Turbulent mixing at the Bussol' Strait in the Kuril Islands using density inversions

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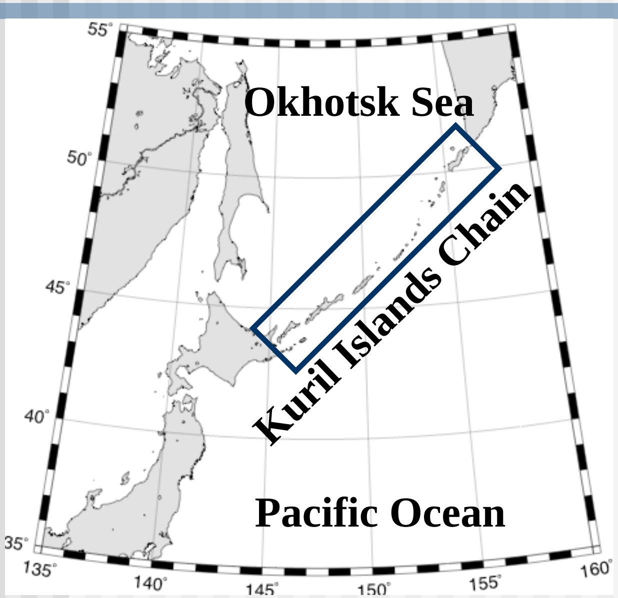
Introduction - Kuril Straits



- Strong diurnal tide
  (Kowalik and Polyakov, 1998; Katsumata *et al.*, 2004)
- Complex topography

Interaction

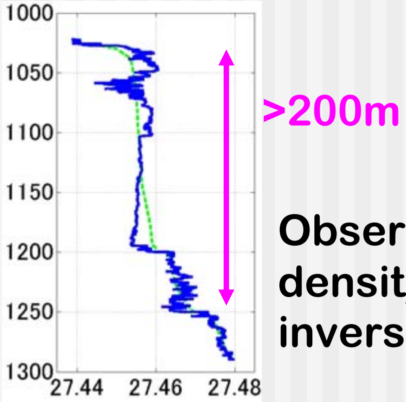
Strong vertical mixing
(Nakamura *et al.*, 2000; Nakamura and Awaji, 2004)

- Strong vertical mixing around Kuril straits impacts on
  - The formation of NPIW (Nakamura and Awaji, 2004; Yasuda, 2004)
  - Southward intrusion of Oyashio (Tatebe and Yasuda, 2004)
  - Bidecadal variability in northwestern Pacific and Okhotsk sea
    (Osafune and Yasuda, 2006; Yasuda *et al.*, 2006)

We need to know turbulence intensity.
But, there has been no direct observation.

Purpose

- Final Goal
  - Quantify turbulent intensities around Kuril Straits
    - We need indirect method for estimating turbulence energy dissipation rate ε as turbulence intensity
    - CTD data is only available data in this data scarce region
- Indirect method
  - Estimating ε using density inversions measured by CTD is useful (Thorpe, 1977)
  - This method is one of representative methods estimating ε



Observed density inversion

- Purpose in the present study
  - Validate and improve this indirect method by comparing with direct turbulence measurement
  - Clarify a part of turbulence distribution at the Bussol' Strait by applying the new method

Indirect method using density inversion

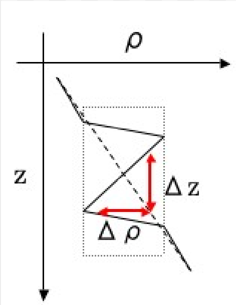
(Thorpe, 1977; Galbraith and Kelly, 1996)

- Ozmidov scale L_o
  - The vertical length scale of the largest eddies may cause density inversion in stratified water

$$L_o = \left(\frac{\varepsilon}{N^3}\right)^{1/2}$$

- Thorpe scale L_T (from CTD)
  - The mean vertical distance of water parcel displacement by turbulent motion

$$L_T = \sqrt{\frac{\sum_{i=1}^{n} \Delta z_i^2}{n}}$$



Empirically, it is shown that L_O can be proportional to L_T.

