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HORIZONTAL TURBULENCE AND DISPERSION IN LOW-WIND STABLE CONDITIONS

Light Metals Flagship

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Introduction

- Wind fluctuations in the streamwise and lateral directions govern horizontal dispersion $(\sigma_x \propto \sigma_u, \sigma_y \propto \sigma_v)$
- When modelling dispersion under low wind conditions:
  - Streamwise dispersion (σ_x) cannot be neglected compared to mean advection – so σ_u is important
  - Vector and scalar average winds need to be distinguished
- How to estimate σ_u and σ_v from routine met data ($\overline{U}, \sigma_U, \overline{\theta}, \sigma_\theta$) typically obtained using 'single-pass' methods?
- How to estimate vector wind ($\overline{u}$) from scalar wind ($\overline{U}$)?
- Influence on modelled dispersion

Calculating σ_u and σ_v: existing relations

- E.g. Hanna (1983), Etling (1990): $\sigma_v = \overline{U} \tan \sigma_\theta$
- Luhar and Rao (1994): $\sigma_v = \overline{U} \sin \sigma_\theta$
- For small σ_θ : $\sigma_v \approx \overline{U} \sigma_\theta$ (most commonly used)
- It is assumed that $\sigma_u = \sigma_v$ (no role of σ_U)
- In the above, no distinction is made between scalar ($\overline{U}$) and vector ($\overline{u}$) averaged winds

- van den Hurk and de Bruin (1995) derived (role of σ_U)

$$\sigma_u^2 = \left[\sigma_U^2 - \overline{U}^2\{\exp(-\sigma_\theta^2) - 1\}\right]/2, \qquad \sigma_v = \sigma_u \text{ assumed}$$

- Cirillo and Poli (1992) assume a Gaussian distribution for θ and a delta function for U

$$\sigma_v^2 = \overline{U}^2 \exp(-\sigma_\theta^2)\sinh(\sigma_\theta^2)$$
$$\sigma_u^2 = \overline{U}^2 \exp(-\sigma_\theta^2)[\cosh(\sigma_\theta^2) - 1]$$

- The vector average wind speed $\overline{u} = \overline{U}\exp(-\sigma_\theta^2 / 2)$
- Or

$$\sigma_v^2 = \overline{u}^2 \sinh(\sigma_\theta^2)$$
$$\sigma_u^2 = \overline{u}^2 [\cosh(\sigma_\theta^2) - 1]$$

No role of σ_U

- Inconsistent use of the CP relations in the scientific literature
- We evaluate the above relations and offer improvements

