Evaluation of WRF-LES for Transport & Dispersion over Complex Terrain

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NCAR NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NC STATE UNIVERSITY

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Boulder, Colorado, USA

NCAR-ASP Graduate Visitor Program (GVP)

- Financial support for graduate students to visit NCAR for 3-6 months to work one-on-one with NCAR scientists on a project of mutual interest
- Warner Internship for Scientific Enrichment (WISE) – Award established in memory of Tom Warner which promotes scientific community service and outreach

Research Interests/Directions

Underlying Theme:

Flow Features Associated with Heterogeneous Terrain

Fundamentals

- ❖ Stably stratified boundary layer flow past obstacles
- ❖ Frequent mesoscale wind phenomena associated with flow near complex terrain
- ❖ Fundamental turbulence modeling and parameterization

Applications

- ❖ Wind Energy
  - ❖ Collaboration with WindSim
- ❖ Optical Turbulence
  - ❖ Collaboration with Univ. of Dayton
- ❖ Atmospheric Dispersion
  - ❖ Collaboration with NCAR

NCAR Project

Quasi-Idealized WRF-LES and Flow over Rugged Terrain

WRF-LES Dispersion Modeling

Objective

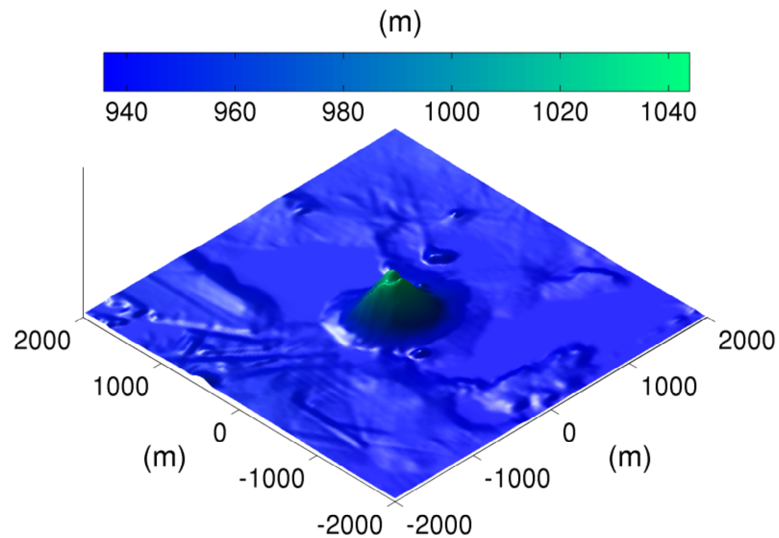
Simulate a dispersion field campaign (over complex terrain) and verify a modified version of WRF-LES which includes passive scalars (implemented by Branko Kosovic)

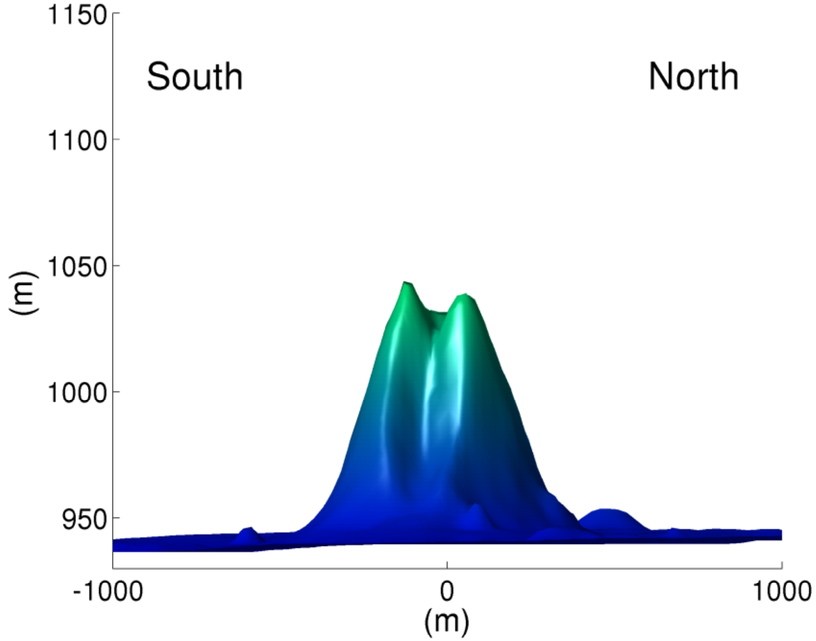
Advantages

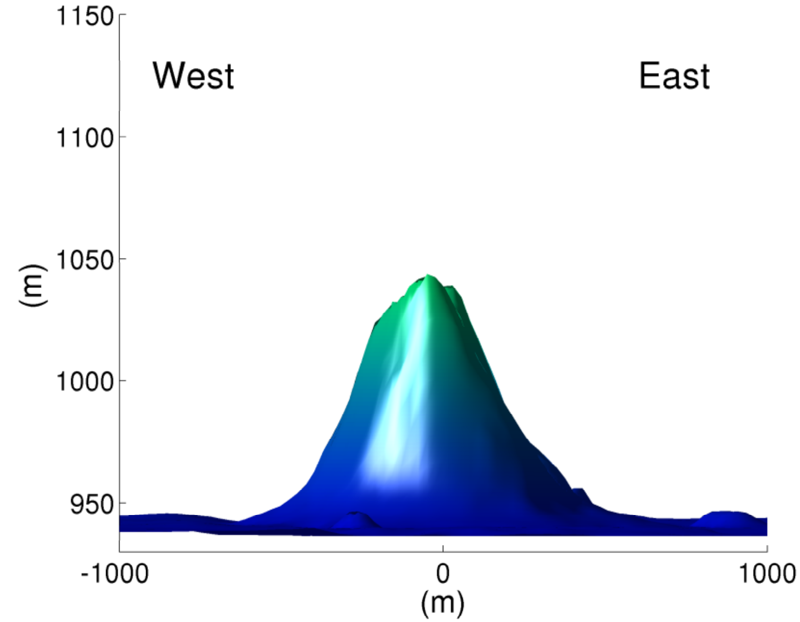
- Large-Eddy Simulation (LES) approach is theoretically superior to linear models when dealing with rugged terrain
- Open source CFD model designed for atmospheric boundary layer flow
- Mesoscale-microscale coupling technology

CCB Experiment (1980)

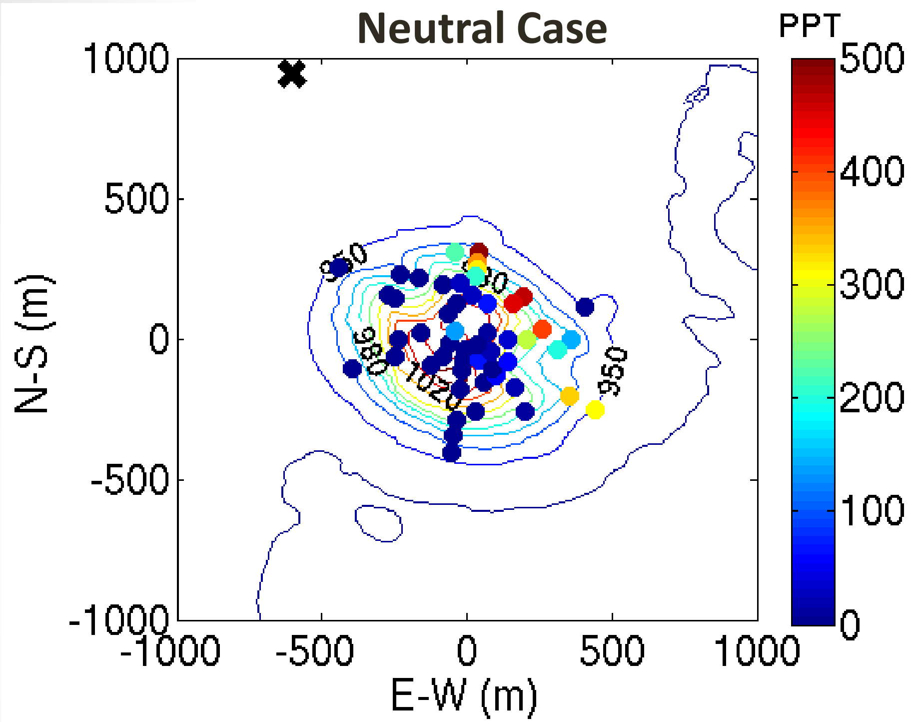
- Cinder Cone Butte, Idaho (SW ID)
- Two tracer gases were released from a mobile crane upwind of the Butte
  - Sulfur Hexafluoride (SF_6)
  - Bromotrifluromethane (CF_3Br)



