On flow separation under stable conditions: results from flow visualization in MATERHORN-X

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September 6th 2013 4:45pm

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MATERHORN

Overview

[1] Quick Background: Dividing Streamline Concept
[2] Site Location and Instrumentation
[3] Goals and Procedure
[4] Atmospheric Conditions during flow visualization
[5] Smoke Visualization
[6] Movie

Quick Background

Based on energy arguments:

Sheppard (1956)

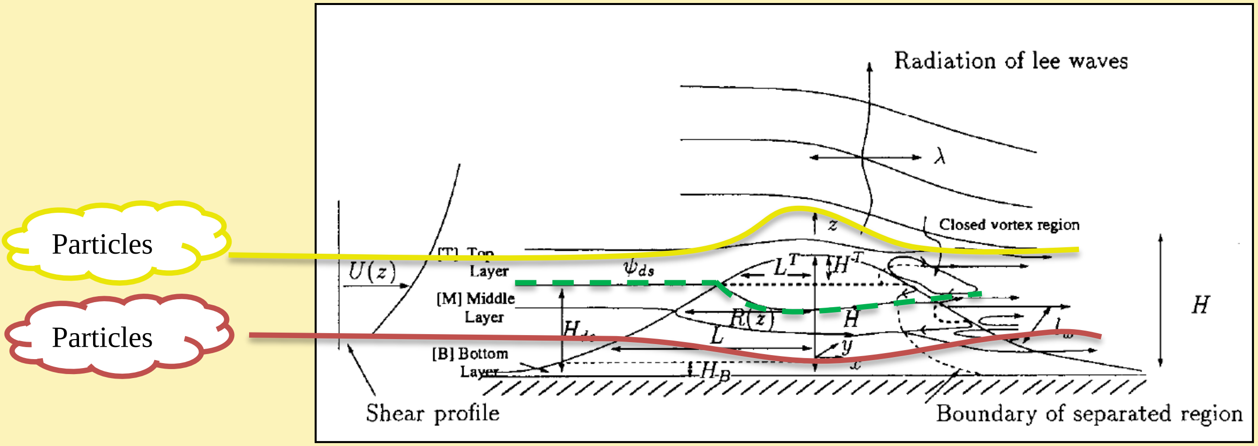
"Under what conditions will an airstream rise over a mountain range?"

Sheppard's Equation:

$$\underbrace{\frac{1}{2}\rho U_0^2(H_s)}_{\text{(a)}} = \underbrace{g\int_{H_s}^{h}(h-z)\left(-\frac{\partial\rho}{\partial z}\right)dz}_{\text{(b)}} \quad \textit{with} \quad Fr < 1$$

(a) The kinetic energy of the parcel far upstream at elevation H_s

(b) The potential energy gained by the parcel in being lifted from the dividing streamline H, to the top of the hill h through the density gradient $\partial\rho/\partial z$



Adopted from Hunt et al. (1997)

Dividing Streamline (ψ_{ds}) : The streamline separating the top and middle regions of flow.

Dividing Streamline Height (H_{ds}) : The height between the ground and ψ_{ds}

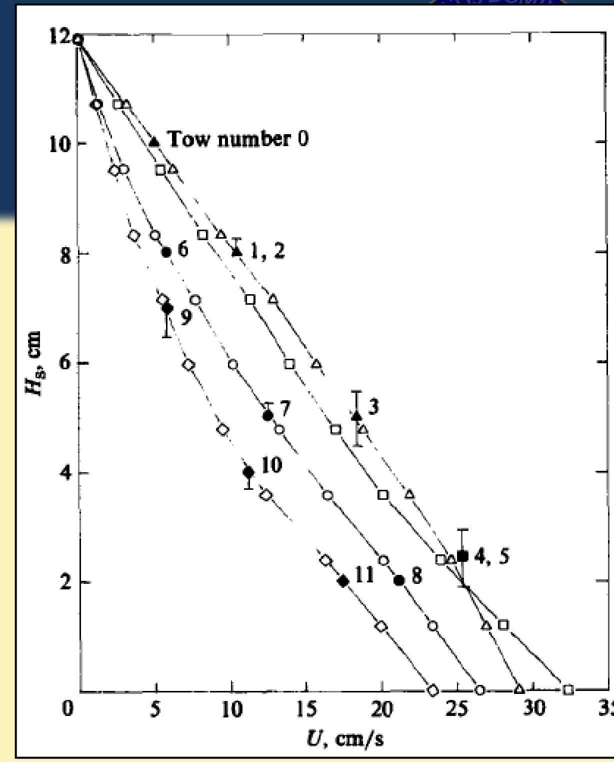
Quick Background

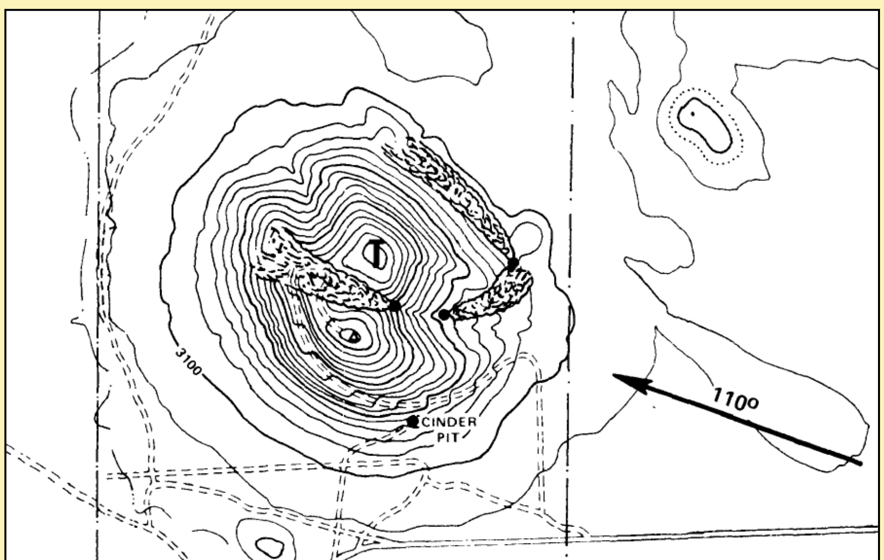
Cinder Cone Butte, ID

- Field experiment originally conducted by USEPA
- Modeled in stratified towing tank using salt gradients
  - Open symbols $\Rightarrow$ Calculated values
  - Closed symbols $\Rightarrow$ Observed values

