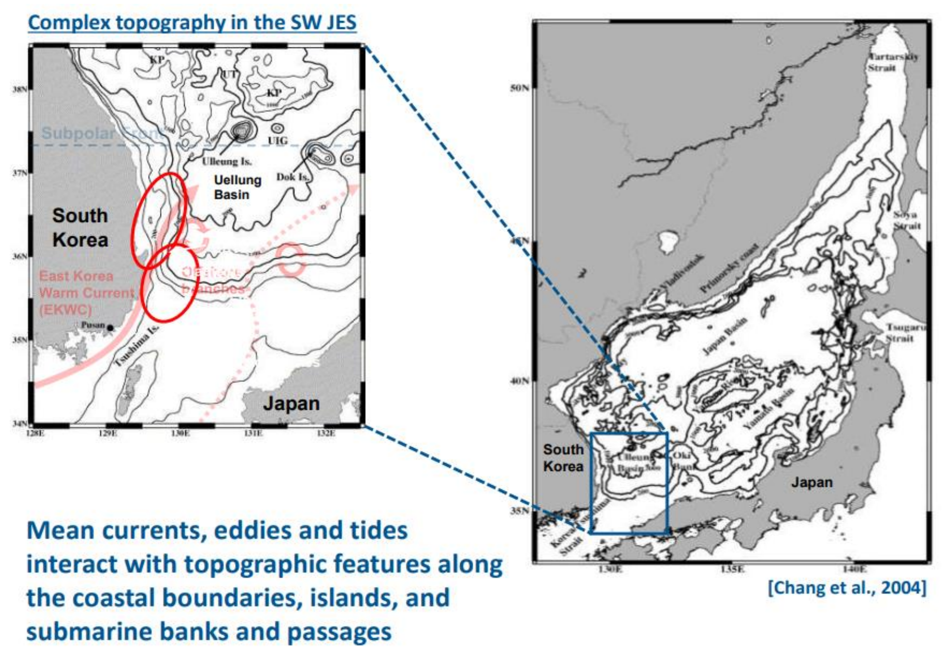
Observations on enhanced mixing over the steep continental slopes in the southwestern East Sea (Japan Sea)

Yeongseok Jeong* and SungHyun Nam
School of Earth and Environmental Sciences, Seoul National University, Seoul, Republic of Korea
(e-mail: jiv187@snu.ac.kr)

Abstract

Diapycnal mixing in a stratified ocean plays a pivotal role in modifying the physical properties of seawater, redistributing nutrients and chemical materials, and influencing regional ocean circulation and ecosystem. However, the detailed mechanisms underlying enhanced and depressed turbulent mixing in the southwestern East Sea (SWES) consisting of steep slopes and shallow banks, have not been well documented primarily due to a lack of observations. In this study, we examined turbulent mixing properties from Conductivity-Temperature-Depth (CTD), Acoustic Current Doppler Profiler (ADCP), and vertical microstructure profiler (VMP) data collected in December 2021. The water column stability was quantified with Richardson number (Ri), resulting in unstable conditions near the surface and bottom boundaries and intermittently near the pycnocline, e.g., at depth of 80 m on the bank or 70-80 m on the slope where S^2 well exceeds N^2, yielding Ri less than 0.25. Consistently, enhanced turbulent kinetic energy dissipation rate of an order of 10^{-4} W kg^{-1} and the eddy diffusivity of ~10^{-2} m^2 s^{-1} derived from the VMP measurements were observed in the region. This study provides observational evidence on enhanced and depressed turbulent mixing over the steep slopes in the SWES.

Introduction



The SWES is featured by

- Main axis of EKWC (East Korea Warm Current)
- Rough bottom topography
- Semidiurnal internal tides
- Sub-mesoscale eddies

