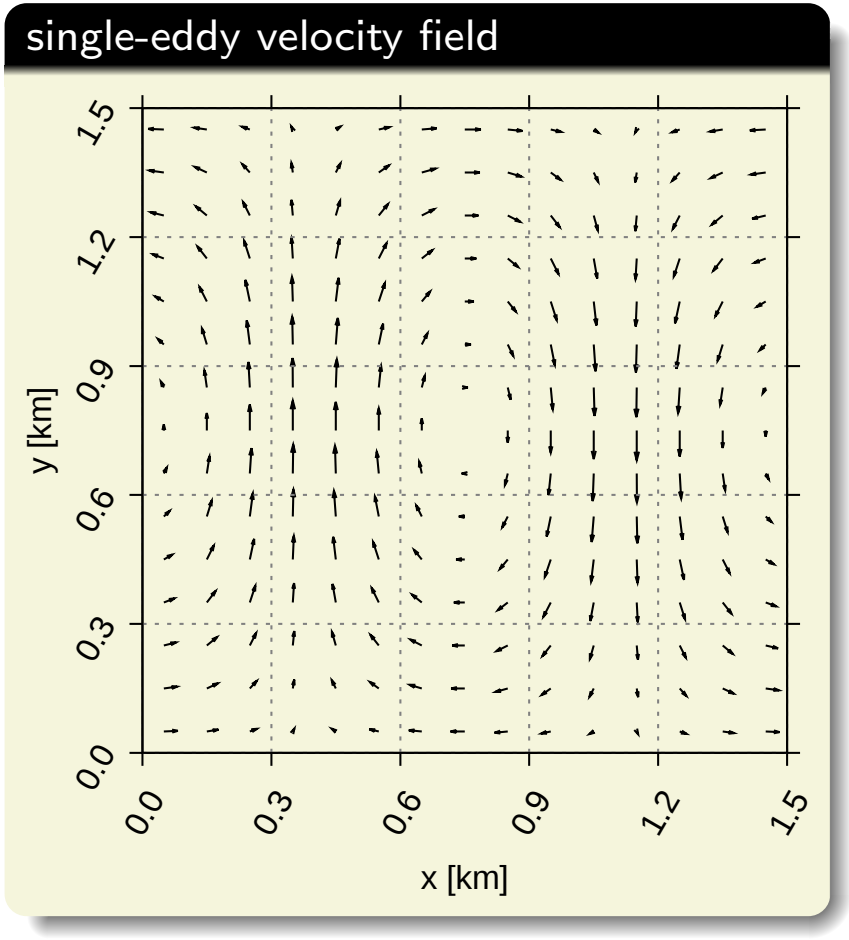
programming interface

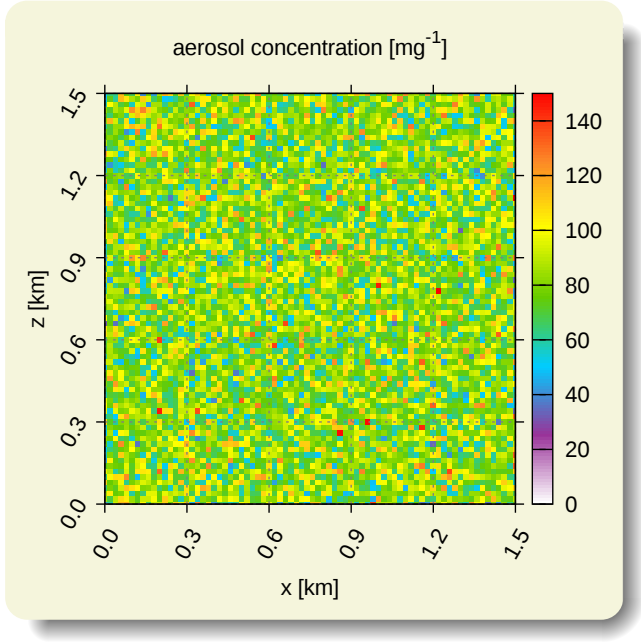
```
template<typename real_t>
struct opts_t
{
  bool
    acti = true, // activation
    cond = true, // condensation
    acnv = true, // autoconversion
    accr = true, // accretion
    sedi = true; // sedimentation

  // RH limit for activation
  real_t RH_max = 44;

  // aerosol spectrum
  struct lognormal_mode_t
  {
    real_t
      mean_rd,   // [m]
      sdev_rd,   // [1]
      N_stp,     // [m-3] @STP
      chem_b;    // [1]
  };
  std::vector<lognormal_mode_t> dry_distros;
};
```

libcloudph++: VOCALS-inspired aerosol processing set-up

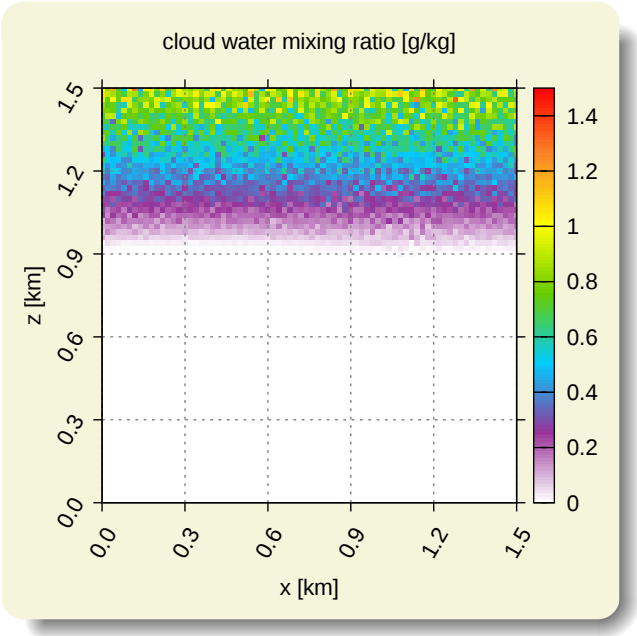


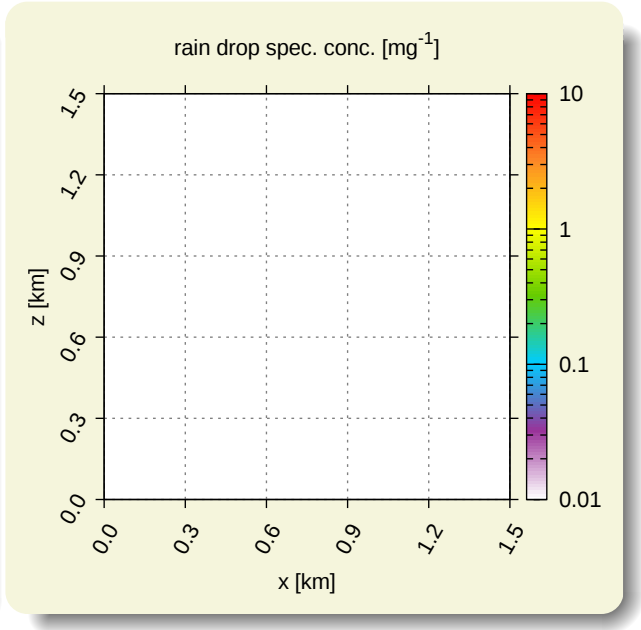


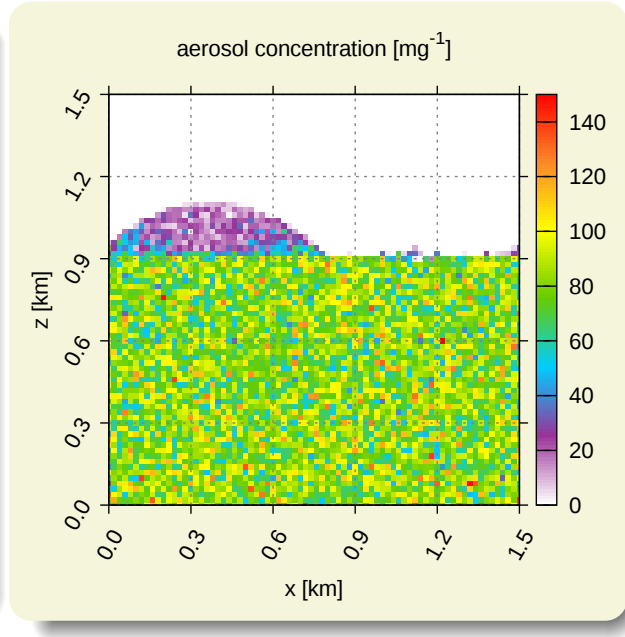
- set-up: Grabowski & Lebo (ICMW 2012)
- 2D prescribed flow
- advection: libmpdata++ (2-pass FCT)
- μ-physics: libcloudph++

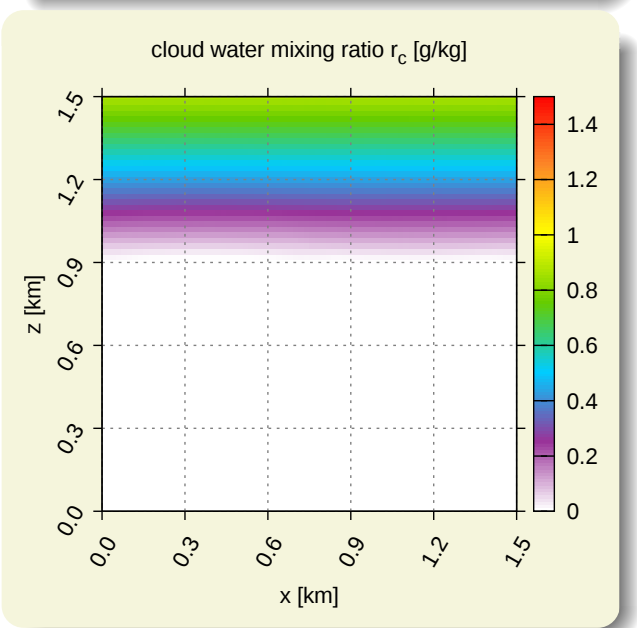
libcloudph++: VOCALS-inspired aerosol processing set-up

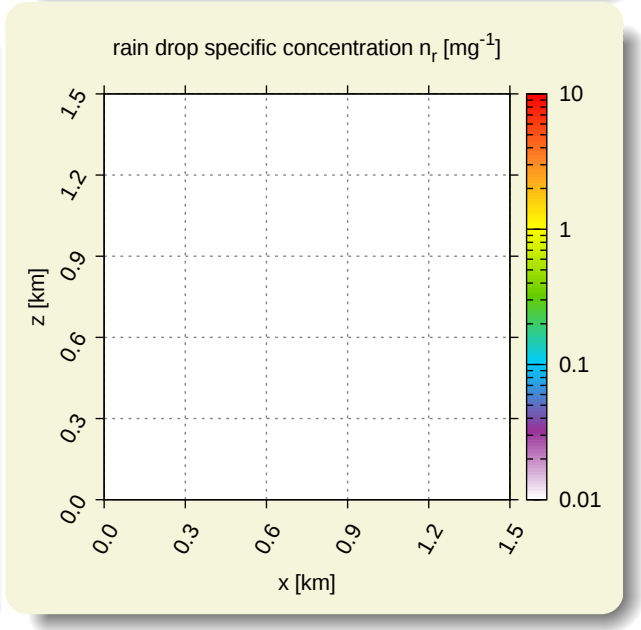
x











Lagrangian/Monte-Carlo scheme
(Shima et al. 2009)

2-moment bulk scheme
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libcloudph++: VOCALS-inspired aerosol processing set-up

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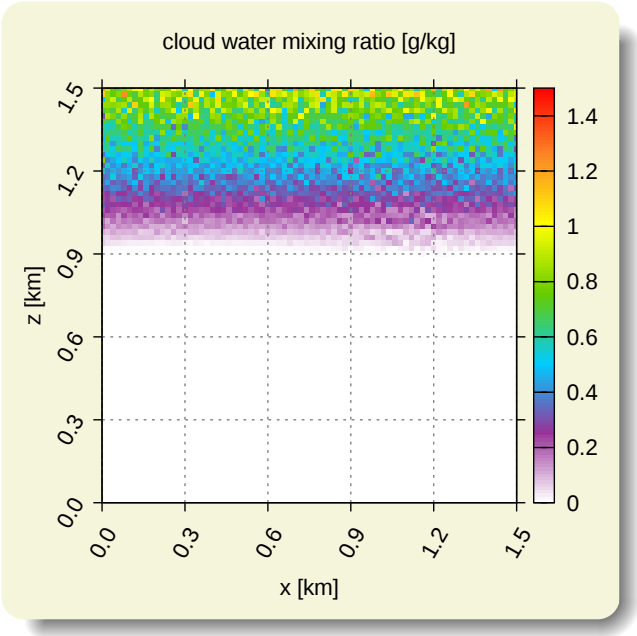

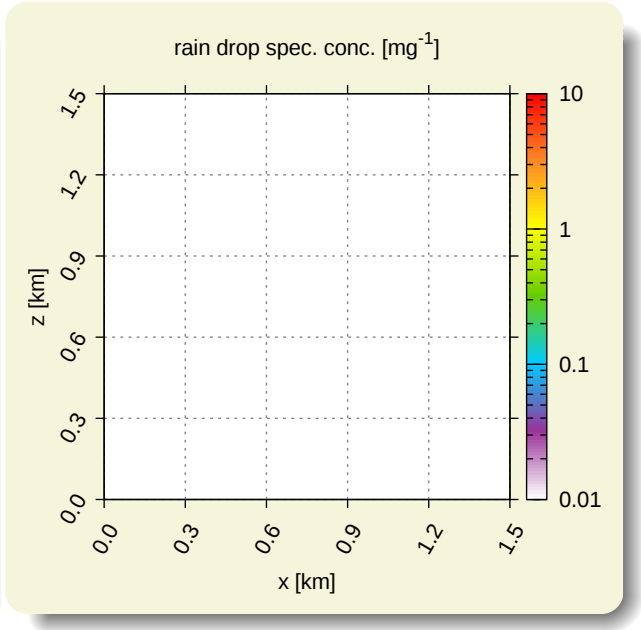

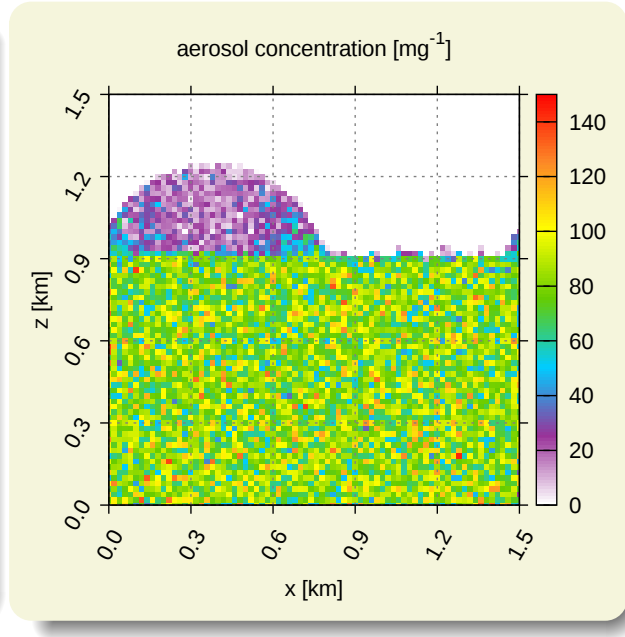

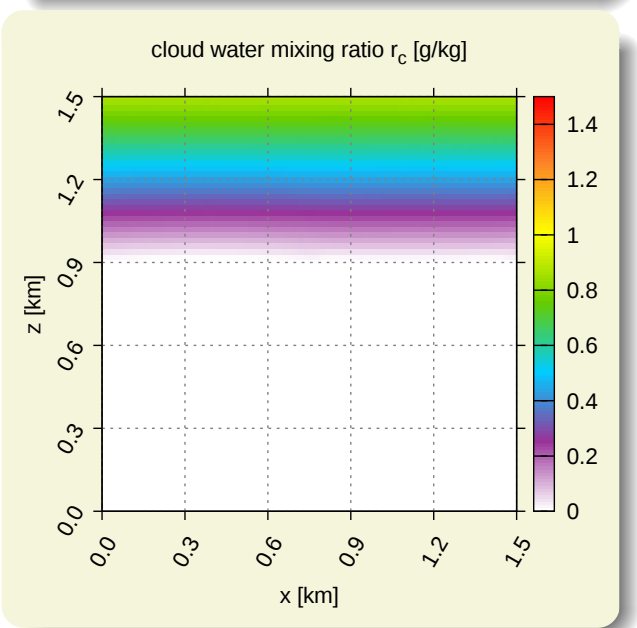

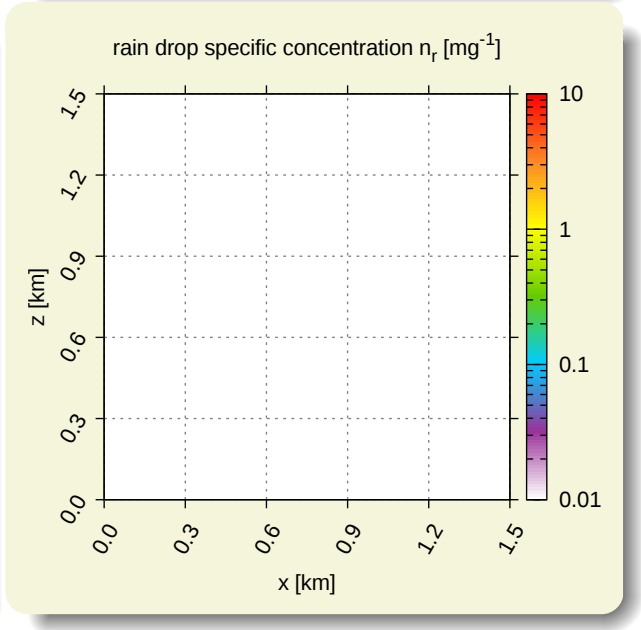

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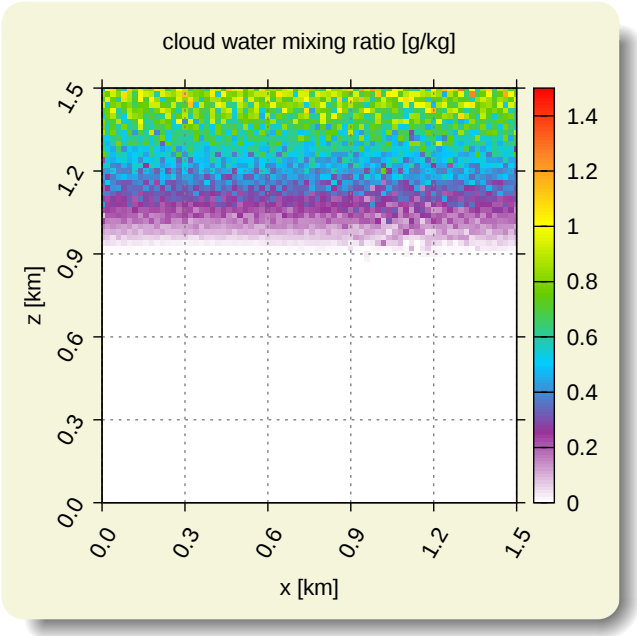

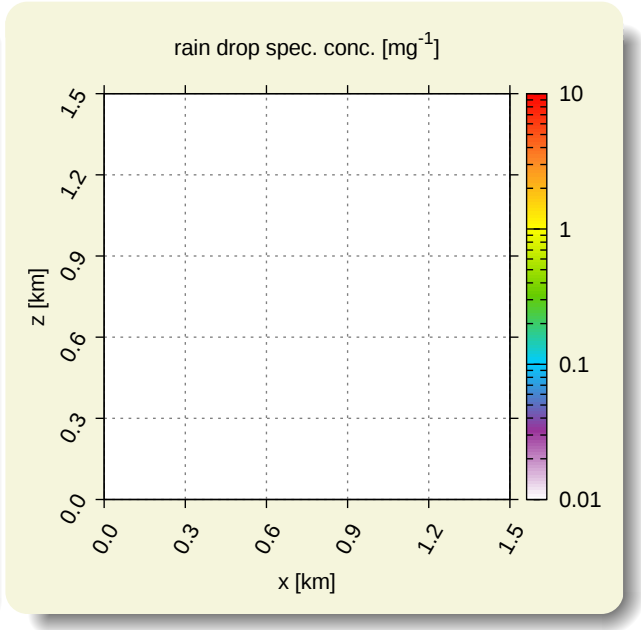

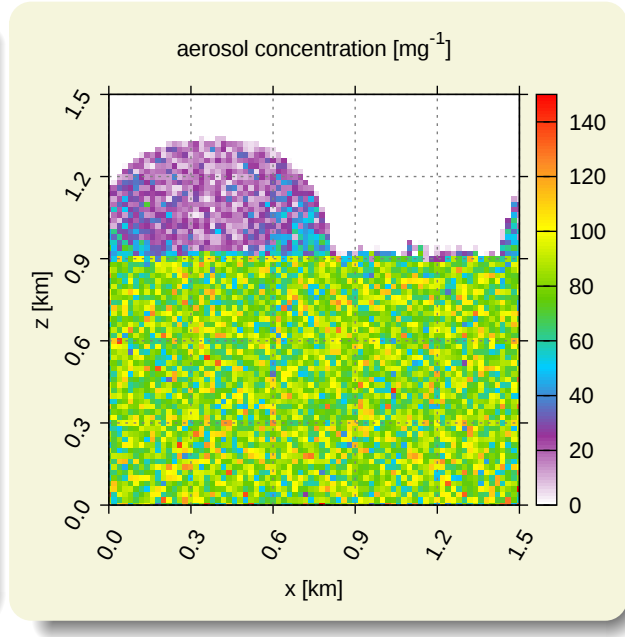

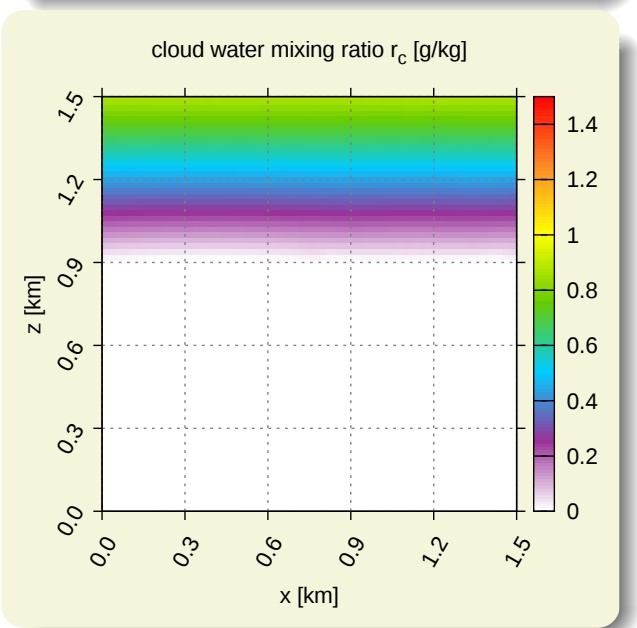

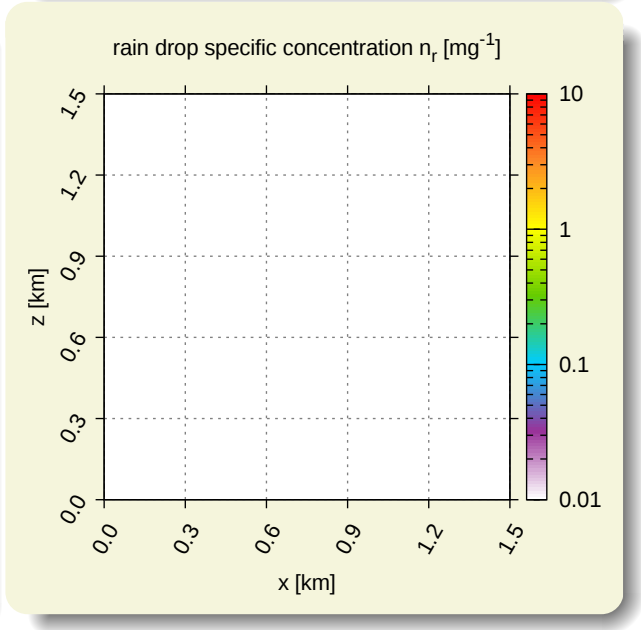

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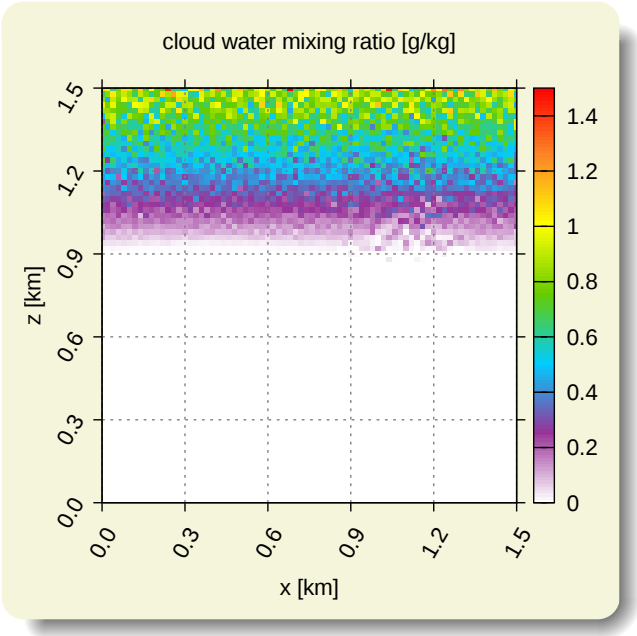

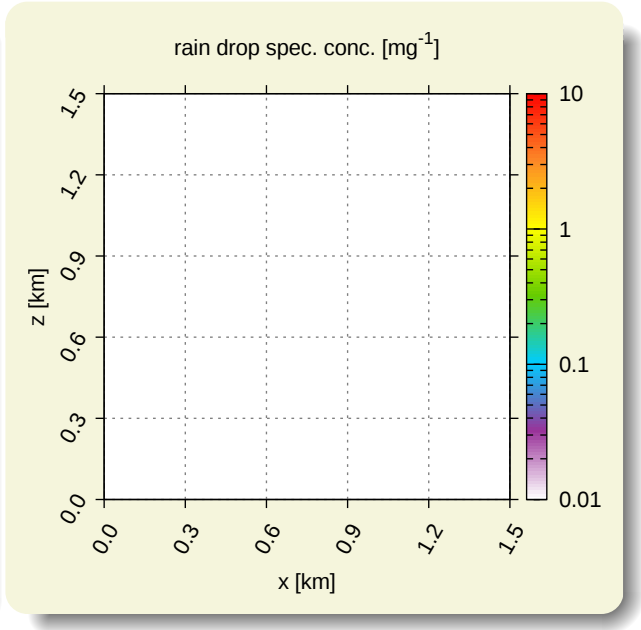

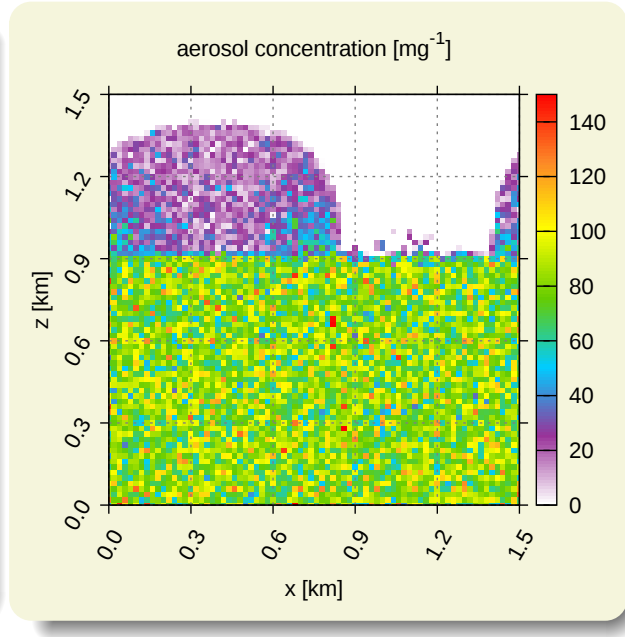

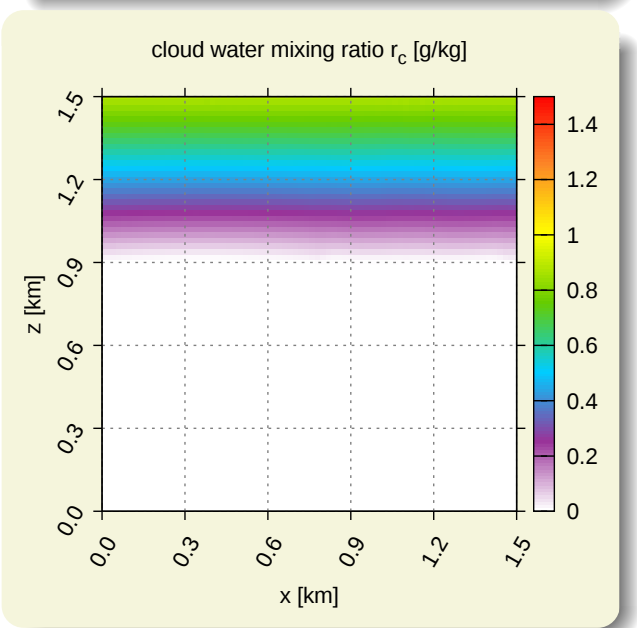

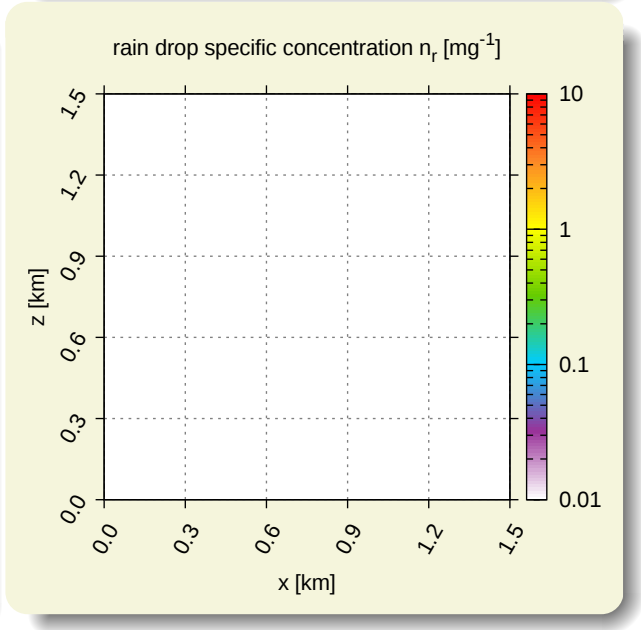

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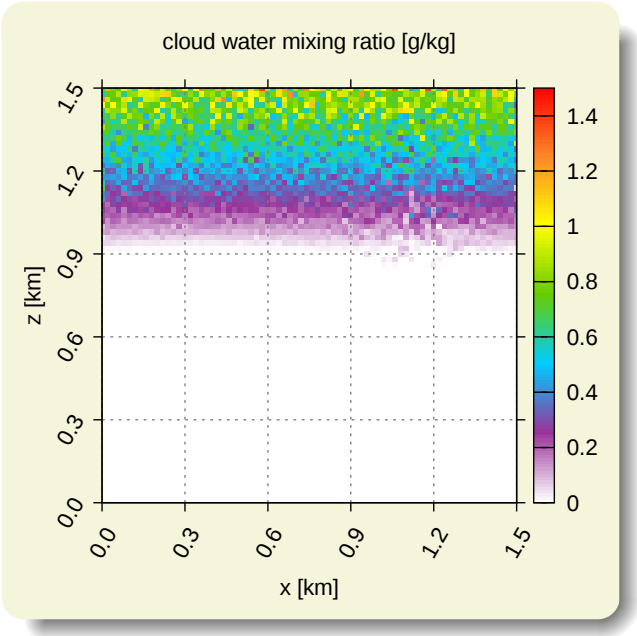

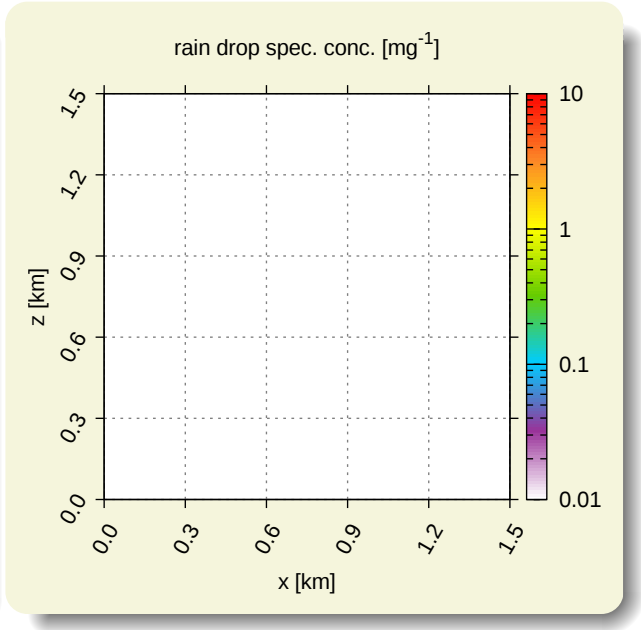

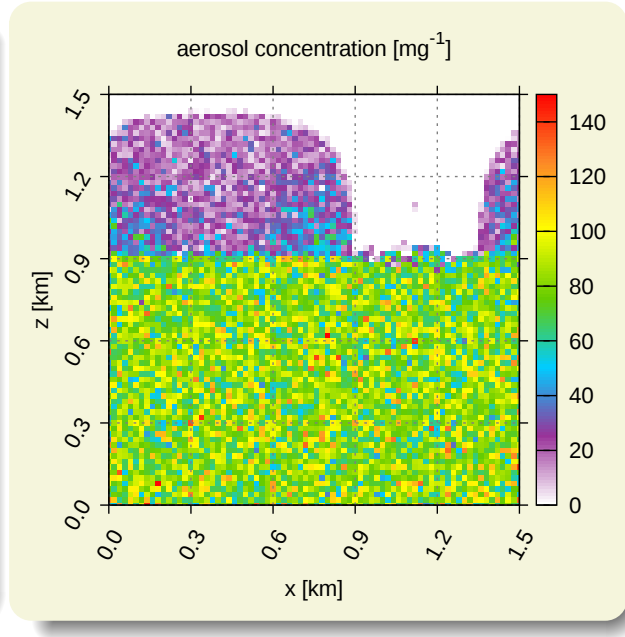

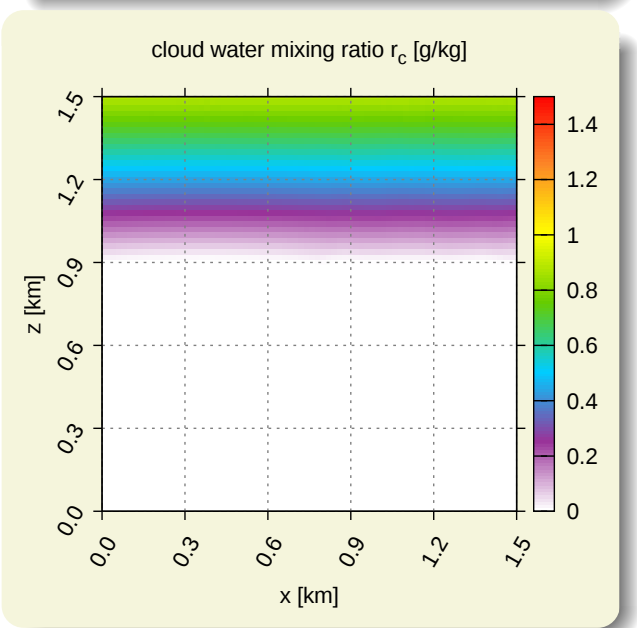

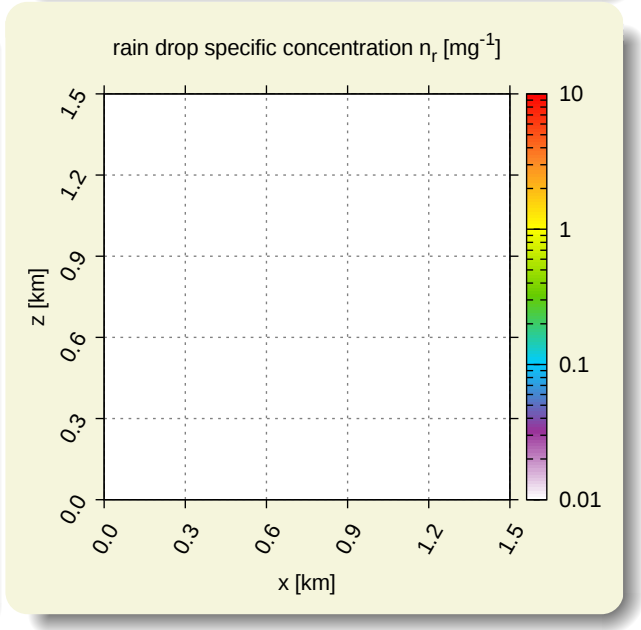

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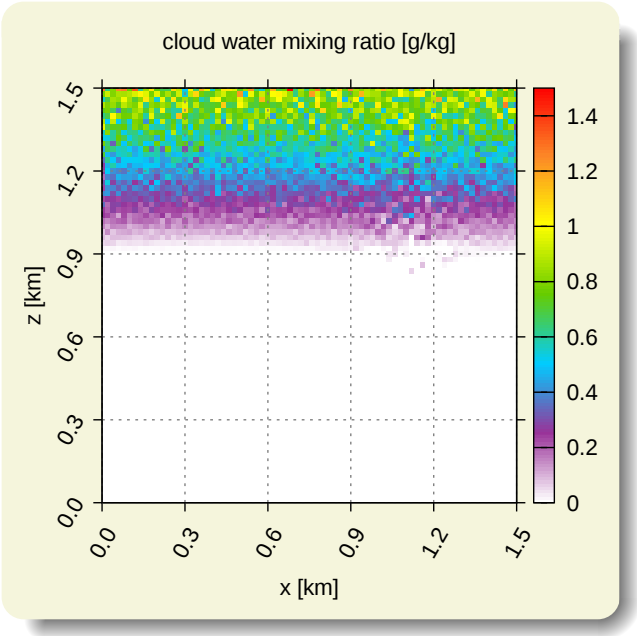