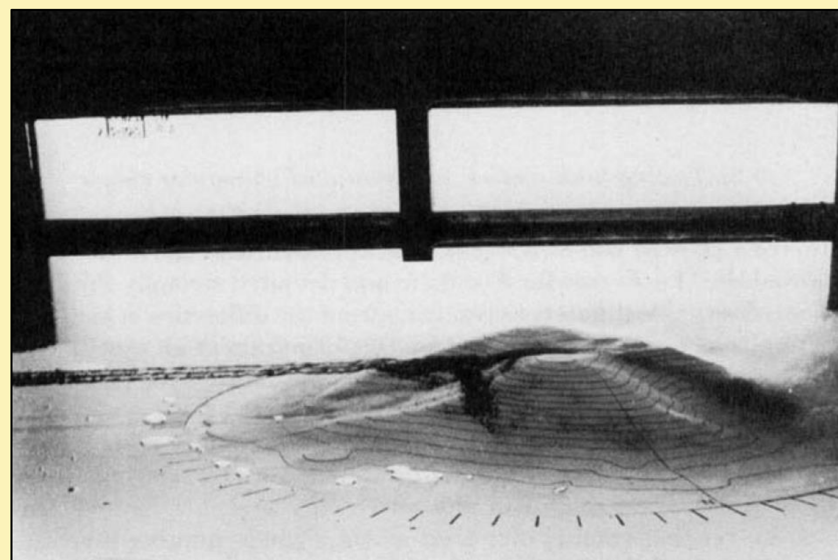
- Sheppard's Equation can be simplified:

$$H_s = h(1 - Fr)$$



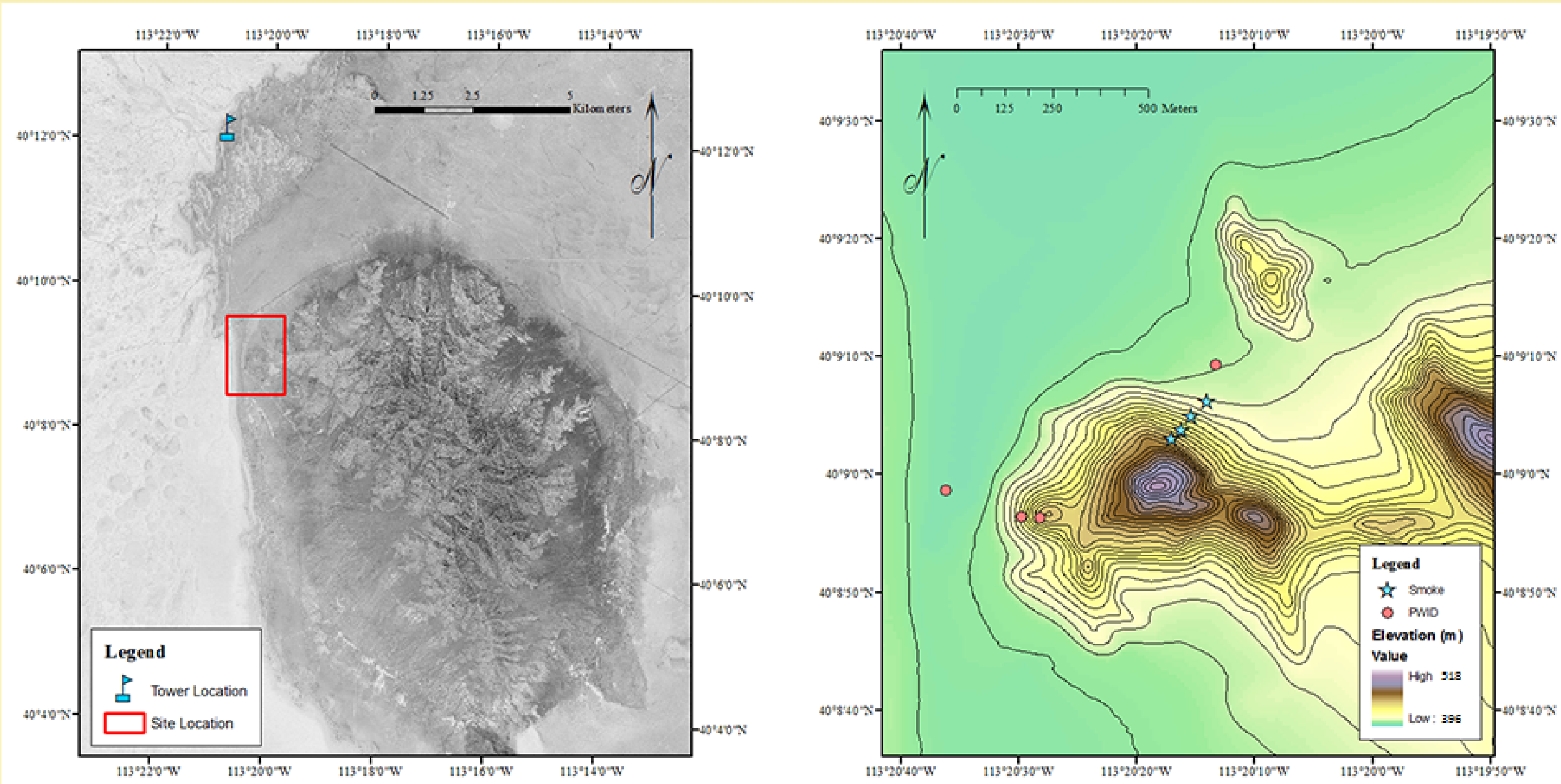


Adopted from Snyder et al. (1980)



Adopted from Snyder et al. (1985)

Site Location and Instrumentation



(*Left*) High resolution 1m orthoimagery of Granite Mountain, portraying the location of the instrumentation tower and smoke visualization site. (*Right*) Ten times magnification of the smoke visualization site; the contours are presented at 5m intervals.

