Numerical modeling of slope flows observed during the VTMX Slope Experiment

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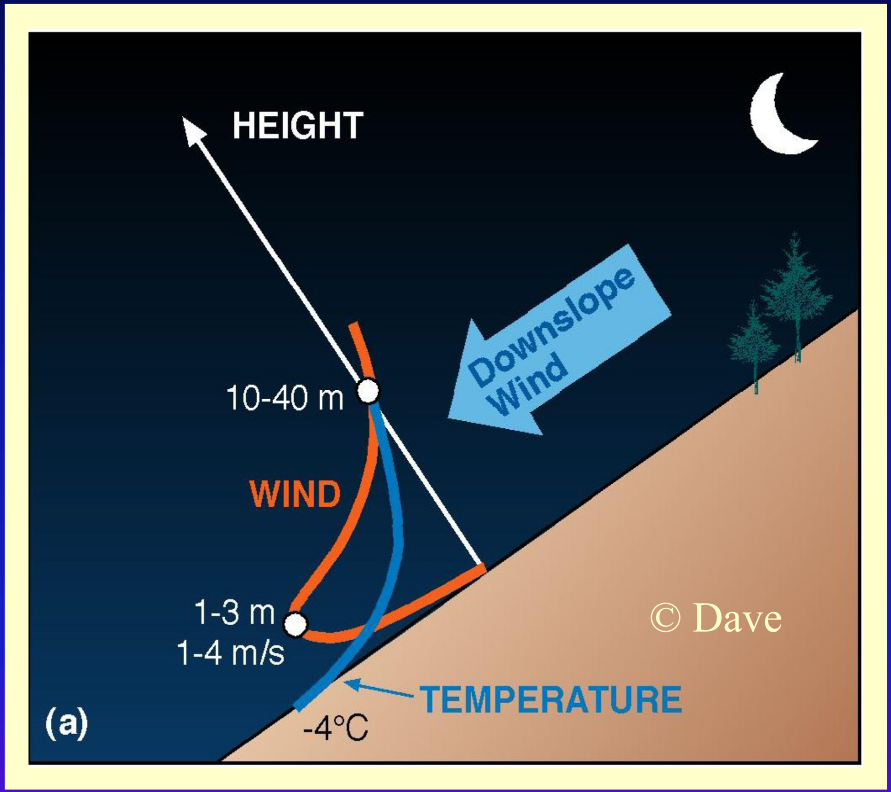
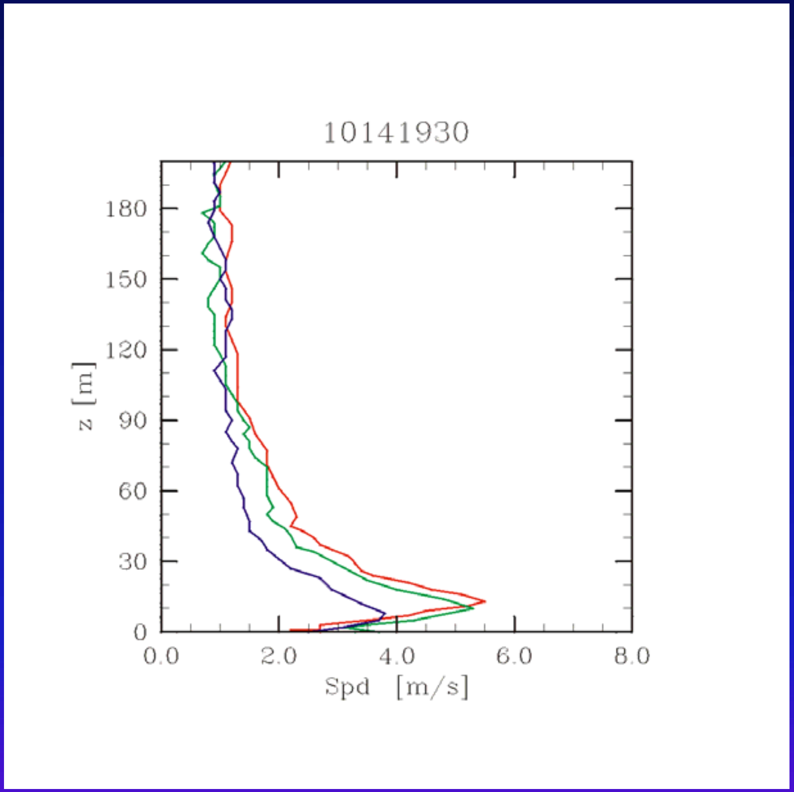
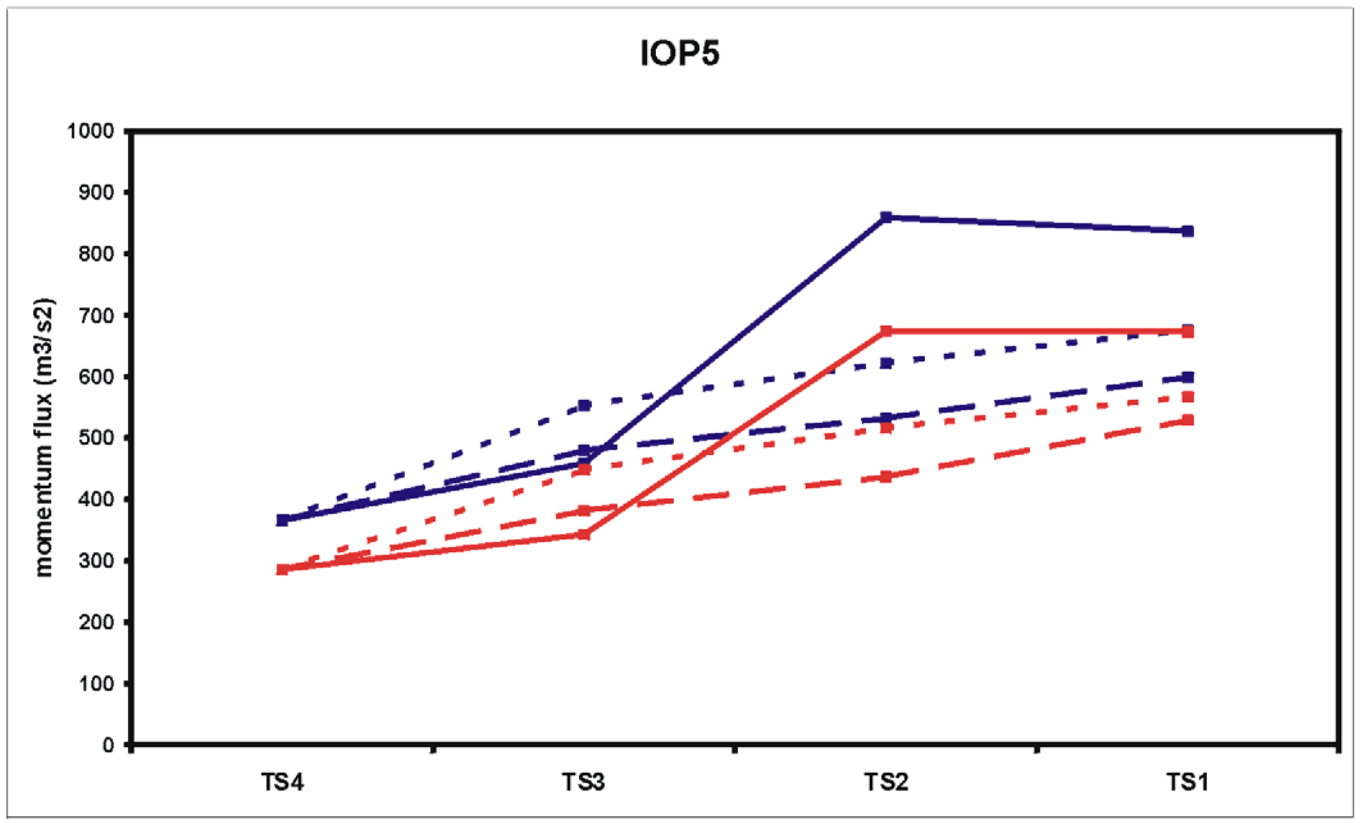
Observed slope flows were stronger and deeper than usual