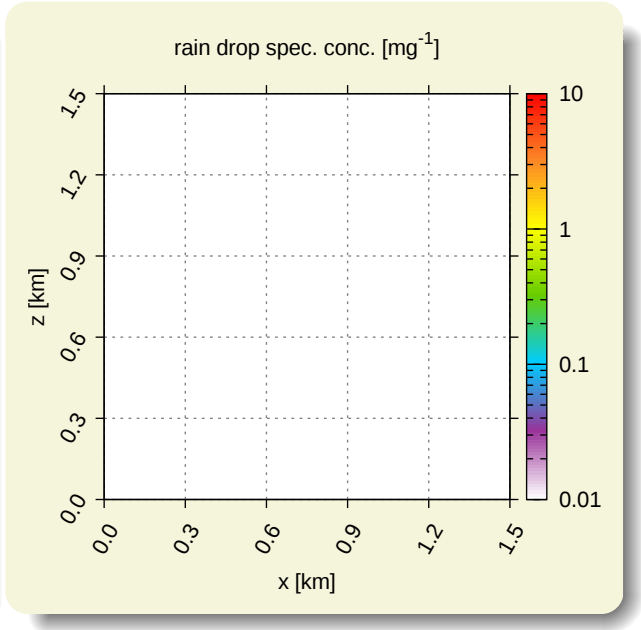

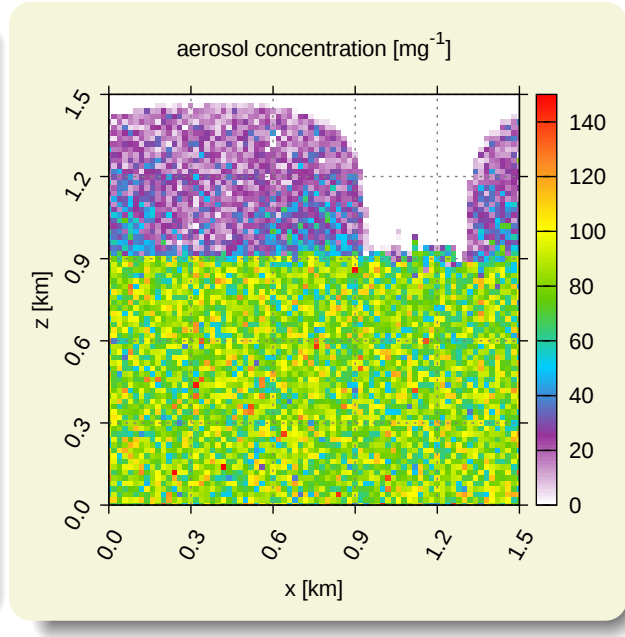

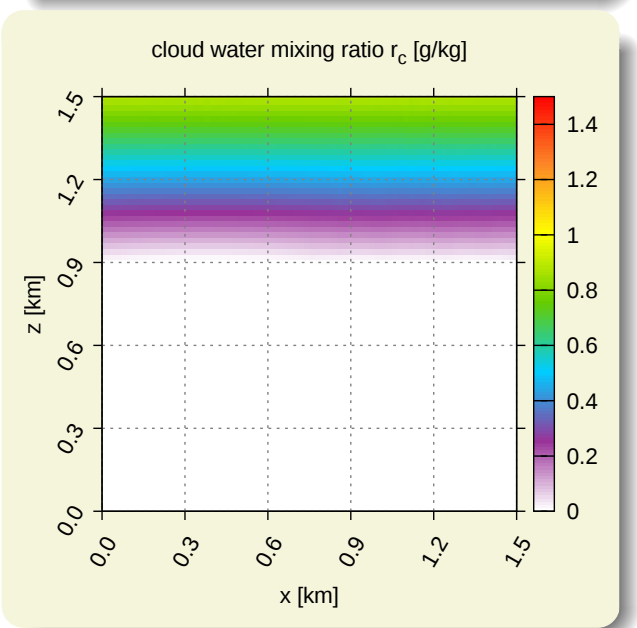

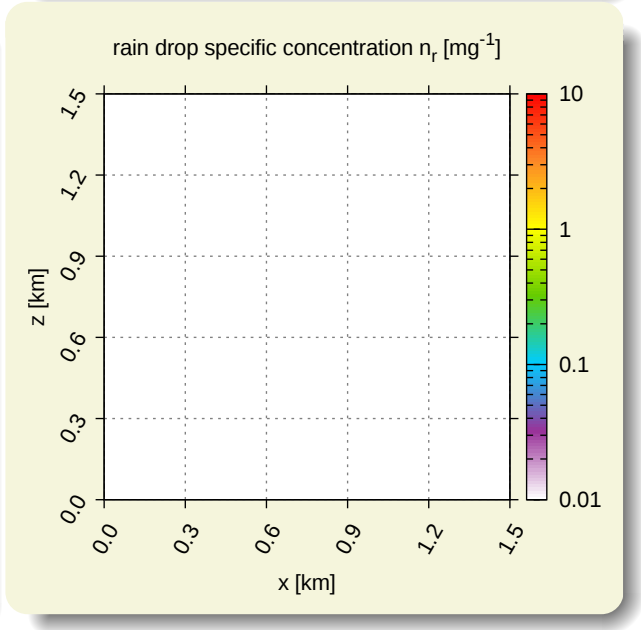

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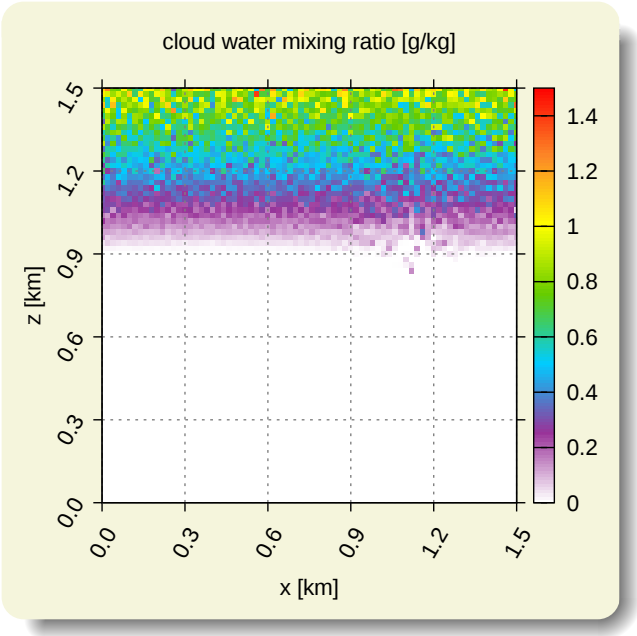

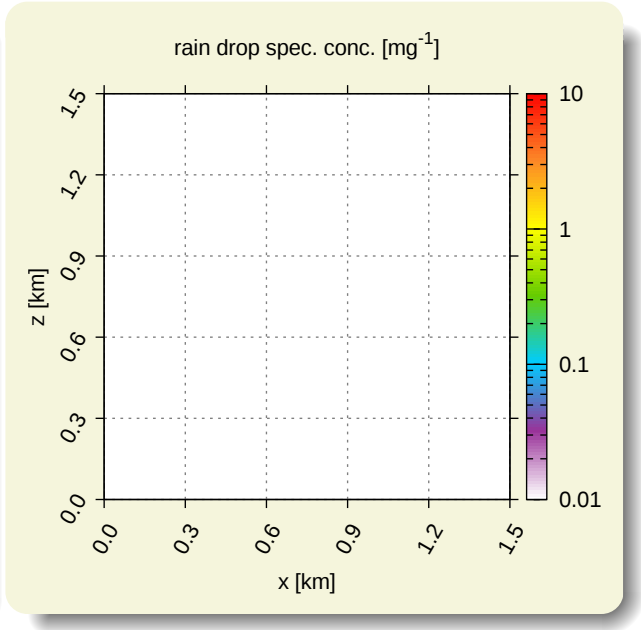

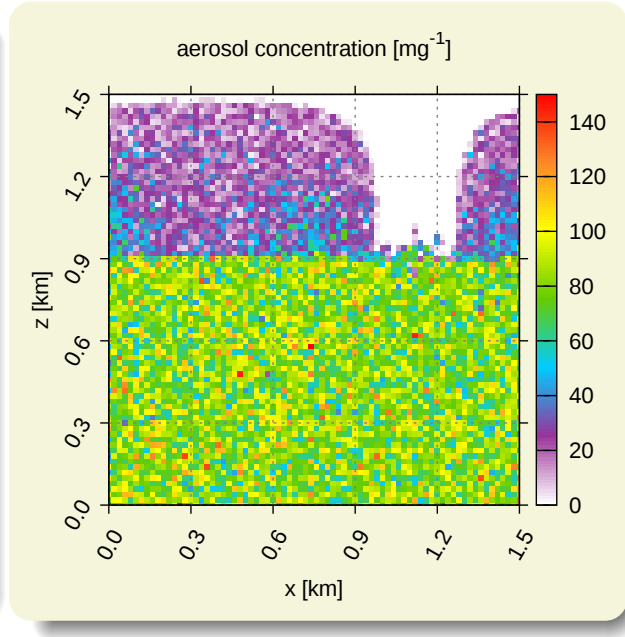

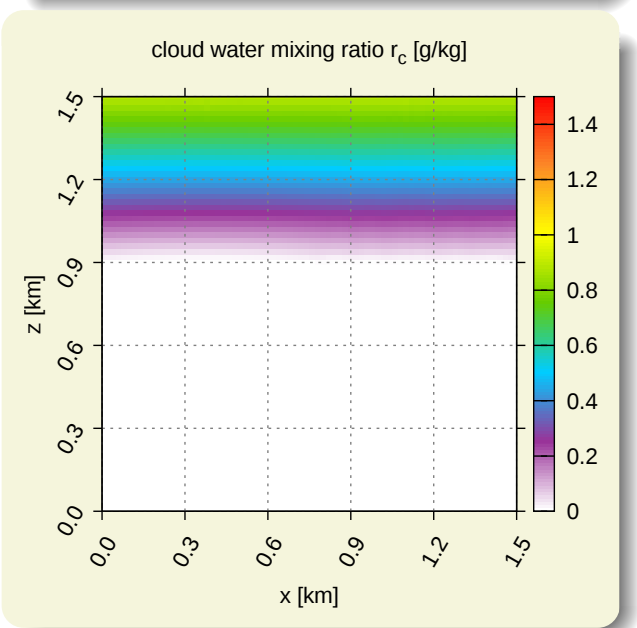

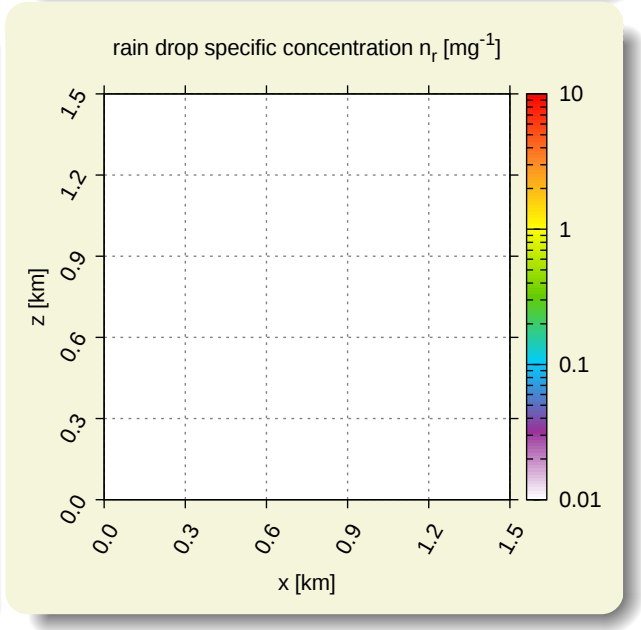

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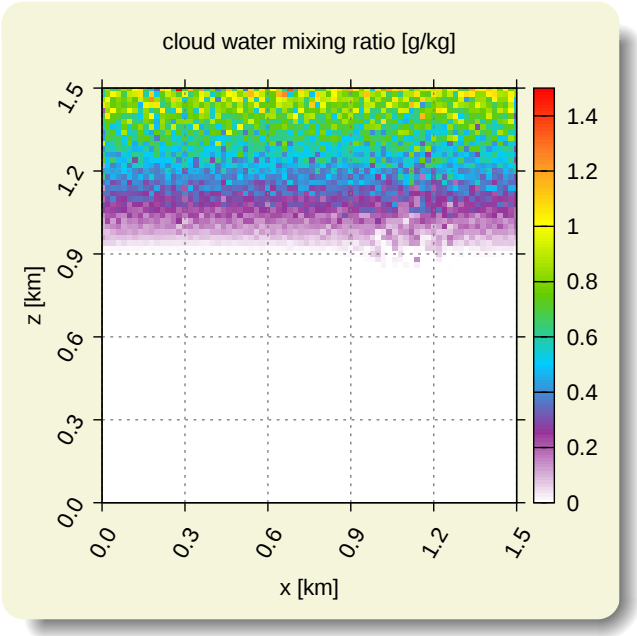

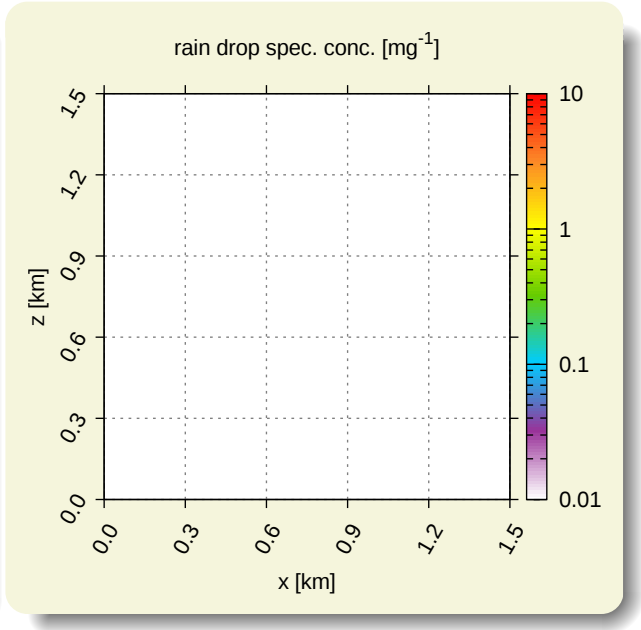

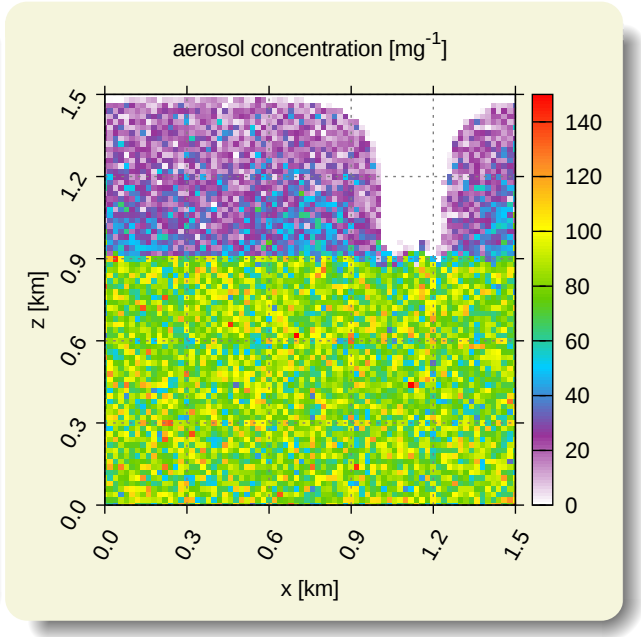

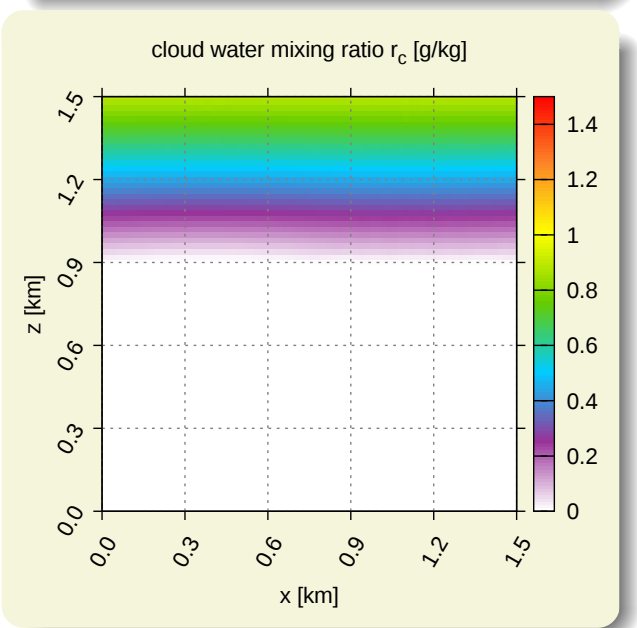

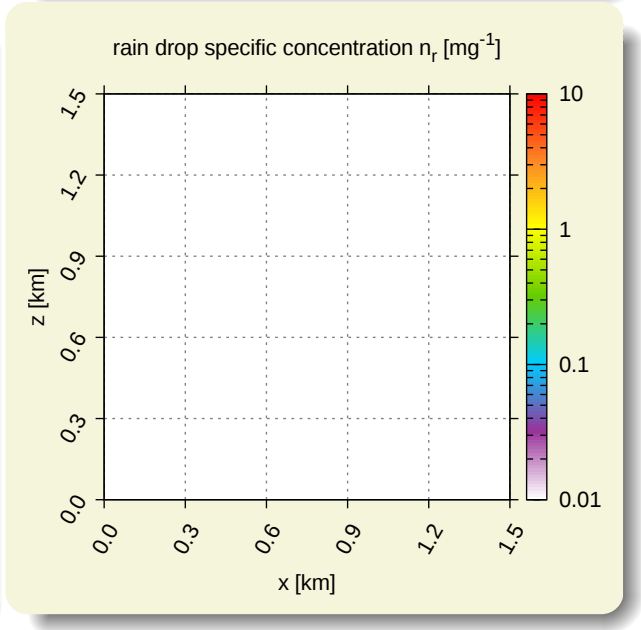

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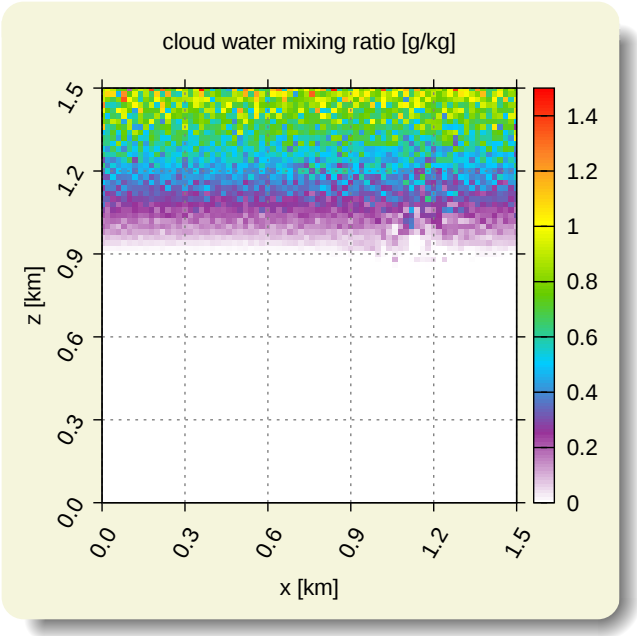

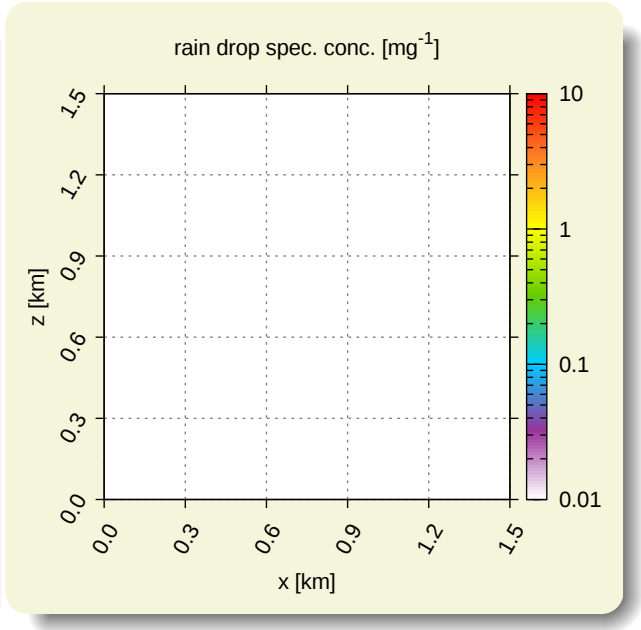

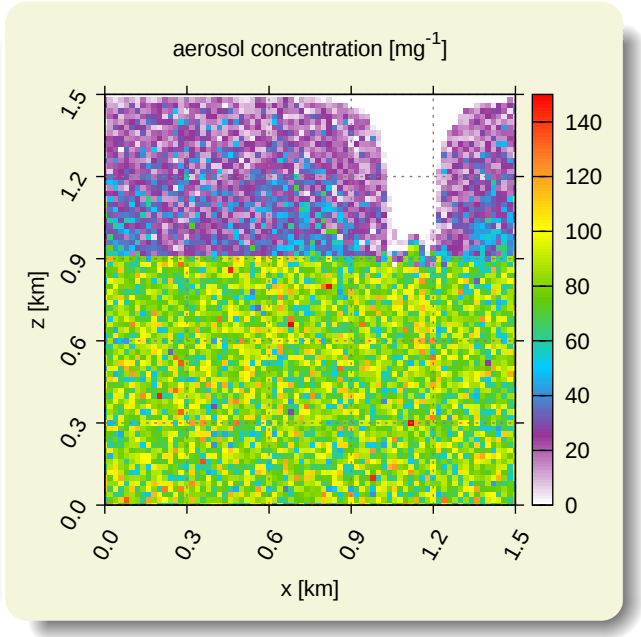

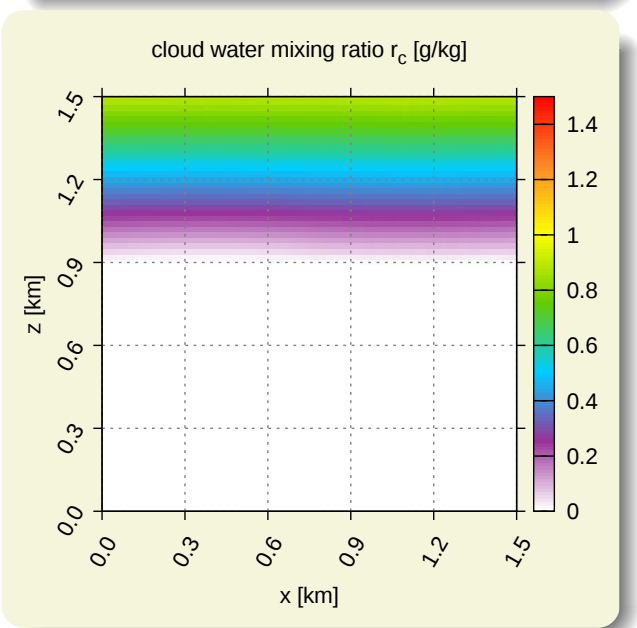

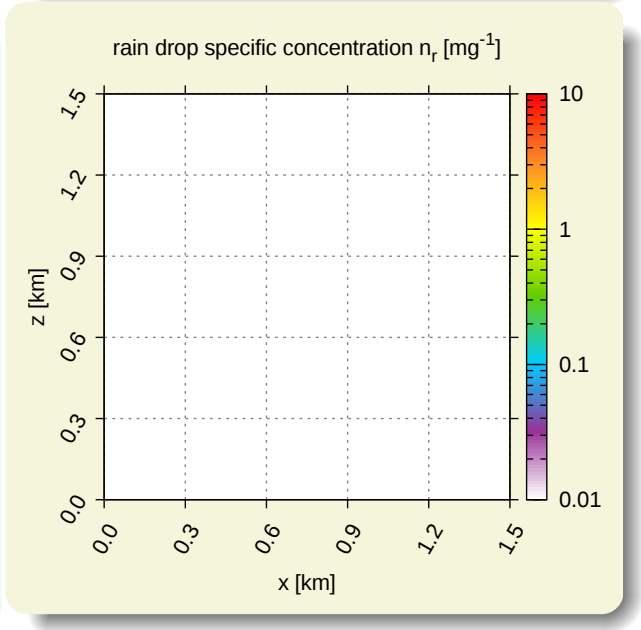

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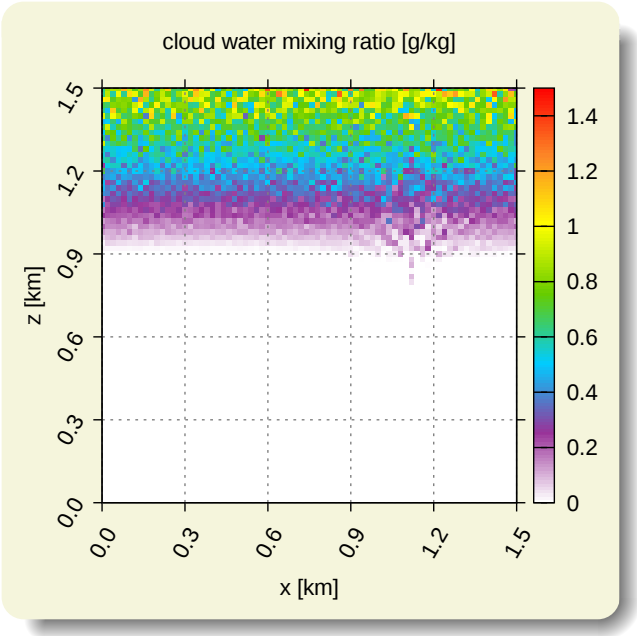

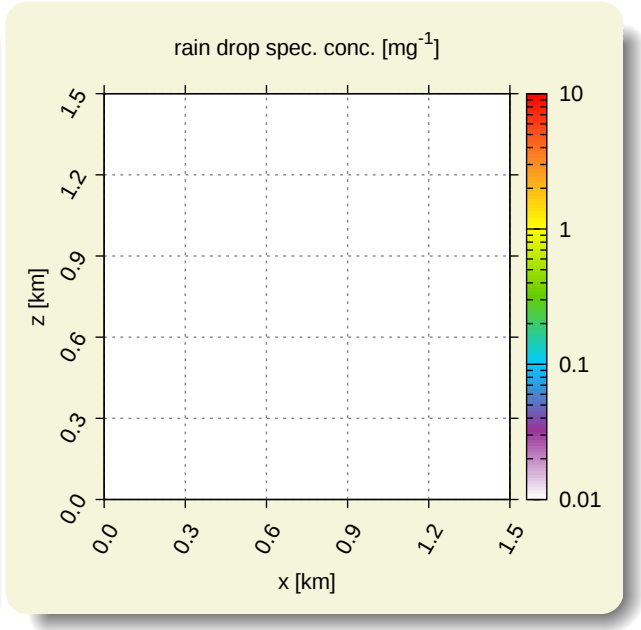

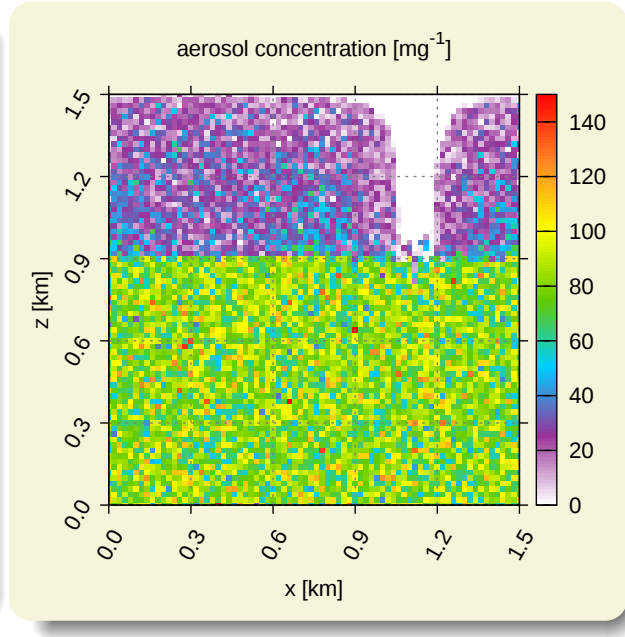

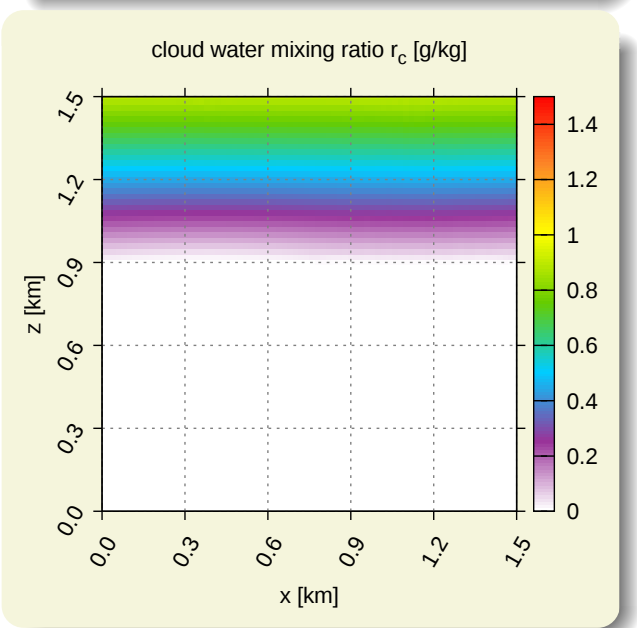

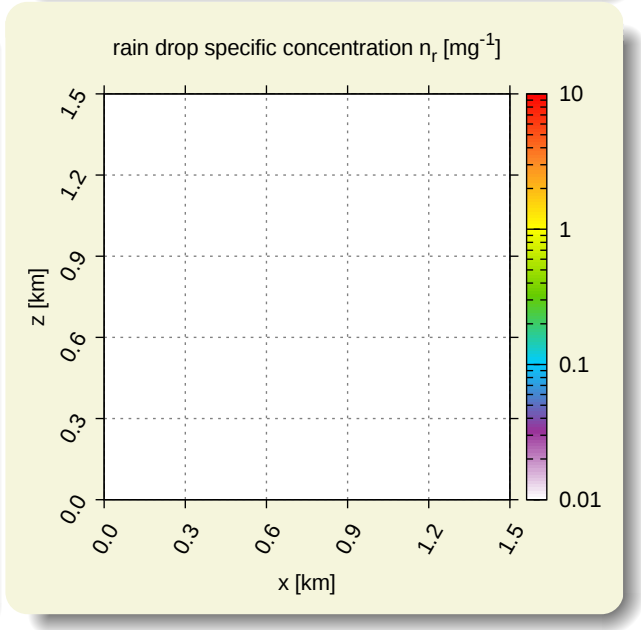

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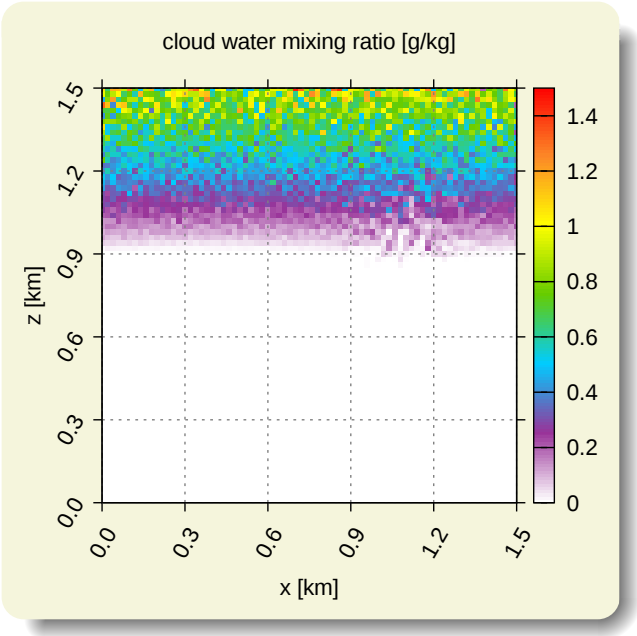

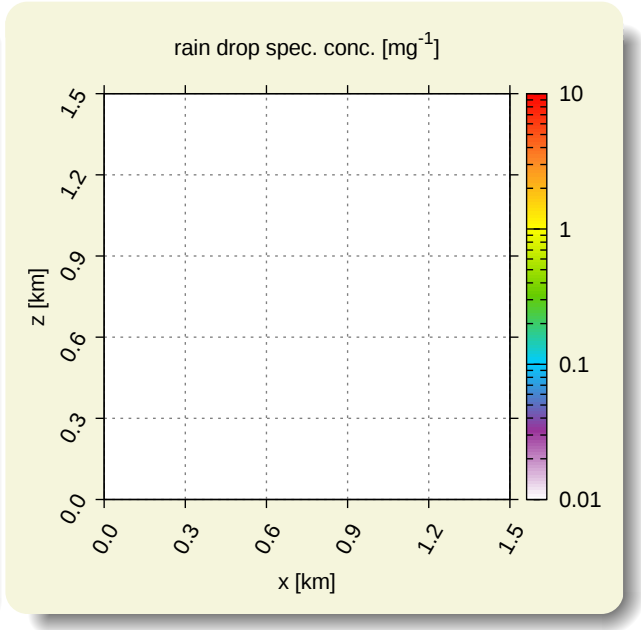

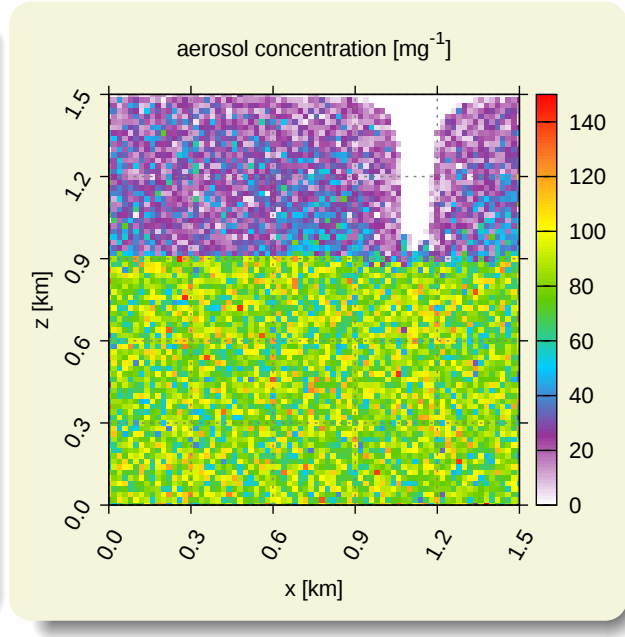

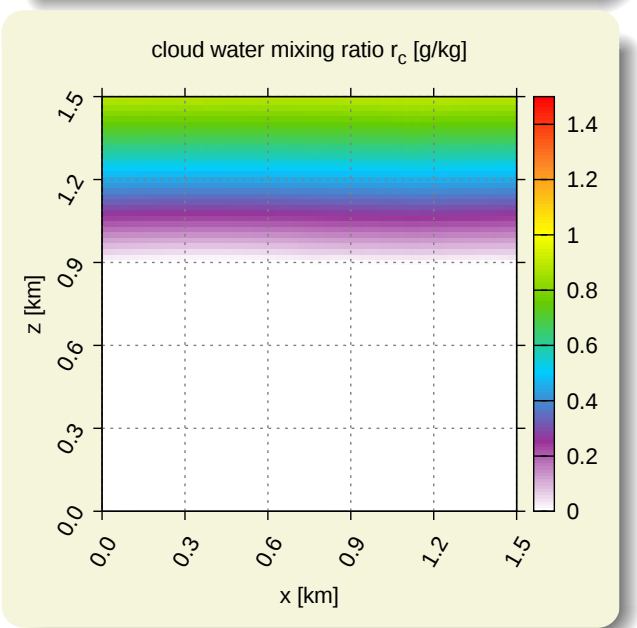

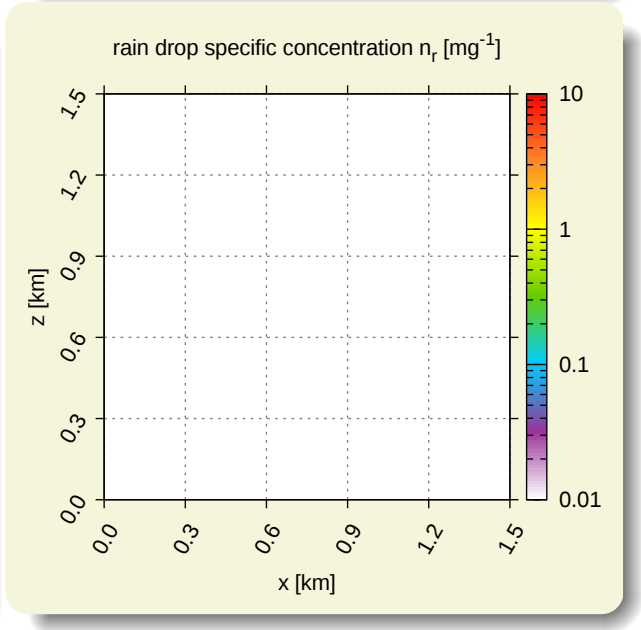

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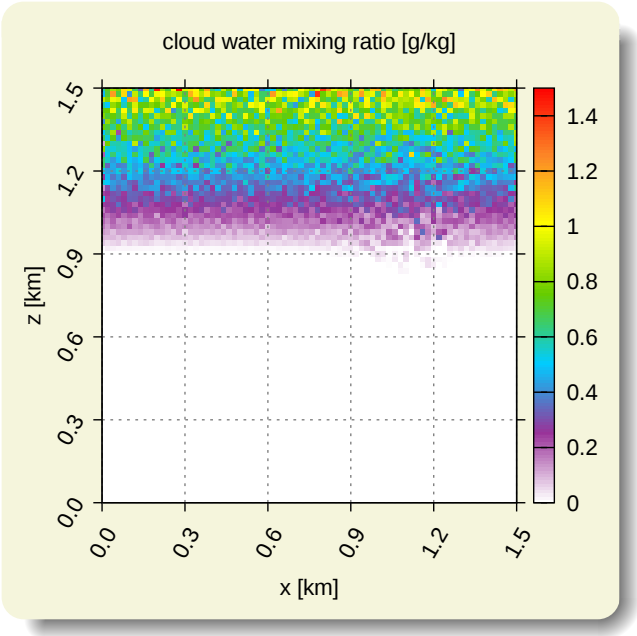

