Downslope Gravity Flows: LES and Mesoscale Results

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With help from Craig Smith

Why Study Slope Flows?

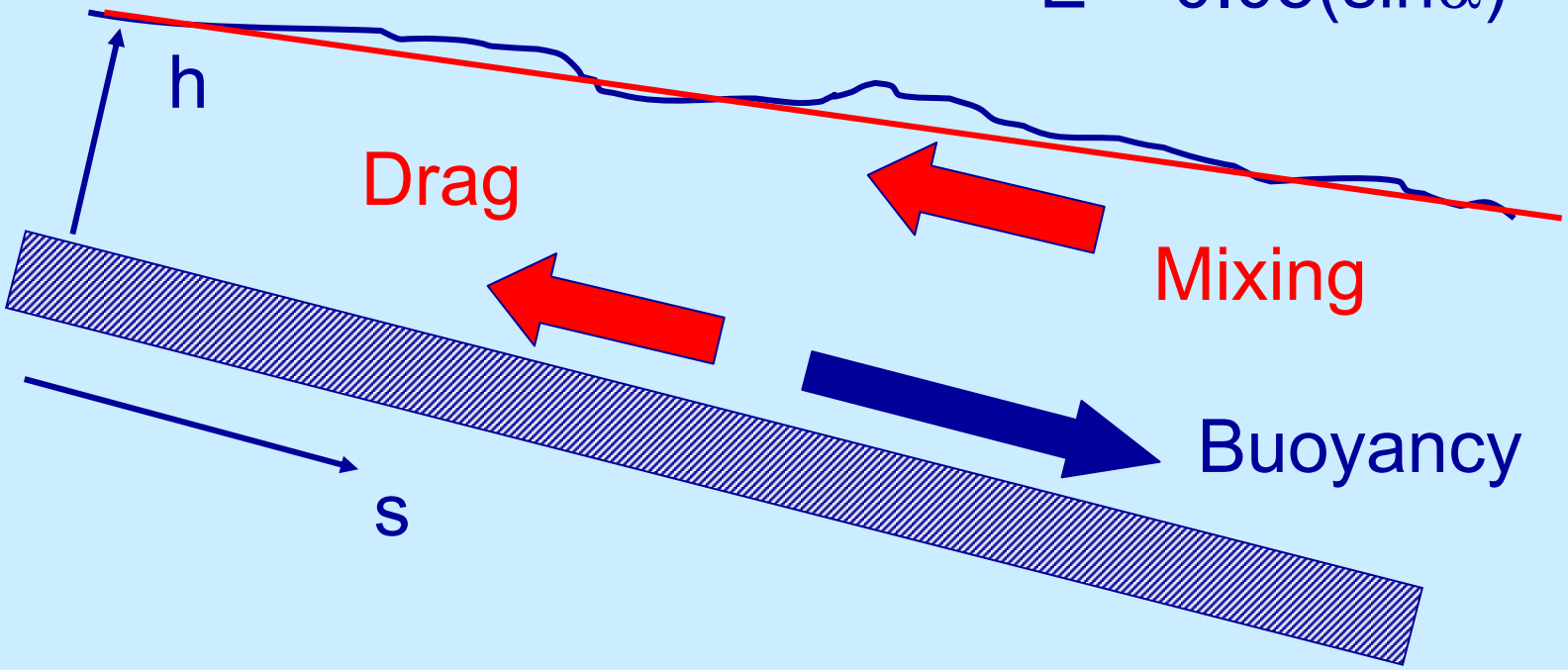
- Frequently define night time boundary layer structure in regions of complex terrain
- Do not fit the “typical” model of a surface boundary layer
- Provide cold air source for stagnation events

Bulk Layer Approach

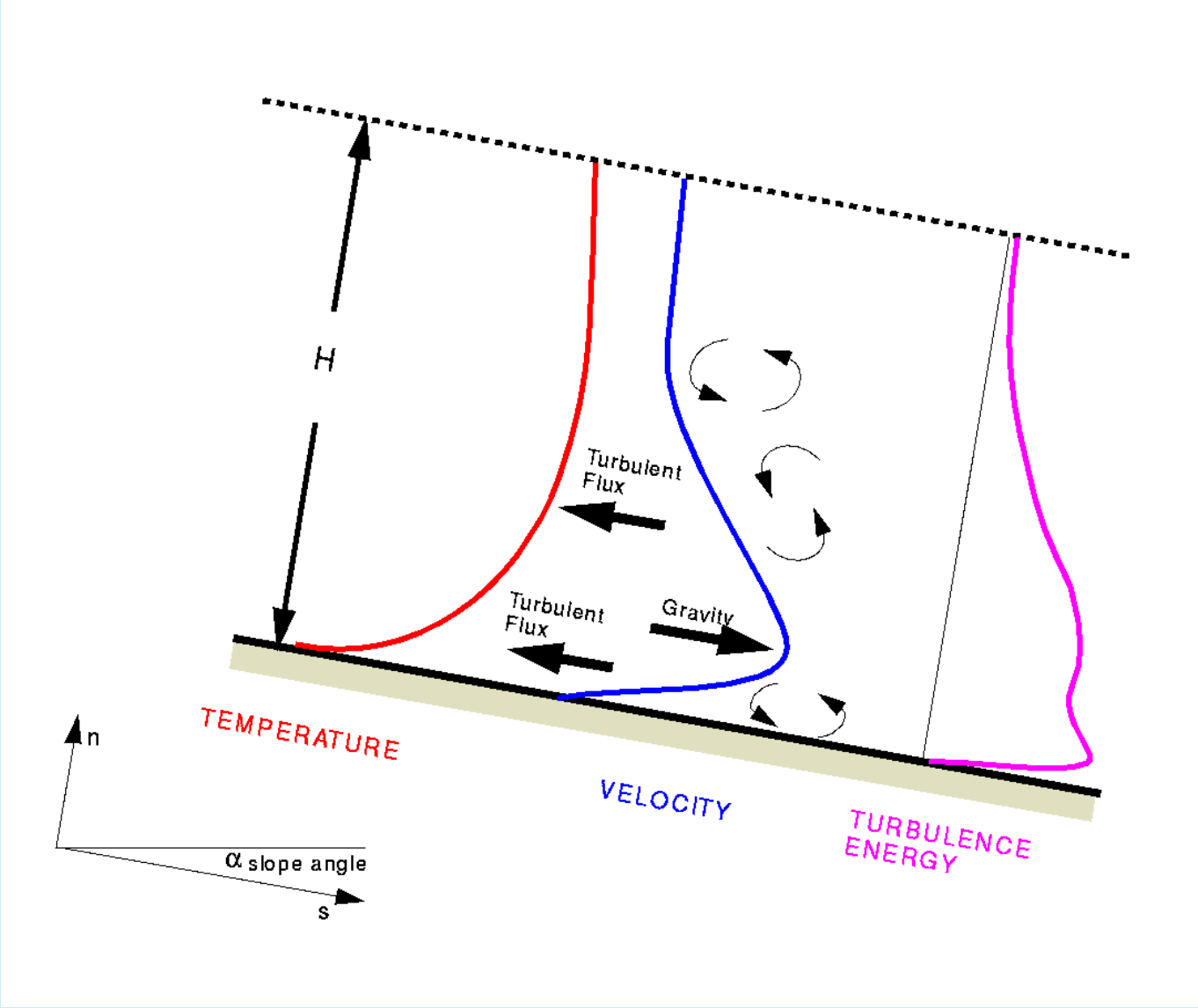
Manins and Sawford (1979)

$$h = 0.75Es$$

$$E = 0.05(\sin\alpha)^{2/3}$$



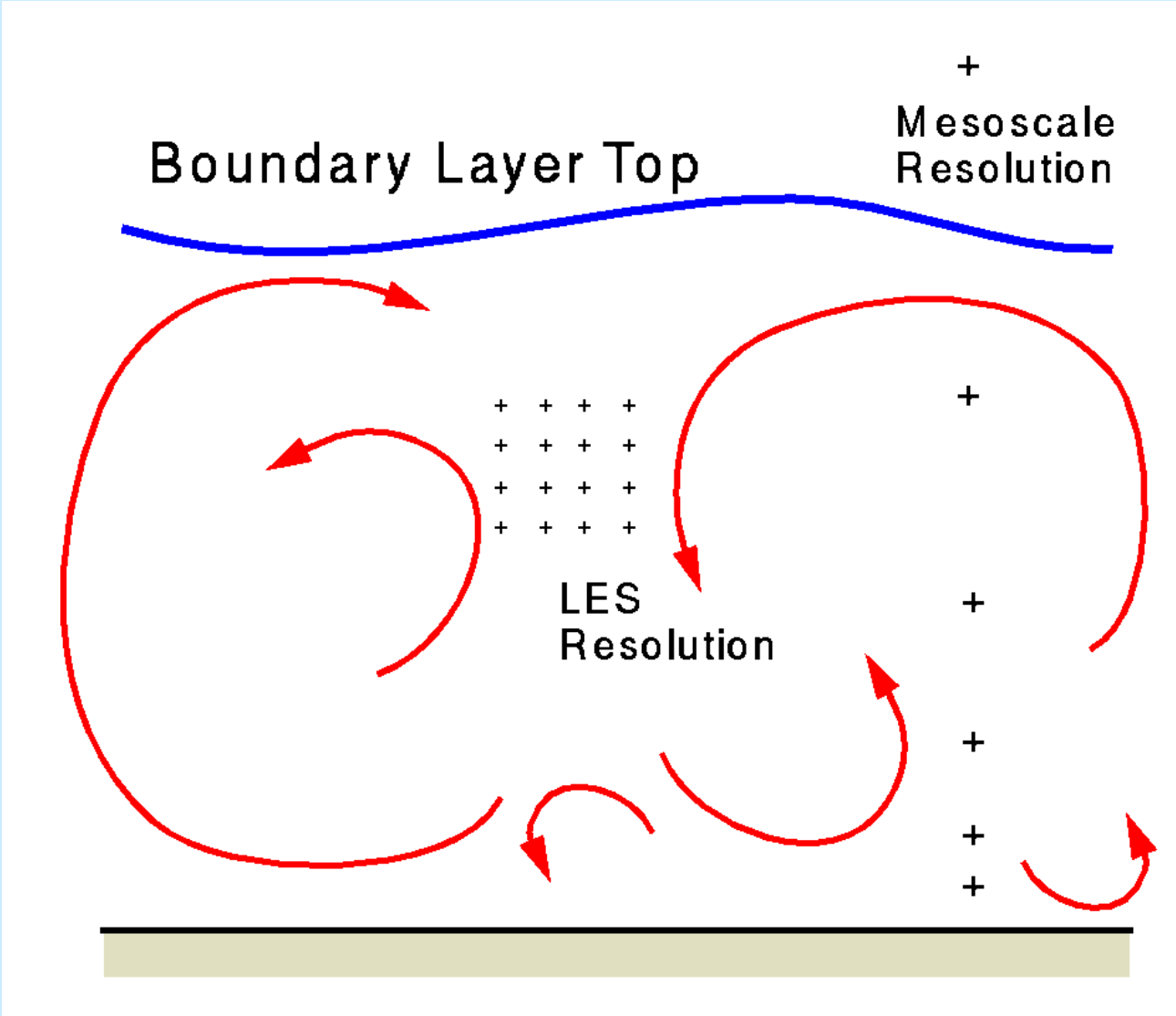
Katabatic Flow Schematic



Outline

- Description of LES model
- Vertical Transport and Mixing Experiment (VTMX) results
- Comparison with ARPS mesoscale model
- New Experiments

