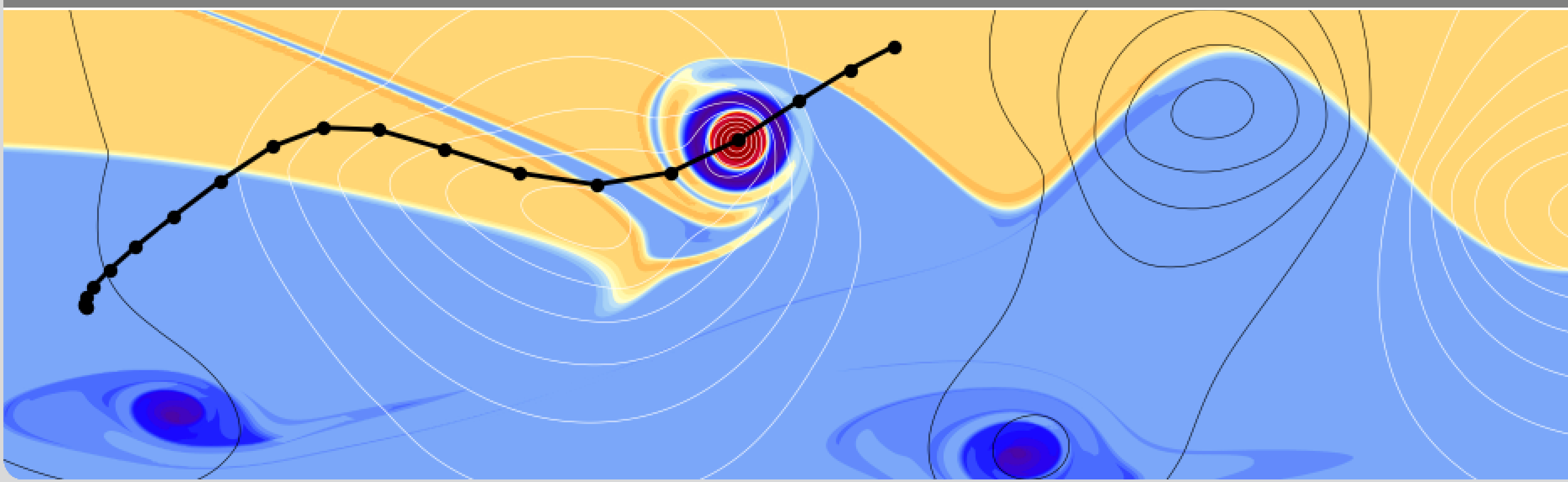
Karlsruhe Institute of Technology

metström

Idealized Tropical Cyclone Scenarios as Test Cases for Goal Oriented Adaptive Methods

Leonhard Scheck, Sarah Jones, Martin Baumann, Vincent Heuveline, Werner Bauer, Almut Gassmann

SPP METSTRÖM / PROJECT *„GOAL ORIENTED ADAPTIVITY FOR TROPICAL CYCLONES“*

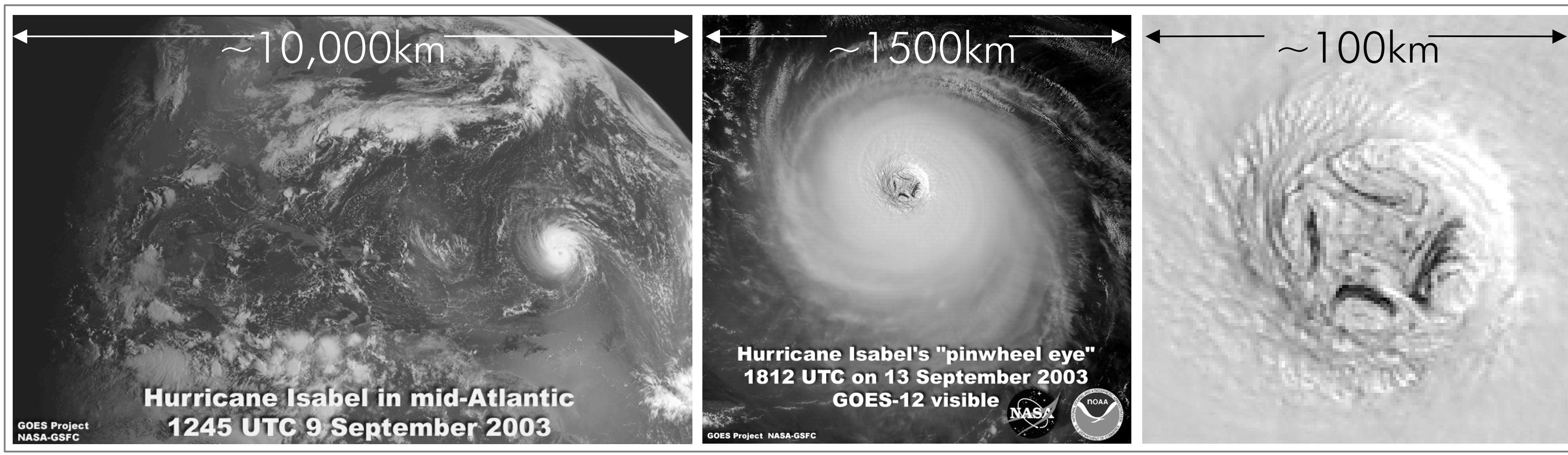


Motivation

Forecasting development and motion of tropical cyclones (TCs):

interacting processes on scales between <1km (convection) and ~10,000km have to be represented adequately

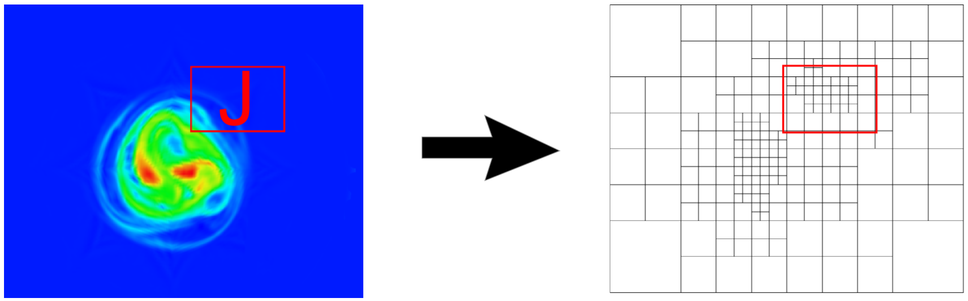
→ **multi-scale problem**



- Common approach: Nesting
- Promising new (for meteorology) technique: Goal oriented adaptivity

Goal oriented adaptivity

Idea: Given a quantity of interest (goal functional) J,
adapt the grid in a way that minimizes the error in J
(e.g. under the constraint that the computational effort is constant)



implemented in
HiFlow^3

Realisation: For each cell, estimate contribution to error in J using an a posteriori error estimator. Increase resolution where error is large.

$$\delta J \approx \underbrace{\nabla_x J} \cdot \delta x$$

error in goal functional

discretization error

dual solution
= adjoint based sensitivity

→ *Baumann et al. poster*

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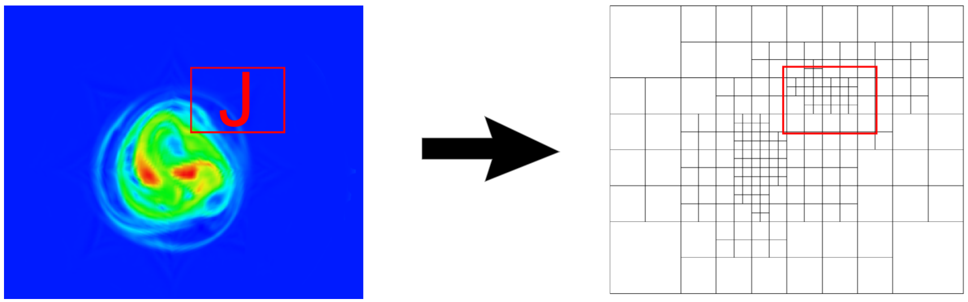


implemented in HiFlow³

Realisation: For each cell, estimate contribution to error in J using an a posteriori error estimator. Increase resolution where error is large.

