

Widespread **Slope Processes** Across the **Tibetan Plateau**: Insights from Large-Scale InSAR Processing Using **FLATSIM**

Fringe meeting - 17/06/2026

India

Nepal

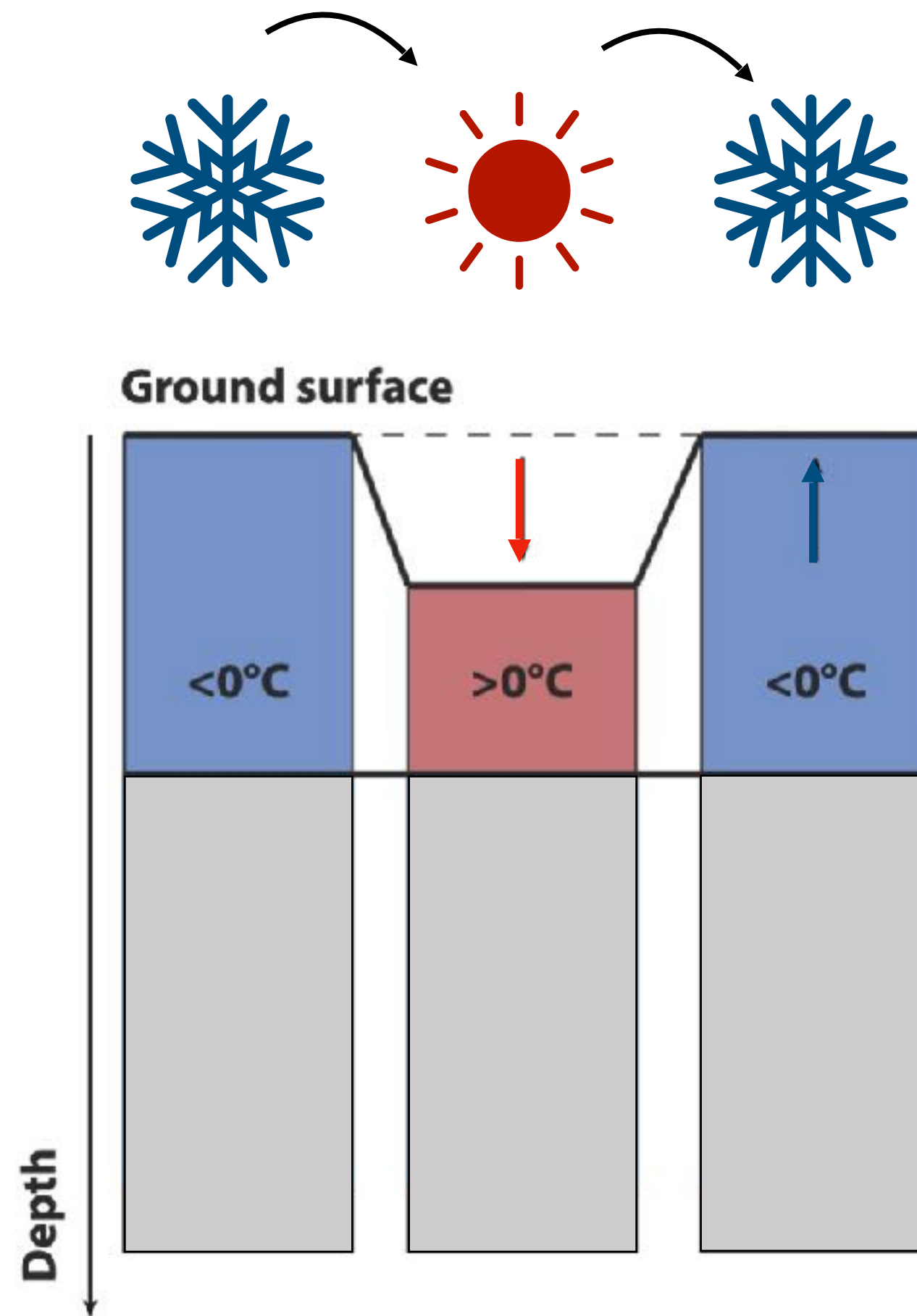
Tibetan plateau

Hugo Watine¹, Simon Daout¹, Jérôme Lavé¹, Marie-Pierre Doin², Phillipe Durand³, FLATSIM working group

1. CRPG, CNRS, Nancy, France ; 2. ISTERre, CNRS, Grenoble, France ; 3. CNES, Toulouse, France



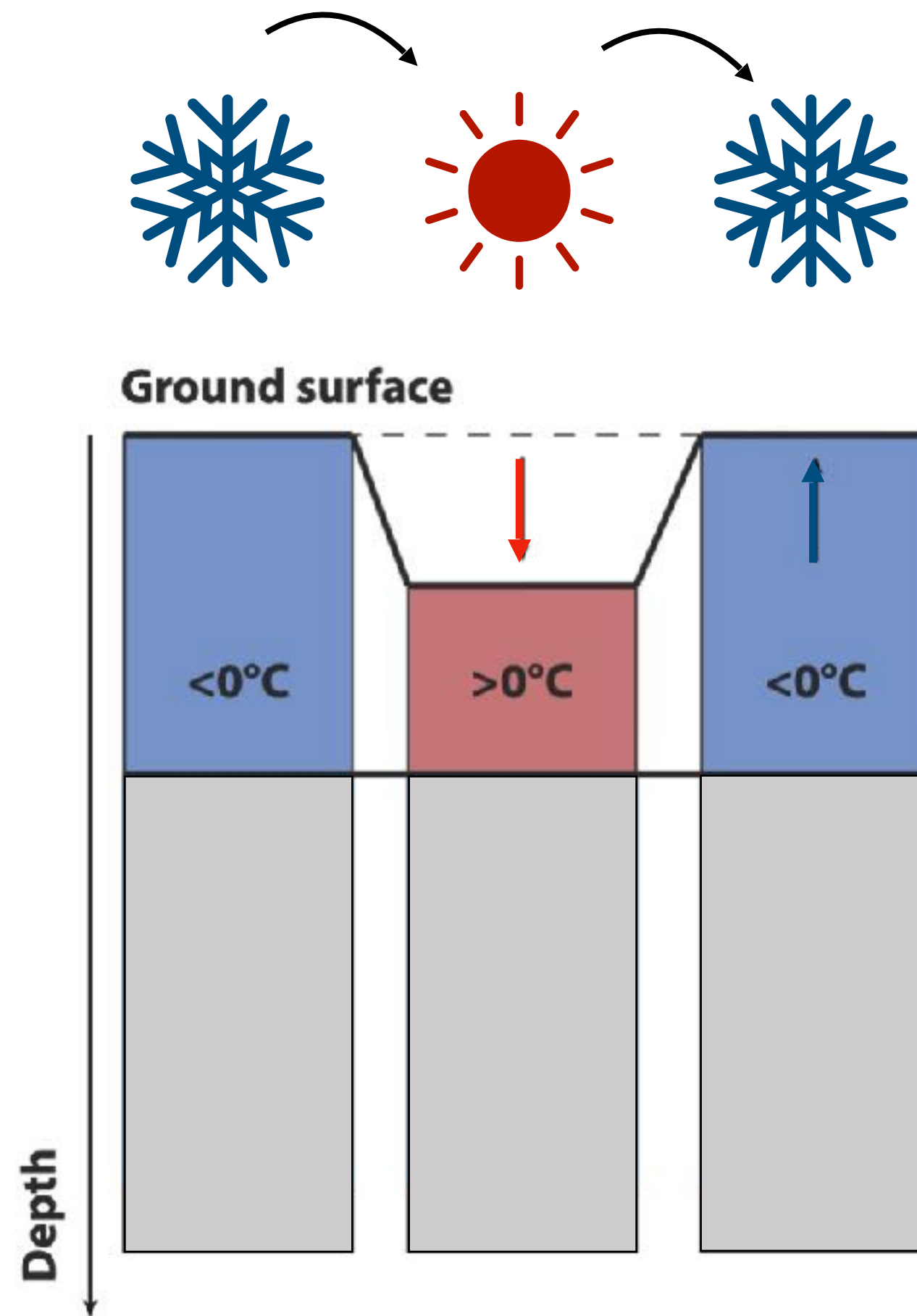
The Tibetan Plateau, a periglacial environment



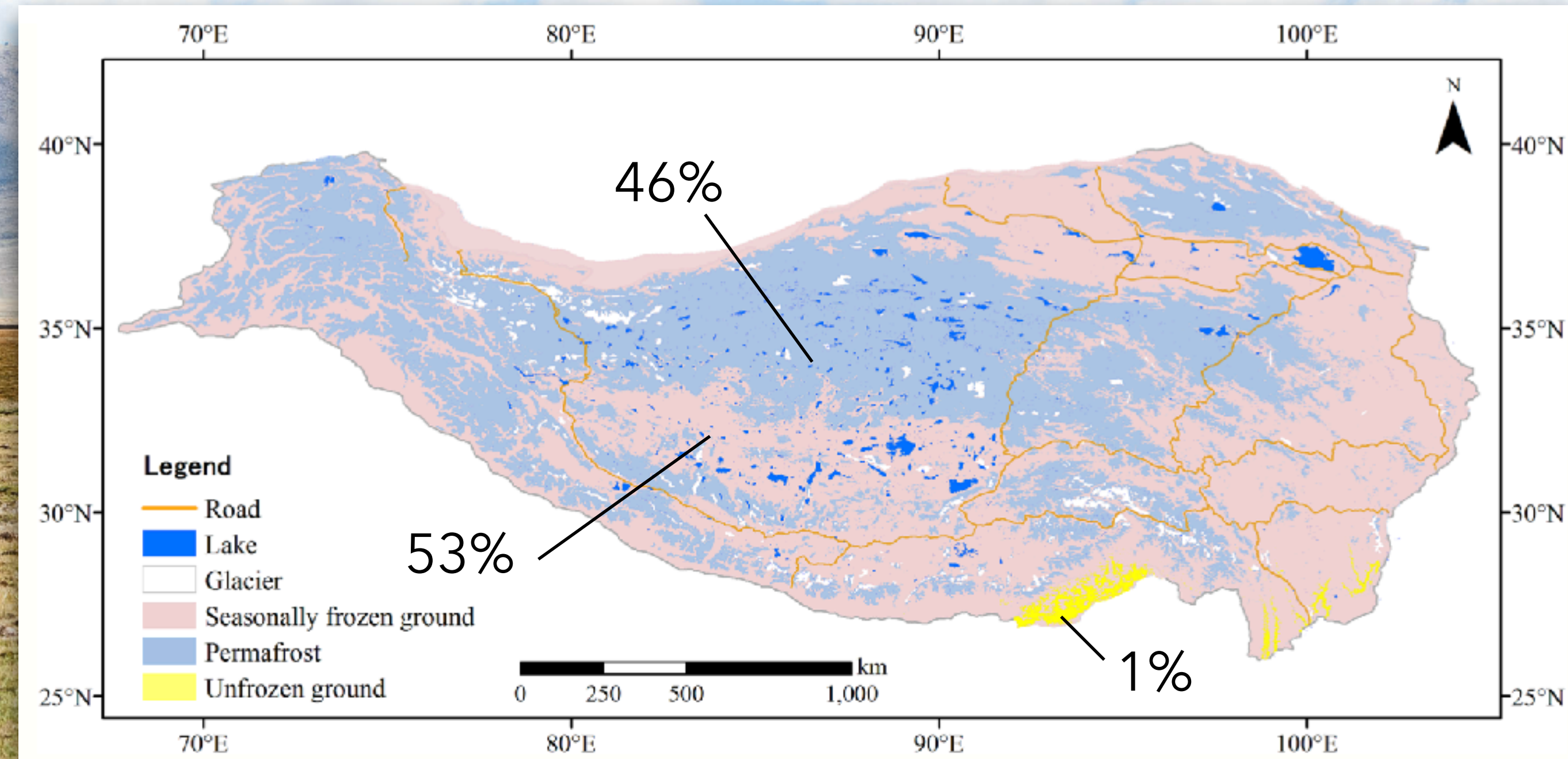
Ground layers dynamics in a periglacial environment



The Tibetan Plateau, a periglacial environment

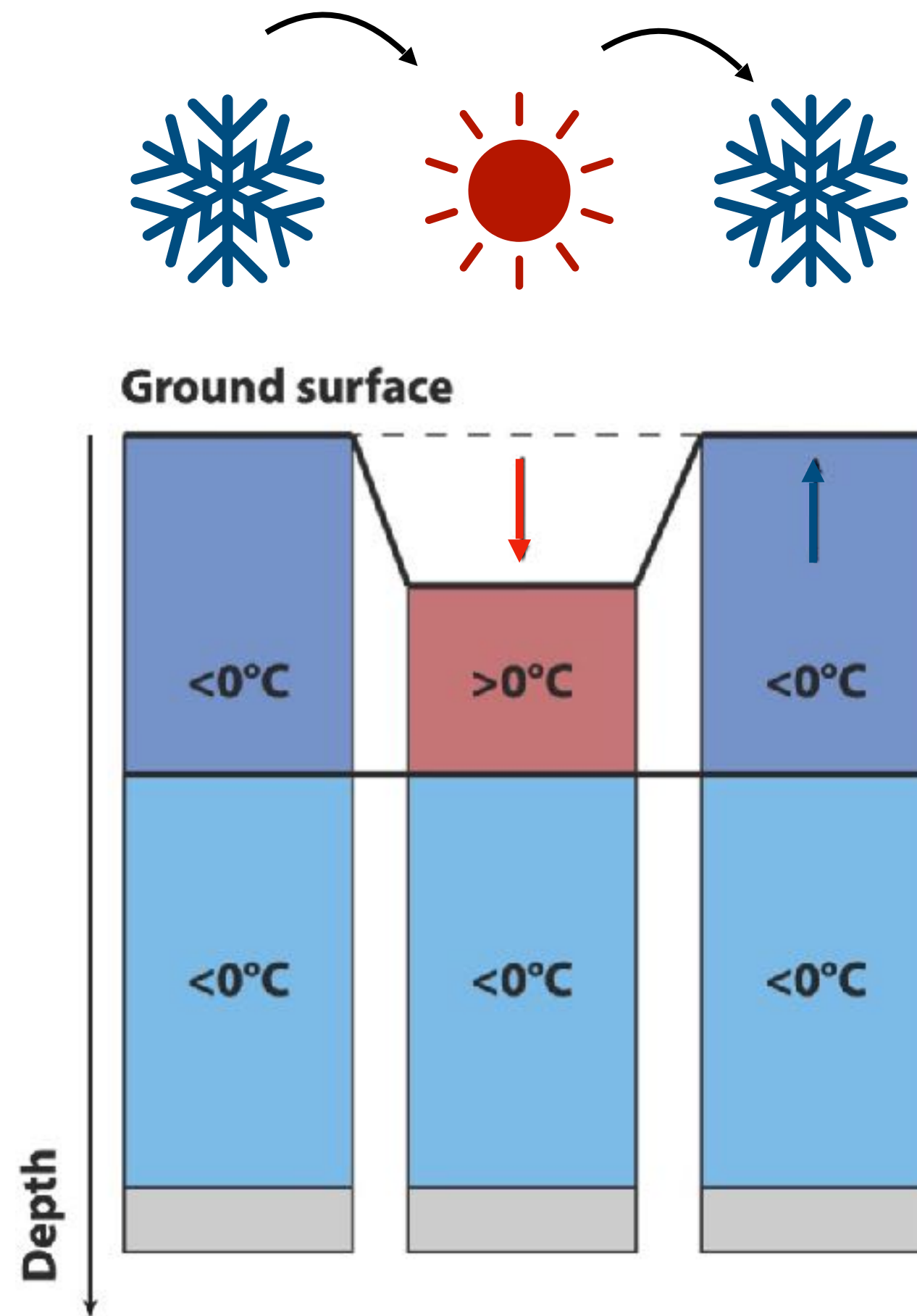


Ground layers dynamics in a periglacial environment

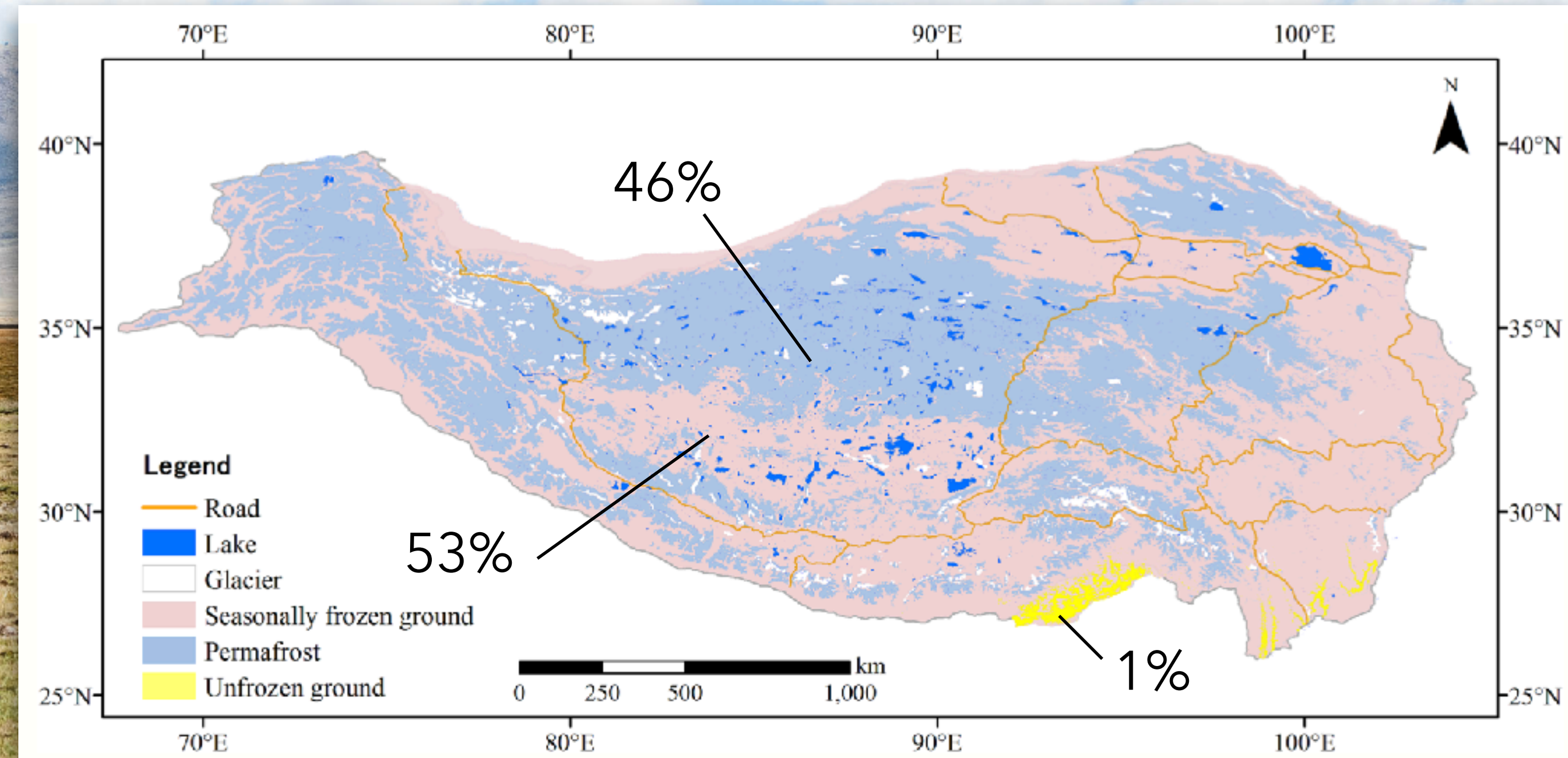


Spatial distribution of frozen ground on the Tibetan Plateau (Zhao et al., 2024)

The Tibetan Plateau, a periglacial environment



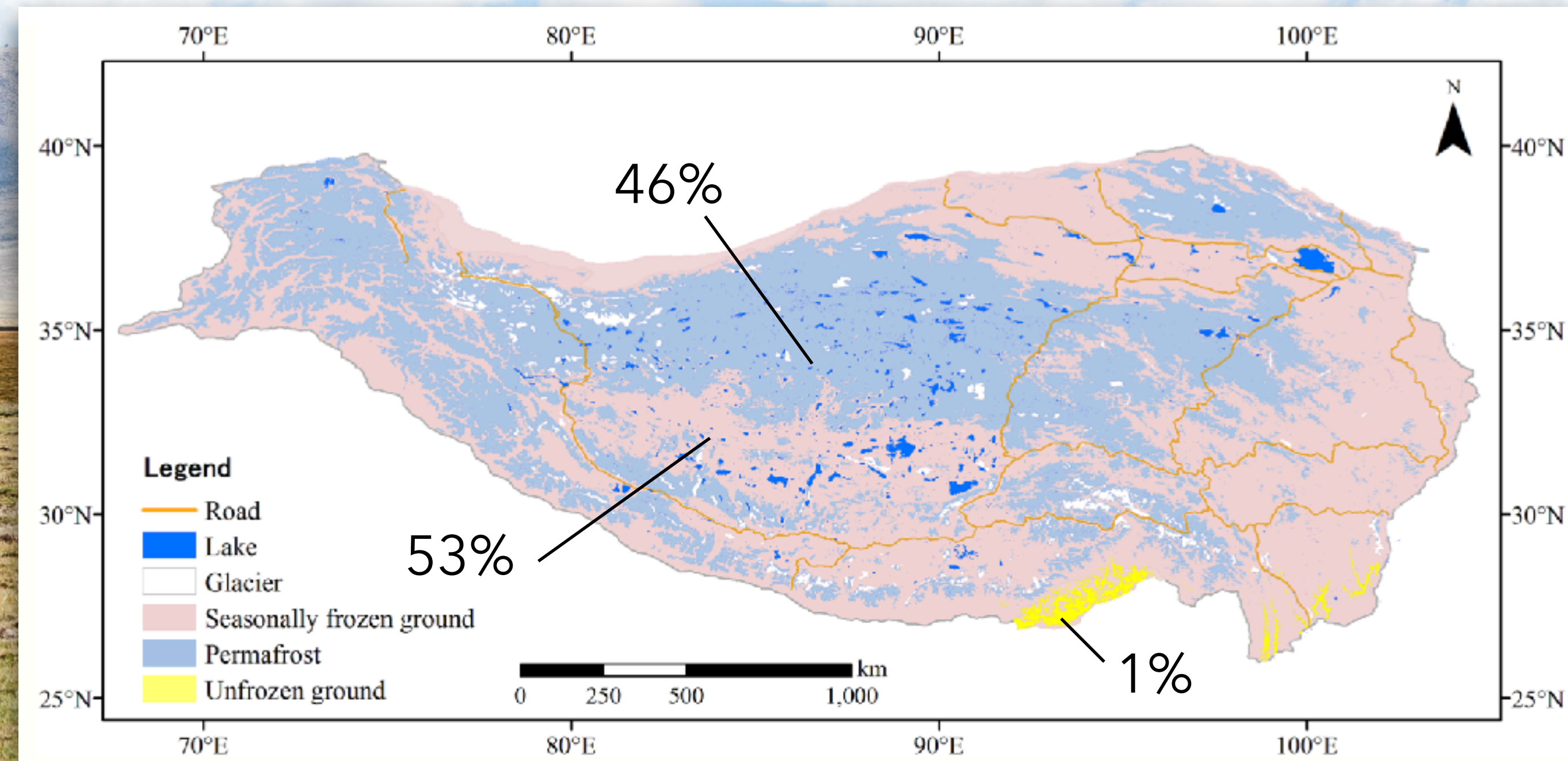
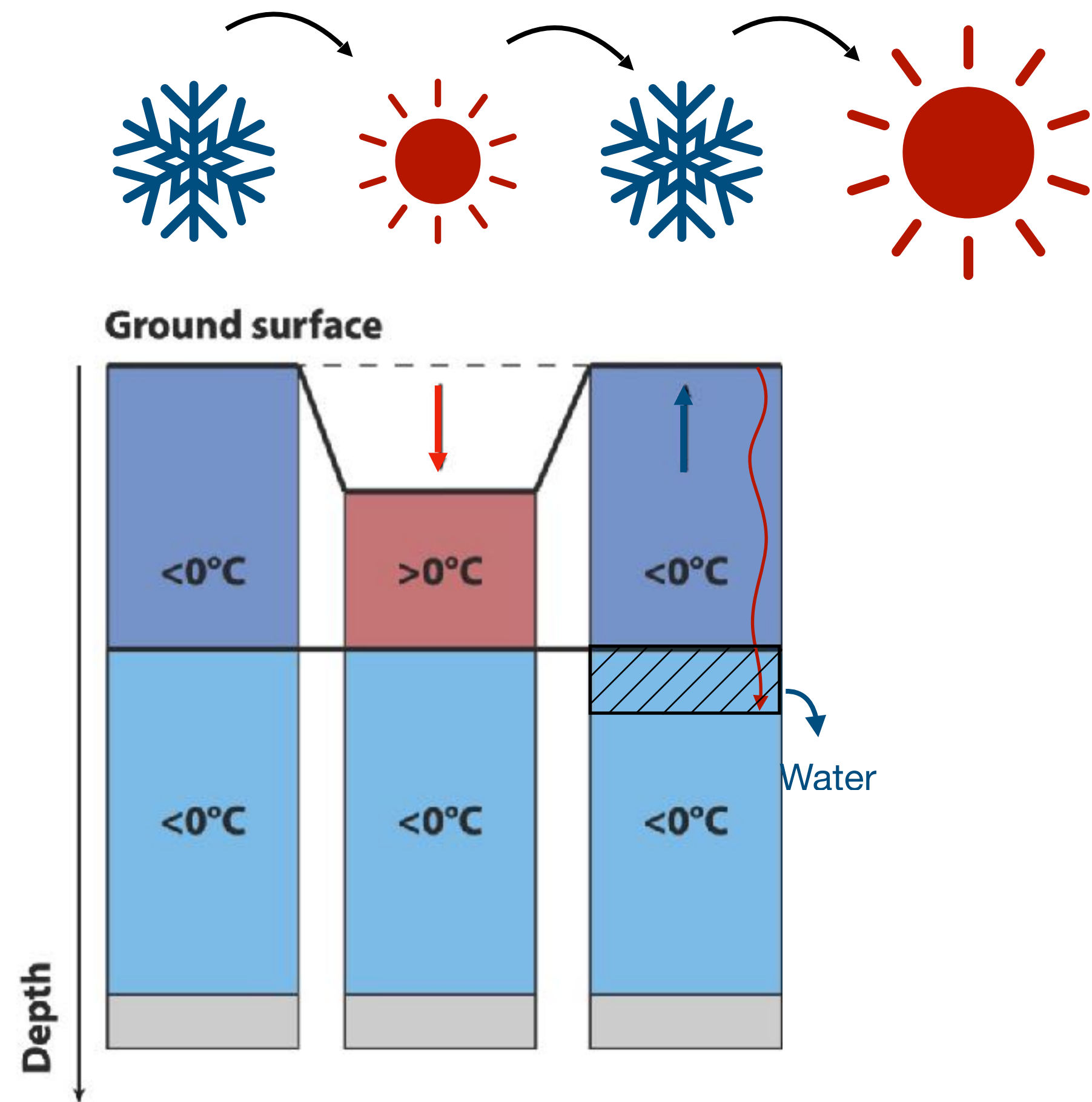
Ground layers dynamics in a periglacial environment



Spatial distribution of frozen ground on the Tibetan Plateau (Zhao et al., 2024)

The Tibetan Plateau, a periglacial environment

Warmer-than-usual summer temperature



Spatial distribution of frozen ground on the Tibetan Plateau (Zhao et al., 2024)

Solifluction: a periglacial slope processes

Solifluction lobe



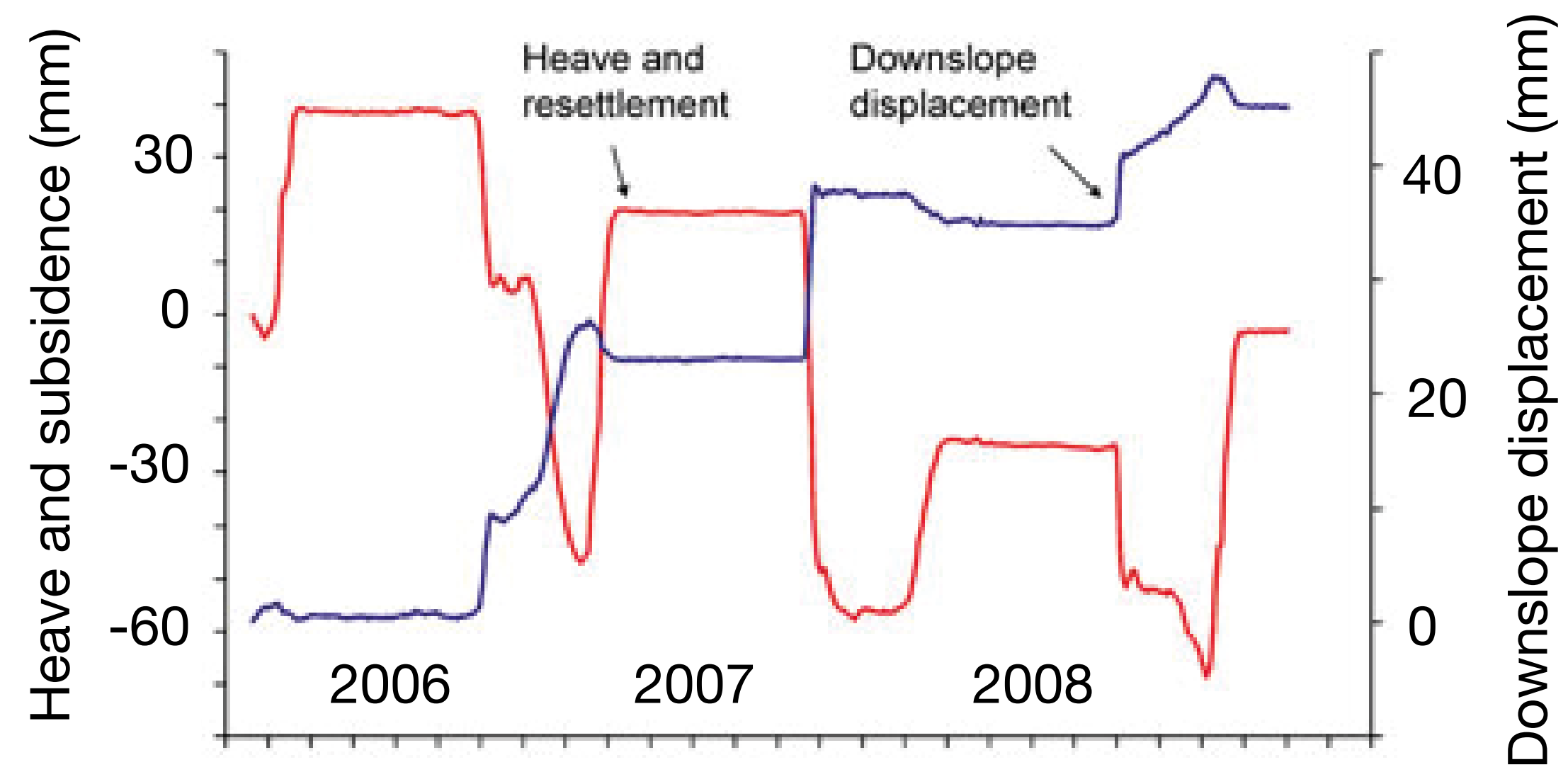
Solifluction: Slow down-slope movement (mm to cm/yr) of soil masses due to freeze-thaw processes (Harris et al., 2011).

Solifluction: a periglacial slope processes

Solifluction lobe



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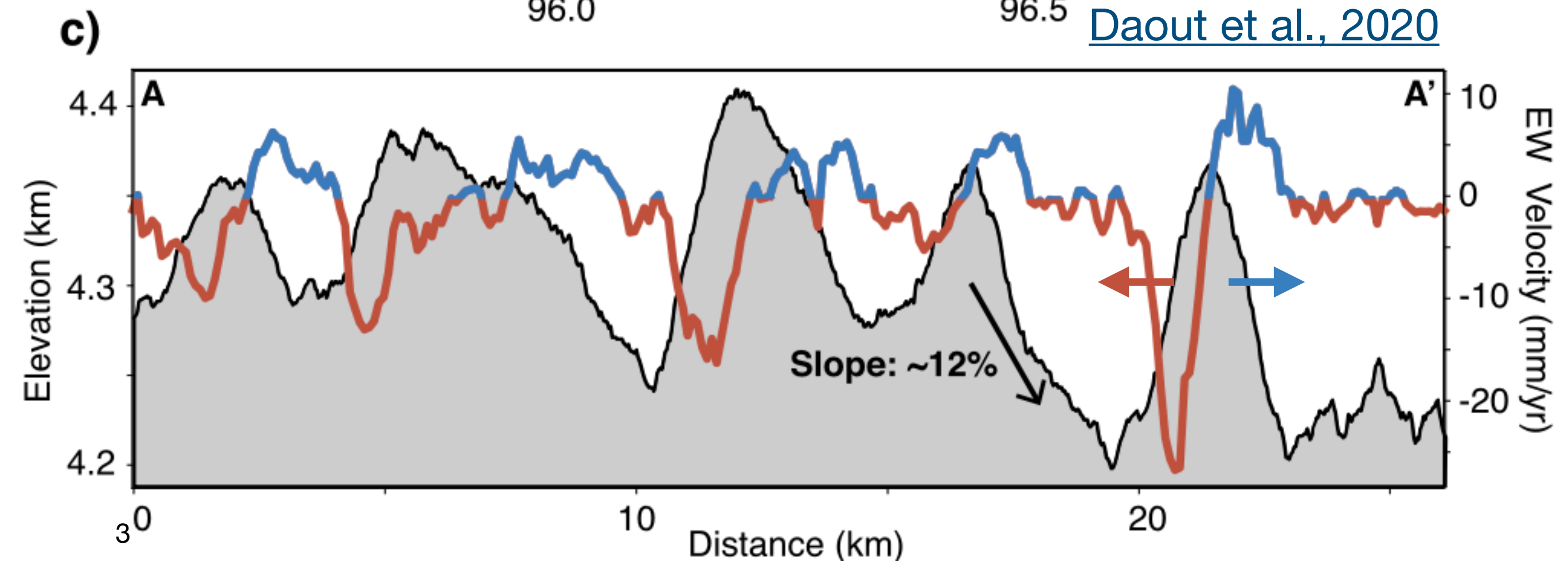
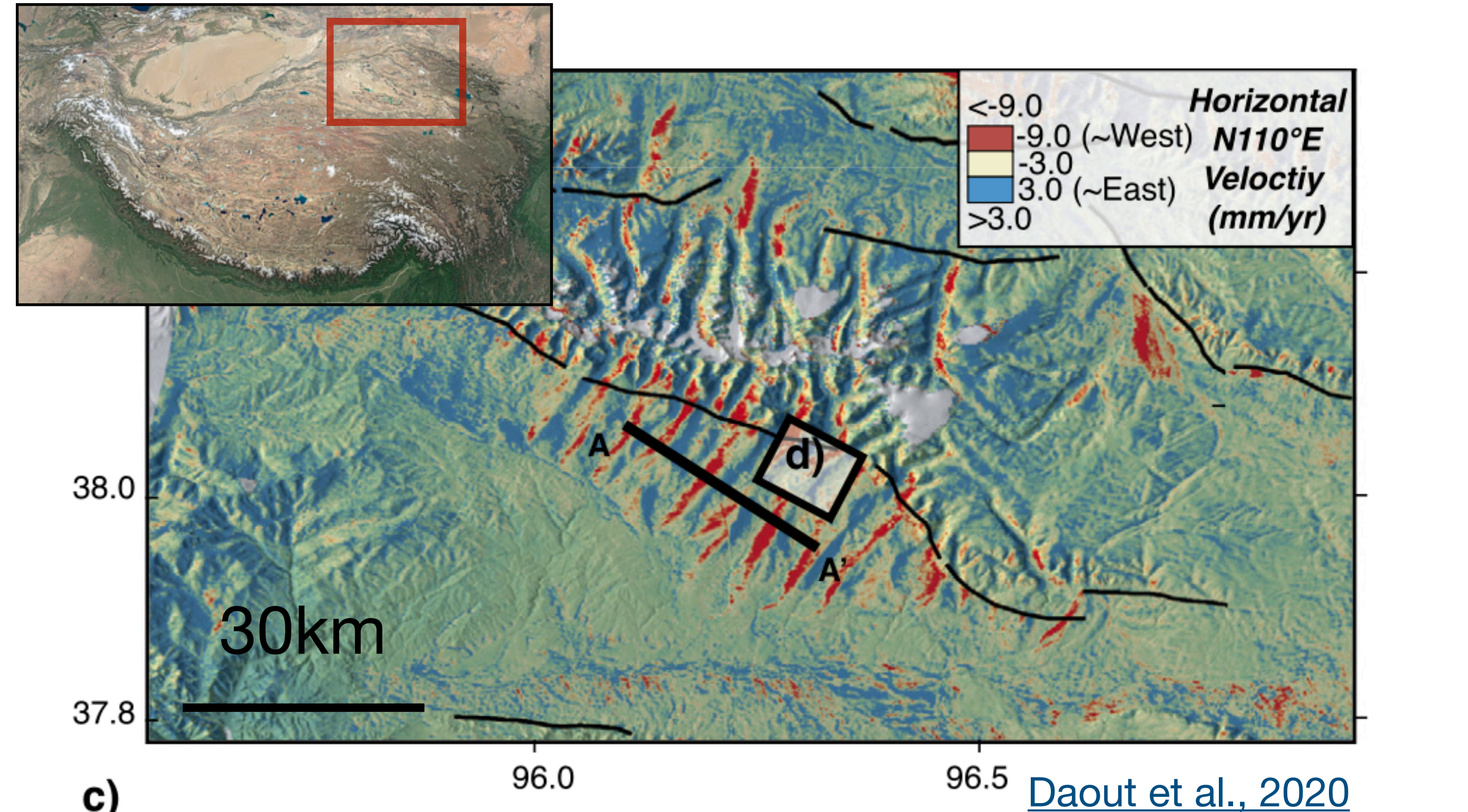
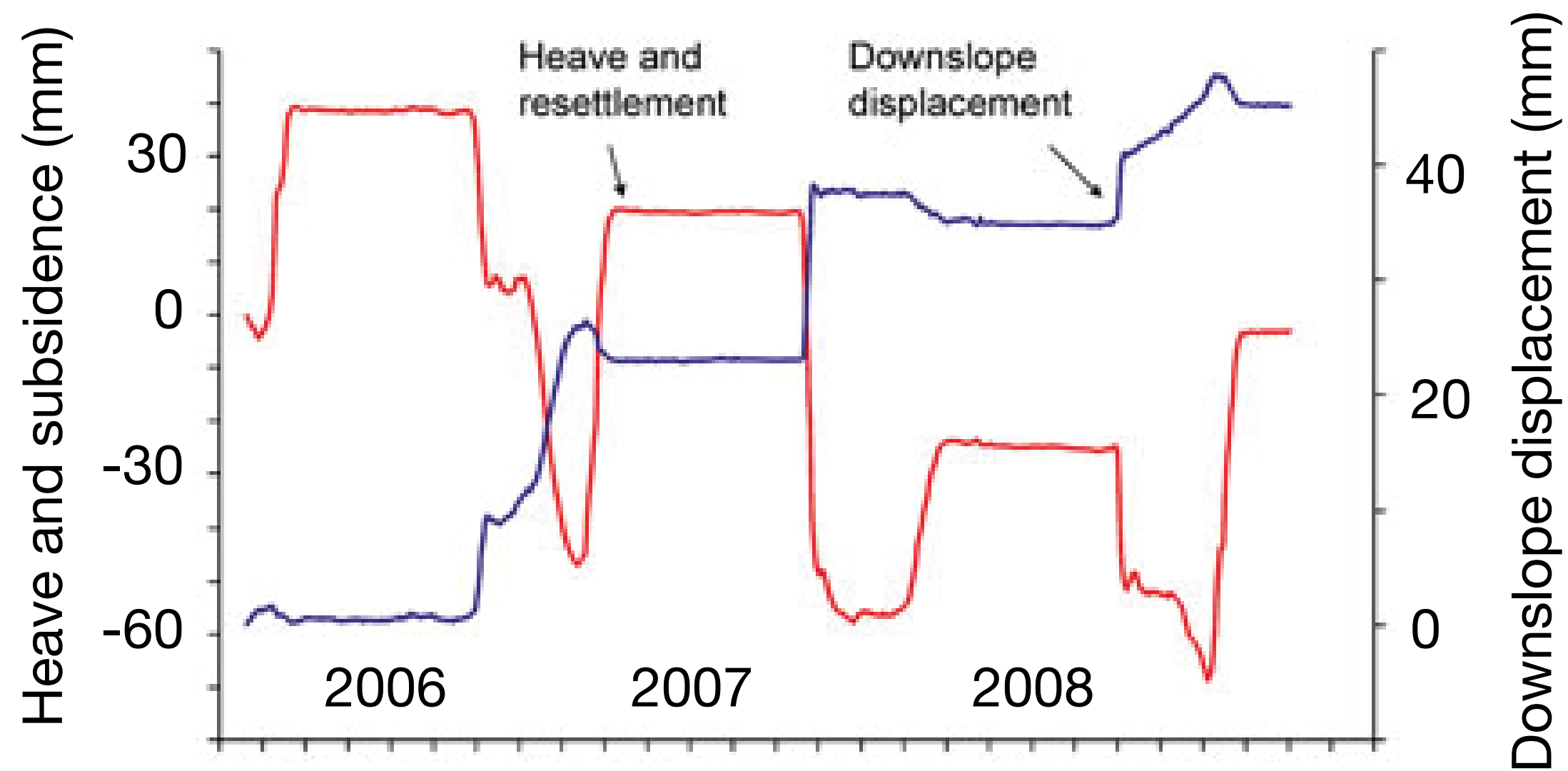


Solifluction: a periglacial slope processes

Solifluction lobe



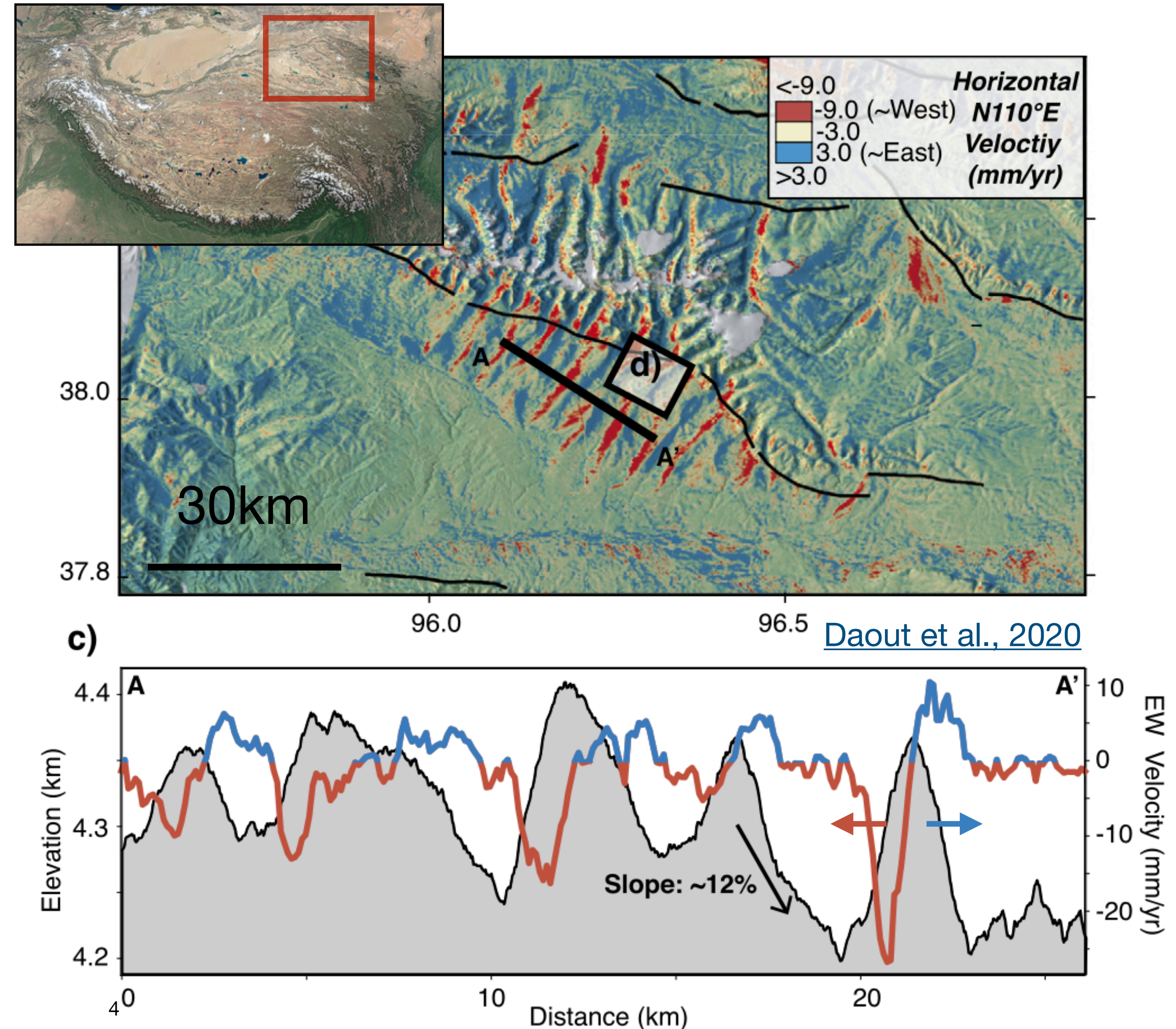
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Daout et al., 2020

Solifluction: a periglacial slope processes

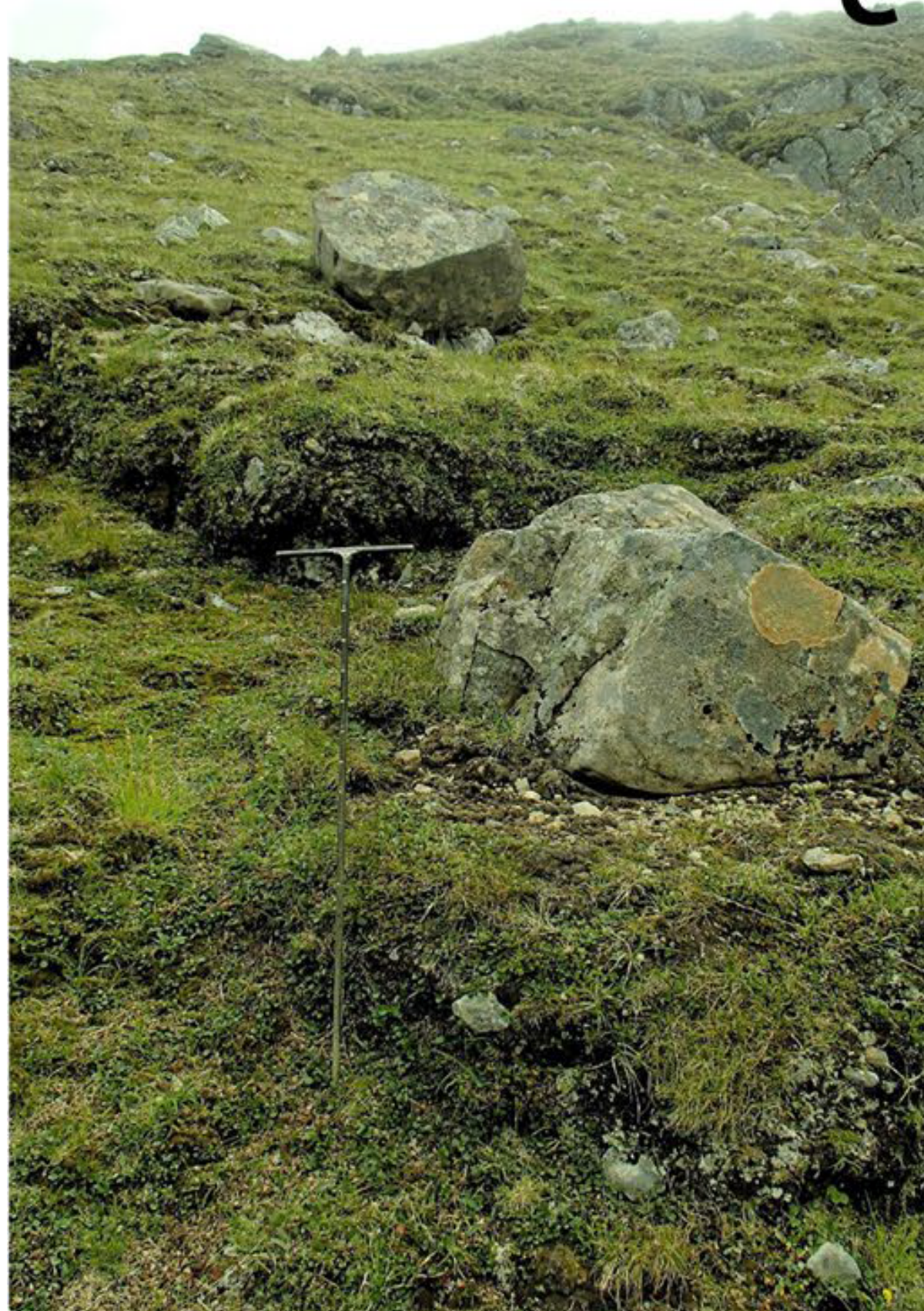
- Same observation in Northern Norway (Rouyet et al., 2021), Iceland (Cao et al., 2023), Tibet (Lemrabet et al., 2022)...



