Accuracy of pathline predicates for flow visualization at the example of the benguela upwelling system

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Start Teaser

Abstract

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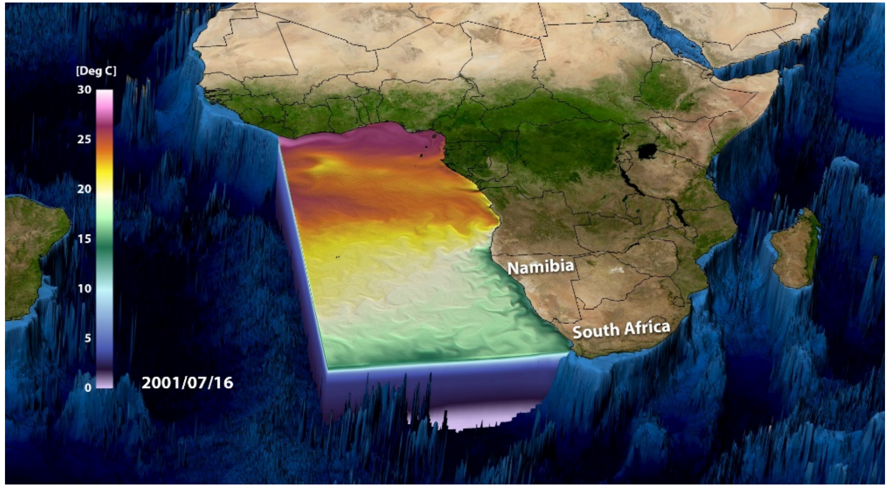
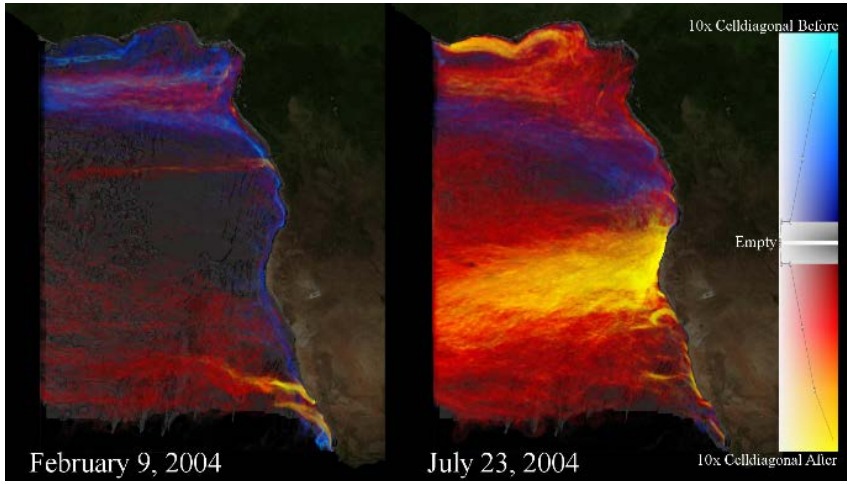
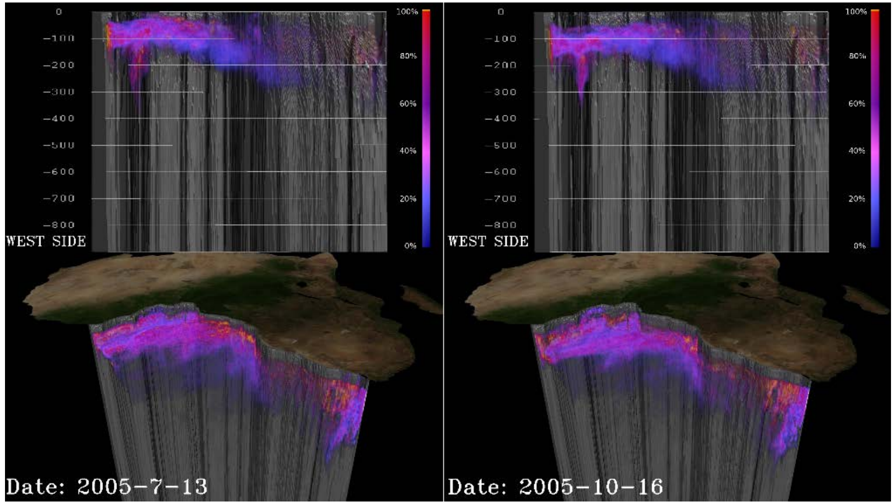
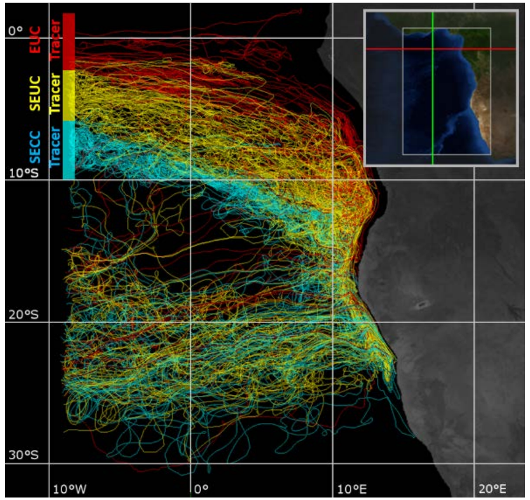
Visual Study of the Benguela Upwelling System using Pathline Predicates

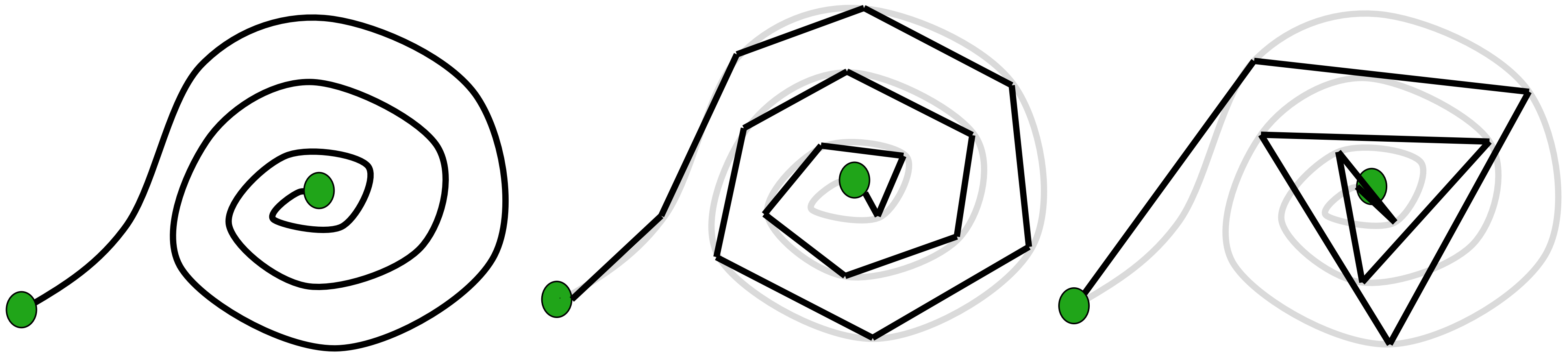








How accurate are Lagrangian techniques?



