Mixing and transformation in the Denmark Strait Overflow in the Irminger Basin

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Abstract

The Denmark Strait Overflow (DSO) supplies one third of the North Atlantic Deep Water and is a key component of the global thermohaline circulation. Mixing processes in the Irminger Basin determine transport and properties of the DSO and thus are important for climate model studies. However, the lack of Lagrangian observations and sparse Eulerian observations hinder development of parameterizations of these processes in climate models.
We employ a high resolution circulation model and a set of Lagrangian particles to investigate mixing in the DSO. Lagrangian diffusivities quantify effect of mesoscale $\mathcal{O}$(10-100km) flows resolved by our model but parameterizable in coarse models. The effect of small scale (<2km) processes is quantified with the K-profile scheme in function of stratification and velocity shear and is relevant for regional ocean model.
The mesoscale vertical mixing is enhanced during the initial descent of the DSO, 125–285 km downstream from the Denmark Strait sill, co-localized with strong transformation and entrainment. In this 'mixing pot', dense water 'boluses' of the DSO and intermittent spilling of waters off the shelf induce vertical diffusivities that are two-three orders of magnitude larger (0.5 m2/s) than those due to small-scale mixing. The latter is intensified in approximately same area due to strong vertical shear in the descending DSO. The mesoscale horizontal mixing rates are enhanced further downstream of the sill and in the Kangerdlugssuaq Trough on the shelf.
Our study suggests that the localized mesoscale mixing in the DSO should be considered in coarse global models, while the mixing schemes in regional models should be improved to include bottom boundary layer of the dense plume. We advocate for an observational campaign that would corroborate these results and help develop novel parameterizations of mixing processes involving the DSO.

Methods

Model - MITgcm

- Hydrostatic, depth-coordinate
- Highest spatial resolution to date of the Irminger Basin: dx ~ 2km, max dz=15m (210 layers)
- Simulation period: summer 2003 (7/1 - 9/1)
- 3rd tracer advection with implicit diffusion
- K-Profile Parametrization for vertical mixing (KPP)

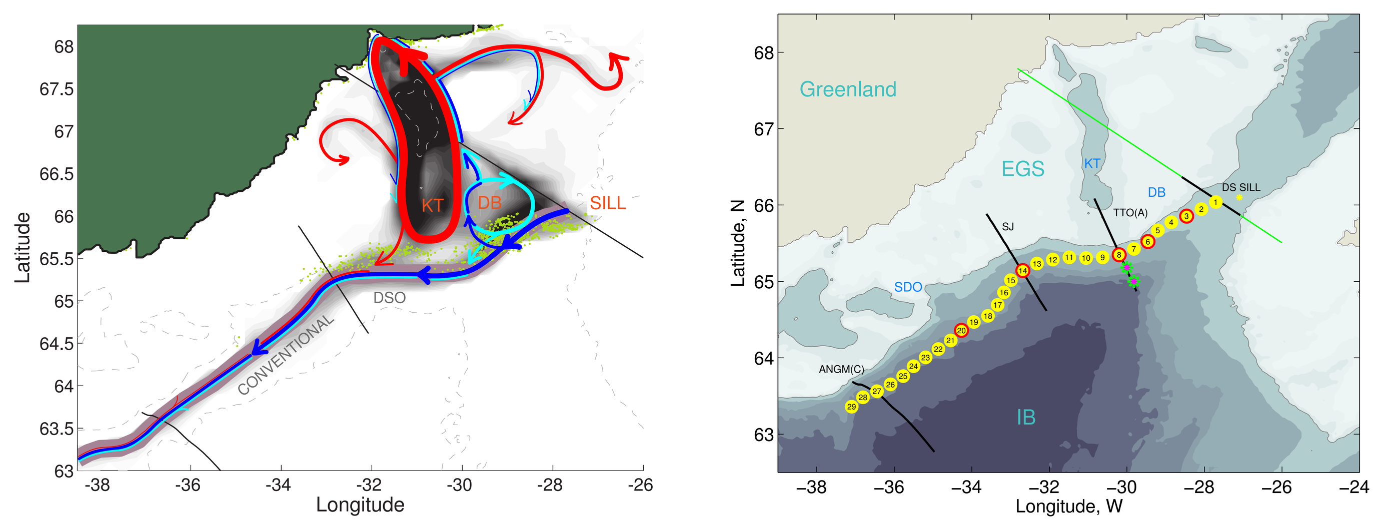
Numerical Lagrangian particles

- Trajectories integrated with model 3D velocities offline using MATLAB (ode23t) and dt=15min
- Velocity & tracers linearly interpolated in space and time on particle positions
- 11813 particles deployed across Denmark Strait. See KHM2013 for more details
- Model validated against observations