32m NW tower:

- 5 81000 R.M. Young ultrasonic sonic anemometers (20Hz sampling rate)

PWIDs:

- 05103 R.M. Young mechanical wind sensors
- Temperature and relative humidity probes

Goals and Procedure

<u>Goals</u>:

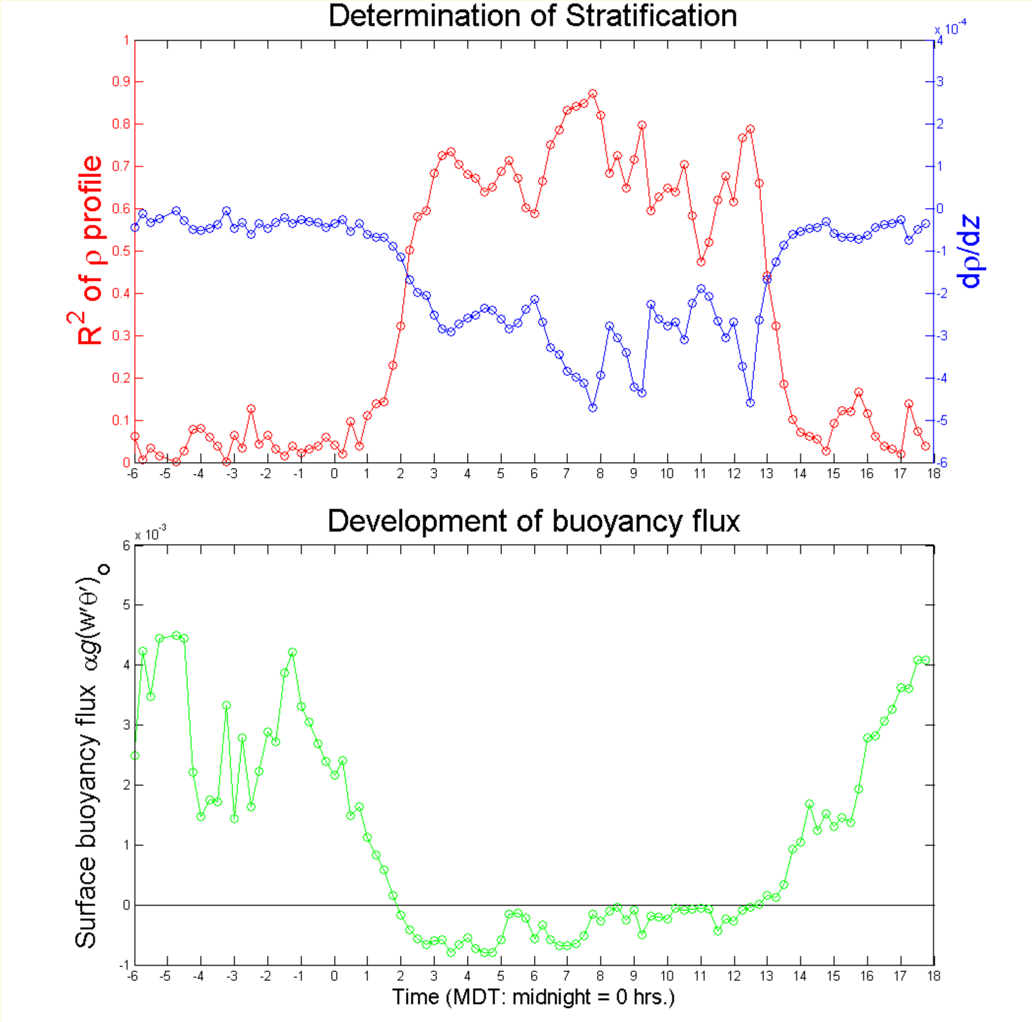
- Multiple smoke releases in time of stratified flow
- Capture with high quality photos and movies
- Be able to quantify observations using DSL concept

<u>Procedure</u>:

1. Wait for appropriate conditions
2. First smoke release
    - Red smoke canisters; (~1.5 min release)
    - 4 simultaneous ground releases (0.0*h*, 0.08*h*, 0.45*h*, 0.88*h*)
3. Second smoke release

- Use crane for elevated release; observation of approaching streamline
- White smoke canisters (~5 min release)
- 3 simultaneous ground releases; 1 elevated release (~0.33h)

Atmospheric Conditions



Density profiles:

- Development of strong linear correlation by 3AM
- R^2 values reaching ~0.7 in the early morning
- Breakdown of linearity around noon

