

Warnemünder Turbulence Days 30.08. – 3.09.2015

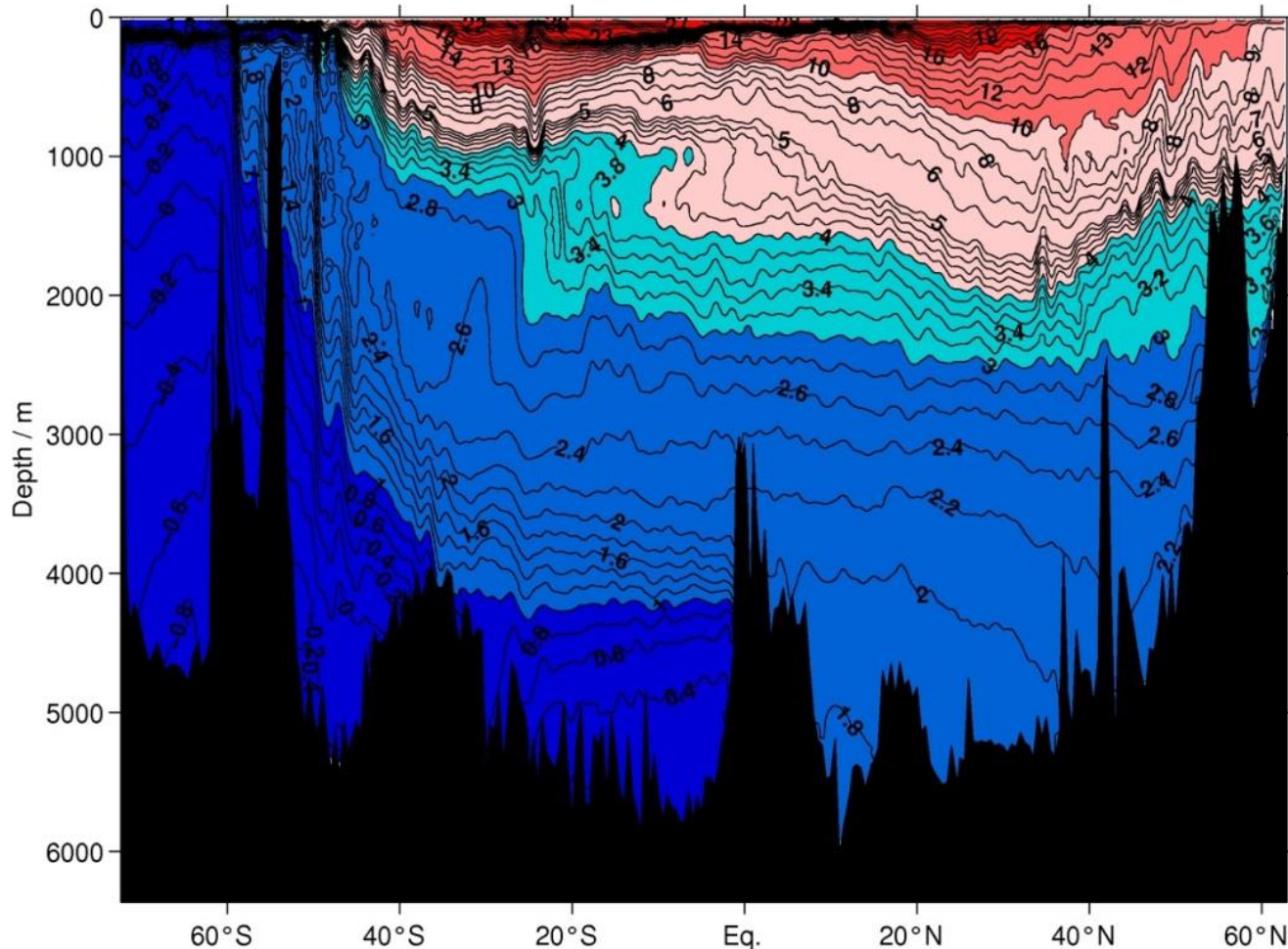
Overflow induced turbulence in a deep ocean channel

Sandra Tippenhauer, Marcus Dengler, Tim Fischer, Torsten Kanzow



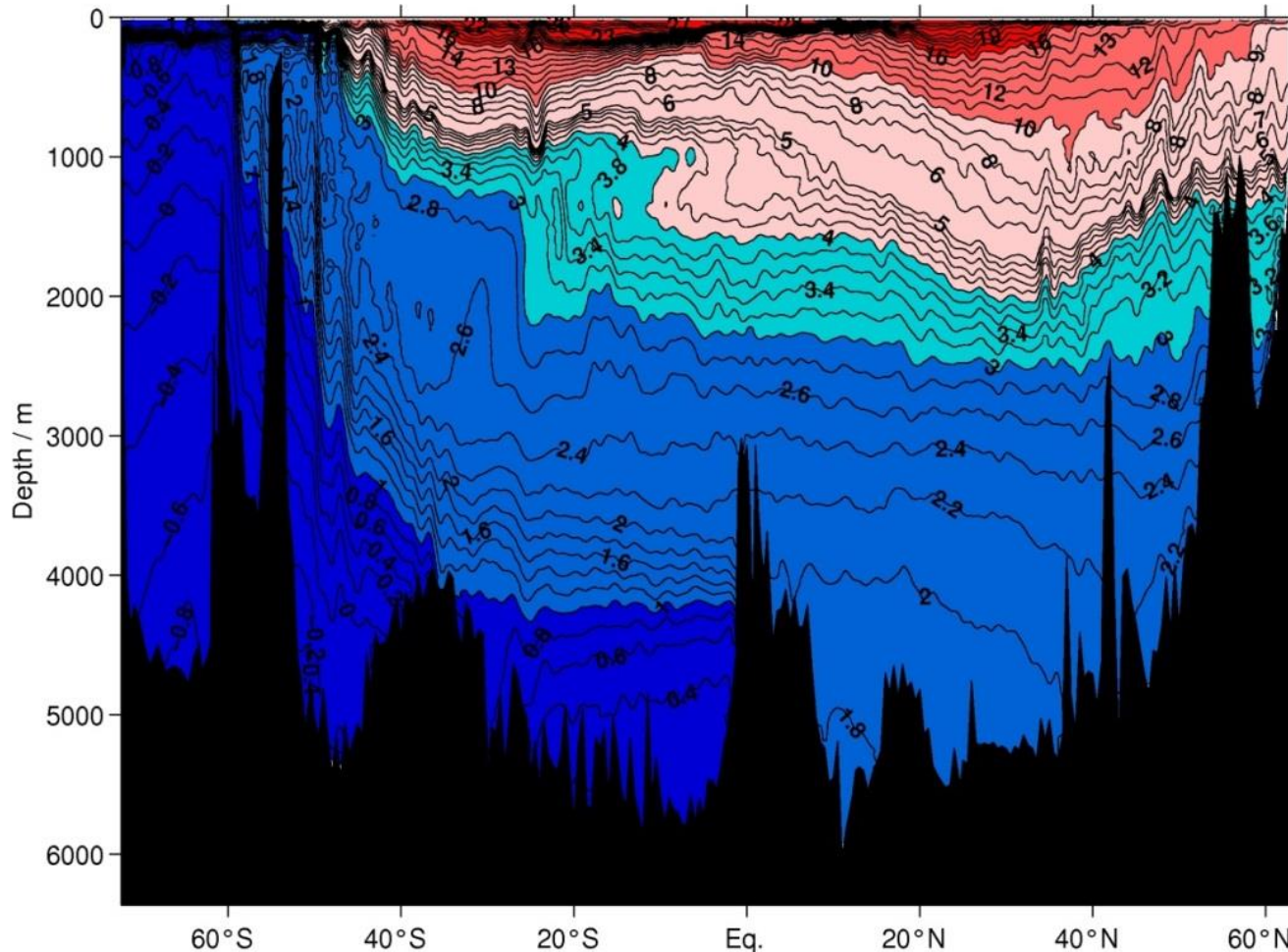
ALFRED-WEGENER-INSTITUT
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UND MEERESFORSCHUNG





Continuously stratified

Meridional temperature distribution across the Atlantic (Kanzow and Visbeck, 2009).



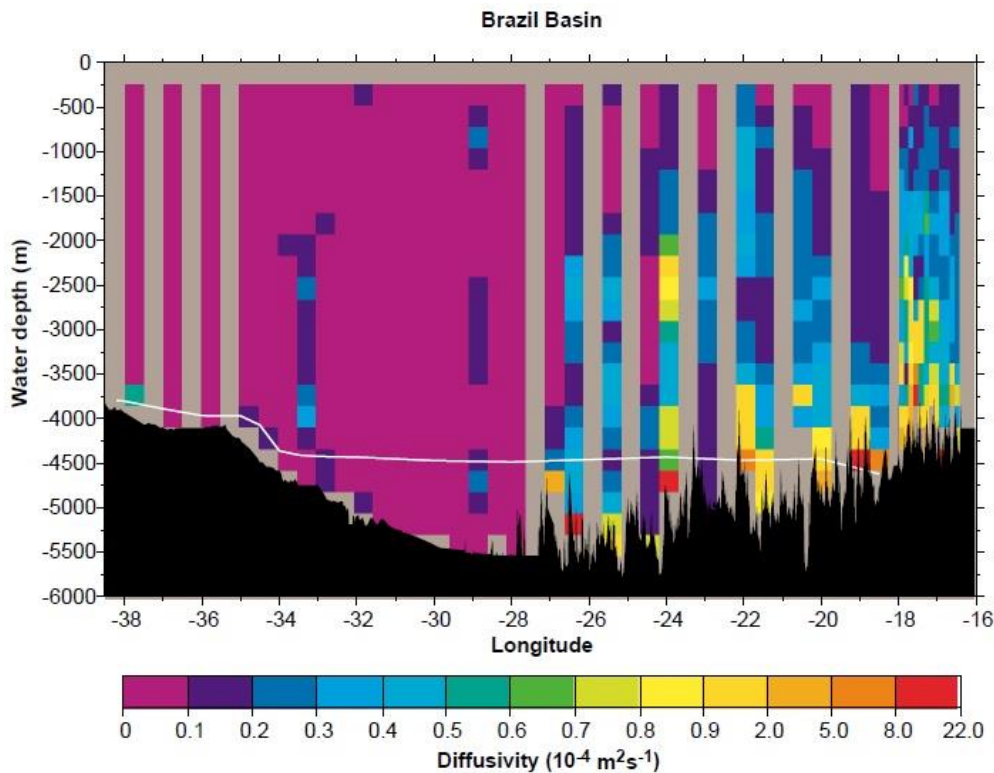
Continuously stratified

To maintain the stratification of the deep ocean and to close the global meridional overturning circulation (MOC) there has to be diapycnal mixing.

Meridional temperature distribution across the Atlantic (Kanzow and Visbeck, 2009).

- Diffusivity of $K = 10^{-4}$ m²/s if mixing is distributed uniformly (Munk, 1966).
- Only $K \sim 10^{-5}$ m²/s observed (Ledwell et al. 1993, Toole et al. 1994).

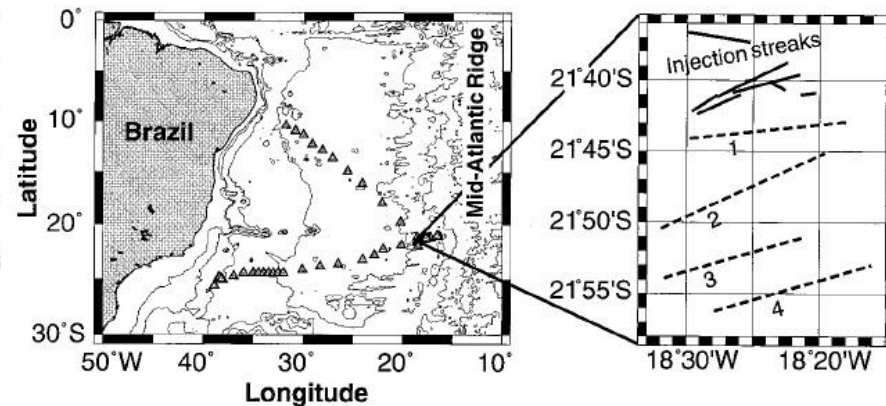
- Diffusivity of $K = 10^{-4} \text{ m}^2/\text{s}$ if mixing is distributed uniformly (Munk, 1966).
- Only $K \sim 10^{-5} \text{ m}^2/\text{s}$ observed (Ledwell et al. 1993, Toole et al. 1994).
- Mixing is distributed non-uniformly.
Elevated close to rough topography of e.g. Mid-Ocean ridges.



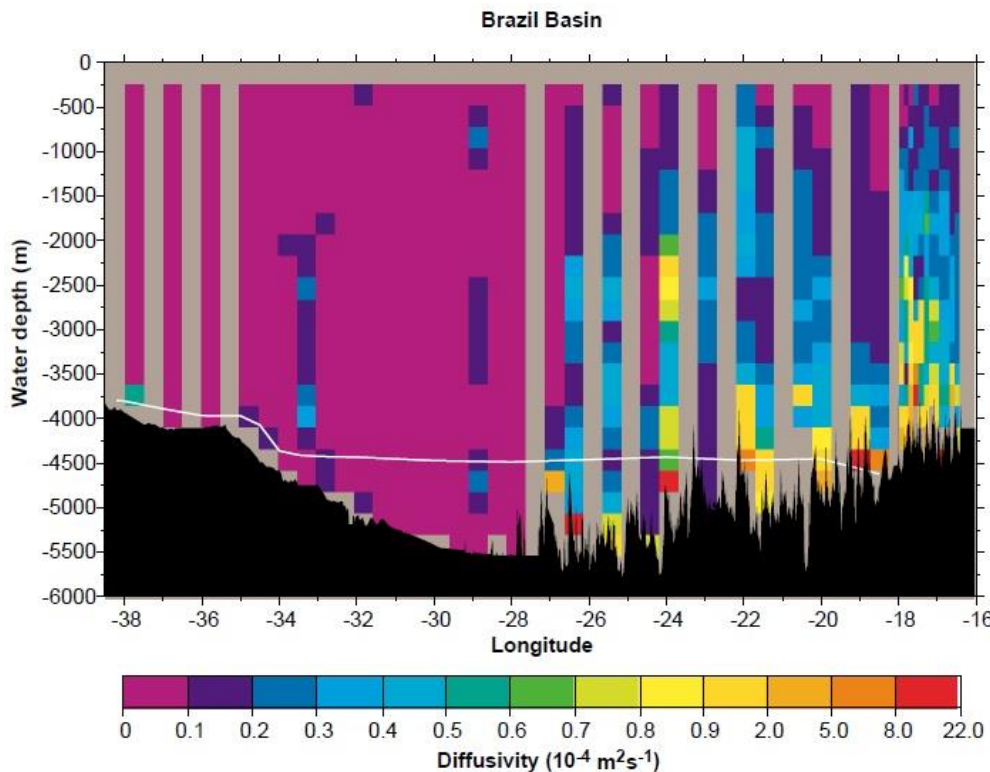
Diffusivity $K = \frac{\gamma \varepsilon}{N^2}$ (Osborn 1980)

ε – observed dissipation rates,
 N – buoyancy frequency,
 $\gamma = 0.2$ – mixing efficiency.

Diapycnal diffusivity in the Brazil basin. White line marks 0.8°C surface (Polzin et al., 1997).



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- Mixing is distributed non-uniformly.
Elevated close to rough topography of e.g. Mid-Ocean ridges.
- Commonly explained by topography-induced breaking of internal waves.



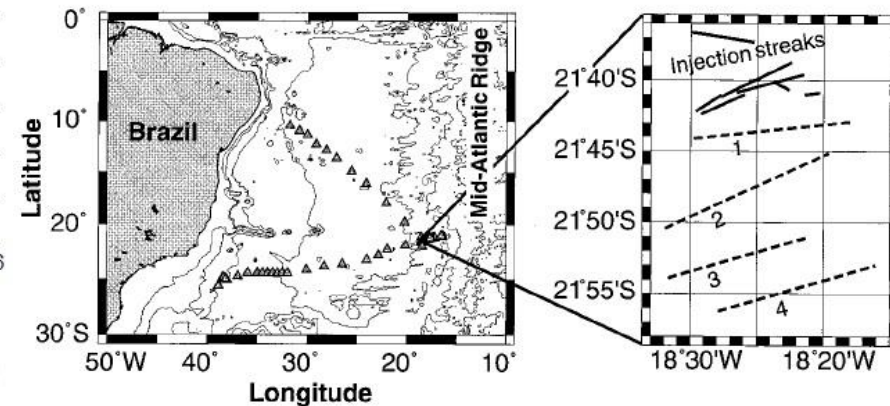
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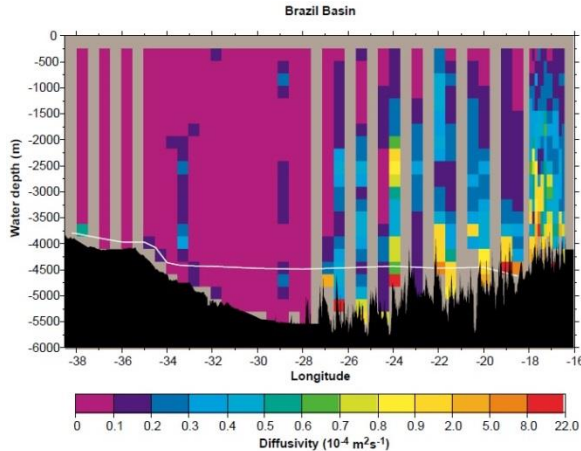
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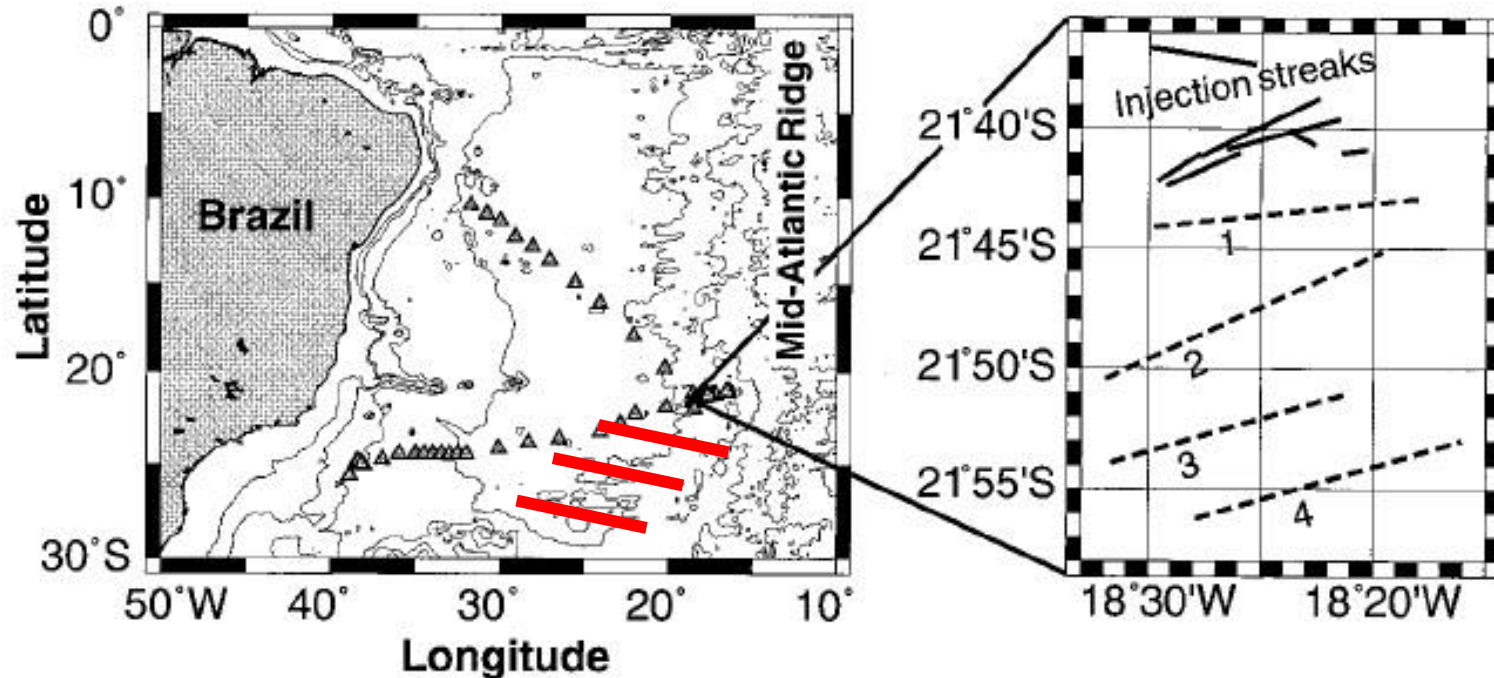




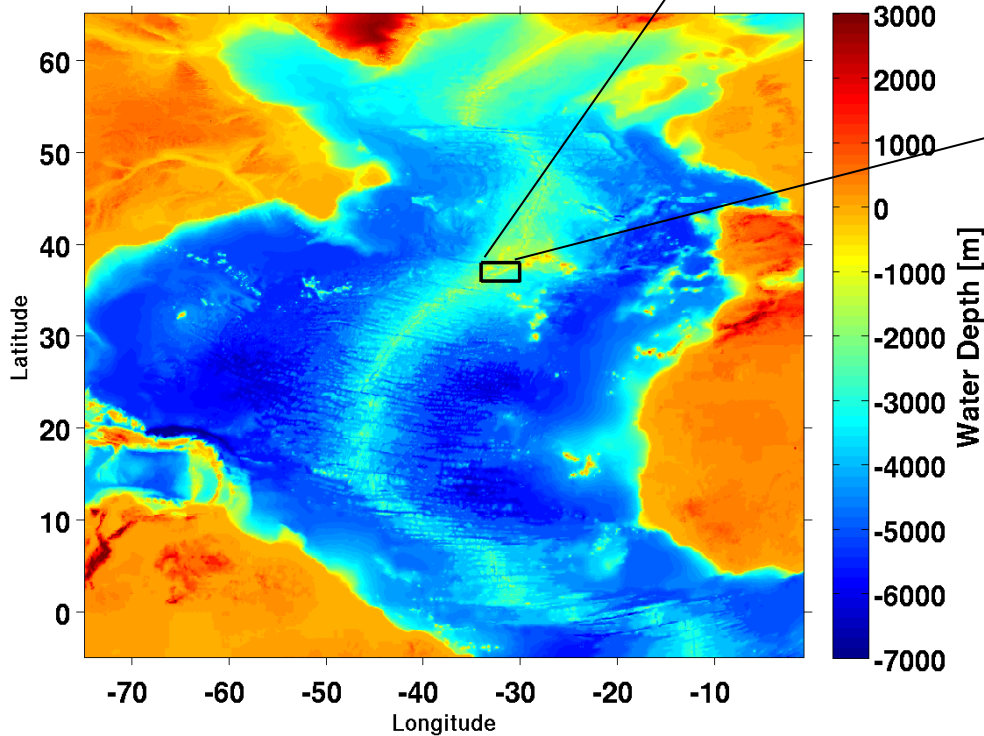
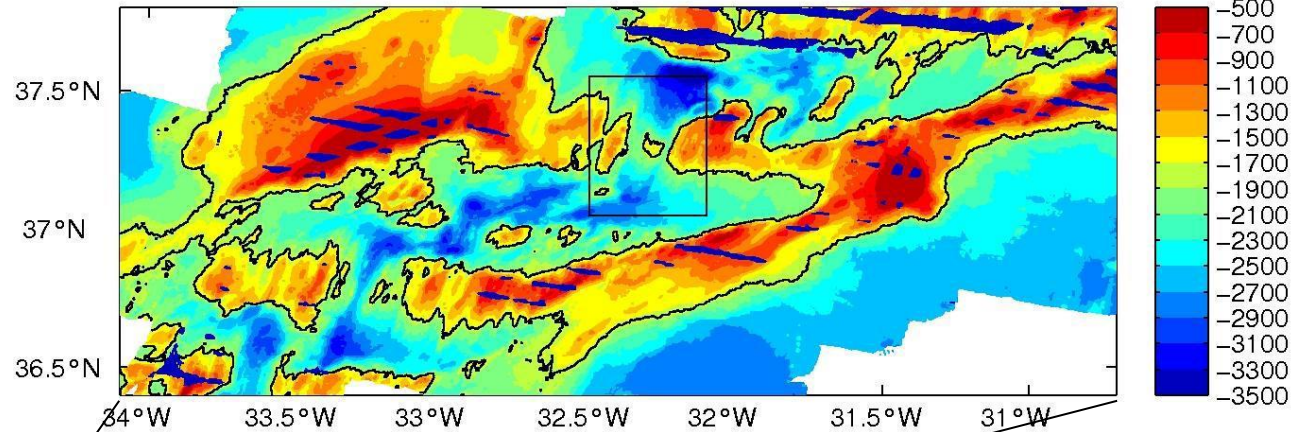
Diapycnal diffusivity in the Brazil basin. White line marks 0.8°C surface (Polzin et al., 1997).