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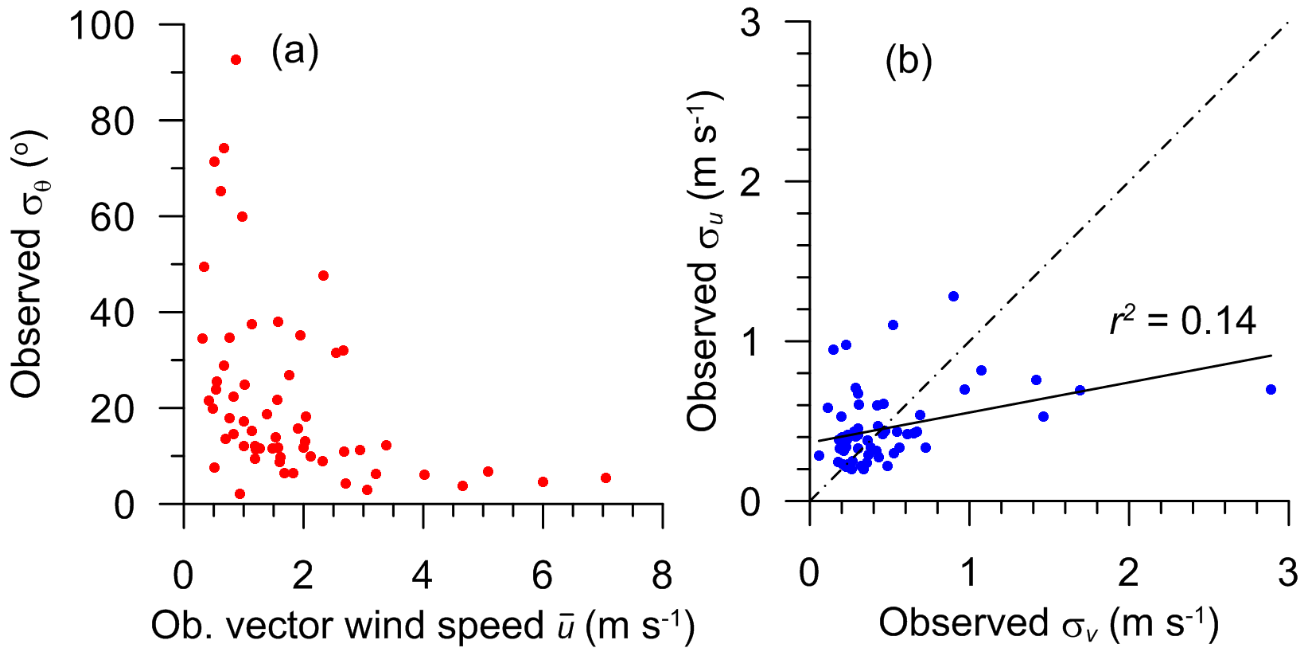
Dataset

- The INEL Idaho Falls dataset (Sagendorf & Dickson, 1974) – widely used for low wind studies (e.g., Sharan and Yadav, 1998; Oettl et al., 2001; Anfossi et al., 2006)
- Winds measured at 2, 4, 8, 16, 32 and 61 m
- GLC data also available
- Data from 9 stable and 1 neutral hours were available

Observed characteristics



- The well-known behaviour of σ_θ increasing with decreasing wind speed is evident
- The assumption that $\sigma_u = \sigma_v$ is not satisfactory
- Later, our analysis shows that the leading order term in σ_v is σ_θ , and that in σ_u is σ_U

