Volumetric Flow Estimation for Incompressible Fluids using the Stationary Stokes Equations

Supplemental Material

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1. PIV Challenge Results

Ground-truth data of test case D of the 4th International PIV Challenge [1] is not publicly available, such that a direct, quantitative evaluation of our approach on the data base is not possible at this point. In order to – nevertheless – provide a comparison to the state-of-the-art for this kind of input data, we show qualitative results of our method and compare them to the results provided in [1].

Test case D consists of 50 snapshots of a particle volume of $4096\times512\times352$ voxels (with 20 vox/mm). Per snapshot, four camera images from different angles are provided at `http://www.pivchallenge.org/pivchallenge4.html#case_d`. Figure 1 shows one of the four camera views for snapshot 23, which has an image resolution of 4512x800 pixel.

In Figure 2 we show the exact displacement field at snapshot 23 for the xy-slice at slice z=78, taken from [1]. Qualitative results for the same slice for all the tested methods in [1] are displayed in Figure 4 (best performing methods are DLR, LaVision and TUD, respectively volume number 3, 8 and 9).

Figure 3 depicts the results of our semi-dense flow approach (SSD with IV size 11^3, QRD_∞, h=4) for snapshot 23 (at slice z=78), once with the same discrete color coding as in Figure 2 and once with a continuous color coding. 3D reconstruction per time step was performed with our simple MART implementation. Our flow estimation visually appears comparable to other methods of the challenge.

2. Experimental Data

To test our algorithm on real data from a lab experiment we use data provided by *LaVision* (Package 9 in `http://fluid.irisa.fr/data-eng.htm`). The authors supply two 3D volumes after tomographic reconstruction, recording a Karman street behind a cylinder (see Figure 5). The cylinder is positioned to the right of the volume with the fluid going to the left. No ground truth is available. However, a *TomoPIV* flow estimation from the software *LaVision* is provided, using a final IV size of 48^3 and an overlap of 75%, *i.e*. one flow vector every 12 voxels in all three dimensions. The data differs from our simulation data in two key aspects. At first 3D reconstruction is not performed by ourselves, but provided by the authors. This might lead to intensity distribution of ghost and true particles that differs from our pipeline. At second, the average magnitude of the 3D displacement is about 11 voxels with a maximum of 24 voxels (estimated from the provided flow field). In contrast, the maximal displacement of our simulated data is only 5.4 voxels. In our coarse-to-fine reconstruction framework, those larger displacements require more levels of our Gaussian pyramid, leading to a stronger downsampling of the volumes at lower levels.

The two input volumes have a dimension of $2107\times1434\times406$ voxel. We split them into subvolumes of size $2107\times717\times406$ and show results of the upper subvolume in Figures 6, 7 and 8. For comparison, we also show the low-resolution flow estimate provided by the authors. The two methods capture similar flow details. The Karman street is best observed by the flow in Z-direction (alternating directions with stronger amplitude close to the cylinder). Please note again that our reconstruction is of a much higher spatial resolution (1 flow vector per 4^3 voxel vs. 1 vector per 12^3 voxel) and thus appears less smooth than the reconstruction provided by *LaVision*.

3. Further Visualizations

We show further visualizations of our $1024\times512\times358$ test volume, using our best setting (SSD with IV size 11^3, QRD_∞, h=2). In Figure 9, 10 and 11, we compare ground truth flow, our flow estimation from noise-free particle distributions and from our MART reconstruction. We show results for the flow in X, Y and Z-direction respectively for xy-slices at positions z=100 and z=200.

References

[1] C. J. Kähler, T. Astarita, P. P. Vlachos, J. Sakakibara, R. Hain, S. Discetti, R. La Foy, and C. Cierpka. Main results of the 4th international piv challenge. *Experiments in Fluids*, 57(6):97, 2016.

[2] D. Michaelis, C. Poelma, F. Scarano, J. Westerweel, and B. Wieneke. A 3d time-resolved cylinder wake survey by tomographic piv. In *12th Int. Symp. on Flow Visualization*, 2006.