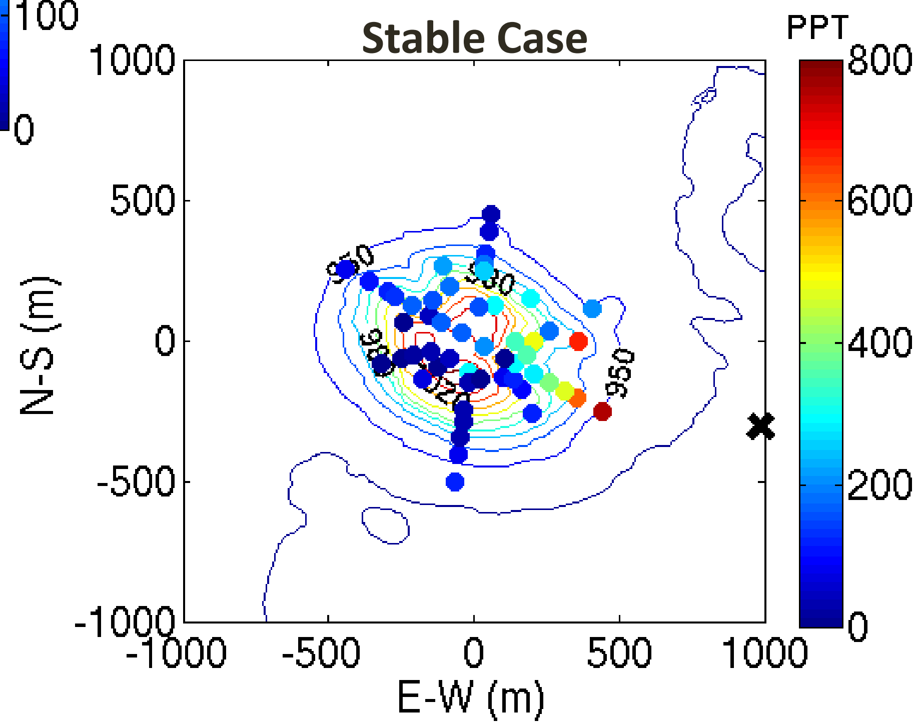




CCB Experiment

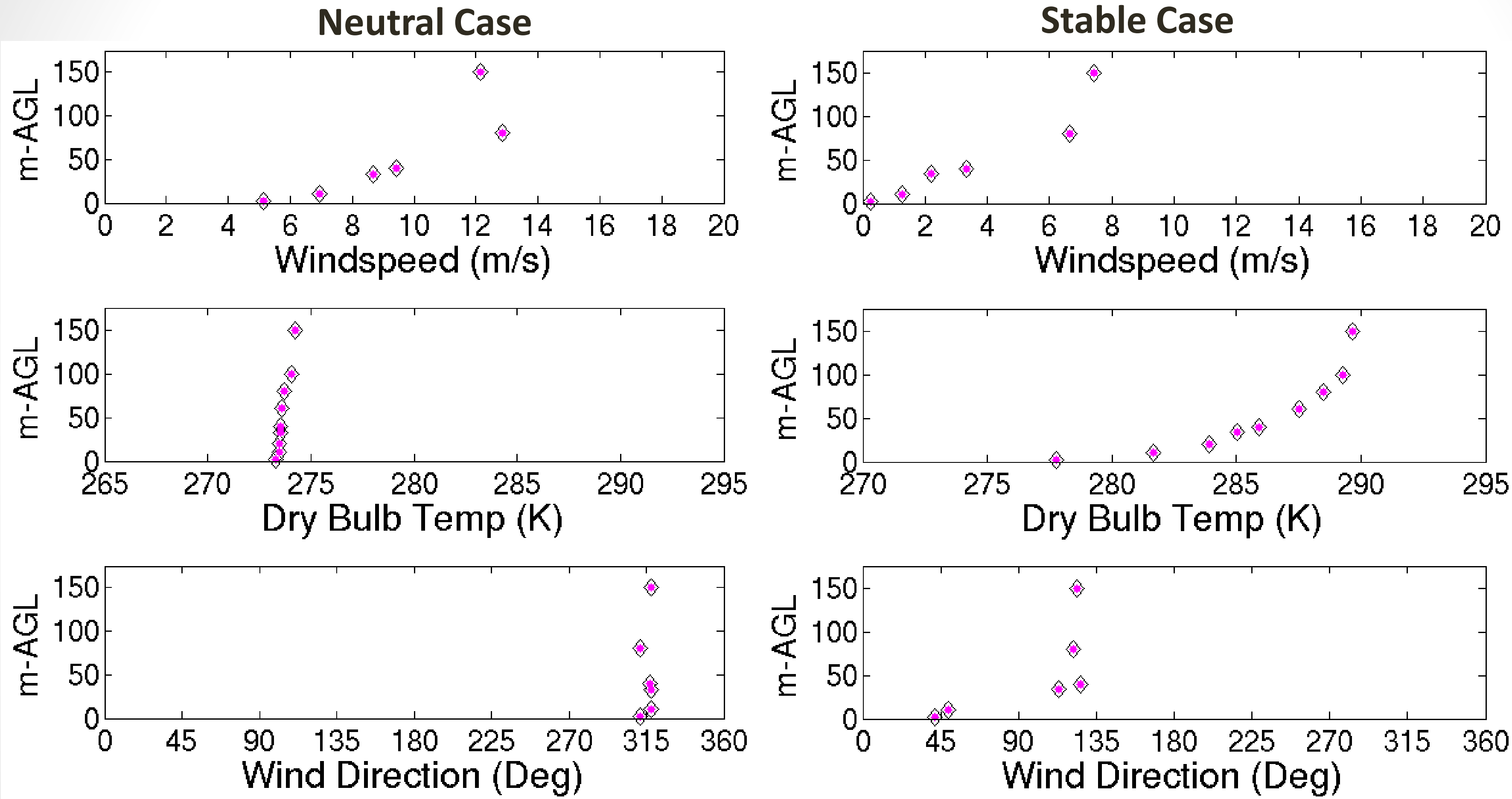


- Concentration measurements were collected from bag samplers 1m above the surface
- Concentrations were averaged over 1 hour



- Black crosses represent tracer release location
  - Height = approx. 30m agl
- Contours represent terrain height

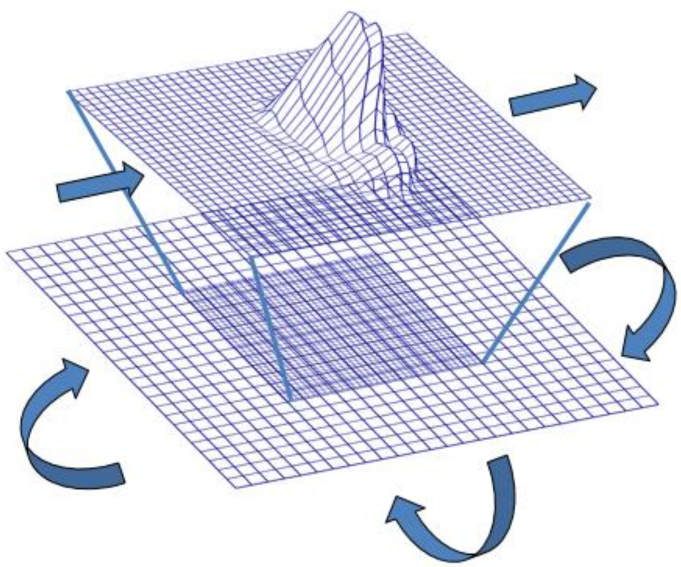
Measured Vertical Profiles



- Wind velocity and temperature were measured by an upstream teathersonde

Methodology

- Specify geostrophic wind speeds and thermal profiles
- Import terrain height, roughness, and time varying heatflux and surface temperature for stable case
- Simulate 6 hours to generate turbulence then release tracer for the 7^{th} hour and average over 7^{th} hour
- Periodic outer domain with flat terrain, 1-way nested inner domain with real terrain



