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Study on flow and turbulence characteristics measured by an on-site meteorological station at a nuclear facility for a real-time atmospheric dispersion simulation

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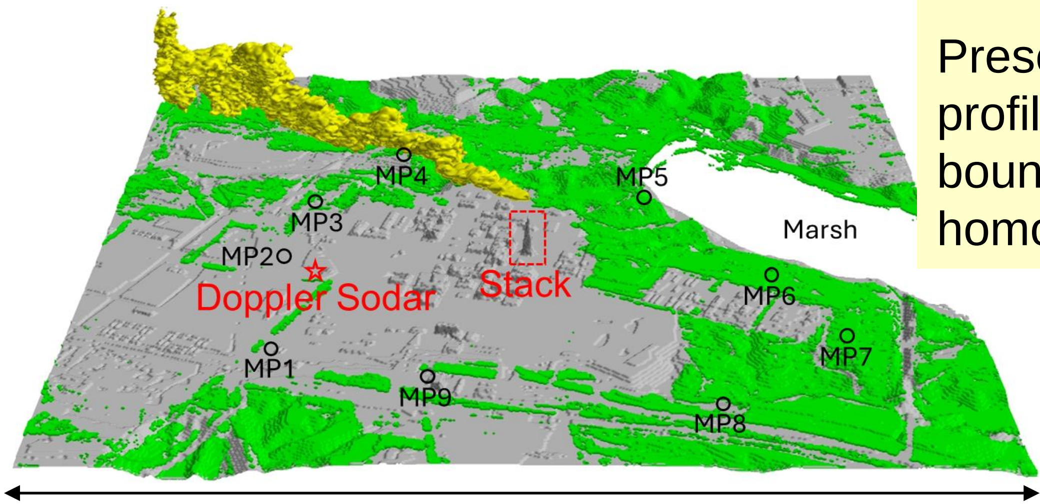
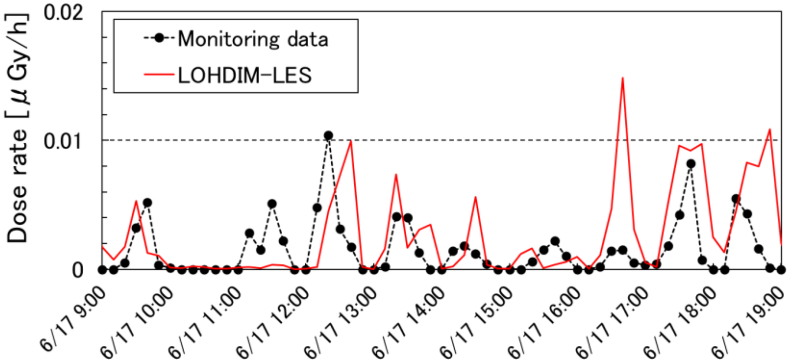
We developed the local-scale high-resolution atmospheric dispersion and dose assessment system designed based on LES model for safety and consequence assessment of nuclear facilities (Nakayama et al., 2022).

LES calculation conditions

Prescribe the Doppler Sodar of vertical profile of the wind velocities at the inflow boundary under the assumption of horizontal homogeneity and a neutral condition



A radioactive plume released from the stack at the nuclear facility



Time variation of air dose rate

- Time variation patterns of the air dose rates were successfully simulated in consideration of individual building effects.
- However, the LES computation time was approximately 1.5 times real-time even using 1200 MPI processes on 50 computing nodes by a JAEA supercomputer.

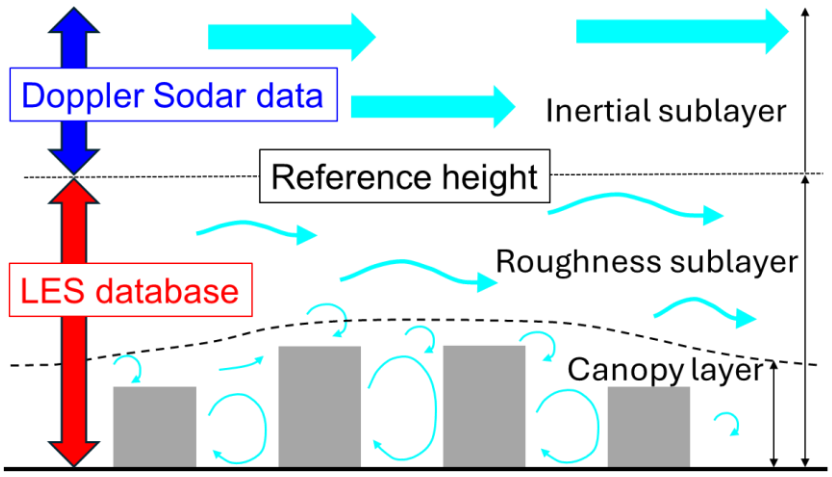
Coupling LES pre-calculations with an on-site meteorological observation