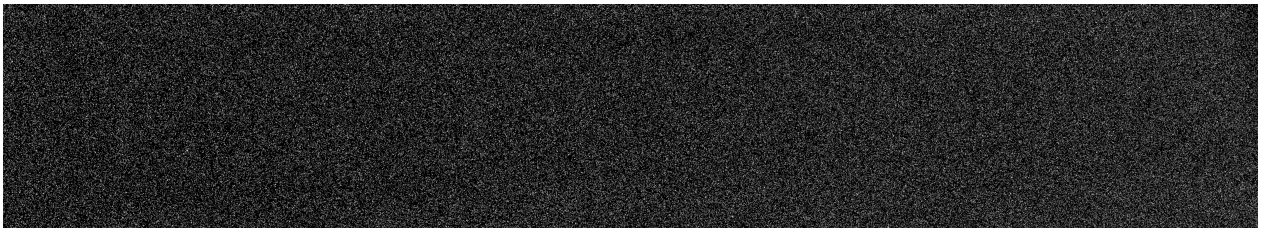

Figure 1. Particle image from one camera view at snapshot 23. Image taken from [1]

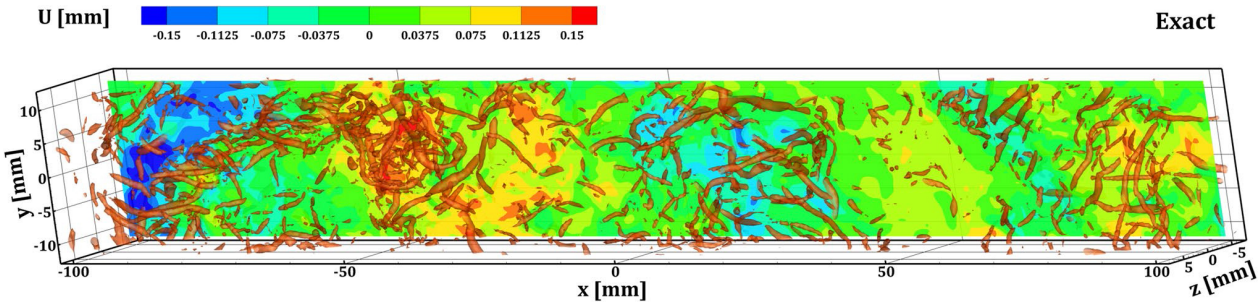

Figure 2. Exact displacement field of snapshot 23. xy-slice of the flow in X-direction on slice z=−5.2mm (corresponding to slice 78). Visualization of vortices at Q/Q_ω=1. Image taken from [1]

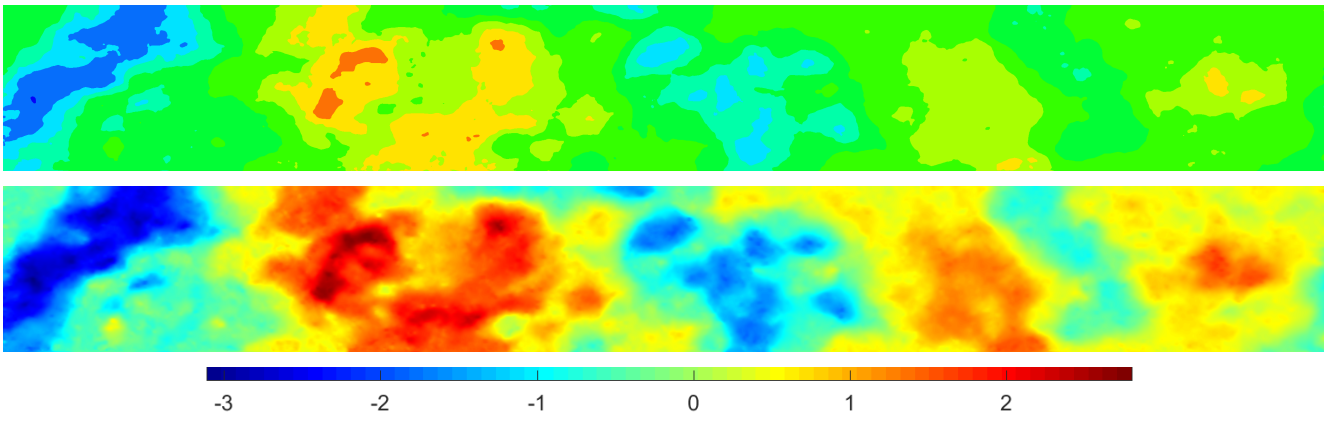

Figure 3. xy-slice of our estimated flow in X-direction. *top:* same color coding as in Figure 2. *bottom:* continuous color coding.