- Simulation calculated with 20 min steps
- Stored time intervals 5 day means

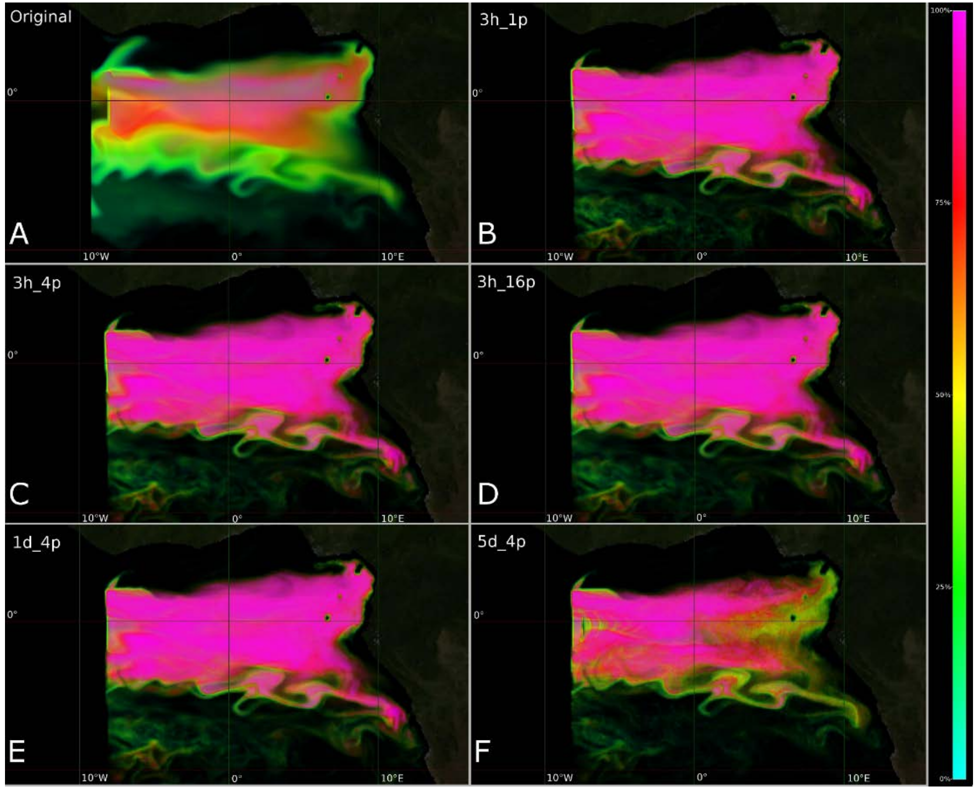
Evaluate the accuracy of pathline predicates for flow visualization

- **Pathline Error Estimation**

- **Trajectory Based Tracer Field**

  – Variations: number of particles

  – Variations: data resolution



Finish Teaser

Abstract

Coastal upwelling systems transport nutrient-rich water to the upper layer of the ocean. These regions are especially important for marine life and fishery. We are using pathline predicates to create visualizations of the spatio-temporal structure of the Benguela upwelling system. Based on a 3D flow field of a regional ocean model, we first derive space-filling trajectories covering the full model grid. With pathline predicates, we select trajectories related to upwelling. Next, we derive a 3D scalar field representing the pathline density, which is visualized using volume rendering techniques. Further analyses of the pathlines show a distinct annual cycle in the upwelling activity, which fits well to observation-based analyses found in literature. These techniques and their application are described in [1].

In this work, we focus on evaluating the accuracy of our techniques. Based on the 3D ocean flow field stored at relatively coarse time interval, we compute trajectories to emulate a retrospectively derived tracer field. For different source regions, our data set contains several synthetic tracer fields directly computed within the ocean model simulation using the original short time steps that we can compare with our trajectory-based tracer field. With our evaluation we aim at determining minimum requirements for the temporal resolution of flow data for retroactively applying particle pathline techniques or visual analyses. By analyzing the skill in reproducing a synthetic model tracer field, we can set up rules for using the particle pathline methods in general.

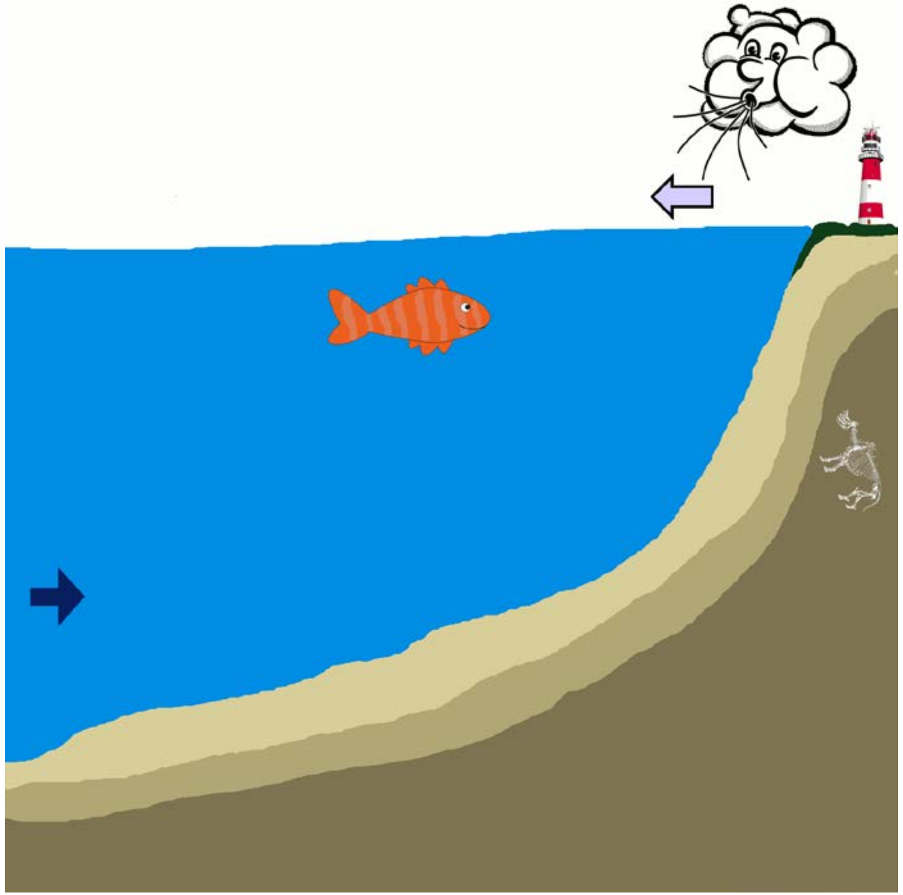
Back

[1] NARDINI P., BÖTTINGER M., SCHEUERMANN G., SCHMIDT M.: Visual Study of the Benguela Upwelling System using Pathline Predicates. In Workshop on Visualisation in Environmental Sciences (EnvirVis) (2017), Rink K., Middel

- Wind stress at the sea surface cause transport of cool water from greater to shallower depths.

- Regions with cool nutrient-rich water, which "disproportionally contribute to the global primary production and host many of the major commercially used fish stocks" [1]

- High importance to marine life and fishery → focus of ongoing scientific observation campaigns and modeling activities.



2.2

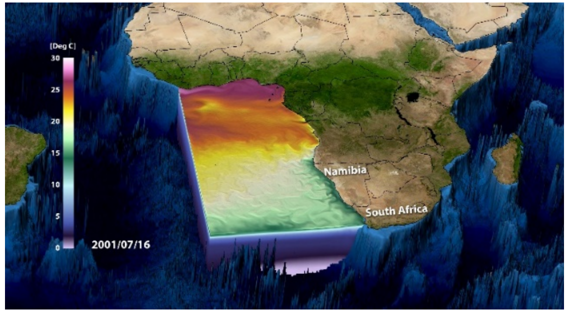
[1] MOHRHOLZ V., EGGERT A., JUNKER T., NAUSCH G.,OHDE T., SCHMIDT M.: Cross shelf hydrographic and hydrochemical conditions and their short term variability at the northern benguela during a normal upwelling season. Journal of Marine Systems 140, Part B (2014), 92 – 110.

- Using the **Benguela system** as an example (see simulation domain in image)

- **Simulation** based on the modular ocean model MOM version 5 [1,2,3].

- **Domain**: rectilinear grid of the size 261 x 351 x 62.