Mean wind:

$$U(x,y,z) = U_{LES}(x,y,z)\frac{U_{DOP}(x,y,h_{ref})}{U_{LES}(x,y,h_{ref})}, \text{ for } z \le h_{ref}$$

$$U(x,y,z) = U_{DOP}(x,y,h_{ref}), \text{ for } z > h_{ref}$$

U_{DOP}	Doppler Sodar wind speed
U_{LES}	LES mean wind speed
h_{ref}	Reference height



Adopted from Britter and Hanna (2003)

Turbulence standard deviation:

The Normal Turbulence Model (NTM) as a reference for fatigue load calculations for wind turbines (IEC61400-1)

$$\sigma_l = I_{ref}(aU_{hub} + b)$$

σ_l	Longitudinal turbulence standard deviation
I_{ref}	Representative value of σ_l
a, b	Constant

Input

Quick calculation by Lagrangian particle dispersion model

Particle position: $x(t + \Delta t) = x(t) + u\Delta t$

Instantaneous velocity: $u = U + u'$

Turbulence velocity: $u'(t + \Delta t) = \alpha u'(t) + \beta\sigma_u\xi$

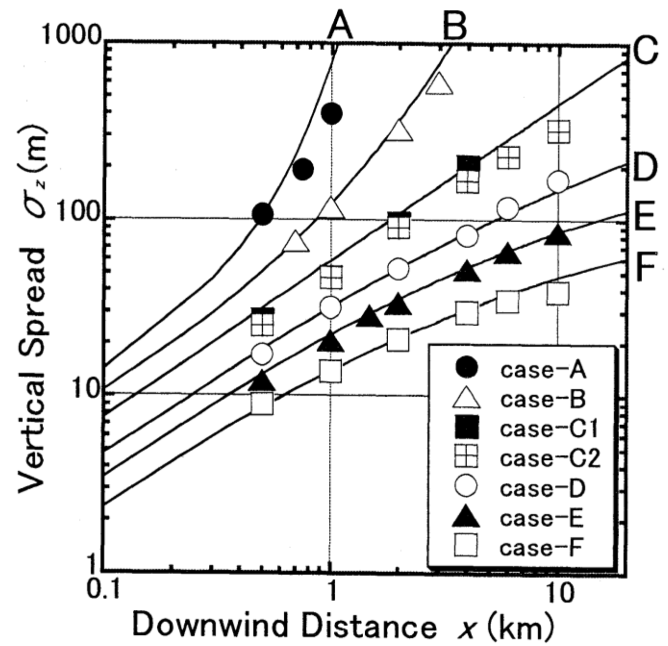
Δt	Time step
U	Mean wind scaled to the Doppler Sodar data
σ_u	Turbulence standard deviation estimated by the NTM
ξ	Normal random number

Objective

However, the turbulence data estimated by the NTM is NOT classified under different atmospheric thermal stability conditions.

Stability class	Condition
A	highly unstable
B	moderately unstable
C	slightly unstable
D	neutral
E	moderately stable
F	extremely stable

Pasquill-Gifford chart (Pasquill, 1961)



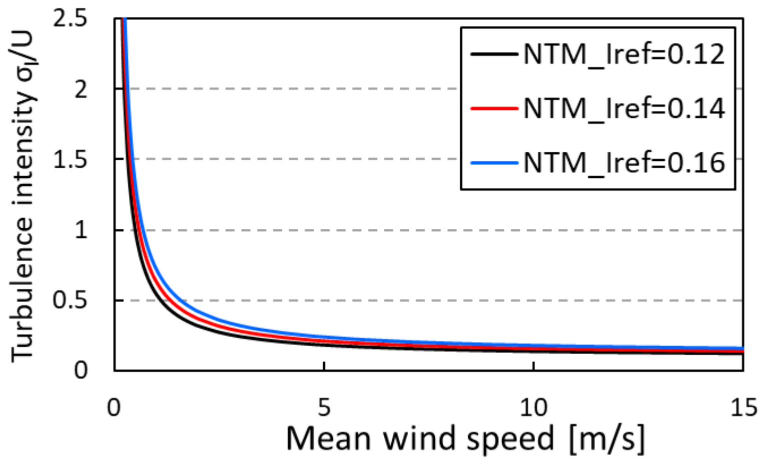
Wind tunnel experimental data of vertical plume spreads in different stability classes (Shirakata et al., 2002)