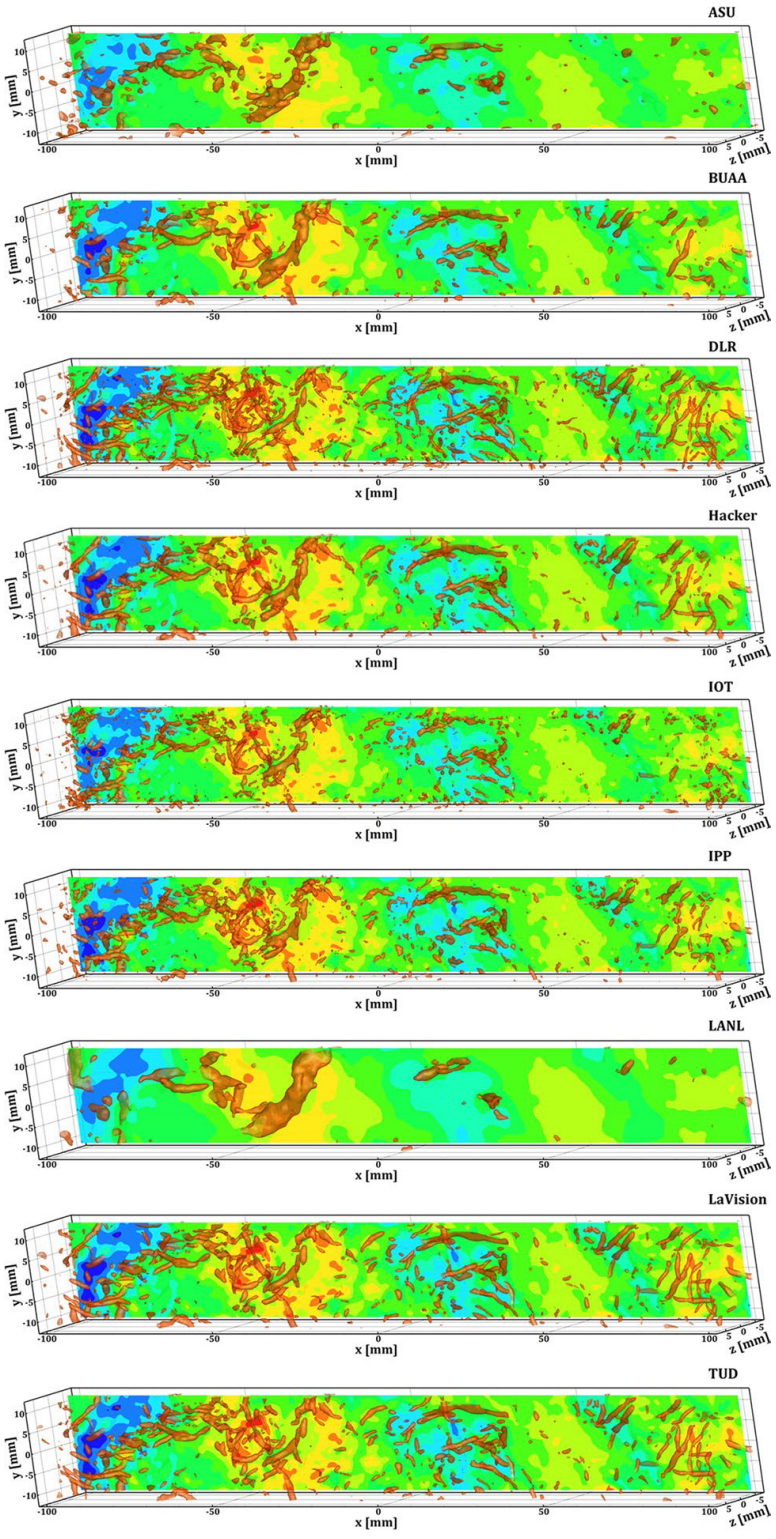

Figure 4. Results of other methods in PIV Challenge. Image taken from [1]