- **Simulation data** include:
    1. time-dependent flow fields (ocean current data)
    2. passive tracer fields



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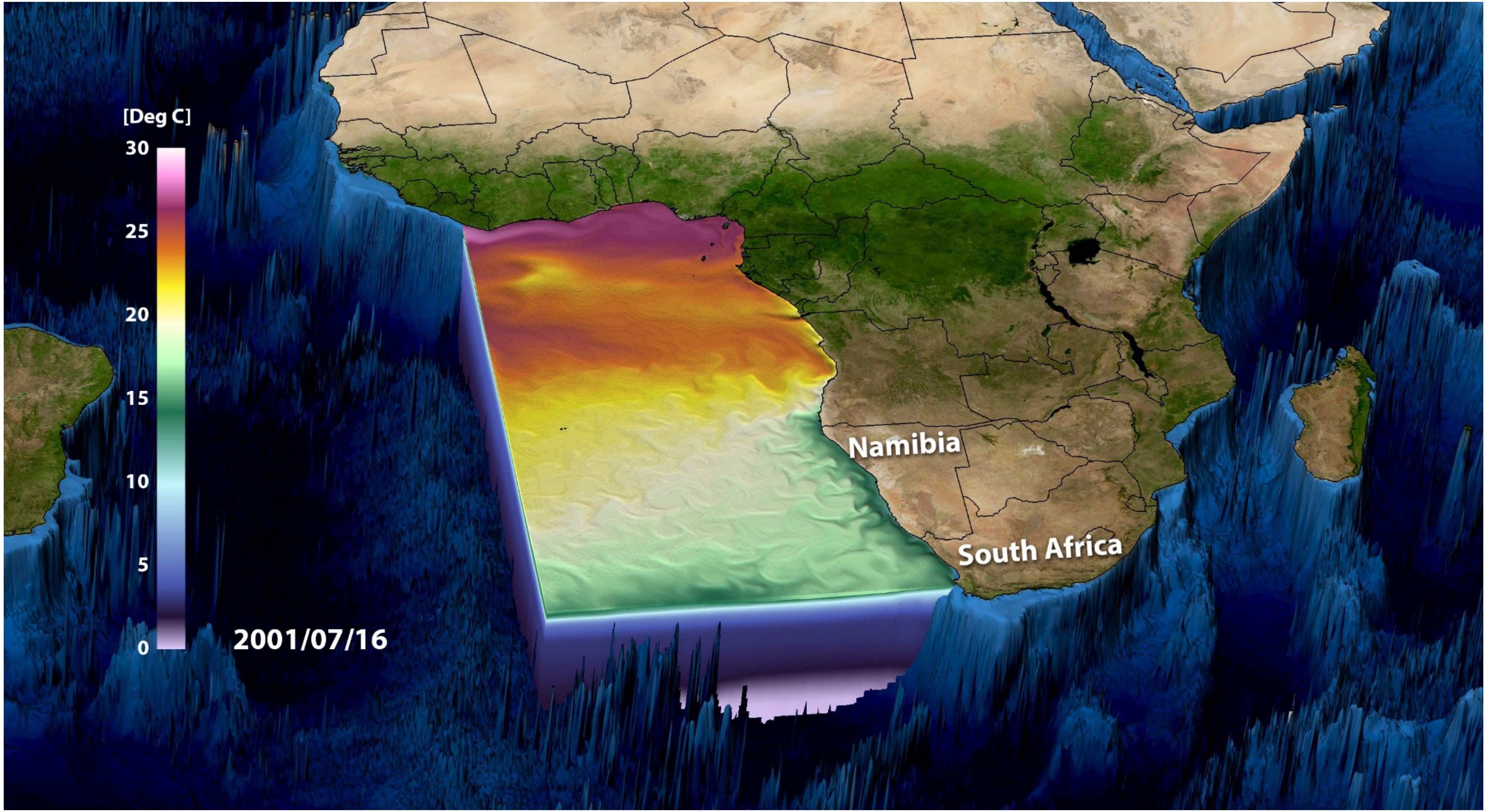
2.1
2.3

[1] GRIFFIES S. M., GNANADESIKAN A., DIXON K. W.,DUNNE J. P., GERDES R., HARRISON M. J., ROSATI A., RUSSELL J. L., SAMUELS B. L., SPELMAN M. J., WINTON M., ZHANG R.: Formulation of an ocean model for global climate simulations. Ocean Science 1, 1 (2005), 45–79.
[2] HERZFELD M., SCHMIDT M., GRIFFIES S., LIANG Z.: Realistic test cases for limited area ocean modelling. Ocean Modelling 37, 1-2 (2011), 1–34.
[3] SCHMIDT M., EGGERT A.: Oxygen cycling in the northern benguela upwelling system: Modelling oxygen sources and sinks.



(Click on image for shrinkage)

1. Compute a space and time filling set of trajectories for the entire model domain.

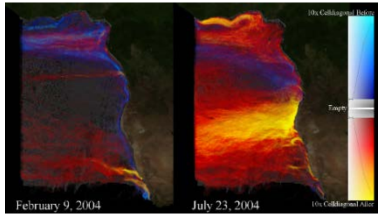
2. Use „upwelling-predicates“ to select trajectories related to upwelling.

3. Use the information of upwelling-trajectories for:
   - Determine a **upwelling time** for each upwelling-trajectories
   - Numeric analysis of upwelling depth or streng
   - Visual analysis „**Local Pathline Density (LPD)**“
   - Visual analysis „**Upwelling Particle Ratio (UPR)**“
   - Additional **specific filters**

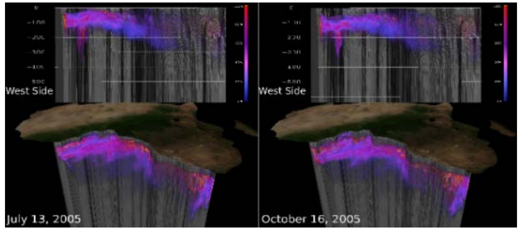
2.2

2.4

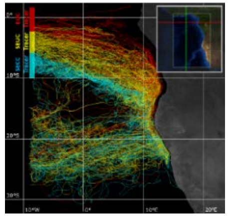
LPD



UPR



Specific Filters



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Local Pathline Density (LPD)

- Describes density of upwelling-trajectories in proportion to the cell diagonal.
- Coloring cell depending on LPD value.
- Figure (top): example of LPD visualization for strong and weak upwelling current. Coloring:
  - blue = before the upwelling
  - yellow-red = after the upwelling time.
- Identification of a distinct annual cycle in the upwelling activity
- Figure (bottom): numeric analysis of the number of upwelling trajectories.