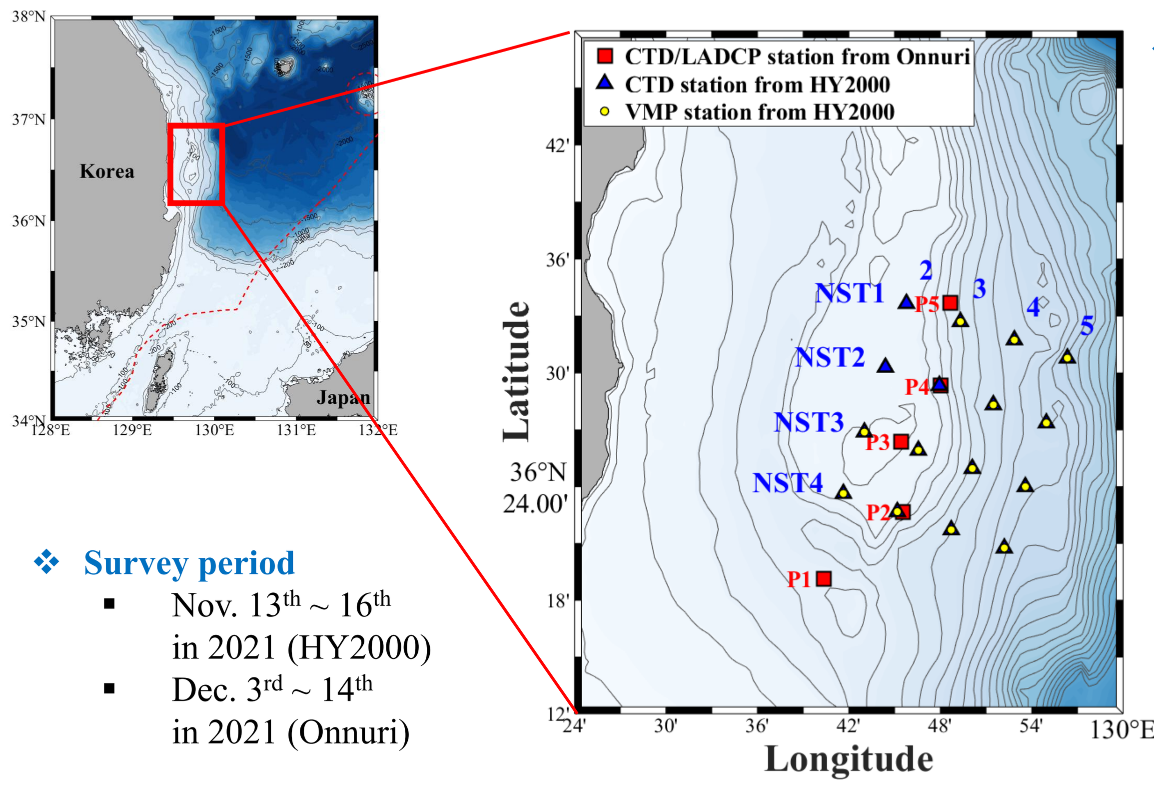
- Strong vertical shear
- Favorable mixing condition (Ri < 0.25), particularly below 150 m
- Generate energetic turbulence (Wijesekera et al. 2022)

Seo et al. (2015) shows indirect estimations of vertical diffusivity according to Thorpe scale method, with turbulent mixing parameters being generated at the steep continental slopes over the southern part of Ulleung Basin. Furthermore, Choi et al. (2019) demonstrates classification of sub-mesoscale turbulence in the East Sea (Japan Sea) with altimetry images, representing physical and parametric characterization. However, microstructure turbulence in-situ observation in the SWES has been poorly constrained due to the difficulties in operating observational instruments.

This study mainly focuses on

- Quantifying turbulent parameters with in-situ observation
- Comparison between mixing-favorable condition derived by stratification structure and measured turbulence

Data and Methods



❖ **Survey period**
- Nov. 13th ~ 16th in 2021 (HY2000)
- Dec. 3rd ~ 14th in 2021 (Onnuri)