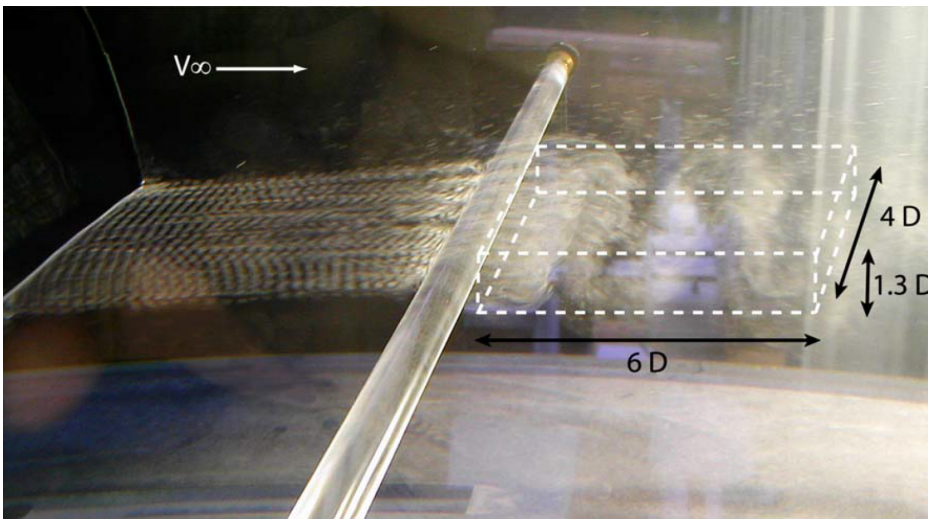

Figure 5. Experimental setup for a wake flow estimation behind a cylinder. Note that in our setup the cylinder is to the right of the volume with a flow direction towards the left. Image taken from [2].

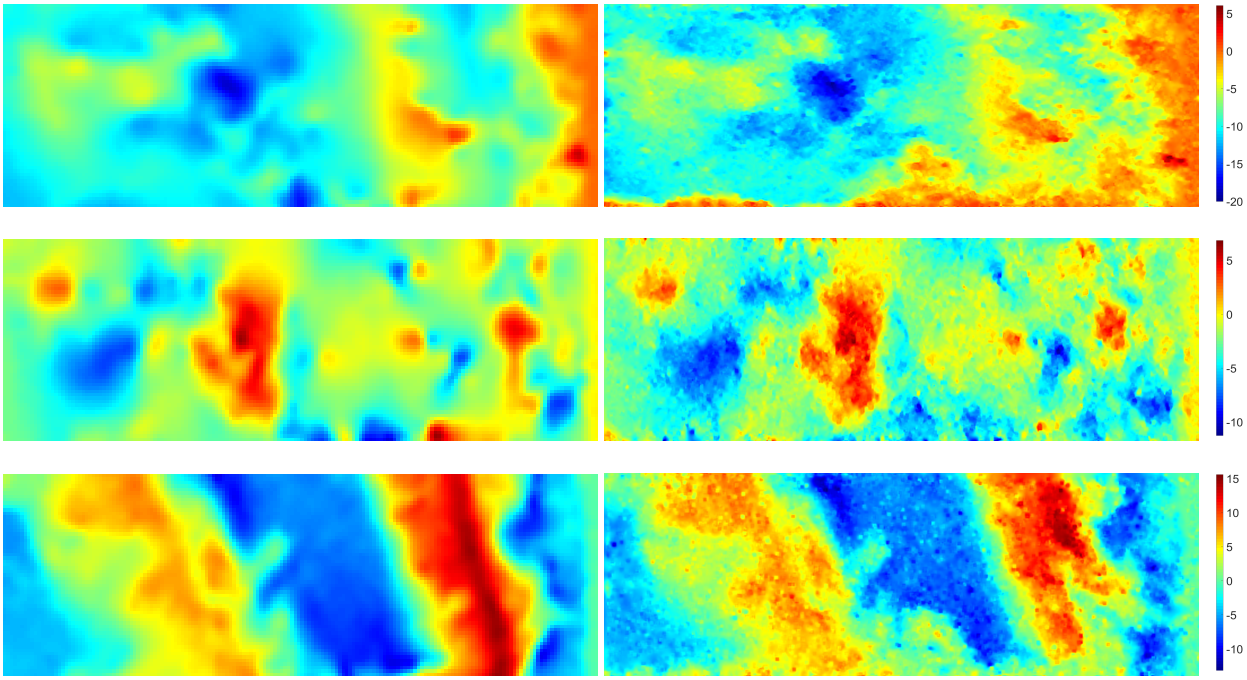

Figure 6. Experimental data: xy-slice of the flow at z=102. *left:* Provided result from LaVision. *right:* Result with our approach. (*top* to *bottom*: flow in X, Y and Z-direction).

