Effect of wind fluctuations on near-range atmospheric dispersion under different types of thermal stratification

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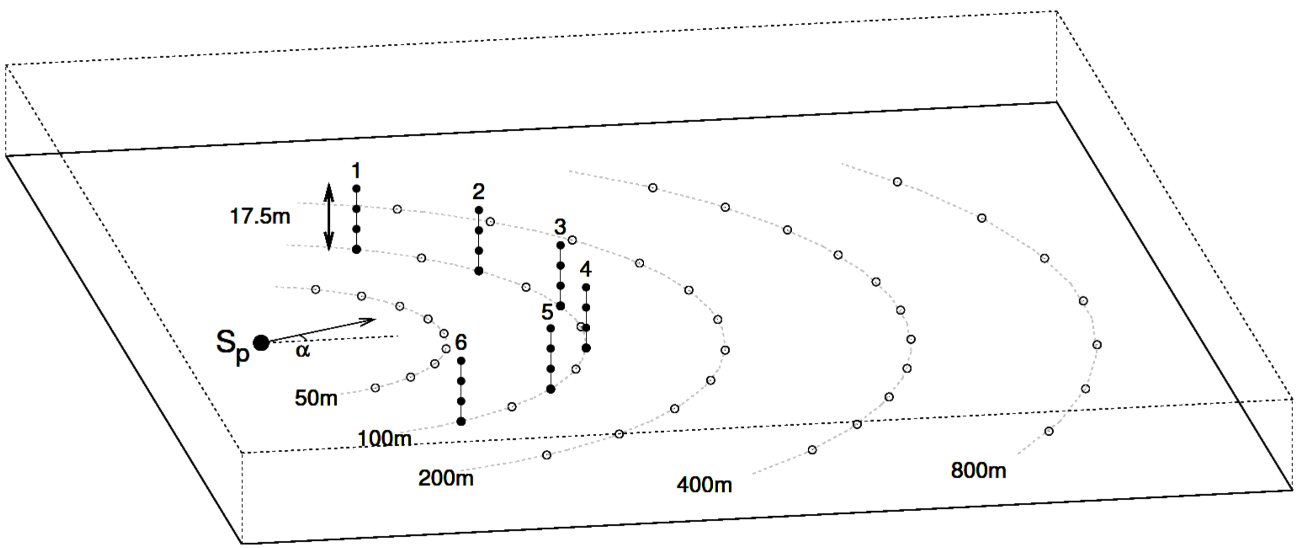
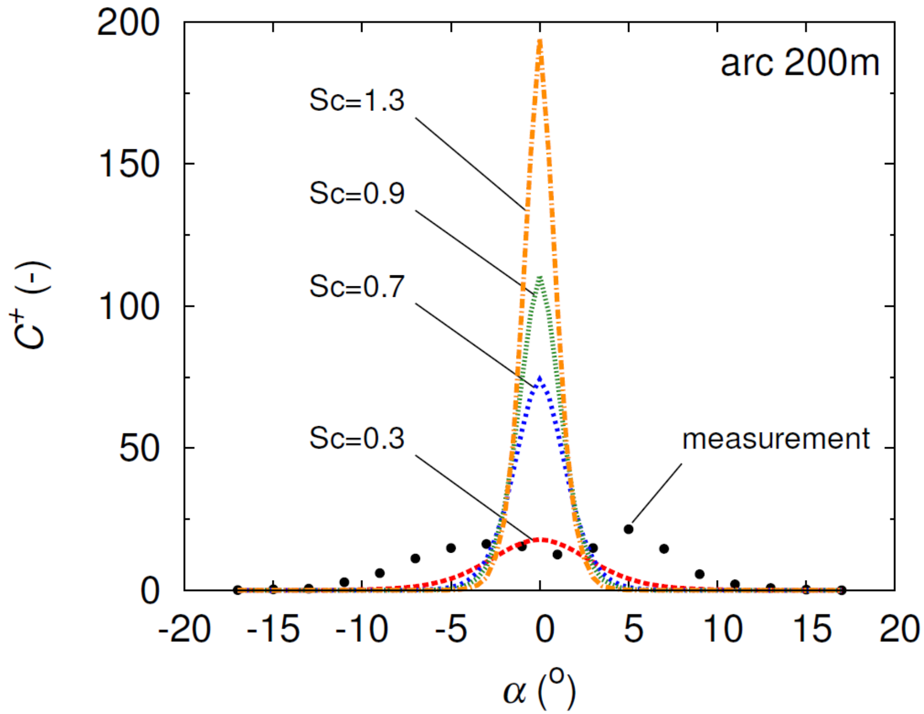
- Near range dispersion
  - Effect of pollutant on people living/working close to release point
  - Gaussian models (often) unstatisfactory
  - Computational Fluid Dynamics (CFD) using RANS or LES
  - → Start with open field



