Identifying Dominant Phenomena in the Dose-Distance Curve for Optimization of Japanese Emergency Planning

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*The views expressed in this presentation are those of the presenter and do not represent the official views of Nuclear Regulation Authority, Japan.

Outline

1. Background and objective
2. Phenomenon affecting the D-D curve
3. Proposed risk-metrics
4. Analytical conditions
5. Results and discussions
6. Conclusion

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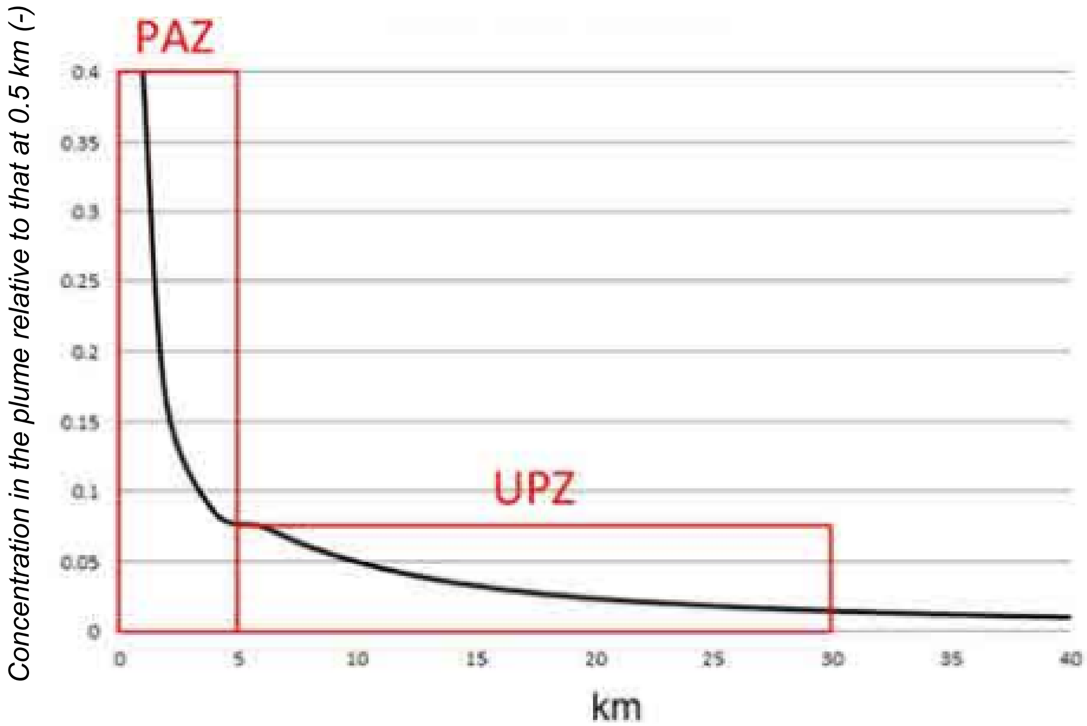
Background

- Mechanistic understanding of the dose-distance curve (D-D curve) is essential for determining the emergency planning zone (EPZ).
- Not only the absolute values of the dose, but also D-D curve's relative profile serves as a crucial factor in decision-making for emergency planning [1].



Concentration in the plume relative to that at 0.5 km for typical meteorological conditions (D stability), as a function of plume travel distance from the release point. (FIG. 24 of IAEA,2013)

Source: Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor, © IAEA, 2013, page 98

[1] IAEA, EPR-NPP-PPA (2013)

Objective

Issue：
Few studies have well-examined which processes primarily govern the distance-dependent dose attenuation while considering the site-specific meteorological conditions.

Objectives：
- To quantitatively clarify which phenomena substantially contributes to distance dependent dose attenuation under annual meteorological conditions at a site in Japan:
  - Wet deposition depletion
  - Radioactive decay
  - Dry deposition depletion
  - Atmospheric dispersion

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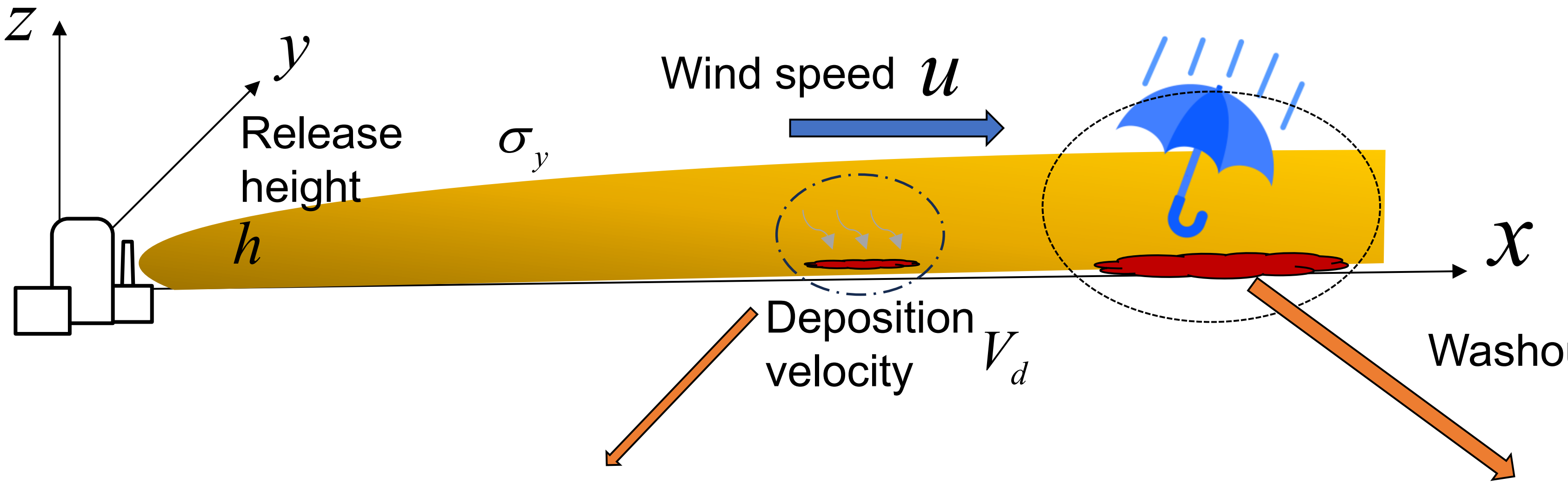
Phenomenon affecting the D-D curve

Phenomenon [2]

(1) Dispersion (Power-law*) $D_{\chi/Q} = \frac{1}{2\pi\sigma_y\sigma_z u}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right\} \approx \frac{1}{\pi u}\times\frac{1}{x^{n_y n_z}}$

Dispersion parameter $\sigma_y \propto x^{n_y},\ \sigma_z \propto x^{n_z}$ * n_y, n_z is around 0.5 to 1 *If $2\sigma_z^2 >> (z-h)^2$ or $2\sigma_z^2 >> (z+h)^2$

(2) Radioactive decay during dispersion (Exponential-law) $D_{decay}(x) = \exp(-\lambda_i t) = \exp(-\frac{\lambda_i}{u}x)$



(3) Dry deposition depletion (Exponential-law)

$$D_{dry}(x) = \exp\left\{-\sqrt{\frac{2}{\pi}}\frac{V_d}{u}\int_0^x \frac{1}{\sigma_z(x')}\exp[-\frac{h^2}{2\sigma_z^2(x')}]dx'\right\}$$

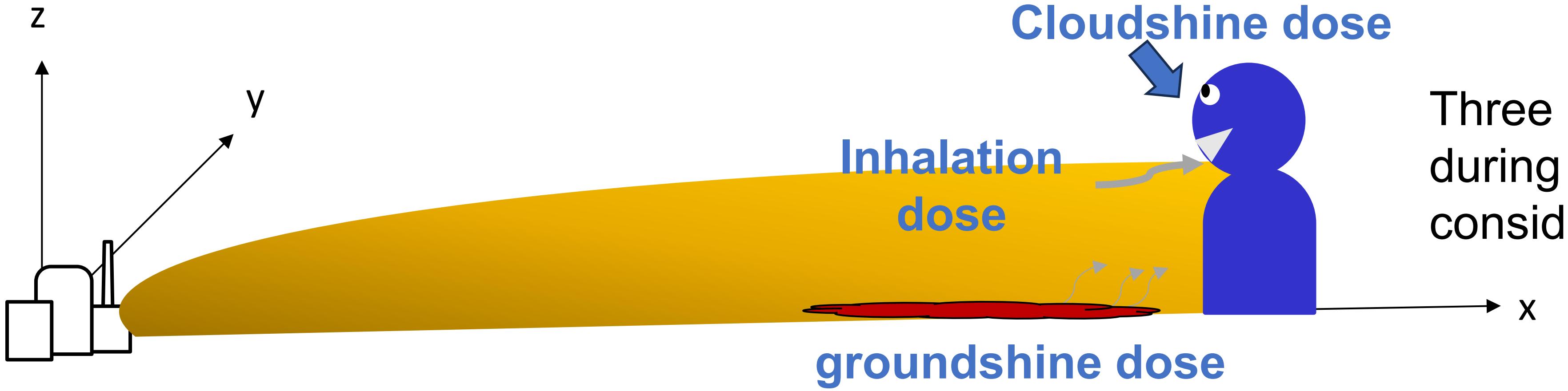
(4) Wet deposition depletion (Exponential-law)

$$D_{wet}(x) = \exp(-\Lambda t) = \exp(-\frac{\Lambda}{u}x)$$

[2] Nosek et.al, SAND2021-11535 (2021)

Exposure pathways

●Exposure pathways for evaluating 7 days effective dose



Three major exposure pathways during the first few days were considered.