nonlinear model

$$\delta J \approx \underbrace{\nabla_x J(N(x))} \cdot \delta x$$

error in goal functional

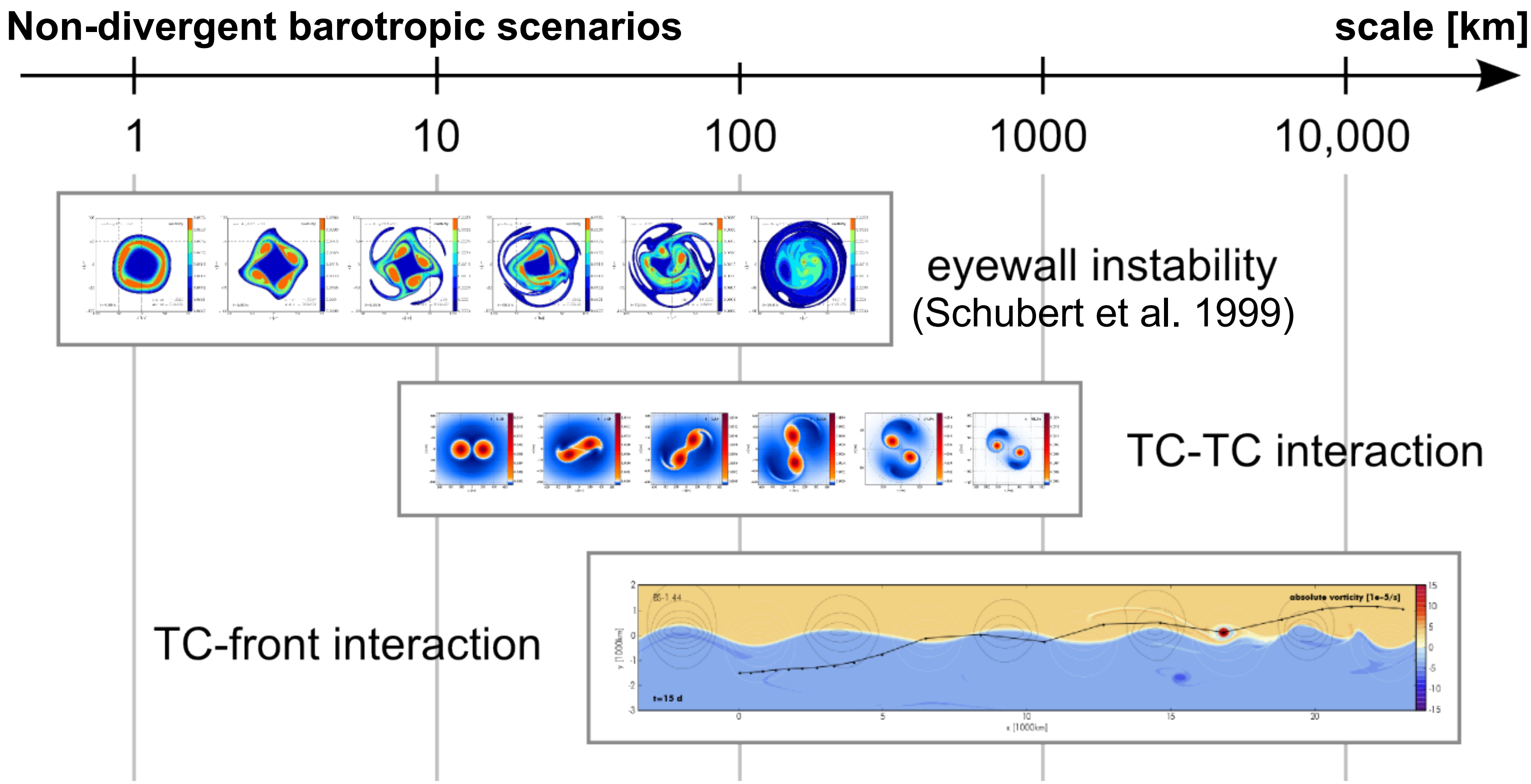
discretization error

dual solution
= adjoint based sensitivity

→ *Baumann et al. poster*

Test Cases: Idealised TC Scenarios

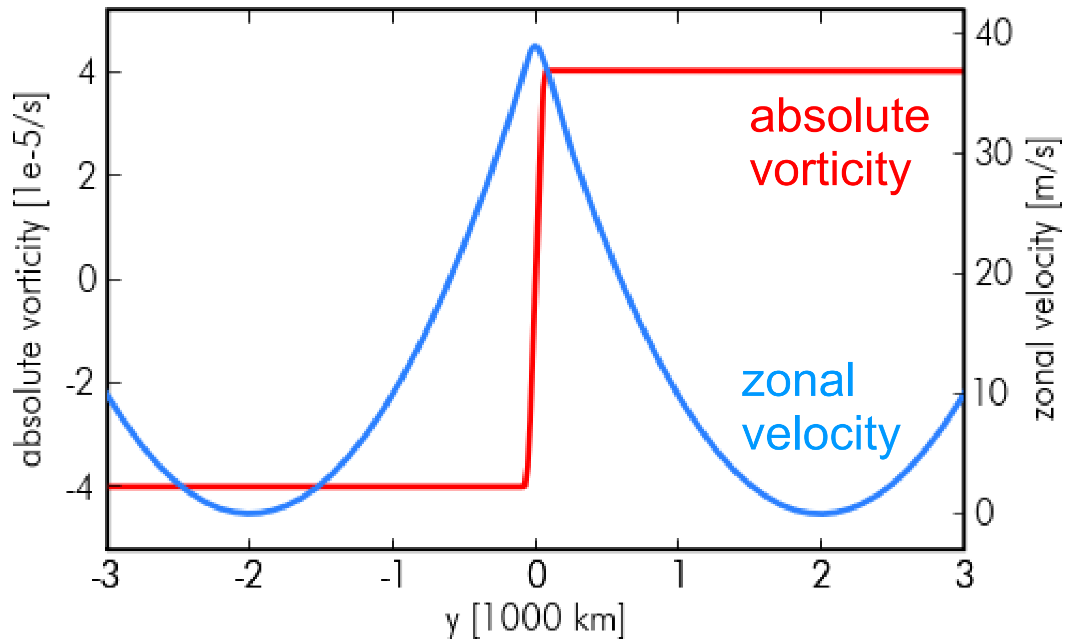
- Wide range of scales, large potential for adaptive grids
- Contain dynamical processes important for real TCs
- Challenging: High sensitivity to small perturbations / numerical errors



- Work in progress: 3D versions, vortex in vertical shear, moisture effects

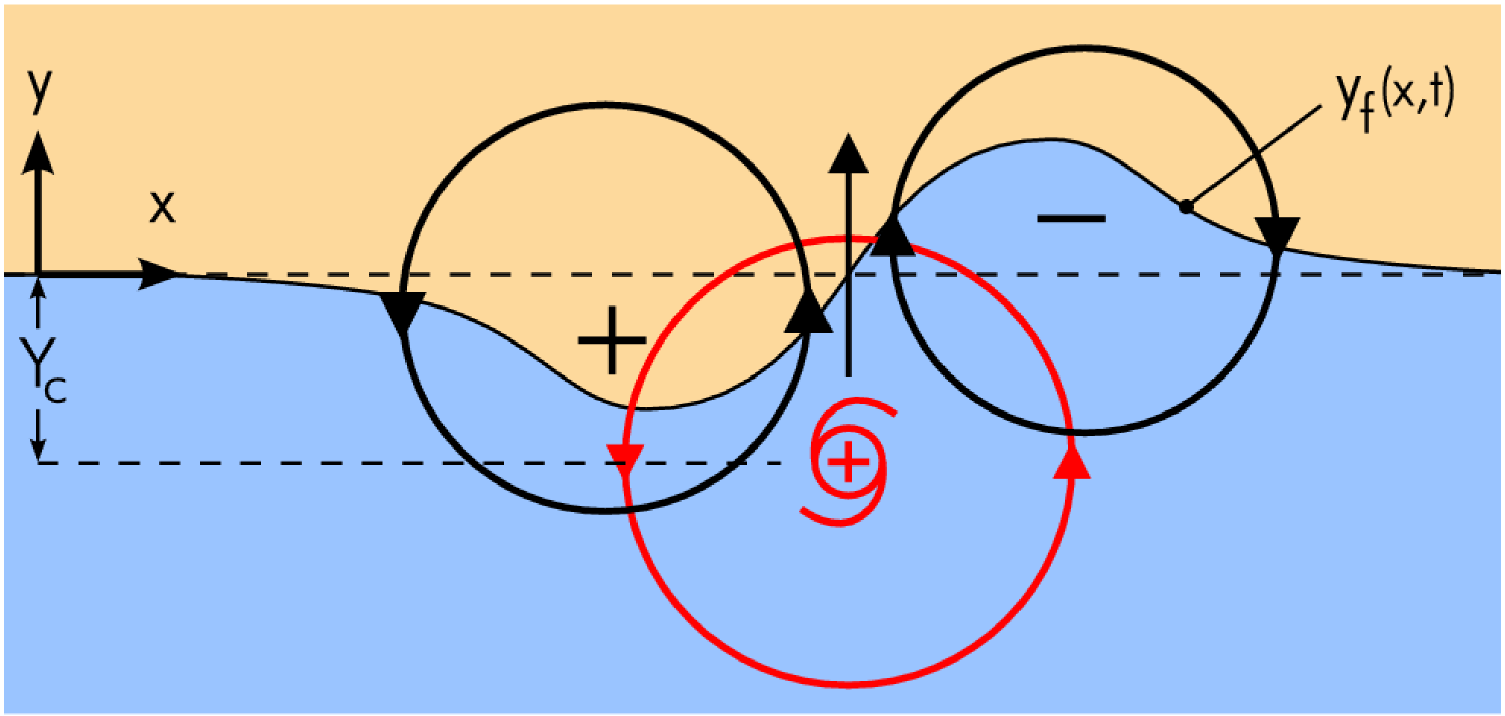
TC-front interaction

- Strongly idealised: non-divergent **barotropic model**
- Finite difference code (non-adaptive) reference runs
- Front modelled as step between two regions of constant absolute vorticity → jet-like velocity profile
- Initial state: jet profile + vortex south of front
- Several different vortex profiles including vortices with core of positive vorticity surrounded by ring of negative vorticity (mimicks TC outflow)



