# Lateral eddy diffusivity estimates from simulated and observed drifter trajectories

a case study for the Agulhas Current system

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## MOTIVATION Dispersal of simulated Lagrangian trajectories not sufficiently diffusive!?

- ***Lagrangian analyses*** of particles advected with the flow fields of ocean models are extensively used to study connectivity (exchange pathways, timescales and volume transports) between distinct oceanic regions.
- ***Lagrangian eddy diffusivity***, which quantifies the rate of particle dispersal due to turbulent processes, influences connectivity.
- Due to spatial and temporal discretization, turbulence is not fully resolved in modelled velocities, and the concept of eddy diffusivity is used for ***stochastic Lagrangian parameterizations*** of the effect of unresolved processes on particle trajectories

Yet, relations between observational- and model-based Lagrangian eddy diffusivities as well as eddy parameterizations are not yet clear.

→ Jointly assess eddy diffusivities from real drifter data and simulated trajectories

## DATA and METHOD Lagrangian eddy diffusivity estimation based on simulated trajectories

TRAJECTORY SIMULATION

**global ocean models**
based on NEMO code
- eddying **INALT01**, 0.1° in Agulhas region (Durgadoo et al. 2013)
- non-eddying **ORCA05**, 0.5° globally

**hindcast simulations**
CORE forcing 1948 – 2009

**simulated velocity fields**
- 5-day means
- monthly means

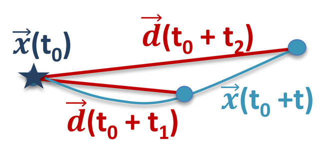
**offline trajectory calculation**
- released particles at 15m depth, every 0.5°, every 30 days between 1996 and 2005
- advected particles 2D (fixed at 15m) using ARIANE code (Blanke and Raynaud 1997)

**~ 900 000 virtual drifter trajectories per experiment**
daily positions for 60 days

**trajectory binning**
sorted all trajectory positions in overlapping 5° x 5° bins with 2° offset

EDDY DIFFUSIVITY ESTIMATION

**pseudo-trajectories**
referenced to their position **x** in bin at time $t_0$




**single-particle statistics**
- displacements $\mathbf{d}(t_0+t|\mathbf{x},t_o)$
- velocities $\mathbf{v_L}(t_0|\mathbf{x},t_o)$

**mean flow estimation**
climatological monthly means
- $\mathbf{V} = \langle \mathbf{v_L}(t_0|\mathbf{x},t_o)\rangle_L$
- $\mathbf{D} = \langle \mathbf{d}(t_0+t|\mathbf{x},t_o)\rangle_L$

**residual components**
- $\mathbf{d}'(t_0+t|\mathbf{x},t_o)$
- $\mathbf{v_L}'(t_0|\mathbf{x},t_o)$

**ensemble-mean (sym) Davis diffusivity tensor**

$$k_{jk}^{davis}(\mathbf{x},t) = (k_{jk}(\mathbf{x},t) + k_{kj}(\mathbf{x},t))/2$$
$$k_{jk}(\mathbf{x},t) = -\langle v_{Lj}'(t_0|\mathbf{x},t_o) \cdot d_k'(t_0-t|\mathbf{x},t_o)\rangle_L$$

**ensemble-mean dispersion tensor**

$$s_{jk}(\mathbf{x},t) = \langle d_j'(t_0+t|\mathbf{x},t_o) \cdot d_k'(t_0+t|\mathbf{x},t_o)\rangle_L$$

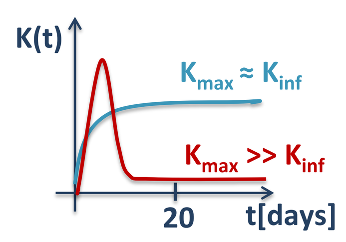
**across-flow projection**
minor princ. components
$s_{p2}(\mathbf{x},t)$
$k_{p2}^{davis}(\mathbf{x},t)$

