Implication of mountain shading on energy for snowmelt

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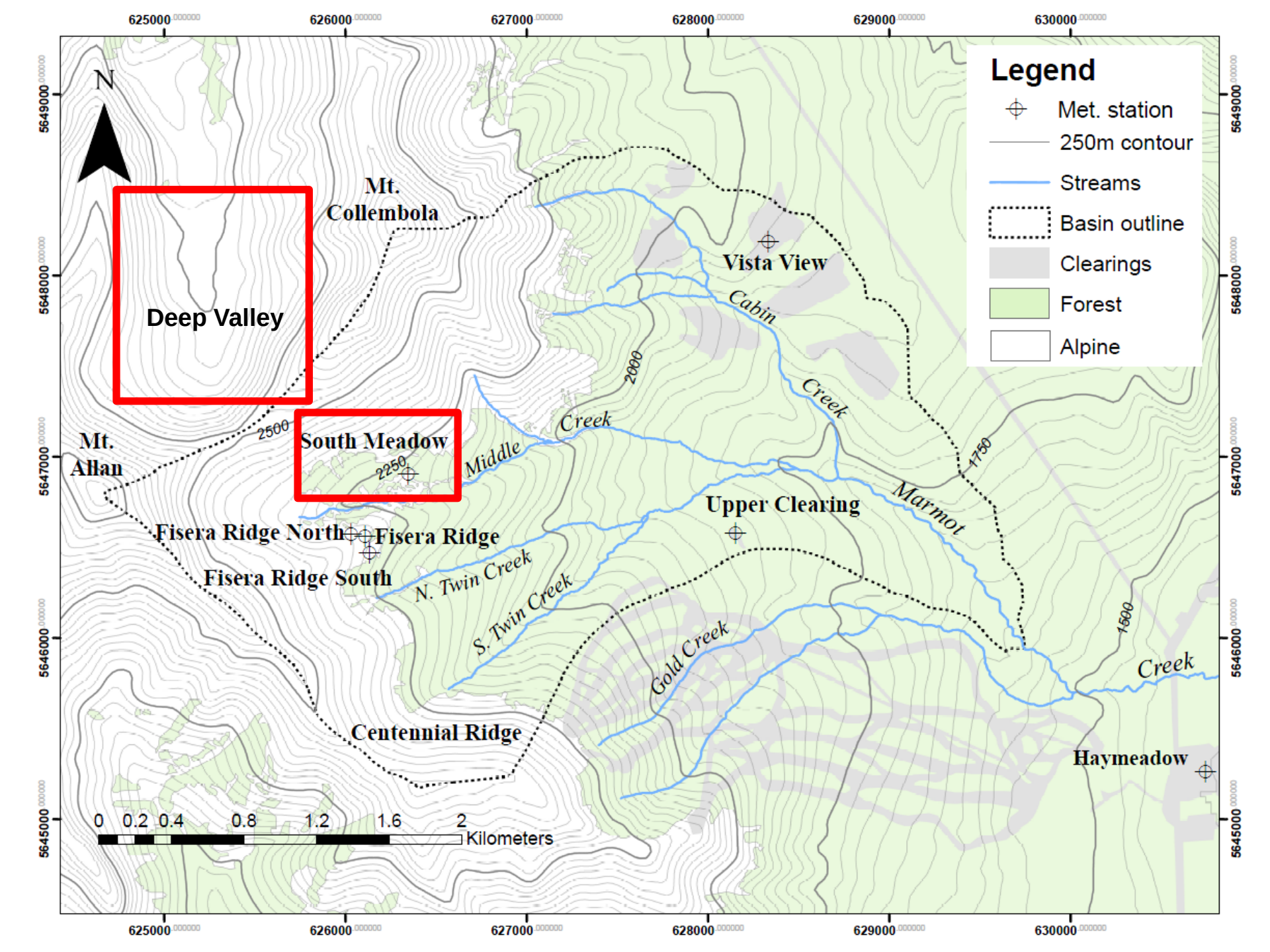
Outline

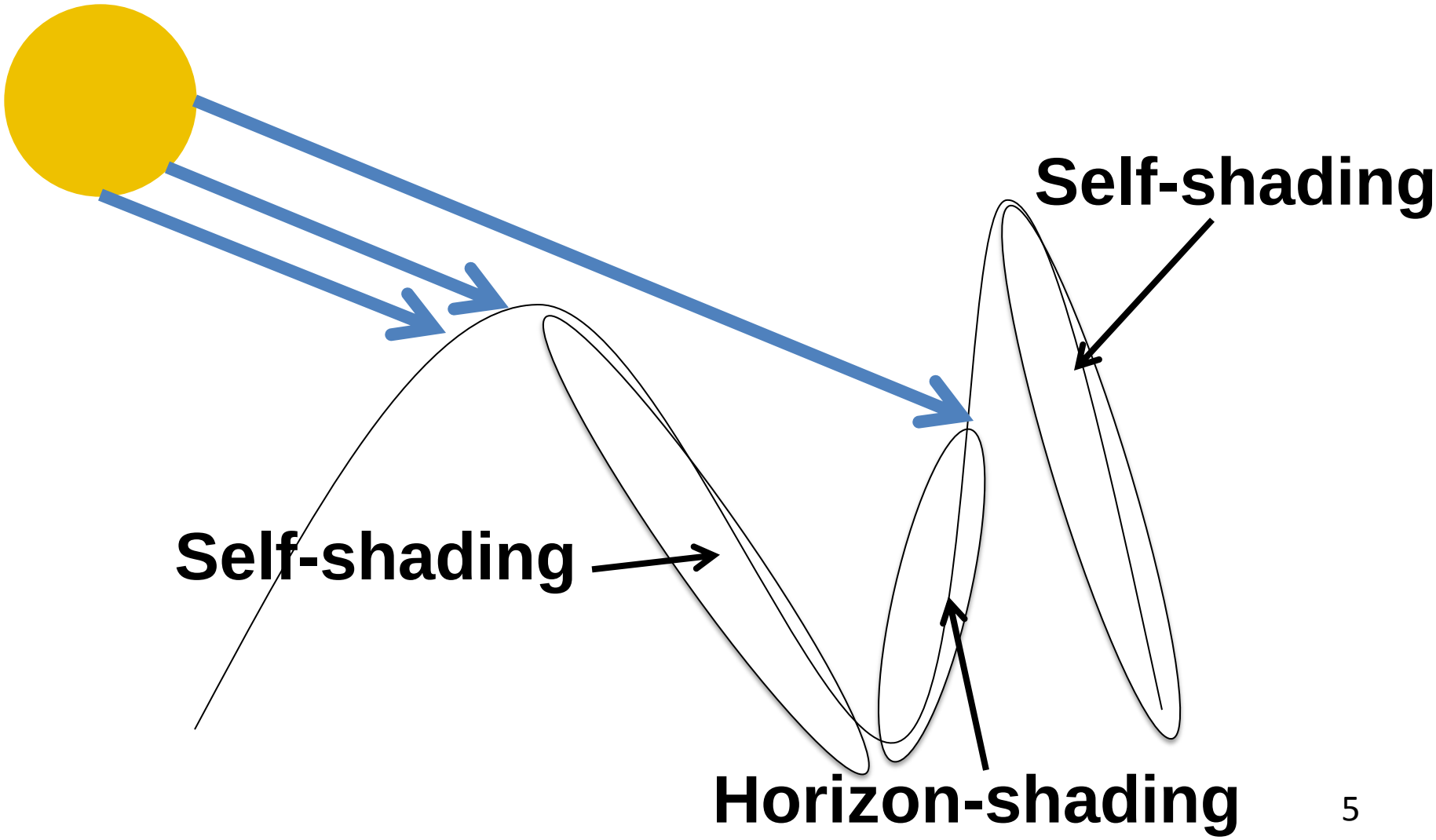
- Research motivation and goals
- Site overview
- Process overview
- Modelling
  - Terrain representation
  - Numerical modelling
- Model verification
- Potential errors by ignoring shadows
- Snowmelt modelling
- Spatial scale sensitivity
- Future work
- Conclusions

Research motivation

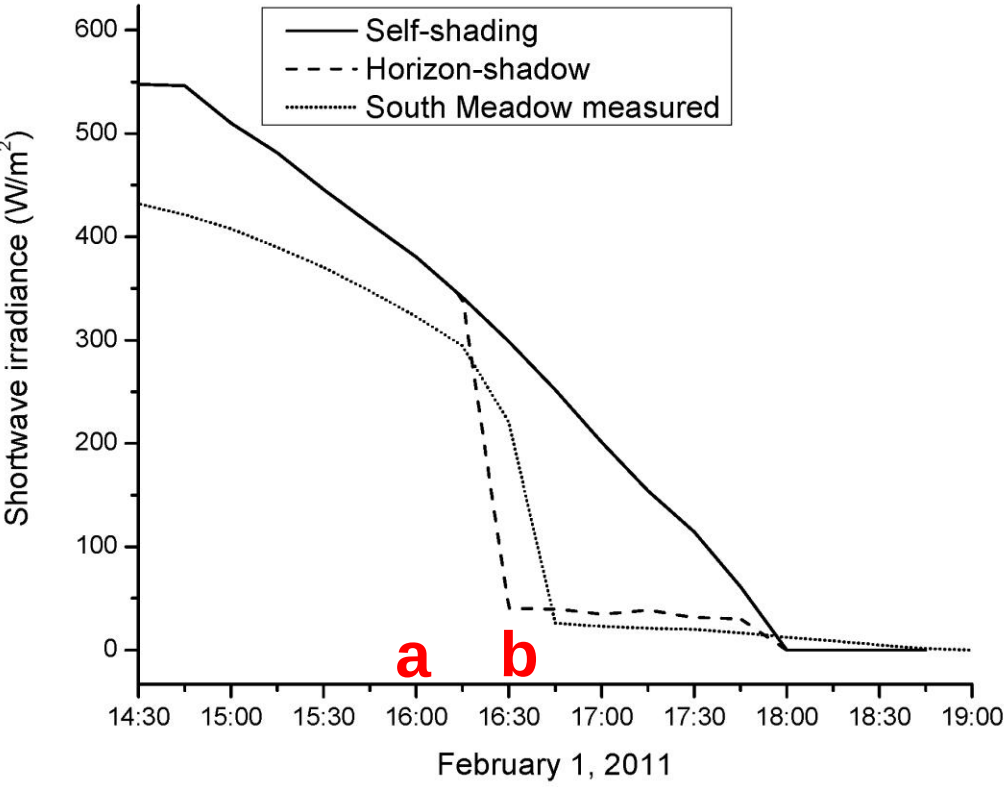
- Net-shortwave is a key energy balance component
  - Energy balance calculations theoretically superior for snowmelt.
  - **High spatial variability in rugged mountain topographic due to horizon-shadows**
- Cumulative errors in net shortwave when shading is ignored.
- Most models of horizon-shading are computationally expensive, potentially inaccurate
- **Horizon-shadowing generally not included in hydrological models**