High mixing rates in canyons of mid-ocean ridges.

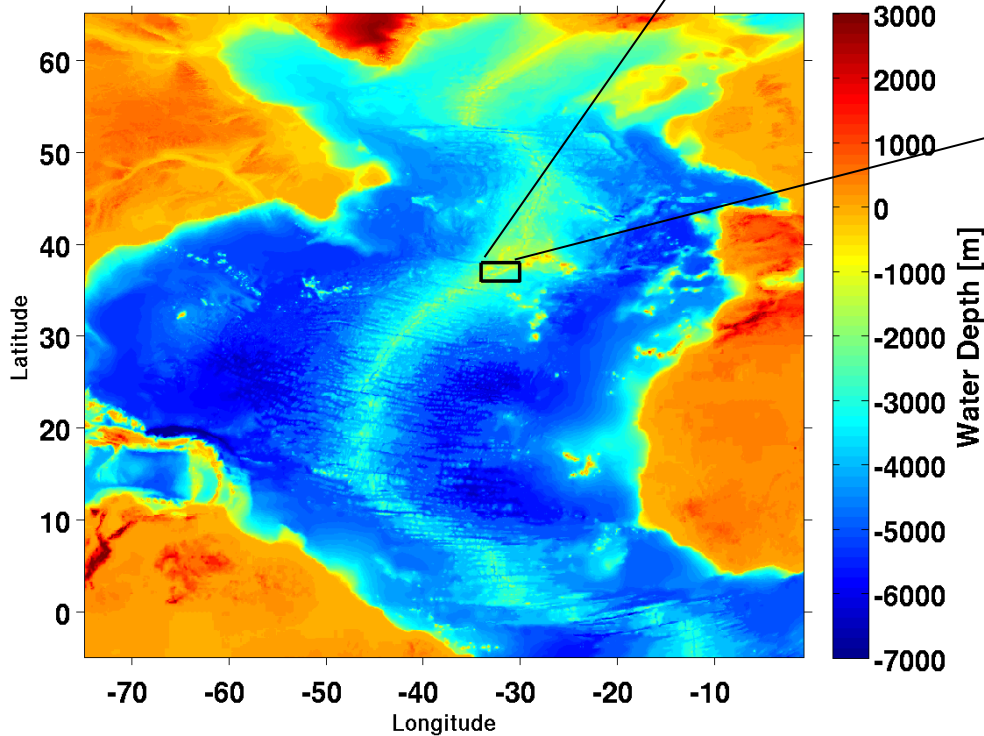
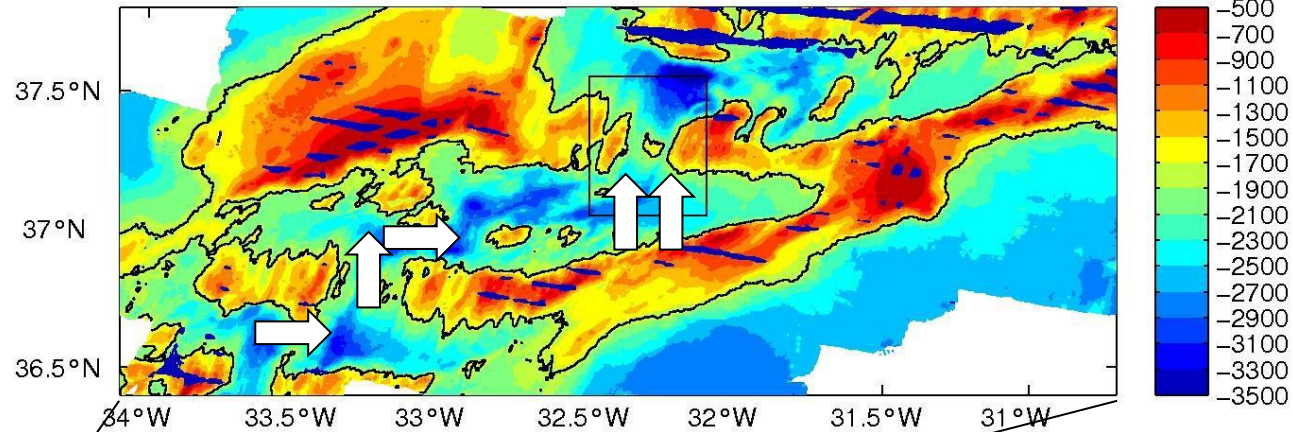
Associated to along-channel flow across sills (e.g. Thurnherr and Speer 2003, Thurnherr et al. 2005, and St. Laurent and Thurnherr, 2007).



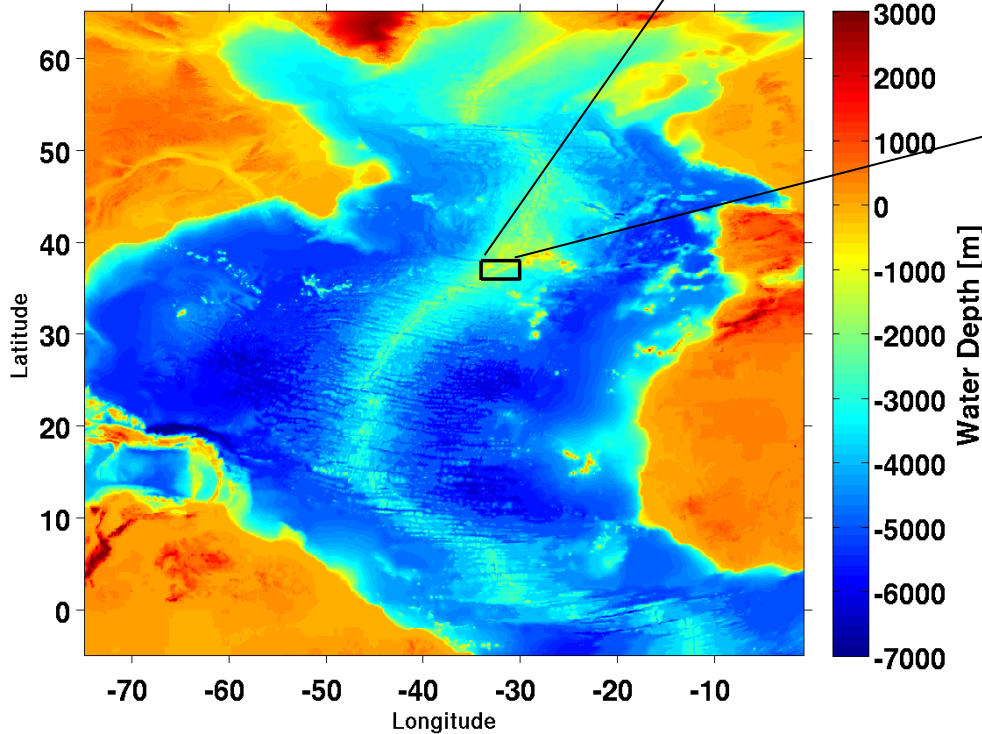
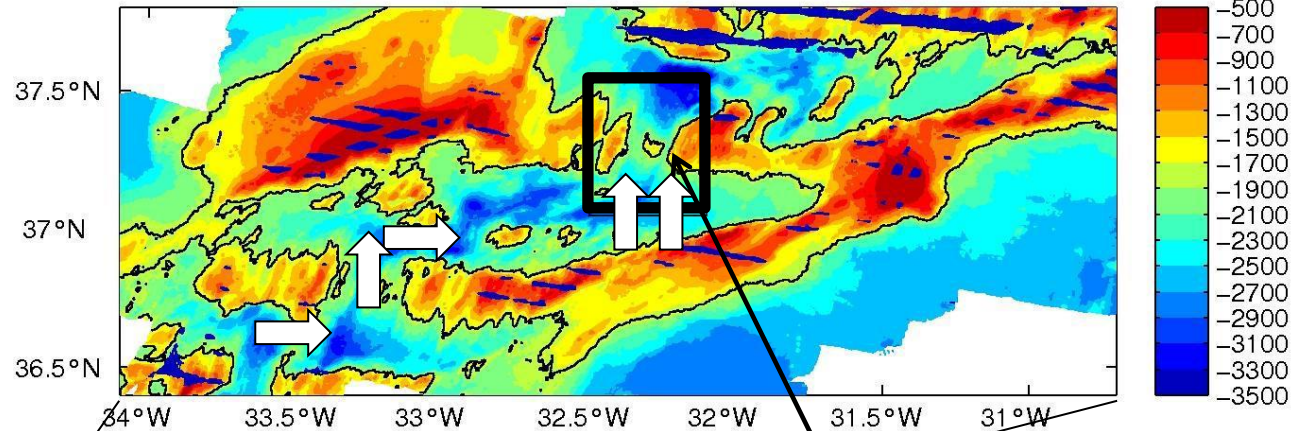
Central Valley of the Mid-Atlantic-Ridge (MAR) near Azores.



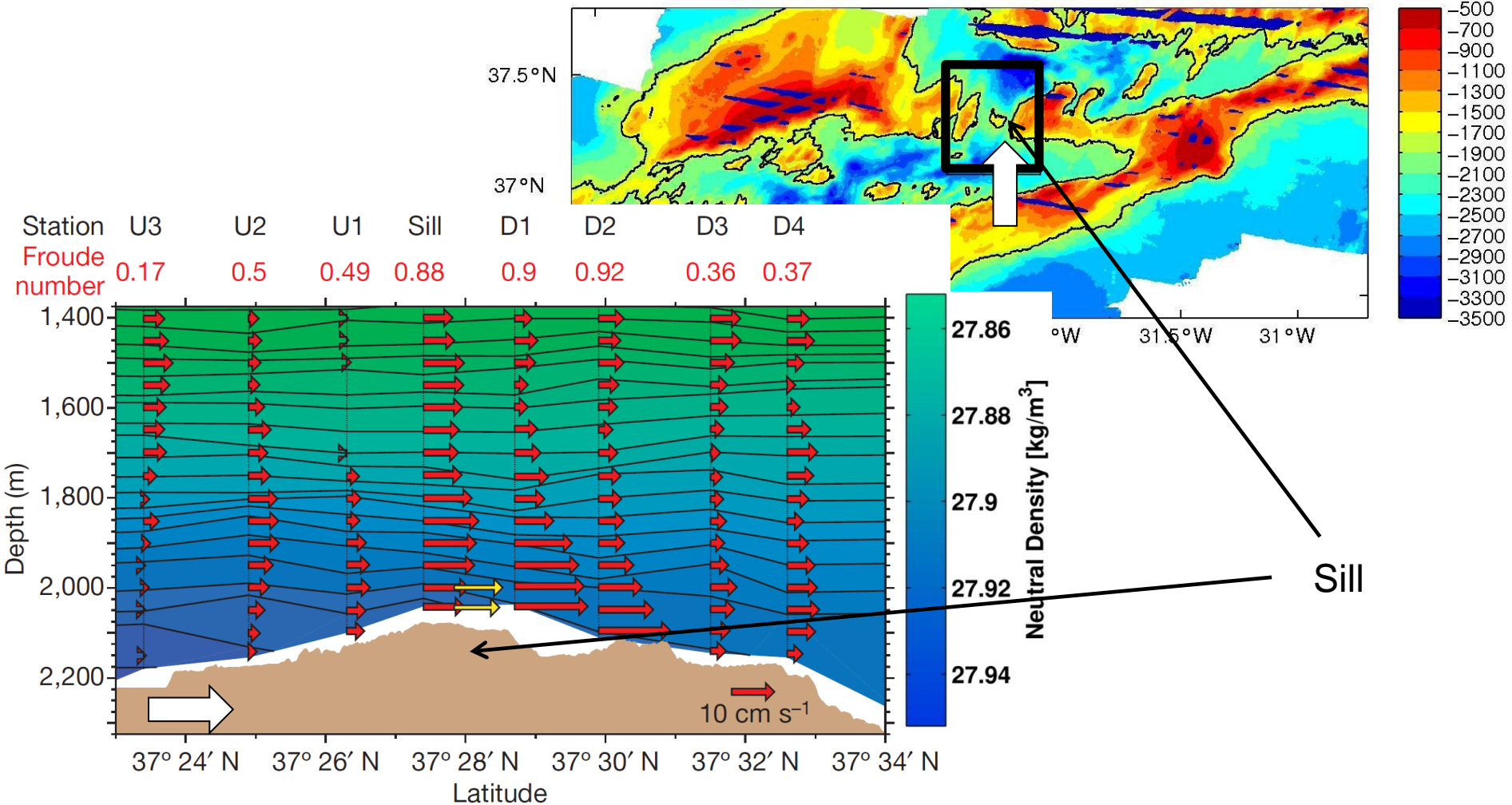
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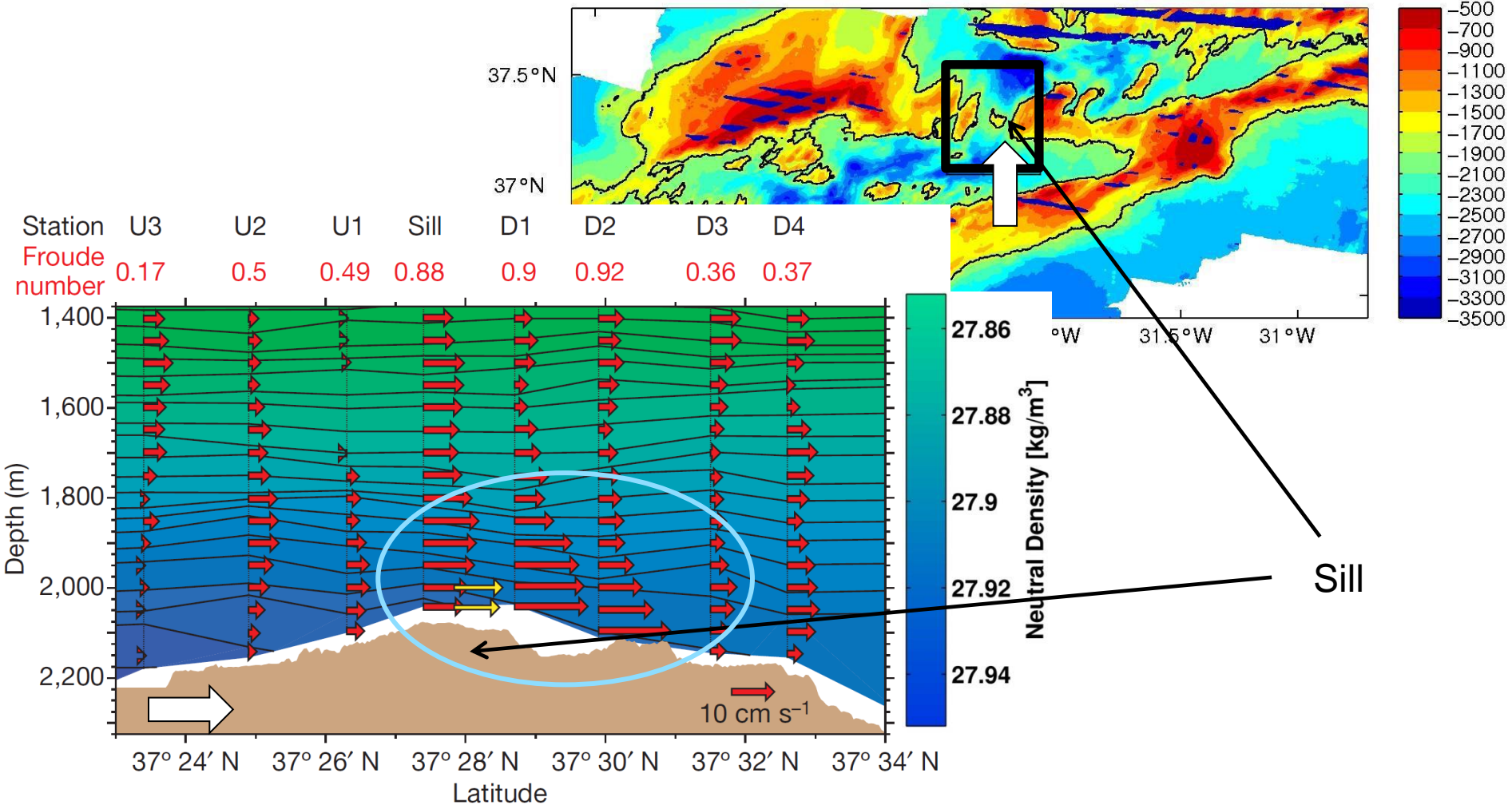


Sill
Lucky Strike segment



Red arrows: 50-m-averaged lowered ADCP data.
 Yellow arrows: the two-week-averaged velocities (St. Laurent and Thurnherr, 2007).

Average velocity $> 10 \text{ cm/s}$
 Maximum velocities $\sim 20 \text{ cm/s}$



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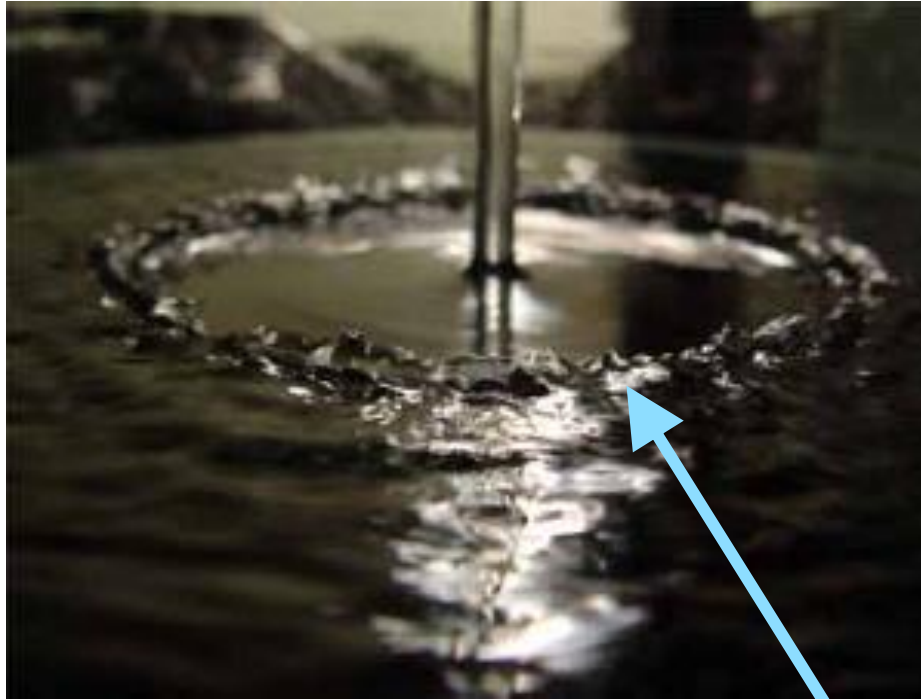
Average velocity > 10 cm/s
 Maximum velocities ~ 20 cm/s



<http://lamanto.blogspot.de/2009/05/circular-hydraulic-jump.html>



https://commons.wikimedia.org/wiki/File:Hydraulic_jump_on_Naramatagawa_River%27s_stream.JPG



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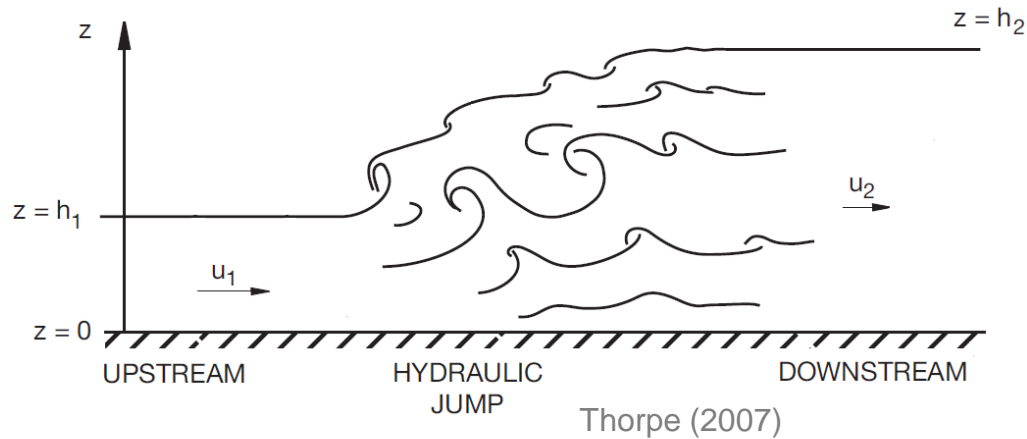
Hydraulic Jump



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Froude Number: ratio of flow speed to speed of waves

$$Fr = \bar{u} / \sqrt{g'H},$$

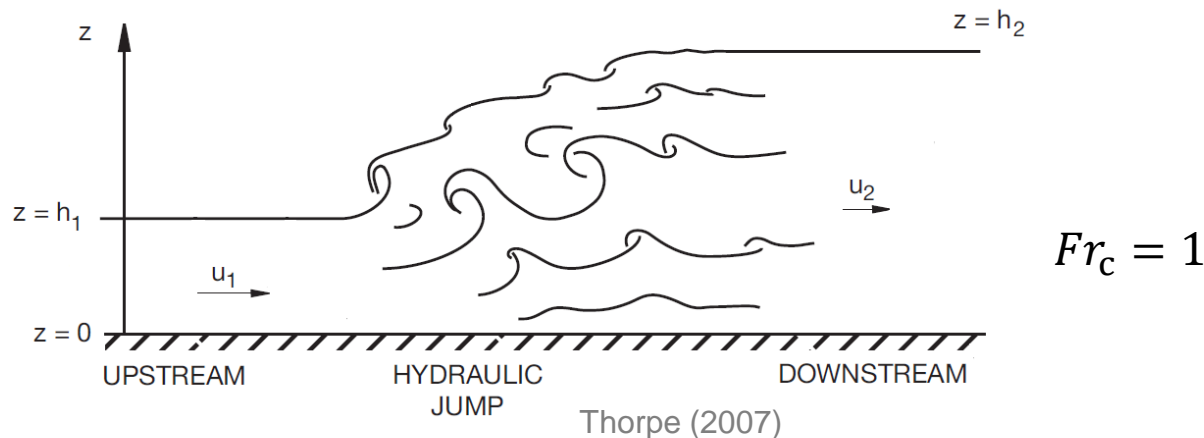
\bar{u} – mean flow speed,
 H – the layer thickness,
 $g' = g \Delta\rho/\rho$ – reduced gravity.

