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Implementation of a fully three dimensional advection scheme for the COSMO dynamical core

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- Advection of positive definite quantities
- Scheme used**:** MPDATA
  - **M**ultidimensional **P**ositive **D**efinite **A**dvection **T**ransport **A**lgorithm developed by P. K. Smolarkiewicz (NCAR) and used in EULAG
- Tests presented (preliminary results):
  - 1d and 2d rotations
- Compared with**:**
  - **Bott** (2nd order with Strang splitting, operational)
  - **Semi-Lagrange** (3 dimensional scheme)

For more,
questions or discussions …
see you at the poster!

Thank you!

Agenda

- Advection in COSMO
- Introduction to the **M**ultidimensional **P**ositive **D**efinite **A**dvection **T**ransport **A**lgorithm, MPDATA
- Implementation of MPDATA
- 1 dimensional tests
- 2 dimensional tests
- Summary and Conclusions

Introduction to advection in COSMO

- Prognostic variables

  u, v, w, T, pp: with upwind scheme 5th order

- Positive definite variables

  qv, qc, qi, qr, qs, qg, tke, density: many choices

  - VanLeer scheme
  - PPM (piecewise parabolic method)
  - Semi-Lagrange scheme (SL)
  - Bott scheme (2nd or 4th order)

- Bott scheme
  - **First** step: advective fluxes multiplied by weighting factor
  - **Second** step: limit fluxes $\Rightarrow$ algorithm is positive definite
  - **Split** scheme: even time steps: xyz, odd time steps: zyx
  - Can lead to oscillations, **can empty a cell**, reduced precision

Introduction to MPDATA (i)

- Aim of the diploma thesis (6 months) was to implement, evaluate and test a fully three-dimensional advection scheme in the COSMO model

- New advection scheme: **MPDATA** (**M**ultidimensional **P**ositive **D**efinite **A**dvection **T**ransport **A**lgorithm)

- Main differences:
  - MPDATA is multidimensional
  - Bott is splitted
  - SL is 3D but not conservative

Introduction to MPDATA (ii)

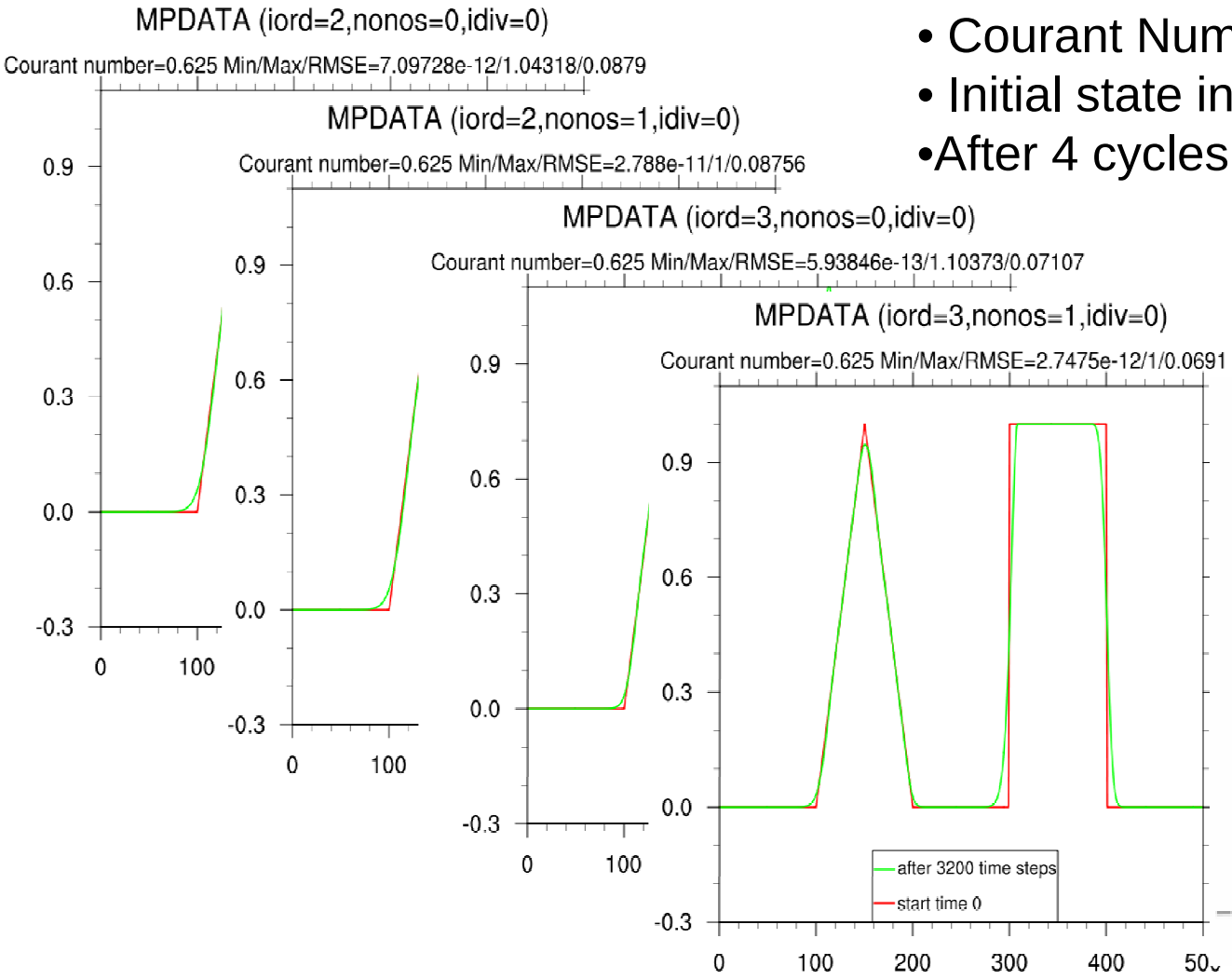
- Developed by P. K. Smolarkiewicz (NCAR) and used in EULAG
- **Iterative** algorithm:
  - **First** step: Upwind-Approximation – positive definite, only 1st order accurate
  - **Second** step: introduction of corrective advection fluxes, which reduce the truncation error produced by Upwind-Solution
- **Optional** further steps to reduce the truncation errors of previous step (at most 2nd order accuracy)
- **Non-oscillatory option**:
  fully monotone (no spurious extremes)

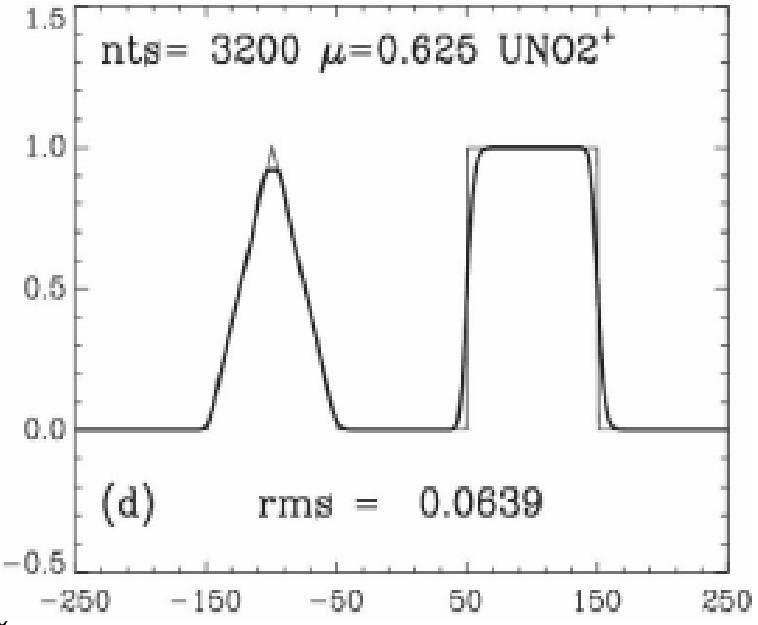
Implementation of MPDATA

- New Namelist parameters:
  - ***iord***:
    - number of iterations
    - possible values: 1,2,…
  - ***nonos***:
    - nonos=0: non-oscillatory option: off
    - nonos=1: non-oscillatory option: on (monotone scheme)
  - ***idiv***:
    - idiv=0: non divergent flows
    - idiv=1: divergent flows