●Effective dose expression

$$E(x) = E_{CS} + E_{GS} + E_{IH} = D_{D/Q}(x)\sum_i \left(K_i^{CS} Q_i D_{decay}(x) D_{wet}(x) D_{dry}(x)\right)$$
$$+ D_{\chi/Q}(x)\sum_i \left(K_i^{IH} Q_i D_{decay}(x) D_{wet}(x) D_{dry}(x)\right)$$
$$+ D_{\chi/Q}(x)\sum_i \left(K_i^{GS} Q_i D_{decay}(x) D_{wet}(x) D_{dry}(x)(V_d + V_R)\right)$$

Dose conversion factor — Released nuclide — Distance-related term

Outline

Proposed metrics: distance semi-elasticity

- Distance Semi-elasticity is defined as a new metrics
  - It is a parameter representing the “value of moving a unit distance.”

$$\eta = \frac{d\log\left(E\left(x\right)\right)}{dx} = \frac{1}{E\left(x\right)}\frac{dE\left(x\right)}{dx}$$

For example, if $E(x) = \frac{1}{x^n}\exp\left(ax\right)$ · · · ·

Concept: Decompose & Extract

$$\Rightarrow \quad \eta = \frac{d\log\left(E\left(x\right)\right)}{dx} = \frac{d\log\left(\frac{1}{x^n}\exp\left(ax\right)\right)}{dx} = \frac{d\log\left(\frac{1}{x^n}\right)}{dx} + \frac{d\log\left(\exp\left(ax\right)\right)}{dx}$$

The semi-elasticity can decompose the product terms of each phenomenon, which enables evaluating the significance of each phenomenon on dose attenuation with distance.

(1)Nuclide-weighting & decomposing

Step1:Total semi-elasticity is decomposed into the contributions of the target nuclide (or pathway) and the remaining nuclides, each weighted accordingly.

Example: Extracting the distance attenuation effect by I-131 decay using distance semi-elasticity.

$$\eta = \frac{d\log\left(E(x)\right)}{dx} = \frac{1}{E(x)}\frac{d\left(E(x)\right)}{dx}$$

$$= \frac{1}{E(x)}\frac{d\left(E_{I-131}(x)\right)}{dx} + \frac{1}{E(x)}\frac{d\left(E(x)-E_{I-131}(x)\right)}{dx}$$

decompose

Multiply $E_{I-131}(x)$ in both side, rewrite the log expression.

$$= \frac{E_{I-131}(x)}{E(x)}\frac{d\log\left(E_{I-131}(x)\right)}{dx} + \frac{E(x)-E_{I-131}(x)}{E(x)}\frac{d\log\left(E(x)-E_{I-131}(x)\right)}{dx}$$

Semi-elasticity with respect to I-131

Semi-elasticity with respect to nuclides other than I-131

Weighting factor

$$\eta_{I-131} = \frac{E_{I-131}(x)}{E(x)}\frac{d\log\left(E_{I-131}(x)\right)}{dx}$$

extract

(2)Extracting the semi-elasticity of interest

Step2:Decompose into the semi-elasticity of various distance decay phenomena and extract the target.

$$\eta_{I-131} = \frac{E_{I-131}(x)}{E(x)} \frac{d\log\left(E_{I-131}(x)\right)}{dx}$$

$$= \frac{E_{I-131}(x)}{E(x)} \frac{d\log\left(D_{decay}^{I-131}(x) D_{wet}^{I-131}(x) D_{dry}^{I-131}(x)\left(K_{I-131}^{CS} Q_{I-131} D_{D/Q}^{I-131}(x) + K_{I-131}^{GS} Q_{I-131}\left(V_d + V_R\right) D_{\chi/Q}^{I-131}(x) + K_{I-131}^{IH} Q_{I-131} D_{\chi/Q}^{I-131}(x)\right)\right)}{dx}$$

$$= \frac{E_{I-131}(x)}{E(x)}\left(\frac{d\log\left(D_{decay}^{I-131}(x)\right)}{dx} + \frac{d\log\left(D_{wet}^{I-131}(x)\right)}{dx} + \cdot\ \cdot\ \cdot\ \cdot + \frac{d\log(N)}{dx}\right)$$

decompose

Semi-elasticity with respect to decay of I-131

Semi-elasticity with respect to effect other than decay of I-131

Terms independent from distance

$$\eta_{I-131Decay,weighted} = \frac{E_{I-131}(x)}{E(x)} \frac{d\log\left(D_{decay}^{I-131}(x)\right)}{dx}$$

extract

Weighting factor

Outline

Analytical Conditions：Source term

Two accident scenarios [3–4] were assumed.

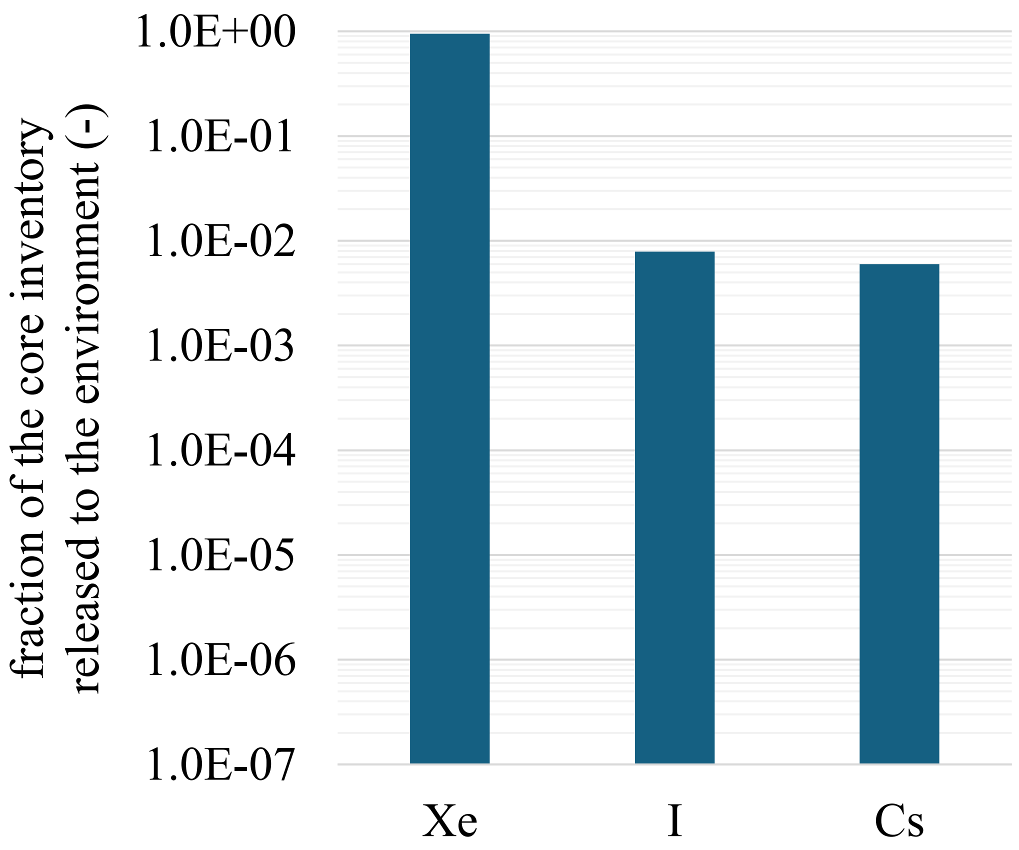
- Release duration: 1 hour
- Release height: 50 m
- Release timing : 24 h after shutdown

Both source term were based on the early in-vessel of NUREG-1465 [5] under a low-pressure RPV sequence:

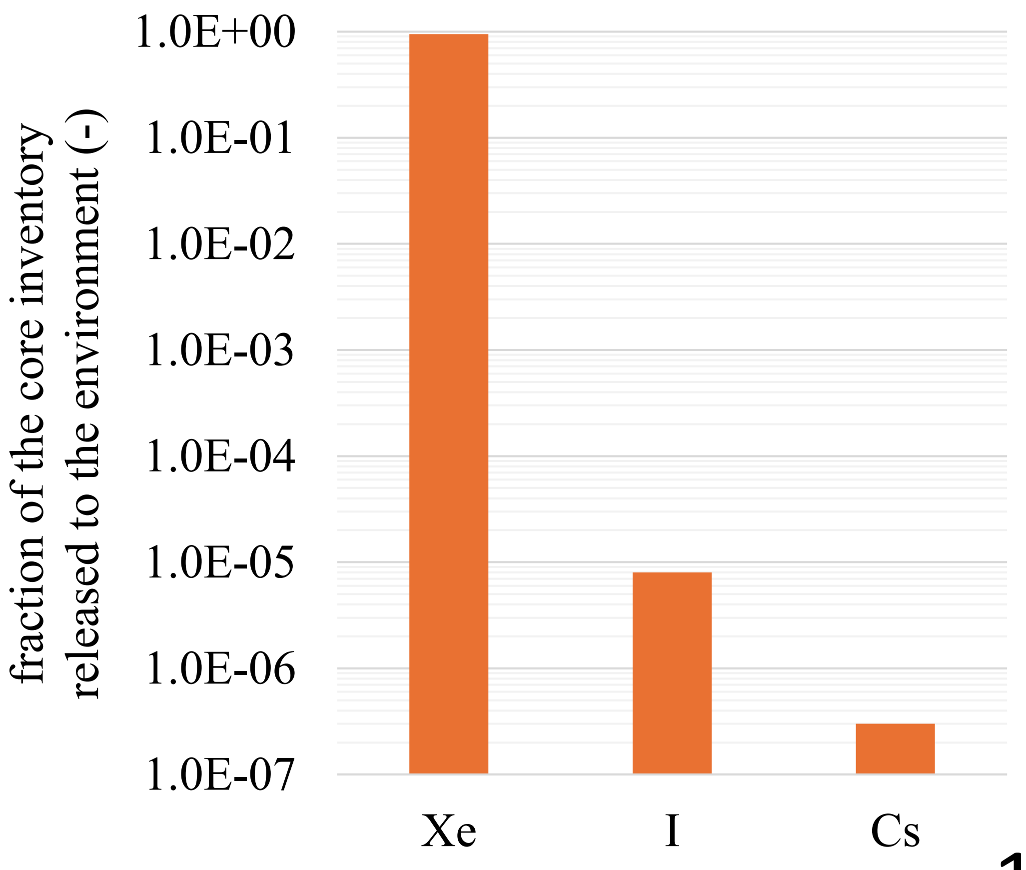
✓ Successful FCVS operation near the containment pressure limit

✓ FCVS failure leading to containment vessel (CV) failure

Containment failure (CF-24h)



Filtered containment venting (FV-24h)

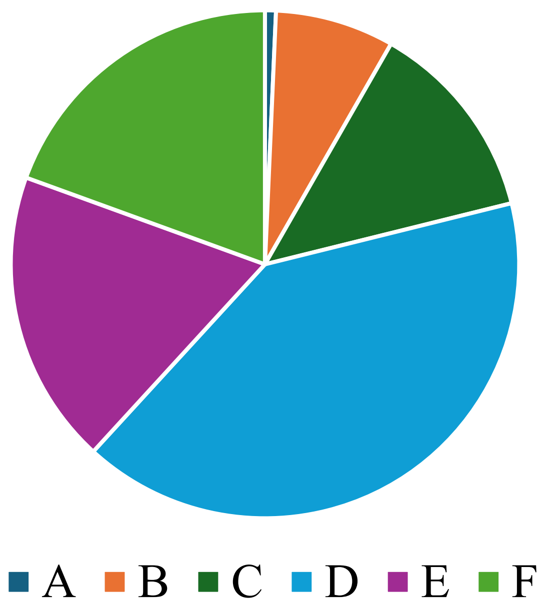


[3] McKenna et al. , RTM-96, NUREG/BR-0150 (1996)
[4] Wadayama et al. , Nuc.Eng.Des. (2026)
[5] Soffer et al. , NUREG-1465 (1995)

Analytical Conditions : Meteorological data

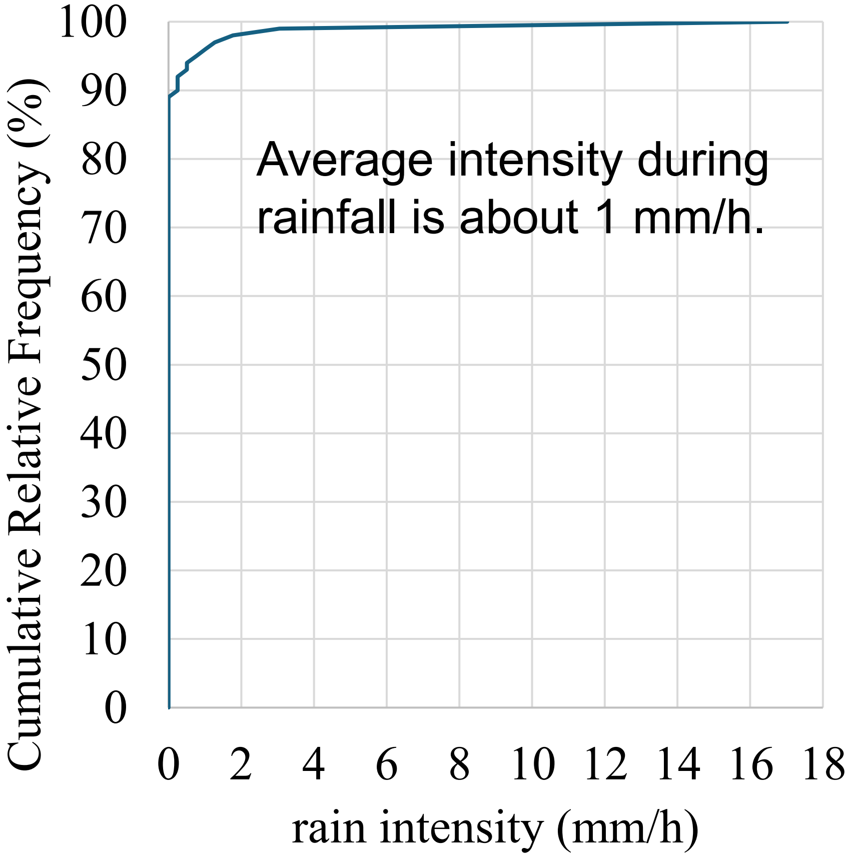
Meteorological data for a specific site on the Pacific coast of Japan was obtained from publicly available GPV data[6–7]. The analysis was conducted across all annual weather conditions, totaling 8,760 cases (24 hours/day × 365 days).

Stability Class



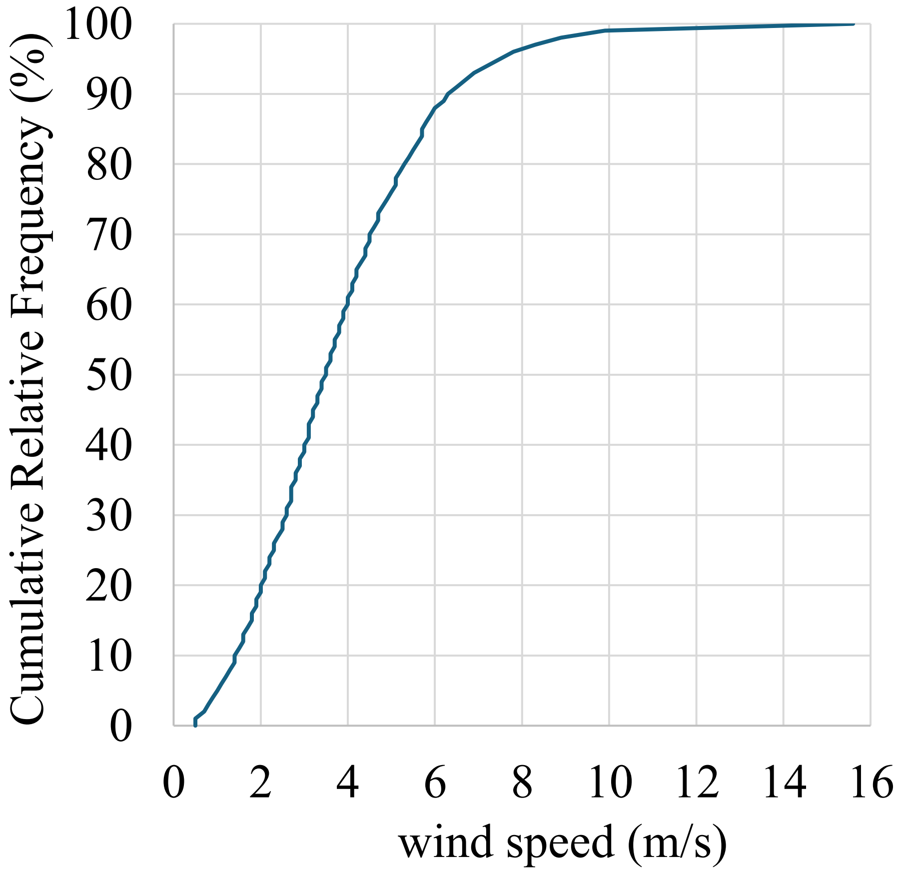
Neutral Stability dominant

Precipitation



Precipitation occurs during approx. 10% of the year.