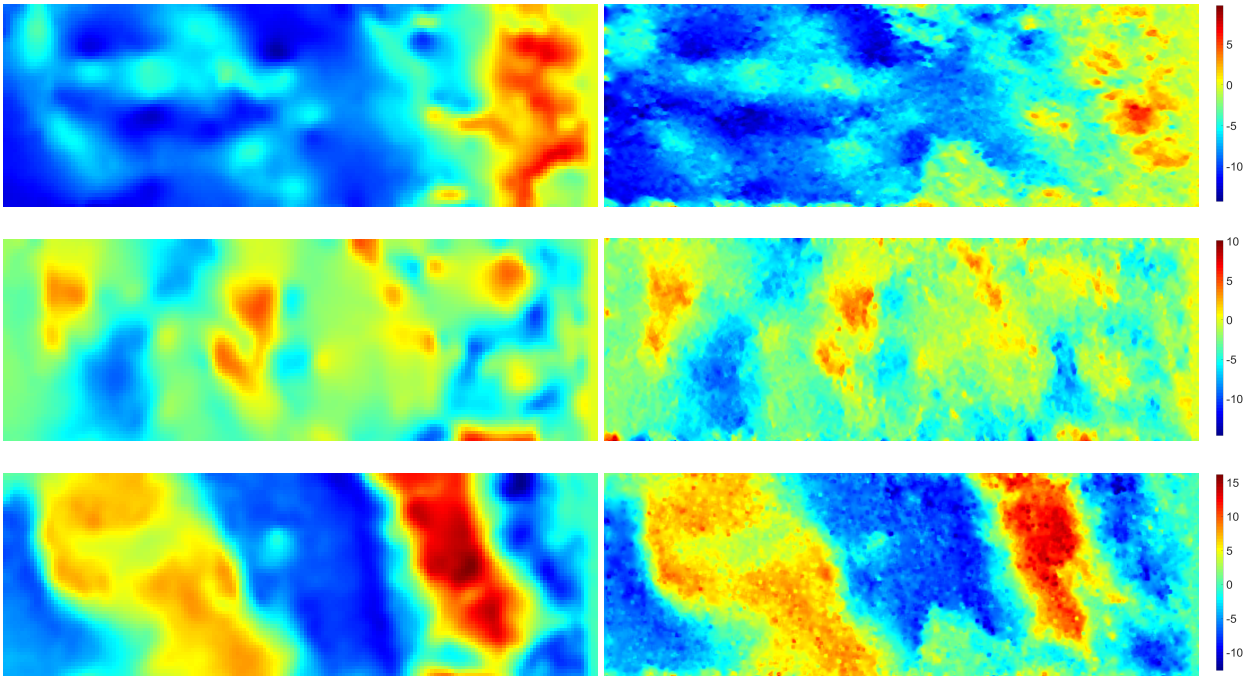

Figure 7. Experimental data: xy-slice of the flow at z=203. *left:* Provided result from LaVision. *right:* Result with our approach. (*top* to *bottom*: flow in X, Y and Z-direction).