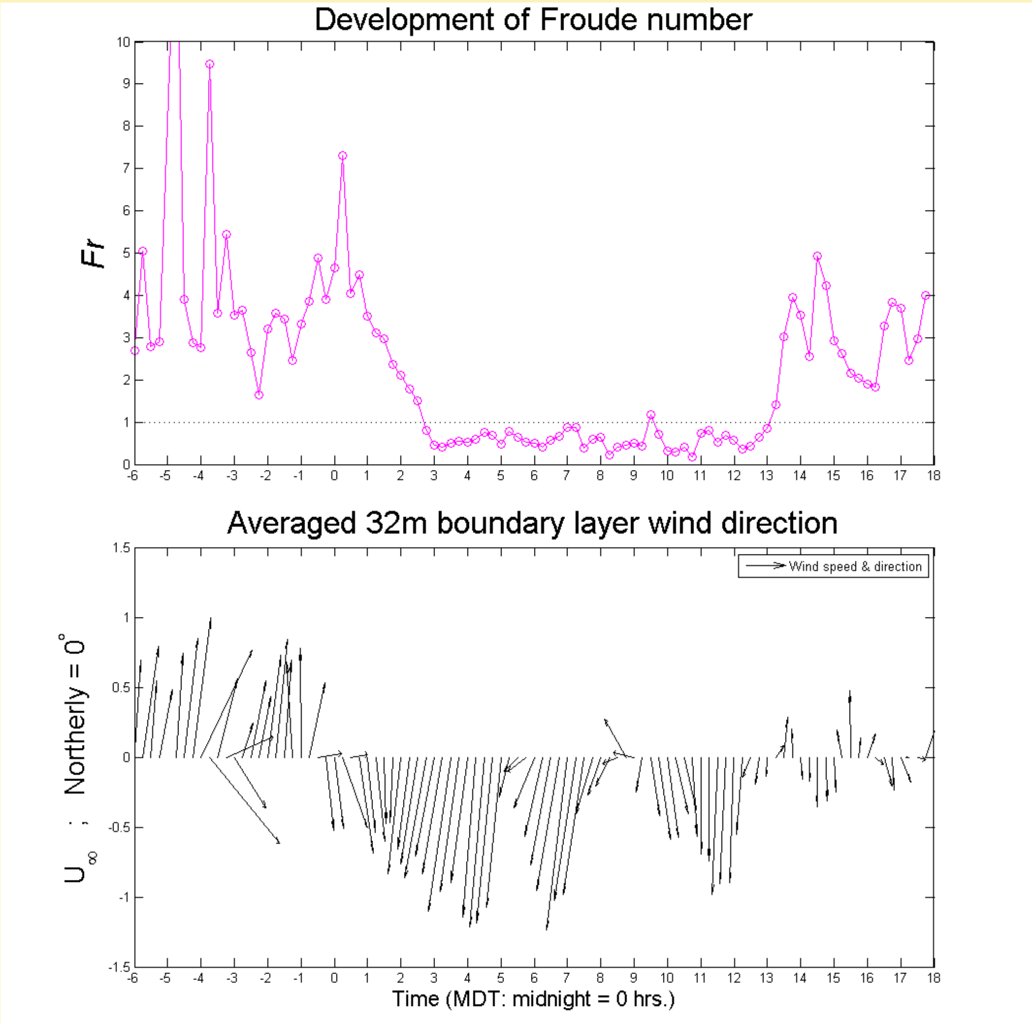
Surface buoyancy flux:

- ***Positive*** when surface is heated – convective overturning
- ***Negative*** when boundary layer tends to be stably stratified (reduce turbulent energy)

(*Top*) Linear regression coefficient of the density profile, calculated from the 32m sonic anemometers; corresponding density gradient strength.

(*Bottom*) Development of the buoyancy flux, as calculated from the tower sonic anemometer positioned 2*m* above the ground.

Atmospheric Conditions



Froude number:

- During period of stratification, *Fr* drops within applicable range

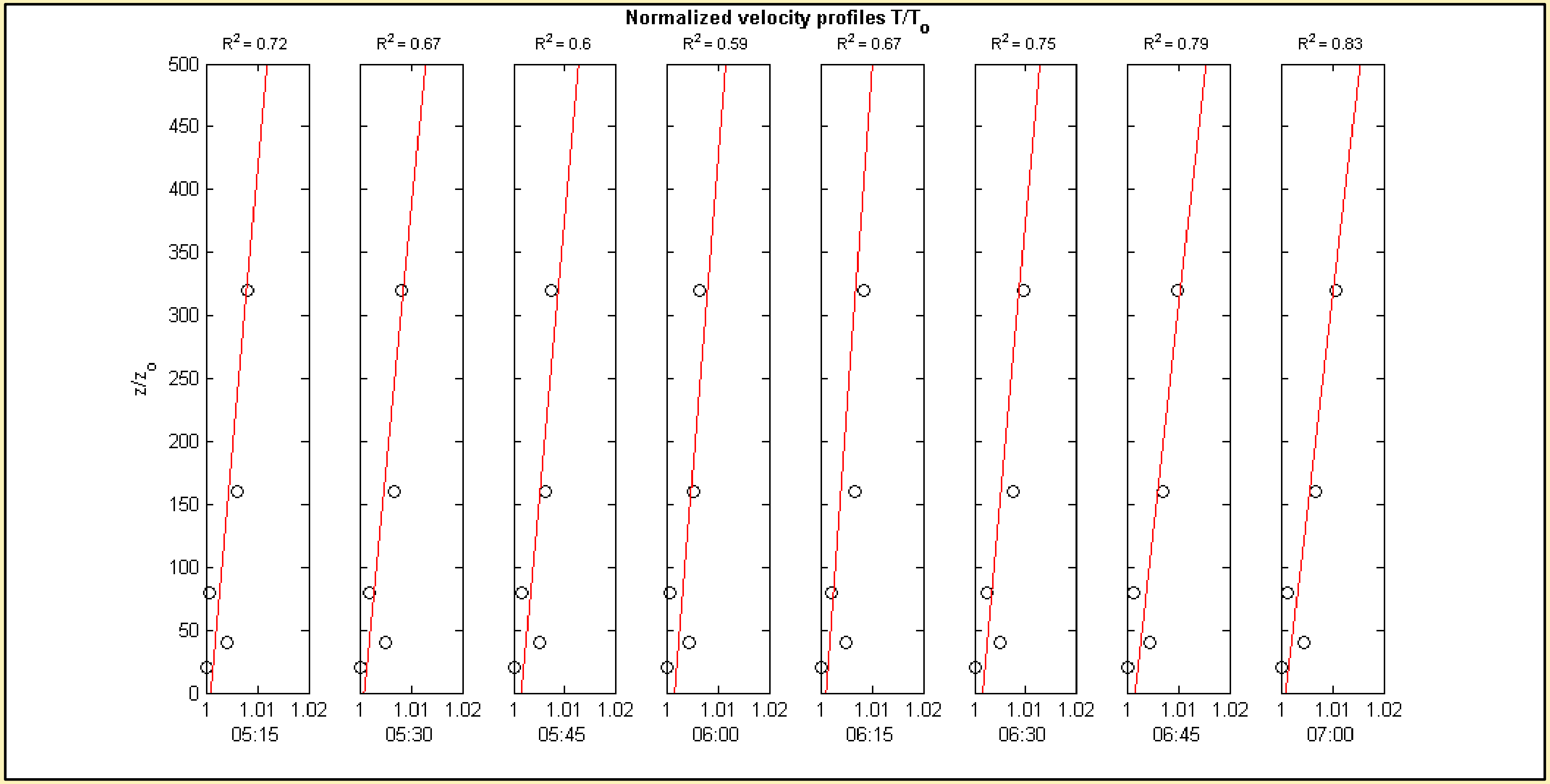
Wind Direction:

- During time of experiment, wind originating from the northeast ~ 30° at about 1 *m*/*s*

(*Top*) Linear regression coefficient of the density profile, calculated from the 32m sonic anemometers; corresponding density gradient strength.