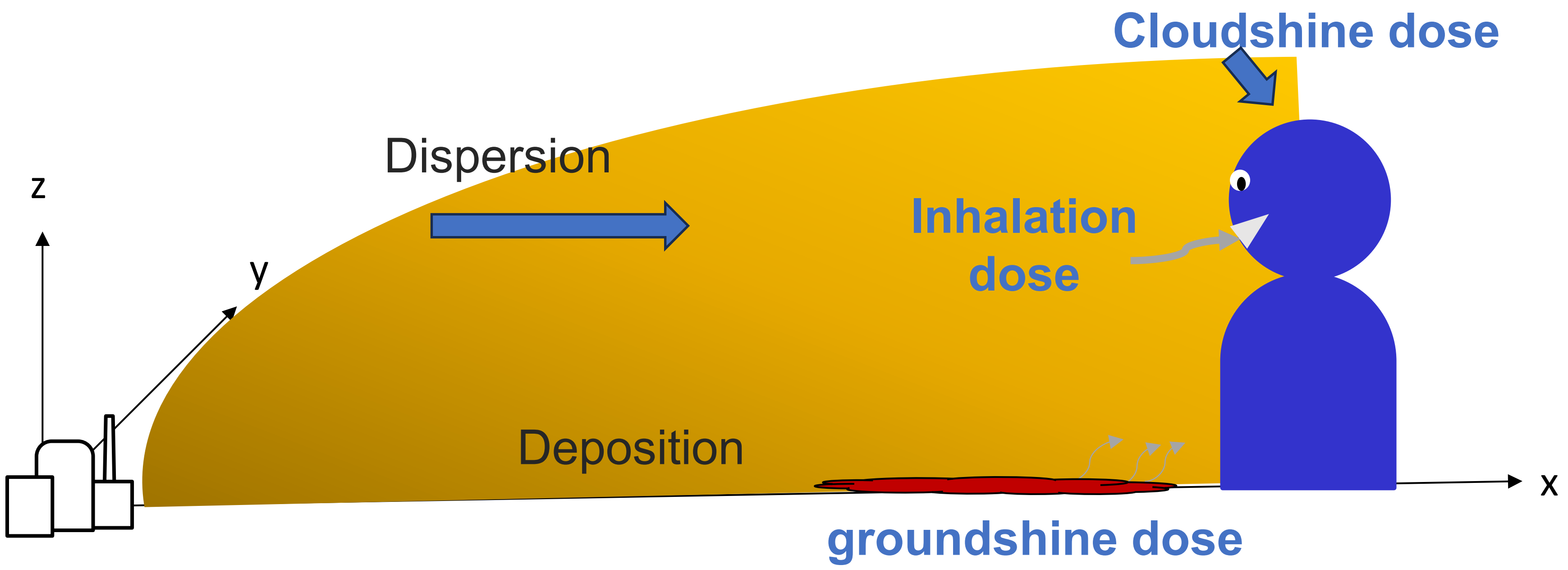
Wind speed



Prevailing wind speed: 2–5 m/s

[6] Japan Meteorological Business Support Center, Meso Scale Model GPV (MSM) [Internet] (2022)
[7]Suzuki, J. Nucl. Sci. Technol., (2025)

●Exposure pathways for evaluating 7 days effective dose [8]



Item	Calculation method
Code	DECISION [4]
Dispersion	Gaussian plume model based on Japanese meteorological guidance [9–10].
Deposition	Dry and wet deposition model based on NUREG-1150 [11].
Dose evaluation	Dose conversion factor based on ICRP119 and 144 [12–13].

[4] Wadayama et al., Nucl. Eng. Des. (2026) [8] IAEA, GSR-Part7. (2015) [9] NSC, Meteorological guidance for reactor safety analysis. (1982)
[10] Pasquill, Meteorol.Mag. (1961) [11] NRC, NUREG-1150. (1990) [12] ICRP, ICRP Publication 119. (2012) [13] ICRP, ICRP Publication 144. (2020)

Focused semi-elasticity in the analysis

(1) Dispersion
(Power-law phenomenon)

$$\eta_{dispersion,weighted} = \frac{E_{cloudshine}(x)}{E(x)} \frac{d\log\left(D_{D/Q}(x)\right)}{dx} + \frac{E_{Groundshine\&inhalation}(x)}{E(x)} \frac{d\log\left(D_{\chi/Q}(x)\right)}{dx}$$

(2) Radioactive decay of top nuclide during dispersion
(Exponential-law phenomenon)

$$\eta_{decay,weighted} = \frac{E_{top\_n}(x)}{E(x)} \frac{d\log\left(D_{decay}(x)\right)}{dx}$$

(3) Dry deposition depletion
(Exponential-law phenomenon)

$$\eta_{dry,weighted} = \frac{E_{aerosol}(x)}{E(x)} \frac{d\log\left(D_{dry}(x)\right)}{dx}$$

(4) Wet deposition depletion
(Exponential-law phenomenon)

$$\eta_{wet,weighted} = \frac{E_{aerosol}(x)}{E(x)} \frac{d\log\left(D_{wet}(x)\right)}{dx}$$

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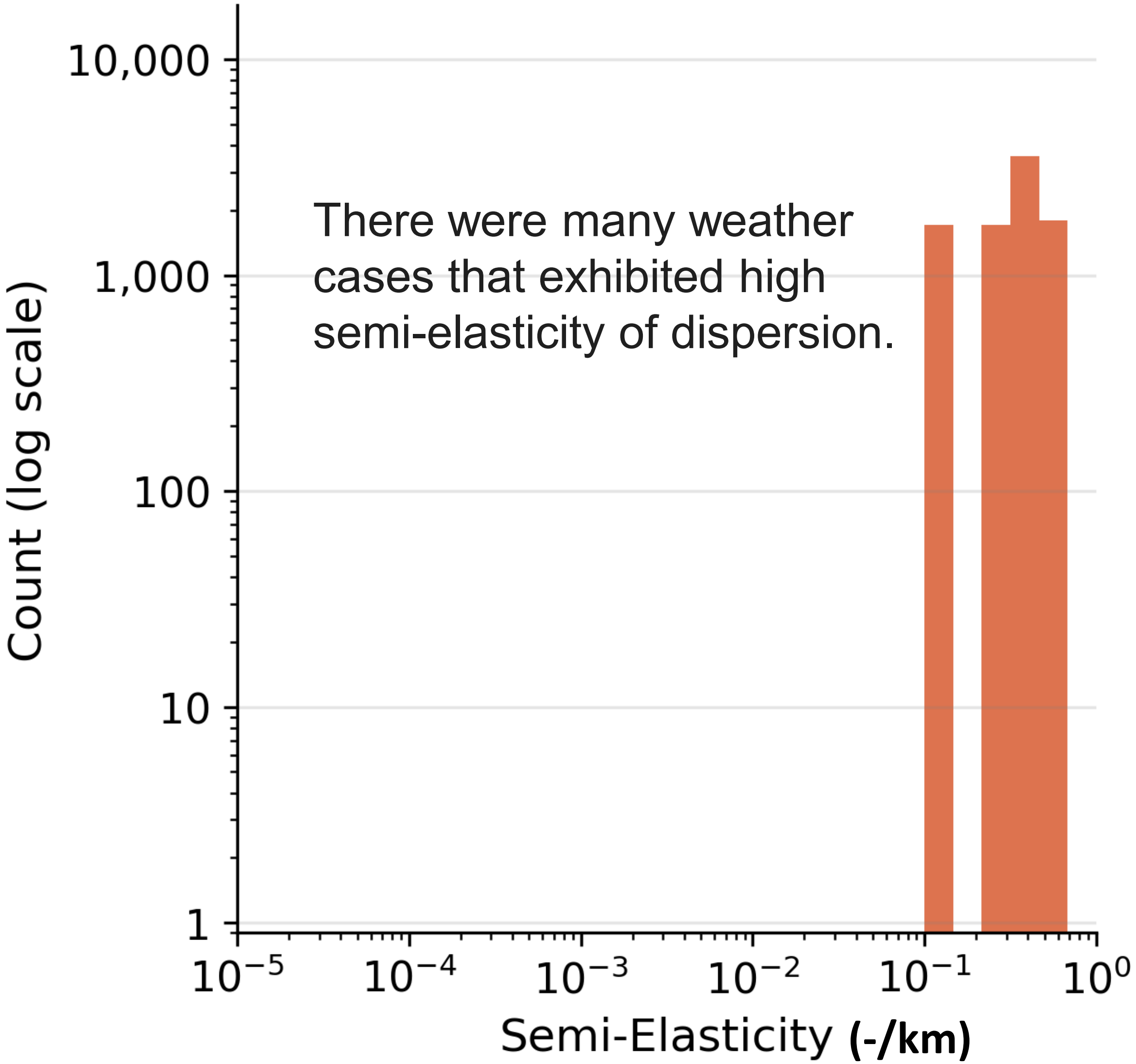
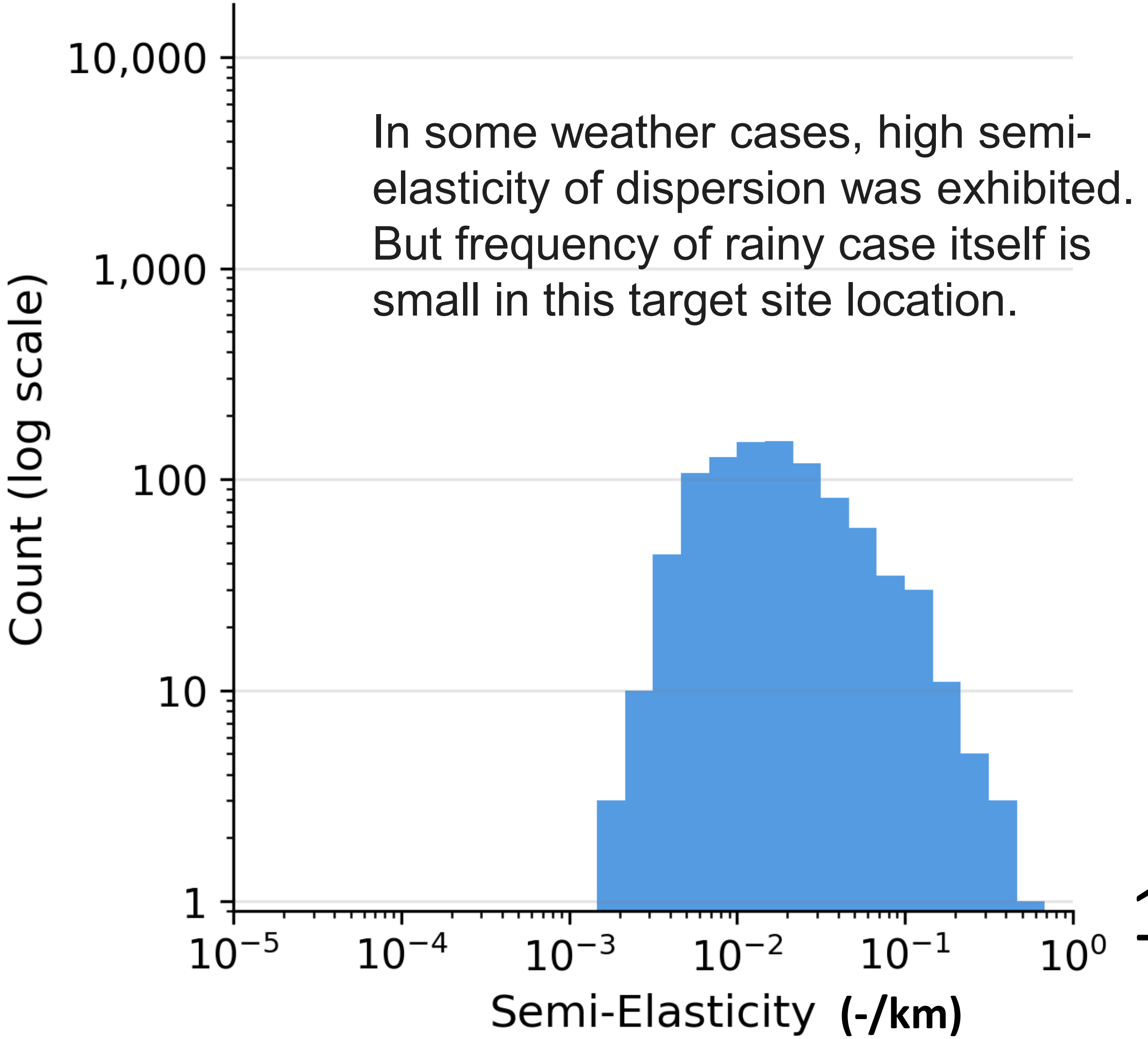
High semi-elasticity phenomena (CF-24 h at 2 km)