- Evaluate the turbulence standard deviation obtained by on-site remote sensing meteorological observation at a nuclear facility
- Investigate the estimation method for the turbulence based on the improved NTM in consideration of different thermal stability conditions

The NTM estimation of the turbulence standard deviation

In IEC61400-1, the representative value of the turbulence standard deviation is given by the 90% quantile for the hub height wind speed U_{hub}.

$$\sigma_{90l} = I_{ref}(0.75U_{hub} + 5.6)$$



I_{ref}: Expected value of the turbulence intensity	
Higher turbulence case	0.16
Medium turbulence case	0.14
Lower turbulence case	0.12

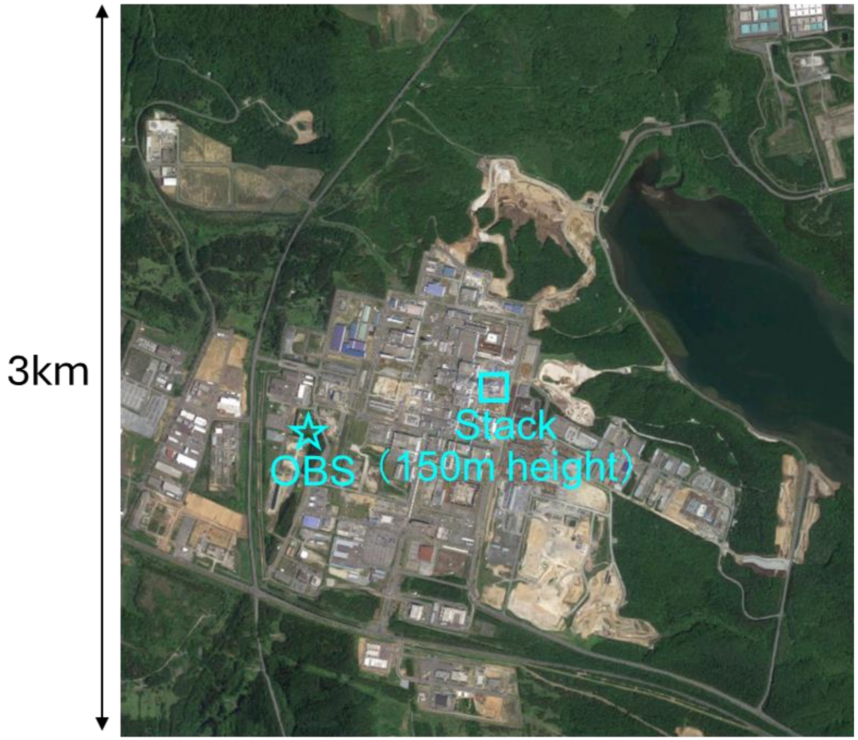
To apply to atmospheric dispersion simulation, not the 90% quantile but the averaged value of the turbulence standard deviation should be used.

$$\sigma_{ave\_l} = I_{ref}(0.75U_{hub} + 3.75)$$

The I_{ref} highly depends on the meteorological conditions and terrain types.

We estimate the I_{ref} values at the nuclear facility site under each atmospheric stability class by regression analysis.

The nuclear facility site



The Rokkasho Reprocessing Plant

Obtained meteorological data	
Target period	12th July – 2nd on January 2007
Doppler sodar data at a 10-minute time interval	Wind direction and speed
	Turbulence standard deviation
	Measurement heights of 50m, 75m, 150m, 250m, and 300m
Surface meteorological observation	Wind velocities, solar radiation, air temperature, and net radiation ⇒Thermal stability class

There are many buildings, structures, and tall trees with a height of up to 30m around the site.

Based on ESDU 85020, the terrain description is “wooded country (many trees)” and the roughness length (z_0) is expected to show 0.3m.