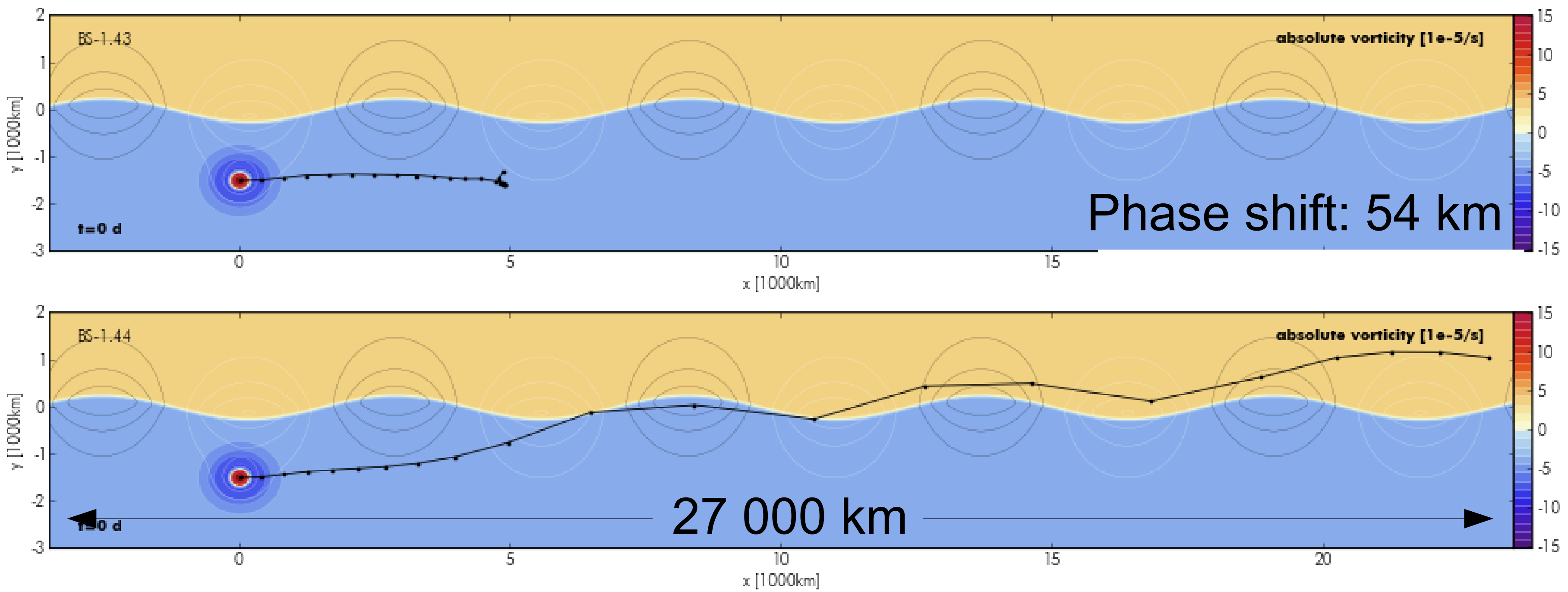
TC-front interaction

- TC circulation deforms interface → vorticity anomalies
- Anomaly circulation → cyclone steered northwards, wave propagates along interface



Sensitivity to inital TC position

- Frontal waves present in initial conditions
  → strong impact on TC-front interaction
- High sensitivity to initial wave phase, extreme case: **bifurcations** due to by arbitrarily small perturbations



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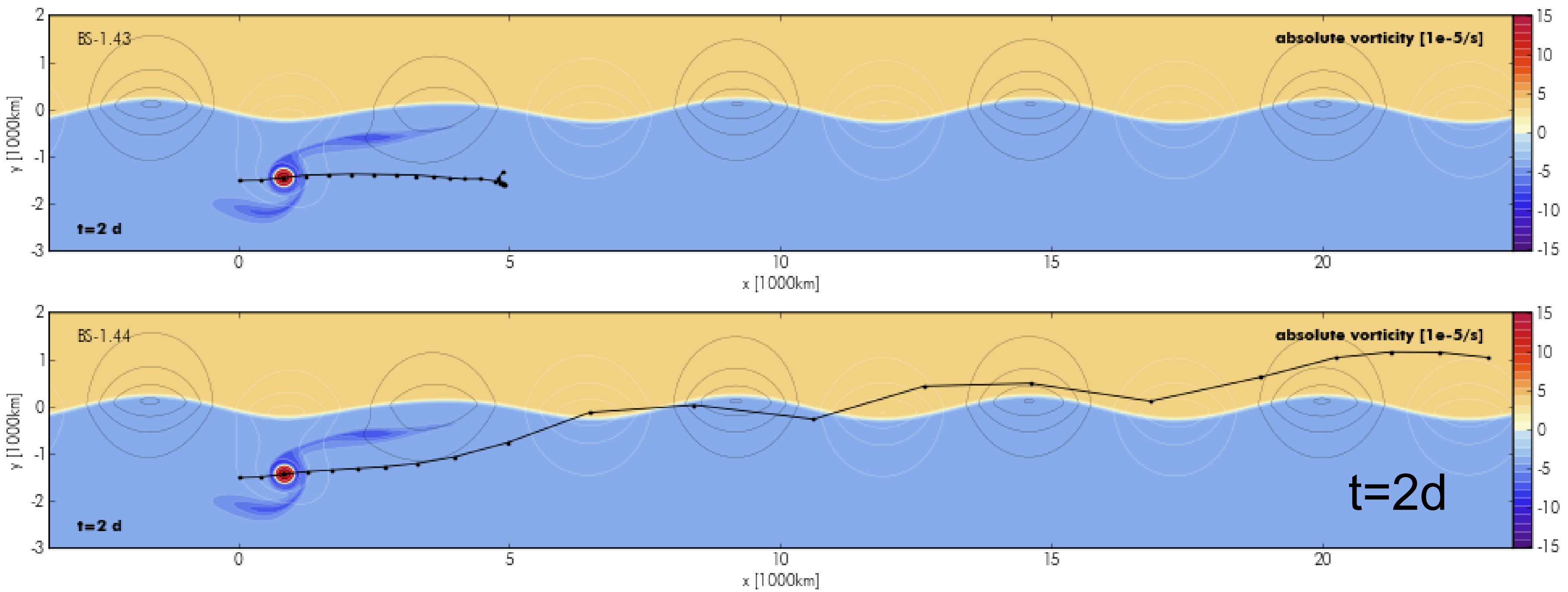

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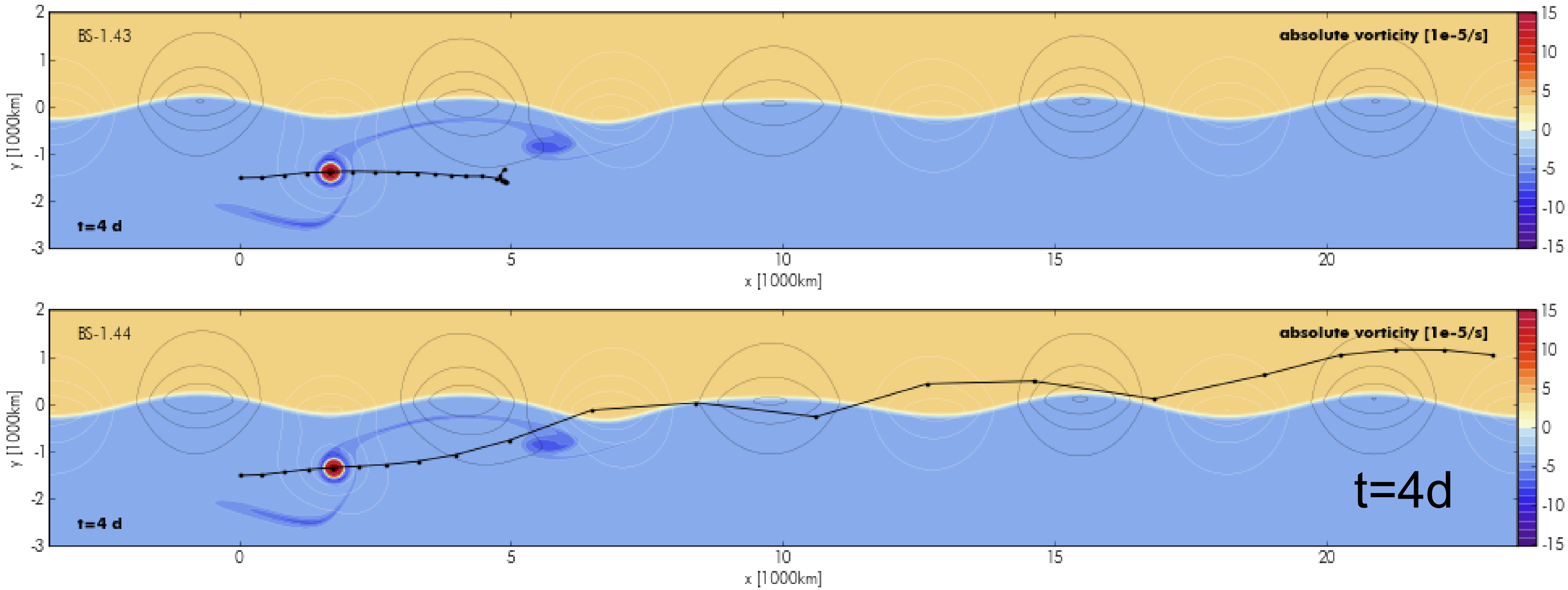

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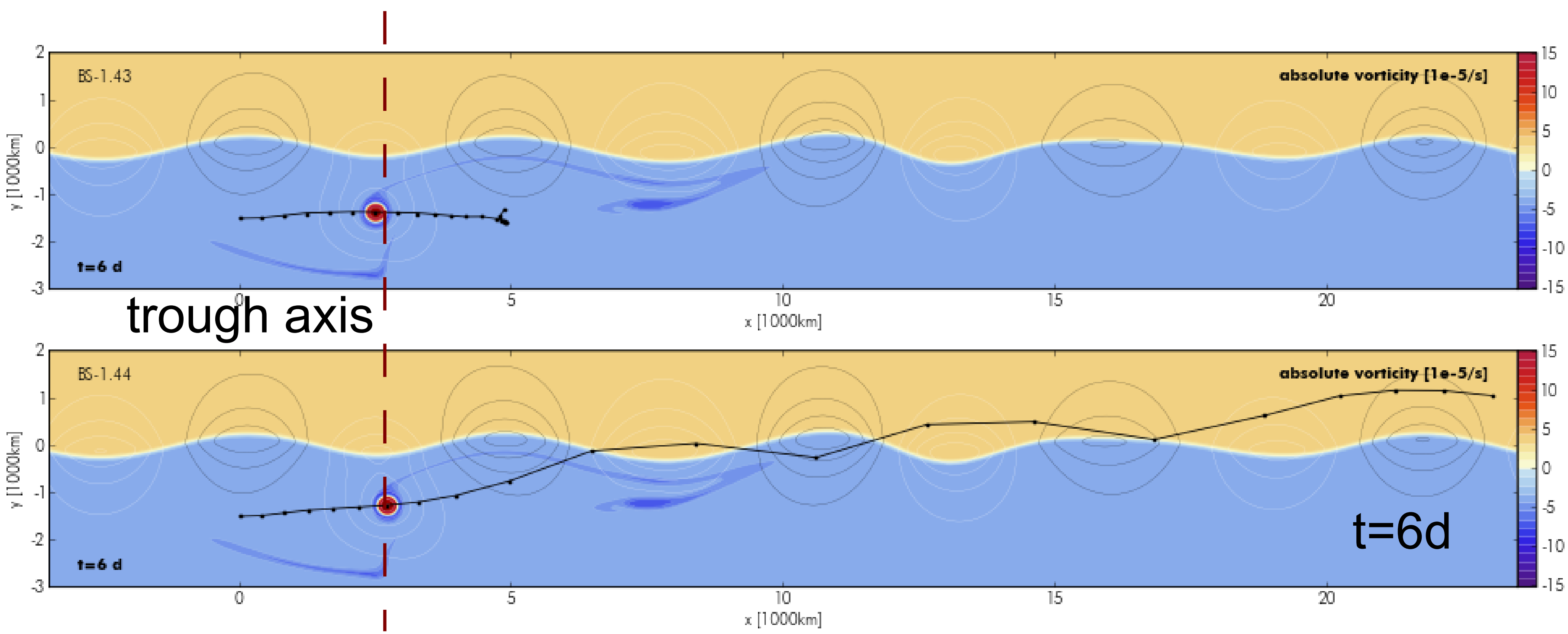