- Recommended: iord=2, nonos=1

1-dimensional tests



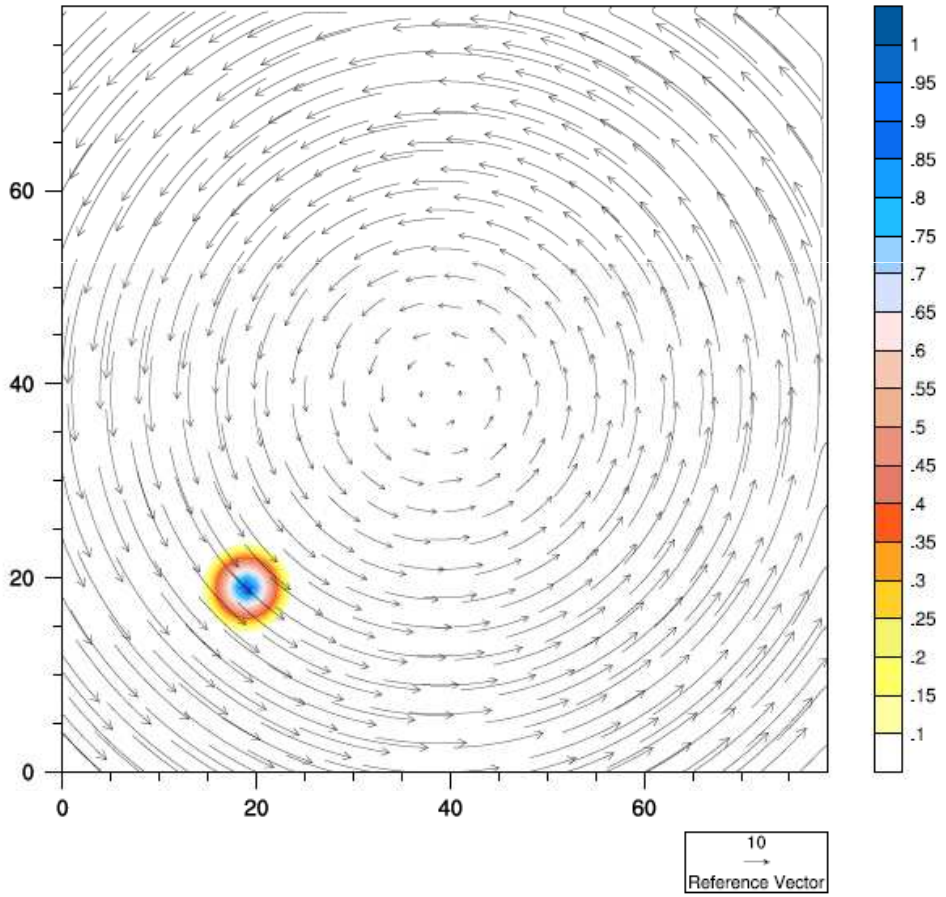


- Courant Number = 0.625
- Initial state in **red**
- After 4 cycles (+3200 time steps) in **green**

- Upstream Non-Oscillatory scheme from Li (2008)

Solid Body Rotation Tests

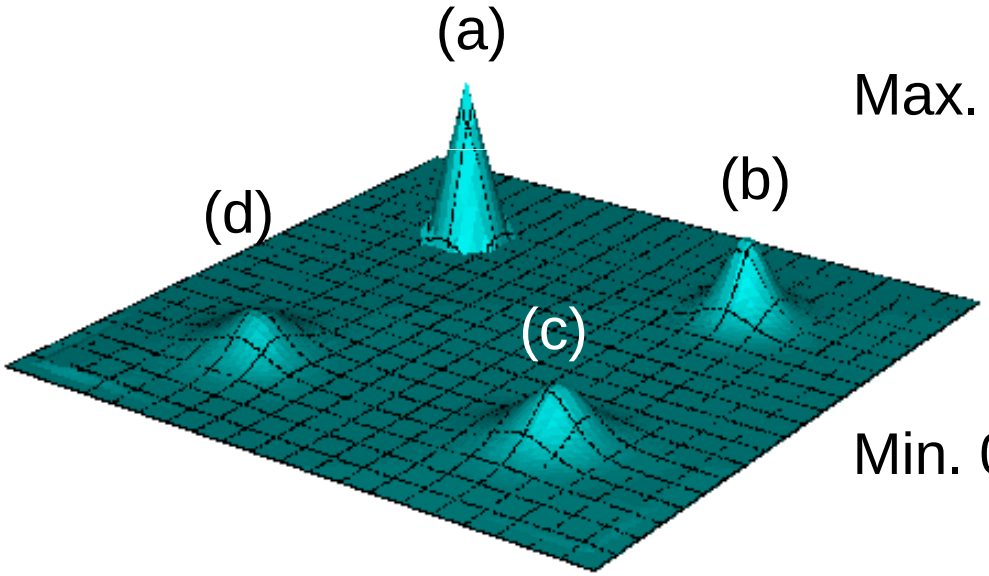
- **Cone** tracer with 5 grid points radius
- **NO** background
- **NO** orography
- Δx = 2.2km
- Δt = 20s
- Courant nb. ~ 0.3



Initial distribution for the solid body rotation tests

Solid Body Rotation Test I

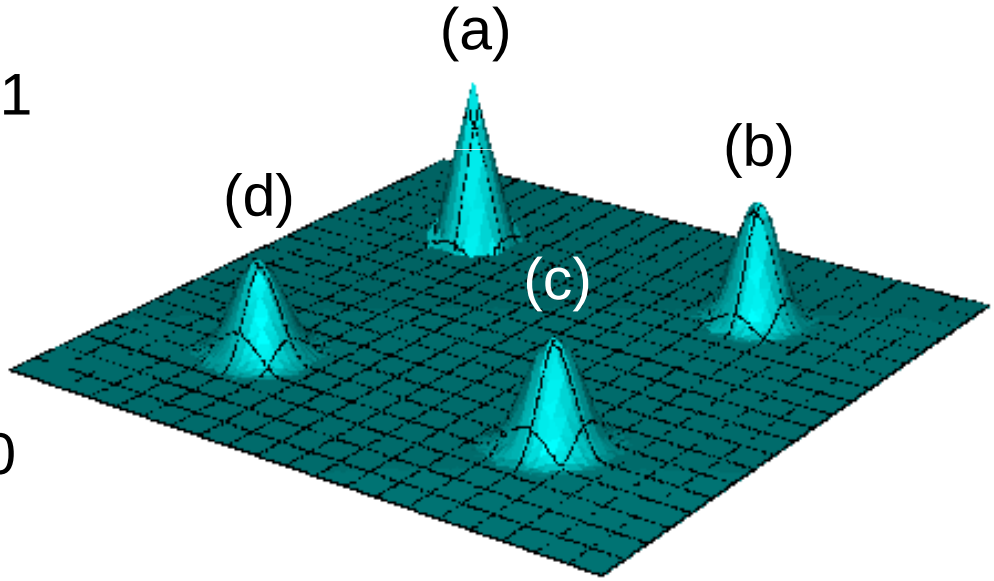
MPDATA (iord=2, nonos=1)