Solifluction: a periglacial slope processes

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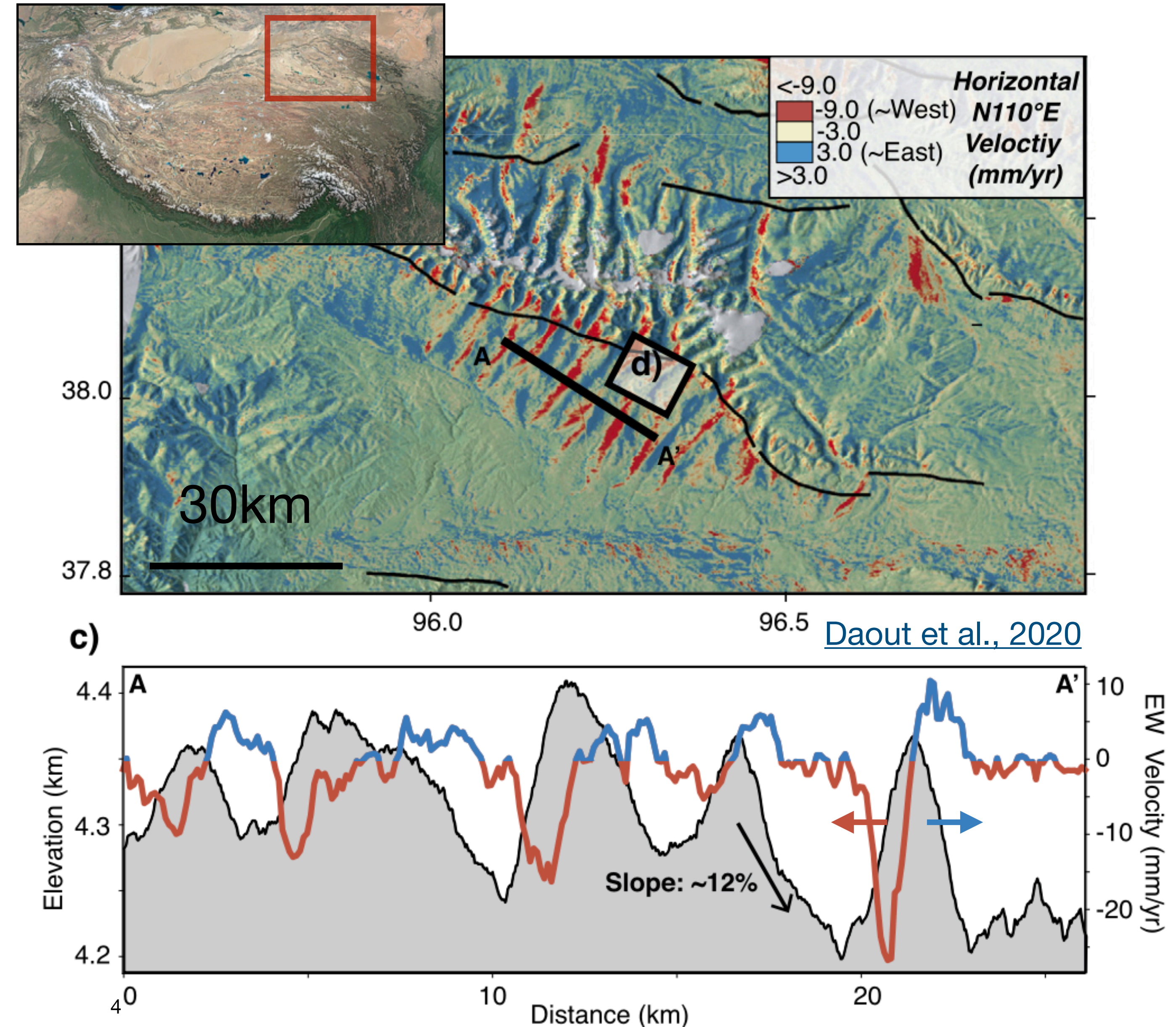
Solifluction



C

Northern
Norway

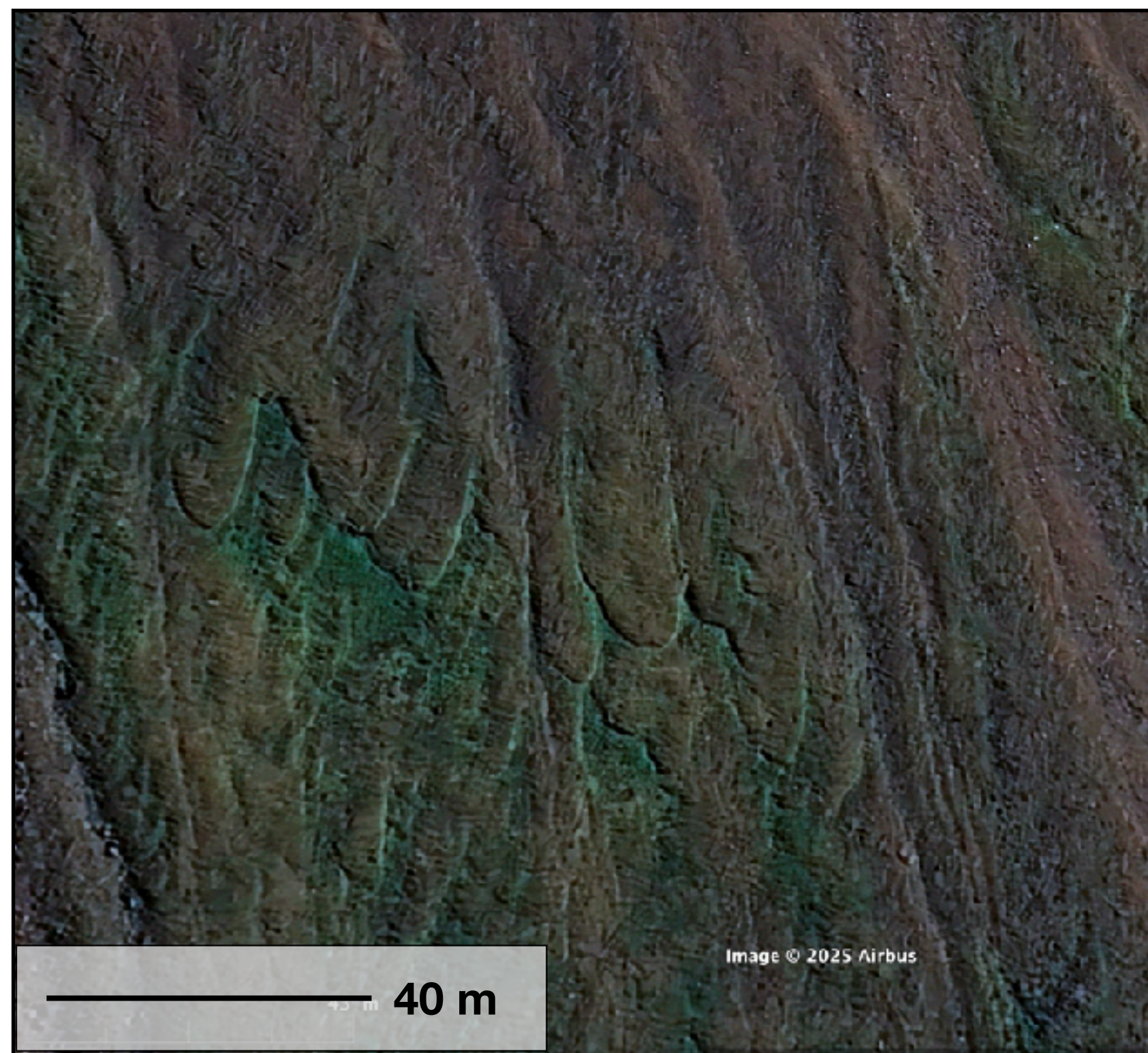
[Rouyet et al., 2021](#)



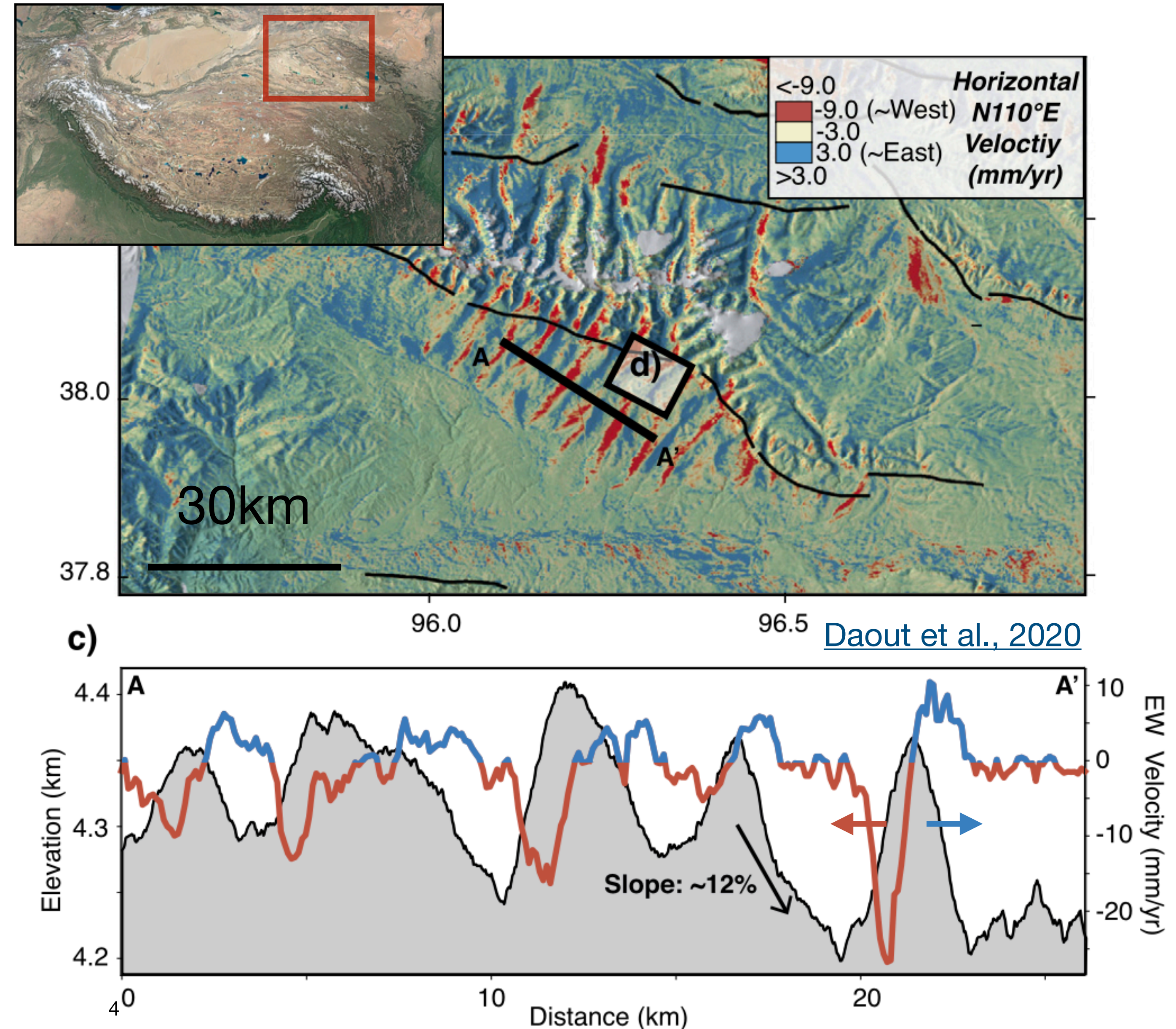
Solifluction: a periglacial slope processes

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Iceland



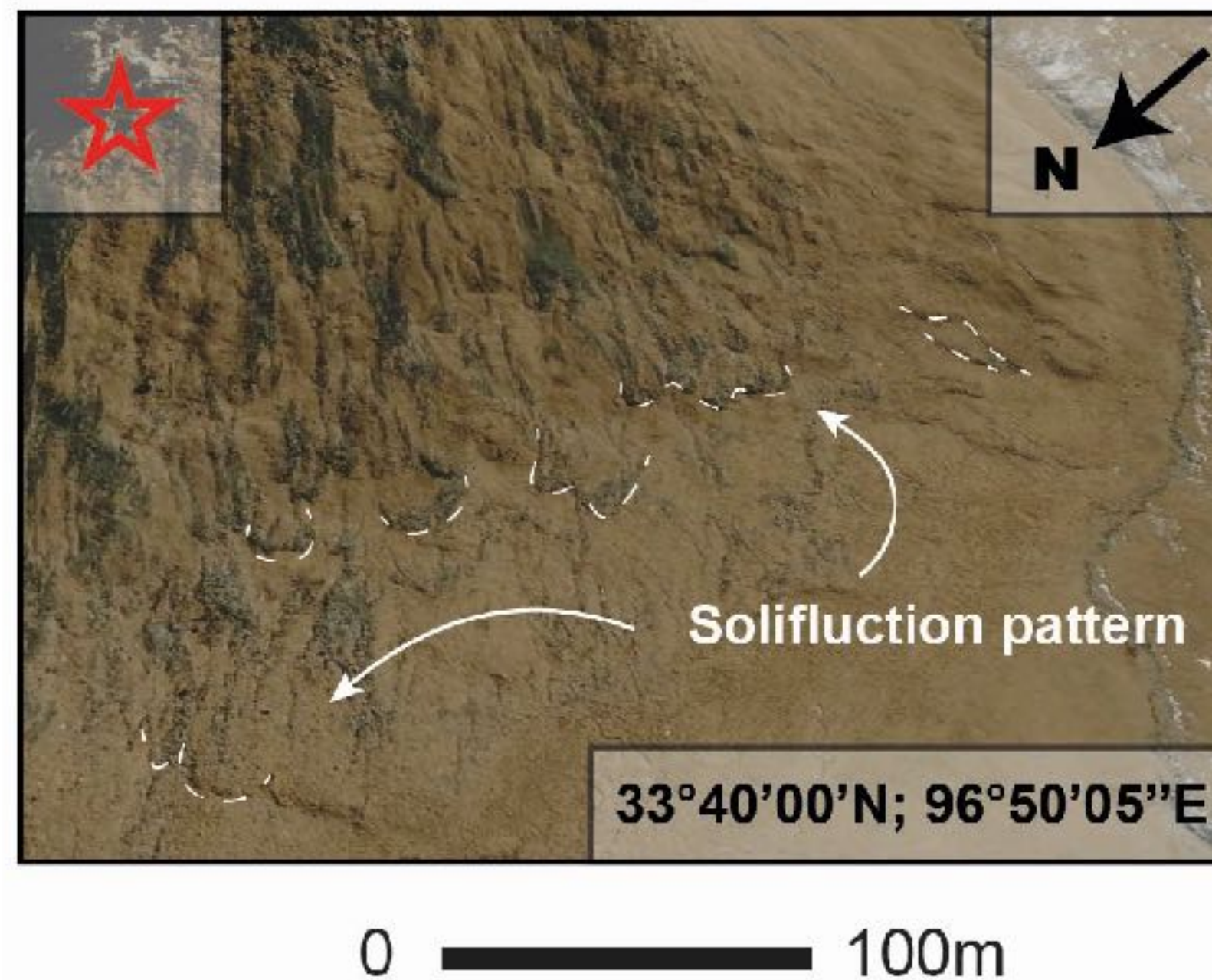
[Cao et al., 2022](#)



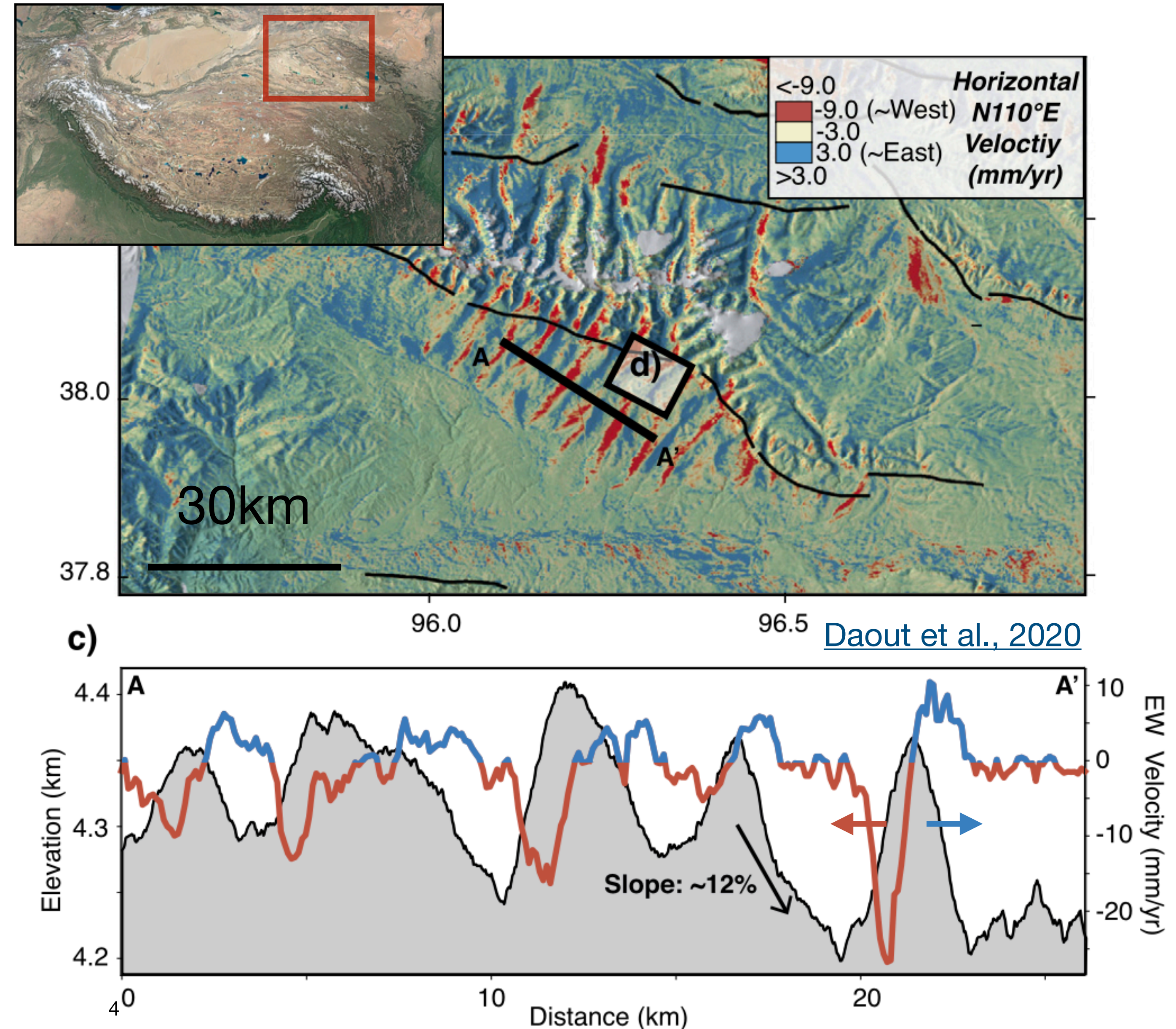
Solifluction: a periglacial slope processes

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Tibet

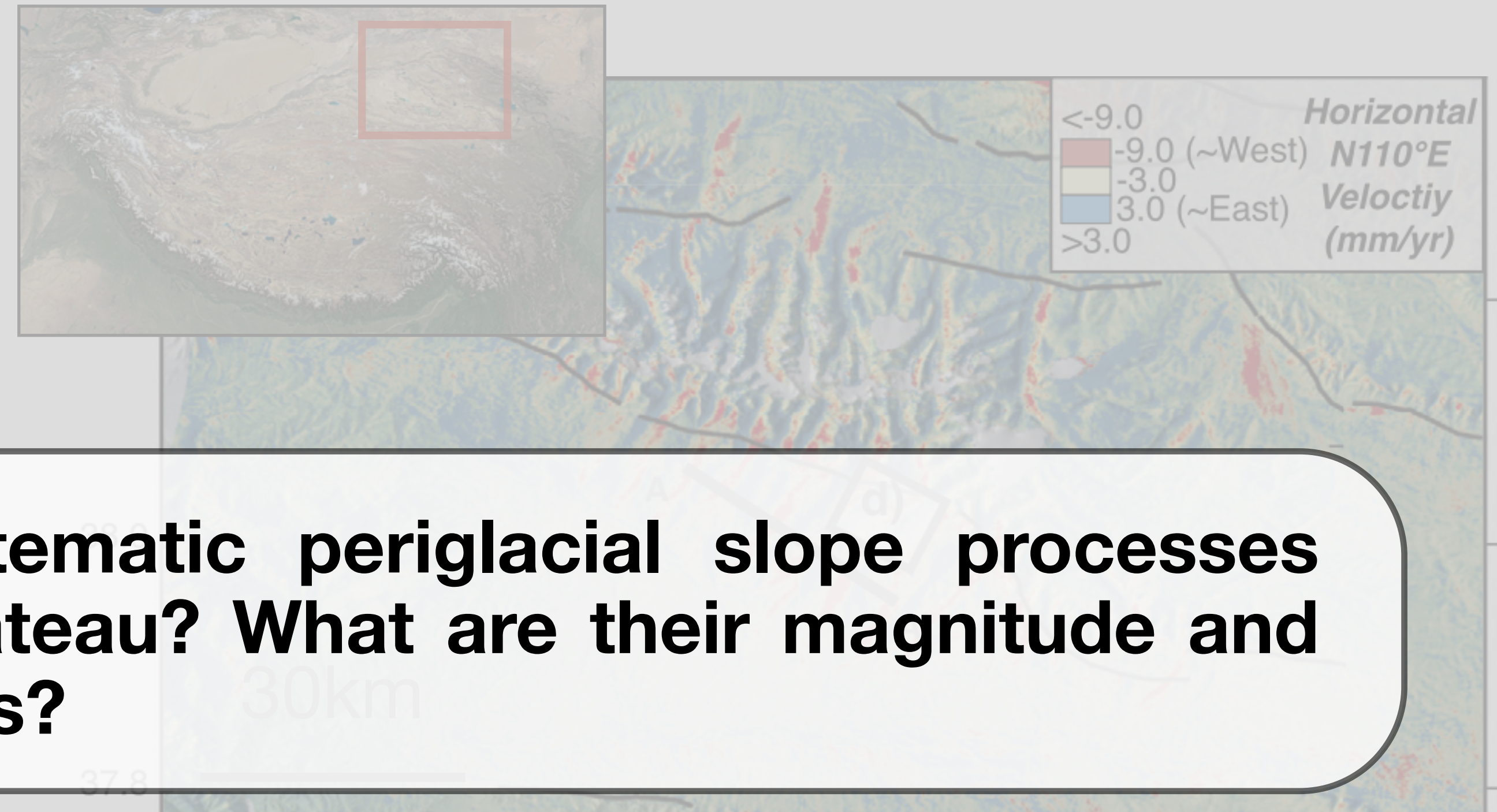


[Watine et al., 2025 \(From Lemrabet et al., 2022\)](#)

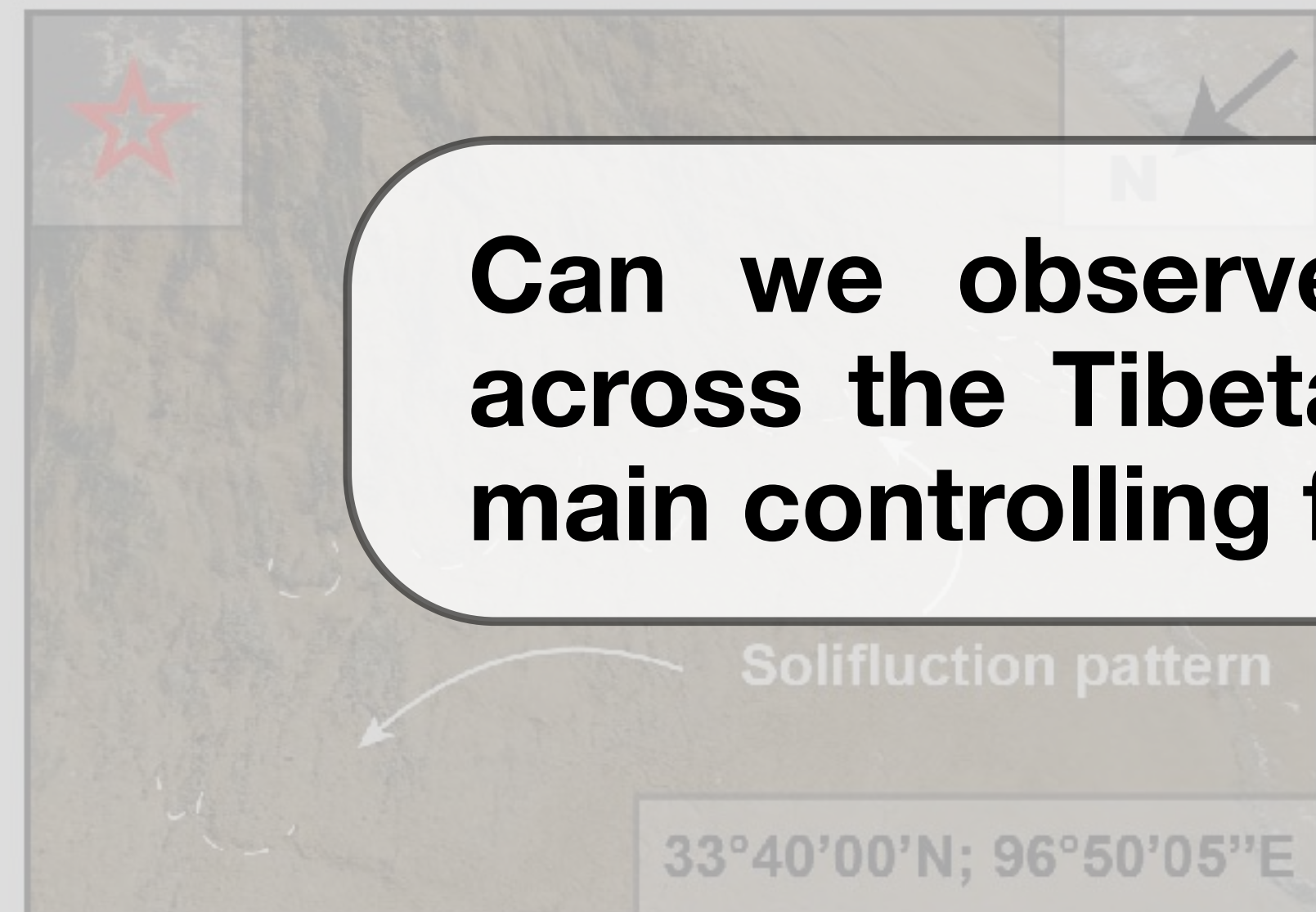


Solifluction a widespread processes on the Tibetan plateau ?

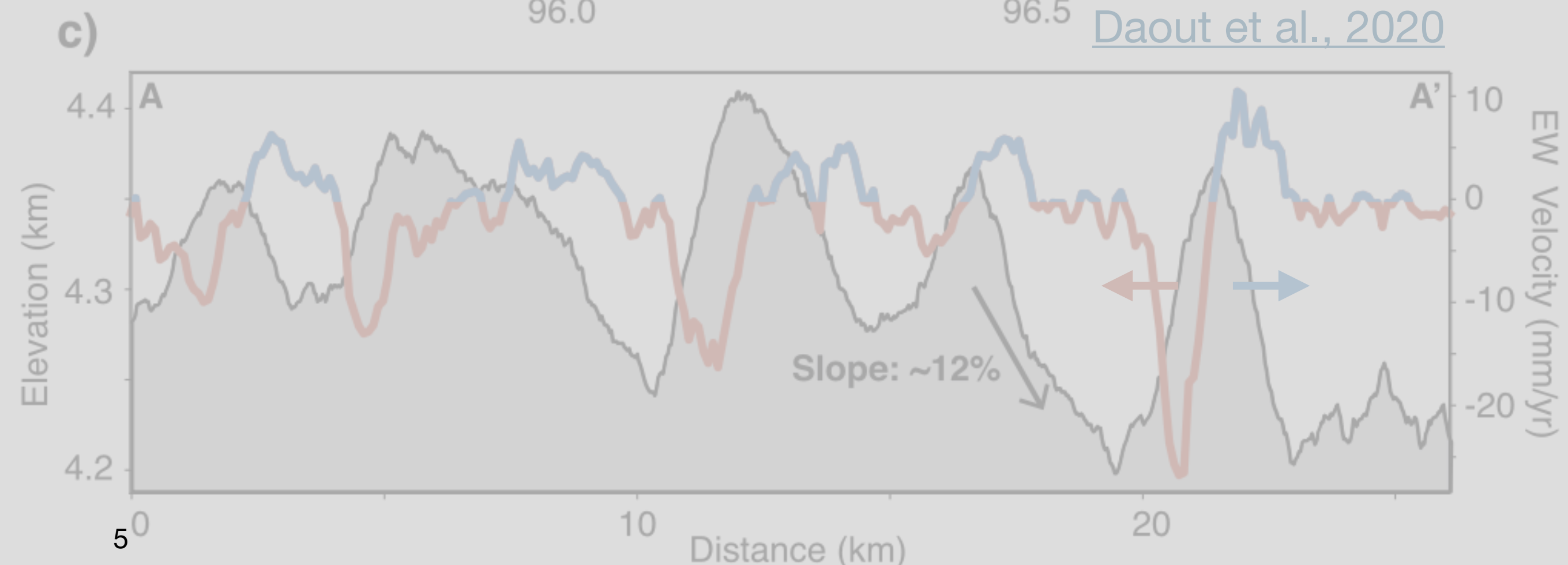
- Same observation in Svalbard (Rouyet et al., 2021), Iceland (Cao et al., 2023), Tibet (Lemrabet et al., 2022)



Can we observe systematic periglacial slope processes across the Tibetan Plateau? What are their magnitude and main controlling factors?



[Watine et al., 2025 \(From Lemrabet et al., 2022\)](#)



[Daout et al., 2020](#)

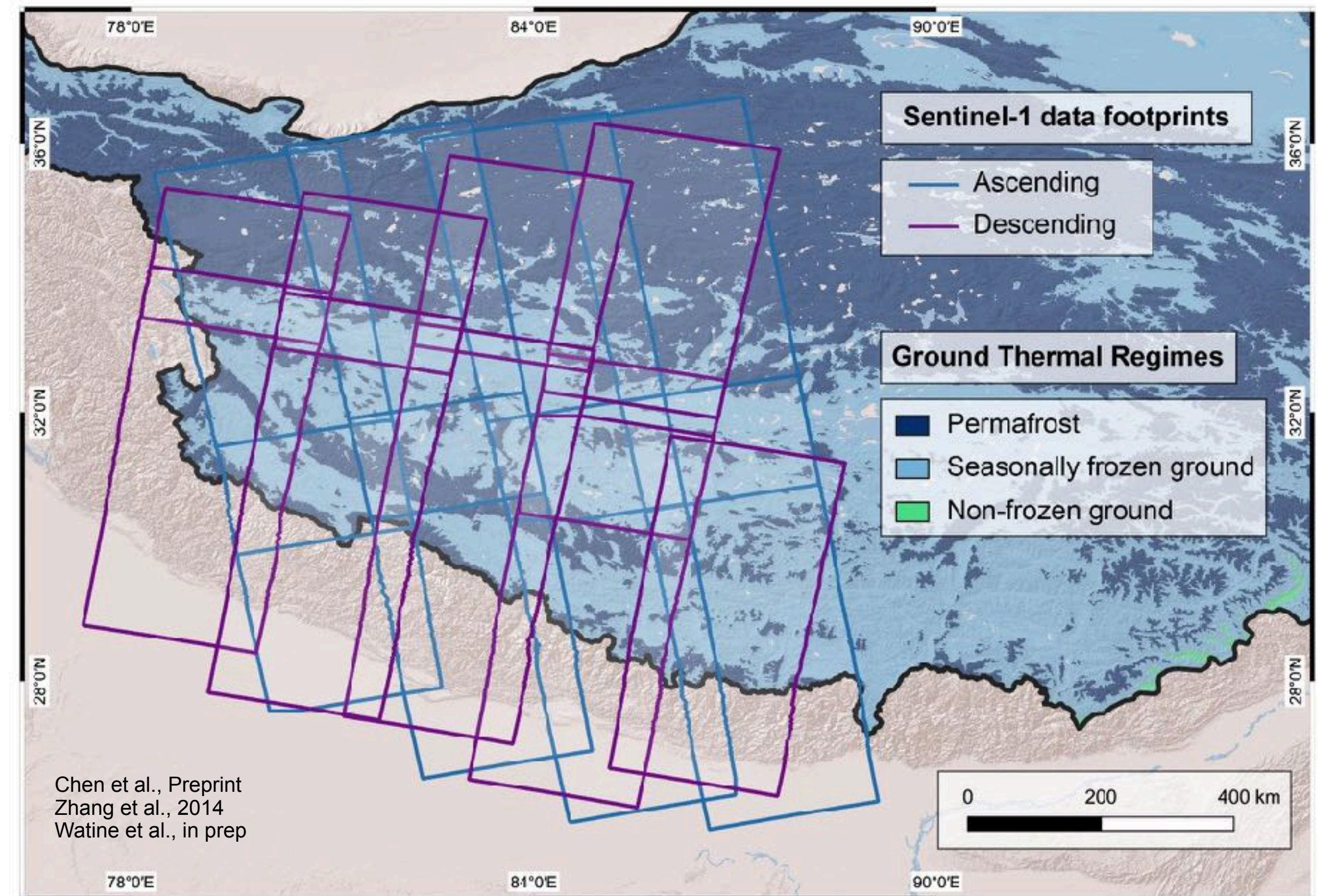
Dataset: advantage of FLATSIM data

ForM@Ter LArge-Scale Multi-Temporal Sentinel-1 InterferoMetry Service

- Automatic processing of Sentinel-1 data based on NSBAS processing chain (Doin et al., 2011)
- Products : interferograms / Los velocity / phase delay time series / validation data sets

Why using FLATSIM data ?

- 600-700 km long tracks
- Early atmospheric correction using ERA5 (Jolivet et al., 2011). Facilitating subsequent unwrapping
- Include 3 month and 1 year temporal baseline to limit phase biases (Ansari et al., 2021; De Zan et al., 2015)



Dataset:

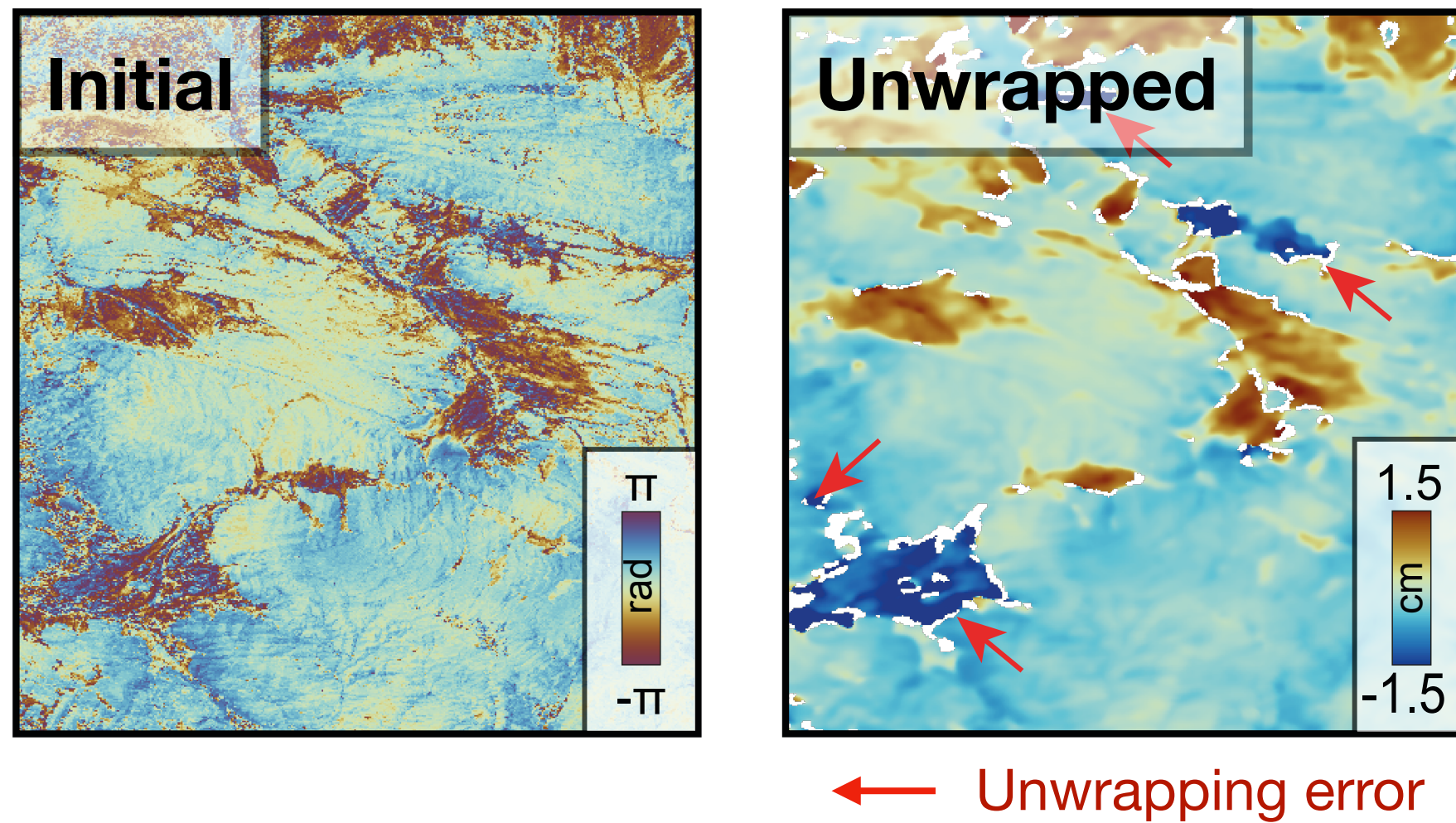
- 7 Ascending & 10 Descending tracks.
- ~13 000 FLATSIM interferograms.
- 2014 - 2020 / 8 looks

Processing InSAR data in periglacial environments: main challenges

Processing InSAR data in periglacial environments: main challenges

1/ Unwrapping errors

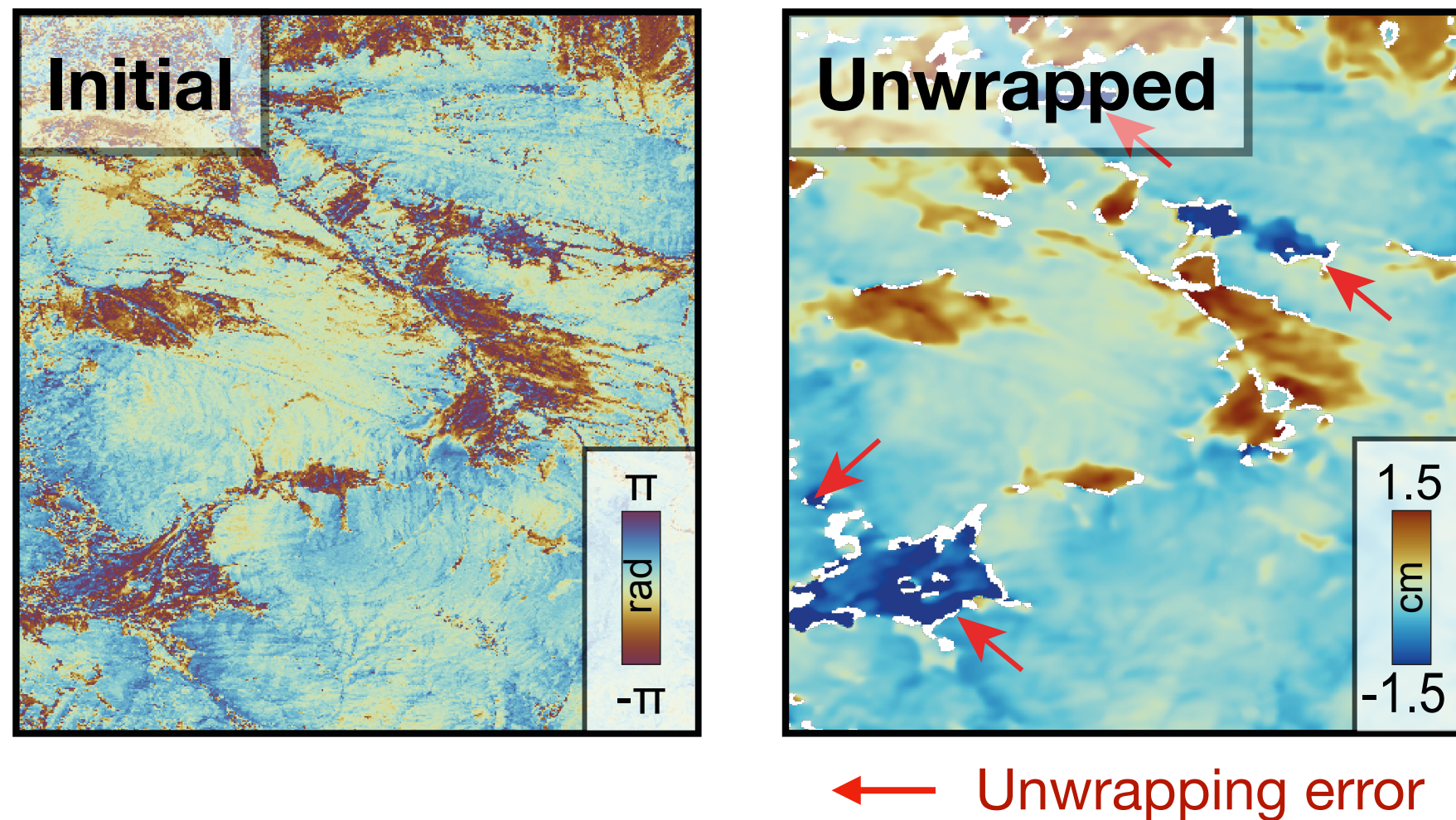
Strong and fast heave of the ground ->
high fringe rate -> difficult to unwrap