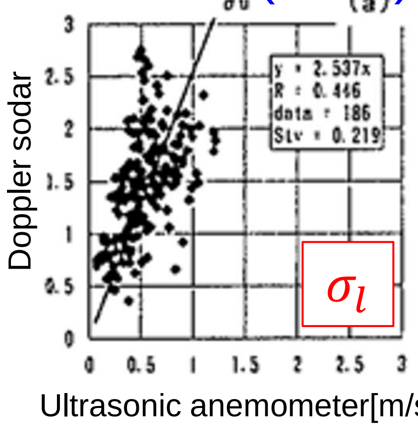
ESDU: The recommended data of comprehensive turbulence characteristics of a neutrally-stratified atmospheric boundary layer

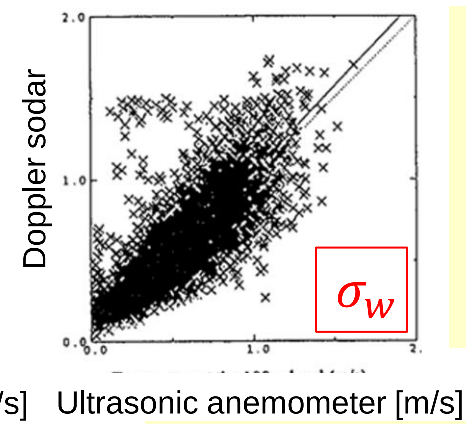
Previous evaluation studies on the Doppler Sodar

Doppler Sodar AR-410N

Main specifications	
Observation method	Triple monostatic
Pulse repetition interval	3-5 second (Obtained time interval: 10-20 second)
Sound beam width	10 deg (The beam diameter is 52 m at 150 m height)

- Ito et al. (1996)





There is a tendency that the longitudinal turbulence intensity σ_l of the Doppler Sodar is overestimated, while the vertical turbulence intensity σ_w is reliable.

- Mitsuta et al. (1989)

Measurement accuracy of σ_w is high especially under higher convective condition because of the problem of the obtained time interval.

Small-scale turbulence under stable conditions is not captured well in principle.

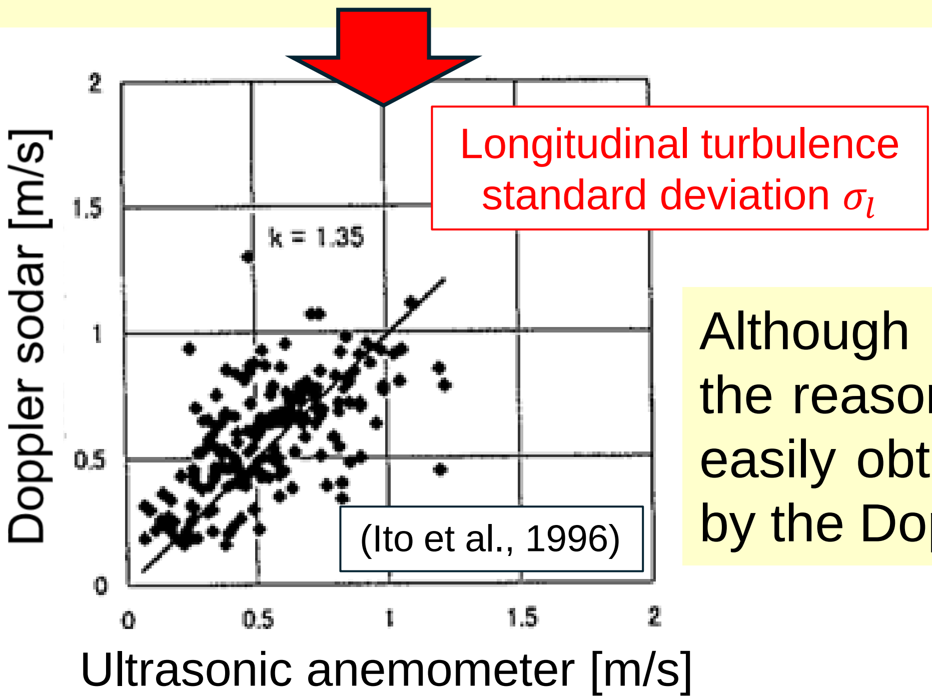
Analysis approach

Step1: Analyze the vertical turbulence standard deviation σ_w

Step2: Estimate the longitudinal one σ_l from the ratio of σ_l/σ_w under the assumption of uniform shear turbulence

