Vertical Mixing in the Beaufort Gyre Atlantic Water: First Steps in Investigating the Role of Thermohaline Staircases

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1. Background and Motivation

- thermohaline staircases are distinctive features in the upper Atlantic Water (AW) thermocline that result from differing rates of diffusion of heat and salt **[1]**
- where present, they are often assumed to play the dominant role in vertical heat and salt transport, however, their contribution to net mixing relative to other mixing mechanisms like shear-driven turbulence is not well constrained **[2]**
- observations show there is large variability in staircase and staircase-like features **[3]** and open questions remain about how this variability impacts the mixing of heat and salt associated with these features

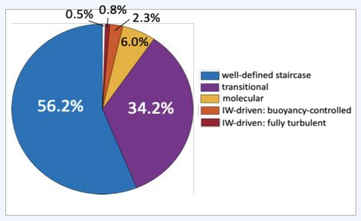


Fig. 1: *The prevalence of mixing regimes in the upper AW thermocline in the Amerasian Basin as diagnosed from Ice-Tethered Profiler data. Note staircase features are associated with the well-defined staircase regime and staircase-like features are associated with the transitional regime [3].*

Goals of this Study:

To use high-density observations of temperature, salinity and turbulence collected by a turbulence-sensing glider in the Beaufort Gyre to characterize:

1. **the prevalence of staircase and staircase-like features**
2. **the variability in staircase characteristics**
3. **how staircase characteristics relate to the background environment**

2. Methods

Data

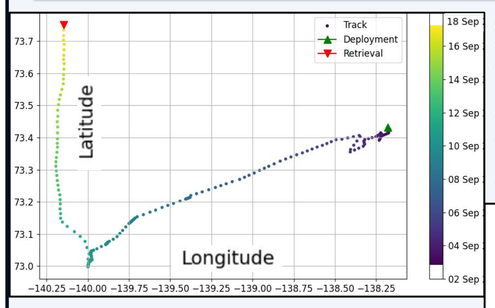
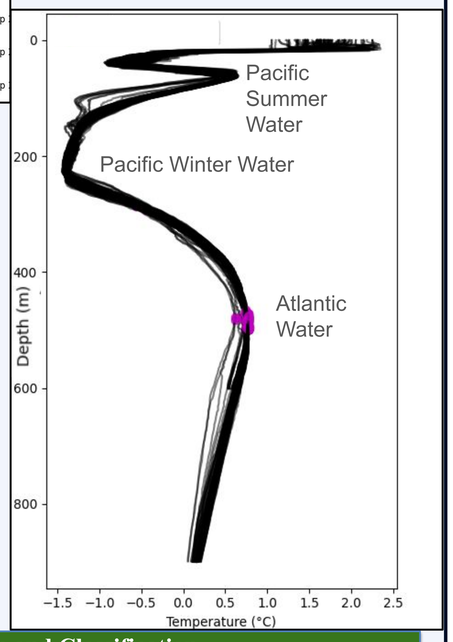


Fig. 2 (left): *Glider transect inside the deep Beaufort Gyre. The glider sampled for 16 days and traversed a distance of 183 km.*

Fig. 3 (below): *The collection of 213 vertical temperature profiles that extended below 600-m depth. These profiles sample the upper AW thermocline above the AW temperature maximum (purple circles).*



- data used in this study consist of 213 vertical profiles of temperature, salinity, pressure & microstructure turbulence (shear and temperature) collected by a turbulence-sensing glider in the deep Beaufort Gyre in September 2024 (Fig. 2)
- profiles often extend to 900-m depth thus sampling the upper Atlantic Water thermocline (above the Atlantic Water temperature maximum) where double-diffusive staircases can form (Fig. 3)

Staircase Identification and Classification

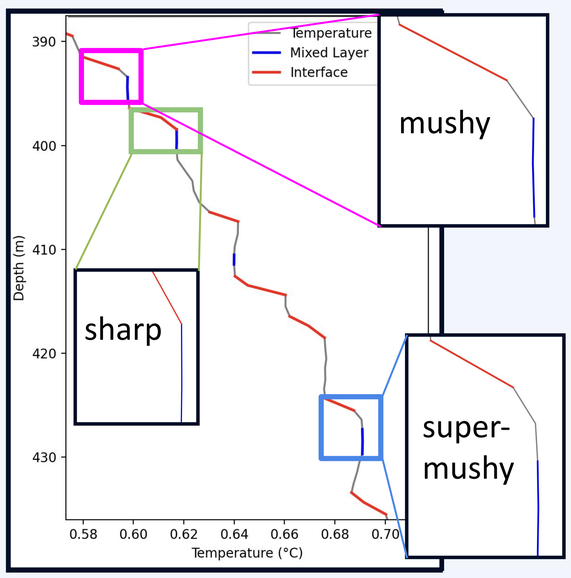


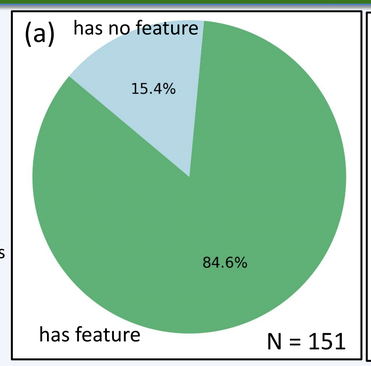
Fig. 4: *A sample temperature profile illustrating the detection of mixed layers and interfaces and the classification of features into the categories of "sharp staircase", "mushy staircase-like feature" and "super mushy staircase-like features"*

