FLACS CFD Model Evaluation with Kit Fox, MUST, Prairie Grass, and EMU L-Shaped Building Data

Steven Hanna (Harvard Univ., Boston, MA)
Olav Hansen (Gexcon, Bergen, Norway)
Seshu Dharmavaram (Dupont Corp., Wilmington, DE)

<shanna@hsph.harvard.edu>

Outline

- Background on FLACS CFD Model
- Evaluations with Kit Fox data
- Evaluations with MUST data
- Evaluations with Prairie Grass data
- Evaluations with EMU L-Shaped building
- Summary

FLACS History

FLACS has been developed within gas explosion research programs at GexCon in Bergen

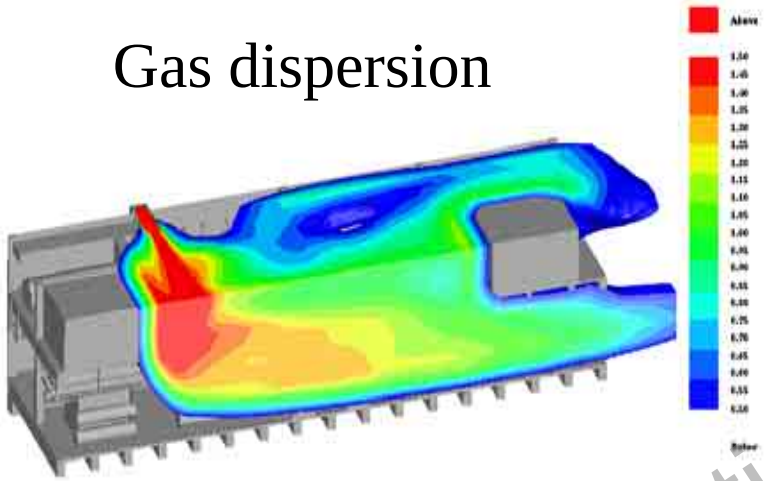
Recently the model has been further developed and applied for standard atmospheric flow and dispersion scenarios

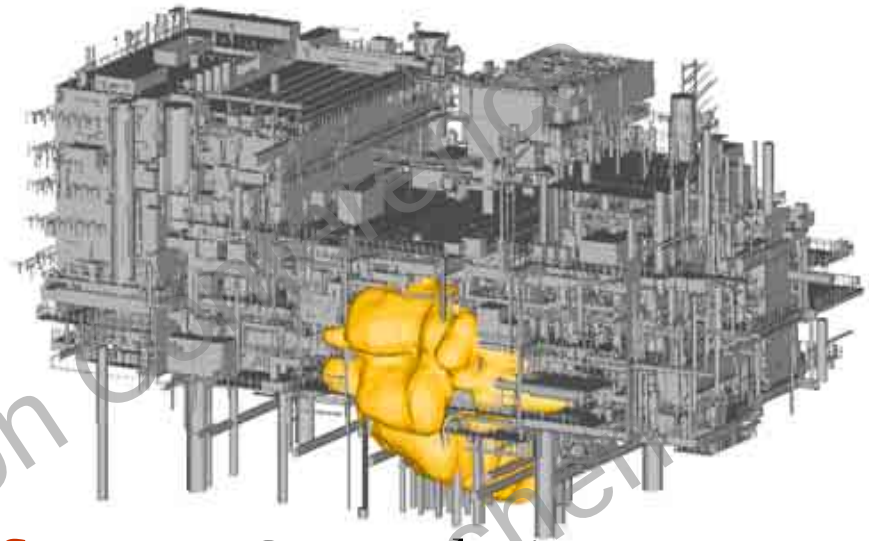
Up to 1996: FLACS only to sponsors

Since 1996: FLACS is commercially available

Piper Alpha Explosion in North Sea

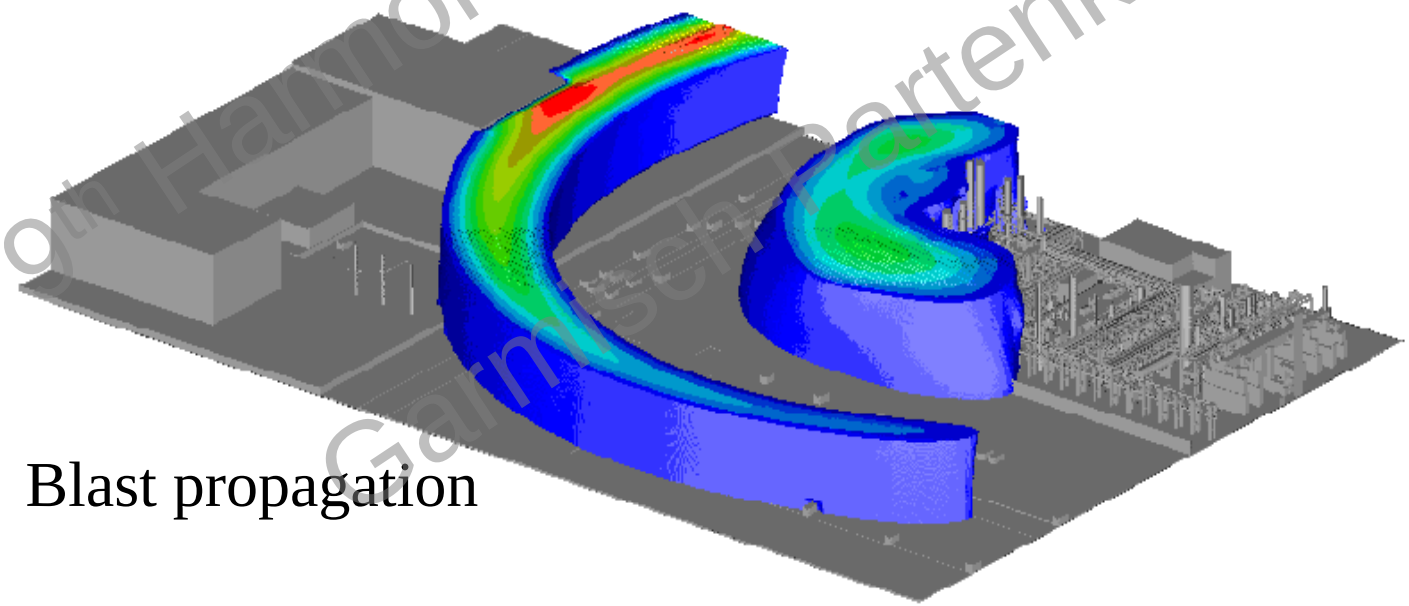
Gas dispersion





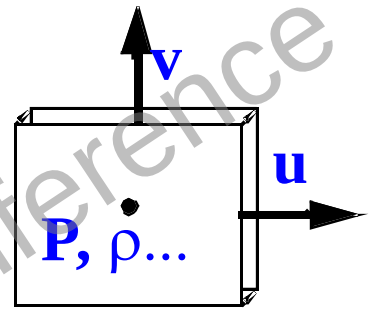
Gas explosion

Initial FLACS Focus



Blast propagation

BRIEF OVERVIEW OF FLACS CFD MODEL



Flow solver:

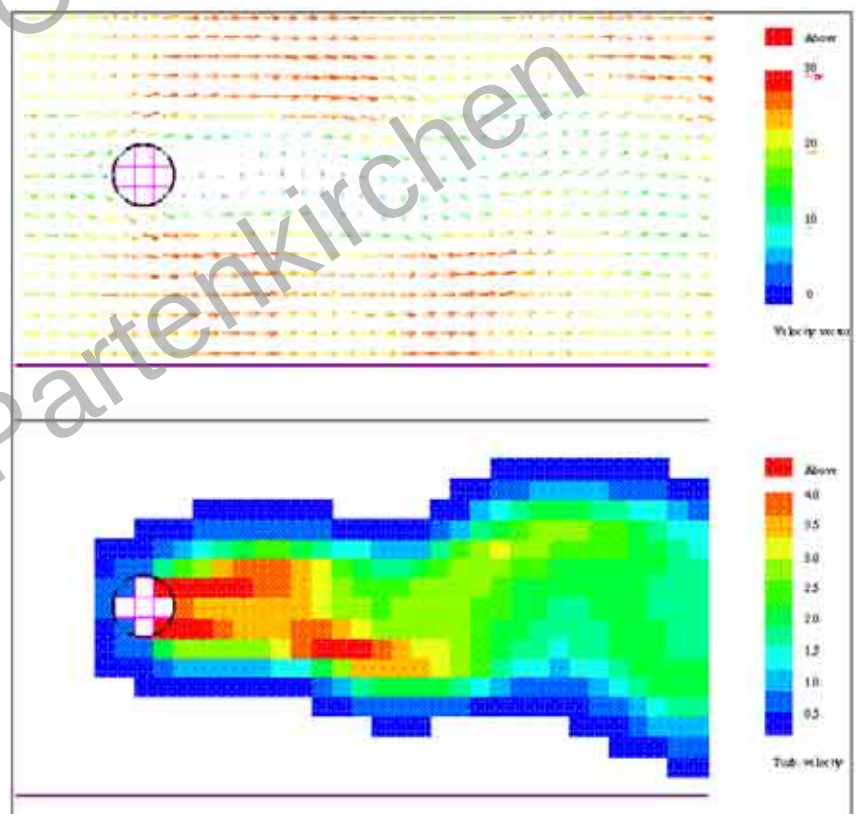
- Full 3D Cartesian N-S flow solver
- SIMPLE method, compressible extension
- Implicit/explicit 2nd order accuracy
- BICGSTAB-solver
- Transport equations for fuel/fuel mix.
- Distributed porosity concept (PDR)
- Source terms for chemical reactions
- Euler-model for droplet transport

Turbulence:

- k-ε model
- wall functions
- sub-grid contributions

Atmospheric stability is input via the sensible heat flux

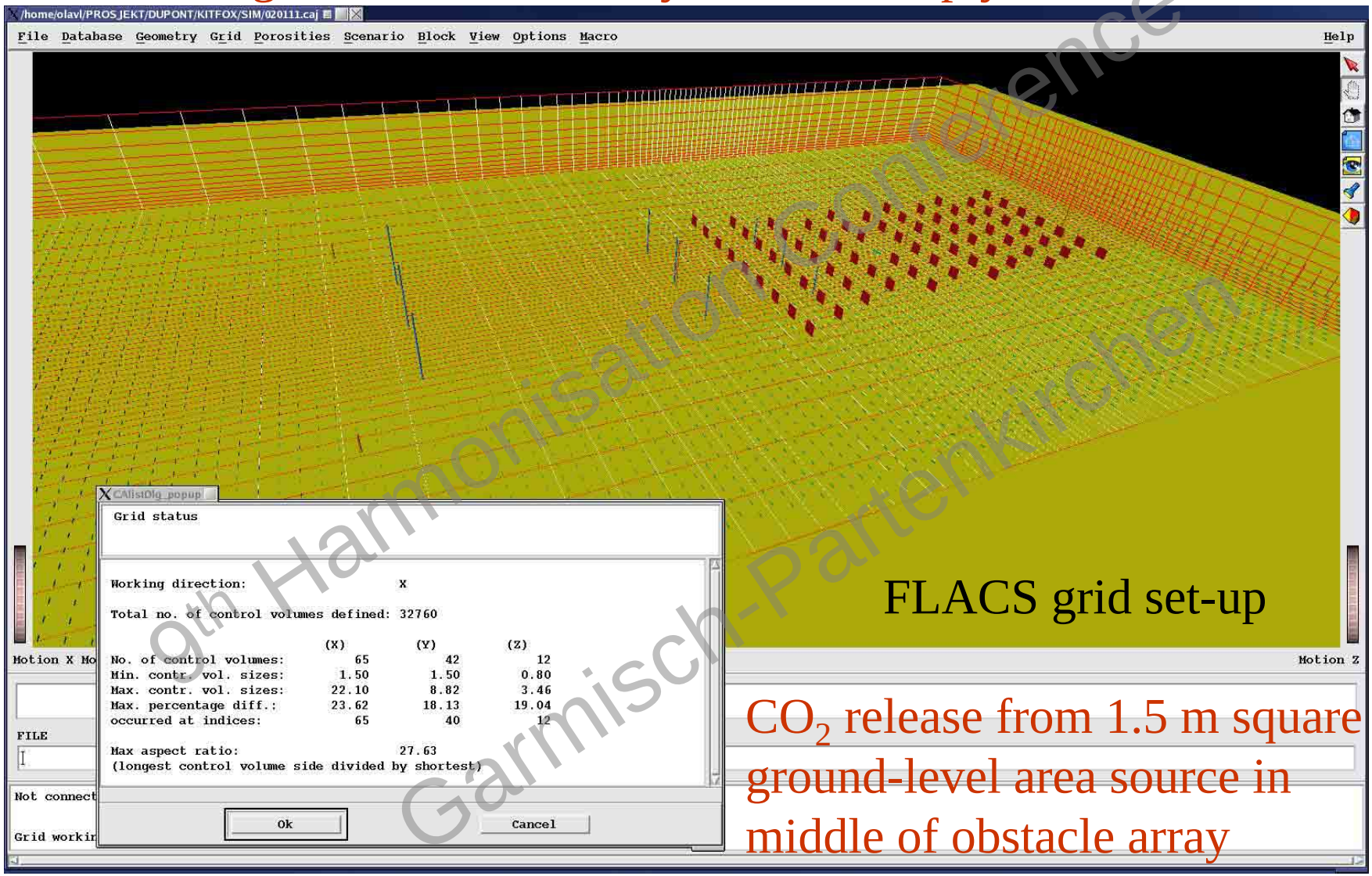
Sinusoidal meandering fluctuations are input