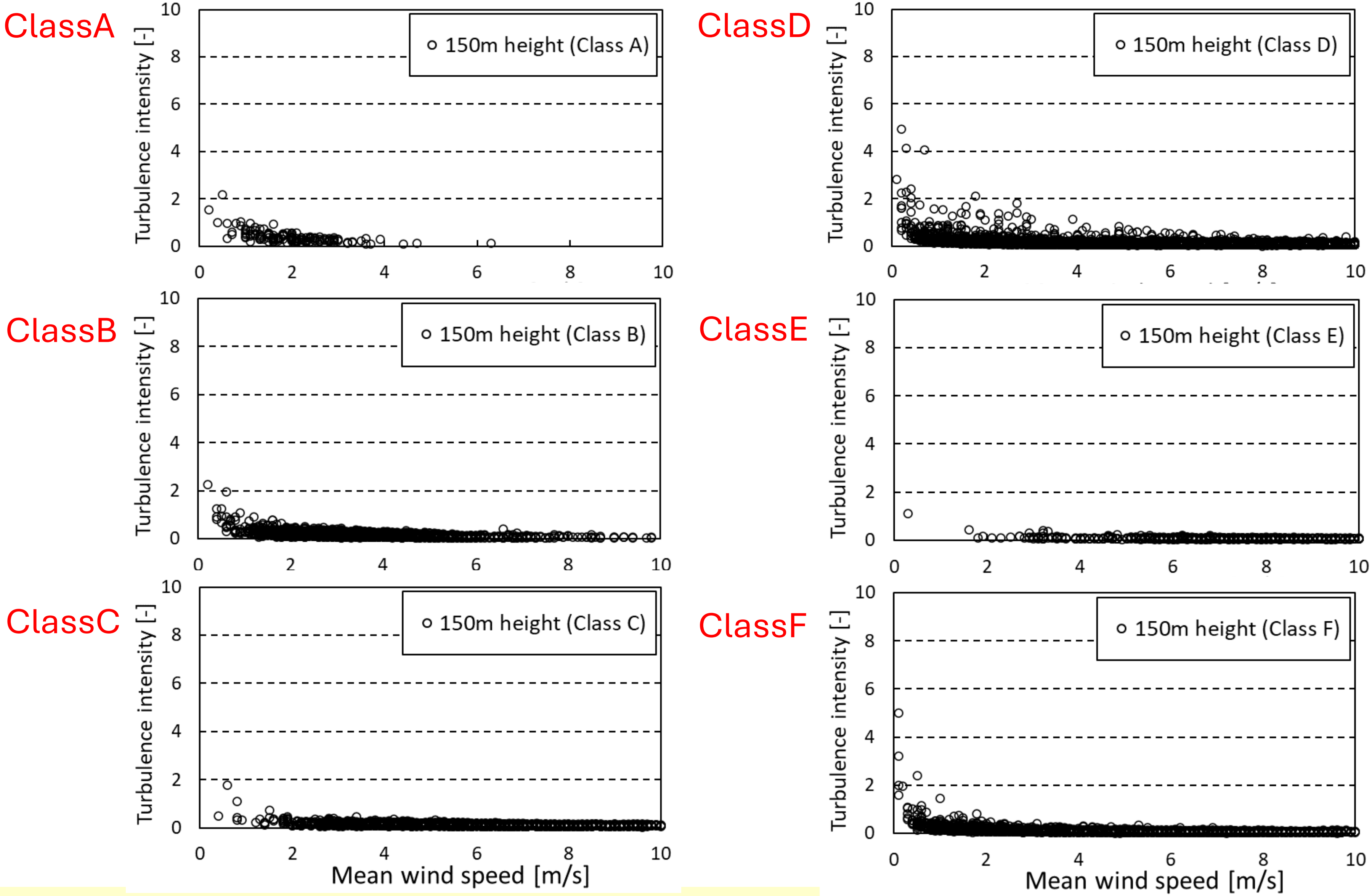
Assumption

- $\frac{\sigma_w}{\sigma_l} \approx 0.5$ Spectral analysis of turbulent velocity fluctuations (Mann, 1998)
- $\frac{\sigma_w}{\sigma_l} = 0.74$ Tuning of the ratio σ_w/σ_l to enhance a correlation with the longitudinal one σ_l of ultrasonic anemometer (Ito et al., 1996)