Mean-wind simulation



[Vervecken et al.. 2013]

- Centerline concentration strongly overestimated
- Lateral spreading underestimated

→ Incorporate effects of variable wind conditions

  - Neutral conditions
  - Thermally stratified = This work

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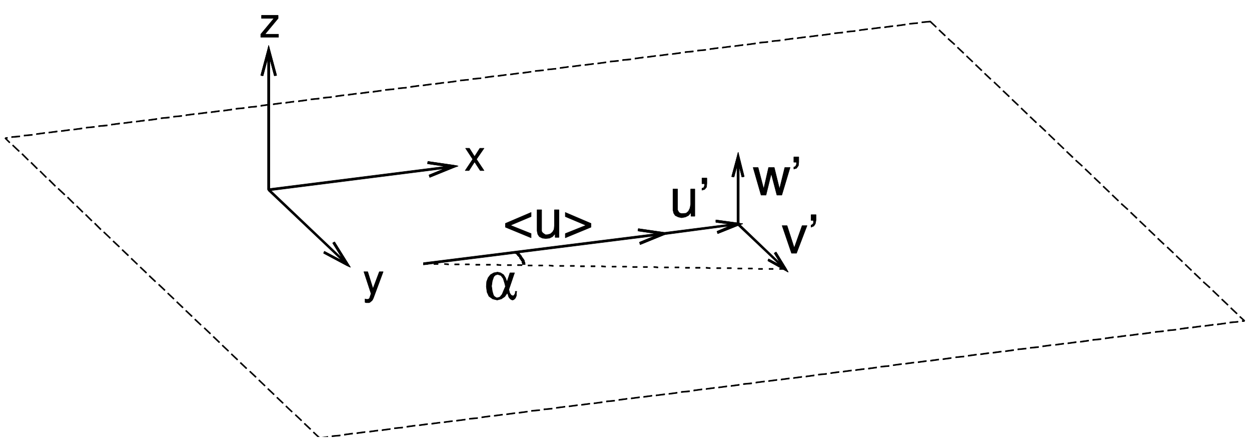
Instant wind direction



- Reynolds averaging

$$\boldsymbol{u} = \langle \boldsymbol{u} \rangle + \boldsymbol{u}'$$

$$\langle \boldsymbol{u} \rangle = (\langle u \rangle, \langle v \rangle, \langle w \rangle)$$

$$\langle \boldsymbol{u}' \rangle = (\langle u' \rangle, \langle v' \rangle, \langle w' \rangle) = \boldsymbol{0}$$

- For our purpose: select the coordinate system such that

$$\langle v \rangle = \langle w \rangle = 0$$

- Presume the fluctuating velocity can be split [Vervecken et al.. 2013]
  1. Internally represented in the CFD ($_m$)
  2. Large-scale part that is not represented ($_e$)

$$u = \langle u \rangle + u'_m + u'_e$$

$$v = v'_m + v'_e$$

$$\Downarrow$$

$$\alpha = \arctan\left(\frac{v'_m + v'_e}{\langle u \rangle + u'_m + u'_e}\right) \approx \frac{v'_m + v'_e}{\langle u \rangle}$$