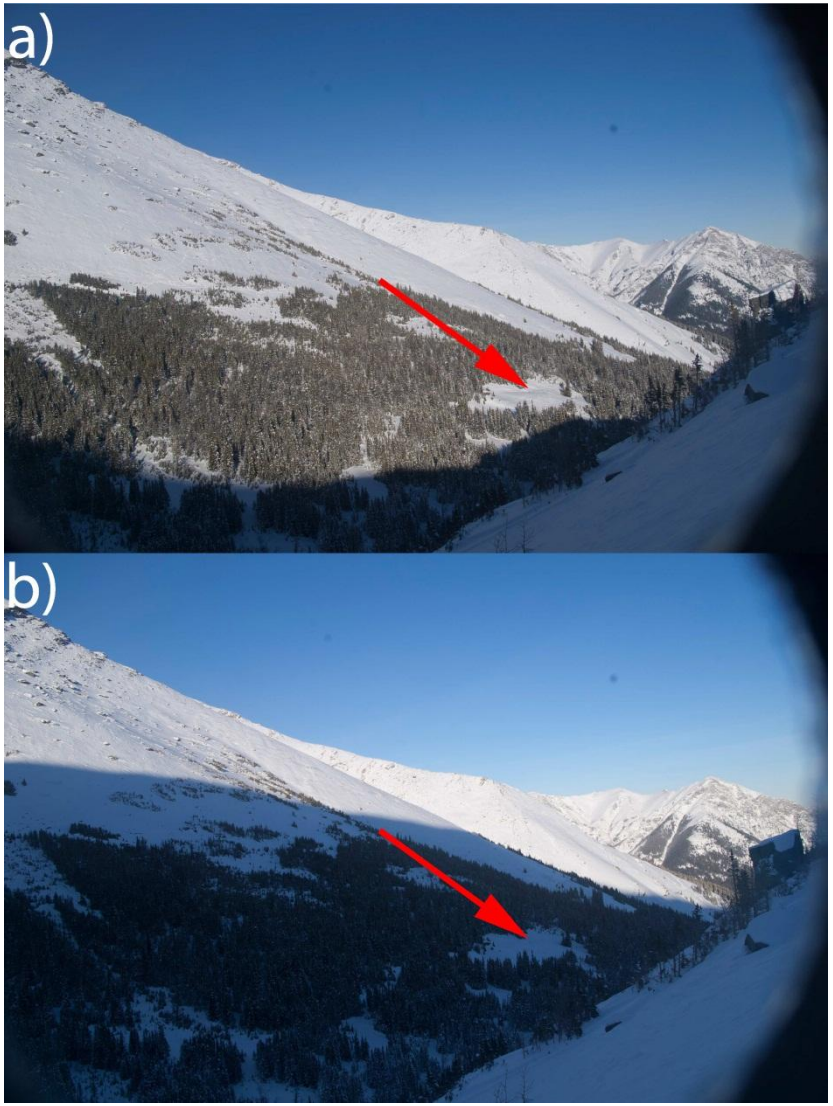

Legend
Met. station
250m contour
Streams
Basin outline
Clearings
Forest
Alpine
N
Deep Valley
Mt. Collembola
Mt. Allan
South Meadow
Vista View
Upper Clearing
Fisera Ridge North
Fisera Ridge
Fisera Ridge South
Centennial Ridge
Haymeadow
Cabin Creek
Middle Creek
N. Twin Creek
S. Twin Creek
Gold Creek
Marmot Creek
2000
2250
2500
1750
1500
0 0.2 0.4 0.8 1.2 1.6 2 Kilometers
625000
626000
627000
628000
629000
630000
5649000
5648000
5647000
5646000
5645000

Shadows



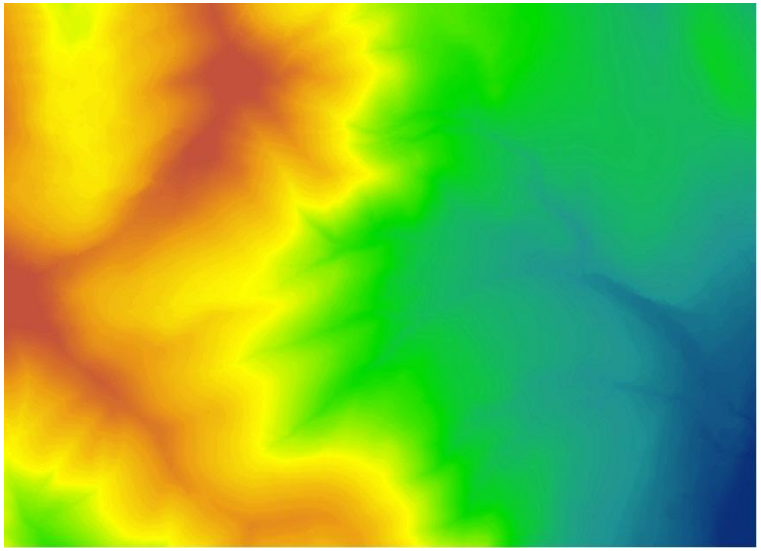
Shadowing example



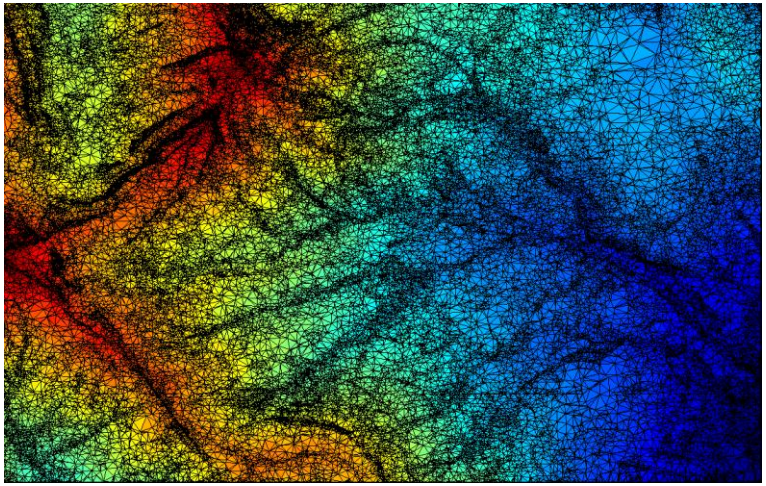


Terrain representation

- Structured mesh
  - Raster or grid in GIS nomenclature
  - Each grid cell is square and represents an average elevation over the area
  - Over/under representation of topography
  - Artefacts in derived data
  - **Fixed spatial resolution**



- Unstructured triangular mesh (USM)
  - a.k.a Triangulated Irregular Network (TIN)
  - Triangles composed of edges and vertices
    - Vertices represent elevation
    - Edges represent connected nodes
  - **Variable spatial resolution**



Benefits of unstructured meshes

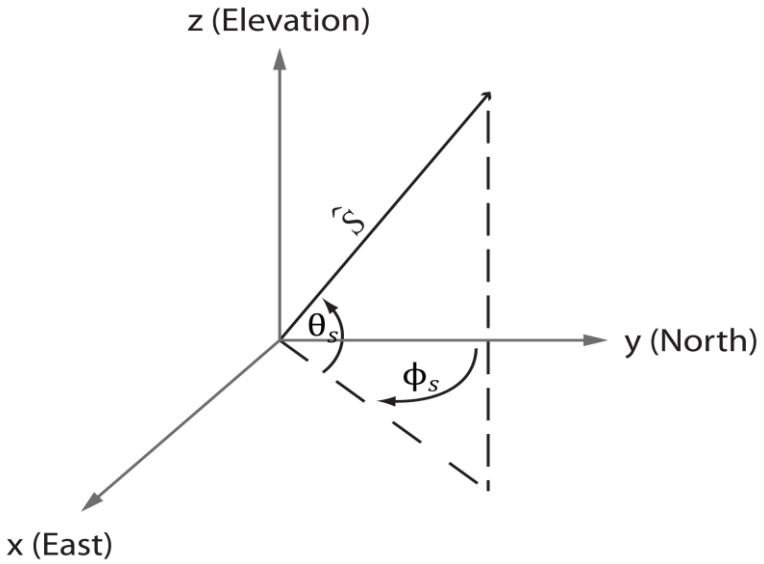
- For Marmot Creek, reduction in computational elements
  - from 20,000,000 elements to 200,000