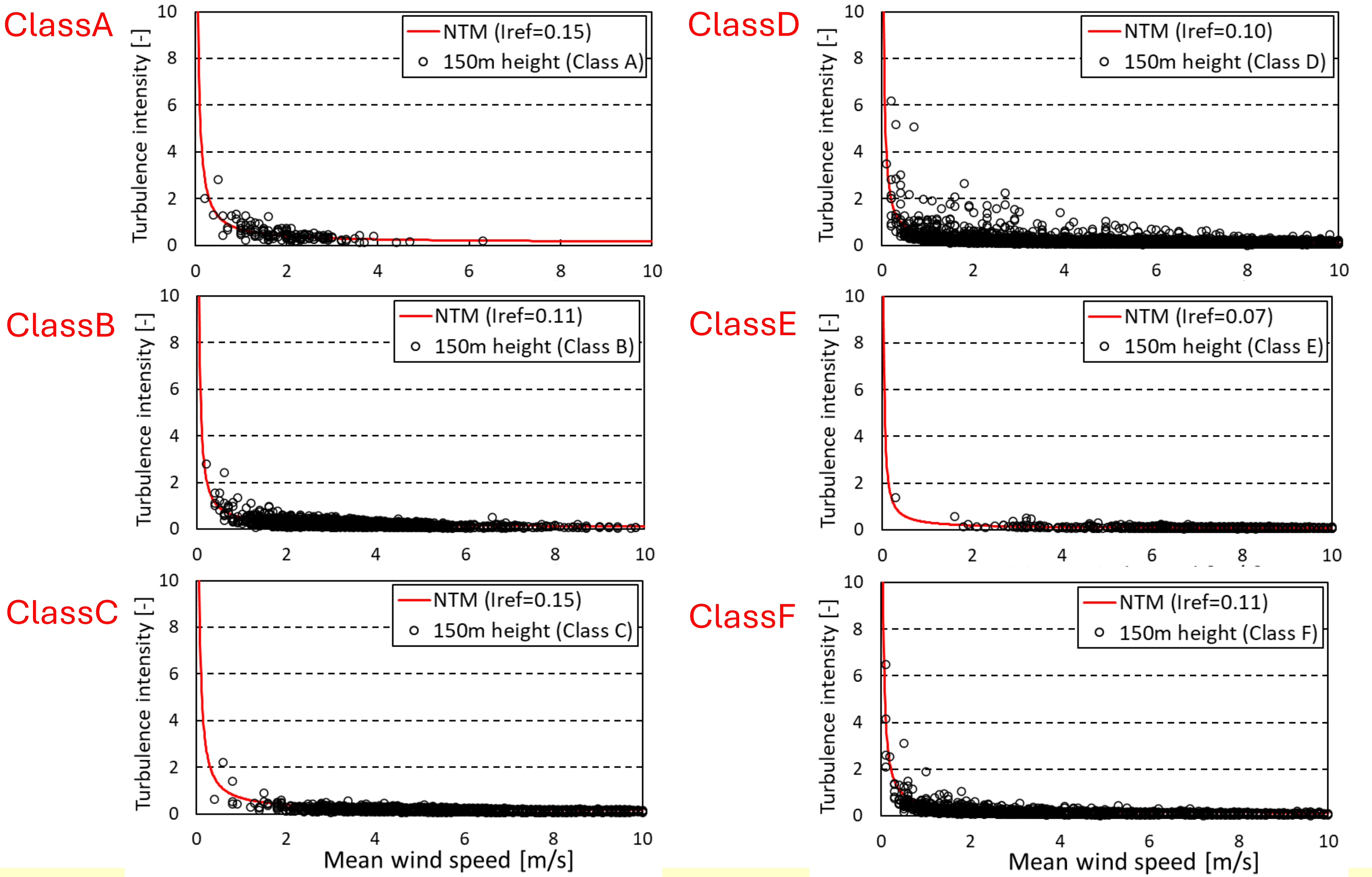
Although it is the simplified method, the reasonable data of the σ_l could be easily obtained from the σ_w measured by the Doppler Sodar.

Measured vertical turbulence intensity σ_w/U at 150m height



At class D, the σ_w/U is largely scattered.
The σ_w/U increases with decrease of the mean wind speed at each class.