Time to Complete FLACS CFD Model Runs

- Linux PC Used
- 52 Kit Fox runs – 80 min to 3 hrs per run with total time of 2 weeks
- 37 MUST runs – 6-10 hrs per run, with total time of 3 weeks
- 43 Prairie Grass runs – 6-10 hrs per run for stable cases, up to 20 hrs for unstable cases, with total time of 3 weeks
- Key point – All runs were made by the lead modeler (Olav Hansen) at Gexcon, who is very experienced and can quickly set up initial grids, etc.

Kit Fox Experiment at Nevada Test Site Fall 1995
Large obstacles are 4’ by 4’ sheets of plywood



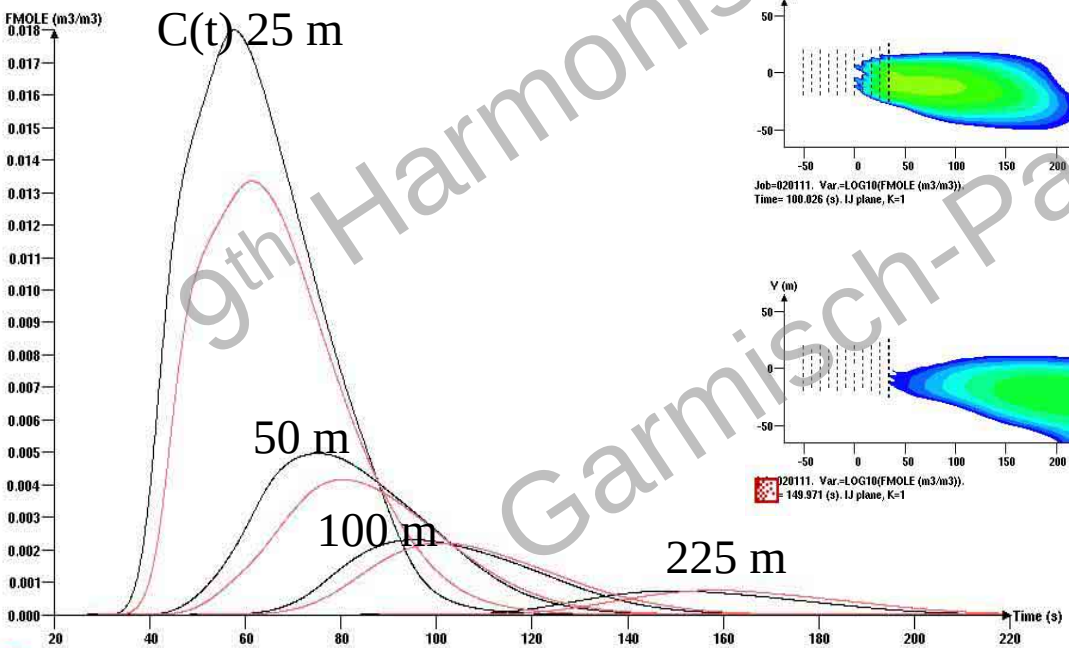
CO_2 release from 1.5 m square ground-level area source in middle of obstacle array

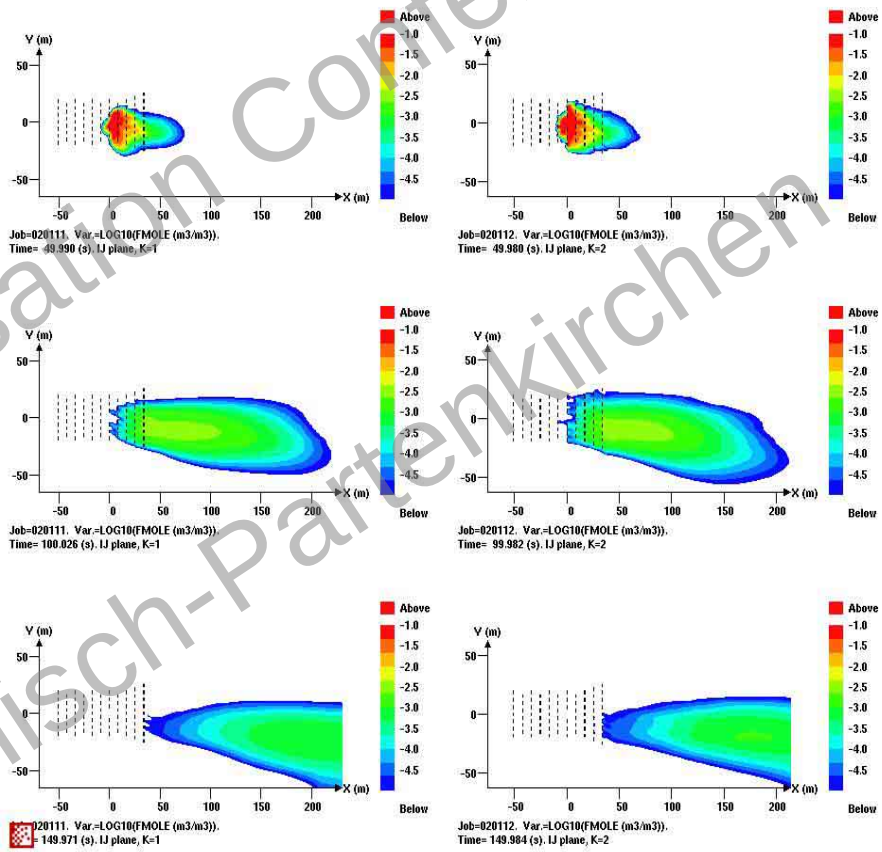
FLACS OUTPUTS FOR KITFOX EXPERIMENTS

Example of FLACS results, URA+ERP puff release

Simulations with two different grid sizes are compared, 1.5m and 0.75m horizontally