Max. 1

Min. 0

Bott_2 advection scheme



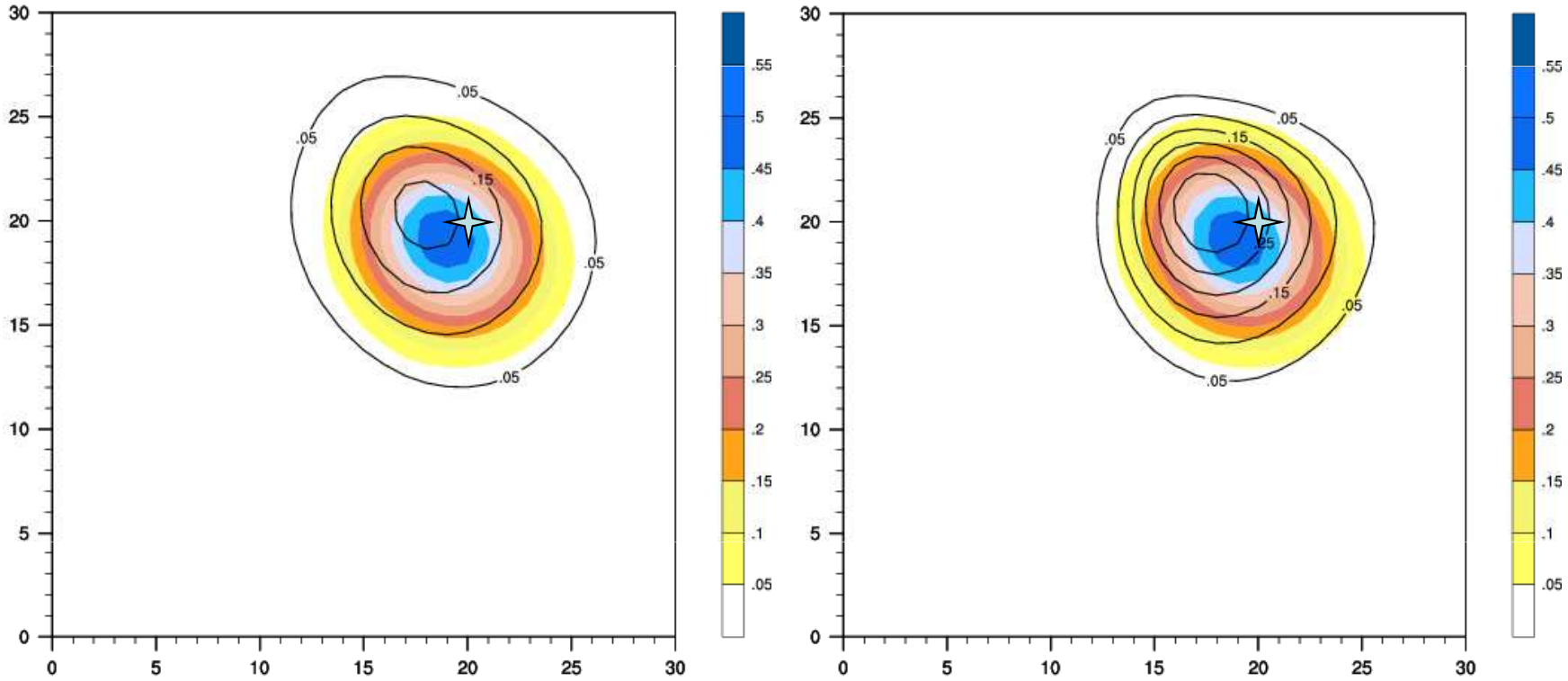
Tracer at the beginning (a), after 1h (b),
after 2h (c) and after 3h (d)

Solid Body Rotation Test I

Zoom of tracer after **one** rotation (4h) (start centre: ✦)

iord=2, nonos=0 Max: 0.2188

iord=3, nonos=0 Bott Max: 0.5009 Max: 0.3480



Bott_2: coloured areas

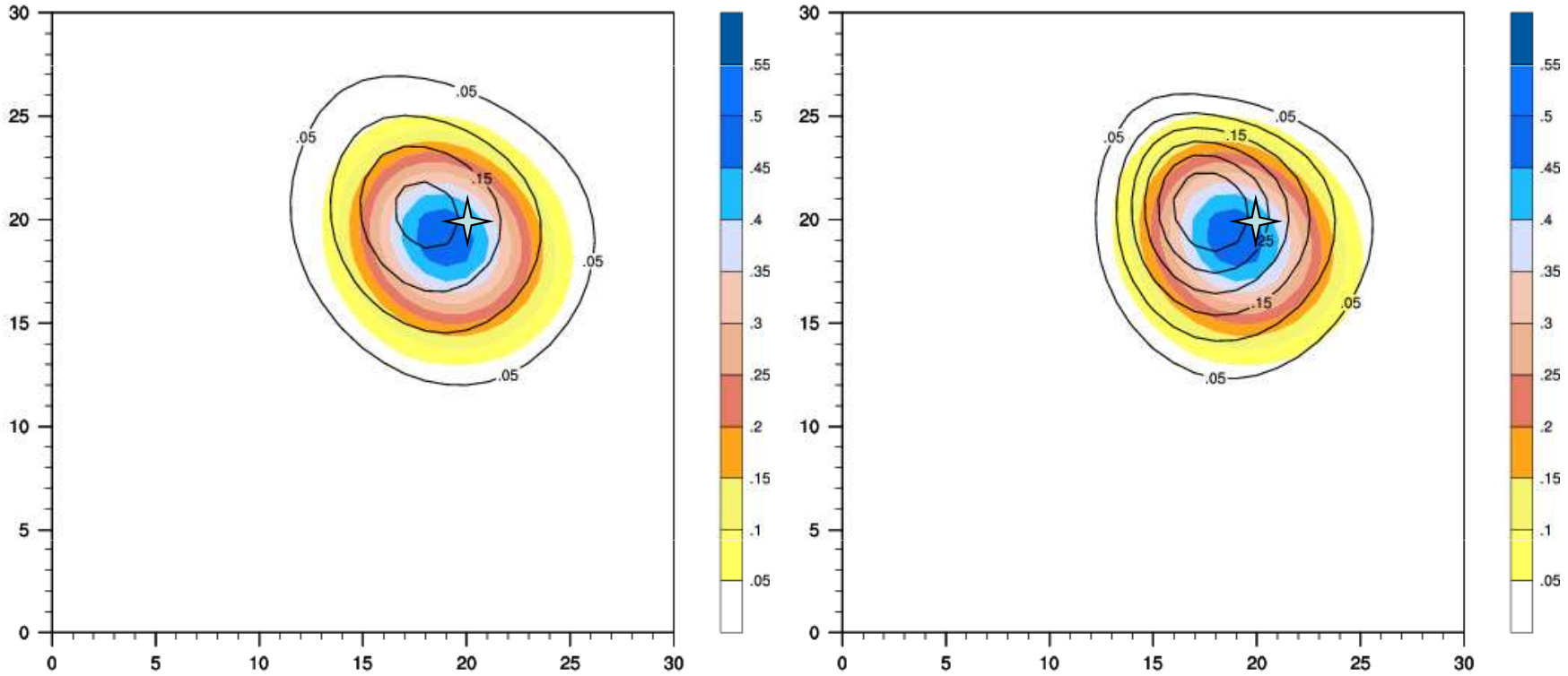
MPDATA: **black** contours

Solid Body Rotation Test I

Zoom of tracer after **one** rotation (4h) (start centre: ✦)

iord=2, nonos=1 Max: 0.2166

iord=3, nonos=1 Bott Max: 0.5009 Max: 0.3439



Bott_2: coloured areas

MPDATA: **black** contours

Error measures

- **Phase** shift: distance of exact maximum to computed maximum

$$E_{Phase} = \sqrt{(i^{exact} - i^{computed})^2 + (j^{exact} - j^{computed})^2}$$