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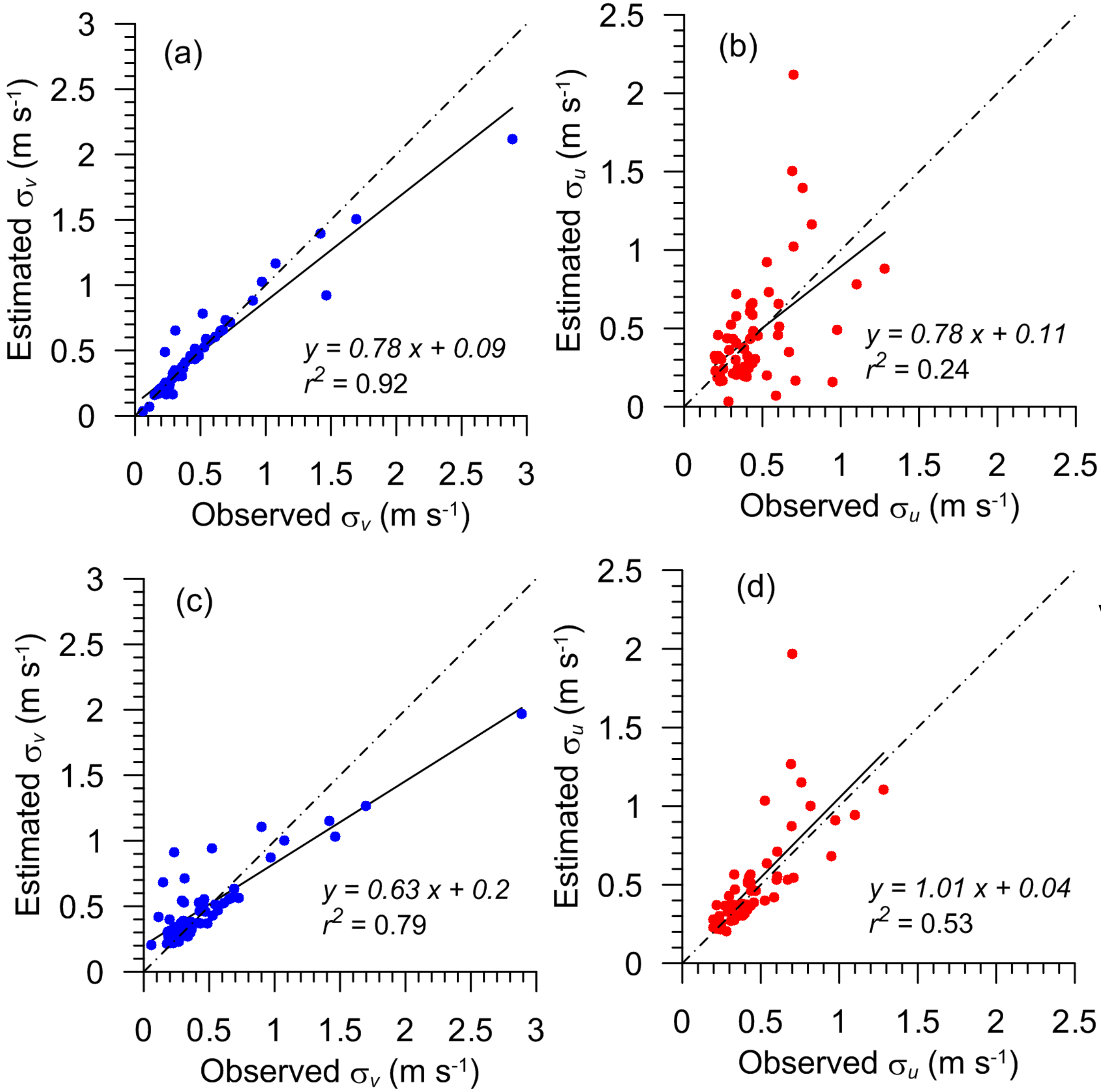
Comparison with the data