- **95x reduction in computational elements**

- Even smaller tolerance unstructured meshes have large improvements
  - 35x reduction in elements

Model construction

- Following Montero (2009), use Euler rotation to orientate to solar position
  - Applied to each vertex at each time-step
  - Eliminates need for computationally expensive ray-tracing
  - O(N logN)
- Introduces triangle ordering w.r.t. sun
- Test for shadow location by looking front to back for obscuring triangles
  - Triangle-Triangle intersection tests



Montero, G., et al (2009), Solar radiation and shadow modelling with adaptive triangular meshes, *Solar Energy*, 83(7), 998–1012

Performance

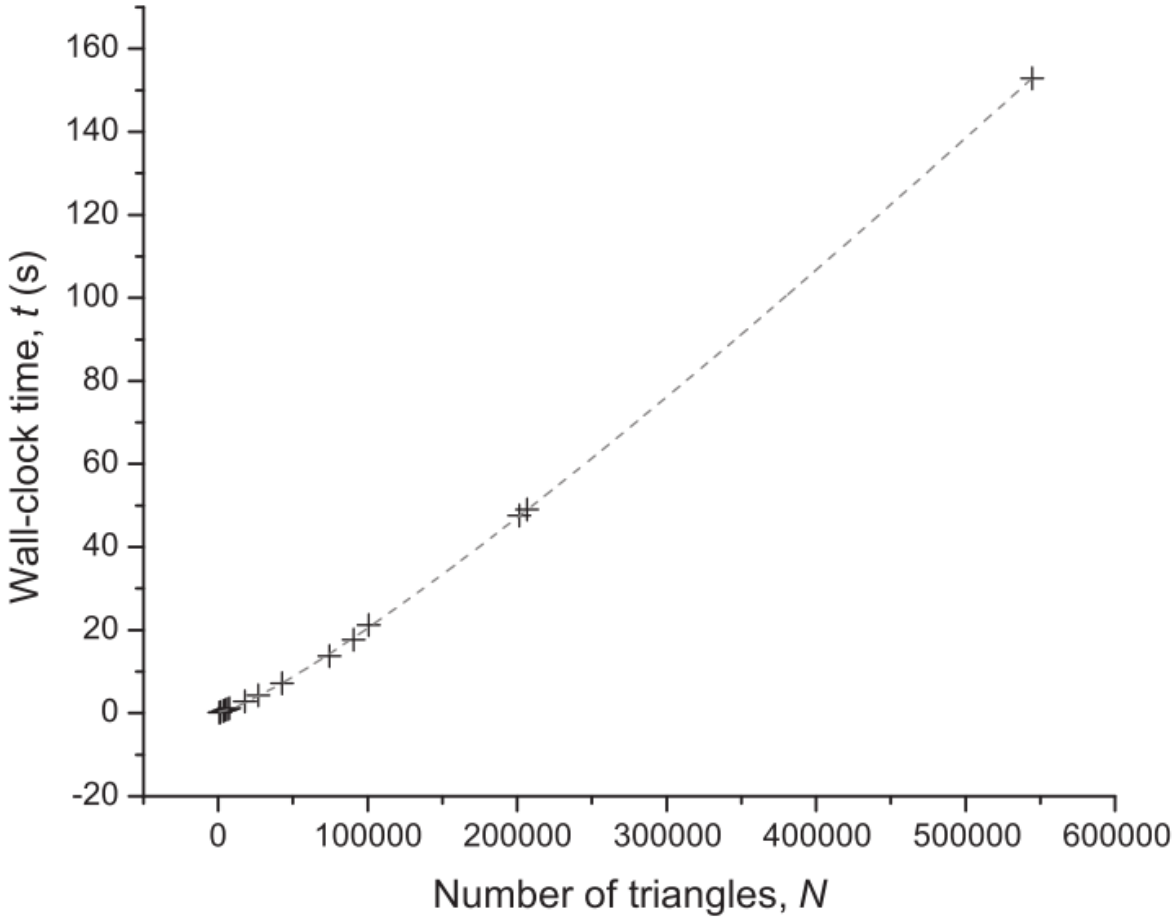
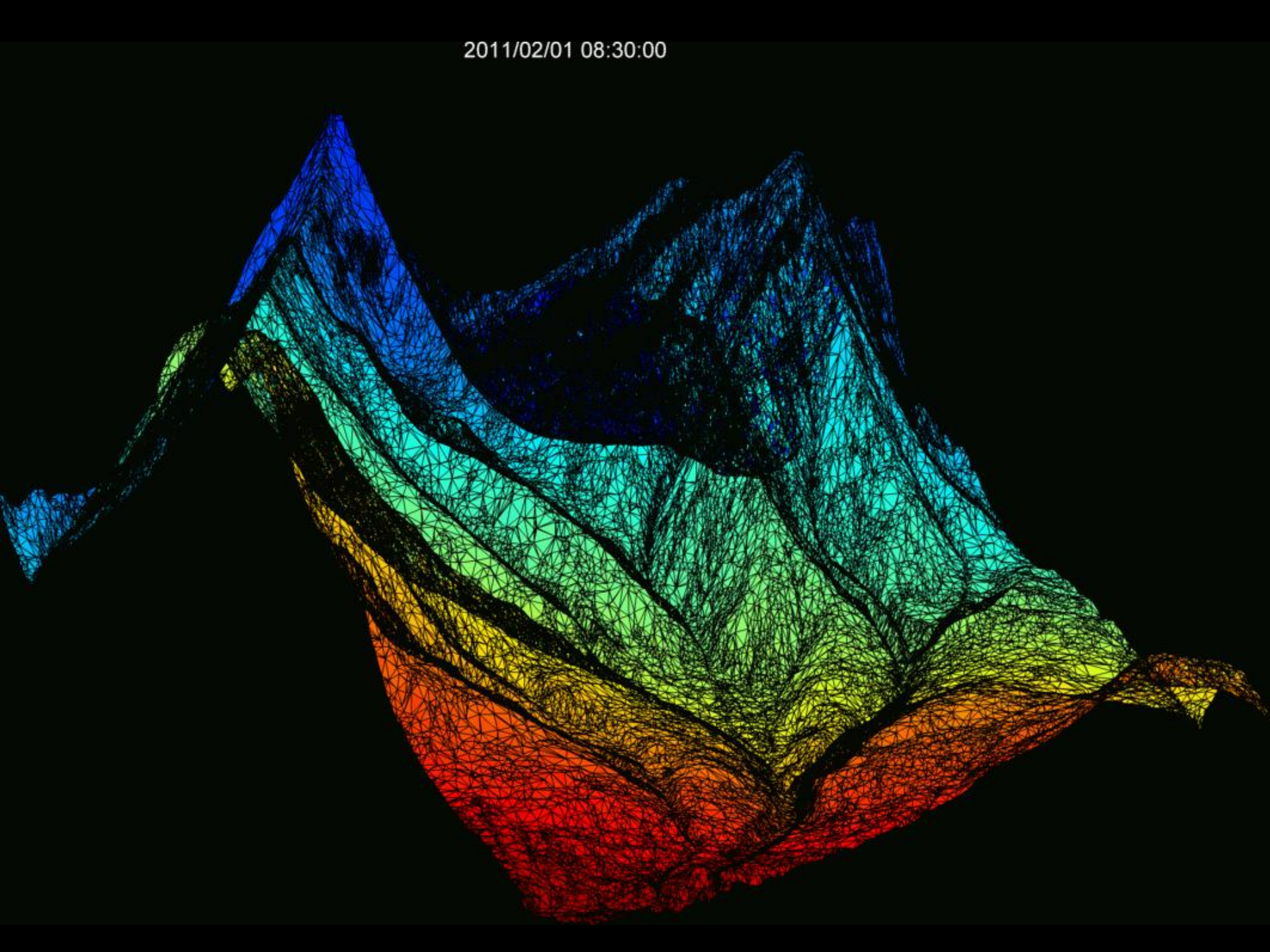
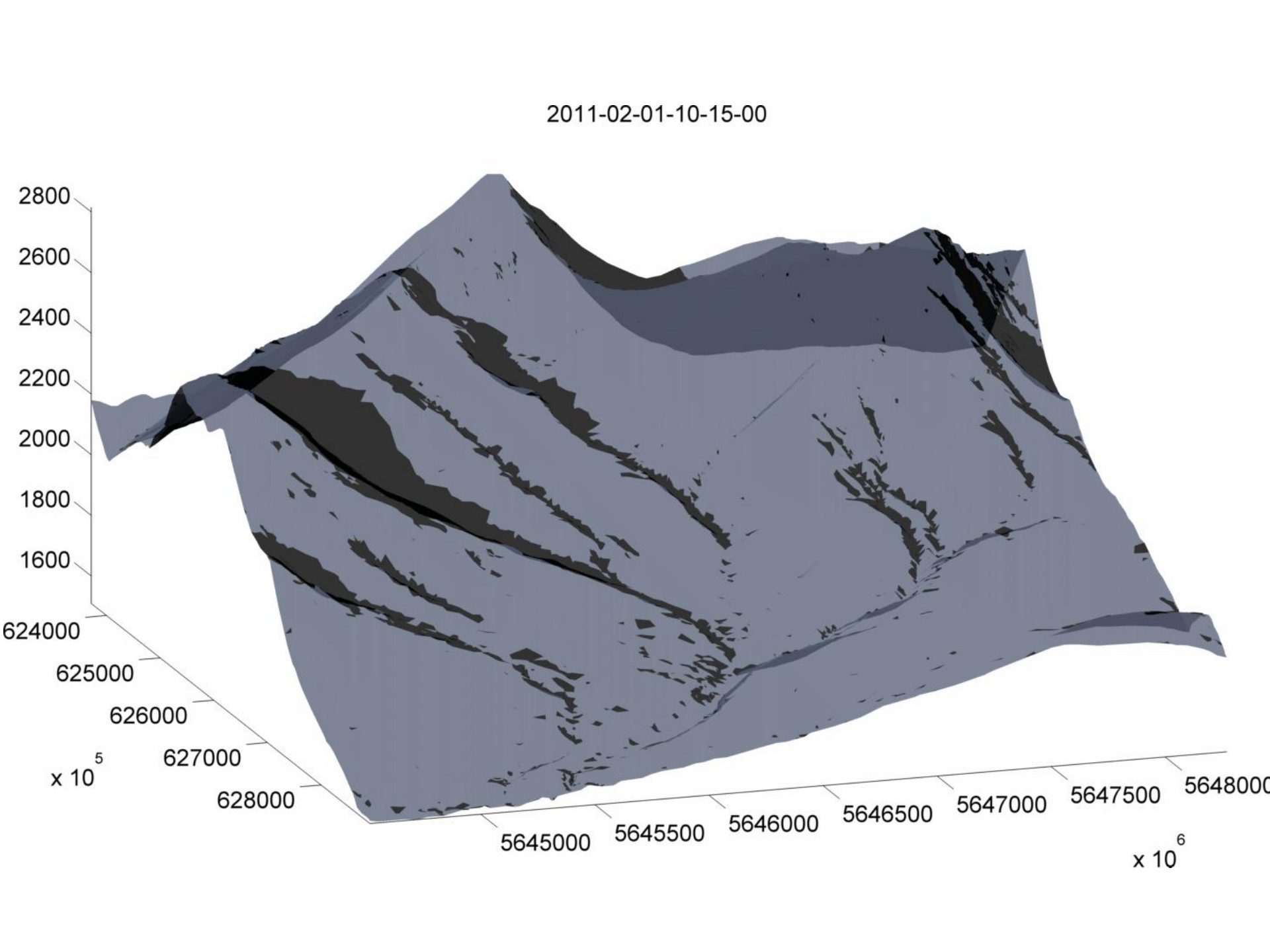
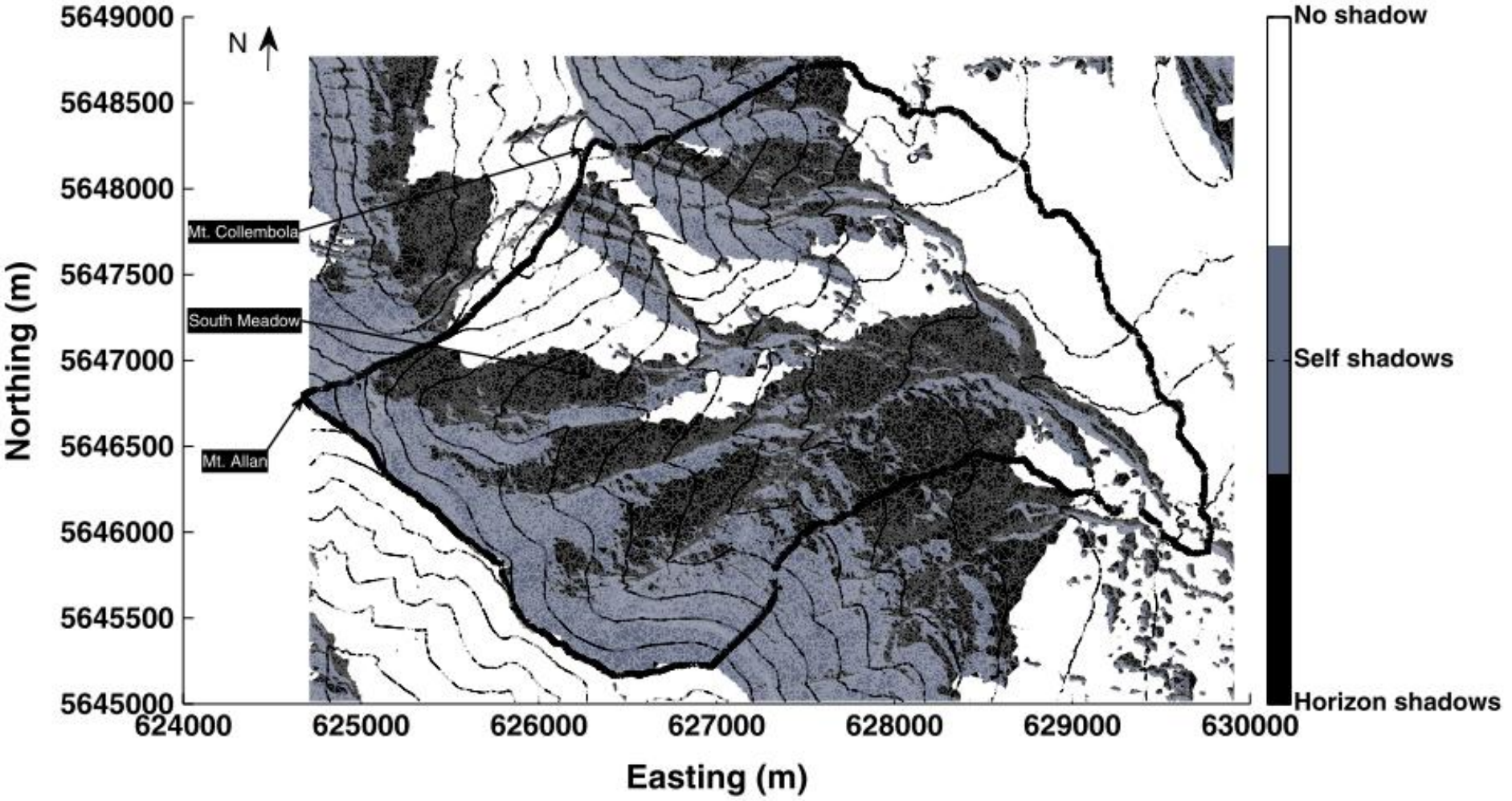