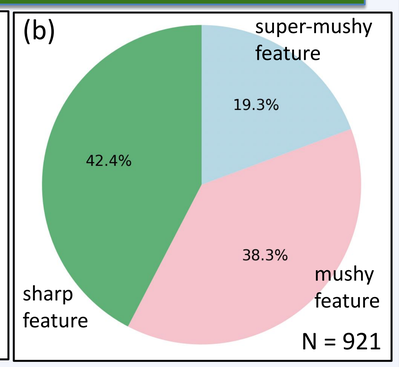
- staircase and staircase-like features are identified via a **feature detection algorithm** that identifies mixed layers and interfaces based on the magnitude of the vertical temperature gradient
- features are then classified into one of 3 categories:
  1. sharp staircase if there is negligible separation between the mixed layer and adjacent interface
  2. mushy staircase-like feature if there is a small transition region between the mixed layer and adjacent interface (specifically 1 point ~ 0.2 m)
  3. super mushy staircase-like feature if there is a larger transition region between the mixed layer and adjacent interface (specifically 2-4 points ~ 0.4 - 0.8 m)

3.a Results
Staircase and Staircase-like Feature Prevalence

Feature Prevalence

Fig. 6: Feature and feature-type prevalence *The relative prevalence of* ***(a)*** *profiles that contain one or more staircase or staircase-like feature vs. profiles that contain no feature; and* ***(b)*** *'sharp', 'mushy' and 'super mushy' features observed.*





- most (~85%) of profiles contain staircase or staircase-like features
- sharp and mushy features account for most features and are equally common

Spatial Distribution

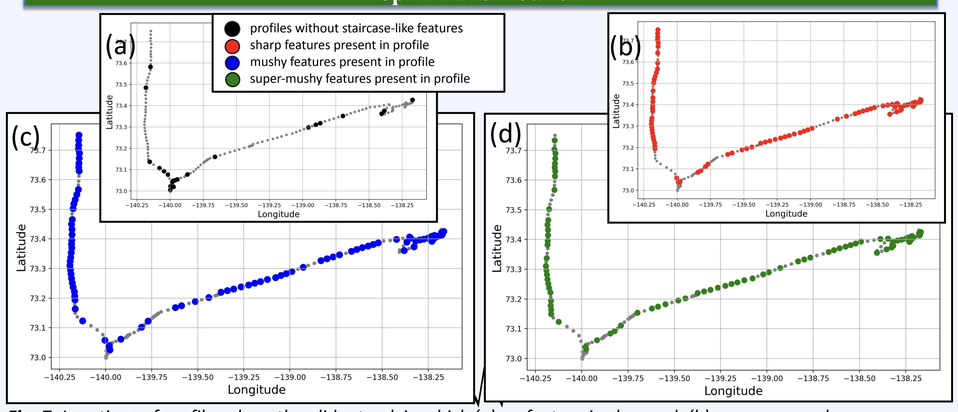


Fig. 7: *Locations of profiles along the glider track in which (a) no feature is observed; (b) one or more sharp features are observed; (c) one or more mushy features are observed; and (d) one or more super mushy features are observed.*

- profiles with no features present tend to be along the southern leg near the deployment location and at 140°W
- profiles with features present are observed along the entire glider track with no clear spatial pattern
- profiles that contain sharp features, typically also contain mushy and super-mushy features

Feature Density

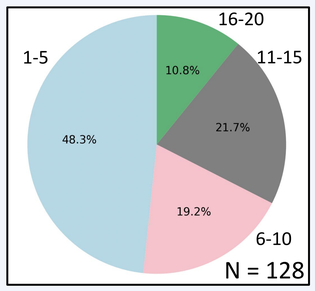


Fig. 8: *The relative prevalence of profiles with one or more features distributed by the number of features per profile.*