Semi-elasticity was evaluated for 8,760 weather cases (1 year = 24 h × 365 days).

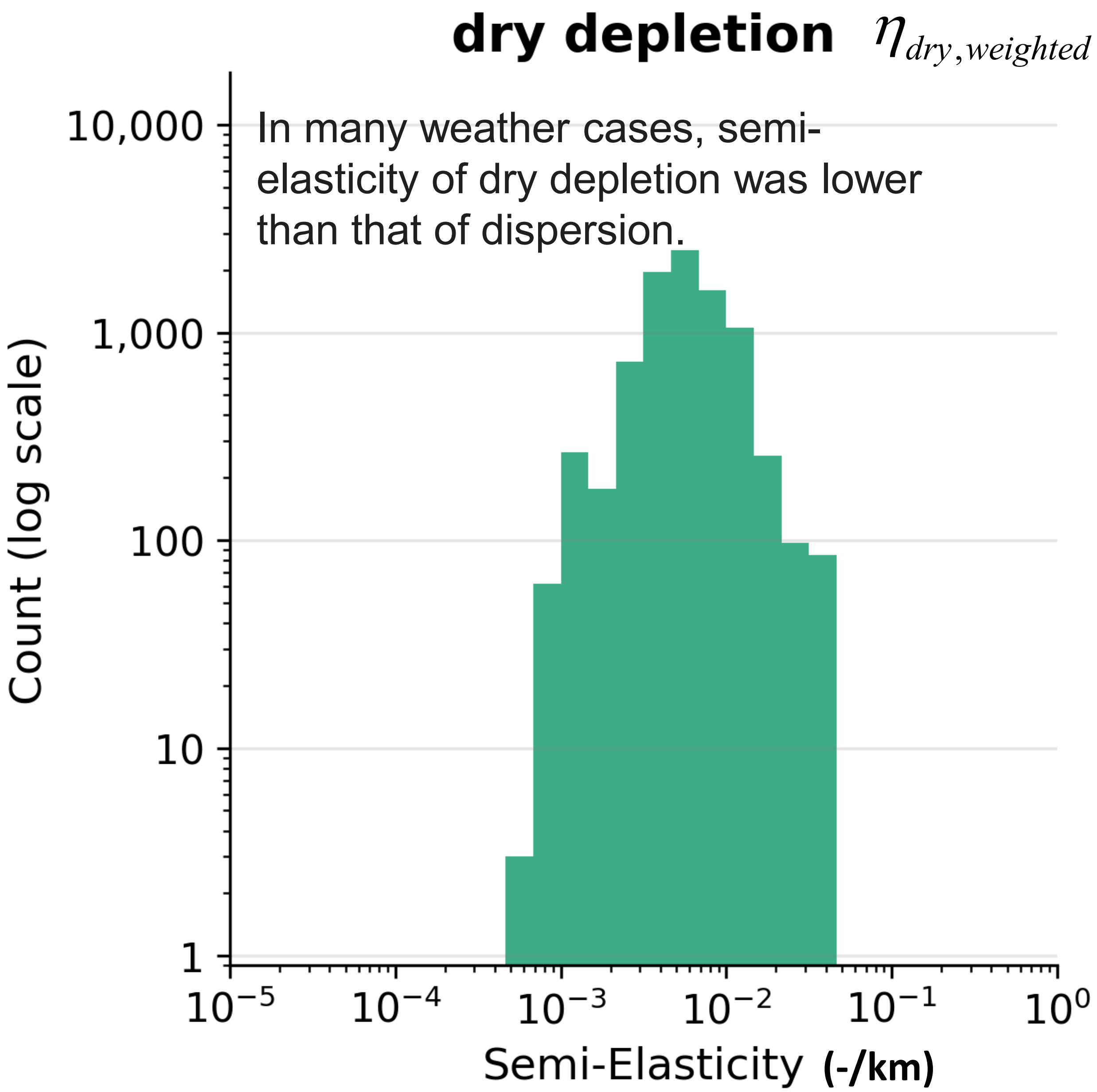
Dispersion $\eta_{dispersion,weighted}$

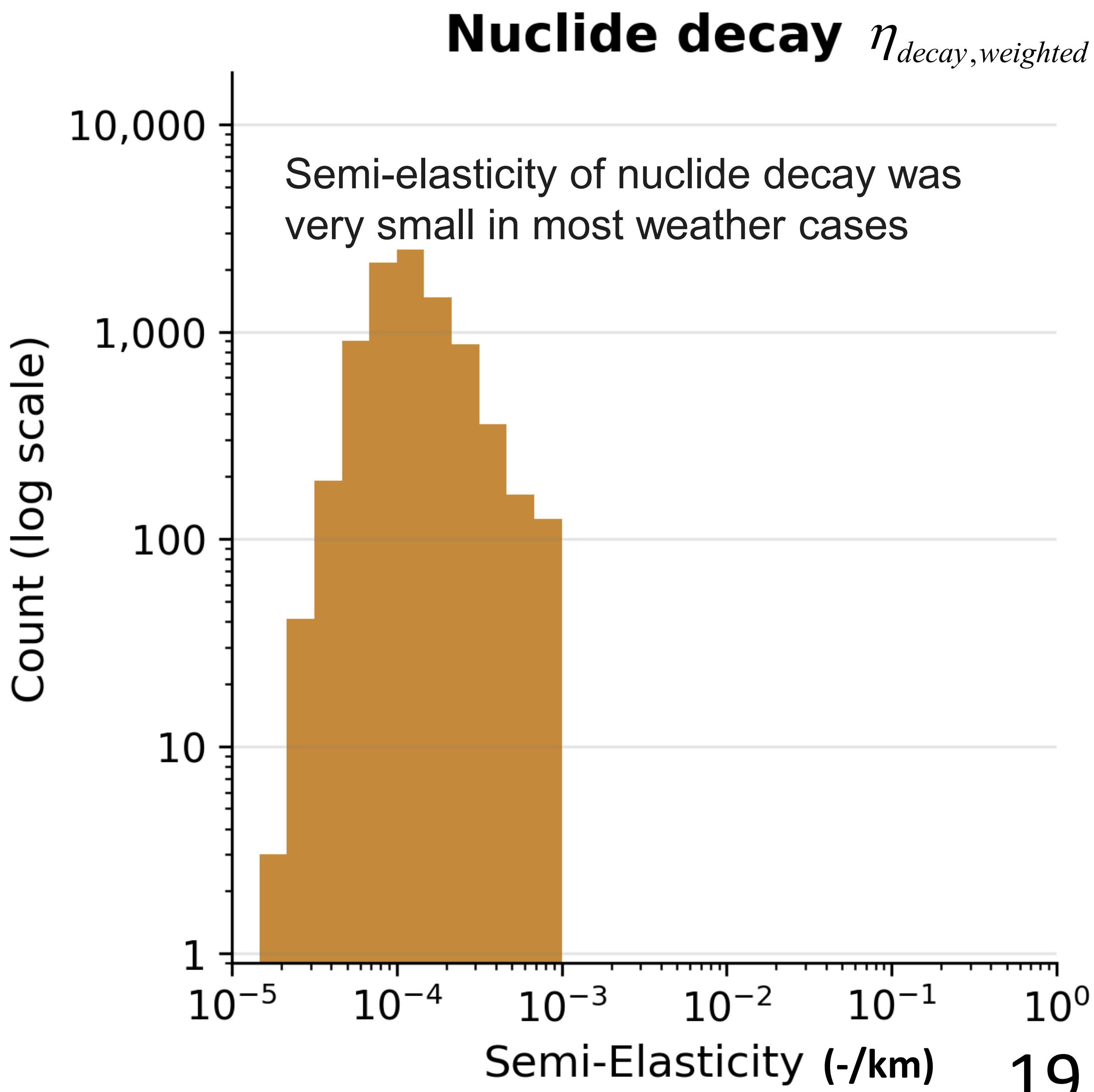