Below: Blue curve is for higher resolution





Performance measures for FLACS at Kit Fox. 52 trials with 4 arcs. ERP = large obstacles. URA = small obstacles. For puff releases and for plume releases

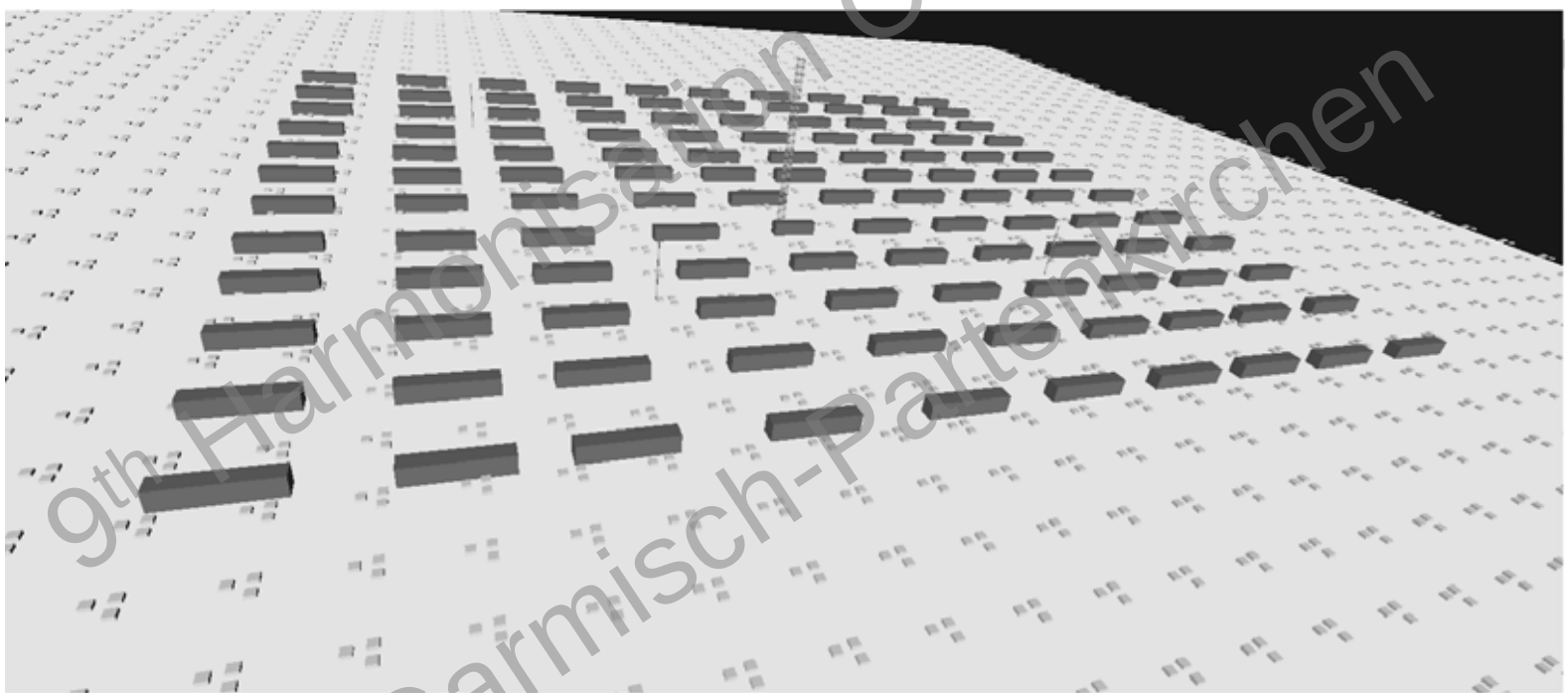
Data Subset	ERP Plumes	ERP Puffs	URA Plumes	URA Puffs	Overall
N	6	13	12	21	52
Mean wind speed	1.7 m/s	2.1	2.9	3.0	2.5
Max C_o/Max C_p	0.64	0.88	1.81	1.51	1.22
FB	0.03	0.07	0.37	0.09	0.08
NMSE	0.30	0.15	0.22	0.12	0.18
MG	1.05	1.19	1.41	1.06	1.12
VG	1.17	1.36	1.22	1.14	1.20
FAC2	1.00	0.90	0.96	0.92	0.94

Summary of Kit Fox Evaluations of FLACS

- 52 trials, four arcs at downwind distances of x = 25, 50, 100, and 225 m
- Basis for evaluation - Maximum short term C on each arc for each trial
- Mean bias < 30 % with no trend with x
- 94 % of predictions are within a factor of two of observations, with no trend with x.