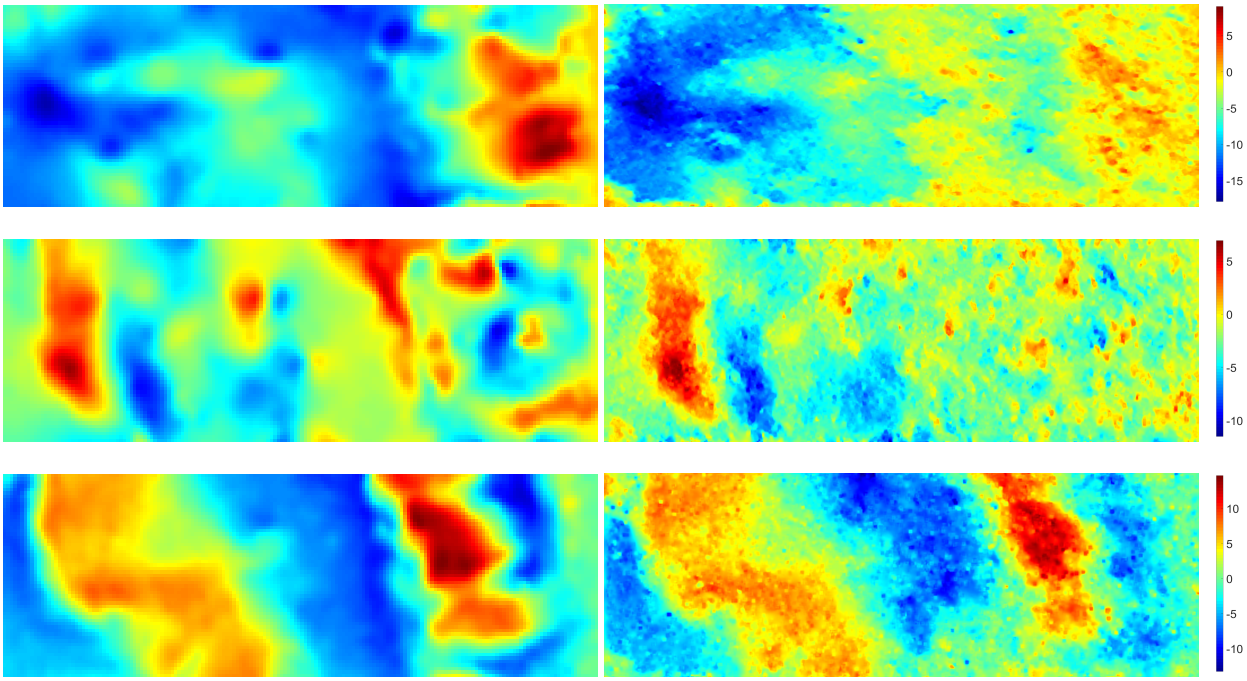

Figure 8. Experimental data: xy-slice of the flow at z=305. *left:* Provided result from LaVision. *right:* Result with our approach. (*top* to *bottom*: flow in X, Y and Z-direction).