$Fr > 1$

supercritical

$Fr < 1$

sub-critical





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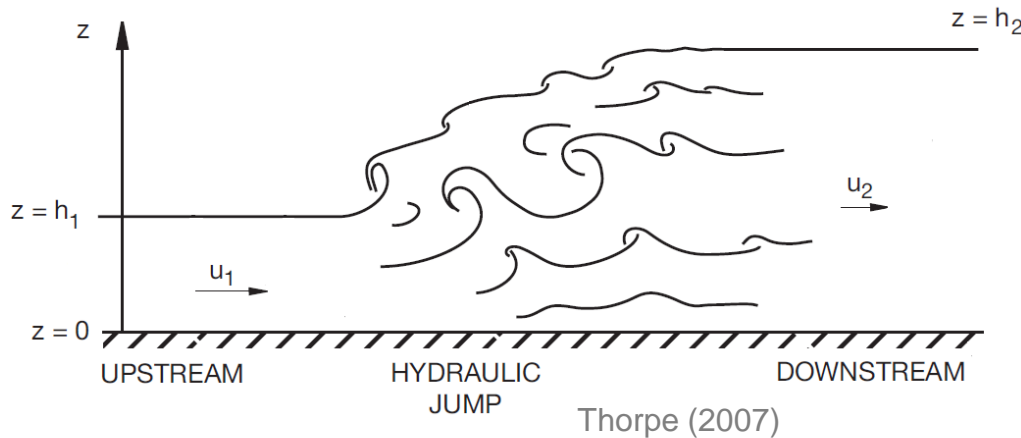
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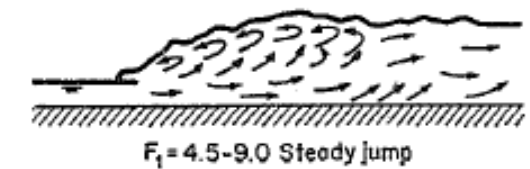
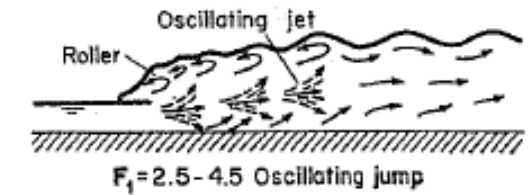
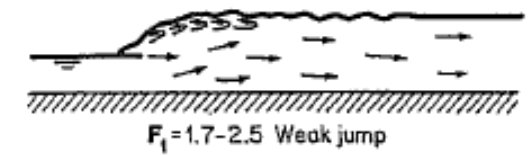
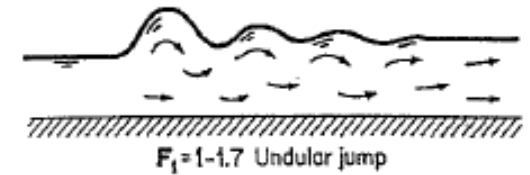
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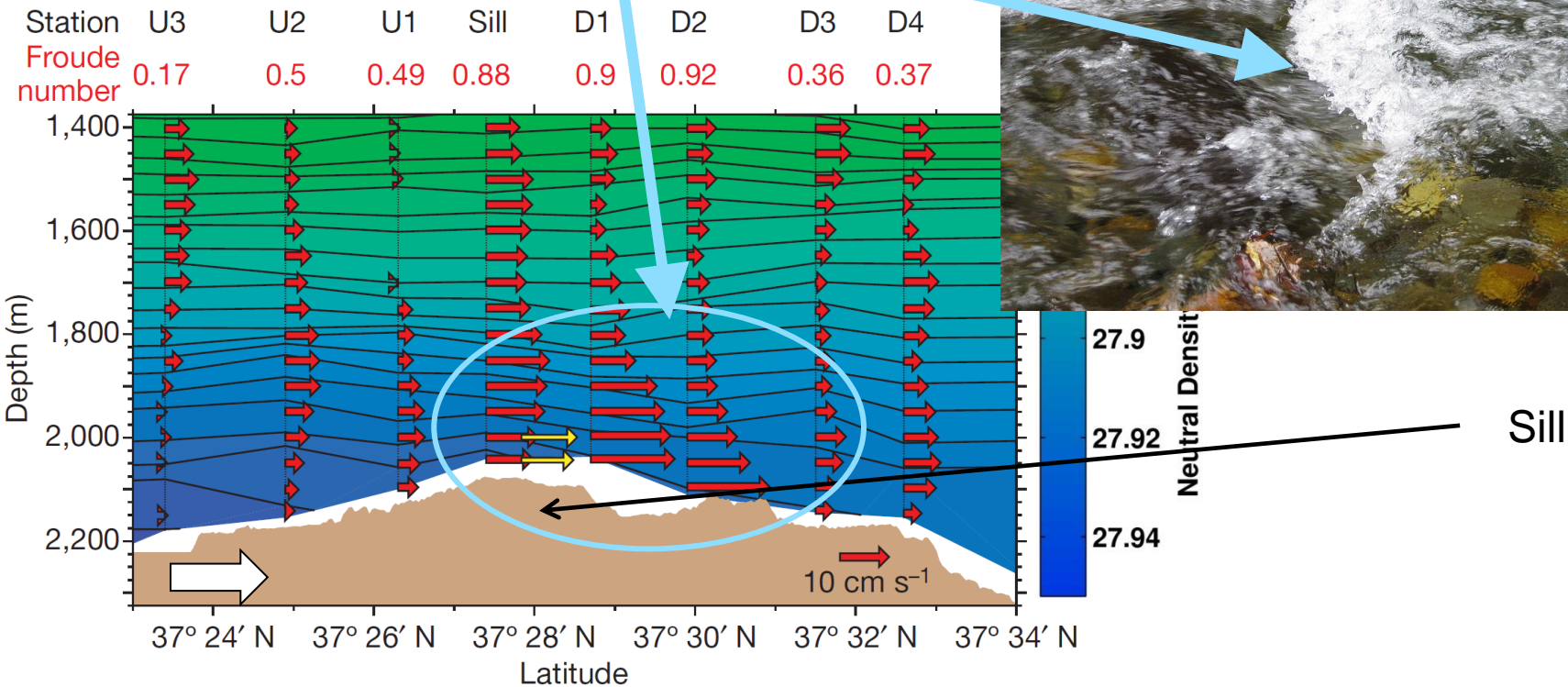


$$Fr_c = 1$$



Chow (1959)

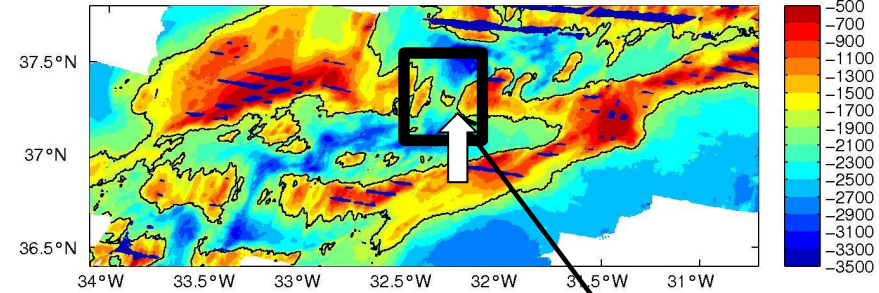
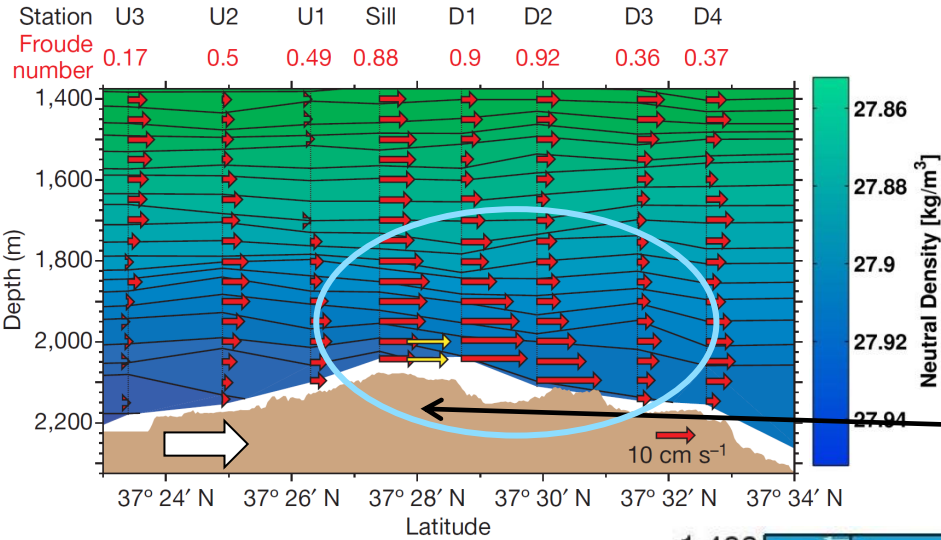
Hydraulic Jump



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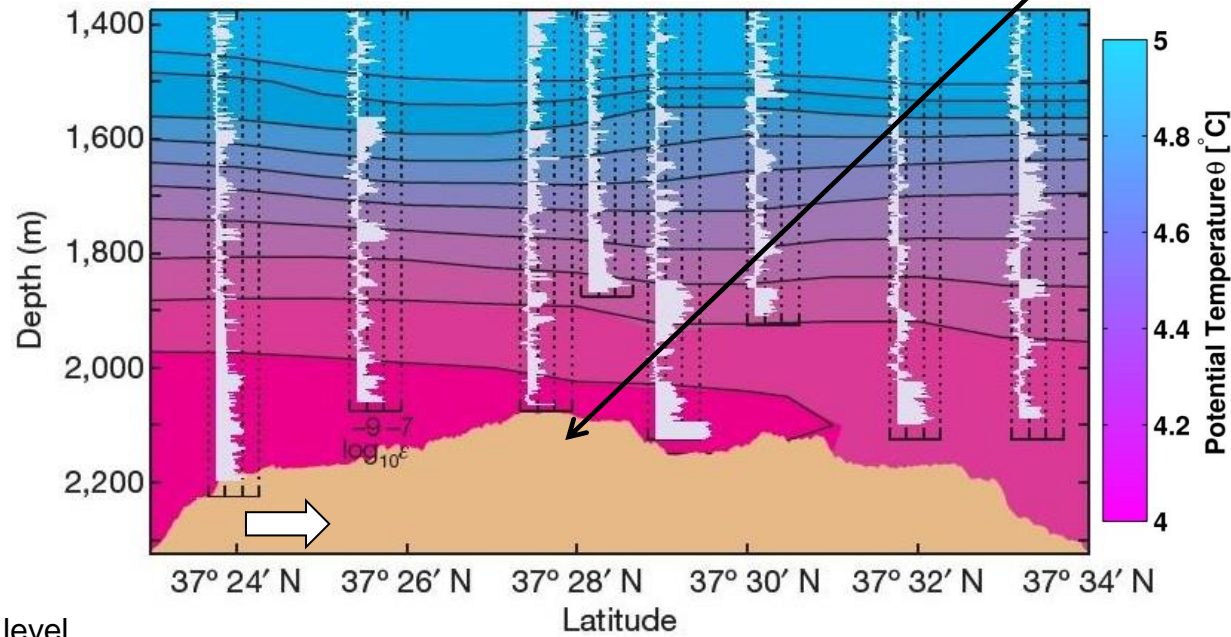
Average velocity > 10 cm/s
 Maximum velocities ~ 20 cm/s

Circulation in the Lucky Strike Segment



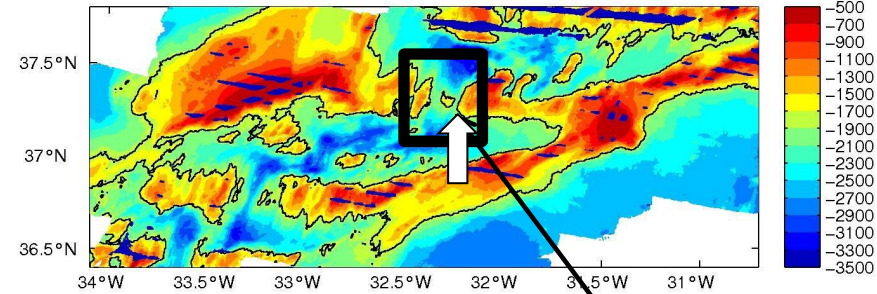
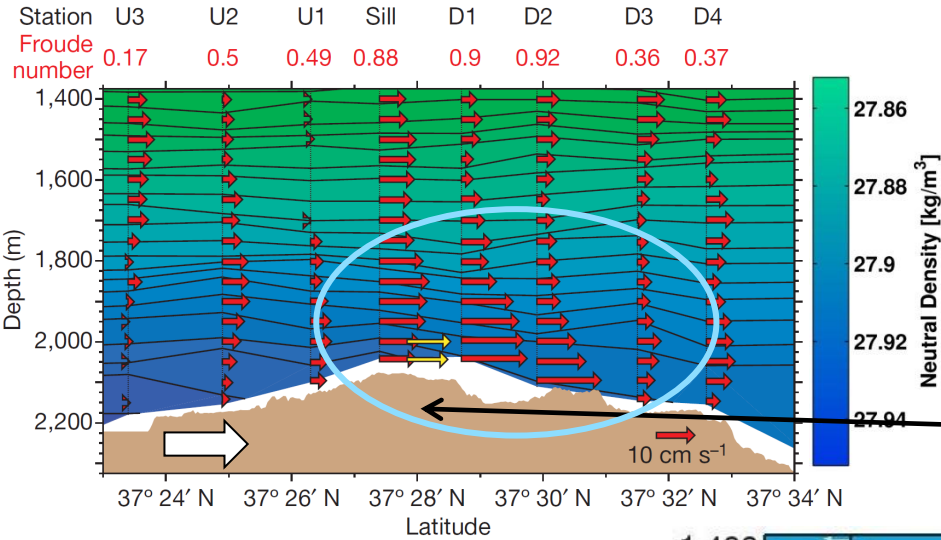
Sill

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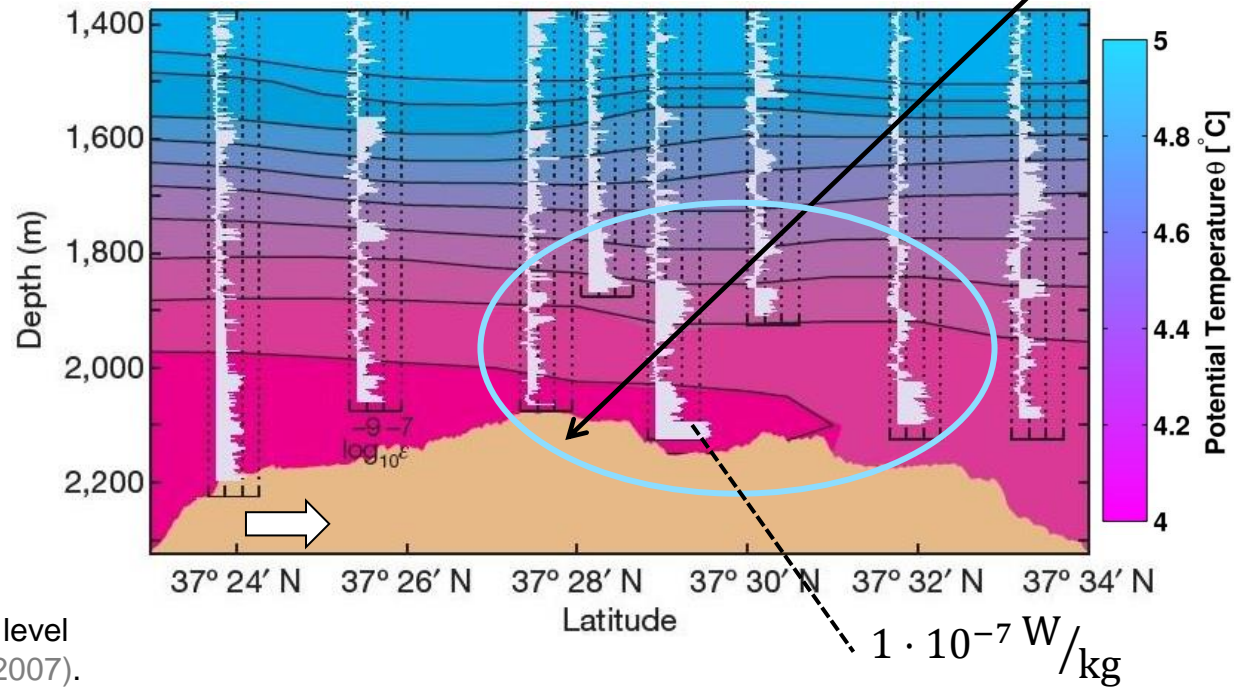
Dissipation [W/kg] along channel. Reference level $3 \cdot 10^{-10}$ [W/kg] (St. Laurent and Thurnherr, 2007).

