Observations of near-surface heat flux and temperature profiles through the early evening transition over contrasting surfaces

DEREK D. JENSEN[1], DANIEL F. NADEAU[3],SEBASTIAN W. HOCH[2], ERIC R. PARDYJAK[1]

[1]MECHANICAL ENGINEERING, UNIVERSITY OF UTAH, SALT LAKE CITY, UNITED STATES
[2]ATMOSPHERIC SCIENCES, UNIVERSITY OF UTAH, SALT LAKE CITY, UNITED STATES
[3]CIVIL, GEOLOGICAL AND MINING ENGINEERING, POLYTECHNIQUE MONTRÉAL, MONTREAL, QC, CANADA

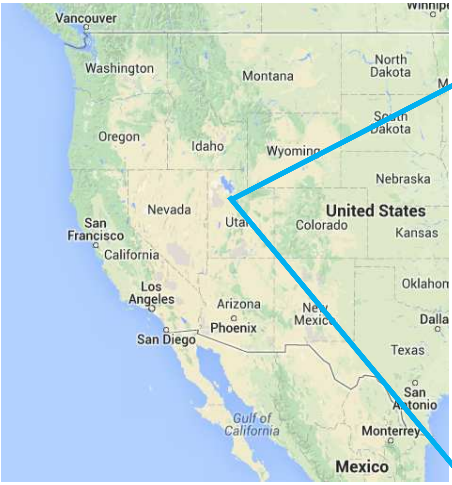
This research was funded by the Office of Naval Research Award # N00014-11-1-0709

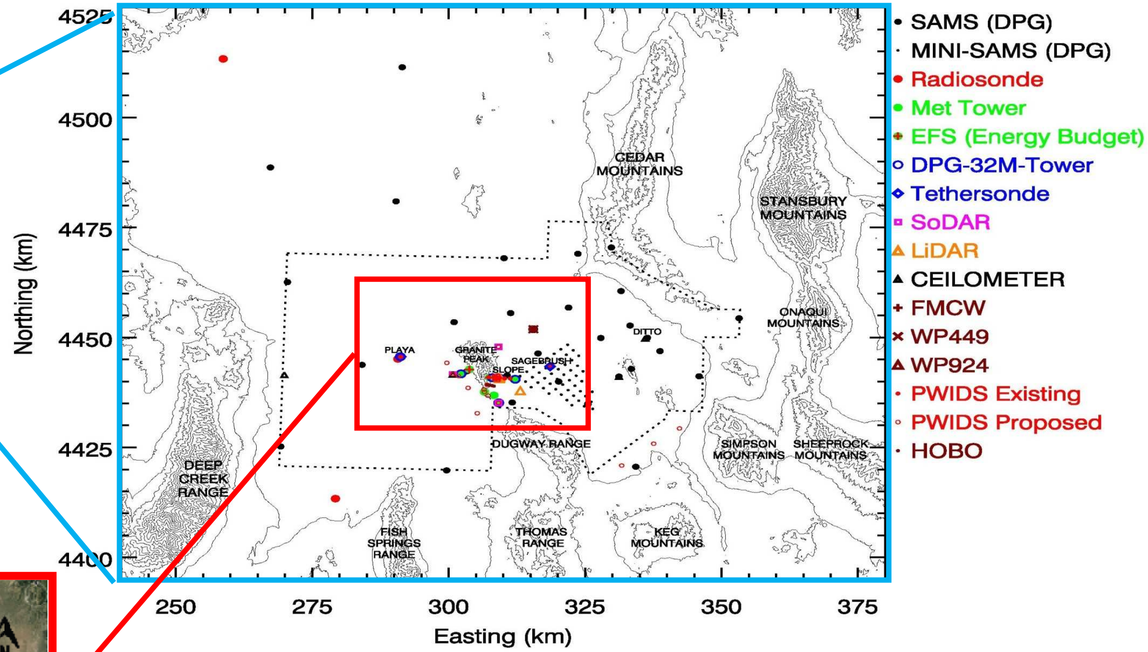
Introduction

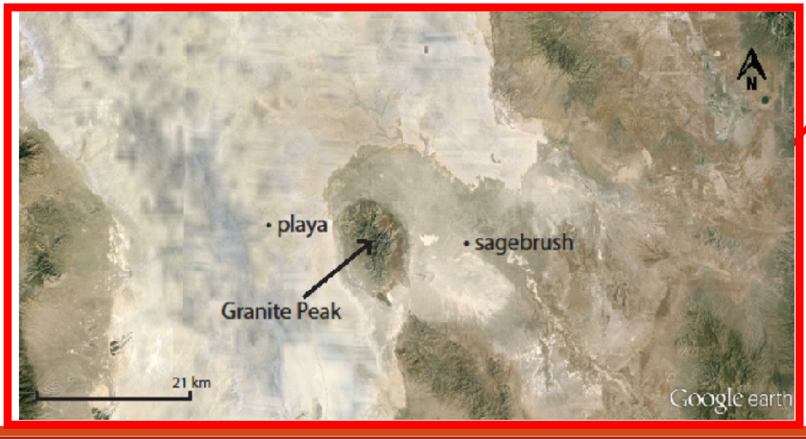
- Flux-gradient relationships, such as Monin-Obukhov similarity theory (MOST), are very poorly formed through much of the afternoon and evening transition (AET).
- Blay et al. 2014 observed near-surface counter-gradient fluxes during the BLLAST campaign with durations of approximately $30 - 80$ minutes.
- We'd like to perform a similar analysis with the MATERHORN data where heat-flux and temperature profiles are considered for 2 contrasting sites.

- ***GOAL: Obtain a more complete understanding of the evolution of near-surface heat flux and temperature through the AET.***

A three-year, multi-institution program designed to improve weather predictability over complex terrain







2 Field Campaigns

- Fall: 25 Sept. 2012 – 21 Oct. 2012
- Spring: 1 May 2013 – 31 May 2013

Sites of Interest

- Sagebrush
- Playa

Relevant Instrumentation

- Sonic Anemometers
- Finewire Thermocouples
- Temperature/RH
- Net Radiometers
- Soil Sensors

Playa

Heights: 0.5, 2, 5, 10, 20, 26 m

- Higher Albedo (0.32)
- High Soil Moisture
- $z_0 \approx 0.5\ mm$
- No vegetation