$$\sigma_v = \overline{U}\sigma_\theta$$

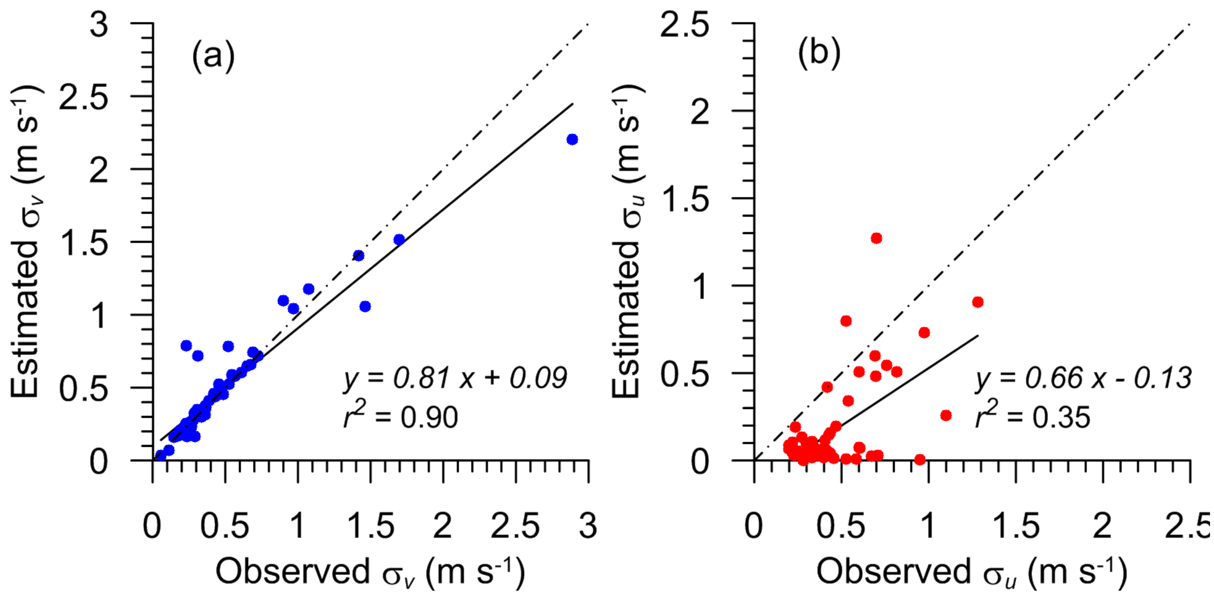
$$\sigma_u = \sigma_v$$

No role of σ_U

van den Hurk and de Bruin (1995) σ_u

$$\sigma_v = \sigma_u$$

Role of σ_U



Cirillo and Poli (1992)

$$\sigma_u \neq \sigma_v$$

No role of σ_U

- The results above indicate that $\sigma_v = \overline{U}\sigma_\theta$ is satisfactory
- For σ_u, the van den Hurk and de Bruin formulation is the best of the three

Improved relations

- We follow the framework of Cirillo and Poli (1992) – but there is no need to assume a particular form of the probability distribution for U (they assumed a delta function)

$$\sigma_v^2 = \overline{U}^2 \exp(-\sigma_\theta^2)\sinh(\sigma_\theta^2)[1+\left(\sigma_U / \overline{U}\right)^2]$$

$$\sigma_u^2 = \overline{U}^2 \exp(-\sigma_\theta^2)[\cosh(\sigma_\theta^2)\{1+\left(\sigma_U / \overline{U}\right)^2\} - 1]$$

- The vector average wind speed $\overline{u} = \overline{U}\exp(-\sigma_\theta^2 / 2)$

- The leading order term in σ_v is σ_θ, and that in σ_u is σ_U

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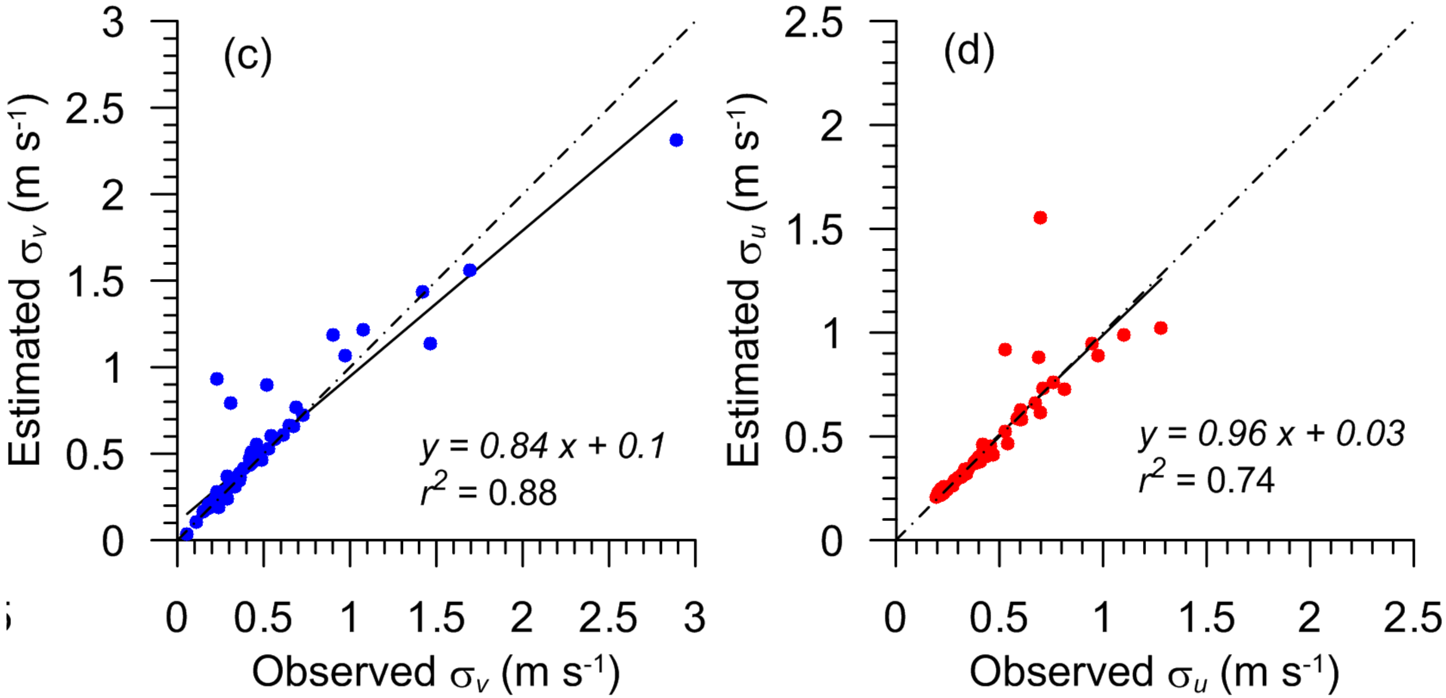
With improved relations