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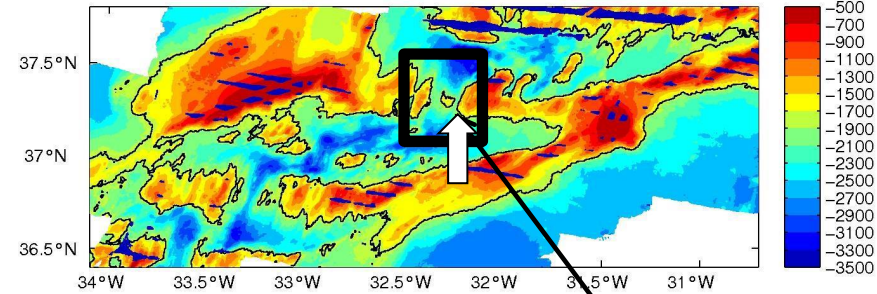
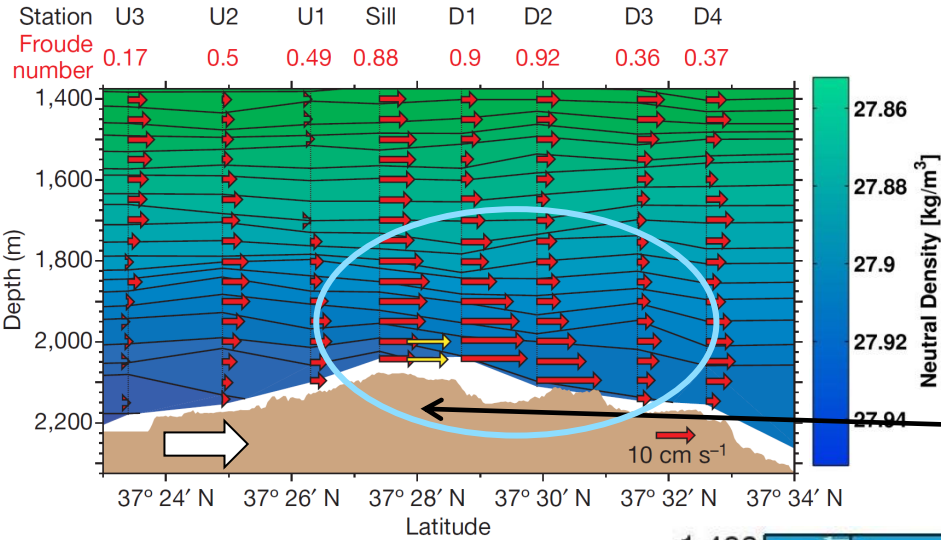
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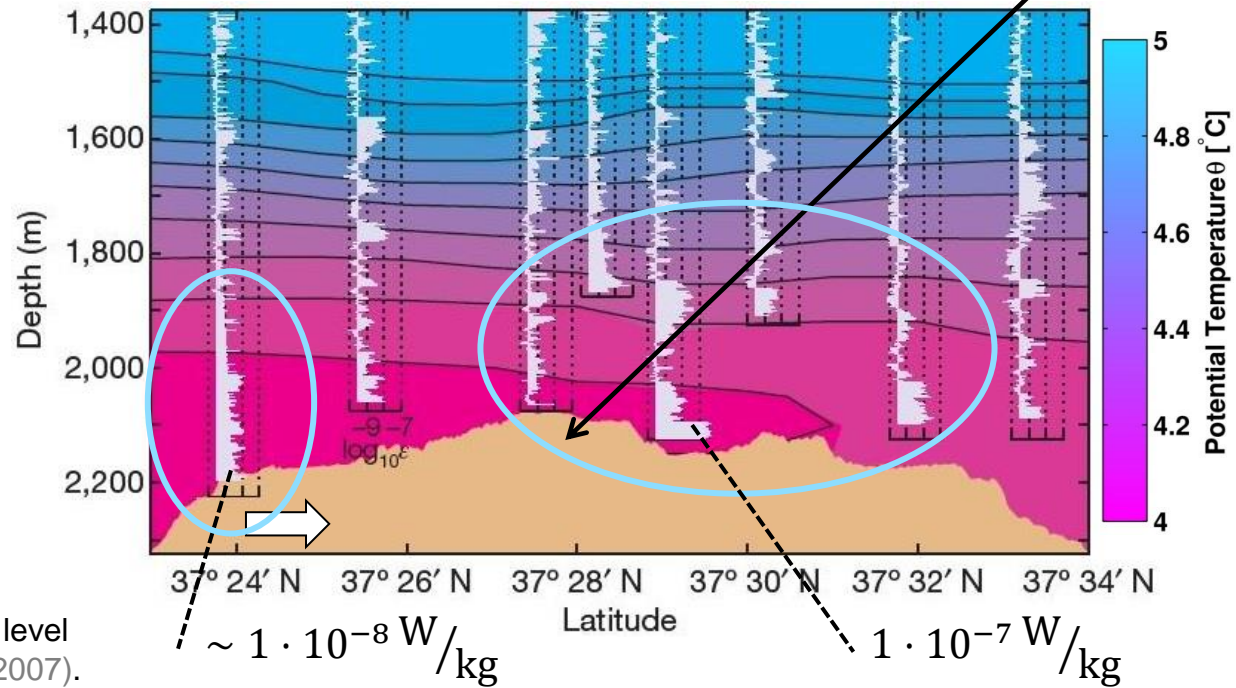
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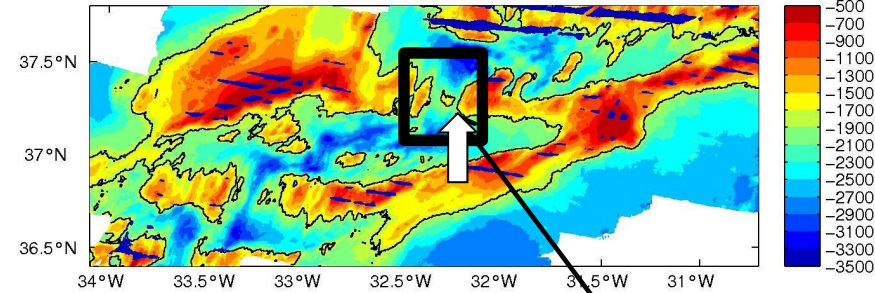
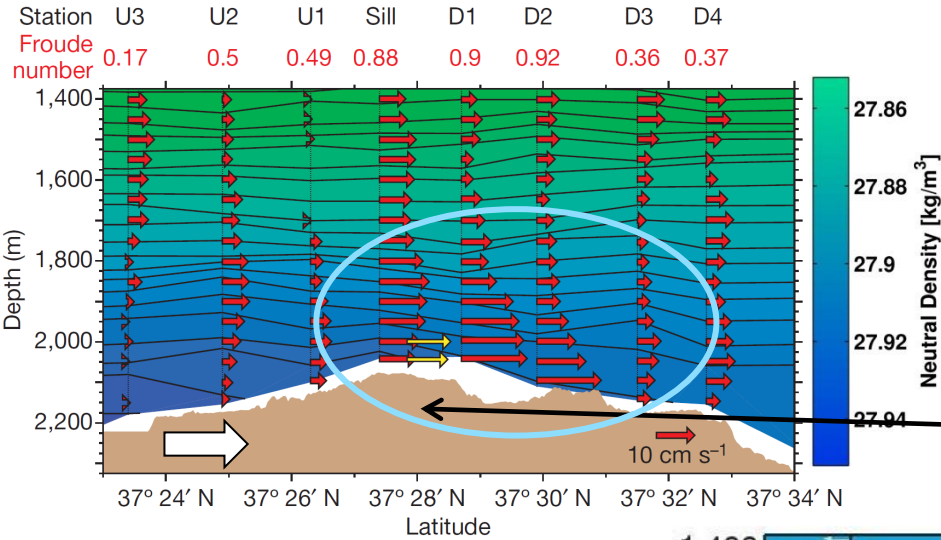
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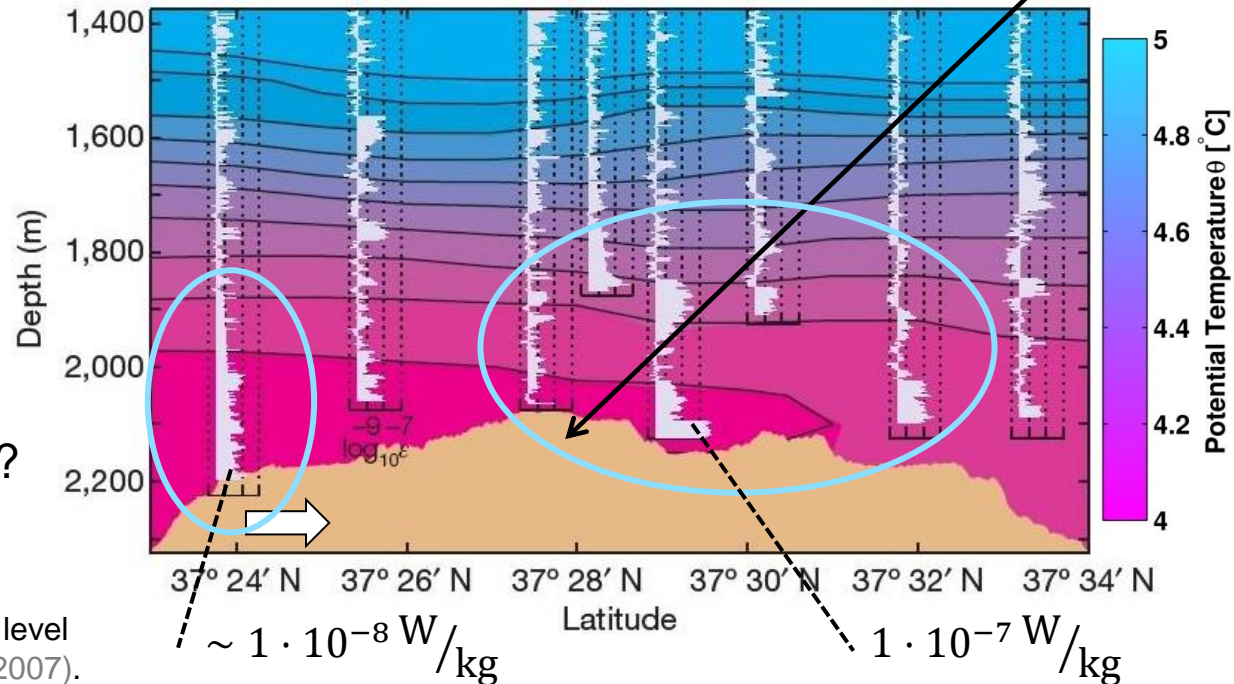
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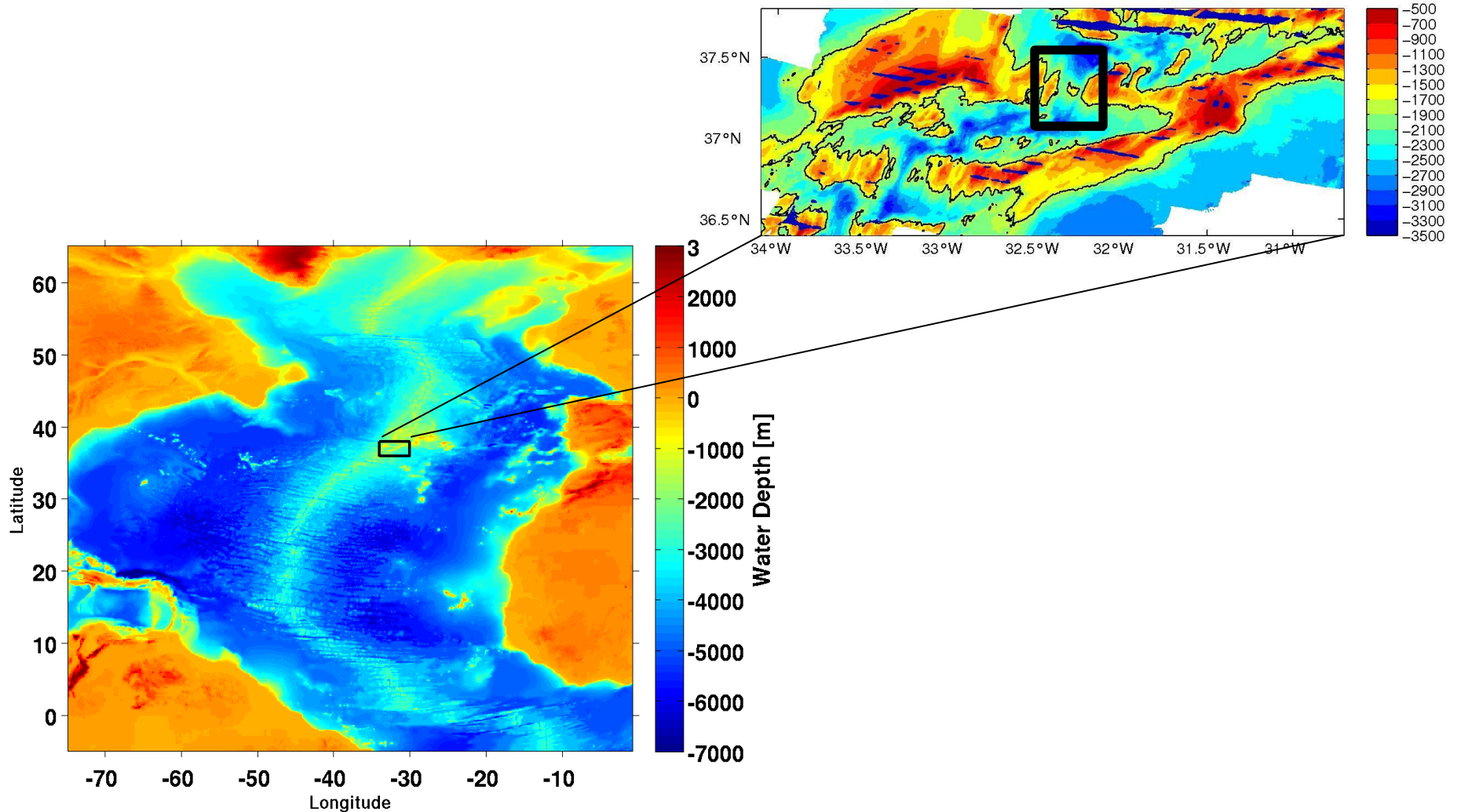
How is the dissipation rate distributed along the channel?



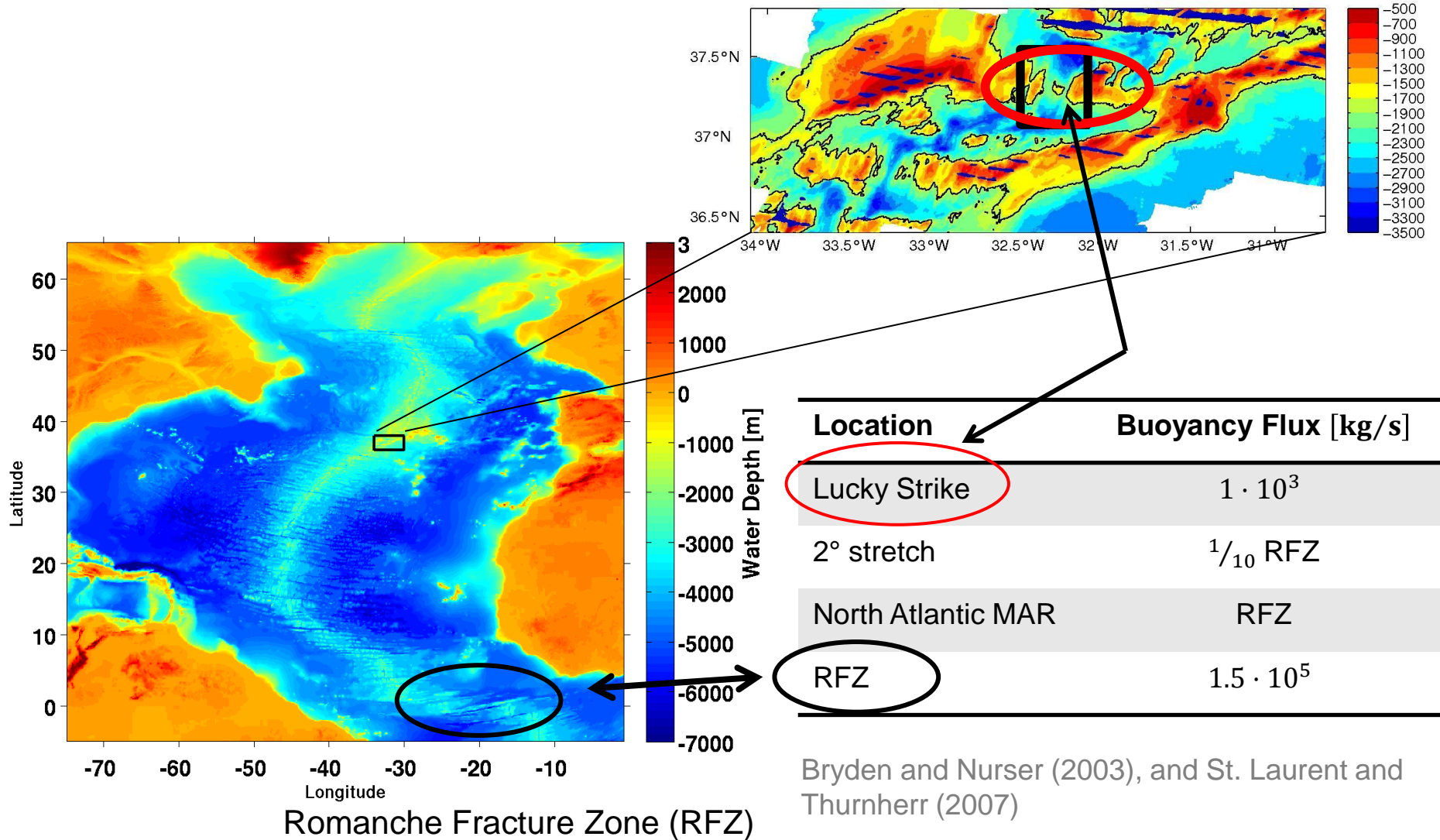
Dissipation [W/kg] along channel. Reference level $3 \cdot 10^{-10} \text{ [W/kg]}$ (St. Laurent and Thurnherr, 2007).

Understand the physical mechanisms controlling the mixing in this channel.

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Scientific questions

- How is the dissipation rate distributed along the channel?
- Is there evidence for hydraulic jumps?
- Do tides have an influence?

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Dataset requirements

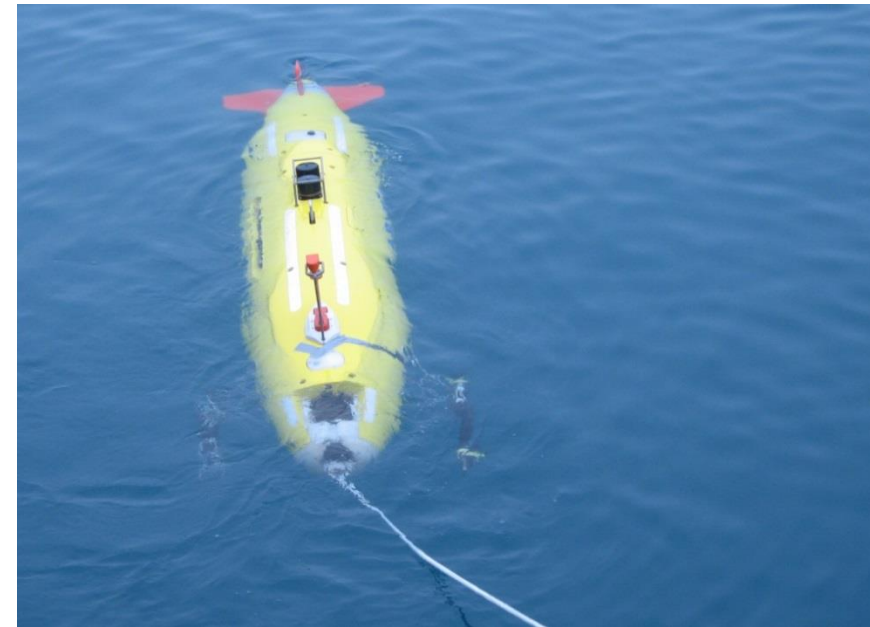
- High spatial and temporal resolution.

Scientific questions

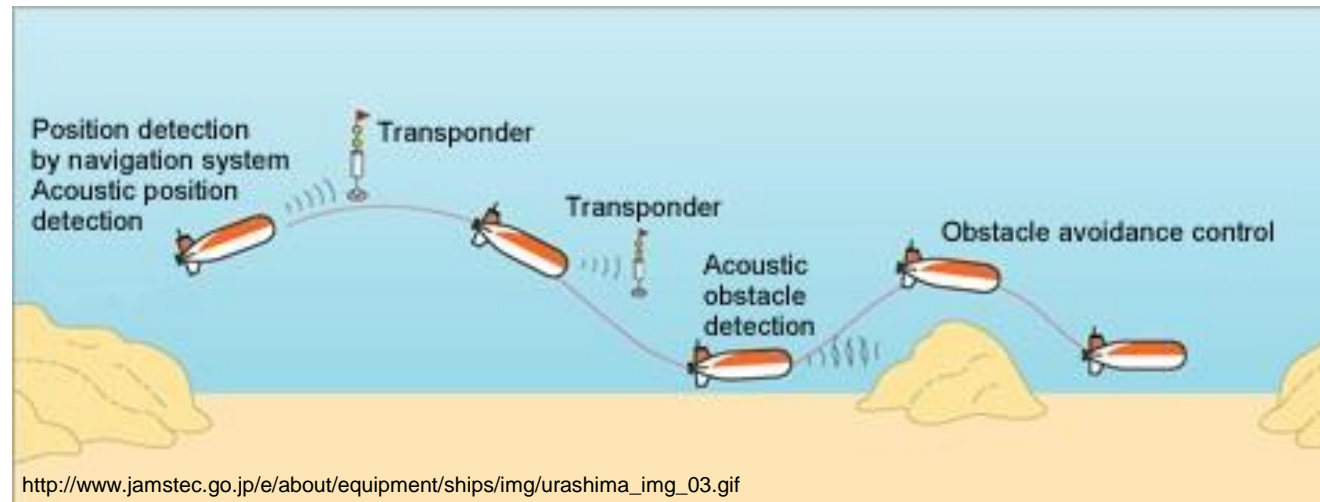
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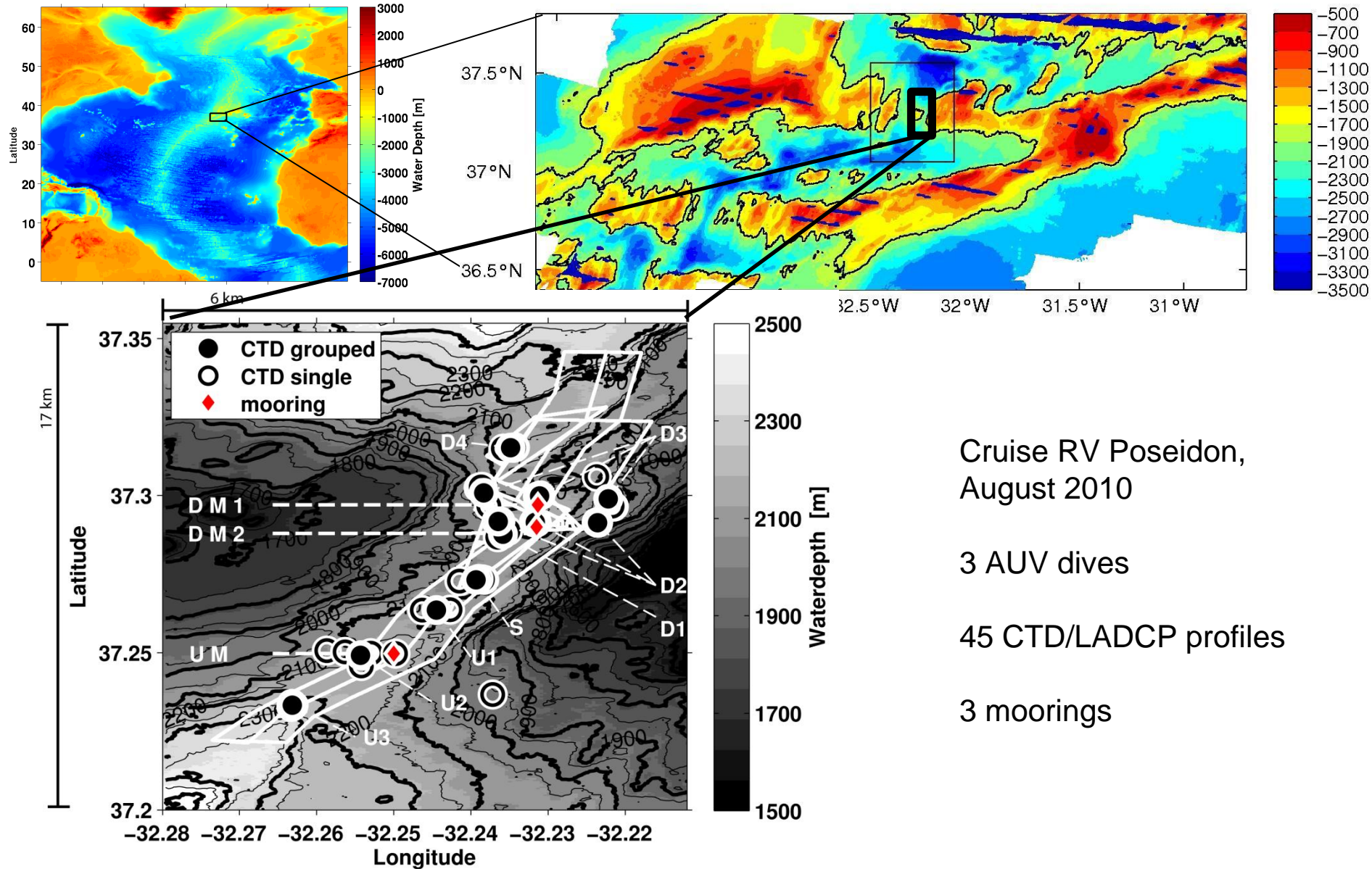
- High spatial and temporal resolution.



Autonomous underwater vehicle (AUV)



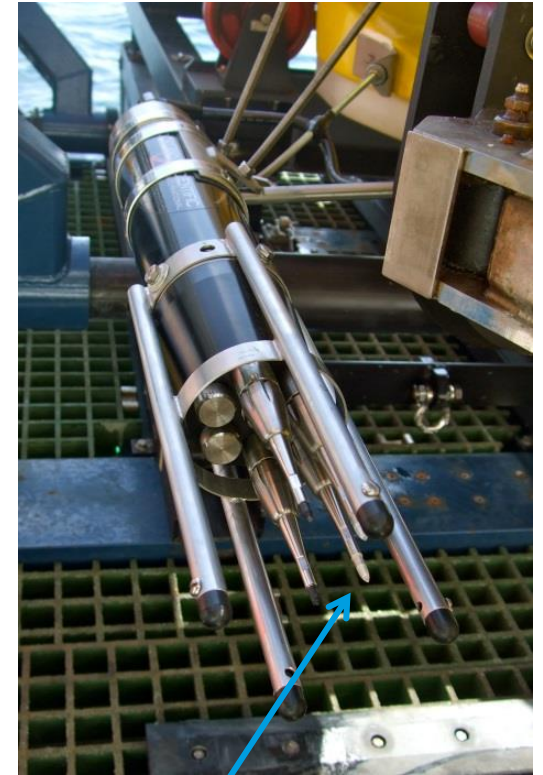
The Lucky Strike Segment at the MAR





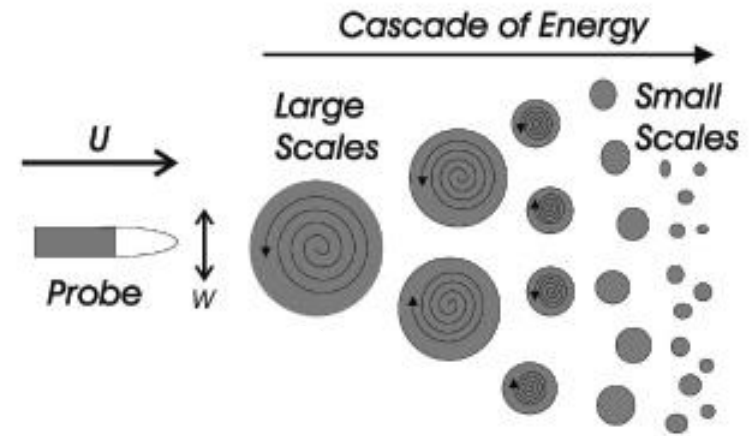
AUV Abyss (autonomous underwater vehicle).