Figure 5. Wall-clock times of the horizon-shadow algorithm run for mesh sizes from 851 to 544 507 triangles. The grey dashed line is a line of best fit of the form $t = a_0 + a_1 N + a_2(N \log N)$. Wall-clock times are for one model timestep 1 February 2011 at 16:30, a time for which there are many triangles in shadow


2011/02/01 08:30:00


2011-02-01-10-15-00
2800
2600
2400
2200
2000
1800
1600
624000
625000
626000
627000
628000
x 10^5
5645000
5645500
5646000
5646500
5647000
5647500
5648000
x 10^6

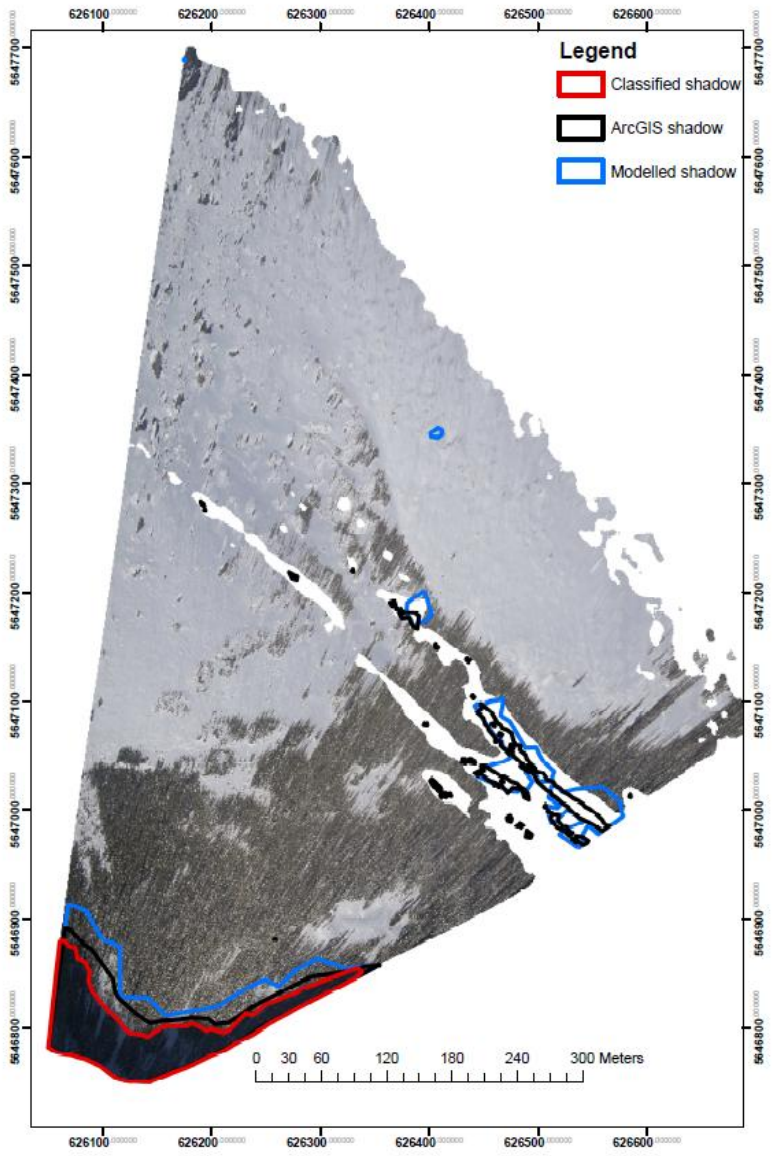
Shadows


N
Mt. Collembola
South Meadow
Mt. Allan
No shadow
Self shadows
Horizon shadows
Northing (m)
5649000
5648500
5648000
5647500
5647000
5646500
5646000
5645500
5645000
624000
625000
626000
627000
628000
629000
630000
Easting (m)