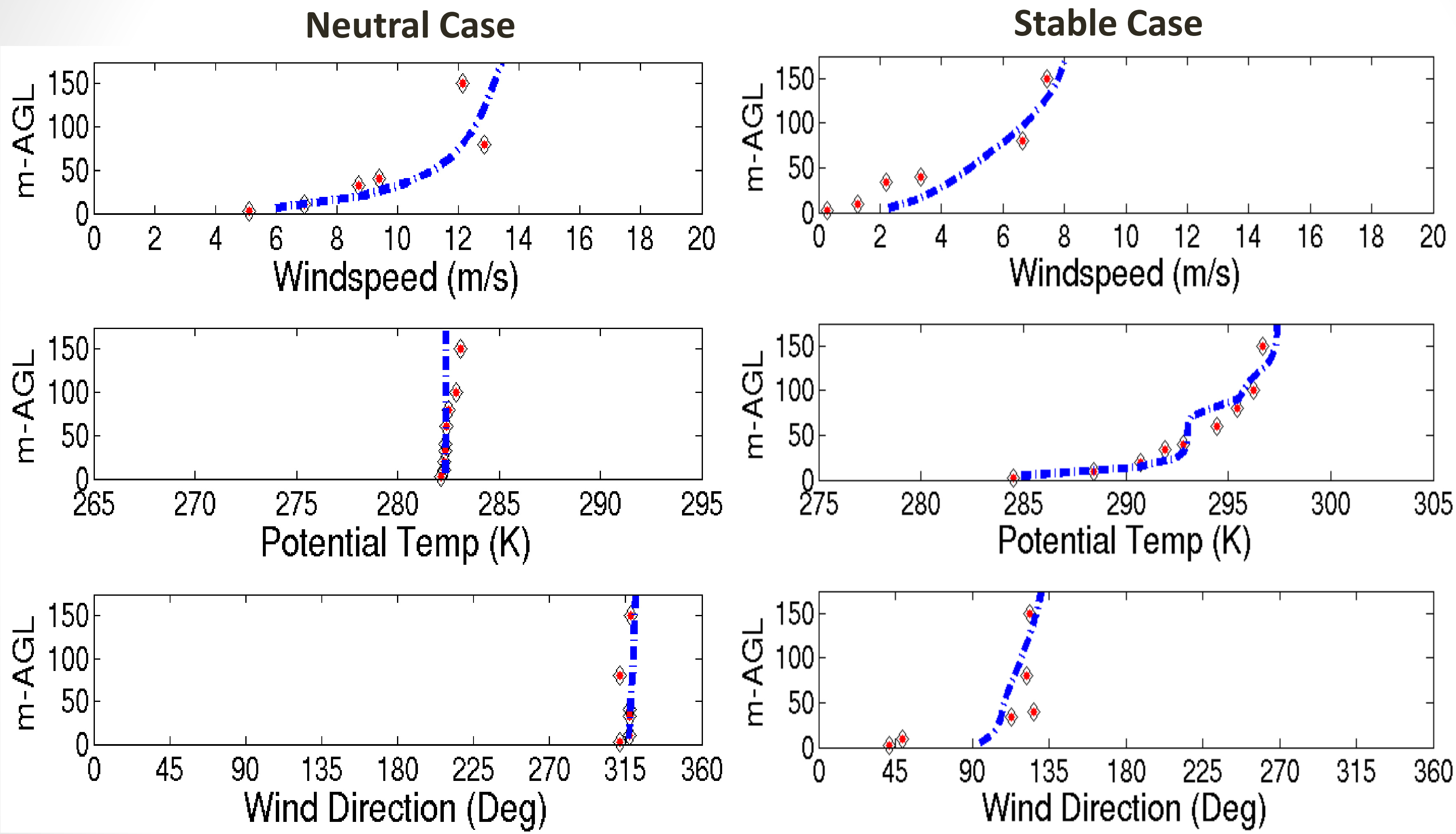
Graphic created by Branko Kosovic

Modeling Configurations

- Drag-based surface layer parameterization
- Rayleigh damping layer and relaxation of vertically propagating pressure waves (latter was critical)
- Scalar emission was a constant release rate quantified in kg/m^2
- Two sub-grid scale turbulence parameterizations were tested
  - Linear eddy-viscosity TKE based scheme (TKE-SGS)
  - Nonlinear Backscatter with Aniostrophy scheme (NBA-SGS)

Domain	Δxy	Δt	Nx	Ny	Nz	Dimensions (x,y,z)
d01	30 m	0.2500 sec.	202	202	98	6060 m × 6060 m × 2204 m
d02	10 m	0.0417 sec.	400	400	98	4000 m × 4000 m × 2204 m