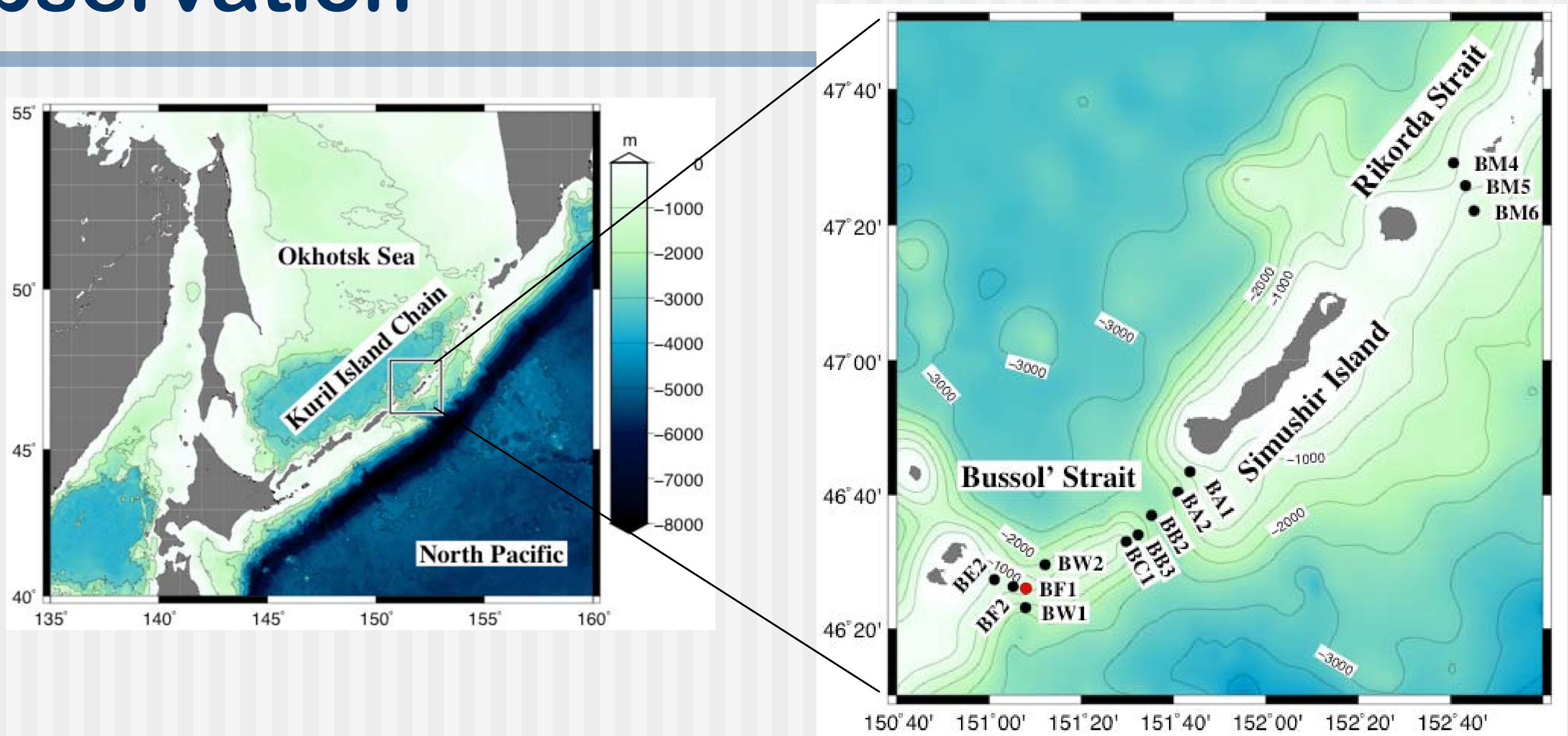
(Dillon, 1982; Ferron et al., 1998; Stansfield et al., 2001)

If $L_O = cL_T$ is assumed, ε can be estimated from CTD data.

$$\varepsilon = c^2 L_T^2 N^3$$

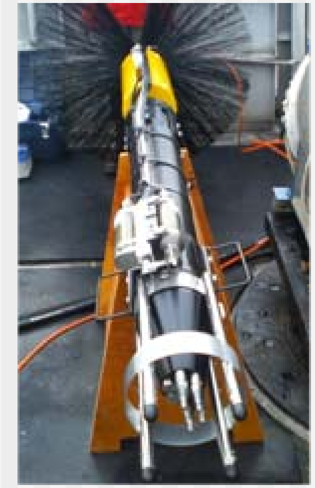
- Difficulties of this method
  - Sensitive to noise in density profiles
    ➔ Galbraith and Kelley's tests are useful for detecting doubtful inversions by noise (Galbraith and Kelley, 1996)
  - Impossible to estimate ε in the ranges without density inversion

Observation



- **Position** Bussol' Strait and Rikorda Strait
- **Date** 13 - 18 Aug. 2007
- **R/V** Professor Khromov
- **Instrument**
  - Standard CTD (SBE911plus) 31 casts
  - Vertical microstructure profiler 31 casts

VMP (Rockland Scientific International Inc.)



- Vertical microstructure Profiler 2000 & 500
  - Tethered free-falling profiler
  - Shear sensors

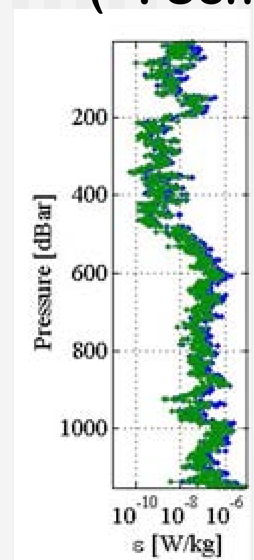
    ➔ Directly measured ε with 1m interval
  - standard CTD

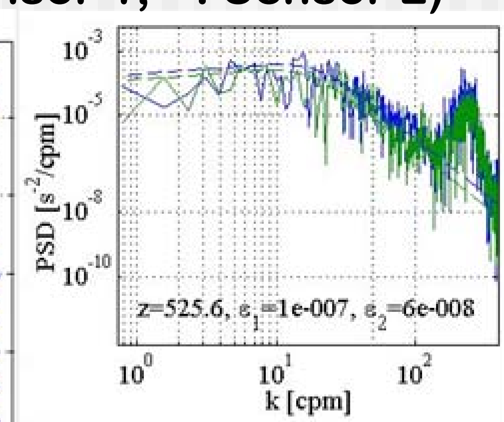
    ➔ Carefully denoised density profile with 0.1m interval

    (ref. Lueck and Picklo, 1990; Morison et al., 1994)

    ➔ Indirectly estimated ε using density inversions

• A example of observed ε
(--: Sensor 1, --: Sensor 2)



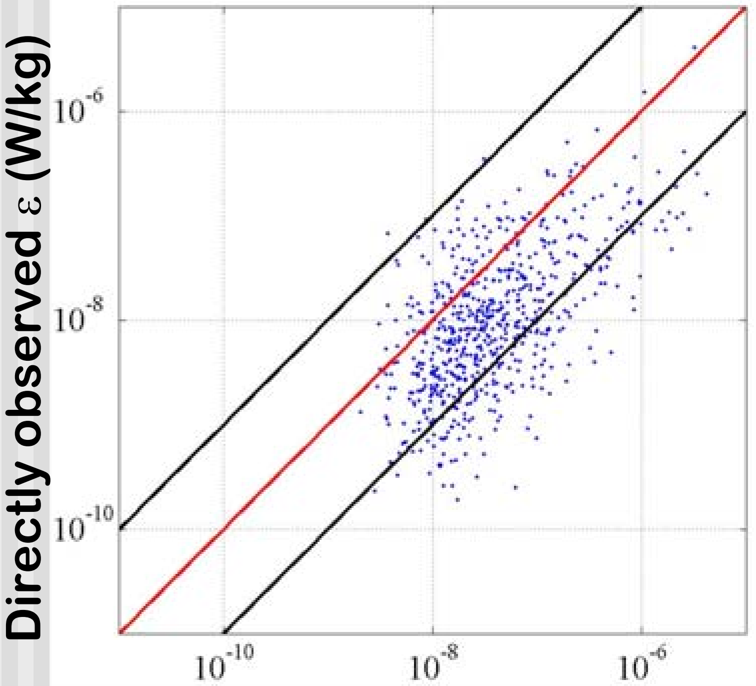


Shear spectra
(Solid: observed)
(Dash: Nasmyth)