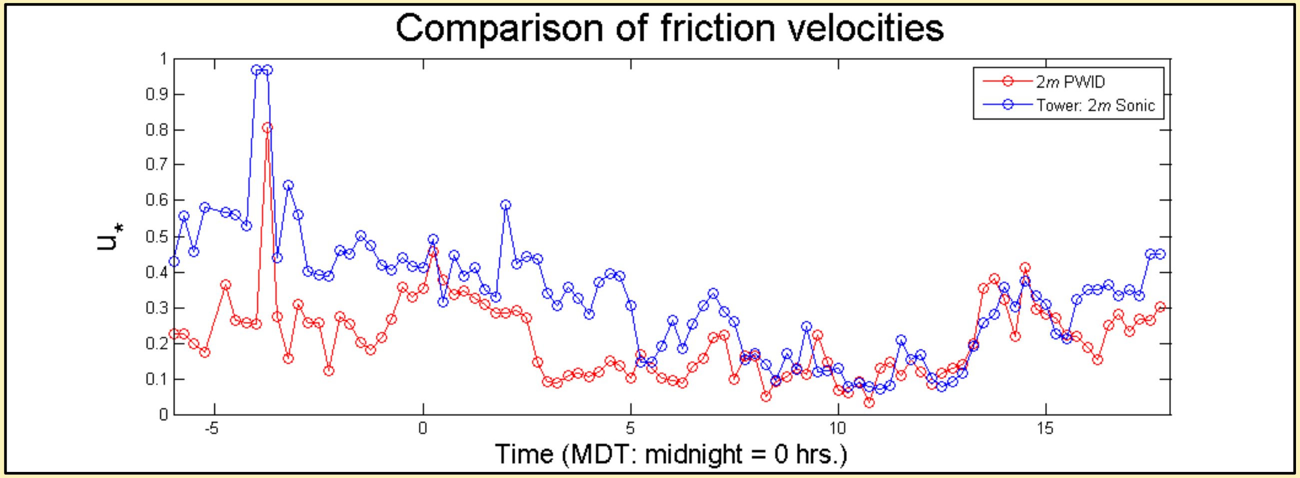
(*Bottom*) Development of the buoyancy flux, as calculated from the tower sonic anemometer positioned 2*m* above the ground.

Temperature Profiles



- Temperature profiles normalized by T_o
- Show good stratification, with $0.67 < R^2 < 0.75$ around the time of flow visualizations

Velocity Profiles



Monin-Obukhov Similarity Theory (**MOST**):

$$\bar{u}(z) = \frac{u_*}{k} ln(\frac{z}{z_o}) \quad \text{where} \quad u_* = ((\overline{u'w'}^2) + (\overline{v'w'}^2))^{\frac{1}{4}}$$

$$L_* = -\frac{u_*^3}{kq_o} \quad \text{where} \quad q_o = \alpha g \overline{(w'\theta')}_o \quad \text{and} \quad \alpha \approx \bar{\theta}^{-1}$$

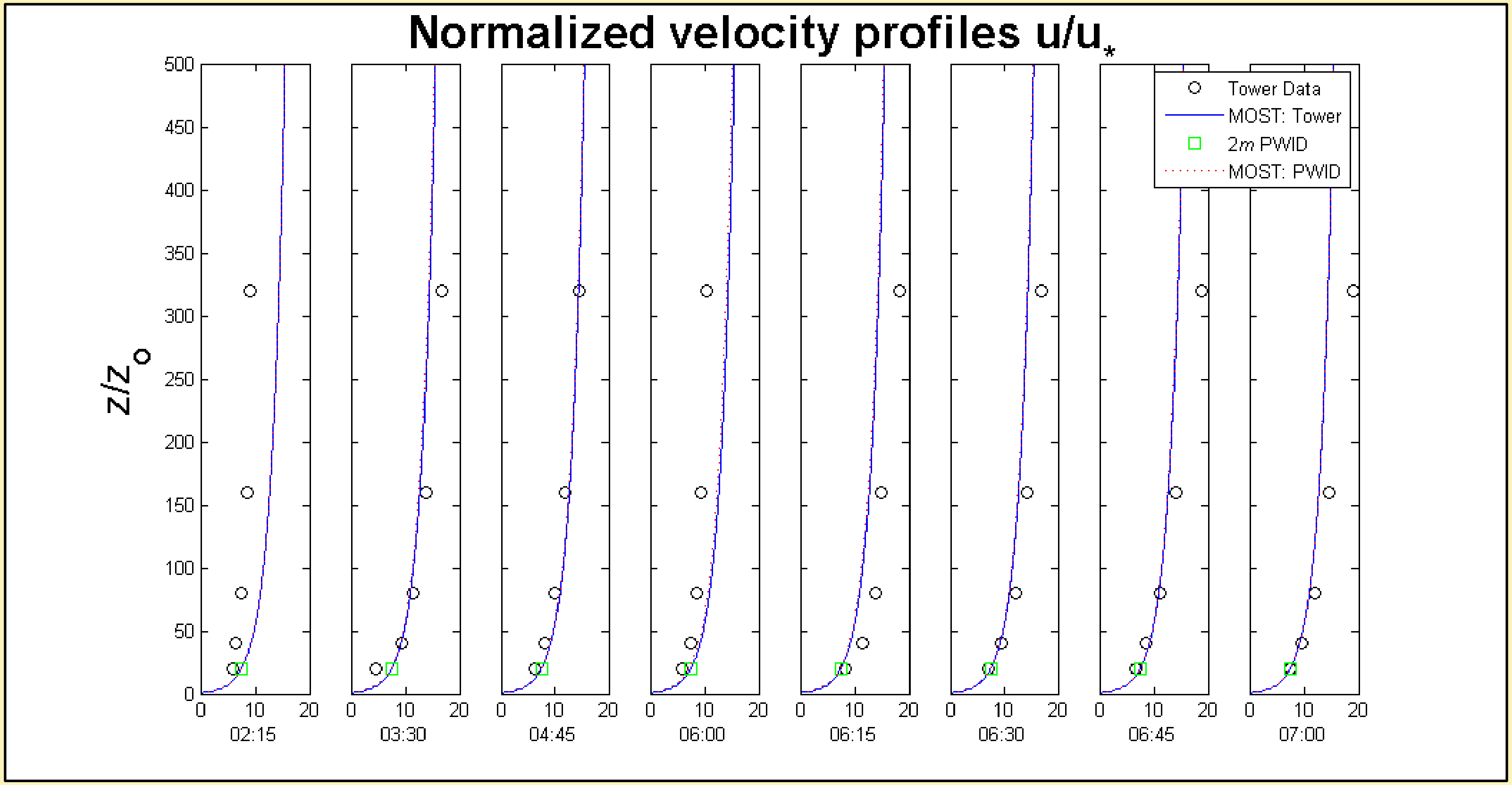
$$\xi = z/L_* \text{ and } \xi_o = z_o/L_*$$