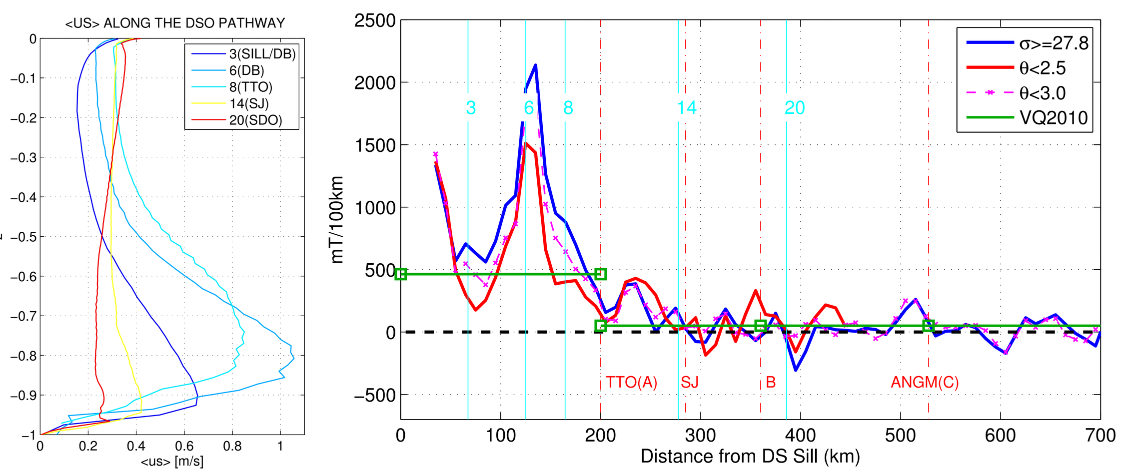
Mixing diagnostics

– Evolution of a tracer C is modeled by the advection-diffusion equation: $\frac{\partial}{\partial t}C + \mathcal{U}\nabla C = \nabla(\mathcal{K}\nabla C)$, where $\mathcal{U}$ is the advection by resolved flows and $\mathcal{K}$ is the diffusivity due to unresolved turbulent processes.
– The magnitude of horizontal diffusivity will depend on scale (e. g., resolution of a given model) until the diffusive regime is reached (>100km, few days).
– In depth coordinate, the vertical diffusivity can be much larger than diapycnal diffusivity in case of sloping isopycnals due to contribution of $\mathcal{K}_{isop} * S_p$ where S_p is isopycnal slope.

Evolution of the DSO in the Irminger Basin



Left: Dense water ($\sigma_\theta \geq 27.8$ kg/m3) pathways derived from Lagrangian particles (see KHM2013). Right: Eulerian stations (yellow dots) and standard sections (black) along the traditional DSO pathway in the Irminger Basin.



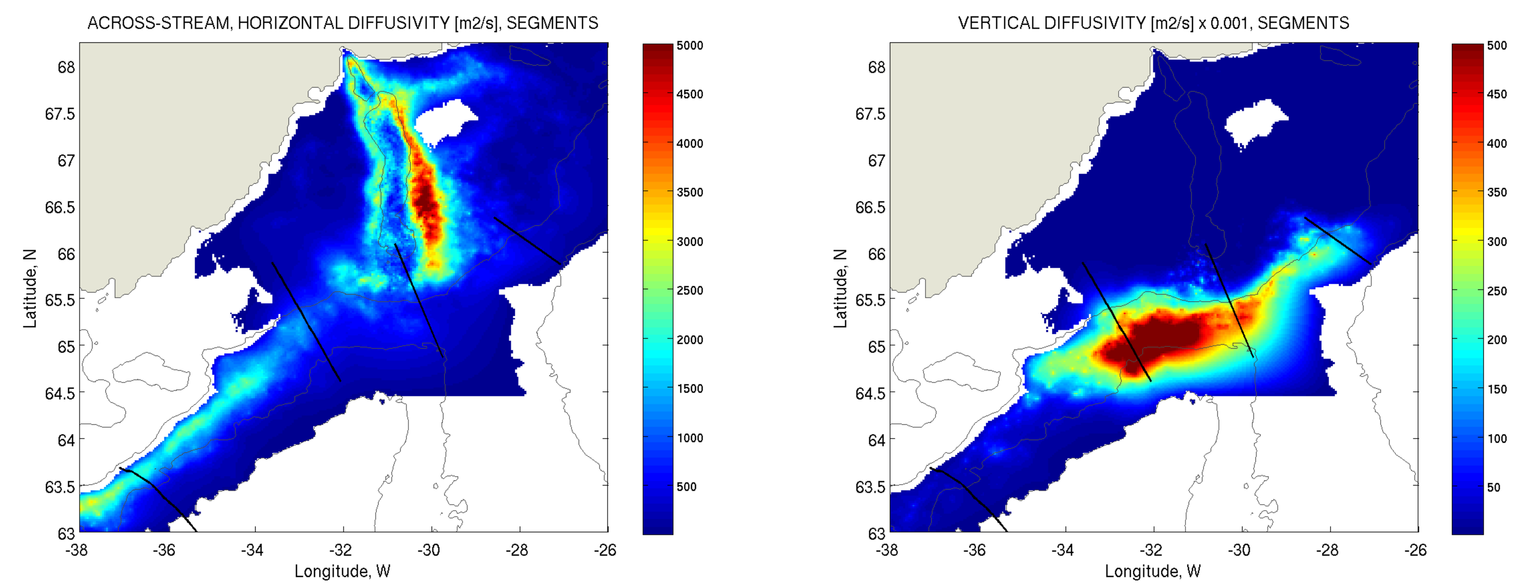
Left: 2-month average of the dense plume velocity in the Irminger Basin. The DSO features typical dense plume structure with high (1 m/s) velocities within 300 km from the sill. Right: Transformation (warming) of the DSO from model particles averaged in distance bins compared to results of VQ2010 from moorings. Note high warming rates in the first 200km from the sill.