It is possible to compare indirect estimation by density inversions with simultaneously observed ε

Comparison

$\varepsilon = L_O^2 N^3 = c^2 L_T^2 N^3$ ($L_O = cL_T$)

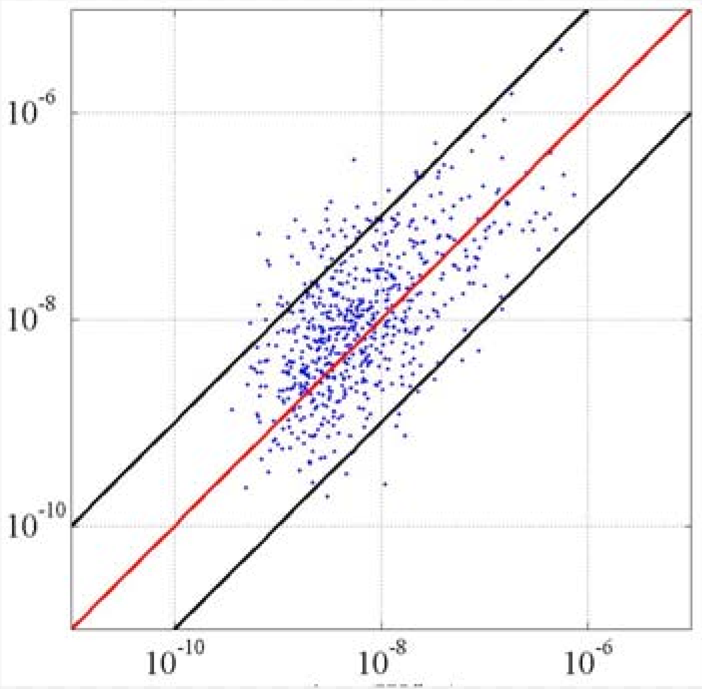


Indirectly estimated ε (W/kg)
($L_O = L_T$ assumed)

- Indirectly estimated ε passed Galbraith and Kelley's test
- Proportional coefficient c is assumed to be 1, which is suggested by previous studies (Ferron et al., 1998; Stansfield et al., 2001)

- Linear relation is confirmed between direct and indirect ε
- But, the assumption of c~1 makes overestimation.
  ➔ Need to determine proportional coefficient c.

Comparison



Directly observed ε (W/kg)

Indirectly estimated ε (W/kg) ($L_O=0.41L_T$)

$\varepsilon = L_O^2N^3 = c^2L_T^2N^3 \; (L_O=cL_T)$

- Proportional coefficient
  - determined by least-squared method using this cost function

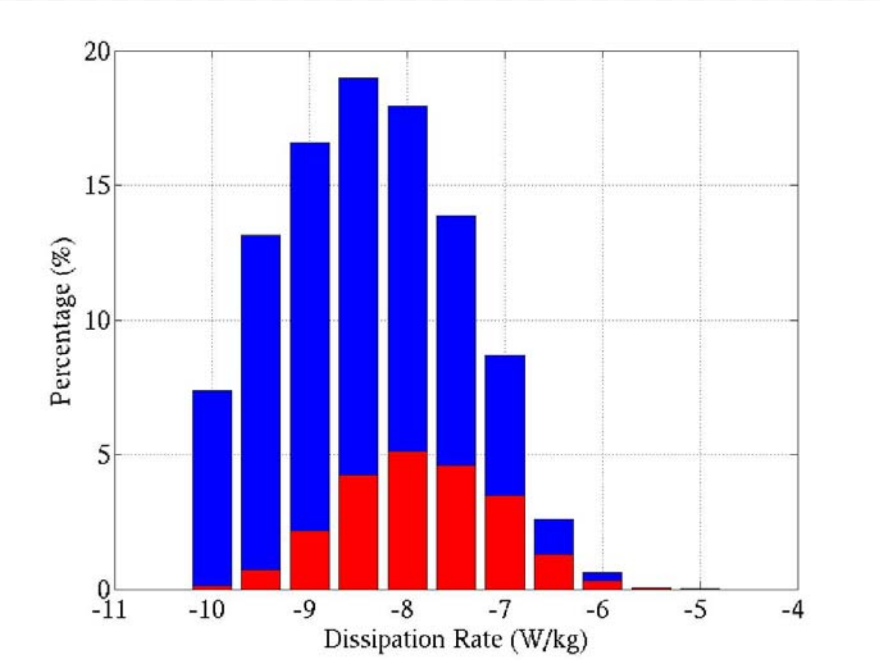
$$I = \sum \left| \log_{10}\left(\frac{c^2L_T^2N^3}{\varepsilon_{\text{observed}}}\right)\right|^2$$

- Error
  - RMS of the logarithmic proportion between direct and indirect ε

$$E = \sqrt{\left(\sum \left|\log_{10}\left(\frac{\varepsilon_{\text{estimated}}}{\varepsilon_{\text{observed}}}\right)\right|^2\right)/n}$$

- $\varepsilon_{\text{observed}} = 0.17L_T^2N^3$ ($c = 0.41$)
- Estimation error using this coefficient is within a factor of 3.4.