wet depletion $\eta_{wet,weighted}$

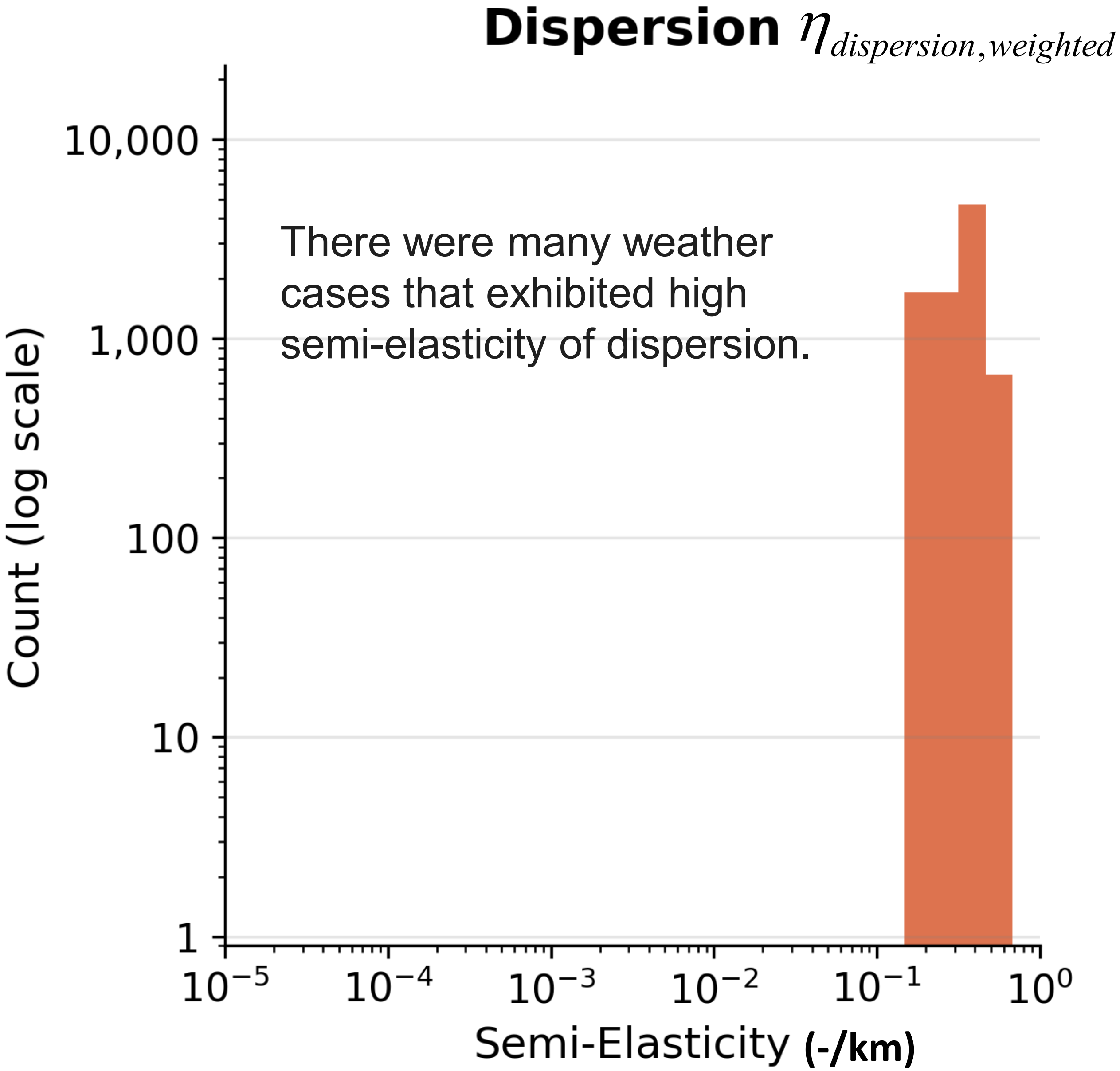


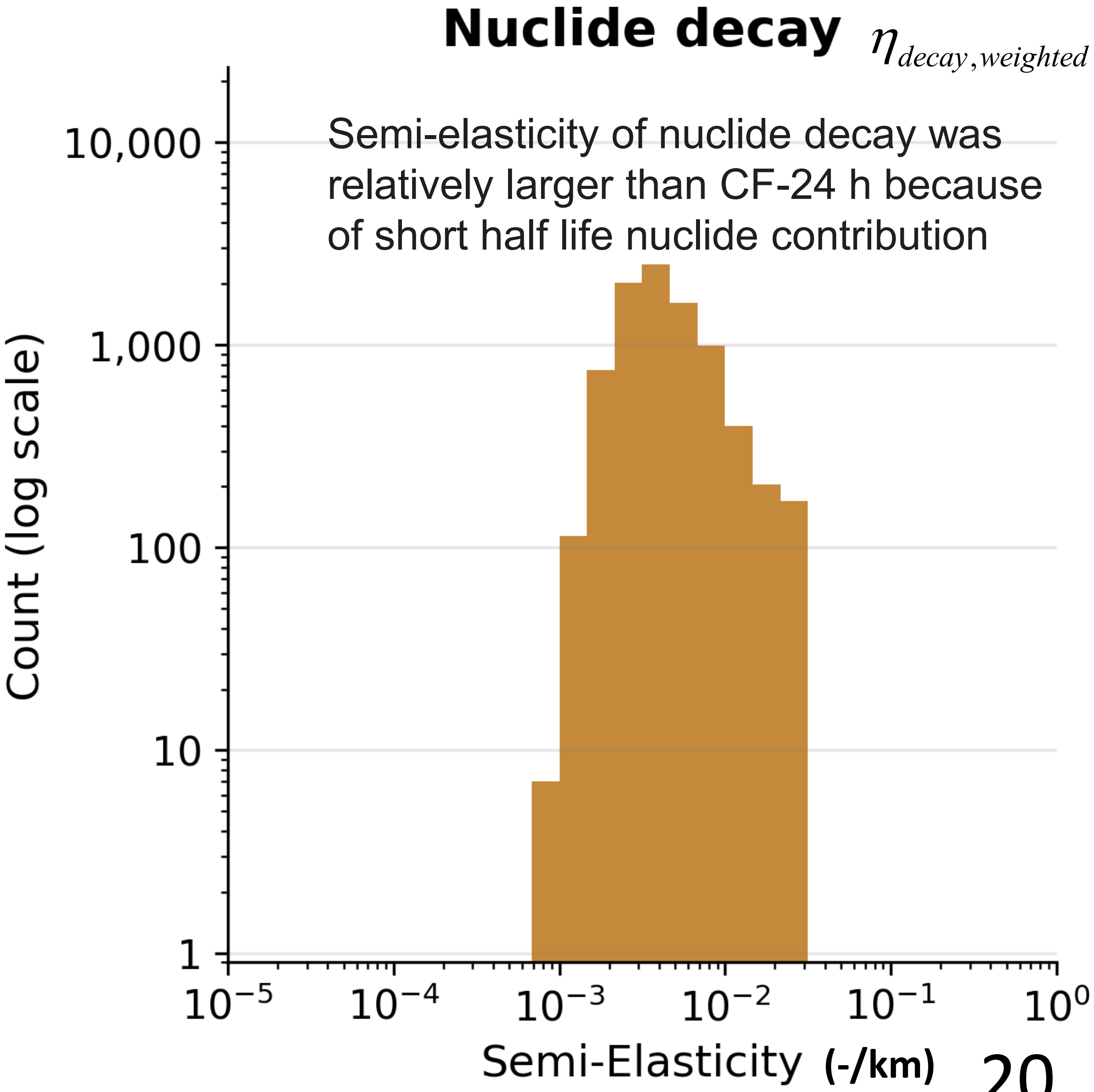
Low semi-elasticity phenomena (CF-24 h at 2 km)