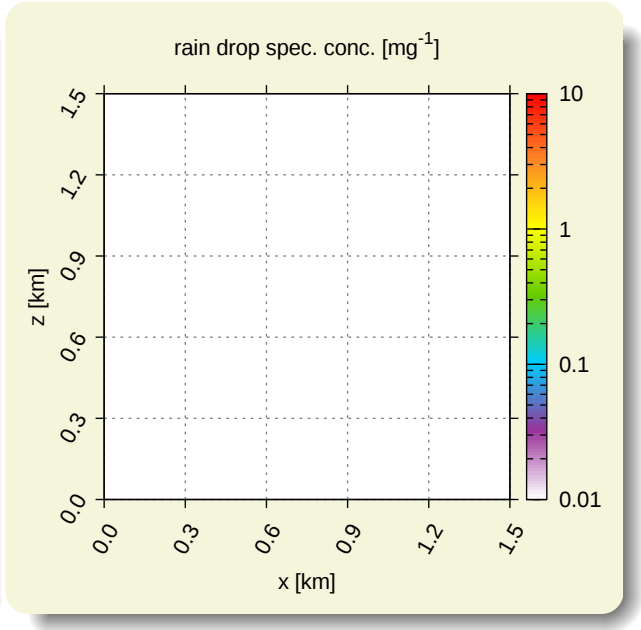

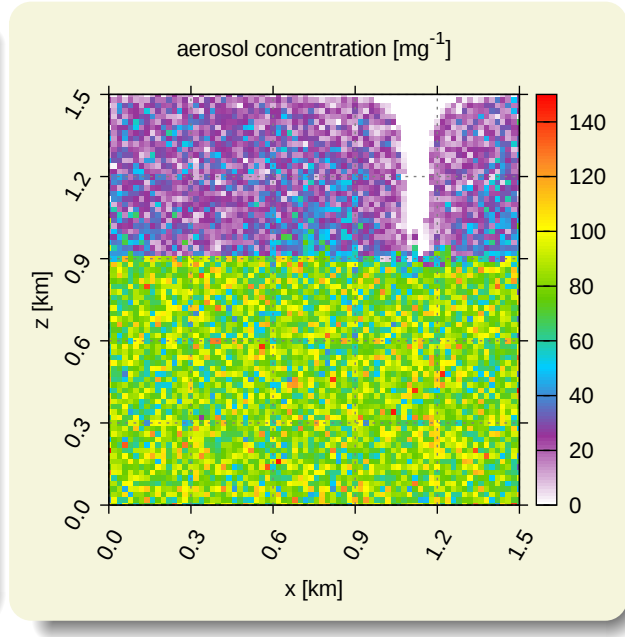

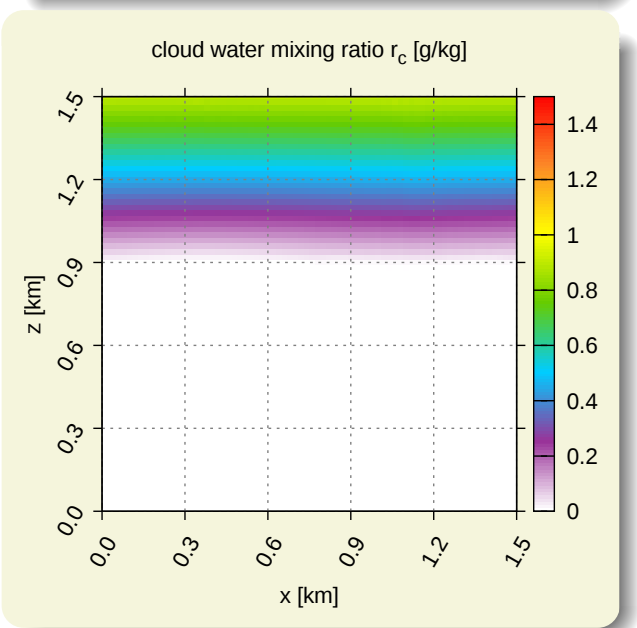

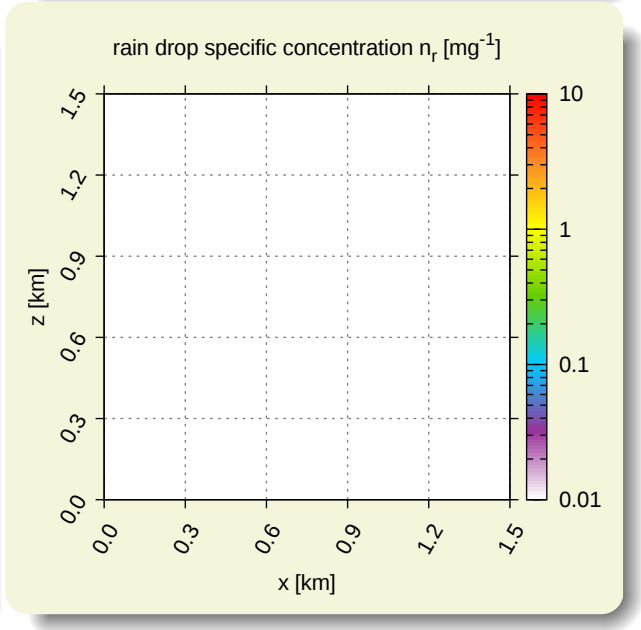

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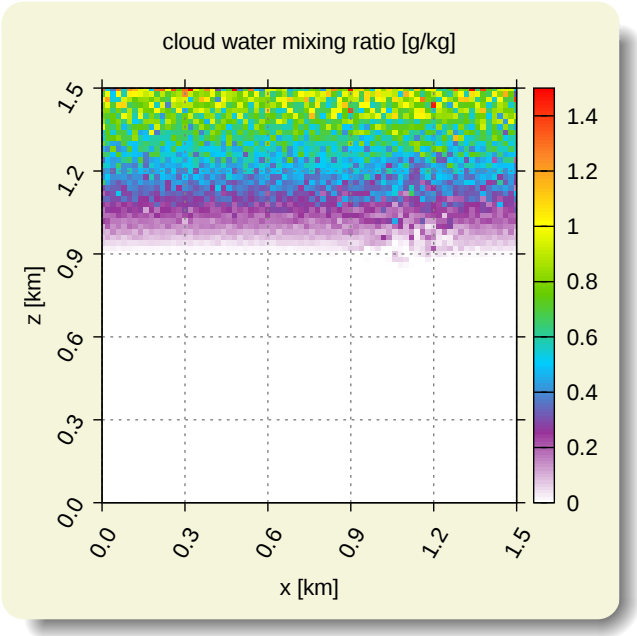

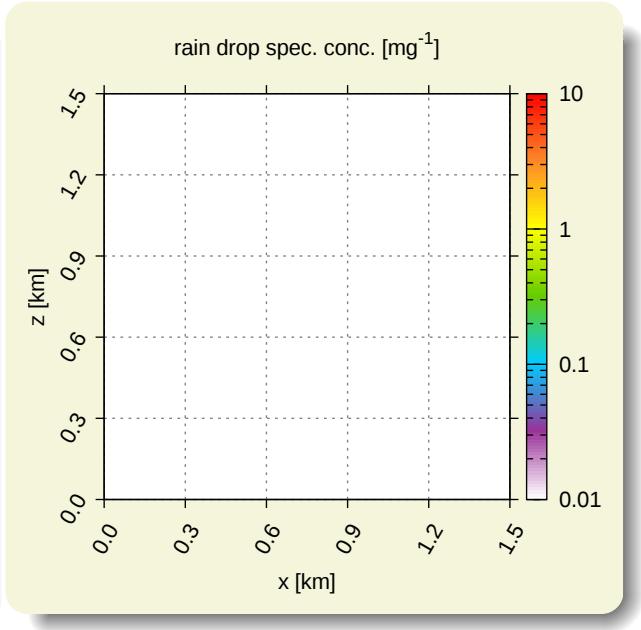

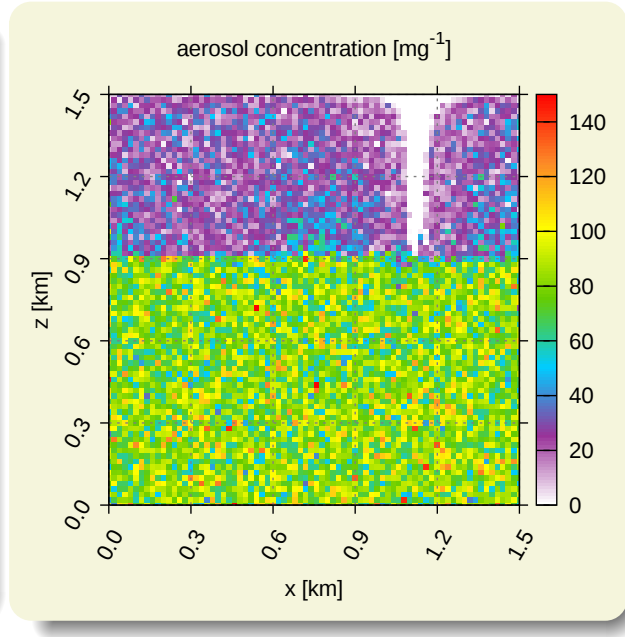

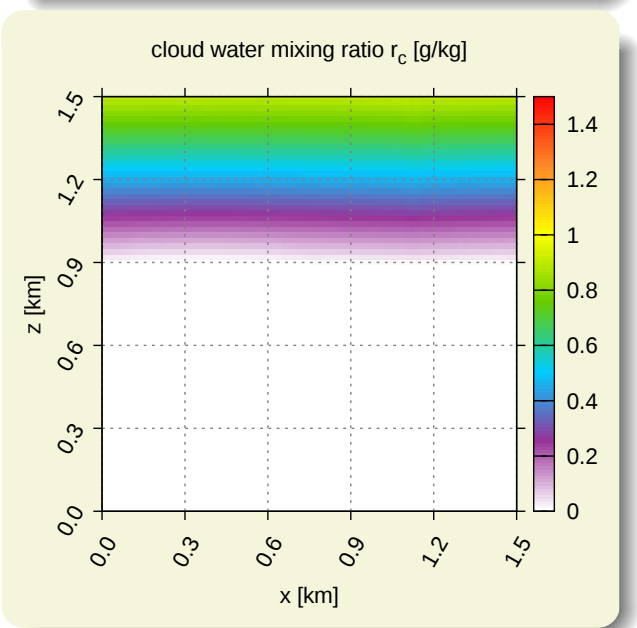

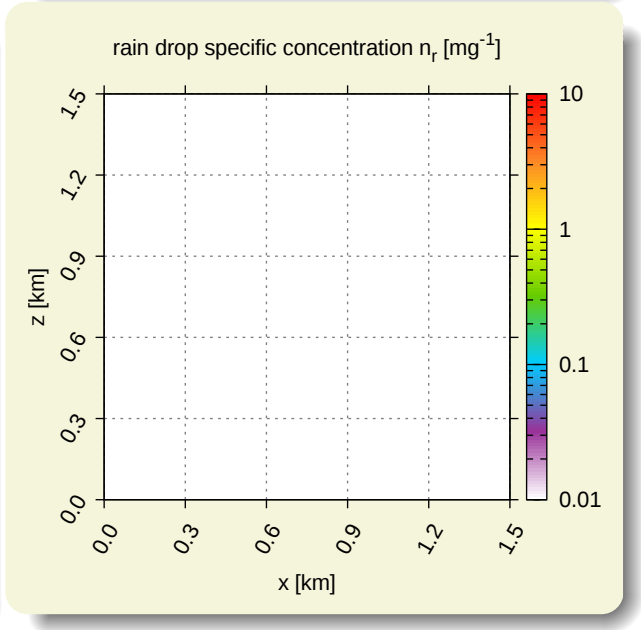

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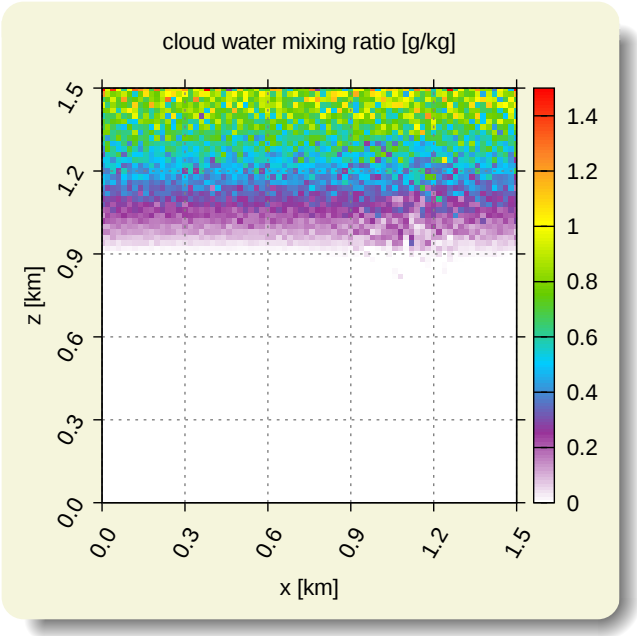

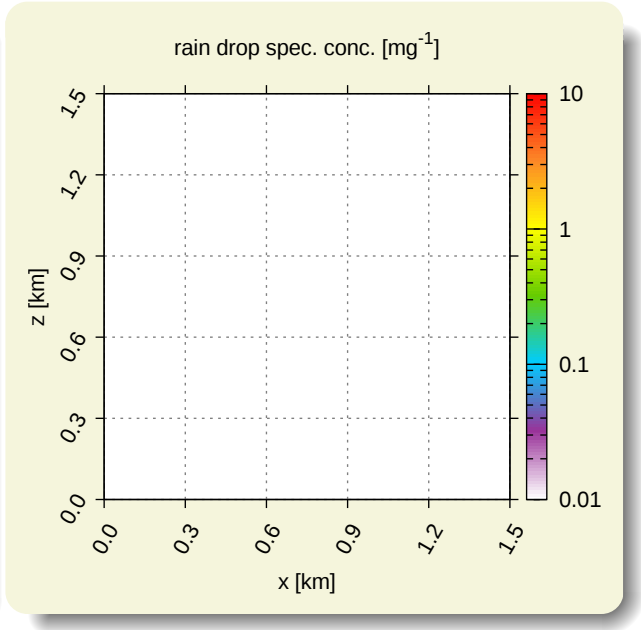

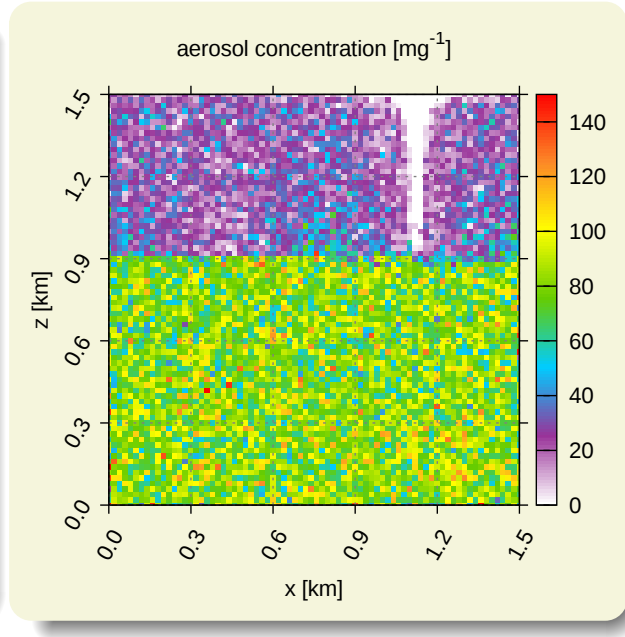

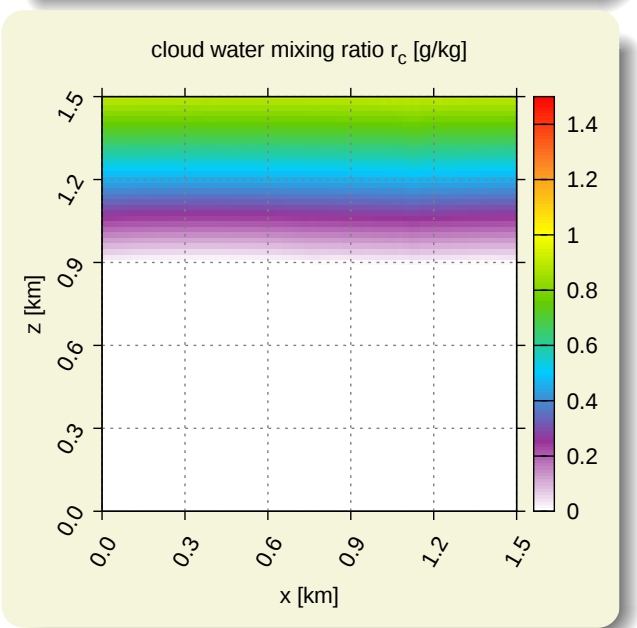

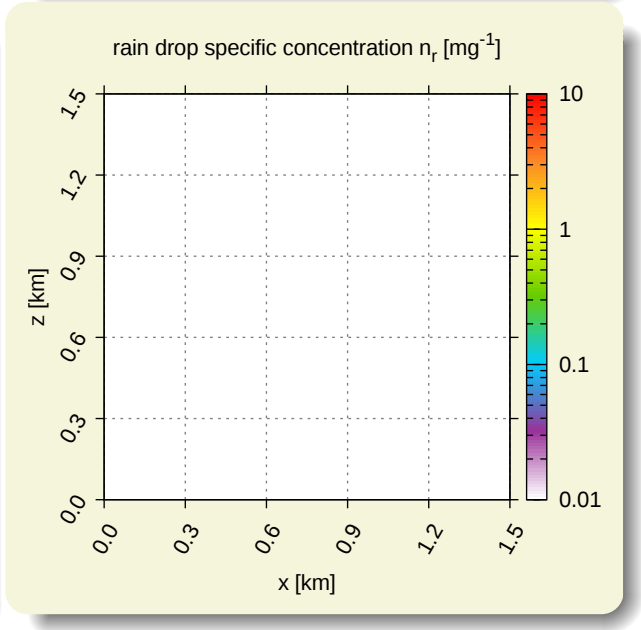

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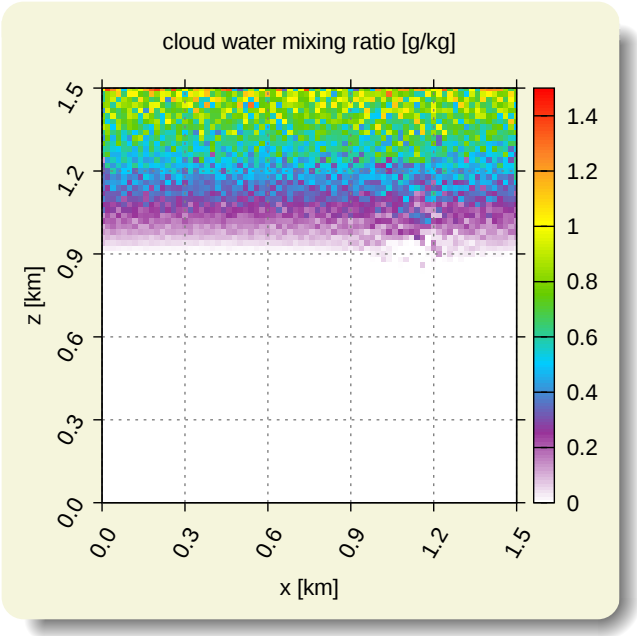

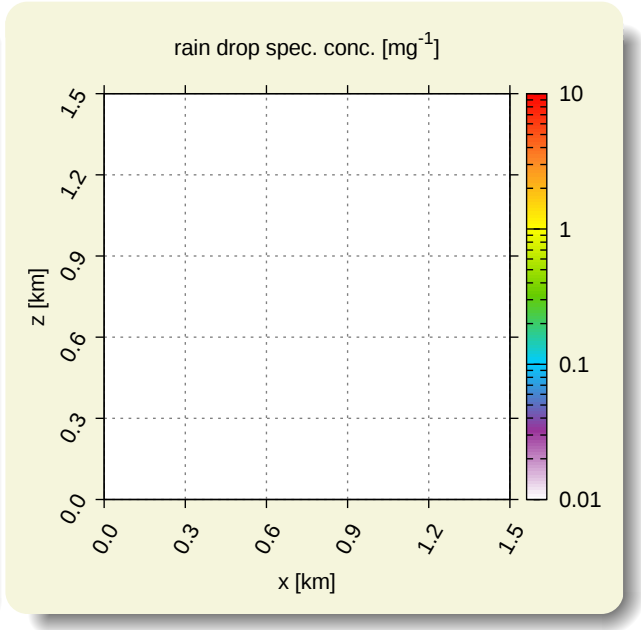

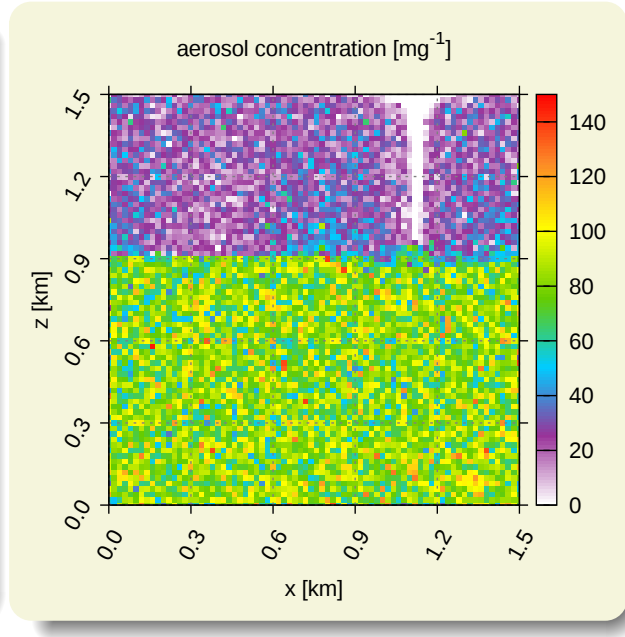

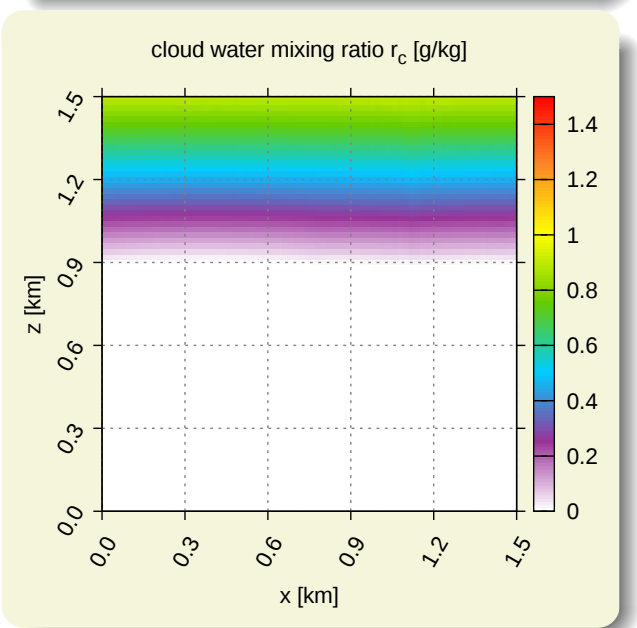

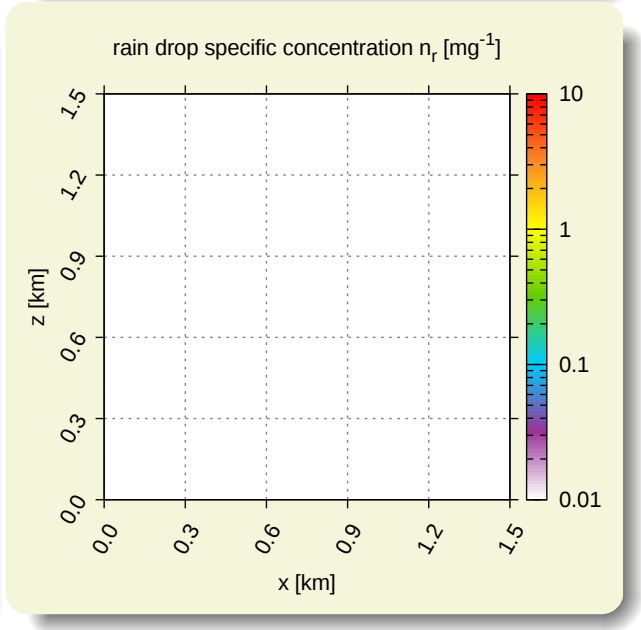

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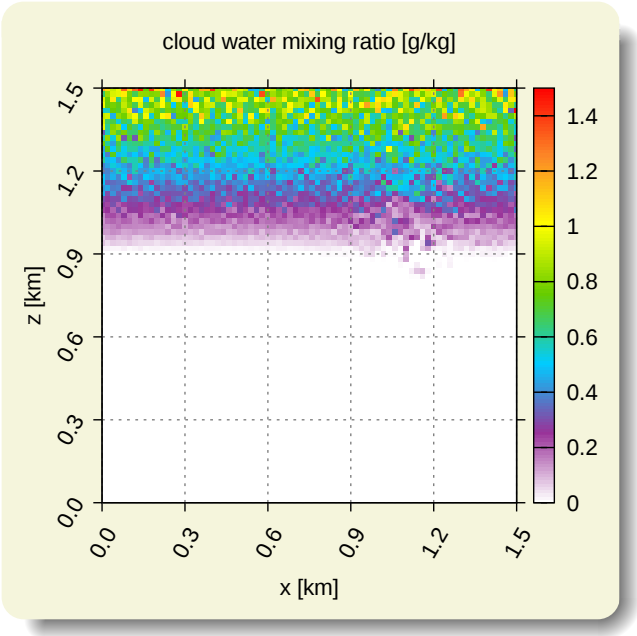

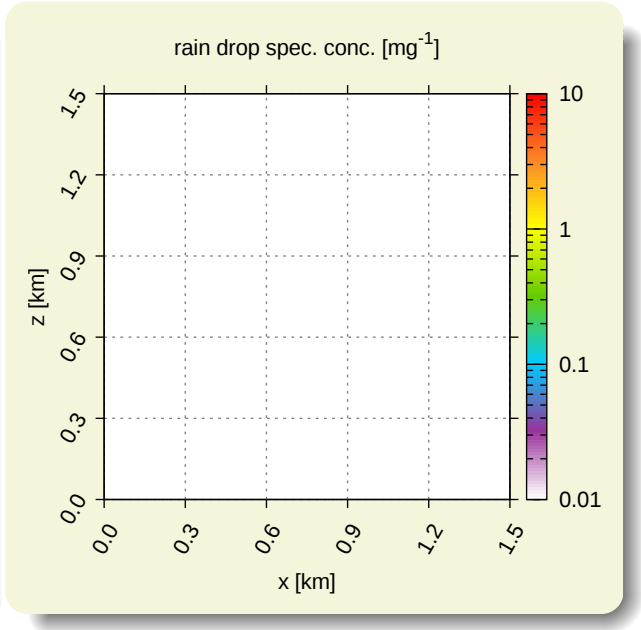

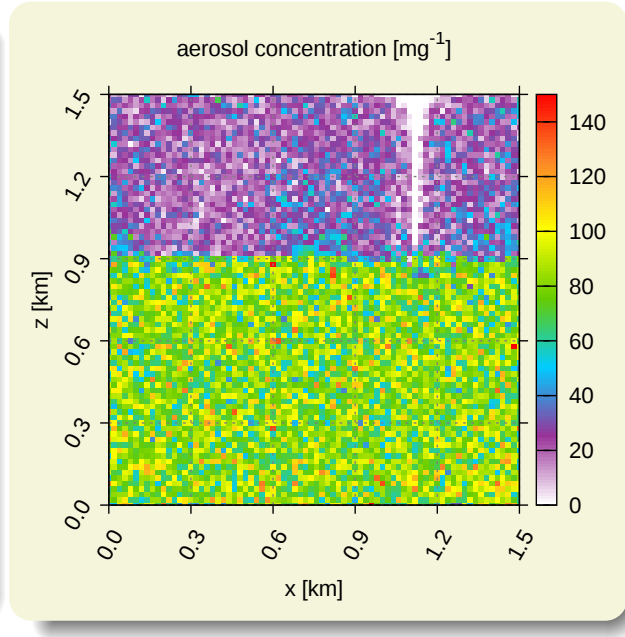

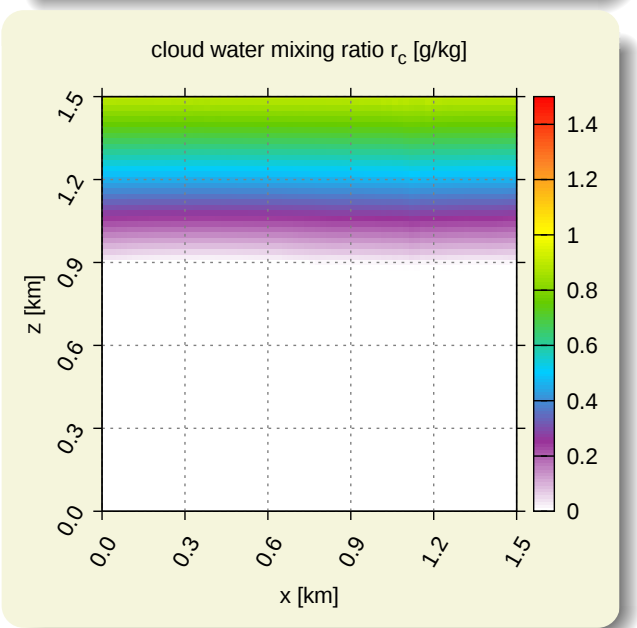

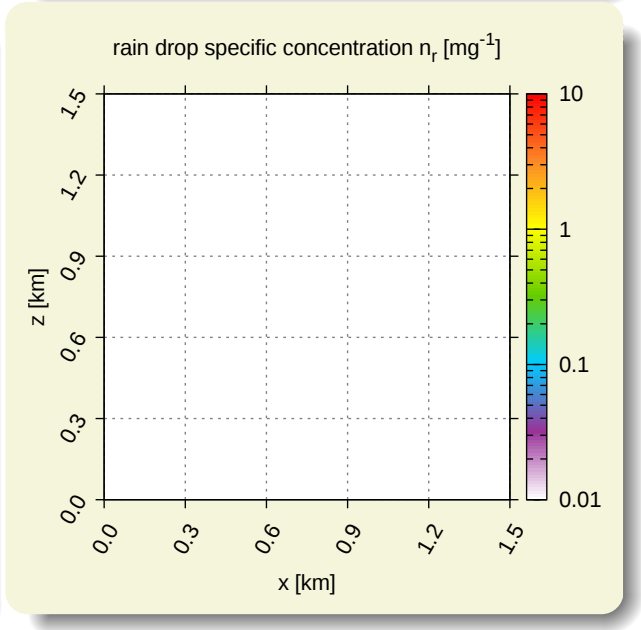

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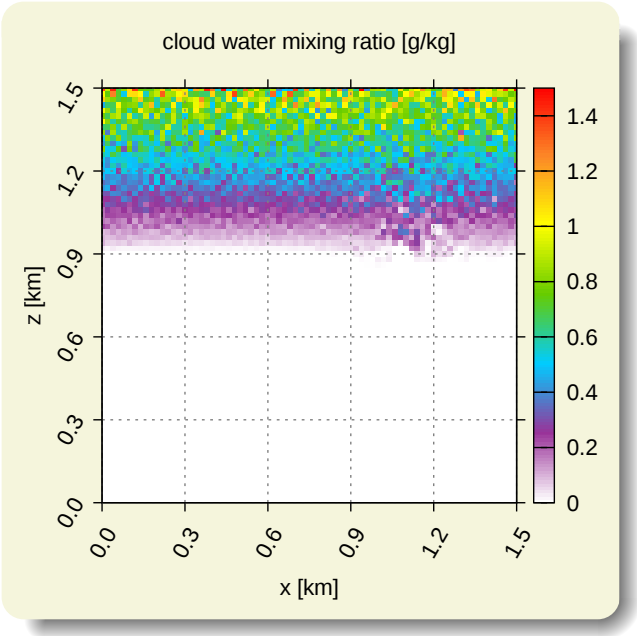