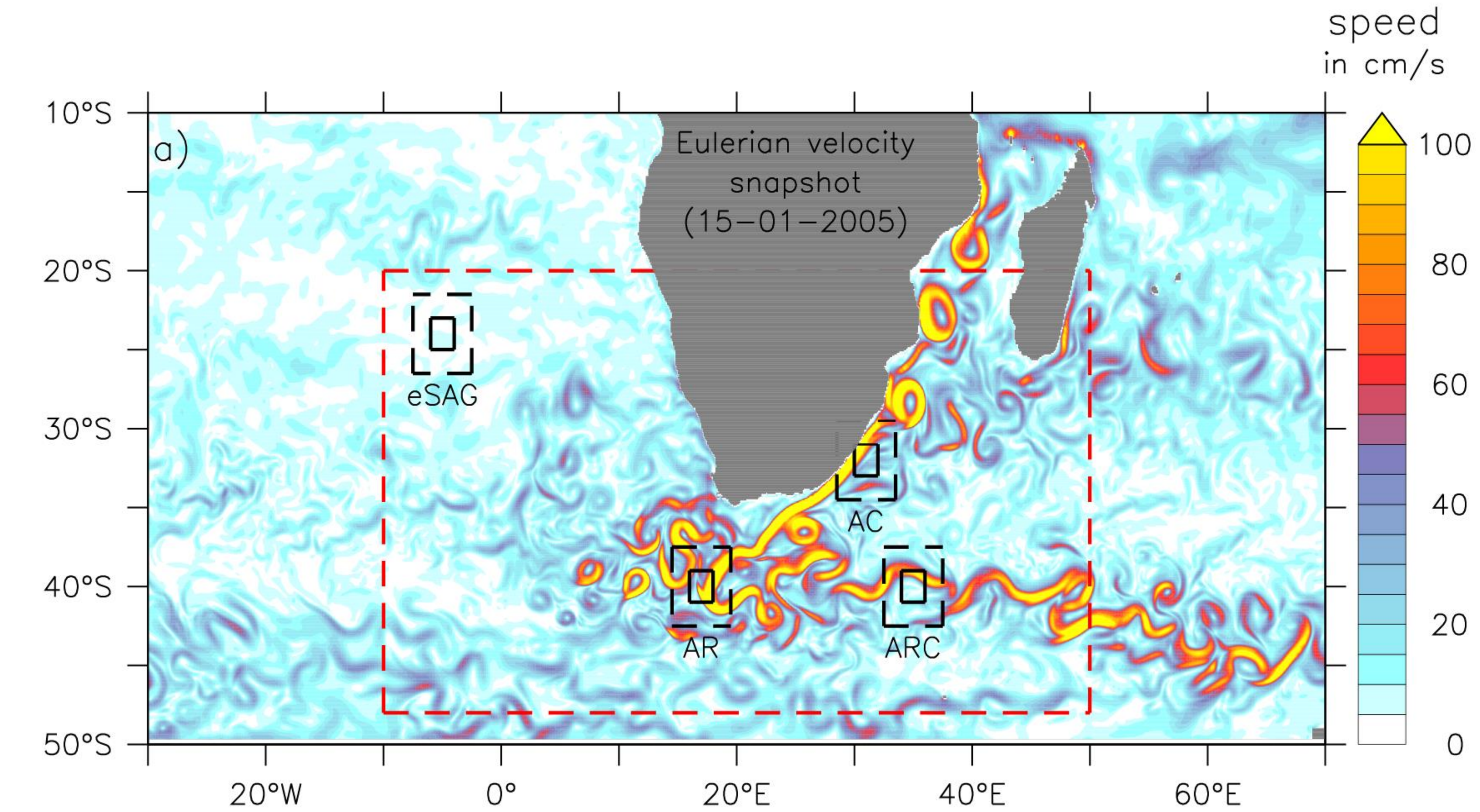
**combined lateral eddy diffusivity estimate**
(Zhurbas et al. 2014)

$$K(\mathbf{x},t) = (k_{p2}^{davis}(\mathbf{x},t) + k_{p2}^{disp}(\mathbf{x},t))/2$$
$$k_{p2}^{disp}(\mathbf{x},t) = 0.5\,\delta s_{p2}/\delta t$$