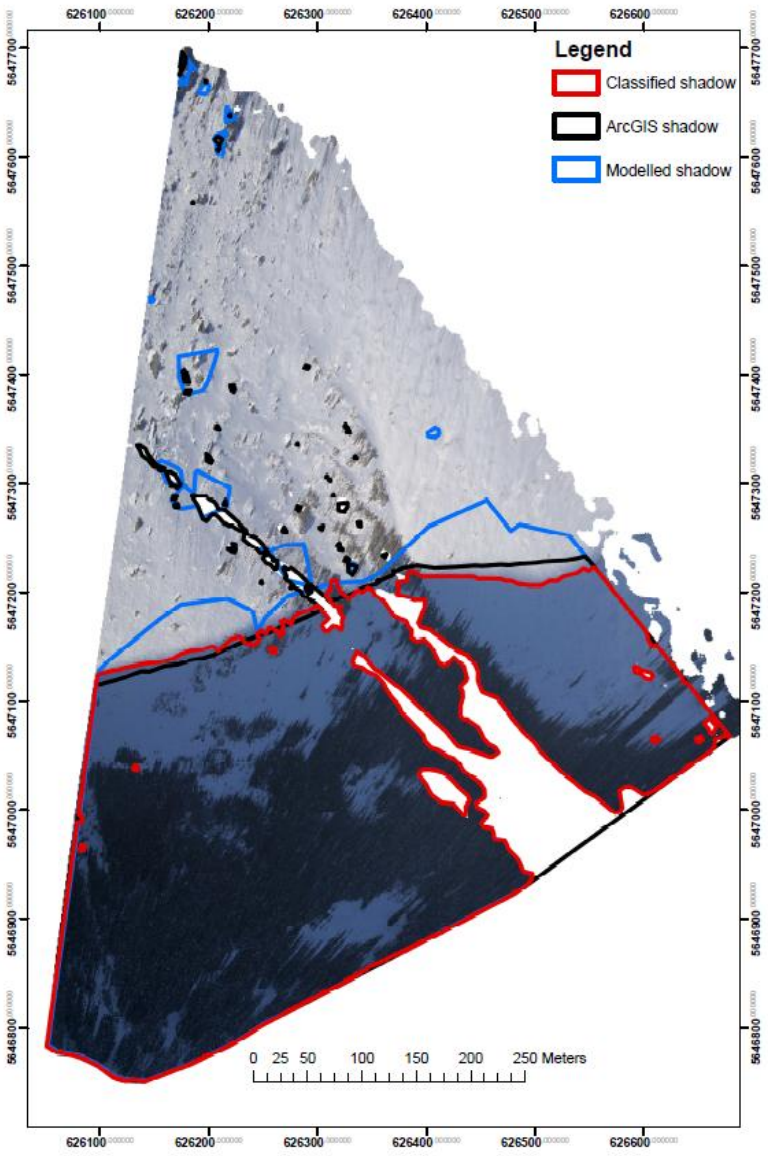
Orthorectification

Corripio, J. G. (2004), Snow surface albedo estimation using terrestrial photography, *International Journal of Remote Sensing*, *25*(24), 5705–5729

Shadow movement at South Meadow

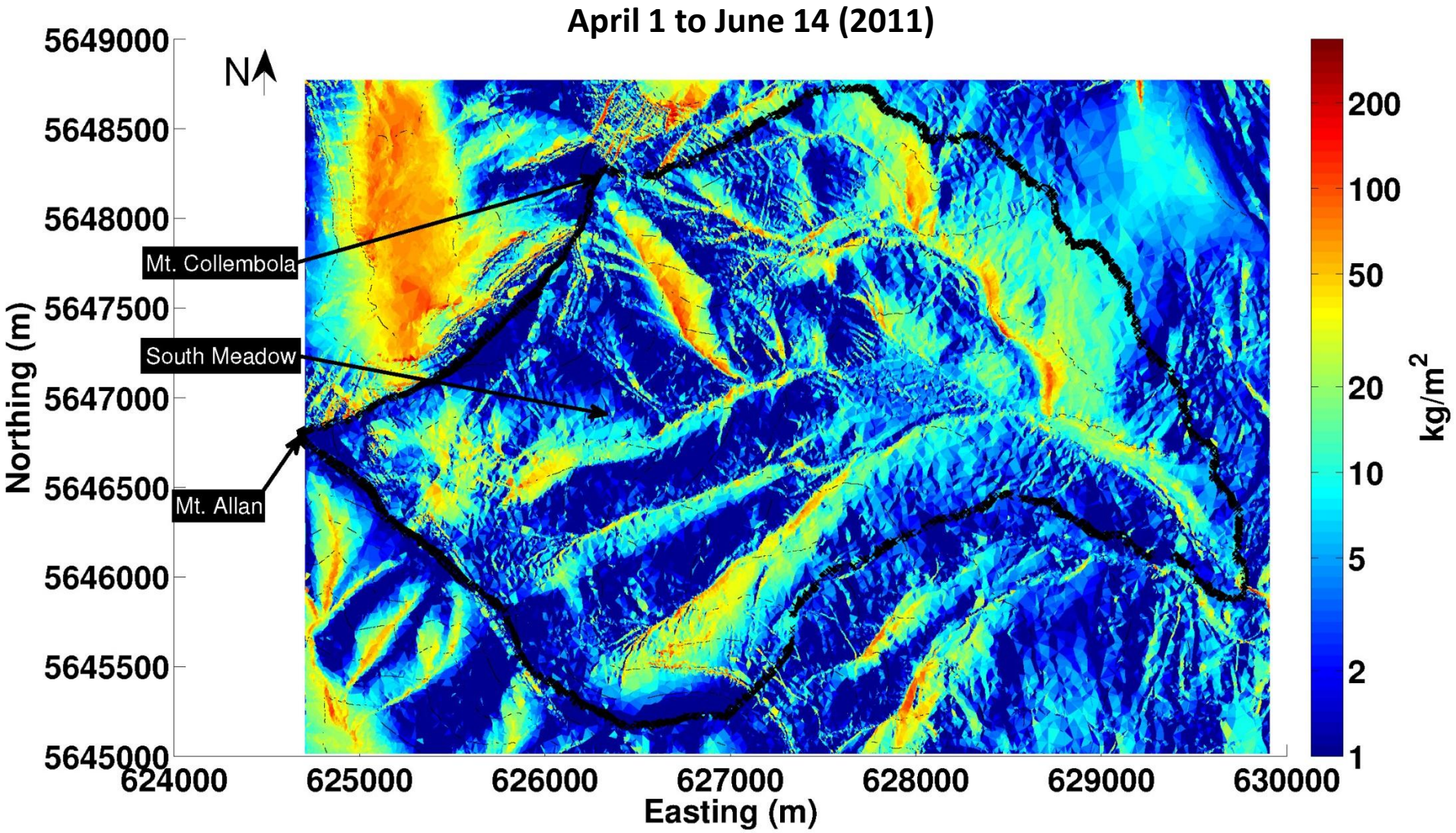


(a) 16:00



(b) 17:00

Difference in spring melt due to topographic shading



Snowmelt modeling

- Energy balance and snow melt

$$Q_m = Q_{sn} + Q_{ln} + Q_h + Q_e + Q_g + Q_p + \frac{dU}{dt}$$

- Net shortwave radiation with shadowing

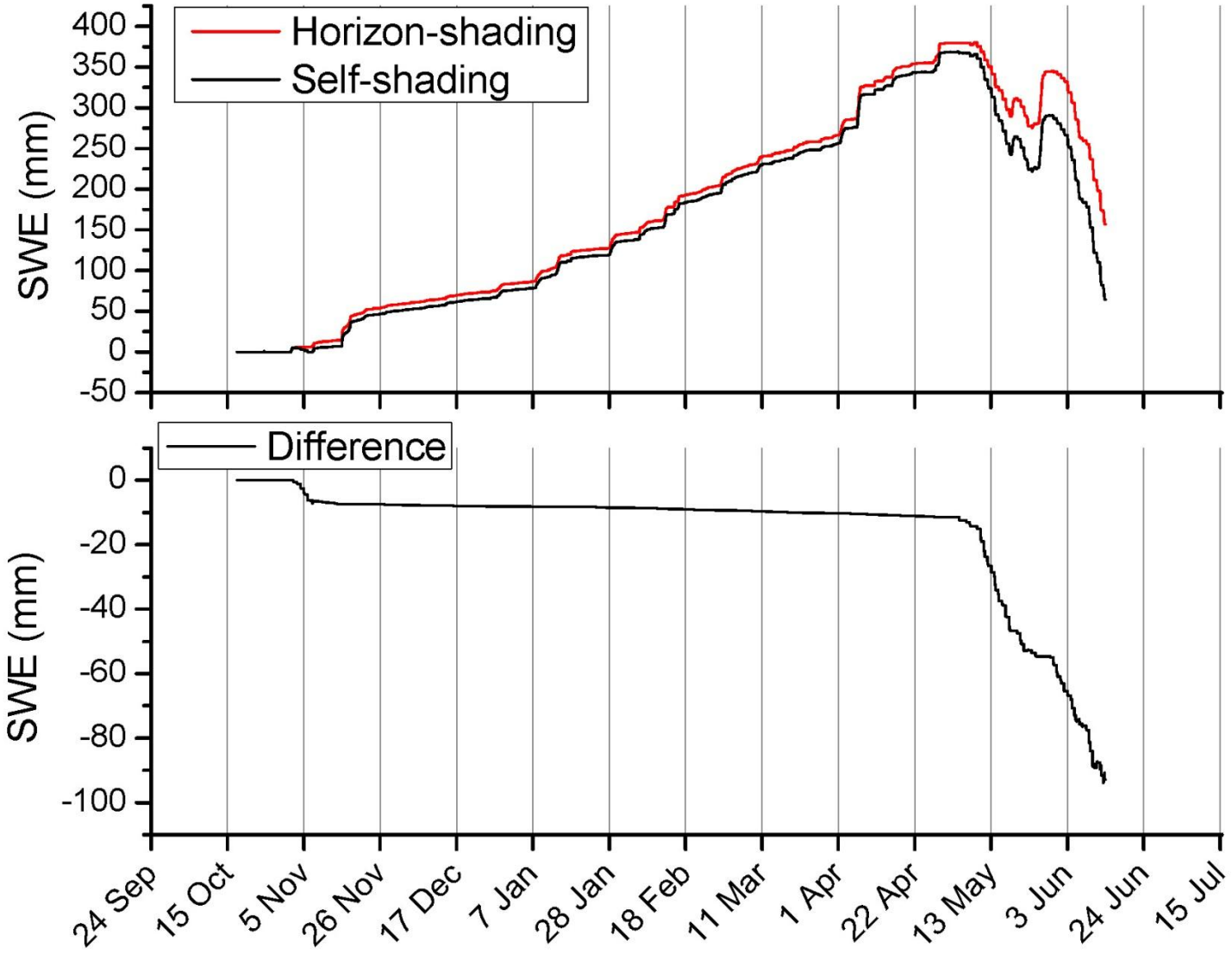
$$Q_{sn} = Q_{ds}(1-\alpha)(1-\zeta) + Q_{diff}(1-\alpha)$$