Histogram of ε

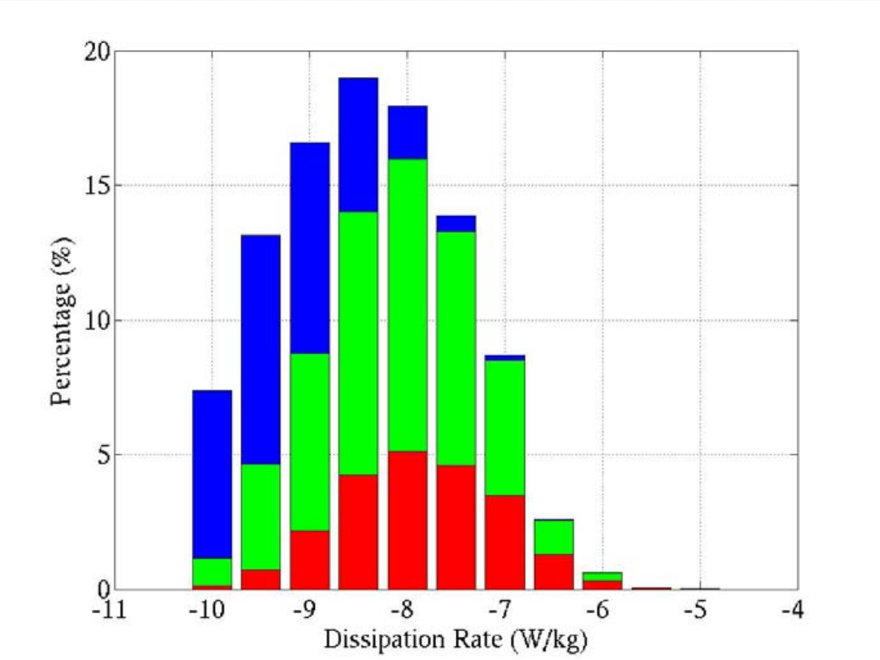


- Directly observed ε
- Indirect ε passed GK tests
  - only cover 22%
  - missed even large ε
  - Error is a factor of 3.4

- Galbraith and Kelley's tests
  - Run-length test: Rejecting density inversions by random noise
  - Water-mass test: Rejecting density inversions by systematic noise of CTD by checking the linearity of T-S relation

- We found out that
  - Water-mass test rejected too much density inversions with large ε

Histogram of ε



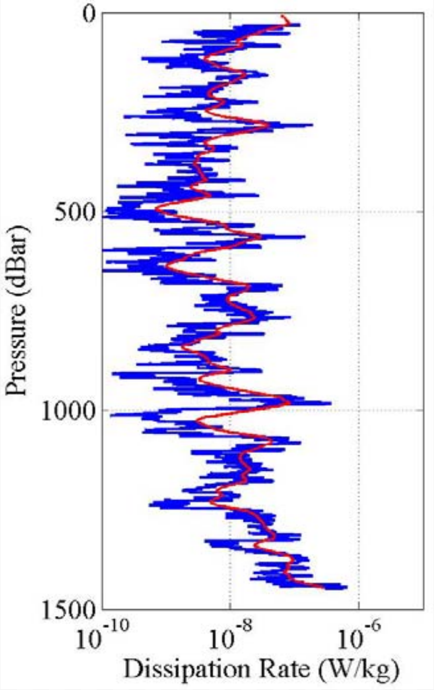
- Directly observed ε
- Indirect ε passed GK tests
  - only cover 22%
  - missed even large ε
  - Error is a factor of 3.4
- Indirect ε without Water-mass test
  - Coverage is increased to 69%
  - Error is increased very small to a factor of 3.6

- Galbraith and Kelley's tests
  - Run-length test: Rejecting density inversions by random noise
  - Water-mass test: Rejecting density inversions by systematic noise of CTD by checking the linearity of T-S relation

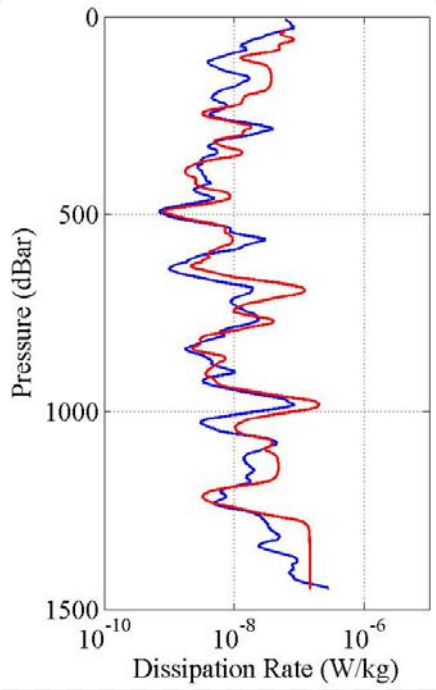
- Indirect method without Water-mass test much improves the coverage with little error increases
- But still 31% region remains as gaps, and we need interpolation

Interpolation (example of vertical ε profiles)

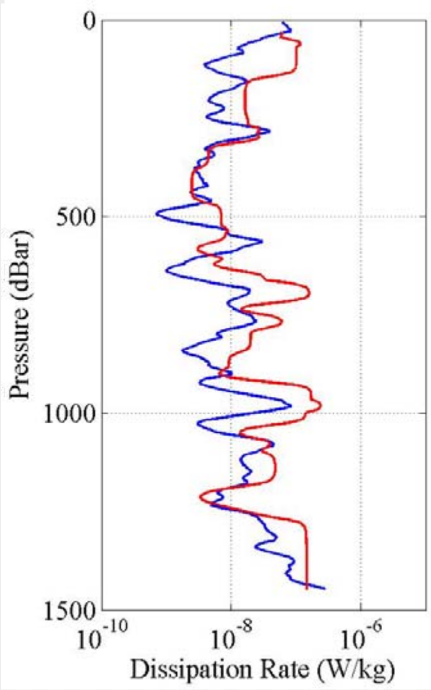
Directly observed ε



Indirectly estimated ε (**Present study**)