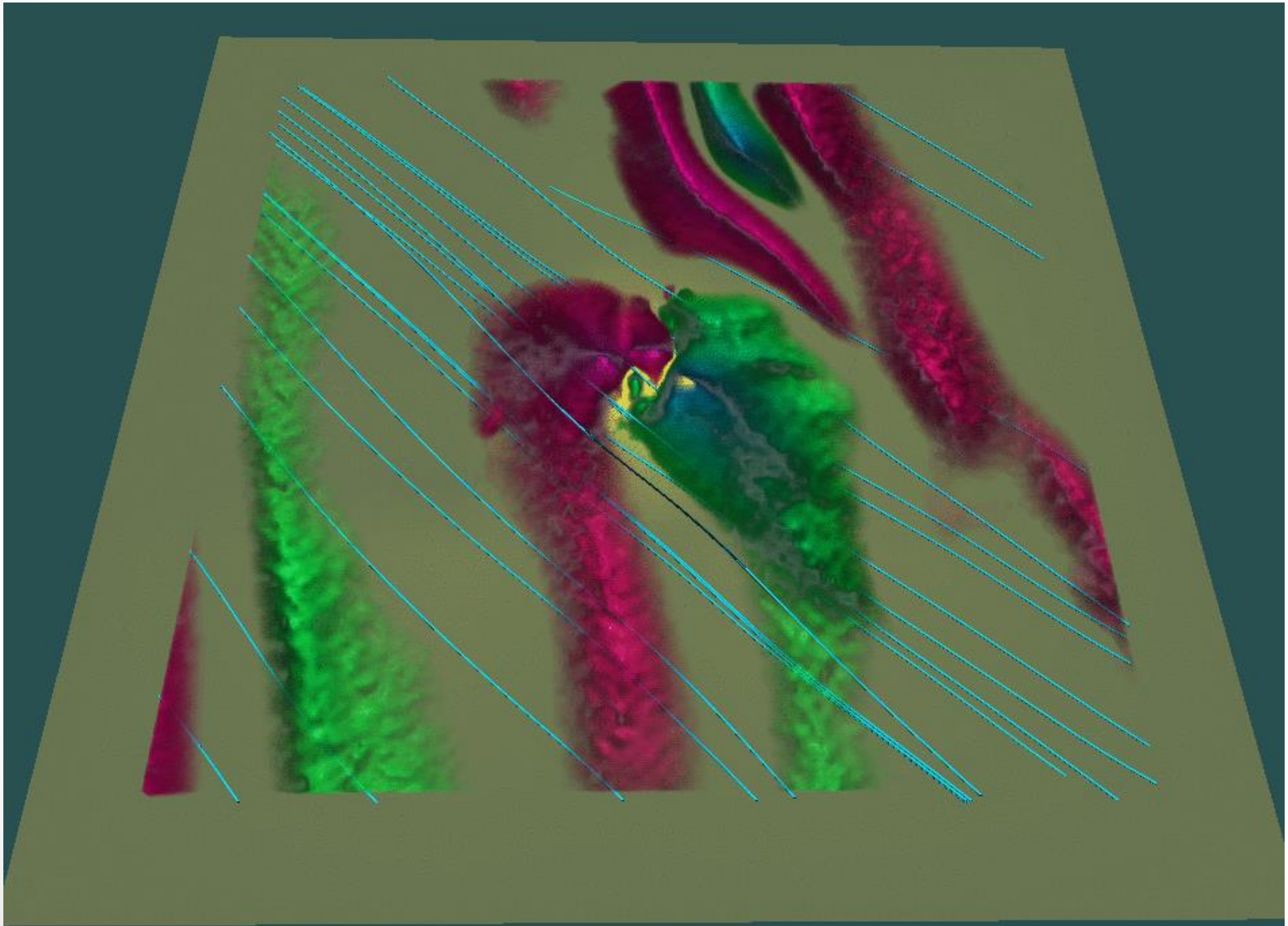
Simulated Vertical Profiles



Neutral Case Simulation

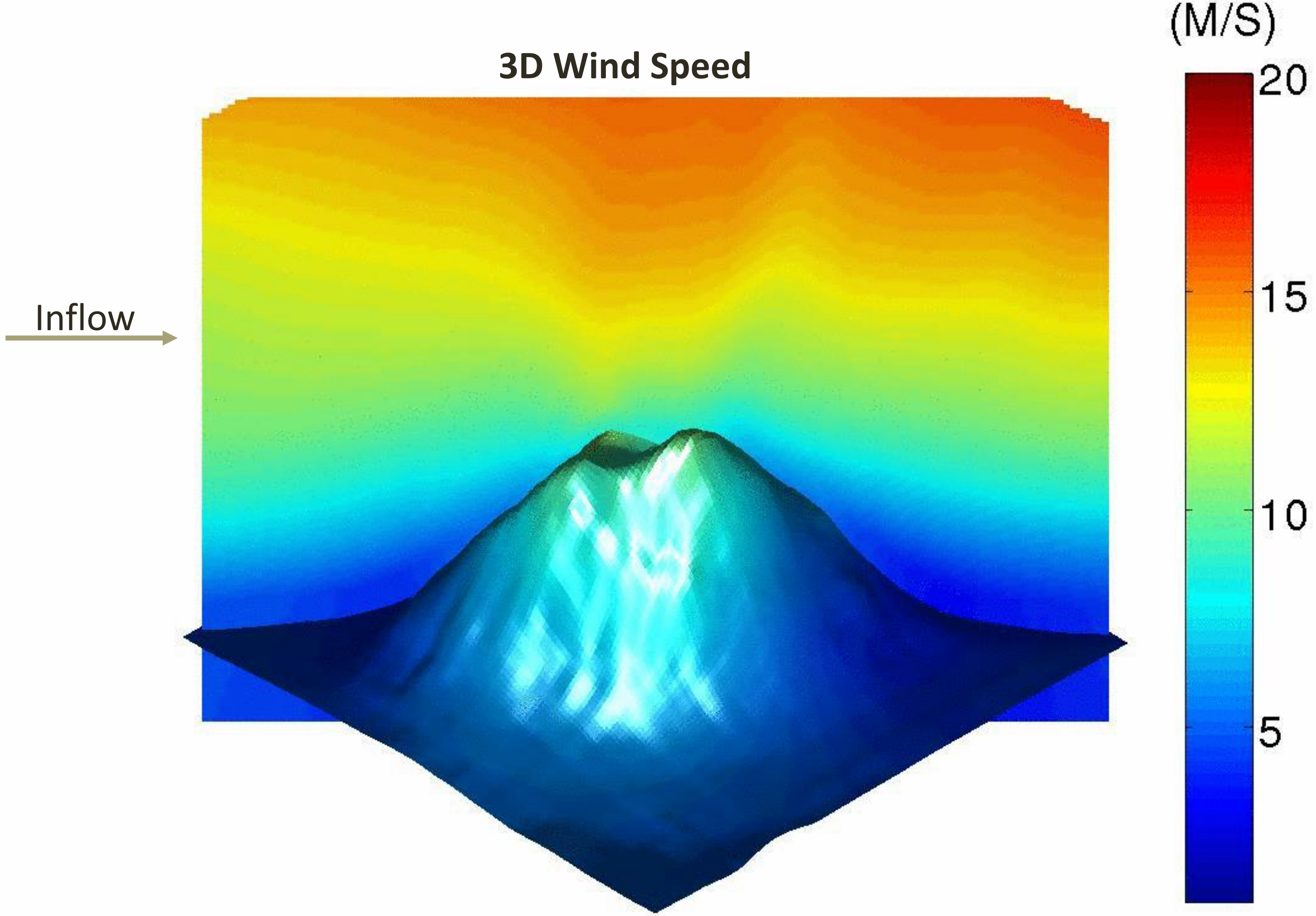
WRF-LES Neutral Case

Vertical Velocity & Streamlines



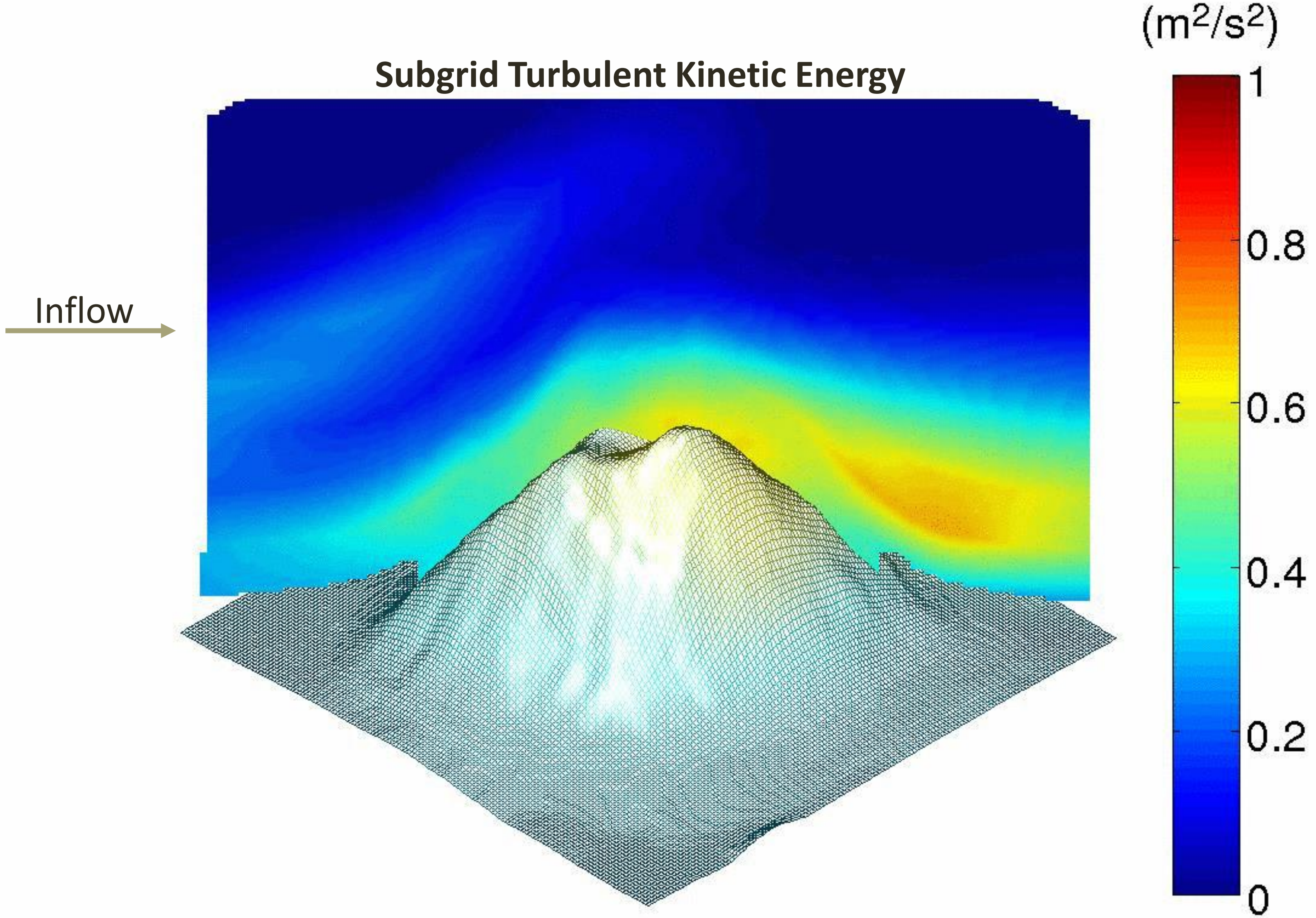
1hour loop

WRF-LES Neutral Case



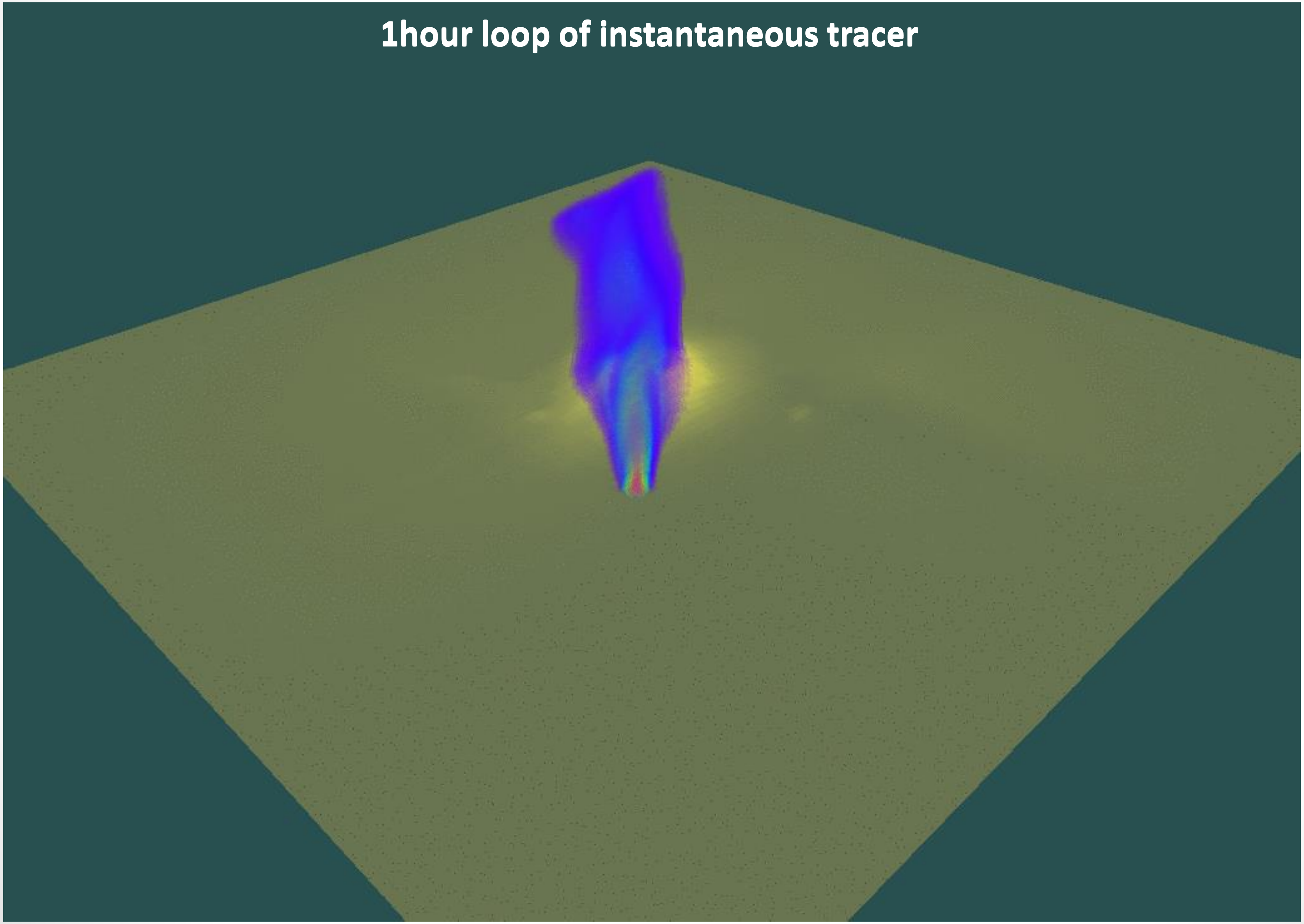
30 minute loop

WRF-LES Neutral Case