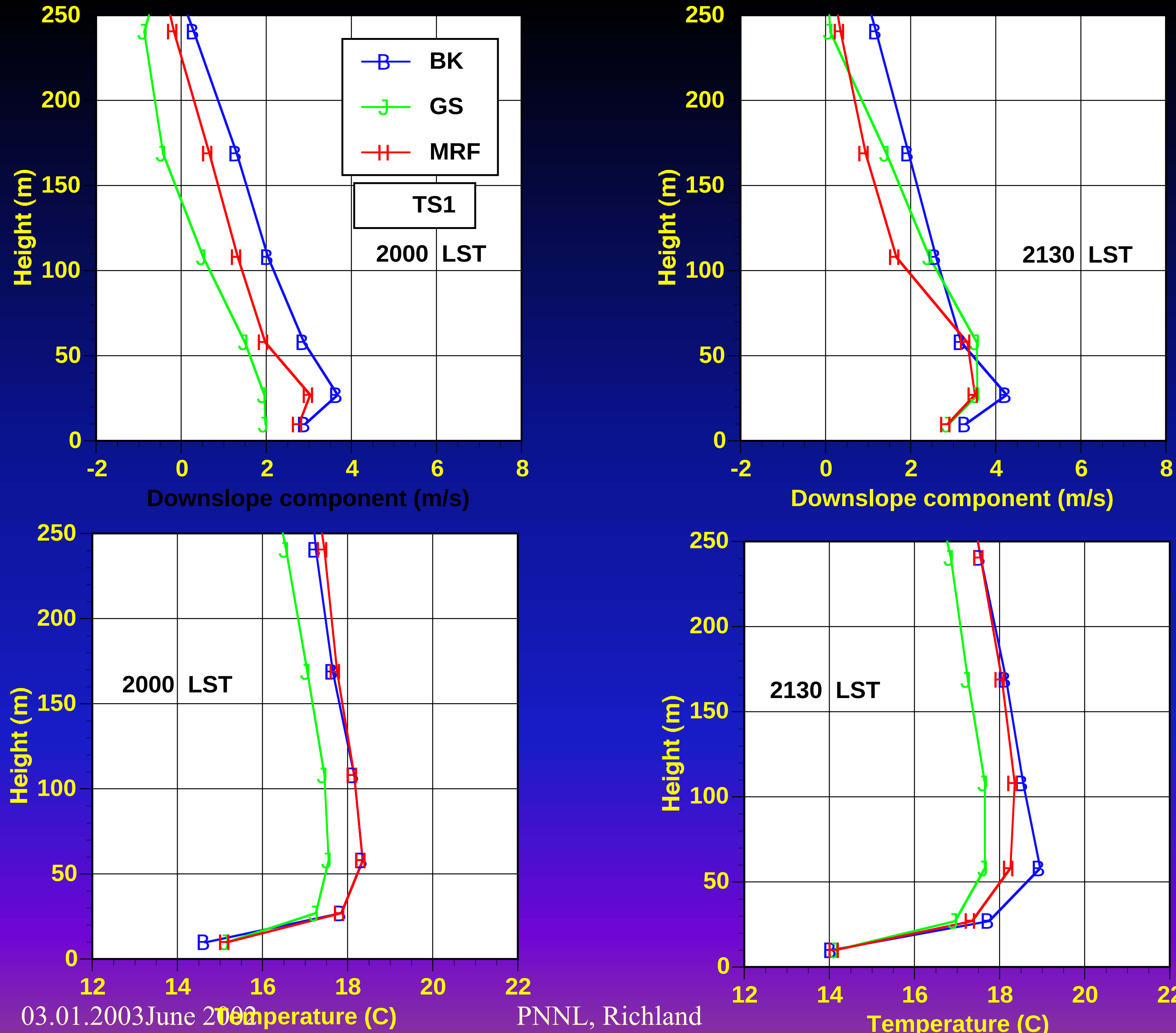




Analytical models fail to explain the observations



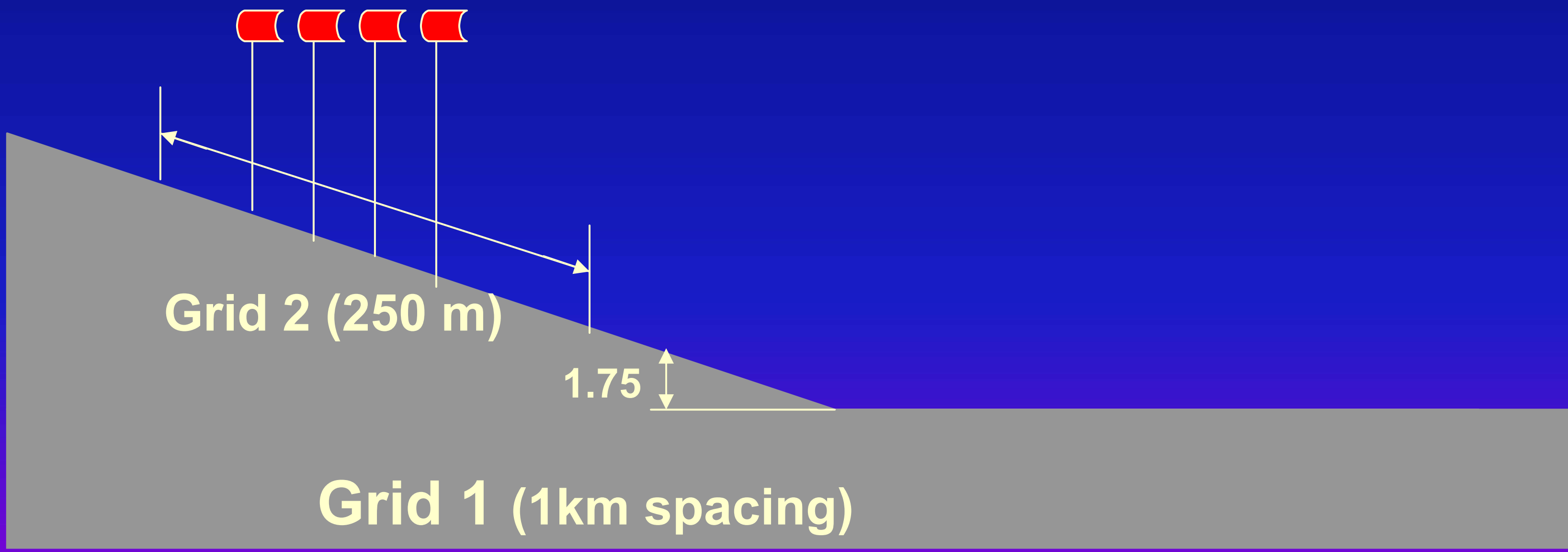
- Can the model simulate the characteristics of the downslope winds (strengths, depths, jet heights, mass and momentum fluxes ..) observed on the low-angle slope in the Salt Lake Valley?
- Can the model simulate the observed along-slope variations and the variations among the IOPs?
- If so, can the model help us understand what's going on ?
- How sensitive are the flow characteristics to external parameters (slope angle, ambient winds, roughness length, ambient stability …) ?
- What else can we learn from the model ?


BK
GS
MRF
TS1
2000 LST
2130 LST
Height (m)
Downslope component (m/s)
Temperature (C)
0
50
100
150
200
250
-2
0
2
4
6
8
12
14
16
18
20
22

RAMS Model Configuration

Two grids using 1000 and 250 m grid spacing

Vertical grid spacing: 1, 3, 5, 7, 10, 13, 16, 19, 23, 27, 31, 36, 41, 49, 57, 64, 71, 87, 96, 105 ...