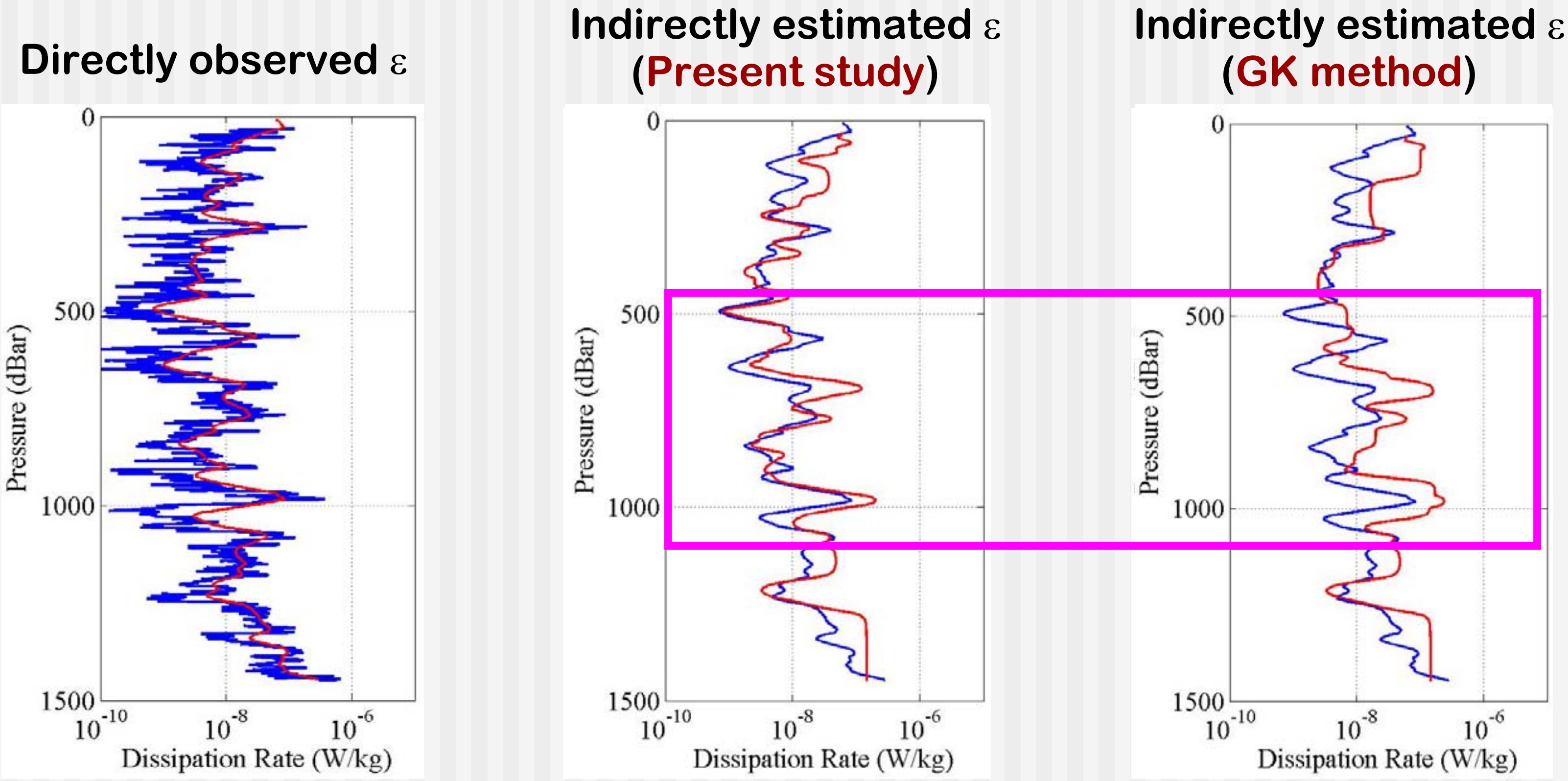


Indirectly estimated ε (**GK method**)



- **Observed vertical de-correlation length scale of ε is about 10m**
- **Both observed and estimated ε are interpolated by 10m scale.**

Interpolation (example of vertical ε profiles)



- Indirect ε by GK methods shows different values from direct observation. Our estimation improve these differences.
- Water-mass test is unsuitable for estimating 10m-scale ε profile because of rejecting too much density inversions.
- Error: a factor of 3; Correlation coefficient: 0.84 (All 31 casts)