- **Diffusion**: difference between computed and exact maximum value

$$E_{Diffusion} = \max(qi^{exact}) - \max(qi^{computed})$$

Error measures for Test I

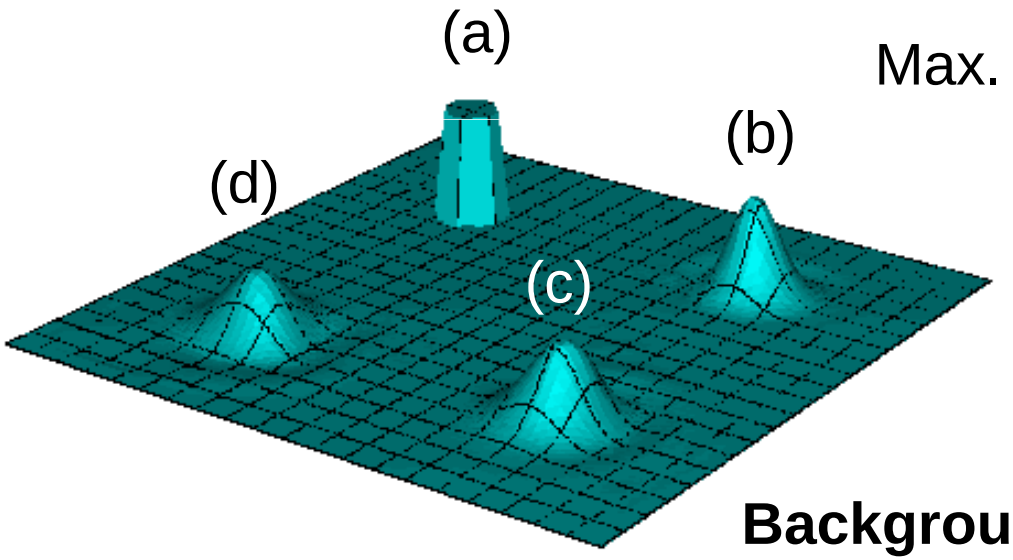
Advection Scheme	Maximum value after one rotation	Phase error	Diffusion error
Bott_2	0.501	1.414	0.499
Semi Lagrange	0.510	1.414	**0.490**
MPDATA:			
iord=2, nonos=0	0.219	2	0.781
iord=3, nonos=0	0.348	2.236	**0.652**
iord=2, nonos=1	0.217	2	0.783
iord=3, nonos=1	0.344	2	0.656

Conclusions**:**

- MPDATA is very **diffusive**
- **large** phase errors for MPDATA
- **smallest** diffusion error for SL

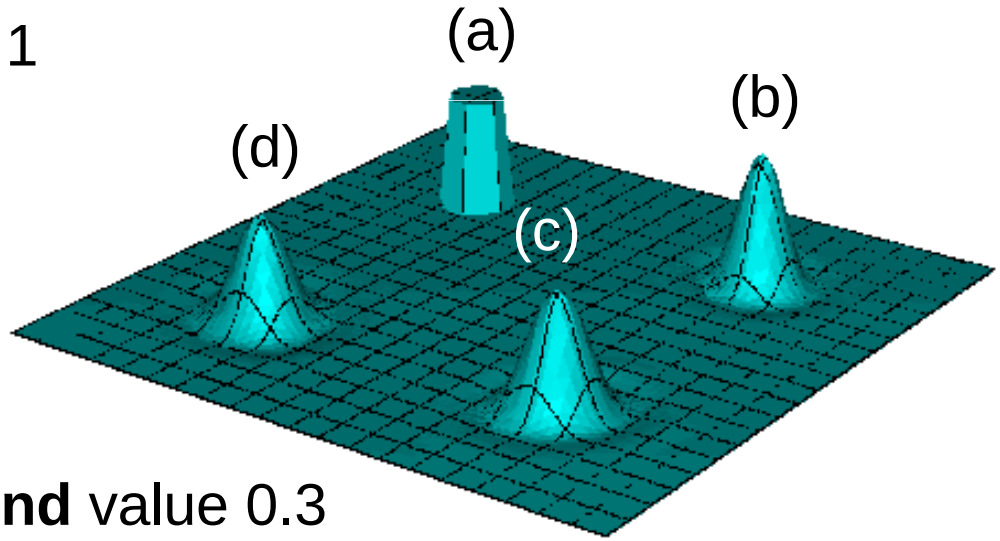
Solid Body Rotation Test II

MPDATA (iord=2, nonos=1)



Max. 1

Bott_2 advection scheme



Background value 0.3

Tracer at the beginning (a), after 1h (b),
after 2h (c) and after 3h (d)

Solid Body Rotation Test II

Tracer after **one** rotation (4h) (start centre: ✦)

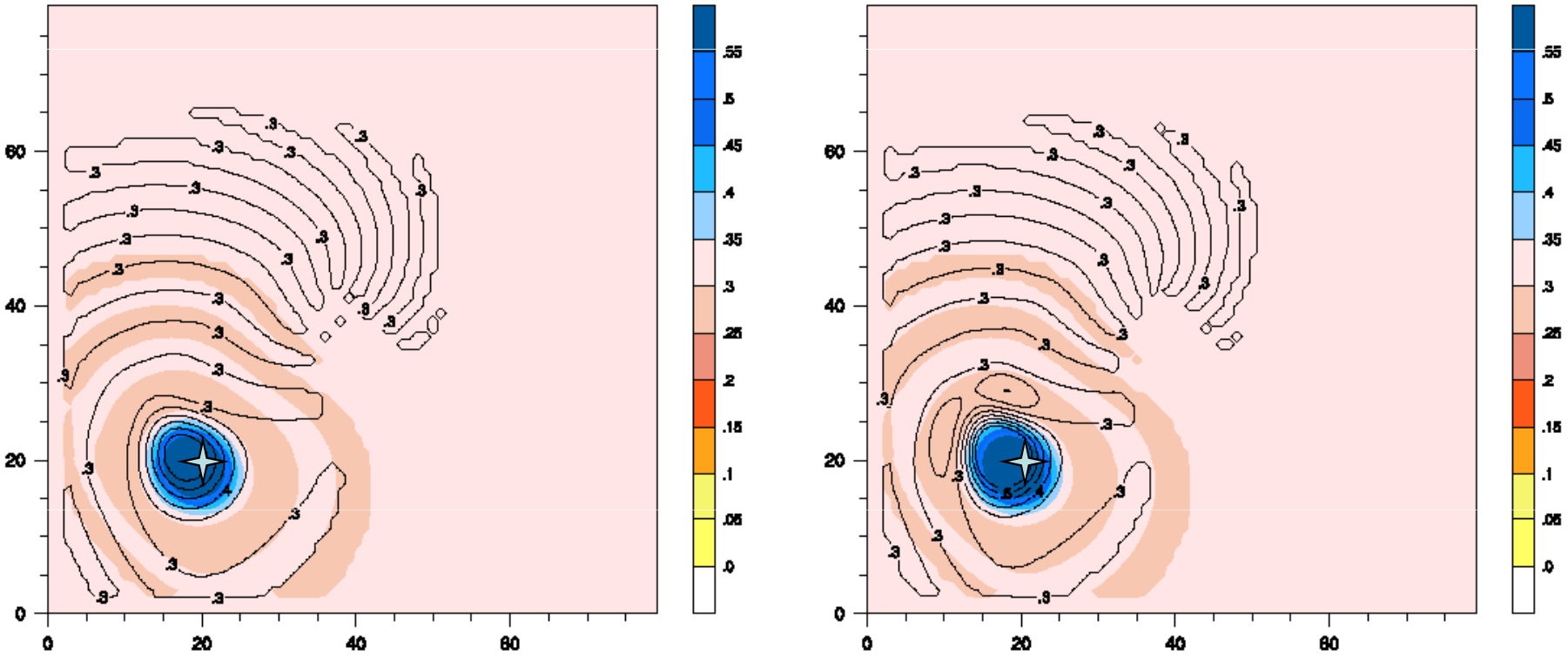
iord=2, nonos=0

Min/Max: 0.2612/0.6333

iord=3, nonos=0

Min/Max: 0.1990/0.7853

Bott Min/Max: 0.2733/0.8439



Bott_2: coloured areas

MPDATA: **black** contours

Solid Body Rotation Test II

Tracer after **one** rotation (4h) (start centre: ✦)