RAMS Model Configuration

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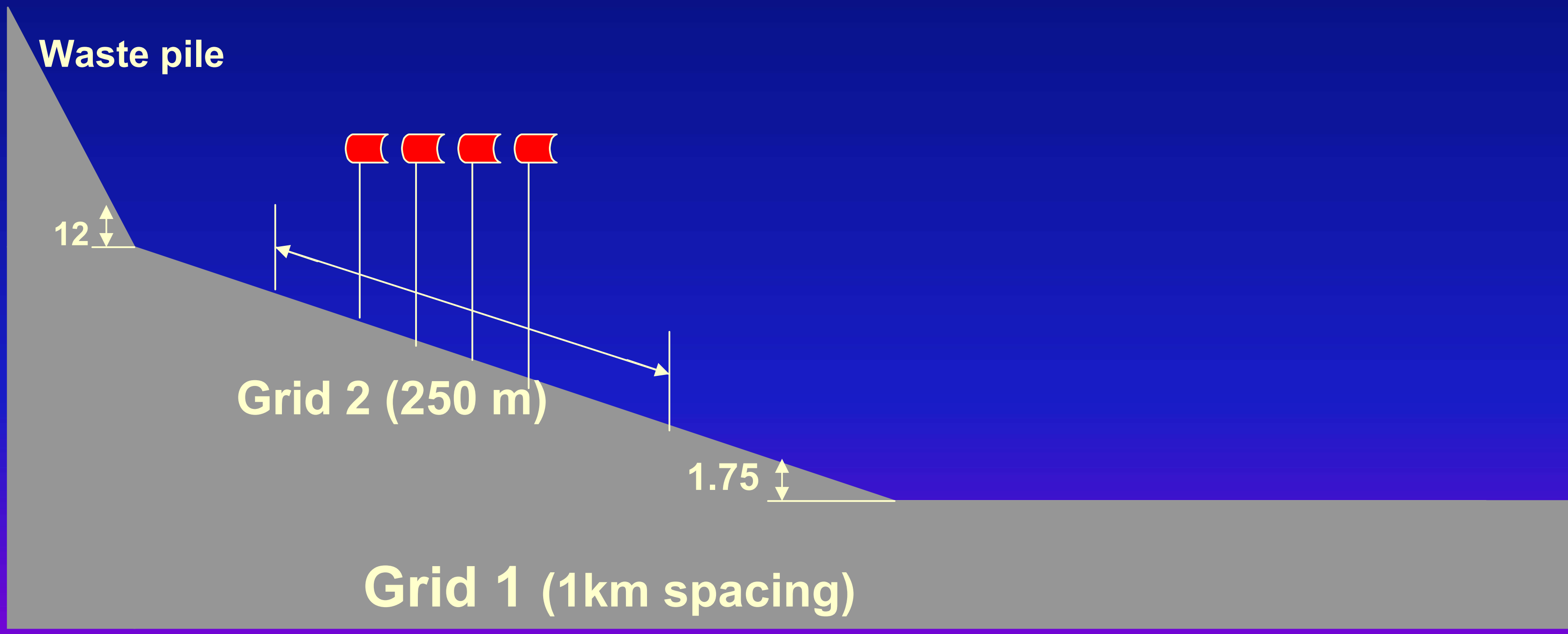
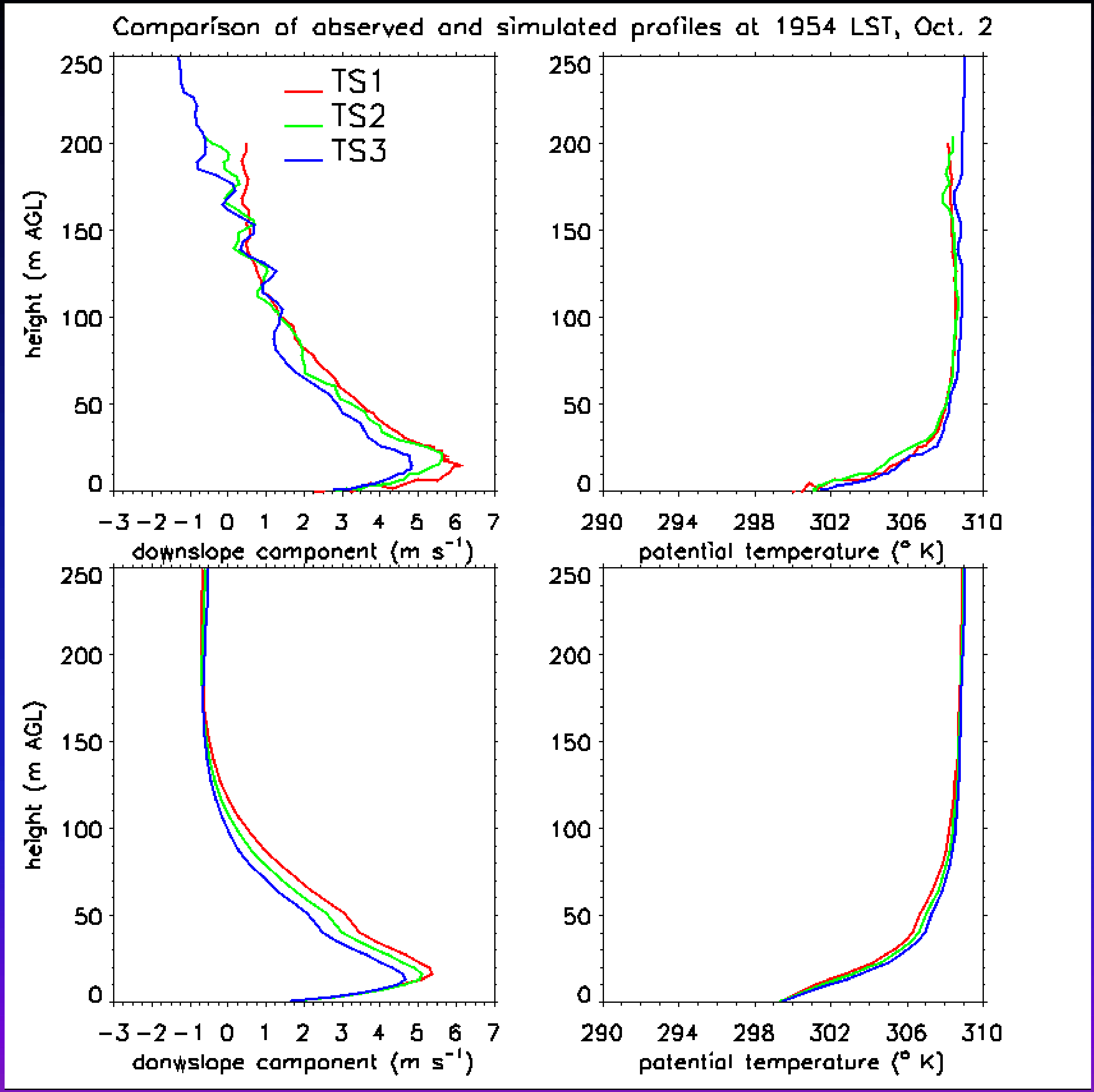
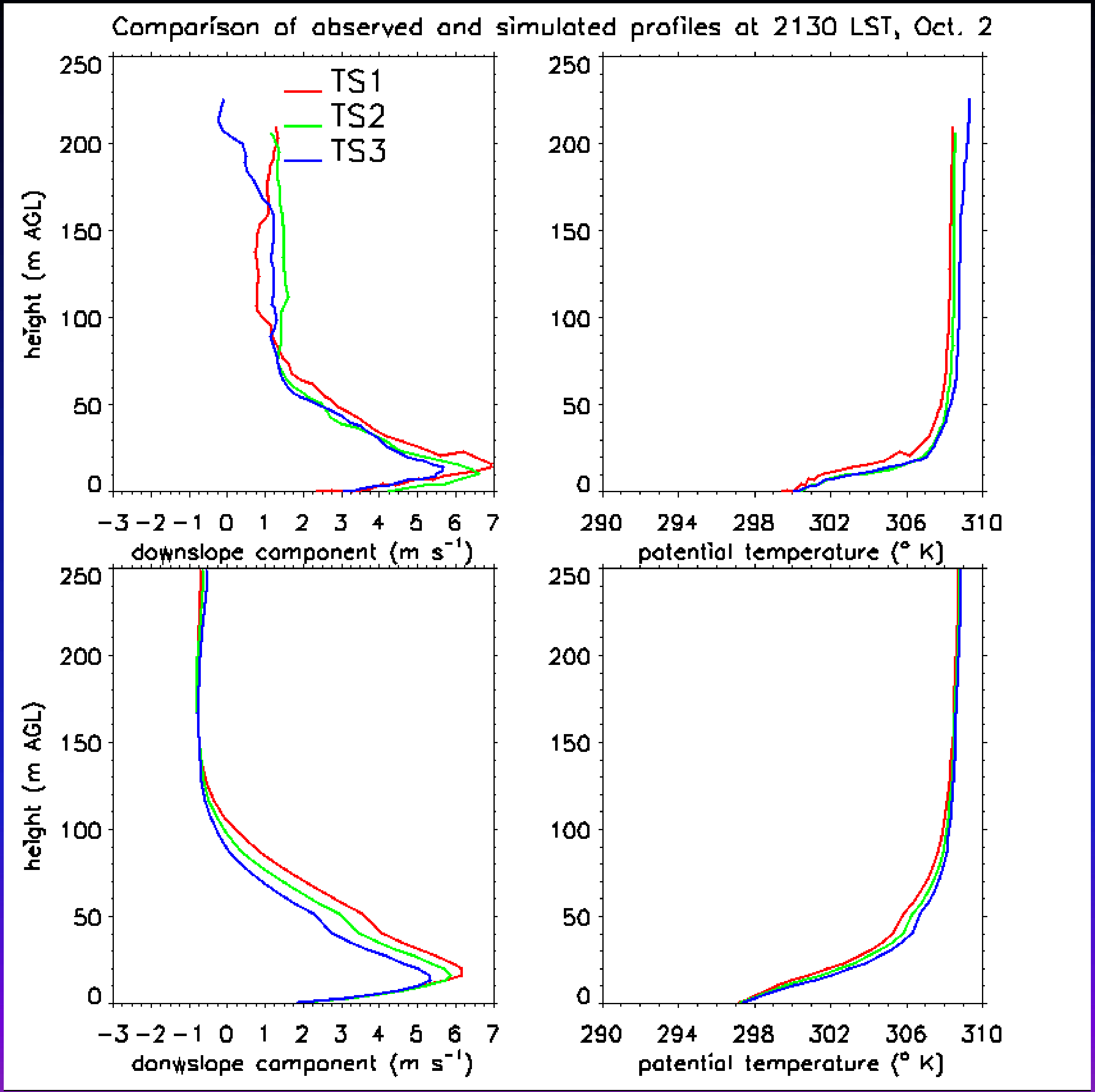
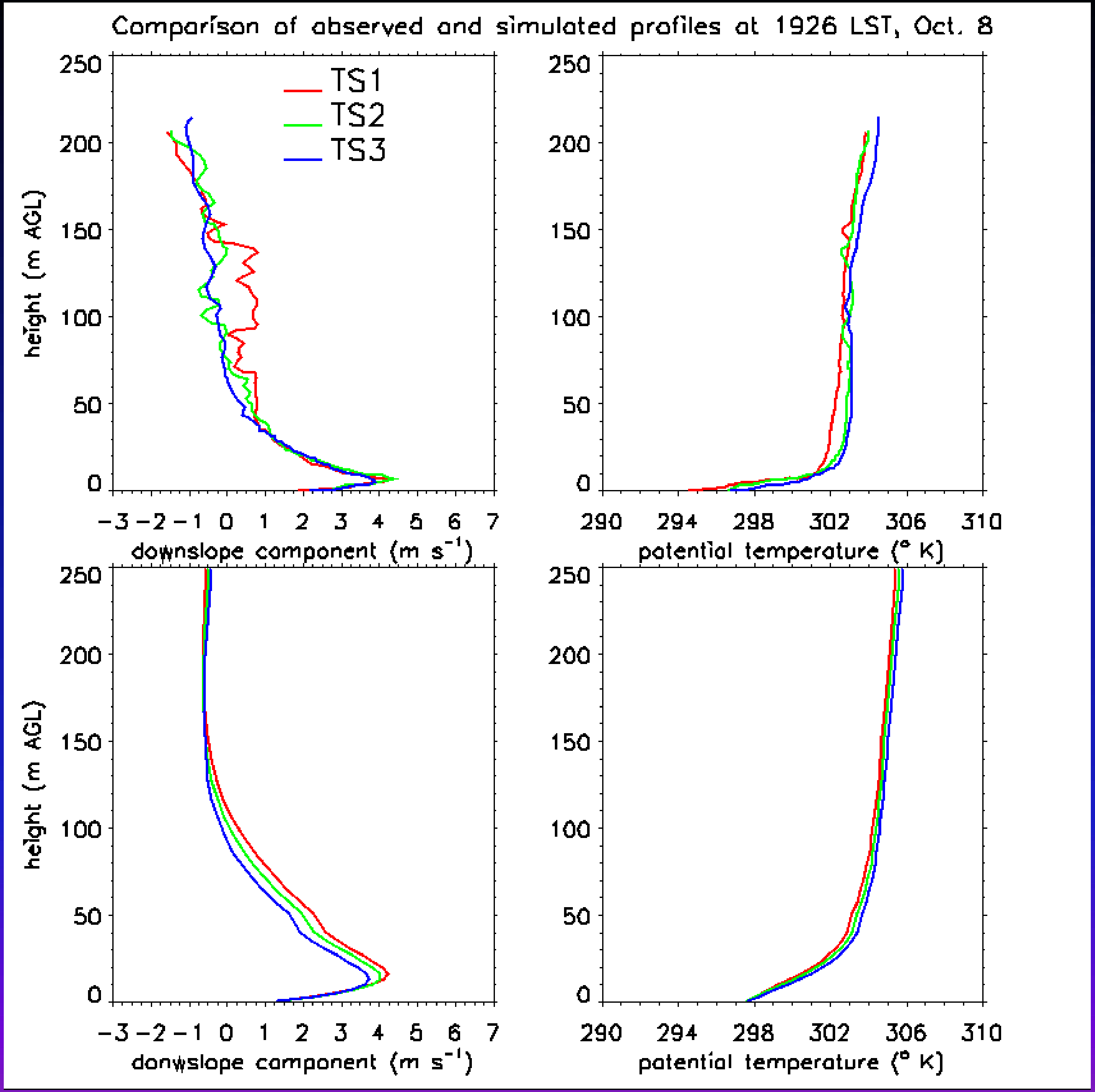
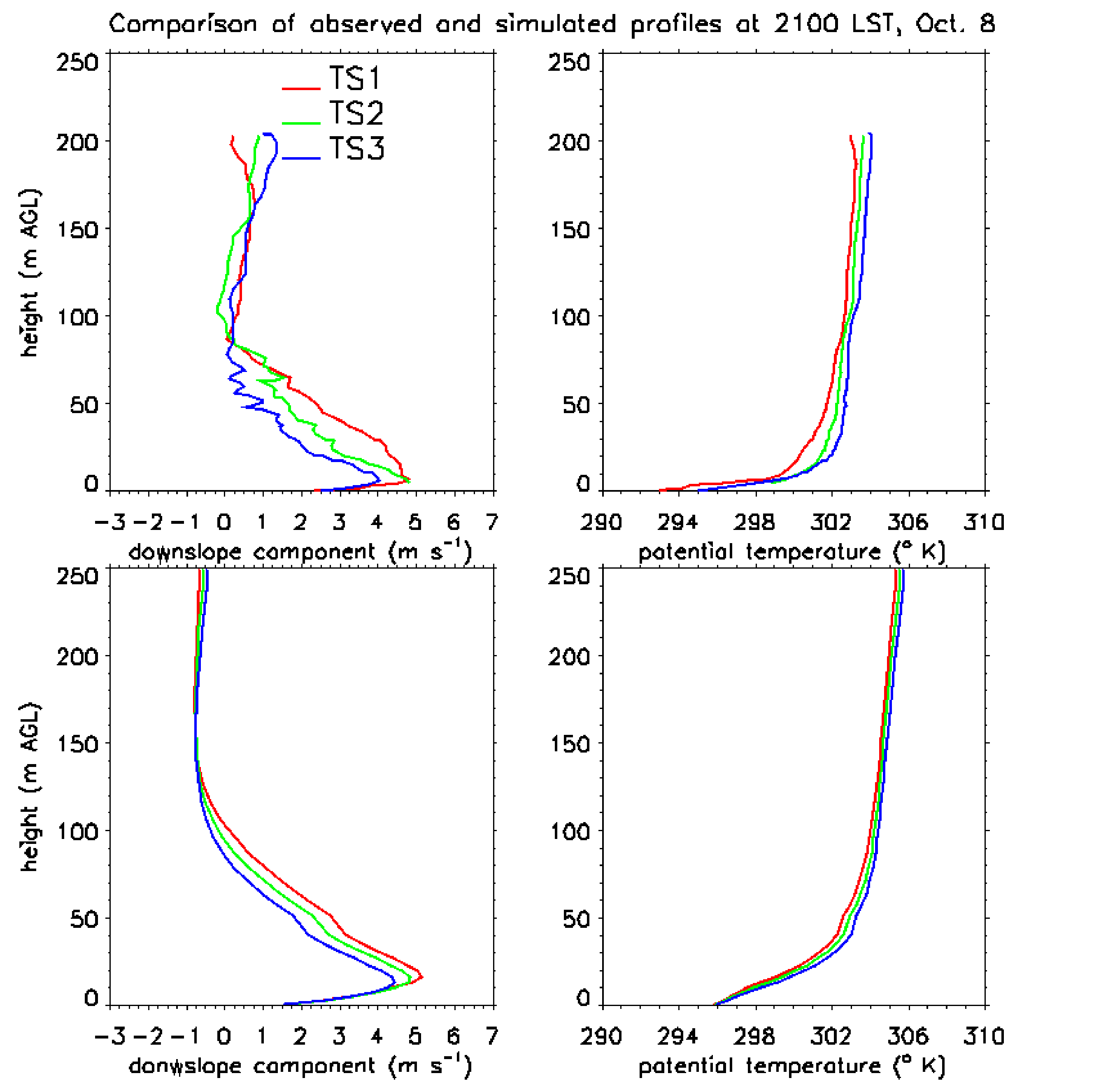