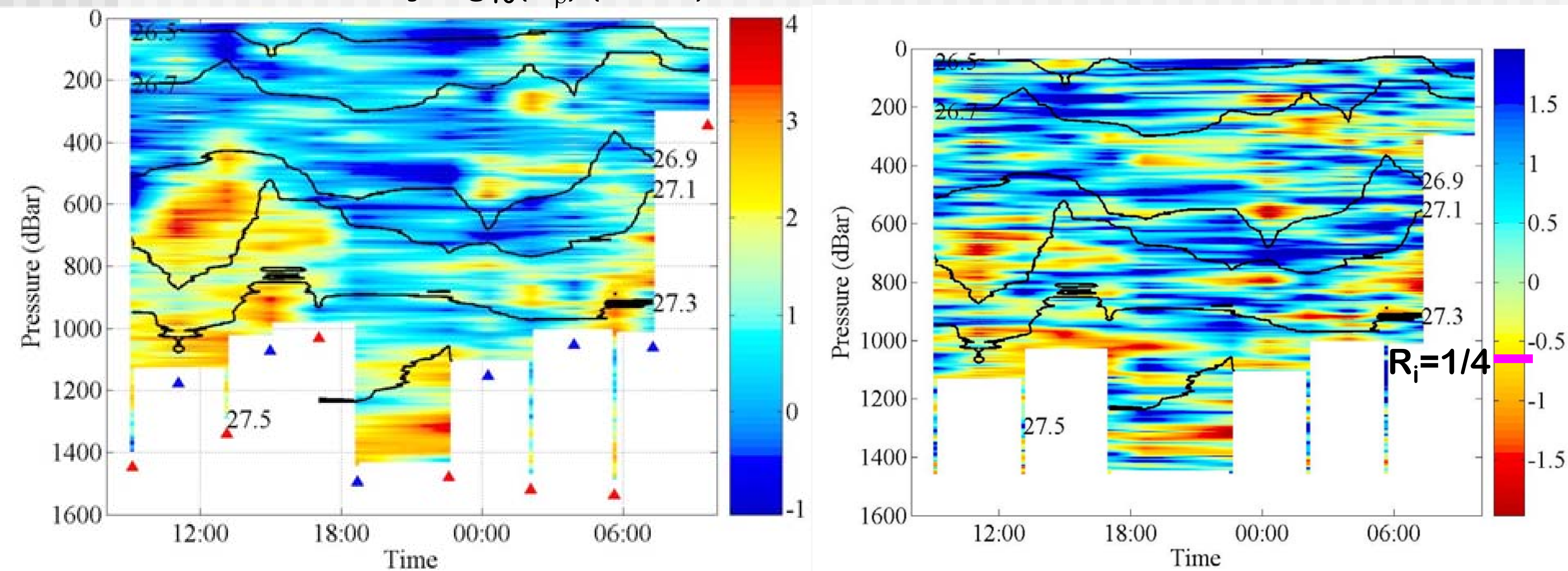
(Error with GK test: a factor of 4.8)

Application of estimation method

- 1-day time series of K_ρ in the Bussol' Strait (at BF1)

Vertical diffusivity $\log_{10}(K_\rho)$ (cm^2/s)

Richardson number $\log_{10}(R_i)$



- Strong vertical mixing over $10^3 cm^2/s$ (600-1200m)
- K_ρ has large temporal variability in a day (600-1200m)
- Simple average is $164 cm^2/s$ (Error range: 57-$476 cm^2/s$)
- Correspondence between large K_ρ and low R_i supports the validity of our new estimation method

Summary

- The new indirect estimation method by using density inversions observed by standard CTD in Kuril Straits
  1. Carefully denoised density profile with 0.1m interval
  2. $L_O = 0.41 L_T$ (smaller coefficient than previous studies)
  3. Galbraith and Kelley's tests without Water-mass test
  4. 10m scale interpolation

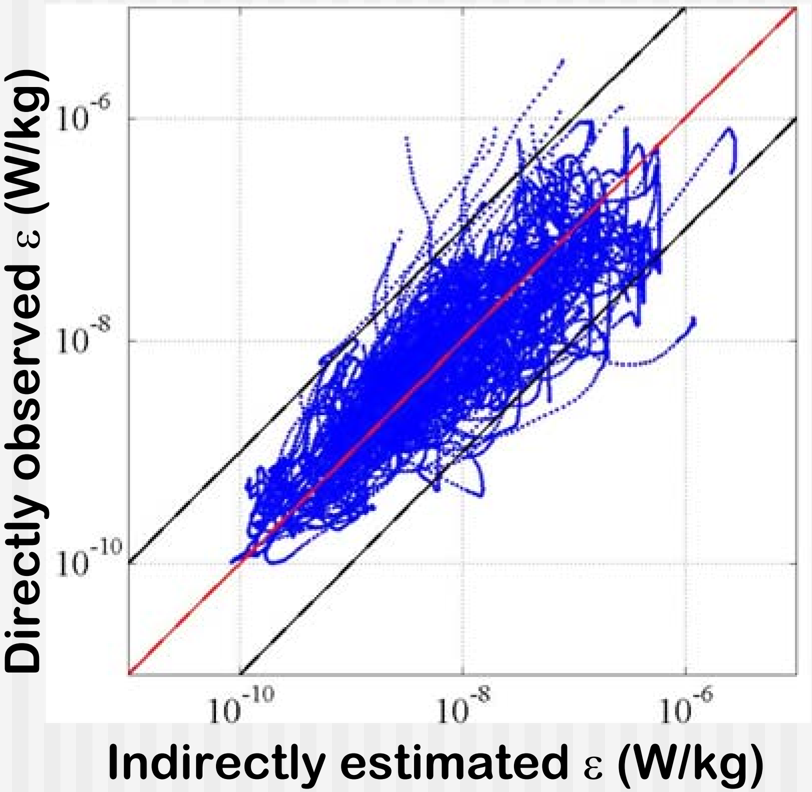
  enables us to estimate ε profile within a factor of 3.

- Application to the Bussol' Strait
  - Strong vertical mixing (Average: 164cm^2/s; Maximum: >10^{3}cm^2/s)
  - Large temporal variability of turbulent intensity in a day
  - Large K_ρ corresponds to low R_i

- Future work
  - Apply to all available CTD data to quantify turbulent intensity around Kuril Straits
  - Reveal the mechanism of the variability of turbulent intensity