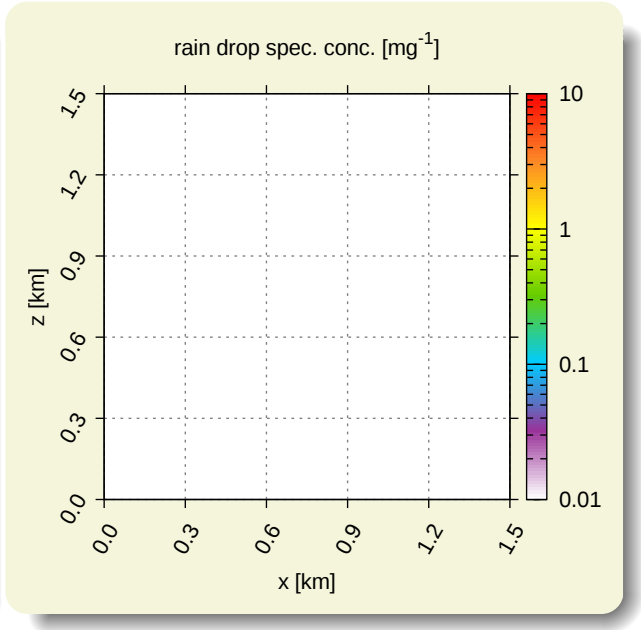

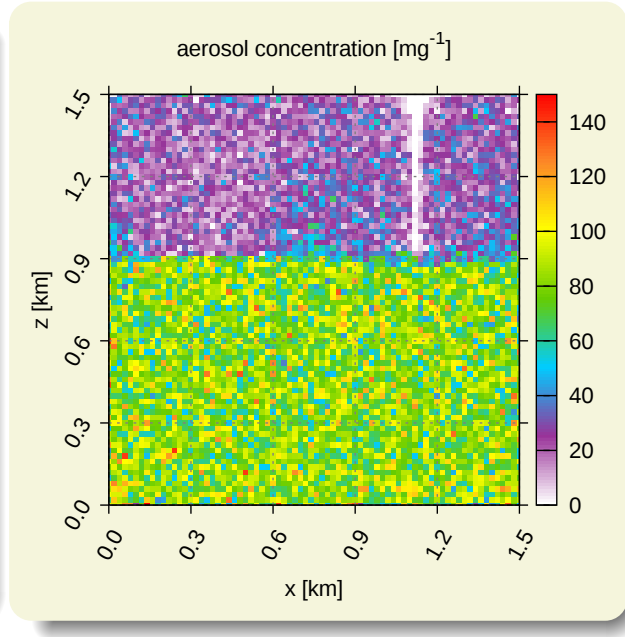

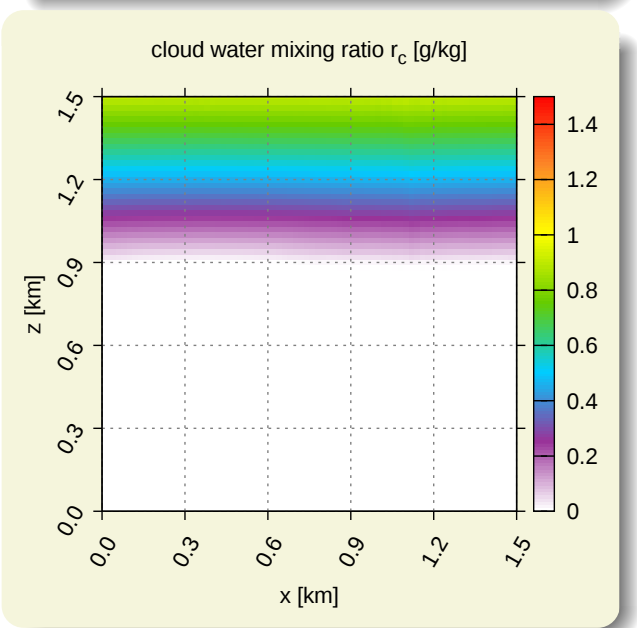

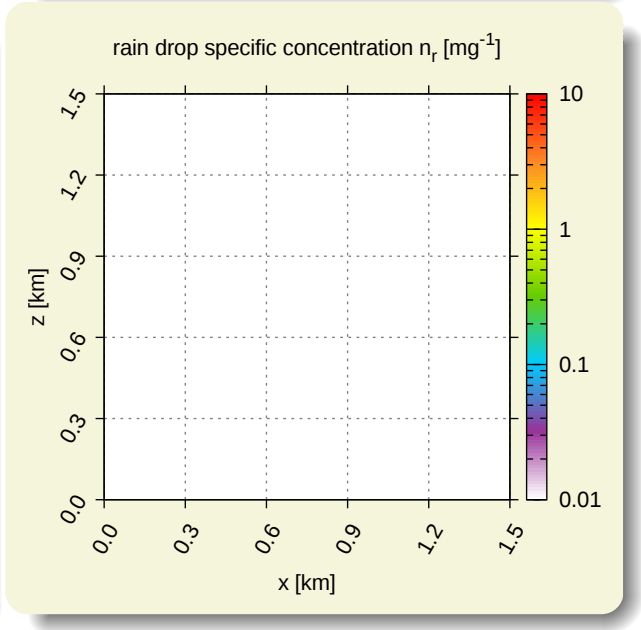

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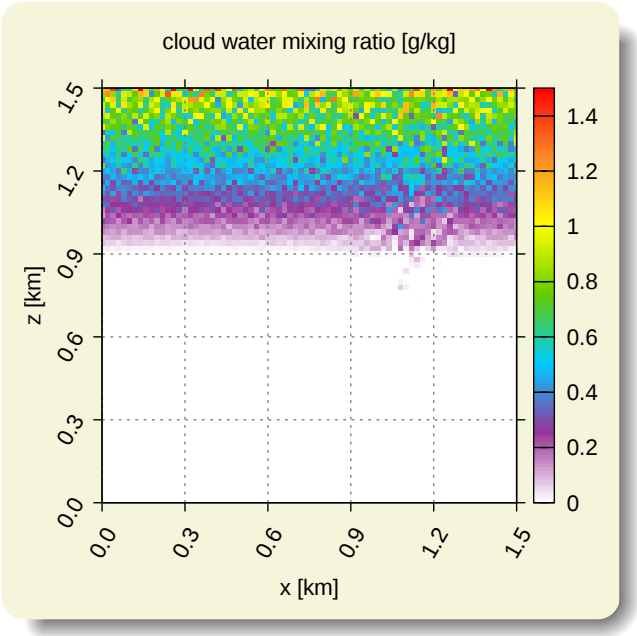

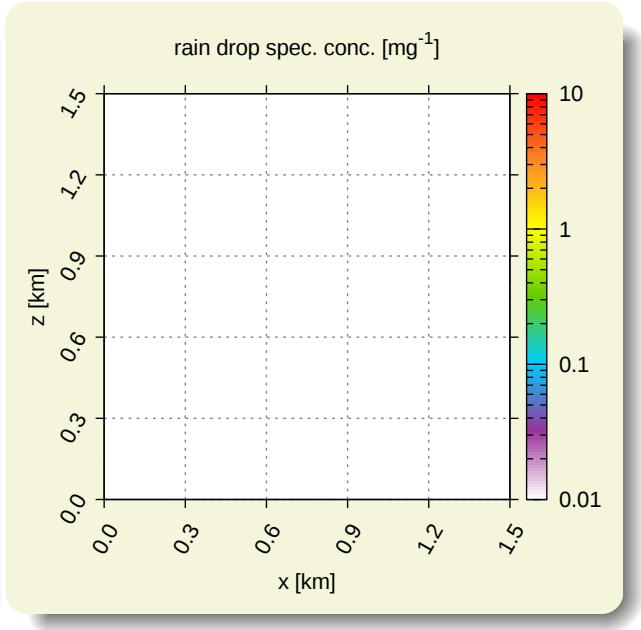

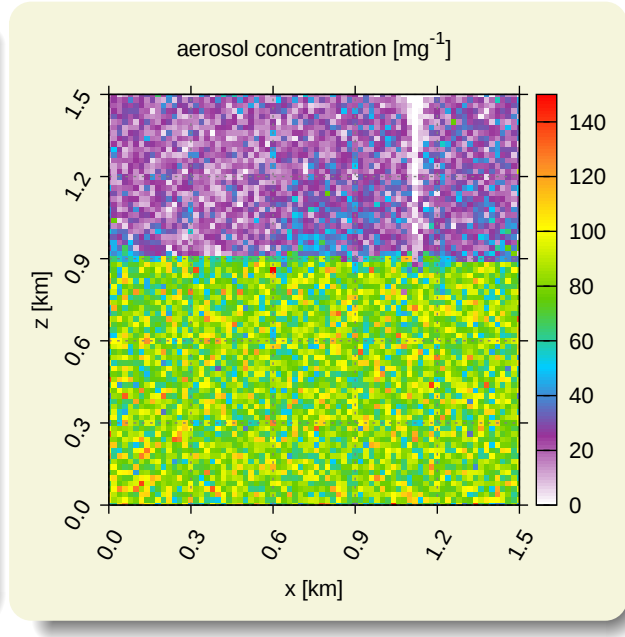

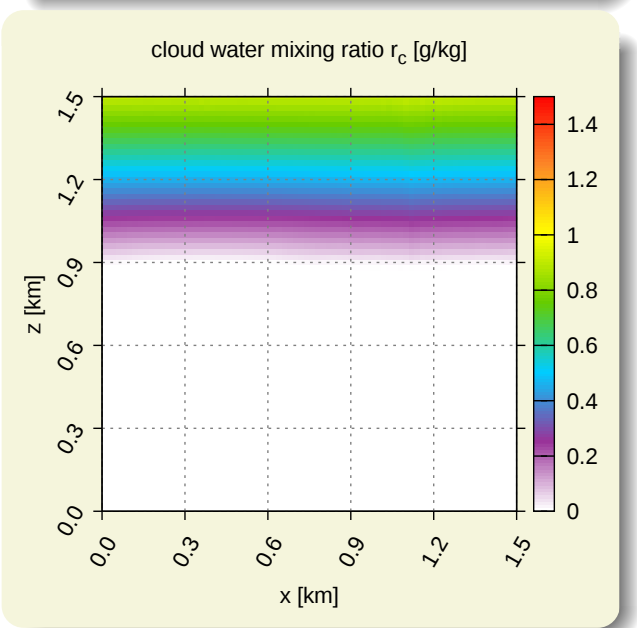

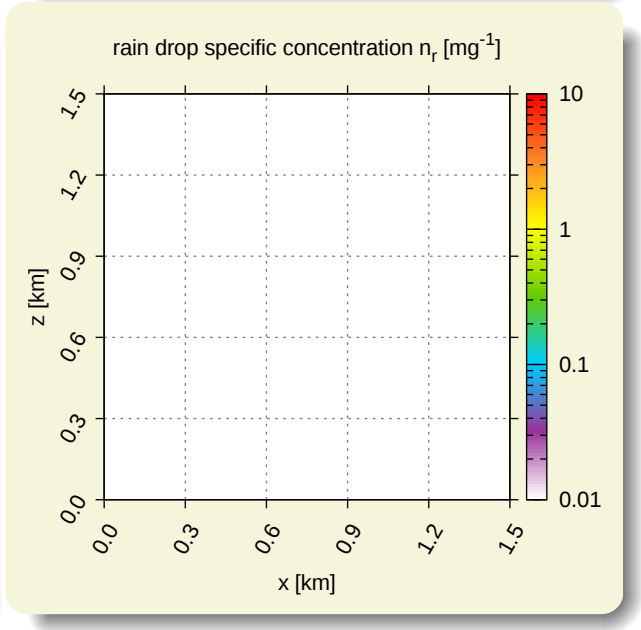

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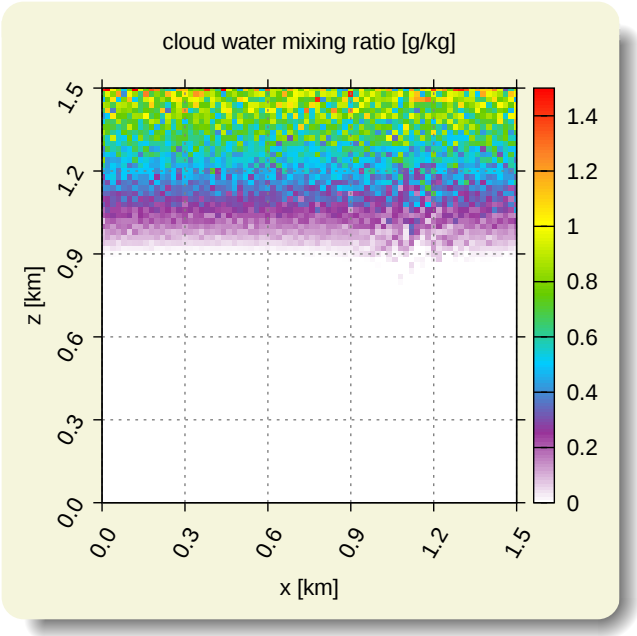

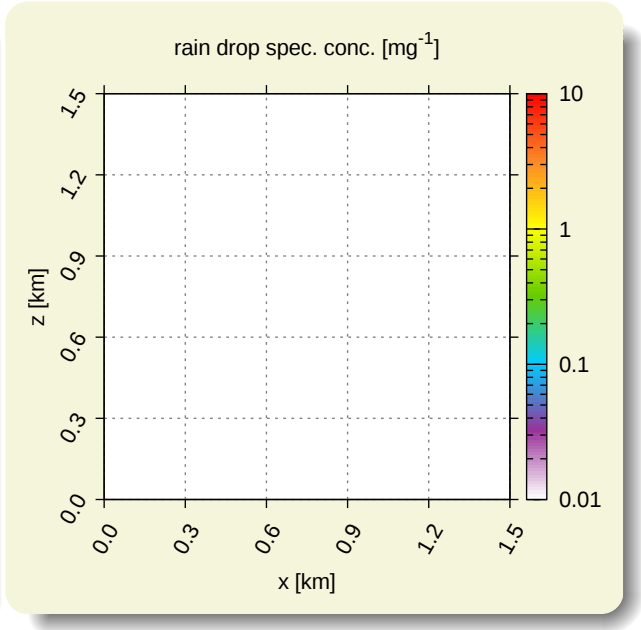

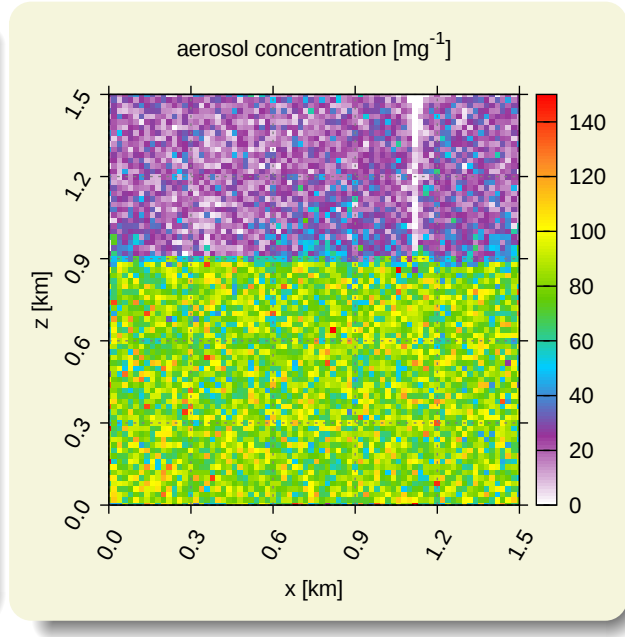

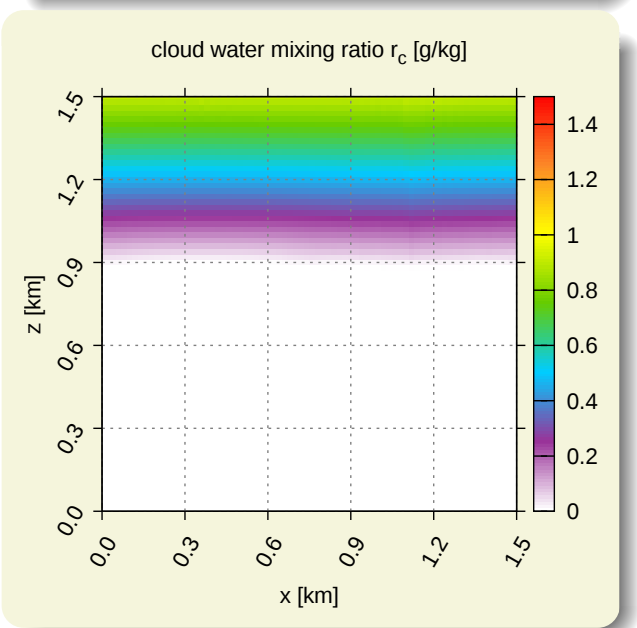

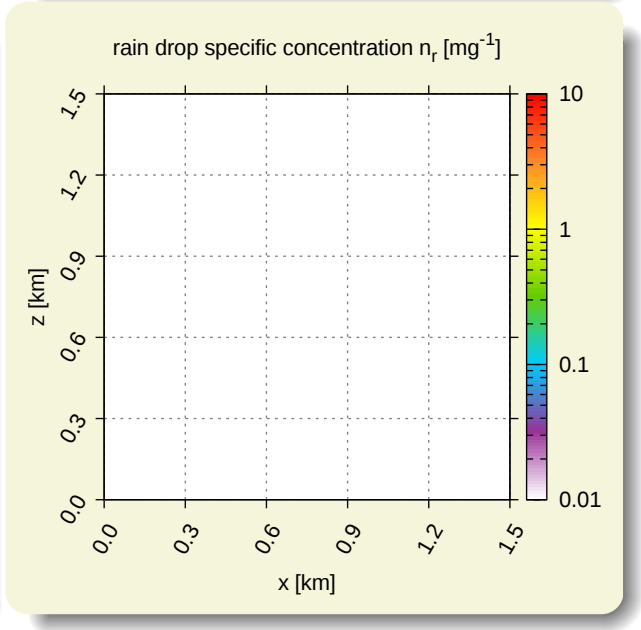

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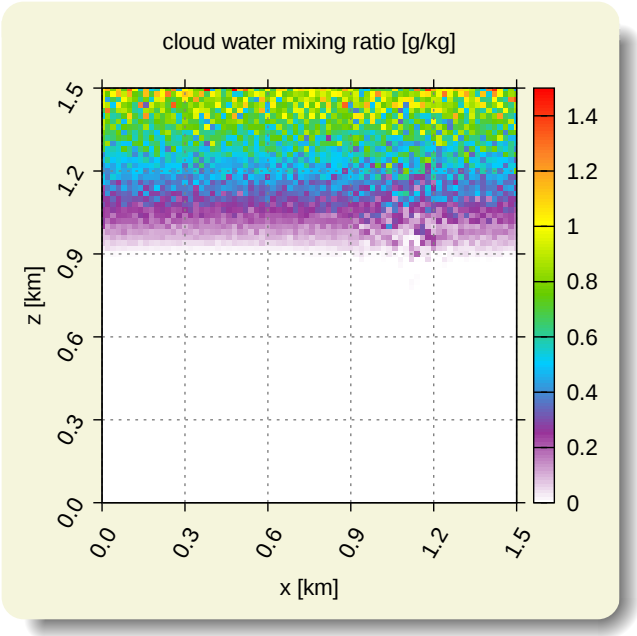

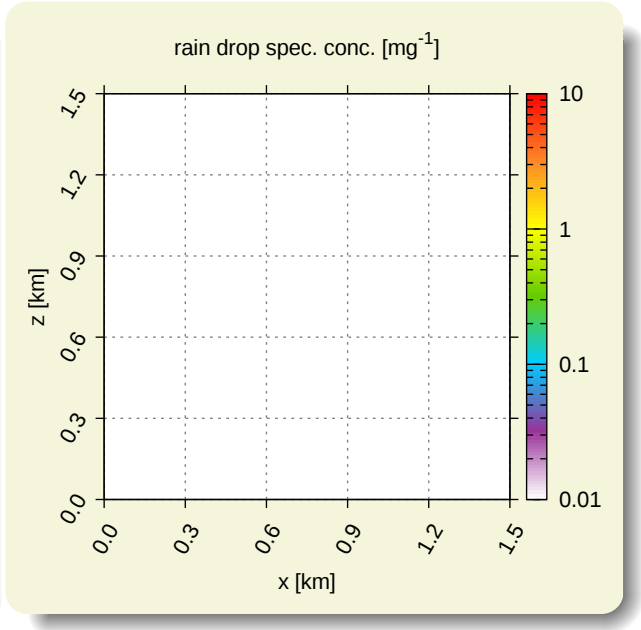

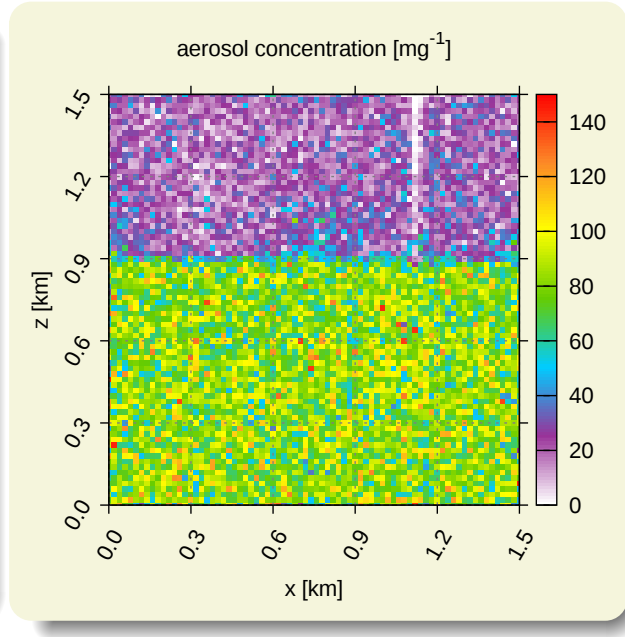

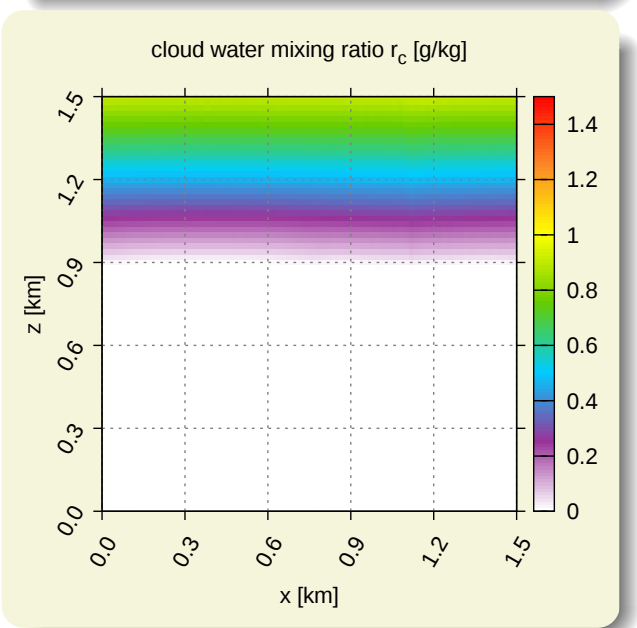

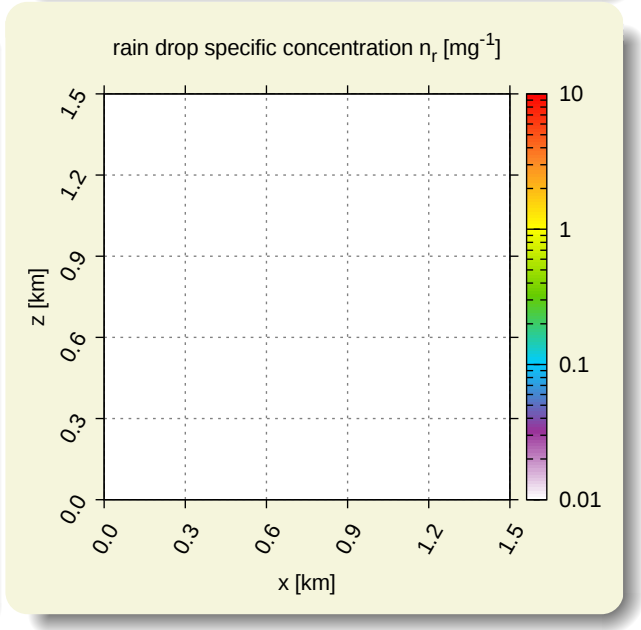

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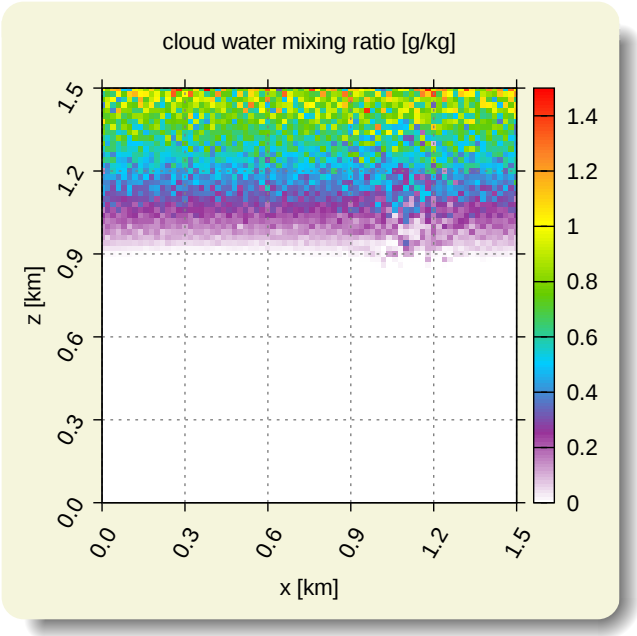

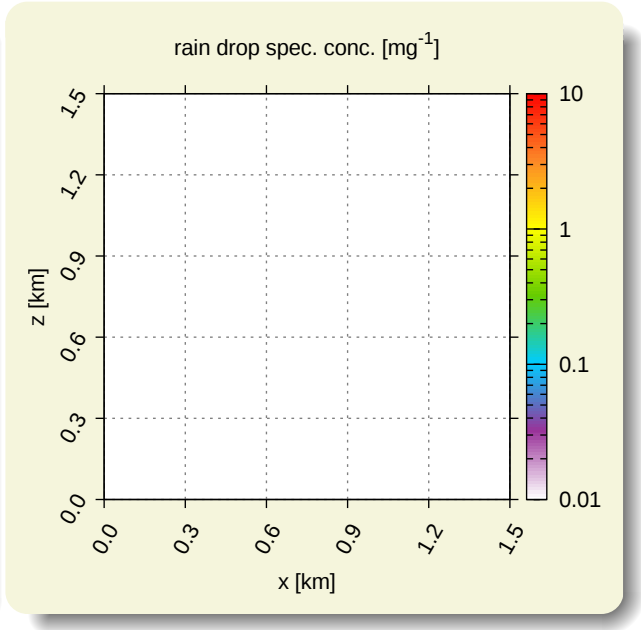

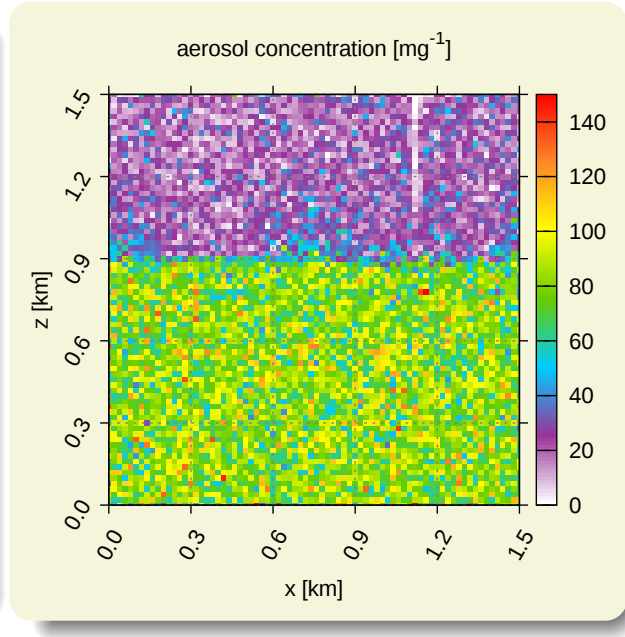

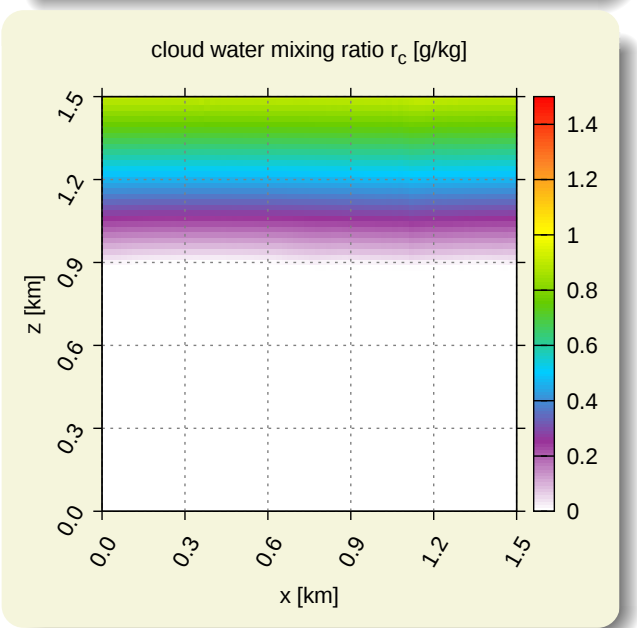

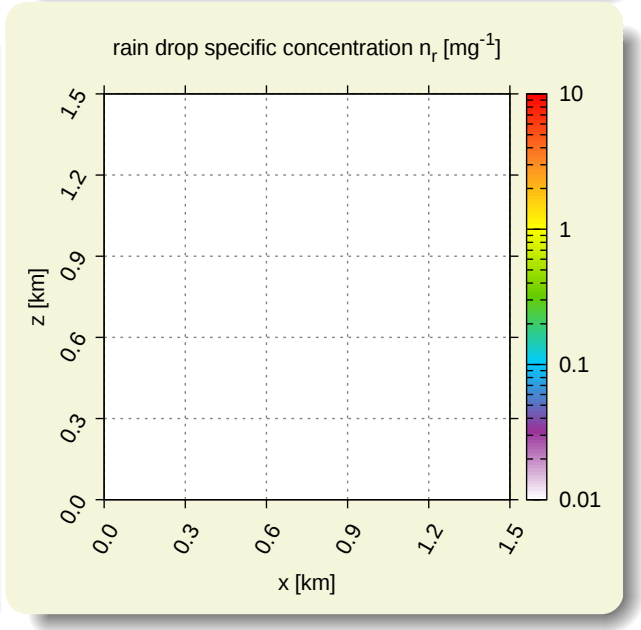

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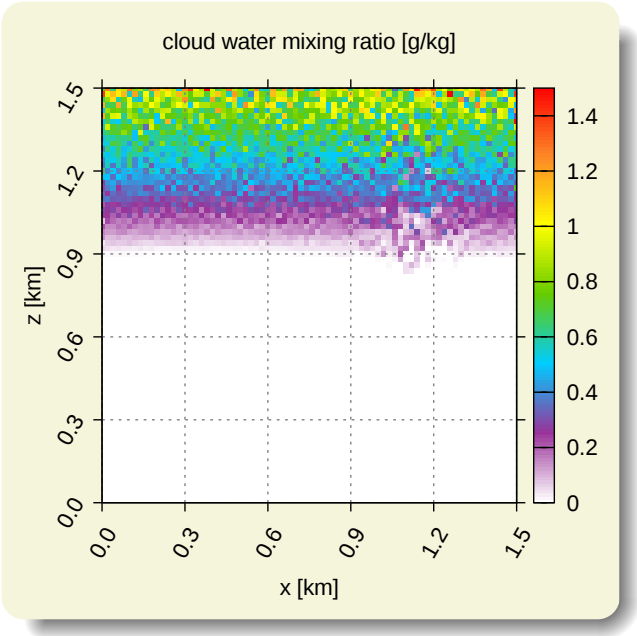

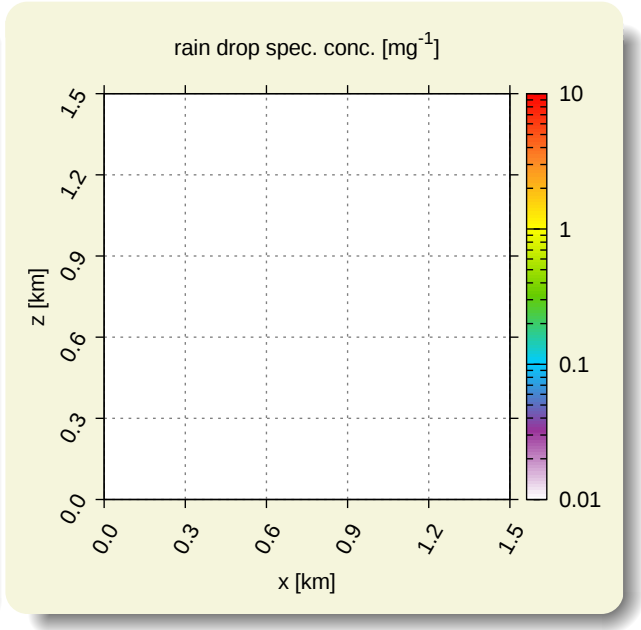

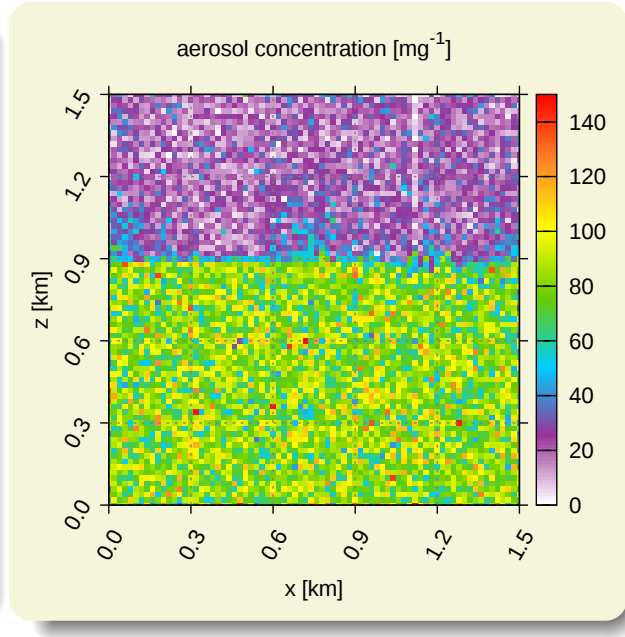

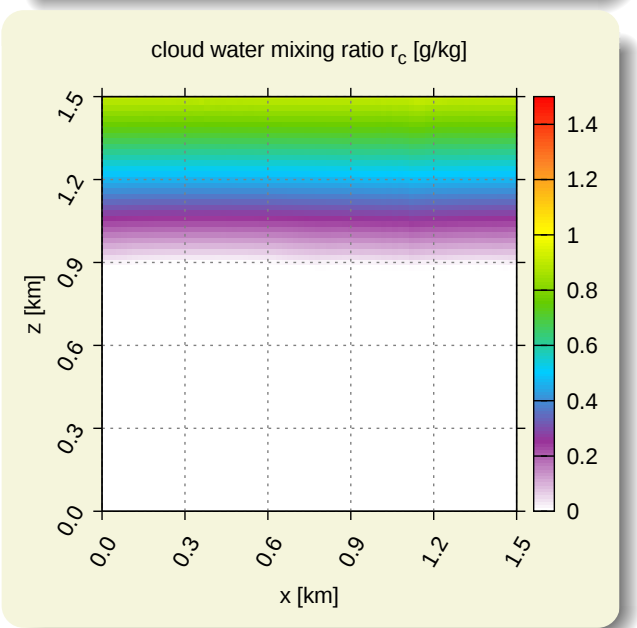

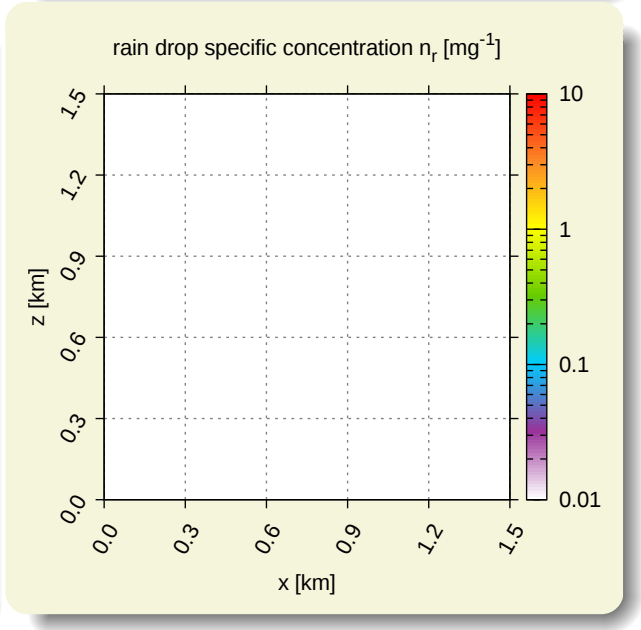

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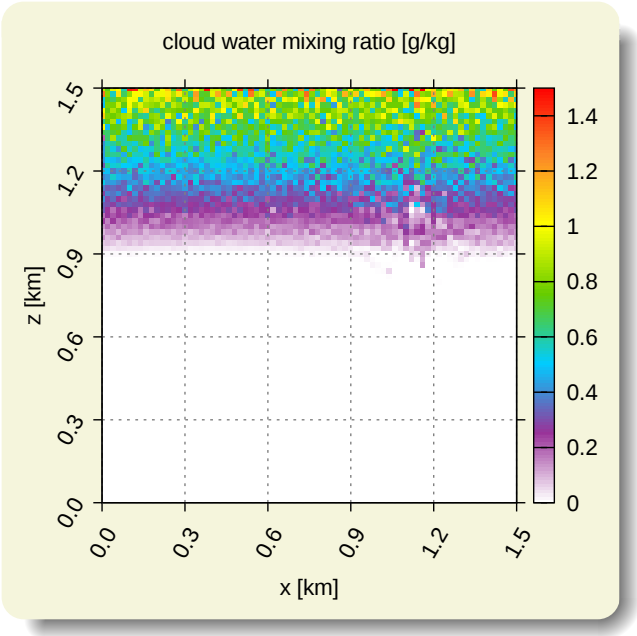