Mesoscale –vs- LES



Rotated Equation of Motion

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial p}{\partial x_i} + g_i - \frac{\partial \langle u_i'' u_j'' \rangle}{\partial x_j}$$

where $x_i = (s, y, n)$ represents the down slope, cross slope, and normal directions, and

$g_i = g(\sin\alpha, 0, -\cos\alpha)\frac{\theta'}{\theta_0}$ is rotated gravity

Bottom Boundary Conditions

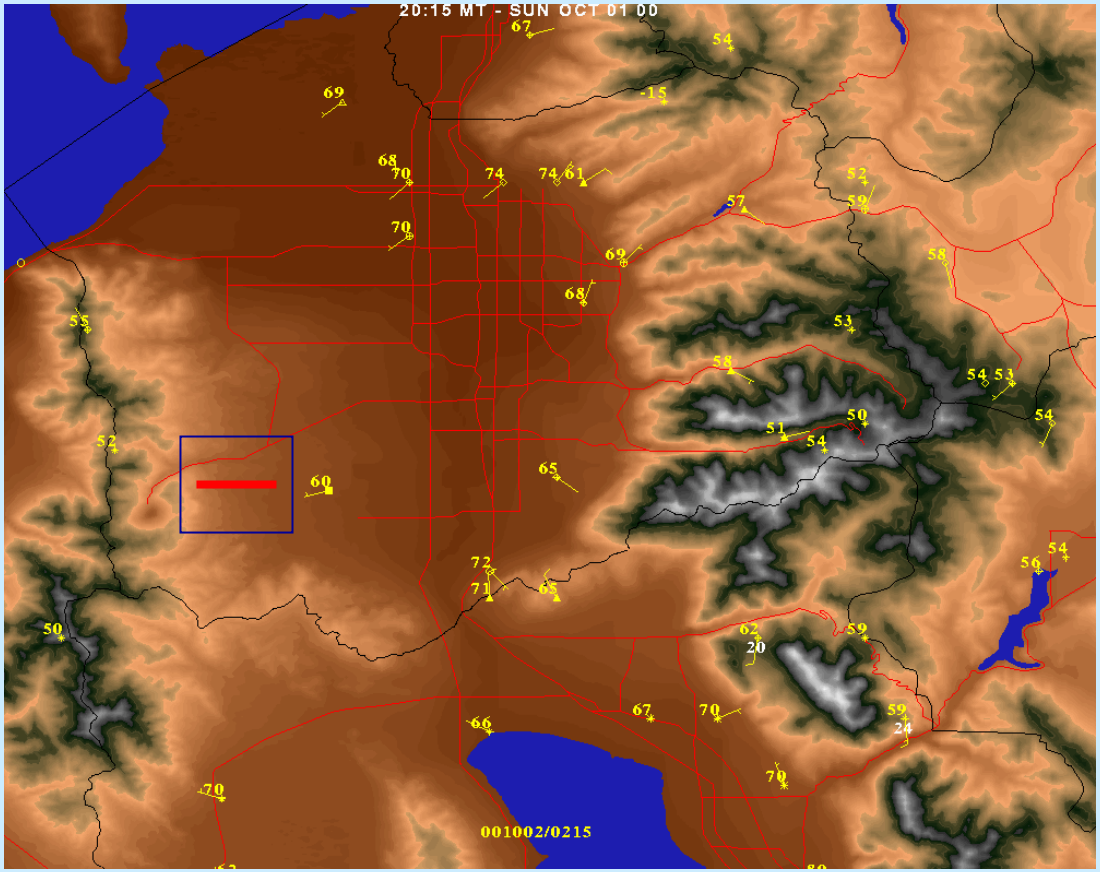
$$\left\langle u''_i u''_3 \right\rangle = C_D u_i \left| u_i \right| \qquad C_D = \left[\frac{\kappa}{\ln\left(\delta z / z_0\right)} \right]^2$$

Where $k = 0.4$, $z_0 = 0.1$, $\delta z = 0.5\ \Delta x$

Heat Flux = 30 W m^{-2}

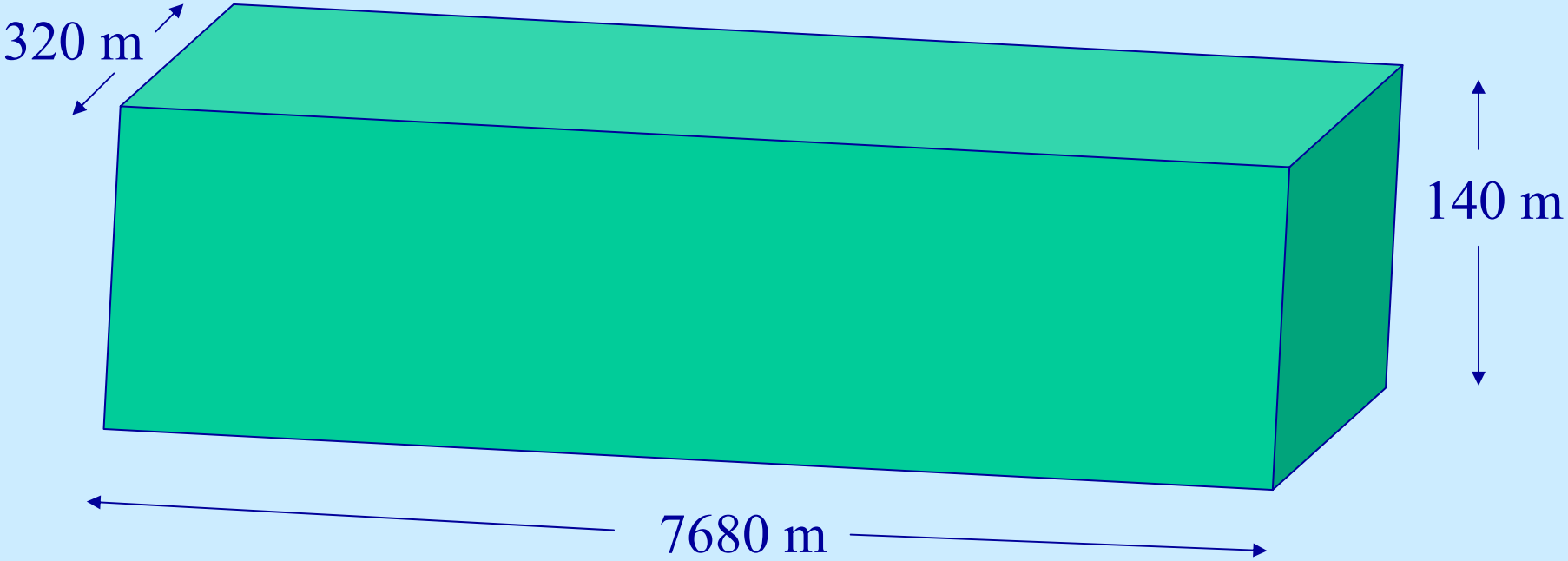
VTMX Slope Flow Study Site

Observations by Dave Whiteman et al., PNNL



Plot from Univ. of

LES Model Domain (Δx = 2.5 m)