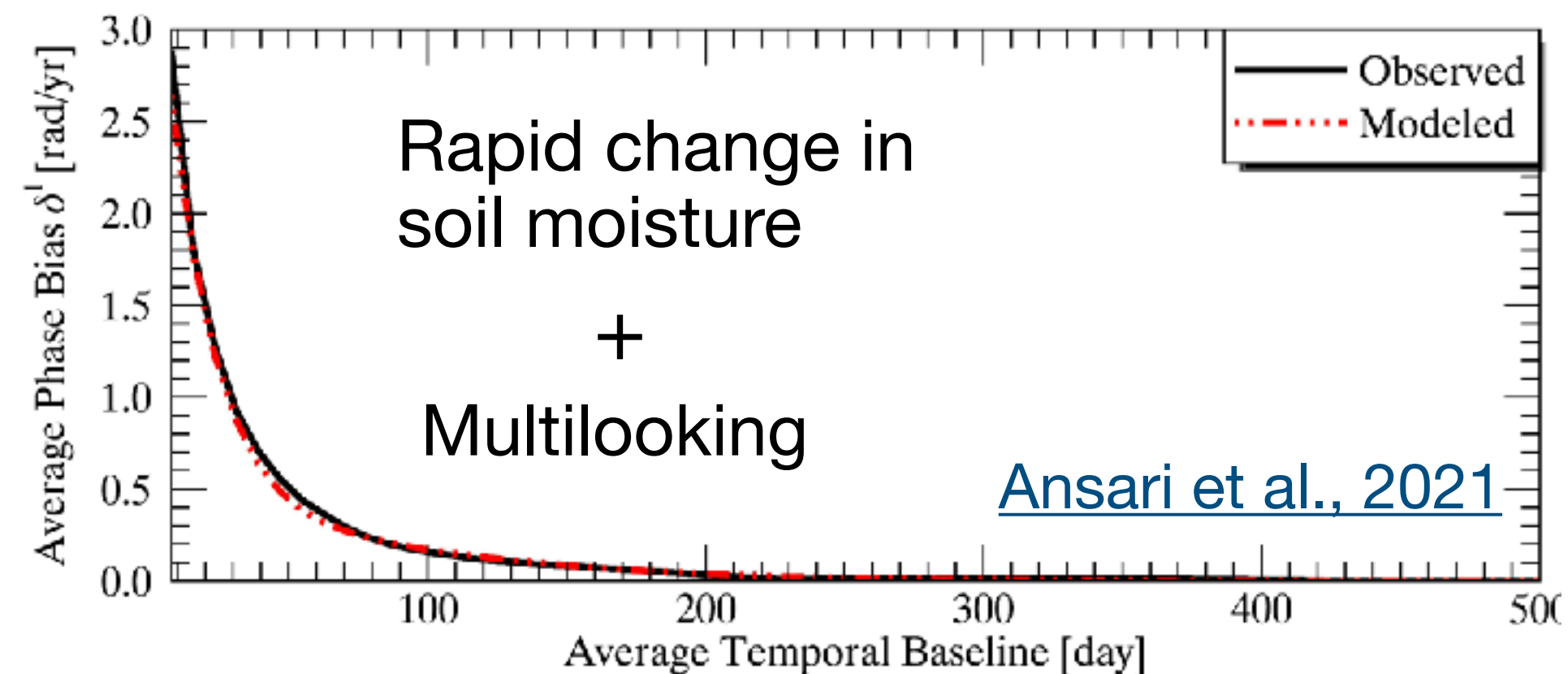
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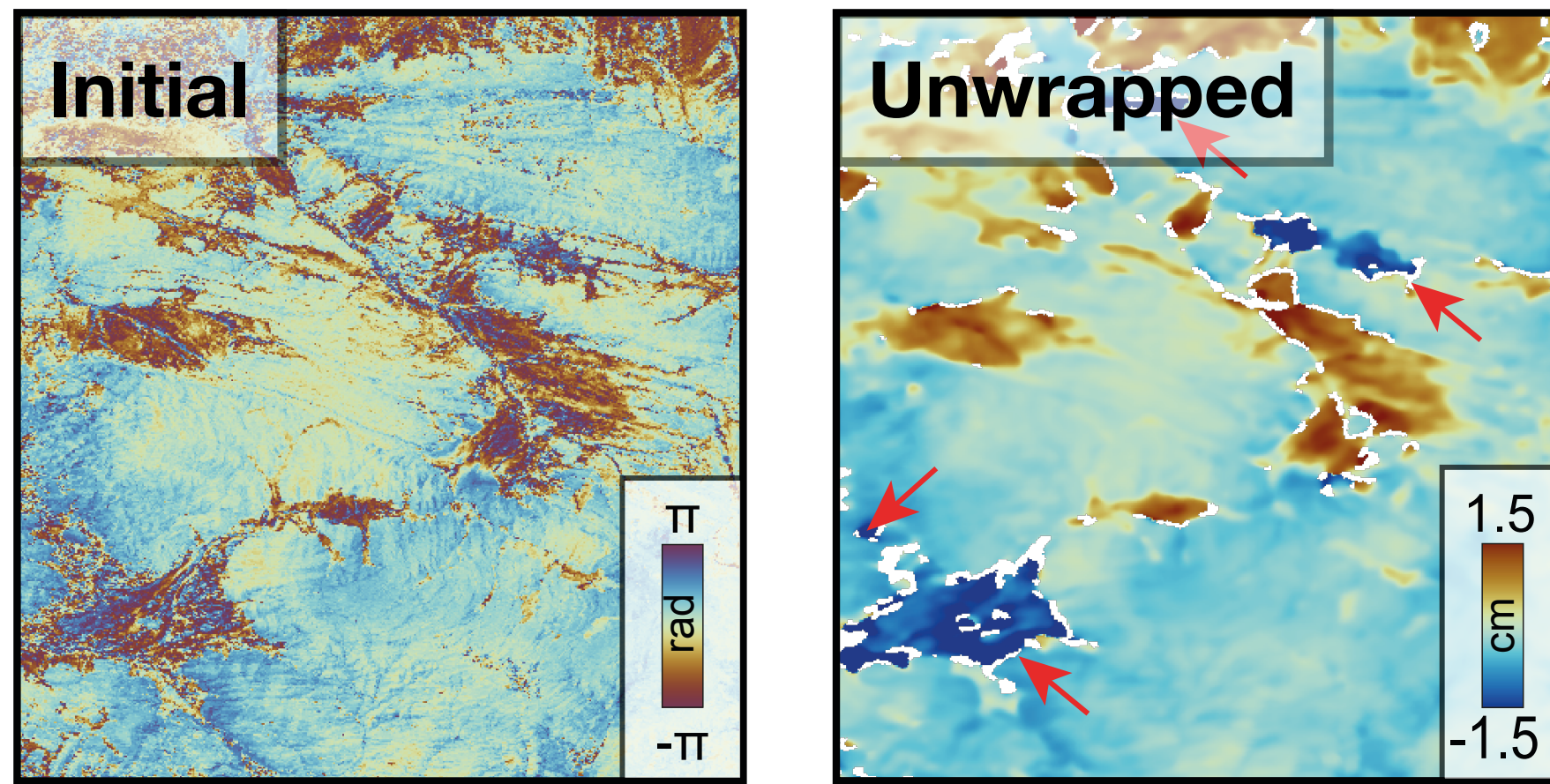
2/ Fading signal



Processing InSAR data in periglacial environments: main challenges

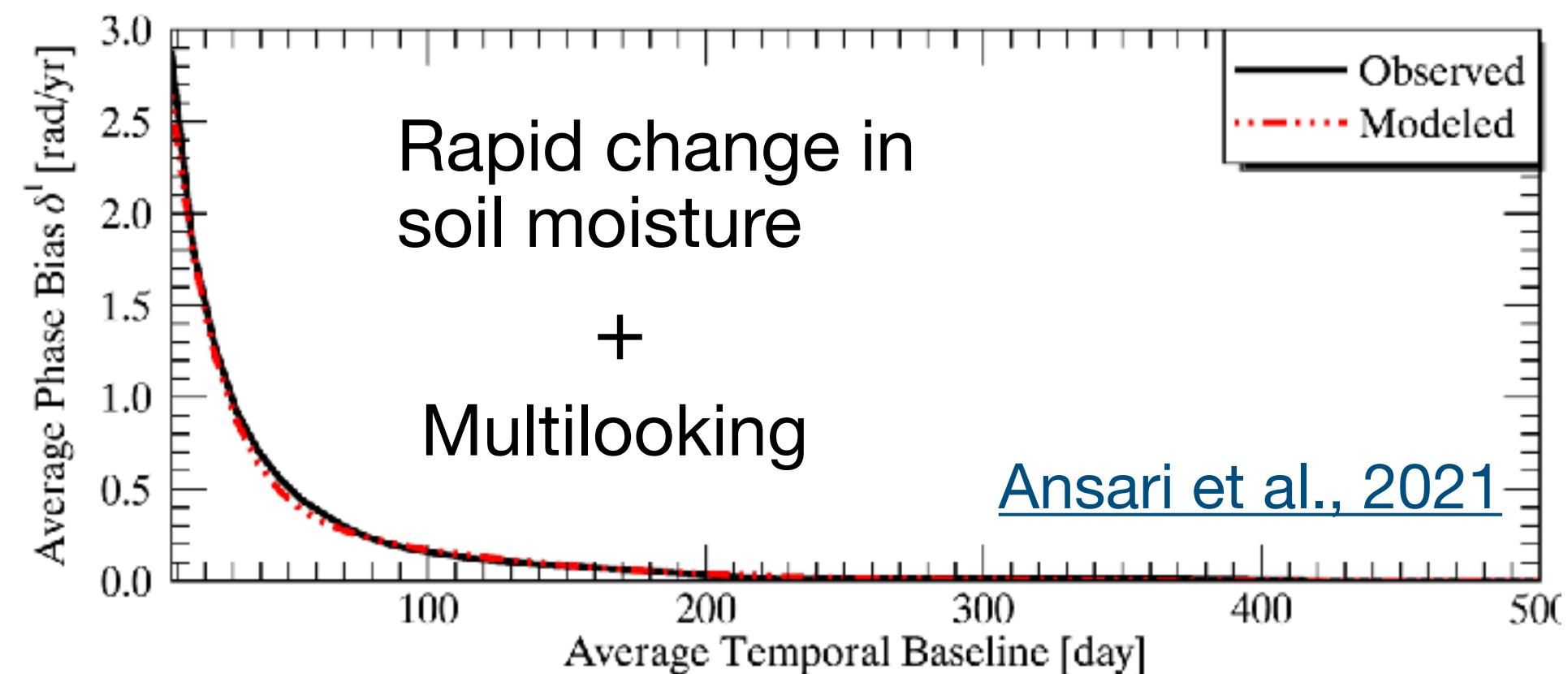
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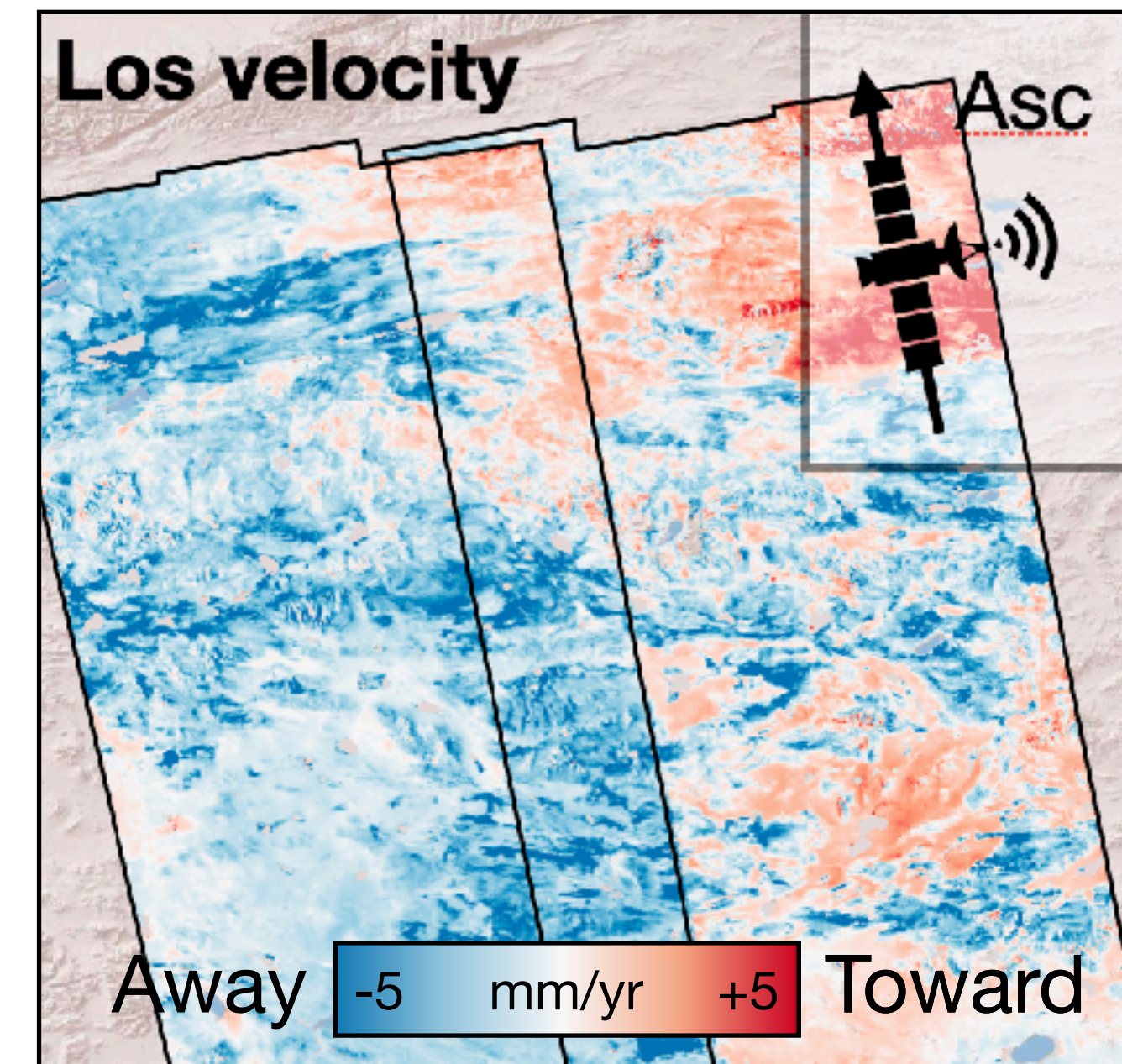
← Unwrapping error

2/ Fading signal



3/ Adjusting all tracks to a common reference frame

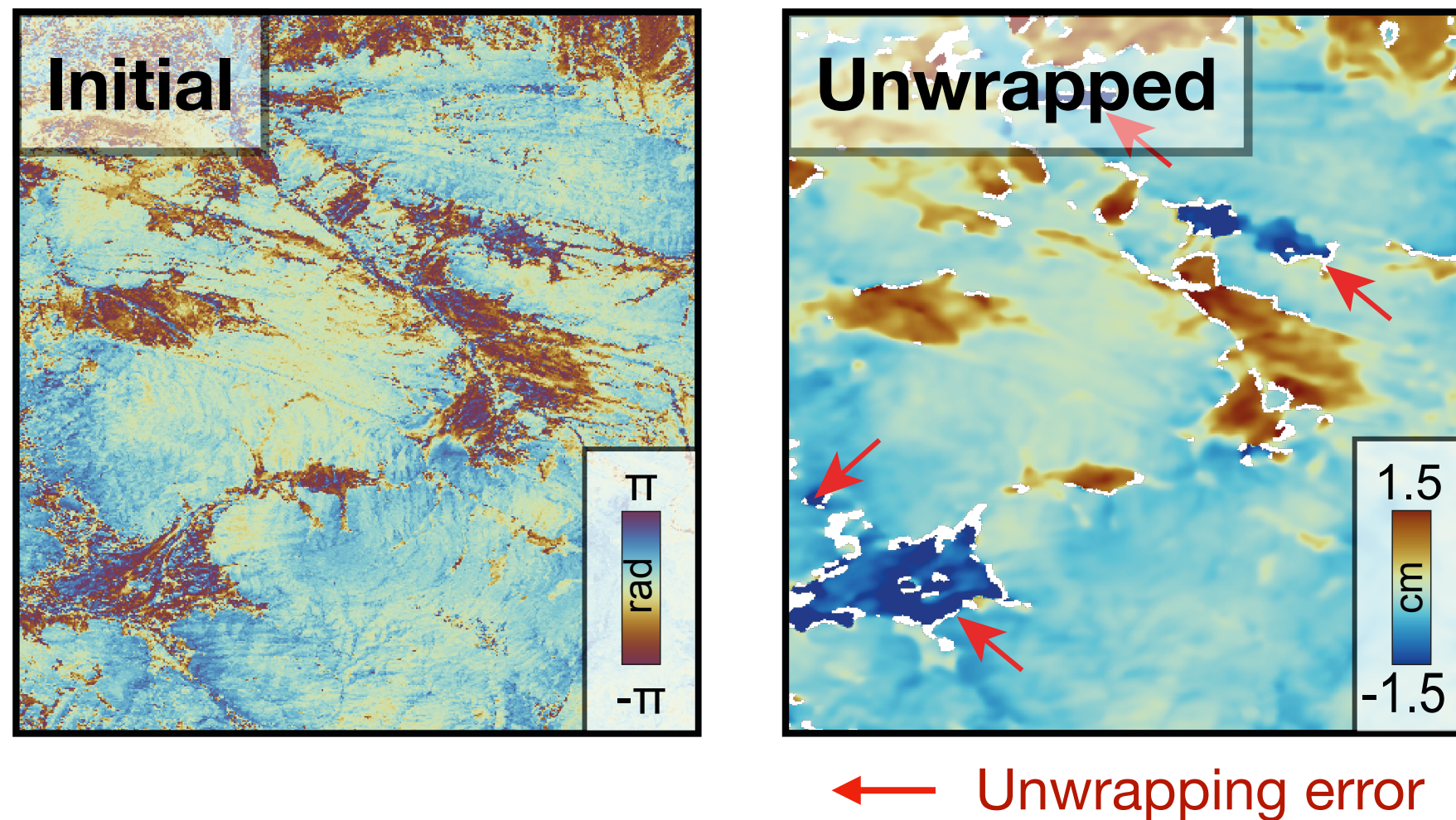
- Discontinuities between tracks
- Referencing on stable area



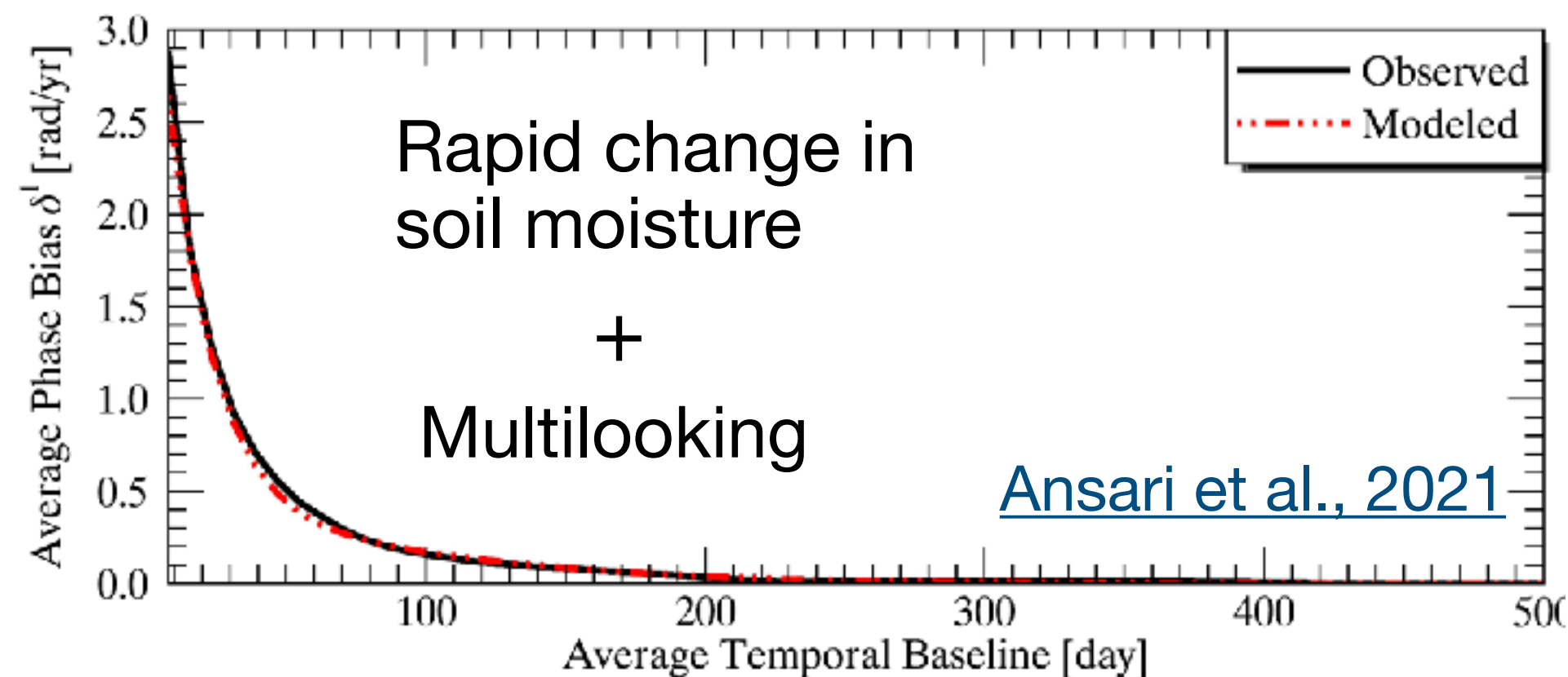
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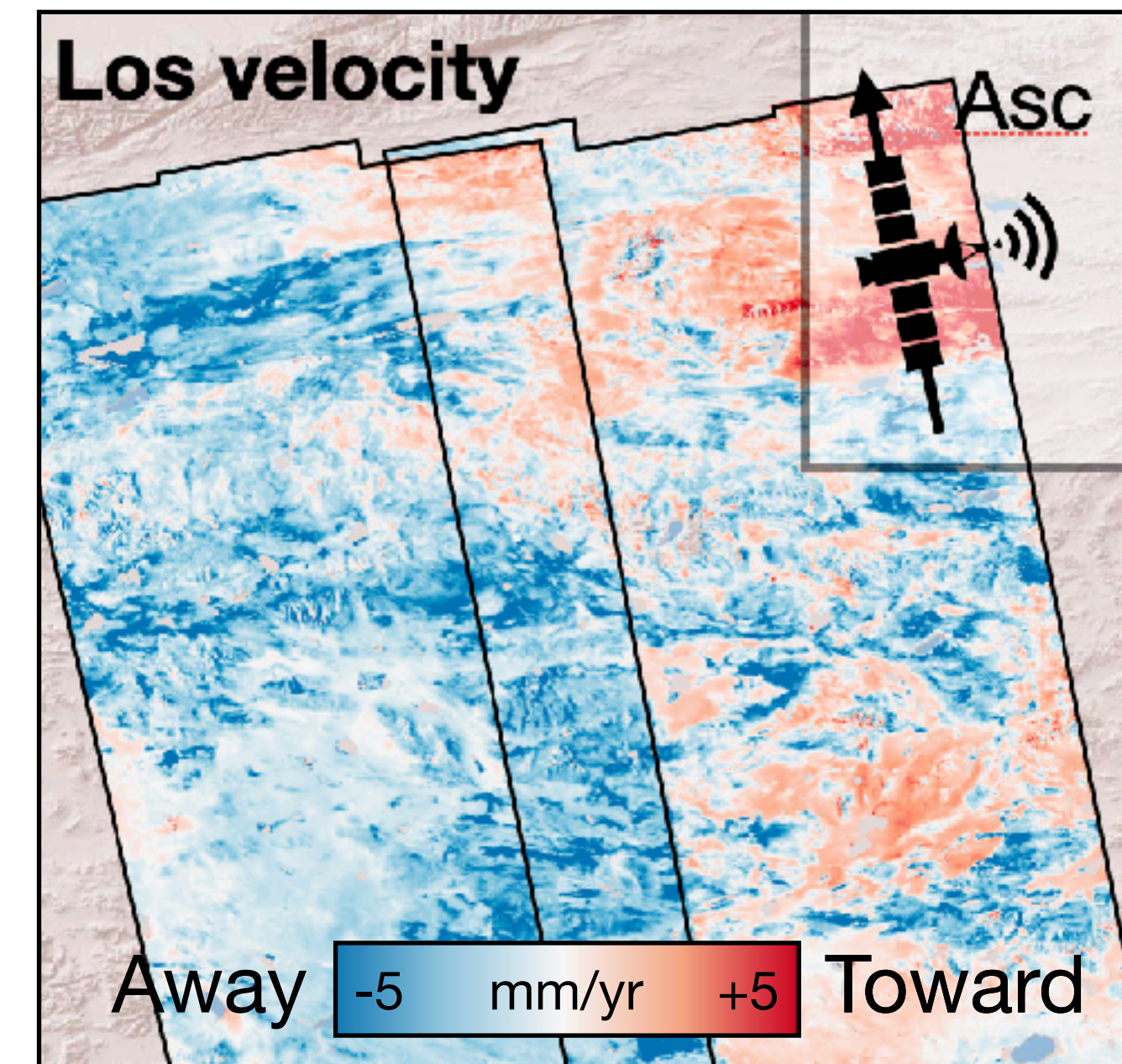


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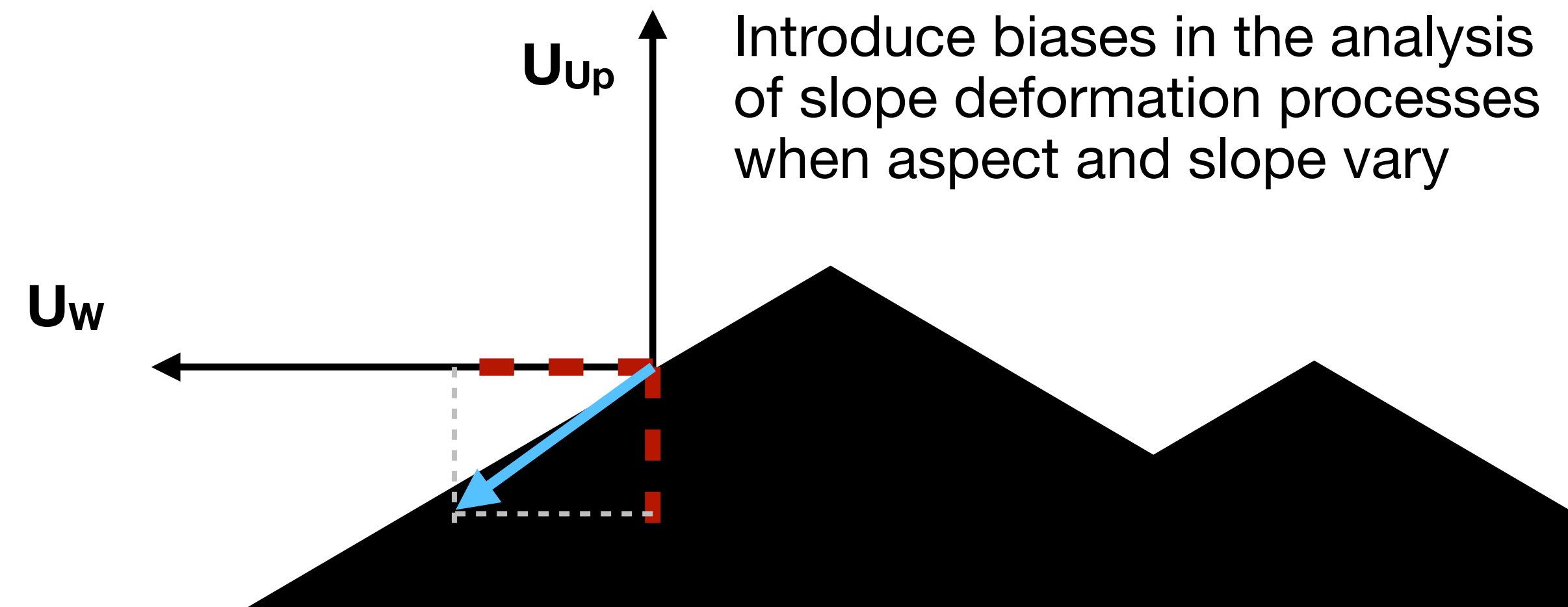


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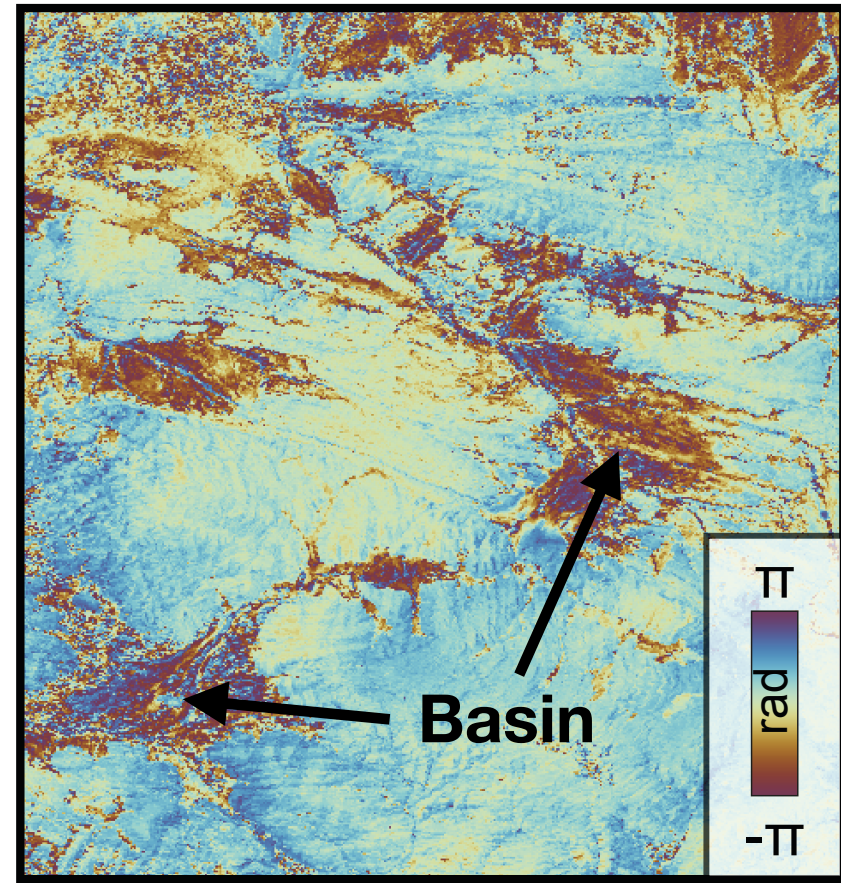


4/ Biases in EW-Up inversion



1/ Minimize unwrapping errors

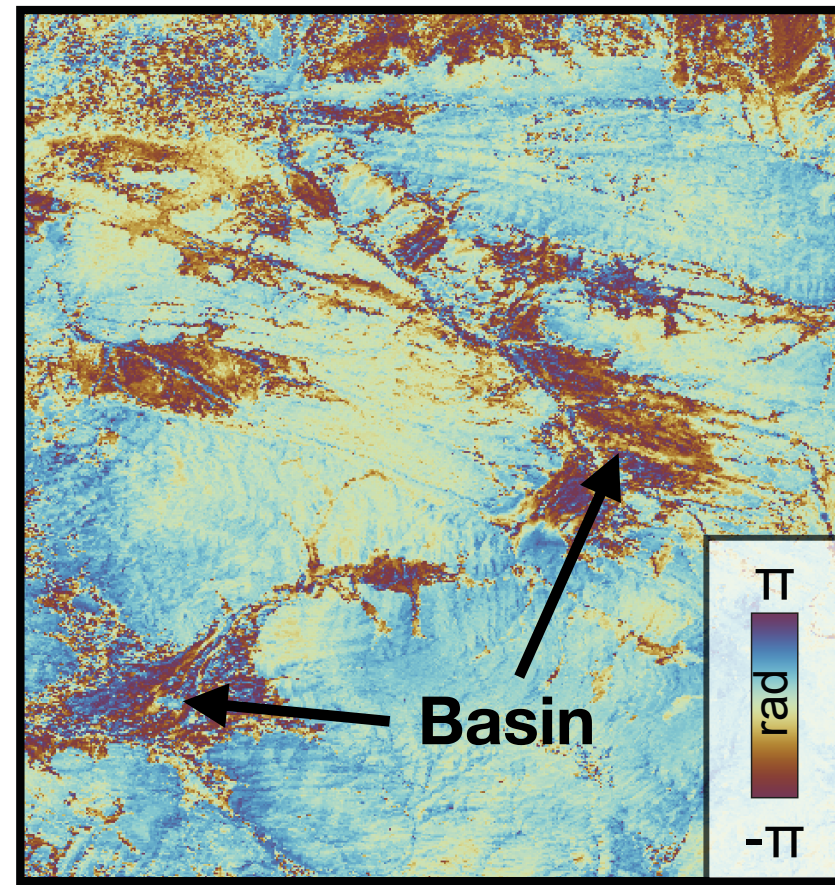
Strong phase gradient



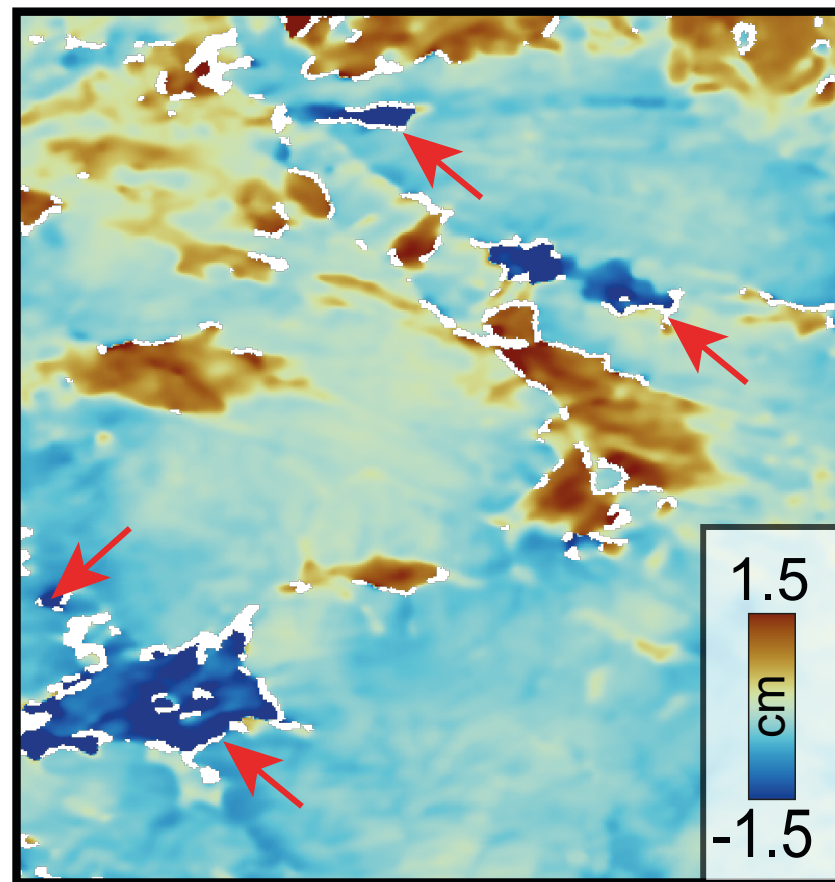
Initial interferogram

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Strong phase gradient



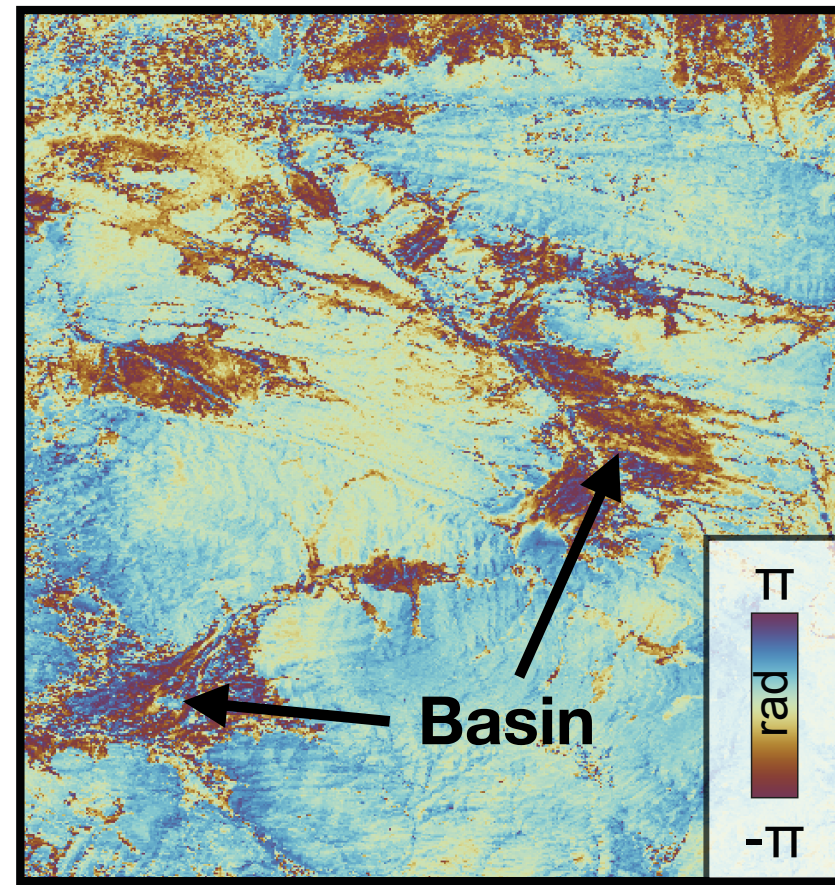
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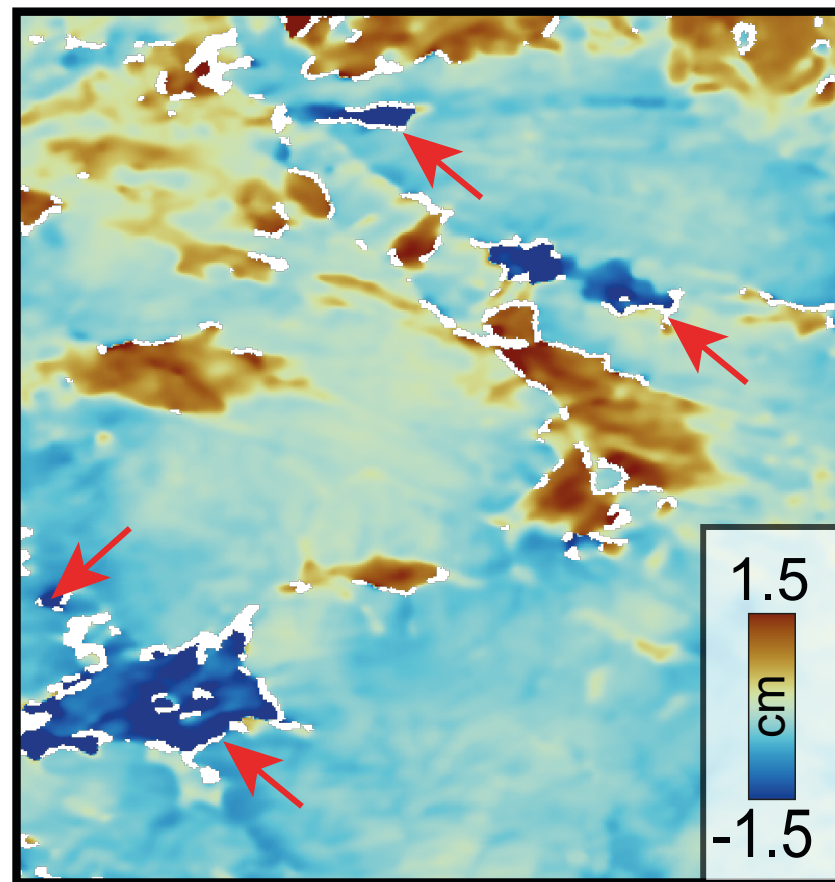
FLATSIM processing

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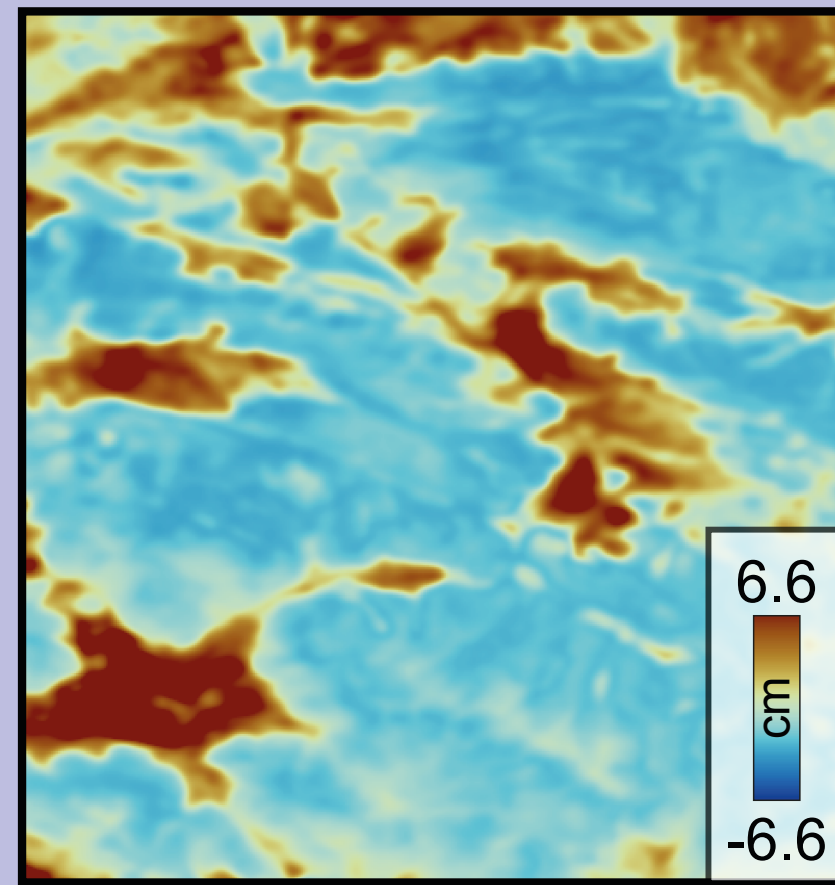
Initial interferogram



FLATSIM processing

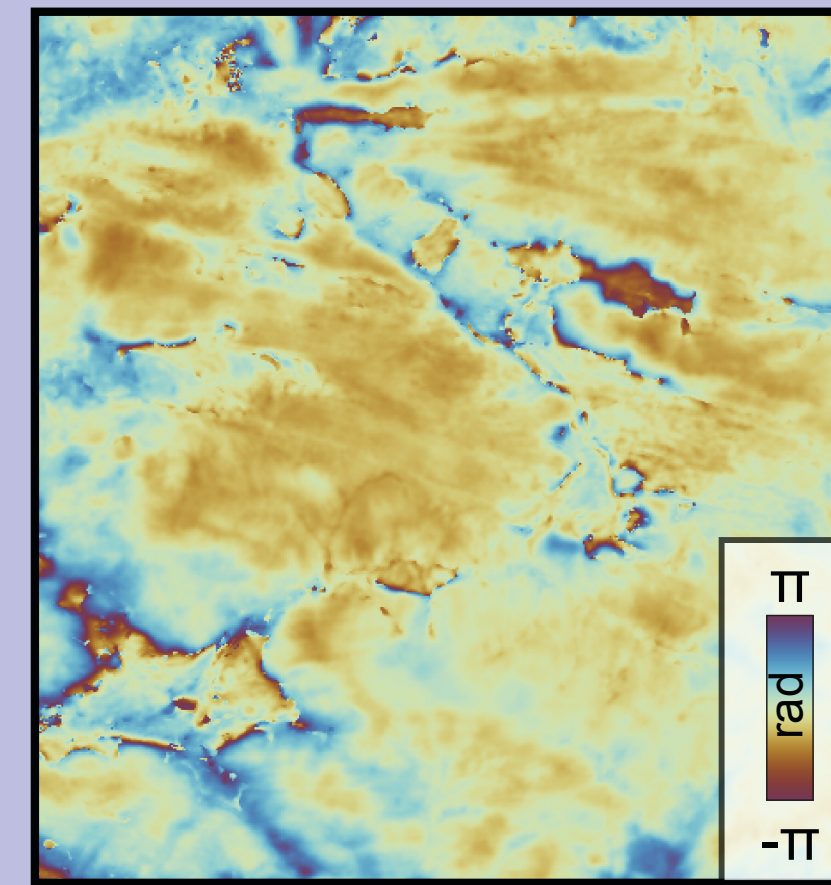
Estimation of the **alpha** coefficient

- **alpha** *



Deformation model

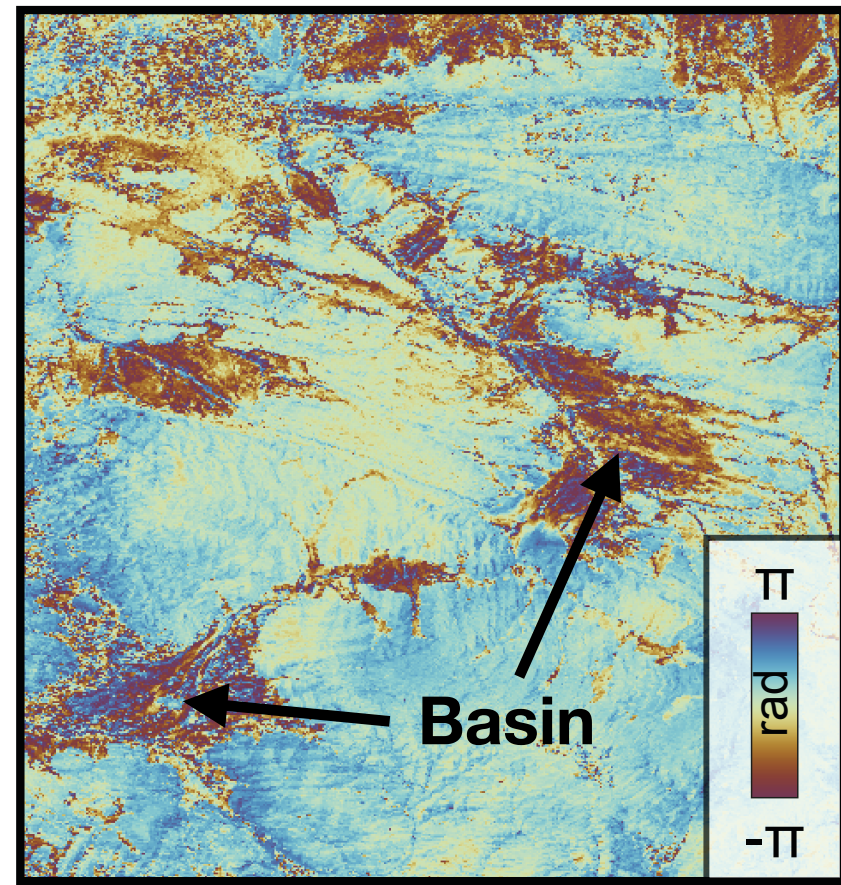
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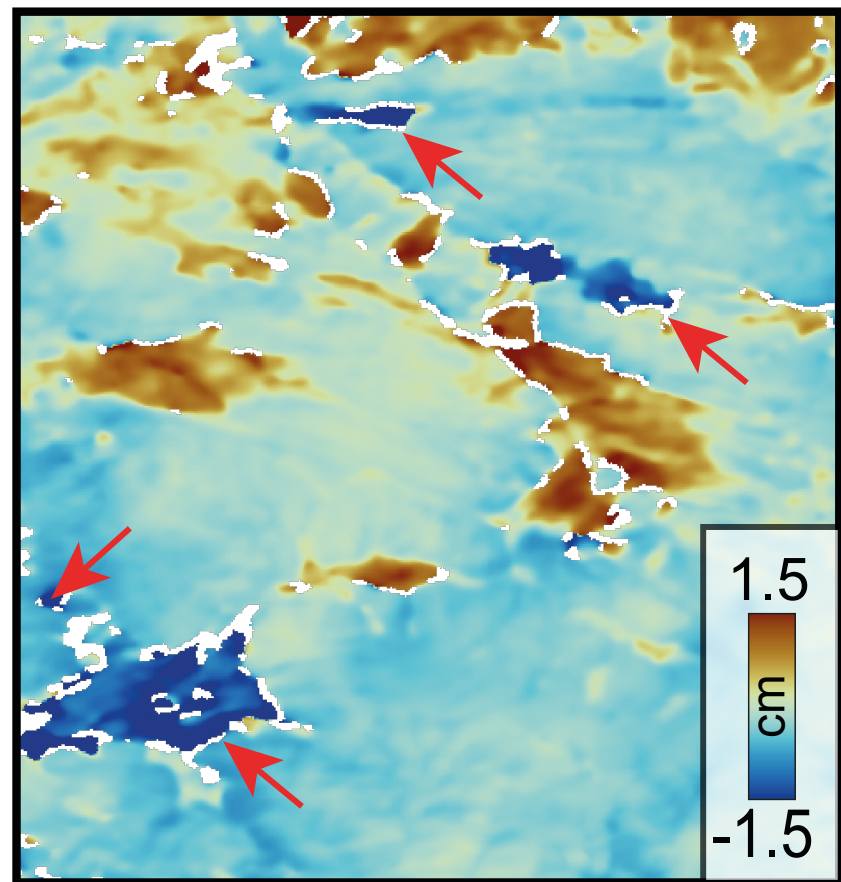
Reduce interferogram