Sagebrush

Heights: 0.5, 2, 5, 10, 20 m

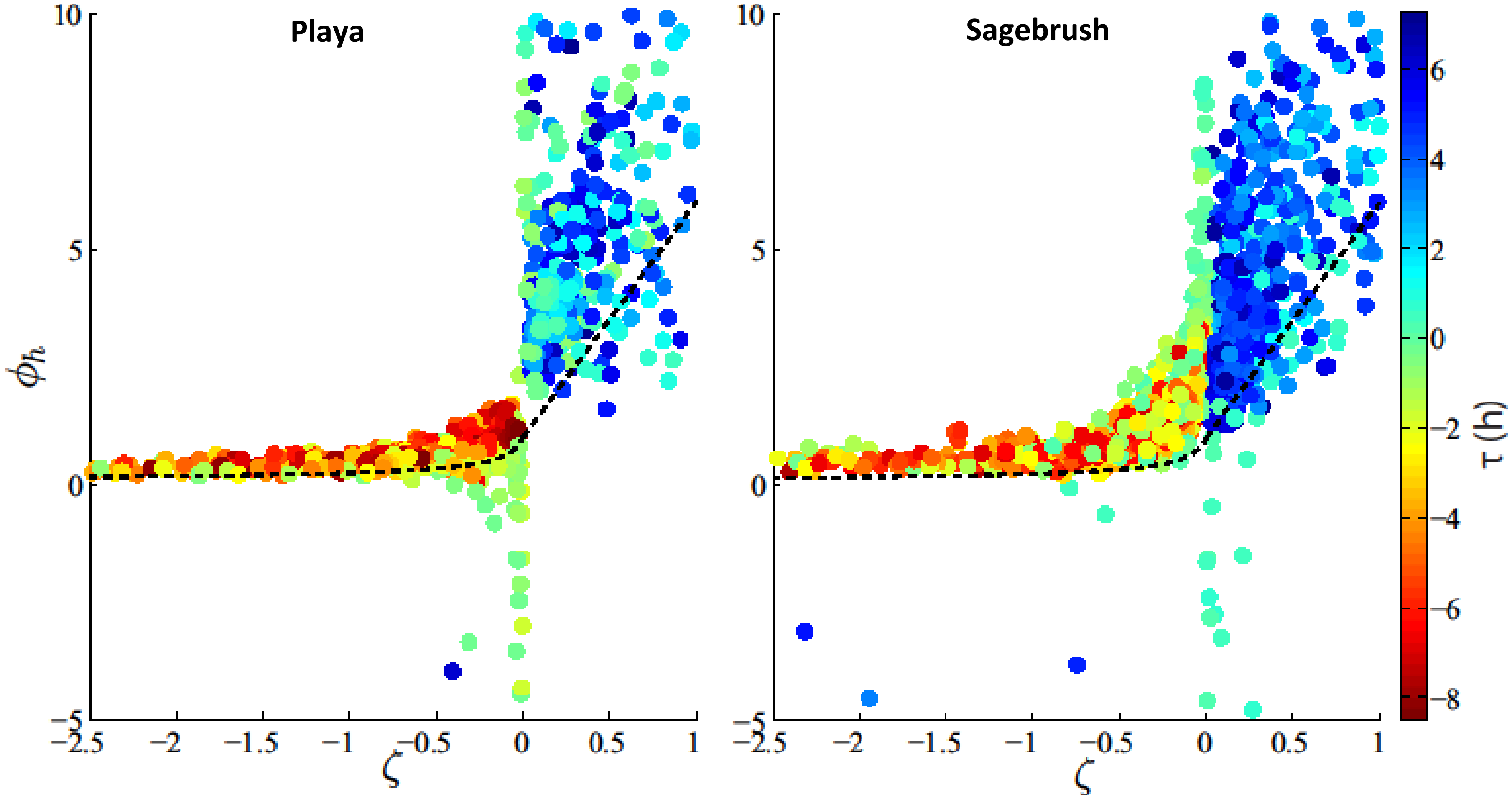
- Lower Albedo (0.26)
- Low Soil Moisture
- $z_0 \approx 10\ cm$
- Desert Steppe

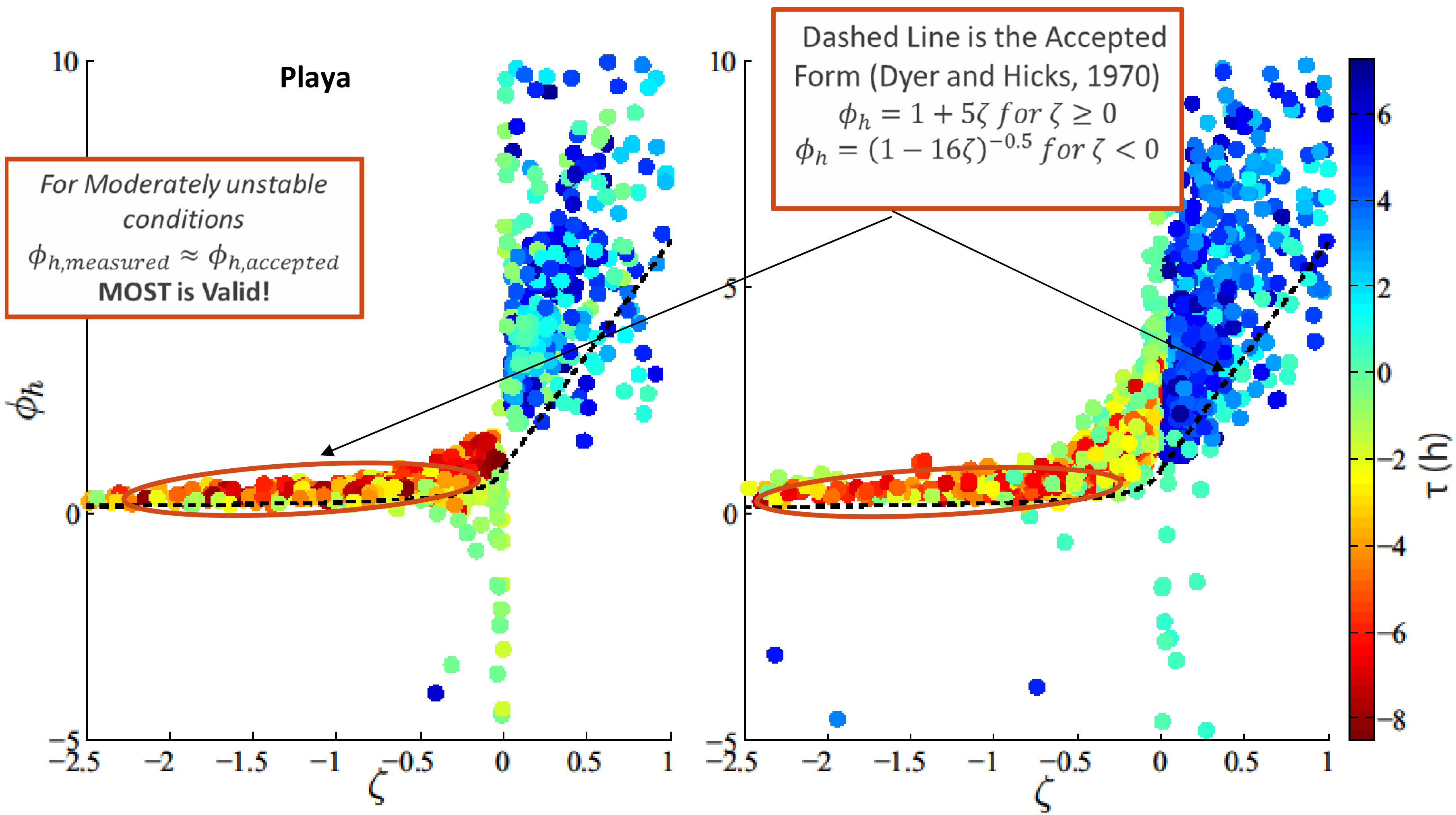
Non-Dimensional Temperature Gradient, ϕ_h

- $\phi_h = \frac{\kappa z}{\theta_*}\frac{\partial\theta}{\partial z}$ where $\theta_* = -\frac{\overline{w'\theta'}}{u_*}$
- Within MOST, $\boldsymbol{\phi_h} = \boldsymbol{f}(\boldsymbol{\zeta})$ where $\zeta = \frac{z}{L}$ and L is the Obukhov Length
- ϕ_h can be used to estimate temperature profiles and heat fluxes
- ϕ_h can be used to explore the validity of MOST