Modeled wind angle

$$\alpha = \frac{v'_m + v'_e}{\langle u \rangle}$$

$$\langle \alpha^2 \rangle = \frac{\langle v'^2_m \rangle + 2\langle v'_m v'_e \rangle + \langle v'^2_e \rangle}{\langle u \rangle^2}$$

$$\approx \frac{\langle v'^2_e \rangle}{\langle u \rangle^2} + \frac{\langle v'^2_m \rangle}{\langle u \rangle^2} = \boxed{\sigma_e^2} + \sigma_m^2$$

$\langle \alpha \rangle = 0$ by construction

$\langle \alpha^2 \rangle = \sigma_\alpha^2$ the measured variance

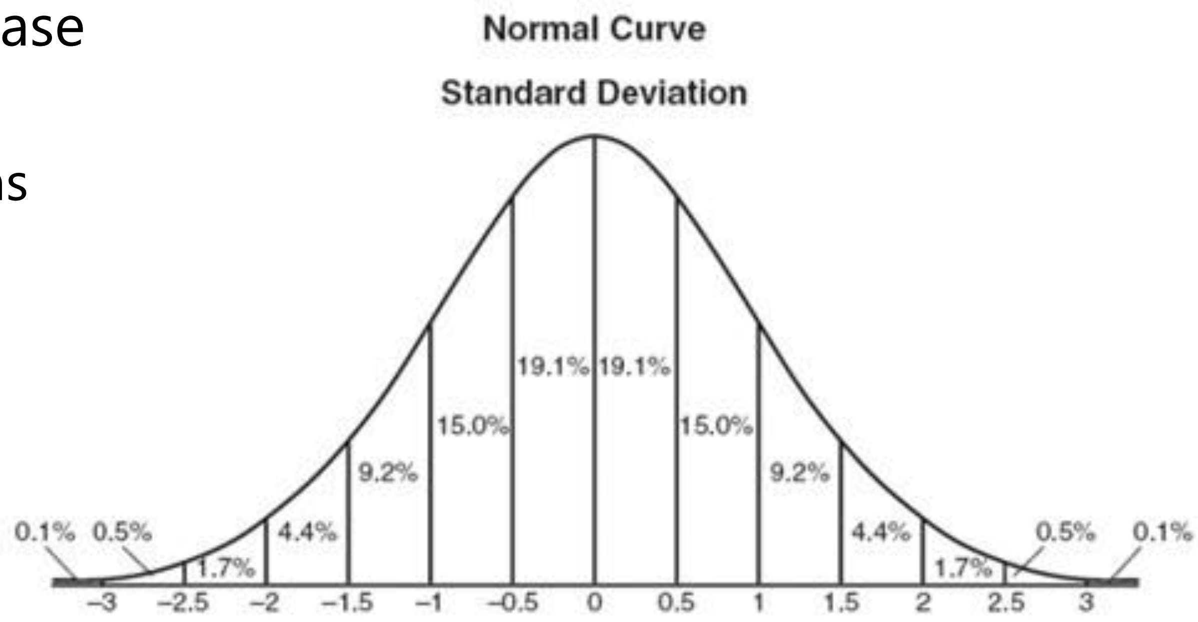
- Level 2 model of Mellor and Yamada (1982)

$$\Rightarrow \sigma_m^2 = \frac{\langle v'^2_m \rangle}{\langle u \rangle^2} \approx \gamma_1 \left(\frac{u_\tau}{\phi_M S_M} \right)^2$$

Additional boundary condition

- Include wind variability
  - Assume normal distribution
  - Finite number of intervals
  - Weigh solution with interval probability

- Open field = special case
  - Rotate grid
  - Keep sensor positions



- Transport of a non-buoyant, passive scalar

$$\nabla . (\langle \boldsymbol{u} \rangle \langle c \rangle) = \nabla . (D \nabla \langle c \rangle - \langle \boldsymbol{u}' c' \rangle) + \langle S_p \rangle$$

- Monin-Obukhov similarity theory
  - Velocity profile

$$u = \frac{u_\tau}{\kappa} \left[\ln \left(\frac{z}{z_0} \right) - \psi_M \right]$$