❖ **Research vessel**
- R/V HY2000
- R/V Onnuri

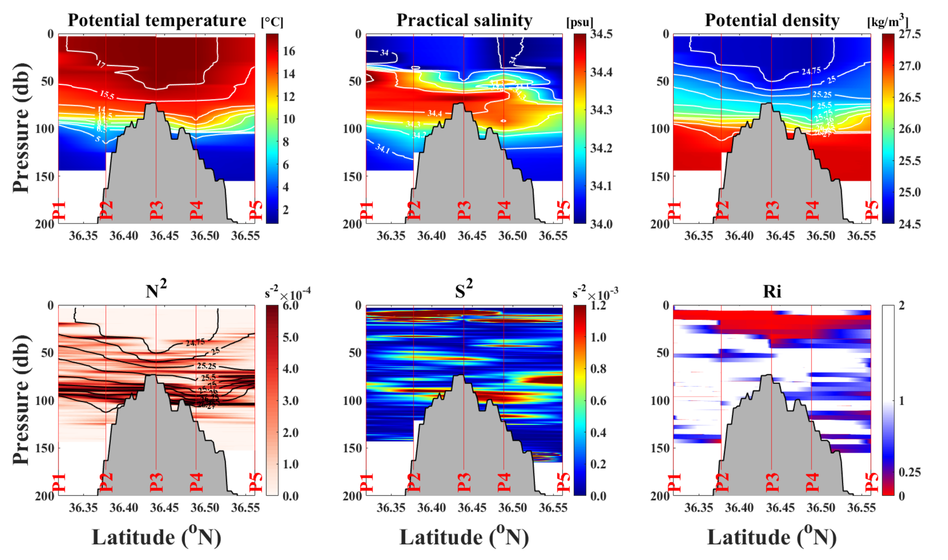
❖ **Data acquisition**
- **CTD**: conductivity, temperature, pressure
- **LADCP (300kHz)**: current velocity (u and v)
- **VMP (250kHz)**: turbulent dissipation rate (ε1, ε2)

❖ **Data processing**
- **CTD**: by Seabird standard data post-processing procedure (AlignCTD, CellTM, LoopEdit, etc.)
- **LADCP (300kHz)**: by LEDO software
- **VMP (250kHz)**: by ODAS software

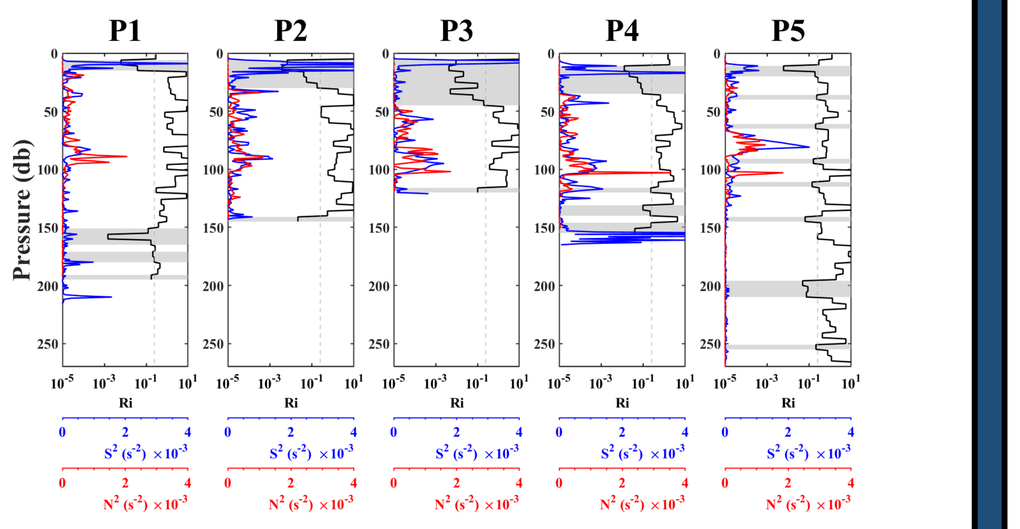
❖ **Calculation of Buoyancy frequency (N^2), Vertical shear (S^2), Richardson Number (Ri), and vertical diffusivity(K_Z)**
- $N^2 = -\frac{g}{\rho}\frac{\partial \rho}{\partial z}$
- $S^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2$
- $Ri = \dfrac{-\frac{g}{\rho}\frac{\partial \rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$
- $K_Z = \Gamma \frac{\varepsilon}{N^2}$ ($\Gamma = 0.2$ assumed)