Scale-dependent mixing in the DSO

We quantified eddy diffusivities ($\mathcal{K}$) at two scales: mixing by 'mesoscale' (2-100km) flows, relevant for coarse resolution models; and 'small-scale' mixing (≤2km), relevant for regional circulation models.

Mesoscale mixing

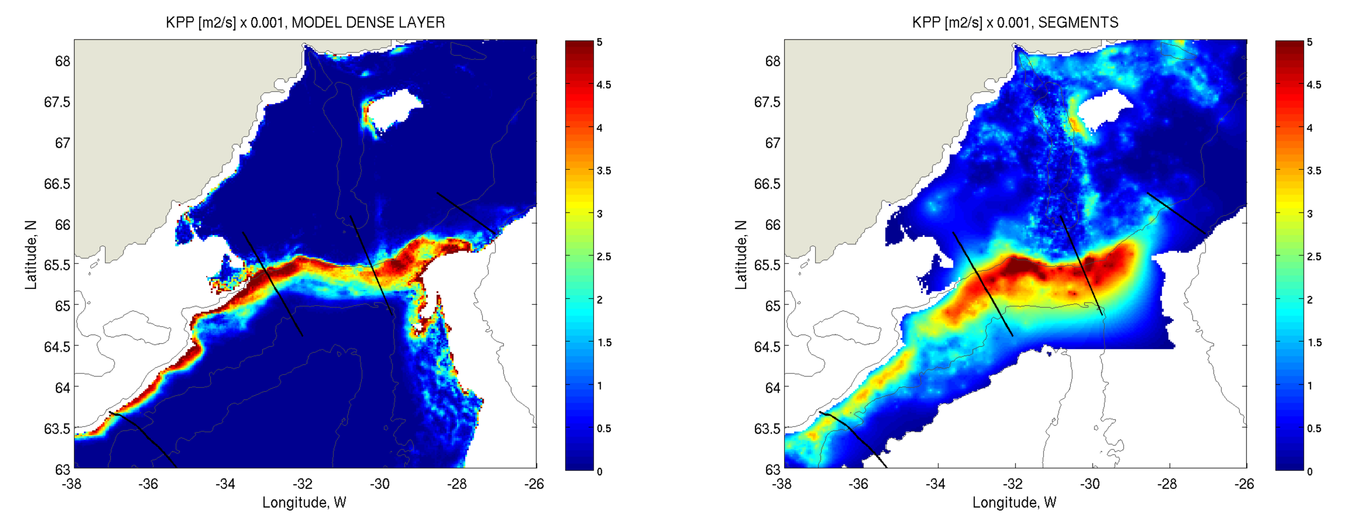
– Mesoscale mixing is derived from integral of 'eddy' velocity autocorrelation (where 'eddy' is the residual from spatially-dependent time-mean) along 10-day trajectory segments. The convergent value of the horizontal (across-mean-velocity component) and the vertical diffusivity is assigned to mid-point segment position and interpolated on horizontal (long-lat) plane.
– This diffusivity coefficient quantifies the effect of mesoscale flows (dense water boluses and intermittent spilling of dense water from the shelf) and is a product of the velocity variance and the decorrelation time scale.