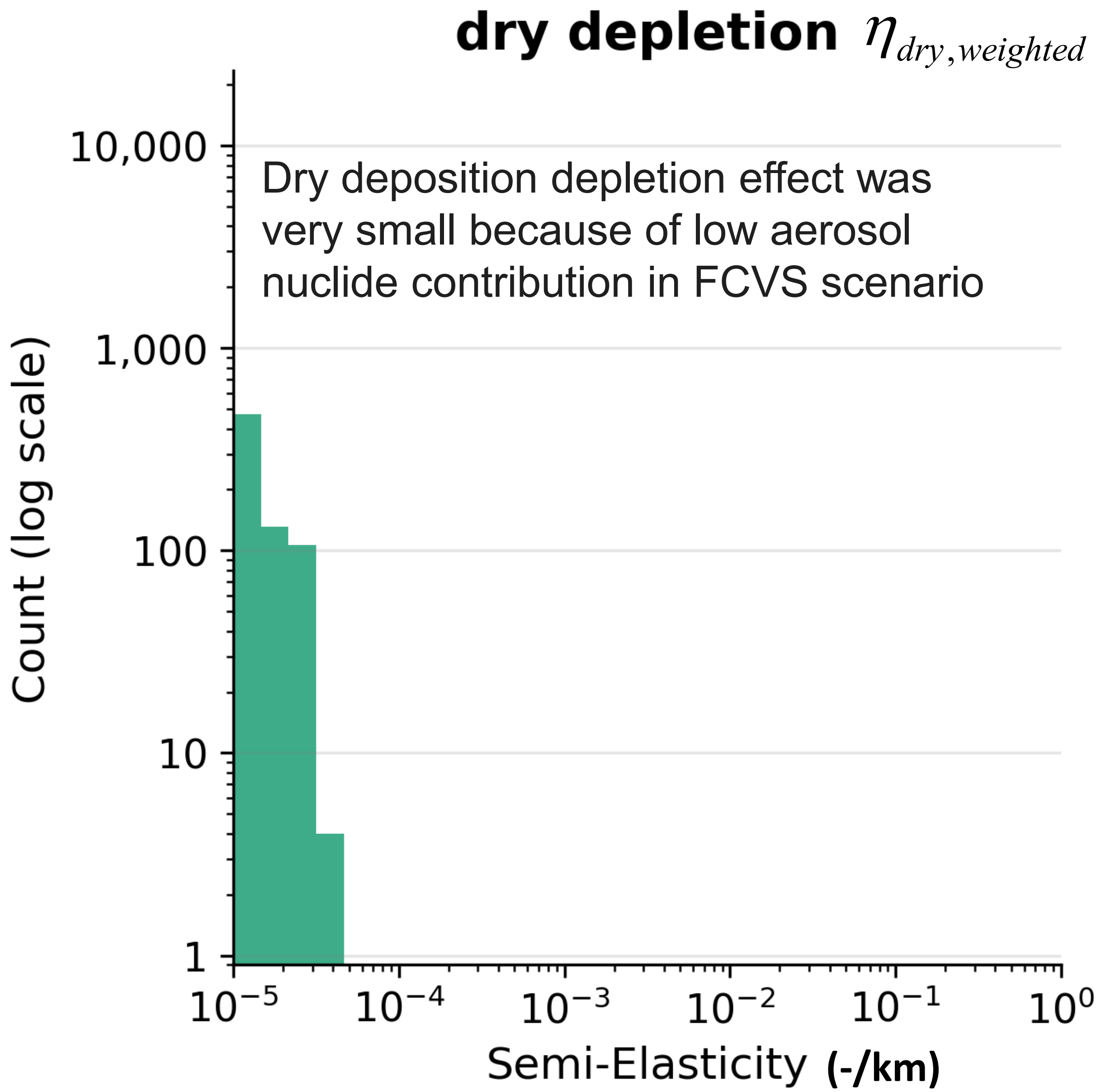


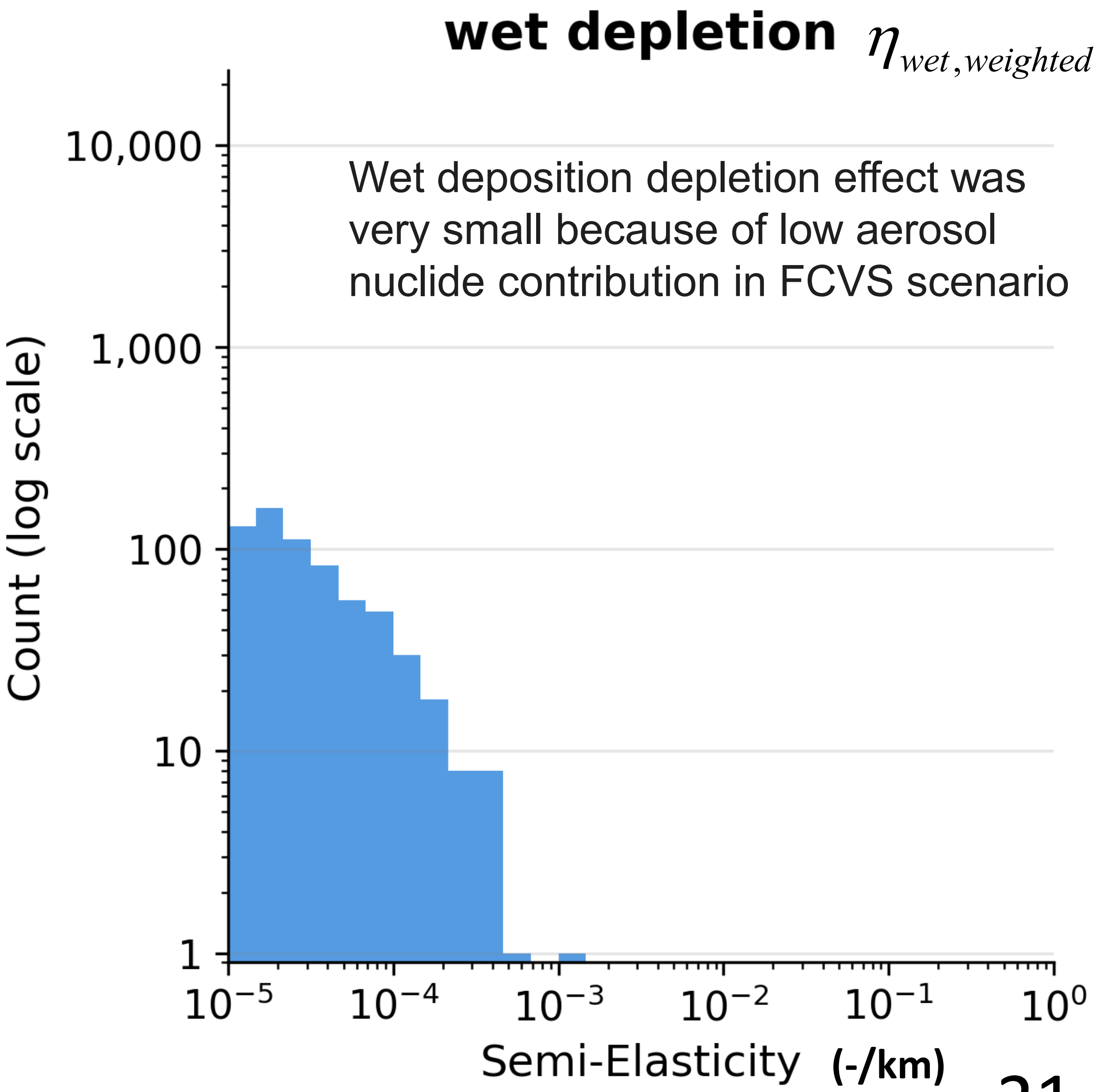
High semi-elasticity phenomena (FV-24 h at 2 km)