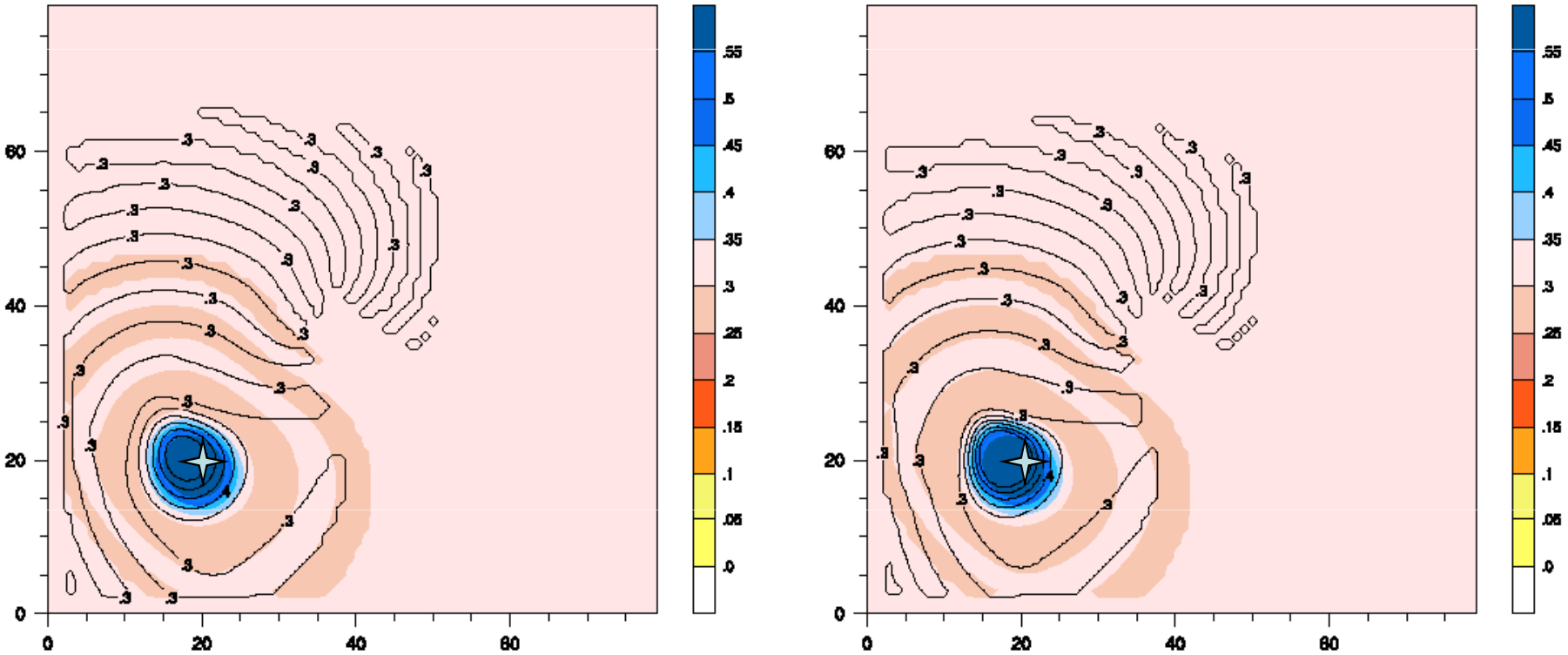
iord=2, nonos=1

Min/Max: 0.2809/0.6249

iord=3, nonos=1

Min/Max: 0.2809/0.7388

Bott Min/Max: 0.2733/0.8439



Bott_2: coloured areas

MPDATA: **black** contours

Error measures for Test II

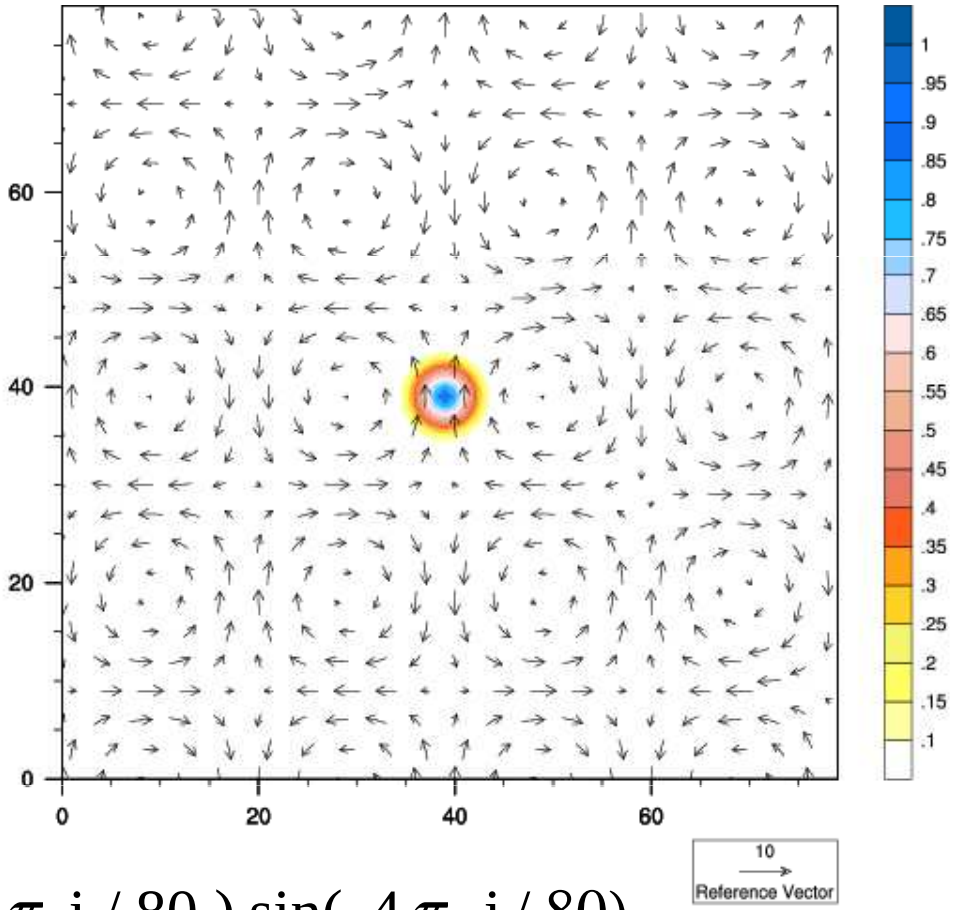
Advection Scheme	Maximum value after one rotation	Phase error	Diffusion error
Bott_2	0.273 / 0.844	1.414	**0.156**
Semi Lagrange	**0.125** / 0.843	1.414	0.157
MPDATA:			
iord=2, nonos=0	0.261 / 0.633	2	0.367
iord=3, nonos=0	0.199 / 0.785	3.162	**0.215**
iord=2, nonos=1	**0.281** / 0.625	2	0.375
iord=3, nonos=1	**0.281** / 0.739	2	0.261

Conclusions:

- under shooting of SL (boundary problem)
- **advantage** of the non-oscillatory option of **MPDATA**