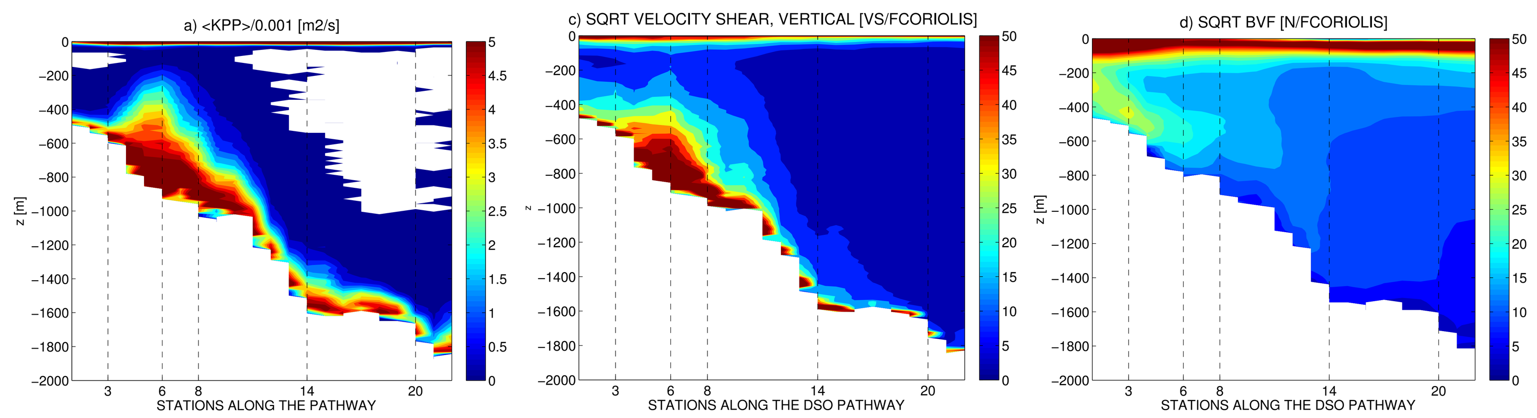
Mesoscale diffusivities, derived from velocity autocorrelation on trajectories and interpolated onto a horizontal plane. Left: Horizontal, across-stream diffusivity. Right: Vertical diffusivity.

Small-scale mixing

– Small-scale mixing is quantified by tracer diffusion coefficient calculated internally by the KPP scheme in function of stratification and shear.
– It quantifies effect of turbulence unresolved by a regional ocean model.