Comparison of observed and simulated profiles at 1954 LST, Oct. 2
TS1
TS2
TS3
height (m AGL)
downslope component (m s⁻¹)
potential temperature (° K)
0
50
100
150
200
250
-3 -2 -1 0 1 2 3 4 5 6 7
290 294 298 302 306 310


Comparison of observed and simulated profiles at 2130 LST, Oct. 2
TS1
TS2
TS3
height (m AGL)
downslope component (m s⁻¹)
potential temperature (° K)
250
200
150
100
50
0
−3 −2 −1 0 1 2 3 4 5 6 7
290 294 298 302 306 310

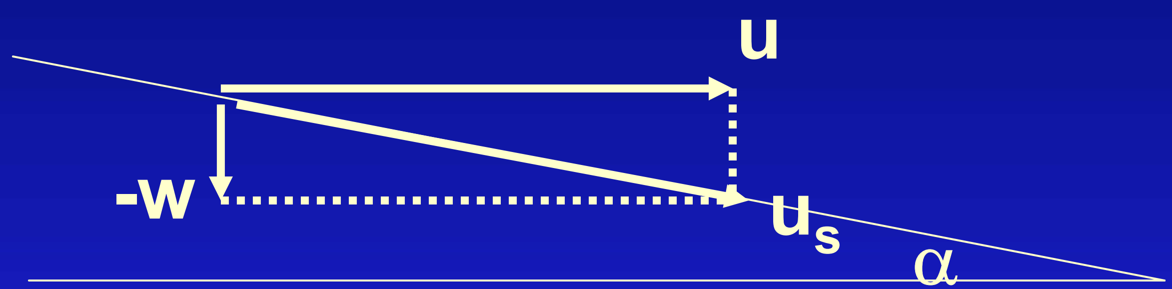

Comparison of observed and simulated profiles at 1926 LST, Oct. 8
TS1
TS2
TS3
height (m AGL)
downslope component (m s^{-1})
potential temperature (° K)
250
200
150
100
50
0
-3 -2 -1 0 1 2 3 4 5 6 7
290 294 298 302 306 310



Comparison of observed and simulated profiles at 2100 LST, Oct. 8
TS1
TS2
TS3
height (m AGL)
downslope component (m s^{-1})
potential temperature (° K)
height (m AGL)
downslope component (m s^{-1})
potential temperature (° K)

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - w\frac{\partial u}{\partial z} - \frac{1}{\rho}\frac{\partial p'}{\partial x} + \frac{\partial}{\partial z}K\frac{\partial u}{\partial z}$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - w\frac{\partial w}{\partial z} - \frac{1}{\rho}\frac{\partial p'}{\partial z} - g\frac{\theta}{\theta_0}$$



$$u_s = u\cos\alpha - w\sin\alpha$$

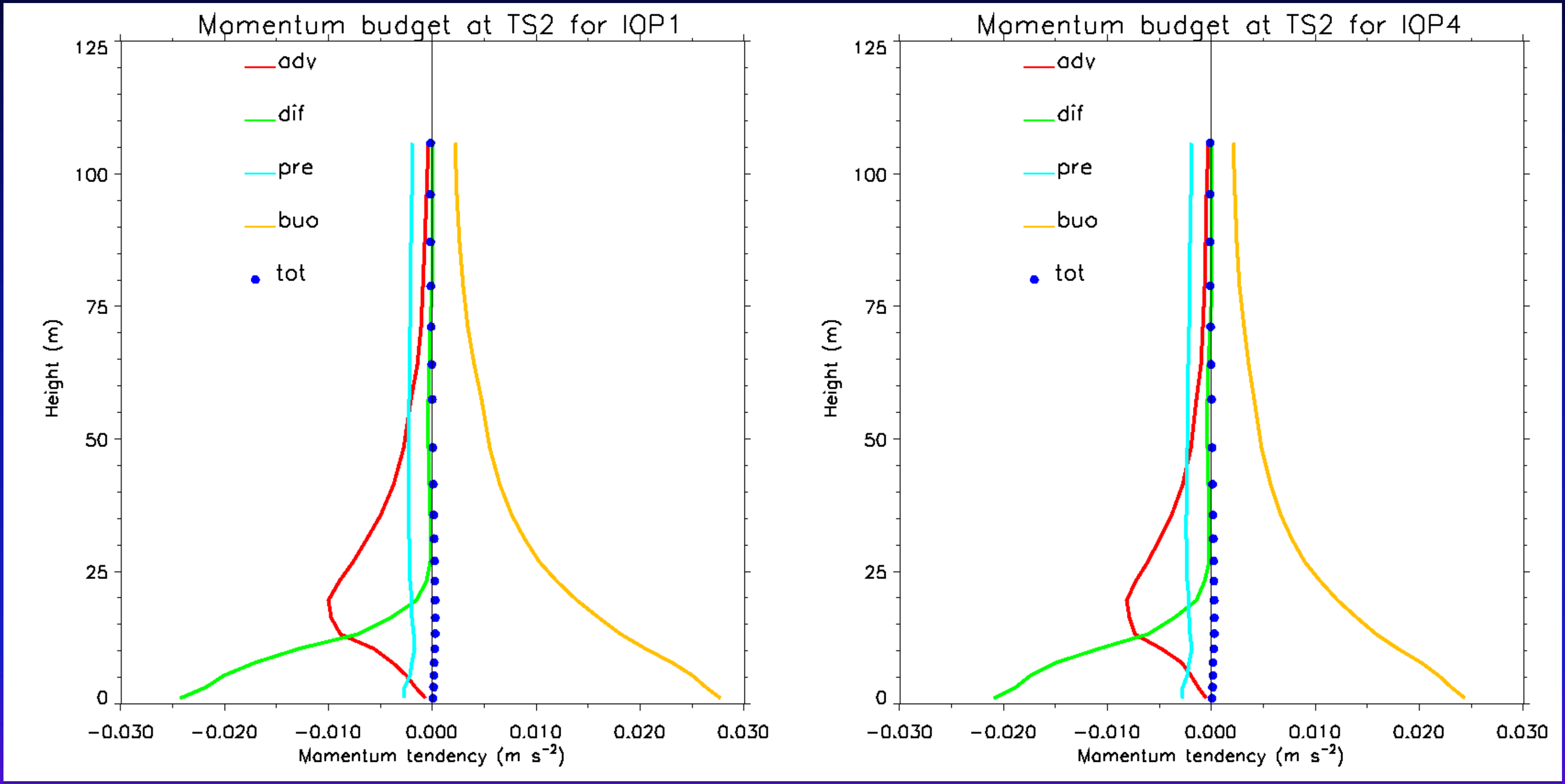
$$\frac{\partial u_s}{\partial t} = \frac{\partial u}{\partial t}\cos\alpha - \frac{\partial w}{\partial t}\sin\alpha$$

Along-slope momentum equation

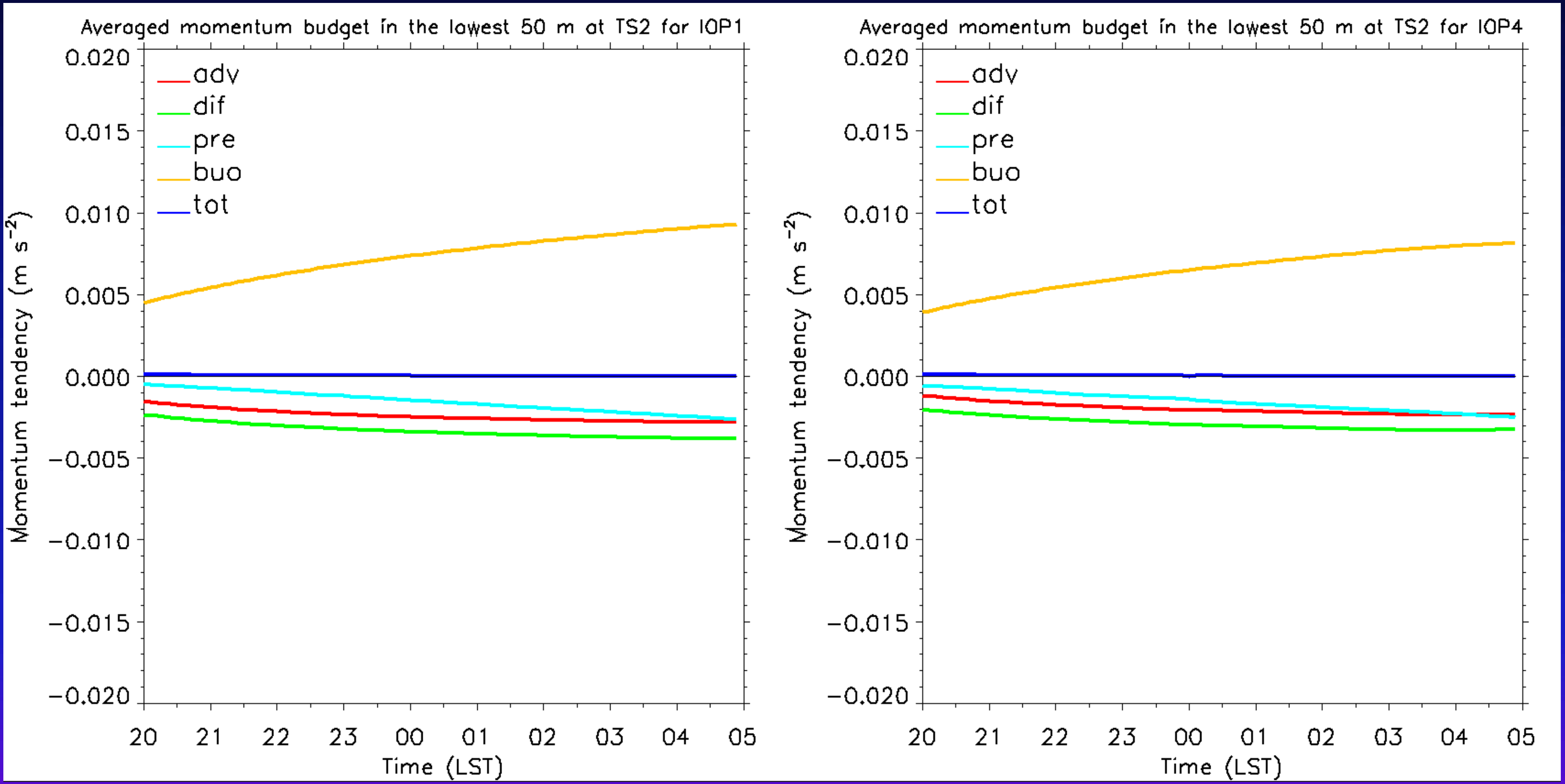
$$\frac{\partial}{\partial t}(u\cos\alpha - w\sin\alpha) = -u\frac{\partial}{\partial x}(u\cos\alpha - w\sin\alpha) - w\frac{\partial}{\partial z}(u\cos\alpha - w\sin\alpha)$$
$$-\frac{1}{\rho}\left(\frac{\partial p'}{\partial x}\cos\alpha - \frac{\partial p'}{\partial z}\sin\alpha\right) + \frac{\partial}{\partial z}K\frac{\partial u}{\partial z}\cos\alpha + g\frac{\theta}{\theta_0}\sin\alpha$$

$$\underbrace{\frac{\partial u_s}{\partial t}}_{Storage} = \underbrace{-u\frac{\partial u_s}{\partial x} - w\frac{\partial u_s}{\partial z}}_{advection} - \underbrace{\frac{1}{\rho}\frac{\partial p'}{\partial s}}_{pressure-gradient} + \underbrace{\frac{\partial}{\partial z}K\frac{\partial u}{\partial z}\cos\alpha}_{diffusion} + \underbrace{g\frac{\theta}{\theta_0}\sin\alpha}_{buoyancy}$$