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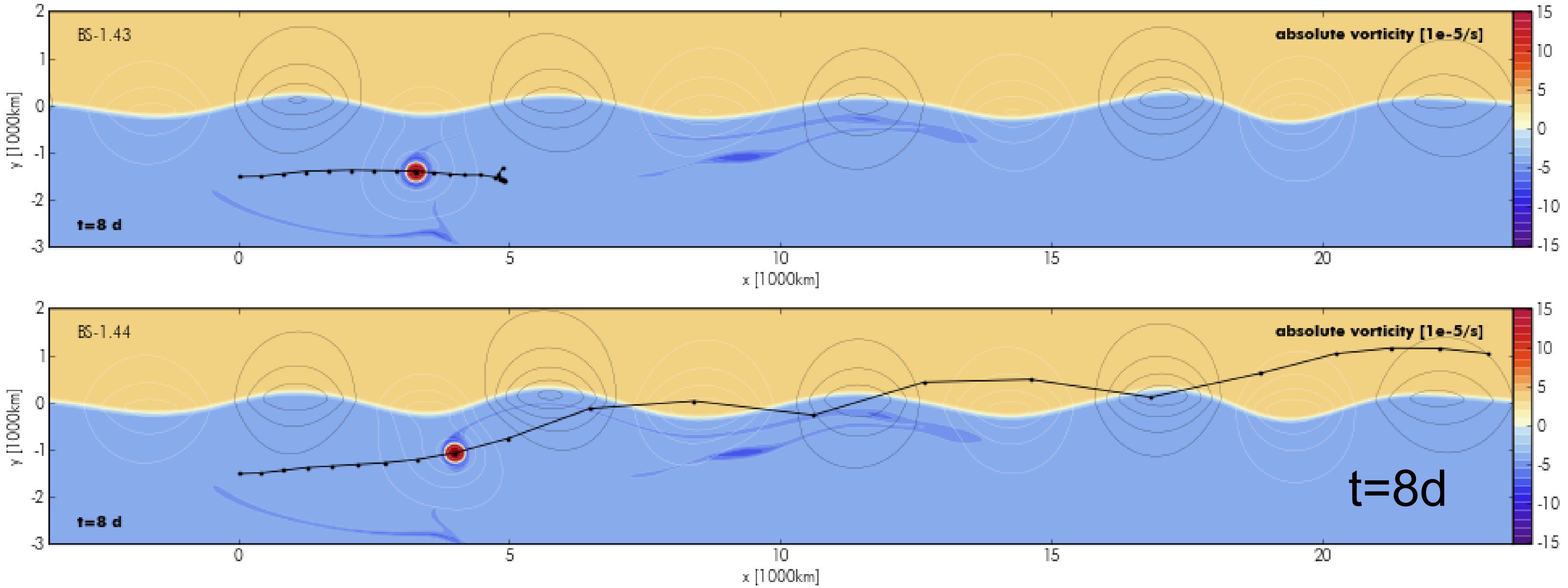

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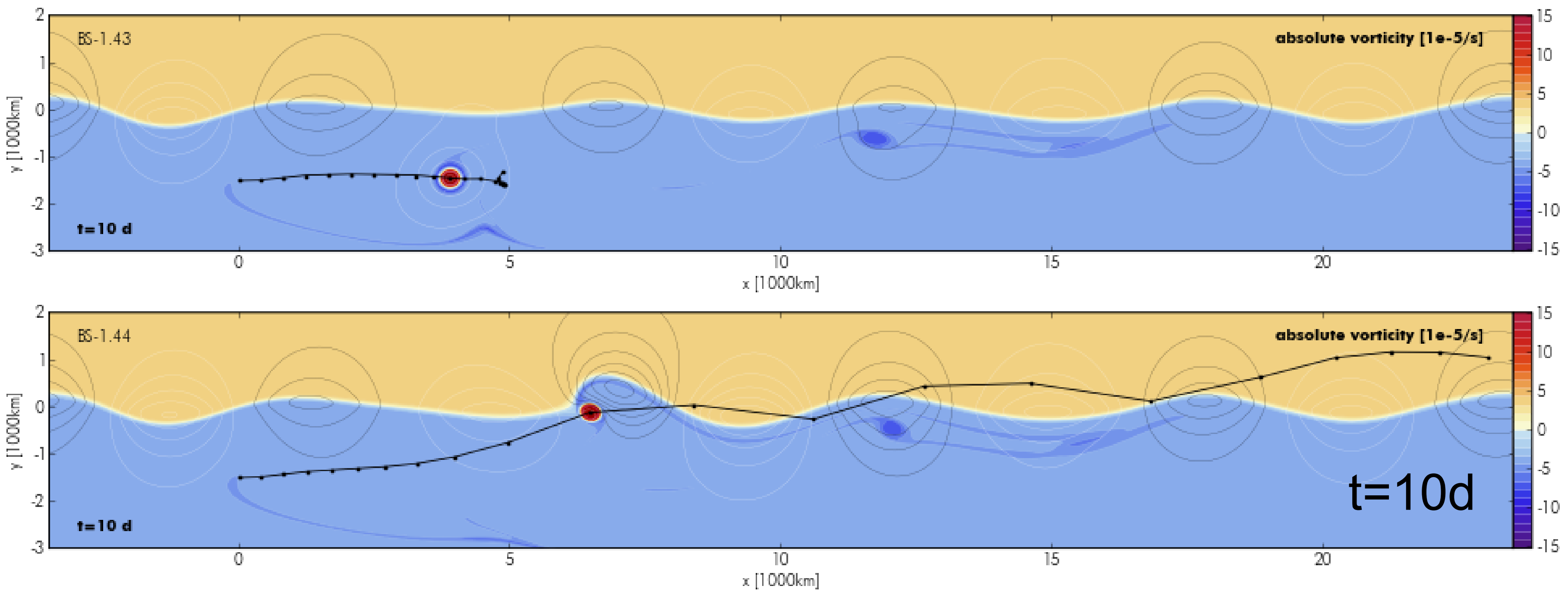

Metström-Konferenz
Juni 2011, Berlin
Scheck, Jones, Baumann, Heuveline, Bauer, Gassmann:
Idealized Tropical Cyclone Scenarios as Test Cases for Goal Oriented Adaptive Methods

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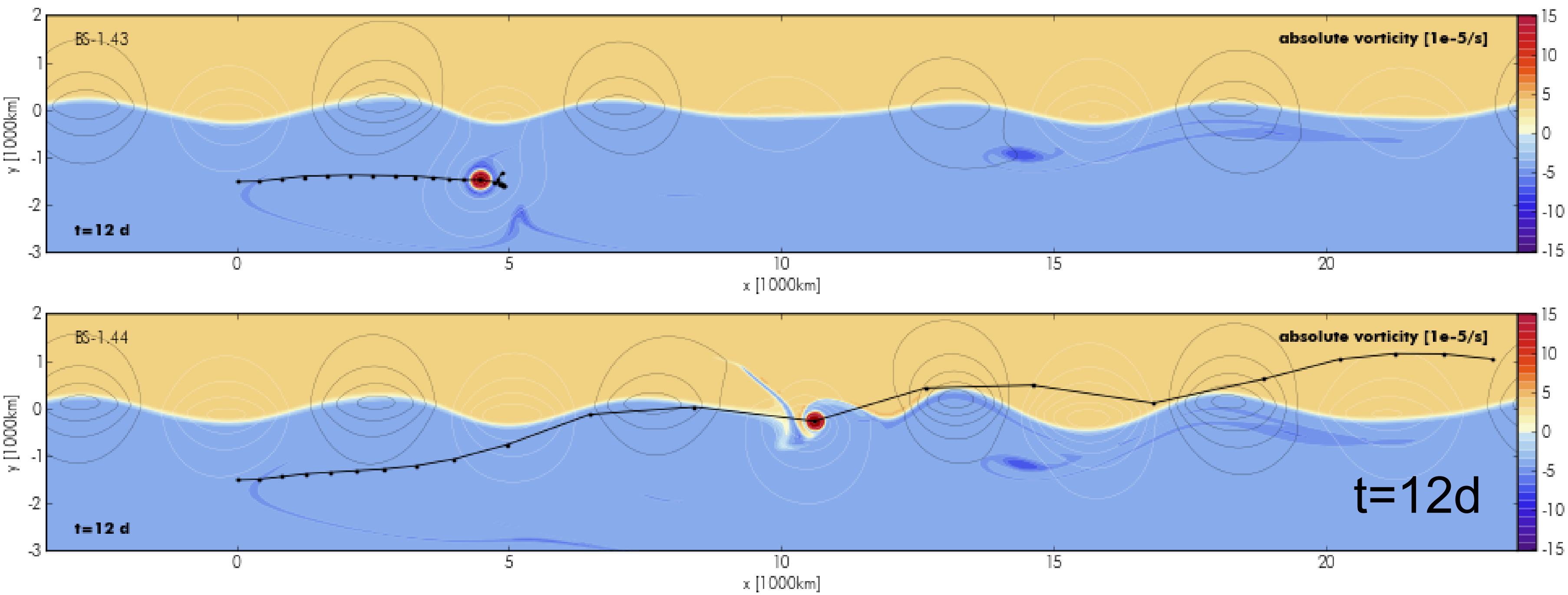