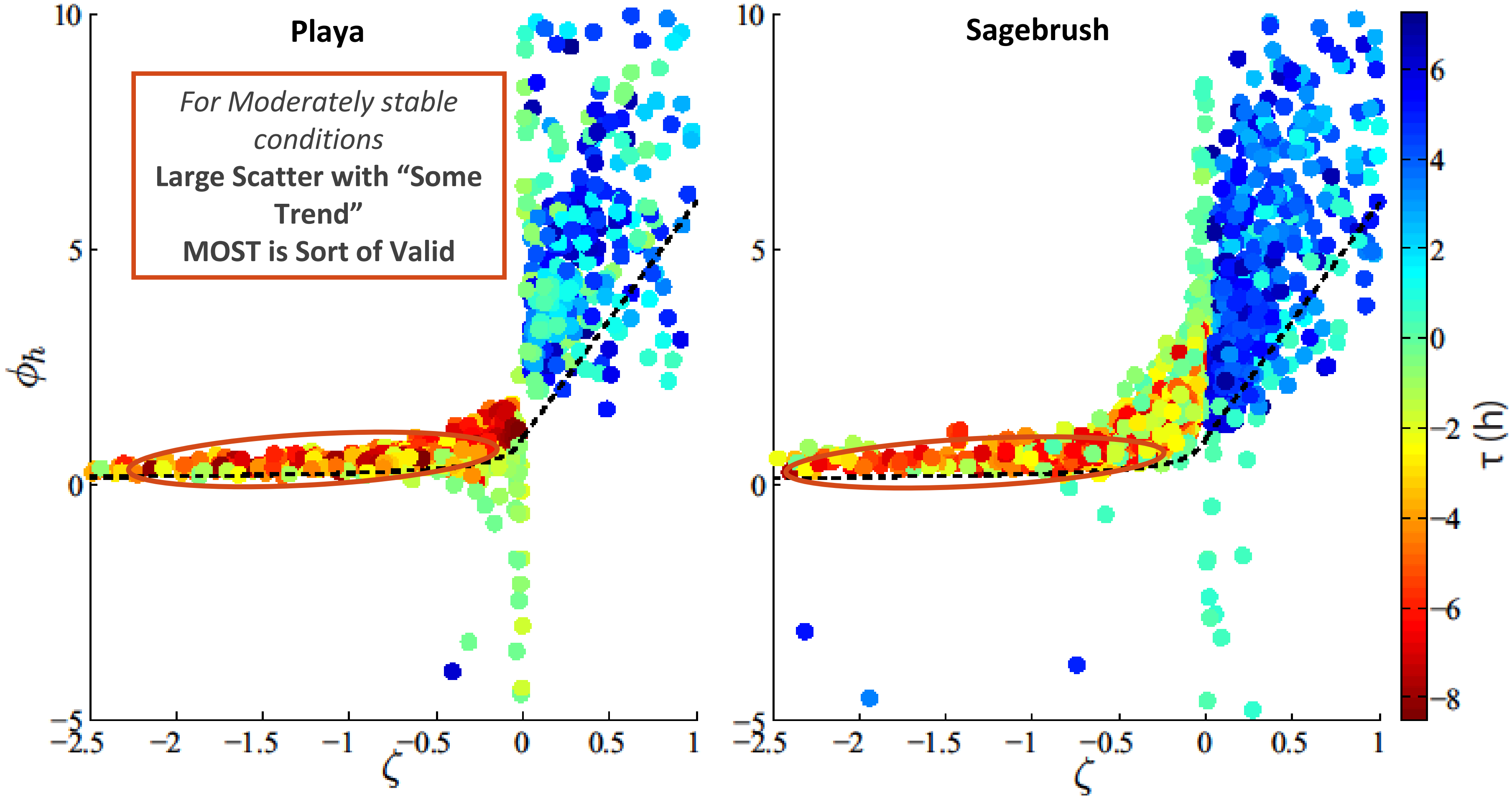
Transition Data Analysis

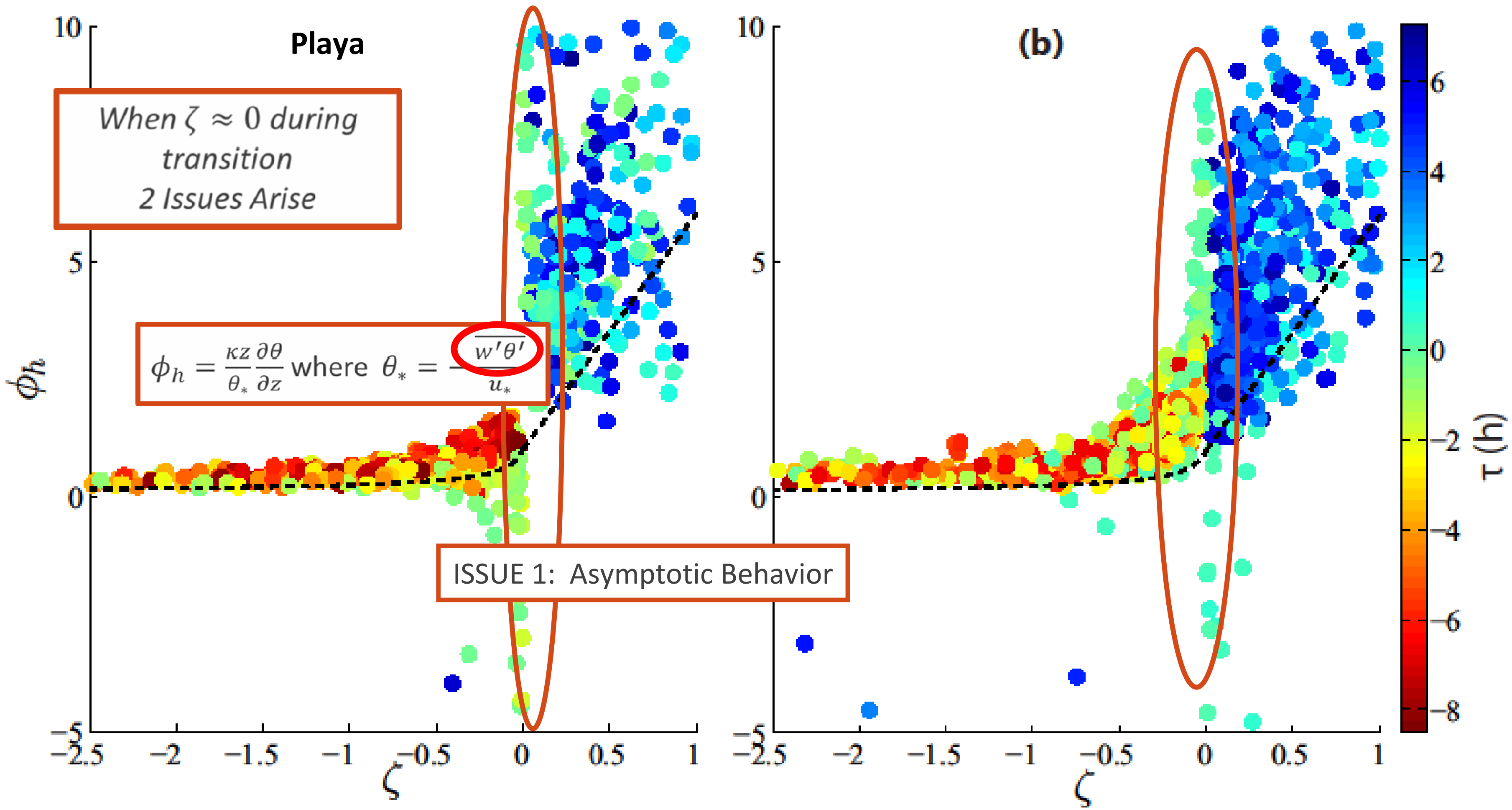
- 5 minute averaging and linear detrending
- Fine wire temperature always used
- Transition periods with high winds (> 7 m s^{-1}) and missing data neglected
- Left with 8 days at Playa, 13 at Sagebrush
- Transitional Relative Time: $\tau \equiv t - t_{Rn=0}$


Playa
Sagebrush
ϕ_h
ζ
10
5
0
−5
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
τ (h)
6
4
2
0
−2
−4
−6
−8