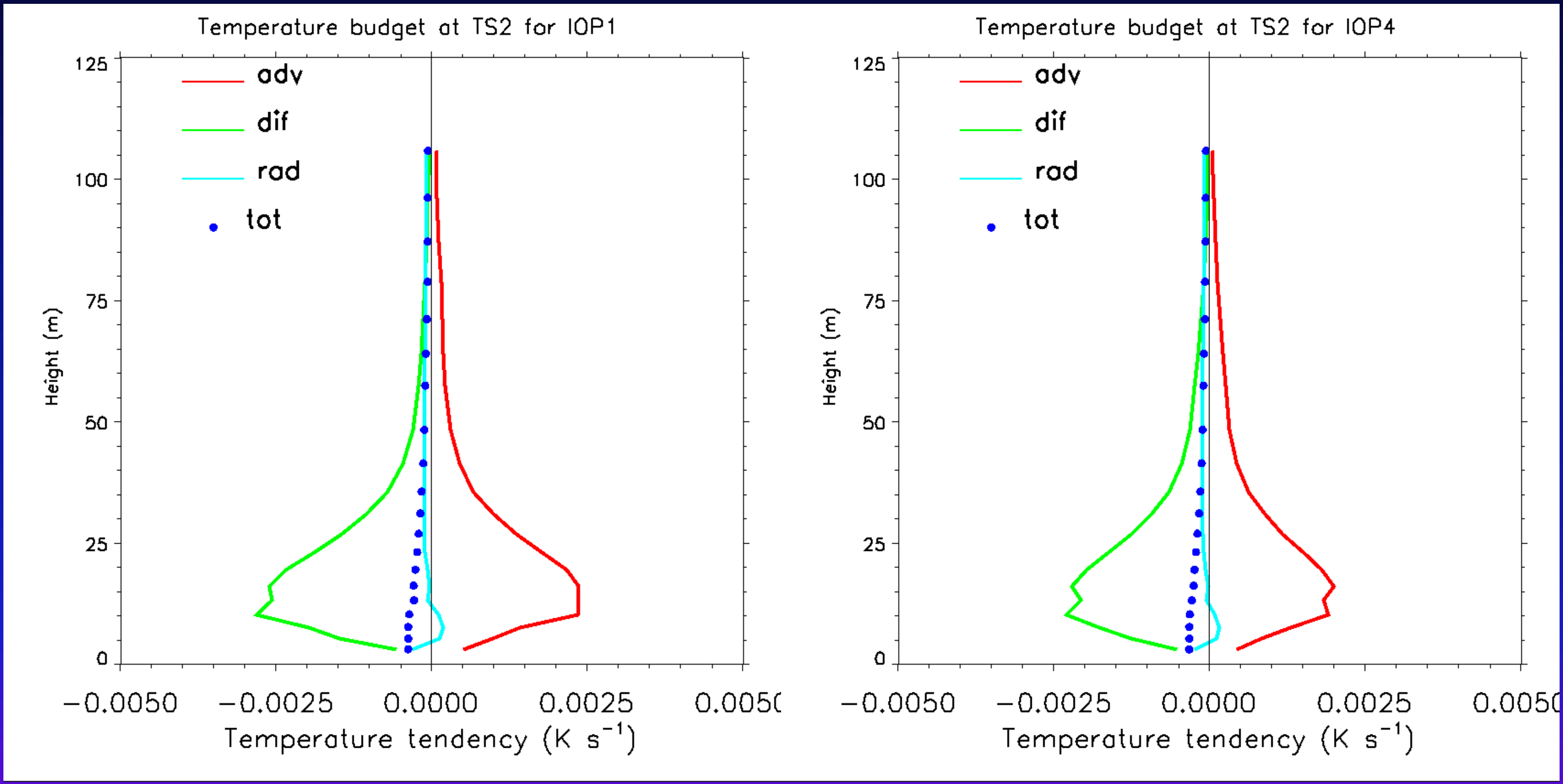
Momentum tendency between 20-22 LST at TS2



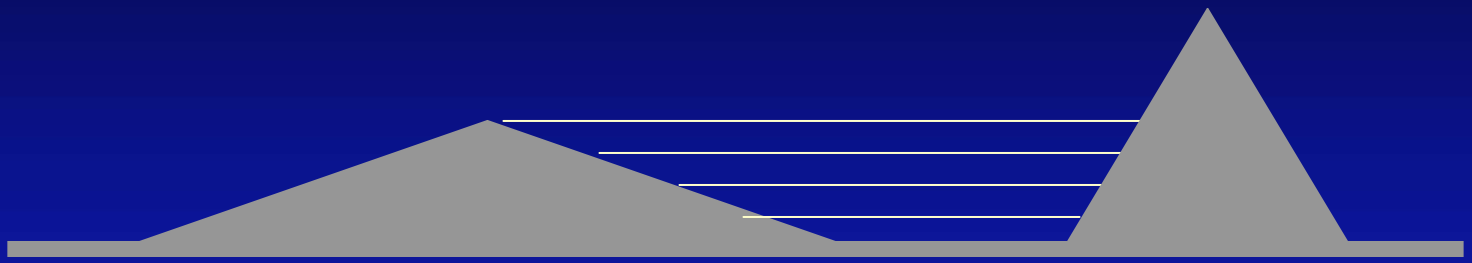
Momentum tendency averaged in the lowest 50 m