**$K_{inf}$**

**$K_{max}$**



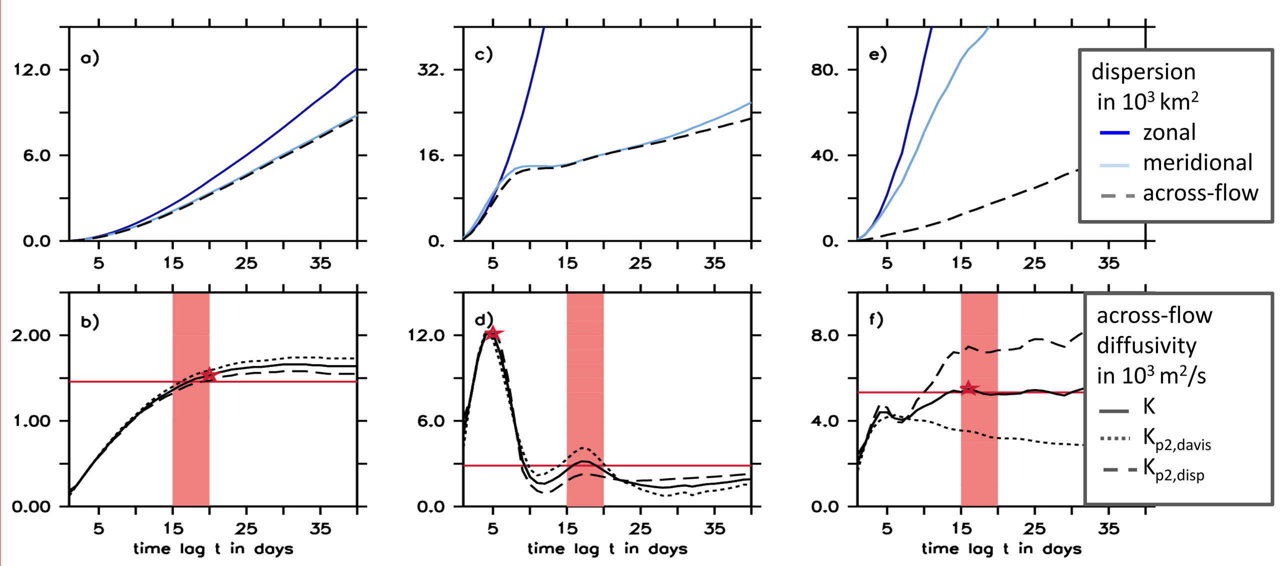

Snapshot of current speed at 15 m depth simulated with the eddying model INALT01; 5° x 5° (2° x 2°) bins used for diffusivity estimations (and plotting) in four areas of interest: Agulhas Current (AC), Agulhas Retroflection (AR), Agulhas Return Current (ARC) and eastern South Atlantic Gyre (eSAG); region where virtual fluid particles were released (red dashed frame).

## RESULT 1 Simulated trajectories capture asymptotic diffusive regimes for dynamically different regions

**Eastern SA Gyre (eSAG)**
- $K_{max} \approx K_{inf} \approx 1500$ m²/s

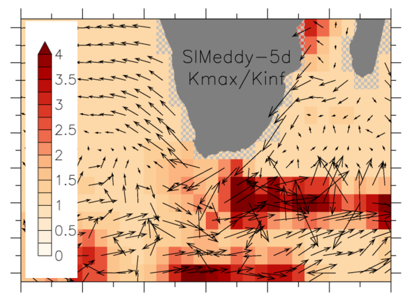
**Agulhas Return Current (ARC)**
- $K_{max} >> K_{inf} \approx 3000$ m²/s

**Agulhas Current (AC)**
- $K_{max} \approx K_{inf} \approx 5500$ m²/s
- But: high uncertainty




Near-surface lateral dispersion (upper) and diffusivity estimates (lower) from trajectories simulated with 5-day mean velocities from the eddying model INALT01 (SIMeddy-5d). Red stars indicate $K_{max}$, red lines $K_{inf}$ estimated considering the shaded time lag interval.

**Suppresion of eddy diffusivities ($K_{max}$>>$K_{inf}$)**
- $K_{max}$ biased estimate $K_{inf}$ sought-after estimate
- In regions where eddies propagate at different speed relative to mean flow (red shading)




Ratio $K_{max}/K_{inf}$ for SIMeddy-5d.