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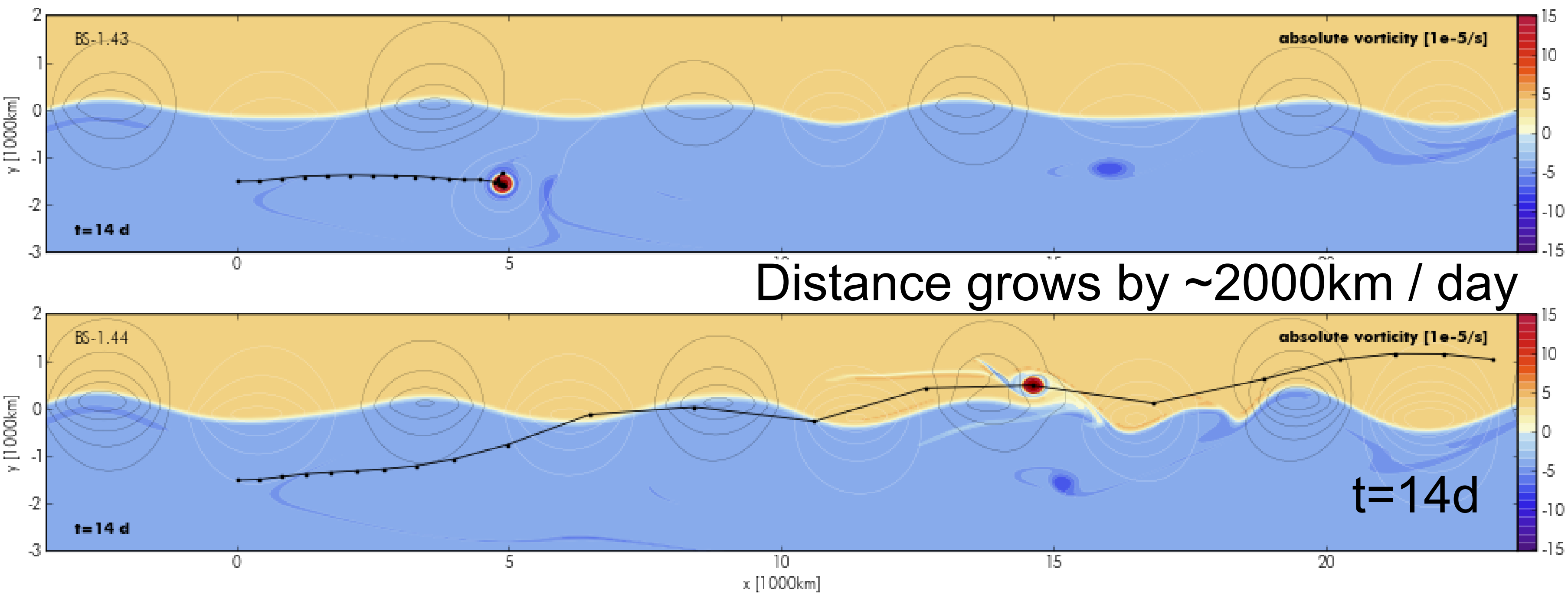
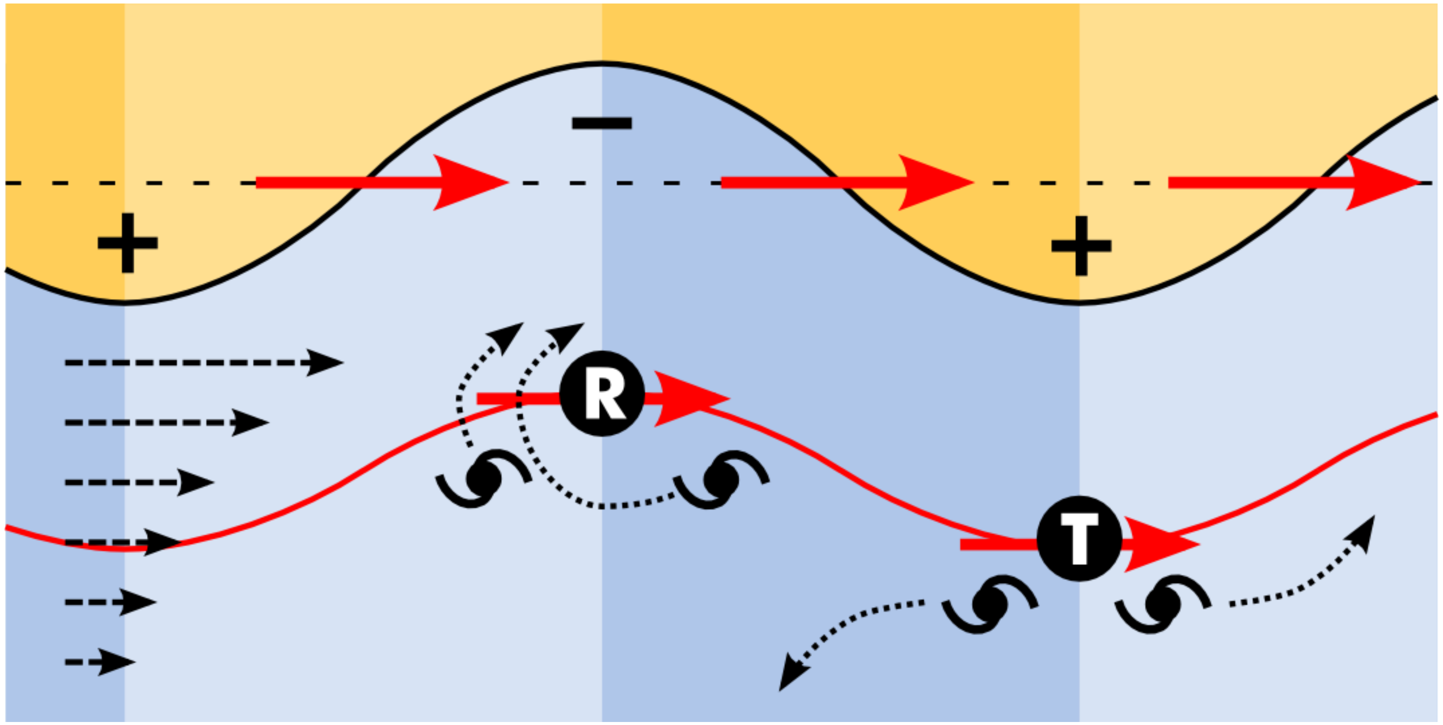