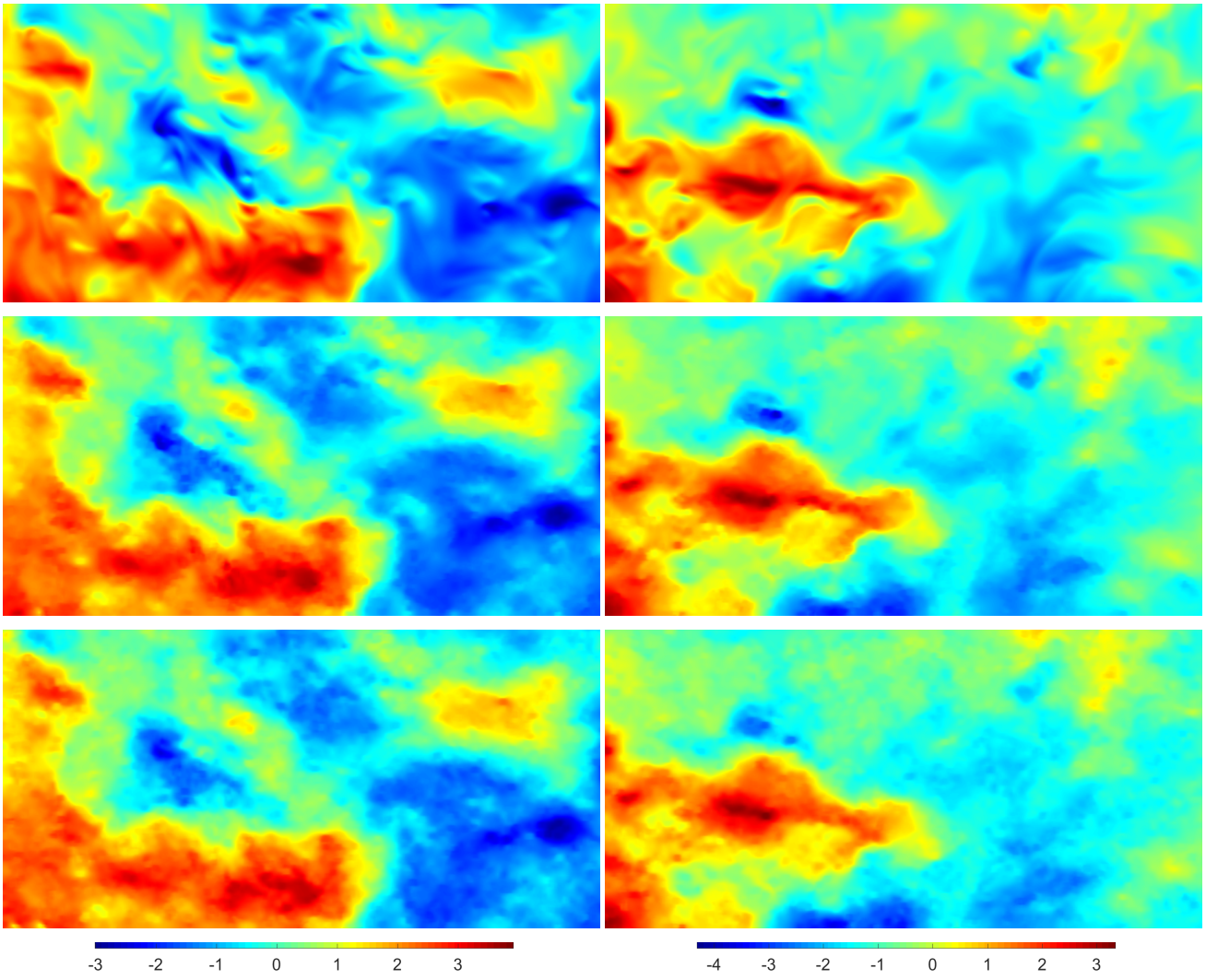

Figure 9. Simulated data: xy-slice of the flow in X-direction at z=100 (*left*) and z=300 (*right*). *top:* ground truth. *center:* estimated from noise-free particle distribution. *bottom:* estimated from MART reconstruction.

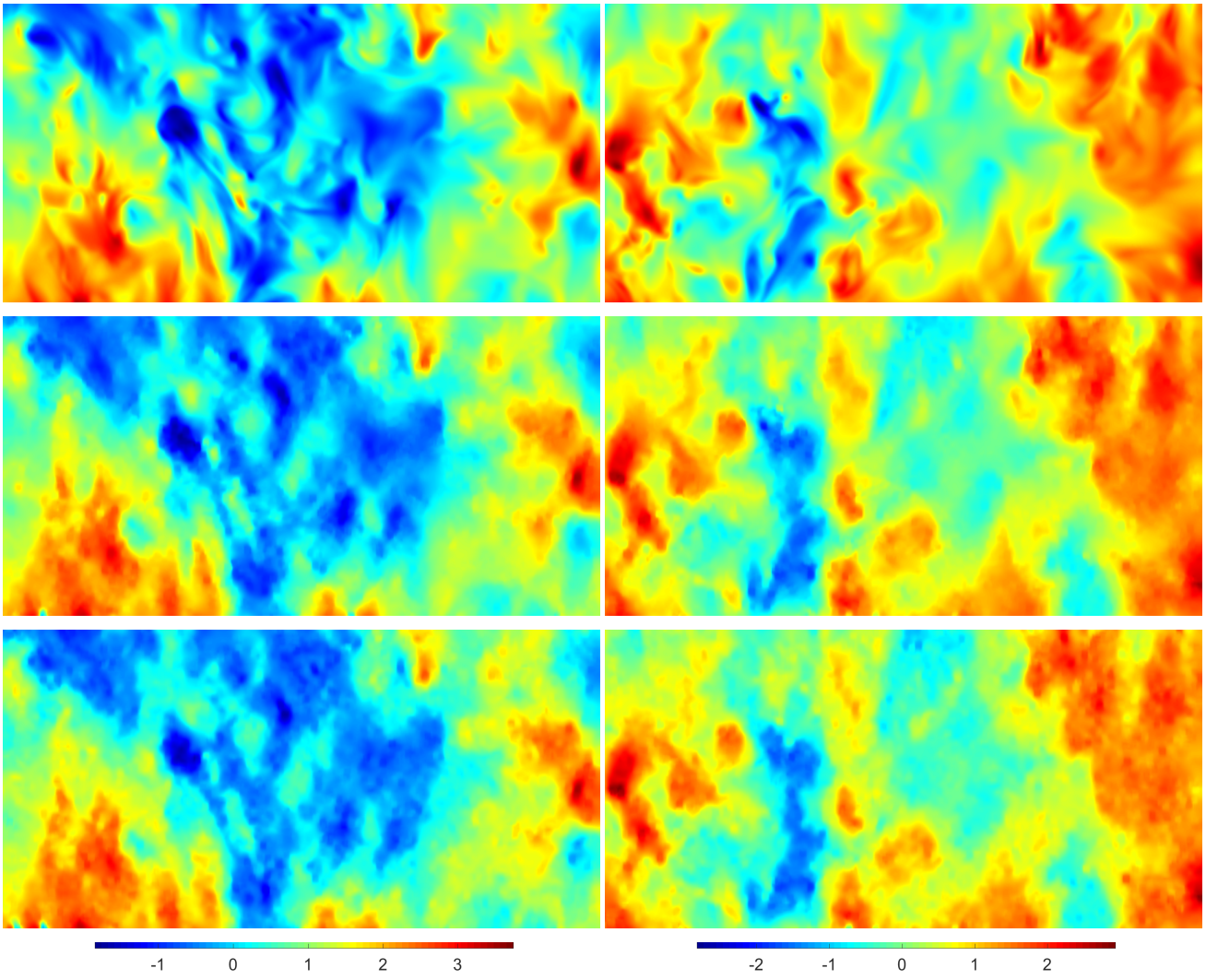

Figure 10. Simulated data: xy-slice of the flow in Y-direction at z=100 (*left*) and z=300 (*right*). *top:* ground truth. *center:* estimated from noise-free particle distribution. *bottom:* estimated from MART reconstruction.