Tracer Test in a deformation flow

- **Cone** tracer with 5 grid points radius
- **NO** background
- **NO** orography
- $\Delta x = 2.2\text{km}$
- $\Delta t = 20\text{s}$
- max. Courant nb. ~ 0.04



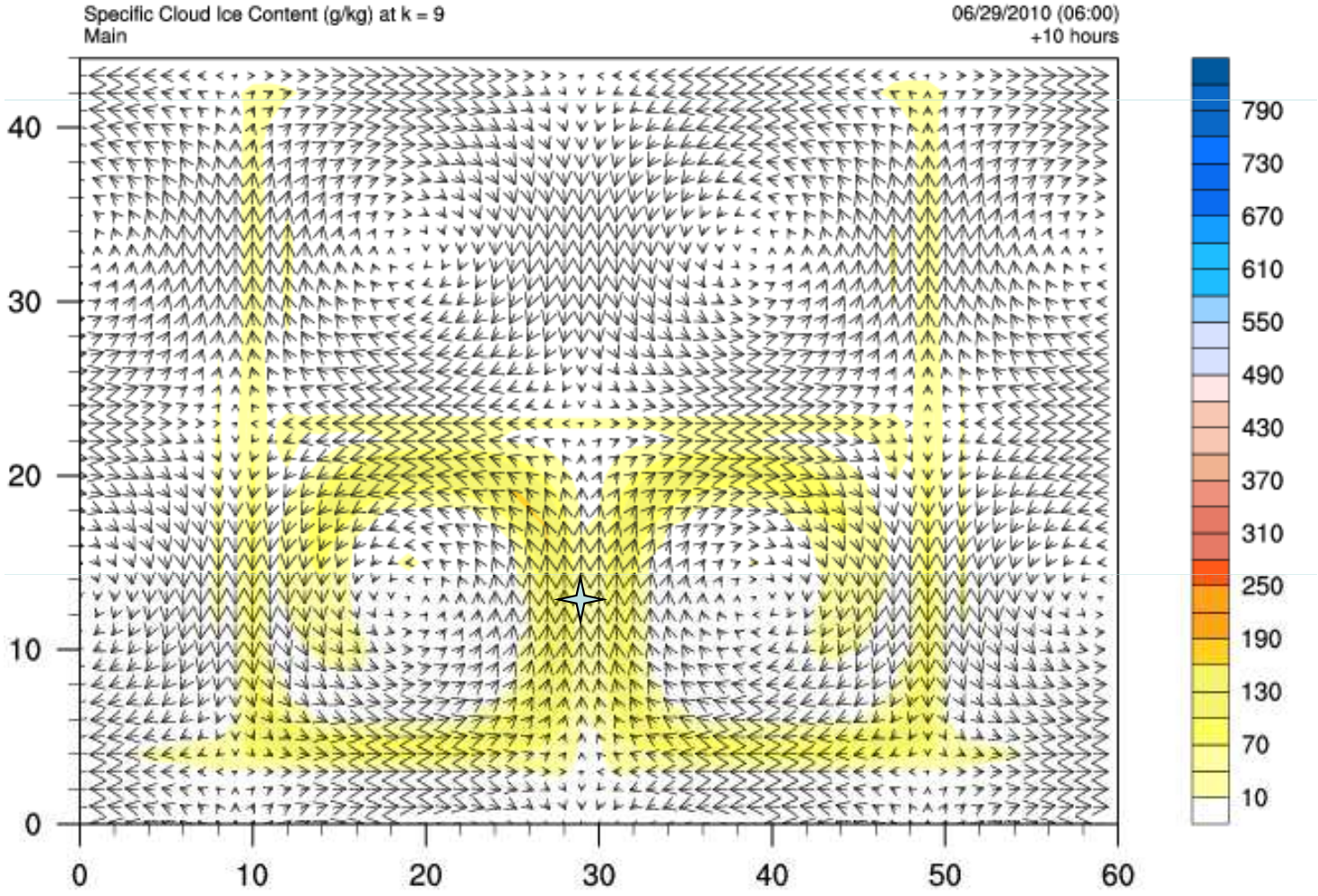
$$u(i,\ j) = 120\ \pi / 80\ \sin(4\ \pi\ i / 80)\ \sin(\ 4\pi\ j / 80)$$