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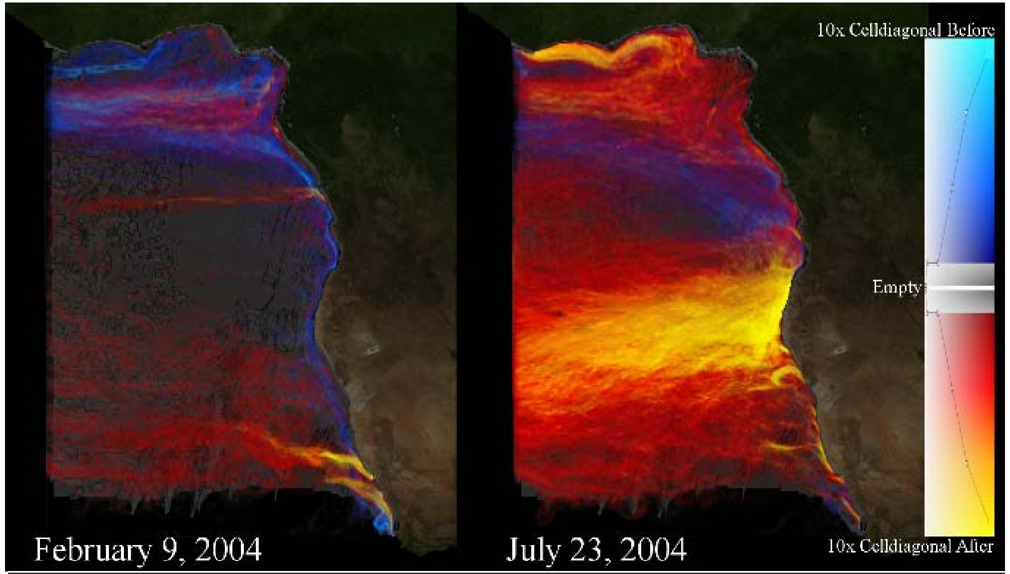
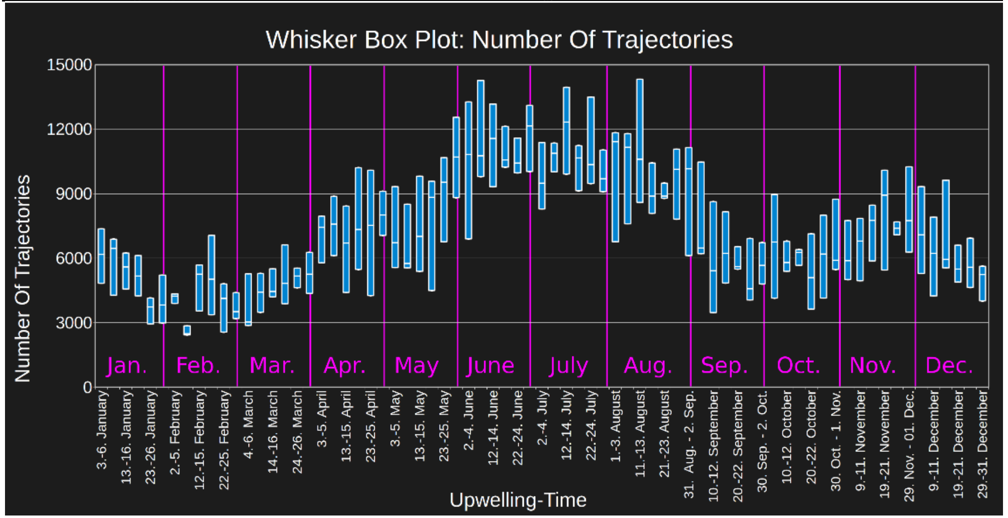
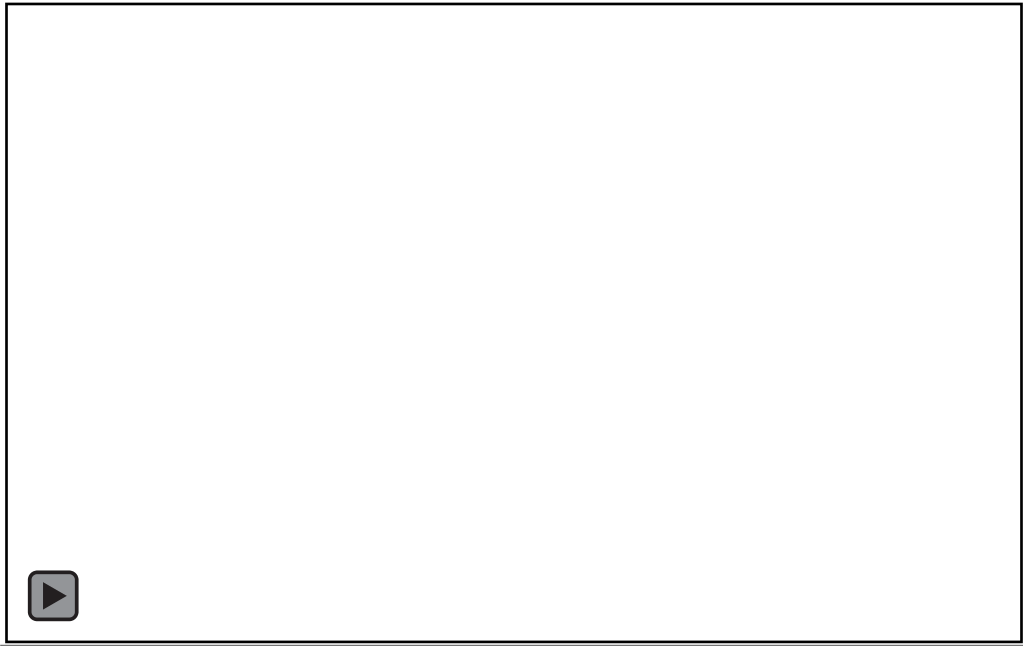
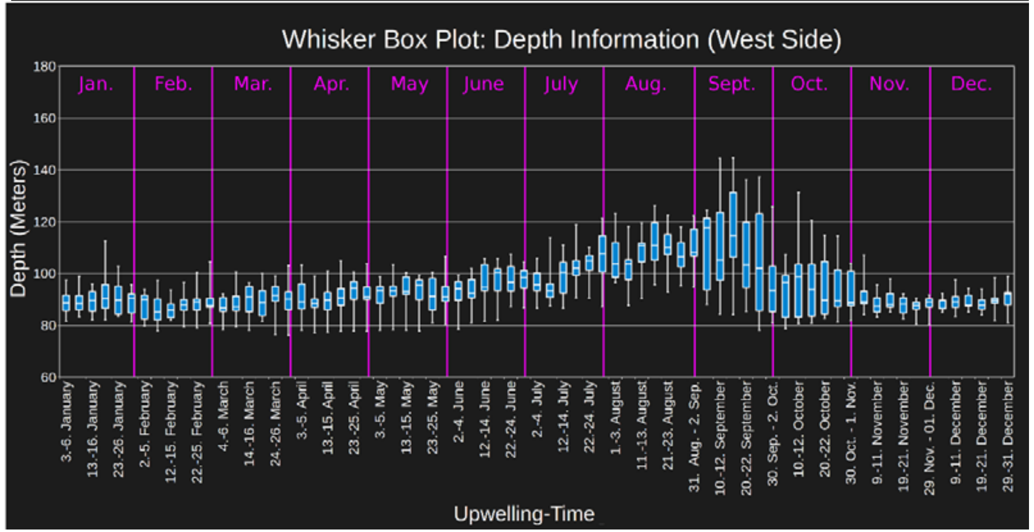




Upwelling Particle Ratio (UPR)

- Describes for each cell the proportion of upwelling particles to non-upwelling particles.
- Video (top): visualization of the UPR values before the upwelling time.
  (high extension of the z-axis)
- Identification of a distinct annual cycle in the upwelling source depth
- Figure (bottom): numeric analysis of the domain-enter-depth of upwelling trajectories coming from the west side.