$$\phi_m = \begin{cases} (1+16|\xi|)^{-\frac{1}{4}}, & \text{for } -2 \le \xi \le 0 \\ (1+5\xi), & \text{for } 0 \le \xi \le 1 \end{cases}$$

$$\bar{u}(z) = \frac{u_*}{k} ln(\frac{z}{z_o} - \Psi_m) \quad \text{where} \quad \Psi_m = \int_{\xi_o}^{\xi} \frac{(1-\phi_m)}{\xi} d\xi$$

u_*	Friction velocity
z_o	Roughness height (0.10m)
k	Von Kármán constant (0.40)
$\overline{u'w'}$ $\overline{v'w'}$	Surface kinematic momentum fluxes to represent the surface stress
L_*	Monin-Obukhov length scale
q_o	Surface buoyancy flux
α	Thermal expansion coefficient
θ	Potential temperature
$\overline{(w'\theta')}_o$	Mean temperature flux at the surface
ϕ_m	Stability function for wind shear
Ψ_m	Correction term

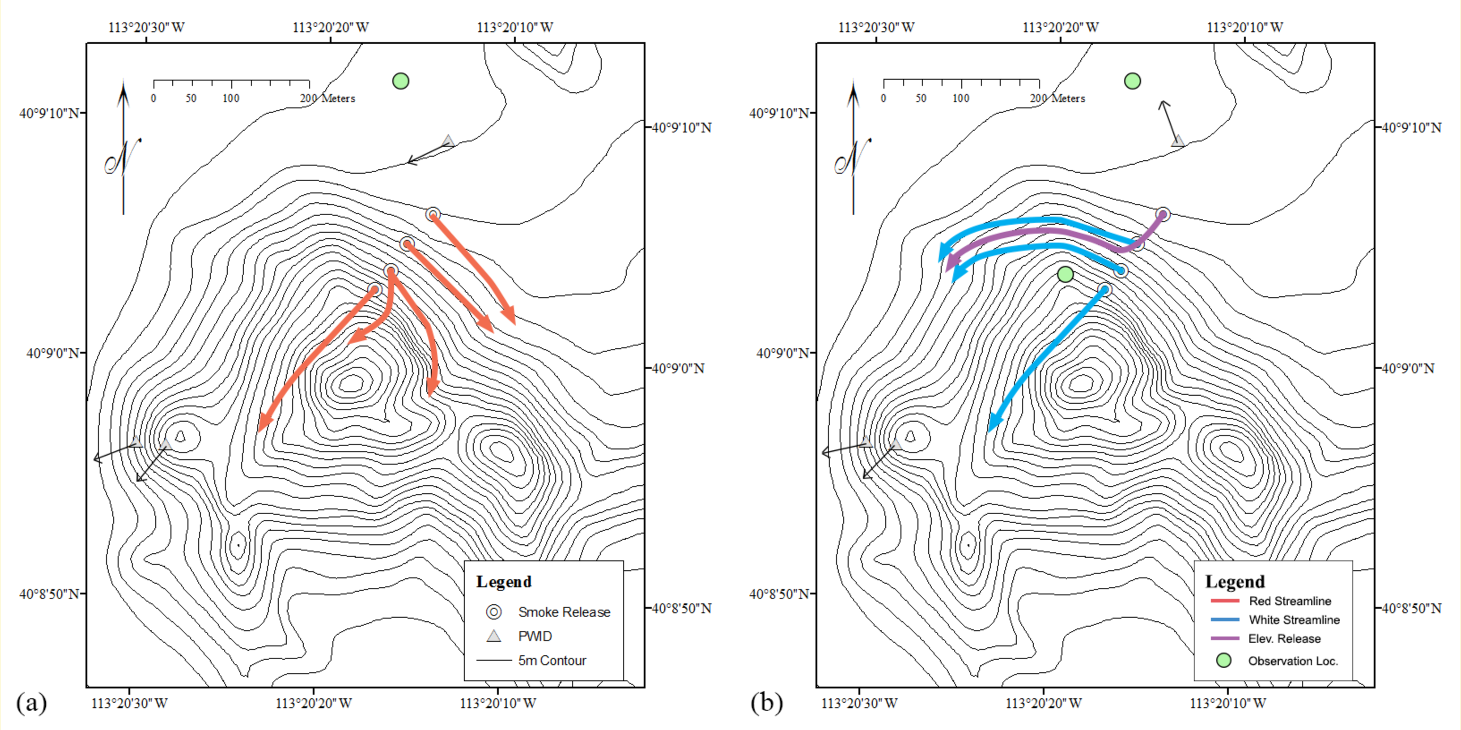
Velocity and Temp Profiles



- Tower data is normalized by the friction velocity computed from the Sonic Anemometer positioned at 2*m* on the 32*m* Tower.
- PWID data is normalized by the u_* needed for the MOST profile to pass through the recorded 2*m* velocity.