$$v(i,\ j) = 120\ \pi / 80\ \cos(4\ \pi\ i / 80)\ \cos(4\ \pi\ j / 80)$$

Deformation flow

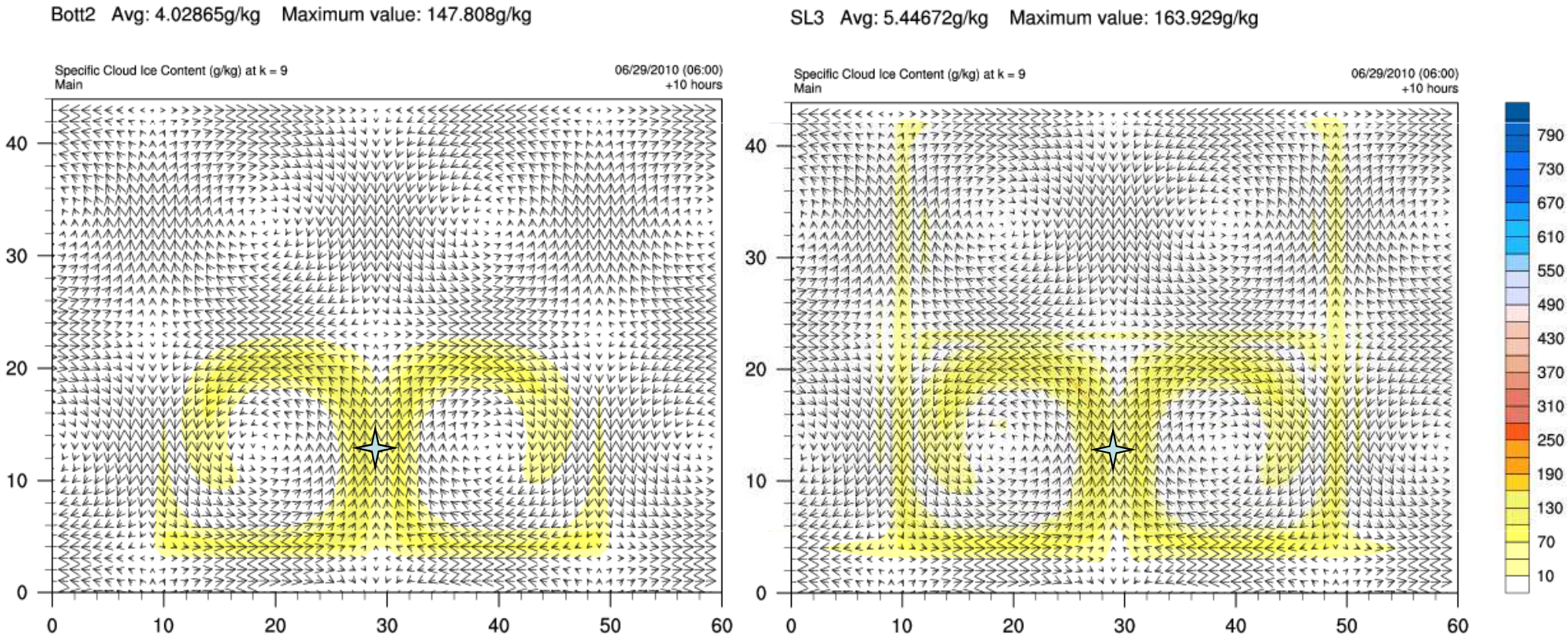
Zoom of tracer around centre

SL3 Avg: 5.44672g/kg Maximum value: 163.929g/kg



Deformation flow

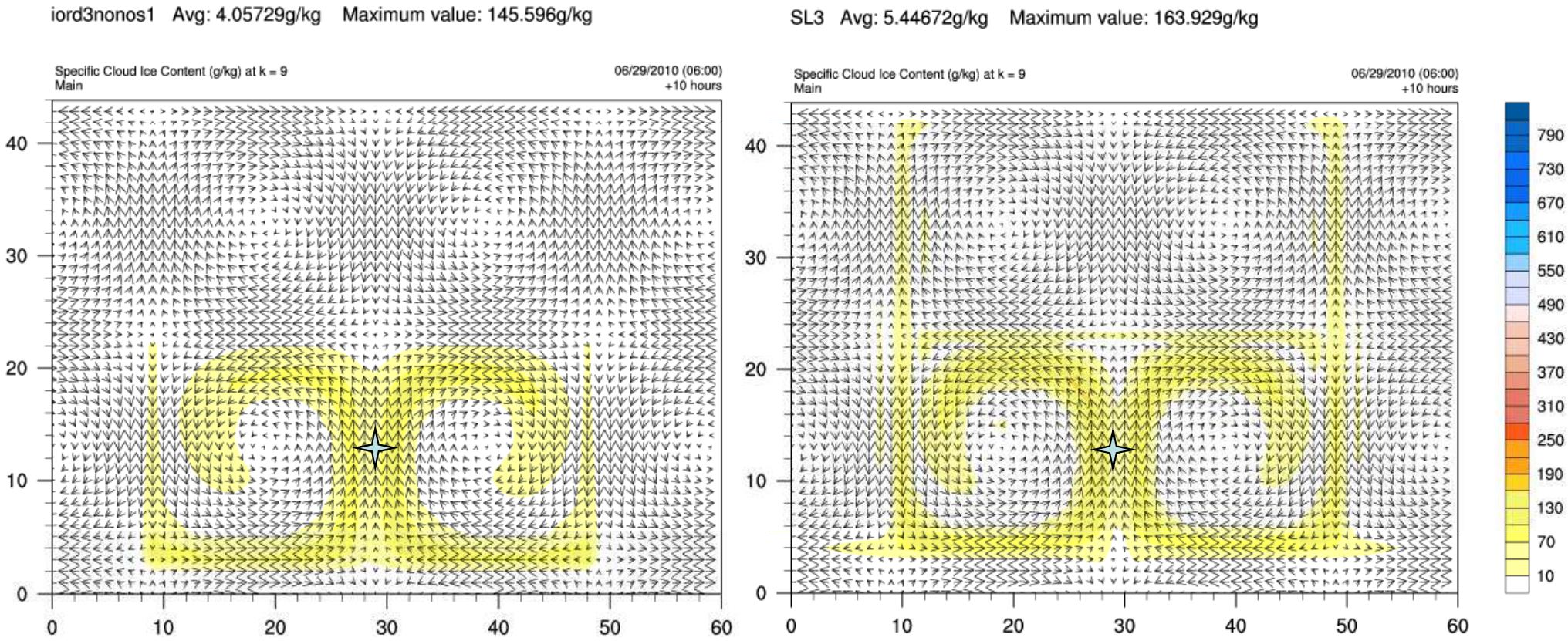
Tracer after 10h (ca. 1.2 rotations) zoom around starting centre