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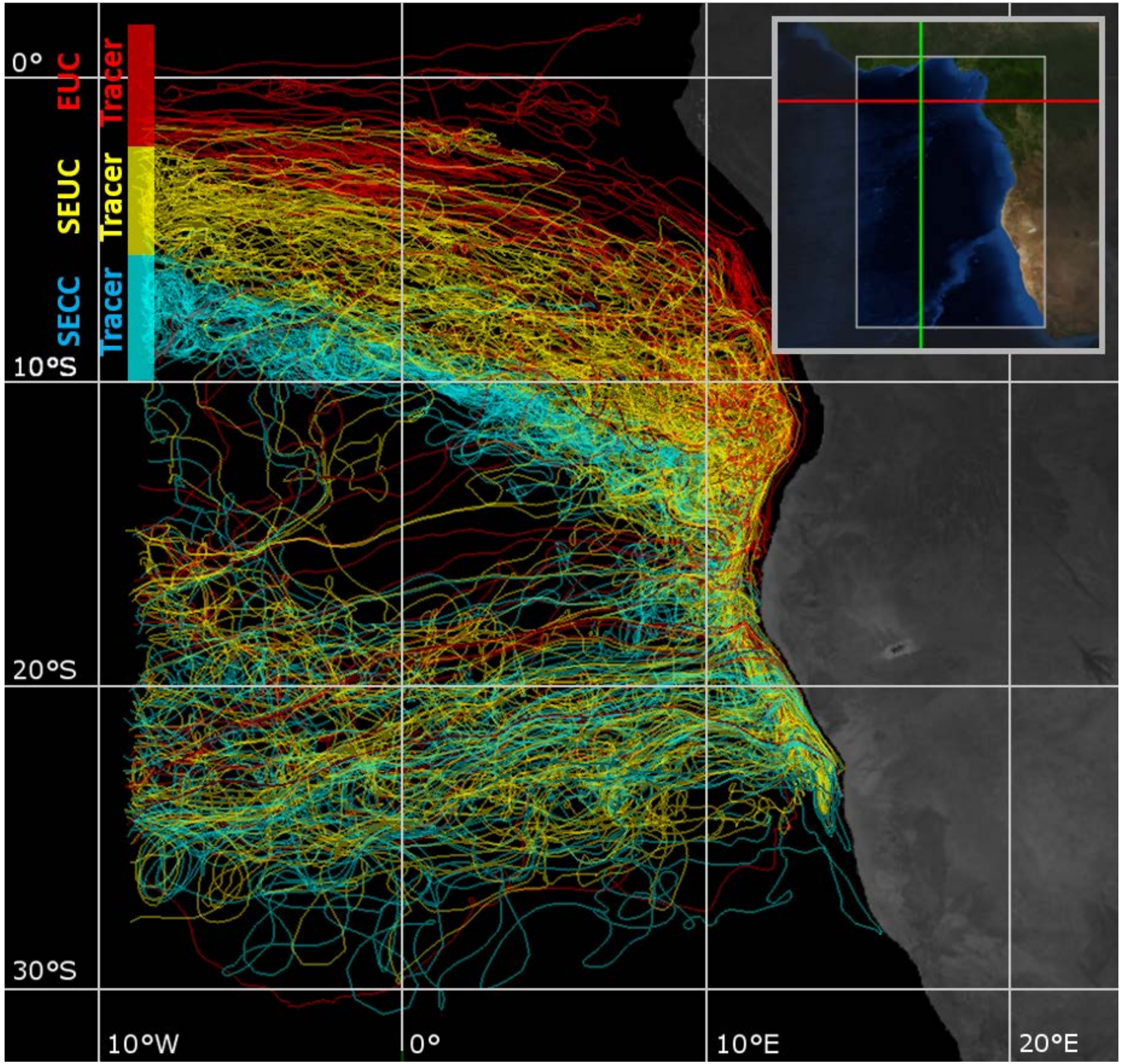
Specific Filters

- Classify the upwelling trajectories by defined characteristics.
- using "predicates" in order to identify upwelling trajectories fulfilling user-defined requirements.
- **Example Figure** shows:
  - filtration of upwelling event between 15°S and 27°S.
  - additional classification into different source



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Problem:

- Stored time intervals are much larger than the model time step
- For our analysis: Simulation calculated with 20 minutes steps stored as 5-day mean data set (Δt = 5d).
- Question: how accurate Lagrangian techniques applied in a postprocessing step can be in spite of relatively coarse temporal sampling of flow field data.

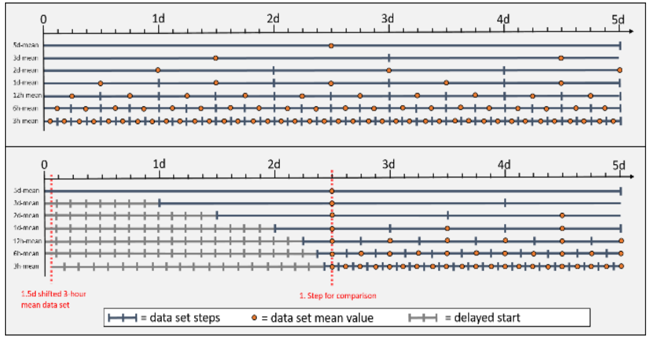
2.3

This work:

- Focus on evaluating the accuracy of our techniques by using data with **different temporal samplings** for:
  1. Compare pathlines with those derived for the fine data set with Δt = 3h .
  2. Compare emulated synthetic tracer fields (based on pathlines) with synthetic tracers computed within the ocean model simulation using Δt = 20m

- Using Δt = 3h data to derive data sets with Δt = 6h, 12h, 1d, 2d, 3d, 5d for comparison. The figure illustrates the scheme used for undersampling.

- For each data set with Δt = 3h, 6h, 12h, 1d, 2d, 3d, and 5d, we calculate a trajectory set with a minimum of *n* particles inside each cell with *n*={1,4,16}. (click for more information)



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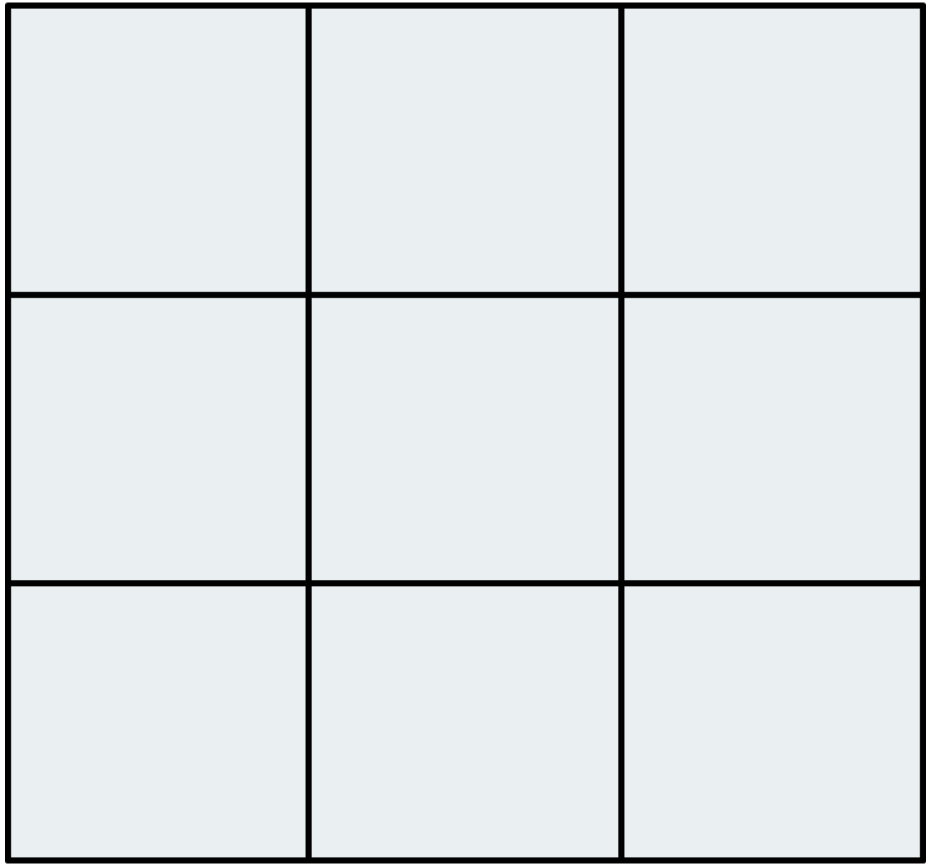
3.2

Method to create the trajectory set



Example with two time steps and *n*=4

1. Initialization by seeding *n* particles at time t = 0 in each of the model's grid cells.

2. Integration of the pathlines (Runge-Kutta 4th-order scheme (RK), Euler).

3. Check at each time step the number of particles in each cell. Seed new particles if necessary.

4. Perform a backward integration for the new particles to use the information of previous time steps (until the very first timestep or until they leave the domain).