  - Turbulent mass flux

$$-\langle \boldsymbol{u}' c \rangle \approx \frac{u_\tau \kappa z \left(1 - {}^{z}/_{\delta} \right)}{Sc_t \phi_M}$$

  - Normalization

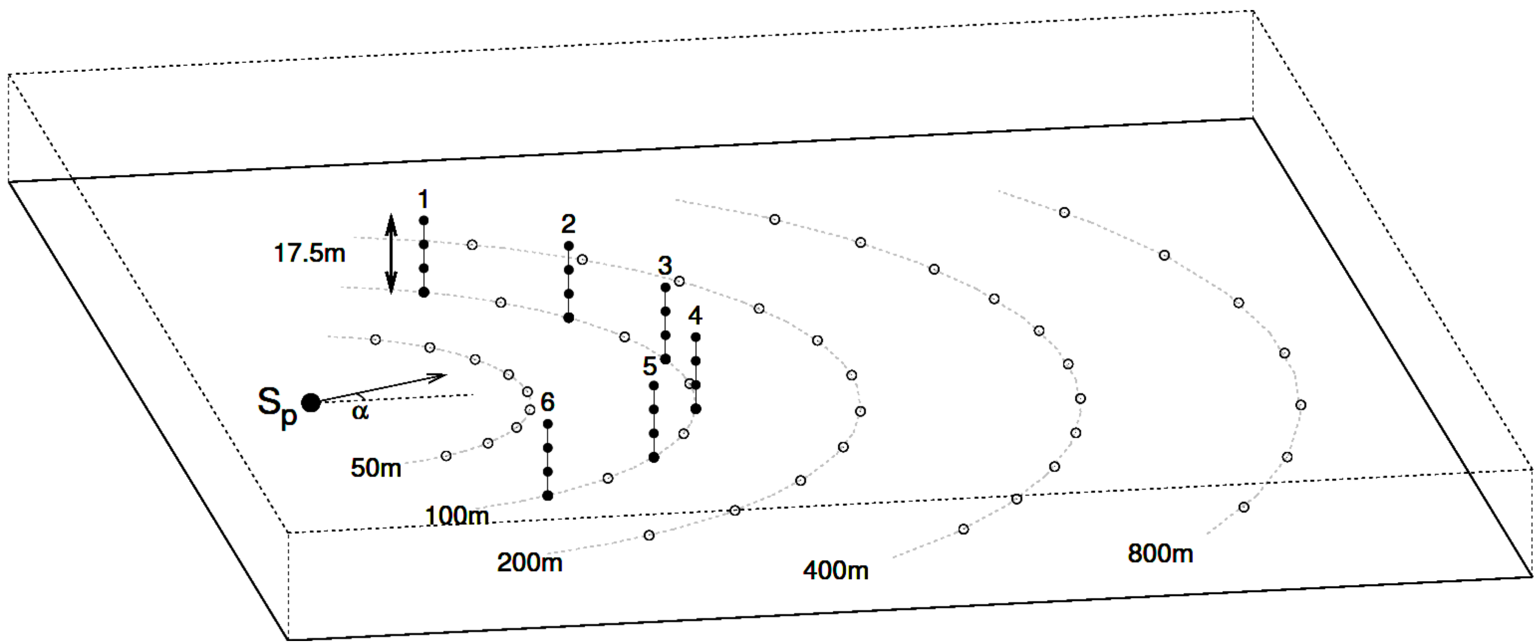
$$C^+ = \langle c \rangle \frac{UL^2}{r}$$

[e.g. Stull, 1988]
[Garrat and Pielke, 1988]

Project Prairie Grass

- 70 experiments from 1956
- 10-min sampling of tracer (SO_2)
- Release at 46 cm and 150 cm
- Concentration measured on 5 arcs and 6 towers

[Barad, 1958]