Results and Discussion

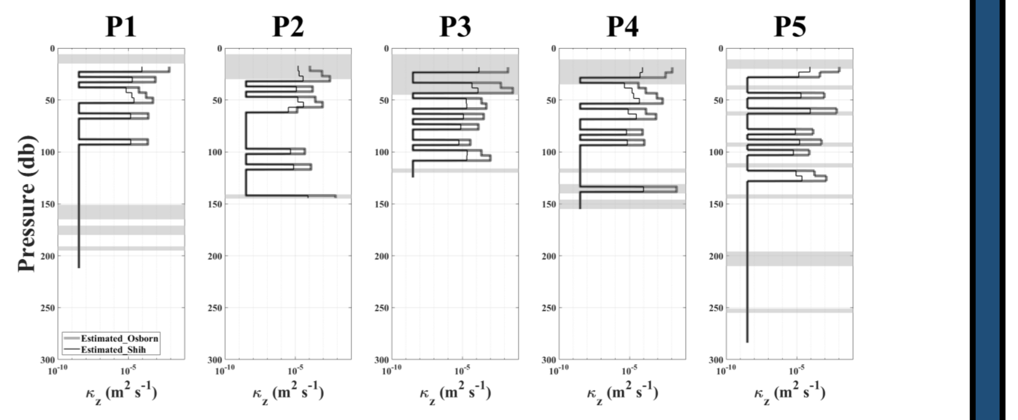
❖ **Cross section of stratification structure by CTD observation**
- Homogeneously well mixed surface layer
- Strong stratification at the depth range 70-110 m
- Relatively deepened thermocline at P2 and P4



❖ **Vertical structure of Buoyancy frequency (N^2), Current shear (S^2), and Richardson number (Ri) by CTD and LADCP observation**
- Vertical dotted gray line: 0.25 of Ri, Gray shaded area: less than 0.25 of Ri
- High vertical shear at the surface and bottom boundaries
- Simultaneous reinforcements of N^2 and S^2 around 80-100m at P1 to P4