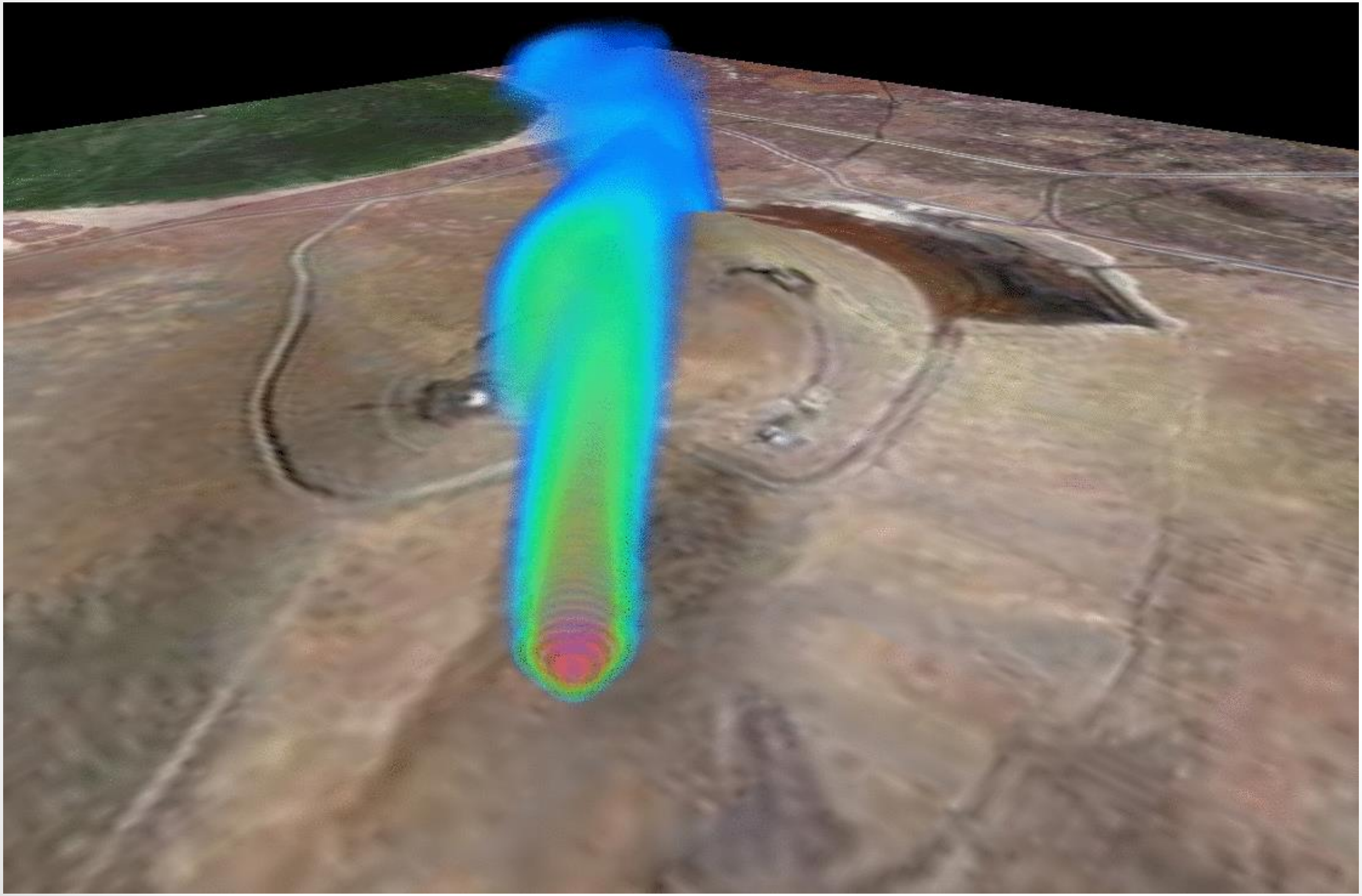


30 minute loop

WRF-LES Neutral Case

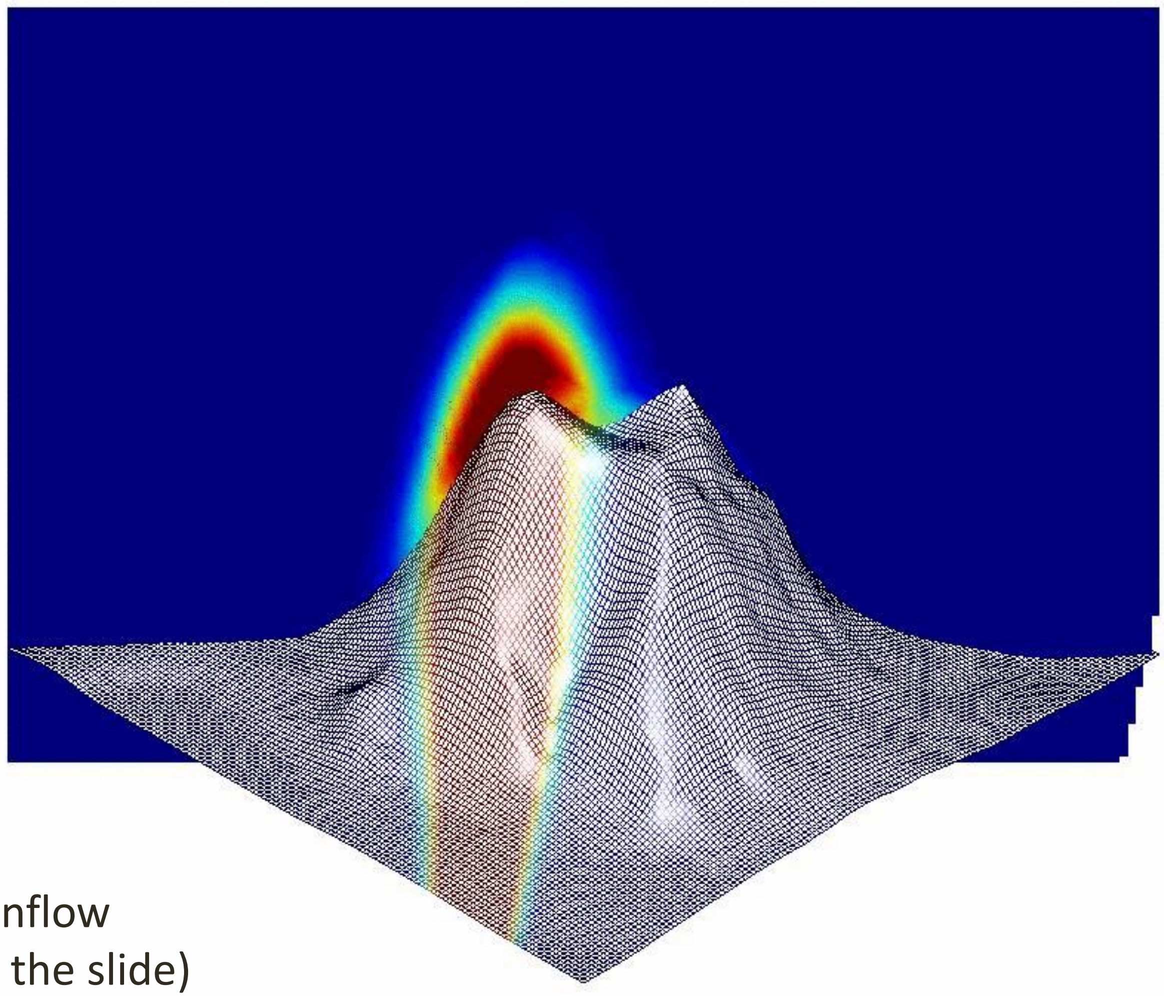


WRF-LES Neutral Case



1 hour loop

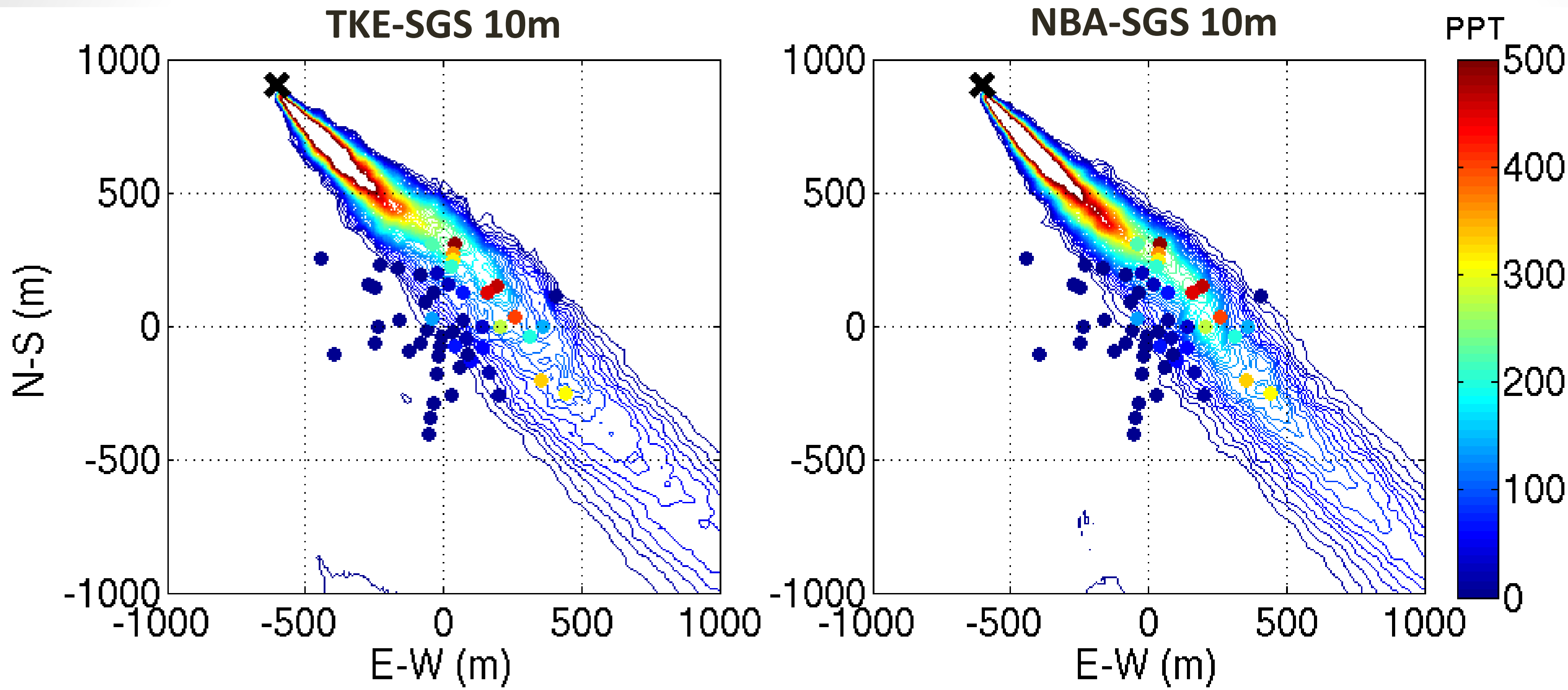
WRF-LES Neutral Case



Inflow
(into the slide)

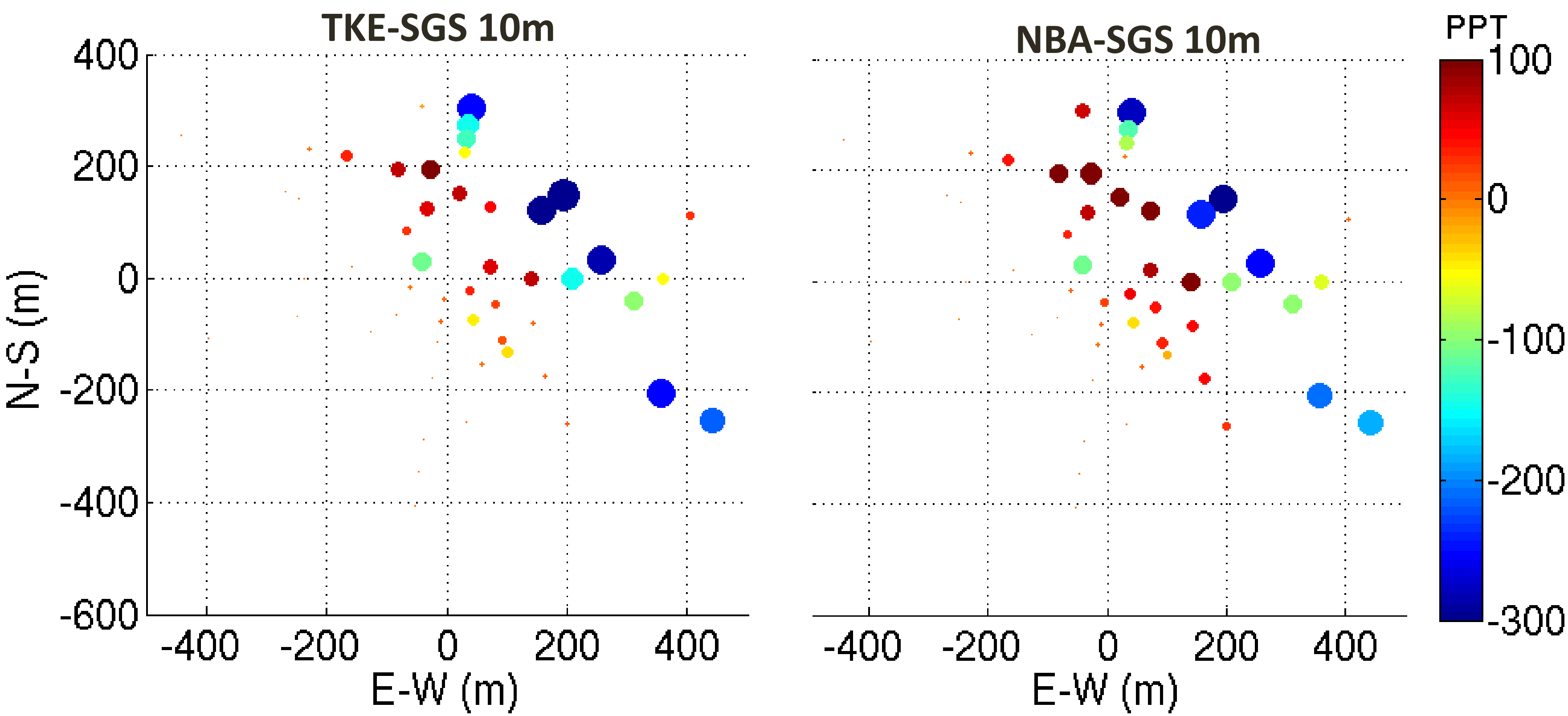
30 minute loop

(Neutral Case) Obs. vs Predicted SF_6



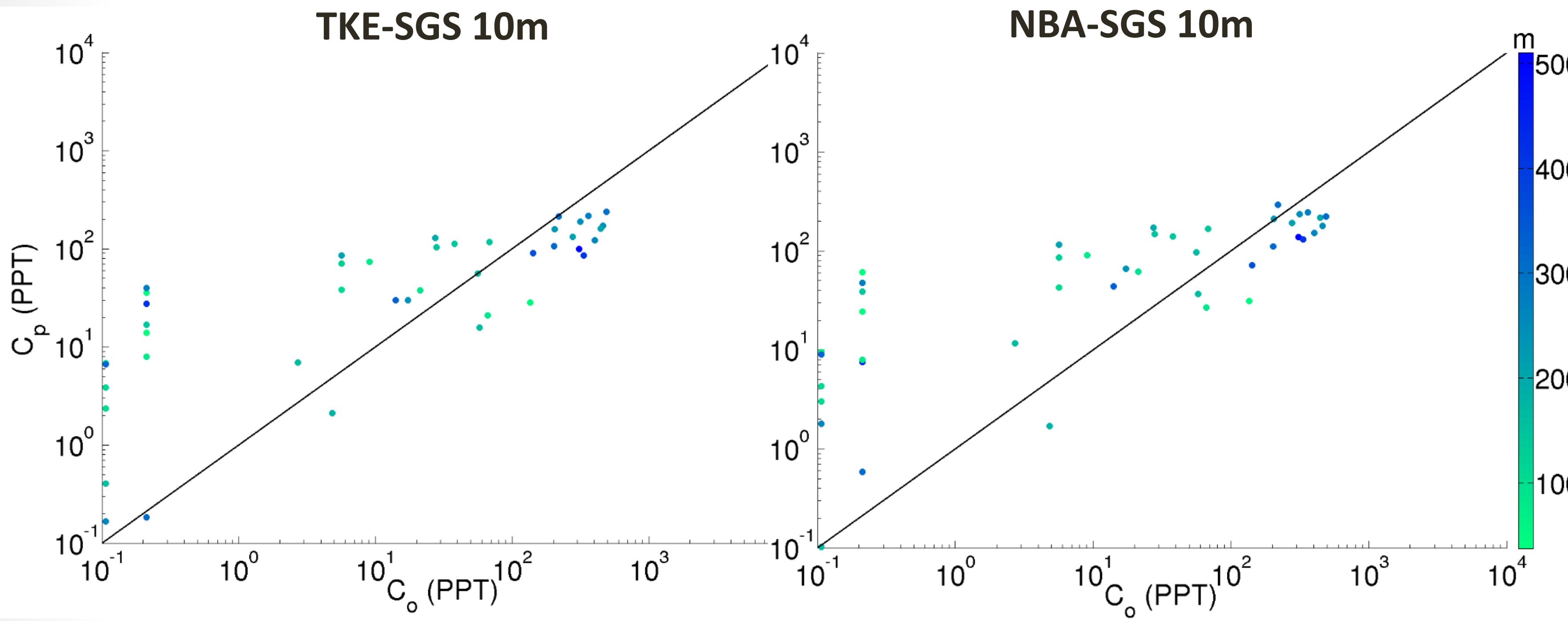
- Underestimation of the peak values
- Width of plume captured reasonably well
- TKE-SGS plume is slightly wider and more diffuse than NBA-SGS plume

Predicted minus Obs. SF_6



- Underestimation of the peak values
- Overestimation of edge values
- Underestimation in plume core was much more significant than the overestimation on the flanks