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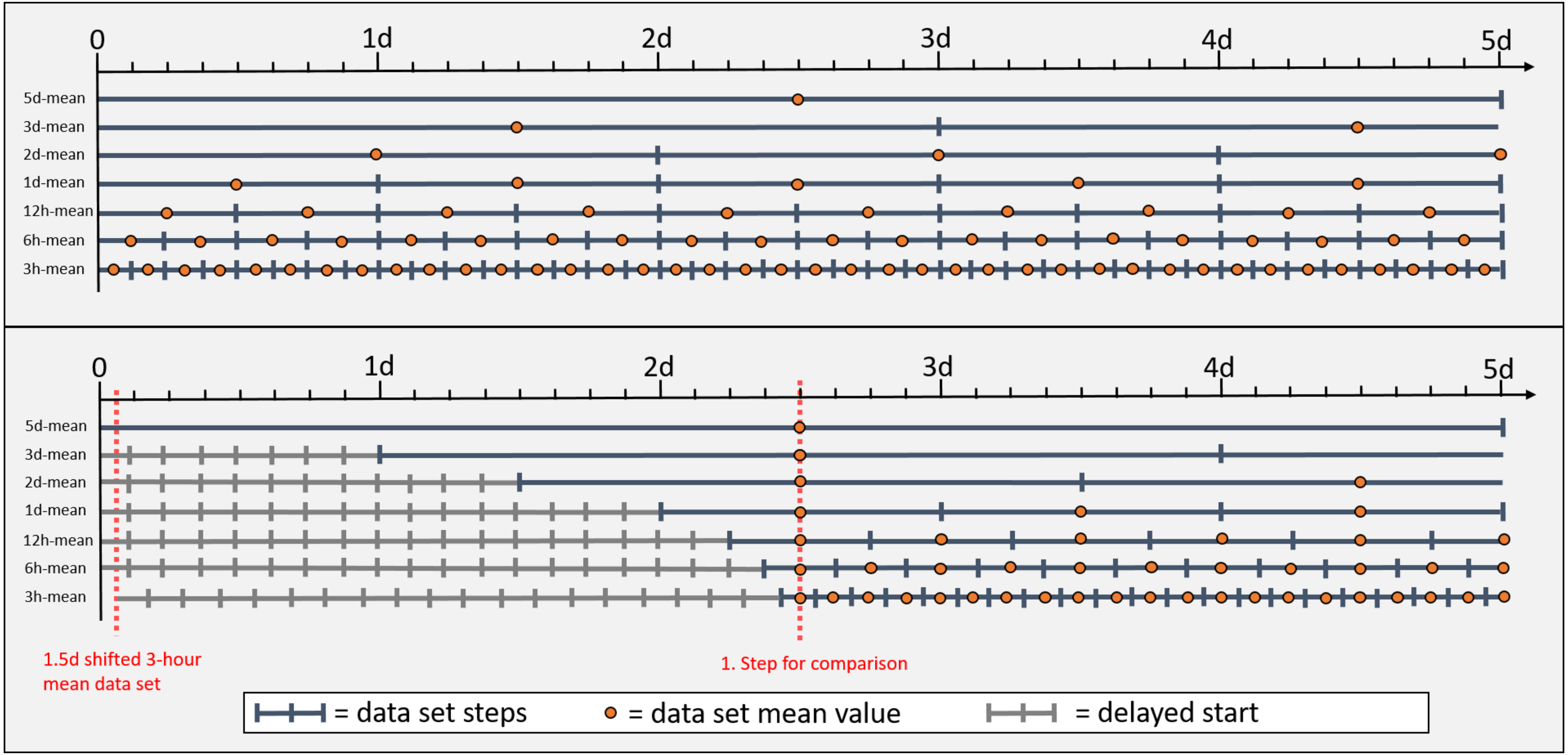
3.1 Data Emulation → 3.2 Pathline Error Estimation → 3.3 Trajectory Based Tracer Field



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- All initial particles calculated with the data sets with Δt = 3h, 6h, 12h, 1d, 2d, 3d, and 5d have the same start position and the same starting time.

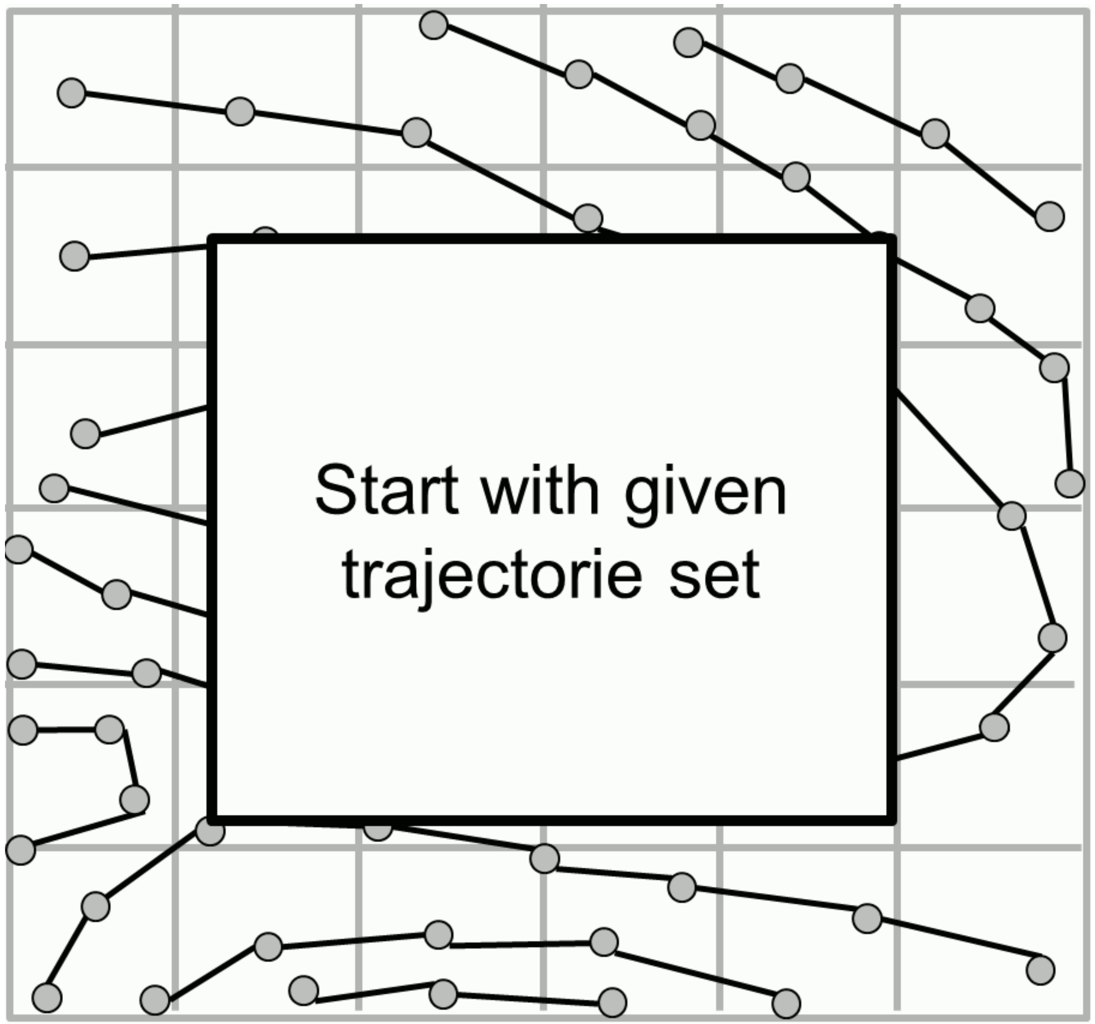
- Idea: compare pathlines of initial particles and use the best available temporal resolution Δt = 3h with a standard RK integration as reference.