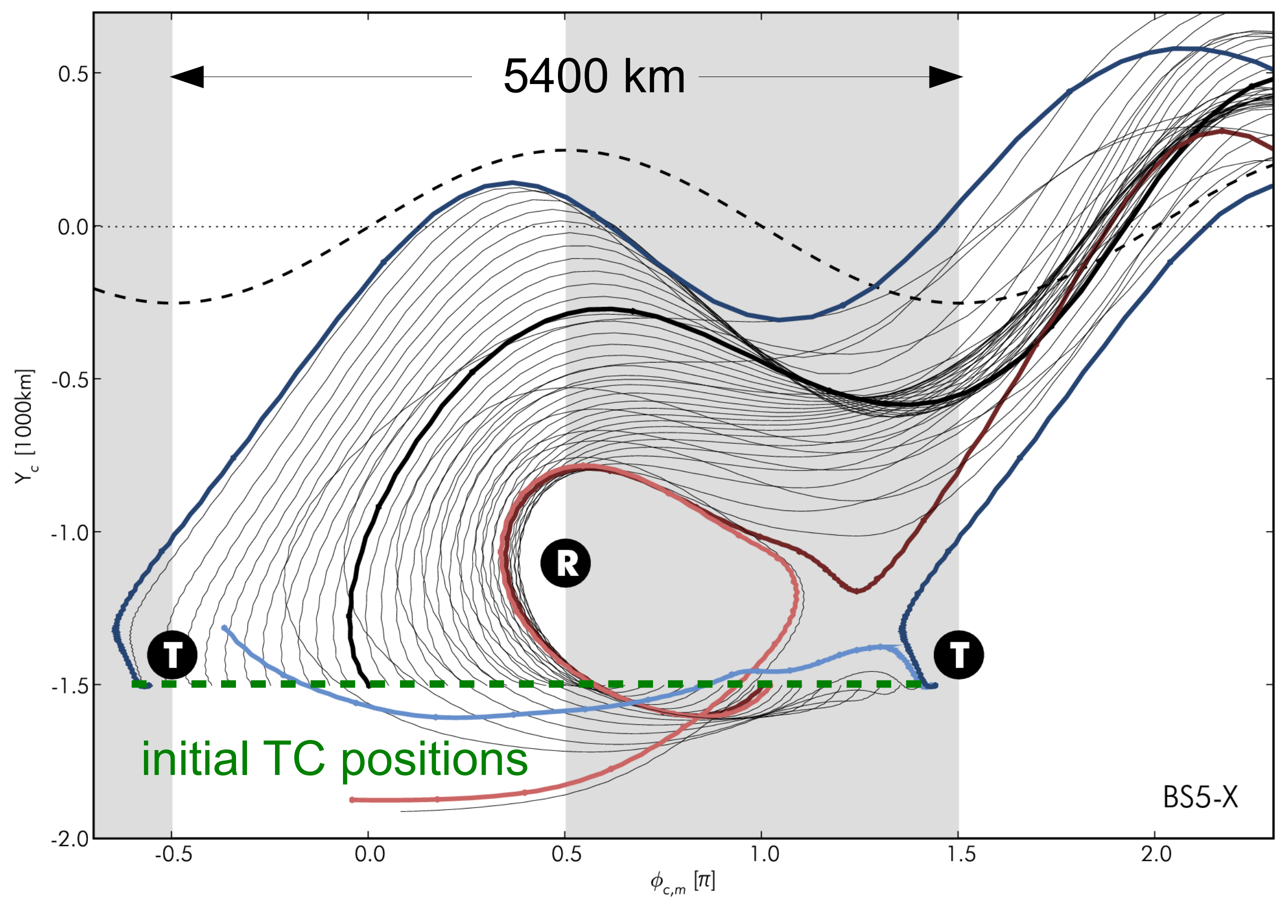
Origin of the bifurcation

- Points R, T : zonal translation velocity = phase speed
  meridional translation velocity = 0
  → stationary points in the frame moving with the wave
- Point T: TC overtakes trough or vice versa?
  Unclear, vastly different consequences → bifurcation



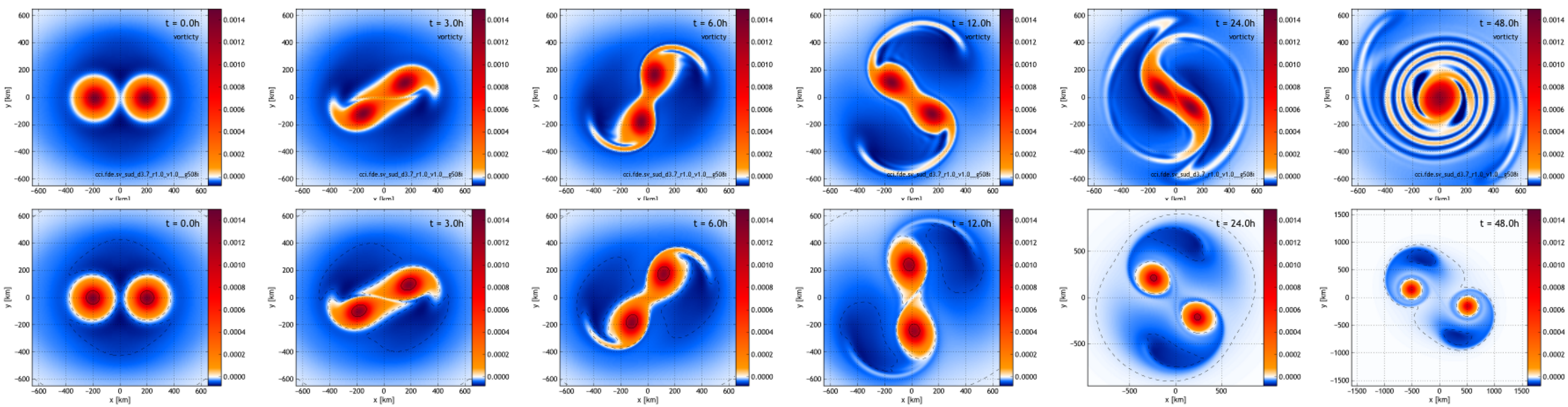
Origin of the bifurcation

Tracks for different initial phases in the frame moving with the wave:
Influence of R, T as expected, deviations due to wave excitation



TC-TC interaction

- Occurs ~2 times per year, can be problematic for track prediction
- Influences motion (Fujiwara) and structure (shear)
- High sensitivity to initial TC separation
  (extreme case: bifurcation between merger and non-merger cases)

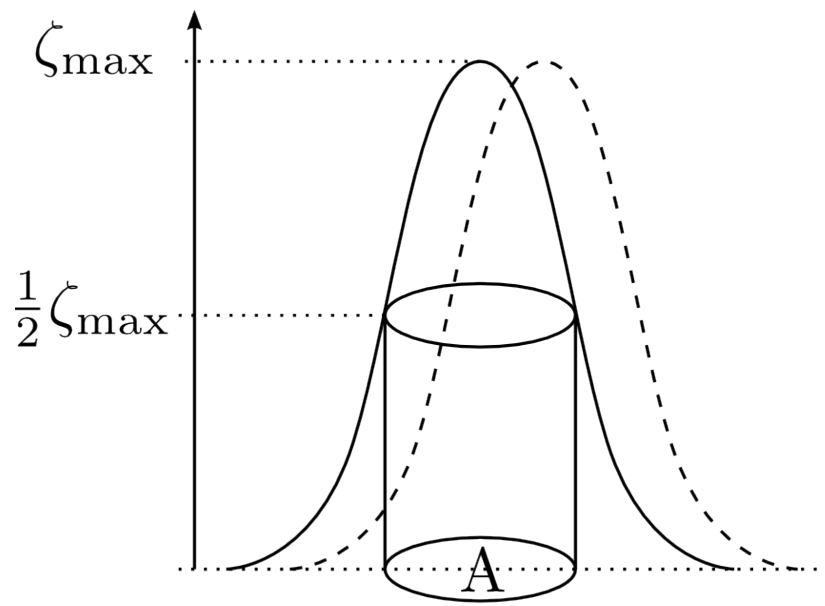


Vorticity evolution for initial TC separations 370km (top) and 400km (bottom) in the first 48 hours.

→ High sensitivity to TC displacement in initial coditions for both scenarios.

Linear sensitivity analysis

- Dual solution / adjoint based sensitivity: **optimal perturbations** that have the largest effect on goal functional J
- Sensitivity information is used for targeted observations, ensemble perturbations, **understanding dynamics, grid adaptation** (by-product sensitivity).
- Idealised scenarios: Interpretation of sensitivity much easier
- Goal functional: energy or vorticity, integrated over TC core, → correlated with **TC position**
- Results similar to leading energy singular vector



$$J = \int_A v^2 + u^2 \mathrm{d}x\mathrm{d}y$$

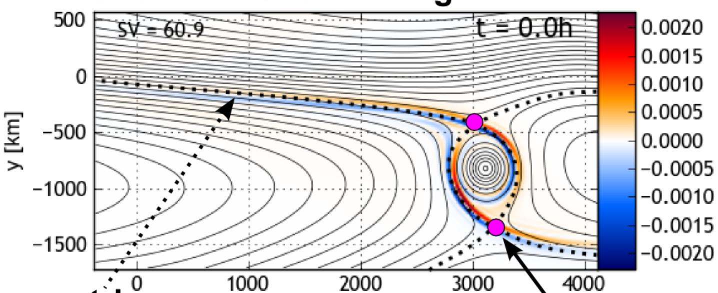
Scheck, Jones, Baumann, Heuveline, Bauer, Gassmann: *Idealized Tropical Cyclone Scenarios as Test Cases for Goal Oriented Adaptive Methods*

Initial and evolved optimal perturbations

Initial perturbations:
Aligned with comoving / corotating streamlines

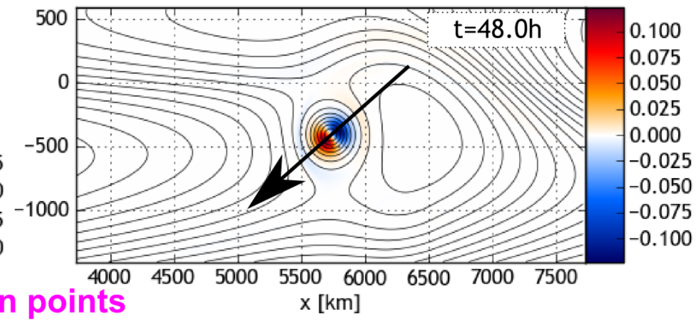
Evolved perturbations:
Vorticity dipoles → effect of prturbations is a displacement of the TCs