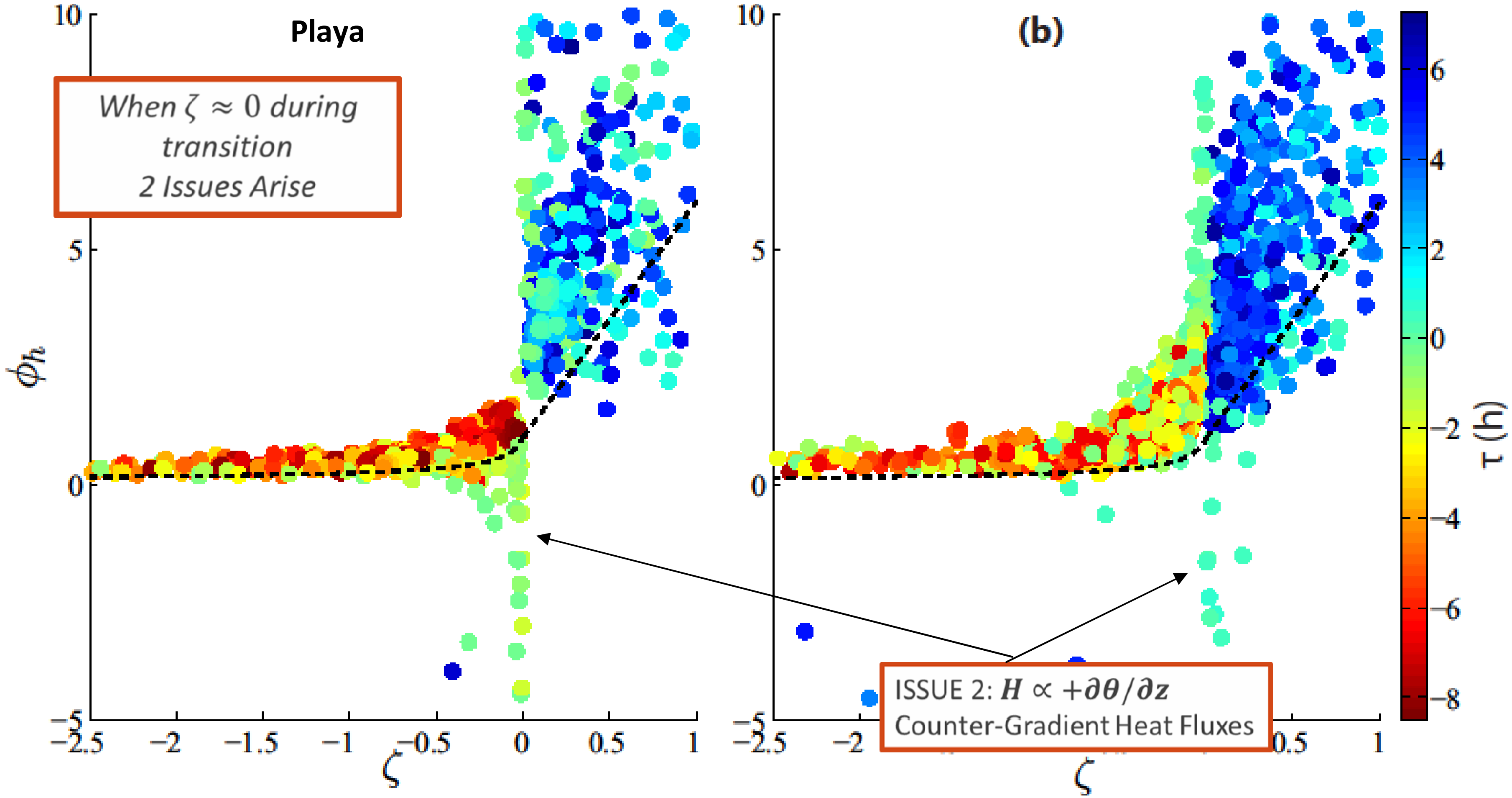


Playa
10
5
0
−5
ϕ_h
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
ζ
For Moderately unstable conditions
$\phi_{h,measured} \approx \phi_{h,accepted}$
MOST is Valid!
Dashed Line is the Accepted Form (Dyer and Hicks, 1970)
$\phi_h = 1 + 5\zeta \; for \; \zeta \geq 0$
$\phi_h = (1 - 16\zeta)^{-0.5} \; for \; \zeta < 0$
6
4
2
0
−2
−4
−6
−8
τ (h)


Playa
Sagebrush
For Moderately stable conditions
Large Scatter with "Some Trend"
MOST is Sort of Valid
ϕ_h
ζ
τ (h)
10
5
0
−5
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
6
4
2
−2
−4
−6
−8

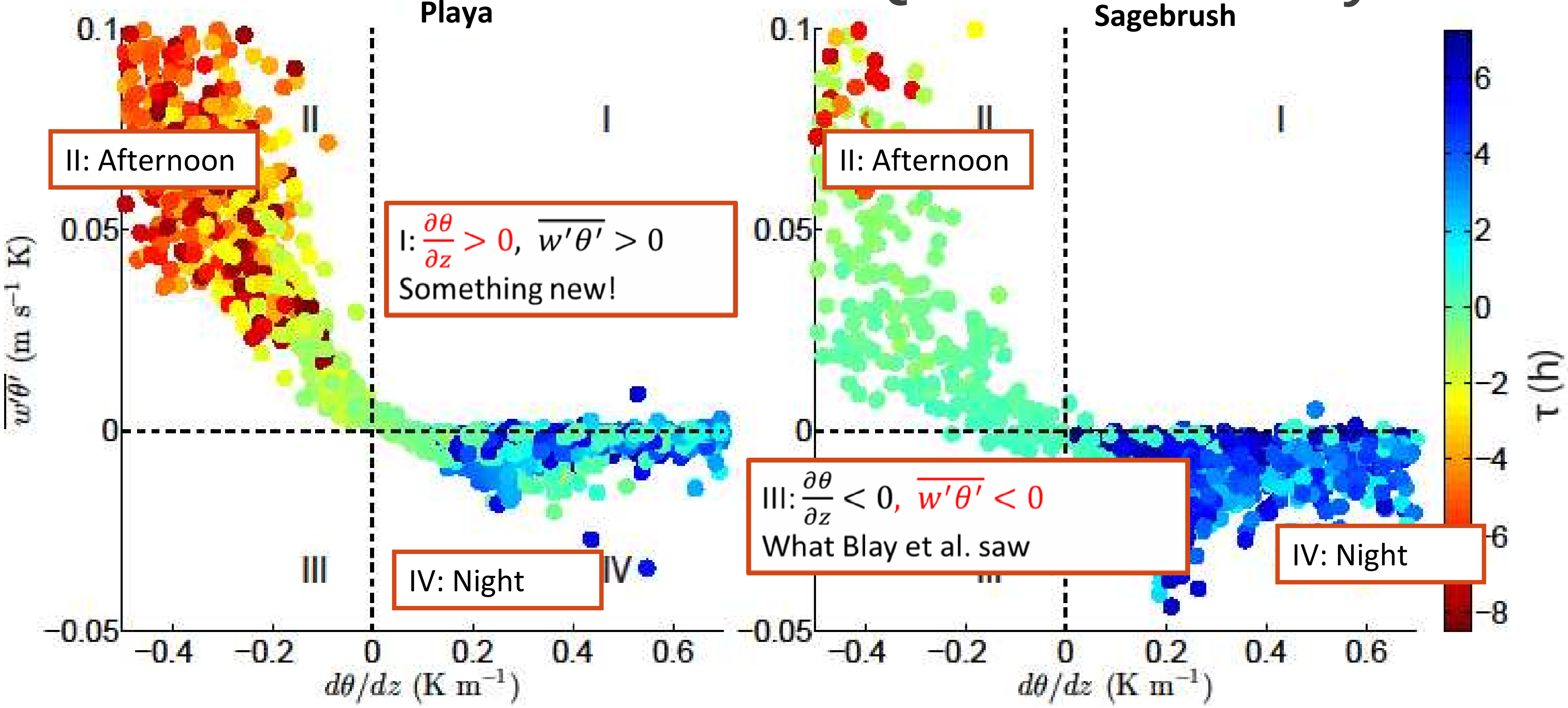


Playa
(b)
When ζ ≈ 0 during transition 2 Issues Arise
$\phi_h = \frac{\kappa z}{\theta_*}\frac{\partial \theta}{\partial z}$ where $\theta_* = -\frac{\overline{w'\theta'}}{u_*}$
ISSUE 1: Asymptotic Behavior
ϕ_h
ζ
τ (h)



Playa
(b)
When $\zeta \approx 0$ during transition
2 Issues Arise
ISSUE 2: $\boldsymbol{H} \propto +\partial\theta/\partial z$
Counter-Gradient Heat Fluxes
ϕ_h
ζ
τ (h)