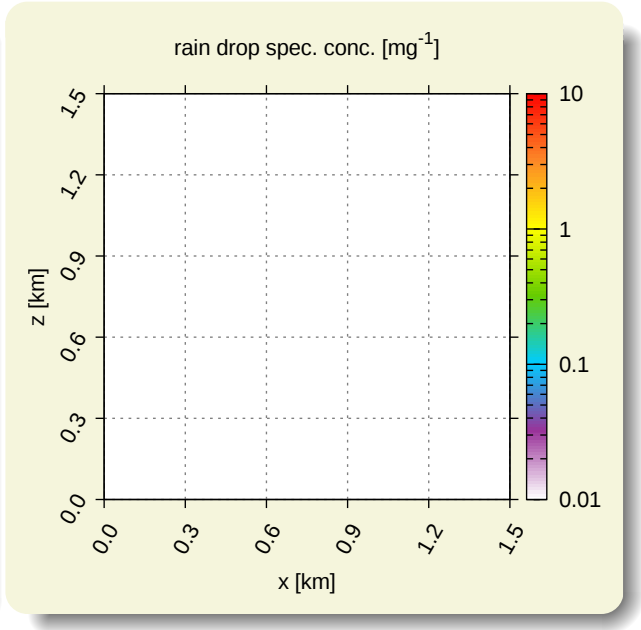

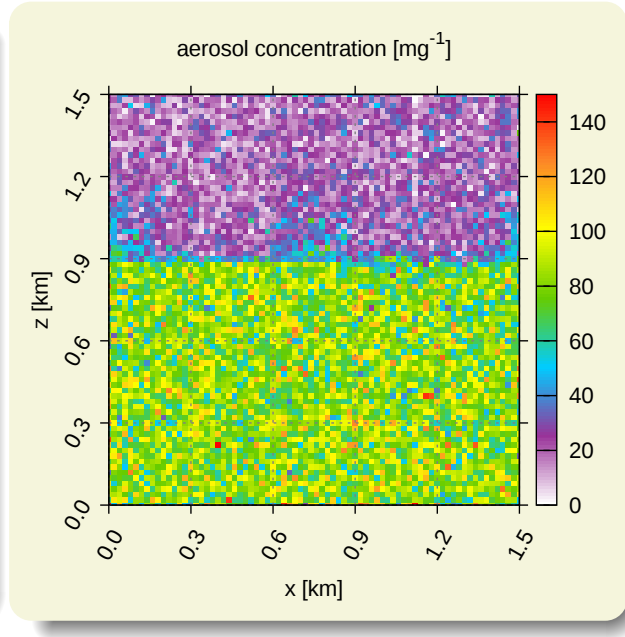

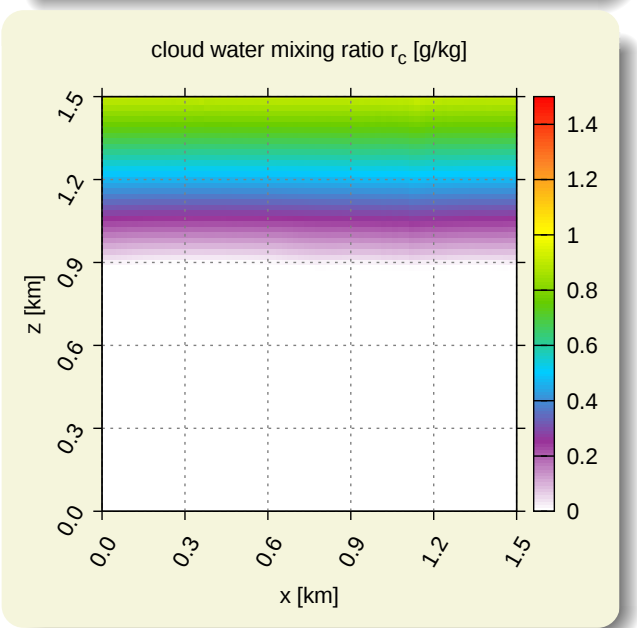

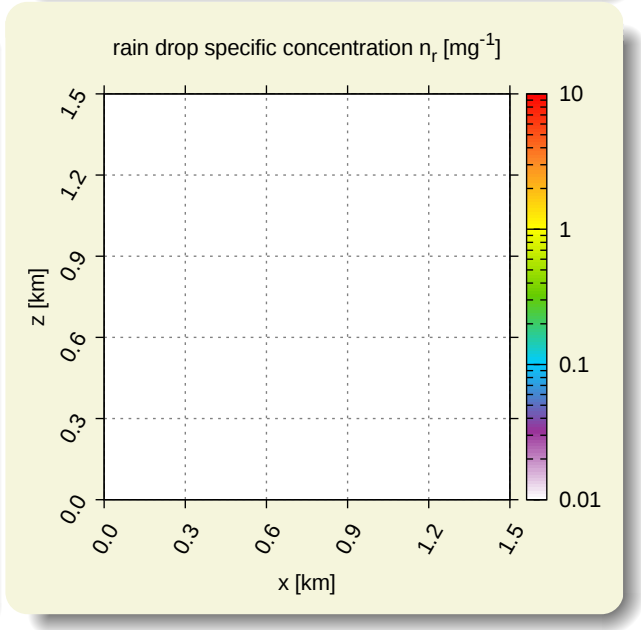

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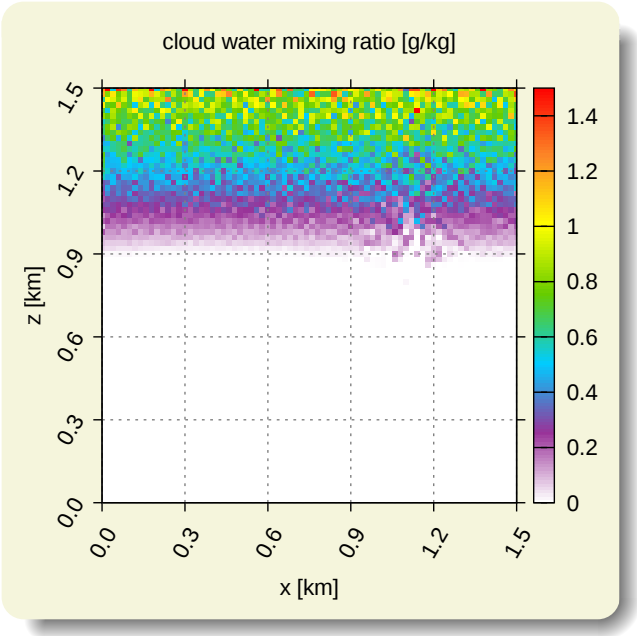

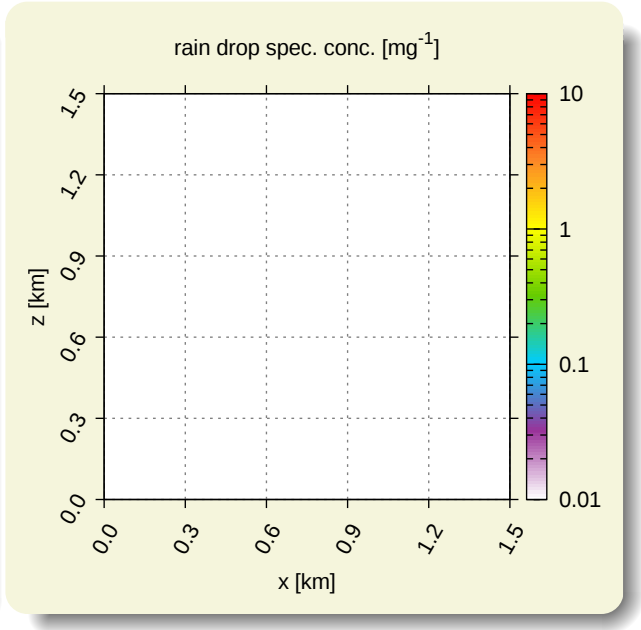

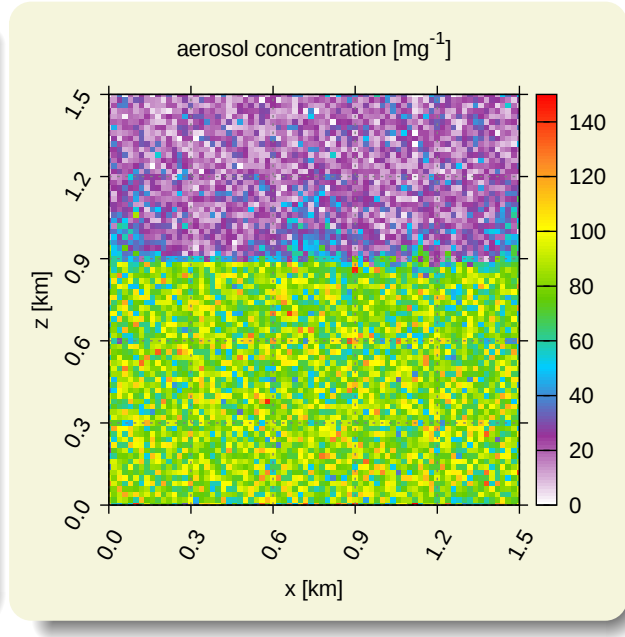

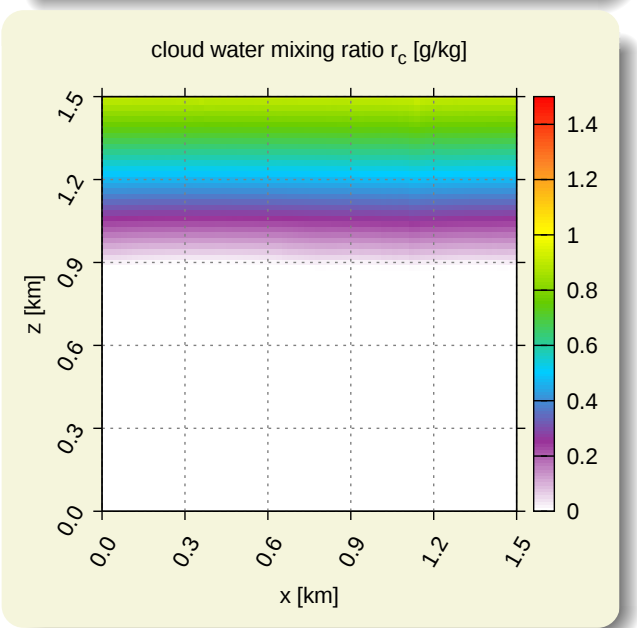

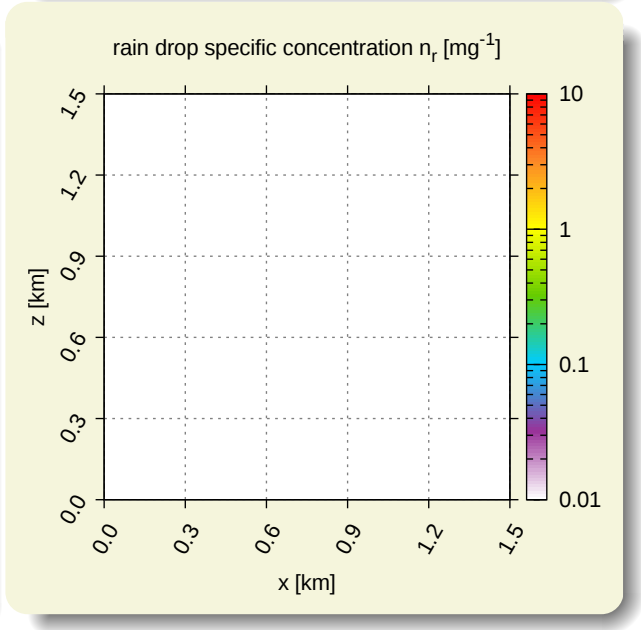

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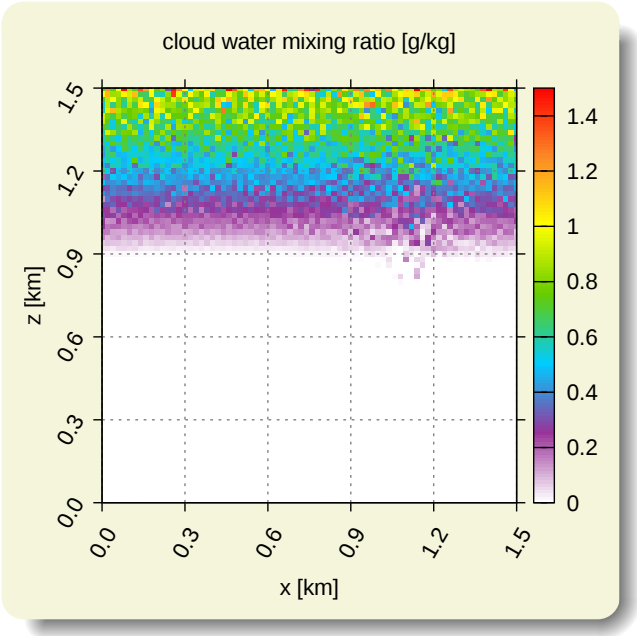
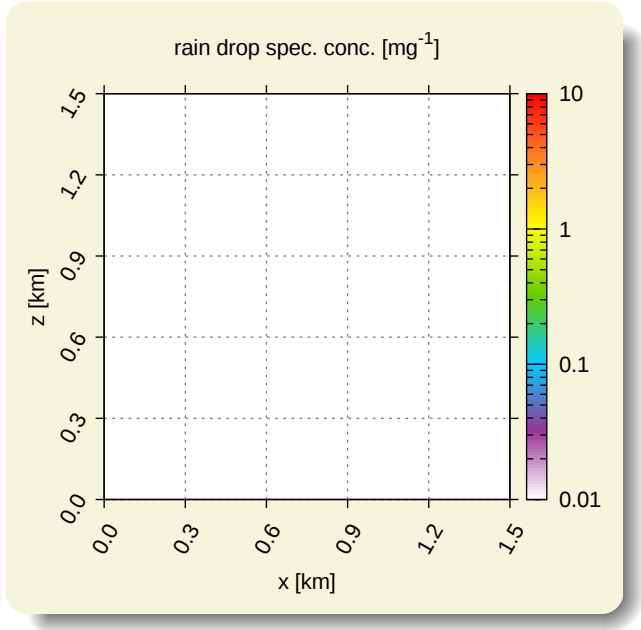
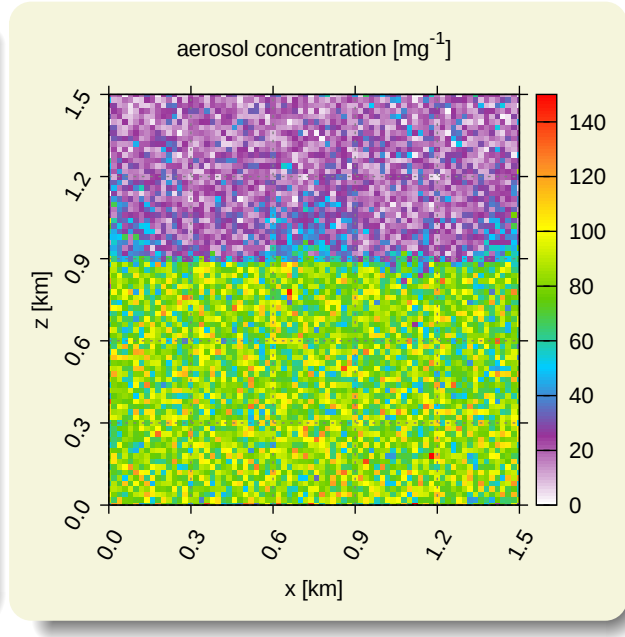
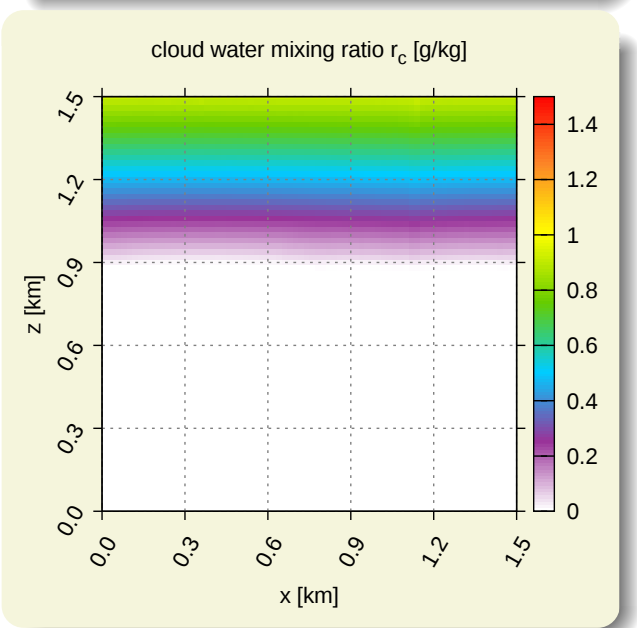
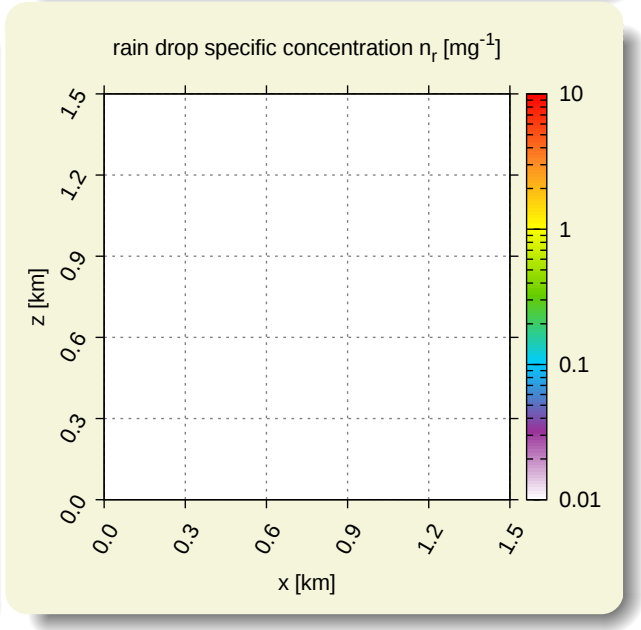
libcloudph++: VOCALS-inspired aerosol processing set-up











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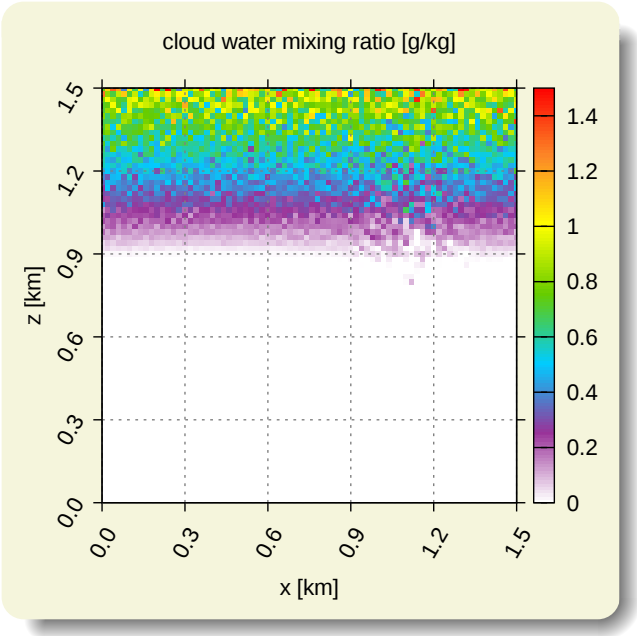

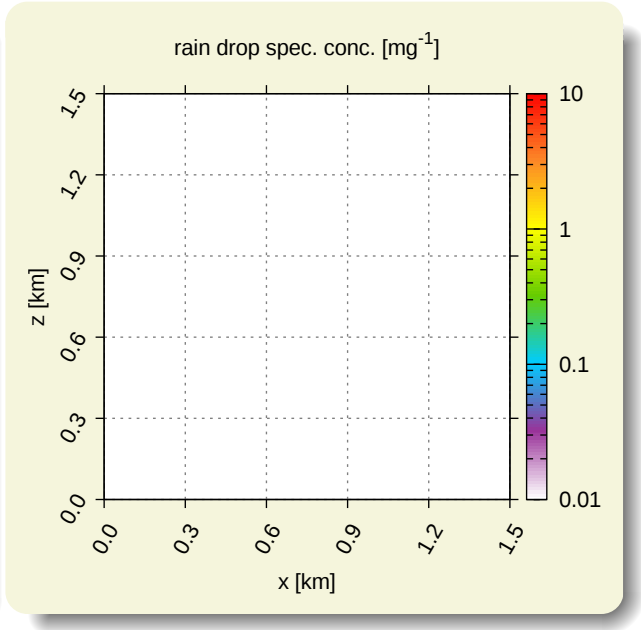

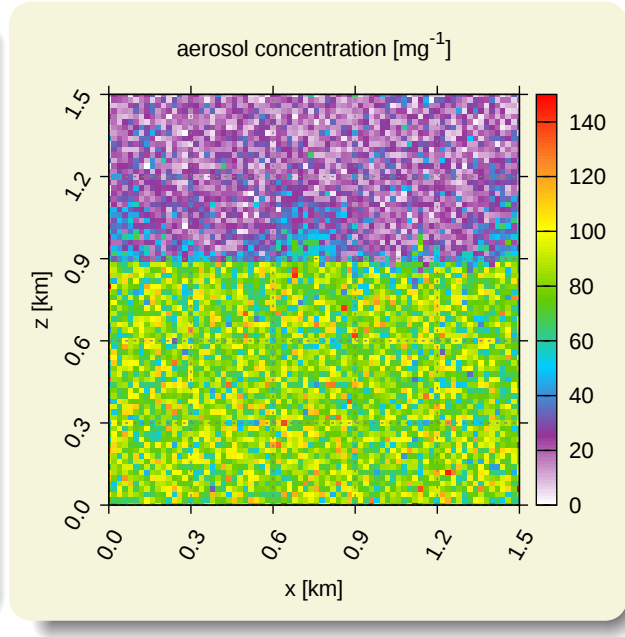

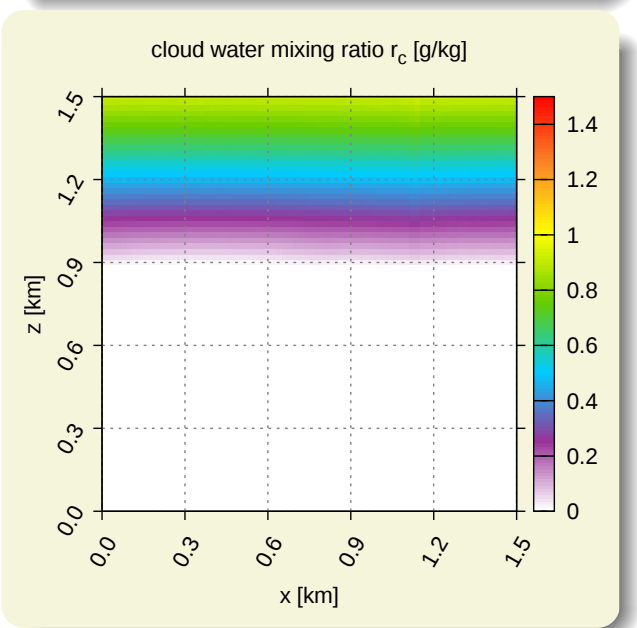

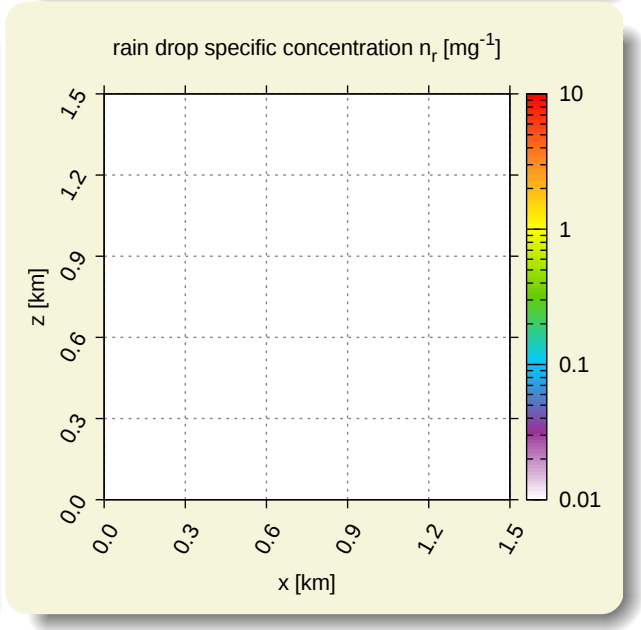

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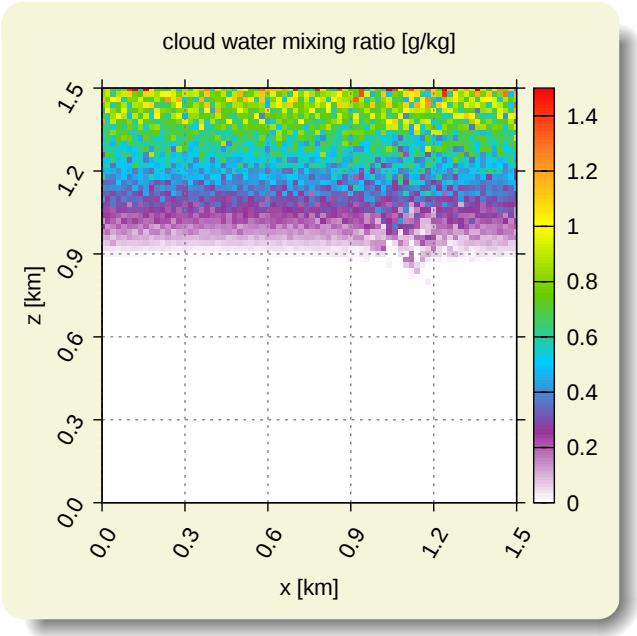

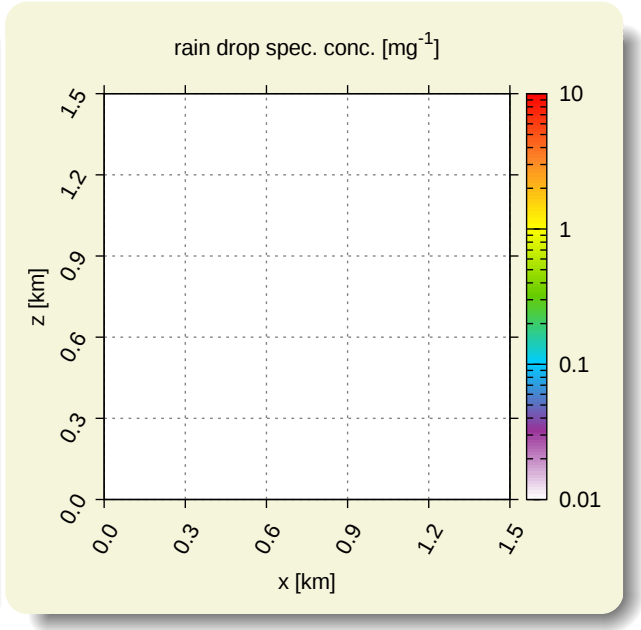

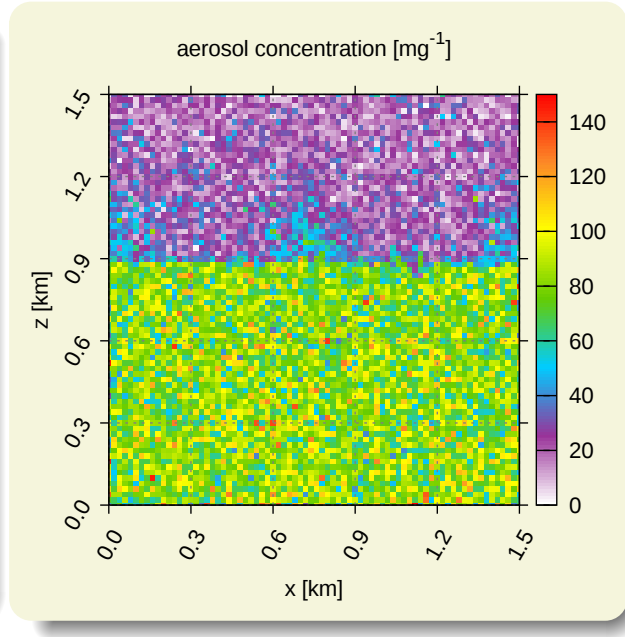

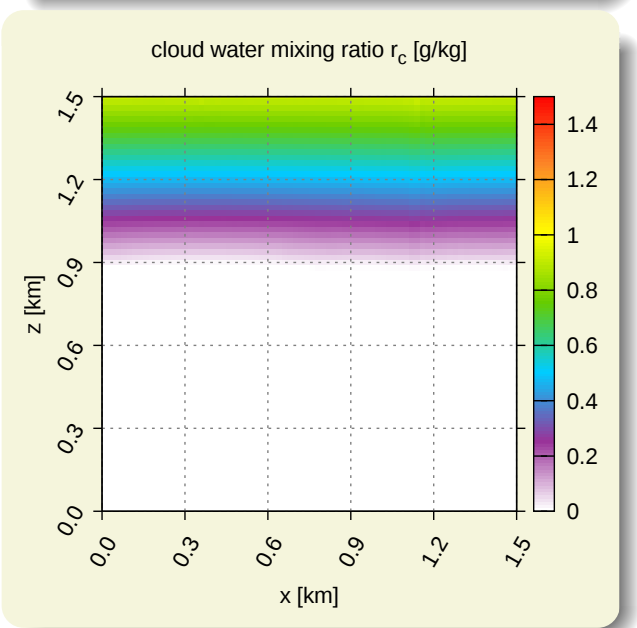

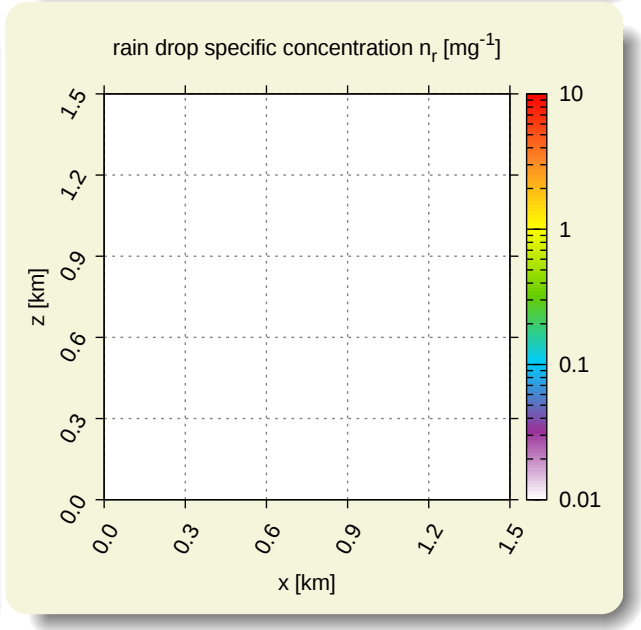

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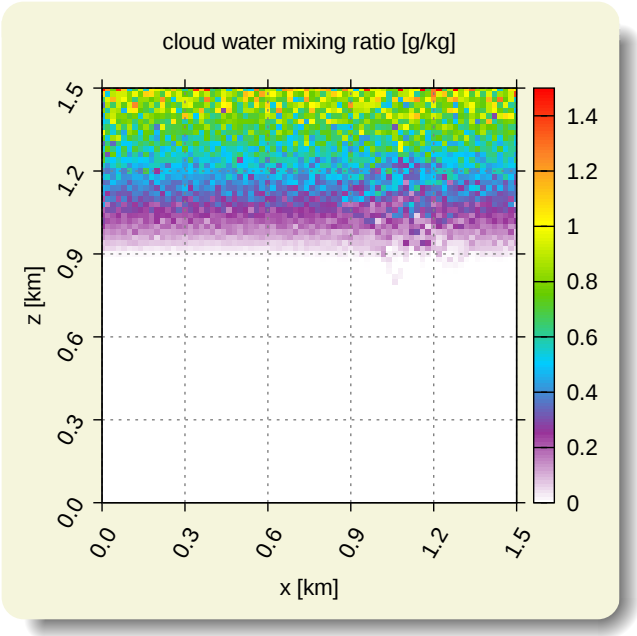

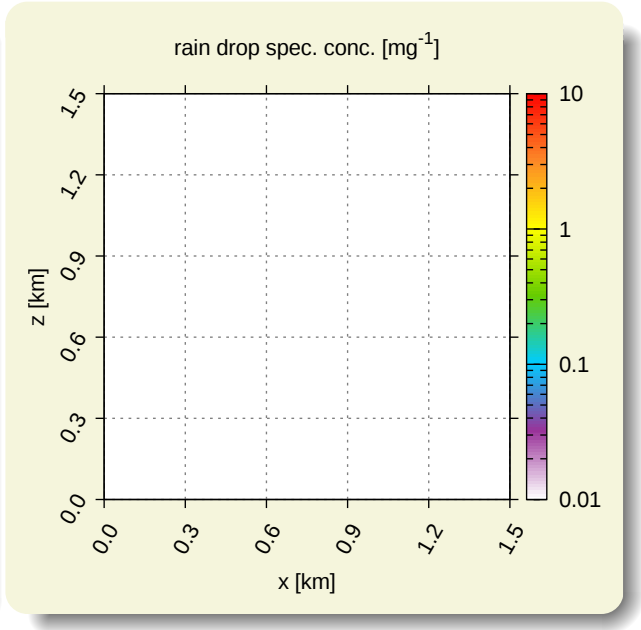

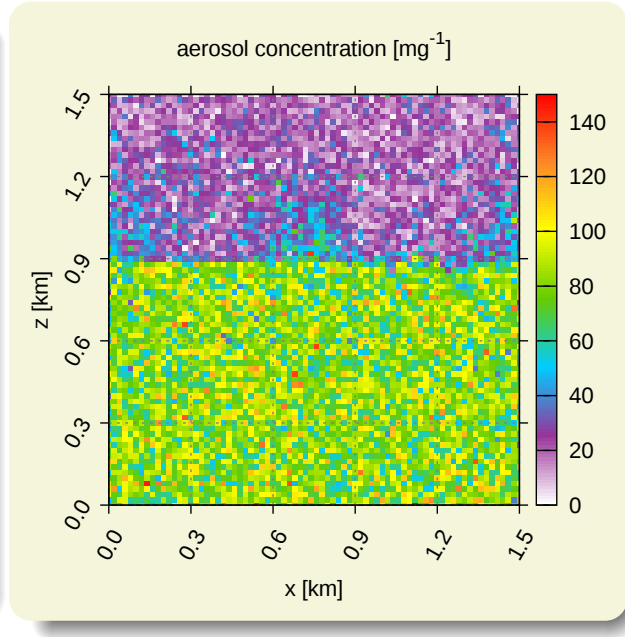

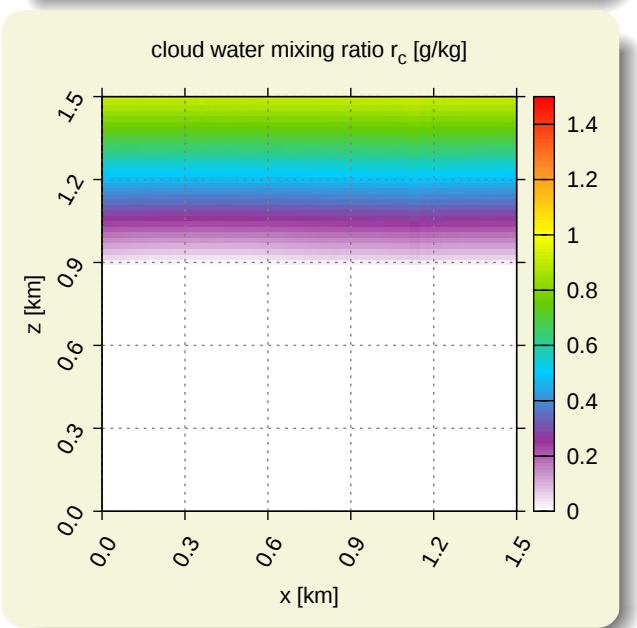

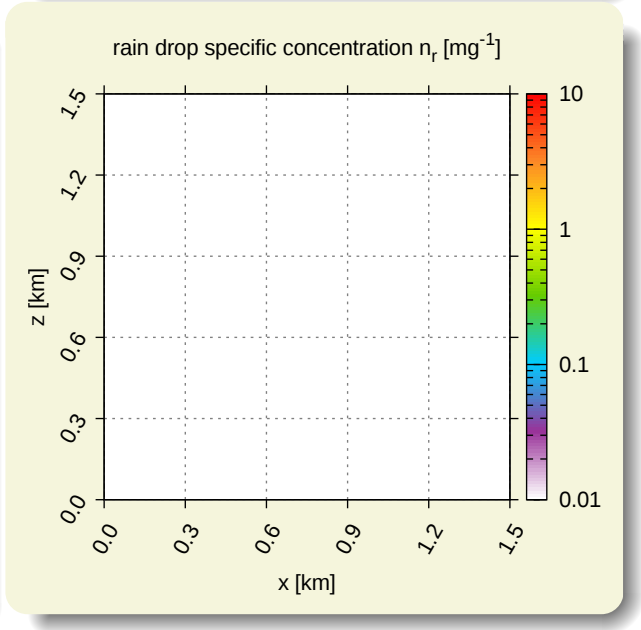

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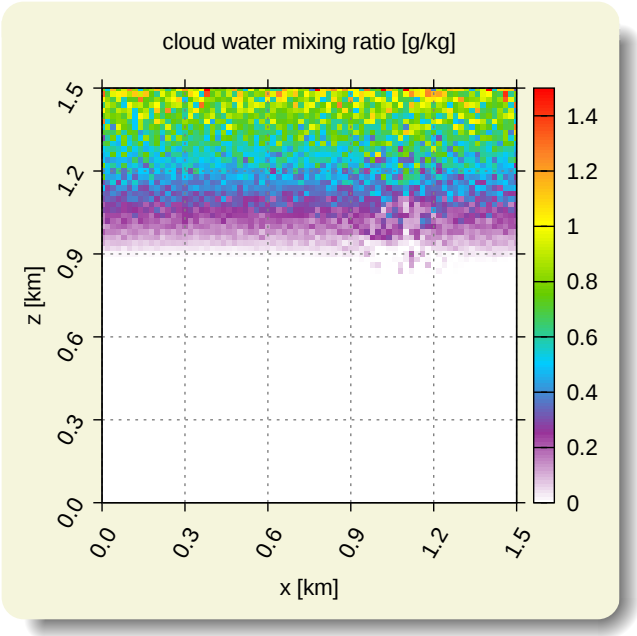