streamlines: comoving



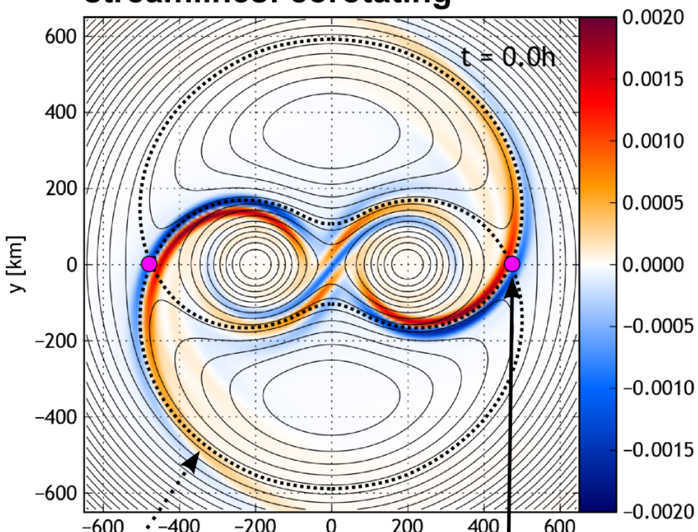
separatrix

stagnation points



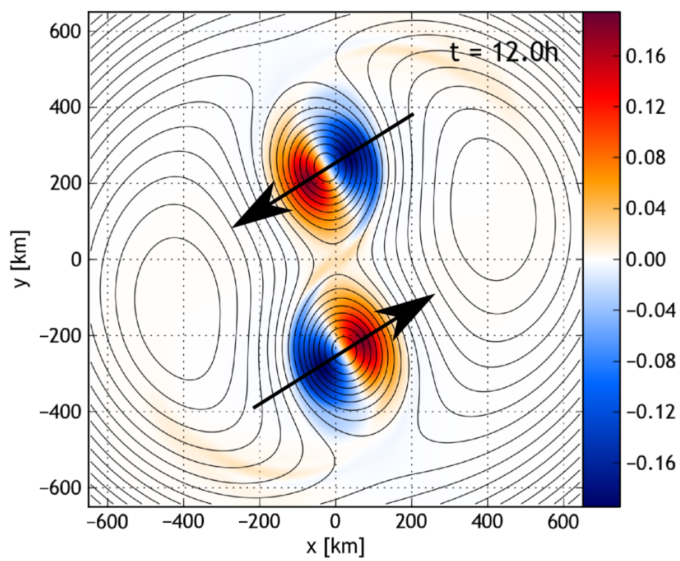
TC-front interaction

streamlines: corotating



separatrix

stagnation point



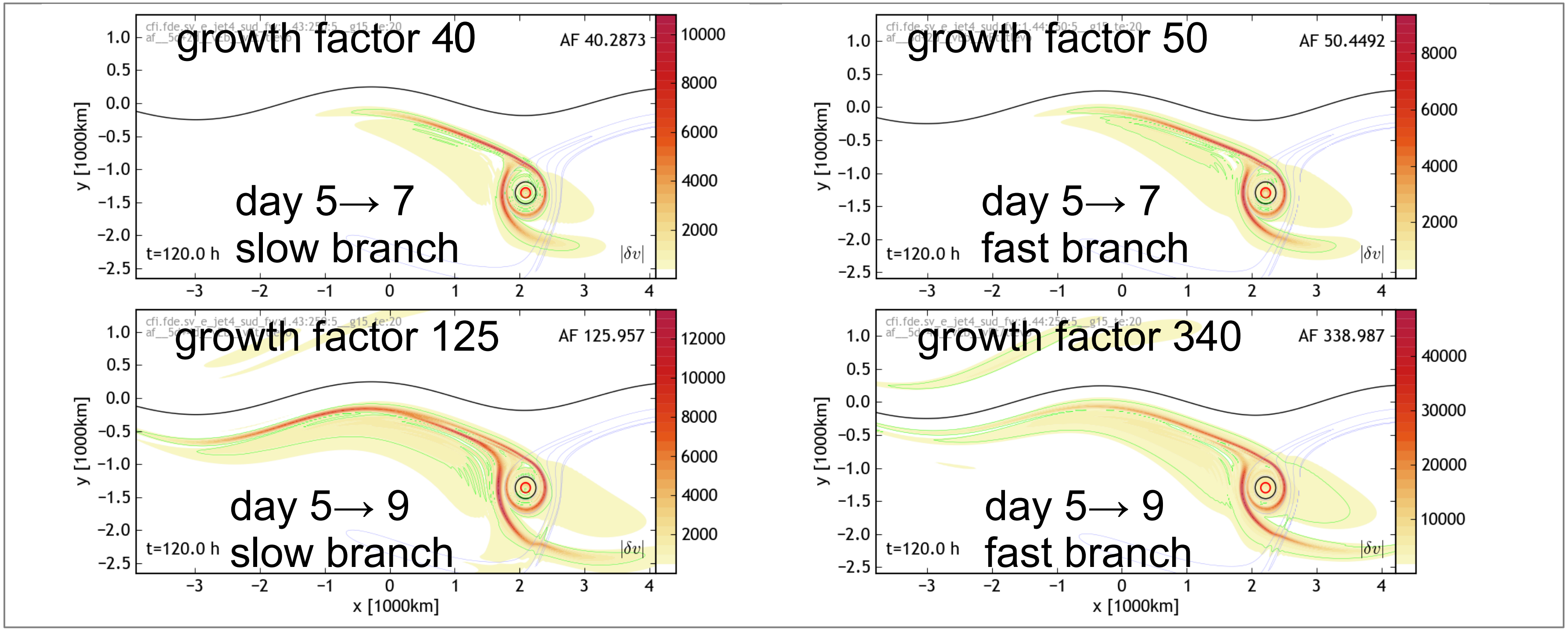
TC-TC interaction

Growth by

- Orr
- TC shift by pert. outside TC core (stagn. Point!)
- Background shear

Linear sensitivity at the bifurcation

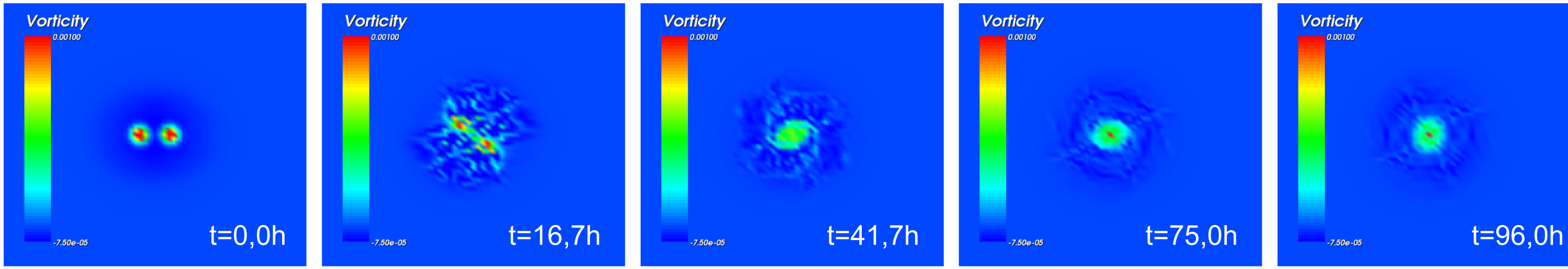
How does bifurcation (non-linear process) influence sensitivity (linearity assumed)?



- differences in growth factor, but similar spatial distribution,

→ even if trajectory is on wrong branch (due to insufficient resolution or observation errors) the sensitive regions close to the ones of the correct branch result (for this scenario)

h-adaptive TC-TC interaction run – cycle 0

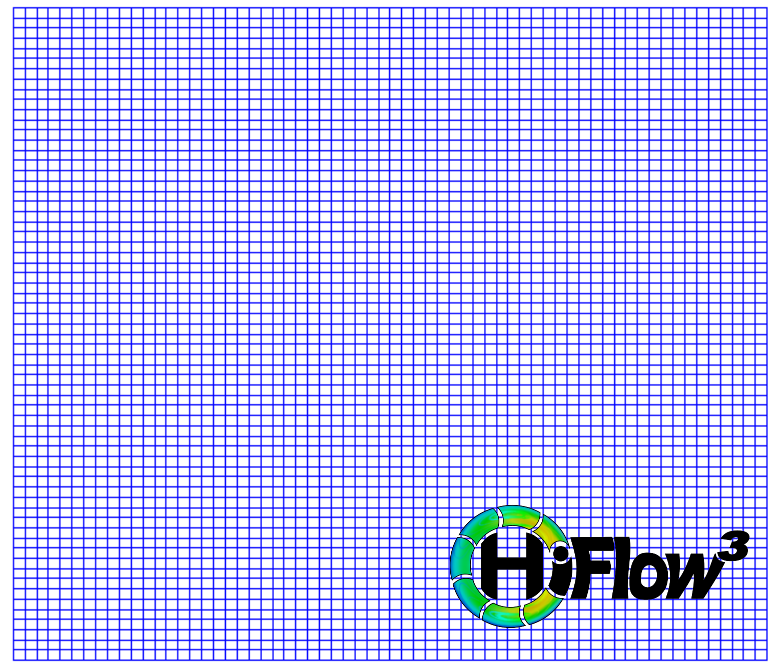


- Degrees of freedom: 36,864
- Position Error [km]: 1504
- Relative error in J: 1

Merged! Wrong branch of the bifurcation!

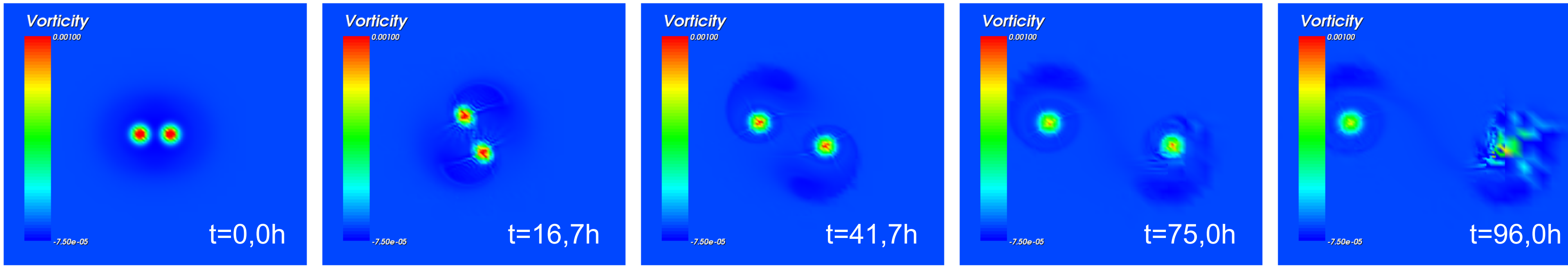
Static grid, refined after each cycle

Goal functional: Vorticity, integrated over core of **left** TC



4000km

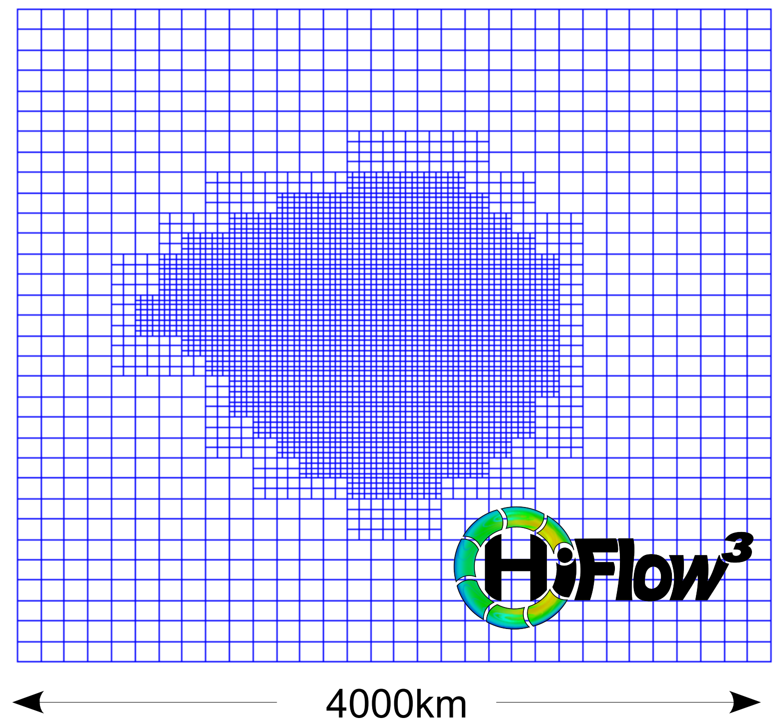
h-adaptive TC-TC interaction run – cycle 1