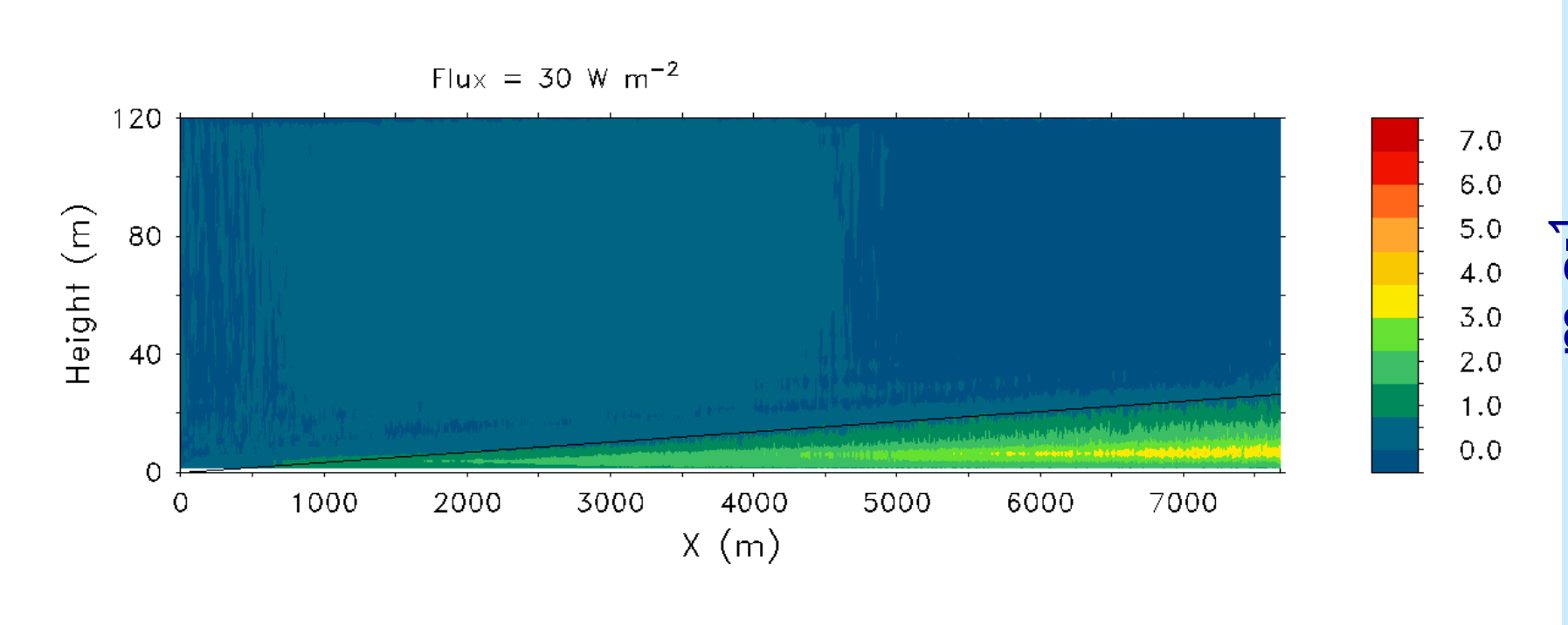


Boundaries: Periodic lateral, open top and downslope

VTMX Slope Cases

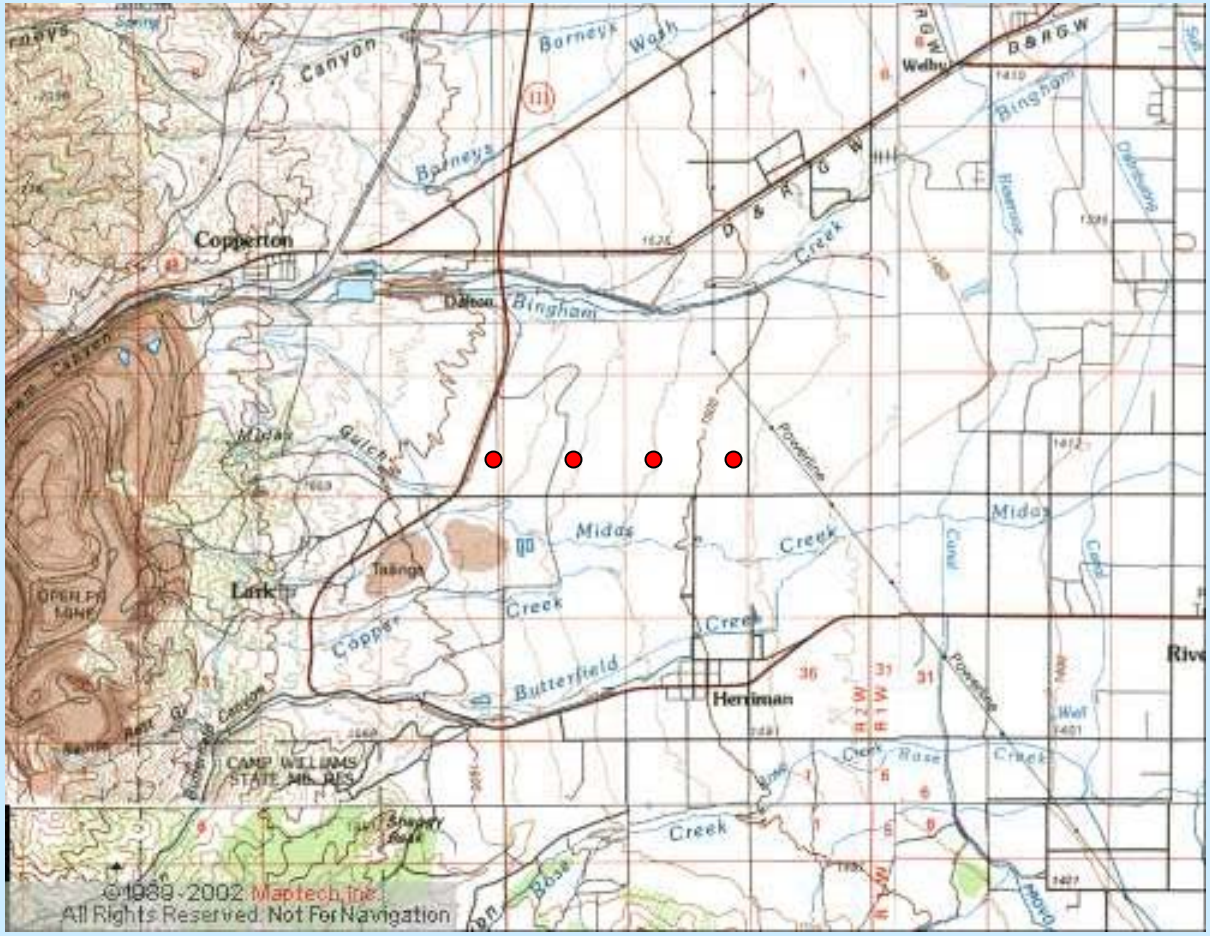
- Slope angles 1.6 and 14°
- Constant potential temperature (18 ^{o}C)
- Cross wind of 0 m s^{-1}
- Surface heat flux of 30 W m^{-2}
- Roughness length = 0.1 m

LES Slope 1.6°

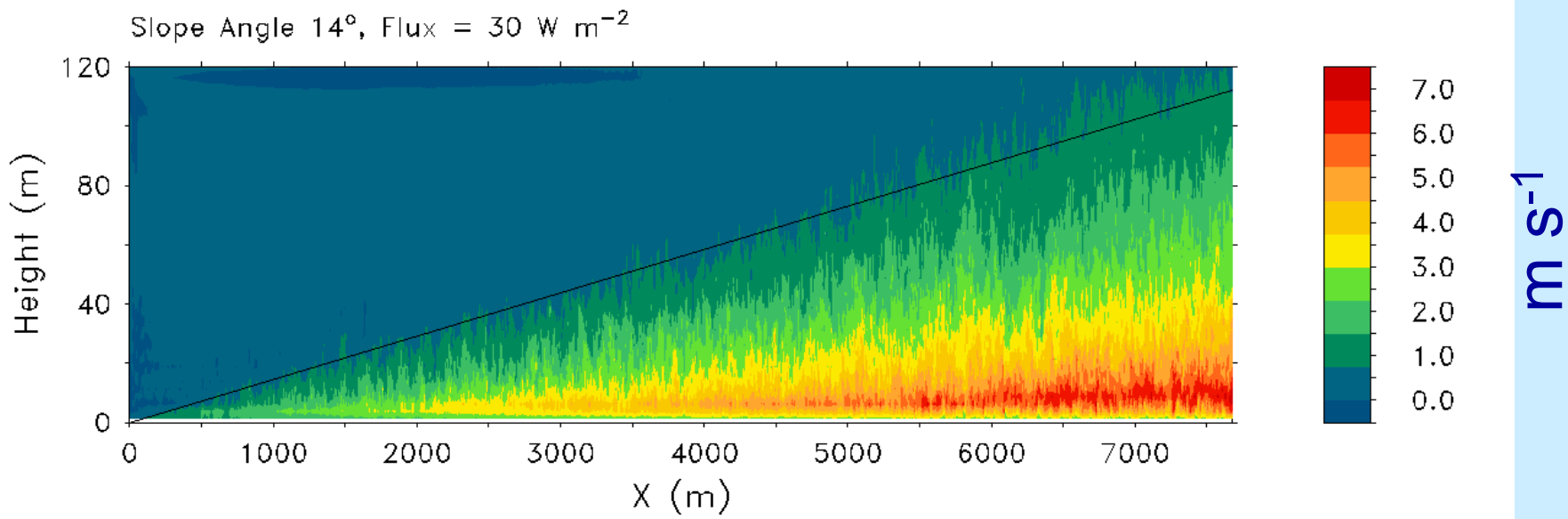

Flux = 30 W m^{-2}
Height (m)
120
80
40
0
0
1000
2000
3000
4000
5000
6000
7000
X (m)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
m s^{-1}

Kennecott Site

Oquirre Mts.



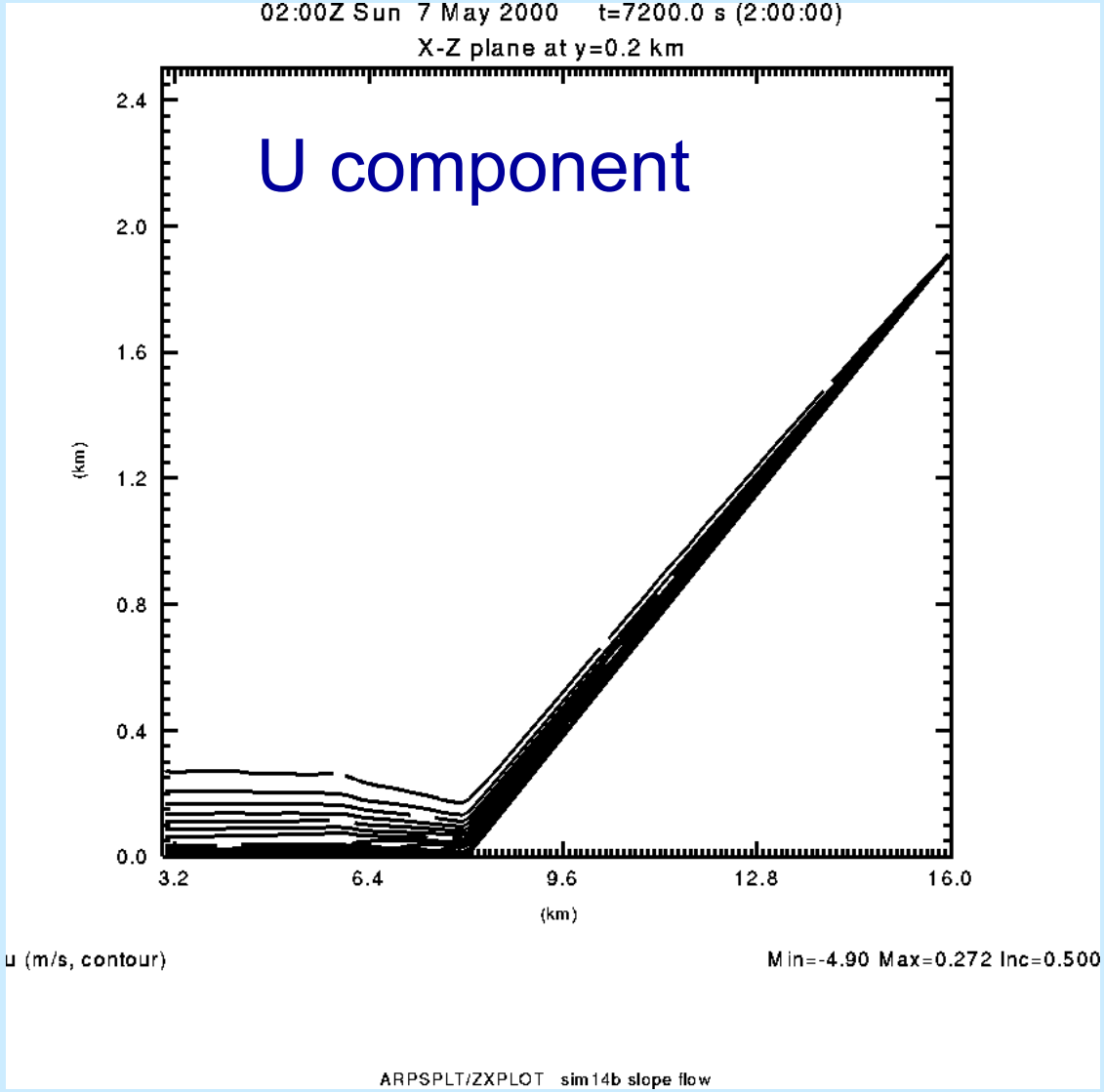
LES Slope 14°


Slope Angle 14°, Flux = 30 W m^{-2}
Height (m)
120
80
40
0
0
1000
2000
3000
4000
5000
6000
7000
X (m)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
m s^{-1}