1/ Minimize unwrapping errors

Strong phase gradient



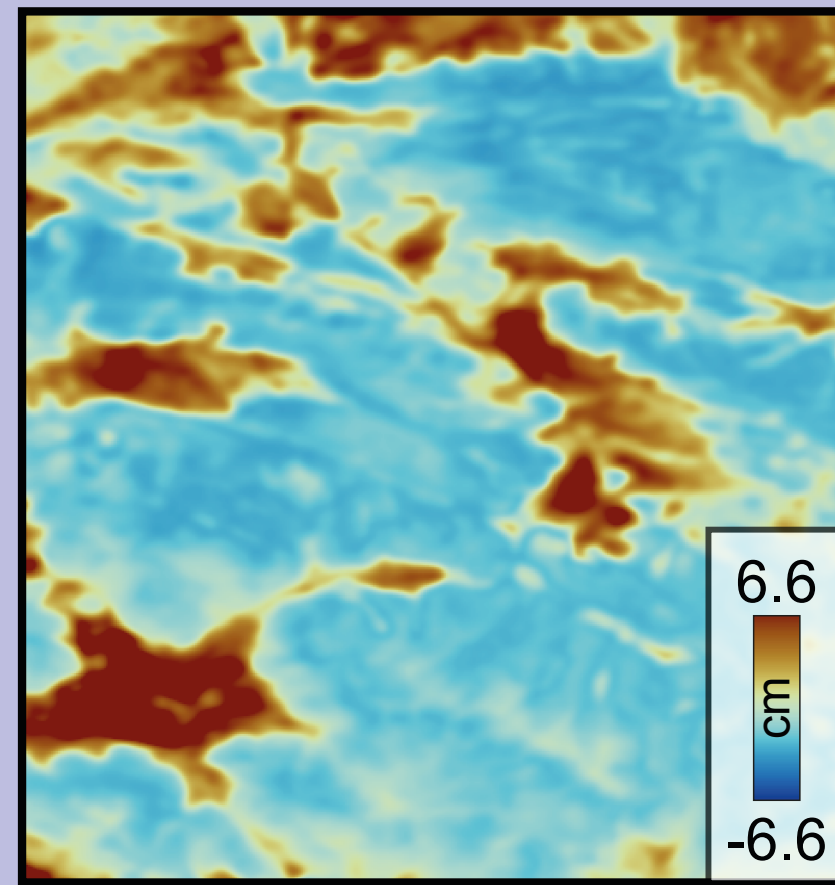
Initial interferogram



FLATSIM processing

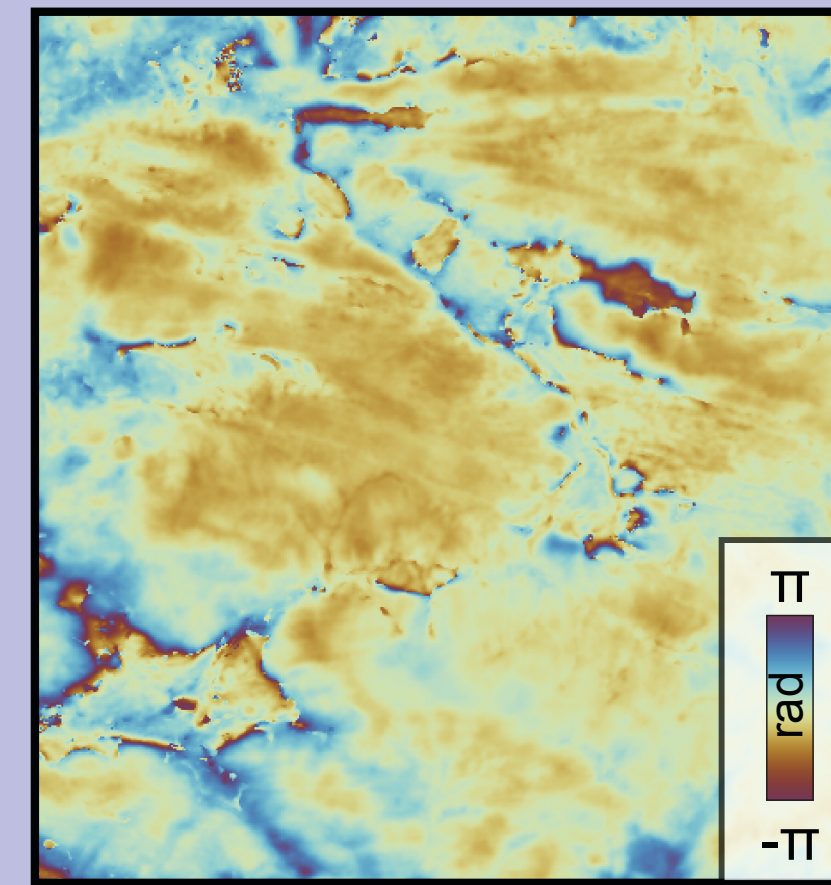
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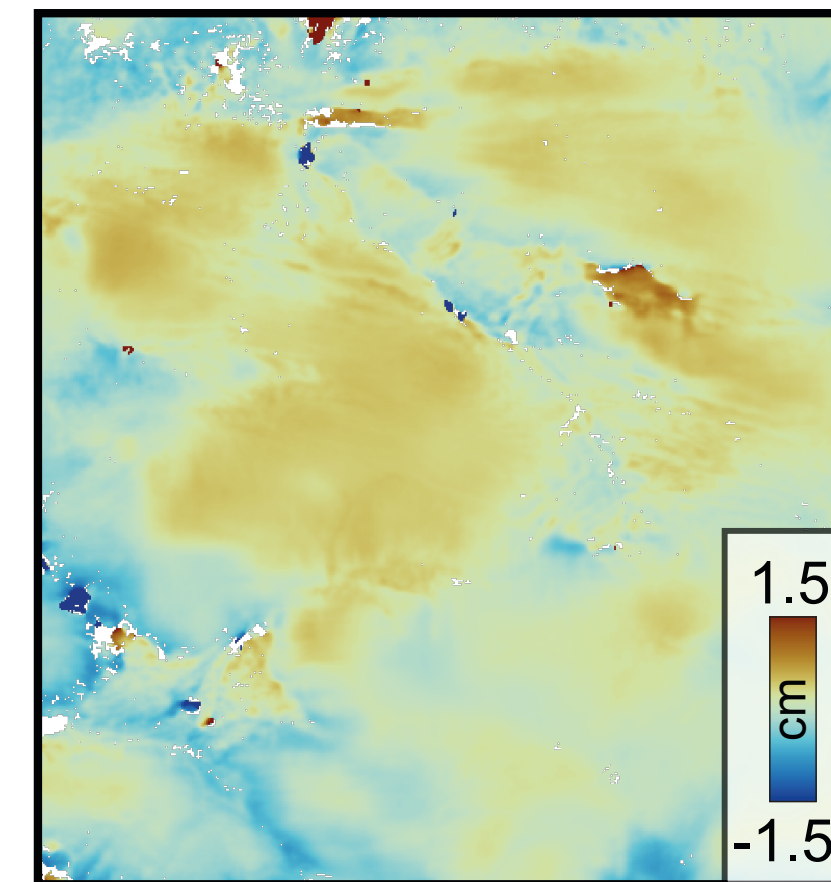


Deformation model

=



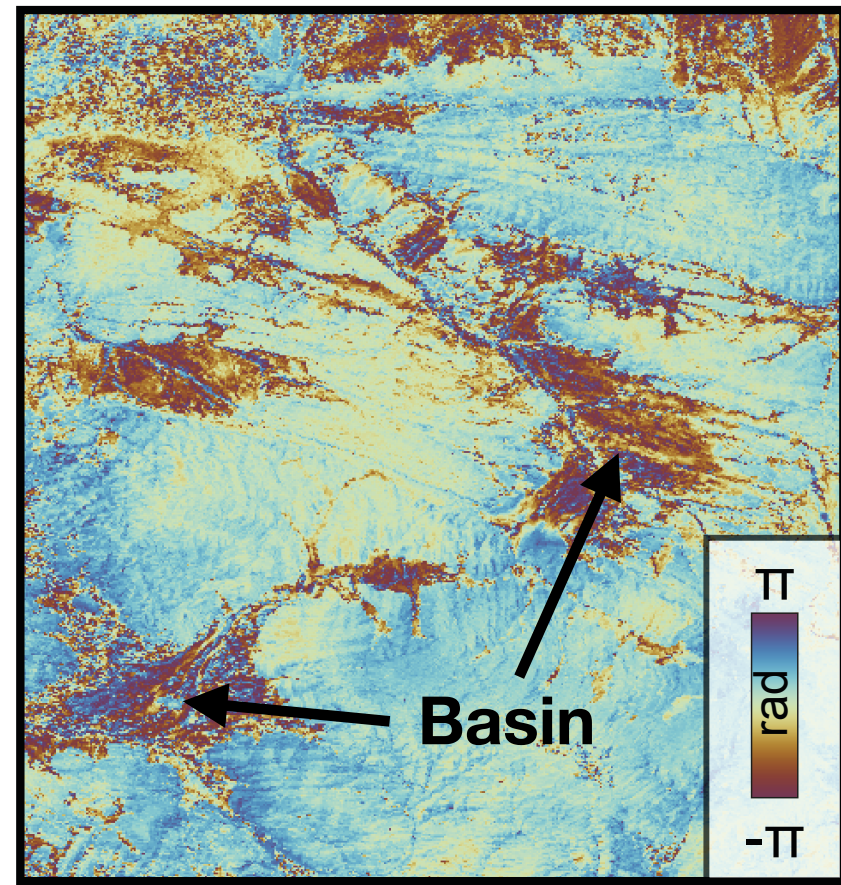
Reduce interferogram



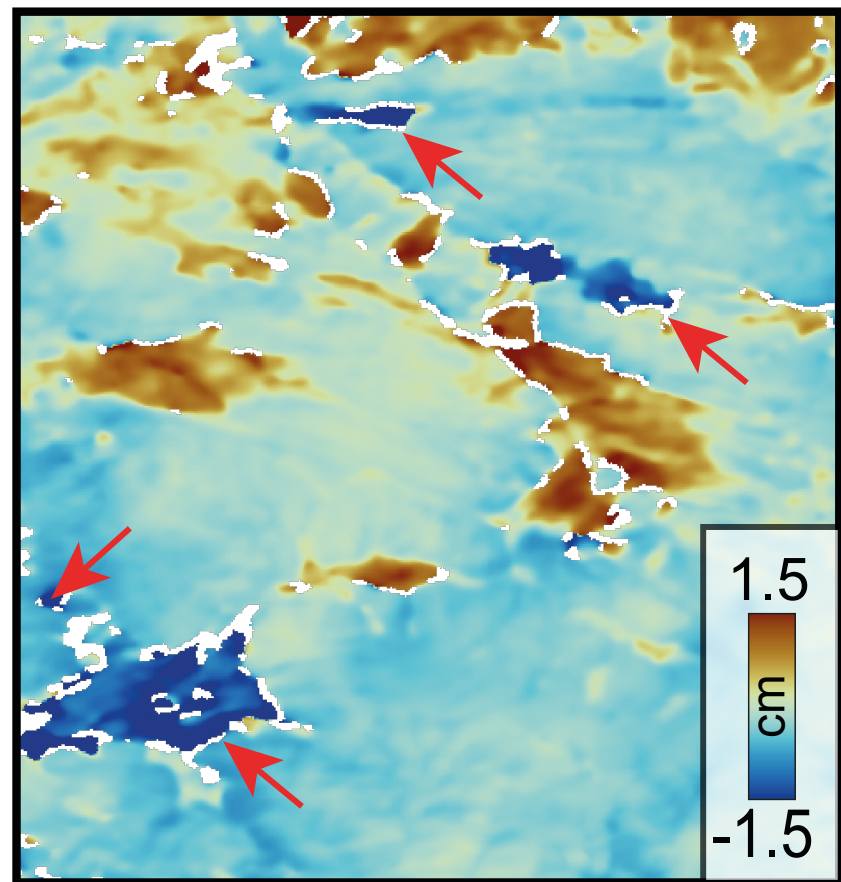
Unwrapping

1/ Minimize unwrapping errors

Strong phase gradient



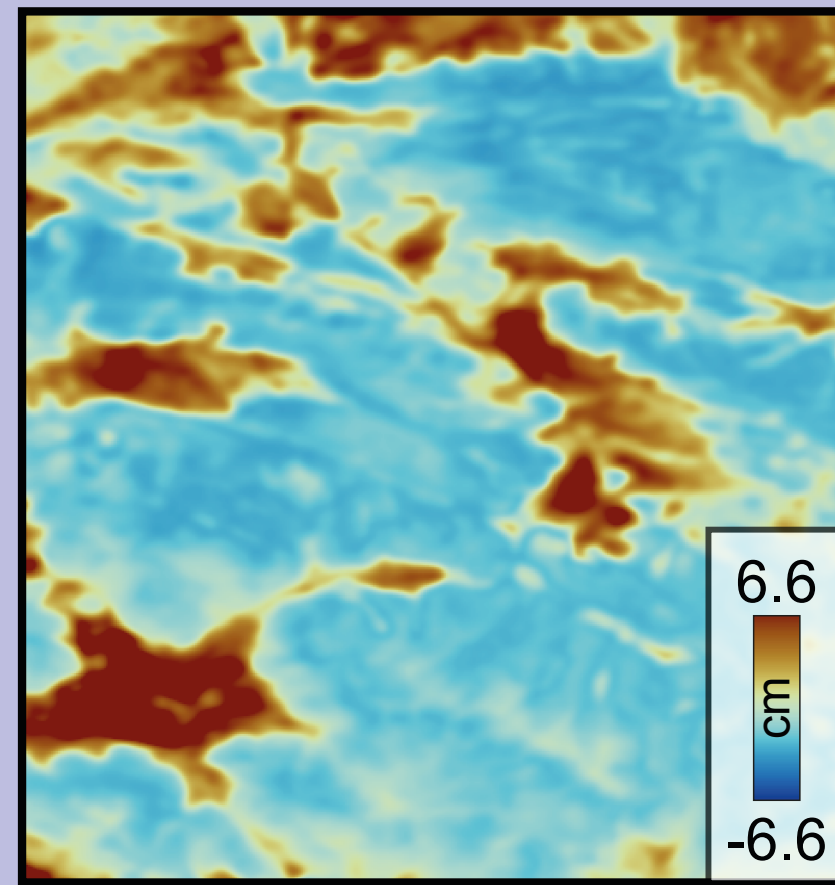
Initial interferogram



FLATSIM processing

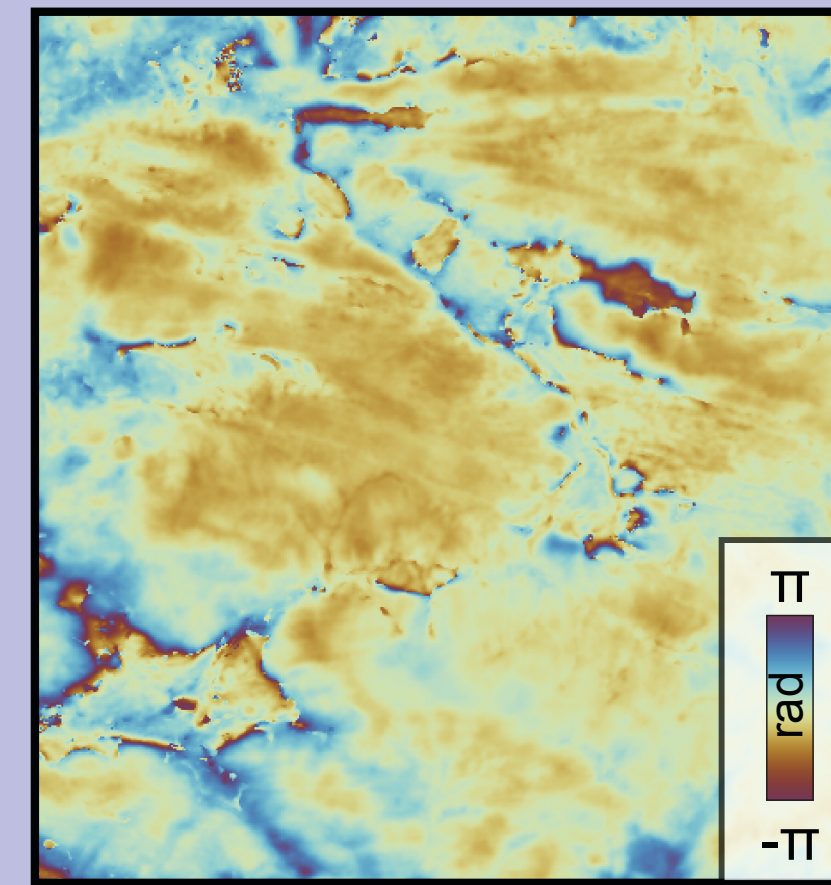
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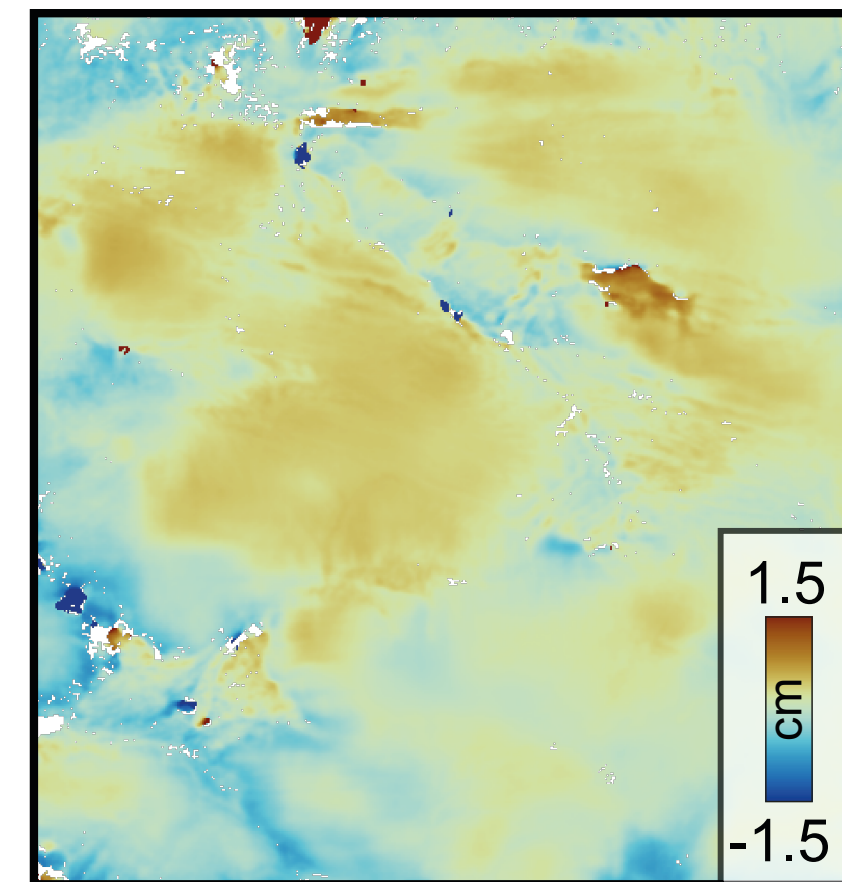


Deformation model

$=$

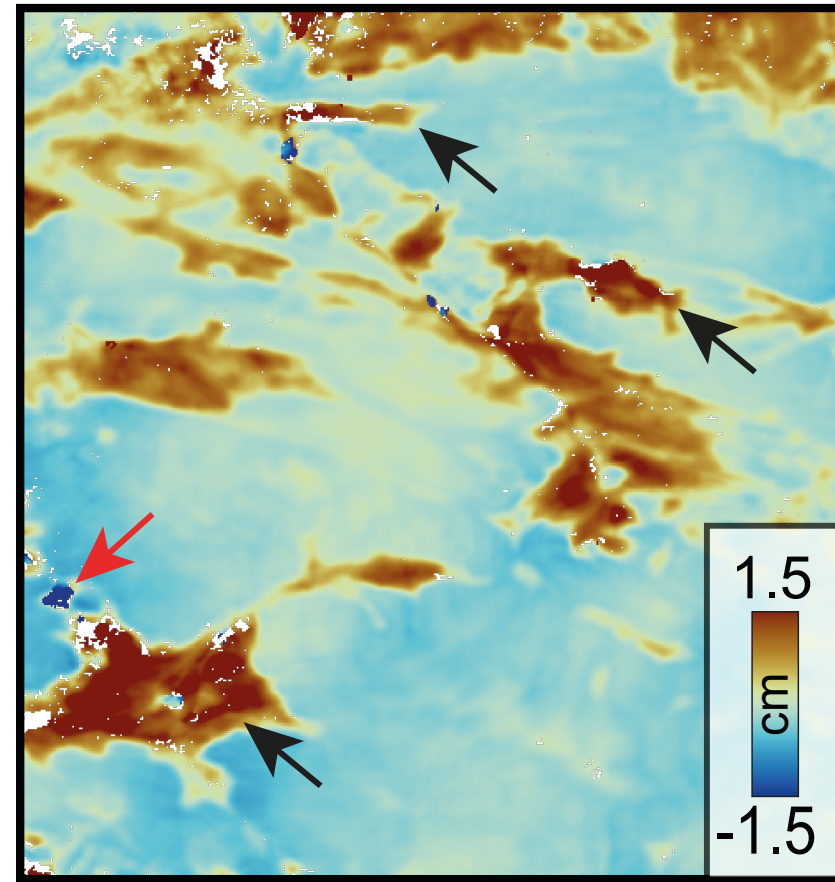


Reduce interferogram



Unwrapping

$\neq$

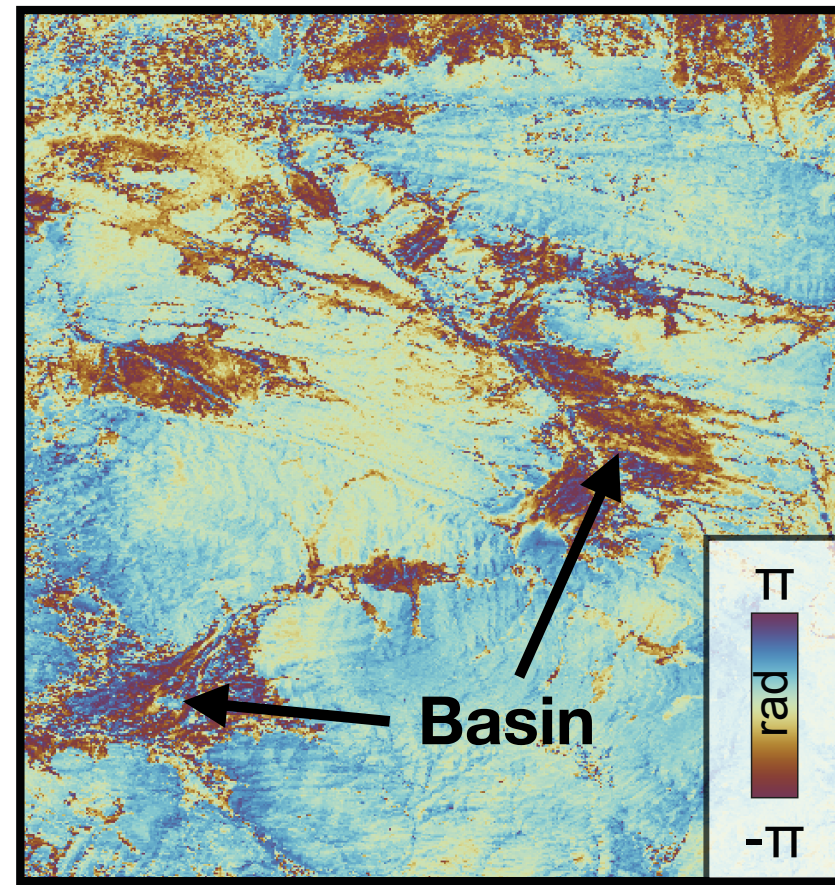


Add back model

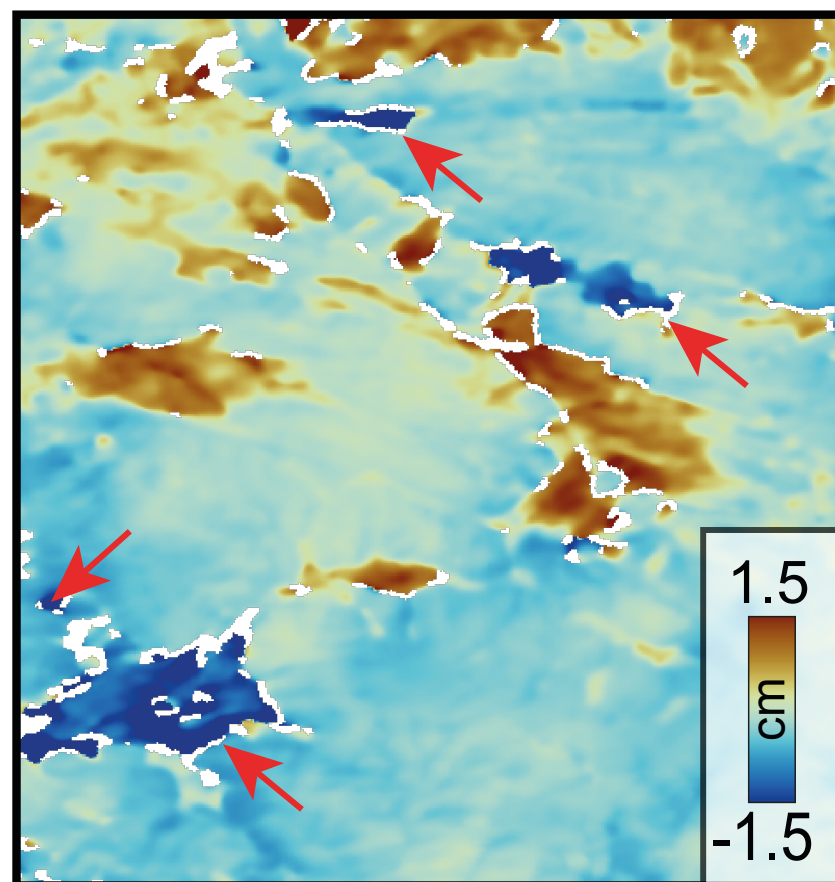


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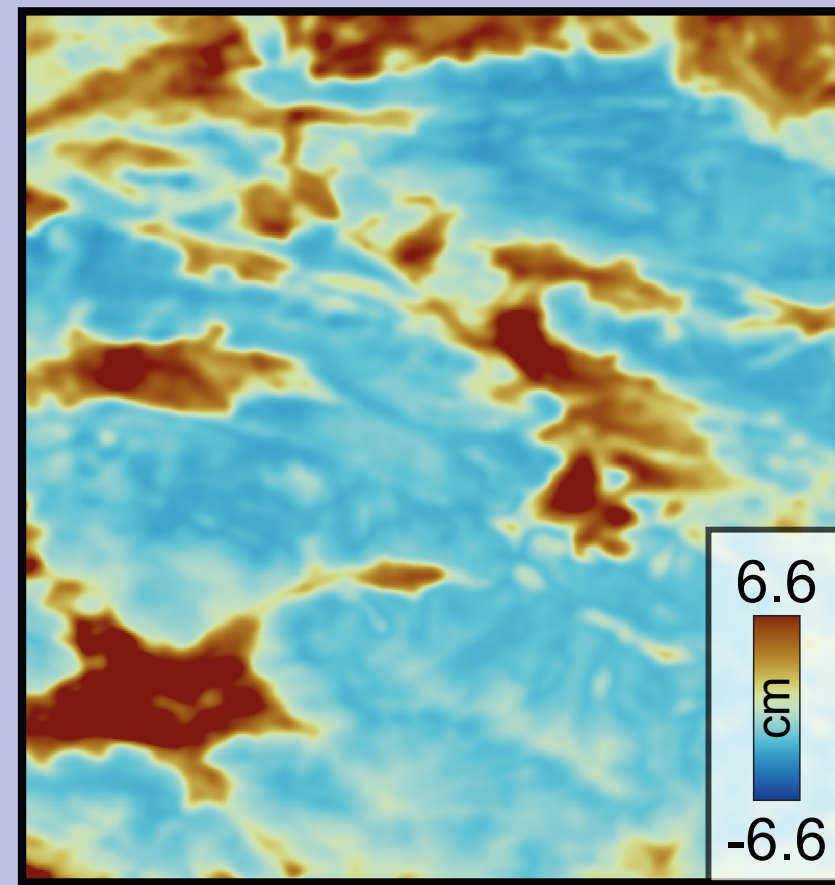
Initial interferogram



FLATSIM processing

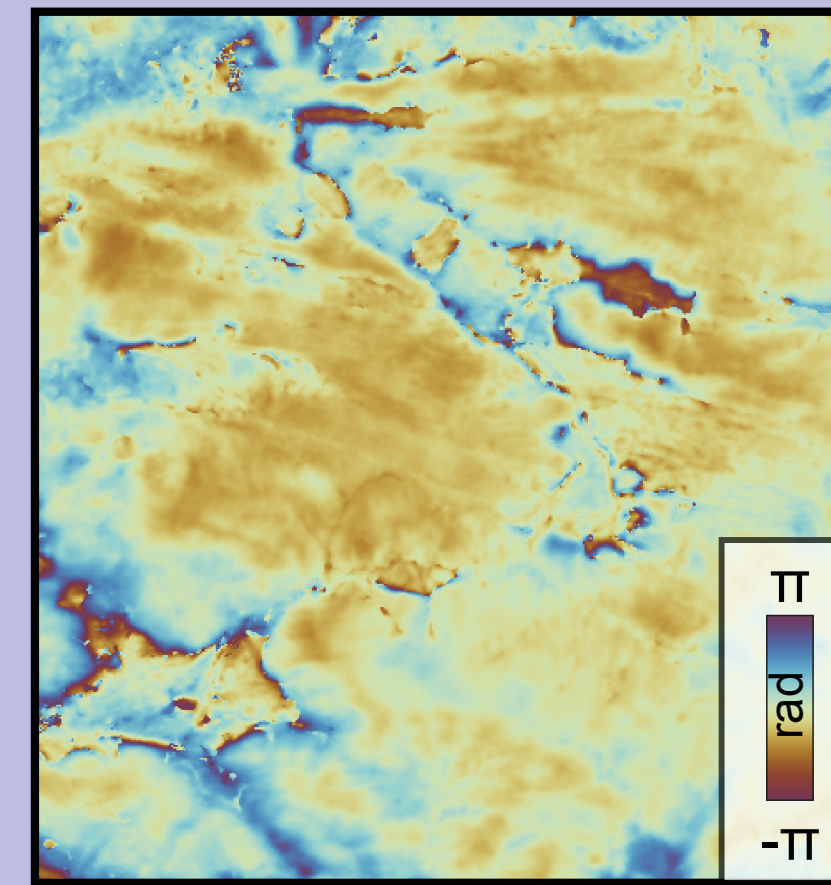
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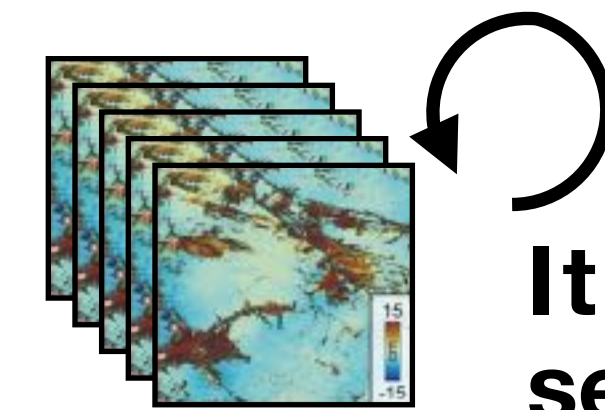


Deformation model

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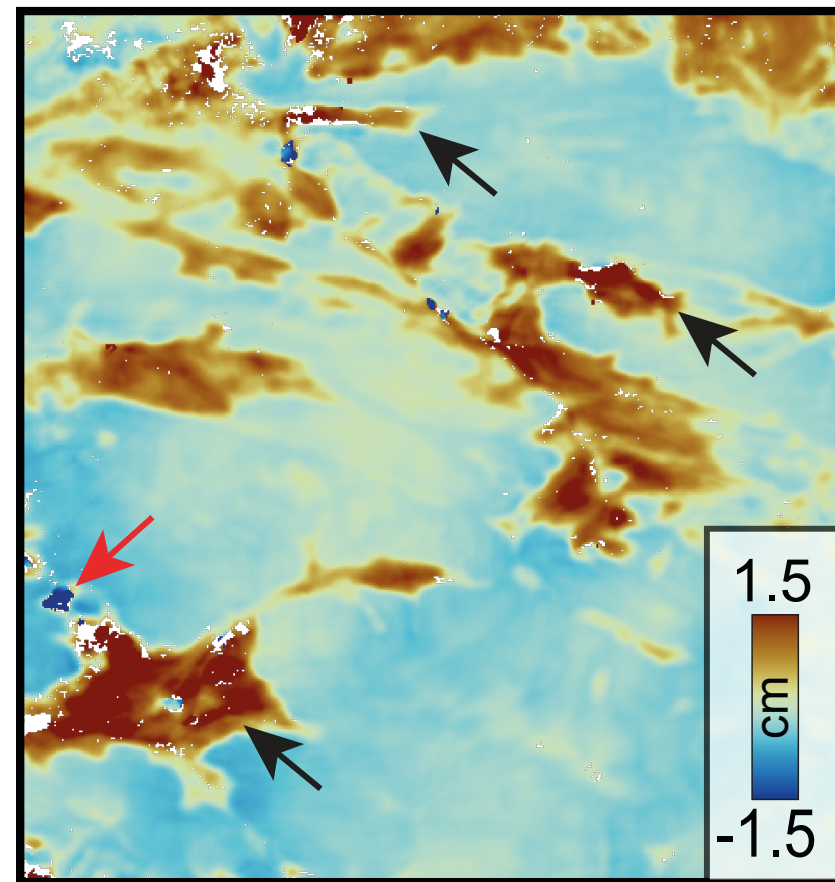
Reduce interferogram



Iterative time series inversion

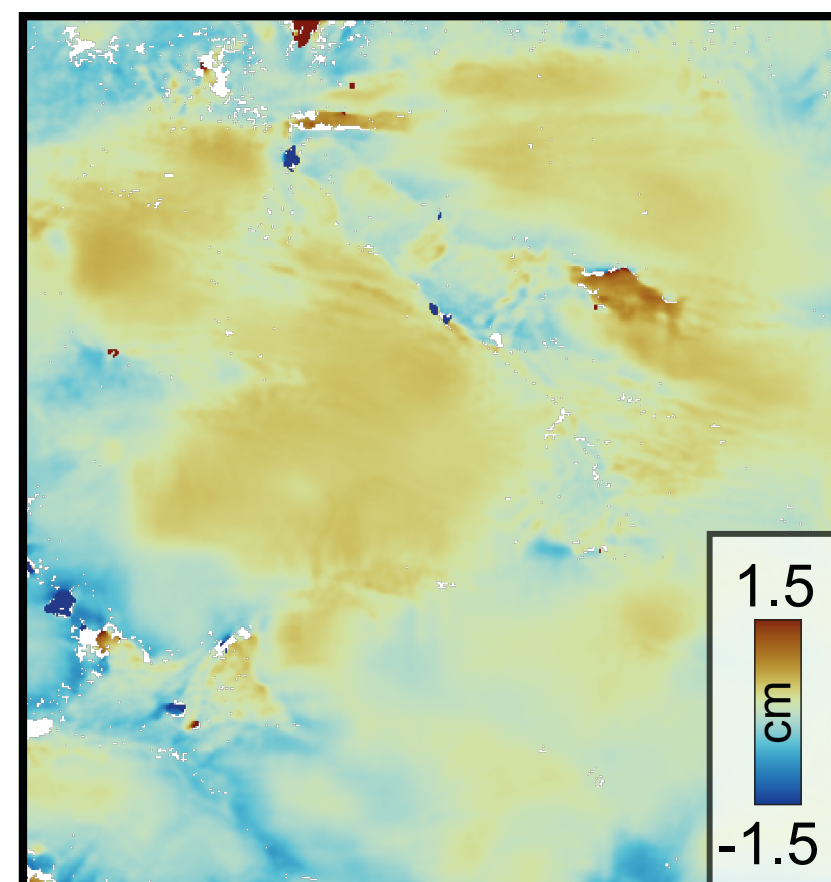
- identify inconsistencies in the network and remove / reprocess associated interferograms

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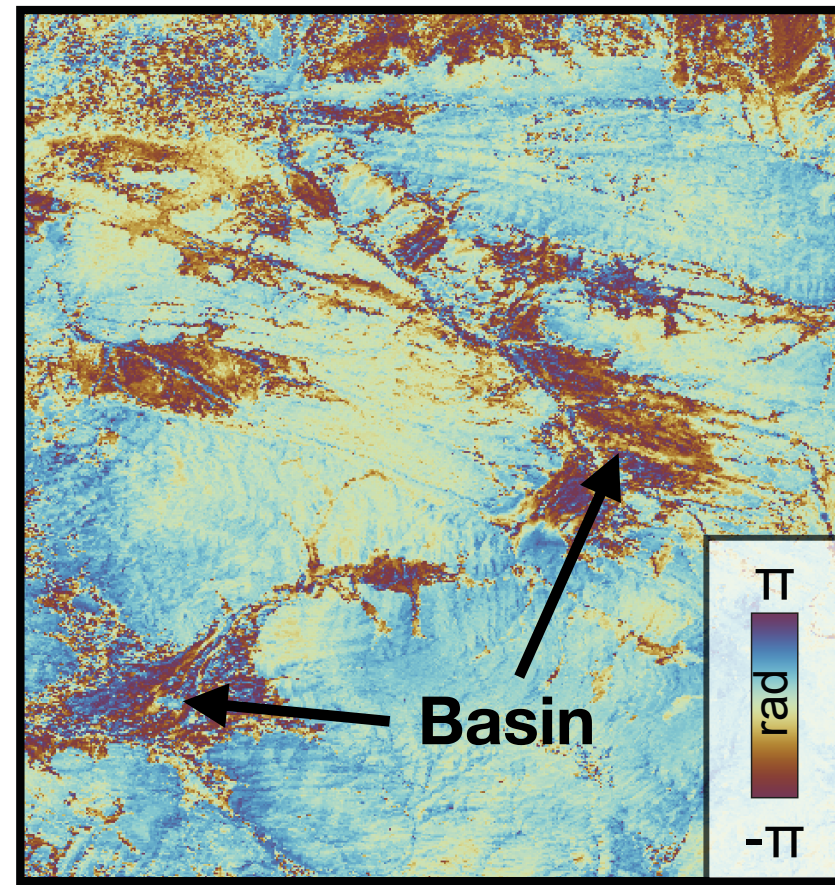
$\leftarrow$