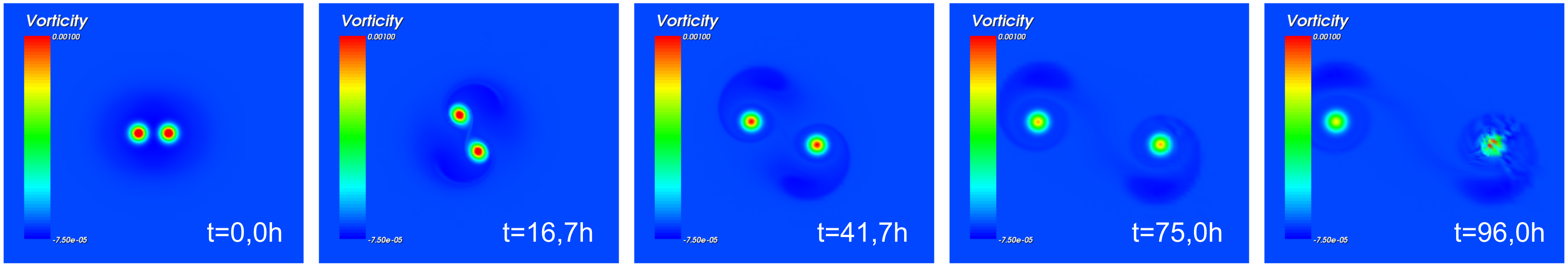
- Degrees of freedom: 39,564
- Position Error [km]: 4.6
- Relative error in J: 0.059

Only slightly increased, but now solution on correct branch of bifurcation.

Goal functional: Vorticity, integrated over core of **left** TC

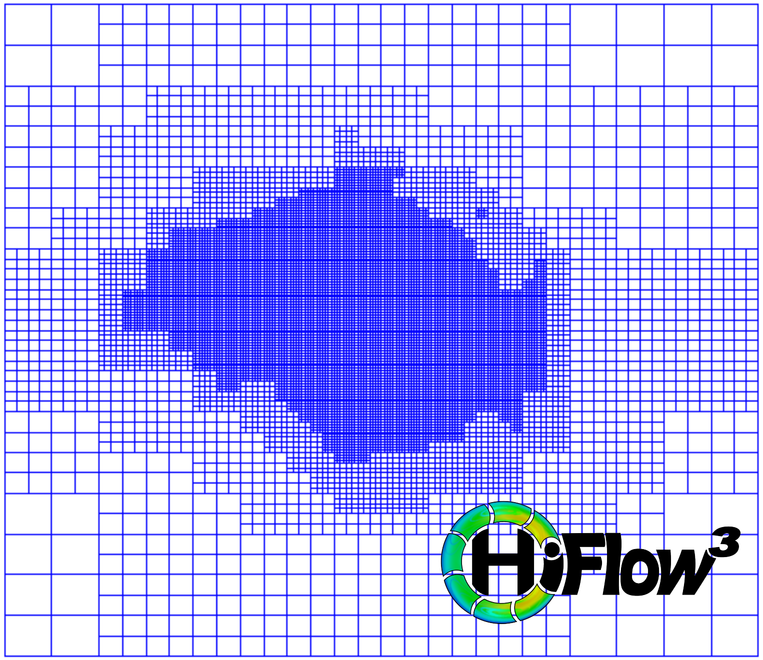


h-adaptive TC-TC interaction run – cycle 2



- Degrees of freedom: 123,172
- Position Error [km]: 3.4
- Relative error in J: 2.9e-3

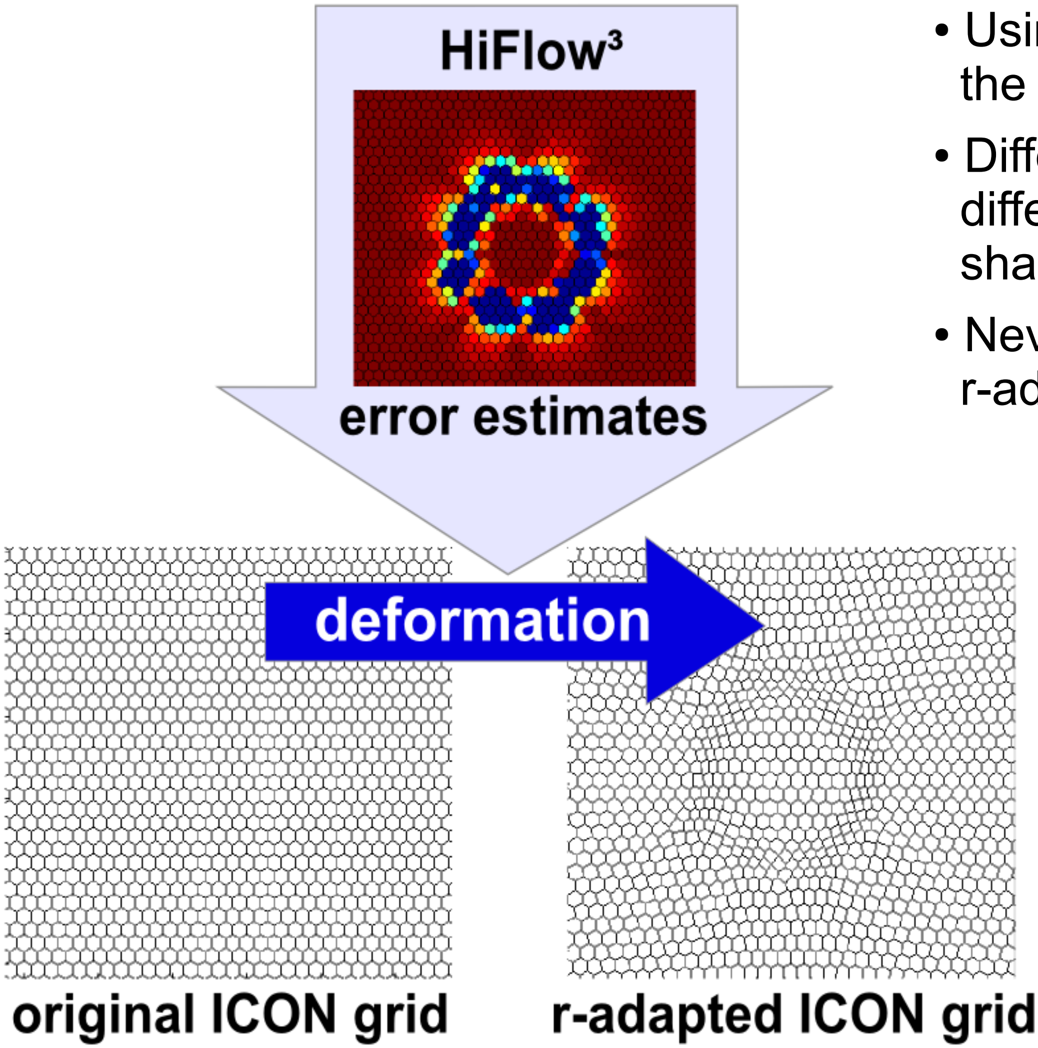
Factor ~20 better than on uniform grid with same number of DoFs



4000km

→ *Baumann et al. poster*

r-adaptive runs with shallow-water ICON



- Using error estimates from HiFlow³ the hexagonal ICON grid is deformed
- Different numerics (FE vs. FD), different model (nondivergent vs. shallow water)
- Nevertheless TC position error on r-adapted grid strongly reduced

↓

This succesfull experiment suggests that computing the error estimates with reduced accuracy (and reduced cost) may be acceptable.

→ *Bauer et al. poster*

Summary

- Goal oriented adaptivity is a promising approach for multiscale problems related to tropical cyclones (TCs)
- We investigated idealised TC scenarios, including TC-front and TC-TC interaction
- We found a high sensitivity of the solutions with respect to the initial TC position, in the most extreme case bifurcations
- Linear sensitivity analysis: Optimal perturbations cause TC displacement, are initially aligned with separatrices
- Structure of optimal perturbations does not change dramatically at bifurcation points
- Adaptive runs yield accurate results for a strongly reduced number of DoFs

Publications on idealised TC scenarios:

- Scheck, Jones, Juckes, 2011: *The resonant interaction of a tropical cyclone and a tropopause front in a barotropic model, Part I: Zonally aligned front,* J. Atmos. Sci., **68**, 3, p. 405-419
- Scheck, Jones, Juckes, 2011: *The resonant interaction of a tropical cyclone and a tropopause front in a barotropic model, Part II: Frontal waves,* J. Atmos. Sci., **68**, 3, p. 420-429
- Scheck et al. 2011: *Singular vectors for the interaction of a tropical cyclone and a tropopause front in a barotropic Model,* in prep.