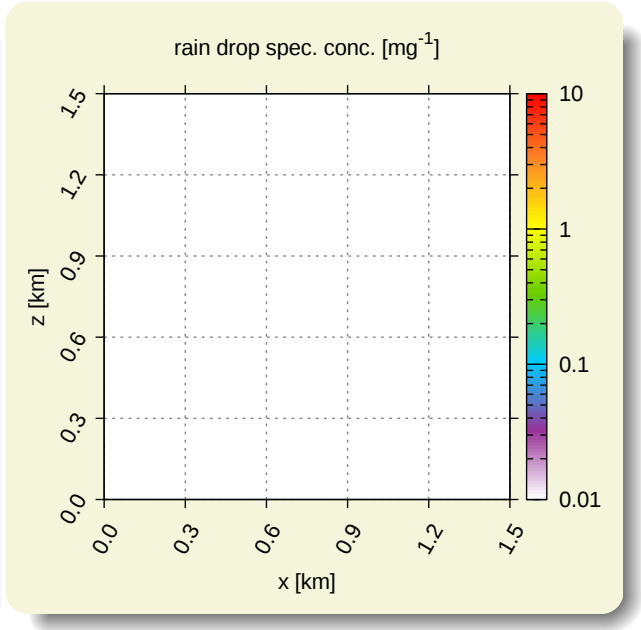

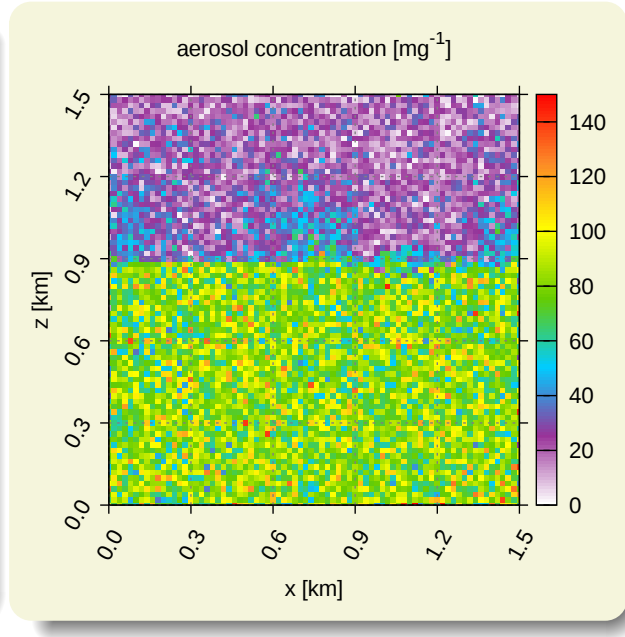

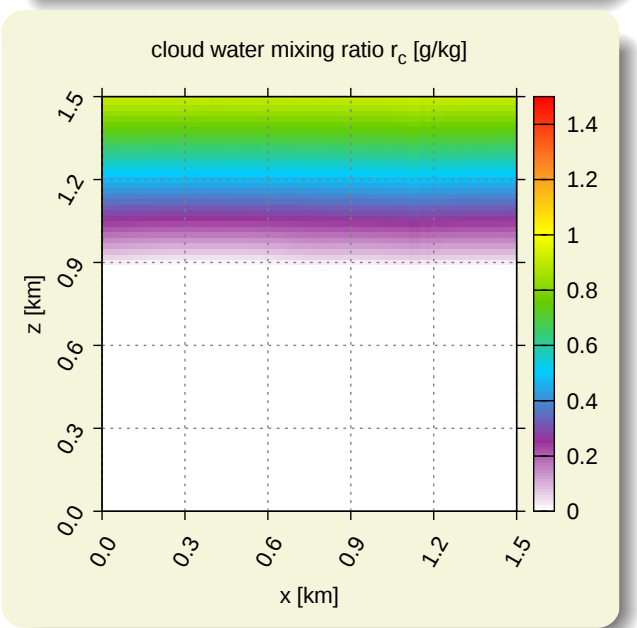

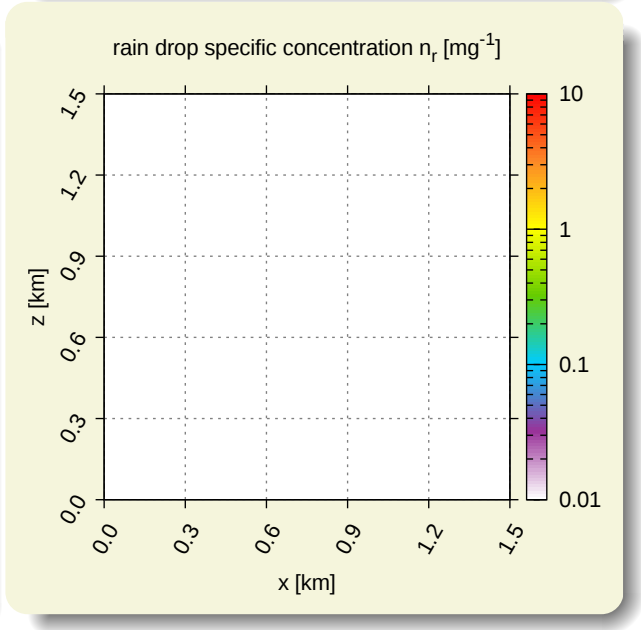

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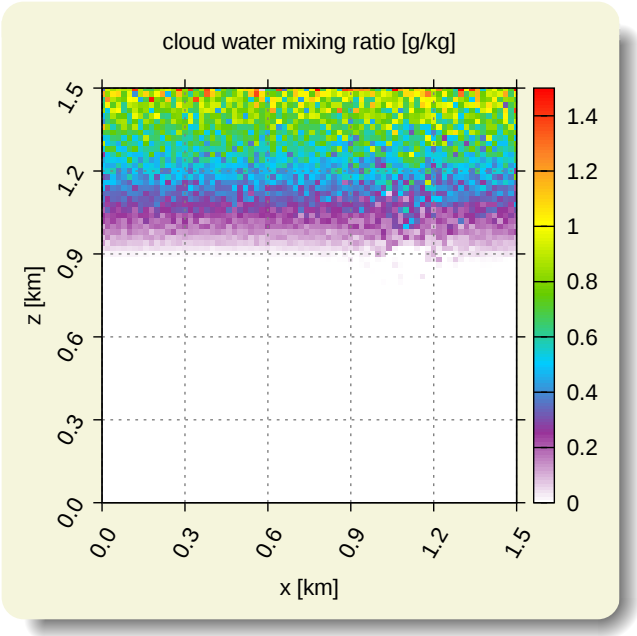

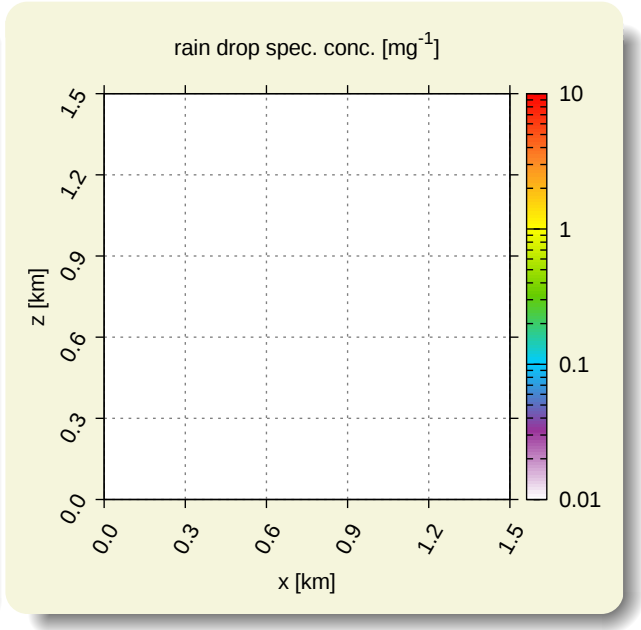

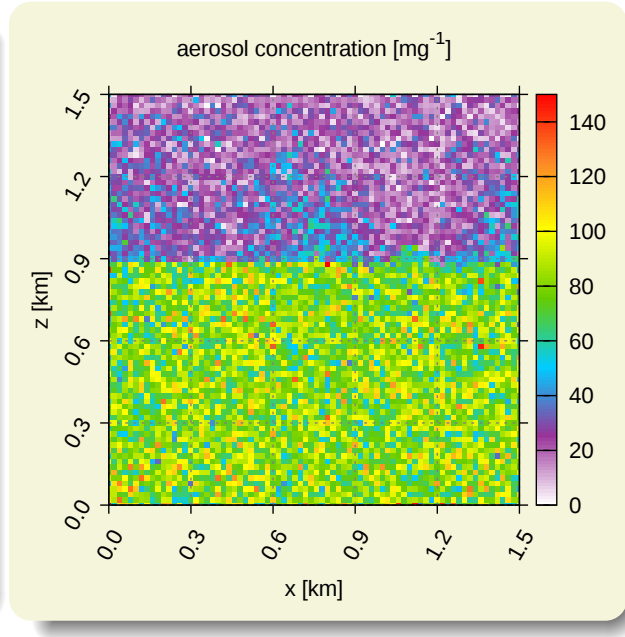

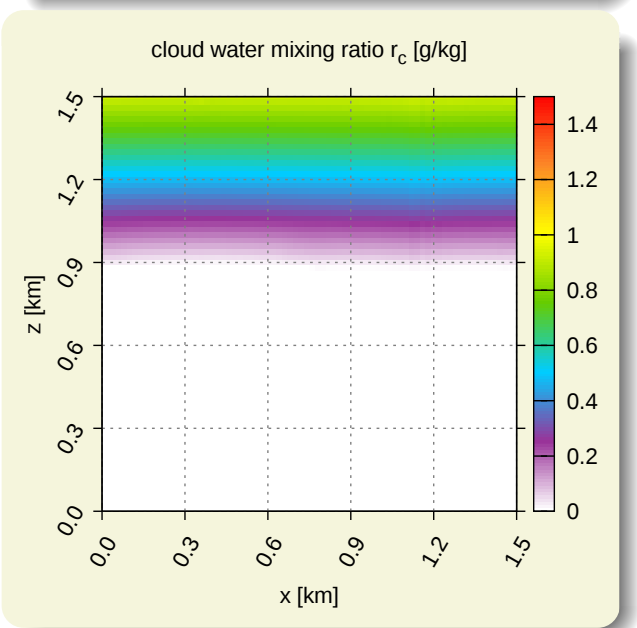

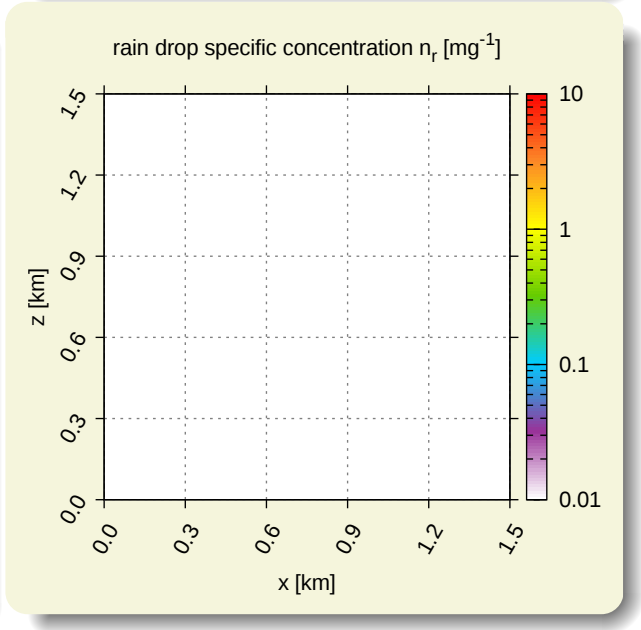

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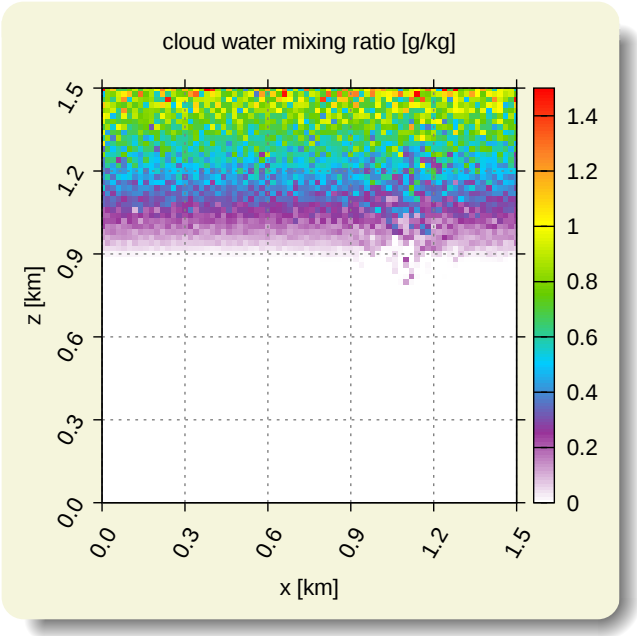

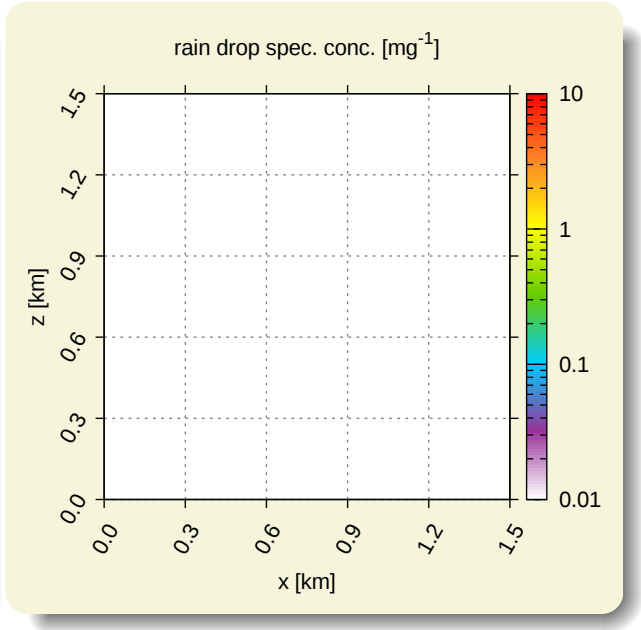

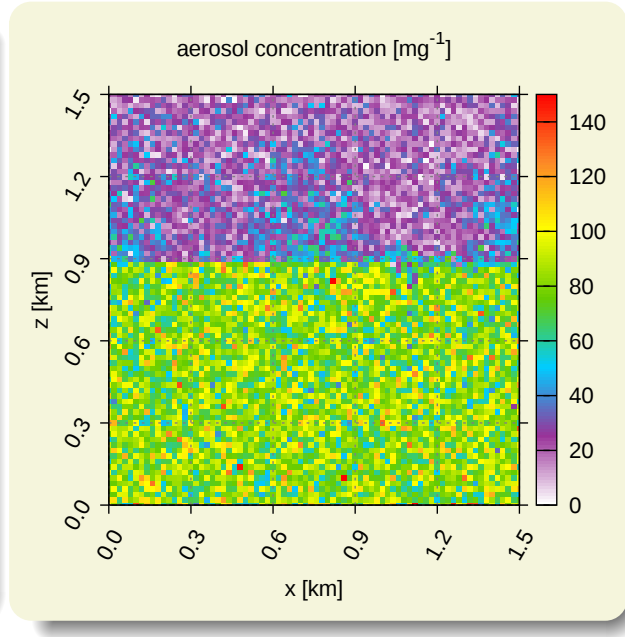

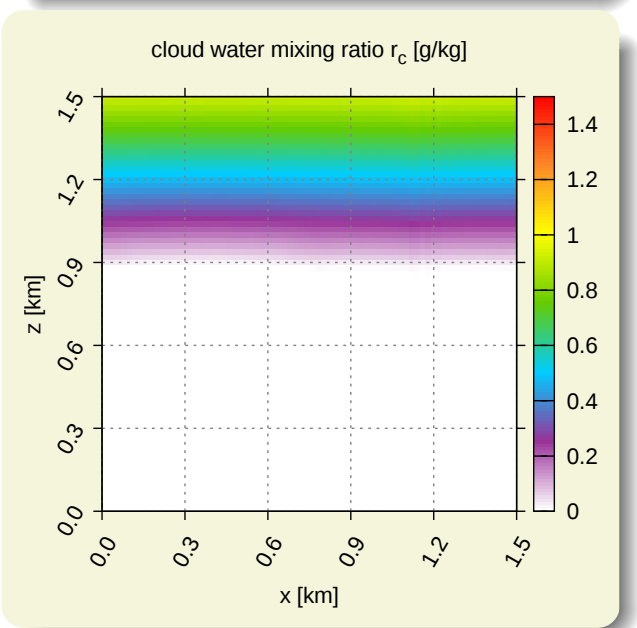

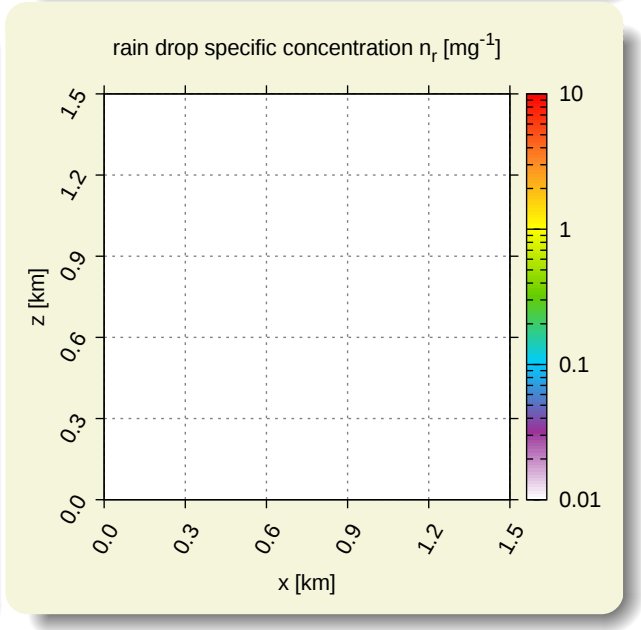

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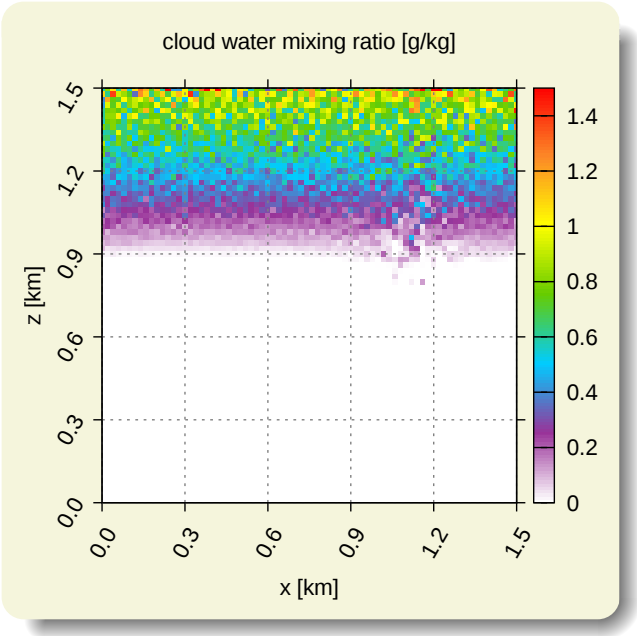

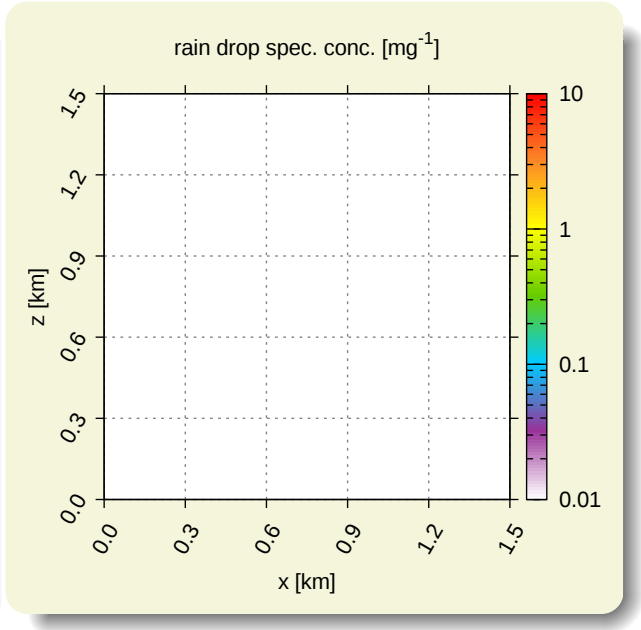

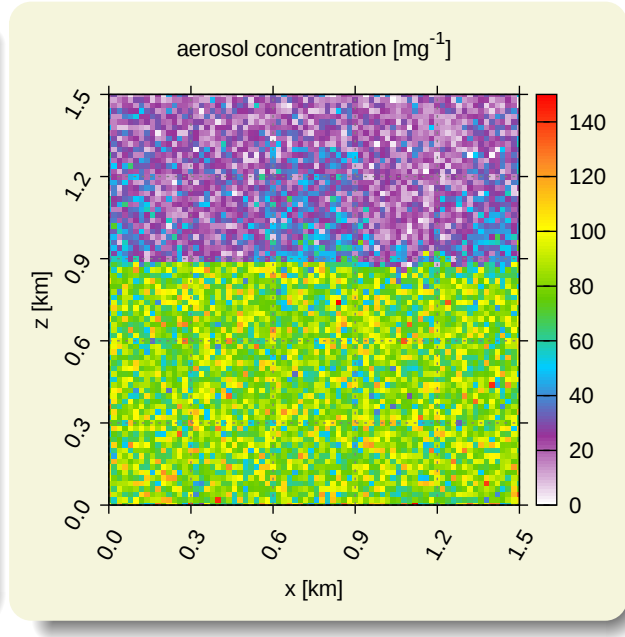

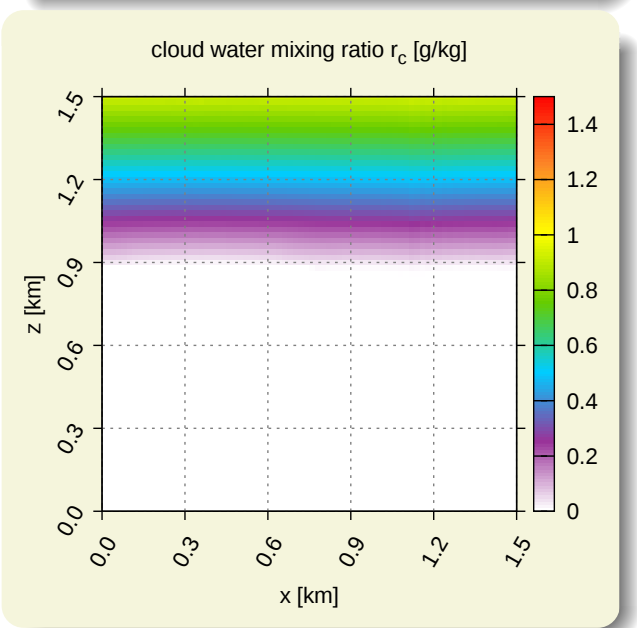

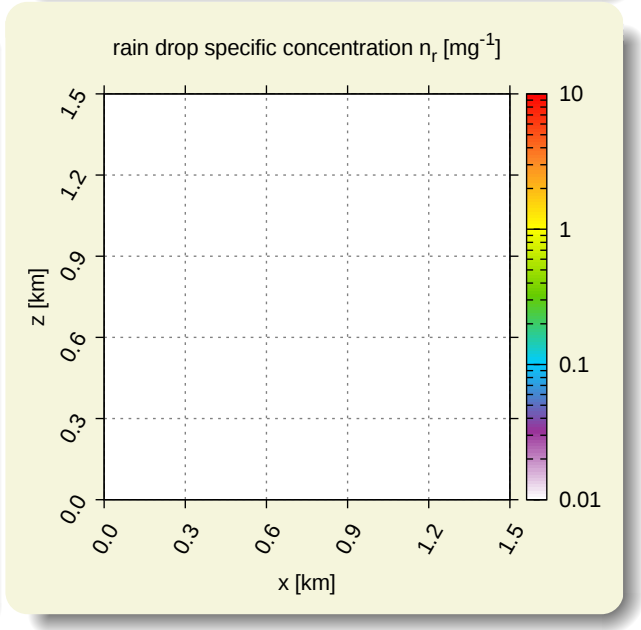

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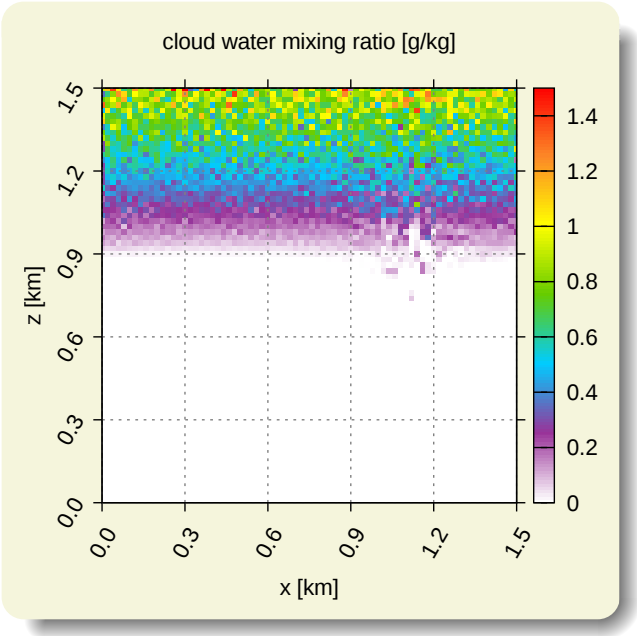

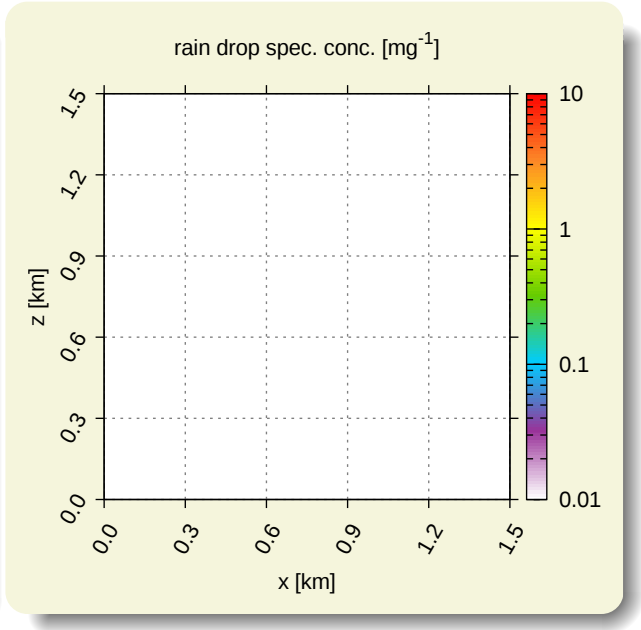

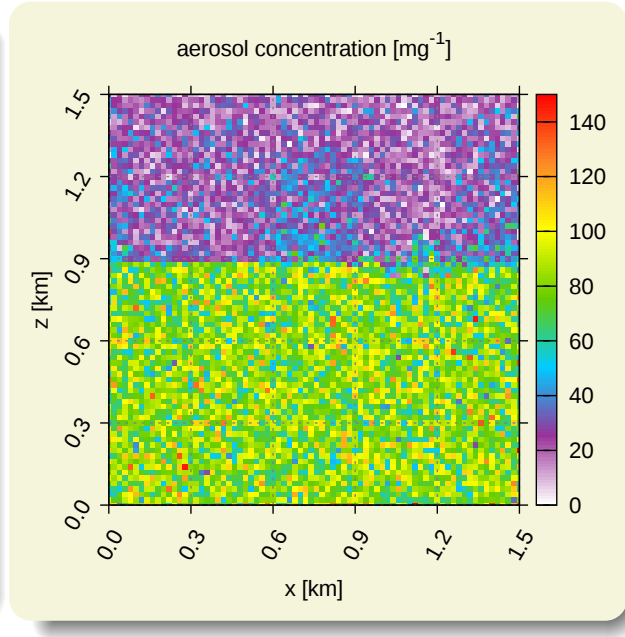

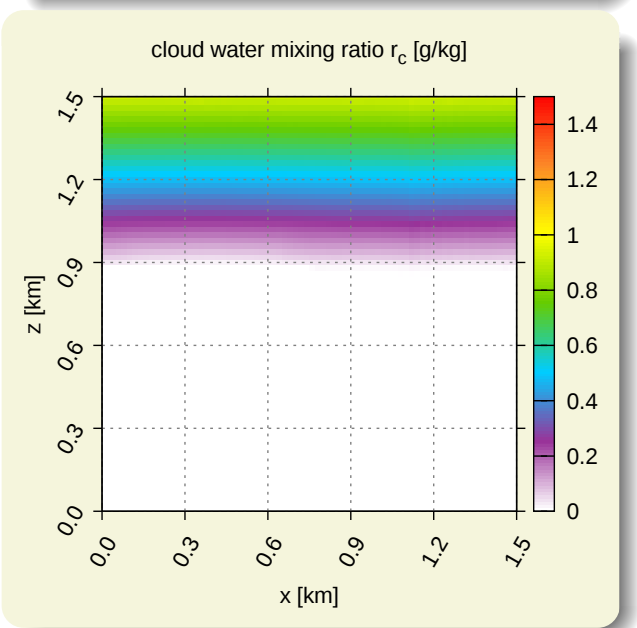

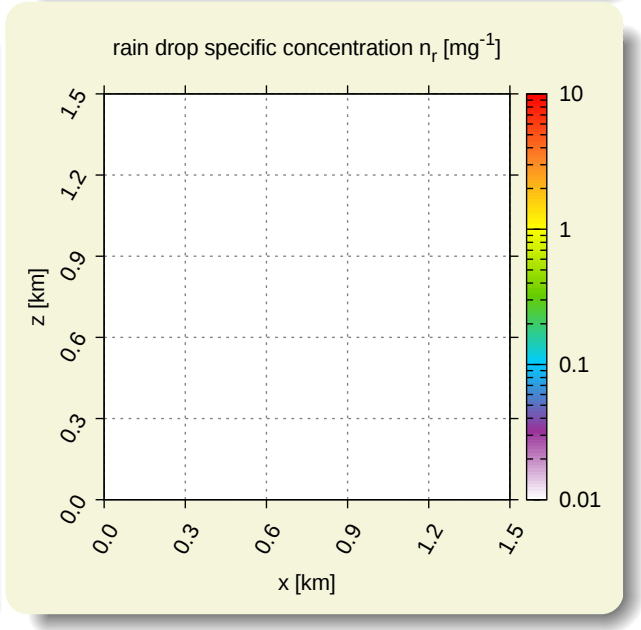

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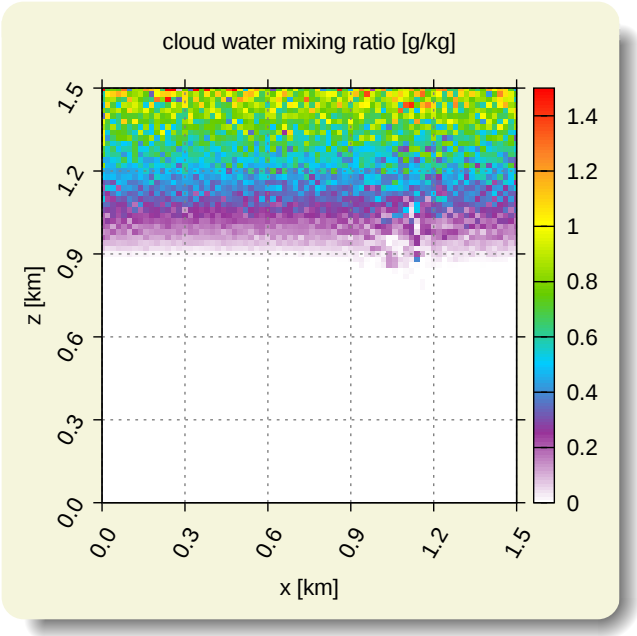