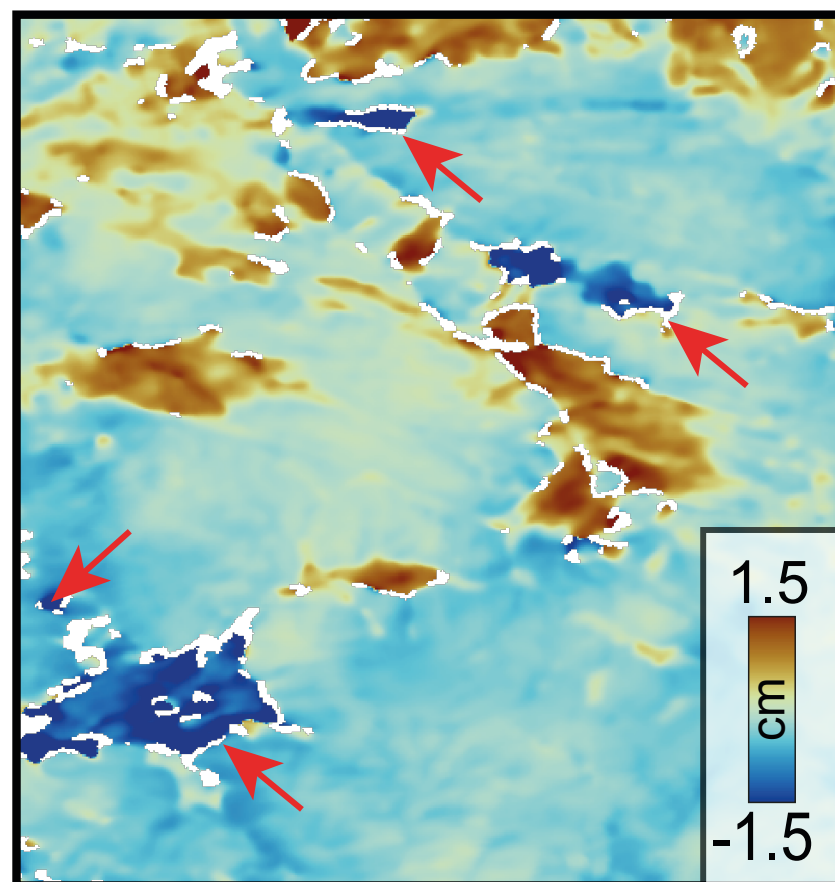
Unwrapping

1/ Minimize unwrapping errors

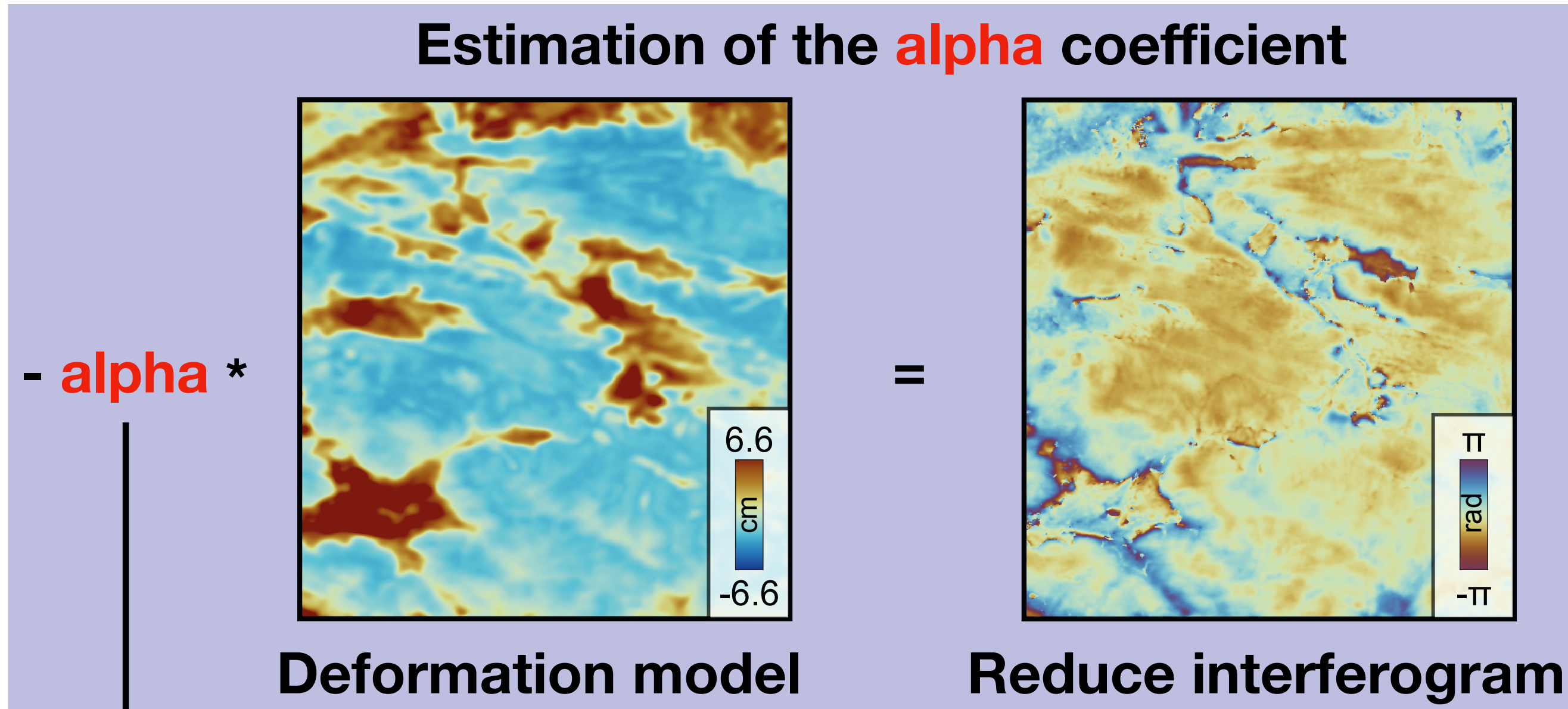
Strong phase gradient



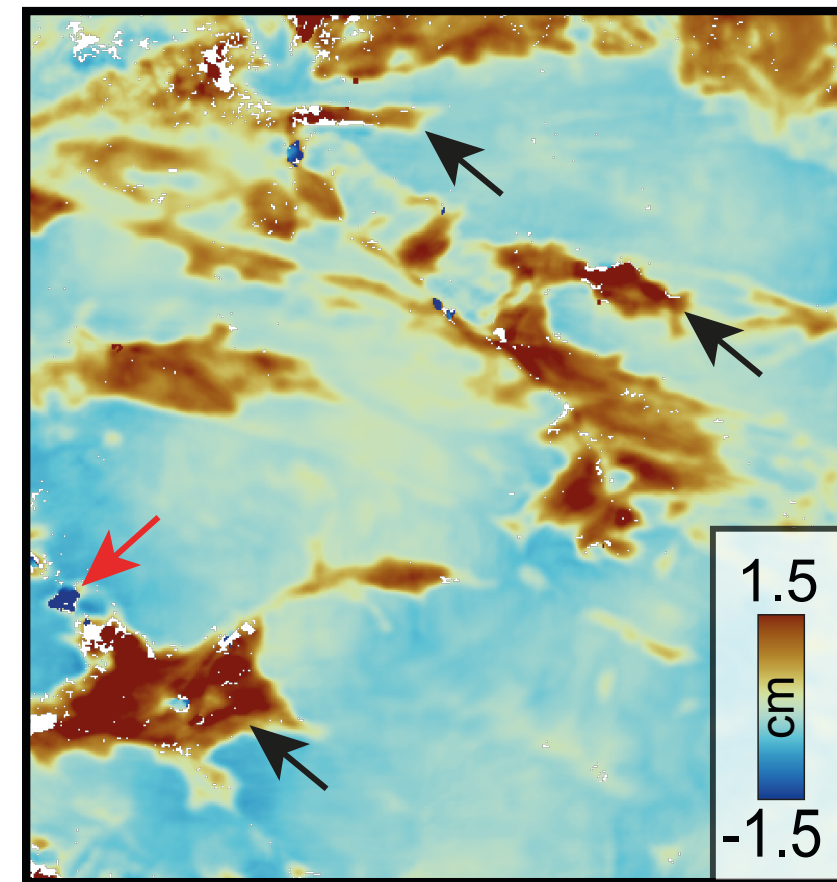
Initial interferogram



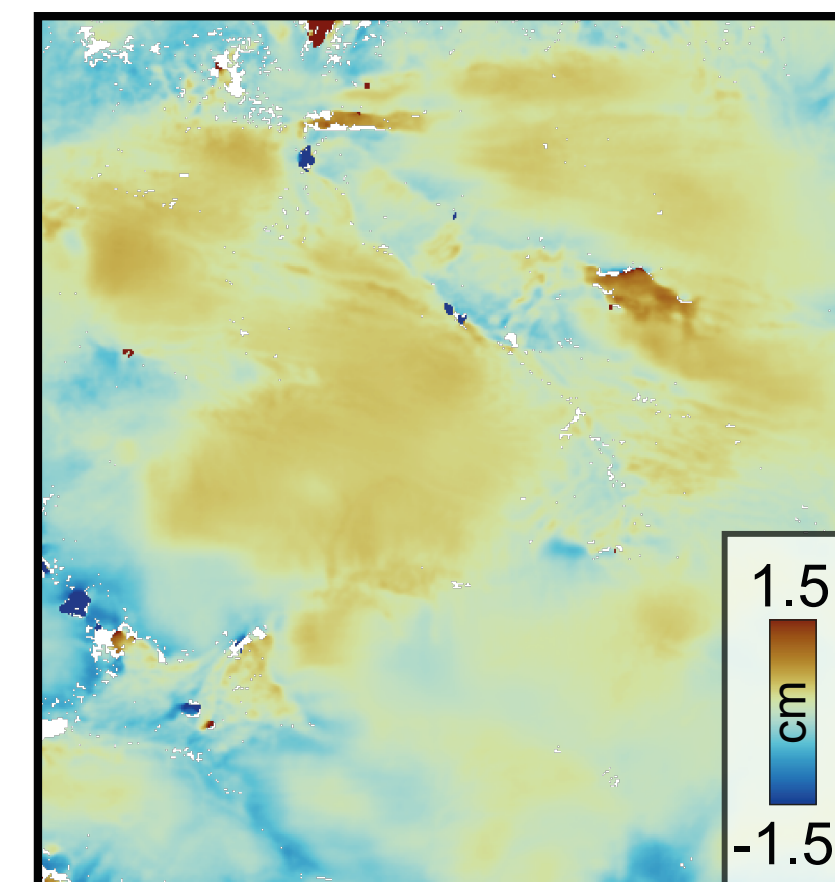
FLATSIM processing



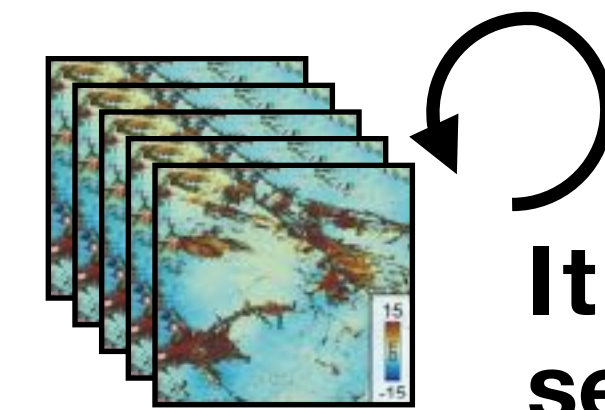
$\neq$



Add back model



Unwrapping



Iterative time series inversion

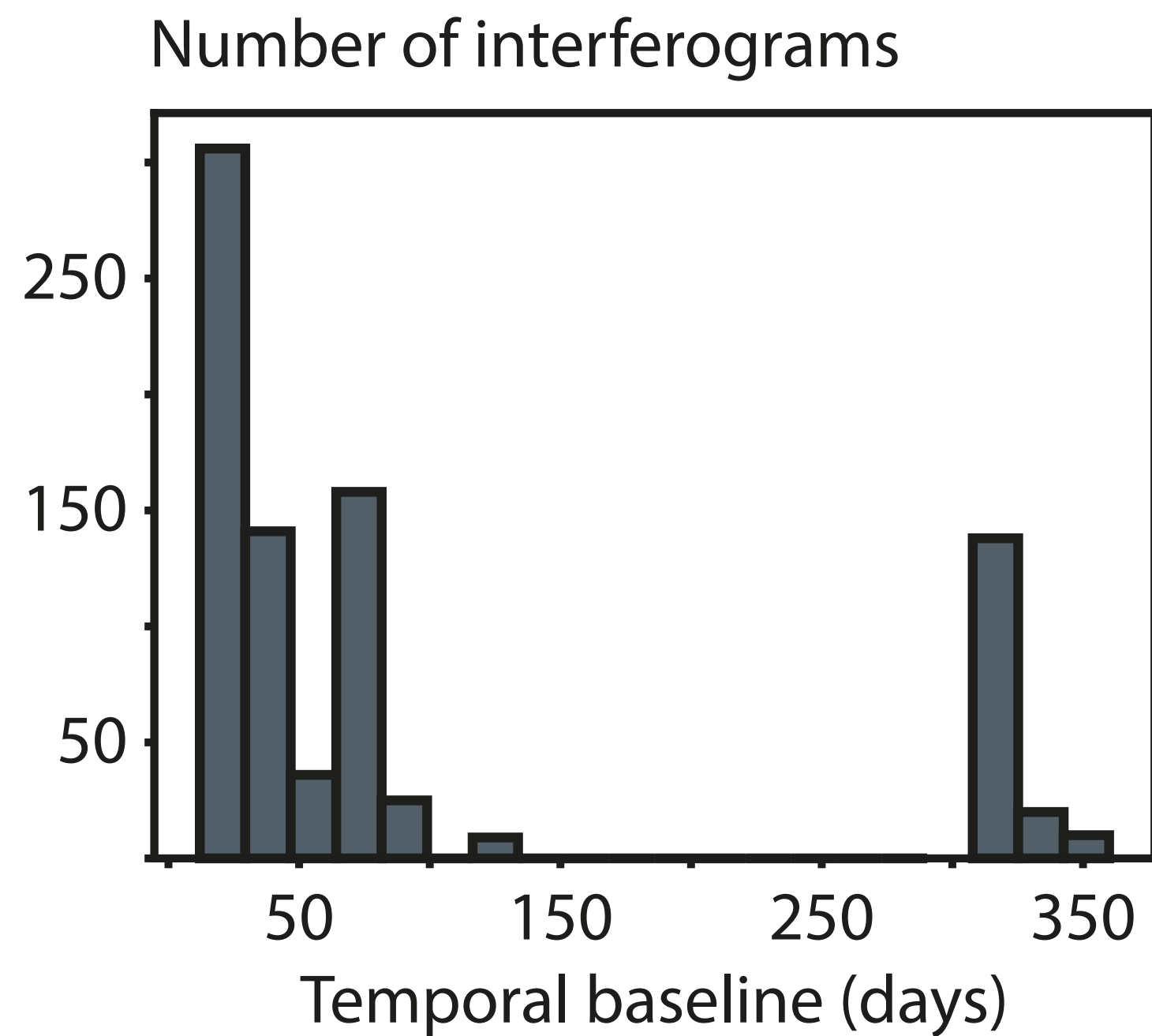
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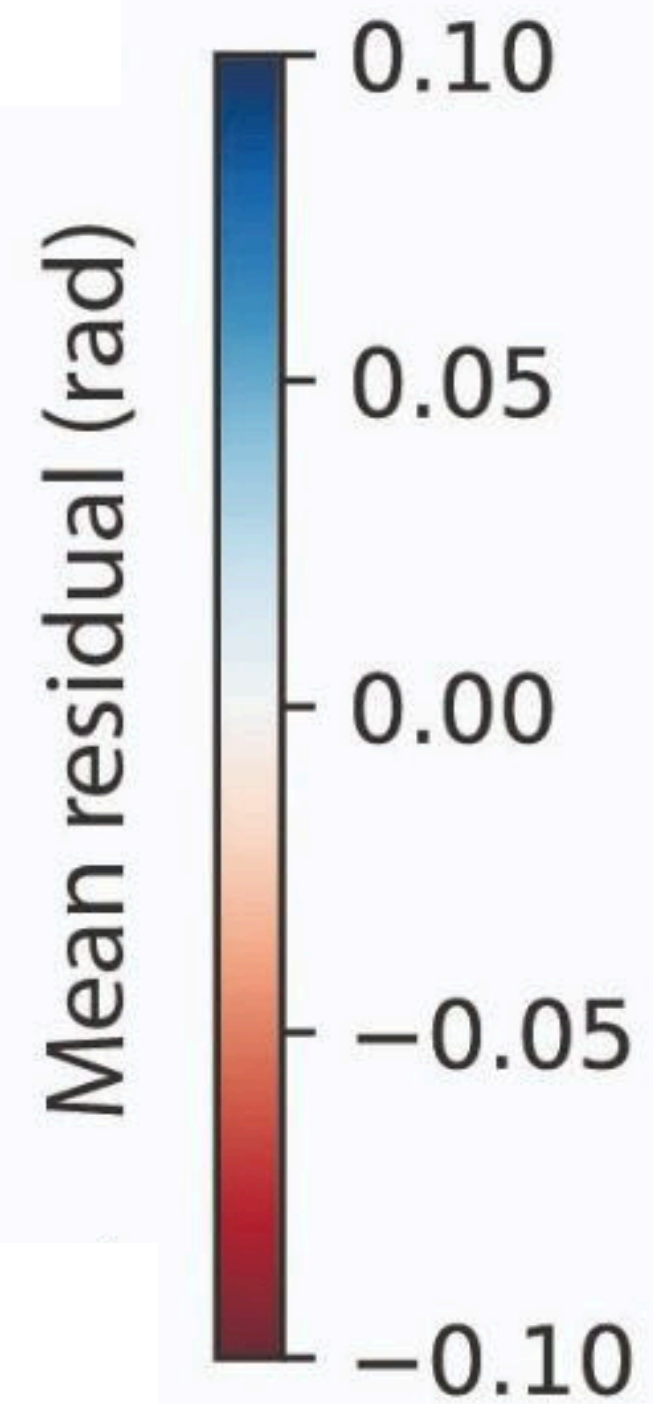
Final time series inversion

- Automatic correction of unwrapping errors

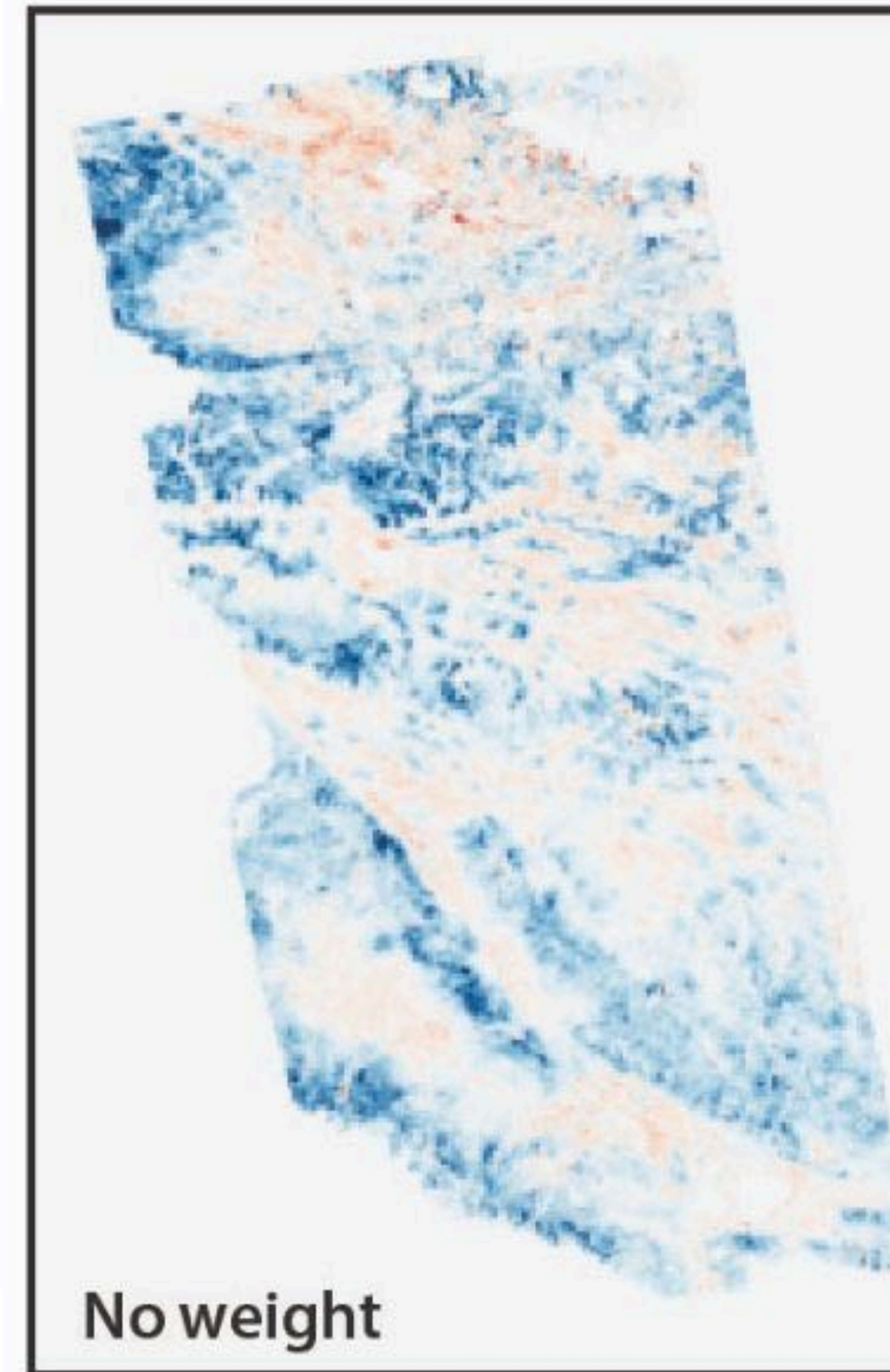
2/ Fading signal mitigation



- $n+1+2+3$, +3month, +1yr



324-360 days

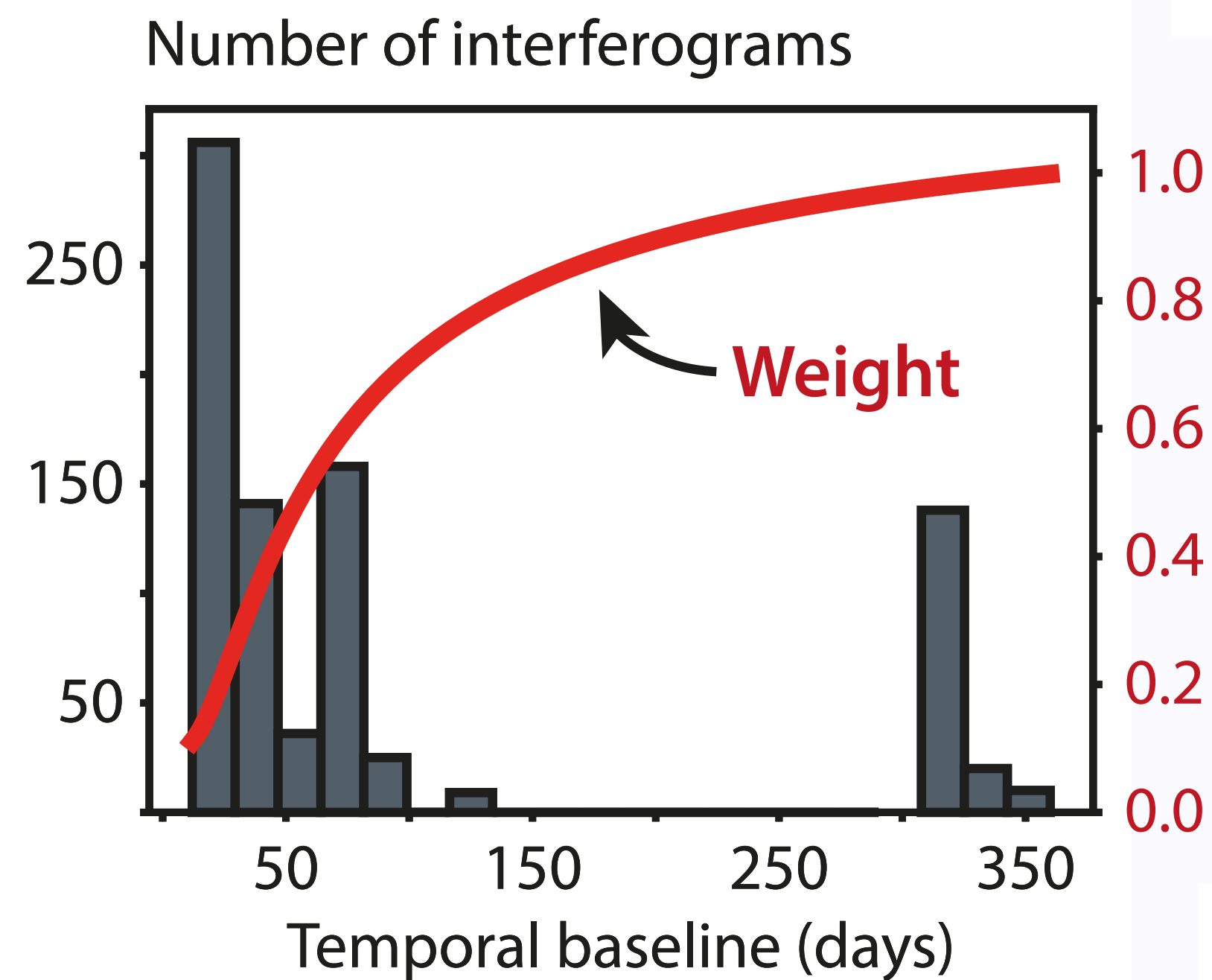


1-year interferograms
are less affected by
systematic biases.

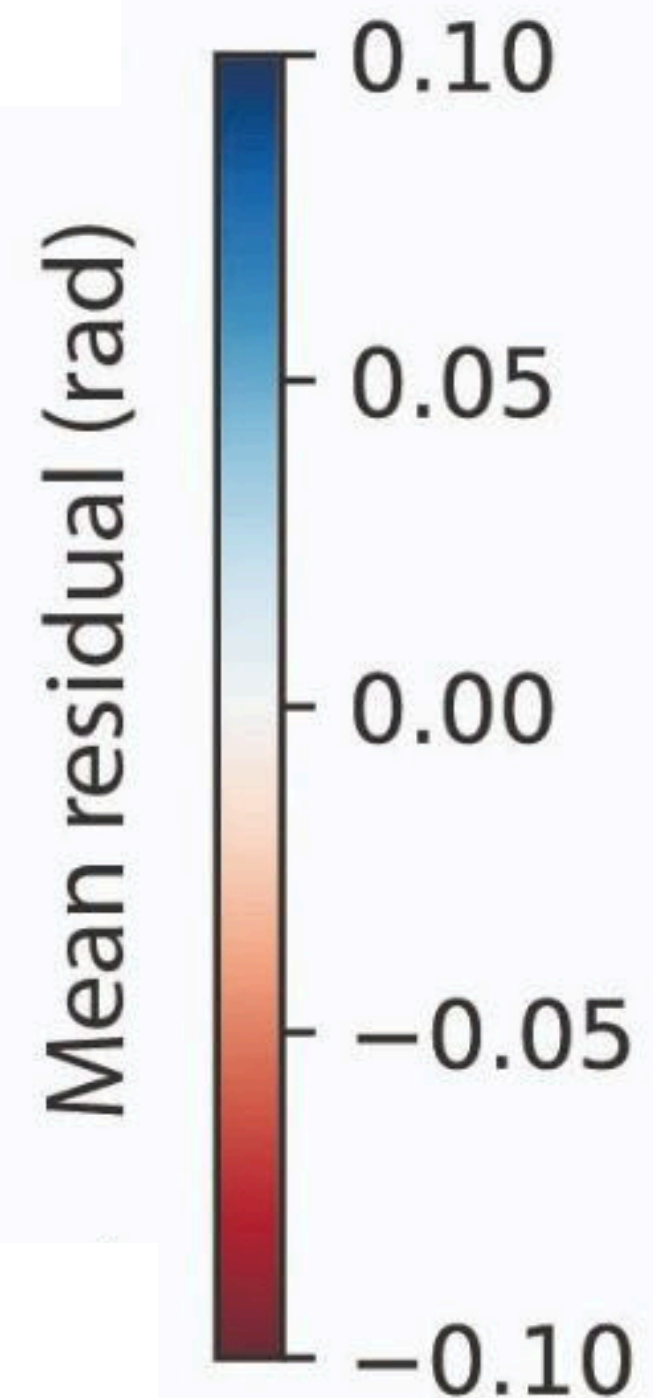


Overweighting
the long temporal
baseline

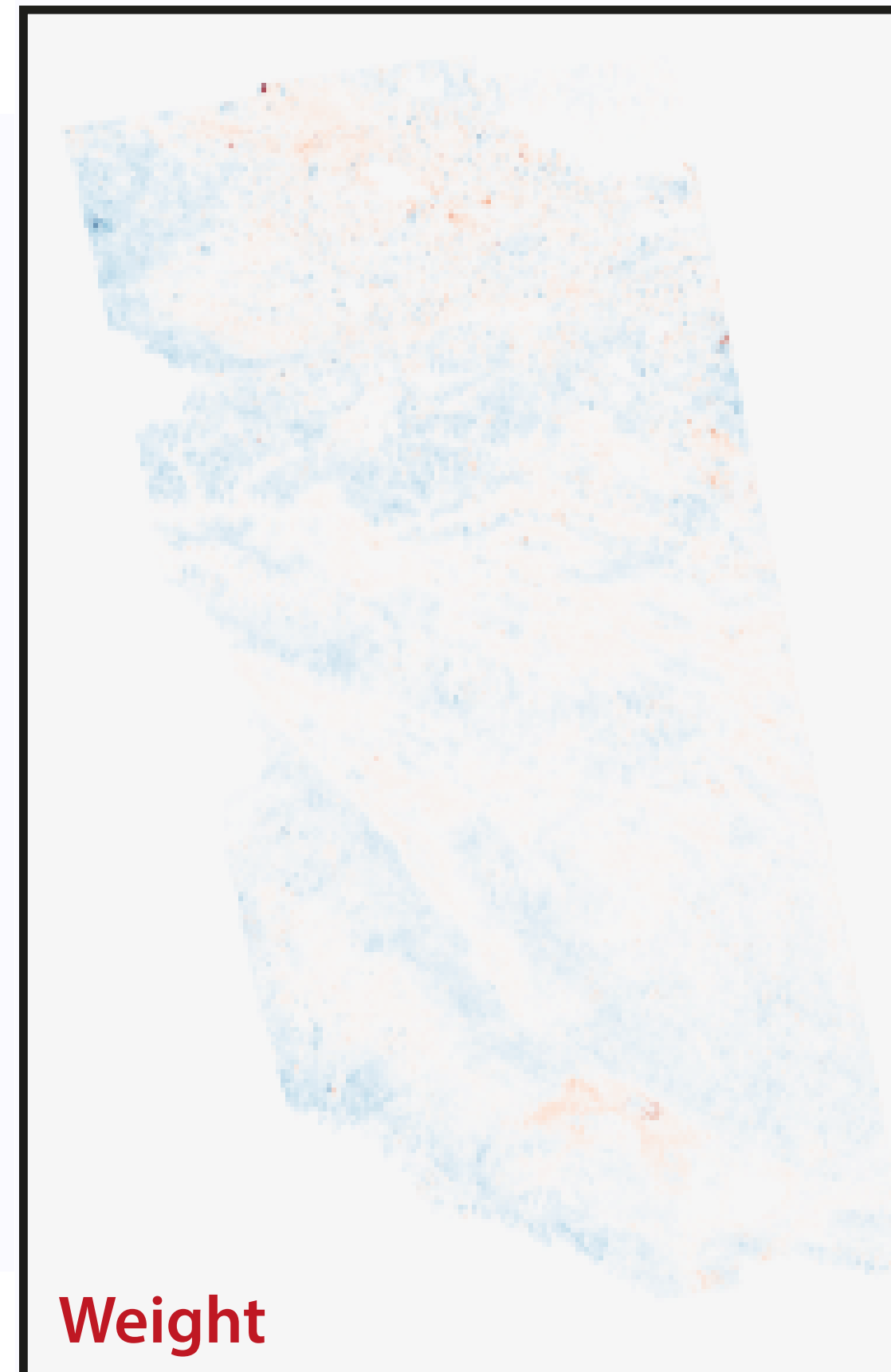
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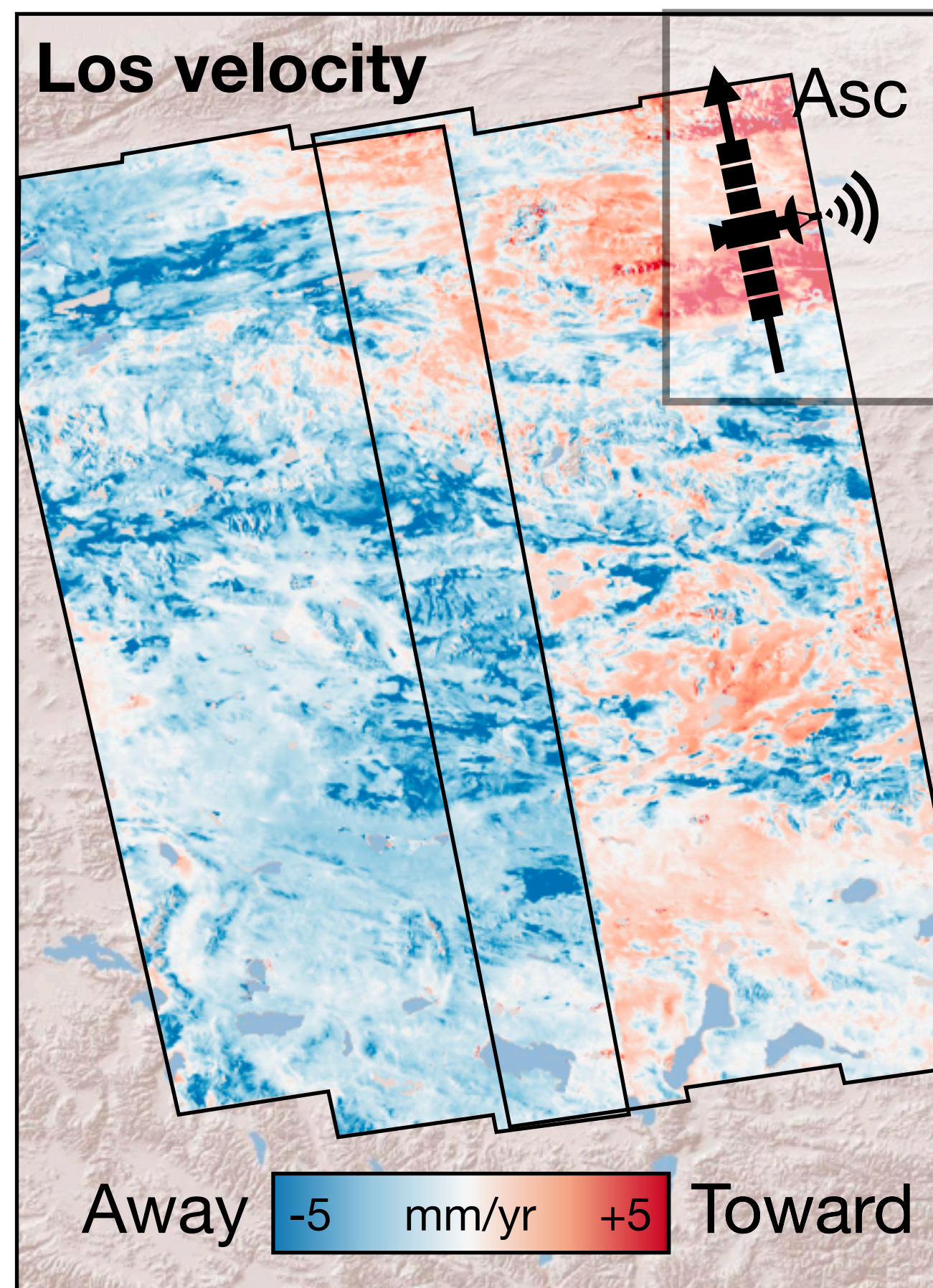


Overweighting
the long temporal
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3/ Adjusting all tracks to a common reference frame

Temporal decomposition

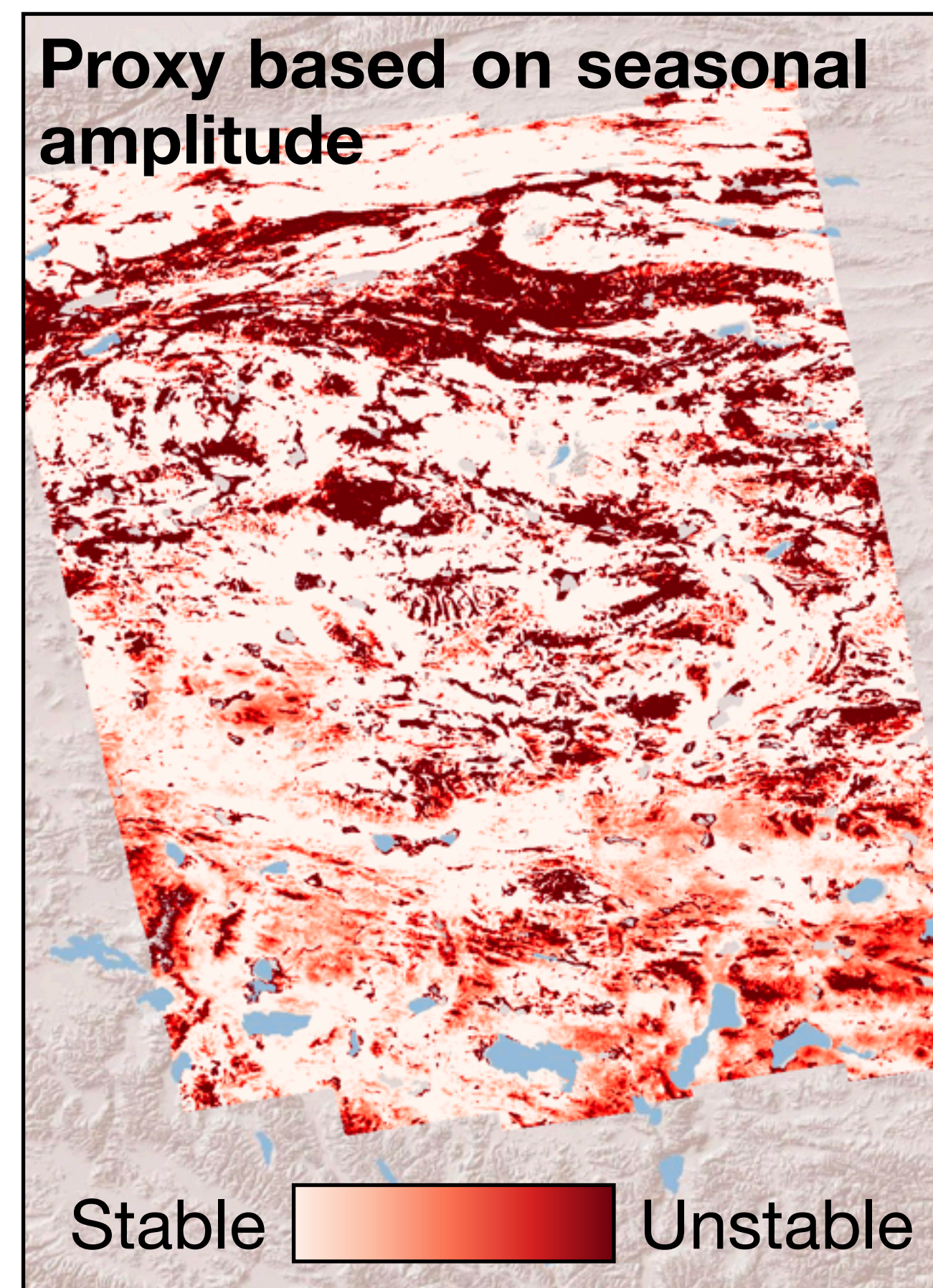
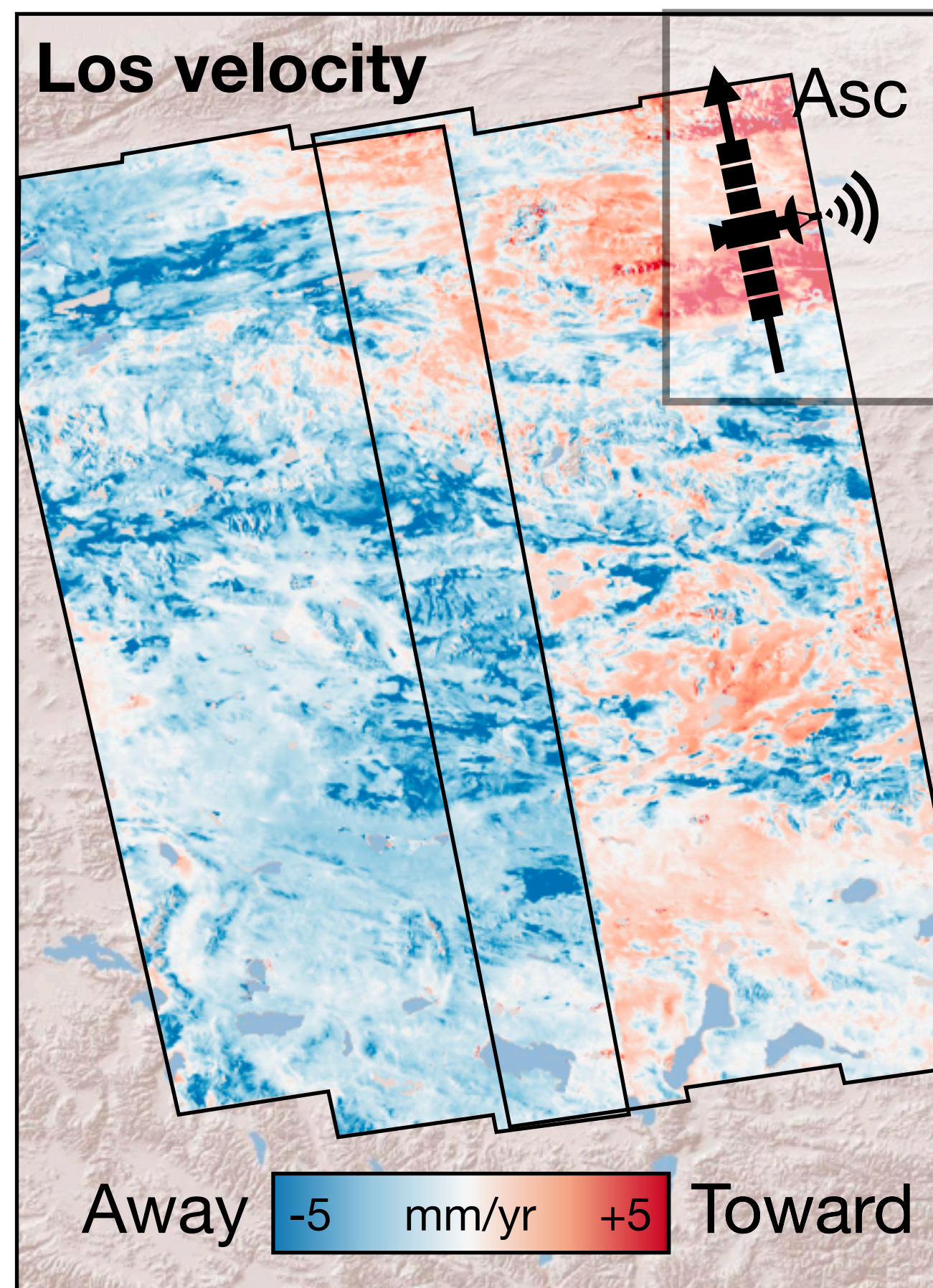
$$\text{Los}(t) = a \cdot t + b + c \cos(\omega t) + d \sin(\omega t)$$



3/ Adjusting all tracks to a common reference frame

Temporal decomposition

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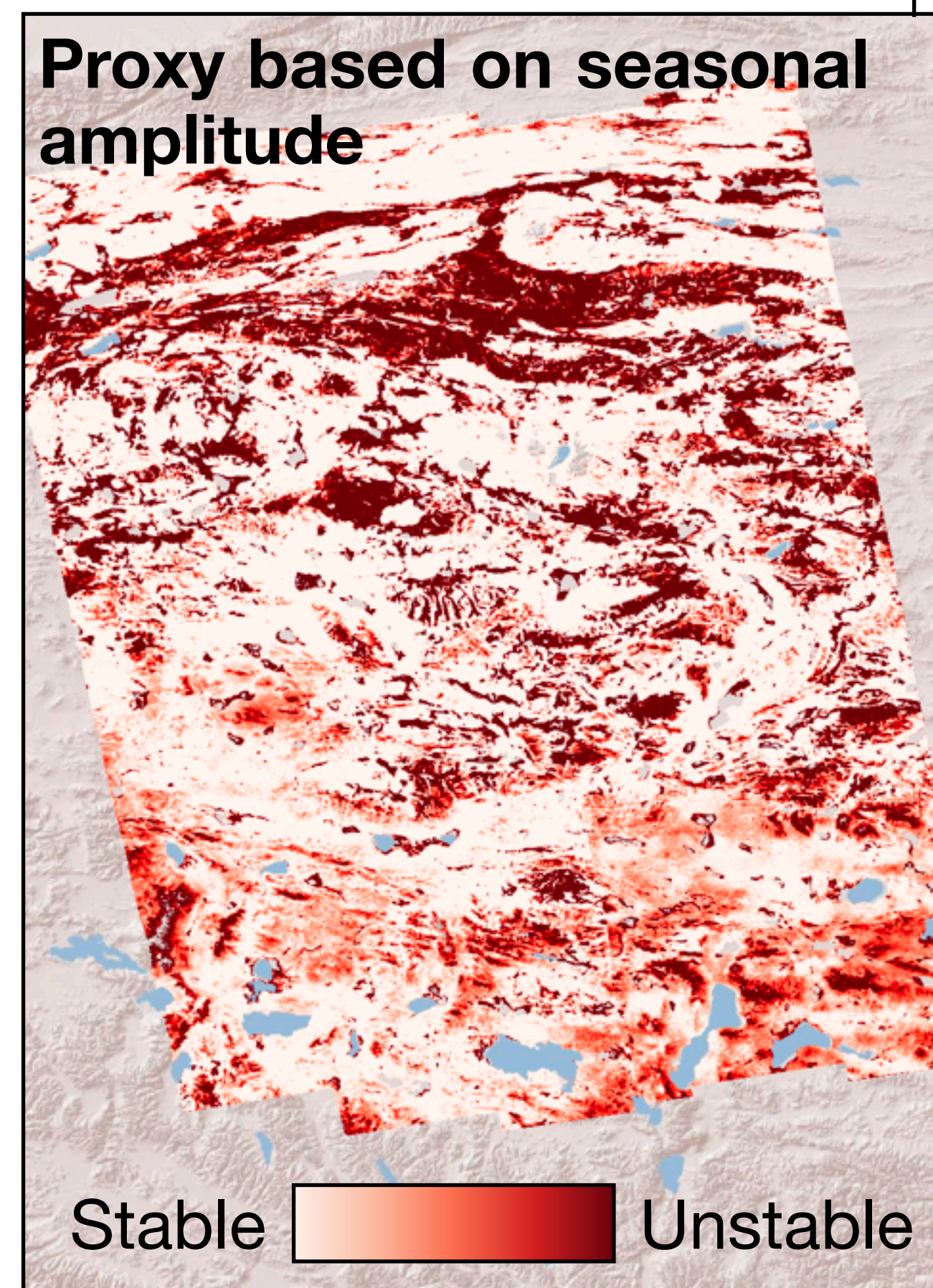
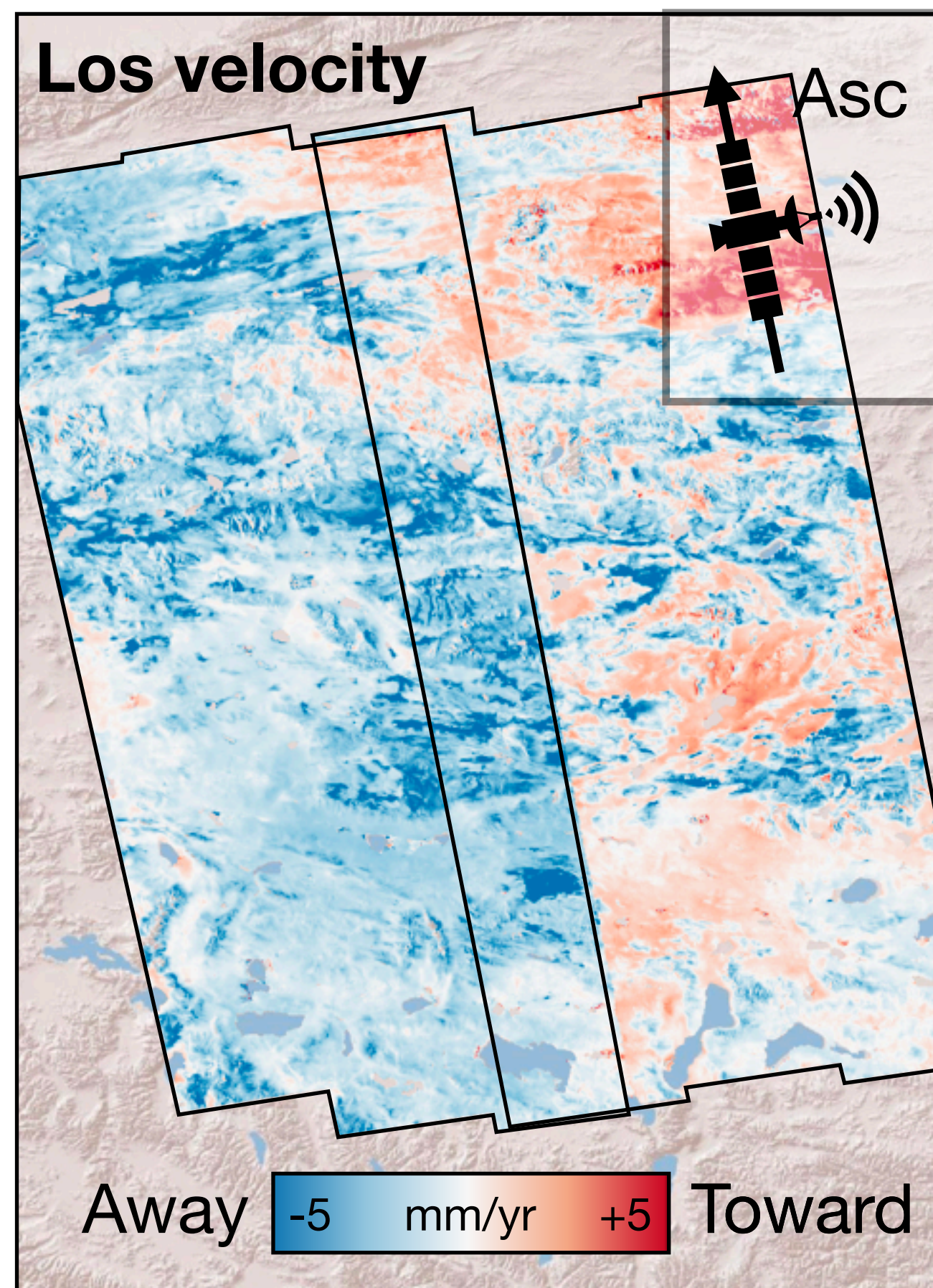


3/ Adjusting all tracks to a common reference frame

Temporal decomposition

$$\text{Los}(t) = a \cdot t + b + \underbrace{c \cos(\omega t) + d \sin(\omega t)}$$