- Best overall agreement – a few substantial deviations, probably due to the assumption that wind direction is normally distributed and is statistically independent of wind speed, not holding valid

Testing σ_u and σ_v in a dispersion model

- Analytical solutions to the Gaussian puff equation – include stream wise diffusion and valid in low wind conditions
- The solution by Thomson and Manning (2001) is consistent with both small time and large time behaviours

$$\hat{C} = \frac{1}{2\hat{r}^2}\exp\left(-\frac{\hat{r}^2}{4} + \hat{x}\hat{\bar{u}} - \hat{\bar{u}}^2\right) + \frac{\sqrt{\pi}}{2\hat{r}^2}\frac{\hat{x}\,\hat{\bar{u}}}{\hat{r}}\exp\left\{-\hat{\bar{u}}^2\left(1-\frac{\hat{x}^2}{\hat{r}^2}\right)\right\}\times$$
$$\left\{1+\mathrm{erf}\left(\frac{\hat{x}\,\hat{\bar{u}}}{\hat{r}} - \frac{\hat{r}}{2}\right)\right\} + \frac{\sqrt{\pi}}{4\hat{r}}\exp\left\{-\hat{\bar{u}}\left(\hat{r}-\hat{x}\right)\right\}\left\{1+\mathrm{erf}\left(\frac{\hat{r}}{2}-\hat{\bar{u}}\right)\right\}$$
$$-\frac{\sqrt{\pi}}{4\hat{r}}\exp\left\{\hat{\bar{u}}\left(\hat{r}+\hat{x}\right)\right\}\left\{1-\mathrm{erf}\left(\frac{\hat{r}}{2}+\hat{\bar{u}}\right)\right\}.$$