- Shadowing factor ζ
  ζ=0, no horizon-shadow
  ζ=1, horizon-shadow

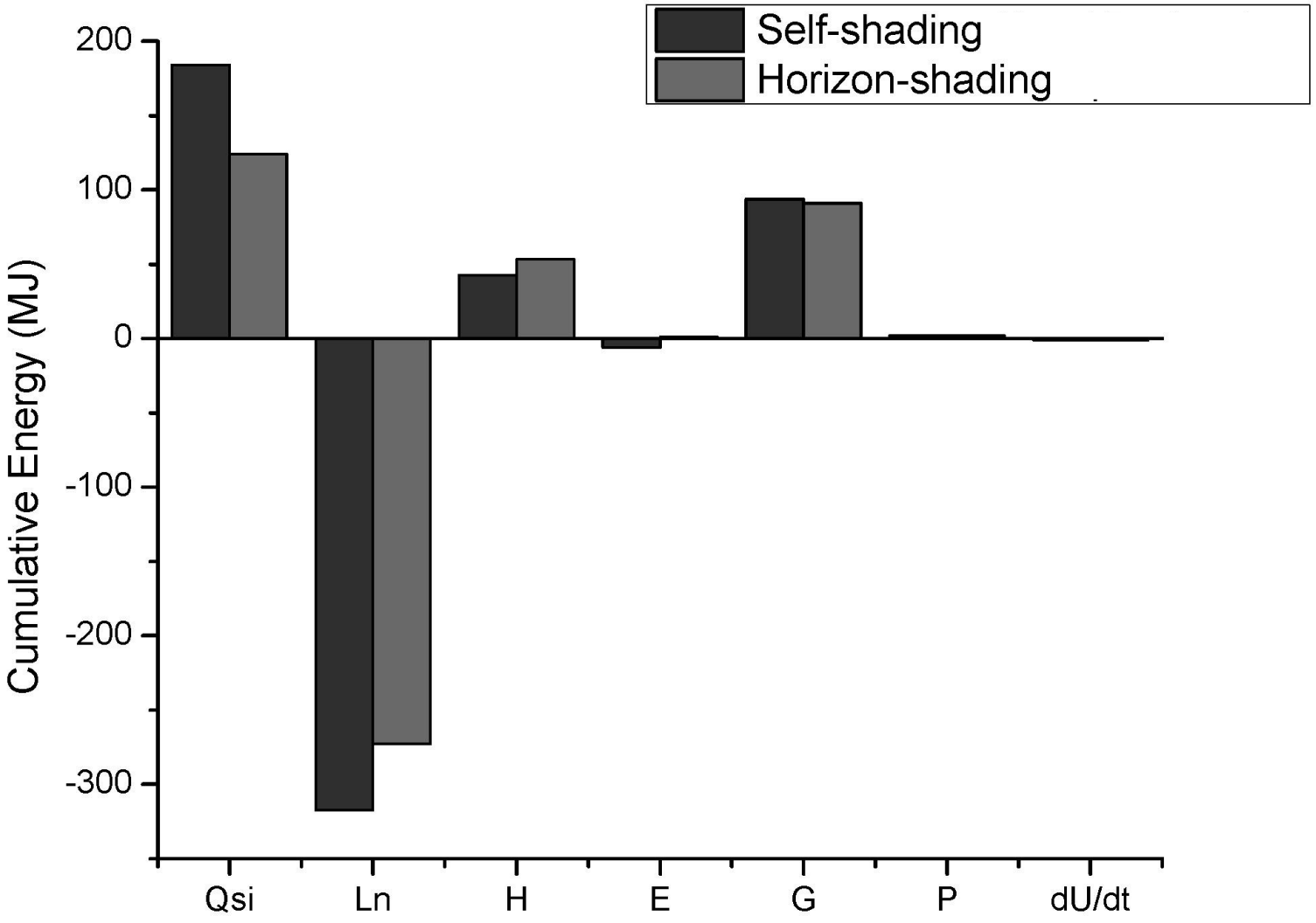
- **Model Methodology:**
  - Used CRHM with SNOBAL for snow melt
  - Used measured metrological observations
  - Corrected measured clear-sky shortwave for horizon-shadows
  - Follow Garnier and Ohmura (1968)
  - We are **NOT** computing transmittance

Garnier, B. J., & Ohmura, A. (1968). A method of calculating the direct shortwave radiation income of slopes. *Journal of Applied Meteorology*, *7*(5), 796–800.

Deep Valley Nov 15—Apr 1



Deep Valley Energy balance

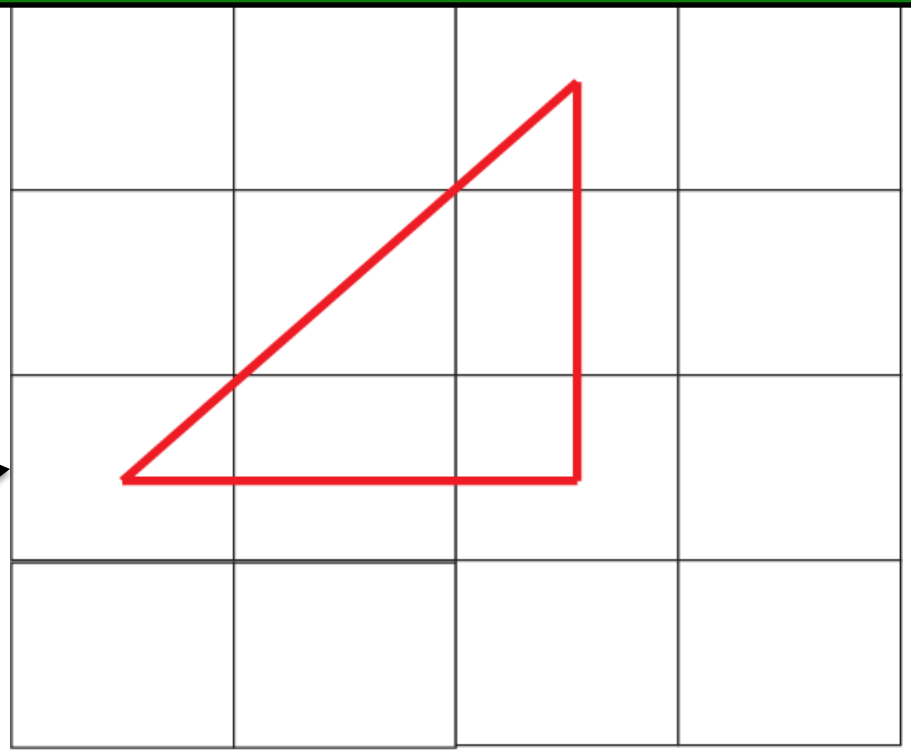


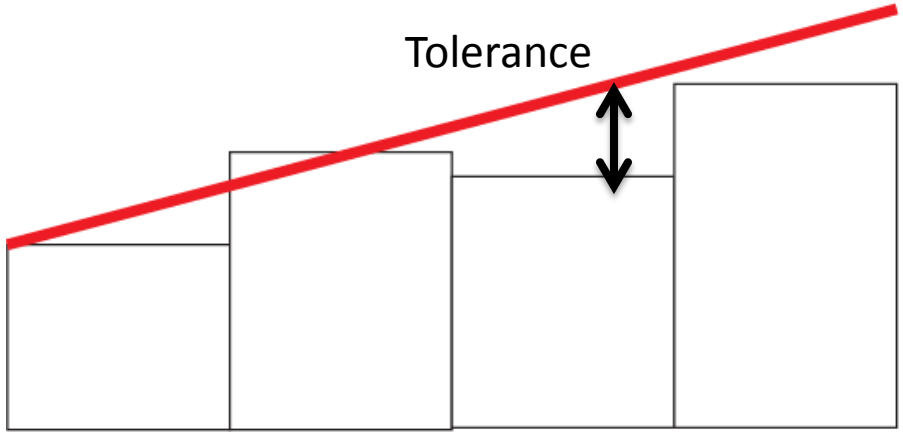
Sensitivity to scale

- Structured mesh
  - Resolution of each cell
    - i.e., 1 m x 1m, 10 m x 10 m
- Unstructured mesh
  - If derived from a structured mesh, resolution of base mesh
  - Triangle **tolerance**
    - Triangles are linear interpolants in 3-space