Estimated longitudinal turbulence intensity σ_l/U at 150m height



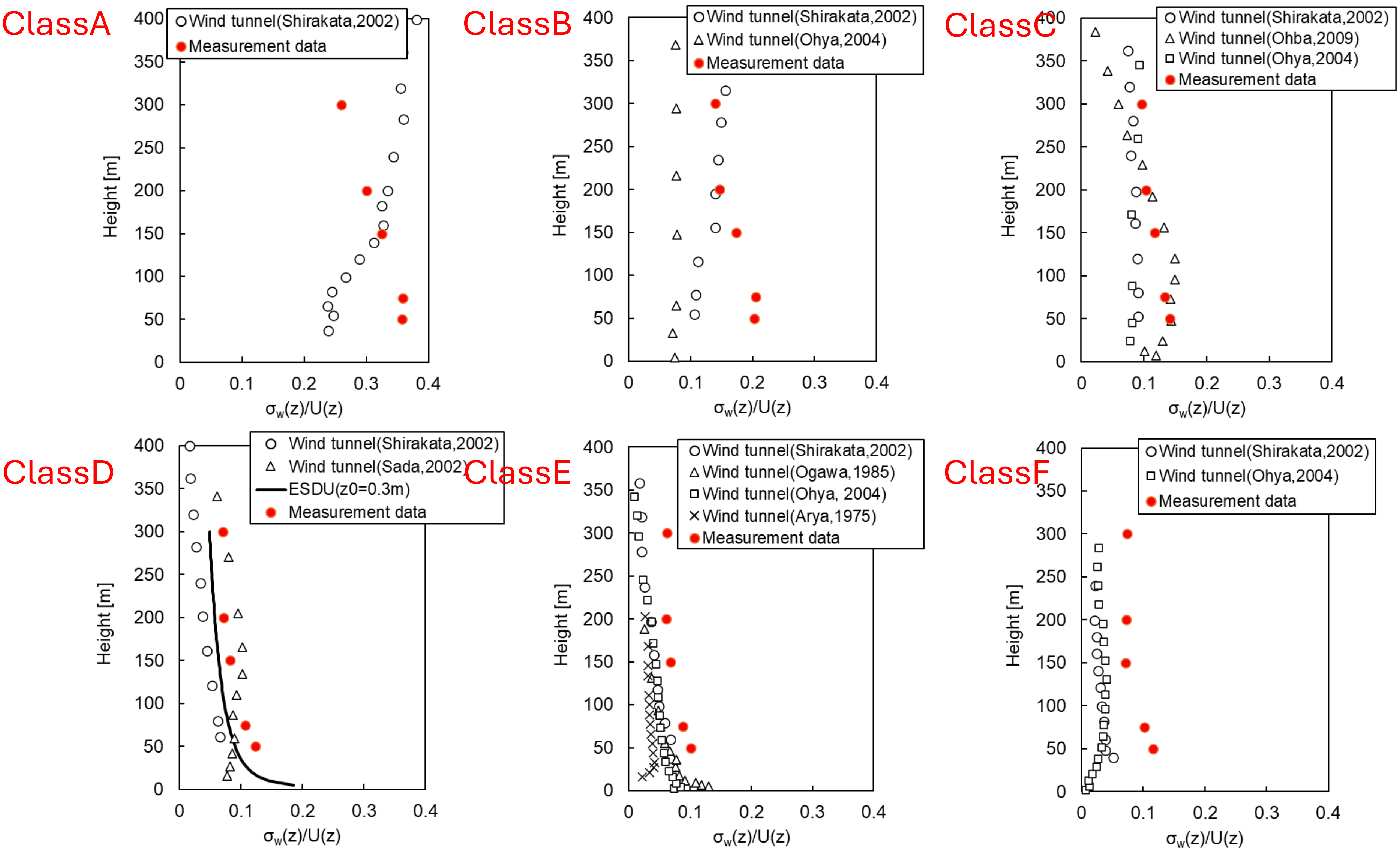
At class D, the σ_l/U is largely scattered because of the largely scattered σ_w/U.
The NTM with I_{ref} generally approximates the scatter of σ_l/U at each class.

The expected value of turbulence intensity I_{ref}

Class / Height	A	B	C	D	E	F	All classes
50m	0.24	0.17	0.17	0.12	0.09	0.09	0.12
75m	0.19	0.12	0.16	0.12	0.08	0.09	0.11
150m (stack height)	0.15	0.11	0.15	0.10	0.07	0.11	0.10
250m	0.15	0.12	0.13	0.09	0.07	0.08	0.09
300m	0.16	0.15	0.13	0.09	0.08	0.07	0.10