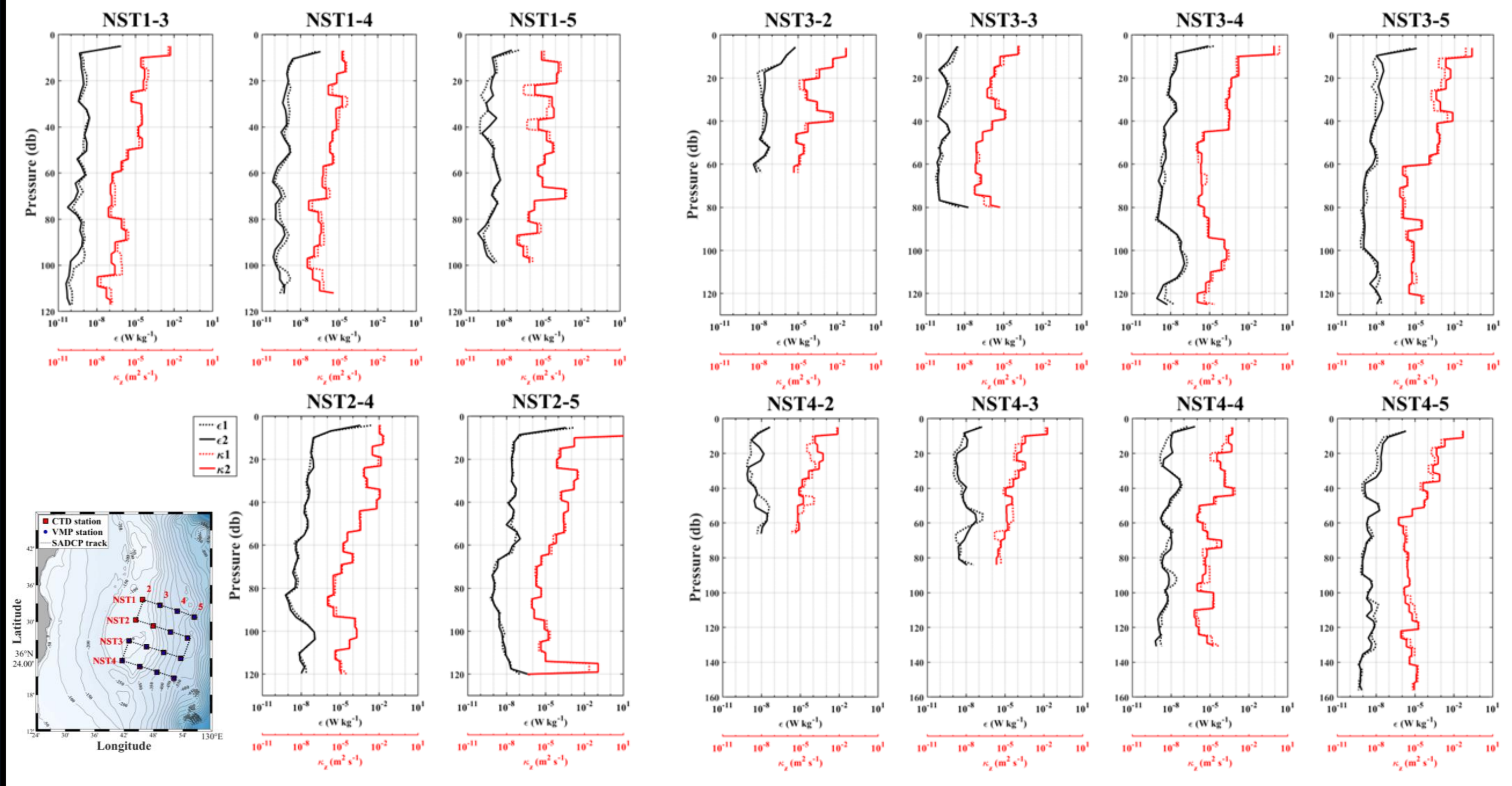


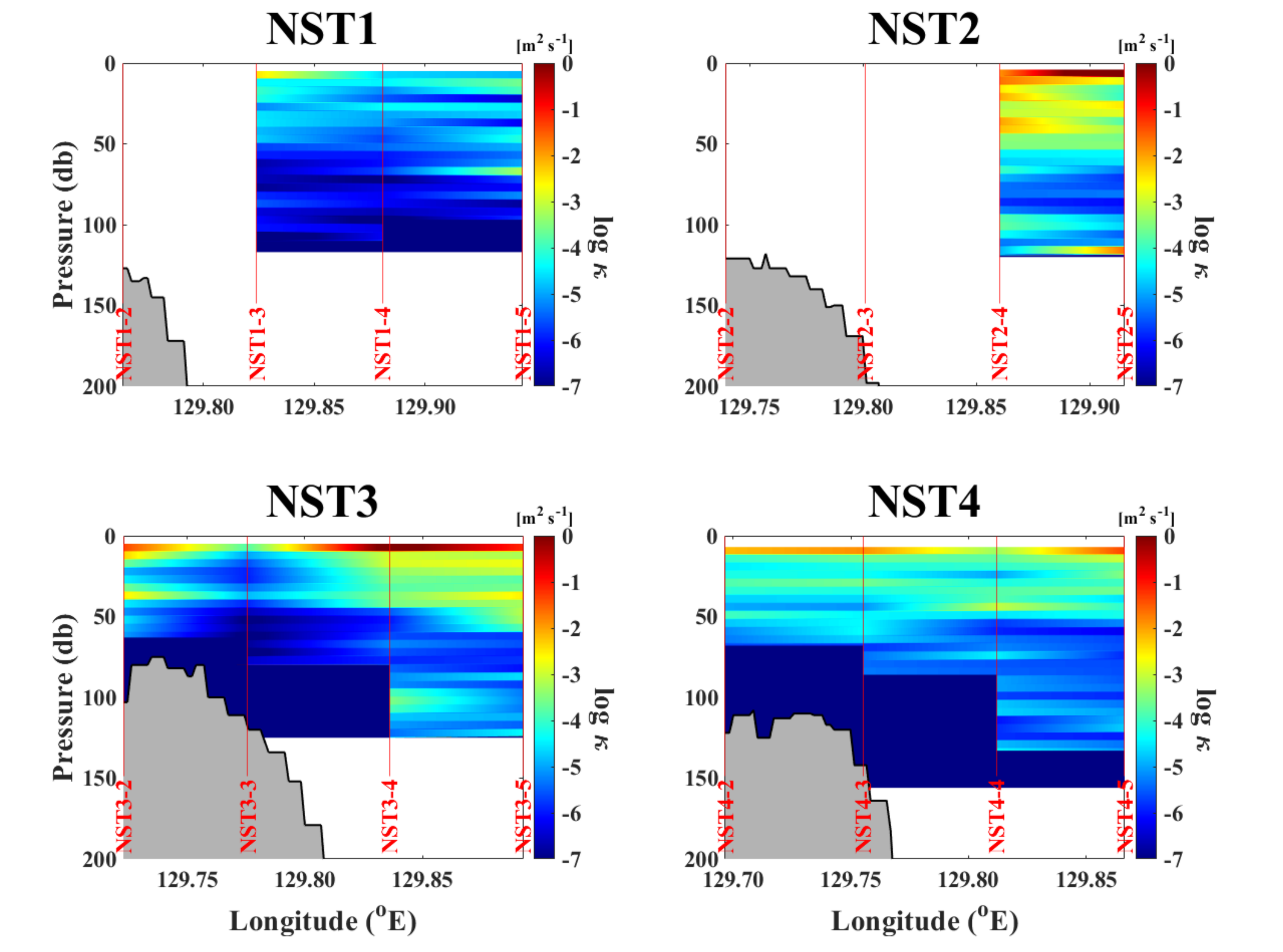
❖ **Thorpe-scale-derived vertical diffusivity**
- Gray shaded area: less than 0.25 of Ri
- Enhanced diffusivity at the surface along low Ri at P2, P3 and P4
- Depth of 145 m at P2 and P4 satisfy Kelvin-Helmholtz instability, leading to strengthened diffusivity