- Normalized profiles show good agreement

Smoke Visualization



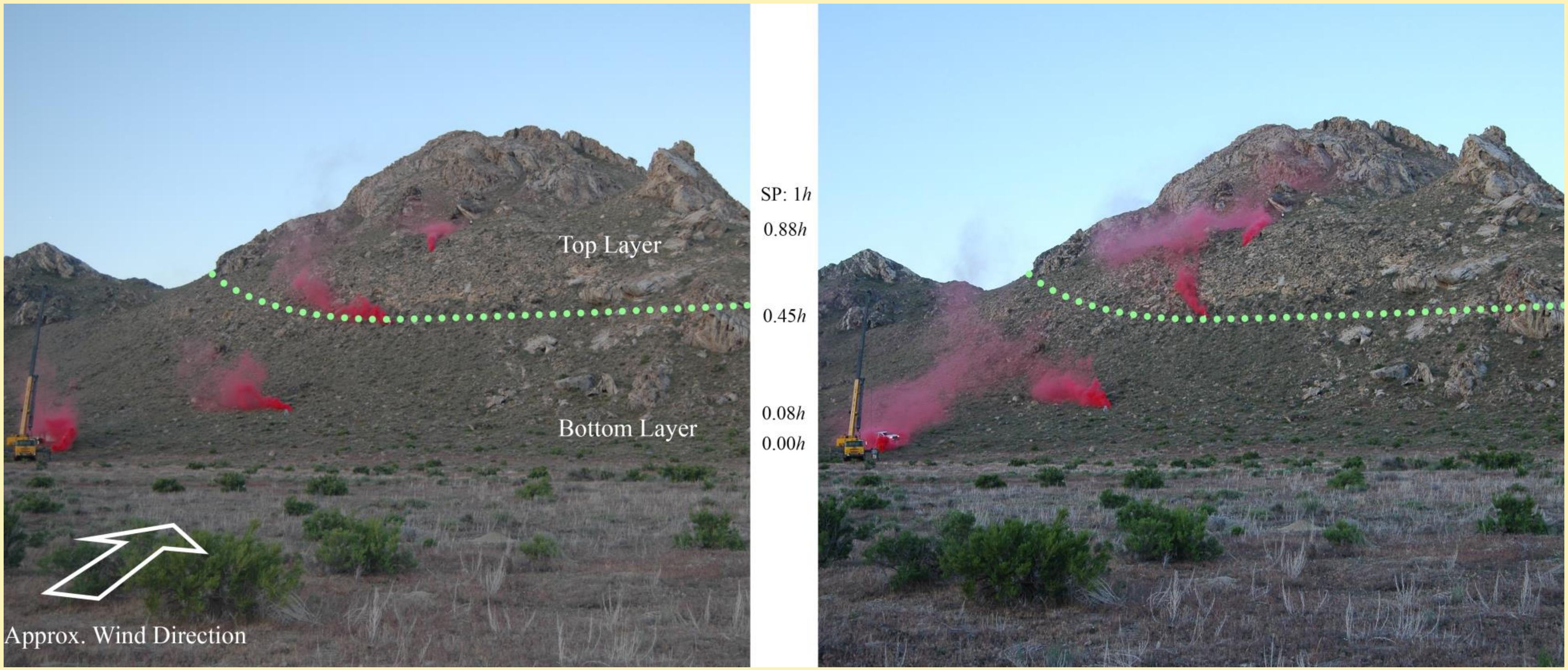
~6:15AM : Red Smoke

~6:30AM : White Smoke

<u>Smoke release plume paths, as determine by observation</u>:

(*Left*) Smoke release plume paths, as determine by observation.
(*Right*) Development of the buoyancy flux, as calculated from the tower sonic anemometer positioned 2*m* above the ground.