Counter Gradient Fluxes: Quadrant Analysis



Time Scales

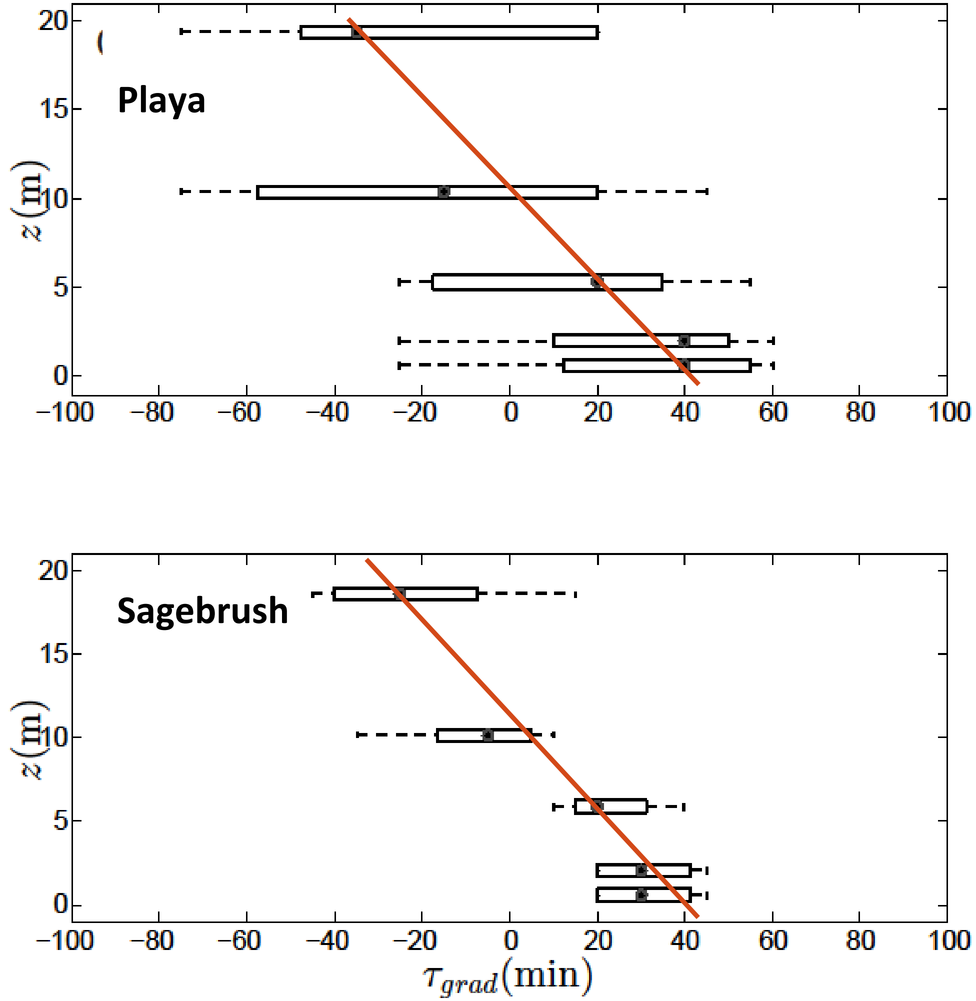
- Flux Reversal Time: $\tau_{flux} \equiv \tau_{H=0}$
- Gradient Reversal Time: $\tau_{grad} \equiv \tau_{\partial\theta/\partial z=0}$
- Lag Time: $t_{lag} = \tau_{flux} - \tau_{grad}$
  - $t_{lag} > 0$ when the **gradient reversal precedes the flux reversal**
  - $t_{lag} < 0$ when the **flux reversal precedes the gradient reversal (Blay et al.)**