- Vibrations due to mounting and engine
- Observed by 3D-accelerometer

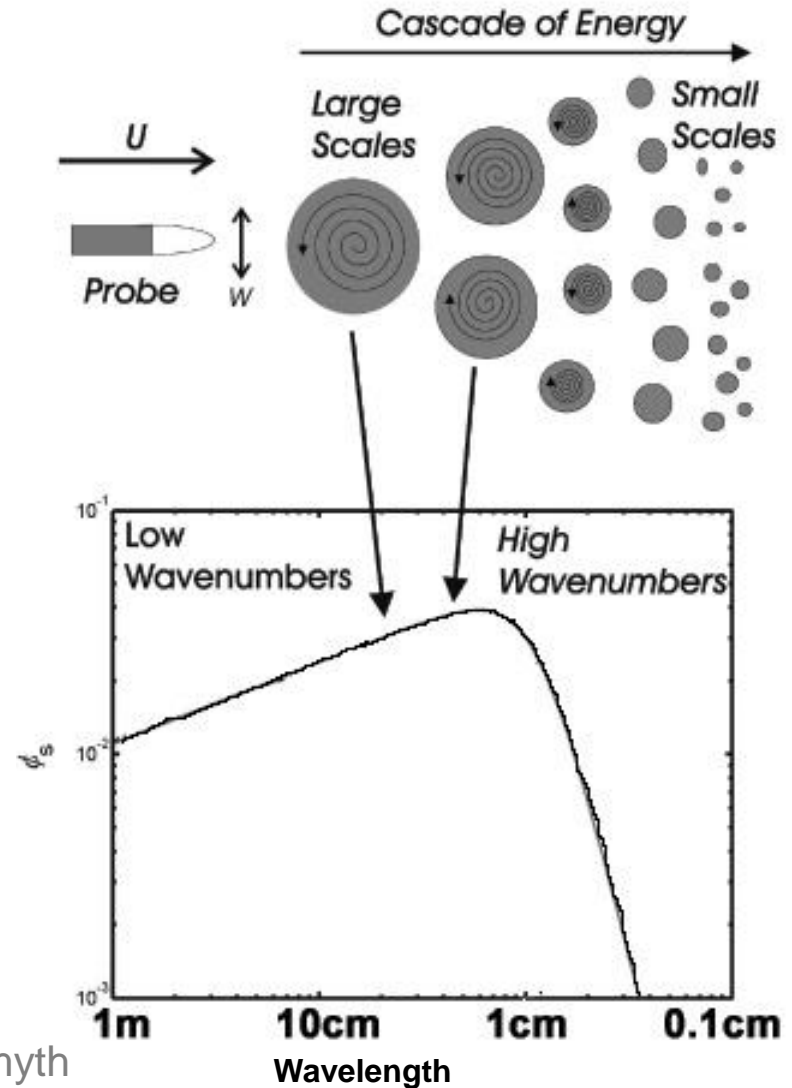


Velocity shear probes

velocity shear →



velocity shear \rightarrow spectrum Φ \rightarrow dissipation rate ε

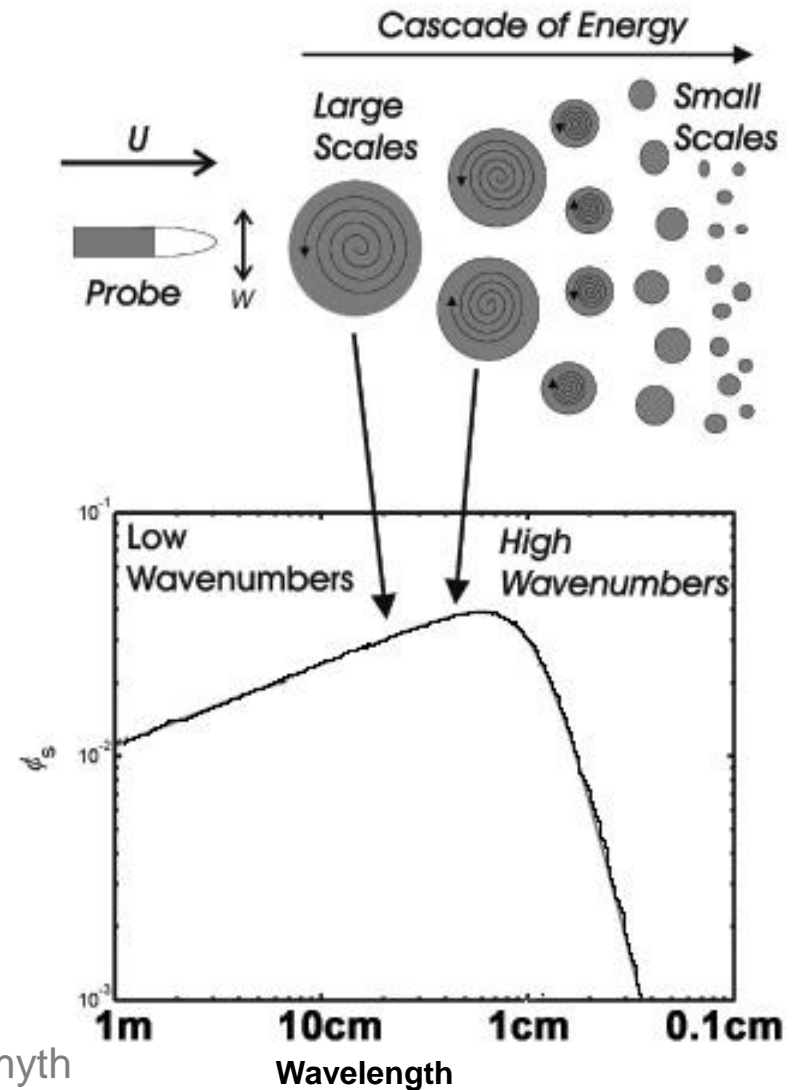


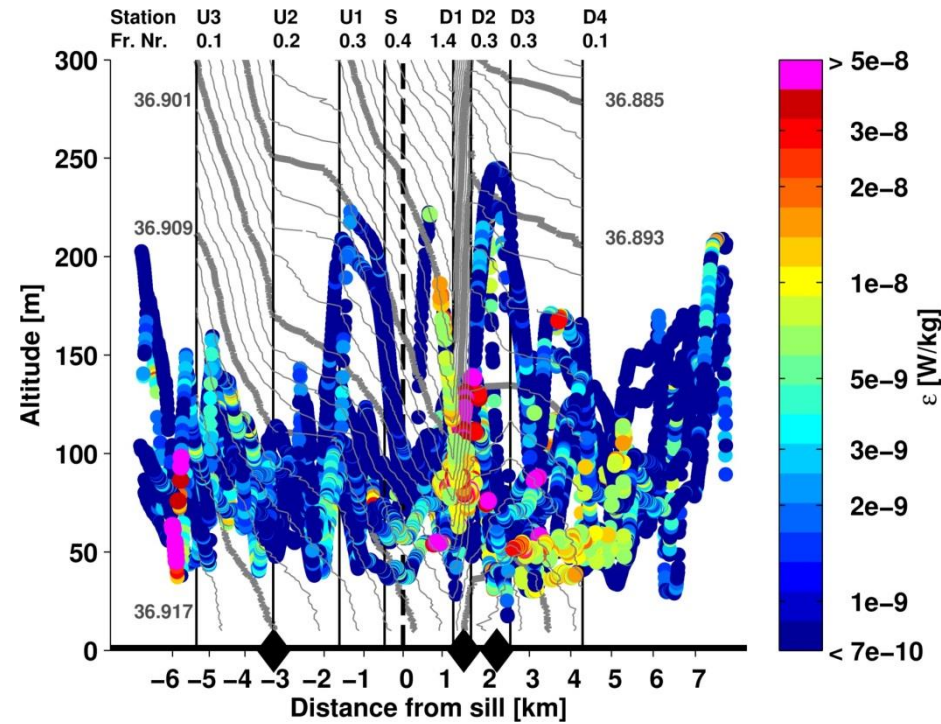
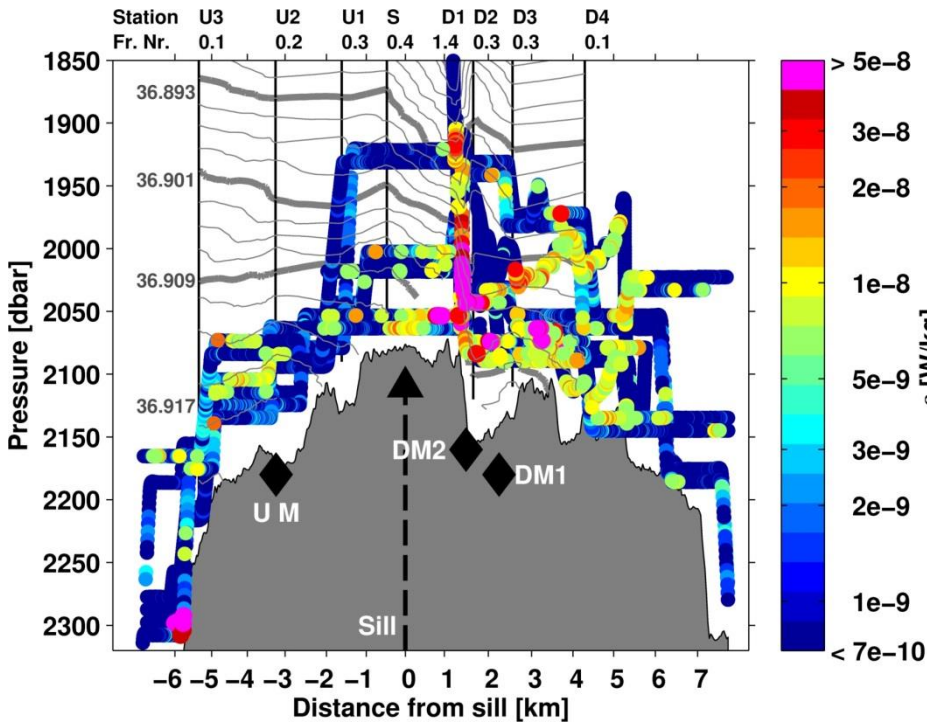
Empirical Nasmyth spectrum (Nasmyth 1970, Oakey 1982).

velocity shear \rightarrow spectrum Φ \rightarrow dissipation rate ε

Method described in
Tippenhauer et al. 2015

Empirical Nasmyth spectrum (Nasmyth 1970, Oakey 1982).



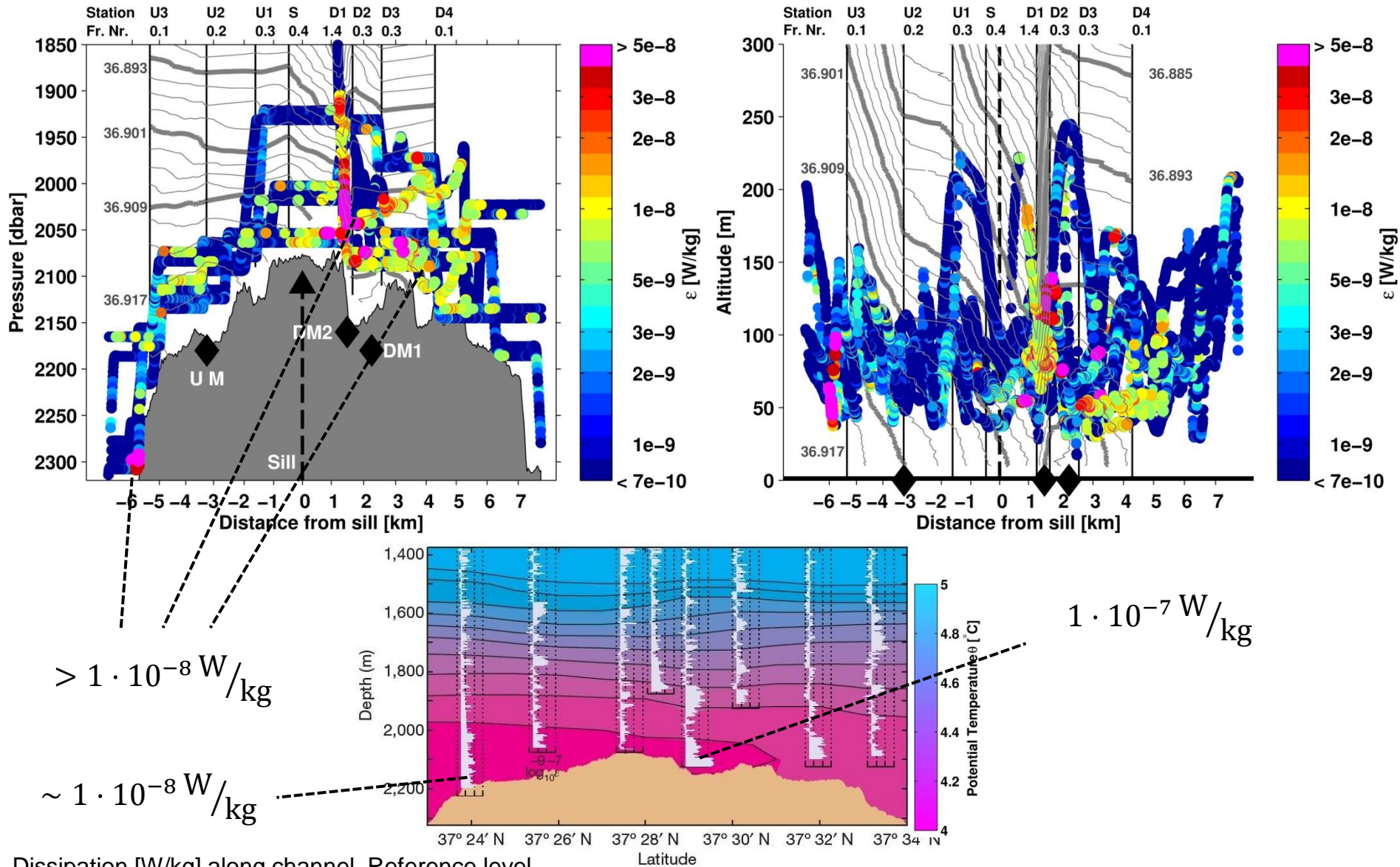


- 20 hours high resolution turbulence data (9 meter or 6 seconds)
- First successful deep ocean, AUV-based turbulence observations

- High mixing downstream of the sill mostly below 100 m altitude
- Pattern consistent with hydraulic jump downstream

Tippenhauer et al. 2015

Dissipation Rate along the Channel



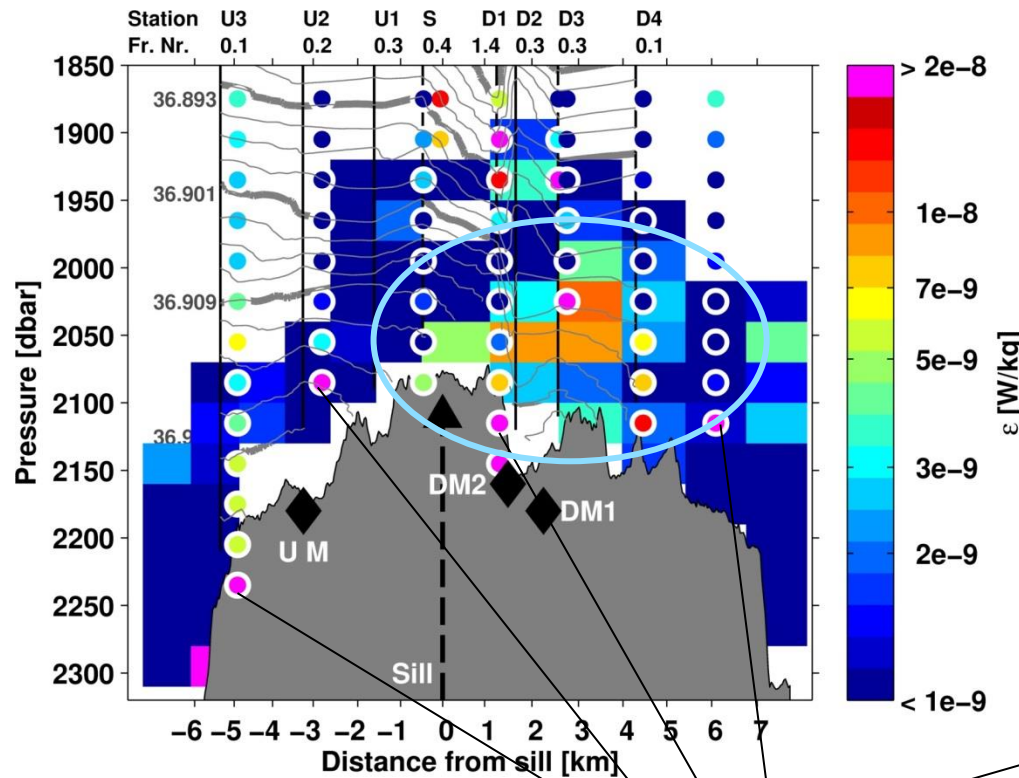
$> 1 \cdot 10^{-8} \text{ W/kg}$

$\sim 1 \cdot 10^{-8} \text{ W/kg}$

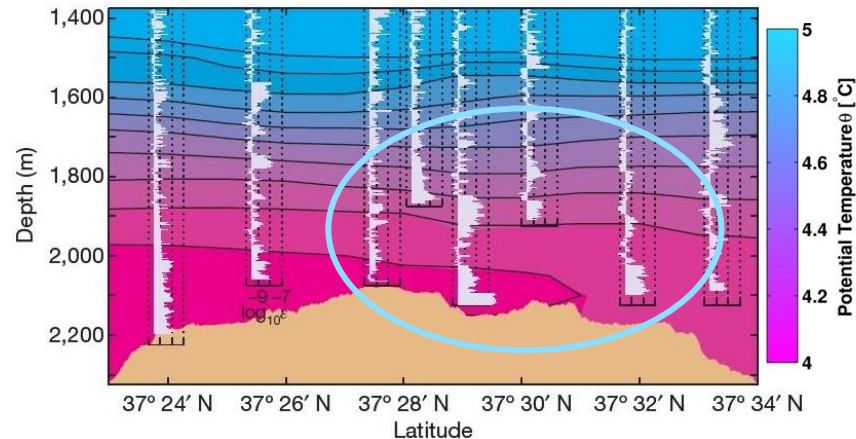
Dissipation [W/kg] along channel. Reference level $3 \cdot 10^{-10}$ [W/kg] (St. Laurent and Thurnherr, 2007).

Tippenhauer et al. 2015

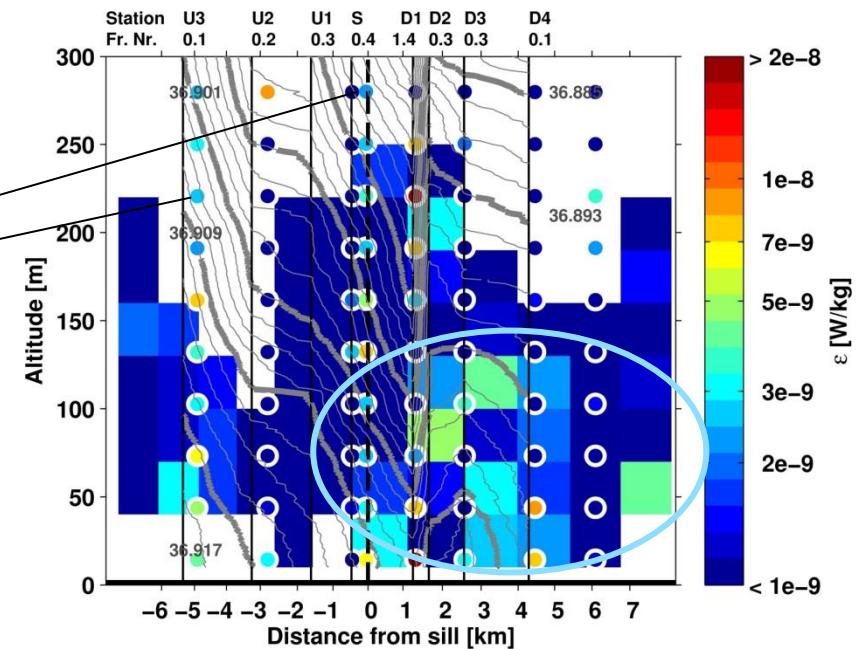
Dissipation Rate along the Channel



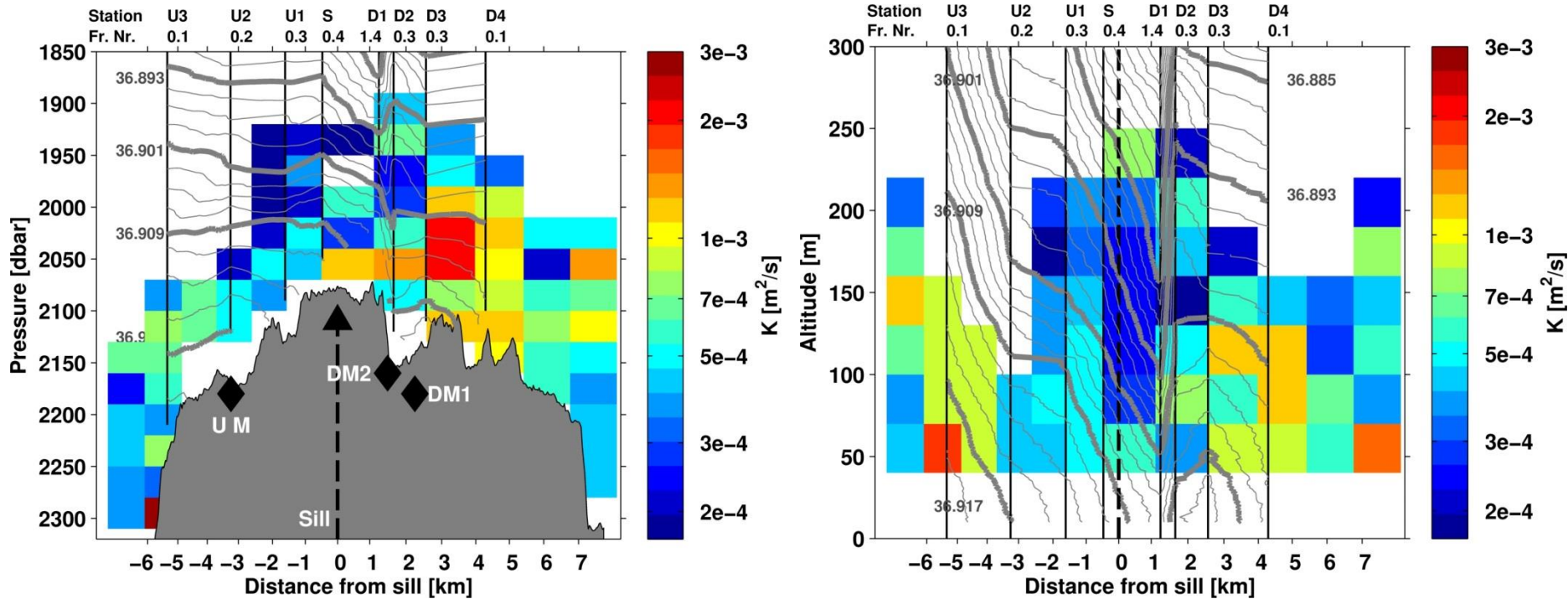
Box-average dissipation rates as function of pressure and altitude.