Smoke Visualization: Red Smoke



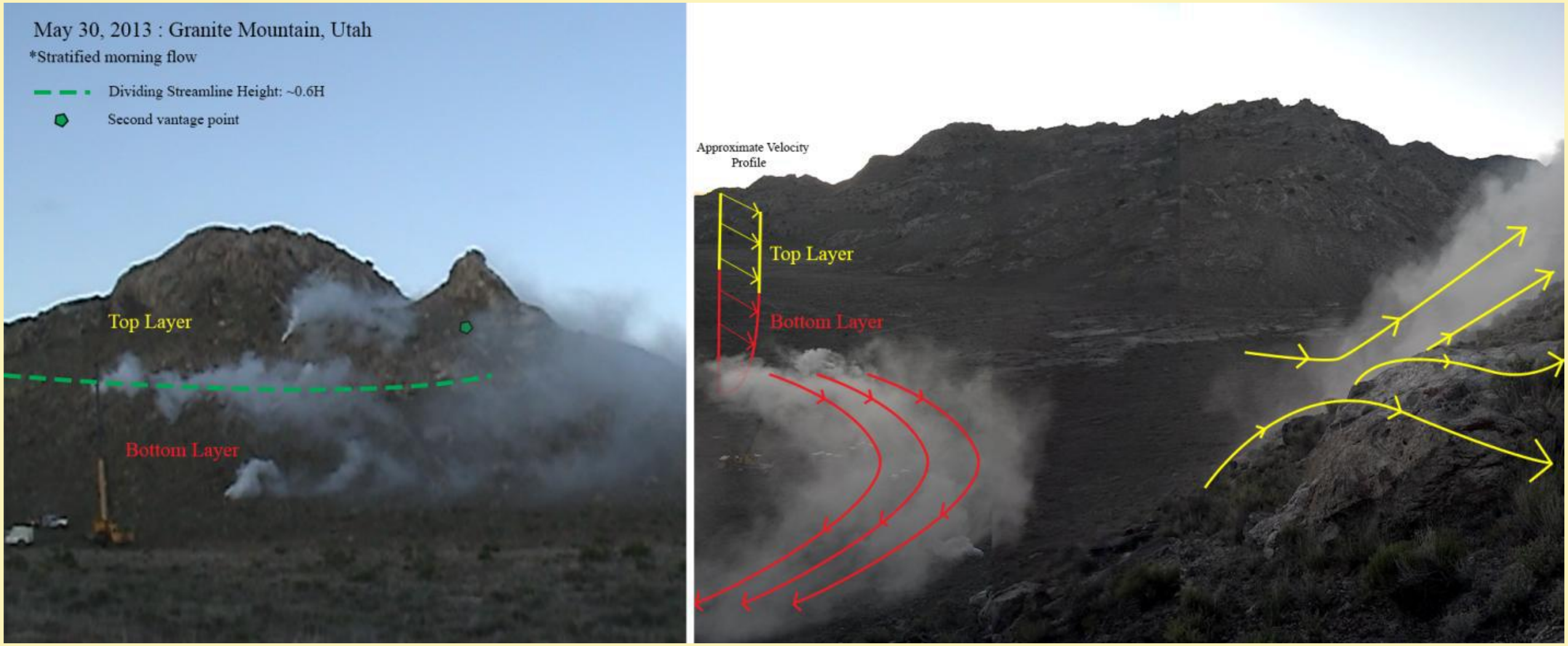
~6:15AM : Red Smoke

~30s after release

Things to note:

- Clear presence of dividing streamline
- Shift in middle release, perpendicular to parallel
- Release within the top layer is carried over the mountain

Smoke Visualization: Red Smoke

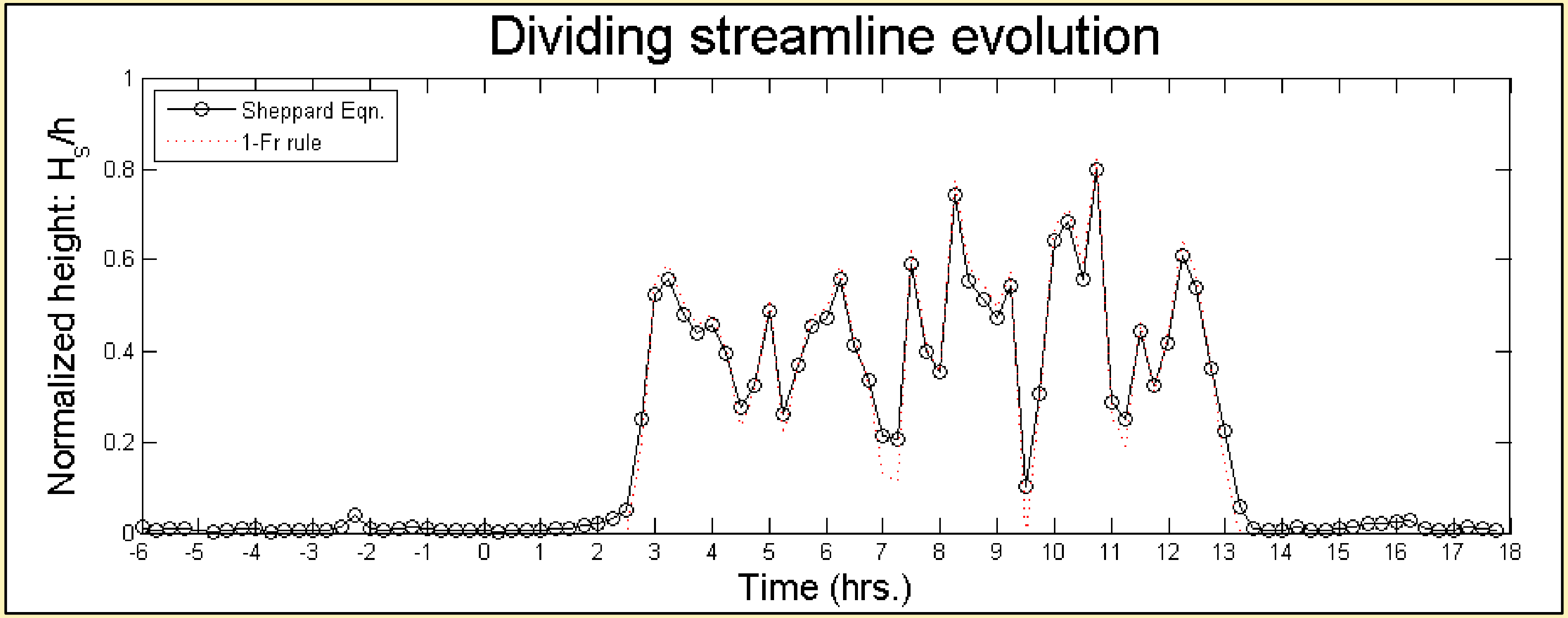


~6:30AM : White Smoke / Elevated Release ~180*s* after release

<u>Things to note</u>:

- Clear presence of dividing streamline
- Approaching streamline in bottom layer is deflected around the mountain
- Release within the top layer is carried over the mountain

Smoke Visualization: DSLH



Solve Sheppard's equation using velocity and temperature profiles previously established.

<u>Things to note</u>:

- As stratification forms, a dividing streamline becomes present
- During the time of the experiment, DSLH ~ 0.5*h*
- Calculation are consistent with field observations

Smoke Visualization: Movie

FlowVisualizationFinal.mov

Granite Mountain Overview

REFERENCES

Hunt, et al. (1997) Low-Froude-number stable flows past mountains. *Il Nuovo Cimento*, ***20***, 261-272.

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ACKNOWLEDGEMENTS

Joe Fernando

Silvana DiSabatino

Laura Leo

+Many helpful people who woke up very early

Thank You