Weighted Gaussian filter on $\text{Los}(t)$ → Temporal decomposition



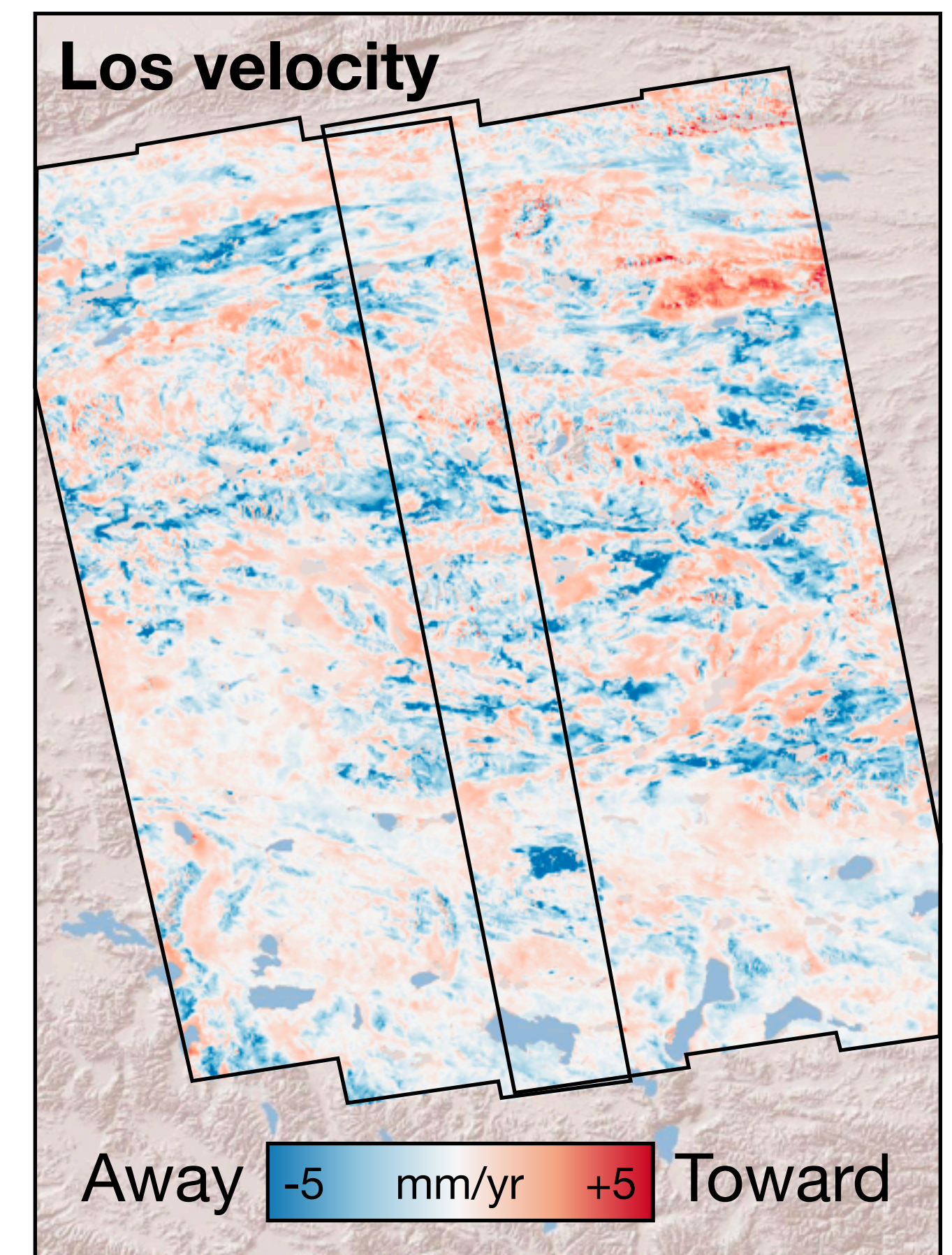
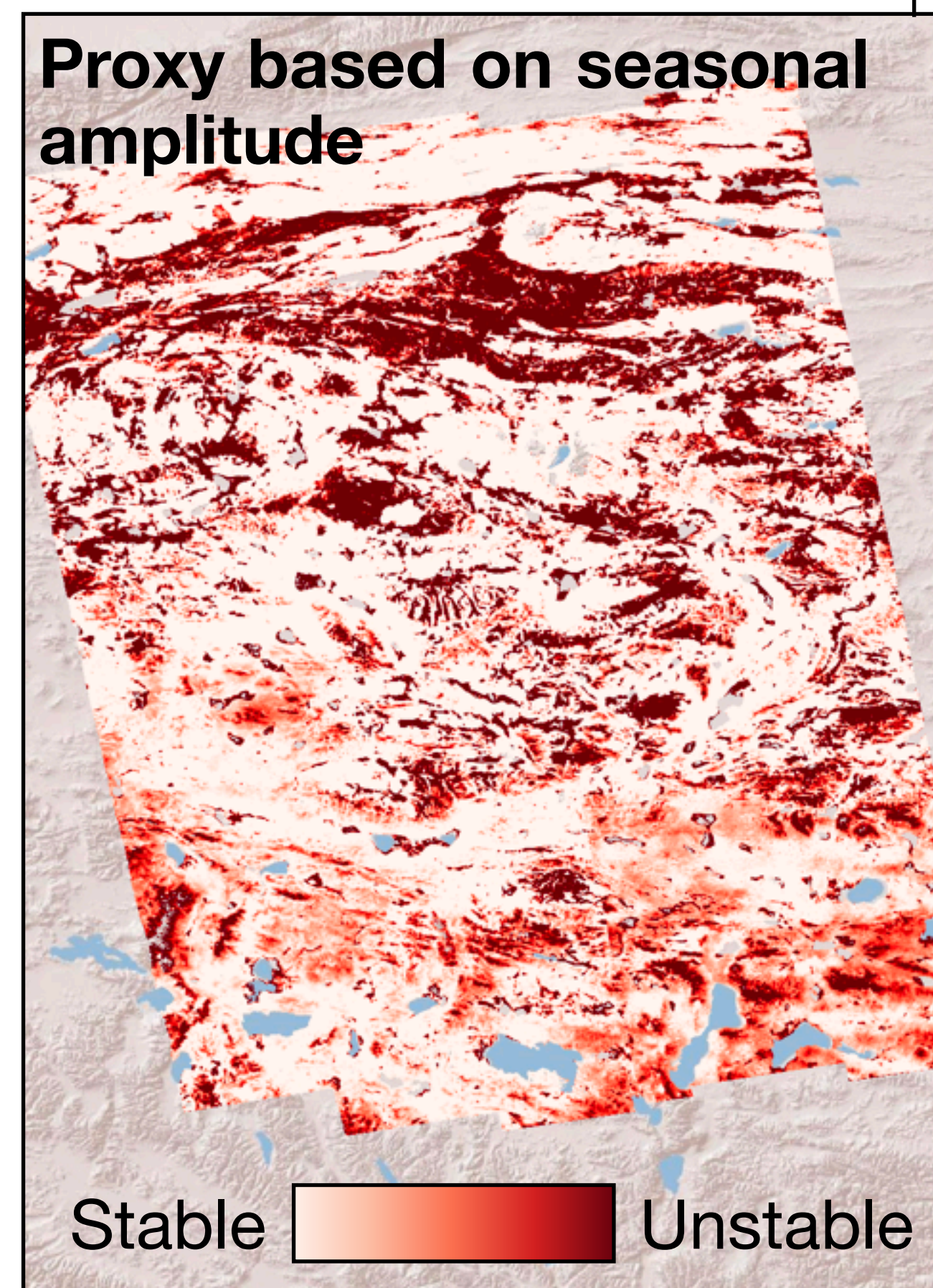
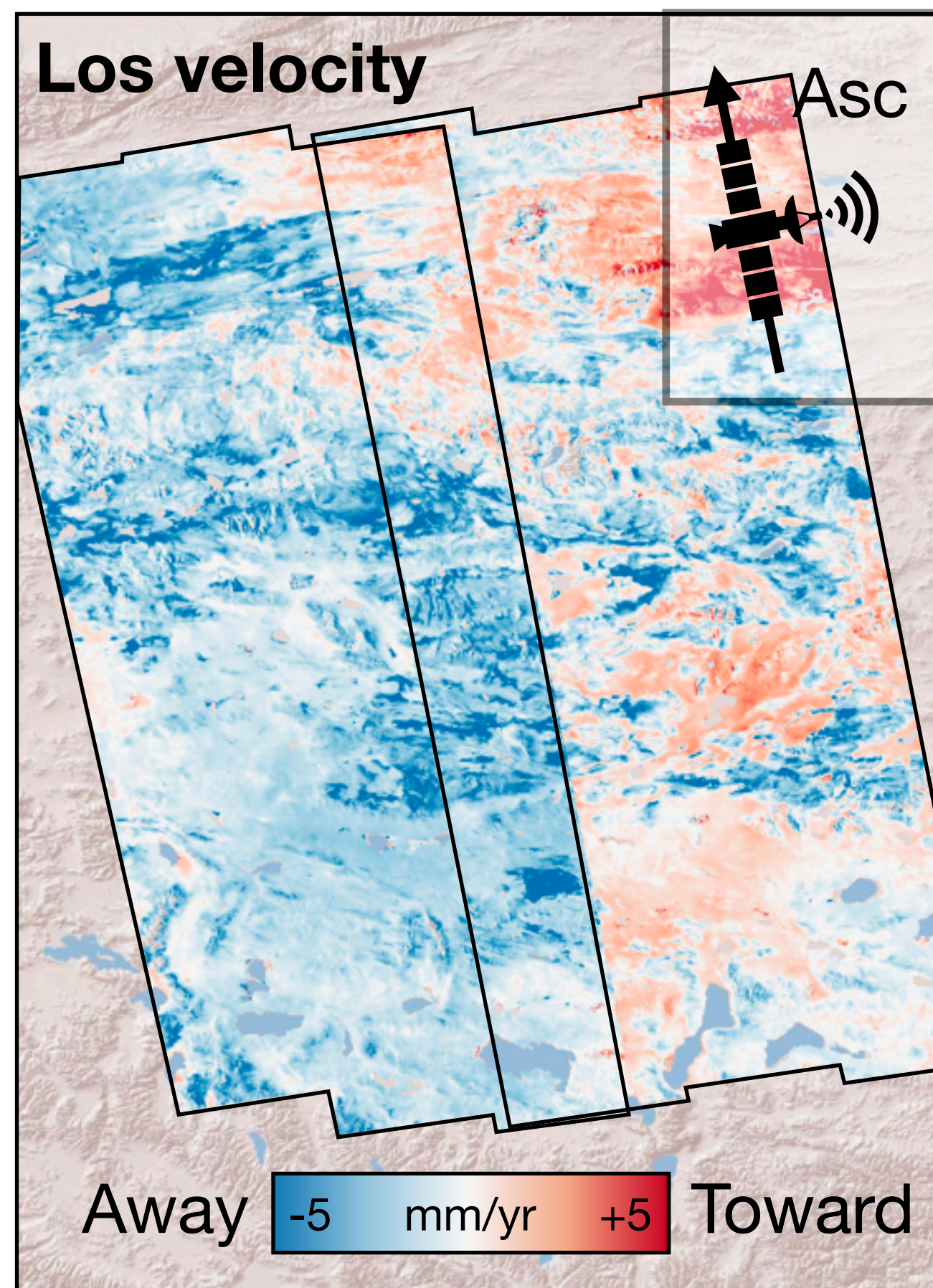
3/ Adjusting all tracks to a common reference frame

Temporal decomposition

$$\text{Los}(t) = a \cdot t + b + \underbrace{c \cos(\omega t) + d \sin(\omega t)}$$

Weighted Gaussian filter on $\text{Los}(t)$

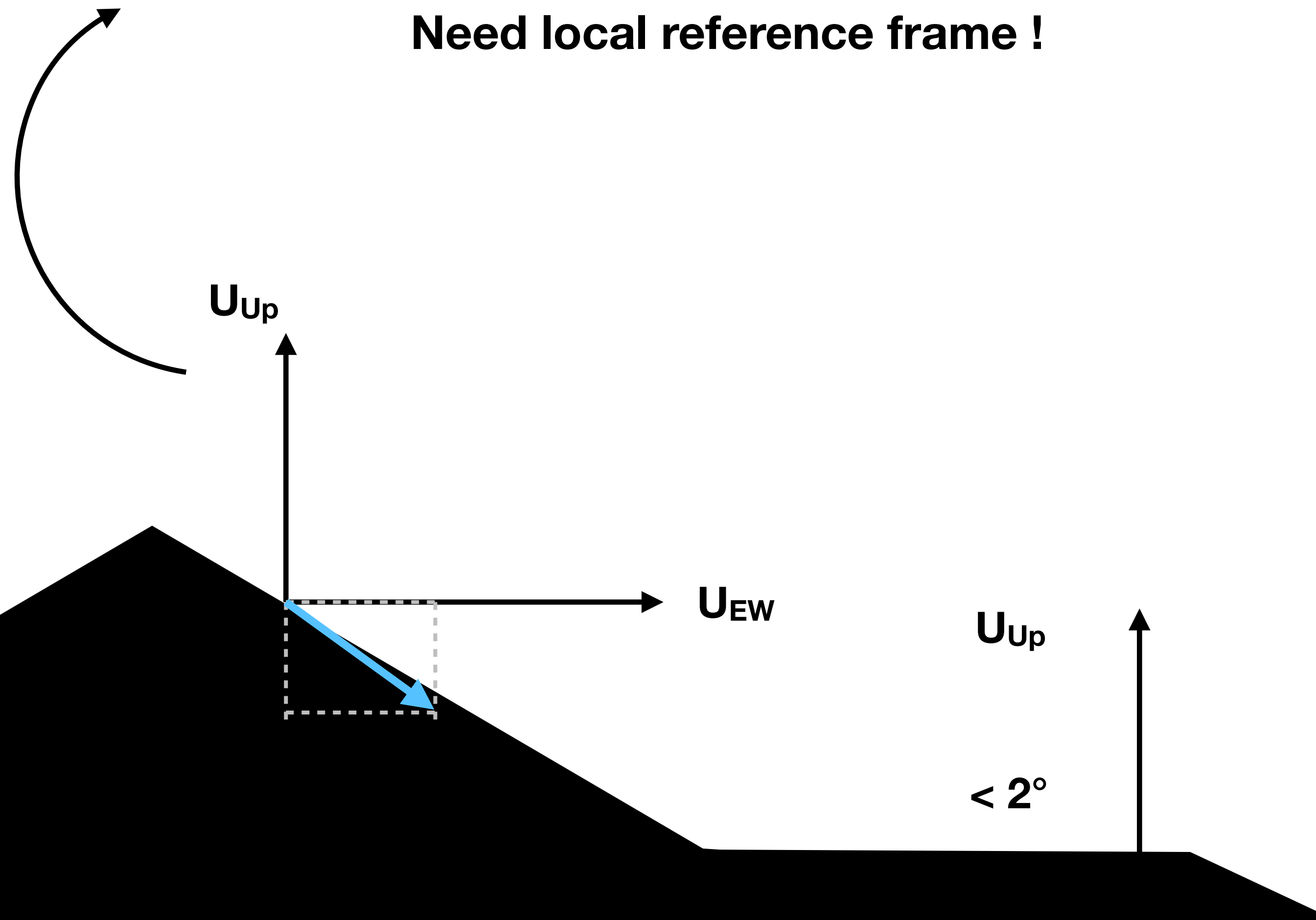
Temporal decomposition



4/ A reference frame to study slope processes

EW-Up: Introduces biases when aspect and slope vary

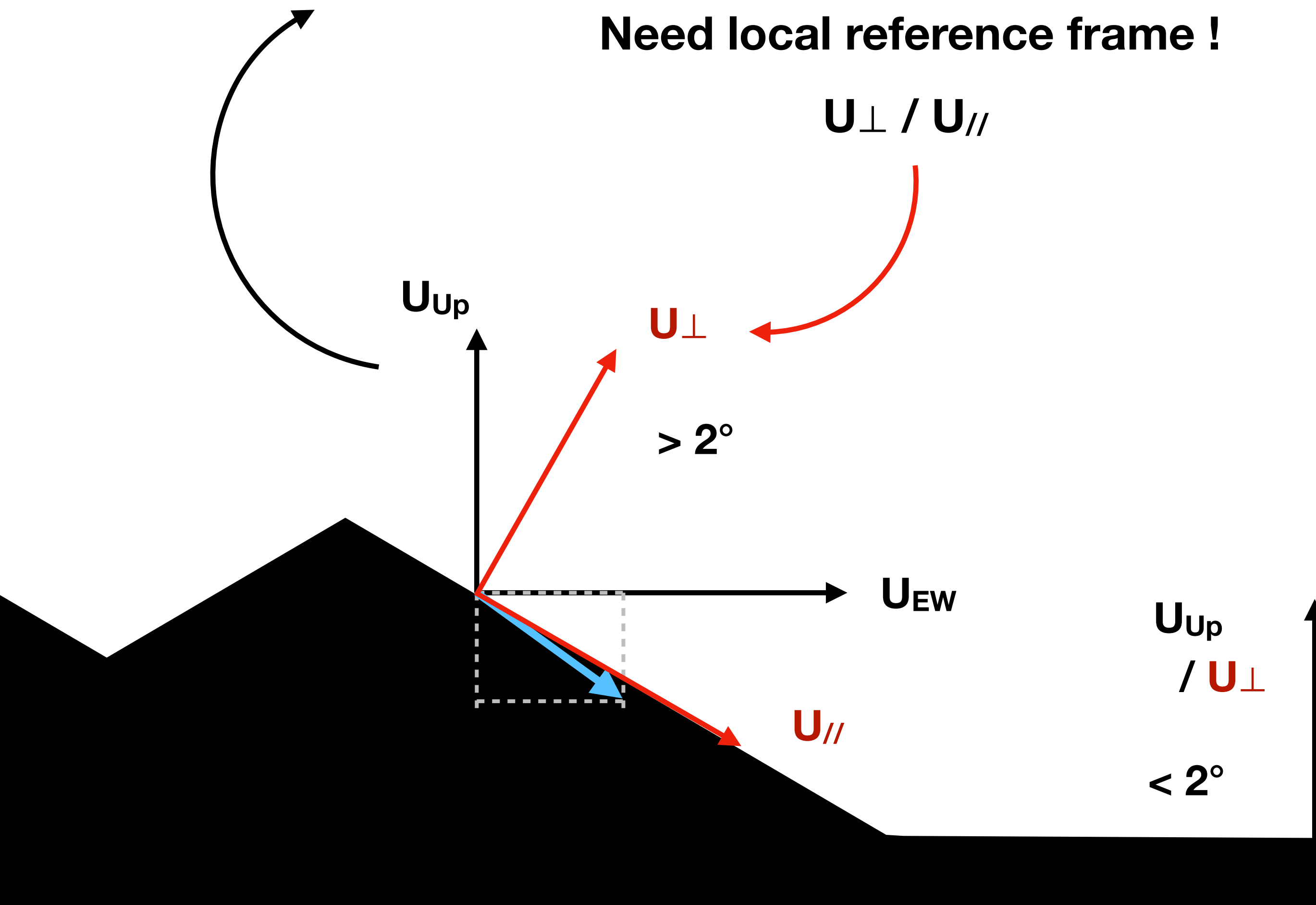
Need local reference frame !



4/ A reference frame to study slope processes

EW-Up: Introduces biases when aspect and slope vary

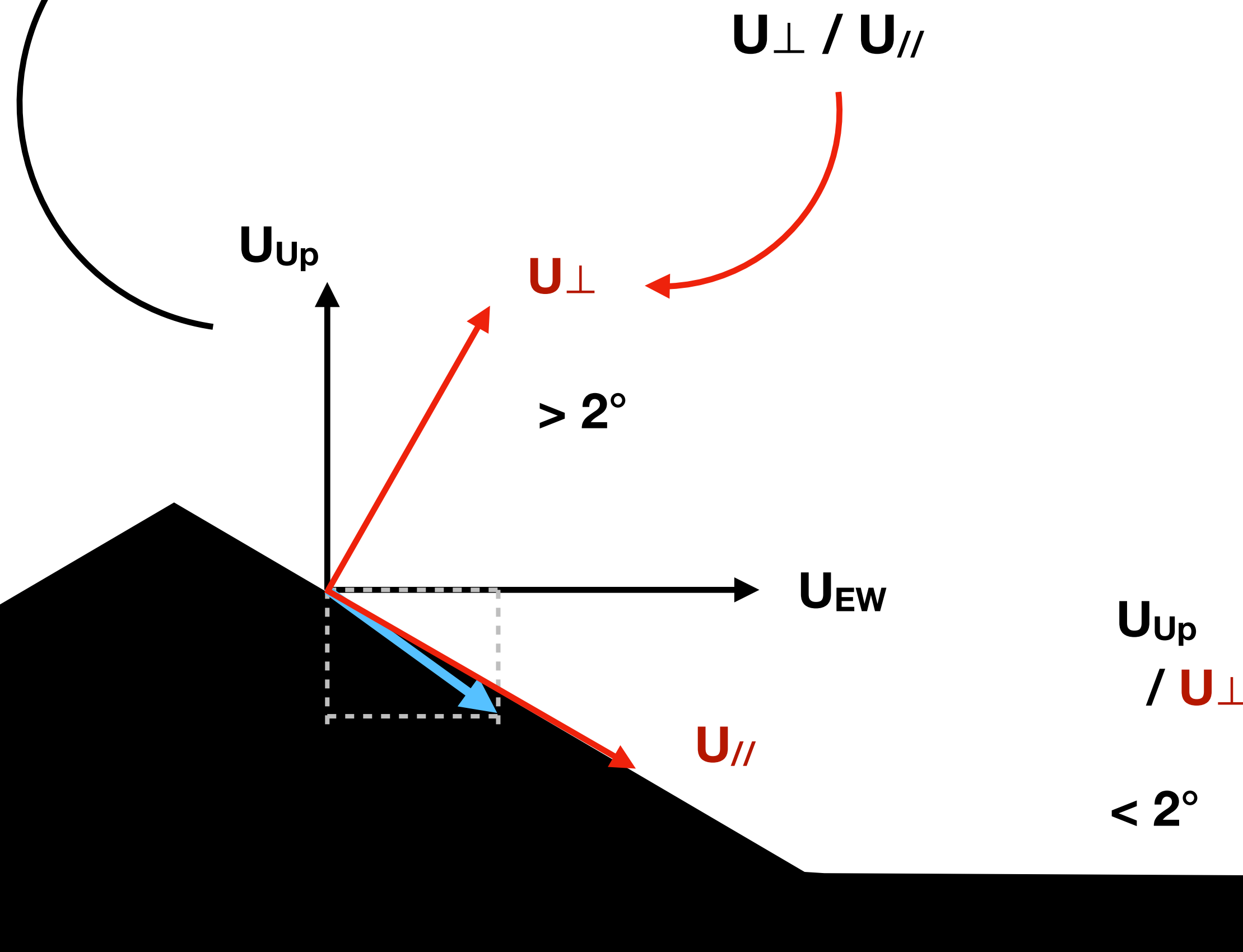
Need local reference frame !



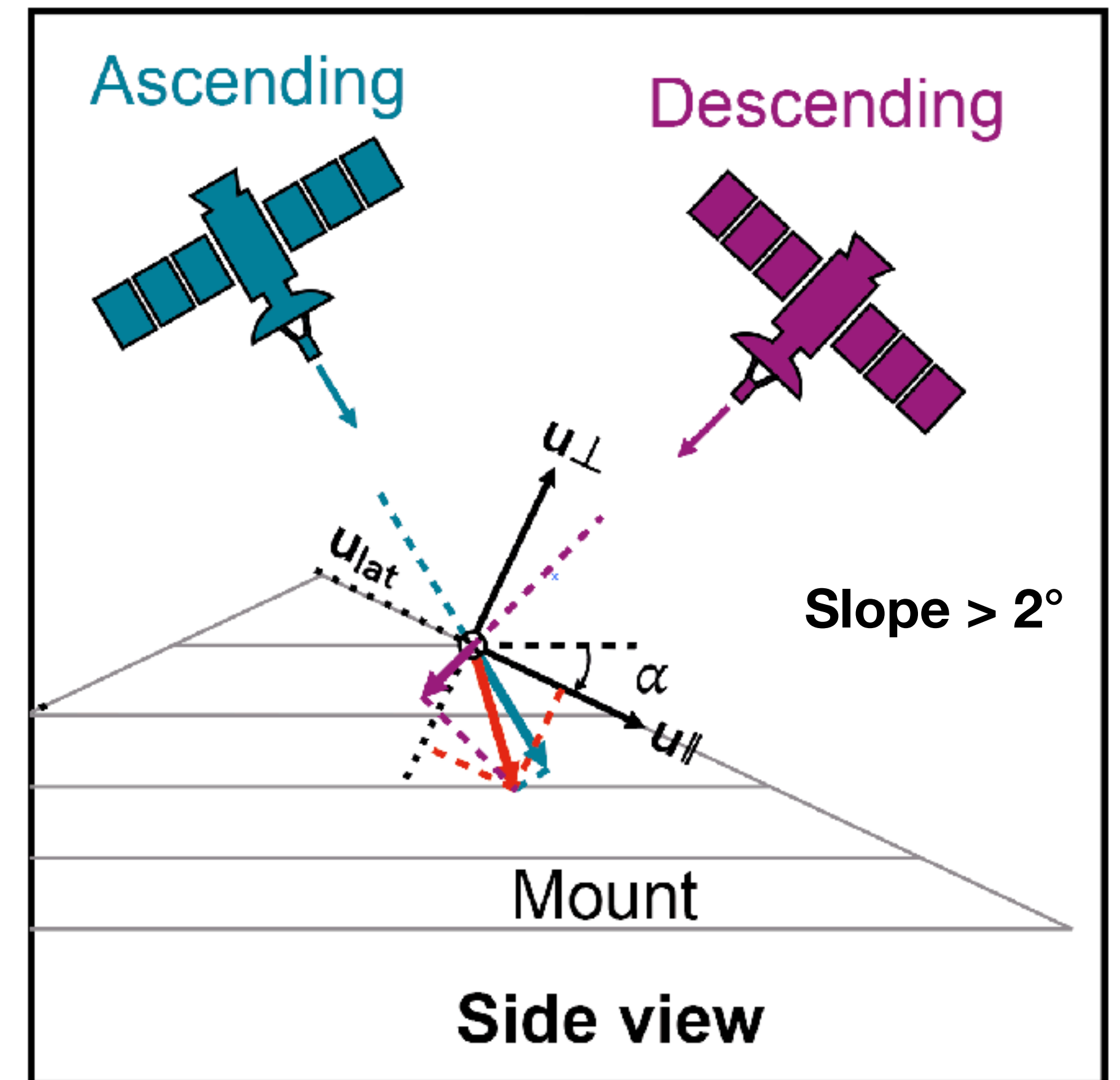
4/ A reference frame to study slope processes

EW-Up: Introduces biases when aspect and slope vary

Need local reference frame !

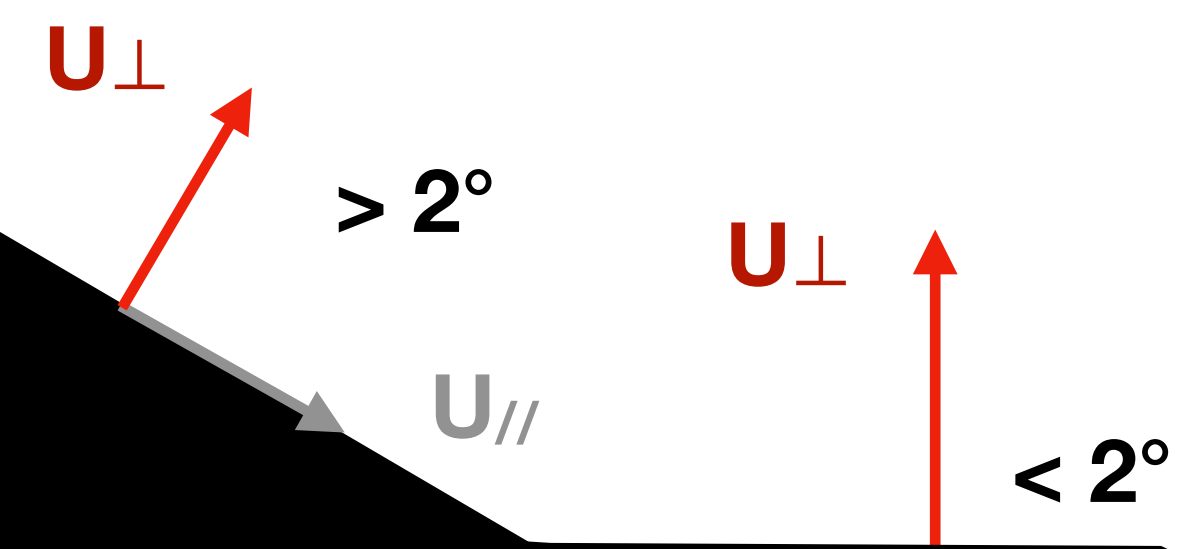
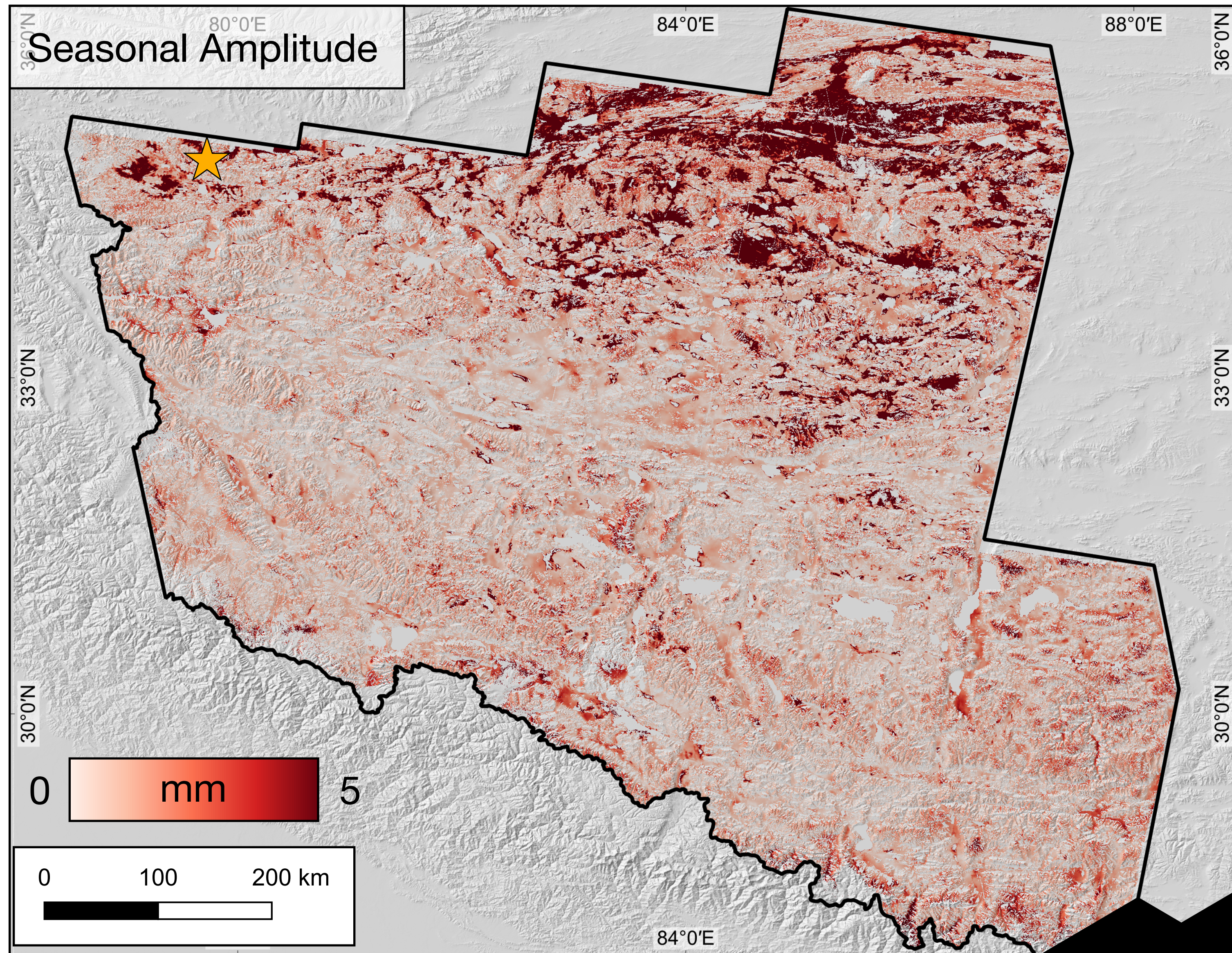


$$\begin{pmatrix} a_{asc} \\ a_{dsc} \end{pmatrix} = \mathbf{Proj}_{E,N,U_p} \cdot \mathbf{R}_{aspect} \cdot \mathbf{R}_{slope} \begin{pmatrix} a_{\parallel} \\ a_{\perp} \end{pmatrix}$$

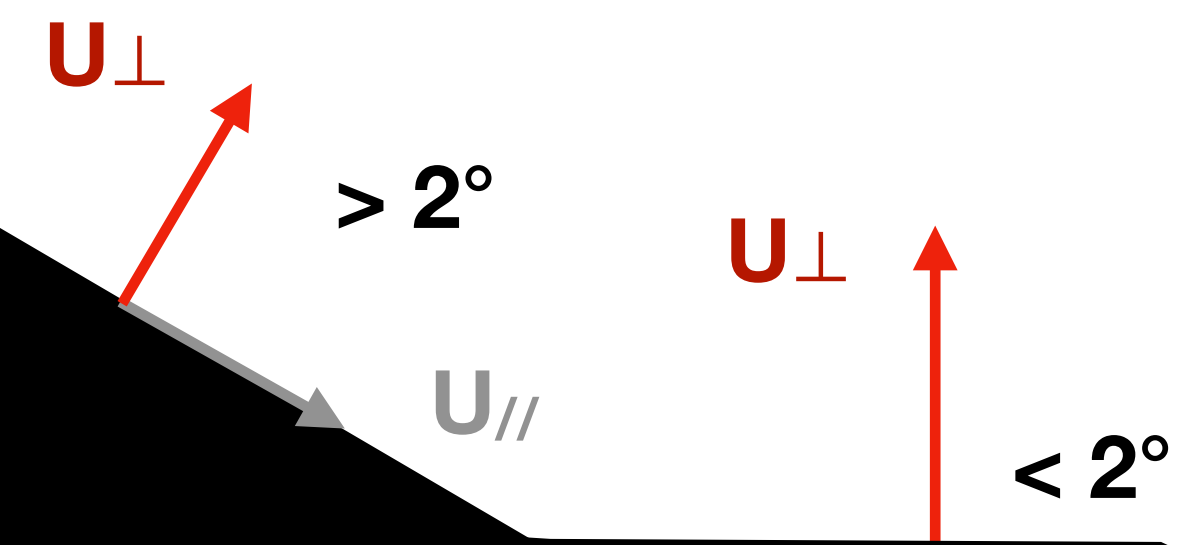
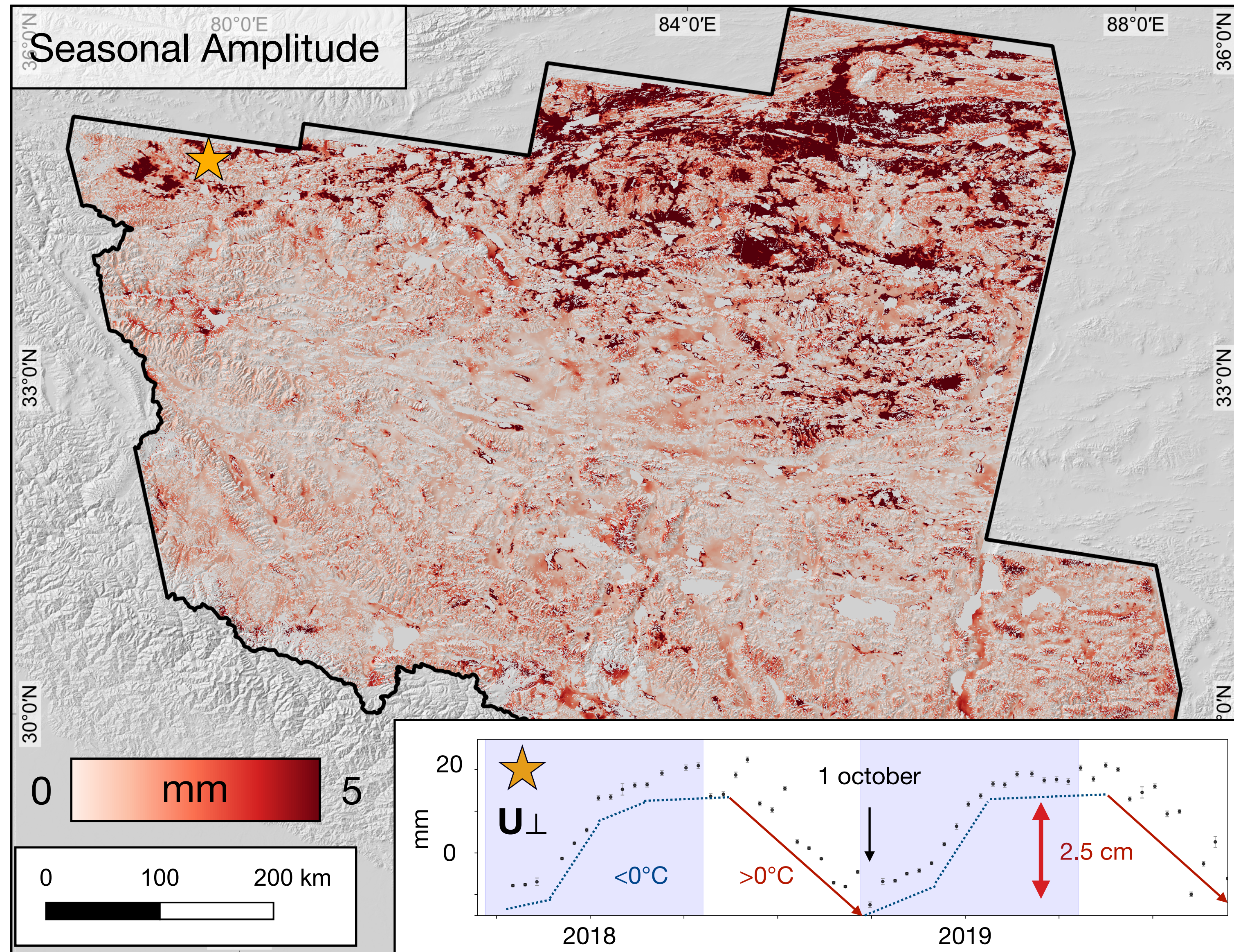


hypothesis: no lateral displacement

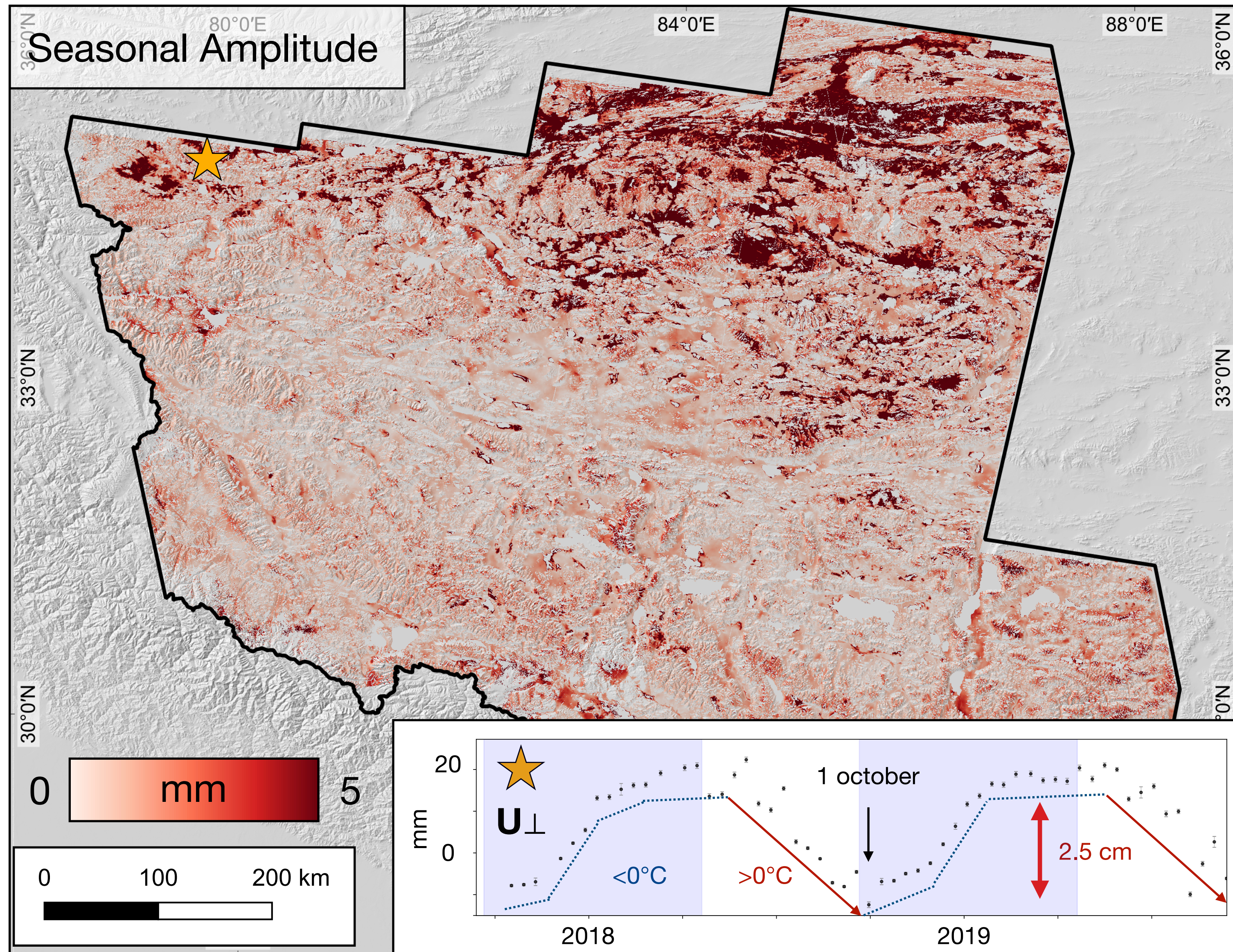
Seasonal freeze-thaw ground deformation



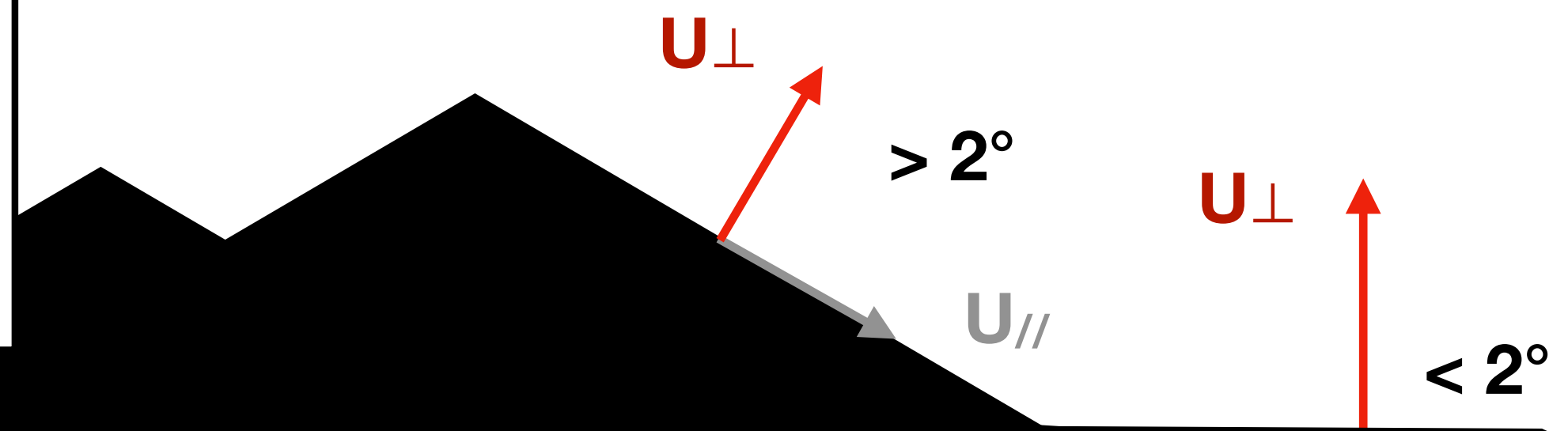
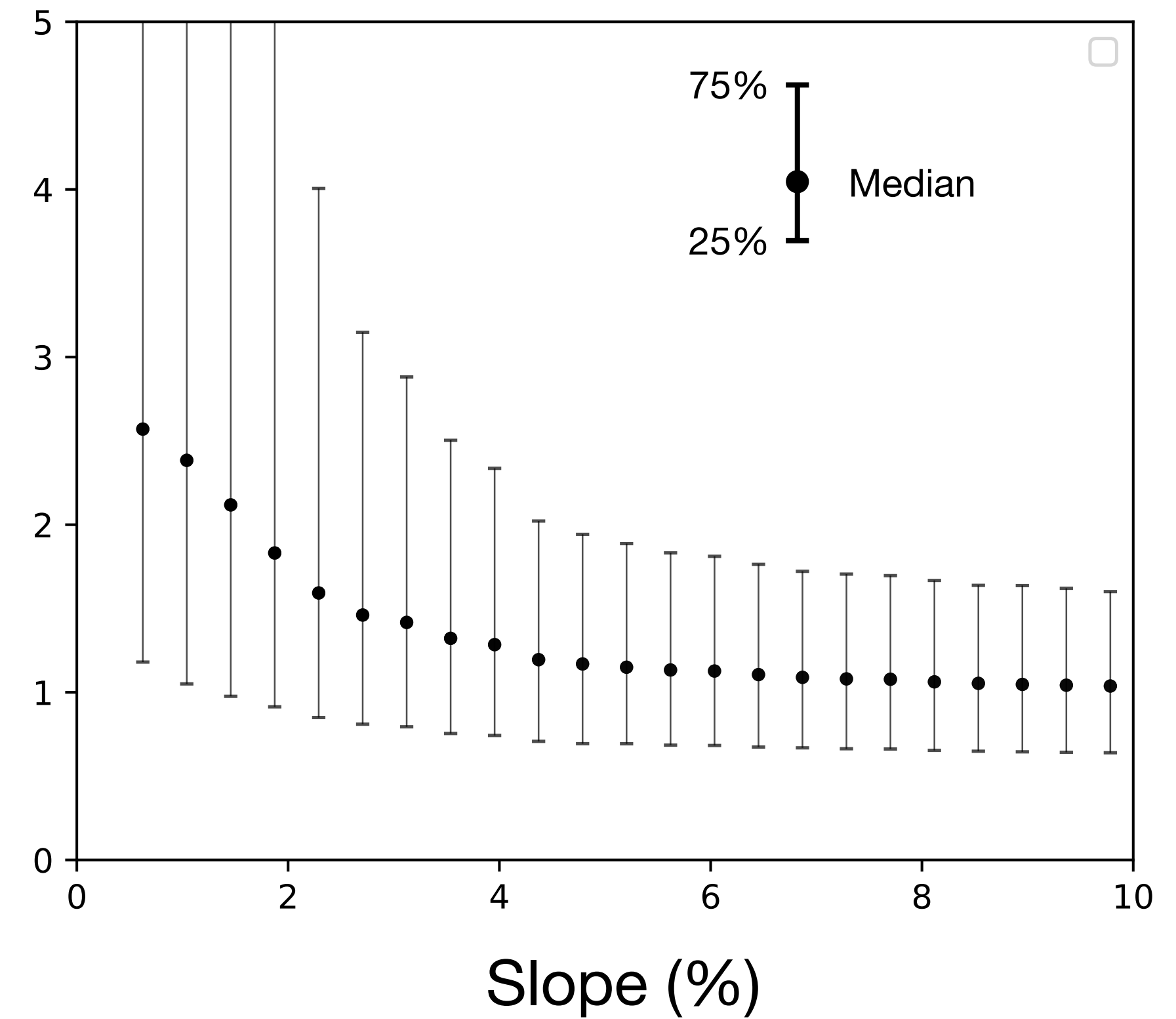
Seasonal freeze-thaw ground deformation



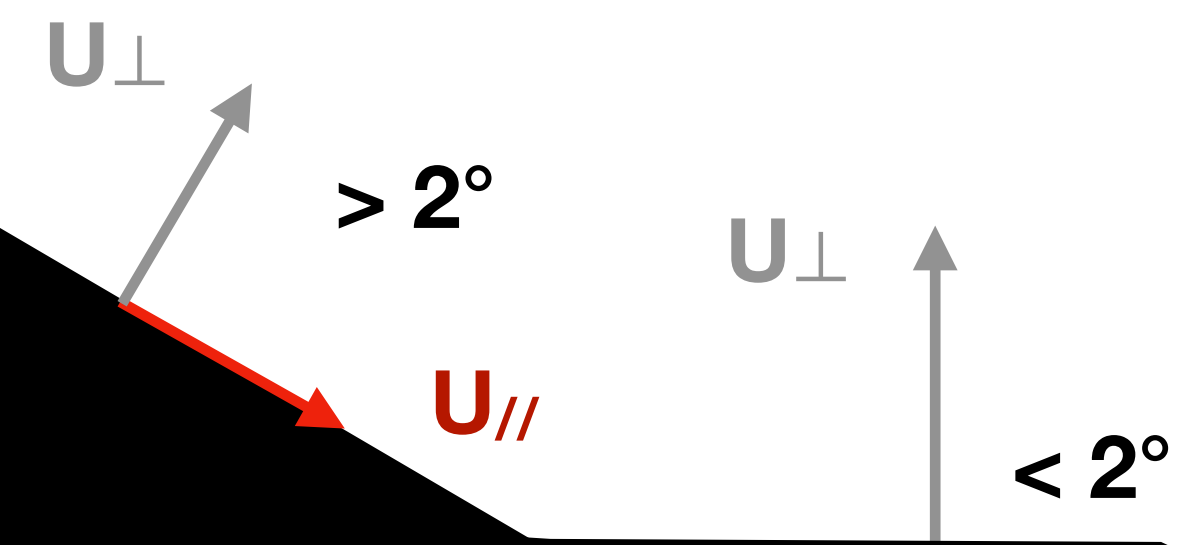
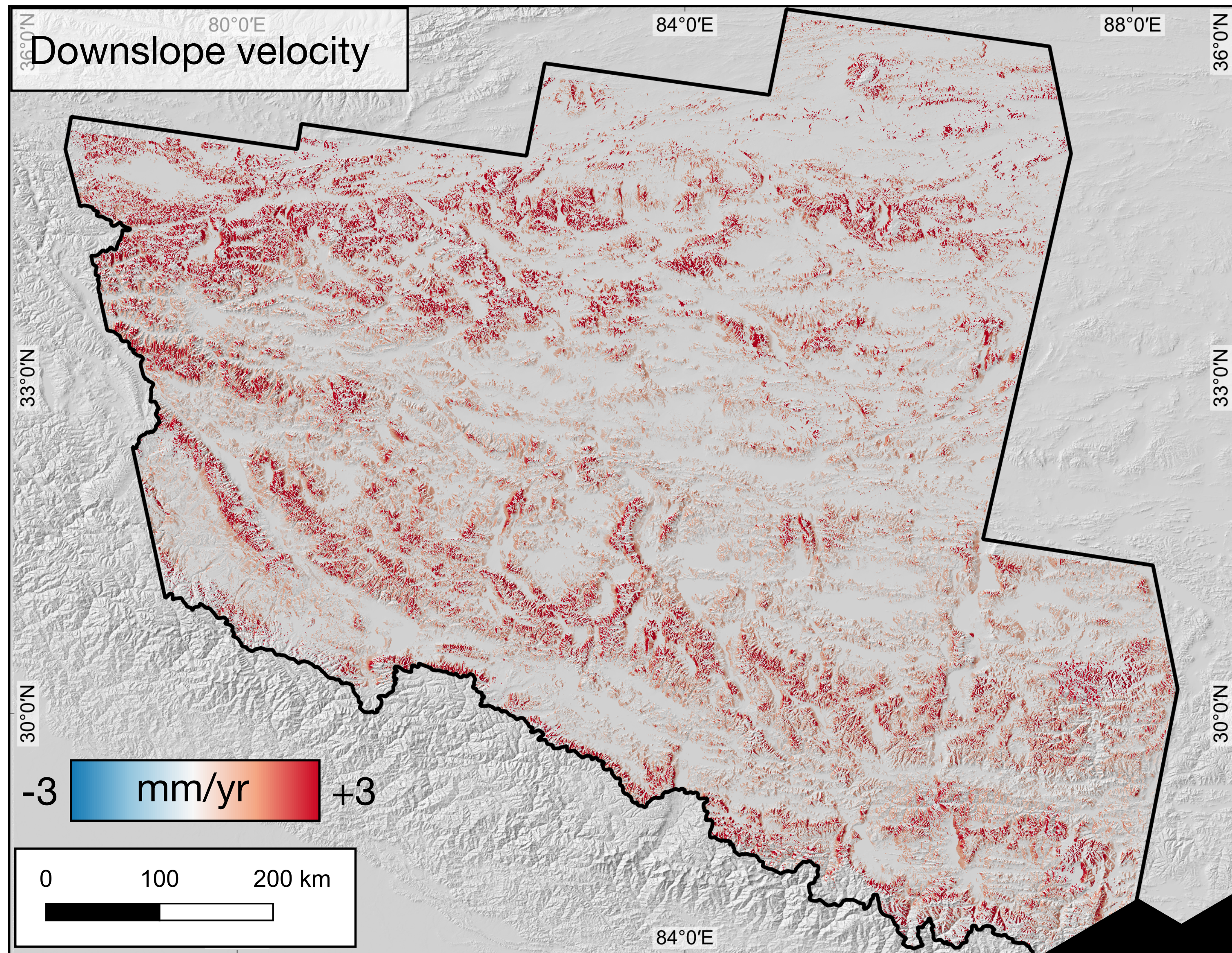
Seasonal freeze-thaw ground deformation