Box Plots of τ_{grad}

1. Variability at Playa is large at all heights

2. Similar Trend at both sites

3. $\frac{\partial \tau_{grad}}{\partial z} \approx -4$ min m^{-1}

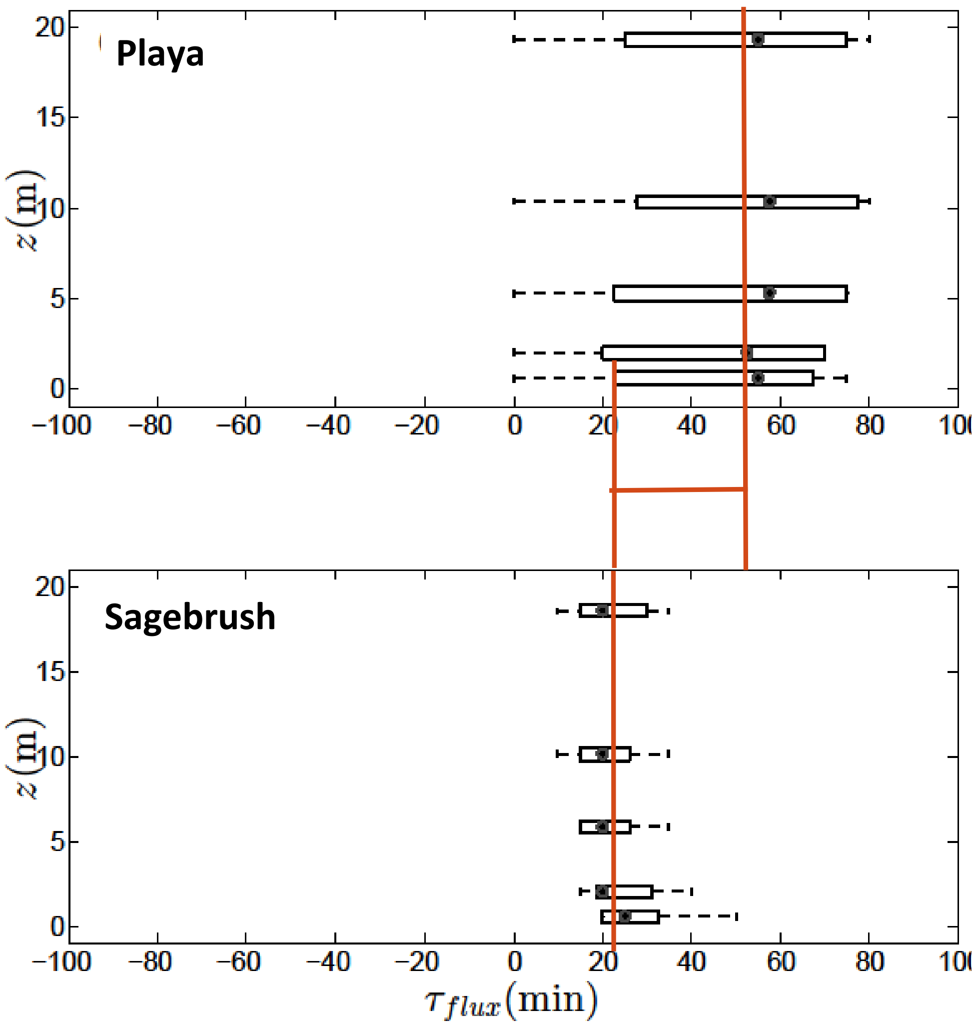


Box Plots of τ_{flux}

1. Again, Playa scatter is large

2. Occurs simultaneously at all heights

3. Median behavior of Playa lags Sagebrush by approximately 30 minutes



Box Plots of t_{lag}

1. Variability grows with height at both sites

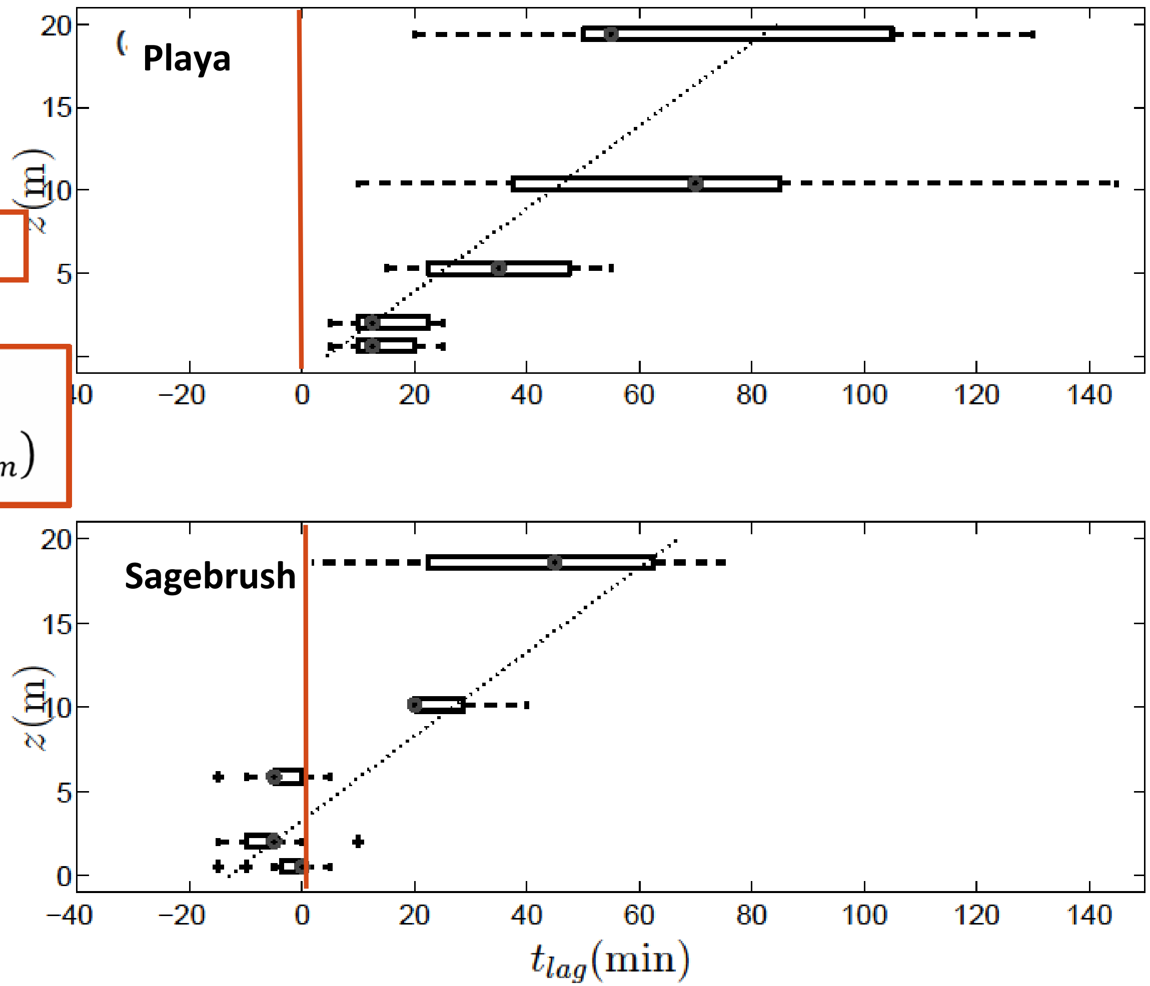
2. Dashed line computed from

$$t_{lag}(z) \approx -\frac{\partial \tau_{grad}}{\partial z}\Delta z - \left(\tau_{grad,2m} - \tau_{flux,2m}\right)$$

3. May be valid at other sites!

4. $t_{lag,Playa}(z) > 0$, i.e. gradient reversal precedes flux reversal

5. $t_{lag,Sagebrush}(z) > 0$ For $z \geq 10$ m
   $t_{lag,Sagebrush}(z) < 0$ For $z \leq 5$ m

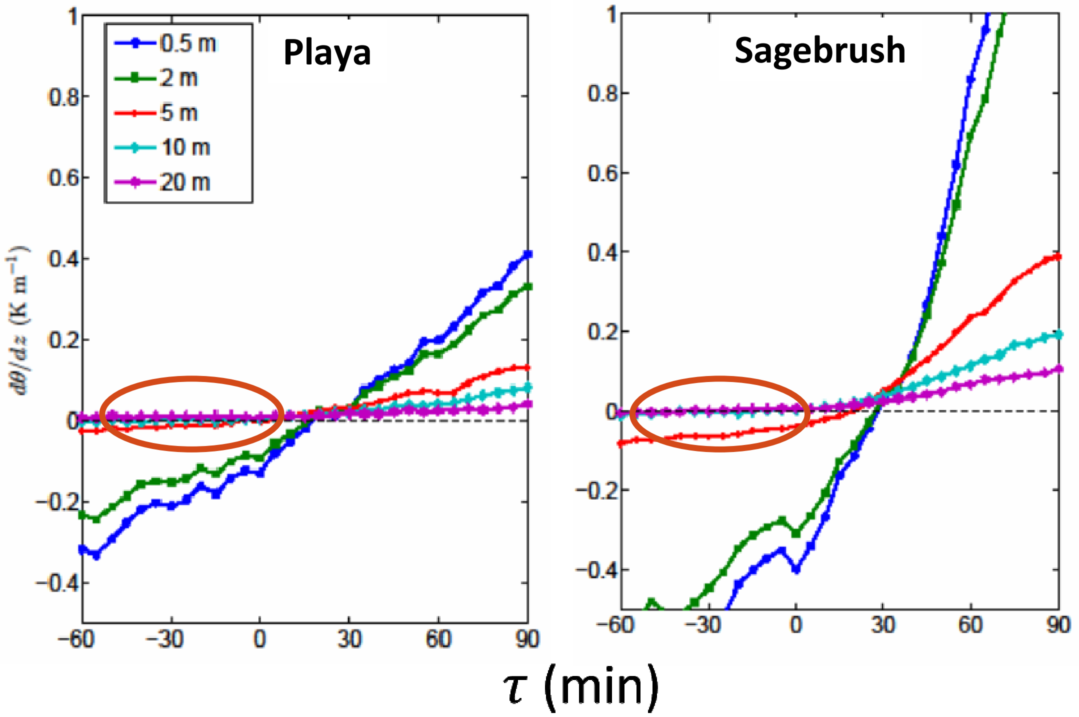


Gradient Evolution

1. Near-Neutral Stratification for 5m and above at Playa

2. Near-Neutral Stratification for 10m and above at Sagebrush with much stronger gradients at all heights

3. Gradient Stabilization occurs aloft, first. Does this mean that reversal is top-down?

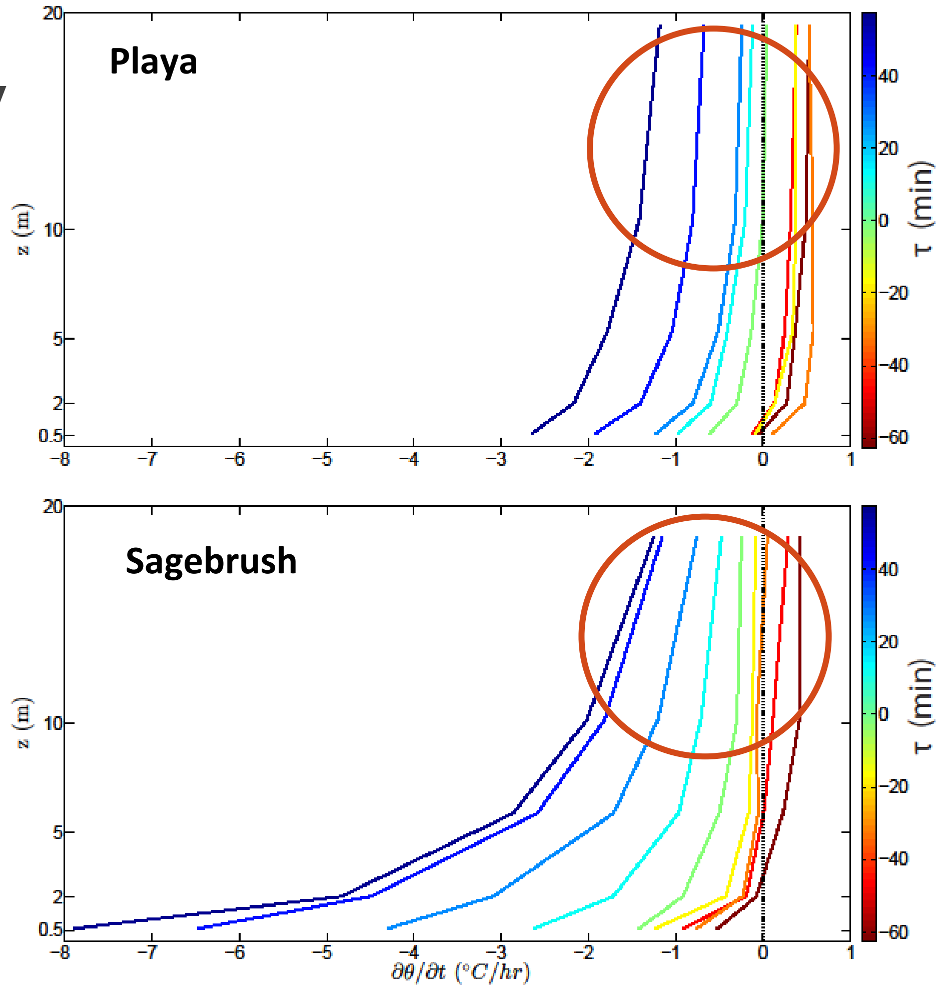


Temperature tendency

1. Cooling begins and is largest at the surface

2. When $\frac{\partial^2\theta}{\partial z \partial t} > 0$ stabilization is occurring

3. Stabilization is strongest at the surface but very weak stabilization is able to reverse the near-neutral gradients aloft.