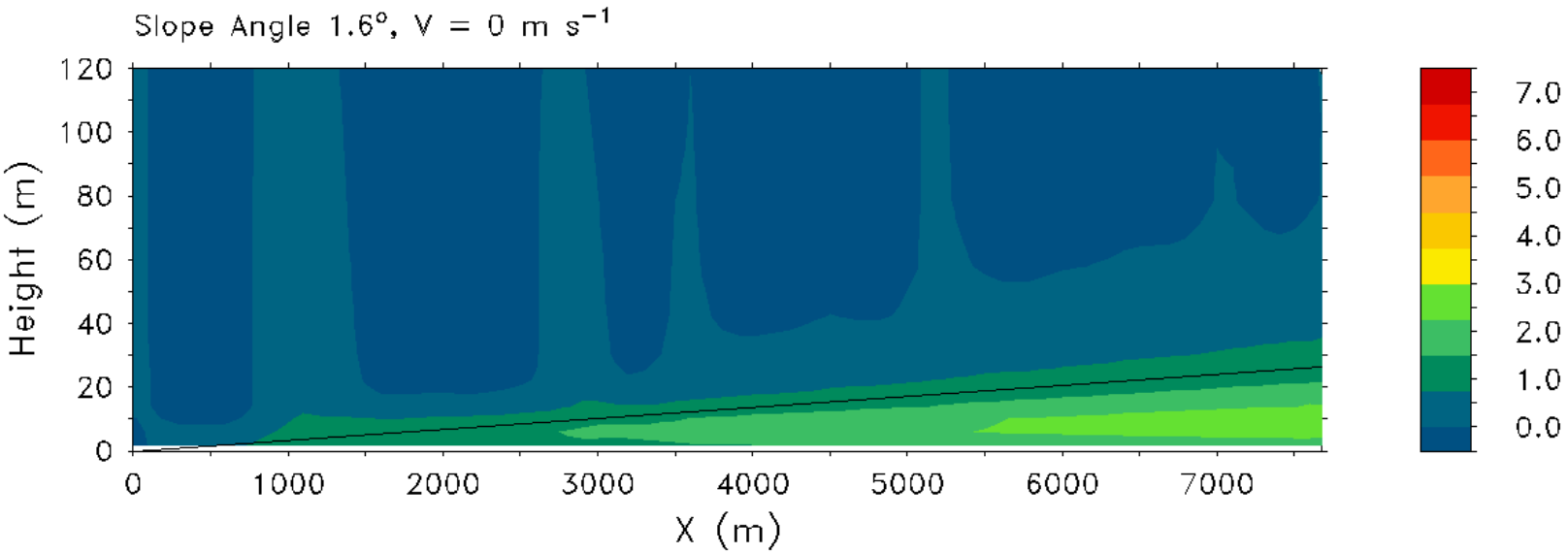
Advanced Regional Prediction System (ARPS) Mesoscale Model

- Non-hydrostatic
- Terrain following coordinate system
- Mellor-Yamada 1.5 Turbulence Closure
- Fixed surface heat flux of 30 W m^{-2}
- Slope angles 1.6 and 14°

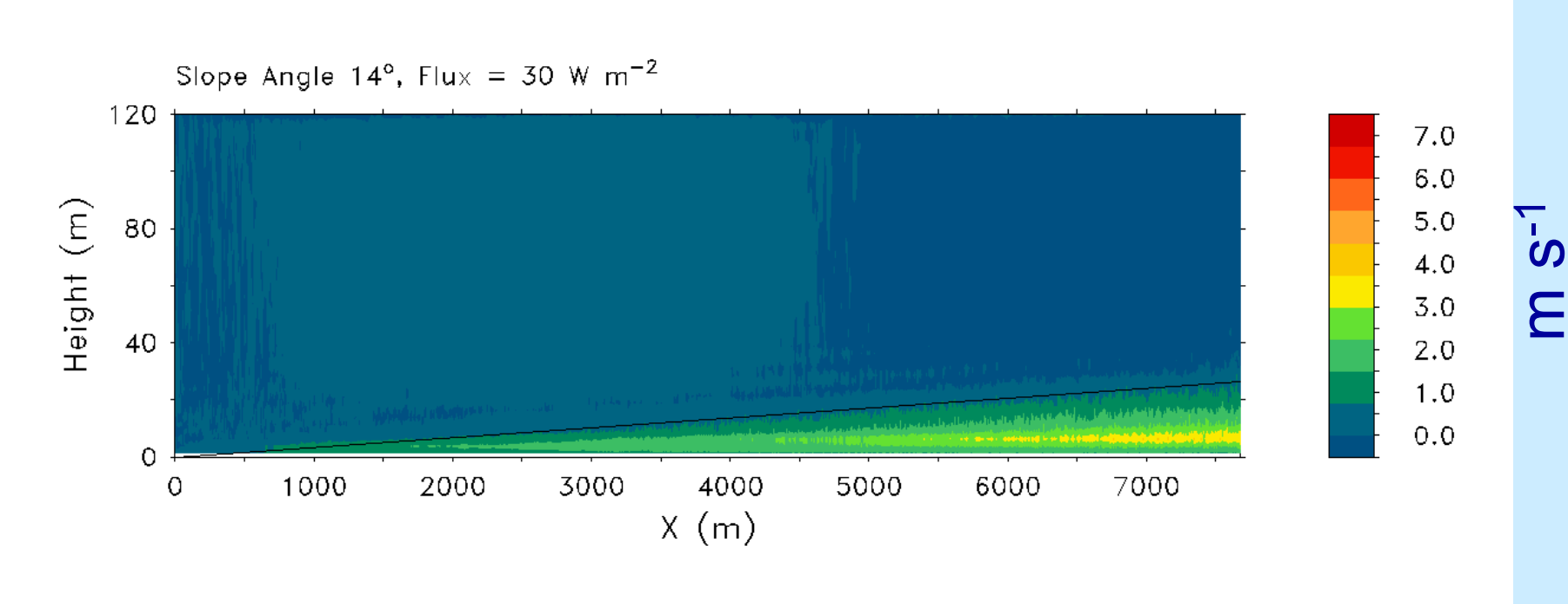
ARPS Domain


02:00Z Sun 7 May 2000 t=7200.0 s (2:00:00)
X-Z plane at y=0.2 km
U component
2.4
2.0
1.6
1.2
0.8
0.4
0.0
(km)
3.2
6.4
9.6
12.8
16.0
(km)
u (m/s, contour)
Min=-4.90 Max=0.272 Inc=0.500
ARPSPLT/ZXPLOT sim14b slope flow

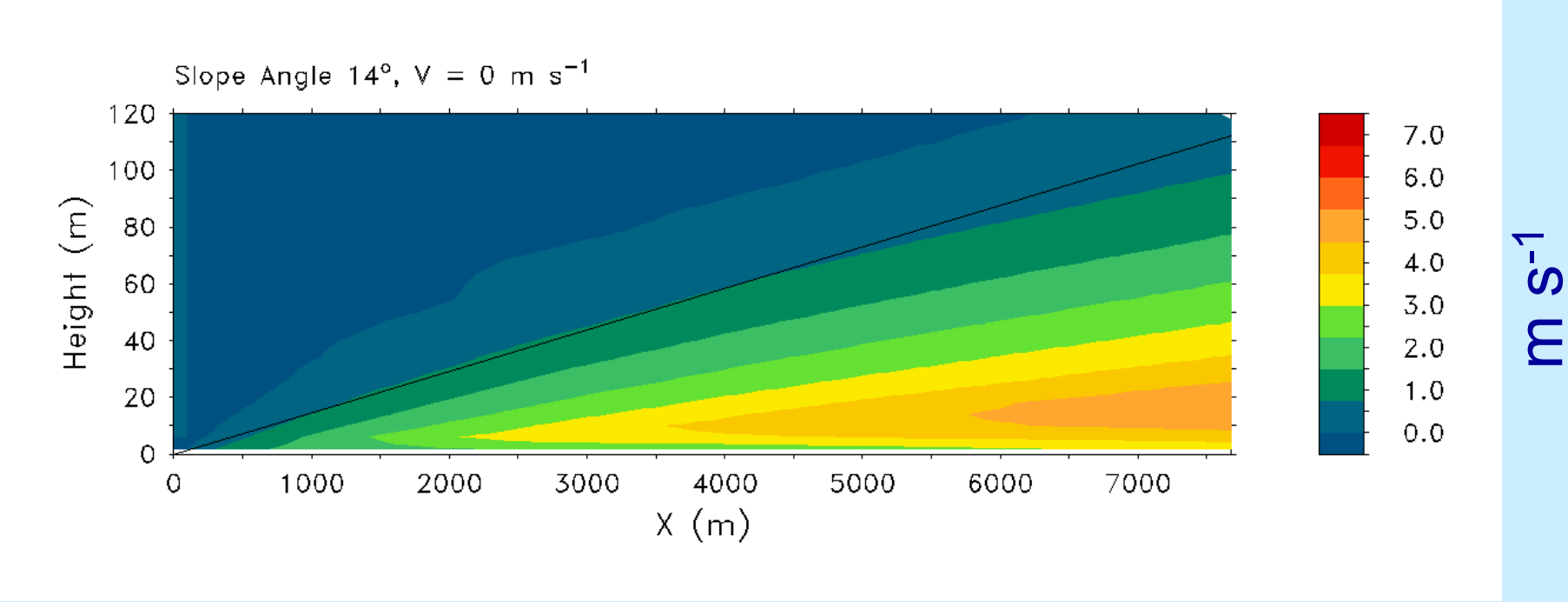
Mesoscale – 1.6°



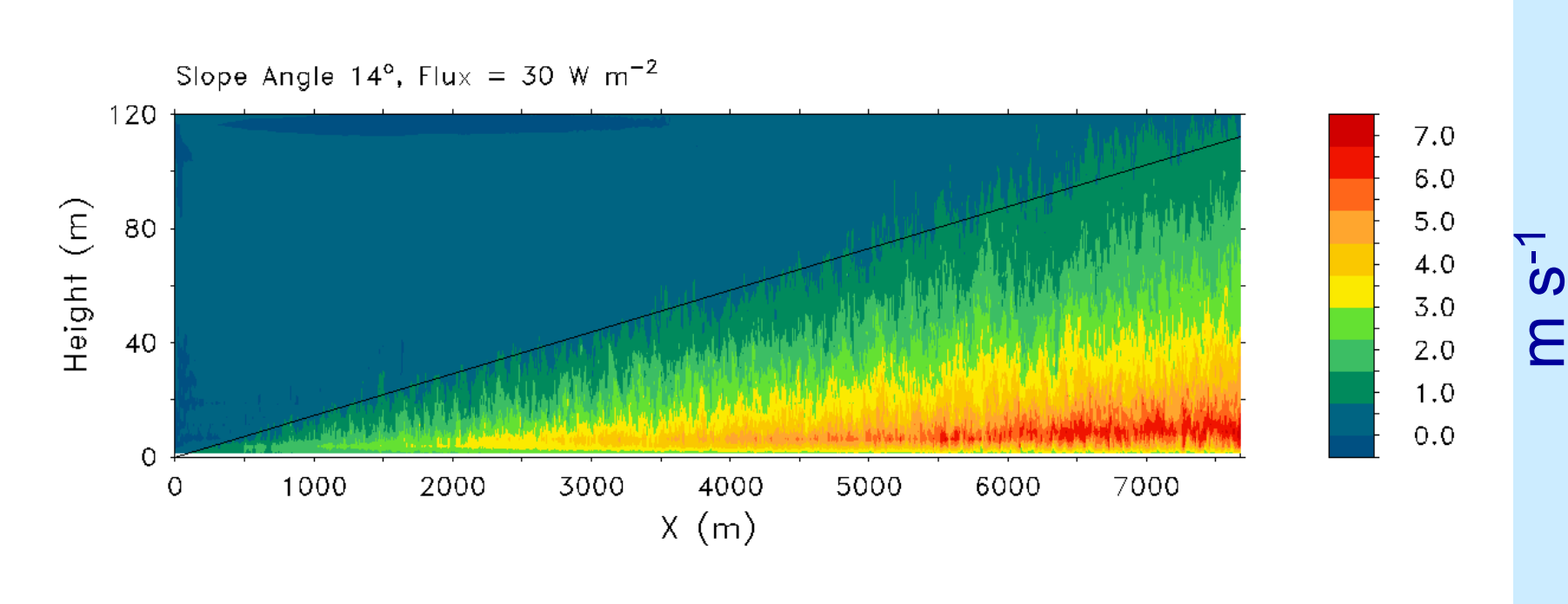
LES Slope 1.6°


Slope Angle 14°, Flux = 30 W m^{-2}
Height (m)
120
80
40
0
0
1000
2000
3000
4000
5000
6000
7000
X (m)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
m s^{-1}