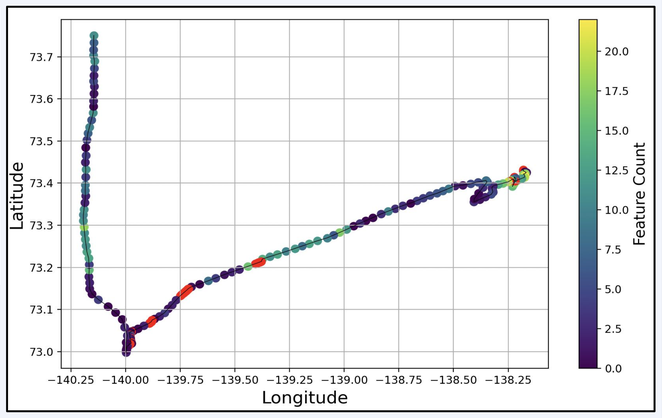
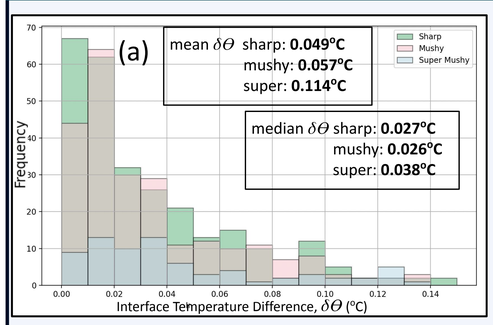


Fig. 9: *Spatial distribution of profiles coloured by the number of features (of any type) observed per profile.*

- most profiles with features present have multiple features in the profile
- profiles with the highest number of features per profile tend to be found near the deployment location and in isolated regions along both legs centred at 139.25°W and 73.3°N

3.b Results
Feature Characteristics



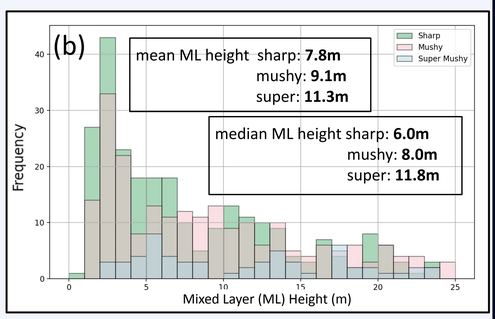


Fig. 10: *The distribution of* ***(a)*** *interface temperature differences and* ***(b)*** *mixed layer heights for sharp, mushy and super-mushy features. Respective means and medians of temperature differences (δΘ) and mean height differences (m) for each type of feature are shown*

- the mean interface temperature difference is smallest for sharp features and largest for super-mushy features
- the mean and median mixed layer heights are smallest for sharp features and largest for super-mushy features

3.c Results
Background Characterization

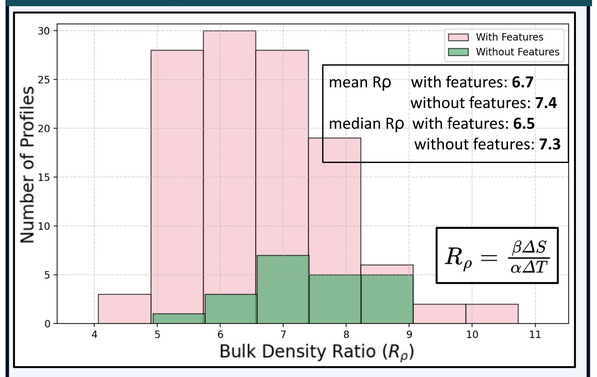


Fig. 11: *The distribution of bulk density rations, R_ρ, computed over the upper AW thermocline for profiles with and without features.*

- the bulk density ratio characterizing the stratification of the upper AW thermocline as a whole ranges between 4 and 11 for all profiles
- mean and median Rρ values are slightly less for profiles that contain staircase or staircase-like features vs. profiles that do not
- there is no clear systematic difference between Rρ distributions for profiles that contain features vs. profiles that do not

4. Next Steps

- **repeat identification and classification of features** in themicrostructure temperature data (vertical structure is more finely resolved here)
- expand on the **analysis of feature characteristics** (e.g. mixed layer thickness, interface thickness, interface salinity difference, interface density gradient ratio)
- explore the **relationships between feature characteristics and properties of the background environment** (e.g. density gradient ratio, background temperature gradient, background stratification, background turbulence intensity)
- diagnose **turbulent vertical heat fluxes** with the **microstructure data** and understand relationships between feature characteristics and turbulent heat flux
- test the validity of the **4/3rd flux law** for sharp, mushy and super-mushy features
  - → 4/3rds flux law assumes the heat flux scales with the interface temperature differences to the 4/3rds power
  - → there are open questions about where and when this parameterization is valid **[5]**, the conditions for which this parameterization may overestimate or underestimate the heat flux **[e.g. 2]**, and how turbulence can modify these fluxes **[6]**
  - → the combination of this type of feature analysis + an analysis of the coincident turbulence data promises to shed light on these issues

5. Summary

- we quantify the prevalence of staircase and staircase-like features:
  - the majority of profiles contain one or more staircase-like features
  - of these, slightly less than half are considered sharp, well-defined staircases
  - features are observed everywhere along the glider track with no clear spatial pattern
  - most profiles with features have multiple features and feature types in the profile
- we assess the variability of feature characteristics:
  - sharp features have the smallest interface temperature differences on average while super-mushy features have the largest
  - sharp features have the smallest mixed layer heights on average while super-mush features have the largest
- we explore relationships between features and the background environment:
  - no clear difference in bulk density ratio for profiles that contain staircase and staircase-like features relative to profiles that do not

6. References

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7. Acknowledgments

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