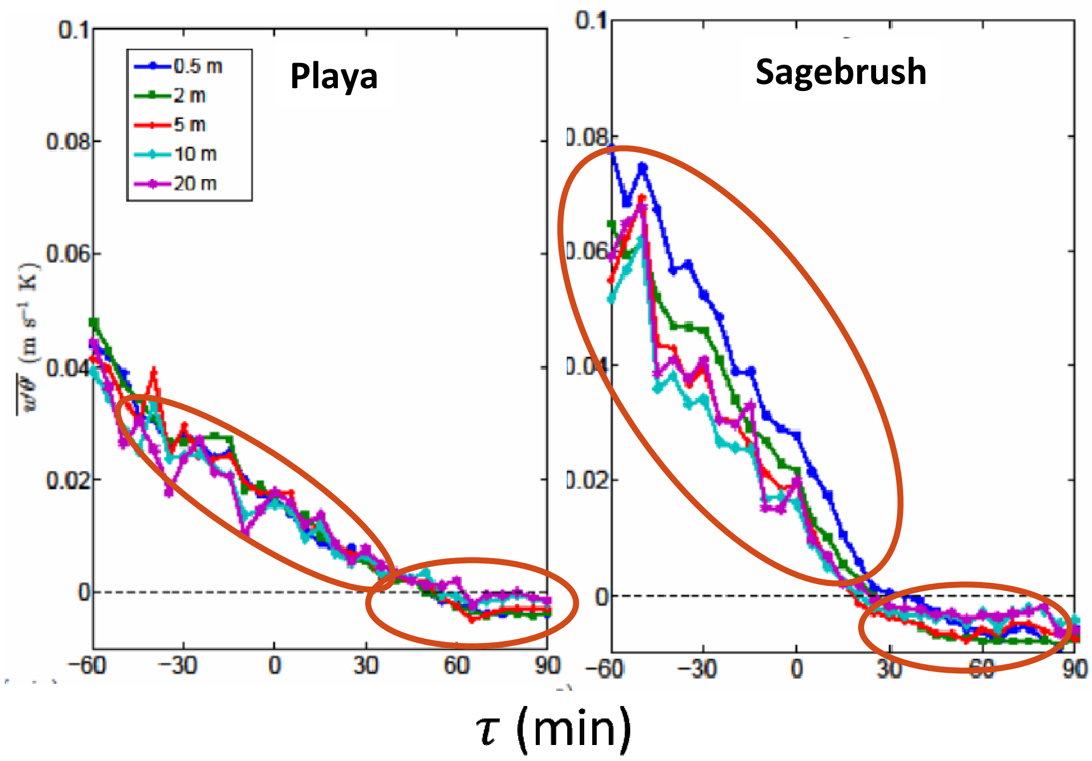


Flux Evolution

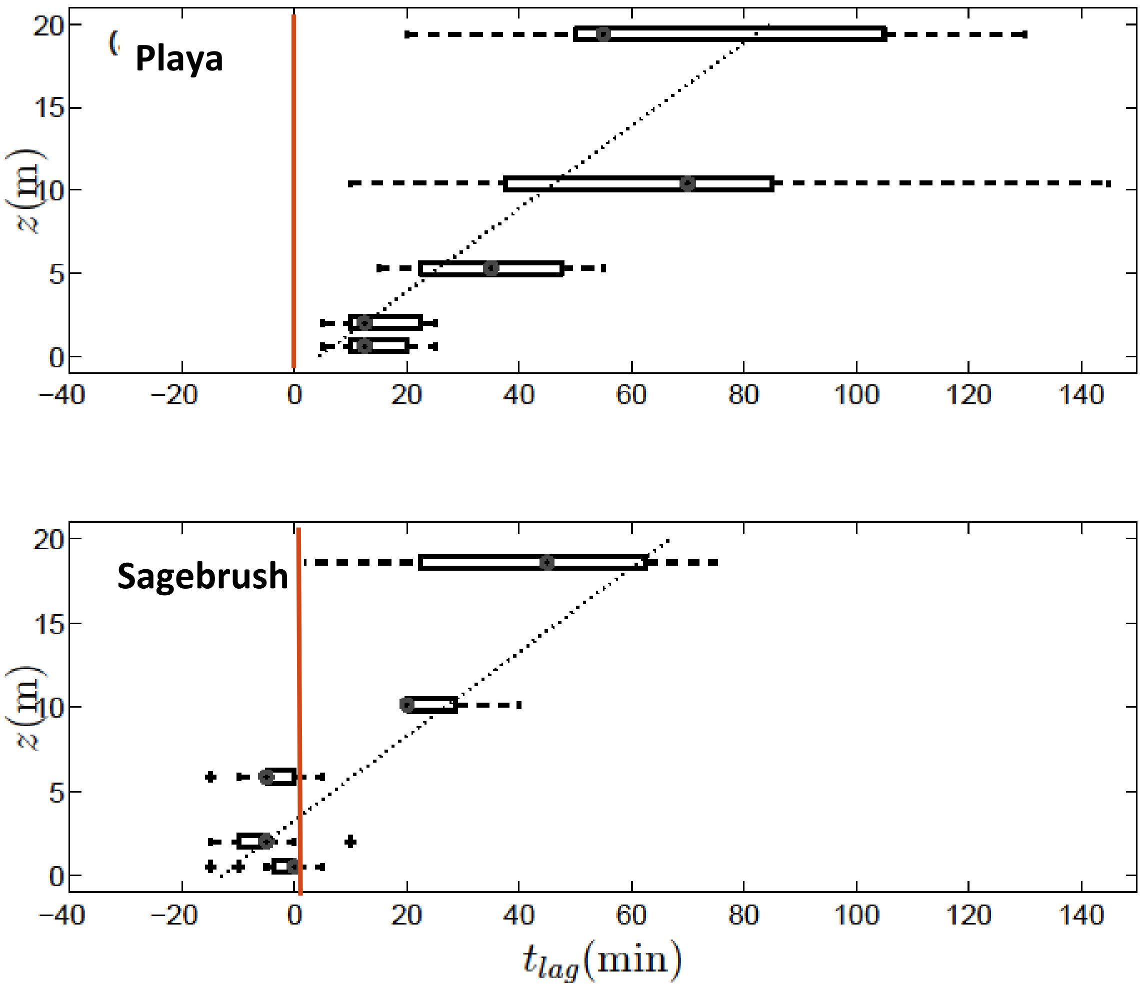
1. Much slower heat flux decay at Playa with little flux convergence

2. Weaker negative fluxes at Playa with some flux divergence developing at both sites.

Question: So what is responsible for the counter-gradient behavior?



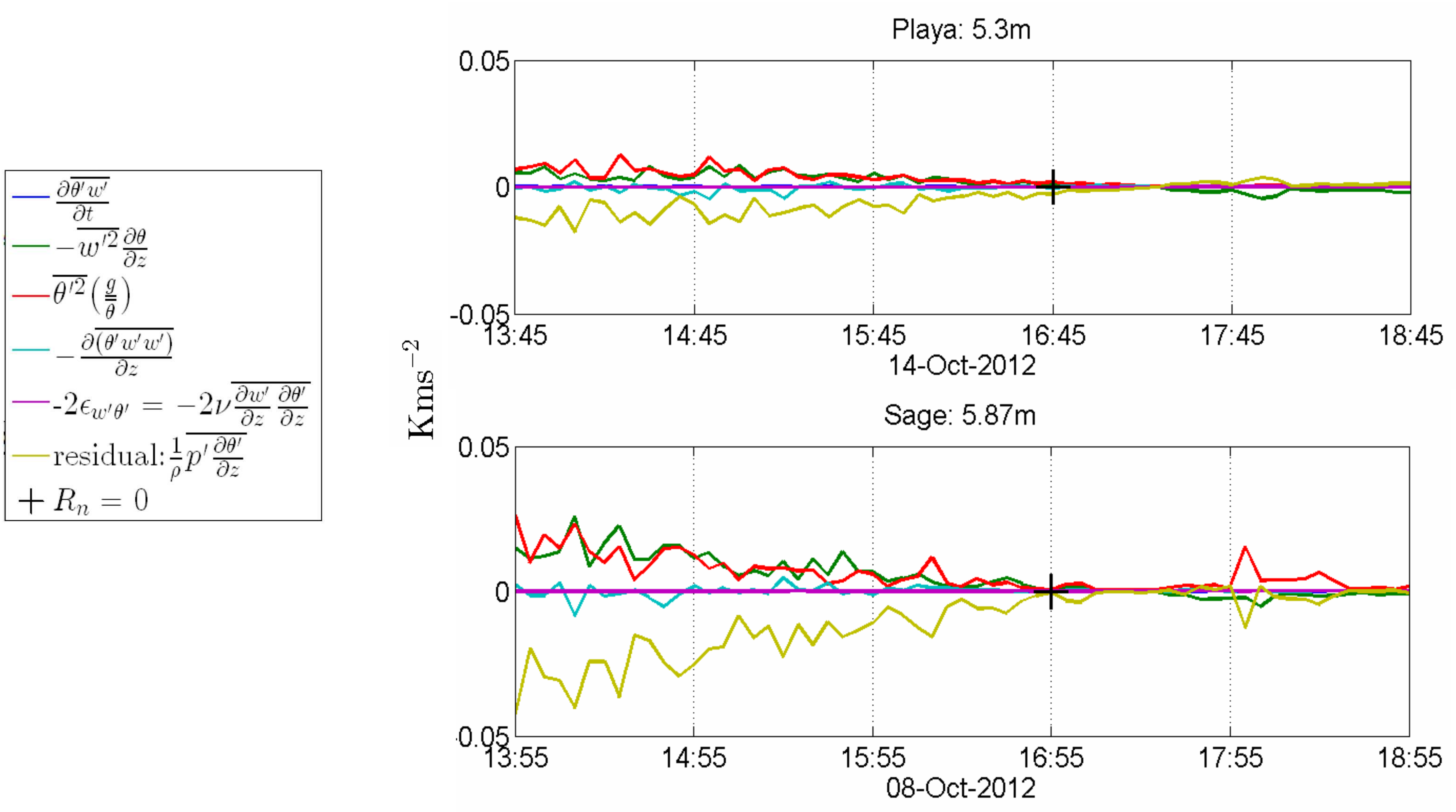
Flux Evolution: Reminder of What We Want to Understand