Mesoscale Model – 14°

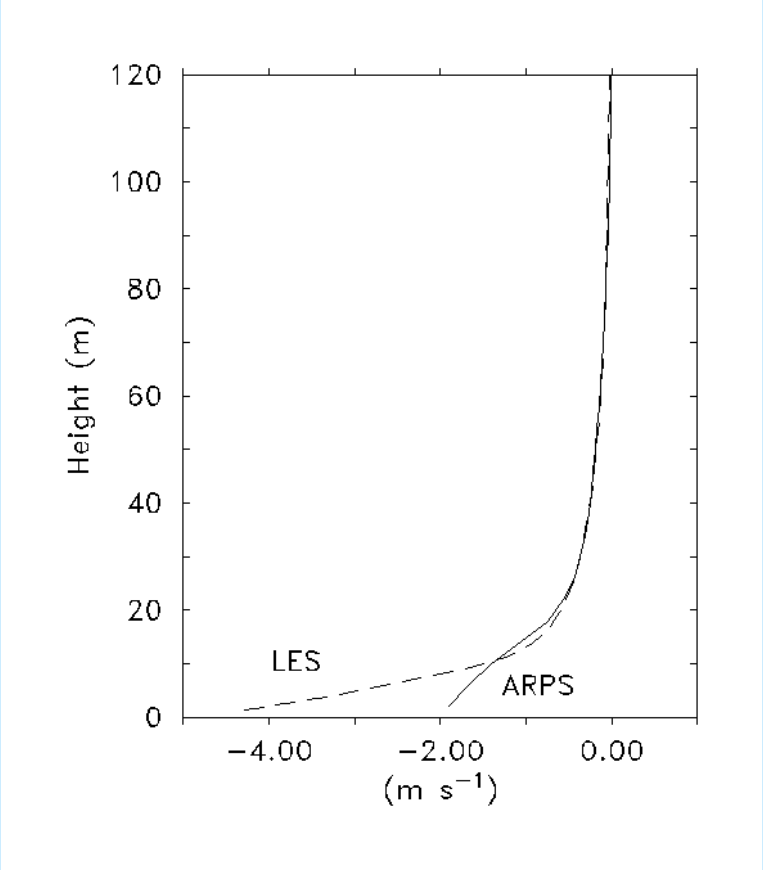


LES Slope 14°

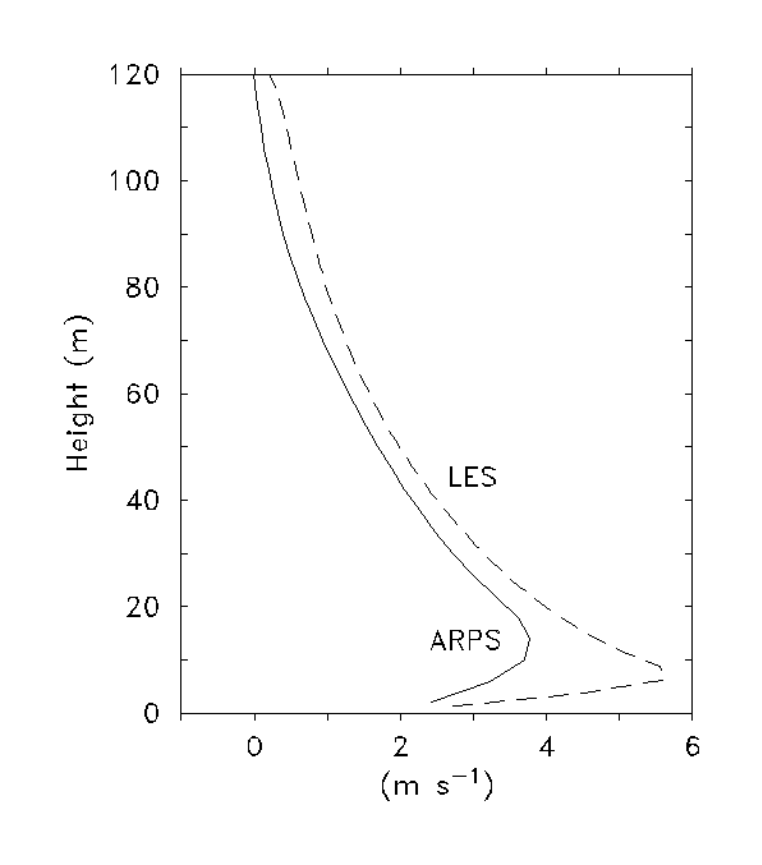

Slope Angle 14°, Flux = 30 W m^{-2}
Height (m)
120
80
40
0
0
1000
2000
3000
4000
5000
6000
7000
X (m)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
m s^{-1}

ARPS vs LES 14 Degree Slope

Perturbation Temperature

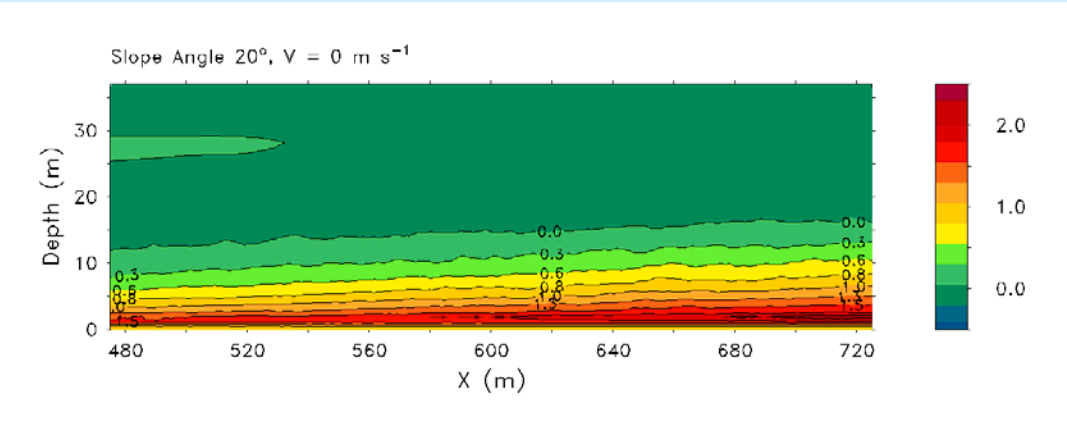


Down Slope Wind



Mean Flow / Turbulence Definition

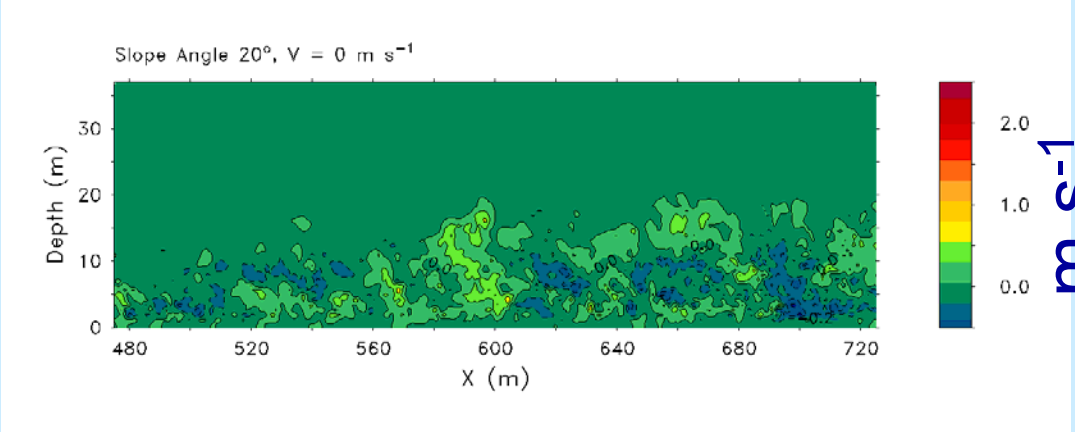
$$\overline{\varphi}(s,n) = \sum_{y=1}^{y_{\max}} \varphi(s,y,n)$$



Average U

$$\varphi' = \varphi(s,y,n) - \overline{\varphi}(s,n)$$

Perturbation U



m s^{-1}

Downslope Flow Momentum Budget

$$\frac{\partial \overline{u}}{\partial t} = -\overline{g\left(\frac{\theta'}{\theta_0}\right)\sin\alpha} - \frac{\overline{\partial uu}}{\partial s} - \frac{\partial \overline{wu}}{\partial n}$$