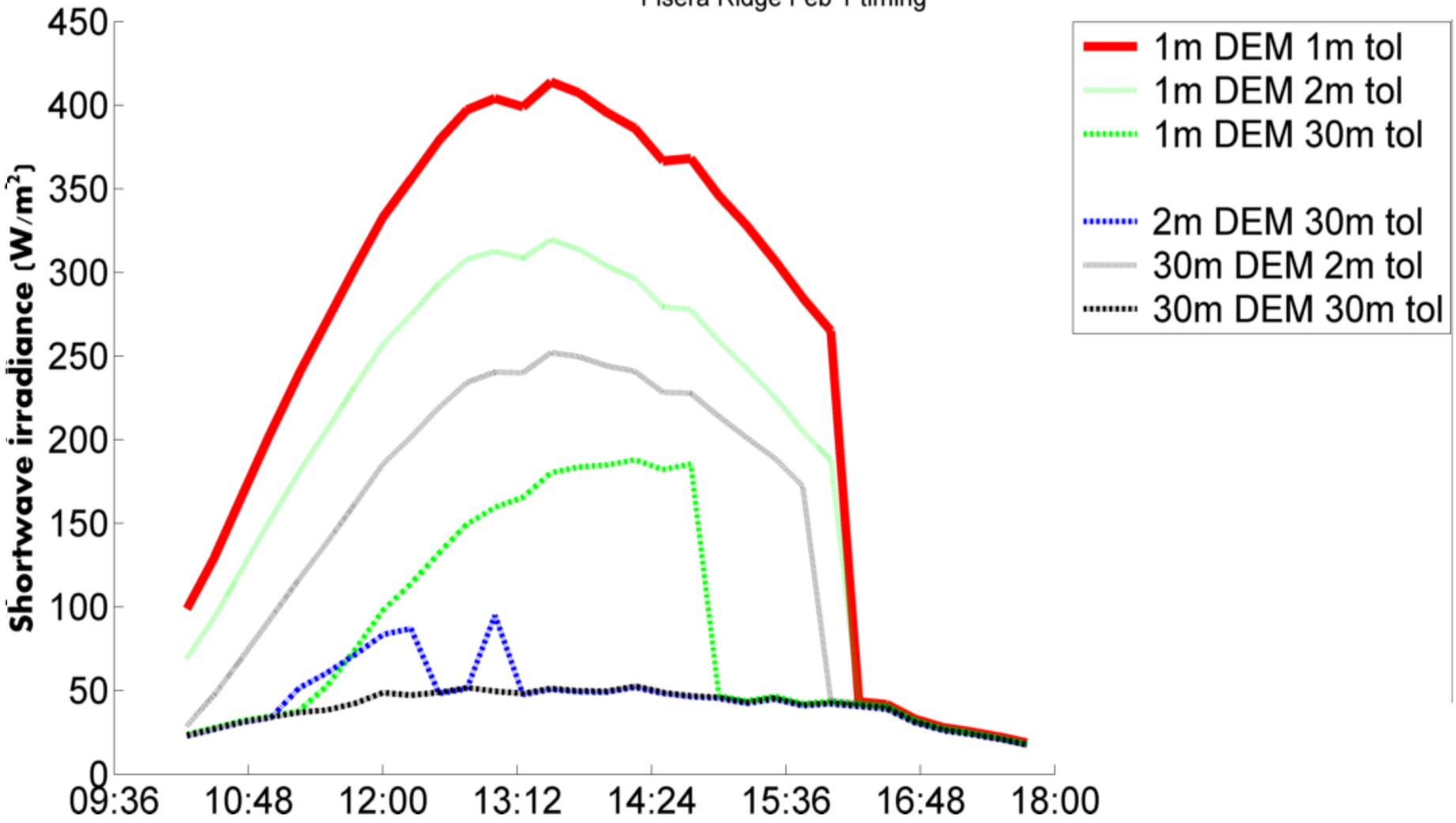
What is tolerance?

Aerial view

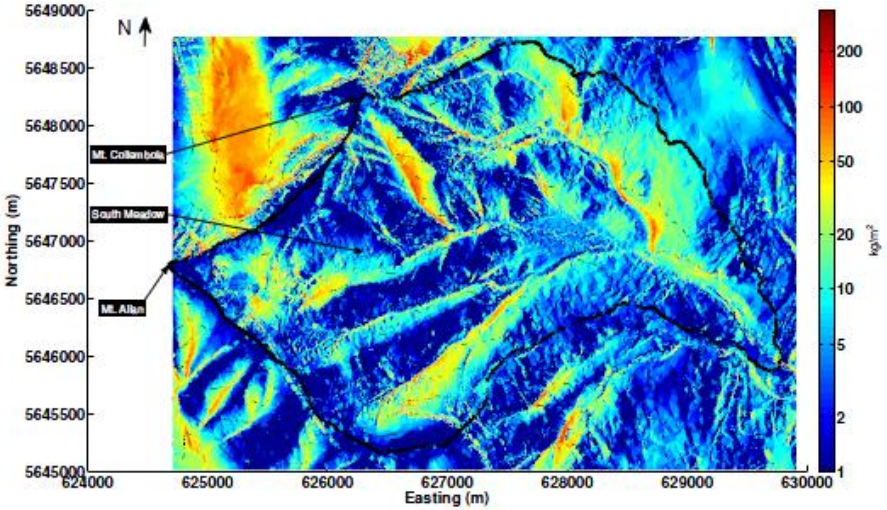




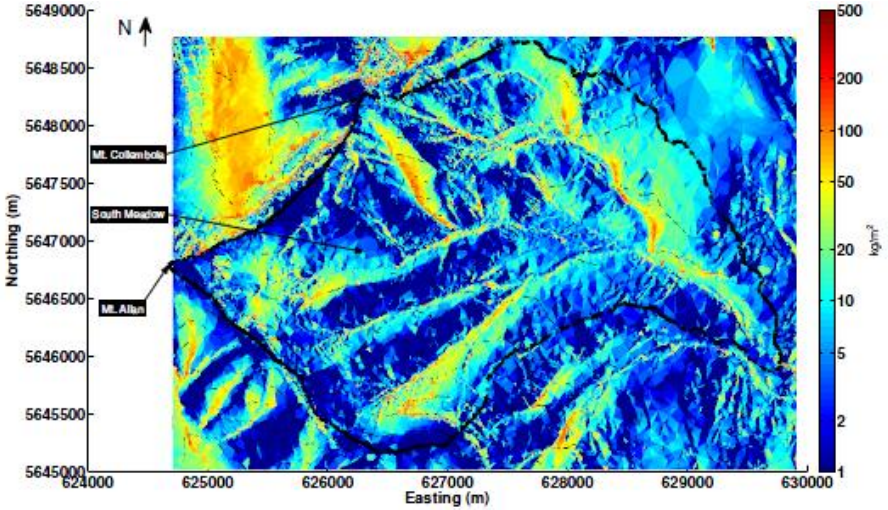
Profile


Fisera Ridge Feb 1 timing
Shortwave irradiance (W/m²)
450
400
350
300
250
200
150
100
50
0
09:36
10:48
12:00
13:12
14:24
15:36
16:48
18:00
1m DEM 1m tol
1m DEM 2m tol
1m DEM 30m tol
2m DEM 30m tol
30m DEM 2m tol
30m DEM 30m tol

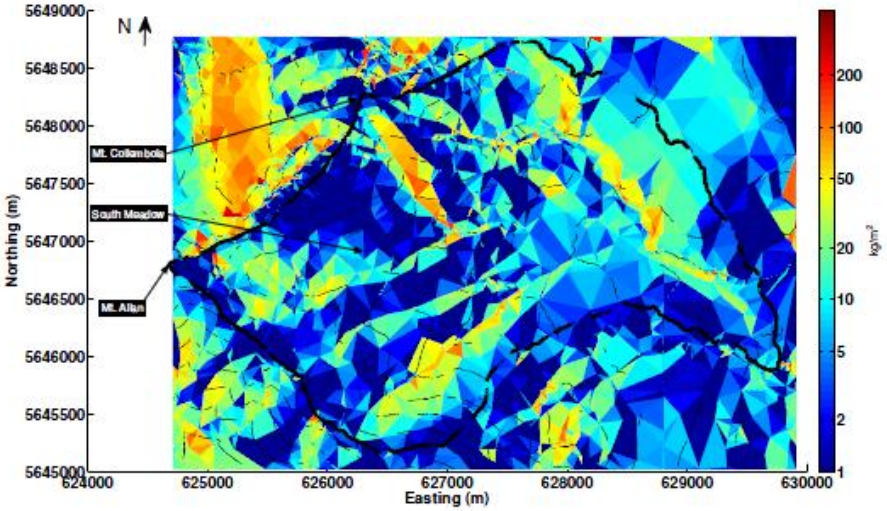
Spatial pattern

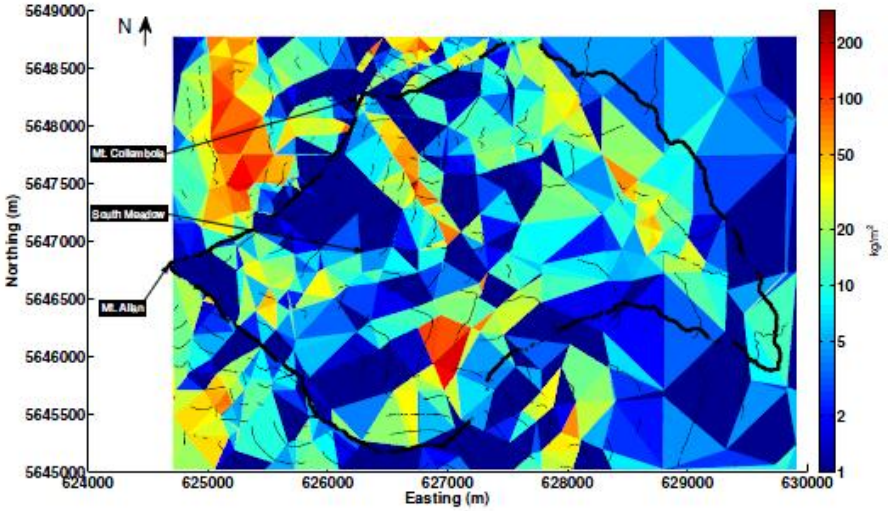


(a)