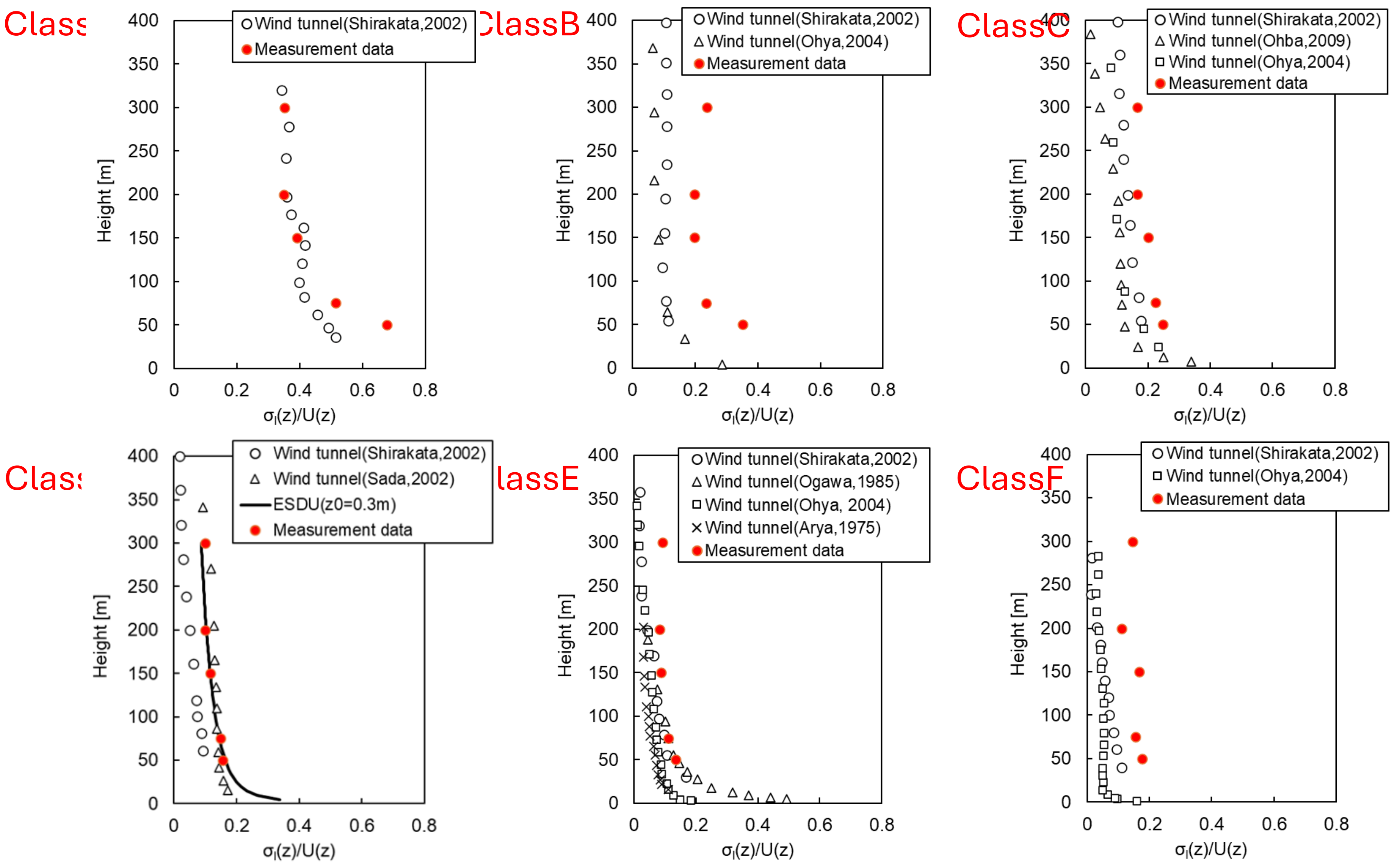
- At each stability class, the expected value of turbulence intensity I_{ref} generally increases with height.
- At each height, the I_{ref} decreases from unstable to stable conditions.
- The variation patterns of the I_{ref} values with stability class and height are qualitatively reasonable.

Vertical profiles of the vertical turbulence intensity $\sigma_w(z)/U(z)$



- Classes C and D are similar in magnitude to the experimental data.
- Class F is highly overestimated in comparison to the experimental data.

Vertical profiles of the longitudinal turbulence intensity $\sigma_l(z)/U(z)$



- Classes C, D, and E are similar in magnitude to the experimental data.
- Classes B and F are overestimated in comparison to the experimental data.

Evaluation of the turbulence data obtained by the Doppler Sodar

Stability class	Evaluation
A	Although the turbulence data can be intrinsically estimated by the Doppler Sodar, there is a large difference from the experimental data. It is necessary to compare with more experimental data and continuously evaluate them.
B	
C	The turbulence data is comparable to the experimental data and/or the ESDU recommended data.
D	
E	Although the vertical turbulence data is overestimated a little, the longitudinal one is similar in magnitude to the experimental data.
F	The turbulence data is highly overestimated because small-scale turbulence cannot be captured well in principle.

It is expected that the turbulence data at C, D, and E classes are reliable from the viewpoint of using input data for atmospheric dispersion model.

Conclusion

When using the turbulence data measured by the Doppler Sodar for atmospheric dispersion model as input condition,

- The longitudinal turbulence data σ_l should be estimated from the ratio of σ_w/σ_l under the assumption of uniform shear turbulence.
- For unstable conditions, the turbulence data at class C should be used because that at classes A and B need to be continuously evaluated.
- For a neutral condition of class D, the turbulence data is reliable and usable.
- For stable conditions, the turbulence data at class E should be used because that at class F is highly overestimated.