Simplified Heat Flux Tendency Equation

$$\frac{\partial\left(\overline{\theta' w'}\right)}{\partial t} = -\overline{w'^2}\frac{\partial\overline{\theta}}{\partial z} - \frac{\partial\left(\overline{\theta' w' w'}\right)}{\partial z} + \left(\overline{\theta'\theta_v'}\right)\left(\frac{g}{\overline{\theta}_v}\right) + \left(\frac{1}{\overline{\rho}}\right)\left[\overline{p'\frac{\partial\theta'}{\partial z}}\right] - 2\epsilon_{w\theta}$$

1. Storage: Explicitly calculated and very small
2. Gradient Production: Explicitly calculated. Pushes $t_{lag} \to 0$
3. Turbulent Transport: Explicitly calculated. Quite noisy and small
4. Buoyant Production: Explicitly calculated. Always positive $\to t_{lag} > 0$
5. Pressure correlation: Calculated as residual.
6. Dissipation: Will be calculated spectrally. It's quite small (Wyngaard, 1972)


$\frac{\partial \overline{\theta' w'}}{\partial t}$
$-\overline{w'^2}\frac{\partial \theta}{\partial z}$
$\overline{\theta'^2}\left(\frac{g}{\theta}\right)$
$-\frac{\partial(\overline{\theta' w' w'})}{\partial z}$
$-2\epsilon_{w'\theta'} = -2\nu\overline{\frac{\partial w'}{\partial z}\frac{\partial \theta'}{\partial z}}$
residual: $\frac{1}{\rho}\overline{p'\frac{\partial \theta'}{\partial z}}$
$+ R_n = 0$
Playa: 5.3m
0.05
0
-0.05
13:45
14:45
15:45
16:45
17:45
18:45
14-Oct-2012
Kms^{-2}
Sage: 5.87m
0.05
0
-0.05
13:55
14:55
15:55
16:55
17:55
18:55
08-Oct-2012

Simplified Heat Flux Tendency Equation

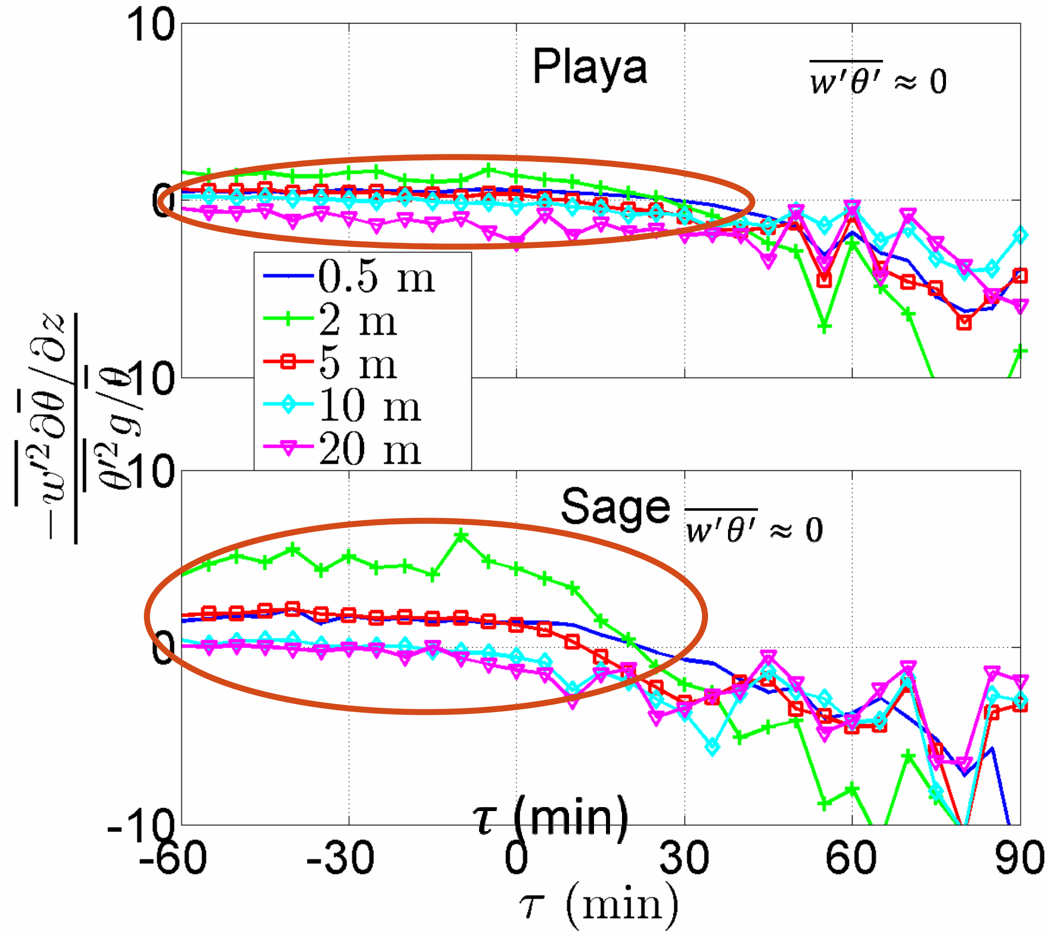
- $$\frac{\partial\left(\overline{\theta' w'}\right)}{\partial t} = -\overline{\boldsymbol{w}'^2}\frac{\partial\theta}{\partial z} - \frac{\partial\left(\overline{\theta' w' w'}\right)}{\partial z} + \left(\overline{\boldsymbol{\theta}'\boldsymbol{\theta}'_v}\right)\left(\frac{g}{\overline{\theta}_v}\right) + \left(\frac{1}{\rho}\right)\left[\overline{p'\frac{\partial\theta'}{\partial z}}\right] - 2\epsilon_{w\theta}$$
- Consider a ratio of 2 terms:
  - Gradient production→ $t_{lag} = 0$
  - Buoyant production (Always Positive) → $t_{lag} > 0$

Gradient Evolution

1. The gradient production (numerator) dominates buoyancy for low-levels at Sagebrush allowing for the same behavior as Blay et al. (Flux flips first).

2. Everywhere else, buoyancy forces the flux to remain positive after the gradient reverses

3. When the ratio is negative, the two terms are working against one another. Flux reversal occurs for a ratio of ~ -2.5 at both sites



Conclusions

- Counter-gradient (CG) heat fluxes occur at both sites. At Playa, the CG flux is always due to the gradient reversal occurring before the flux reversal.
- Sagebrush has the same CG behavior as Playa above 5 m and the opposite for 5 m and below.
- Although cooling is bottom-up, gradient reversal is top-down at a rate of ~4 min m^{-1}.
- Flux reversal occurs nearly simultaneously at all heights.
- The CG behavior is due to the relative importance of the gradient and buoyant production terms in the heat flux budget equation.

Thank you!