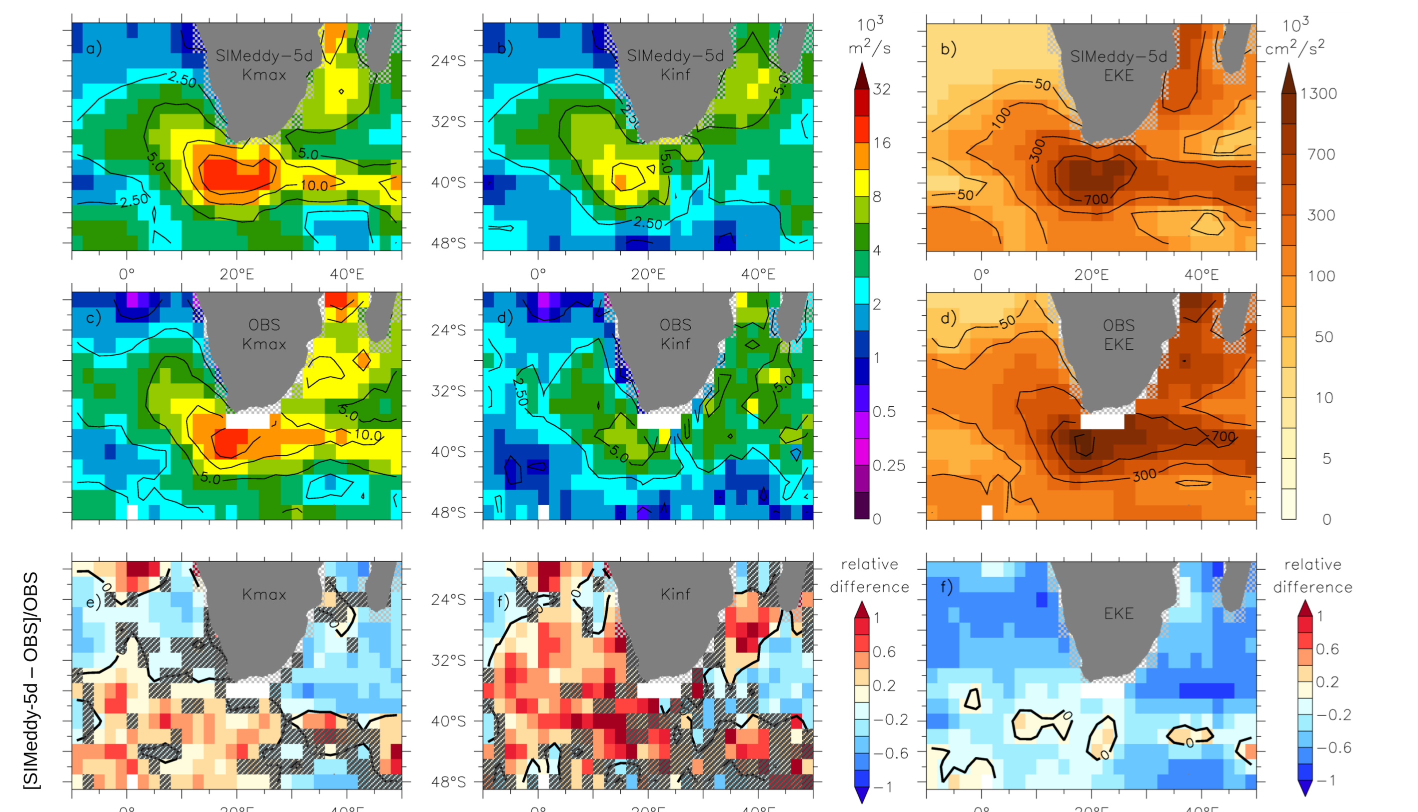
## CONCLUSIONS Implications for stochastic Lagrangian parametrizations

- Our study does not reveal the need for Lagrangian eddy parametrizations in Lagrangian analyses of daily to 5-day mean output of the eddy-resolving model INALT01
- Stochastic Lagrangian parametrizations in diffusion form may indeed be appropriate to mimic the effect of mesoscale turbulence for coarser resolution models
- Sensitivity of the diffusivity parameter to the temporal and spatial model resolution, as well as its spatial variability should be considered, which do not necessarily scale with EKE