Dissipation [W/kg] along channel by St. Laurent and Thurnherr, 2007).



Data vertical profiler



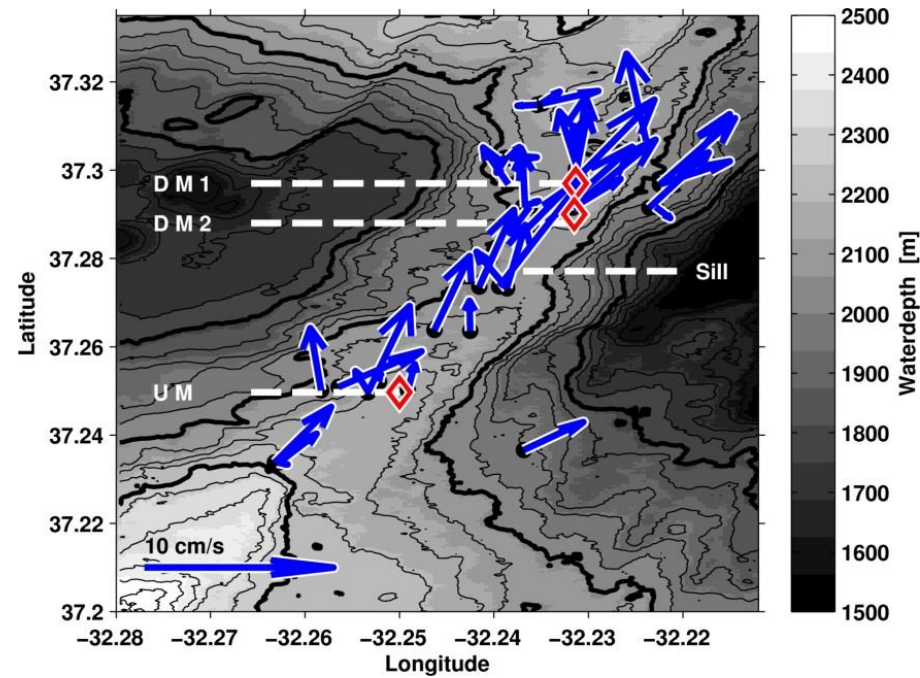
$$\text{Diffusivity } K = \frac{\gamma \varepsilon}{N^2} \text{ (Osborn 1980)}$$

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Average velocity $> 8 \text{ cm/s}$
 Maximum velocities $> 17 \text{ cm/s}$

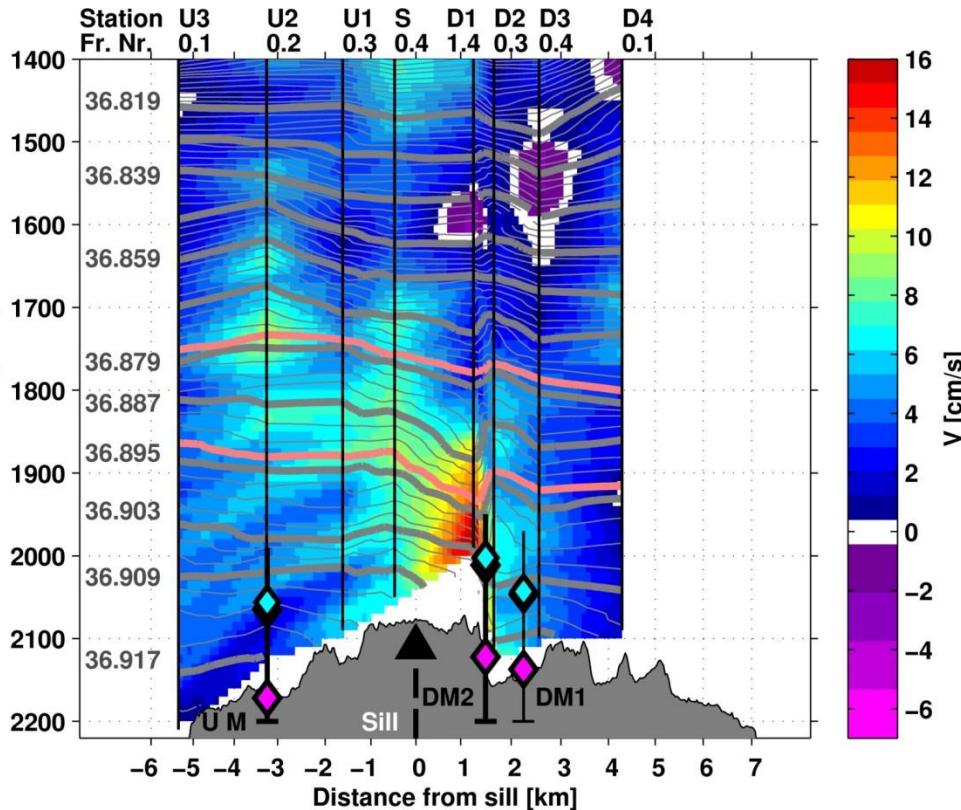


Averaged between 1800m and the bottom

Velocity along the channel.

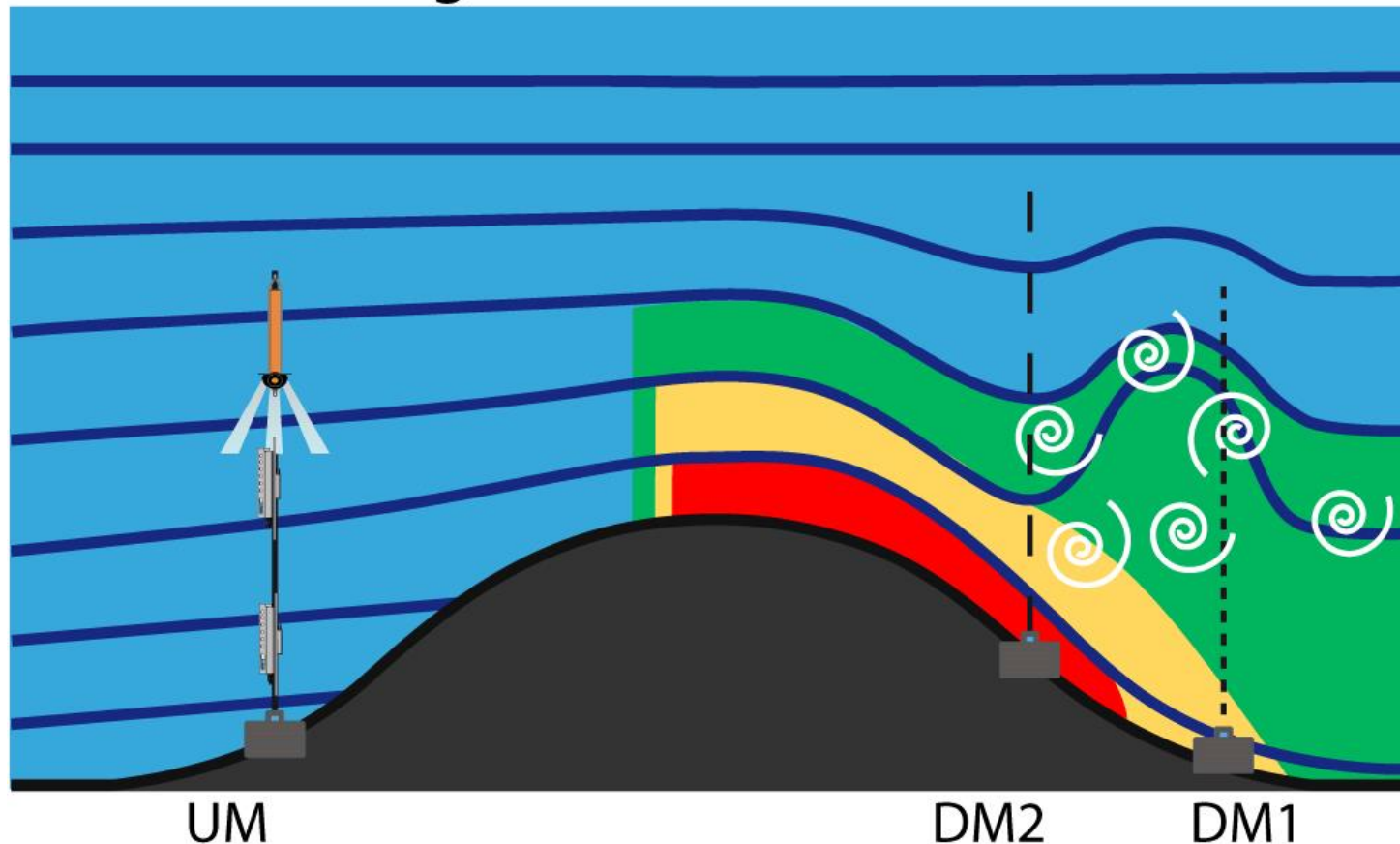
Froude Number computed between isopycnals $\sigma_2 = 36.893$ (lower red) and $\sigma_2 = 36.877$ (upper red).

Tippenhauer et al. 2015

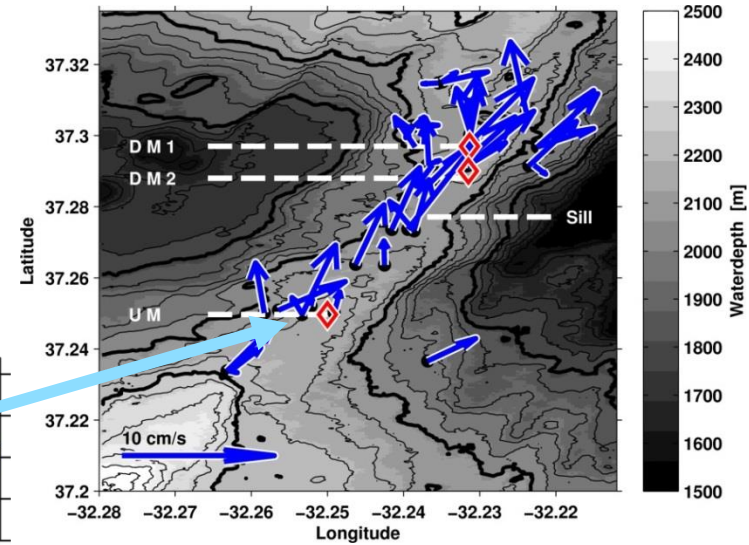
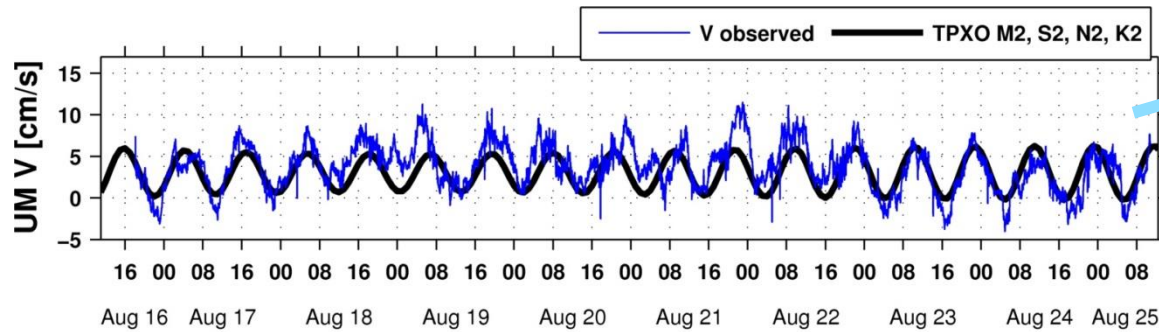


Hydraulic jumps were identified as the main source for the elevated mixing downstream of the sill.

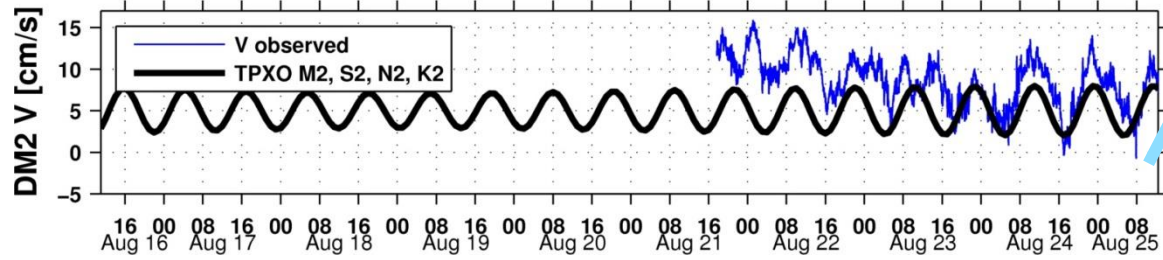
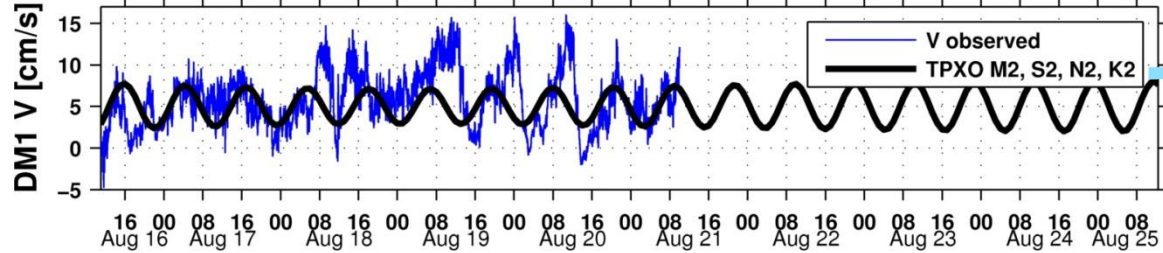
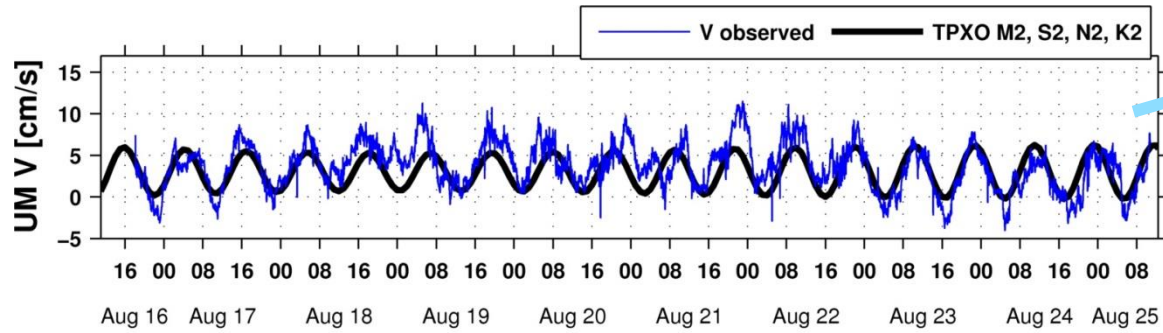
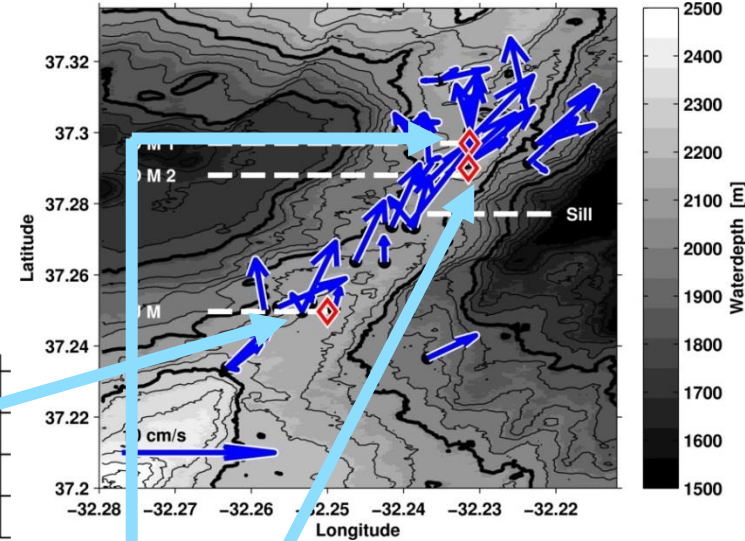
Along-channel



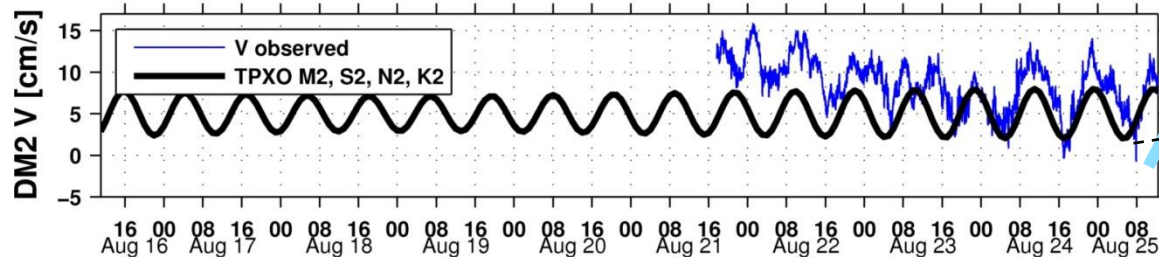
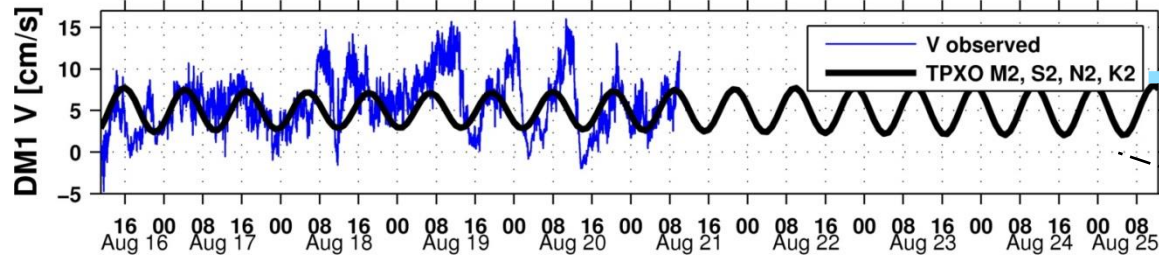
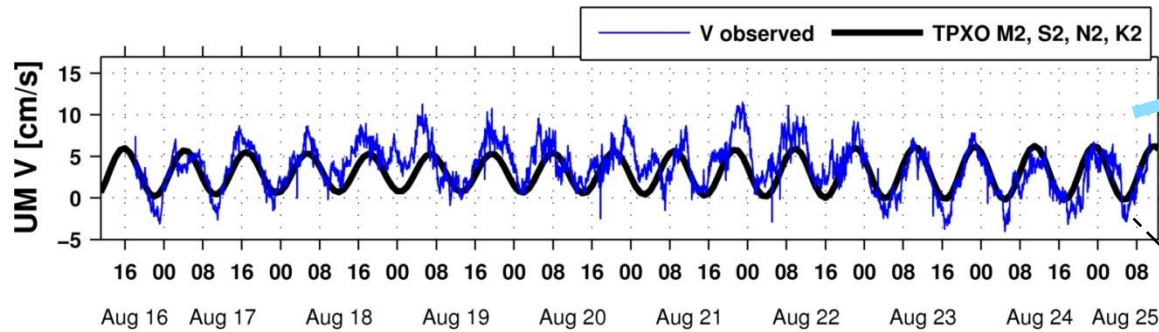
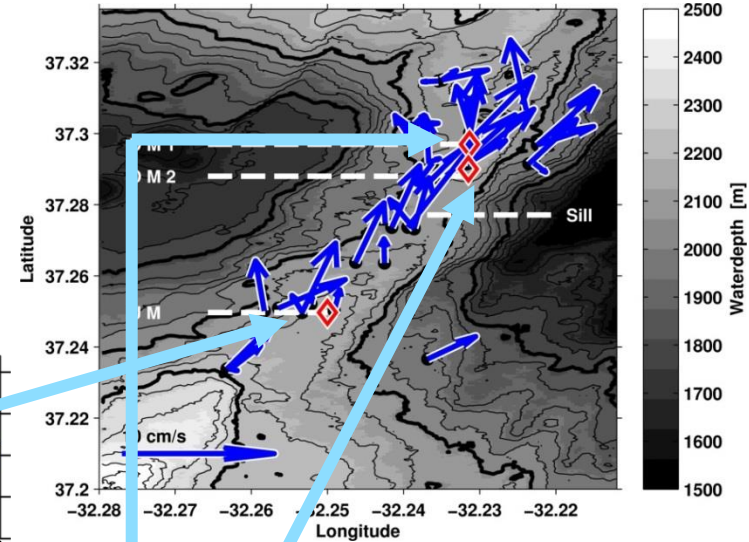
Barotropic tides from TPXO
global model of ocean tides
(Egbert and Erofeeva, 2002).