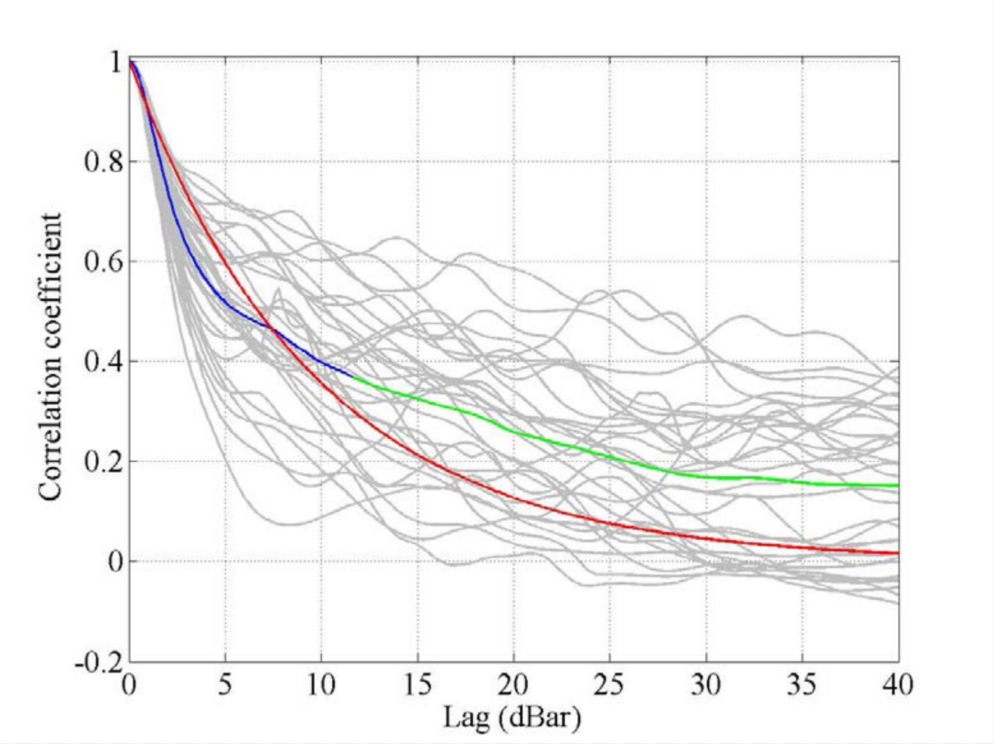
Scatter plot

- **Comparison of interpolated ε over all 31 casts**



- **The new method supposed by this study enables us to estimate dissipation rate ε within a factor of 3.**

De-correlation vertical length scale of ε



--. Self-correlation function of each profiles

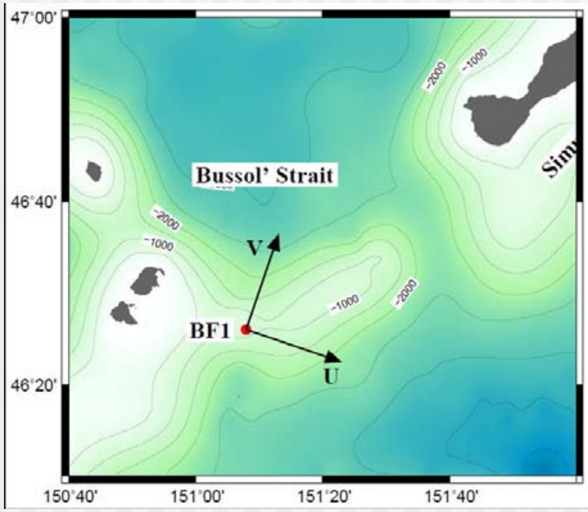
--. Average of self-correlation function

--. The range that correlation coefficient is greater than e^{-1}

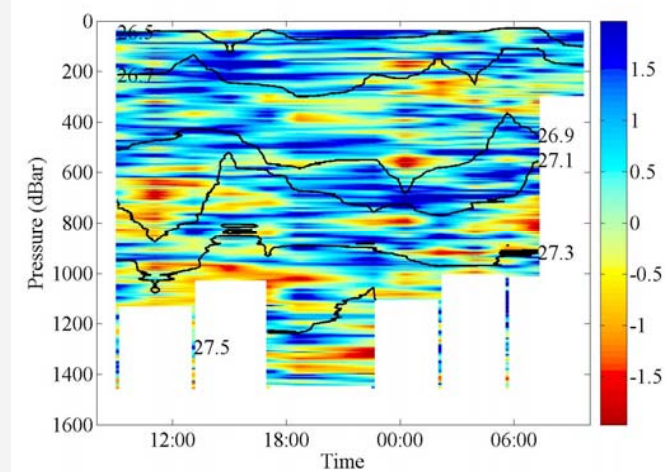
--. The function fitted for the average of self-correlation function

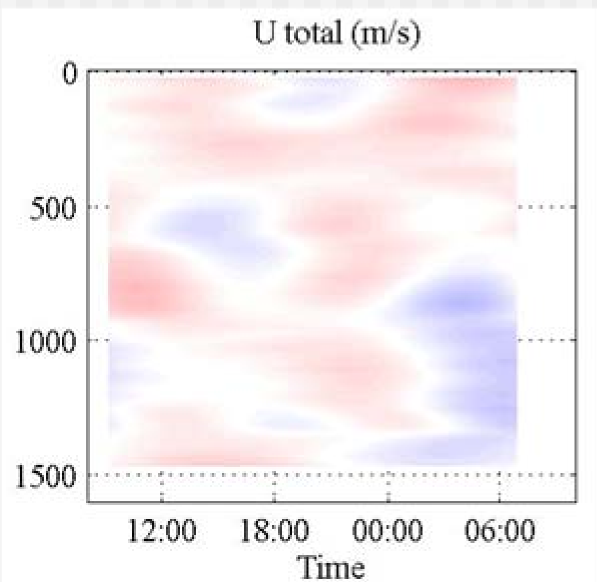
- It is possible to fit exp(-r/R) to the self-correlation function of directly observed ε
- Fitting using least-square method reveals that the de-correlation vertical length scale of ε is about 10m (R=9.69 dbar)