Pointwise Comparison SF_6



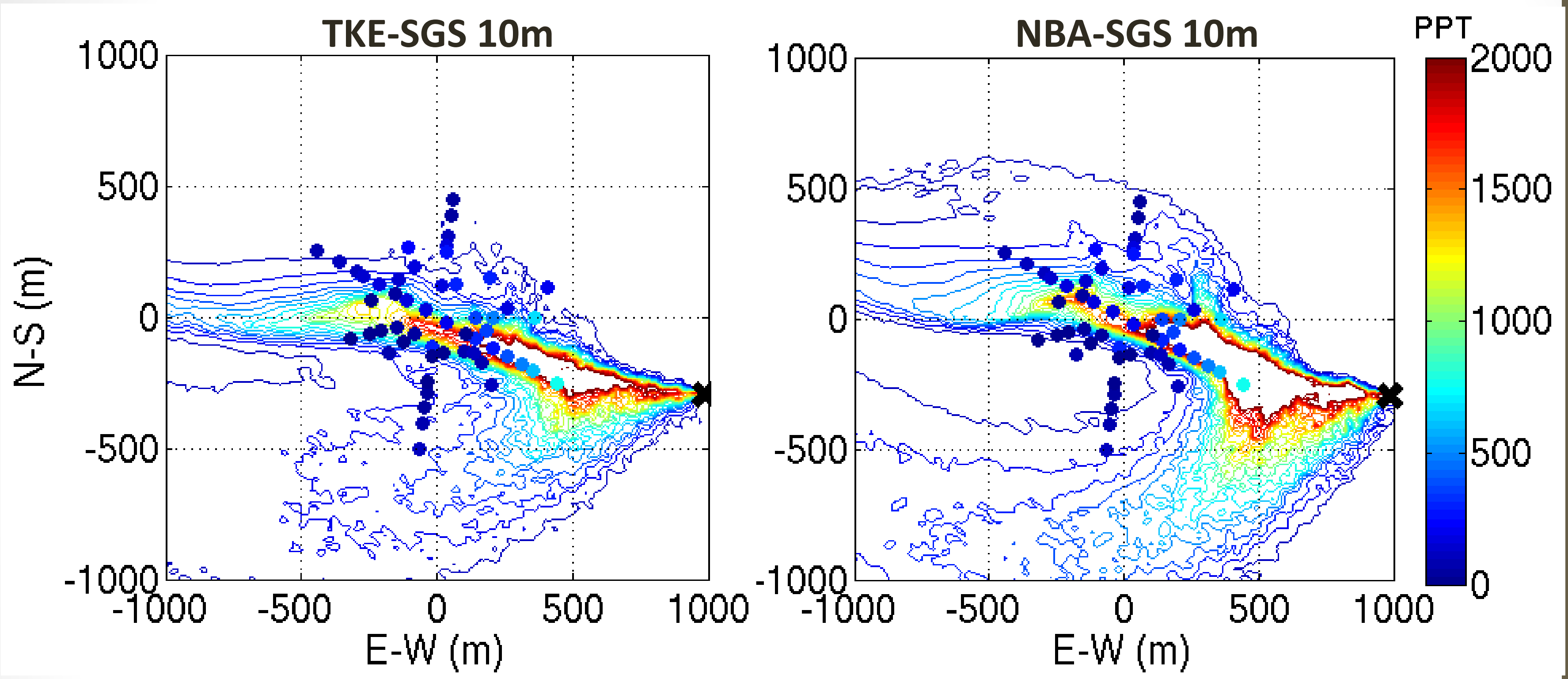
- Decent correlation between predicted and observed samples for both schemes
- Erroneous outliers present near the low and high concentrations

Neutral Case Accuracy Metrics

Metric	Formulation	TKE10	NBA10
Bias	$\overline{C_p} - \overline{C_o}$	-34.340	-19.216
Root Mean Squared Error	$\frac{\sqrt{\overline{(C_p - C_o)^2}}}{\overline{C_p}}$	1.794	1.342
Fractional Bias	$\frac{(\overline{C_p} - \overline{C_o})}{0.5(\overline{C_o} + \overline{C_p})}$	-0.464	-0.235
Normalized Mean Square Error	$\frac{\overline{(C_p - C_o)^2}}{\overline{C_o}\,\overline{C_p}}$	2.007	1.421
Linear Pearson Correlation Coefficient	$\frac{\overline{(C_o - \overline{C_o})(C_p - \overline{C_p})}}{\sigma_{C_p}\sigma_{C_o}}$	0.806	0.765
Logarithm-Based Correlation Coefficient	$\frac{\overline{(lnC_o - \overline{lnC_o})(lnC_p - \overline{lnC_p})}}{\sigma_{lnC_p}\sigma_{lnC_o}}$	0.909	0.906
Fraction of data within a factor of 2	$\frac{1}{2} \leq \frac{C_p}{C_o} \leq 2$	0.654	0.635
Fraction of data within a factor of 5	$\frac{1}{5} \leq \frac{C_p}{C_o} \leq 5$	0.923	0.885
Fraction of data within a factor of 10	$\frac{1}{10} \leq \frac{C_p}{C_o} \leq 10$	0.962	0.942