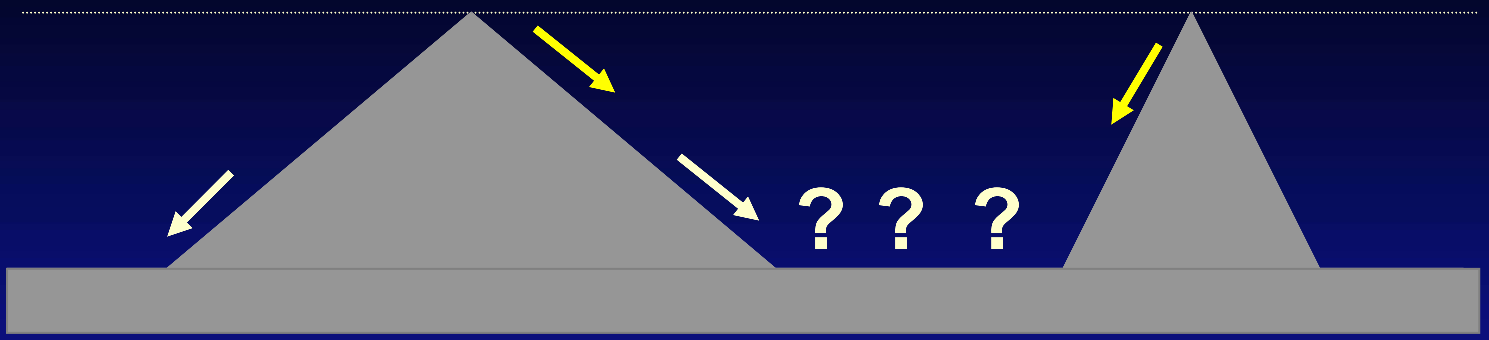


Slope flow heat budget at TS1



Interaction of slope flow with cold pool buildup

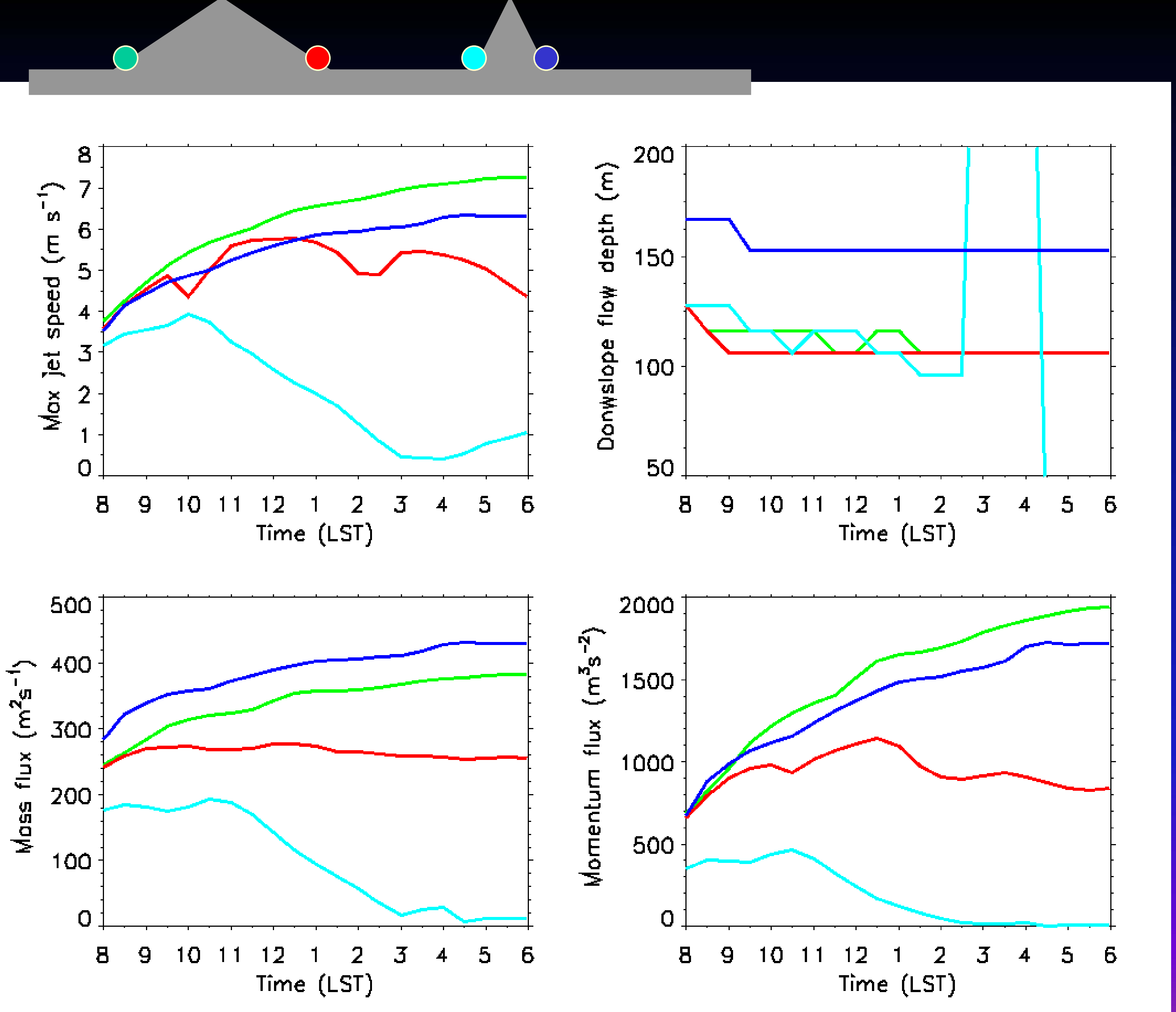




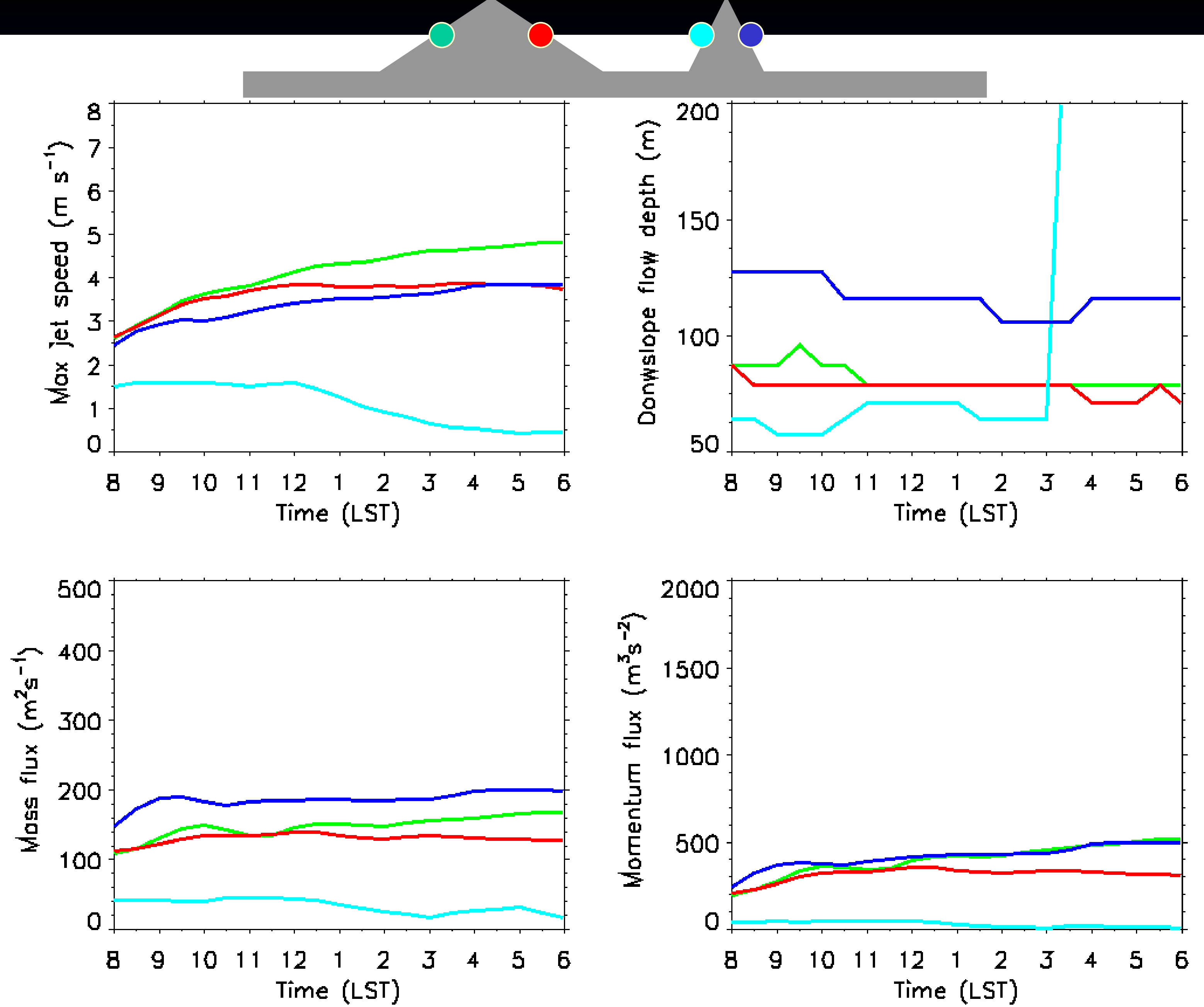
Where does the convergence zone occur ?

On which side is the downslope flow stronger, plain or valley side?

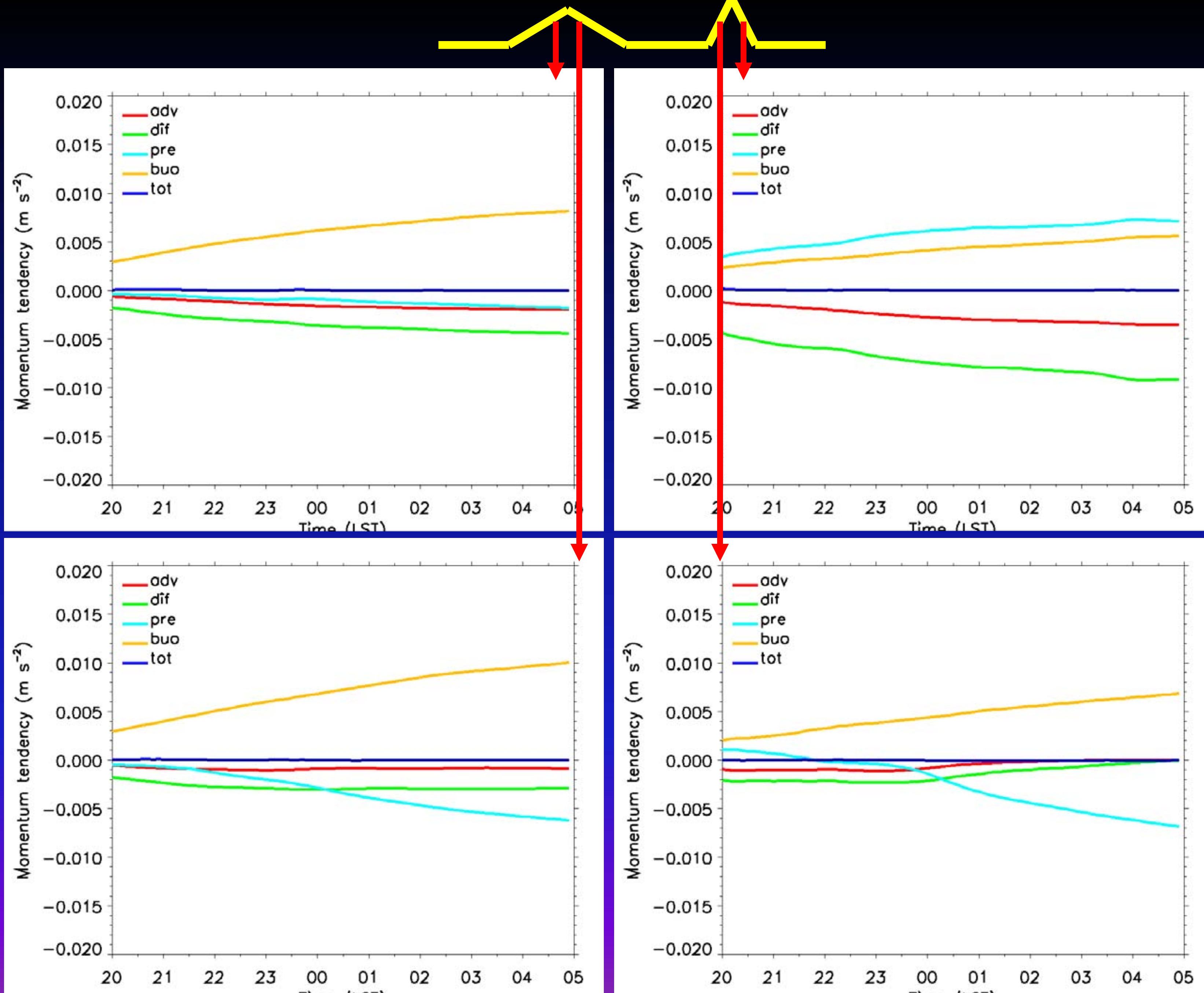
Over which slope is the flow stronger, shallow or steep ?