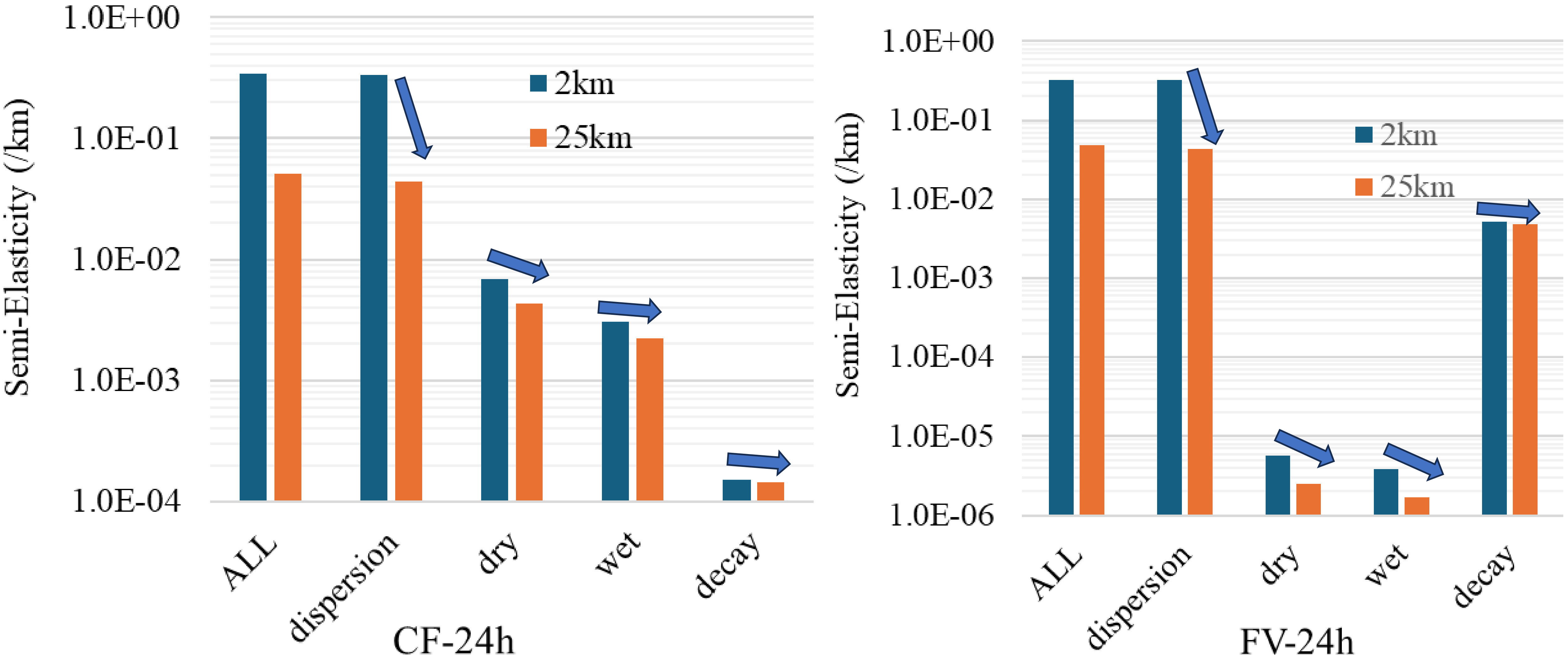


Low semi-elasticity phenomena (FV-24 h at 2 km)





Differences in semi-elasticity with distance (mean value of all weather trial)

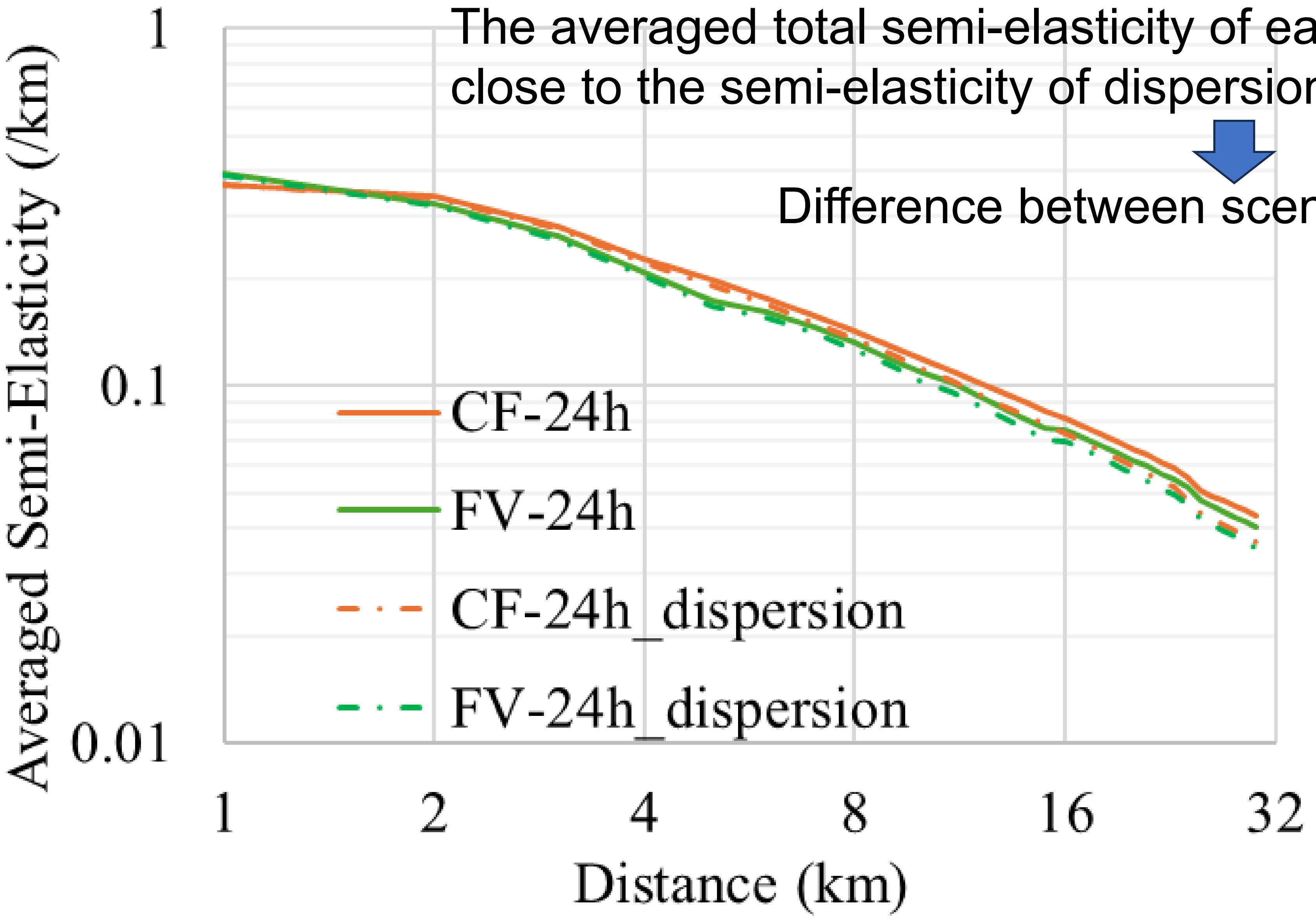


While the semi-elasticity of dispersion varied significantly with distance, that of deposition (dry, wet) and radioactive decay remained relatively constant.

Semi-Elasticity of each Distance Averaged across All Meteorological Conditions

The averaged total semi-elasticity of each scenario was very close to the semi-elasticity of dispersion (power-law).

Difference between scenarios was small.



D-D curve characteristics to inform emergency planning

Shape of D-D curve

Emergency planning

	Power-law	Exponential-law
EPZ setting	Simple scaling by thermal power approach can be considered. $E(x) \sim \frac{1}{x^2} \Rightarrow x_{100mSv} = \left(\frac{P}{P_{ref}}\right)^{1/2} x_{100mSv}^{ref}$	The variation in the distance to reach the 100 mSv across different thermal power is highly scenario-dependent.
Protective action reccomend	Evacuation at short distance. Shelter-in-place at long distance.	The dose reduction efficiency of moving unit distance is similar across all distances, thus, it depends on the case.

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Conclusion

- We introduced the distance semi-elasticity as a novel metrics for evaluating the relative importance of phenomena affecting the dose distance (D–D) curves.
  - It can decompose the product terms of each phenomenon, which enables evaluating the significance of each phenomenon on dose attenuation with distance.

- Importance of phenomena was evaluated using semi-elasticity at a site in Japan.
  - In most meteorological conditions, atmospheric dispersion, characterized by power law attenuation, was the dominant factor controlling distance-attenuation.
  - In some meteorological conditions, exponential term was also large. (deposition depletion in CF-24h, radioactive decay in FV-24 h)

- Whether the shape of D-D curve is power-law or exponential law affects the decision-making for emergency planning.
  - If D-D curve follows an ideal power-law relationship, dose reduction per unit distance is larger in short distance, and simple scaling by thermal power approach for setting EPZ can be considered.