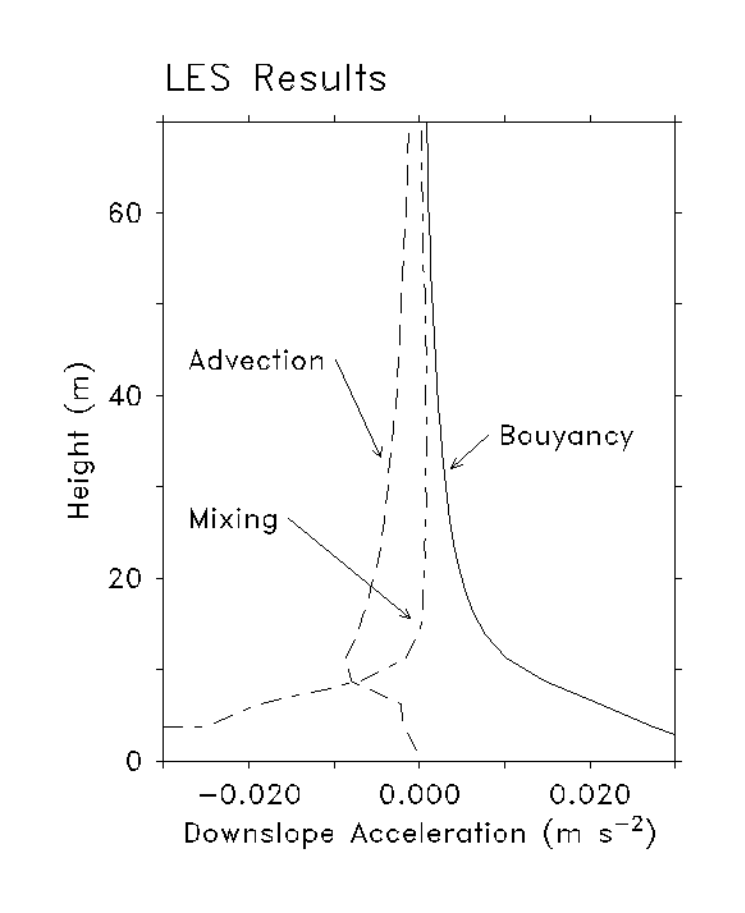
Buoyancy

Horizontal Advection

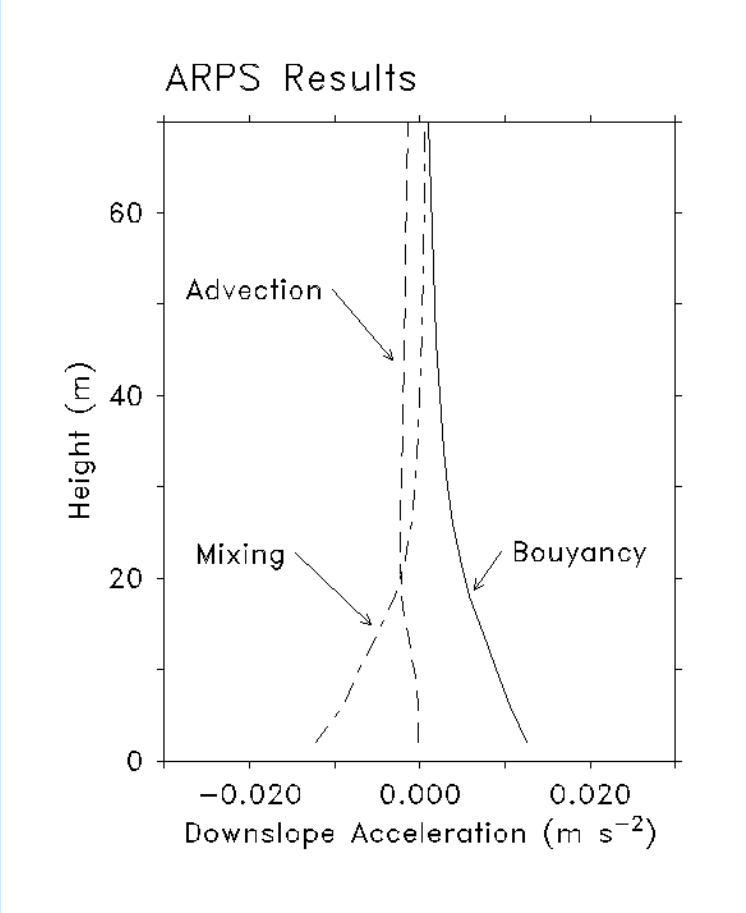
Mixing

Momentum Budget

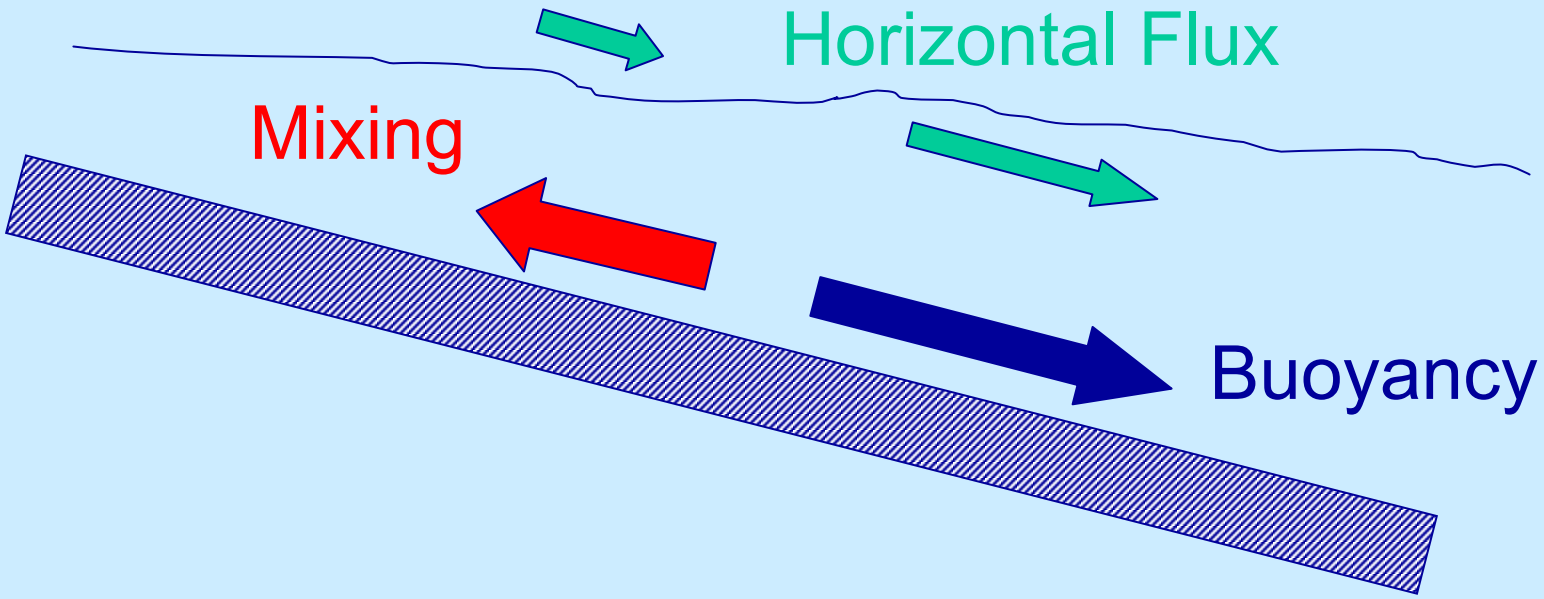
LES



ARPS



Momentum Budget Schematic



Turbulent Kinetic Energy

$$\frac{\partial E}{\partial t} = \overline{u_i u_3} \frac{\partial \overline{u}_i}{\partial x_3} - \overline{u_3 \cdot g \frac{\theta'}{\theta_0}}$$

Shear Production

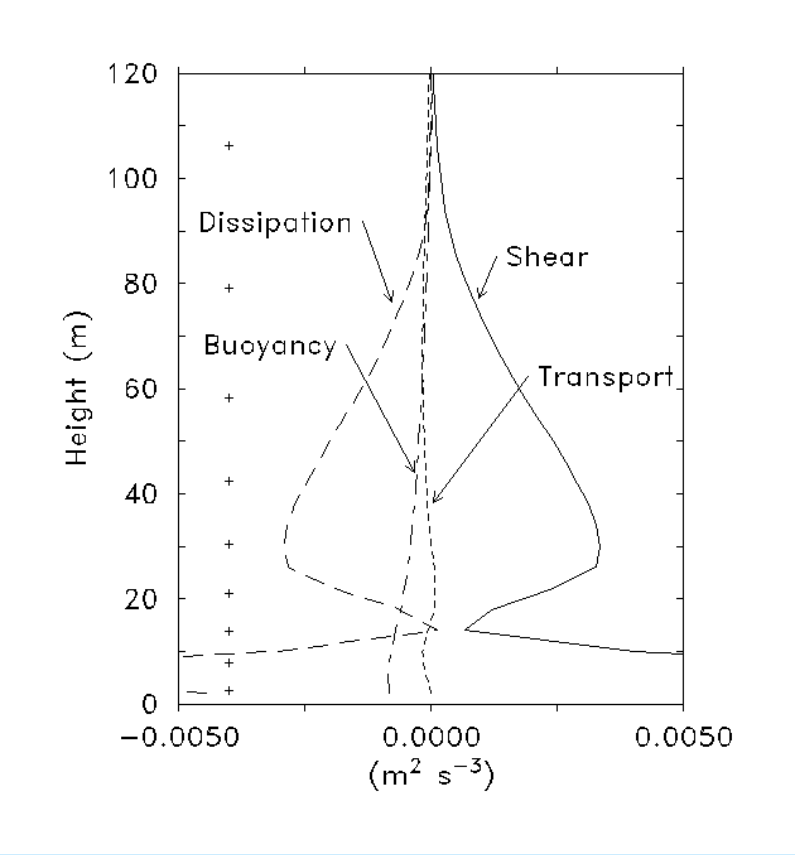
Buoyancy

$$+ \overline{u_i \frac{\partial}{\partial x_j} \left\langle u''_i u''_j \right\rangle} + \overline{\frac{\partial u_i P}{\partial x_i}} + \overline{\frac{\partial u_i E}{\partial x_i}}$$