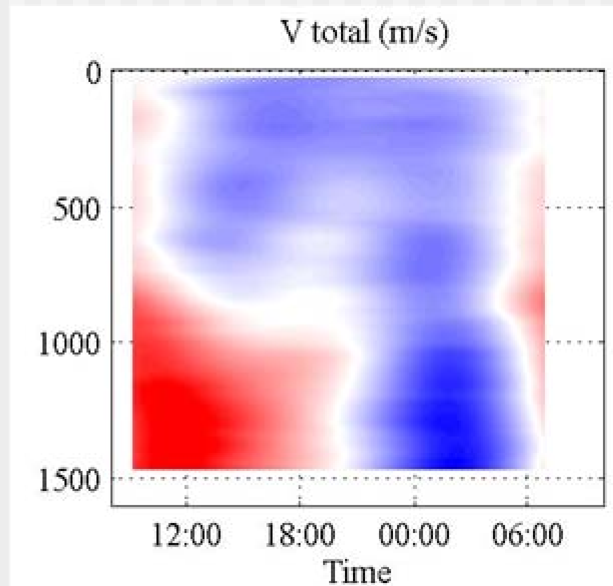
Velocity

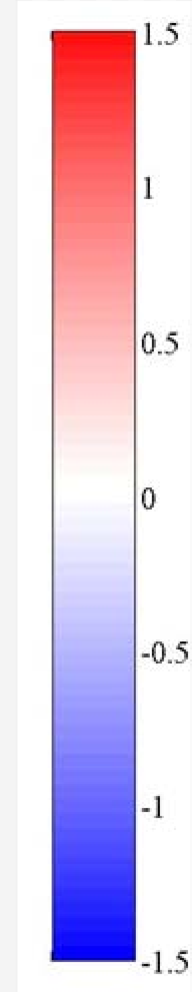


Richardson number $\log_{10}(R_i)$



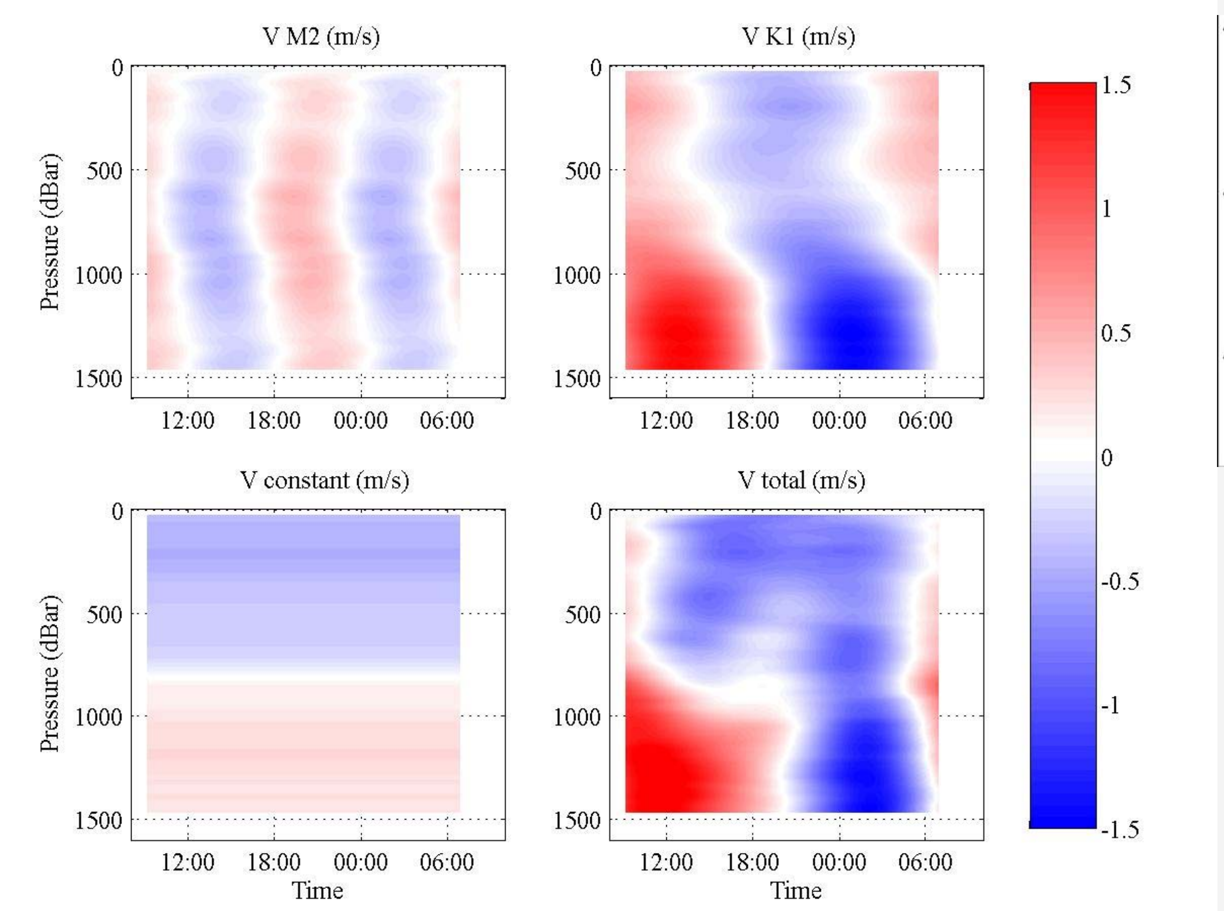


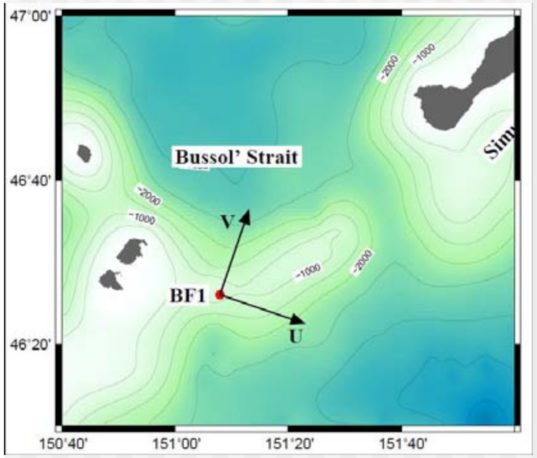




- **The shear of the across-strait velocity is predominant**

Velocity





- The constant V flows different way between top and bottom
- The amplitude of diurnal tide is different between top and bottom