MUST Array at Dugway Proving Ground

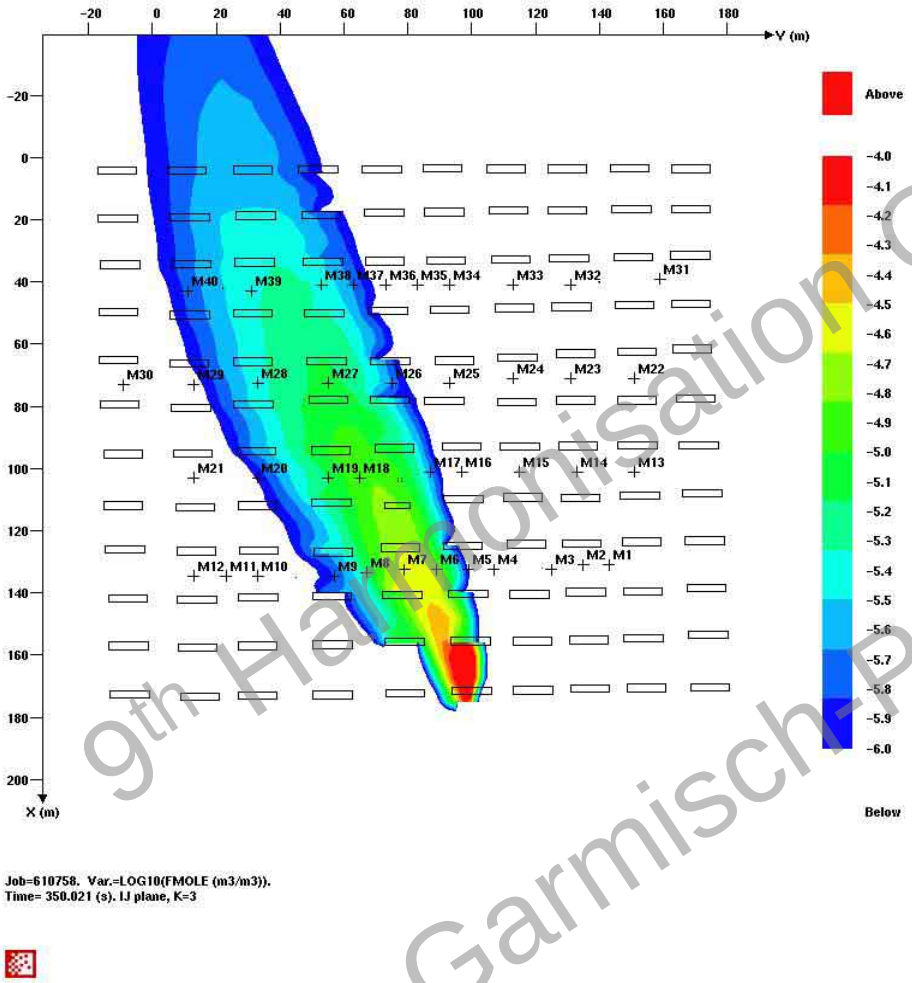
120 MUST obstacles (2.54 m high). Tracer gas was released from various locations at the near edge of the array. Four sampling “arcs” were located at about x = 25, 60, 95, and 120 m. This is the set-up for the FLACS runs.



Photos from Macdonald's University of Waterloo water flume for the MUST array for a wind angle of 30 degrees and a source behind row 3 gap

Observed: **Exp: Mon 7 = 23.9 ppm, Mon 18 = 12.6 ppm, Mon 27 = 6.0 ppm, Mon 38=3.1 ppm**

FLACS predicted: **Sim(max): Mon 7 = 25 ppm, Mon 18=15 ppm, Mon 27 = 8 ppm, Mon 39 = 5 ppm**



FLACS MUST Simulation Run 610758

FLACS performance measures for 37 MUST trials, where max observed and predicted concentrations on an arc are compared.

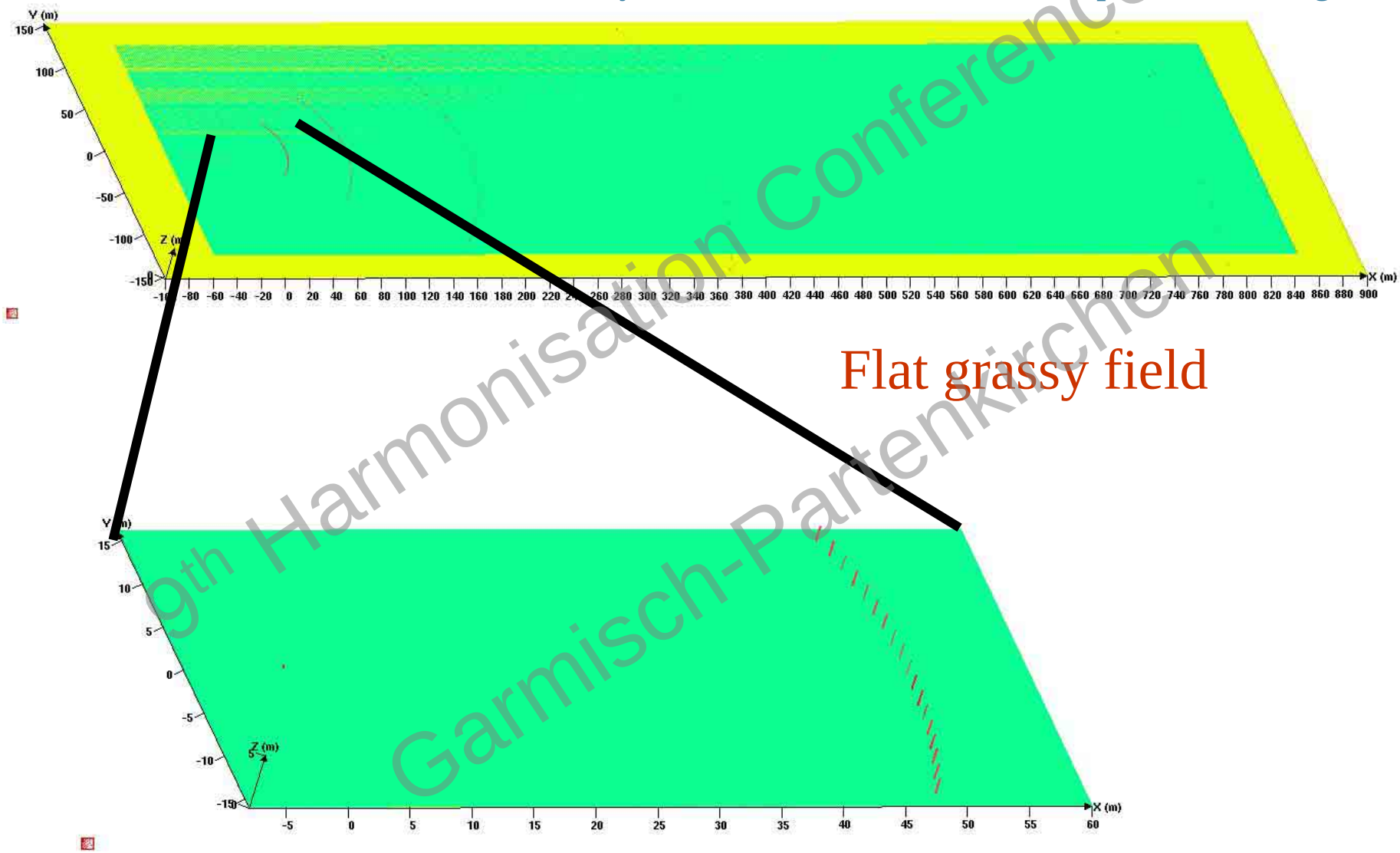
	Median over 4 arcs	Arc 1 25 m	Arc 2 60 m	Arc 3 95 m	Arc 4 120 m
Max C_o		99.5	35.7	17.2	10.1
Max C_p		47.2	13.9	7.73	10.0
Mean C_o		25.5	8.9	5.5	4.2
Mean C_p		14.6	5.3	3.0	3.7
FB	0.53	0.55	0.51	0.60	0.45
NMSE	1.64	2.03	1.85	1.44	1.24
MG	1.57	1.44	1.43	1.72	1.70
VG	1.69	1.71	1.44	1.67	2.65
FAC2	0.64	0.68	0.60	0.78	0.59