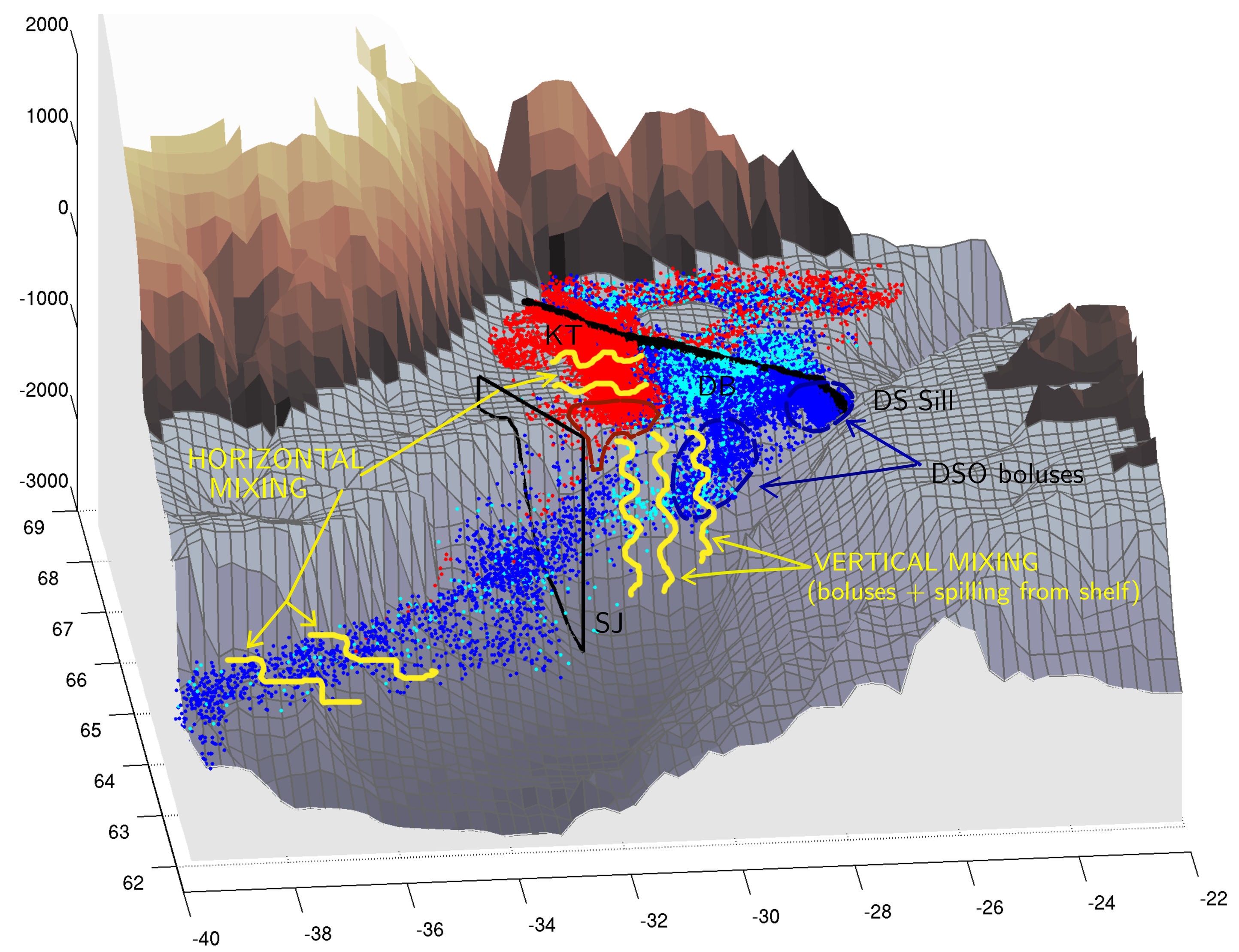


Left: Time- and depth average (in the dense water layer) of the KPP coefficient from model. Right: same but interpolated on trajectory segments and mapped back from the mid-segment position. The difference between the two panels quantifies smoothing effect of the Lagrangian method and the contribution of entrained dense waters that are not sampled by particles deployed in the DSO in the Denmark Strait.



Time-averaged along the DSO pathway (from left to right): KPP coefficient, velocity shear, stratification. The KPP is enhanced between the sill and the SJ section, mainly due to vertical shear in dense water boluses cascading from the sill. However, occurrences of neutral stratification under the leading edge of the boluses are frequently recorded at most stations (not shown) and are simply capped by a set maximum value of the KPP scheme which does not include the physics of dense overflow (no bottom boundary layer of the dense plume).

Summary



The schematic above, based on composite of particle positions on 2,7,14,21 and 28 day (see KHM2013), visualizes the results:
– The mesoscale vertical mixing is enhanced at (125-285km) from the sill where dense water boluses cascading to the Irminger Basin and intermittent spilling of dense waters off the shelf generate high vertical velocities (~ 0.01 m/s) and vertical diffusivities up to 0.5 m2/s. The small-scale vertical mixing is large (up to 0.01 m2/s) in the same area due to vertical shear induced by mesoscale flows. Elsewhere in the domain the vertical diffusivities are 2-6 magnitudes lower. Downstream of the SJ section, and near the Kangerdlugssuaq Trough on the shelf the horizontal mixing becomes important.
– These results are consistent with estimates of VQ2010, and co-locate with region of intense transformation of DSO Water. This localized 'mixing pot' should be considered in depth-coordinate global models that do not resolve mesoscale processes.
– The popular KPP scheme in a regional model identifies areas conducive to strong small-scale mixing, but is not tailored for dense overflow - it lacks physics of the bottom boundary layer specific to dense plume.
– We advocate for an observational campaign that would corroborate these results and help develop novel parametrizations of mixing processes involving the DSO.

References

KHM2013: Koszalka, Haine, Magaldi, 2013, JPO, 43, p.2611, doi:10.1175/JPO-D-13-023.1 (see qr code below)
VQ2010: Voet & Quadfasel, 210, Ocean Sci, 6, p.301

More information

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More information and results can be found at the project webpage:
http://blaustein.eps.jhu.edu/~koszalka/dsow_webpage/DSOW.html

Particle animations can be viewed here: http://blaustein.eps.jhu.edu/~koszalka/dsow_webpage/MOVIES.html

Webpage | KHM2013 | Particle animations (m4v & mp3)