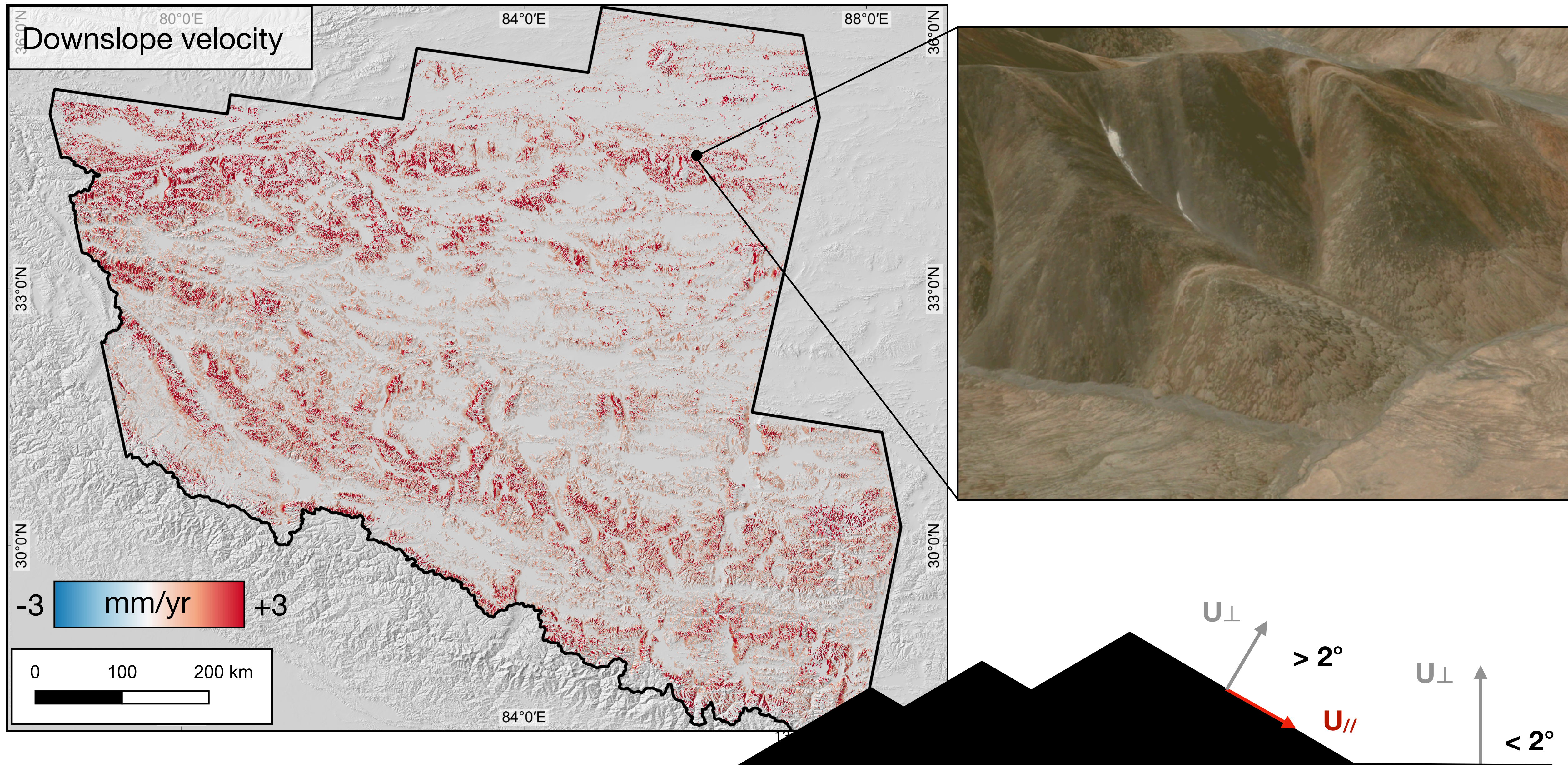
Seasonal amplitude (mm)



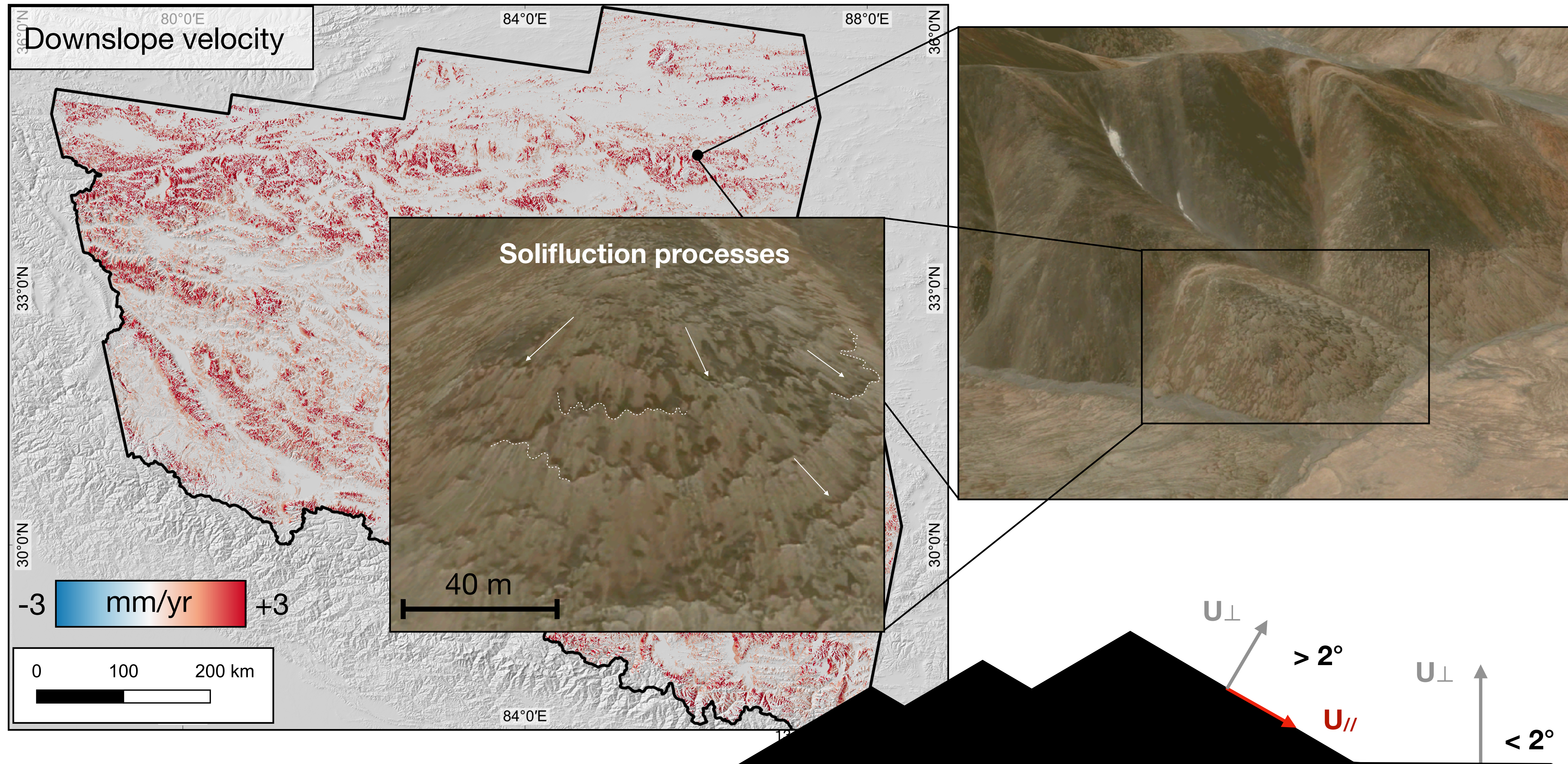
Widespread hillslope processes across the Tibetan Plateau: landforms



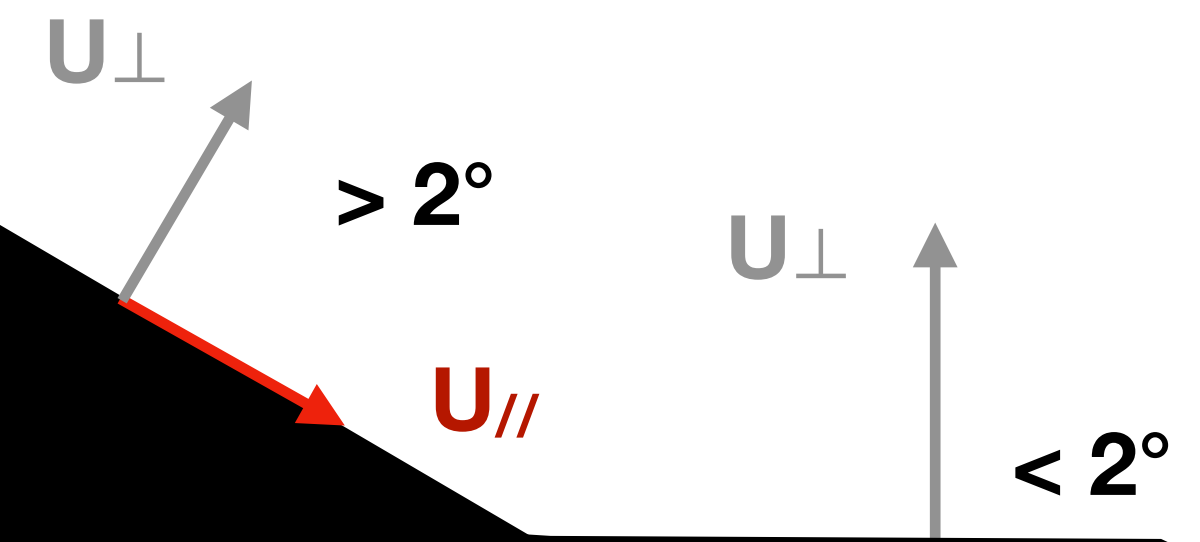
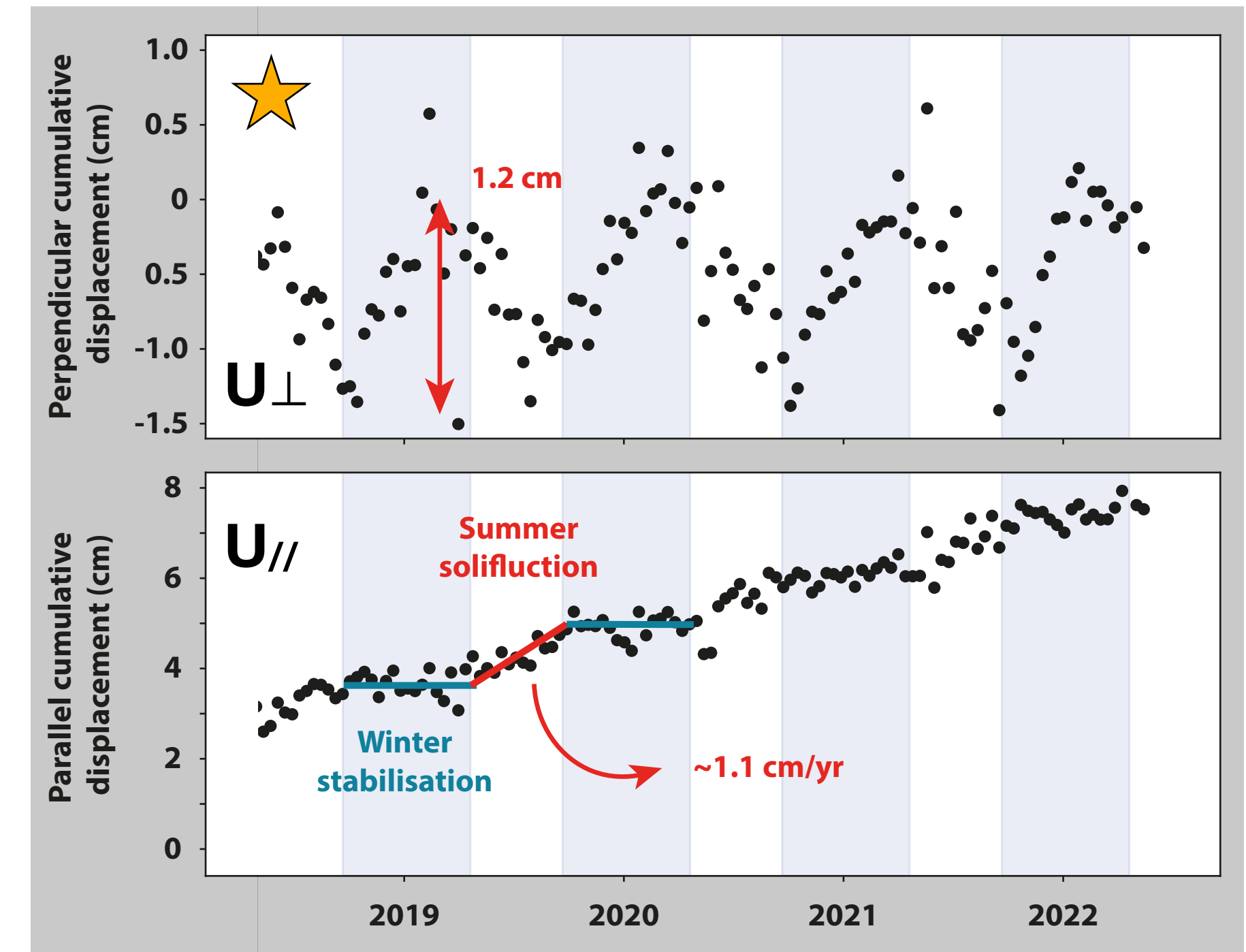
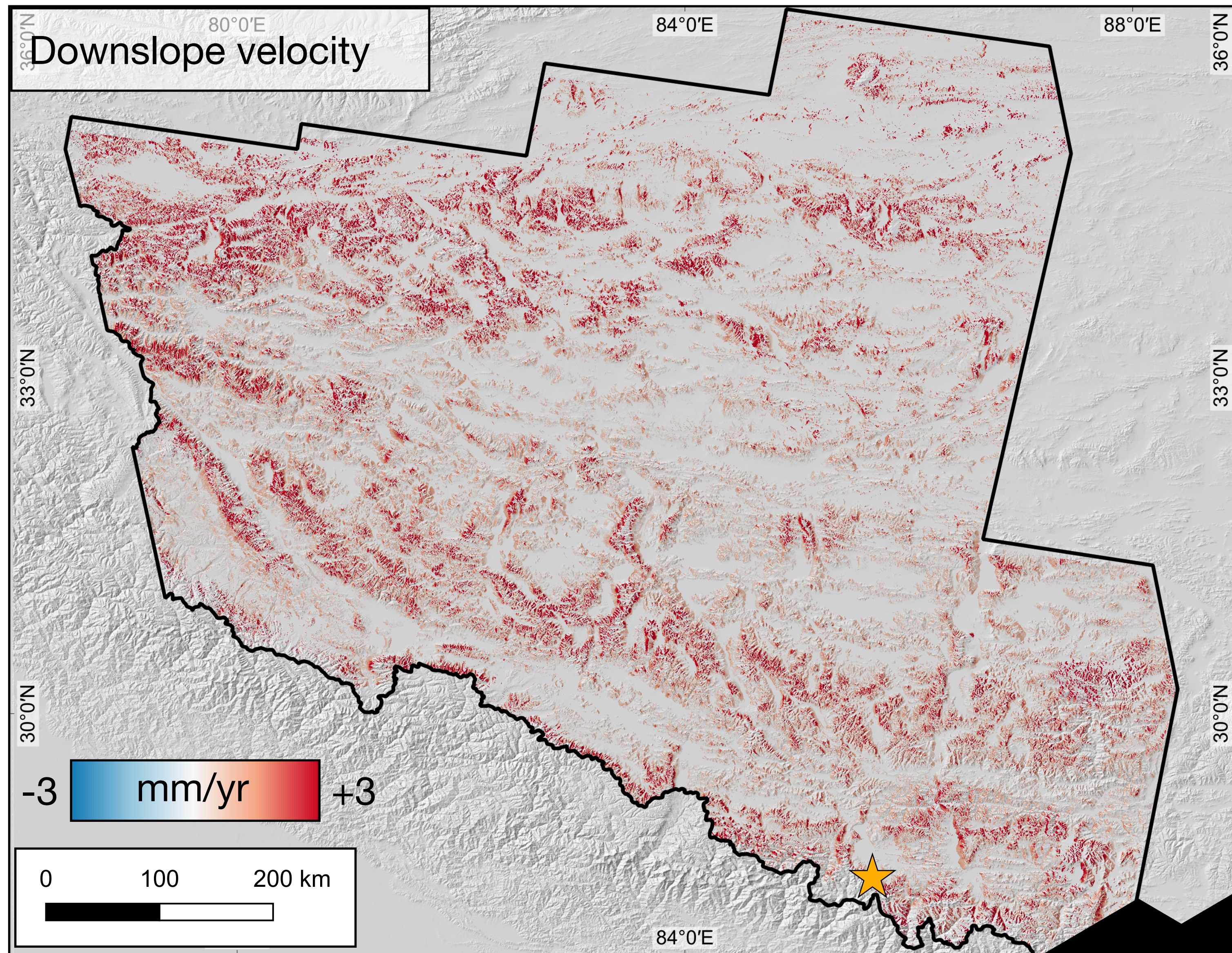
Widespread hillslope processes across the Tibetan Plateau: landforms



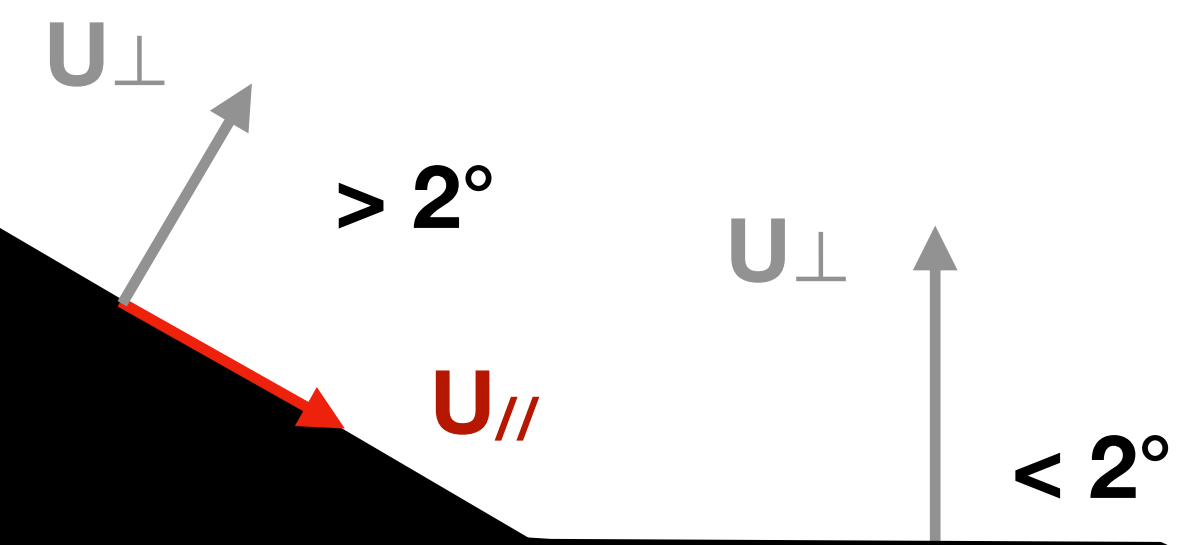
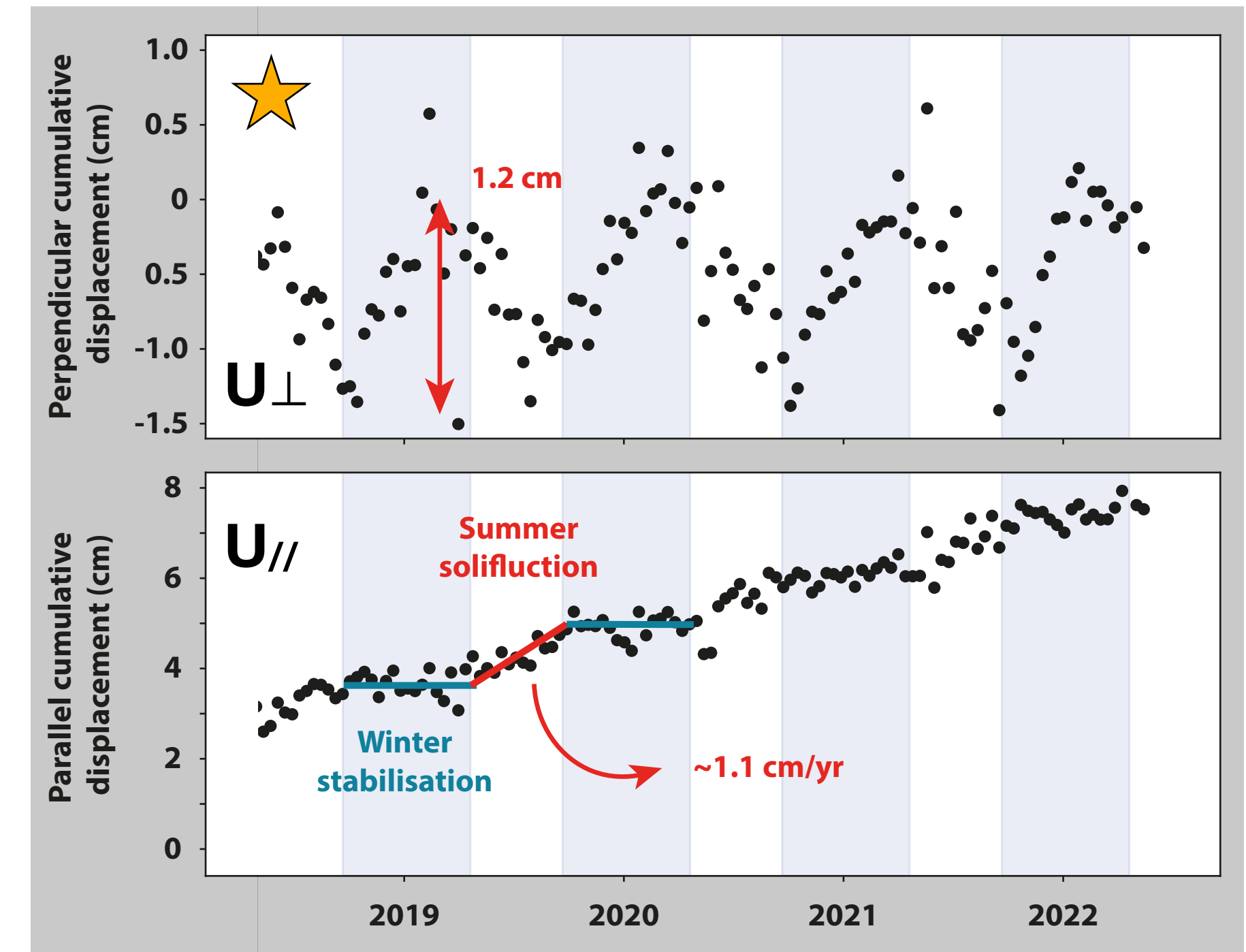
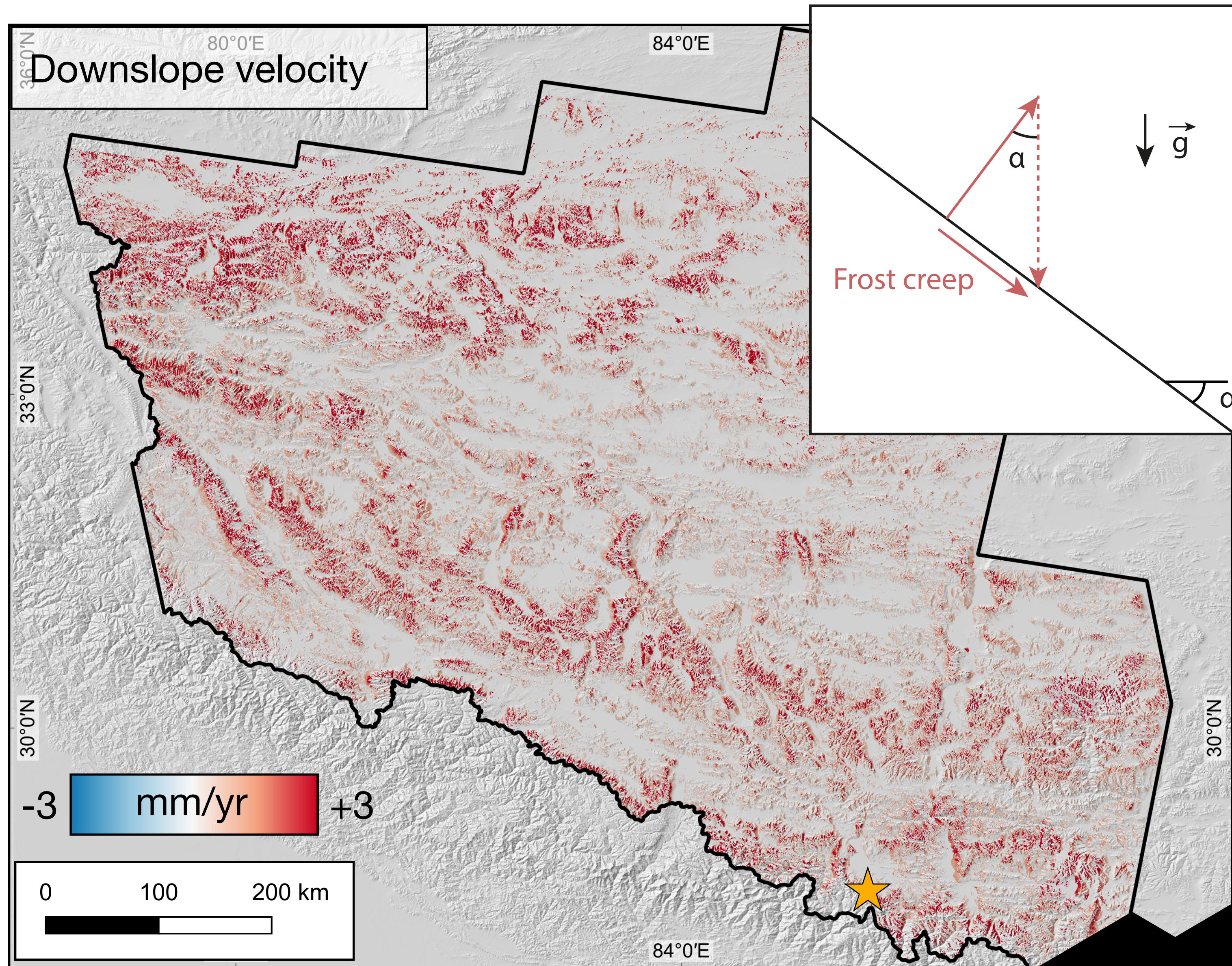
Widespread hillslope processes across the Tibetan Plateau: landforms



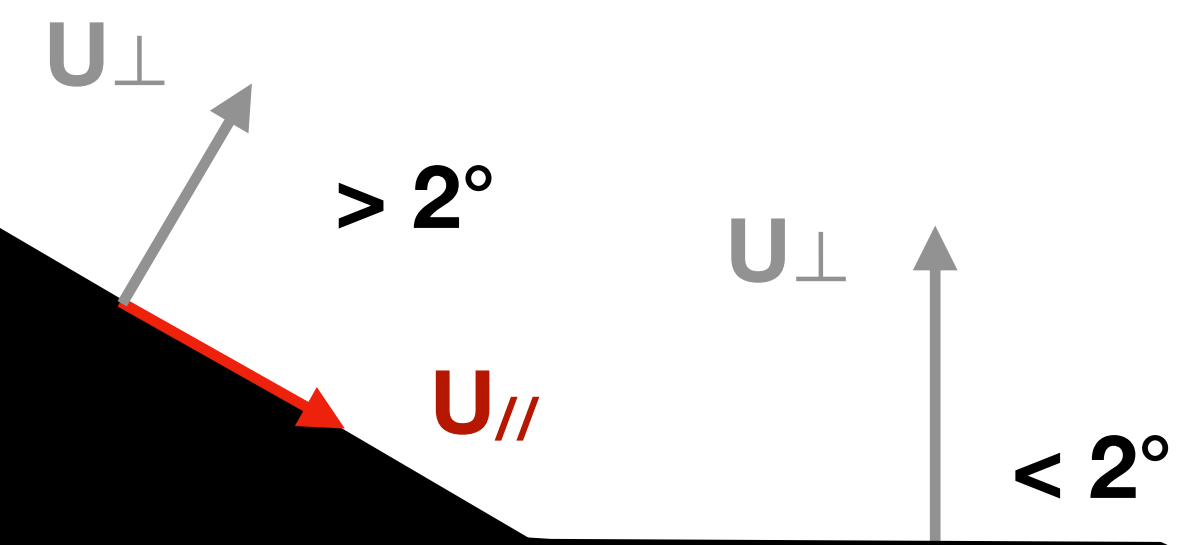
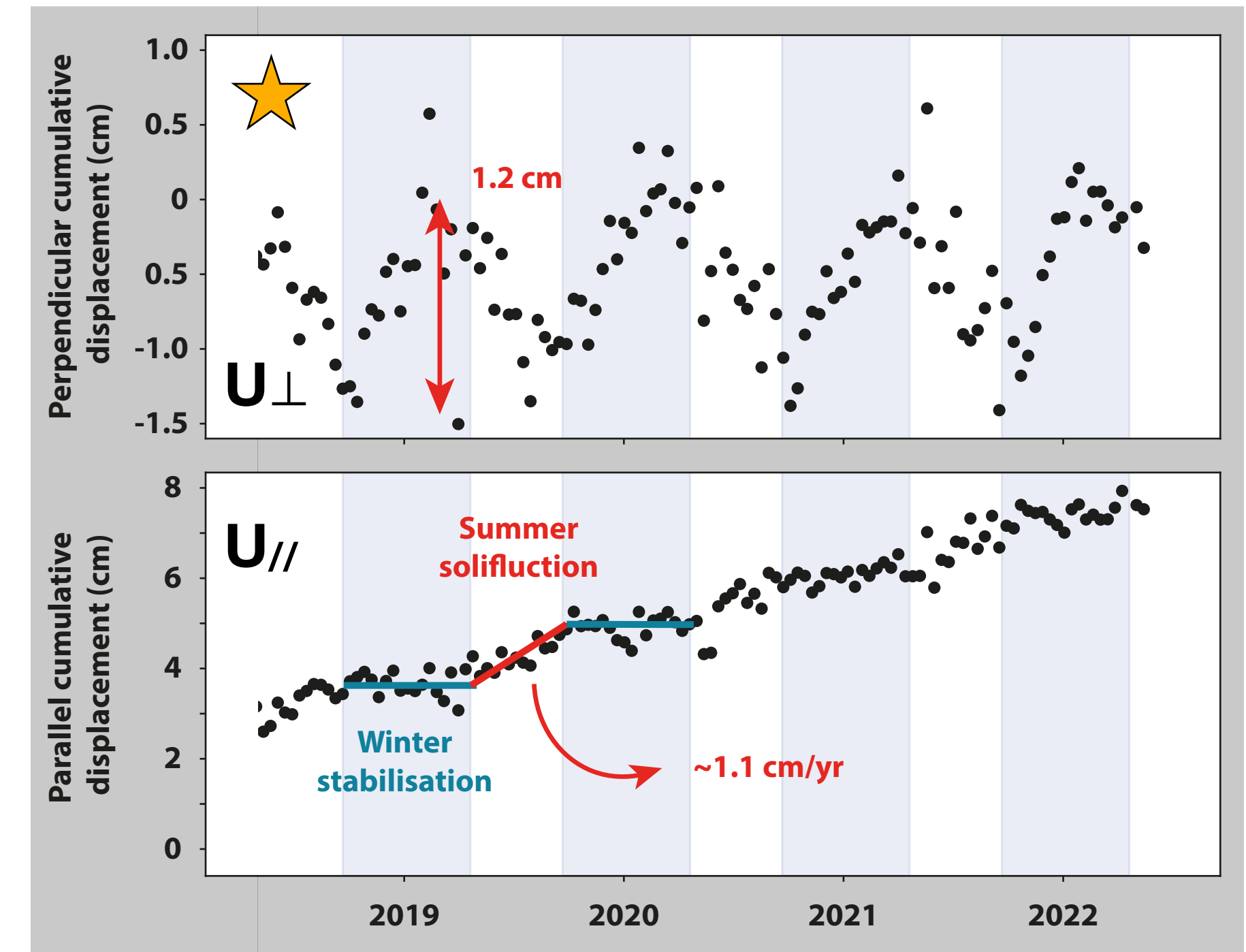
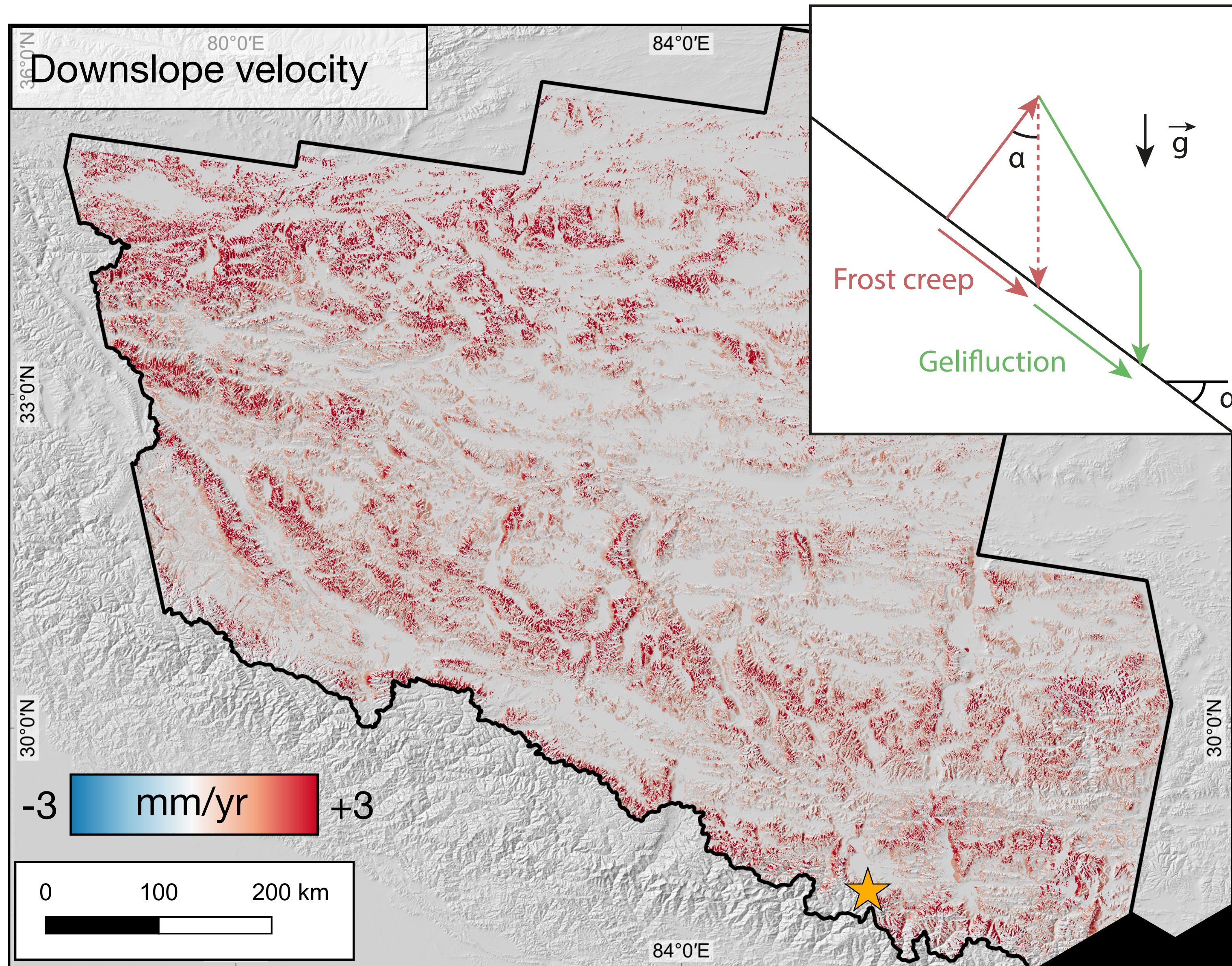
Widespread hillslope processes across the Tibetan Plateau: mechanisms



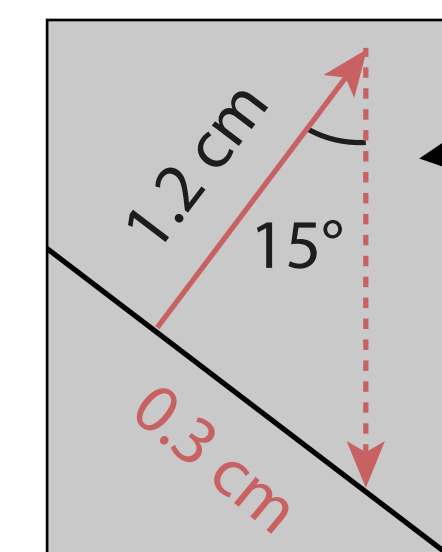
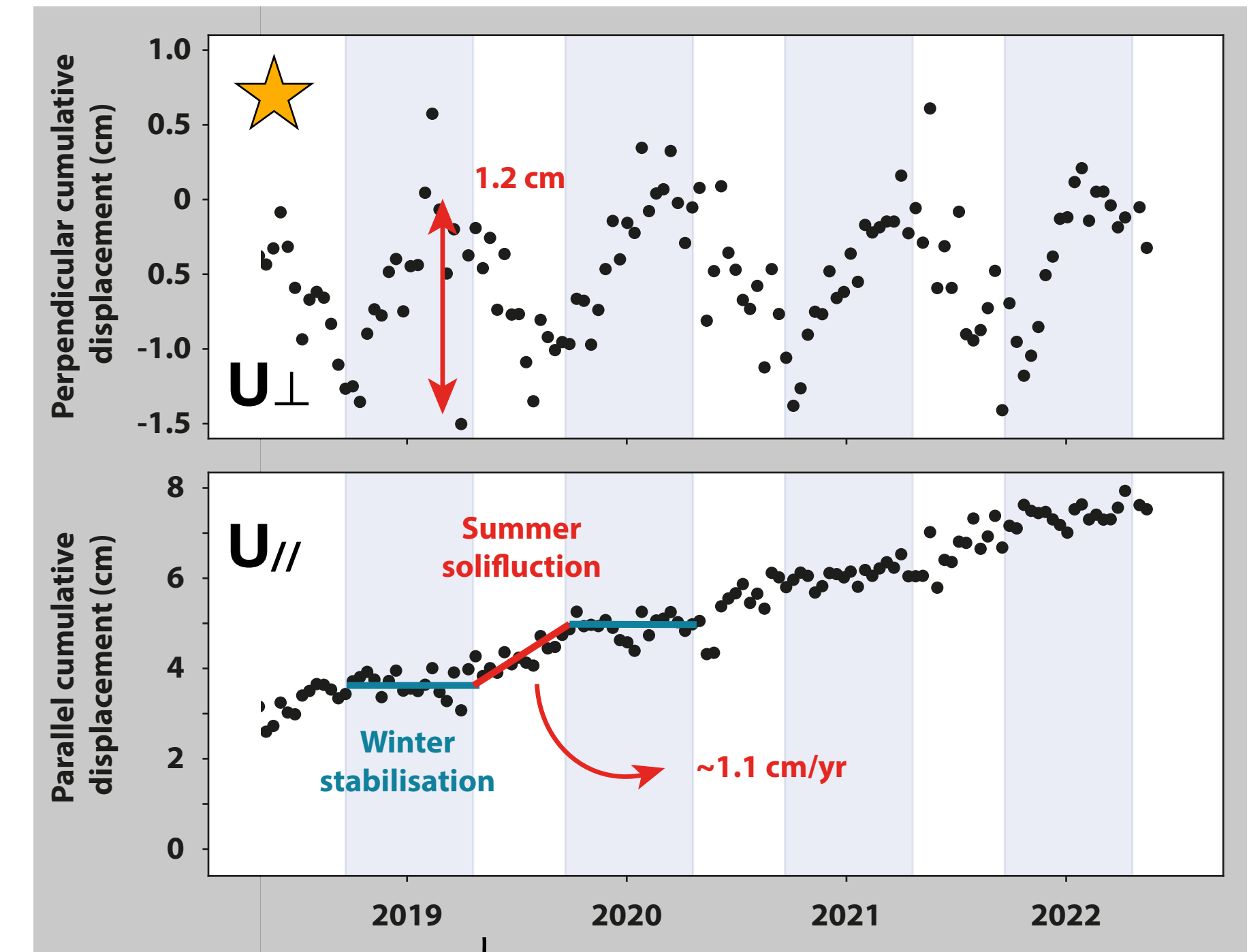
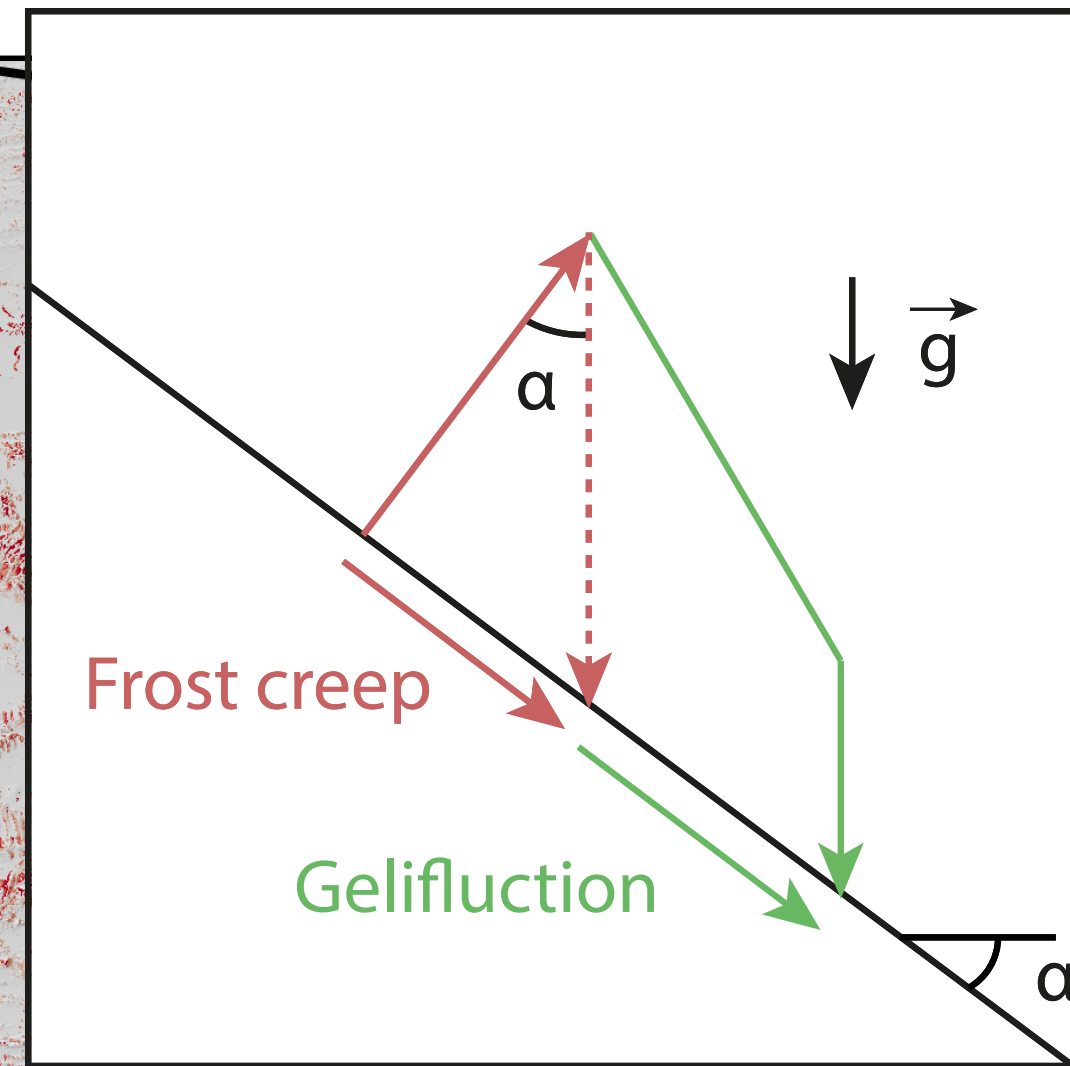
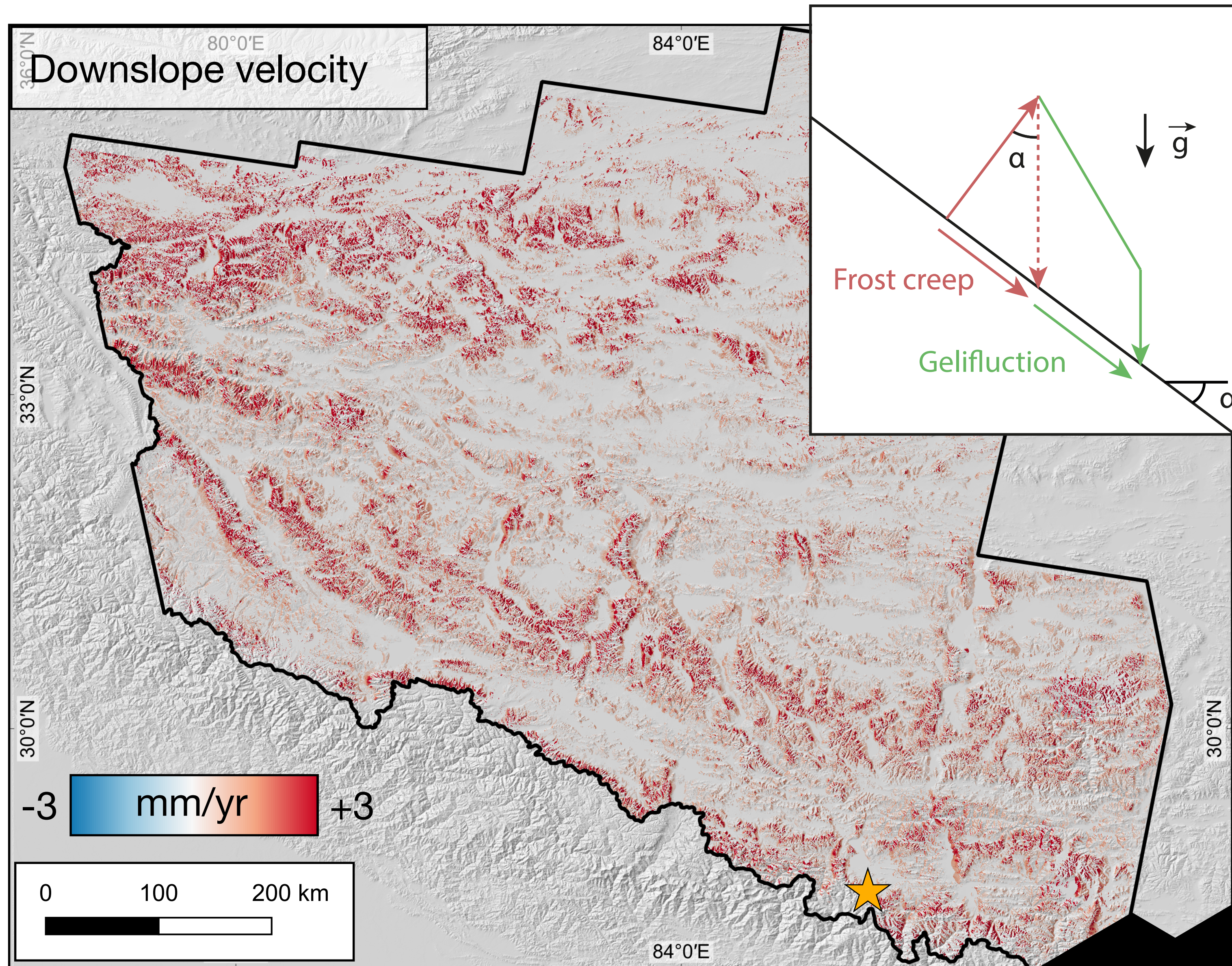
Widespread hillslope processes across the Tibetan Plateau: mechanisms