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explained variance:

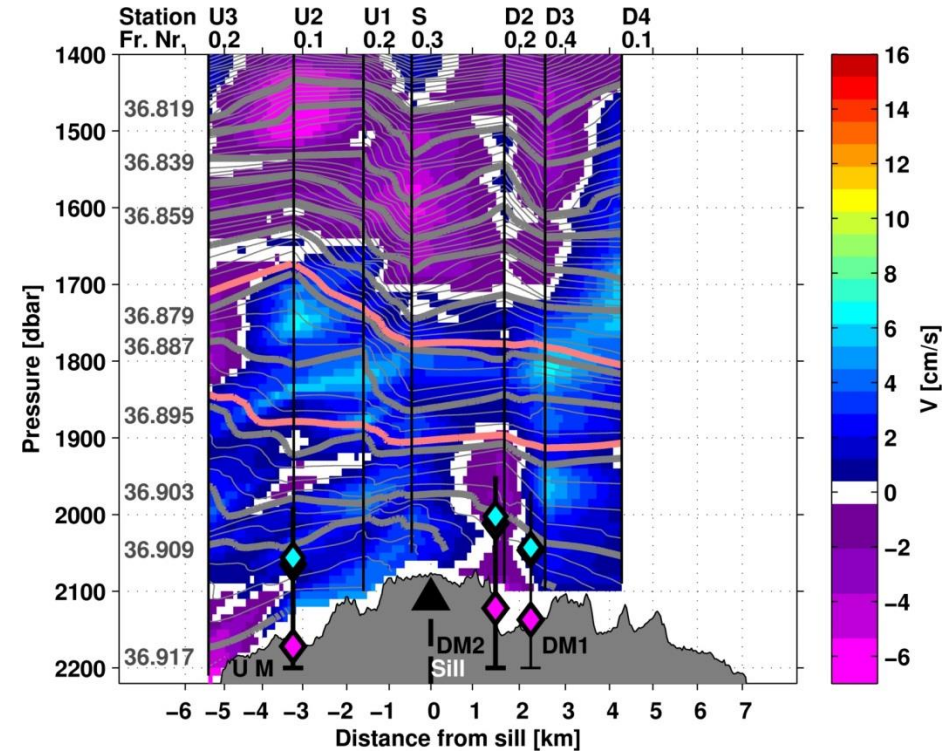
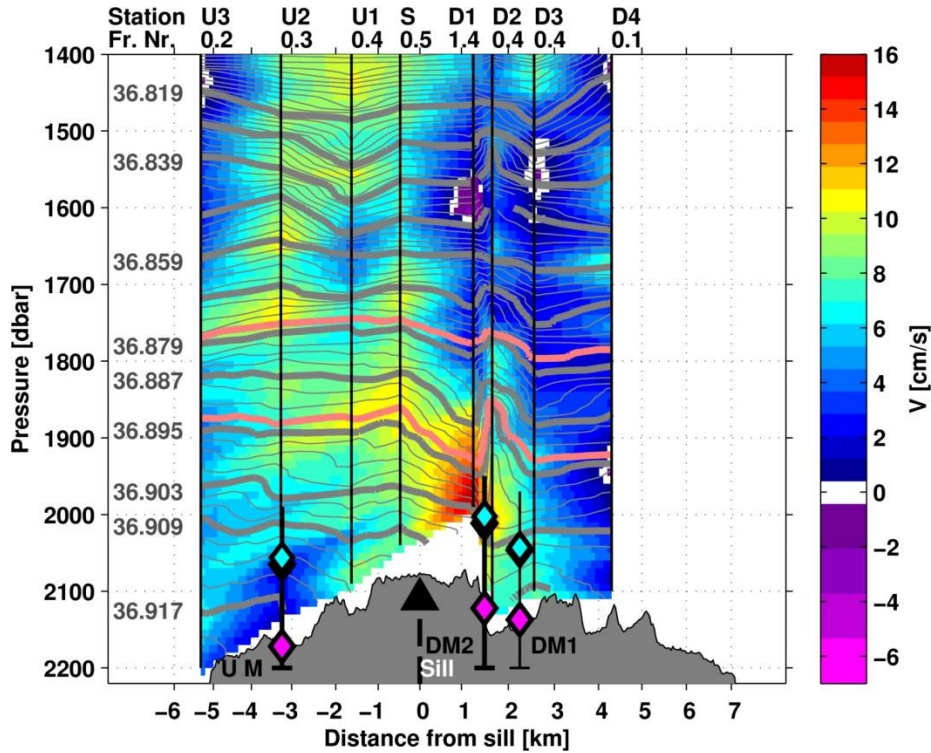
$$R^2 = 0.5$$

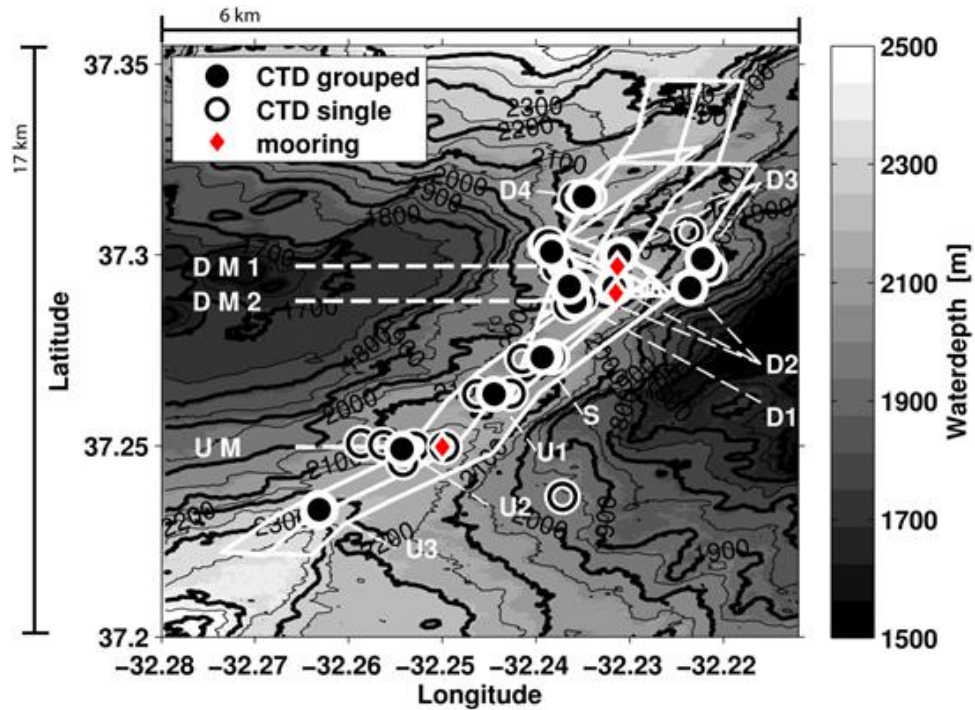
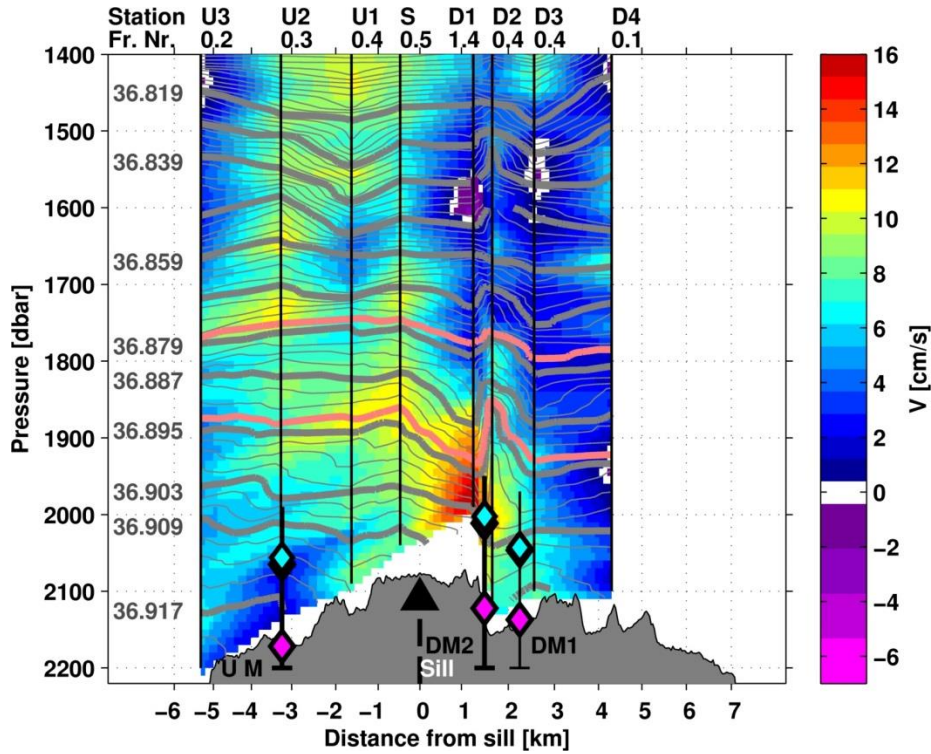
correlation not
significant

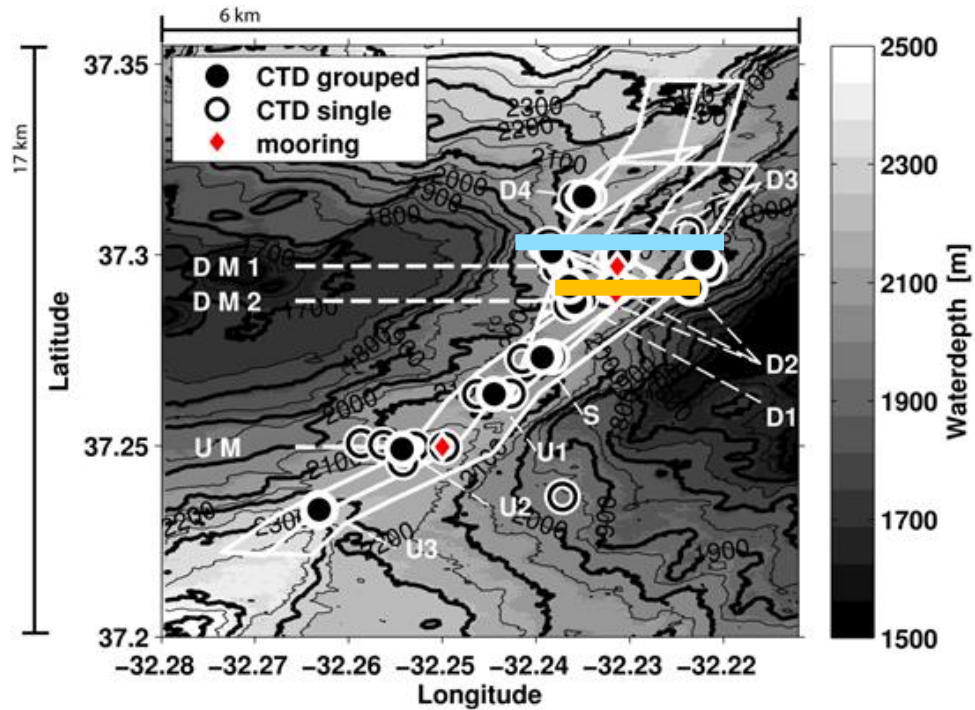
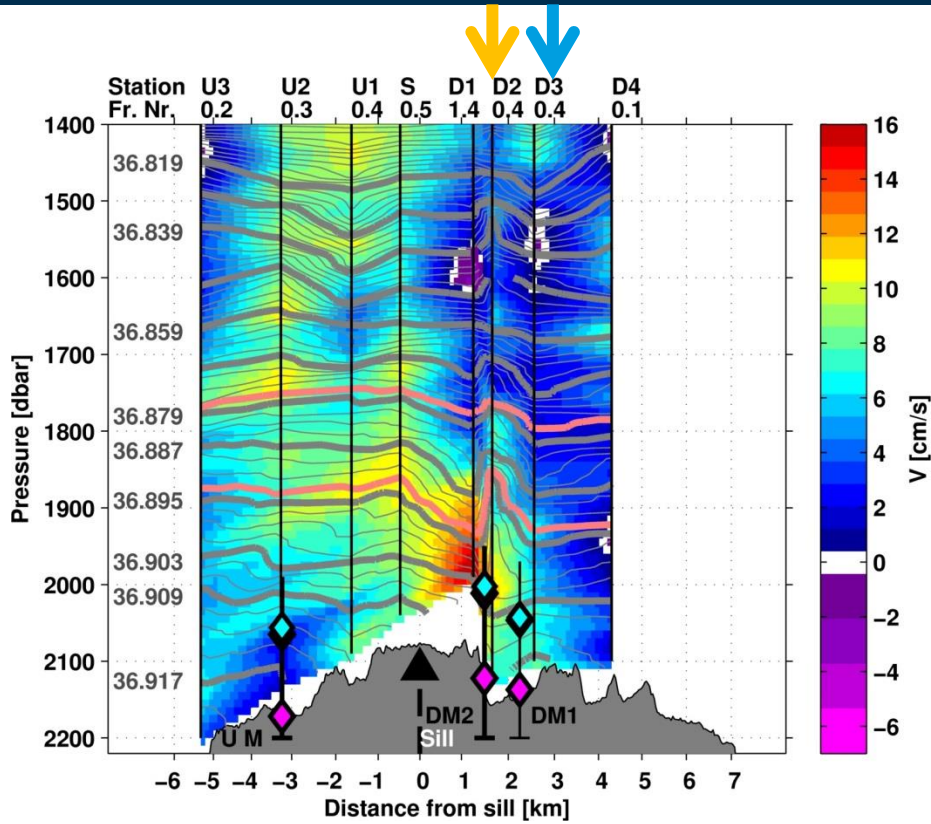
$$R^2 = 0.3$$

High flow velocity along the channel

Low flow velocity along the channel

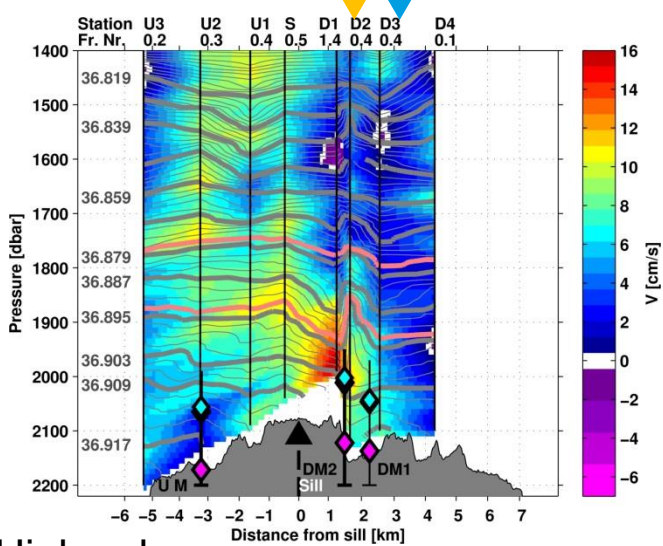




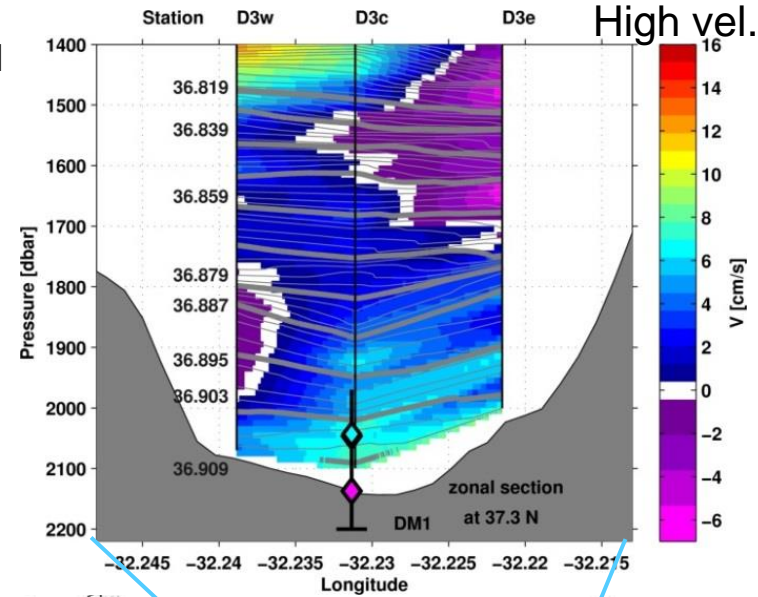


High Velocity Phase – Across-Channel Structure

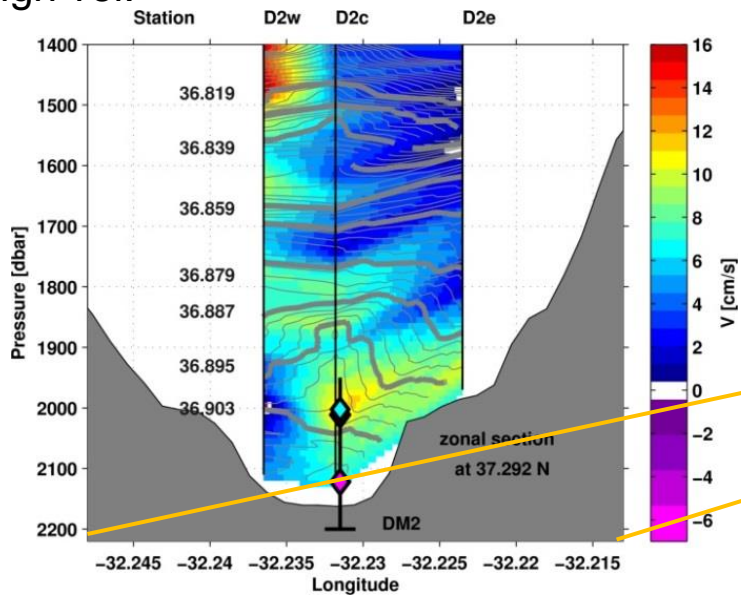
Along the channel



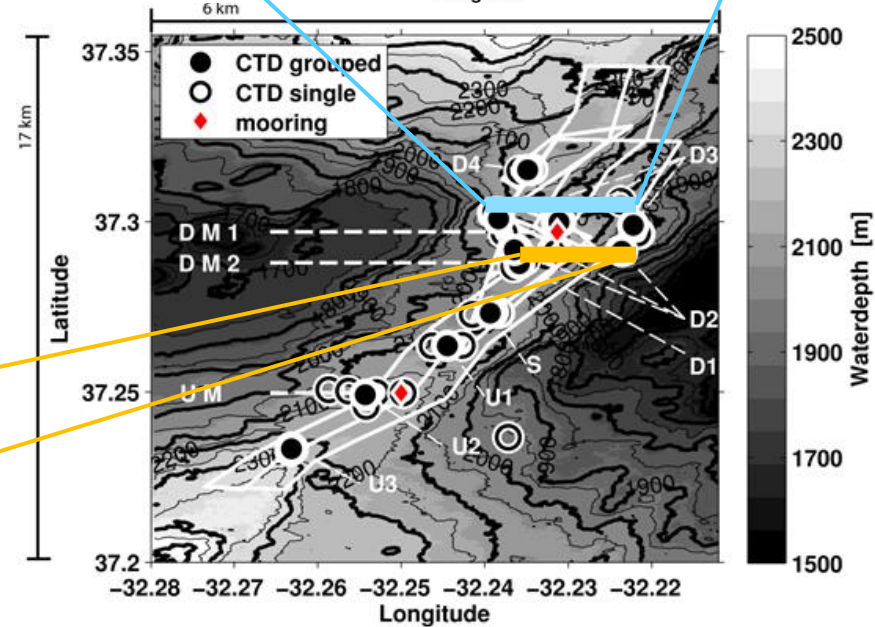
Across the channel at D3

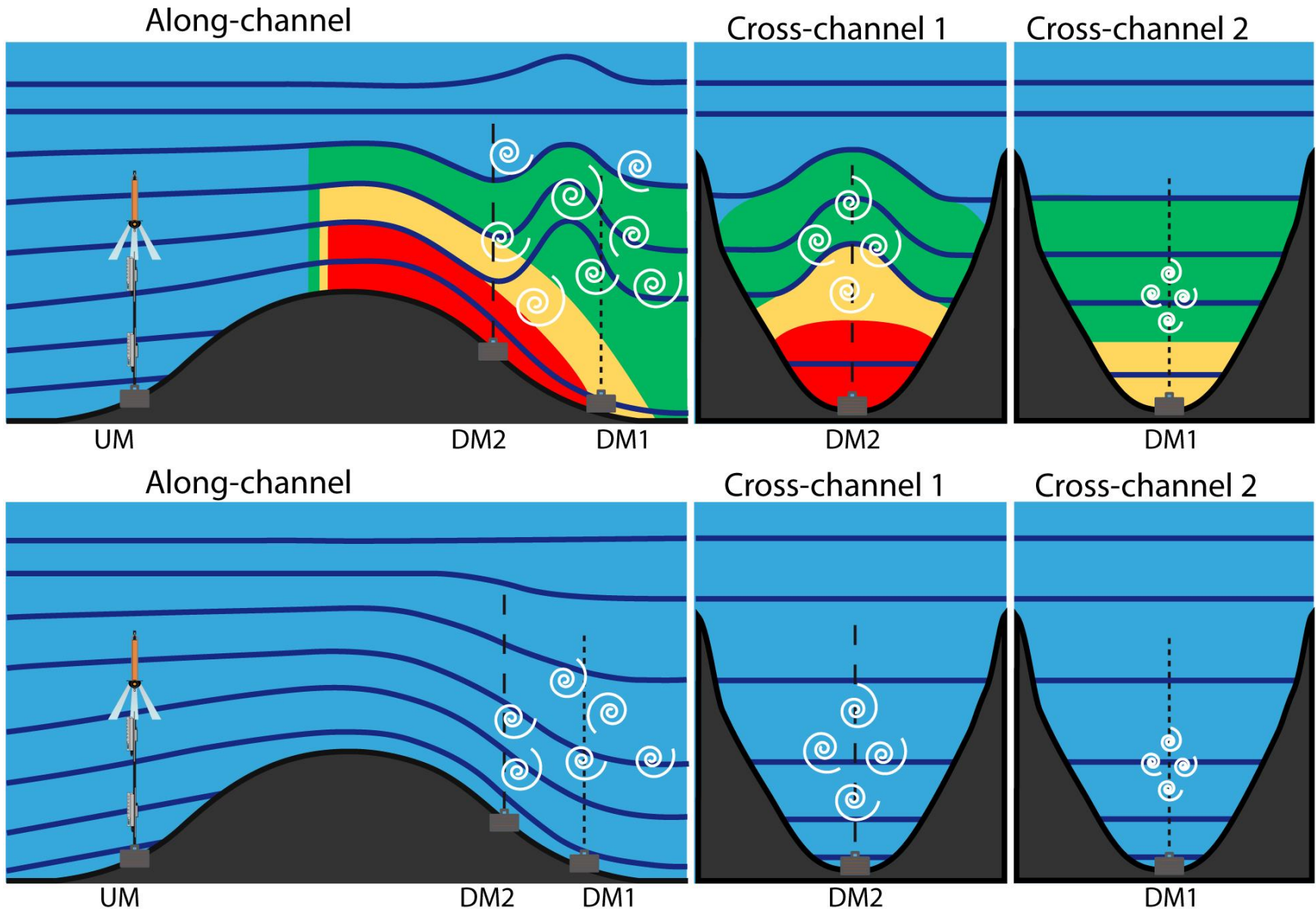


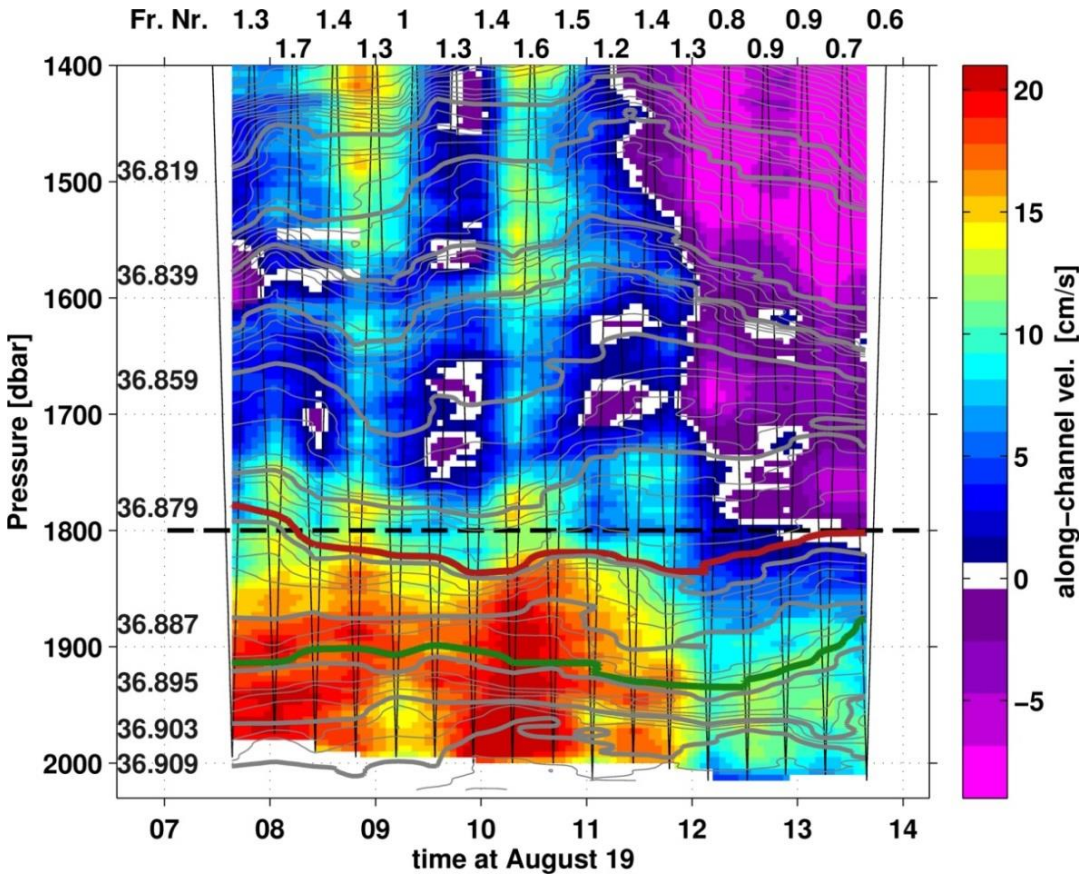
High vel.