Overview of MUST Evaluations with FLACS

- 37 trials, four arcs
- Max C on each arc
- Relative mean bias of 30 or 40 % underprediction, with little trend with x
- 64 % of predictions are within a factor of 2 of observations

Prairie Grass

Geometry: Grass = Porous green object
10cm high, 1% volume blockage, 10% area blockage
Axisymmetric arcs, i.e. all simulations performed along axis

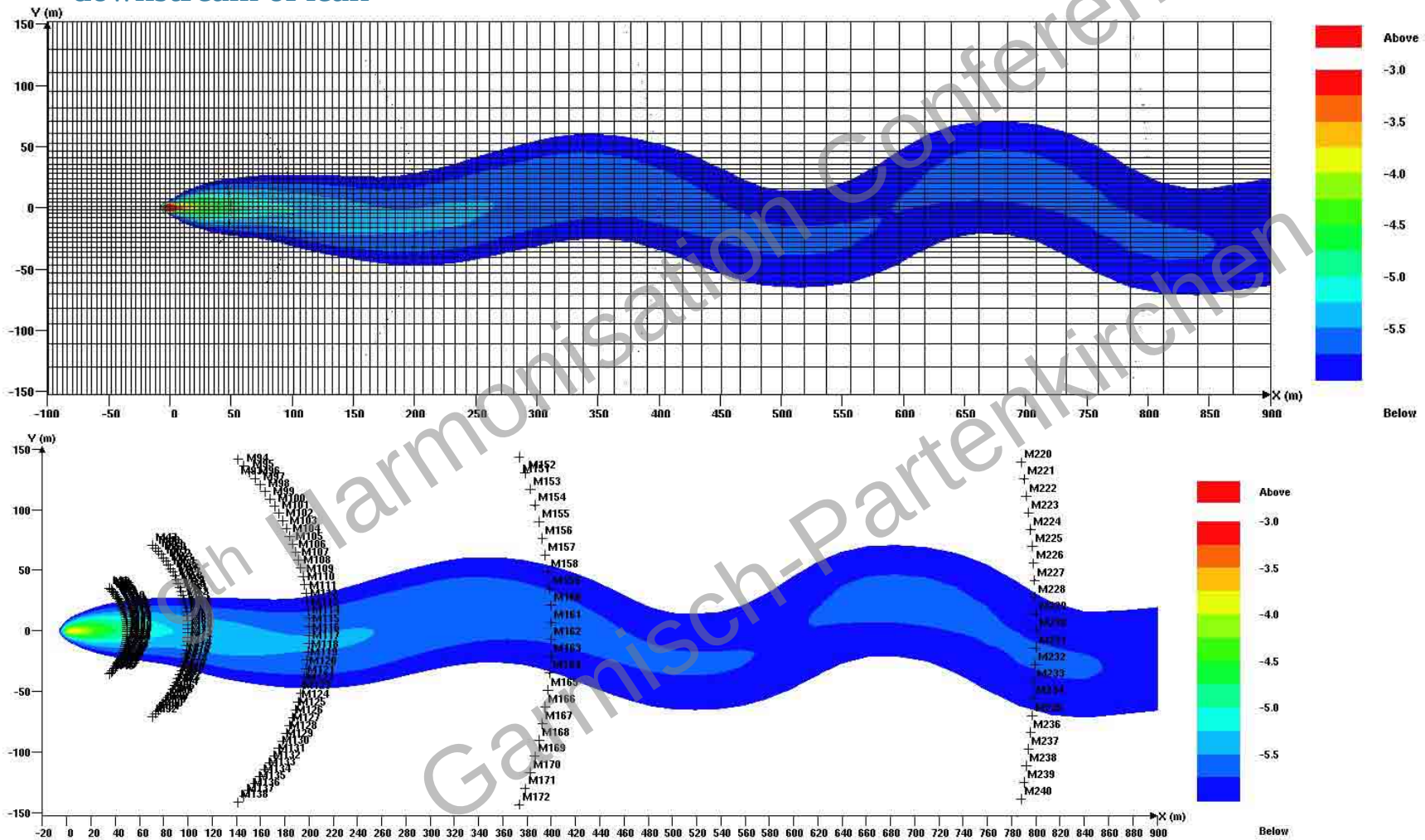


Flat grassy field

Prairie Grass FLACS Prediction, Showing Meandering

FLACS Grid applied is coarse with strong stretching

Monitor points located at arcs 50m, 100m, 200m, 400m and 800m downstream of leak



Performance measures for Prairie Grass field experiment, where maximum observed and predicted concentrations on five arcs (50, 100, 200, 400, and 800 m) are compared for 43 trials.