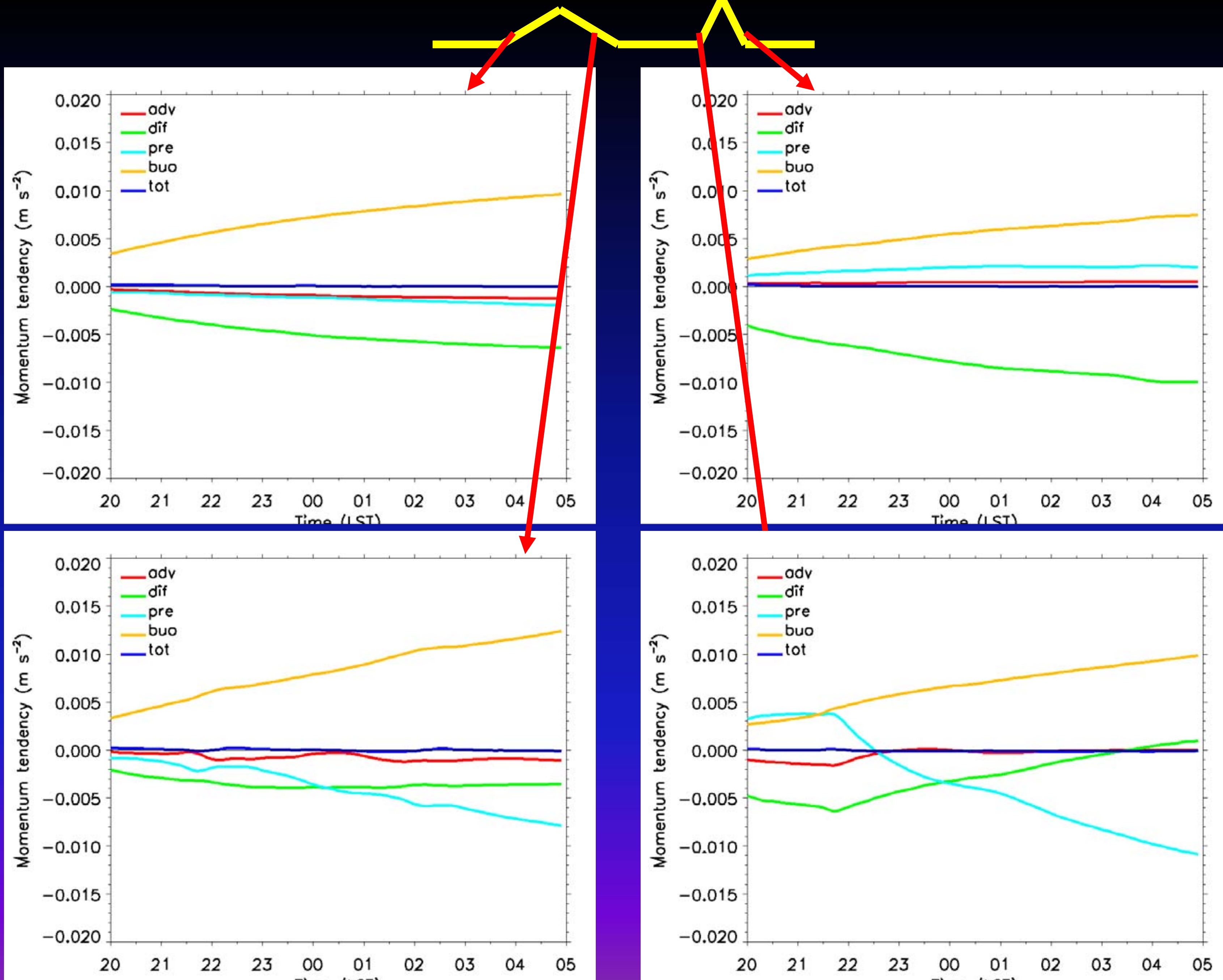


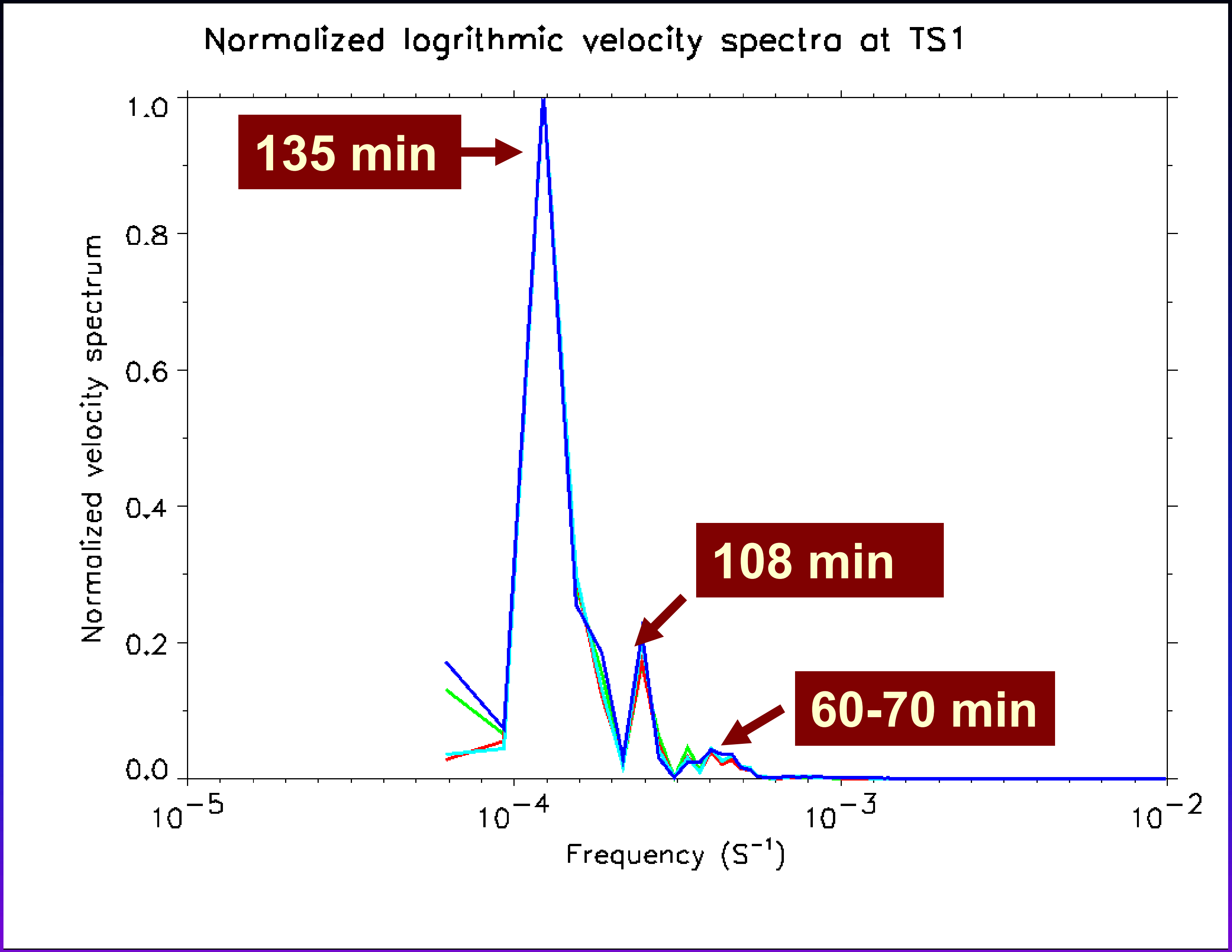
Max jet speed (m s⁻¹)
0
1
2
3
4
5
6
7
8
8 9 10 11 12 1 2 3 4 5 6
Time (LST)
Downslope flow depth (m)
50
100
150
200
8 9 10 11 12 1 2 3 4 5 6
Time (LST)
Mass flux (m^2s^{-1})
0
100
200
300
400
500
8 9 10 11 12 1 2 3 4 5 6
Time (LST)
Momentum flux (m^3s^{-2})
0
500
1000
1500
2000
8 9 10 11 12 1 2 3 4 5 6
Time (LST)