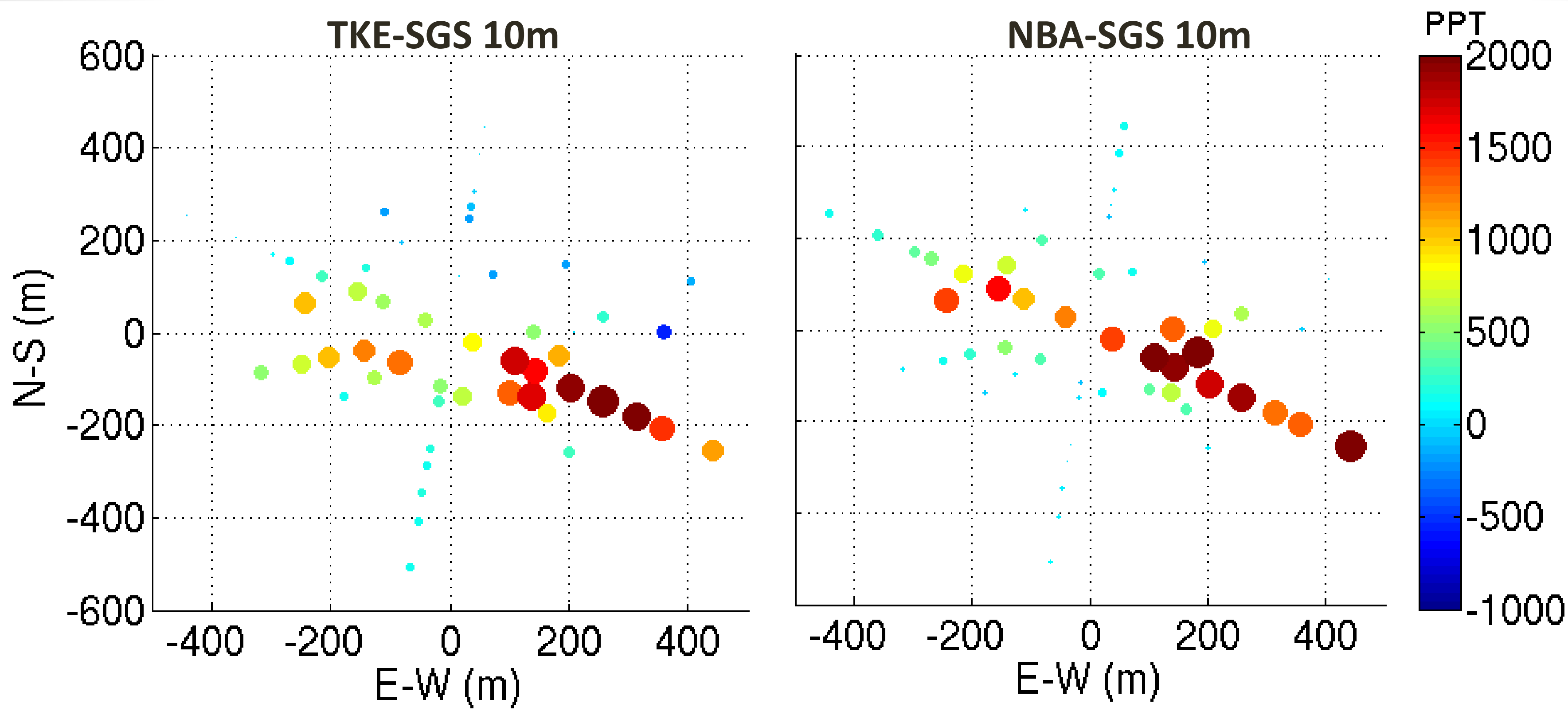
Stable Case Simulation

(Stable Case) Obs. vs Predicted SF_6



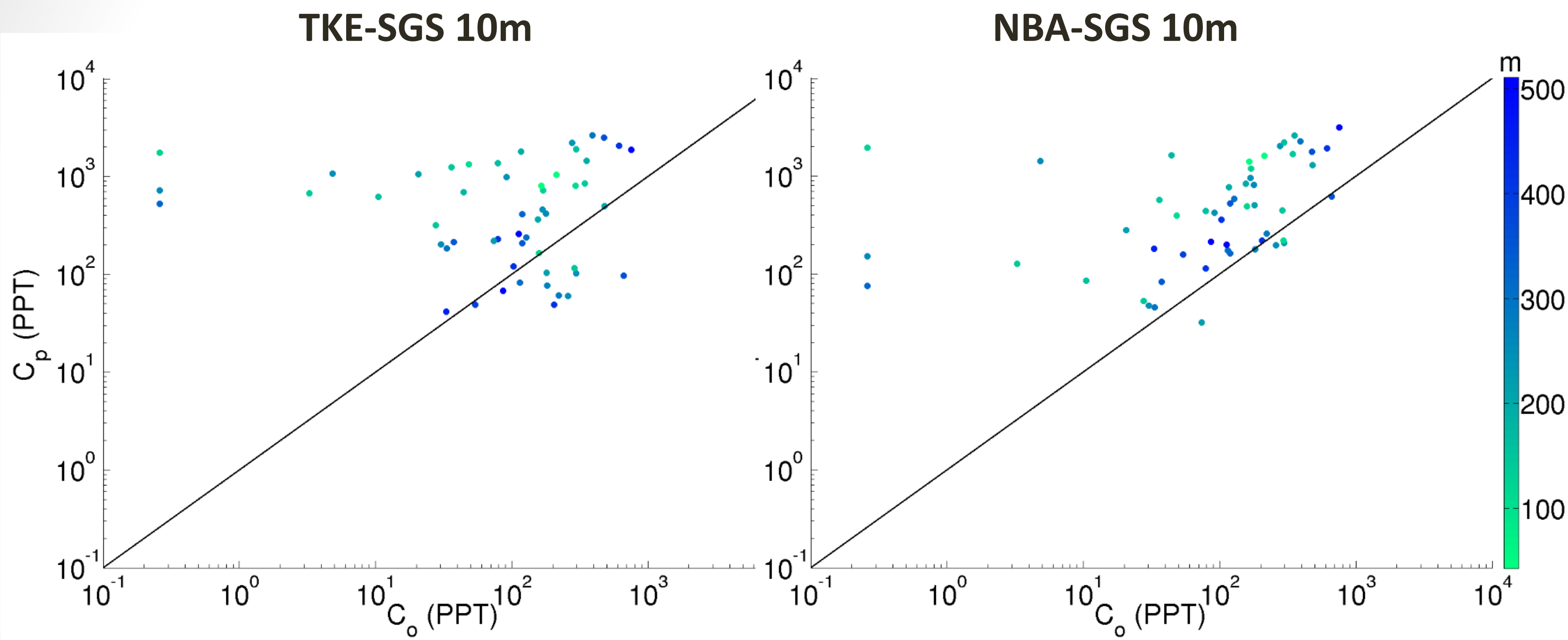
- Overestimation of the peak values
- Splitting flow below dividing streamline captured
- Higher mean concentrations in lowest grid level in NBA-SGS simulation vs TKE-SGS

Predicted minus Obs. SF_6



- Generally, overestimation everywhere except for a few points
- Distribution was captured much more accurately with NBA but it also had a larger positive magnitude bias
- More predicted vertical transport of scalar than what was measured

Pointwise Comparison SF_6



- Higher bias but better correlation in NBA simulation

Stable Case Accuracy Metrics

Metric	Formulation	TKE10	NBA10
Bias	$\overline{C_p} - \overline{C_o}$	453.611	514.870
Root Mean Squared Error	$\frac{\sqrt{\overline{(C_p - C_o)^2}}}{\overline{C_p}}$	1.258	1.214
Fractional Bias	$\frac{(\overline{C_p} - \overline{C_o})}{0.5(\overline{C_o} + \overline{C_p})}$	1.122	1.184
Normalized Mean Square Error	$\frac{\overline{(C_p - C_o)^2}}{\overline{C_o}\,\overline{C_p}}$	5.632	5.752
Linear Pearson Correlation Coefficient	$\frac{\overline{(C_o - \overline{C_o})(C_p - \overline{C_p})}}{\sigma_{C_p}\sigma_{C_o}}$	0.474	0.685
Logarithm-Based Correlation Coefficient	$\frac{\overline{(lnC_o - \overline{lnC_o})(lnC_p - \overline{lnC_p})}}{\sigma_{lnC_p}\sigma_{lnC_o}}$	0.734	0.883
Fraction of data within a factor of 2	$\frac{1}{2} \leq \frac{C_p}{C_o} \leq 2$	0.283	0.377
Fraction of data within a factor of 5	$\frac{1}{5} \leq \frac{C_p}{C_o} \leq 5$	0.679	0.679
Fraction of data within a factor of 10	$\frac{1}{10} \leq \frac{C_p}{C_o} \leq 10$	0.830	0.943

Conclusions

- WRF-LES captures the physics of flow over complex terrain well enough to model scalar transport and dispersion
- Statistical accuracy metrics such as RMSE, correlation coefficient, and factor analysis are at par with or better than previous CFD studies of CCB
- SGS parameterization can be responsible for significant accuracy variability in itself
- Magnitude bias was the greatest concern

Future Directions

- Add scalar density effects
- Add surface sinks for scalar
- Conduct additional verifications

WISE Service Project Sponsored by RAL

WISE Service Project

Central Theme: Inspire students to pursue careers in the applied sciences and expose them to the exciting and unexpected opportunities available in graduate school

Part 1.) Create and man a wind energy exhibit at NCAR's annual Super Science Saturday Event (ages: <13)

Part 2.) Visit local mid/high school and give a tutorial on the wind resource assessment and turbine micro-siting processes (ages: 13-18)

Part 3.) Give seminar to early college undergrads and share my experiences of grad school (ages: >18)

Super Science Saturday

Super Science Saturday
Mesa Lab (10/26/2013)

Wind Resource Estimation & Park Design Tutorial

Tutorials are scheduled to take place at Turrentine Middle School in Burlington, NC in late January. This will be integrated into a renewable energy segment of the student curriculum which teachers can carry on into future school years

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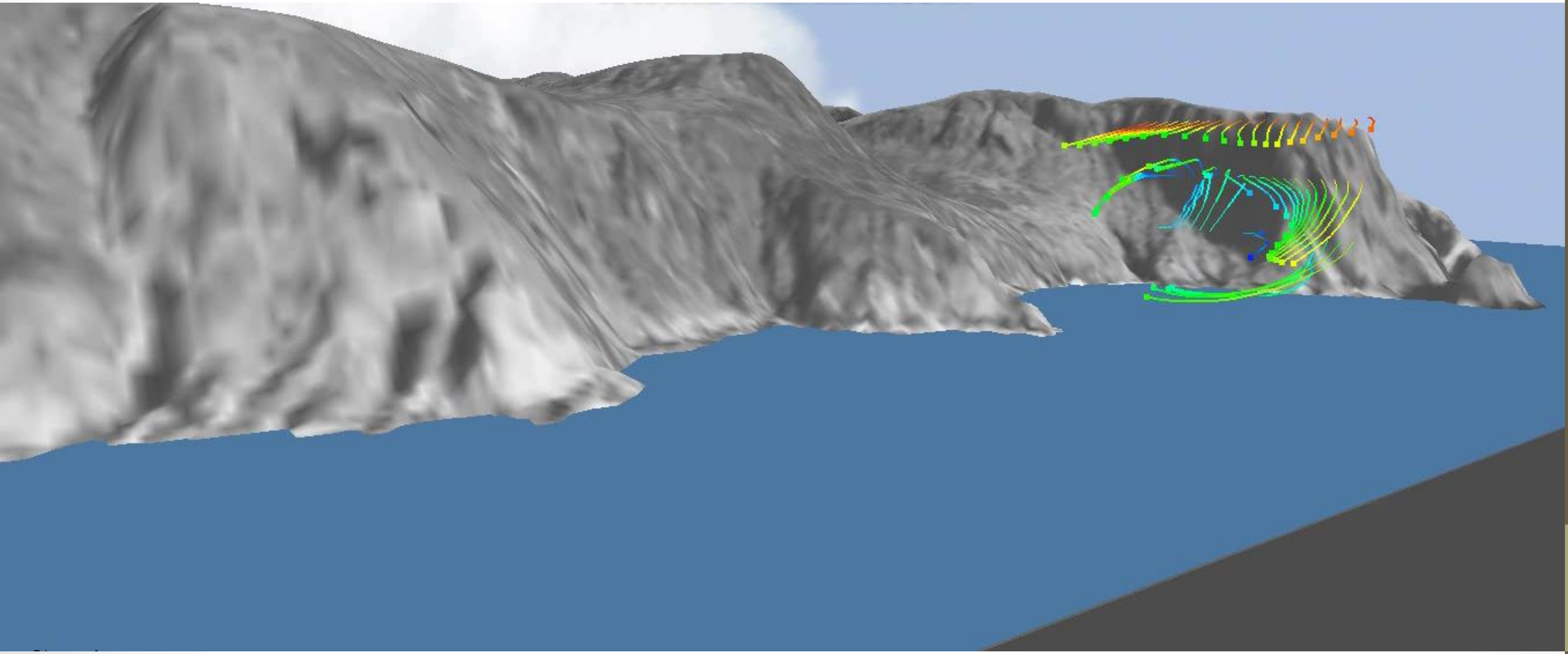
Wind Resource Estimation & Park Design Tutorial

Tutorials will emphasize the important physics at play and how understanding and mitigating them can substantially improve wind farm efficiency



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Thank you for your attention!