- As values for comparison we are using:
  - **mean absolute distance (MAD)**
    $$MAD(m,t) = \frac{\sum_{i=1}^{n} \sqrt{||pos_{3h}^{t}(i) - pos_{m}^{t}(i)||}}{n}$$
  - **mean squared distance (MSD)**
    $$MSD(m,t) = \frac{\sum_{i=1}^{n} ||pos_{3h}^{t}(i) - pos_{m}^{t}(i)||}{n}$$
  - **mean line difference (MLD)**
    $$MLD(m,t) = \frac{\sum_{i=1}^{n} |\sqrt{||pos_{3h}^{0}(i) - pos_{3h}^{t}(i)||} - \sqrt{||pos_{m}^{0}(i) - pos_{m}^{t}(i)||}|}{n}$$

3.1

3.3

3.2



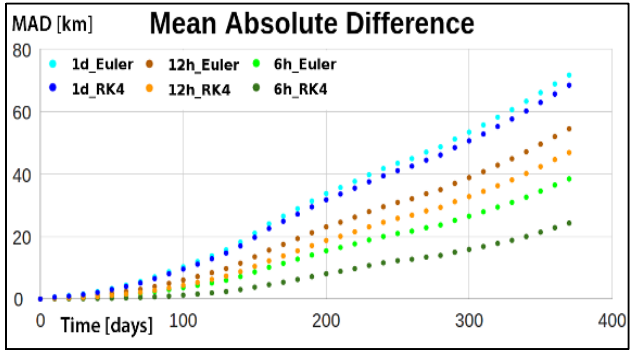
The following steps explain how we created our simulated tracer field for the comparison with the original tracer.

1. Check each trajectory for intersection points with a defined tracer source area and mark them.

2. Determine all particles for each cell and point in time.

3. Calculate tracer concentration ratio as simulated tracer value.

MAD-Plot



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- All three values show nearly the same result (MAD example in left figure).
- The graphs show that the error grows with time.
- As expected, the lowest MAD is achieved by using the RK integration using the Δt = 6h data.
- **BUT:** Even with the Δt = 6h data, the average error after one year is around 40 kilometers (equivalent to a deviation of about four cells)

→ Any storage intervals larger than the model time step lead to an error. The larger the difference, the larger the error.

4.2

4.1 Pathline Error Estimation

4.2 Trajectory Based Tracer Field

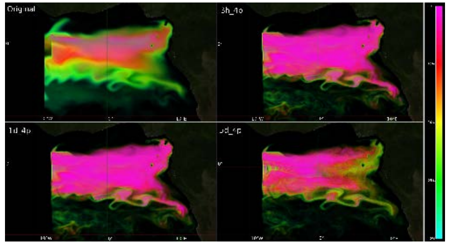
4.1

Pattern Analysis:

- Figure (left): good agreement of the shape of the emulated tracer cloud with that of the original tracer, even with the coarse data set with Δt = 5d.

→ Despite the unsatisfying results of the Pathline Error Estimation, the shape of the emulated synthetic tracer pattern matches reasonably well.

Storage Step Size Analysis

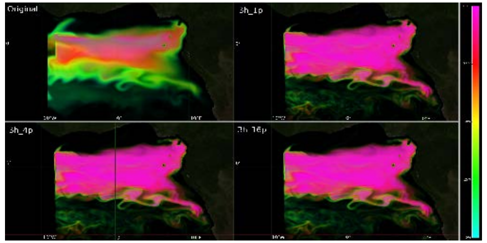


Magnitude Analysis:

- Figure (left): For all temporal samplings our method overestimates the tracer concentration.
- Figure (right): Even with a larger number of particles we could not improve the results

→ Further analysis and improvment of our method is nessecary

Number of Particles Analysis



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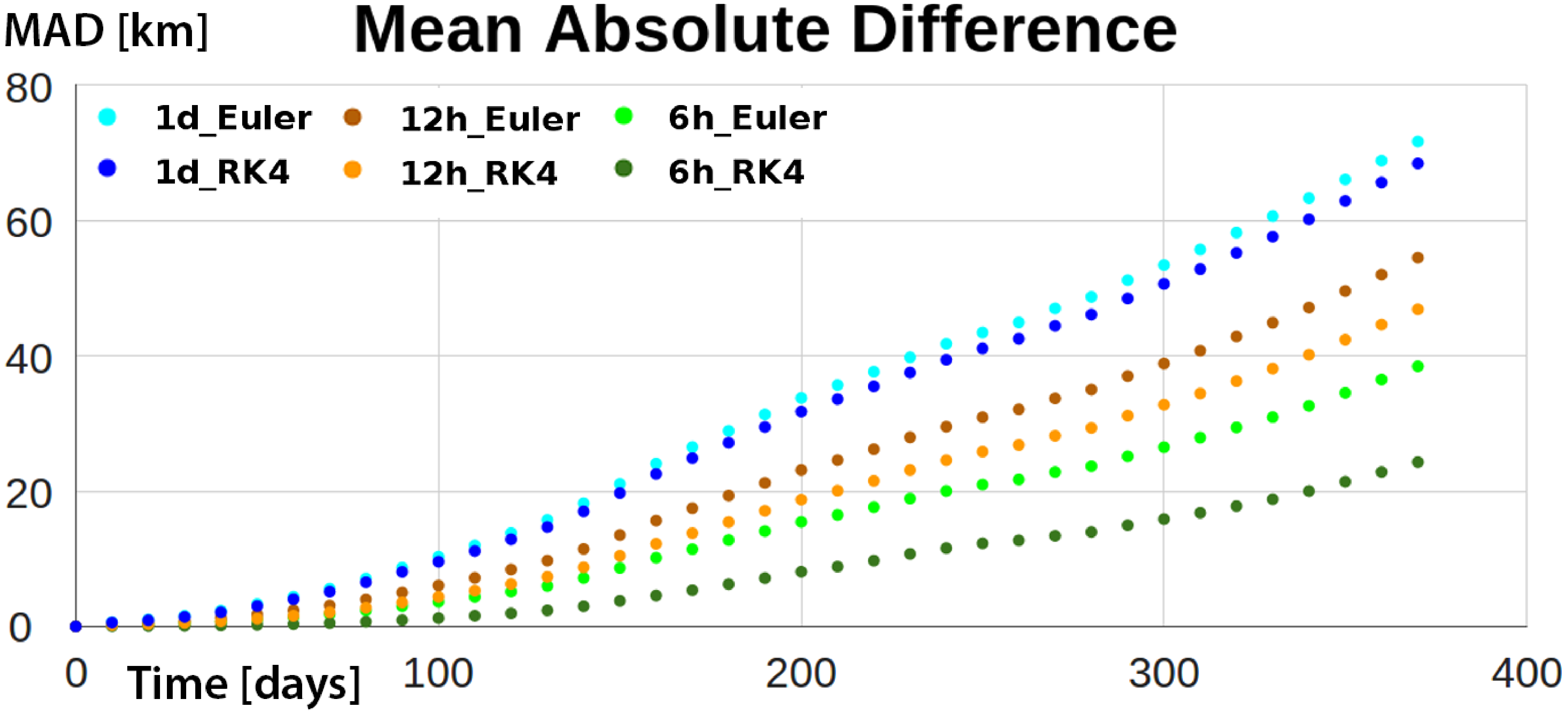
Mean Absolute Difference