- Not previously tested with data

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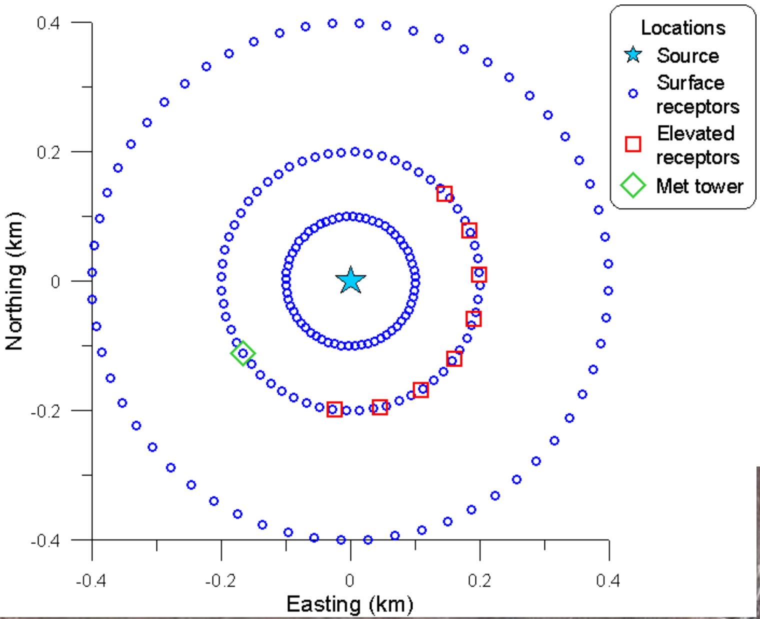
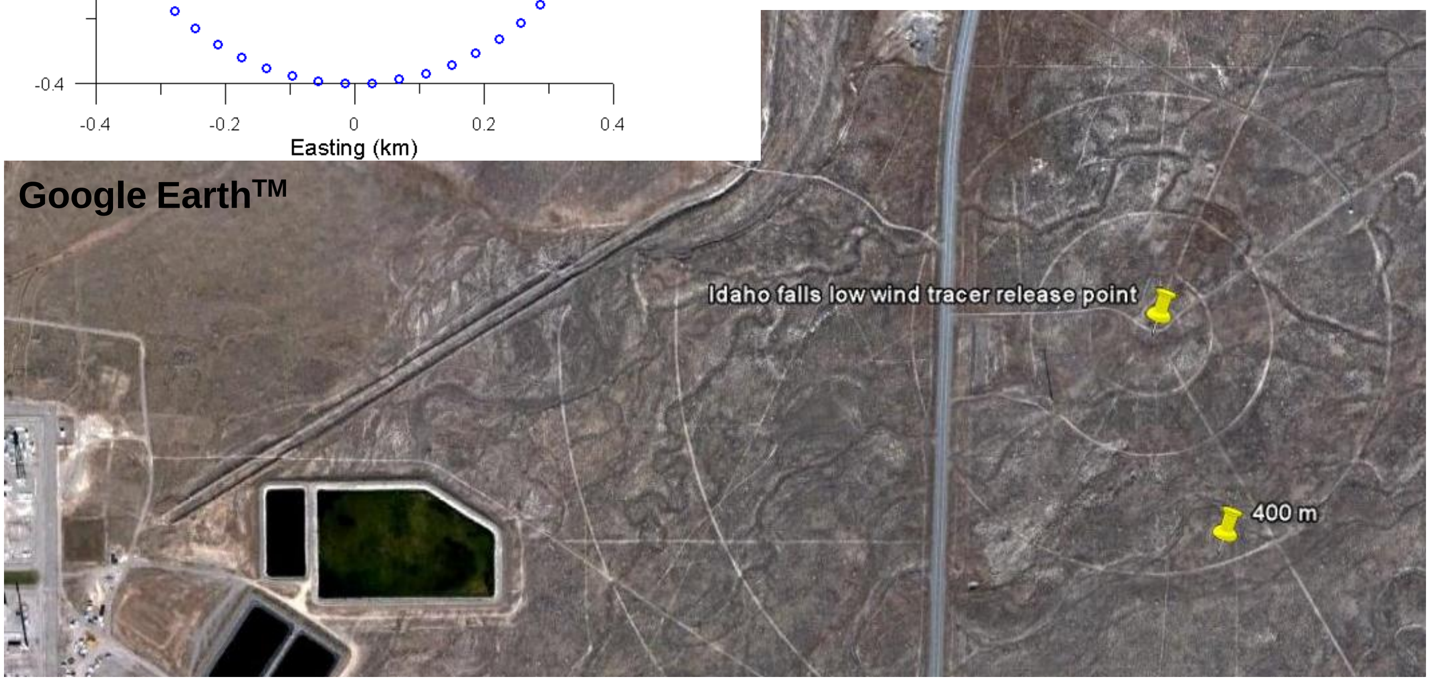
Dispersion data