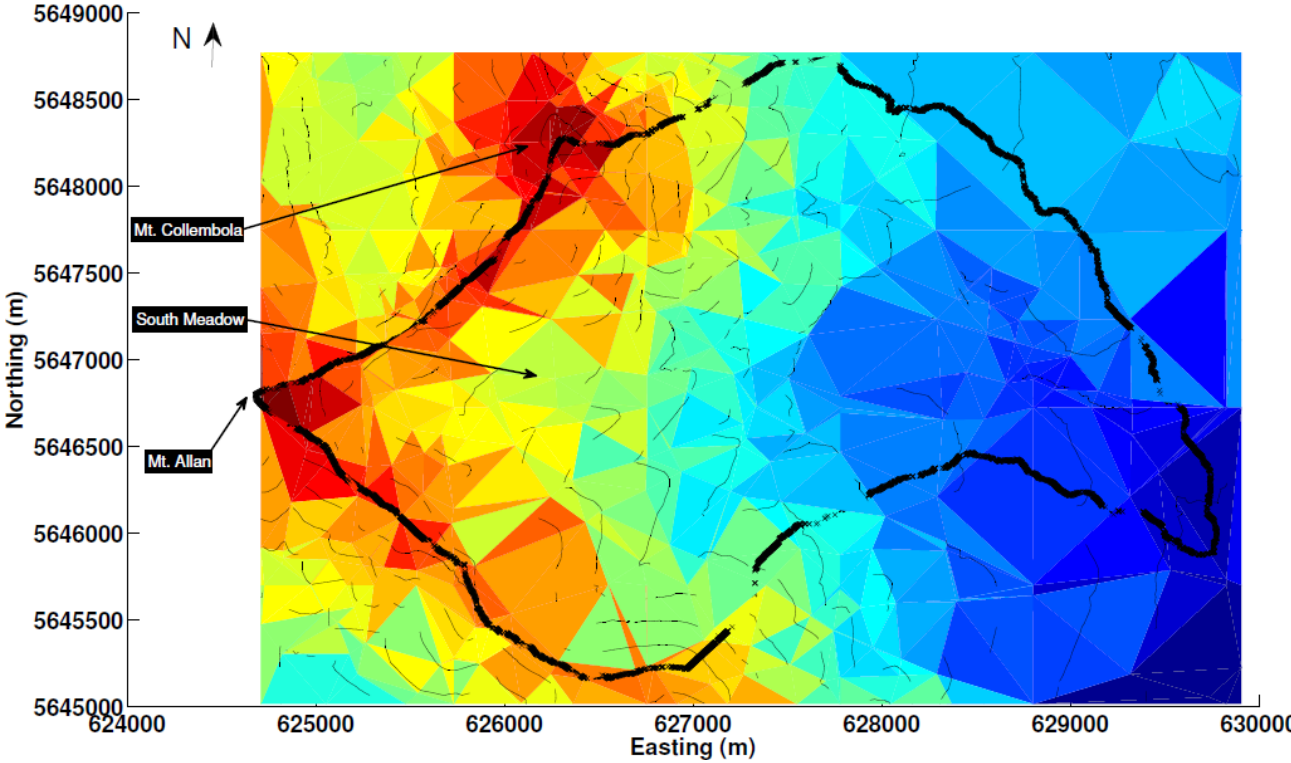
(b)





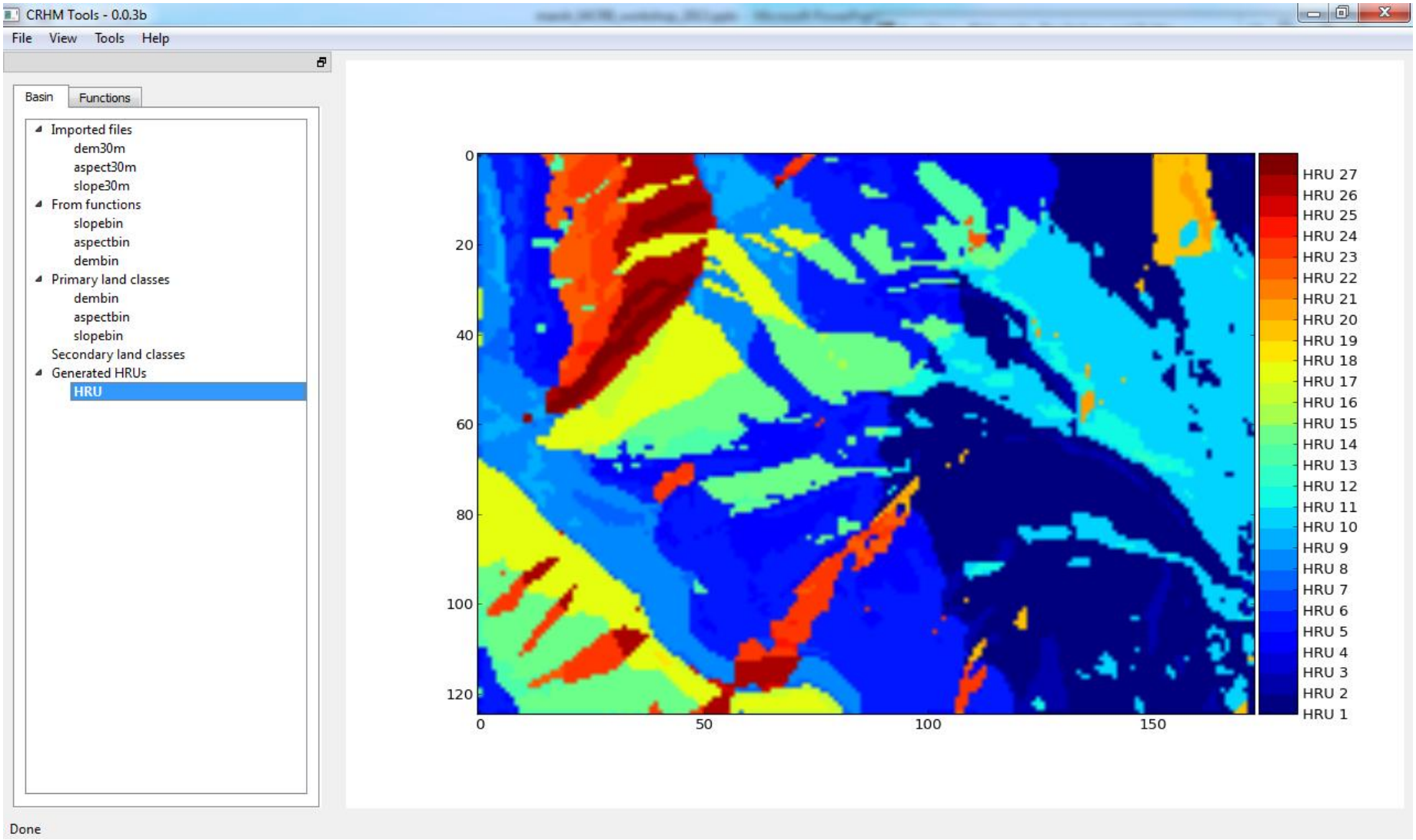
Next steps

- Hydrological Response Units (HRUs)
- HRUs group chunks of the landscape into a model element
- Relationship between USM and HRU with changing spatial resolution?



1m DEM, 30m tolerance showing elevation

Addressing HRU construction with CRHM-tools



HRUs from 3 slope, aspect, and elevation bins based off a 30m DEM

Conclusions

- **Shadow model**
  - Shadows accurately captured
    - Compared to observed shortwave measurements
    - Compared to observed shadow locations
  - On par with existing algorithms
  - Improvements should be made to triangle-triangle intersection test
- **Impact of shadowing on snow melt**
  - 3-4 day delay in melt
  - Large tea-cup basins could be heavily impacted
  - Worth considering further
- **Impact of ignoring these shadows**
  - Model suggests the energy balance compensated
  - Increased/decreased gradients at snow-air boundary and increased/decreased longwave loss from snowpack
  - Suggests a possible feedback at small scale with atmospheric energy balance
  - Sensitivity to scale
  - Small triangles generally better
  - Some failure cases were not anticipated a priori, thus care should be taken
  - Small triangles don't guarantee good results with coarse DEMs
  - Large tolerances led to poor point scale timing

- **Further reading**
  - Marsh, C. B., J. W. Pomeroy, and R. J. Spiteri (2012), Implications of mountain shading on calculating energy for snowmelt using unstructured triangular meshes, *Hydrological Processes*, 26(12), 1767–1778
  - Link at chrismarsh.ca