	Median over five arcs	Arc 1 (50 m)	Arc 2 (100 m)	Arc 3 (200 m)	Arc 4 (400 m)	Arc 5 (800m)
Max C_o		339	195	111	49.9	37.0
Max C_p		259	174	93.7	65.7	30.2
Max C_o/Max C_p	1.18	1.31	1.12	1.18	0.76	1.22
Mean C_o		122.1	47.8	20.4	8.10	3.69
Mean C_p		65.7	28.7	17.1	8.19	4.11
FB	0.18	0.60	0.44	0.18	-0.01	-0.11
NMSE	0.43	0.543	0.426	0.236	0.437	0.348
MG	1.53	2.63	2.20	1.53	0.84	0.35
VG	2.75	4.31	2.75	1.61	1.94	16.9
FAC2	0.49	0.49	0.48	0.62	0.67	0.47

Summary of Prairie Grass Evaluations with FLACS

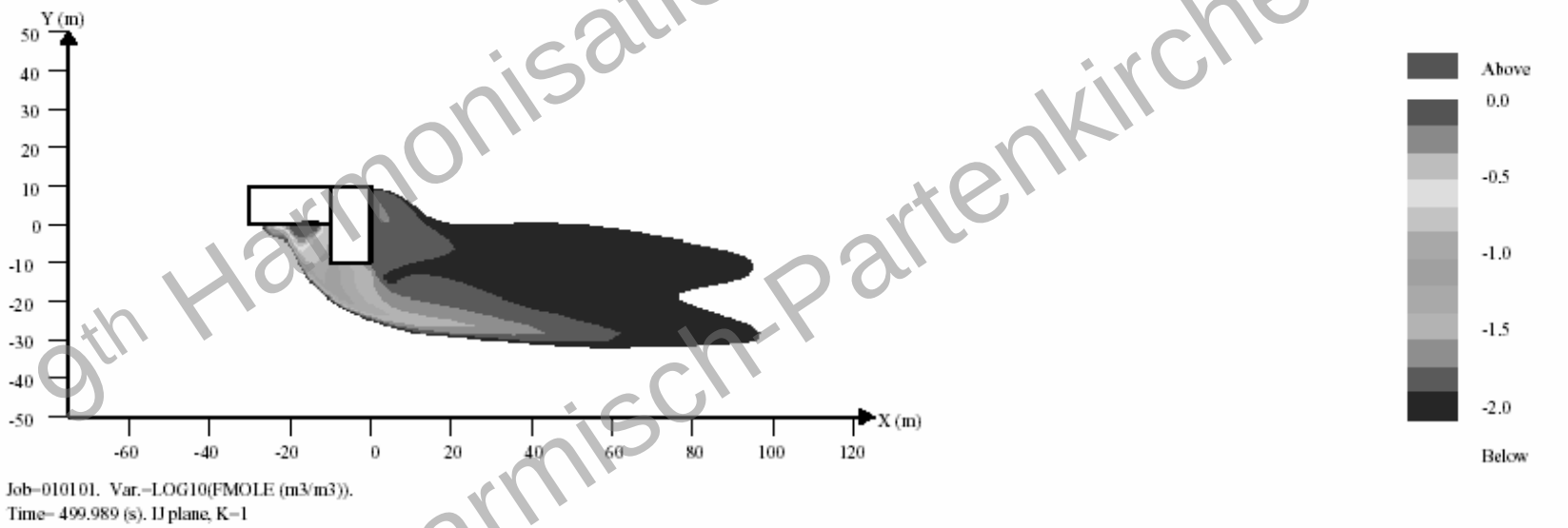
- 43 trials, arcs at five distances
- C (20 min avg) max on each arc
- Half are within a factor of 2
- Minimal trend with x except at last (800 m) arc in unstable conditions, when model overpredicts. This was also found for other models and has led to the new convective scaling models

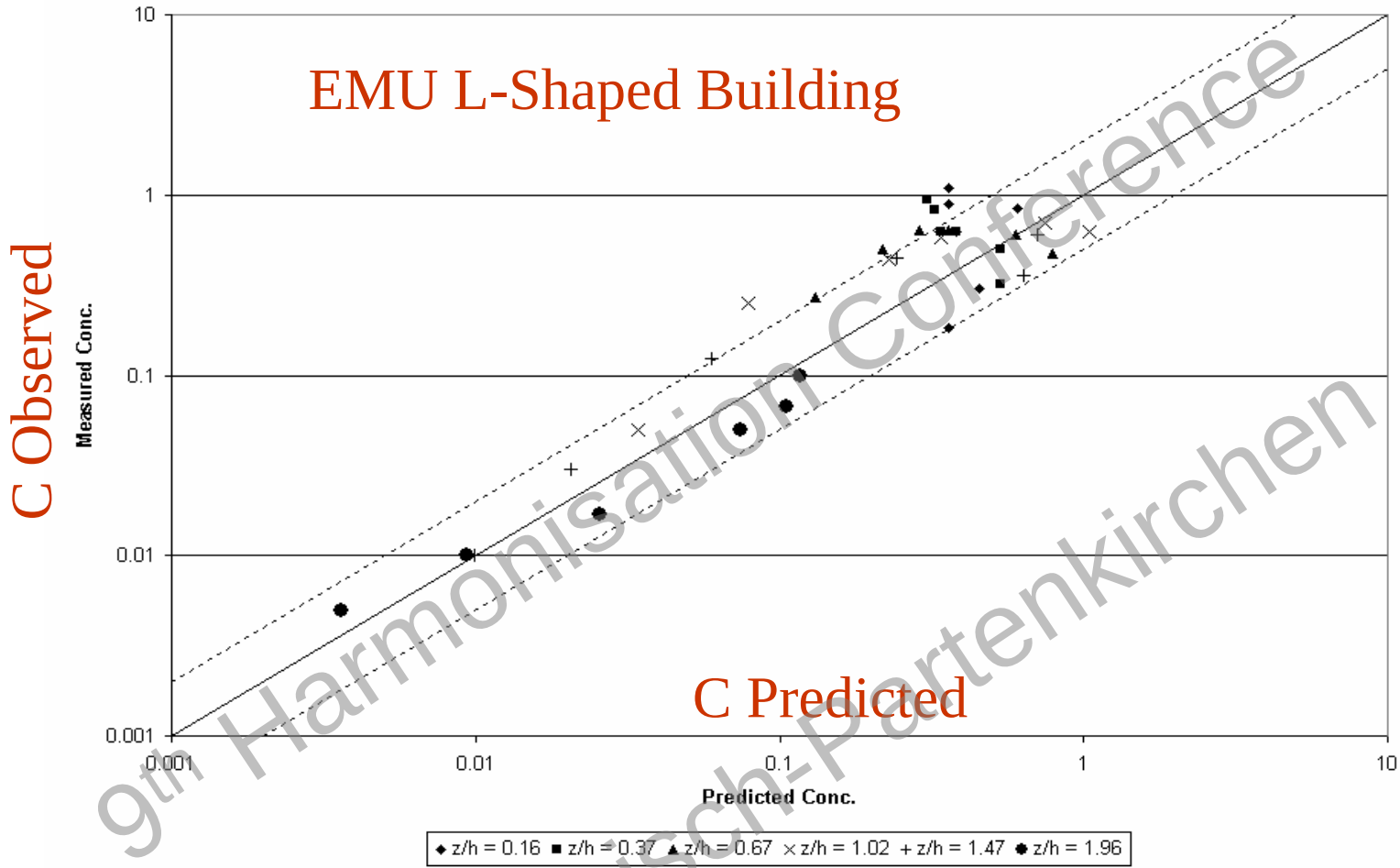
Evaluation of Model Uncertainty (EMU) L-Shaped Building