## RESULT 2 Model-based eddy diffusivity estimates agree in pattern and magnitude with observational-based estimates

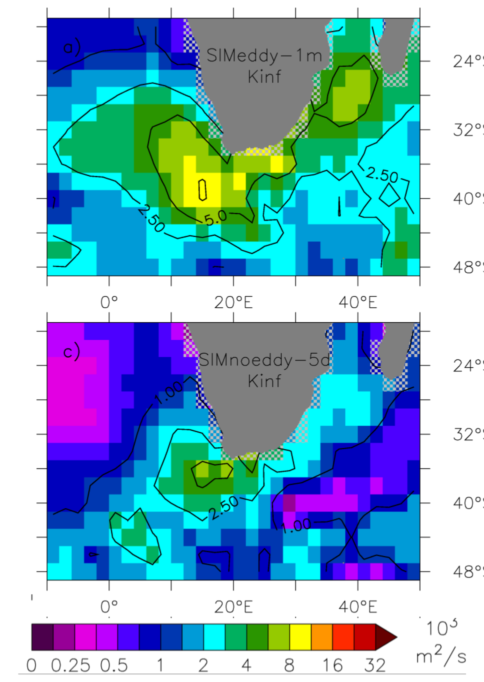
Averaging over all bins yields
- $K_{max}$ lower in SIM than in OBS (5000 vs 5300 m²/s)
- $K_{inf}$ higher in SIM than in OBS (3300 vs 2800 m²/s)

Why?
- Pseudo-Eulerian mean EKE lower in SIM than in OBS (223 vs 310 cm²/s²)
- But also suppression of eddy diffusivities lower in SIM than in OBS




Near-surface $K_{max}$ (left), $K_{inf}$ (middle), and pseudo-Eulerian EKE (right) obtained from simulated (SIMeddy-5d) and real (OBS, Zhurbas et al. 2014) surface drifter trajectories, and relative difference.

## RESULT 3 Model-based eddy diffusivity estimates are less sensitive to model output resolution than EKE

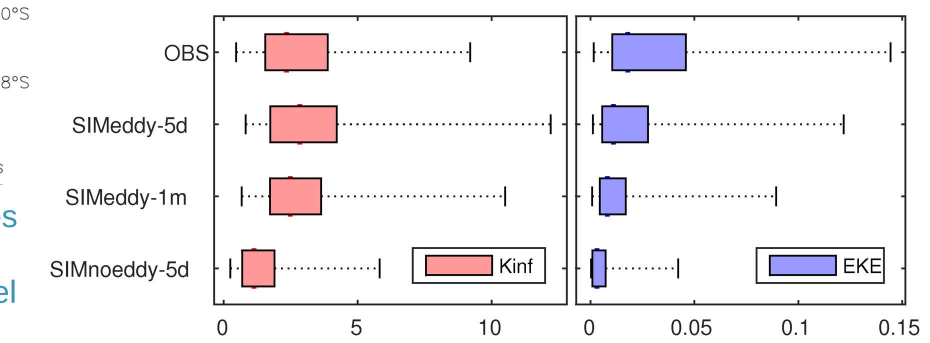



Near-surface $K_{inf}$ from trajectories simulated with monthly mean velocities from the eddying model INALT01 (SIMeddy-1m, upper) and 5-day mean velocities from the non-eddying model ORCA05 (SIMnoeddy-5d, lower).

**Sensitivity to temporal model output resolution**
Using SIMeddy-1m decreases spatially averaged
- Kinf by 12% to 3000 m²/s
- Pseudo-Eulerian EKE by 38% to 139 cm²/s²

**Sensitivity to spatial model resolution**
Using SIMnoeddy-5d decreases spatially averaged
- Kinf by 59% to 1400 m²/s
- Pseudo-Eulerian EKE by 76% to 54 cm²/s²

Non-zero EKE/Kinf due to numerical variability and imperfect scale separation of mean-flow and eddies




Boxplots of the spatial distributions of $K_{inf}$ and EKE. Central mark: median, left and right edges of box: 25th and 75th percentiles, whiskers extend to min and max values.

**References:**
- Blanke, B., & Raynaud, S. (1997). Kinematics of the Pacific Equatorial Undercurrent: An Eulerian and Lagrangian Approach from GCM Results
- Durgadoo, J. V. et al. (2013). Agulhas Leakage Predominantly Responds to the Southern Hemisphere Westerlies.
- Zhurbas, V. et al. (2014). Drifter-derived estimates of lateral eddy diffusivity in the World Ocean with emphasis on the Indian Ocean and problems of parameterisation

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