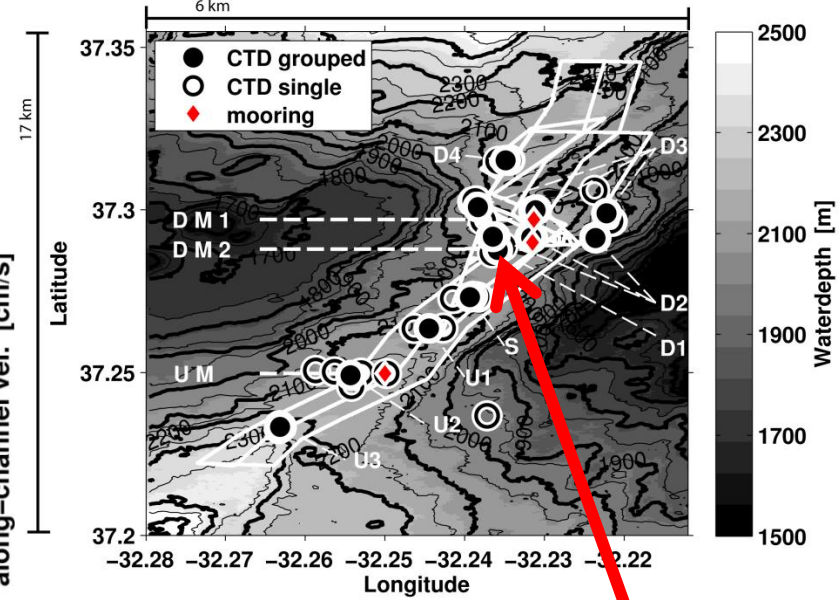
Across the channel at D2



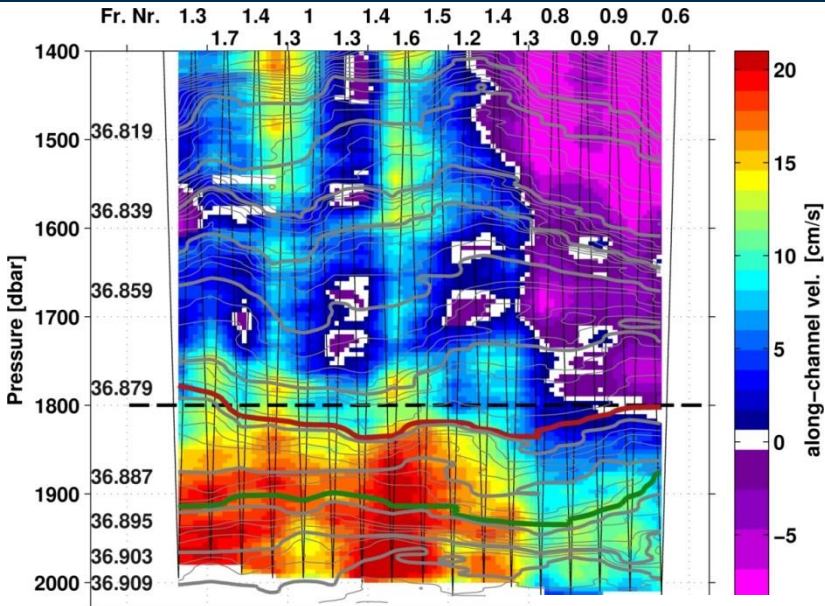




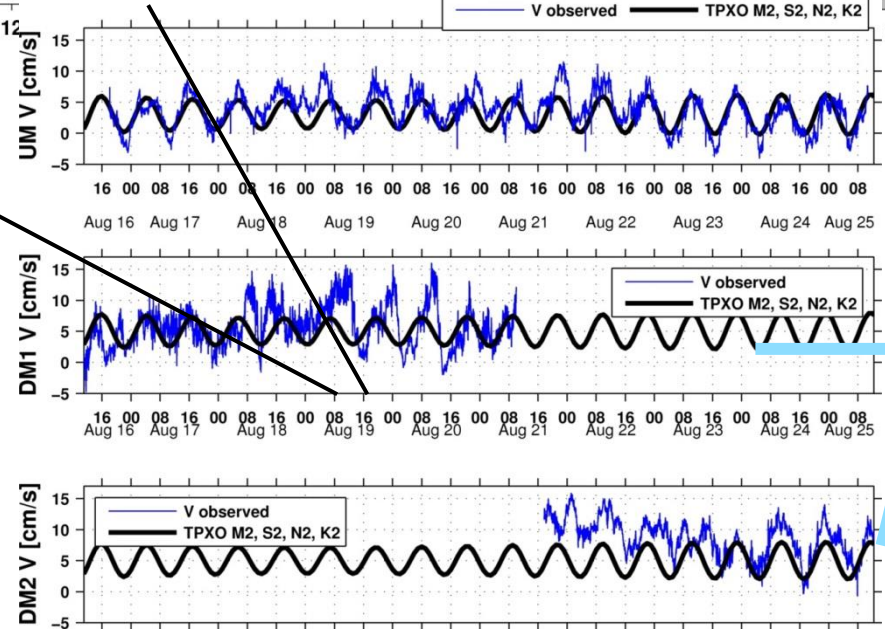
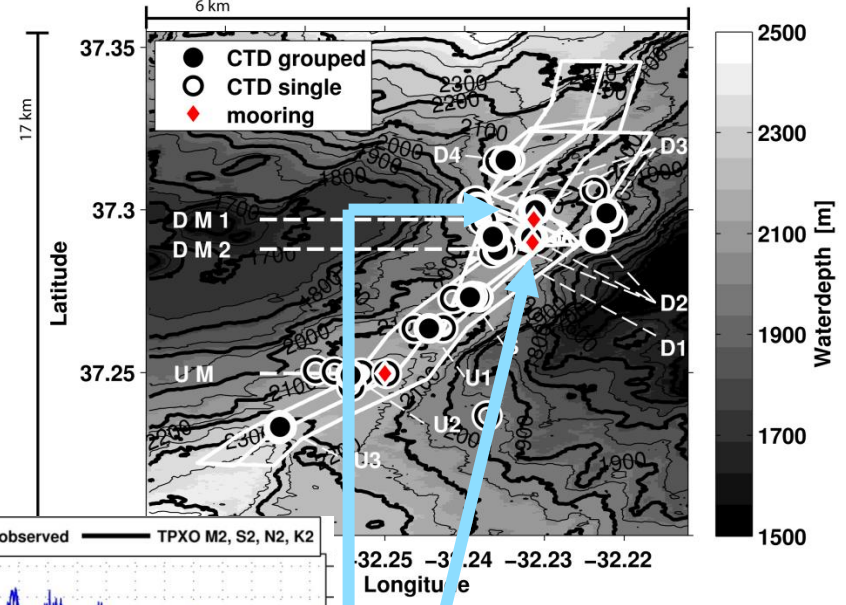
7 hour station at D1 (yoyo-cast)



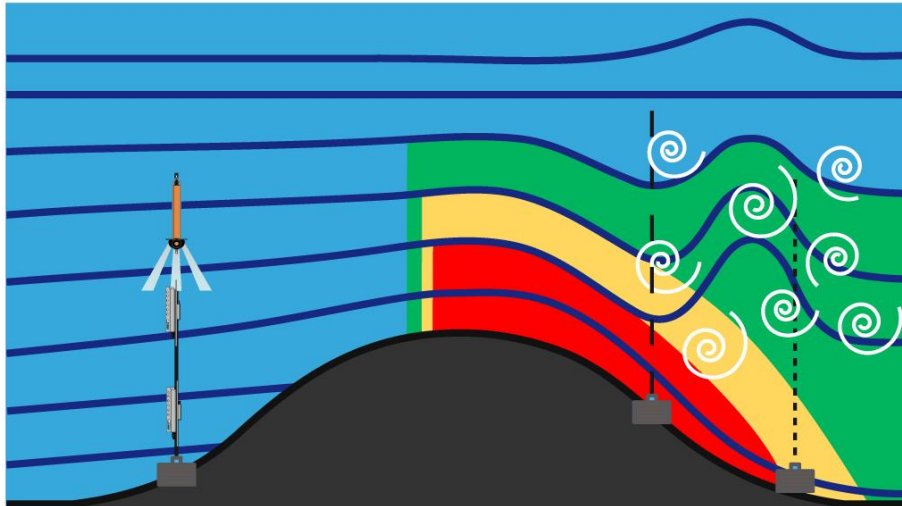
Evolution of the Flow and Density Field



7 hour station at D1 (yoyo-cast)



Along-channel



UM

DM2

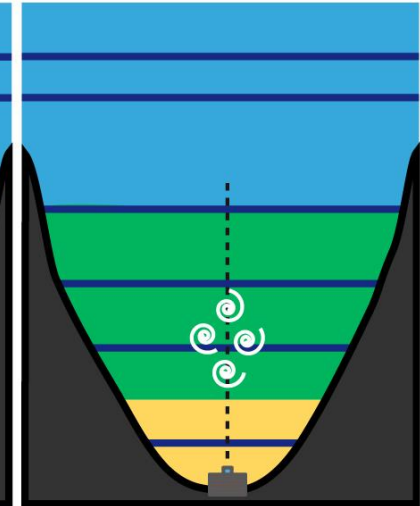
DM1

Cross-channel 1



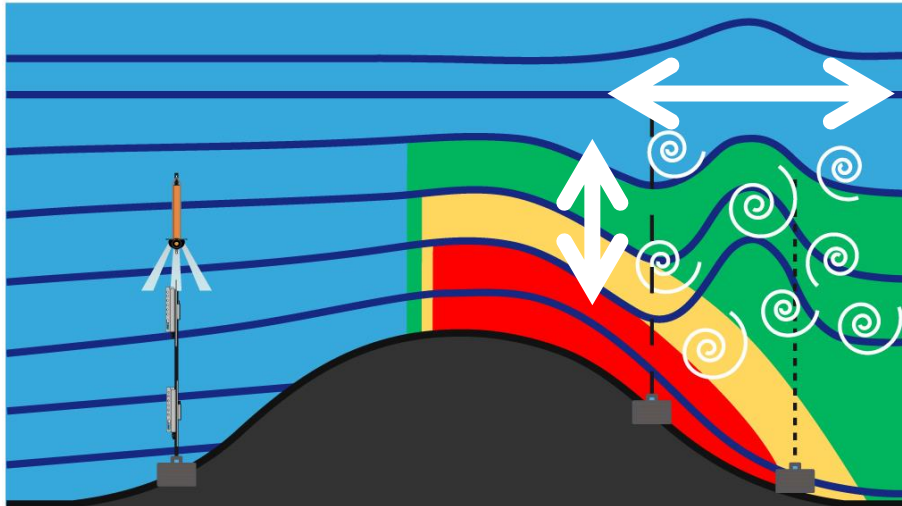
DM2

Cross-channel 2



DM1

Along-channel

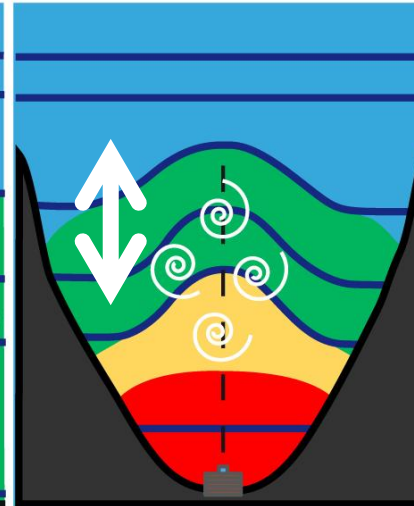


UM

DM2

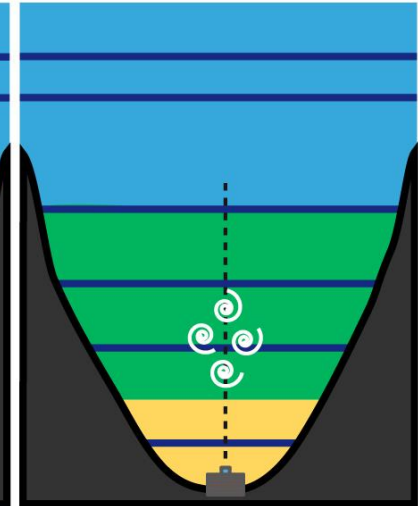
DM1

Cross-channel 1



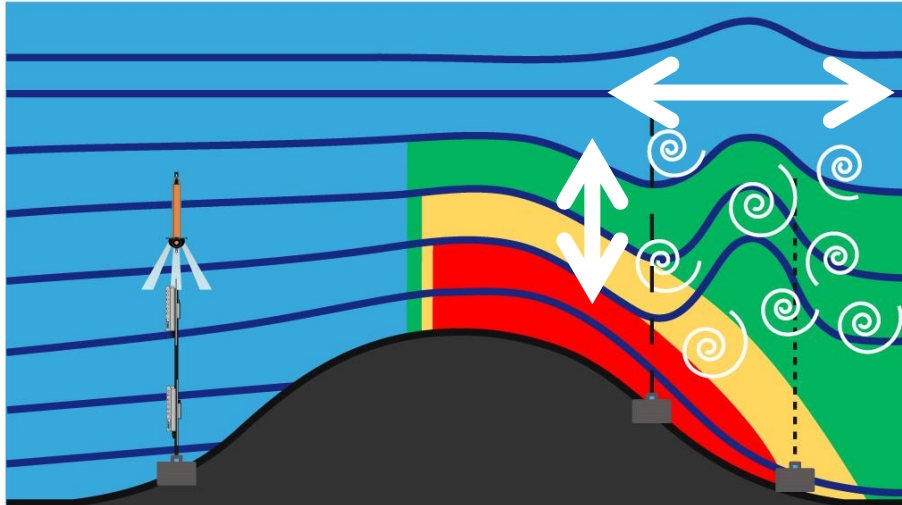
DM2

Cross-channel 2



DM1

Along-channel

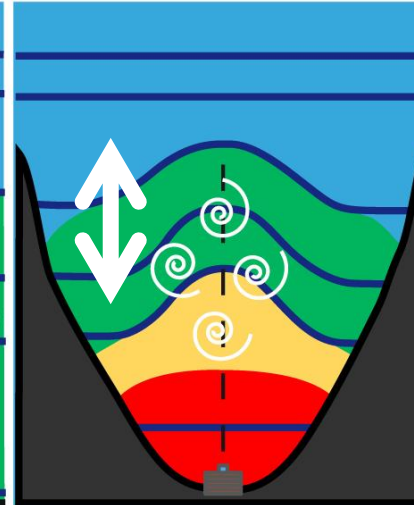


UM

DM2

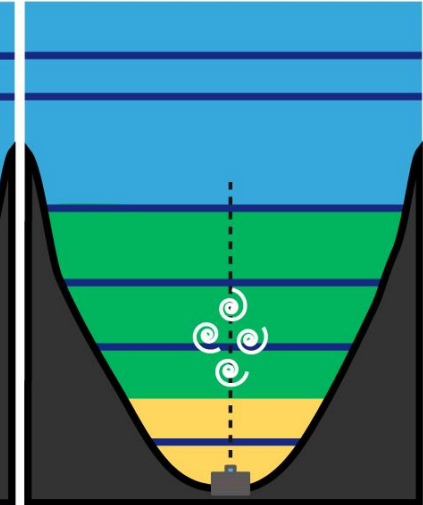
DM1

Cross-channel 1



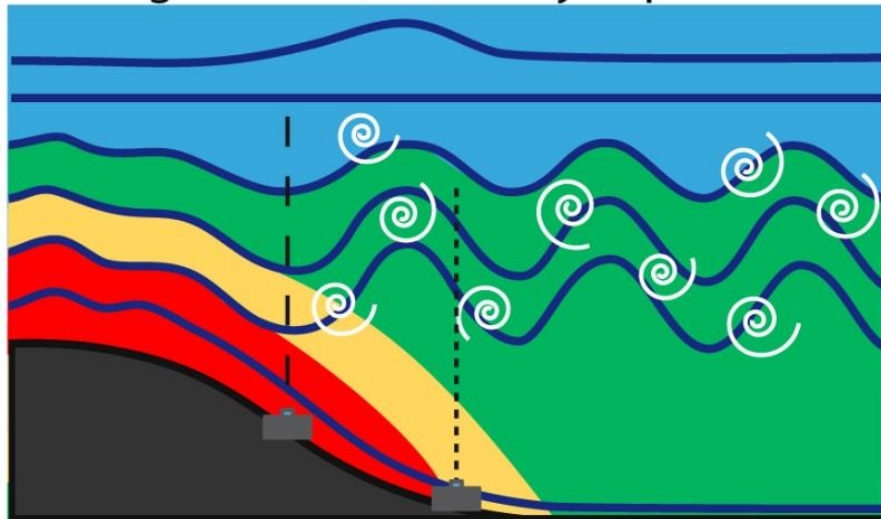
DM2

Cross-channel 2



DM1

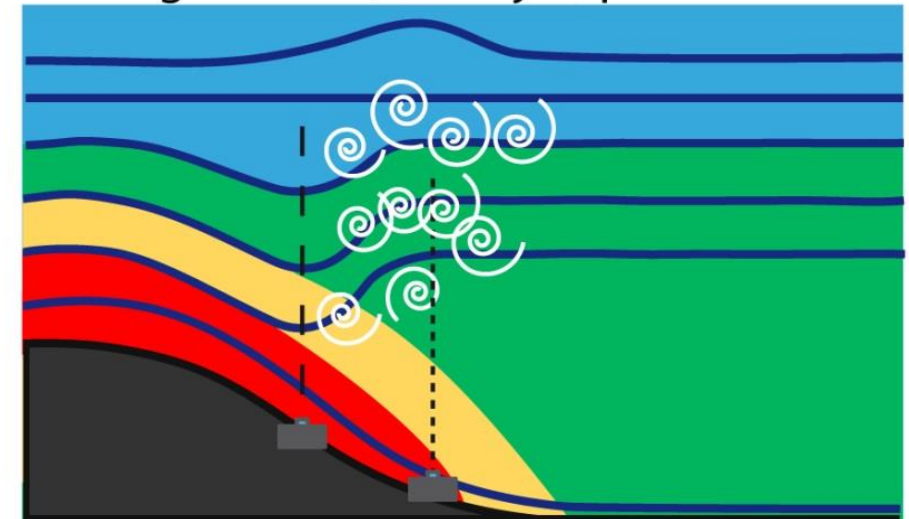
Along-channel, undular jump



DM2

DM1

Along-channel, weak jump



DM2

DM1

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The mixing is distributed non-uniformly. Consistent with the average flow.

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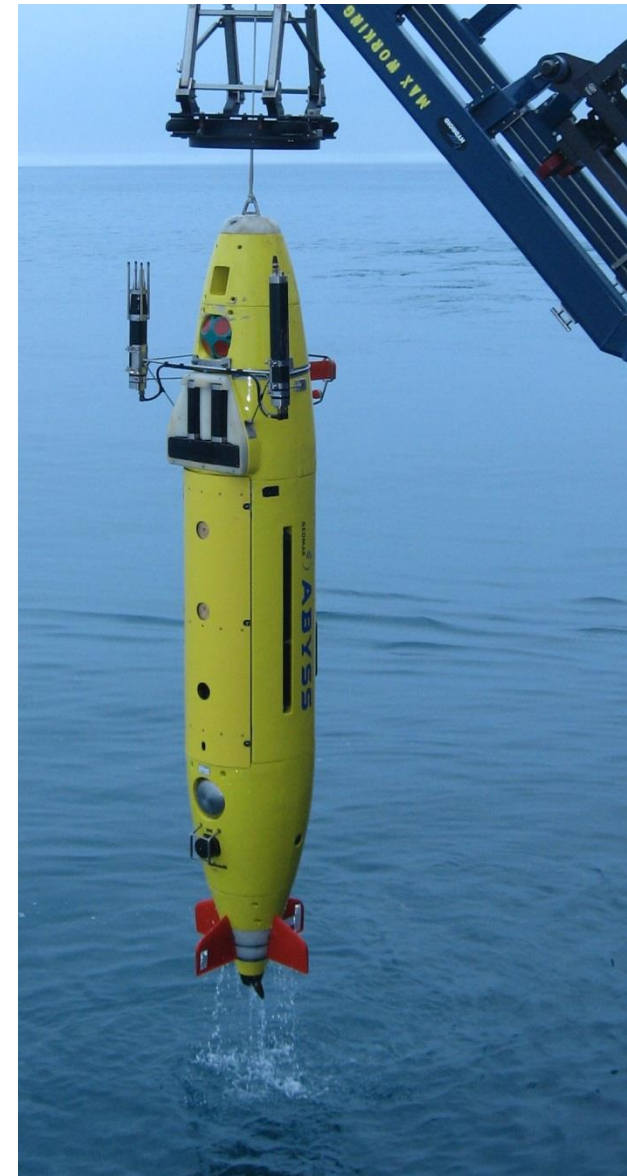
Open questions:

- Dependence of mixing on the flow and topography conditions, especially in the tidal cycle.
- Role of upstream propagating hydraulic jumps.
- Origin of long-term variability (e.g. *Thurnherr et al., 2005*).

Scientific-technological achievements

- A new processing software was adapted. Filter to reduce the noise.
- AUVs are suitable for deep ocean turbulence observations. This widens the measurement range for horizontally profiling techniques especially in areas which are hard to access e.g. the
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 - under the ice.

Allows to study small scale interactions of flow, topography, turbulence and tracers.



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Thank you for your attention