- Comprehensive EU Study
- Several Wind Tunnel Data Bases for Single and Multiple Buildings
- Evaluations of Many Dispersion Models and CFD Models
- We Picked Simplest Case – L-Shaped Building with Neutral Conditions and Emission from Door in Courtyard

EMU L-shaped building, showing predicted FLACS concentrations. Building height, H, equals 10 m.

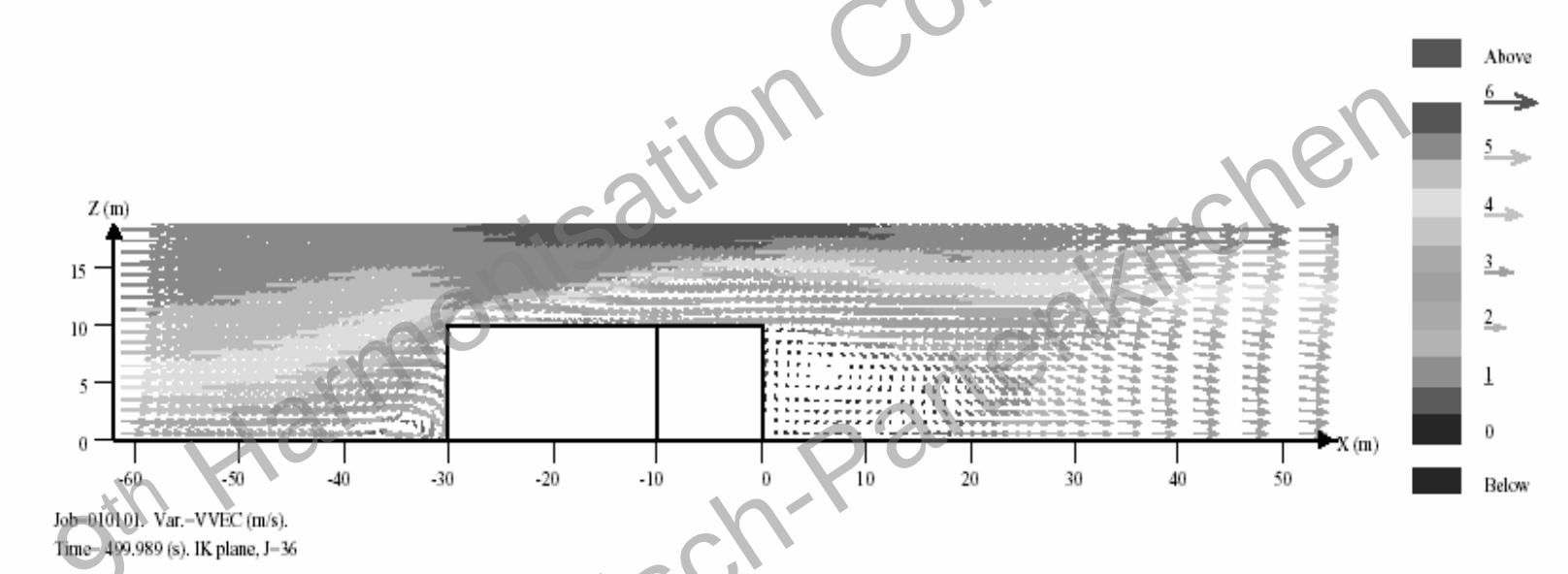
The tracer gas release was from a door shown as a thick line at y = 0.0 m and between about x = - 18 m and x = -14 m.





Observed versus FLACS predicted concentrations at x/H = 1.0
for z/H = 0.16, 0.37, 0.67, 1.02, 1.47, and 1.96
and for y/H = -2. –1.5, -1.0, -0.5, 0.0, and 0.5.

Cross-section in x and z of wind vectors predicted by FLACS for EMU L-shaped building.



Predicted sizes of wake cavity, roof cavity, and upwind cavity are similar to observed dimensions for this and for general building obstacles

Median performance measures and their range over Kit Fox, MUST, and Prairie Grass field experiments for FLACS CFD model.

	Median	Range
Max C_o/Max C_p	1.22	0.56 to 2.56
FB	0.18	-0.32 to 0.60
NMSE	0.29	0.07 to 2.03
MG	1.32	0.35 to 2.63
VG	1.28	1.07 to 17.9
FAC2	0.86	0.47 to 1.00

Conclusions from Quantitative Performance Evaluation

- 86 % within a factor of two for arc max
- Mean 20 % underprediction for arc max
- Median 50 % relative scatter for arc max
- Mean 20 % underprediction of overall experiment max
- Well within the criteria of acceptance for dispersion models.
- EMU L-shaped building, 72 % of predictions are within a factor of two of observations, and the dimensions of the recirculating cavity behind the building are within a factor of two.

Overall Conclusions

- Never before has a CFD model been evaluated with anywhere close to this number of observations.
- Evaluations with Kit Fox, Prairie Grass, MUST, and EMU data show satisfactory relative mean bias and scatter and minimal trend with distance.
- The FLACS CFD model runs quickly because it has a relatively large grid size, but can still simulate obstacle arrays well
- These results can form a basis for comparative evaluations using other CFD models. Such comparisons are already underway (with CFD-Urban and with FEFLO)