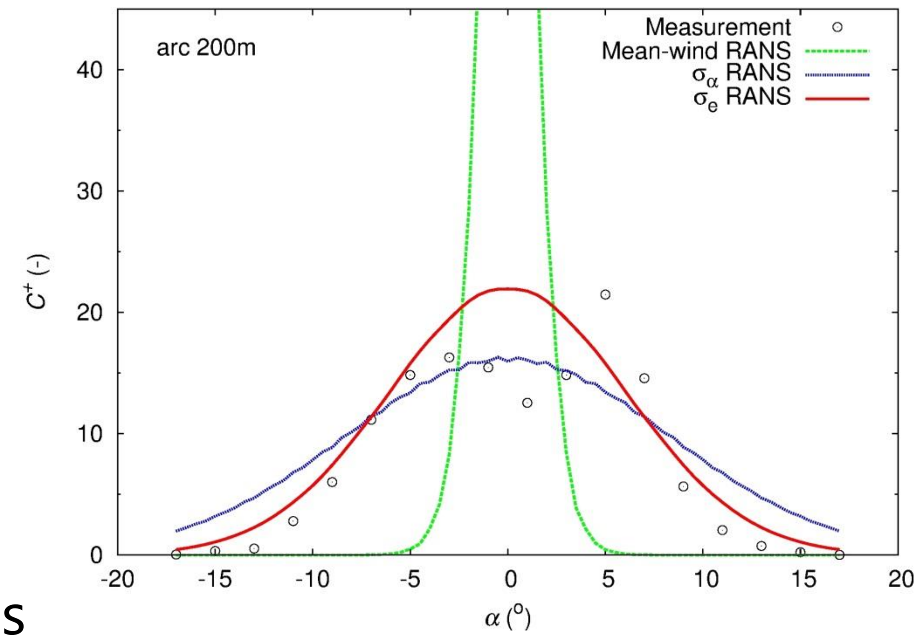
Computational setup

$$\sigma_\alpha^2 = \sigma_e^2 + \sigma_m^2$$

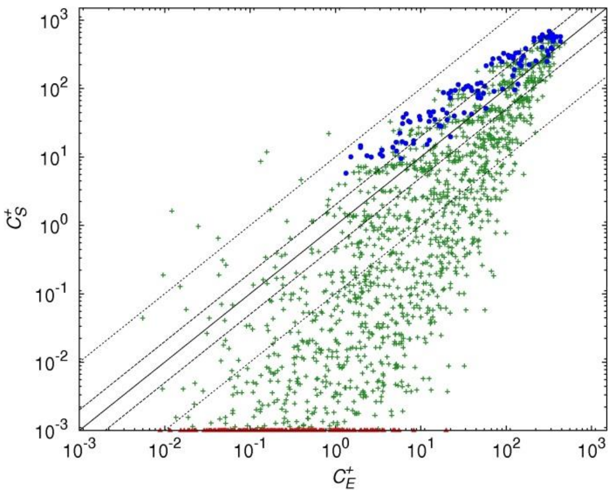
- Three models ($Sc_t = 0.9$)
  - $\sigma_e = 0$: Mean-wind RANS
  - $\sigma_m = 0$: σ_α-RANS
  - $\sigma_\alpha \neq \sigma_e$: σ_e-RANS
- Stability class based on σ_α [e.g., Zanetti, 1990]
- All experiments except for
  - Insufficient data
  - $U_{2\mathrm{m}} < 2\,\frac{\mathrm{m}}{\mathrm{s}}$
  - $\sigma_\alpha > 17.5°$