Bott_2 Semi-Lagrange

Deformation flow

Tracer after 10h (ca. 1.2 rotations) zoom around starting centre

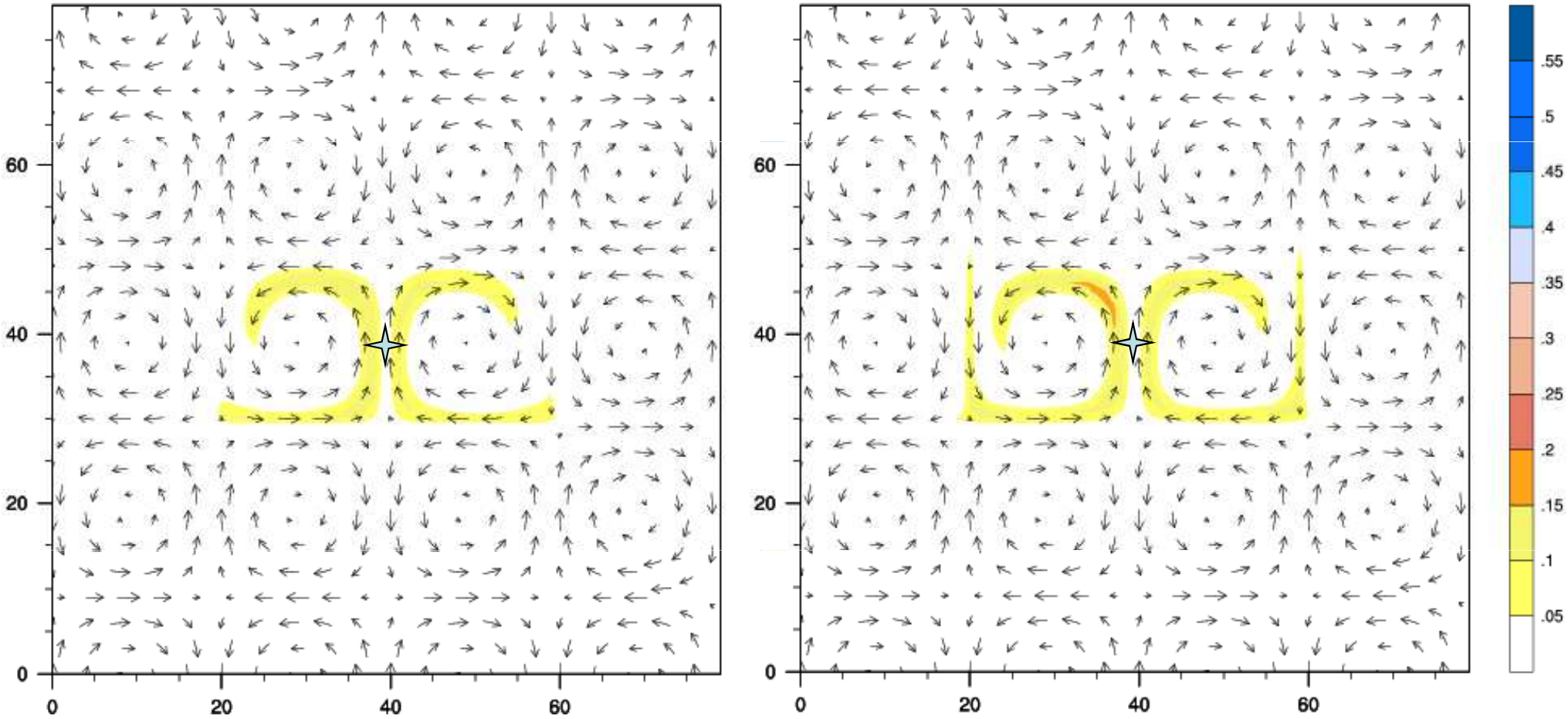


iord=3, nonos=1

Semi-Lagrange

Deformation flow

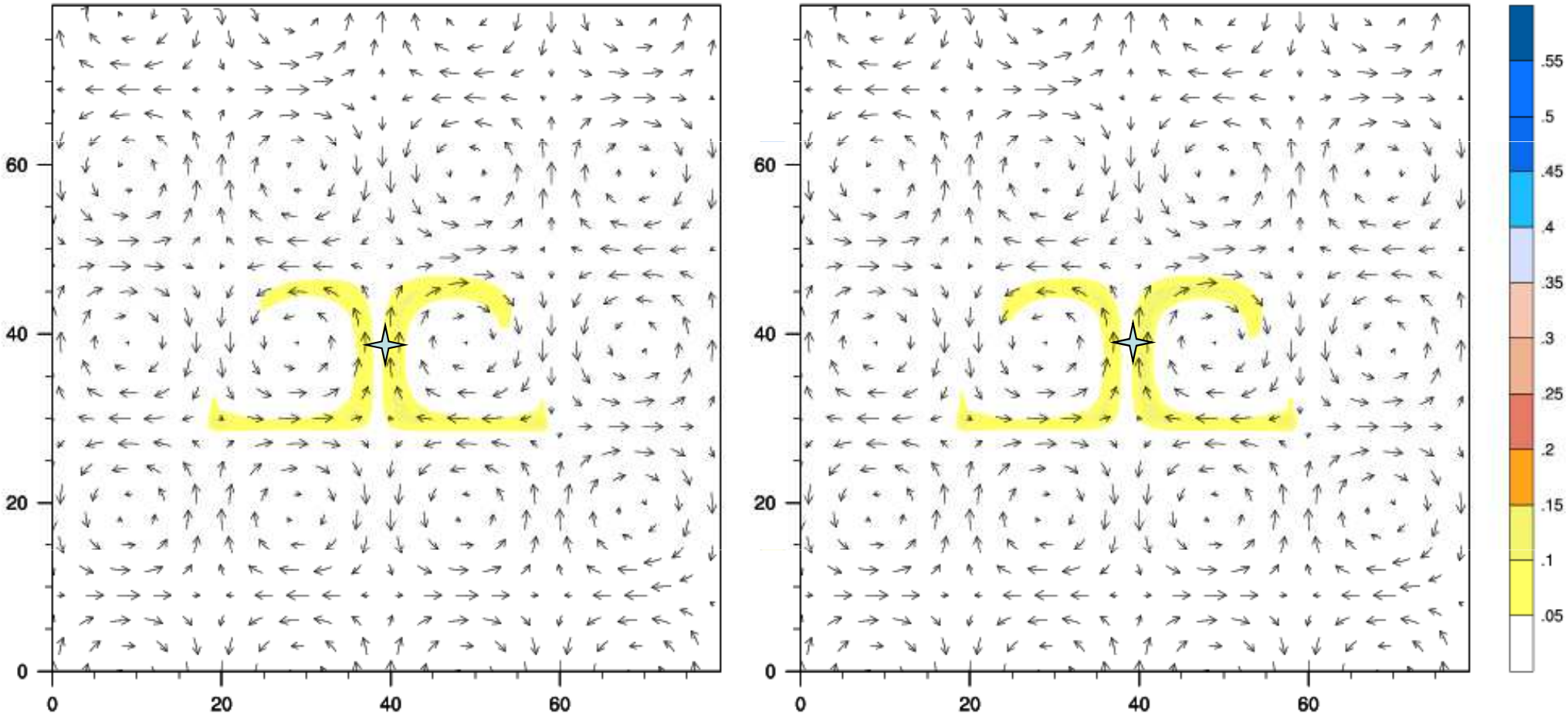
Tracer after 10h (ca. 1.2 rotations) **start centre:** ✦



Bott_2 **Semi-Lagrange**

Deformation flow

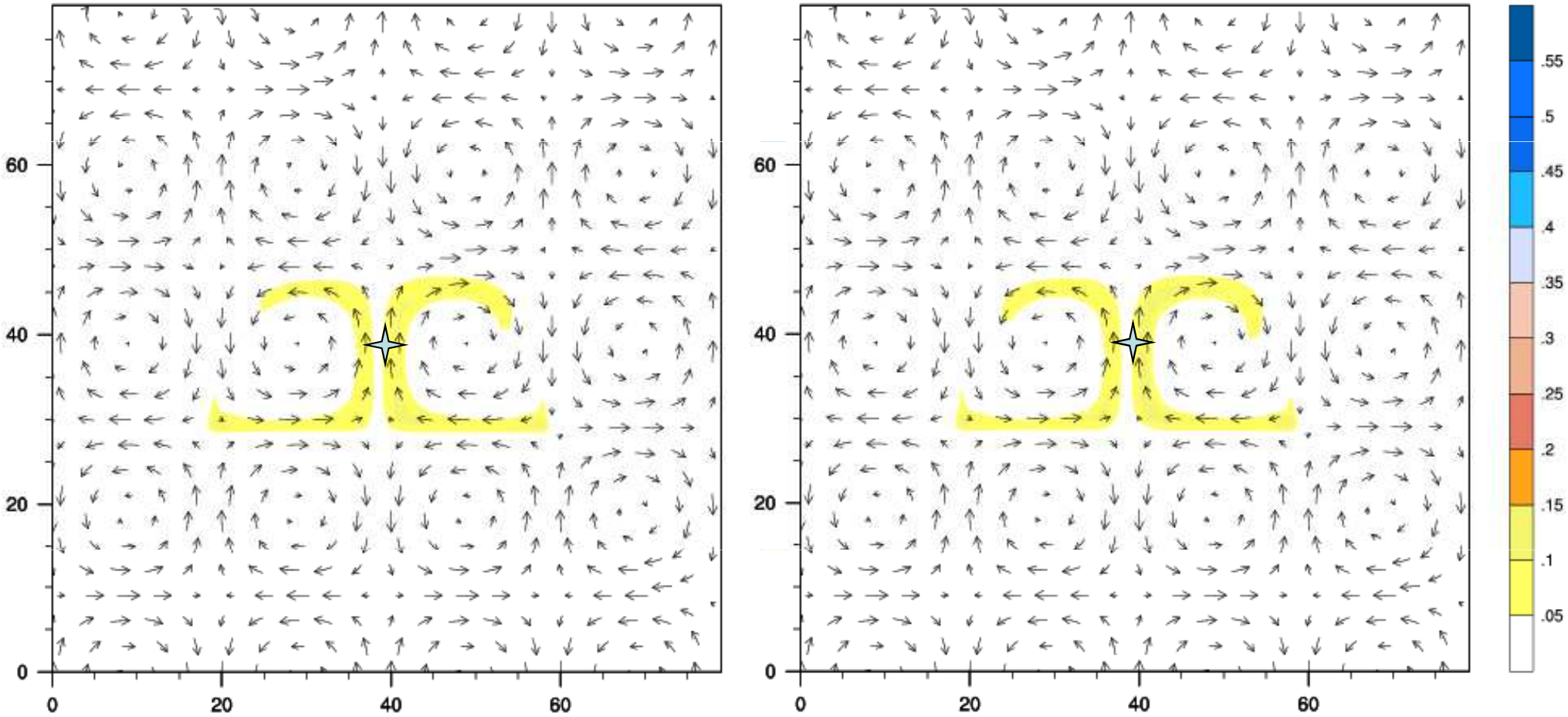
Tracer after 10h (ca. 1.2 rotations) **start centre:** ✦



iord=2, nonos=0 **iord=3, nonos=0**

Deformation flow

Tracer after 10h (ca. 1.2 rotations) **start centre:** ✦



iord=2, nonos=1 **iord=3, nonos=1**

Error measures for deformation flow

Advection Scheme	Maximum value after 5h	Maximum value after 10h
Bott_2	0.297	0.148
Semi Lagrange	**0.334**	**0.164**
MPDATA:		
iord=2, nonos=0	0.278	0.126
iord=3, nonos=0	**0.299**	**0.149**
iord=2, nonos=1	0.267	0.128
iord=3, nonos=1	0.287	0.146

Conclusions:

- **best** performance for SL
- **small** impact of MPDATA parameter choice
- **small** advantage of MPDATA over Bott

Summary and Conclusions

- MPDATA can be much more diffusive than Bott and SL schemes
- High phase errors with MPDATA in rotation tests
- MPDATA is better than the Bott scheme for divergent/convergent flows
- More computer time needed for MPDATA
- MPDATA scheme was not tested in a 3D configuration
- For the moment MPDATA runs only on one processor
- What would the results of Bott with a full strang splitting at each time step (zyxyz) be?

Thank you for your attention!