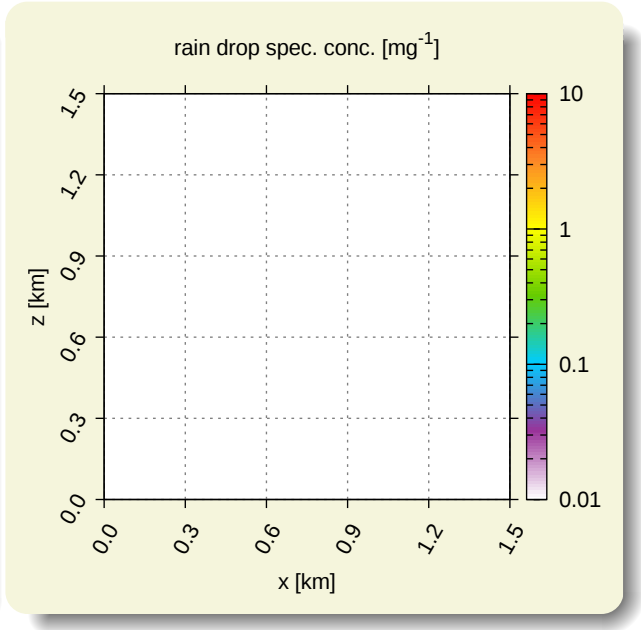

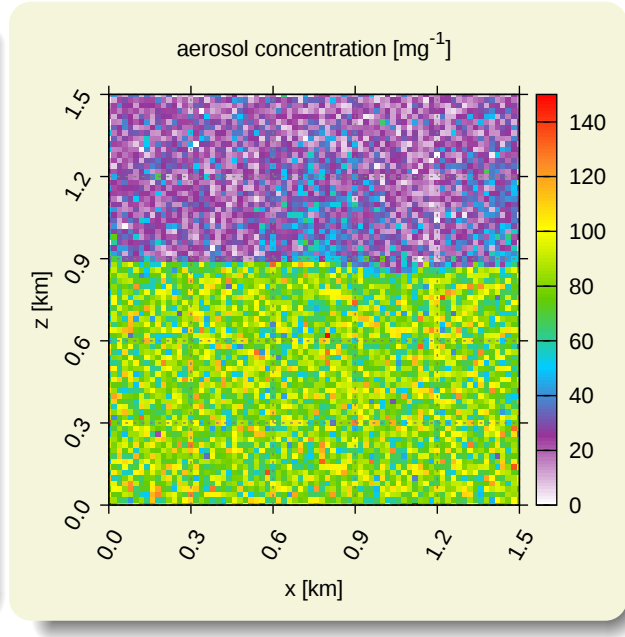

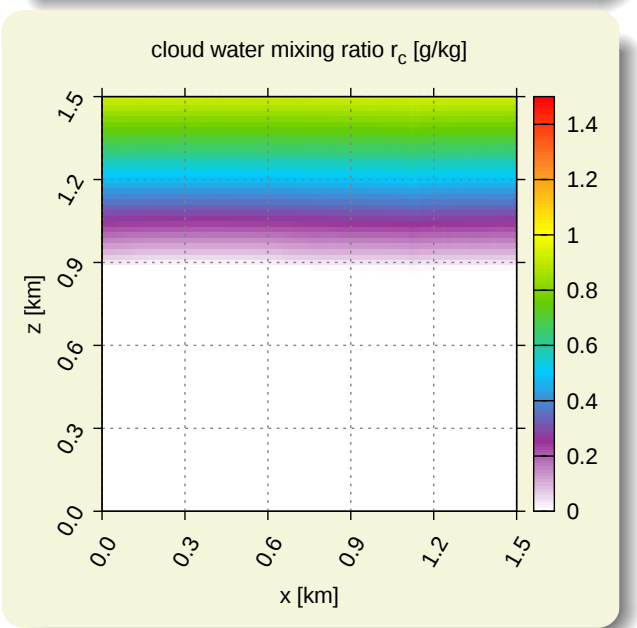

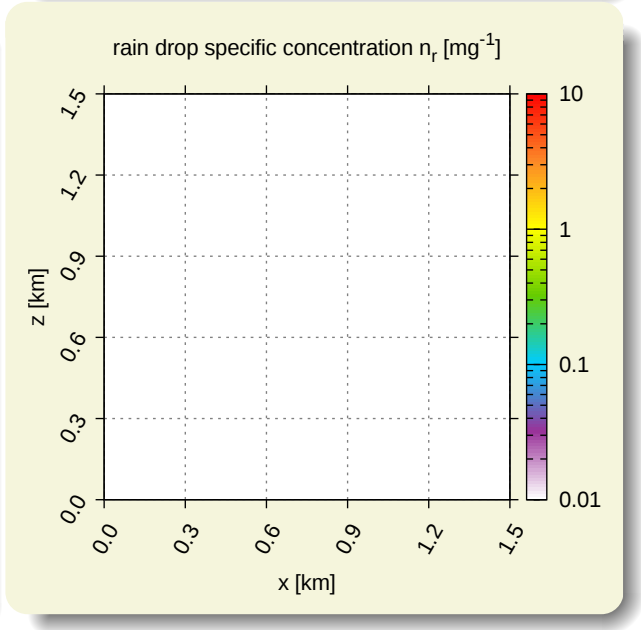

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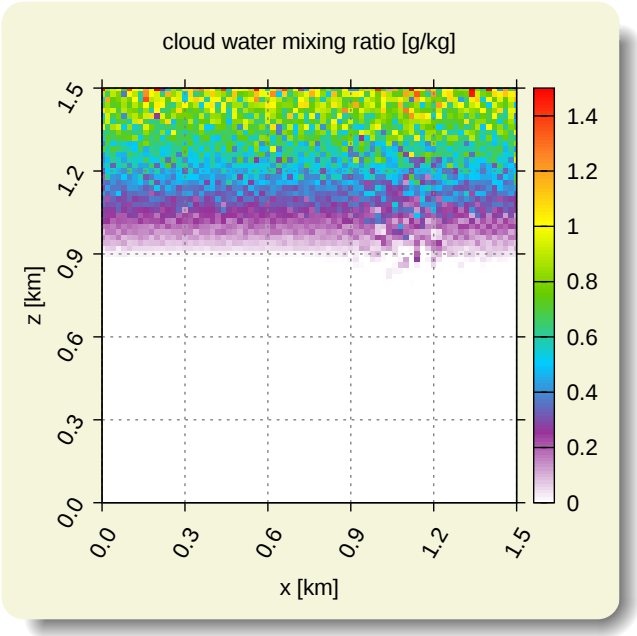
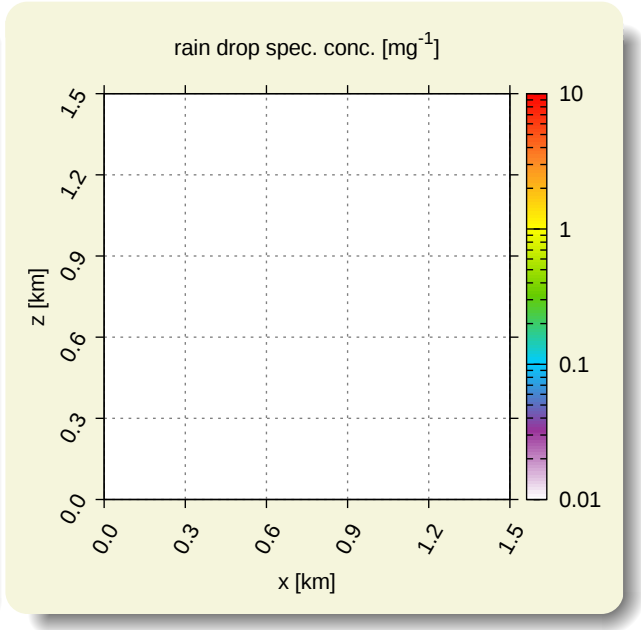
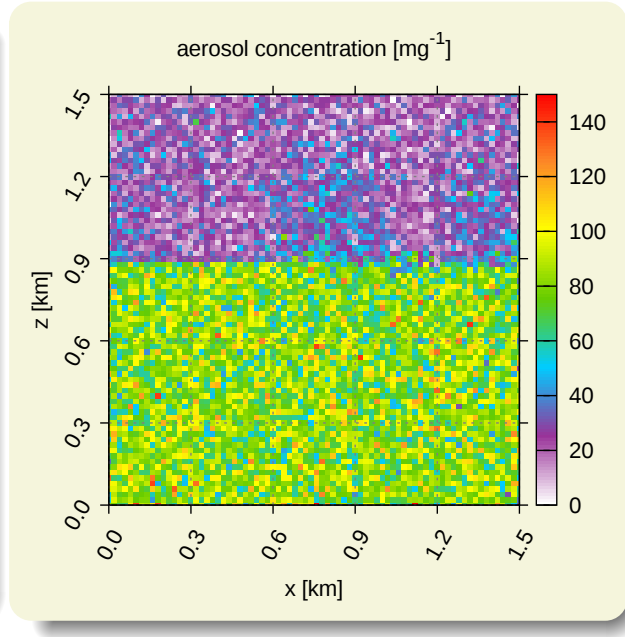
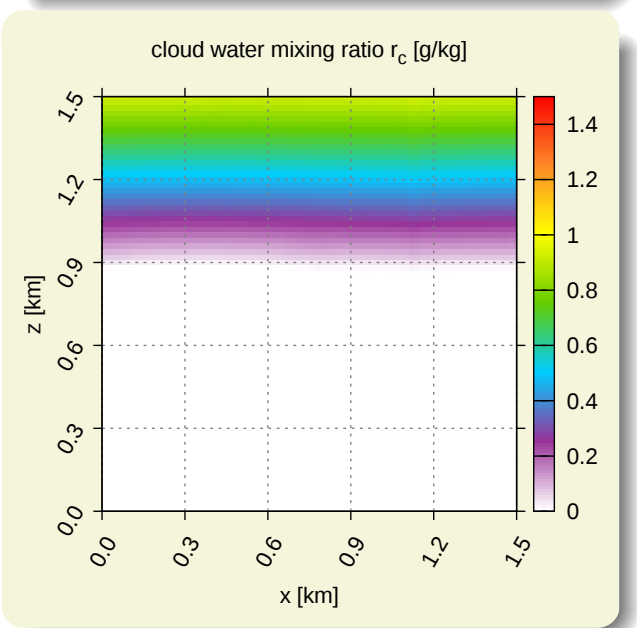
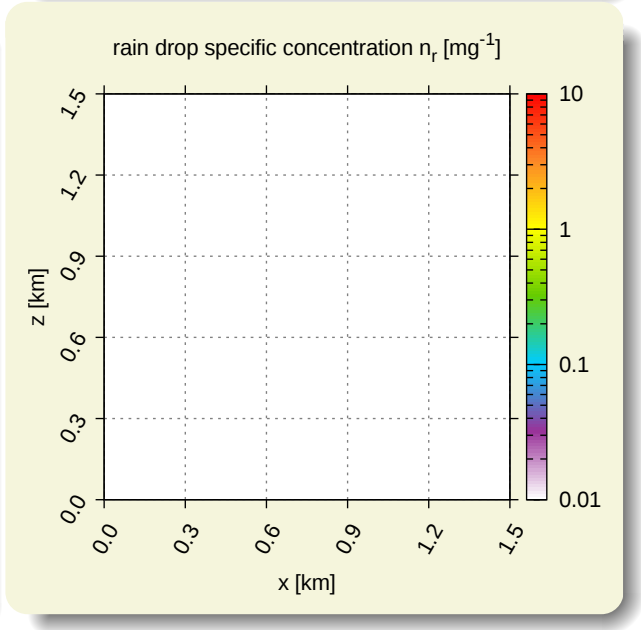






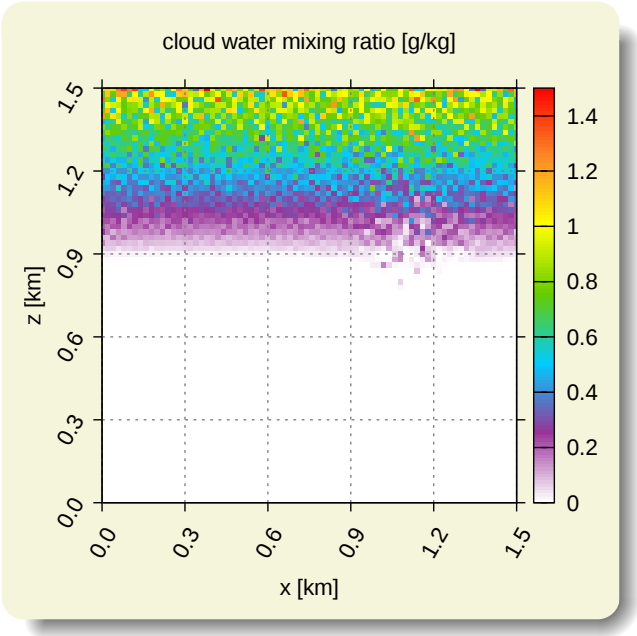


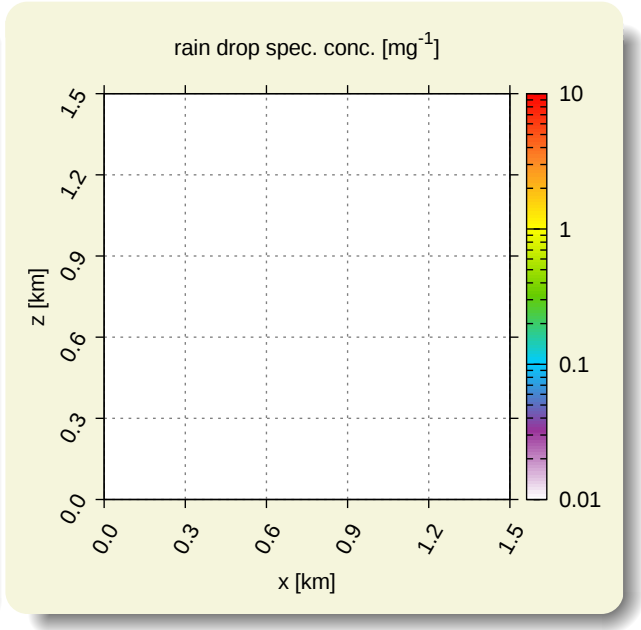


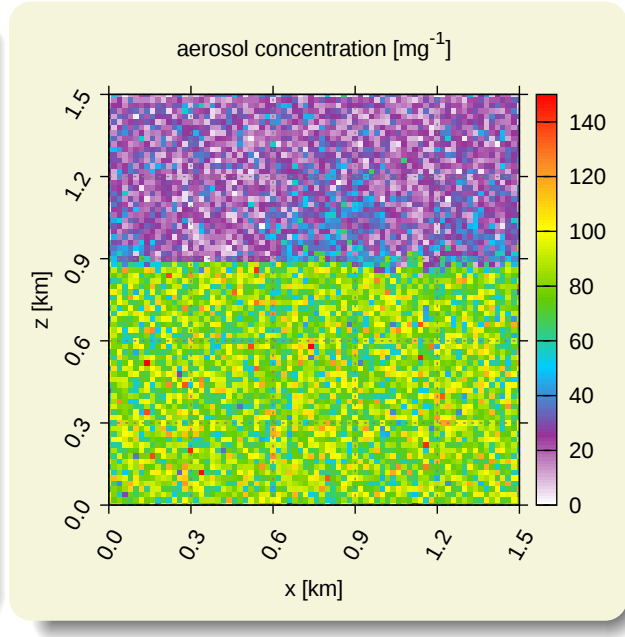
Lagrangian/Monte-Carlo scheme
(Shima et al. 2009)

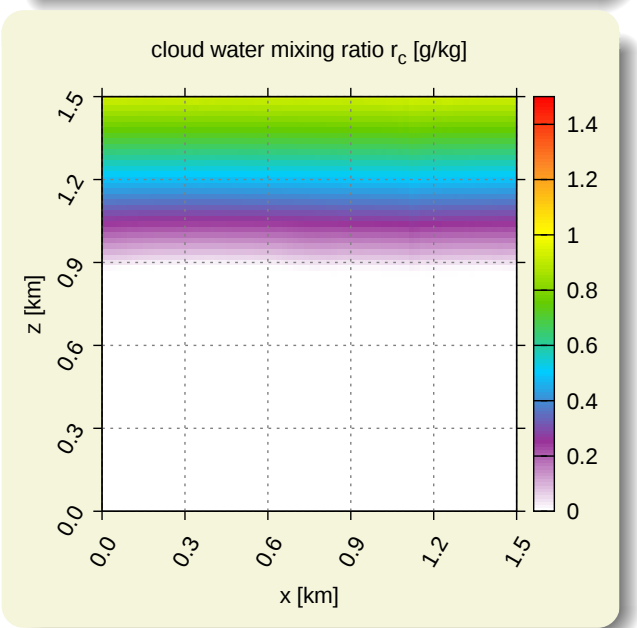
2-moment bulk scheme
(Morrison & Grabowski 2007)

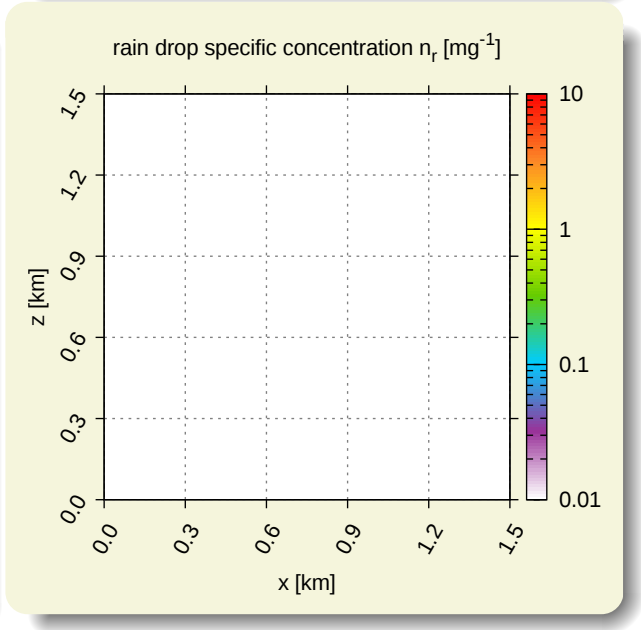
libcloudph++: VOCALS-inspired aerosol processing set-up











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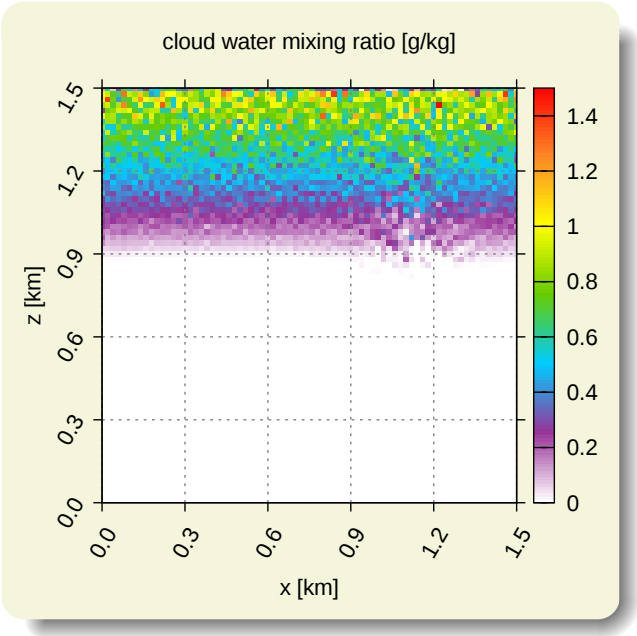

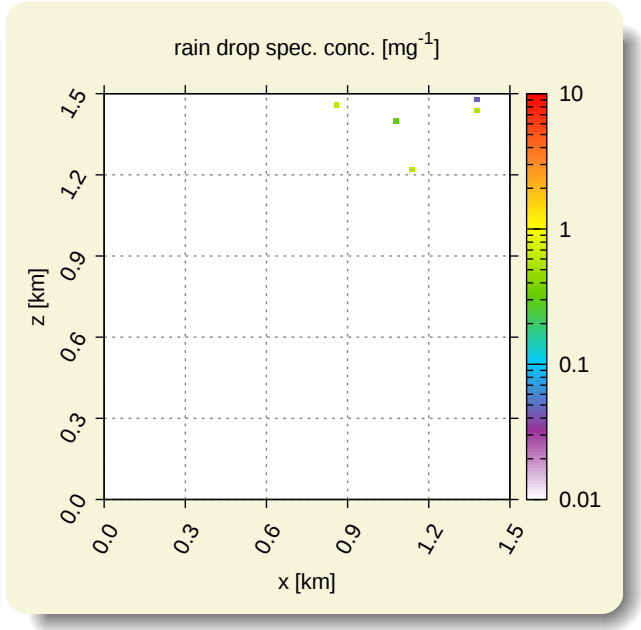

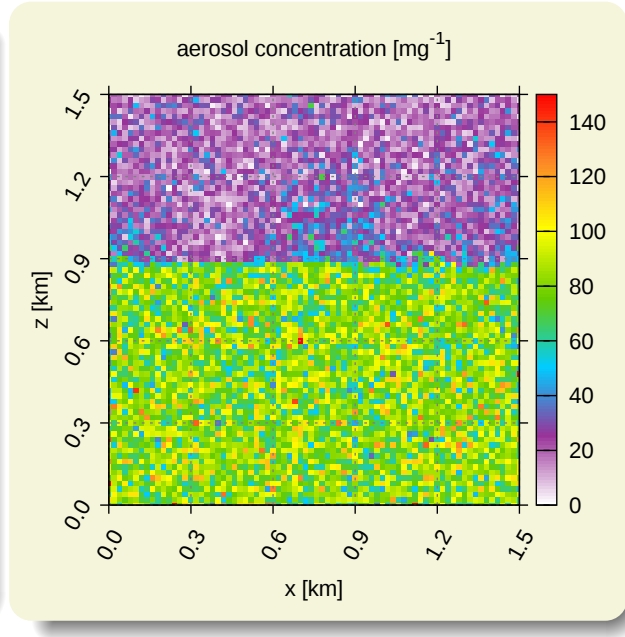

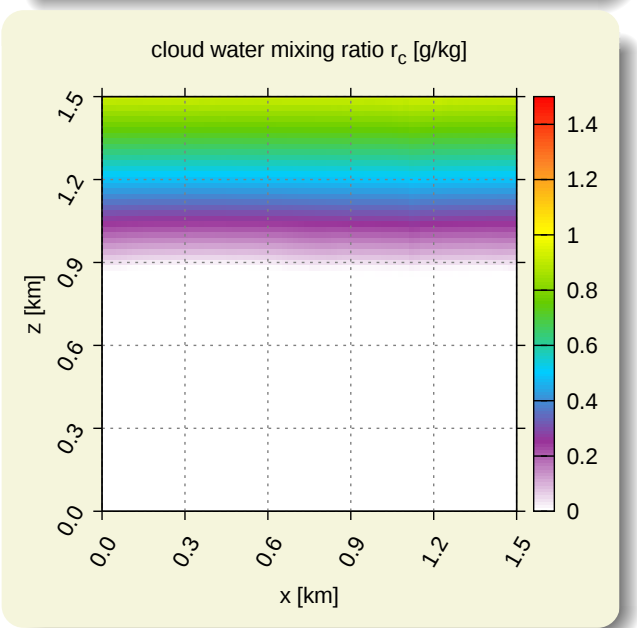

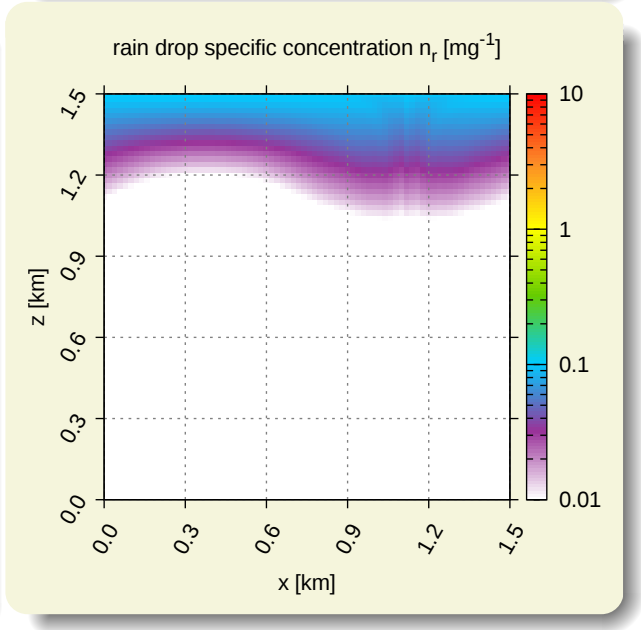

Lagrangian/Monte-Carlo scheme
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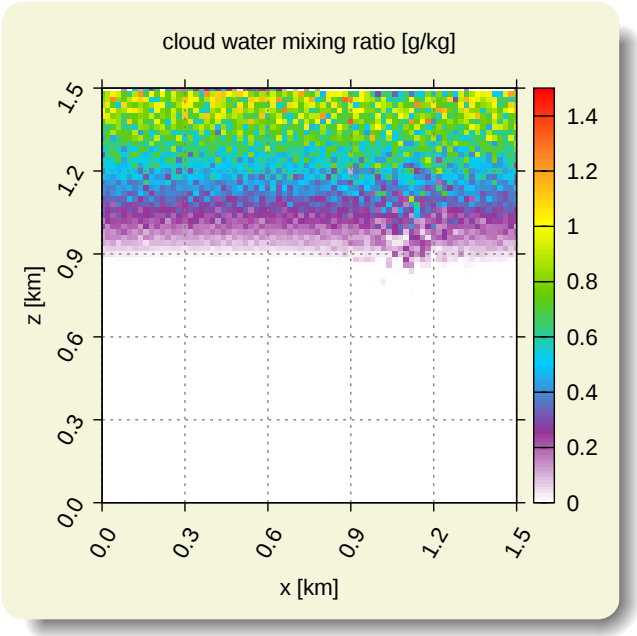
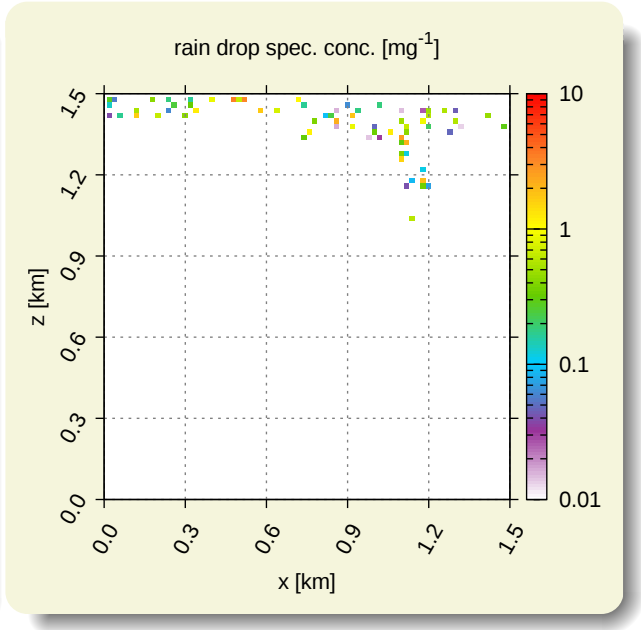
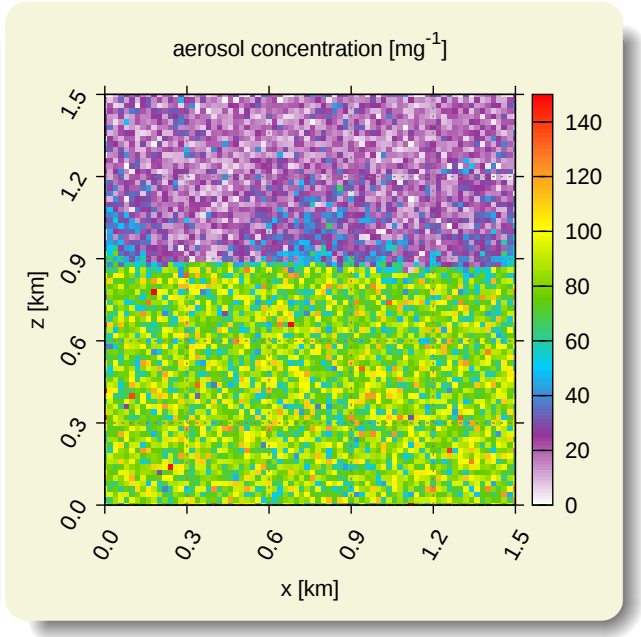
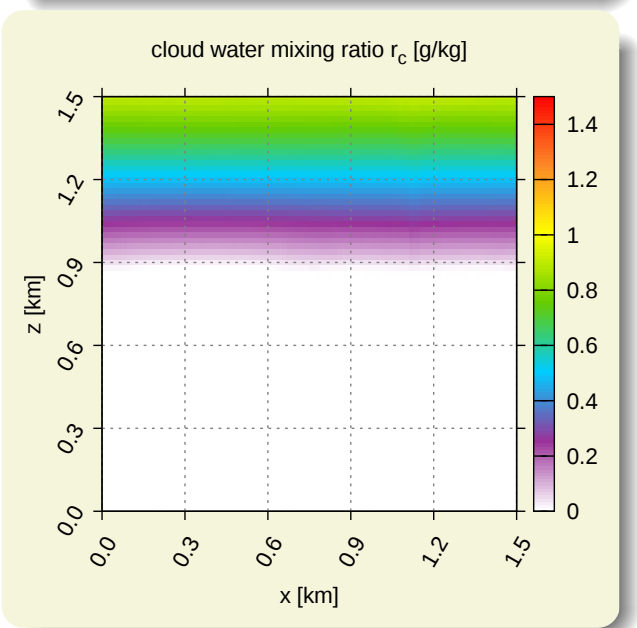
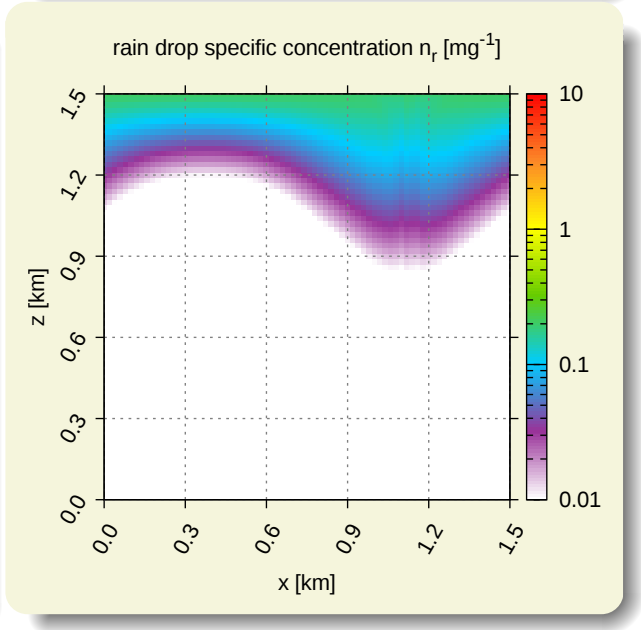
libcloudph++: VOCALS-inspired aerosol processing set-up











Lagrangian/Monte-Carlo scheme
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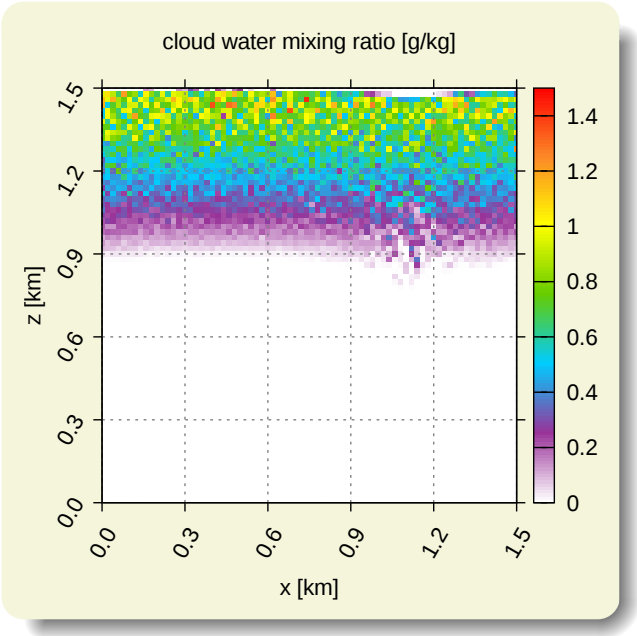
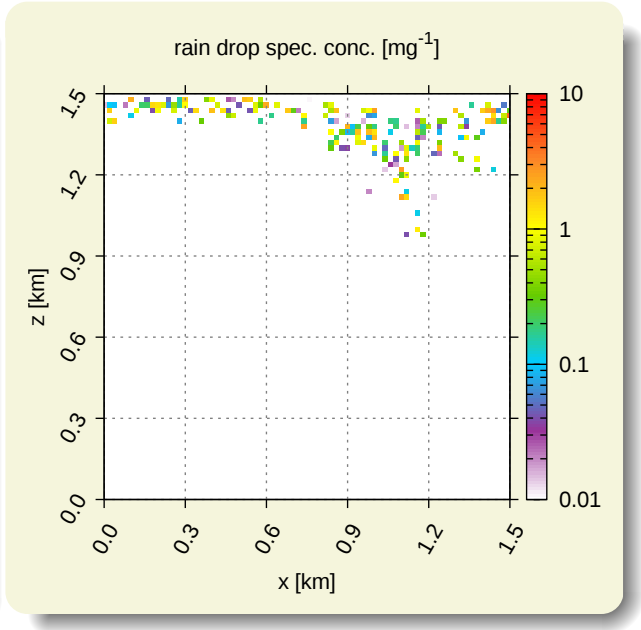
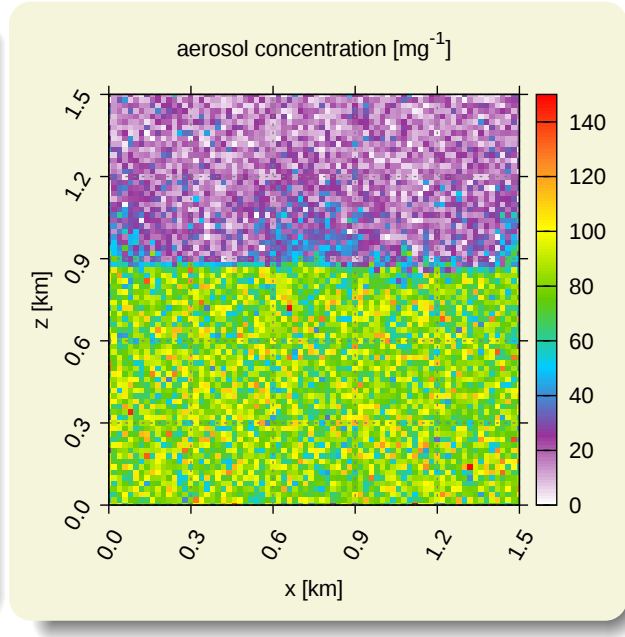
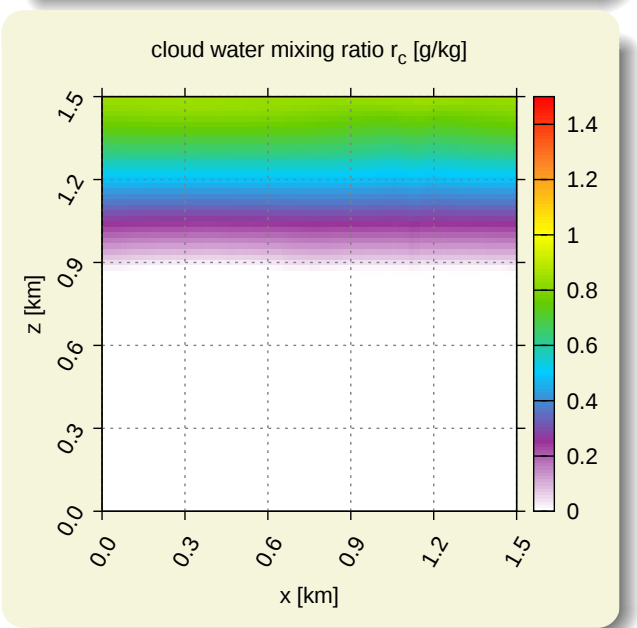
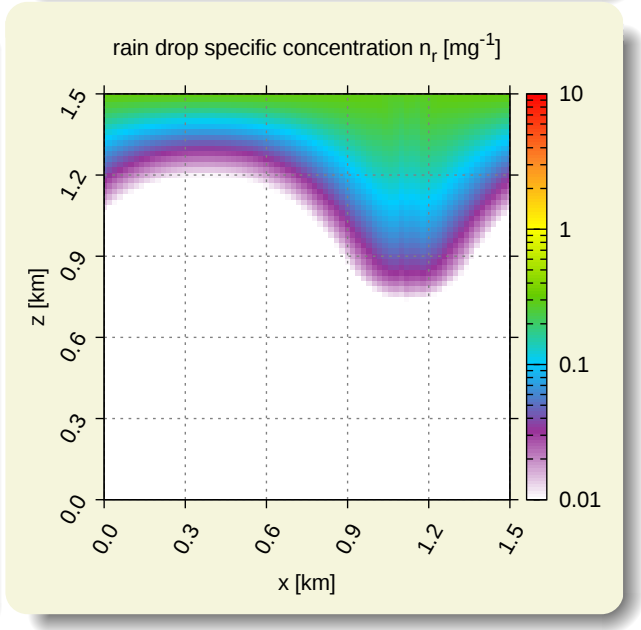
libcloudph++: VOCALS-inspired aerosol processing set-up







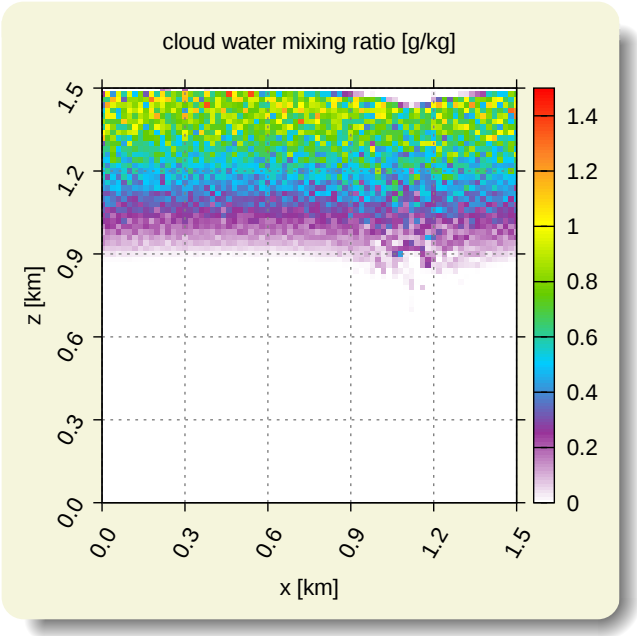


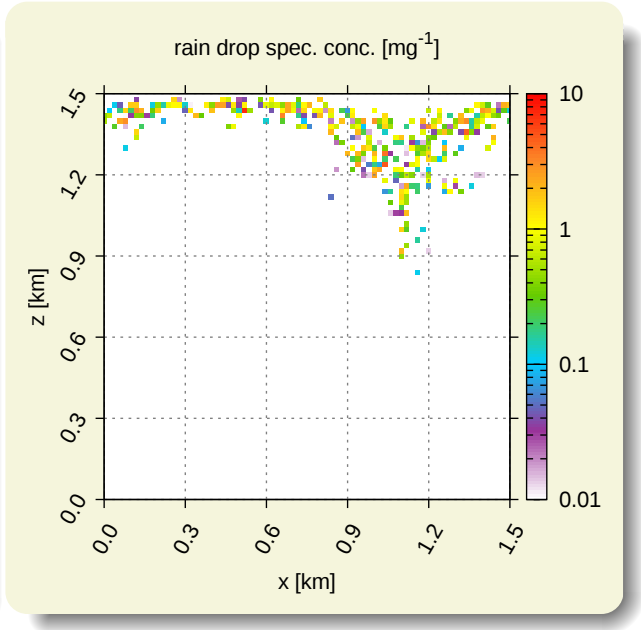


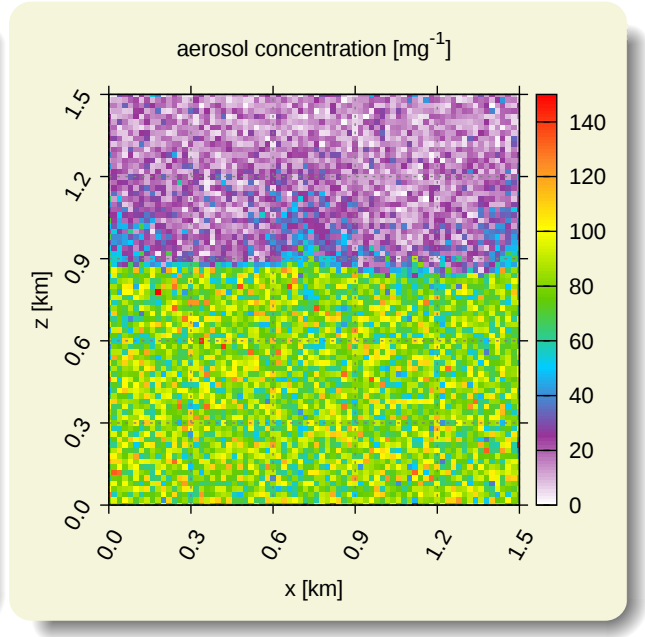
Lagrangian/Monte-Carlo scheme
(Shima et al. 2009)