Results

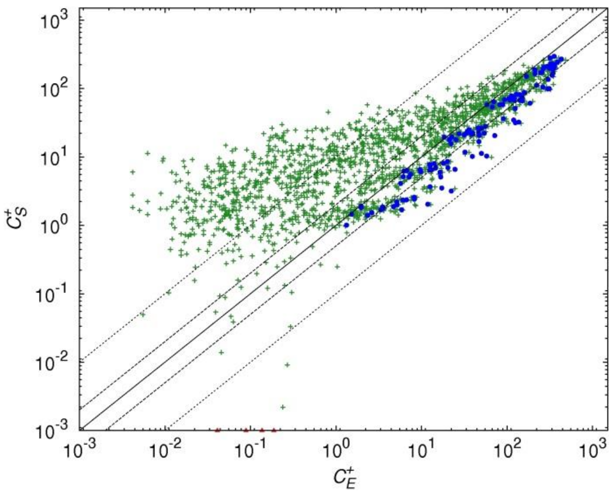
Experiment 45



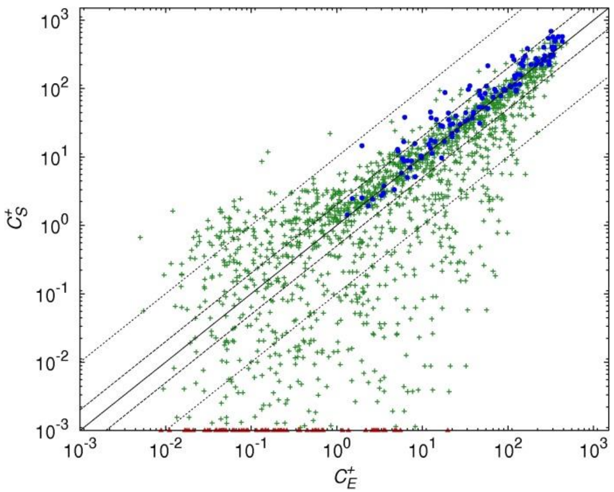
Stable experiments



Mean-wind RANS



σ_α-RANS



σ_e-RANS

Statistical performance measures

Performance measure		Exact	Tolerable [Hanna, 2004]
FB	$\frac{\langle C_o \rangle - \langle C_p \rangle}{0.5(\langle C_o \rangle + \langle C_p \rangle)}$	0.0	$-0.3 < \mathrm{FB} < 0.3$
MG	$\exp(\langle \ln C_o \rangle - \langle \ln C_p \rangle)$	1.0	$0.7 < \mathrm{MG} < 1.3$
NMSE	$\frac{\langle (C_o - C_p)^2 \rangle}{\langle C_o \rangle \langle C_p \rangle}$	0.0	$\mathrm{NMSE} < 4.0$
VG	$\exp\left(\left\langle (\ln C_o - \ln C_p)^2 \right\rangle\right)$	1.0	$\mathrm{VG} < 1.6$
FAC2	fraction $0.5 \leq \frac{C_p}{C_o} \leq 2.0$	1.0	$\mathrm{FAC2} > 0.5$
FAC10	fraction $0.1 \leq \frac{C_p}{C_o} \leq 10.0$	1.0	

C_o = Observed concentrations C_p = Predicted concentrations

Centerline measurements

		FB	MG	NMSE	VG	FAC2	FAC10
		-0.3 < FB < 0.3	0.7 < MG < 1.3	< 4	< 1.6	> 0.5	-
unstable	mean-wind	-1.295	0.104	6.483	168.7	0.000	0.500
unstable	σ_α-RANS	0.356	**0.889**	1.148	**1.014**	**0.767**	**0.967**
unstable	σ_e-RANS	**0.293**	0.835	**0.968**	1.033	**0.767**	**0.967**
neutral	mean-wind	-1.176	0.150	4.446	36.73	0.010	0.750
neutral	σ_α-RANS	0.190	**0.931**	0.349	**1.005**	**0.875**	**1.000**
neutral	σ_e-RANS	**0.004**	0.781	**0.196**	1.063	0.837	**1.000**
stable	mean-wind	-0.569	0.444	0.786	1.931	0.436	**1.000**
stable	σ_α-RANS	0.518	1.904	0.691	1.514	0.615	**1.000**
stable	σ_e-RANS	**-0.264**	**0.757**	**0.349**	**1.080**	**0.855**	**1.000**

- 'σ_e-RANS' meets model acceptance criterion
- With all points: significant improvement of lower concentrations

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Summary

- New simulation boundary condition
  - Account for 'external' wind fluctuations
- Transport of non-buoyant, passive scalar
  - Advection-diffusion equation
  - Monin-Obukhov similarity theory
- Simulation of Prairie Grass experiments
  - Simulations improve significantly
  - Reproducing centreline concentrations
  - Improving estimation of lower concentrations