Results and Discussion

❖ **Vertical structure of turbulent dissipation rate (ε) rate and vertical diffusivity (K_Z) by VMP observation**
- Intermittent enhancement and depression of vertical diffusivity along with the rate of turbulent dissipation
- NST2-4 and NST3-4 show increased ε around 100m, which is in consensus with vertical stability diagnosis by Ri
- 70m from NST1-5, 38m from NST3-2, and 90m from NST3-5 contain enhanced vertical diffusivity, with turbulent dissipation rate representing monotonous movement





Conclusion

- Surface layers represent unstable condition, caused by Kelvin-Helmholtz instability, showing enhanced vertical diffusivity. However, certain points of depth, for instance 20-100 m at P1, where denotes strengthened diffusivity, cannot be explained by Ri.
- VMP observation from dataset of HY2000 consistently displays high turbulent dissipation rate and vertical diffusivity, specifically at the surface, which is intensified over an order of 10^{-4} W kg^{-1} for ε and 10^{-2} m2 s^{-1} for κ.
- Increasing both buoyancy frequency and vertical shear at P1 to P4 around the depth 80-100m corresponds to the enhanced rate of turbulent dissipation around 100m at NST2-4 and NST3-4 where are at the middle of the topographic bank.

References

- J. Choi, Y. G. Park, W. Kim, Y. H. Kim. (2019). Characteristics of submesoscale turbulence in the East/Japan Sea using geostationary ocean color satellite images. *Geophysical Research Letter*, 46, 8214-8223, https://doi.org/10.1029/2019GL083892
- H. W. Wijesekera, Jarosz, E., D. W. Wang, Luecke, C. A., W. J. Teague, Chang, K.-I., et al. (2022). Tidally driven mixing "hot spot" at the entrance of the Japan/East Sea. *Geophysical Research Letters*, *49*, e2022GL100315. https://doi.org/10.1029/2022GL100315
- Jonathan D. Nash, Eric Kunze, John M. Toole and Ray W. Schmitt. (2003). Internal tide reflection and turbulent mixing on the continental slope. *Journal of Physical Oceanography,* 34(4), 1117-1134. https://doi.org/10.1175/1520-0485(2004)034%3C1117:ITRATM%3E2.0.CO;2
- K. I. Chang, W. J. Teague, S. J. Lyu, H. T. Perkins, D. K. Lee, D. R. Watts, Y. B. Kim, D. A. Mitchell, C. M. Lee, and K. Kim. (2004). Circulation and currents in the southwestern East Sea/Japan Sea: Overview and review, Progress in Oceanography, 61, 105-156, https://doi.org/10.1016/j.pocean.2004.06.005
- S. B. Seo, Y. G. Park, J. H. Park, and H. D. Jeong. (2015). Thorpe scale analysis using CTD observation on the continental slop of the Southwestern East Sea. *Ocean and Polar Research*, 37(2), 107-117, http://dx.doi.org/10.4217/OPR.2015.37.2.107