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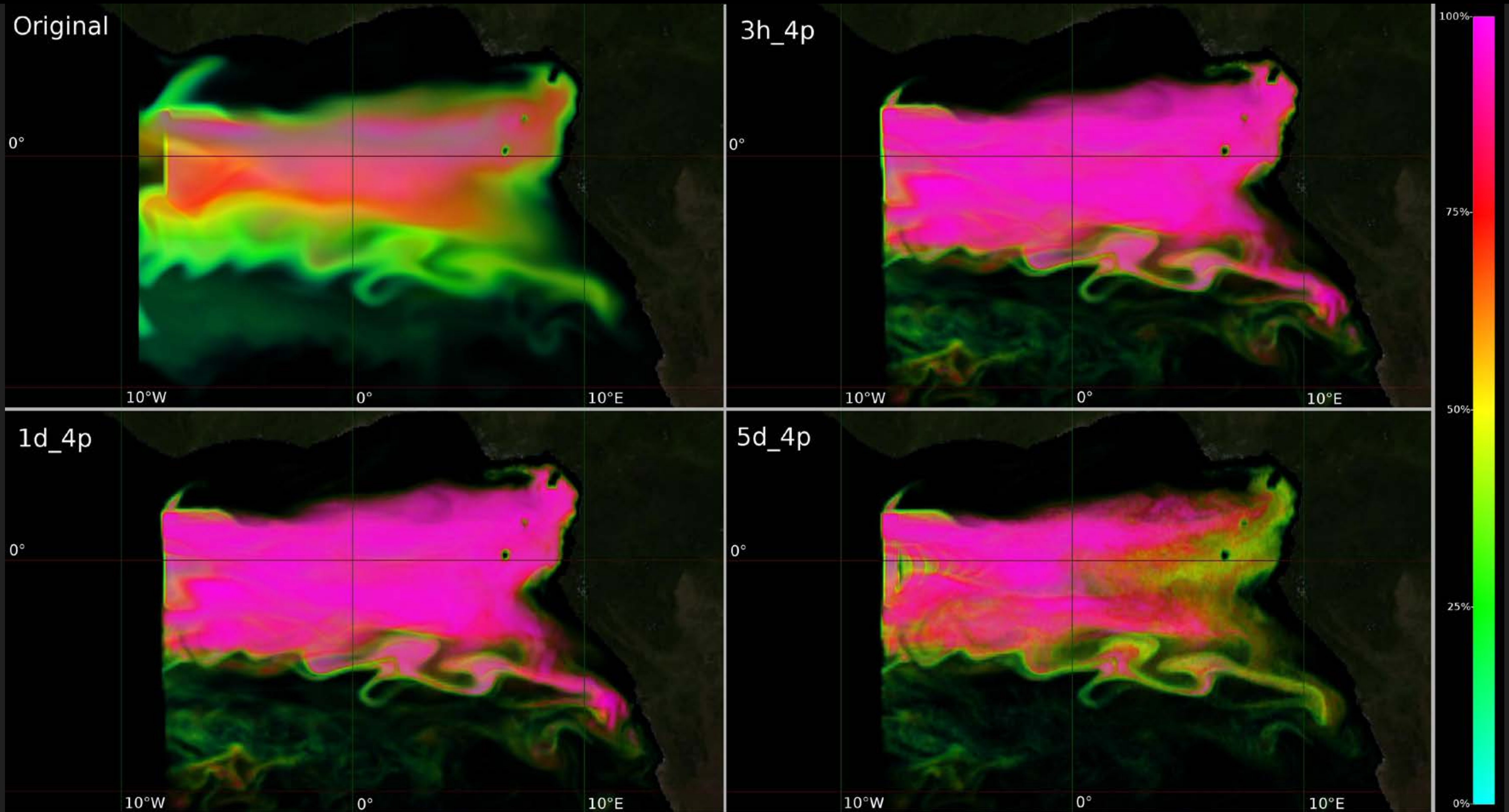
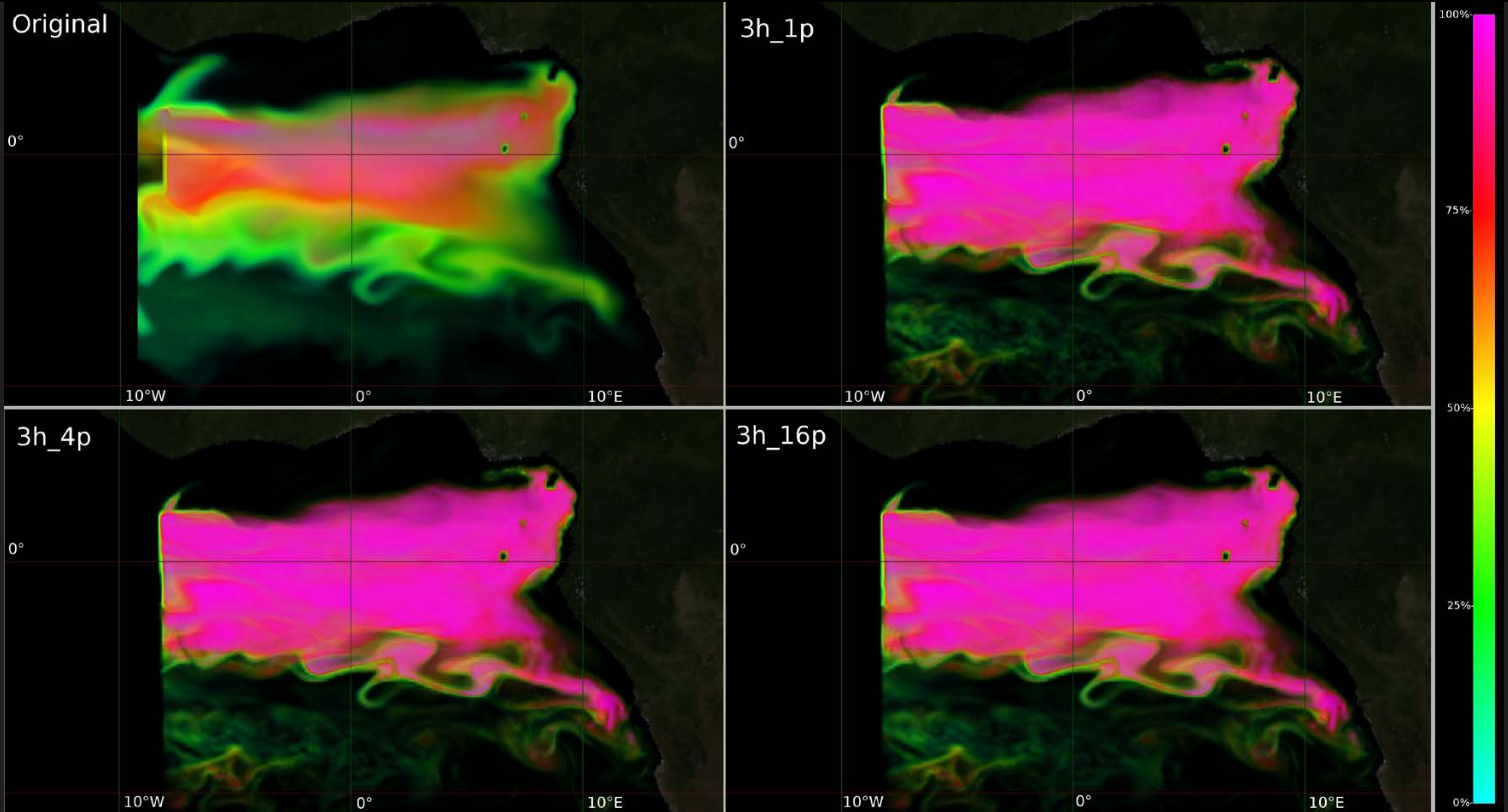

Original
3h_4p
1d_4p
5d_4p
0°
10°W
0°
10°E
100%
75%
50%
25%
0%


Original
0°
10°W
0°
10°E
3h_1p
0°
10°W
0°
10°E
3h_4p
0°
10°W
0°
10°E
3h_16p
0°
10°W
0°
10°E
100%
75%
50%
25%
0%