- The 1974 Idaho Falls dataset
- SF_6 released at an effective height of 3 m
- GLC measured by 180 samplers on three arcs (100, 200 & 400 m)



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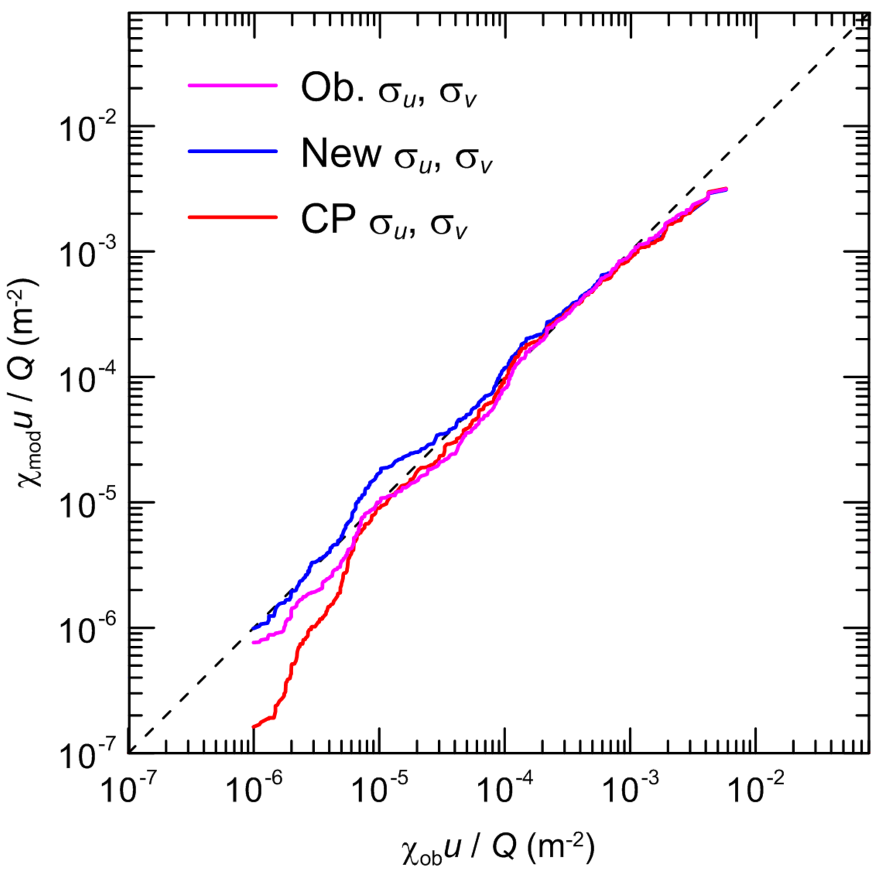
Dispersion Results



- Quantile-quantile plot
  - The new relations perform slightly better than the σ_u and σ_v data for lower concentrations – demonstrates some uncertainty in the dispersion model with regards to its formulations and/or other inputs
  - When the Cirillo and Poli (CP) relations are used, the model considerably underestimates the lower concentrations (doesn't include correct σ_u)

Conclusions

- Evaluated existing relations for estimating σ_u and σ_v from routine wind measurements under stable conditions
- The commonly-used assumption of $\sigma_u = \sigma_v$ is not necessarily valid
- The leading order term in determining σ_v is σ_θ, whereas that in determining σ_u is σ_U
- Inconsistencies with some of the existing expressions highlighted
- The new relations for σ_u and σ_v provide better estimates, and lead to better simulation of the observed dispersion
- The vector wind speed, to be used as the transport wind speed, can be obtained from the scalar wind speed using $\bar{u} = \bar{U}\exp(-\sigma_\theta^2/2)$
- The present analysis can also be applied to unstable conditions

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