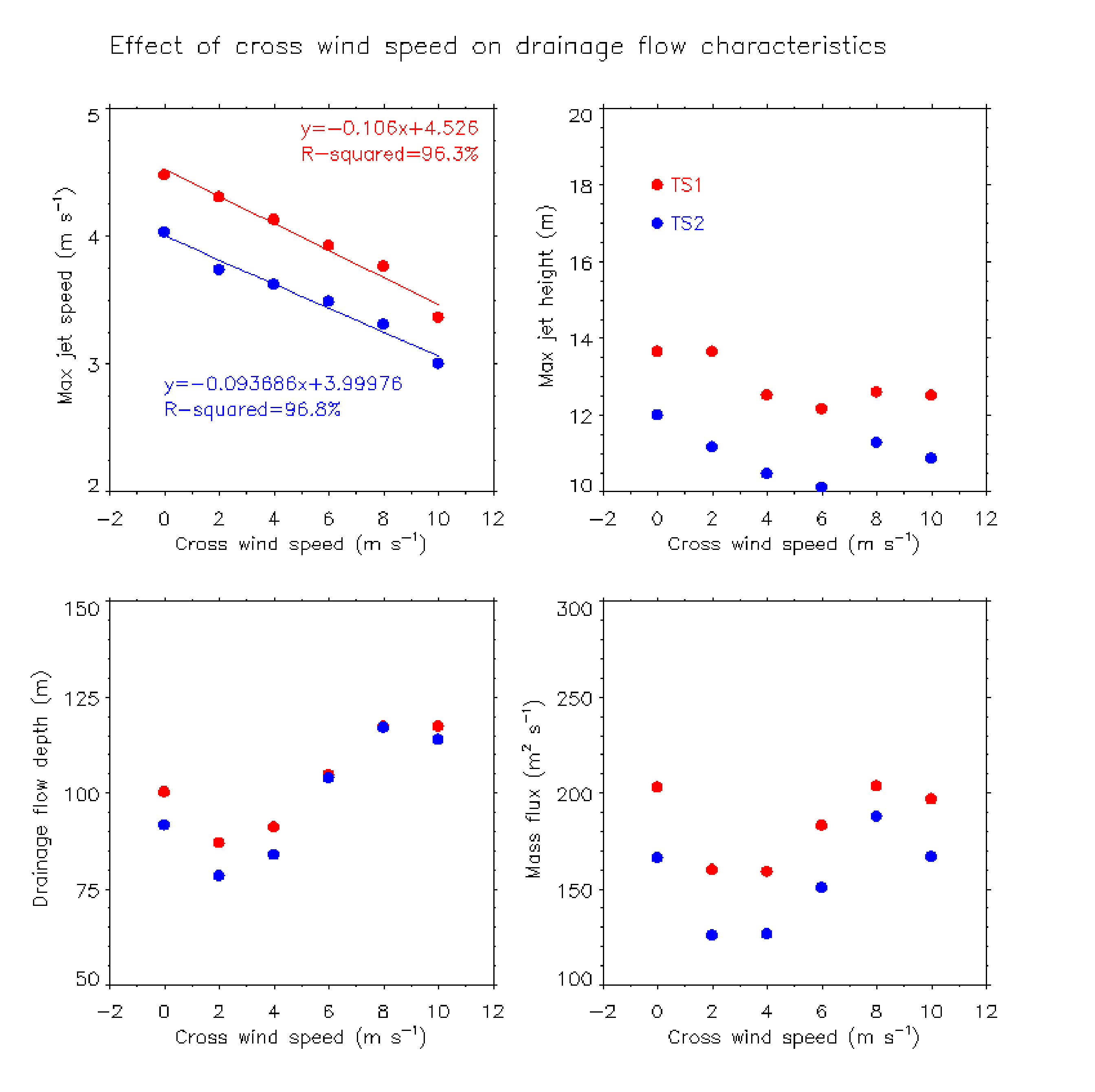


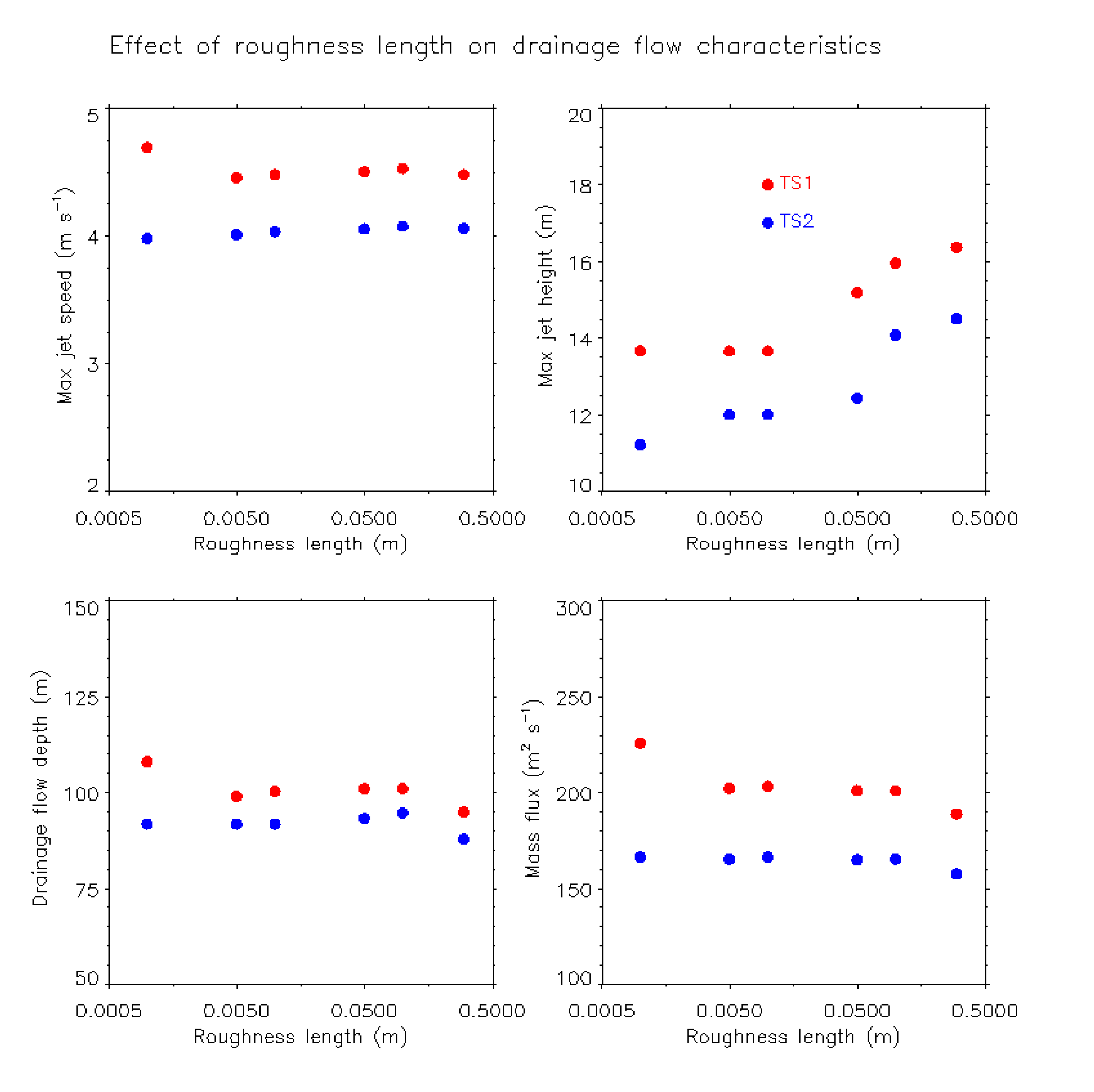
Max jet speed (m s⁻¹)
Time (LST)
Downslope flow depth (m)
Time (LST)
Mass flux (m²s⁻¹)
Time (LST)
Momentum flux (m³s⁻²)
Time (LST)


adv
dif
pre
buo
tot
Momentum tendency (m s⁻²)
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020
20
21
22
23
00
01
02
03
04
05

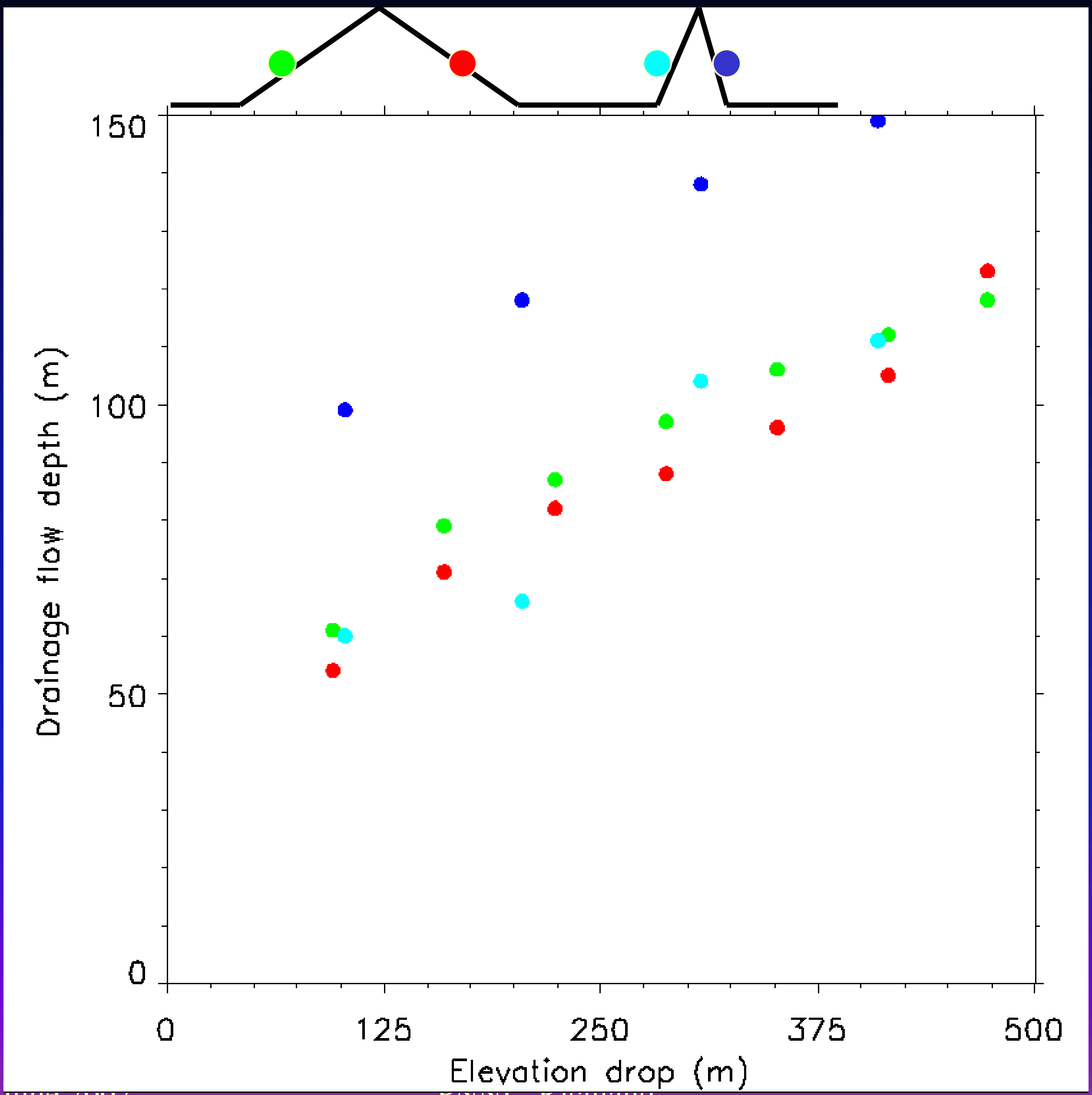

adv
dîf
pre
buo
tot
Momentum tendency (m s^{-2})
Time (LST)
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020
20
21
22
23
00
01
02
03
04
05


Normalized logrithmic velocity spectra at TS1
Normalized velocity spectrum
1.0
0.8
0.6
0.4
0.2
0.0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Frequency (S^{-1})
135 min
108 min
60-70 min

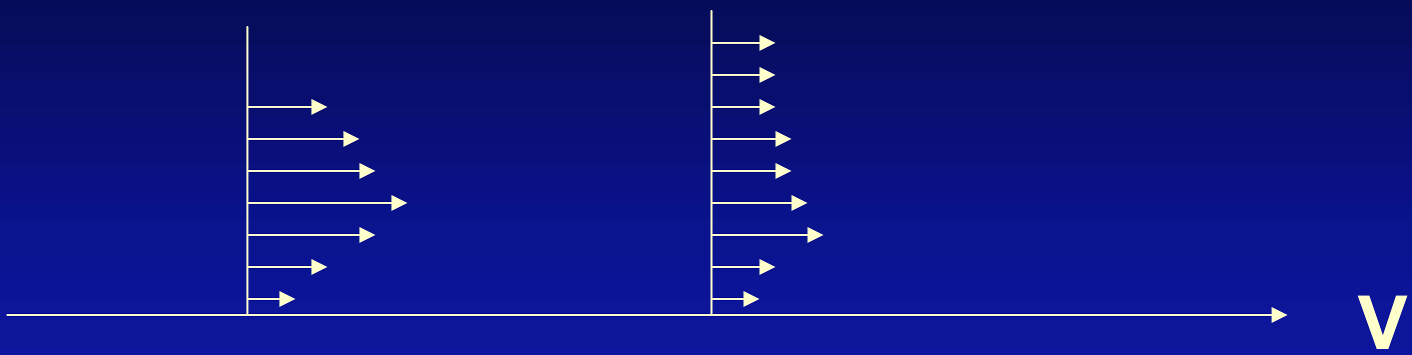

Effect of cross wind speed on drainage flow characteristics
y=−0.106x+4.526
R−squared=96.3%
y=−0.093686x+3.99976
R−squared=96.8%
Max jet speed (m s−1)
Cross wind speed (m s−1)
TS1
TS2
Max jet height (m)
Cross wind speed (m s−1)
Drainage flow depth (m)
Cross wind speed (m s−1)
Mass flux (m2 s−1)
Cross wind speed (m s−1)


Effect of roughness length on drainage flow characteristics
Max jet speed (m s^{-1})
5
4
3
2
Max jet height (m)
20
18
16
14
12
10
TS1
TS2
Drainage flow depth (m)
150
125
100
75
50
Mass flux (m^2 s^{-1})
300
250
200
150
100
0.0005
0.0050
0.0500
0.5000
Roughness length (m)

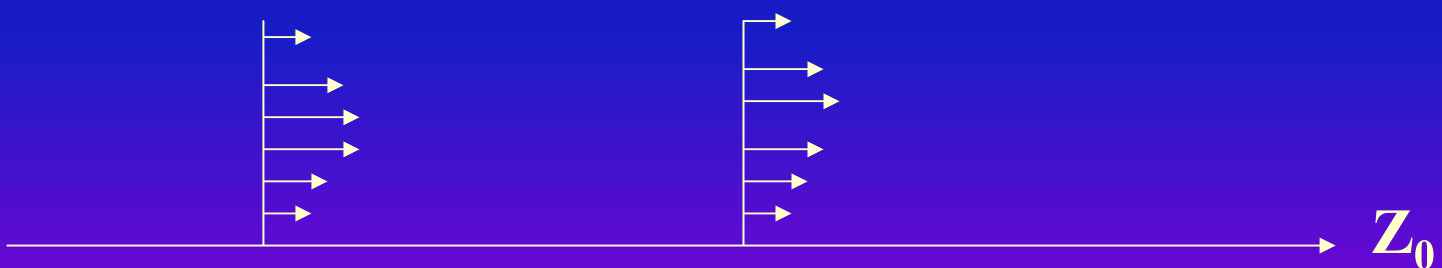
Downslope flow depths as a function of elevation drop




Time=t1
Time=t2
Time=t3



Cross wind speed



Roughness length

Vertical structure of the flow

Prandtl solution

$$\Delta\theta(z) = \boxed{\Delta\theta_0} \exp(-z/l)\cos(z/l)$$

$$u(z) = u_0 \exp(-z/l)\sin(z/l) \qquad \textit{where } u_0 = \Delta\theta_0 \sqrt{\frac{g}{\theta_0}\left(\frac{d\theta_0}{dz}\right)^{-1}\frac{K_h}{K_m}}$$

$$l^4 = \frac{4K_h K_m}{N^2 \sin^2\alpha} \qquad \textit{vertical length scale}$$

$$\boxed{z_{\max}} = \frac{\pi}{4} l \qquad \textit{jet height}$$

$$\boxed{u_{\max}} = u_0 \exp(-\pi/4)/\sqrt{2} \approx 0.322\, u_0 \qquad \textit{jet speed}$$