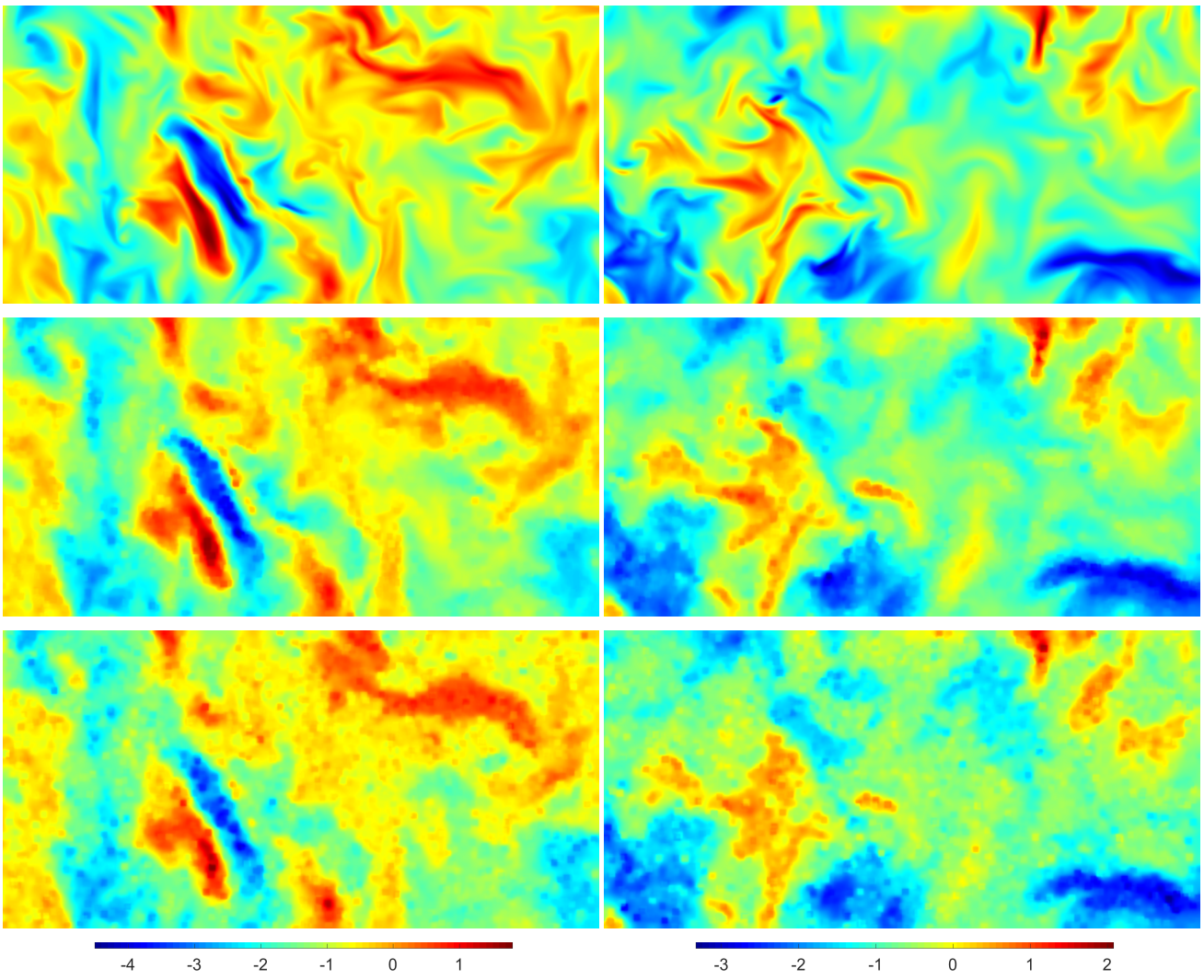

Figure 11. Simulated data: xy-slice of the flow in Z-direction at z=100 (*left*) and z=300 (*right*). *top:* ground truth. *center:* estimated from noise-free particle distribution. *bottom:* estimated from MART reconstruction.