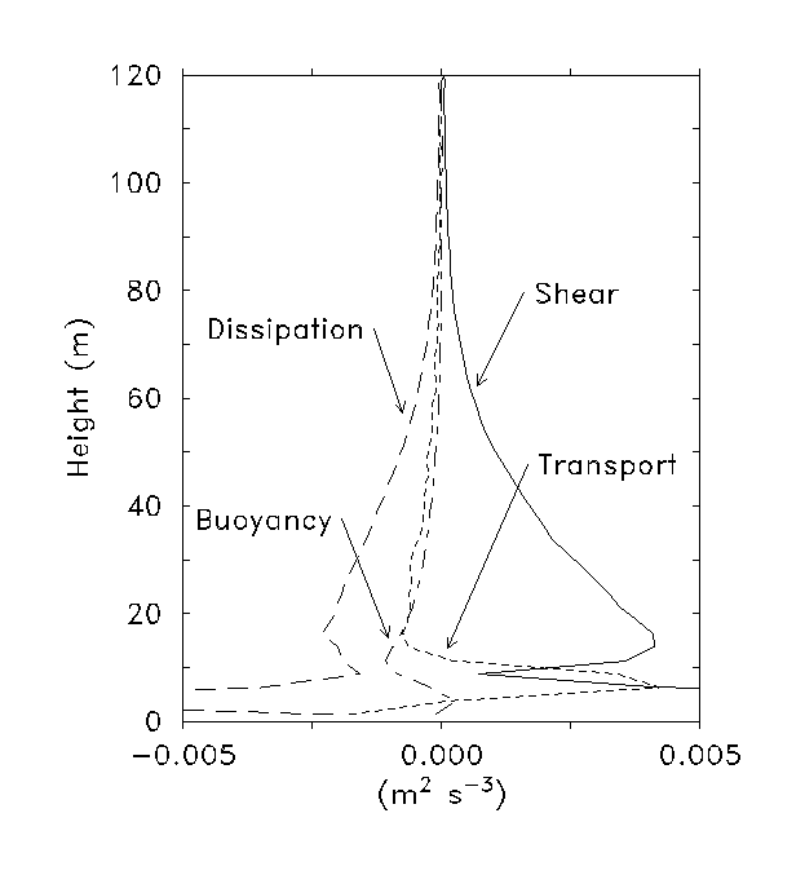
Subgrid

Transport

TKE Budgets

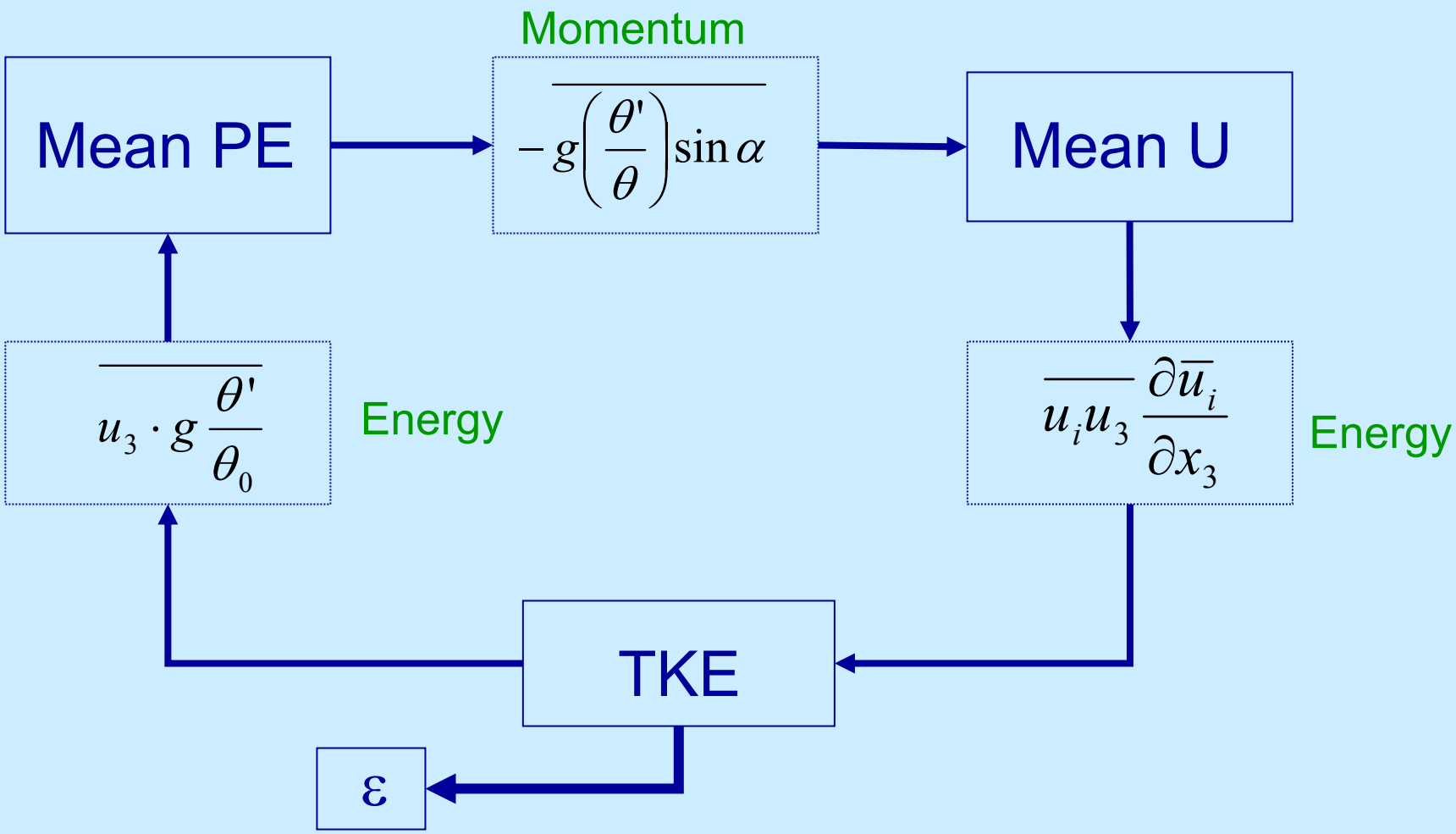


ARPS



LES

Energy-Momentum Pathways



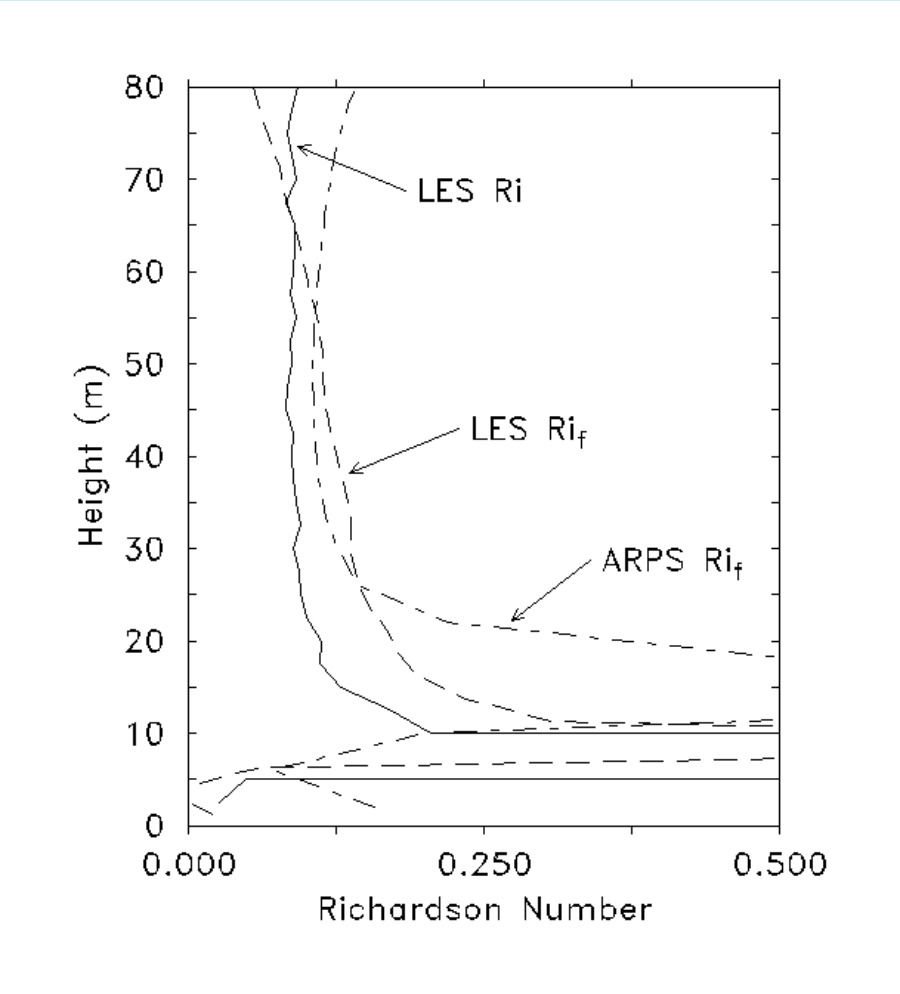
Richardson Numbers

Flux

$$Ri_f = \frac{\overline{u_3 \cdot g \frac{\theta'}{\theta_0}}}{\overline{u_i u_3} \frac{\partial \overline{u}_i}{\partial x_3}}$$

Gradient

$$Ri = \frac{\frac{g}{\theta} \frac{\partial \theta}{\partial z}}{\left(\frac{\partial u}{\partial z} \right)^2}$$



Lengthscales

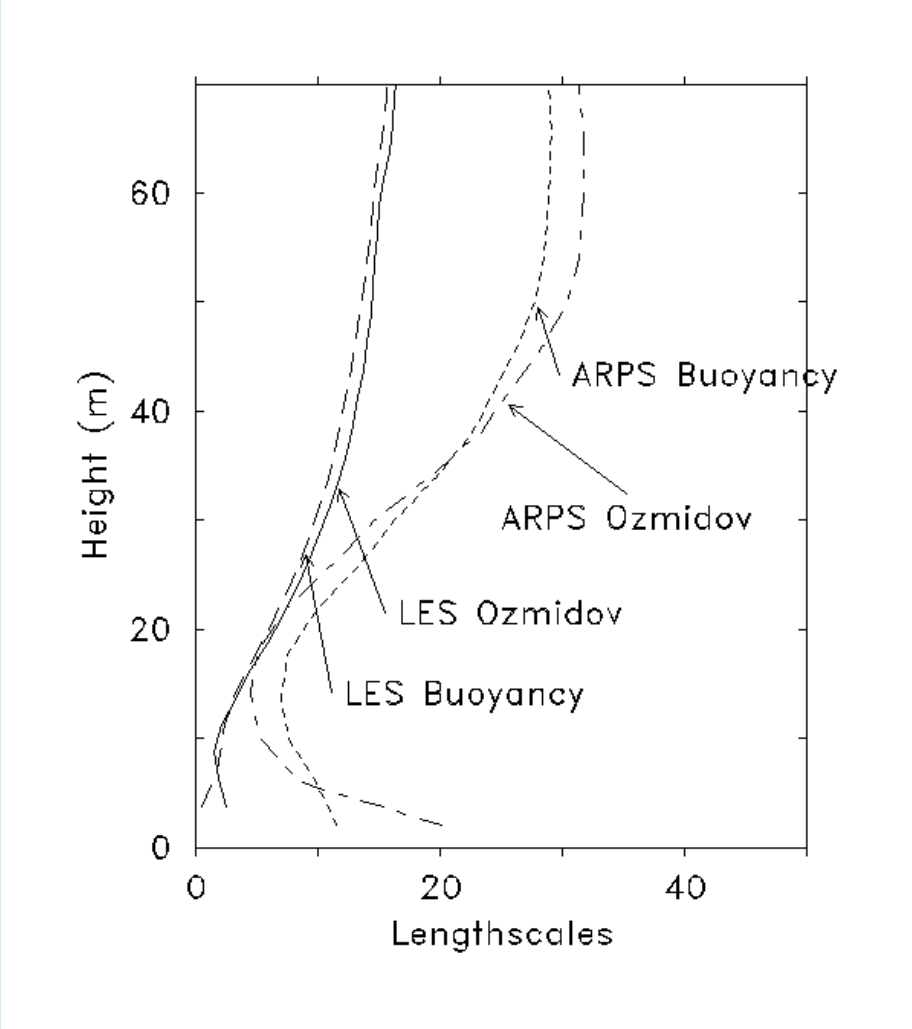
$$L_o = \left(\frac{\varepsilon}{N^3} \right)^{1/2}$$