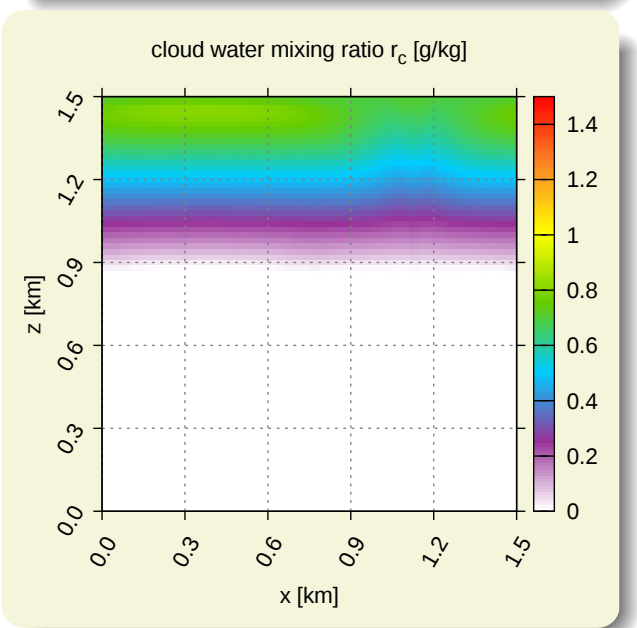
2-moment bulk scheme
(Morrison & Grabowski 2007)

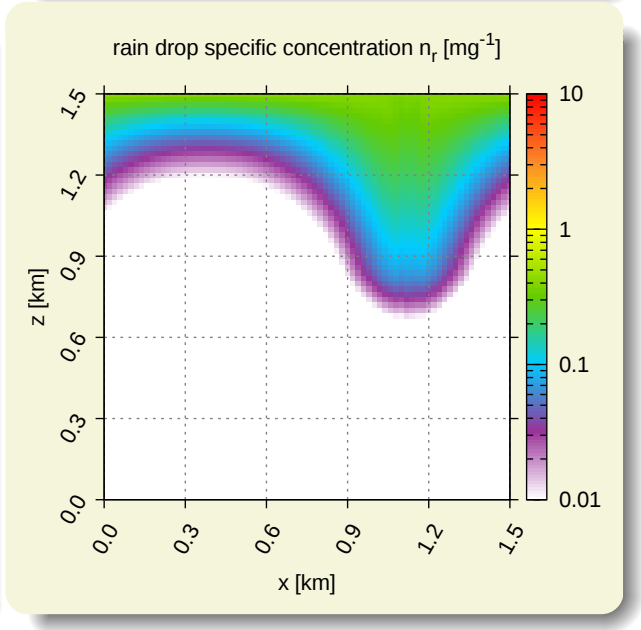
libcloudph++: VOCALS-inspired aerosol processing set-up











Lagrangian/Monte-Carlo scheme
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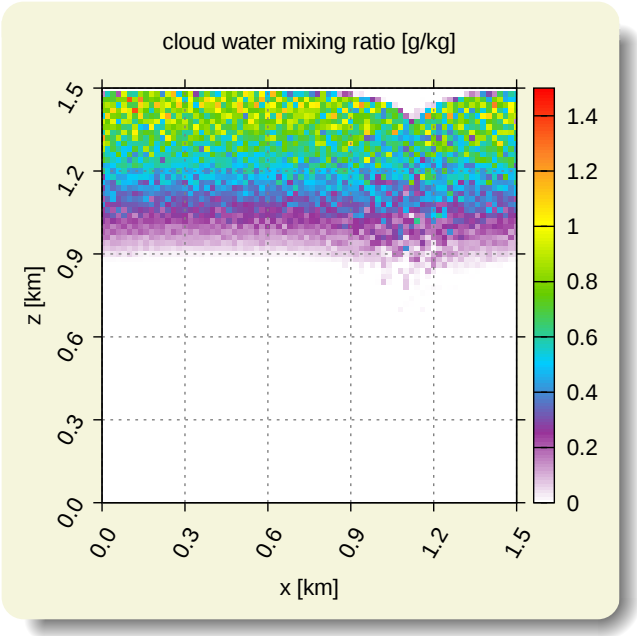
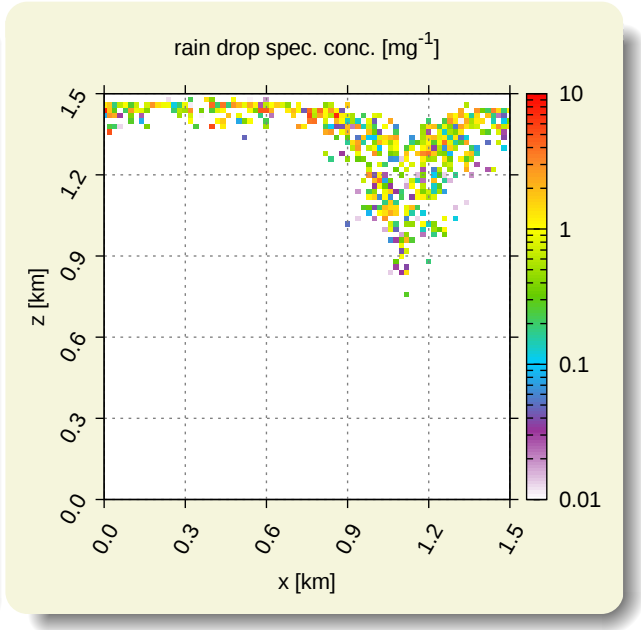
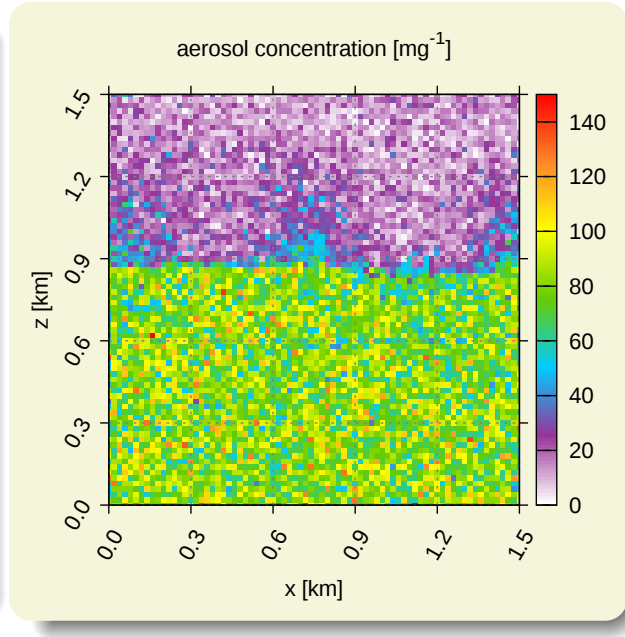
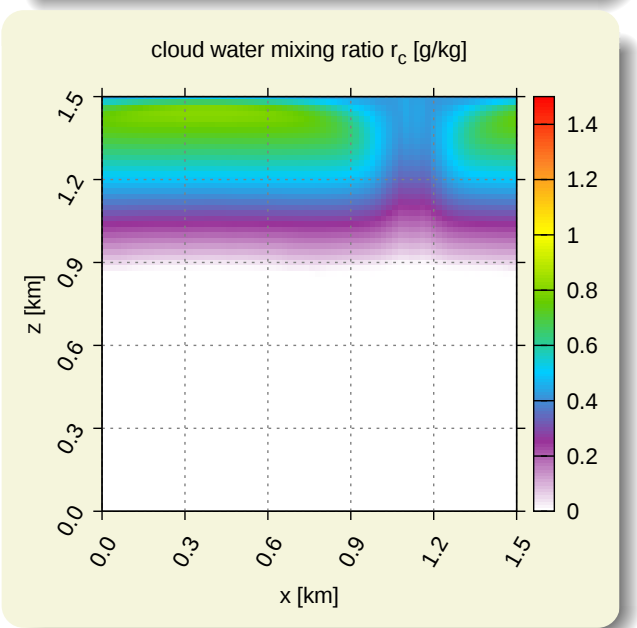
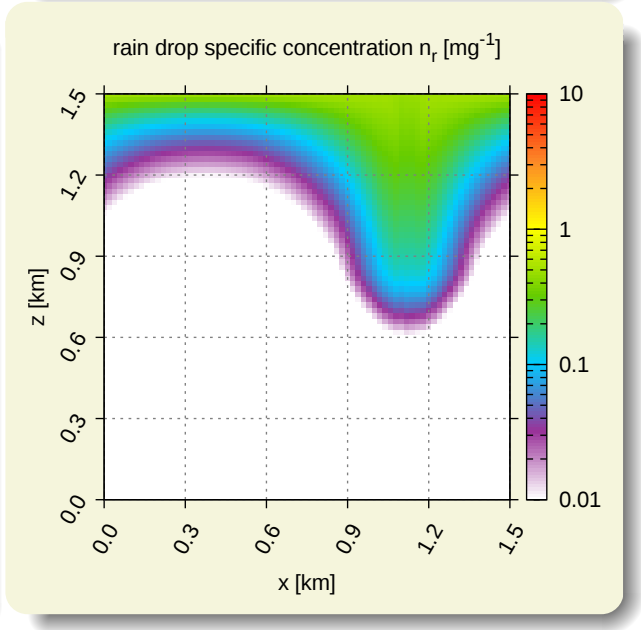
libcloudph++: VOCALS-inspired aerosol processing set-up











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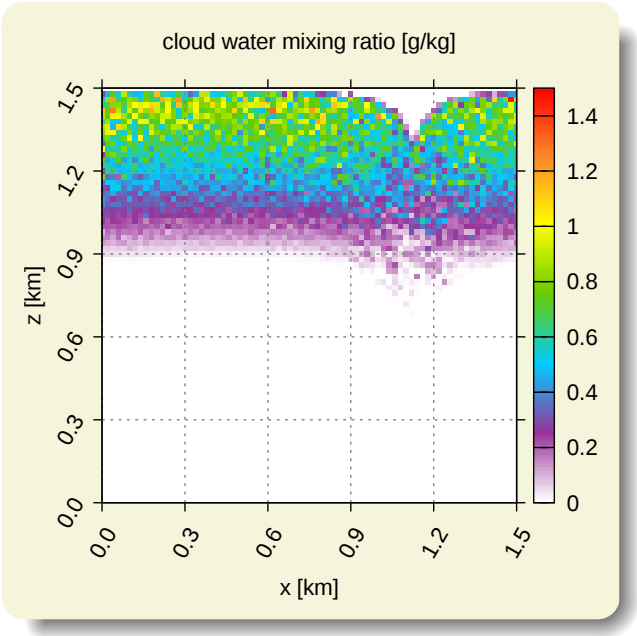
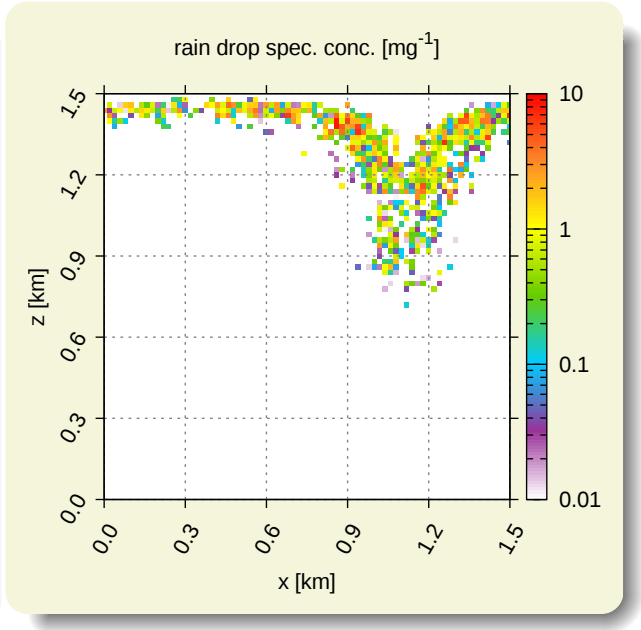
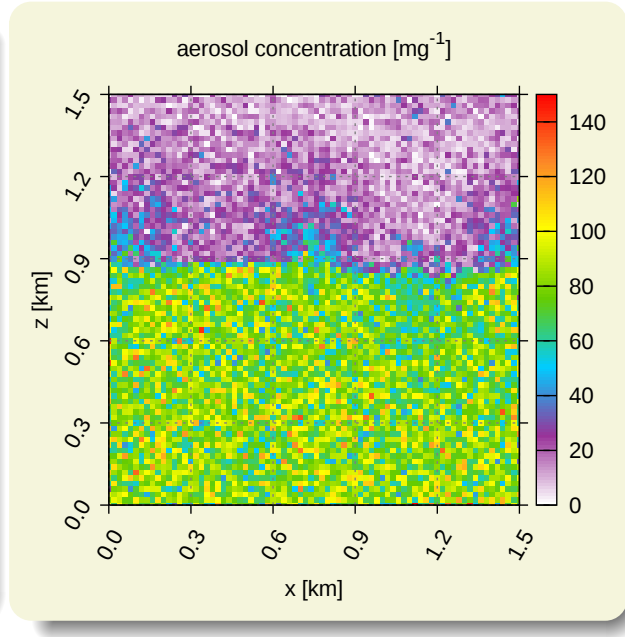
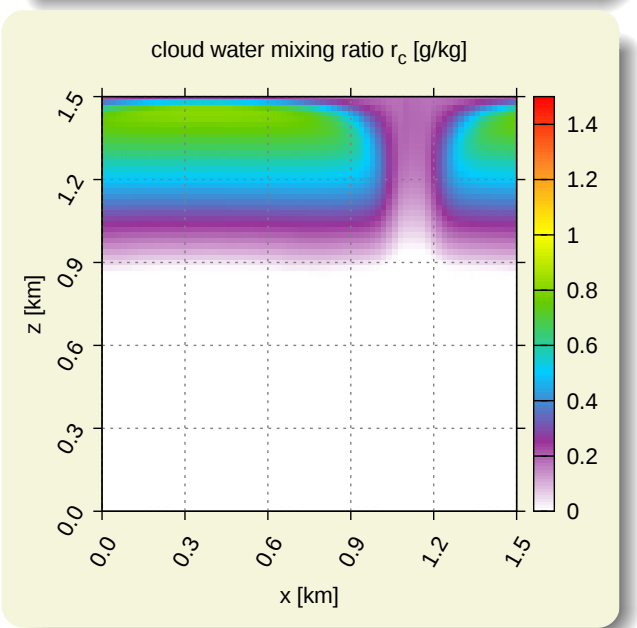
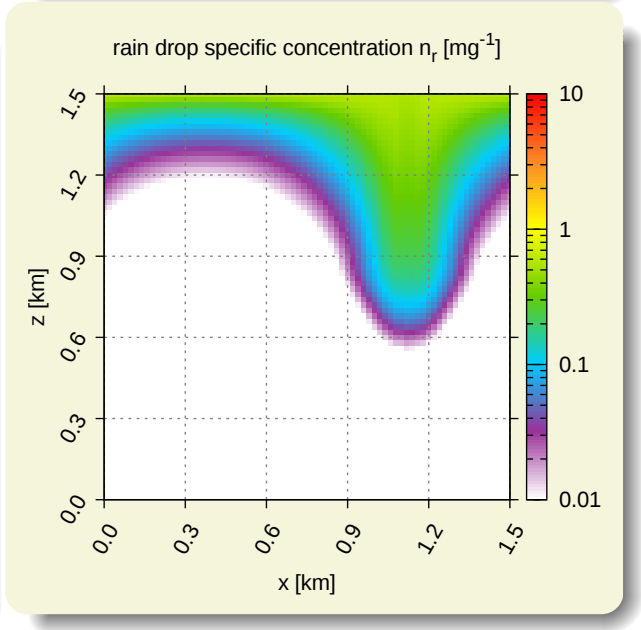
libcloudph++: VOCALS-inspired aerosol processing set-up











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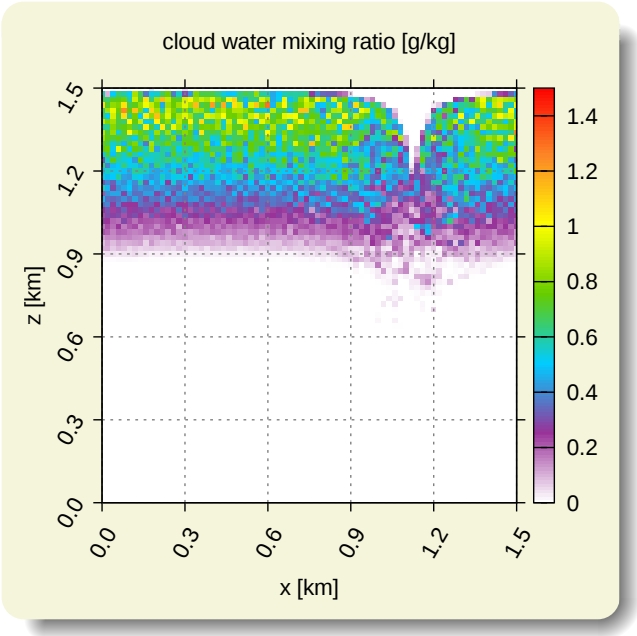

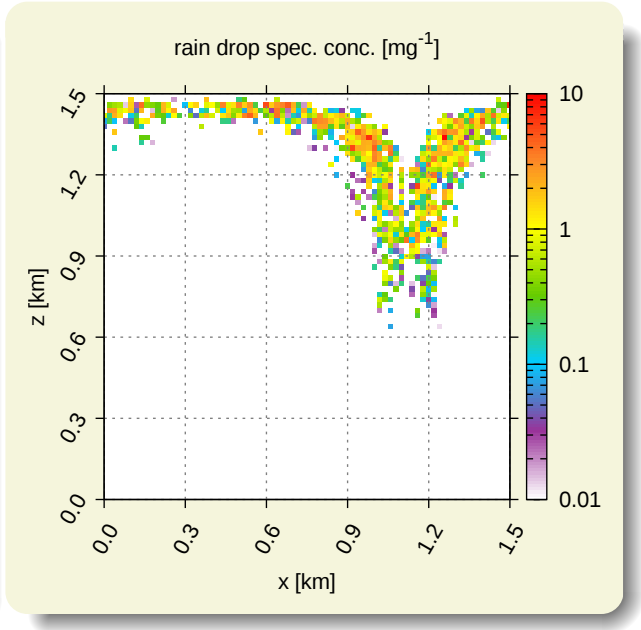

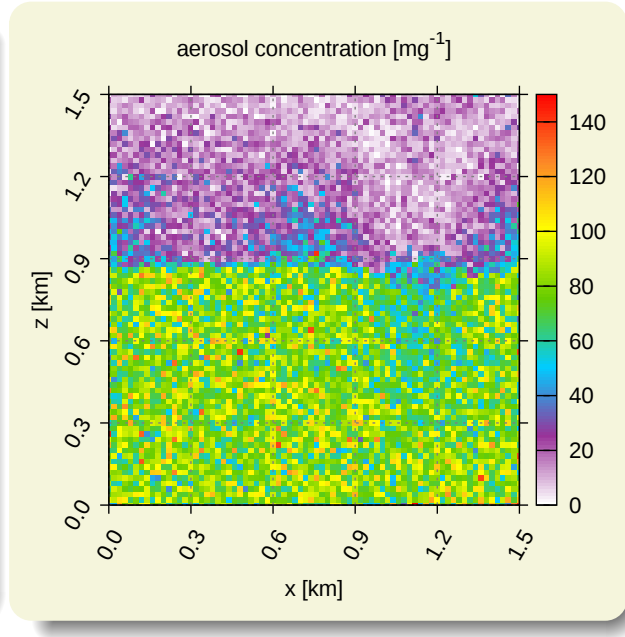

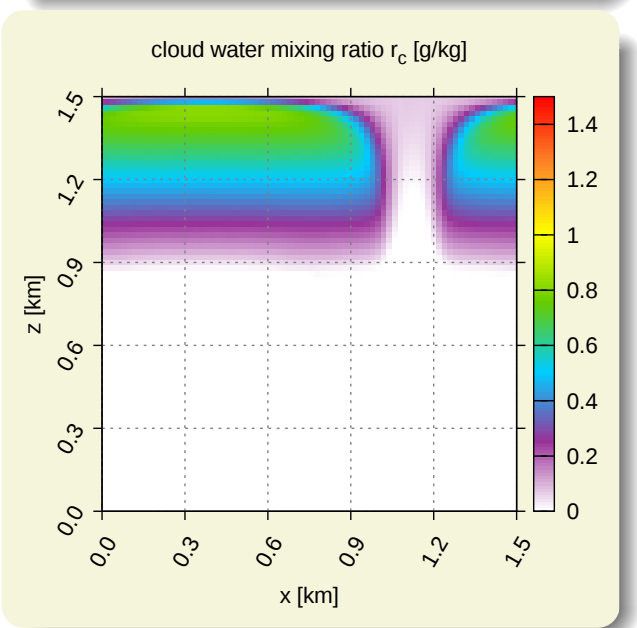

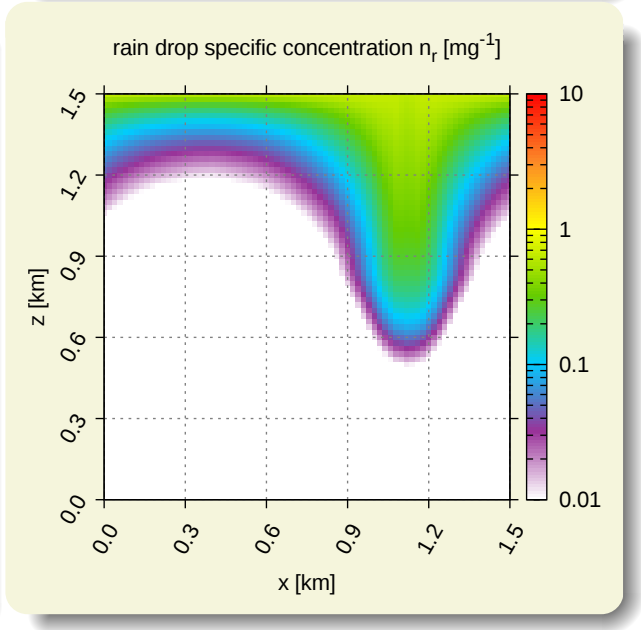

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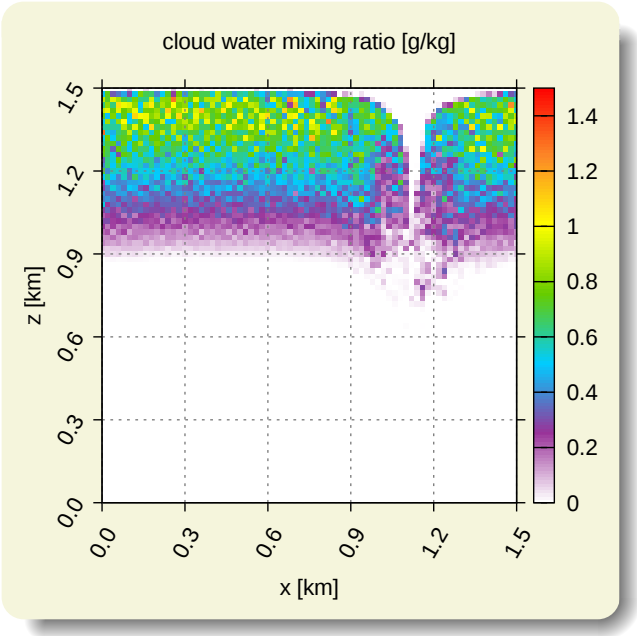

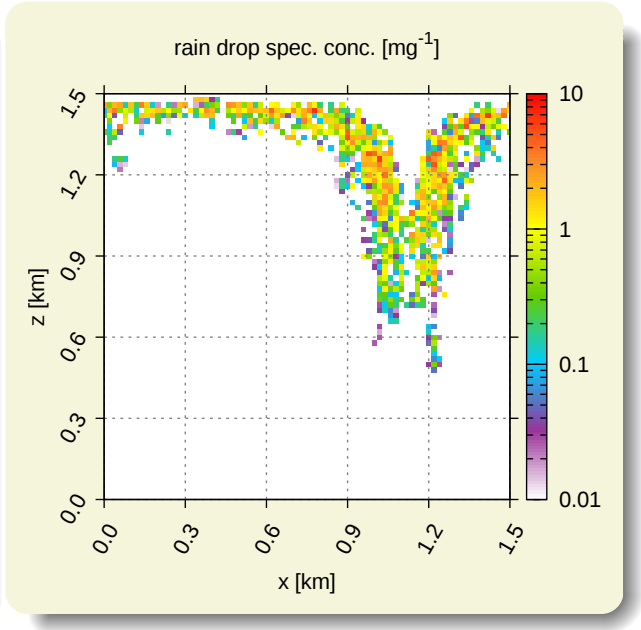

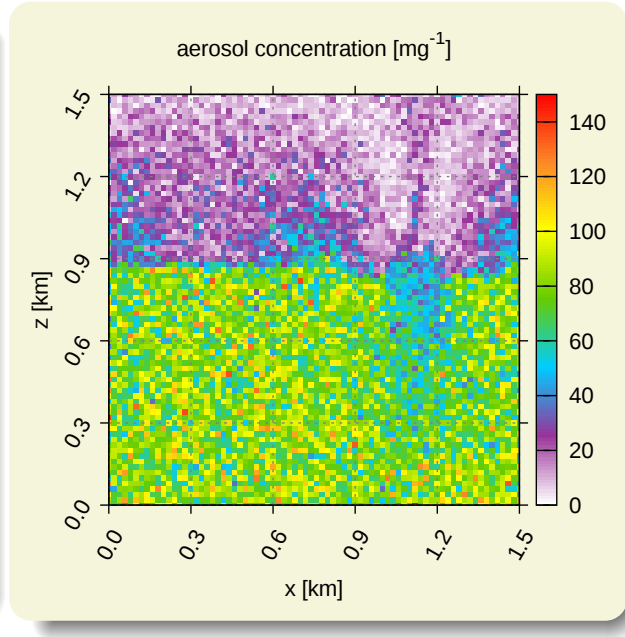

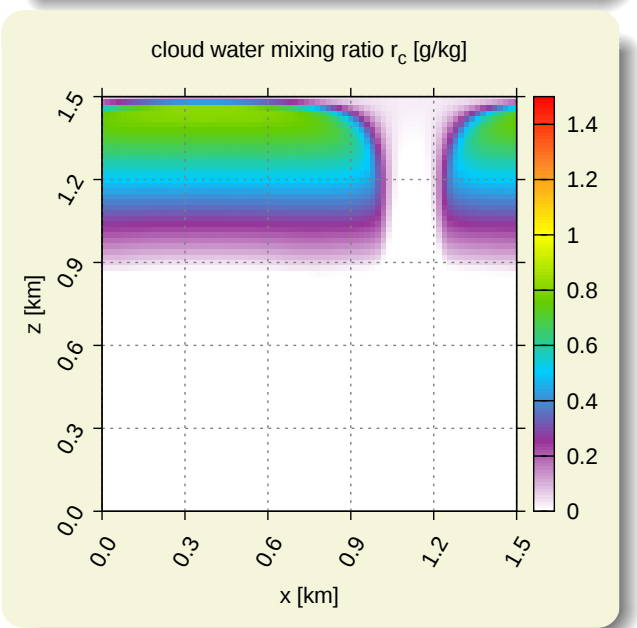

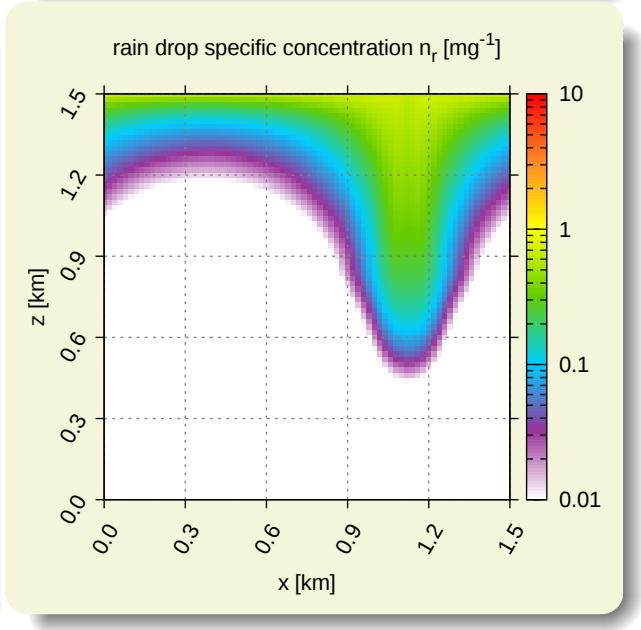

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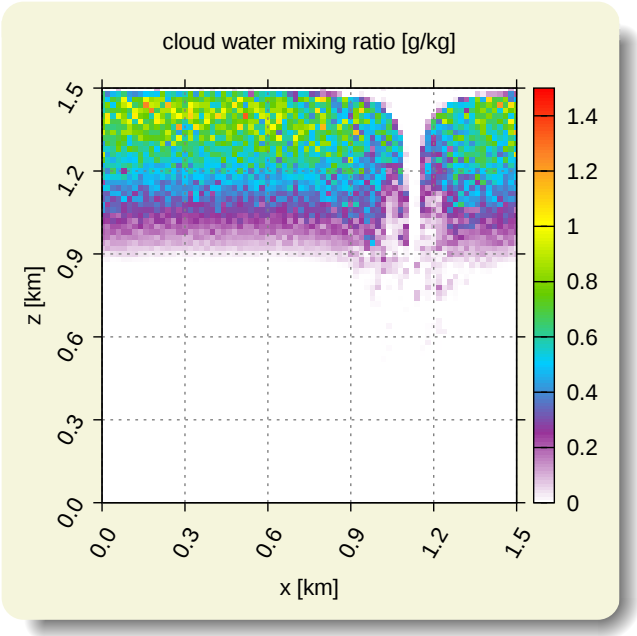

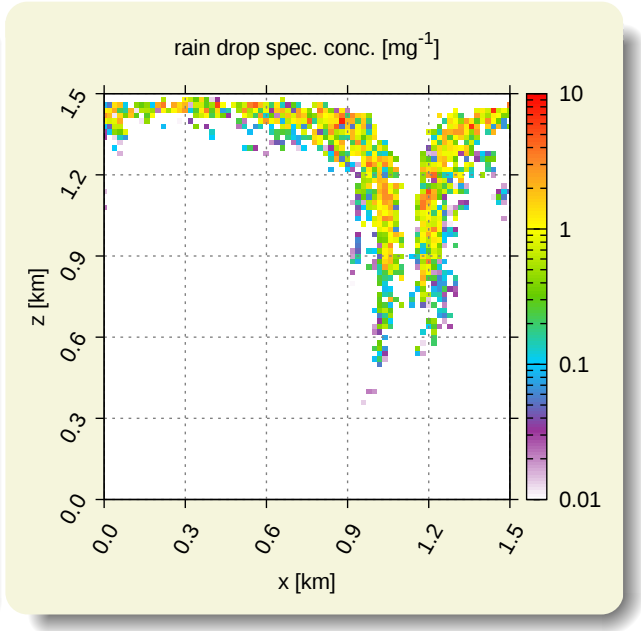

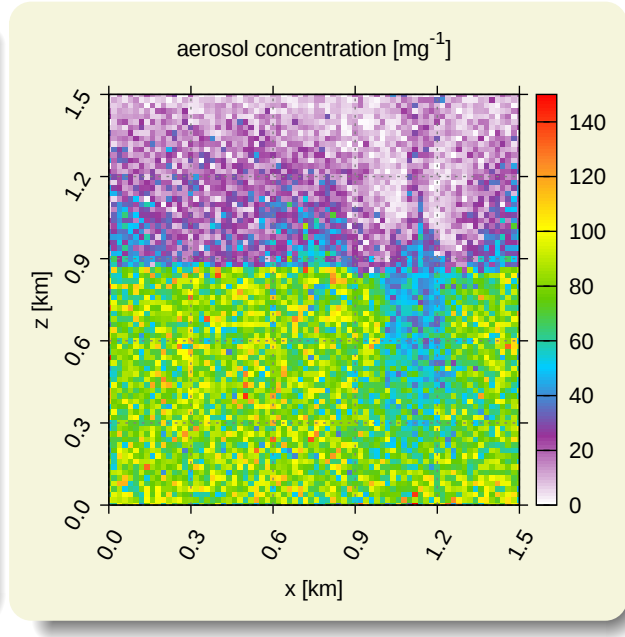

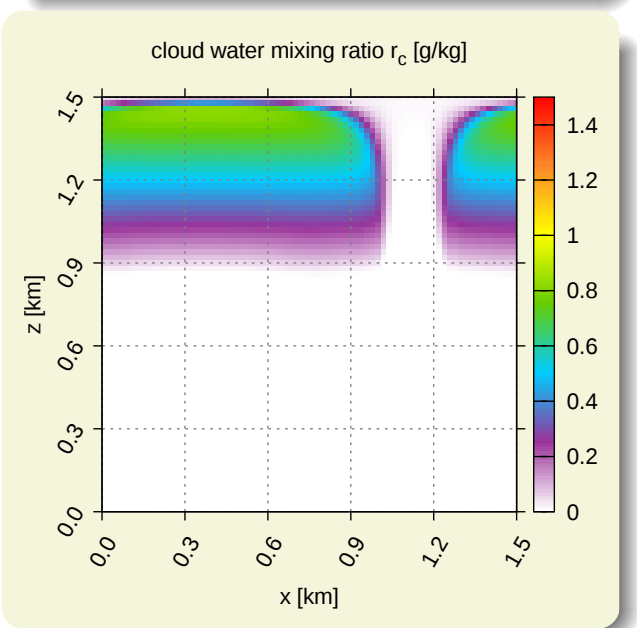

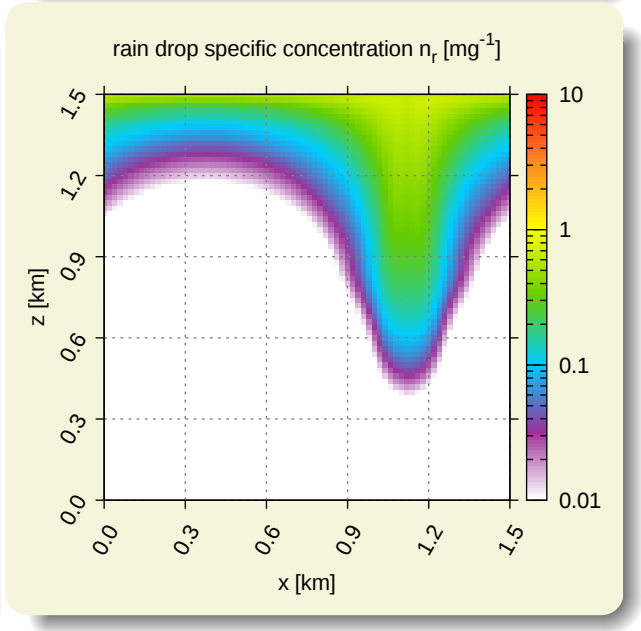

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2×2 cell particle-derived spectra