Ozmidov

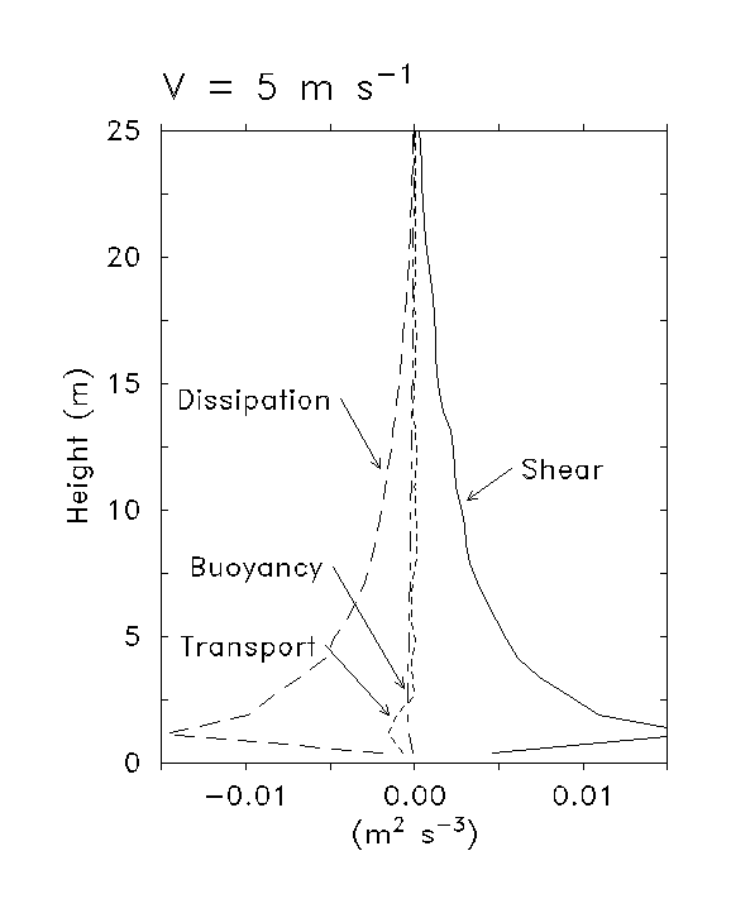
$$L_b = \frac{w}{N}$$

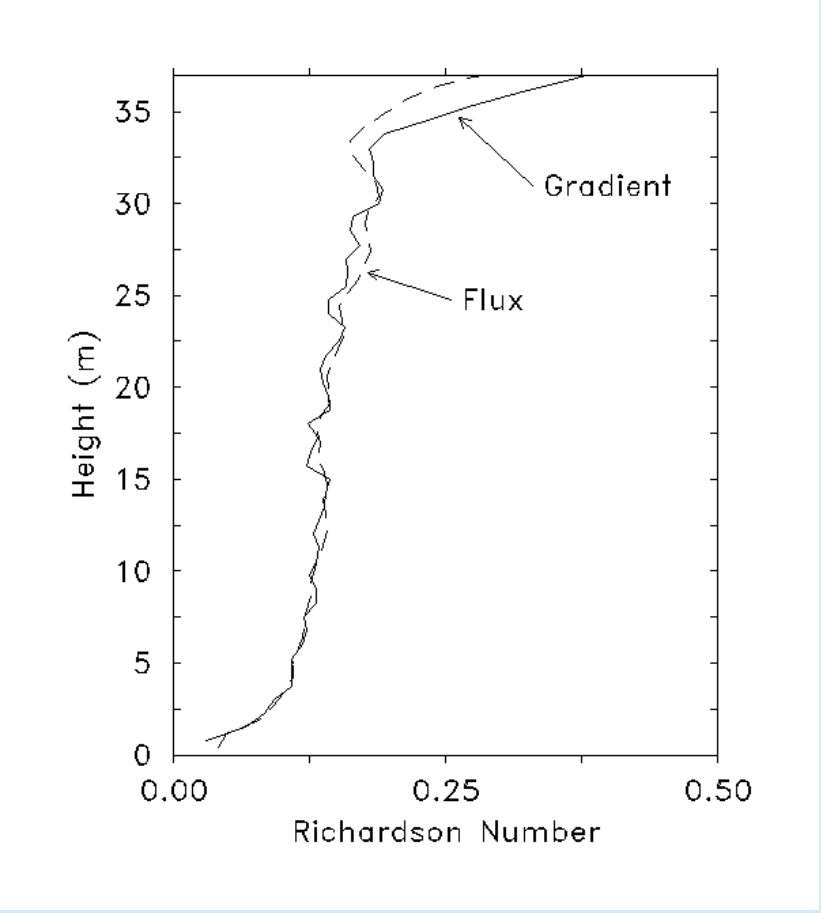
Buoyancy

ARPS w comes from TKE



Geostrophic Flow
Flat Surface





Mellor-Yamada 1.5 TKE Budget

Dissipation Rate

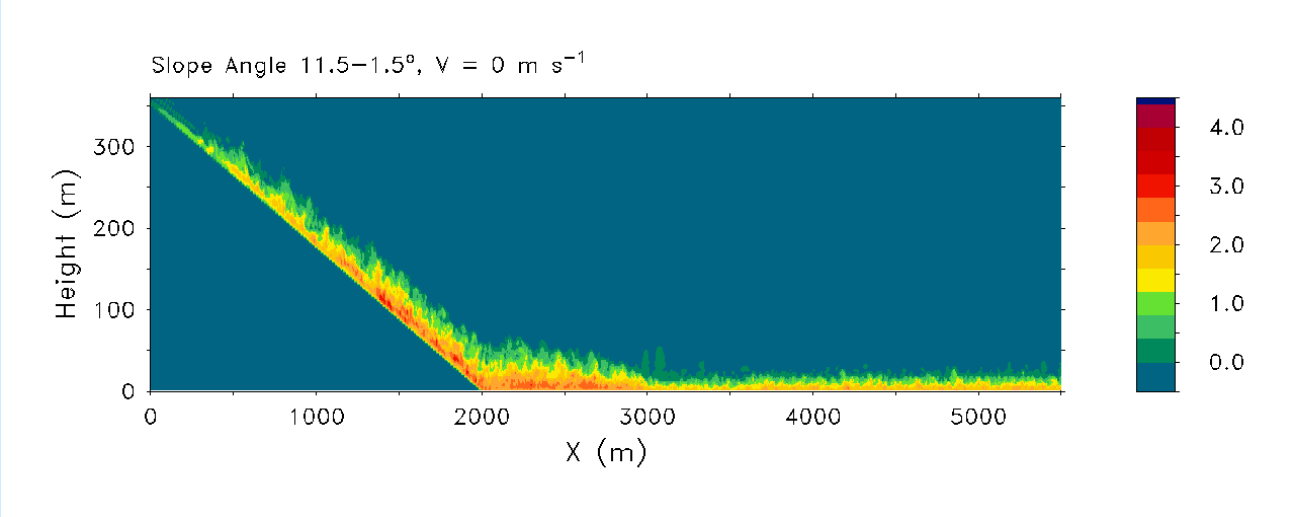
$$\varepsilon = \frac{C}{l} E^{2/3}$$

Where l is a mixing length: $l = 0.76 E^{1/2} \left| \frac{g}{\theta} \frac{\partial \theta}{\partial z} \right|^{-1/2}$

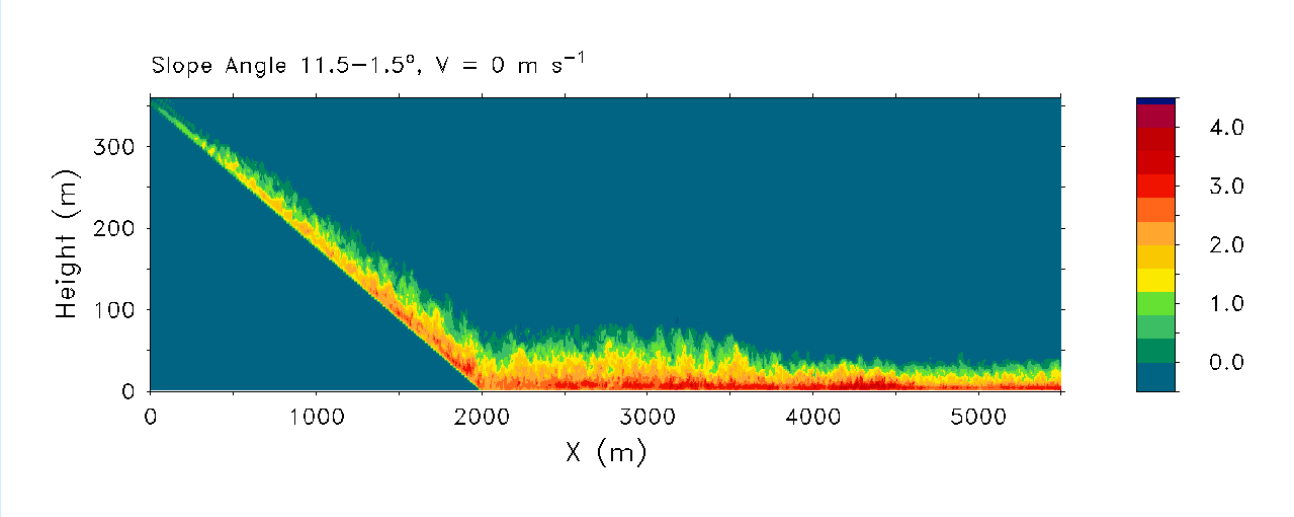
Similar to buoyancy lengthscale if $w \approx E^{1/2}$

Combined Slopes

T = 20 min

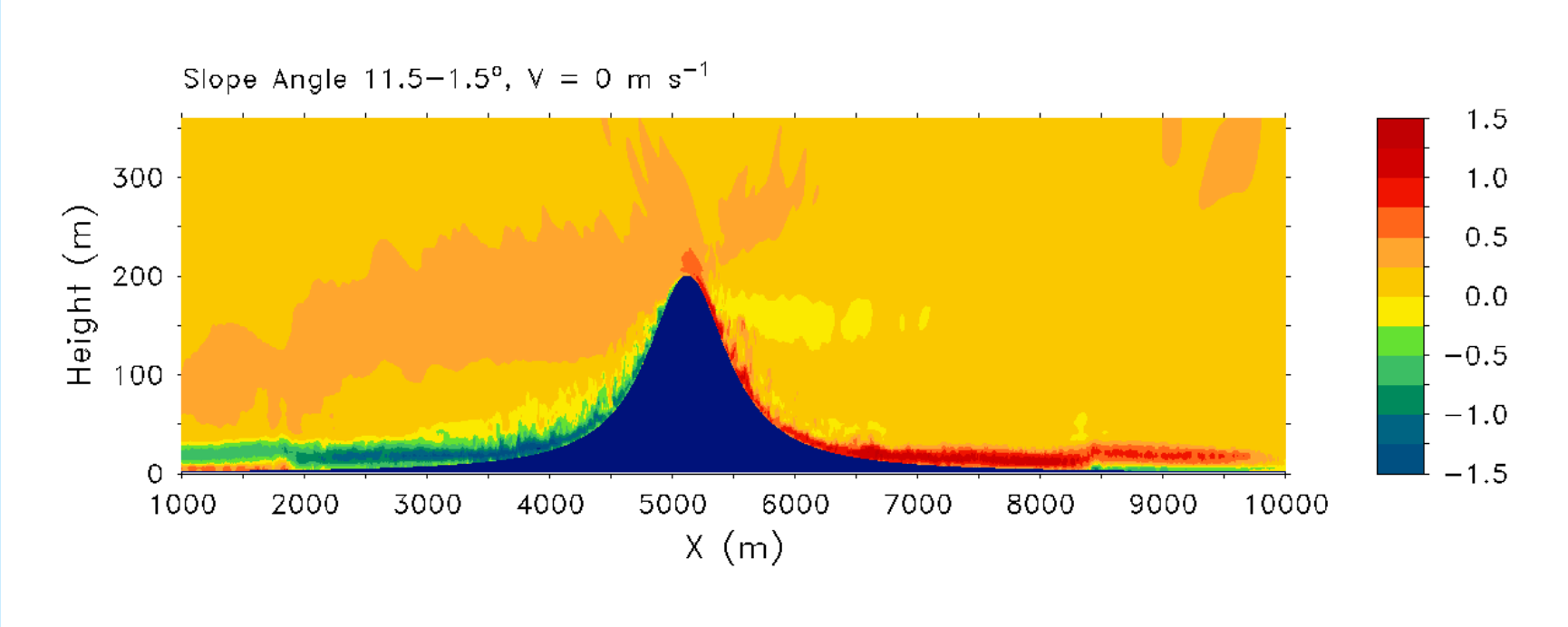


T = 20 min



11.5° 1.5°

Basin-Mountain Interaction



Summary

- Flow above jet has turbulence structure similar to weakly stable BL
- Bulk model entrainment process similar to shear driven mixing
- Steep terrain generates deep slope flows affecting the BL structure over broad areas
- Mixing parameterizations do an OK job.

Subgrid Scale Parameterization

$$\left\langle u''_i u''_j \right\rangle = -K_m \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Filtered Structure Function

$$K_m = 0.0014\, C_k^{-3/2} \left[F(\hat{x}) \right]^{1/2}$$

$$F(\hat{x}) = \overline{\left\| u(\hat{x}) - u(\hat{x} + r) \right\|^2}_{\|r\| = \Delta x}$$

Ducros et al. (1996)