Widespread hillslope processes across the Tibetan Plateau: mechanisms

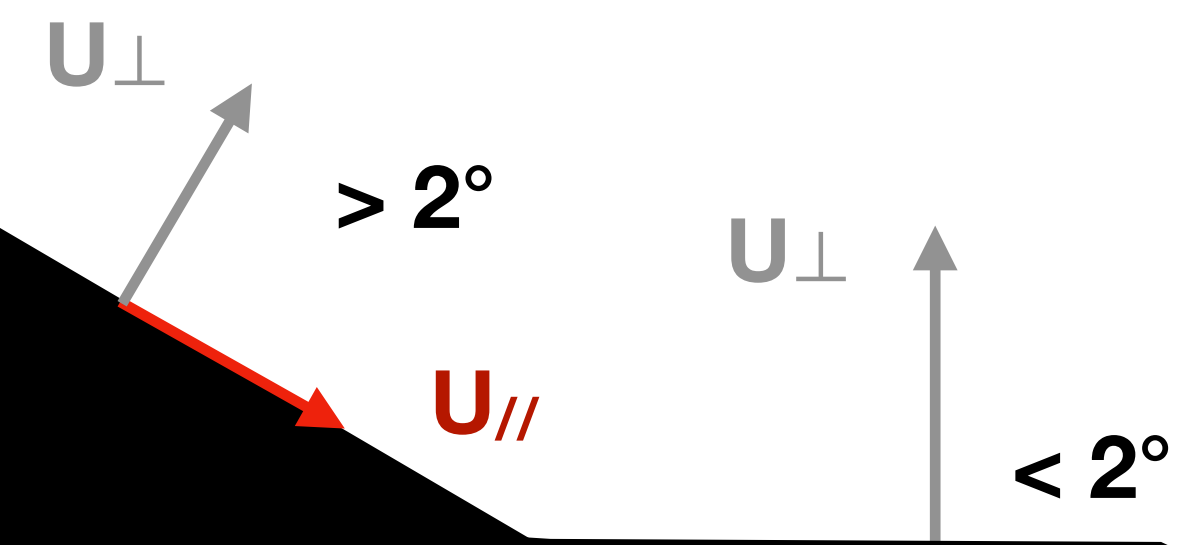


Widespread hillslope processes across the Tibetan Plateau: mechanisms

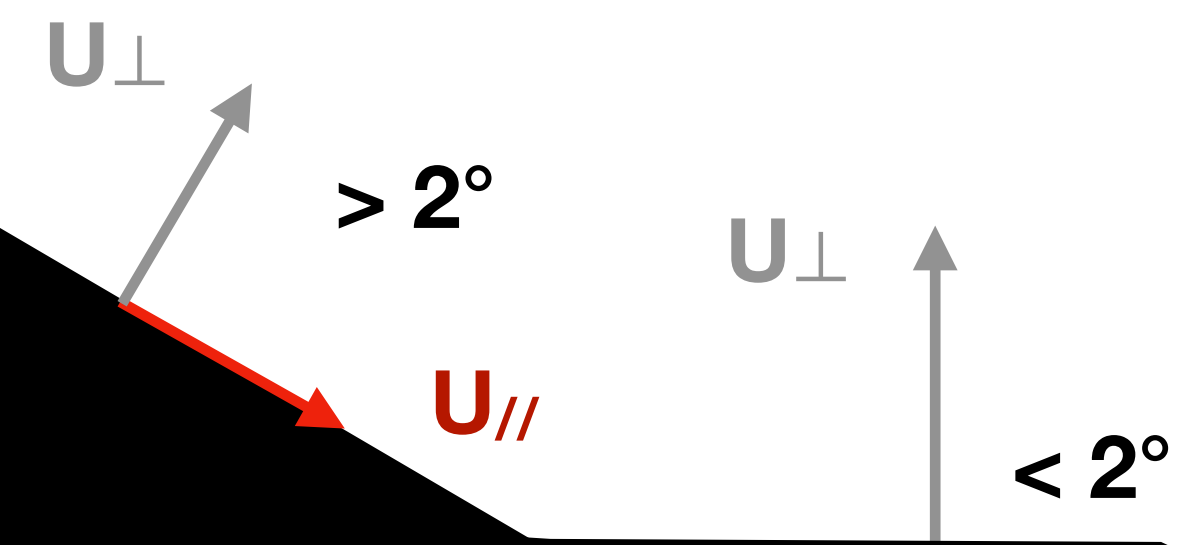
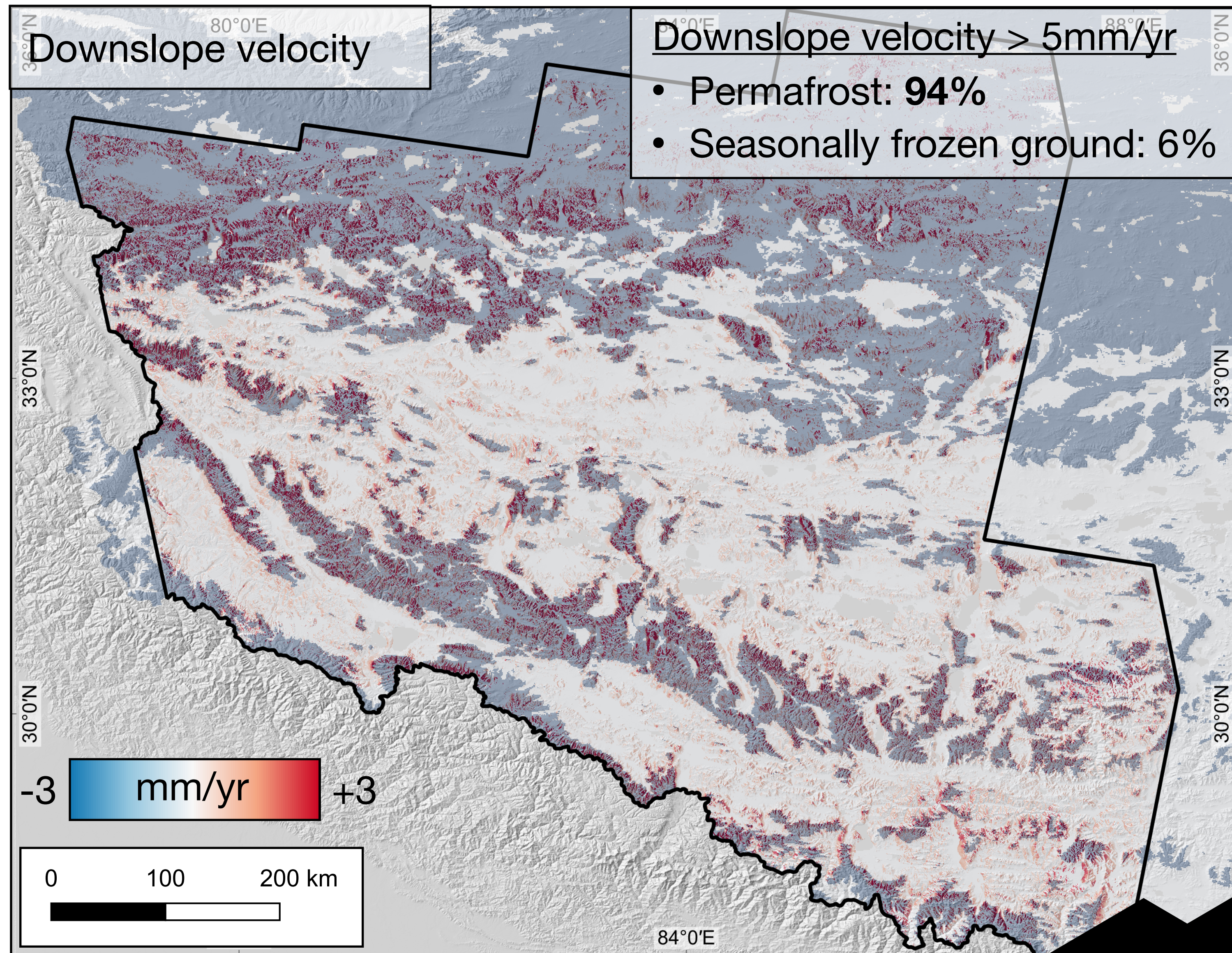


Frost creep = 27%

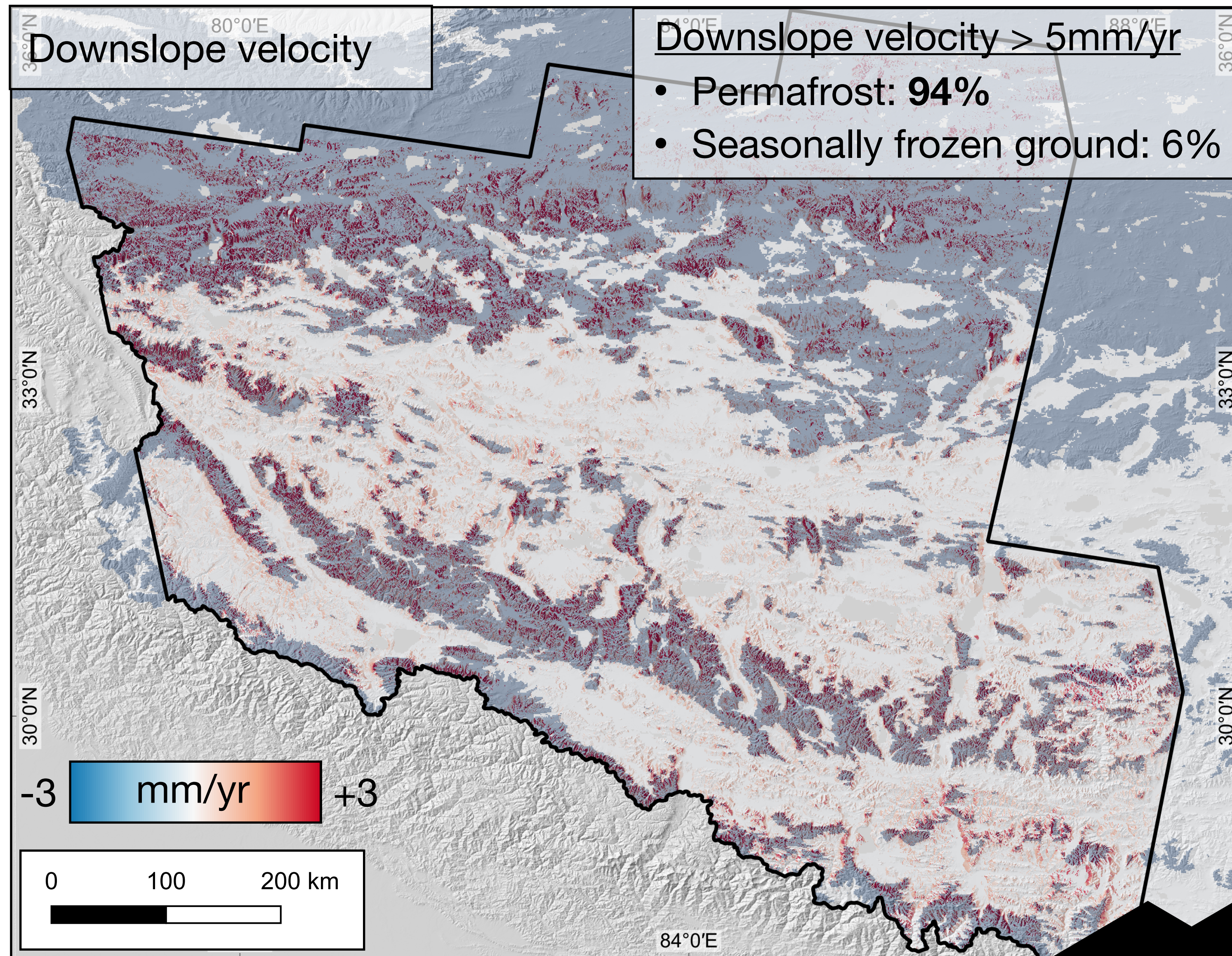
Gelifluction = 73%



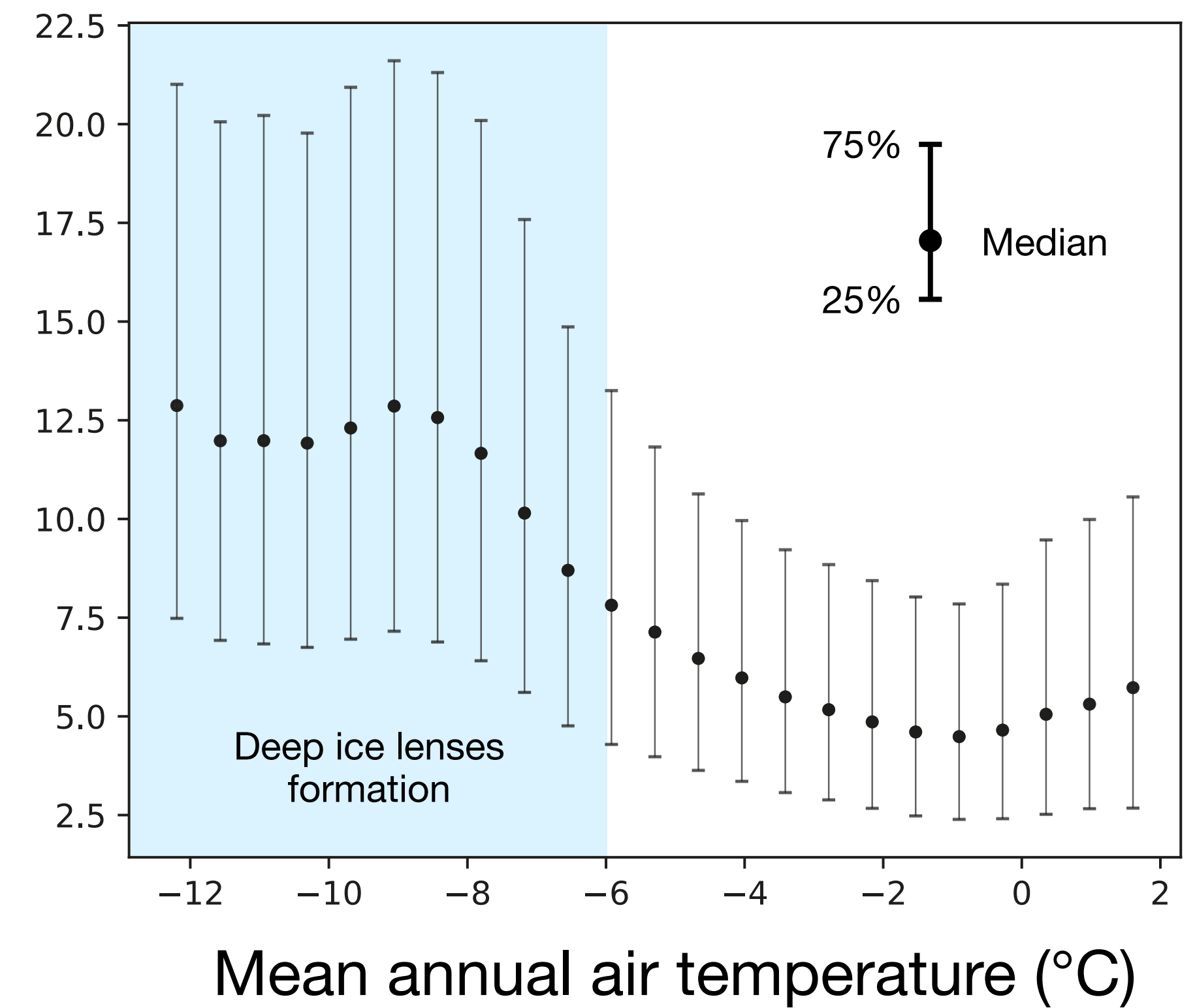
Widespread hillslope processes across the Tibetan Plateau: MAAT (°C)



Widespread hillslope processes across the Tibetan Plateau: MAAT (°C)



Downslope velocity / slope (mm/yr)



$U_{\perp}$

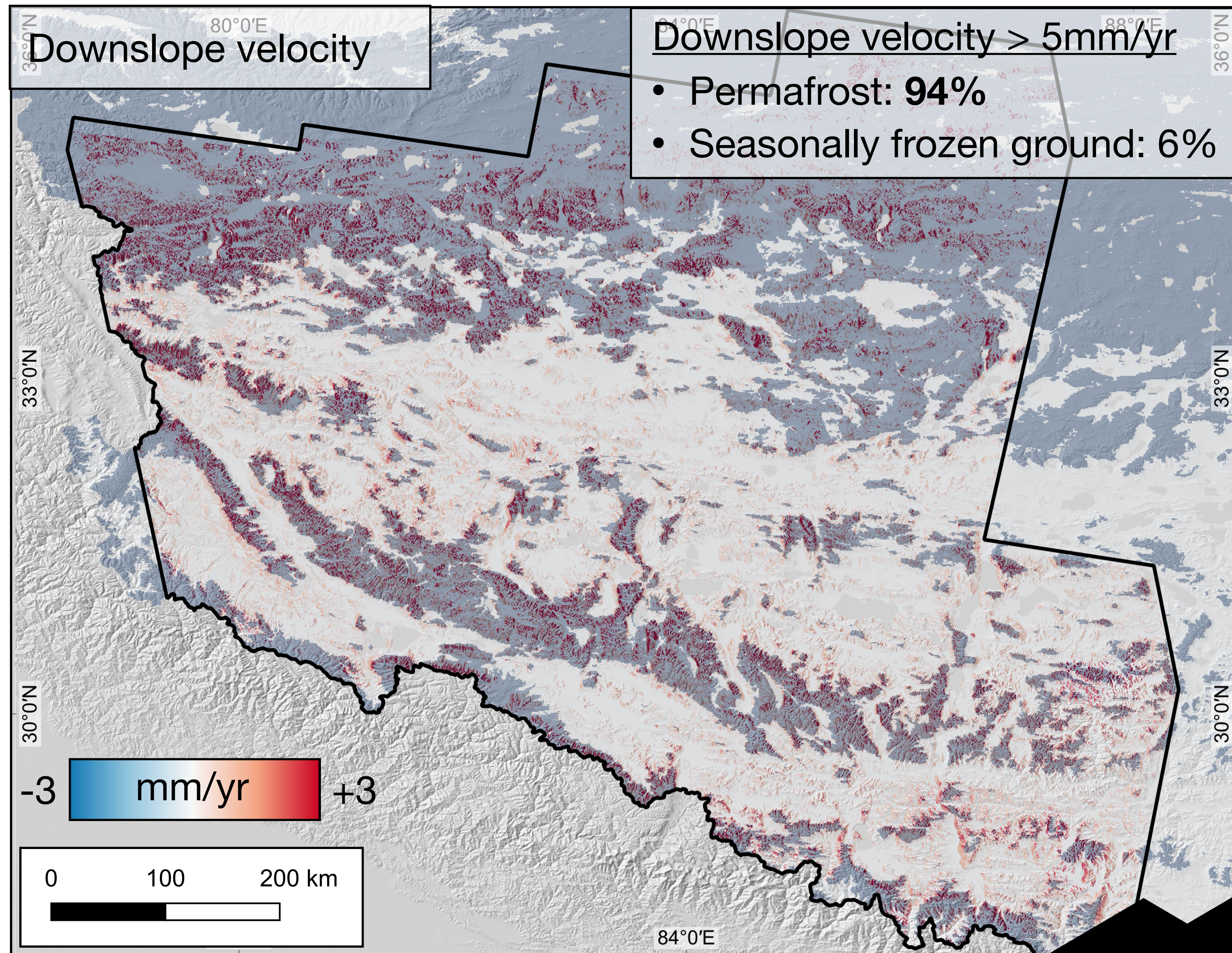
$> 2^{\circ}$

$U_{\perp}$

$U_{//}$

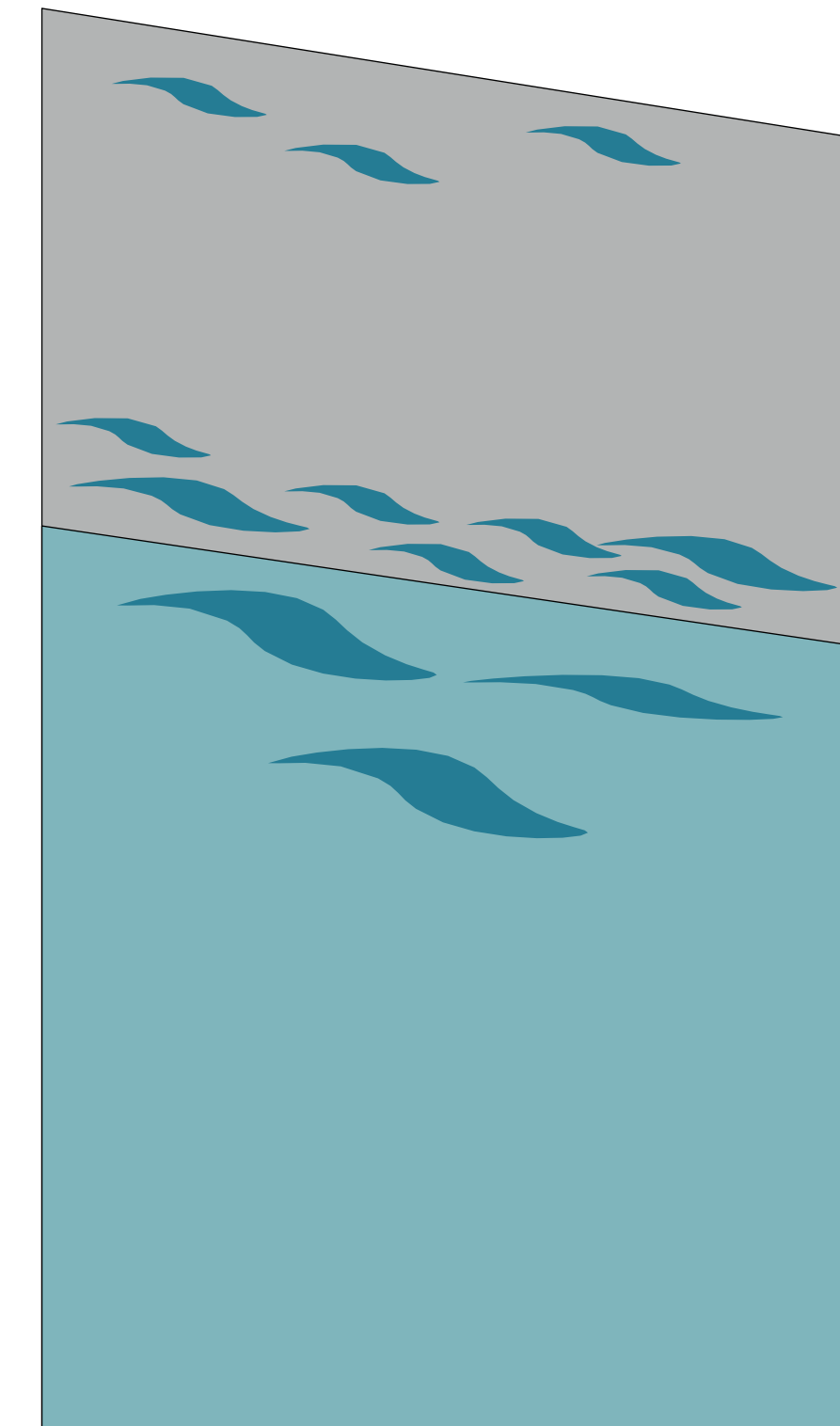
$< 2^{\circ}$

Widespread hillslope processes across the Tibetan Plateau: MAAT (°C)



Active layer (~2m)

Permafrost

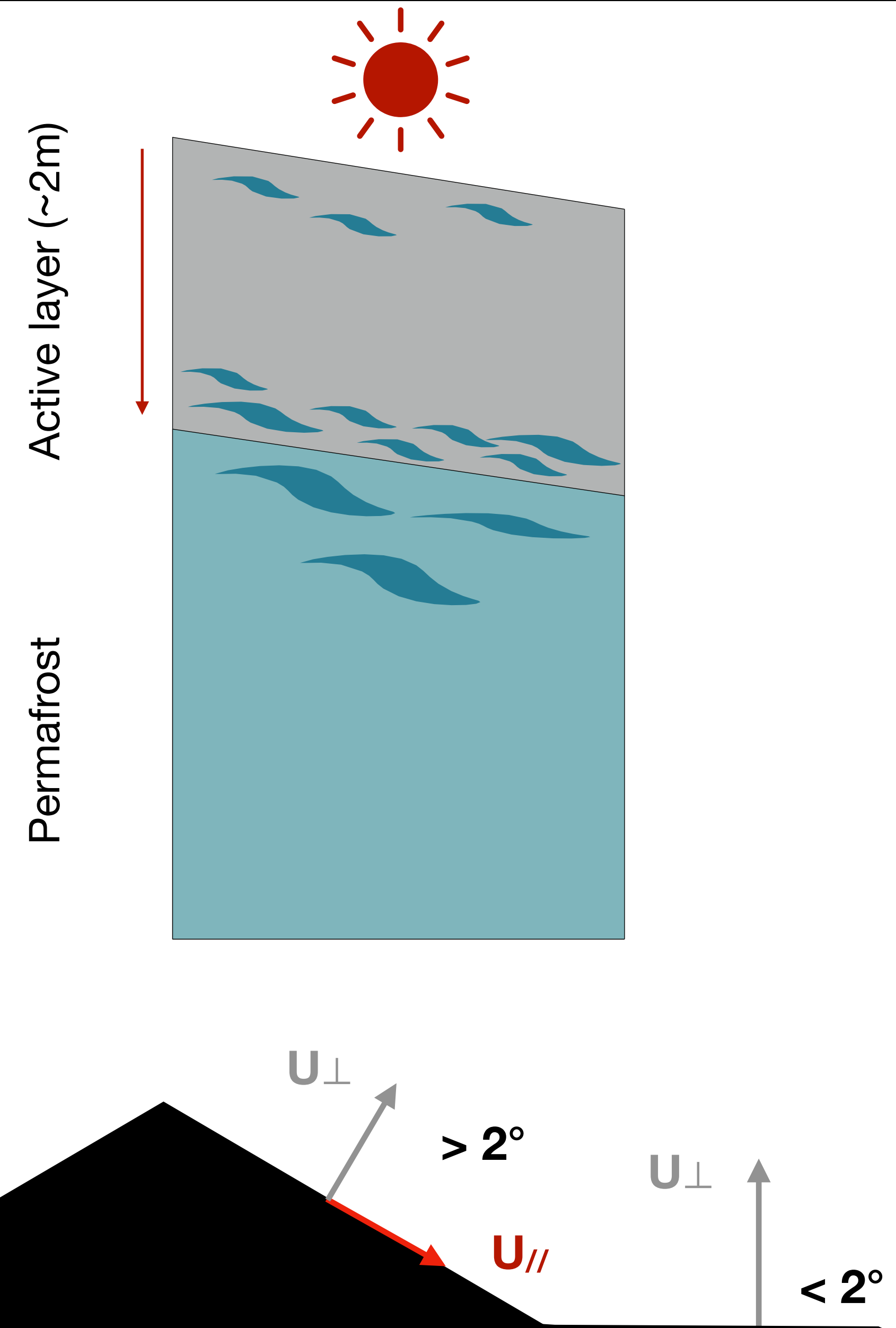
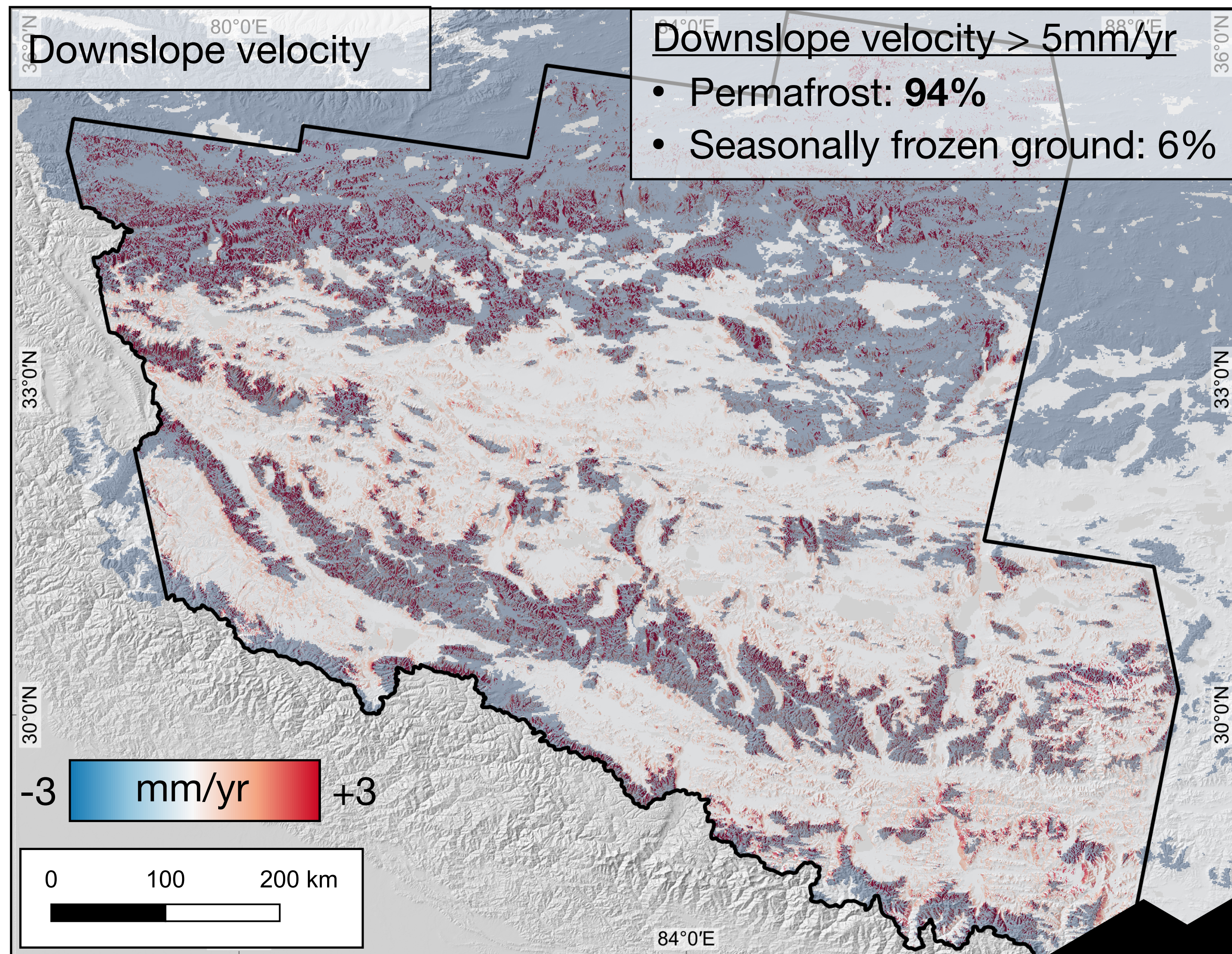
 $U_{\perp}$

> 2°

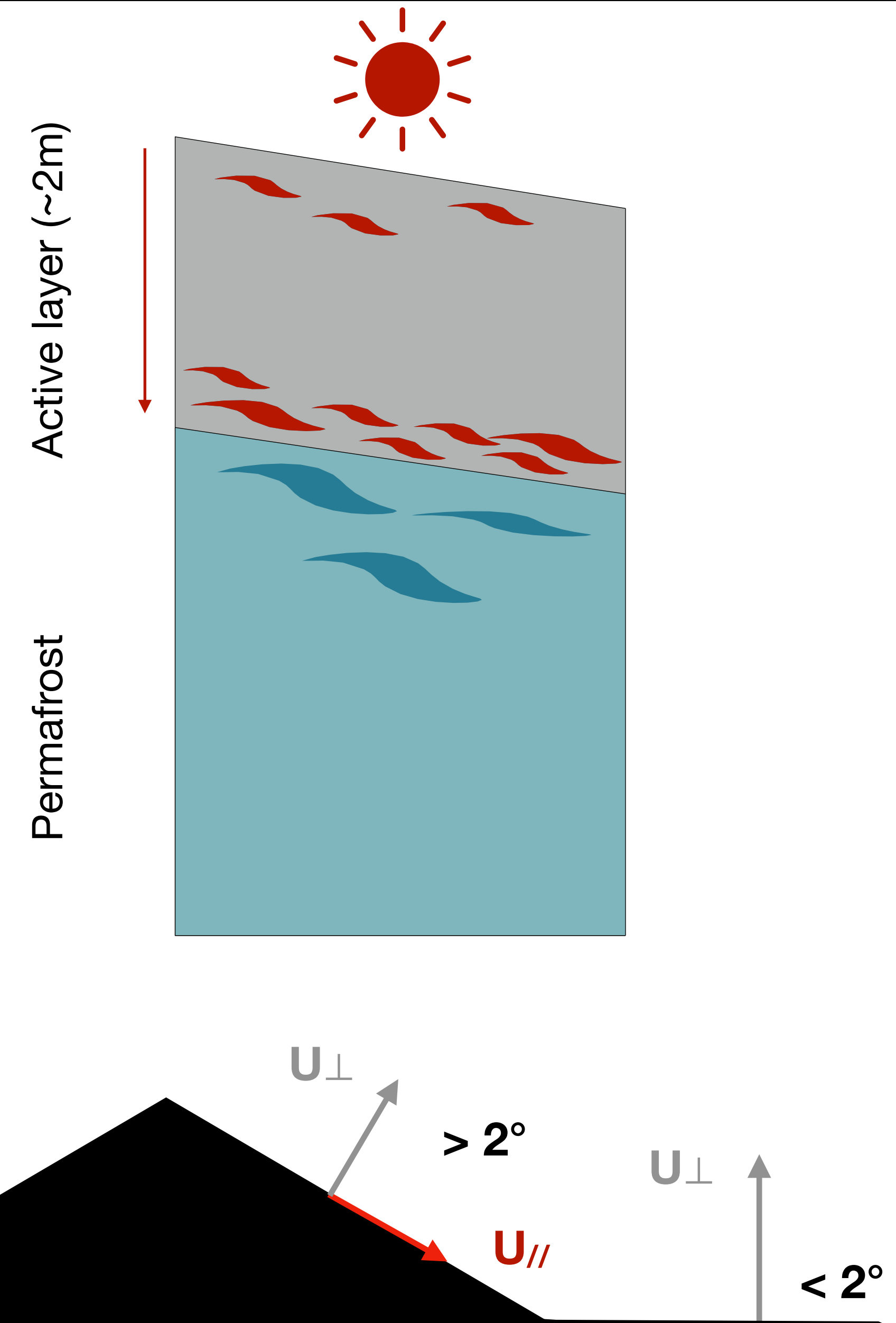
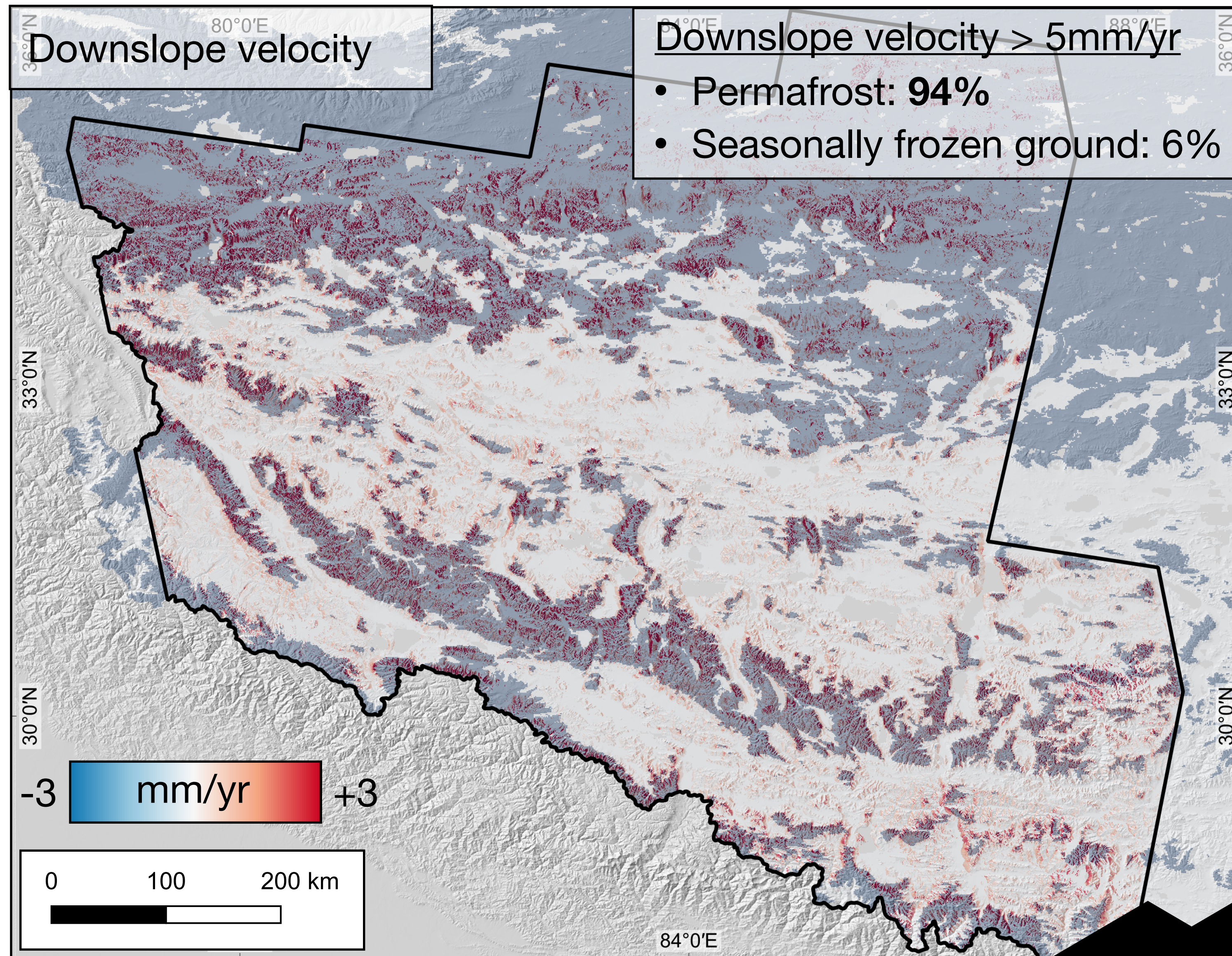
 $U_{\perp}$ $U_{//}$

< 2°

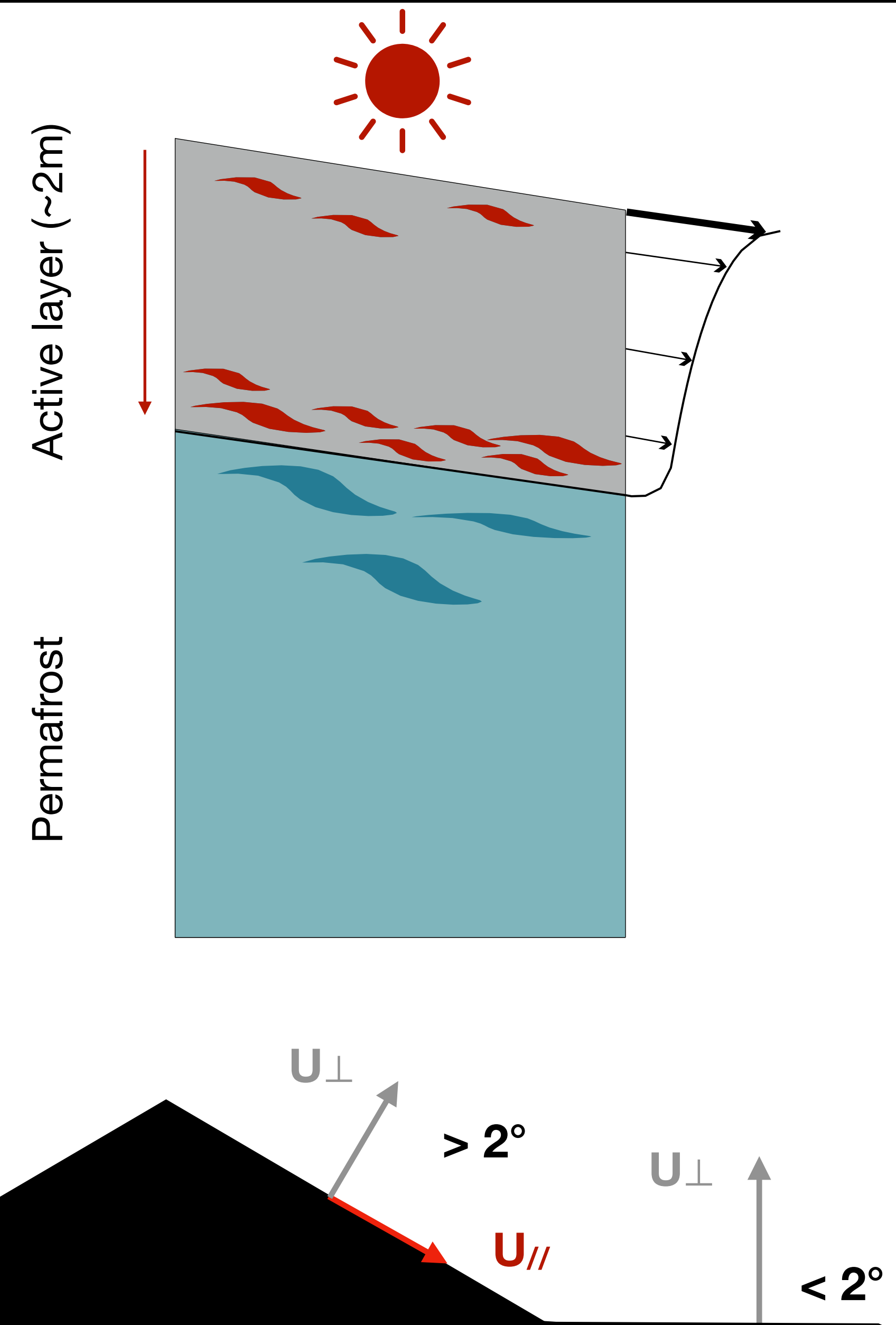
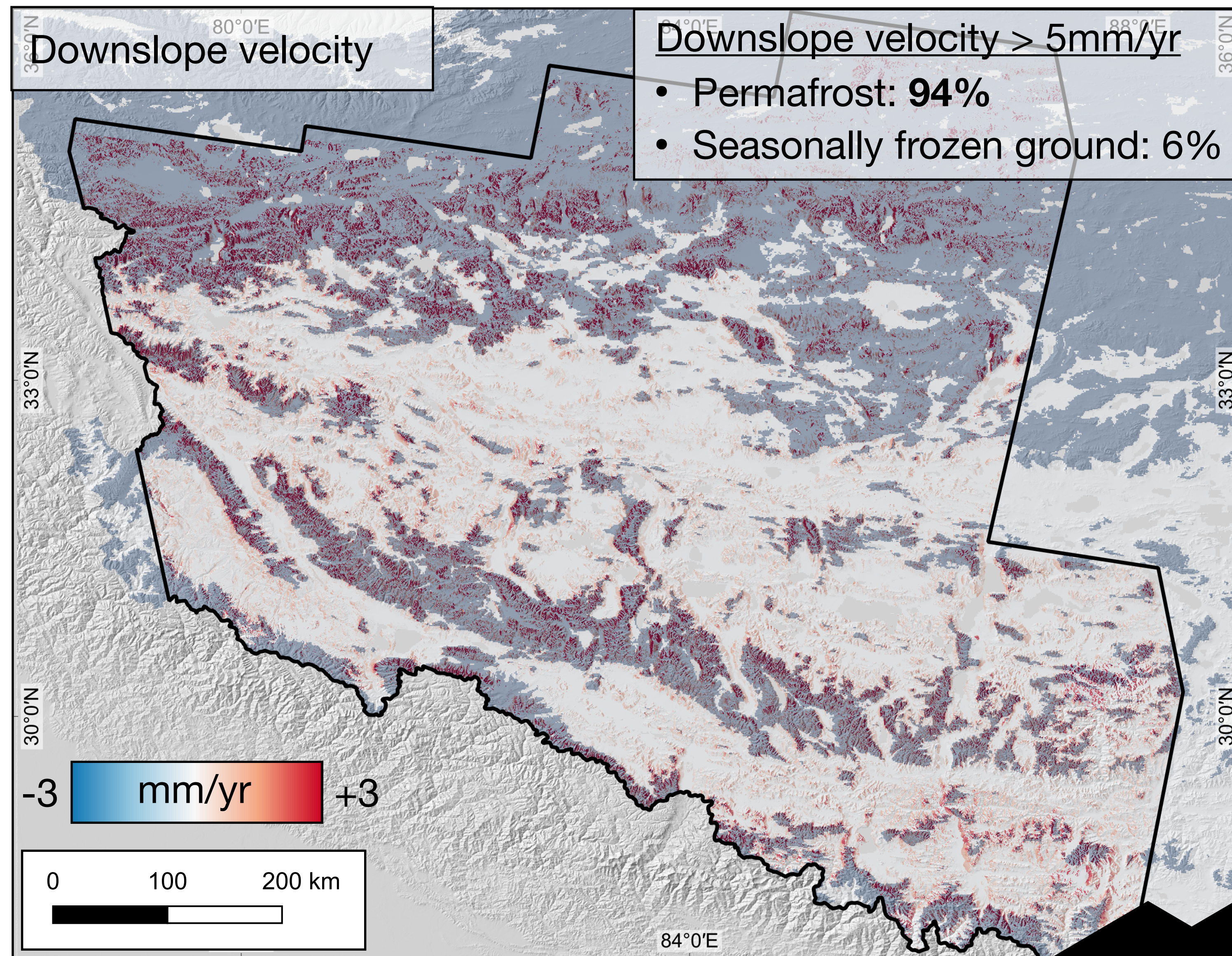
Widespread hillslope processes across the Tibetan Plateau: MAAT (°C)



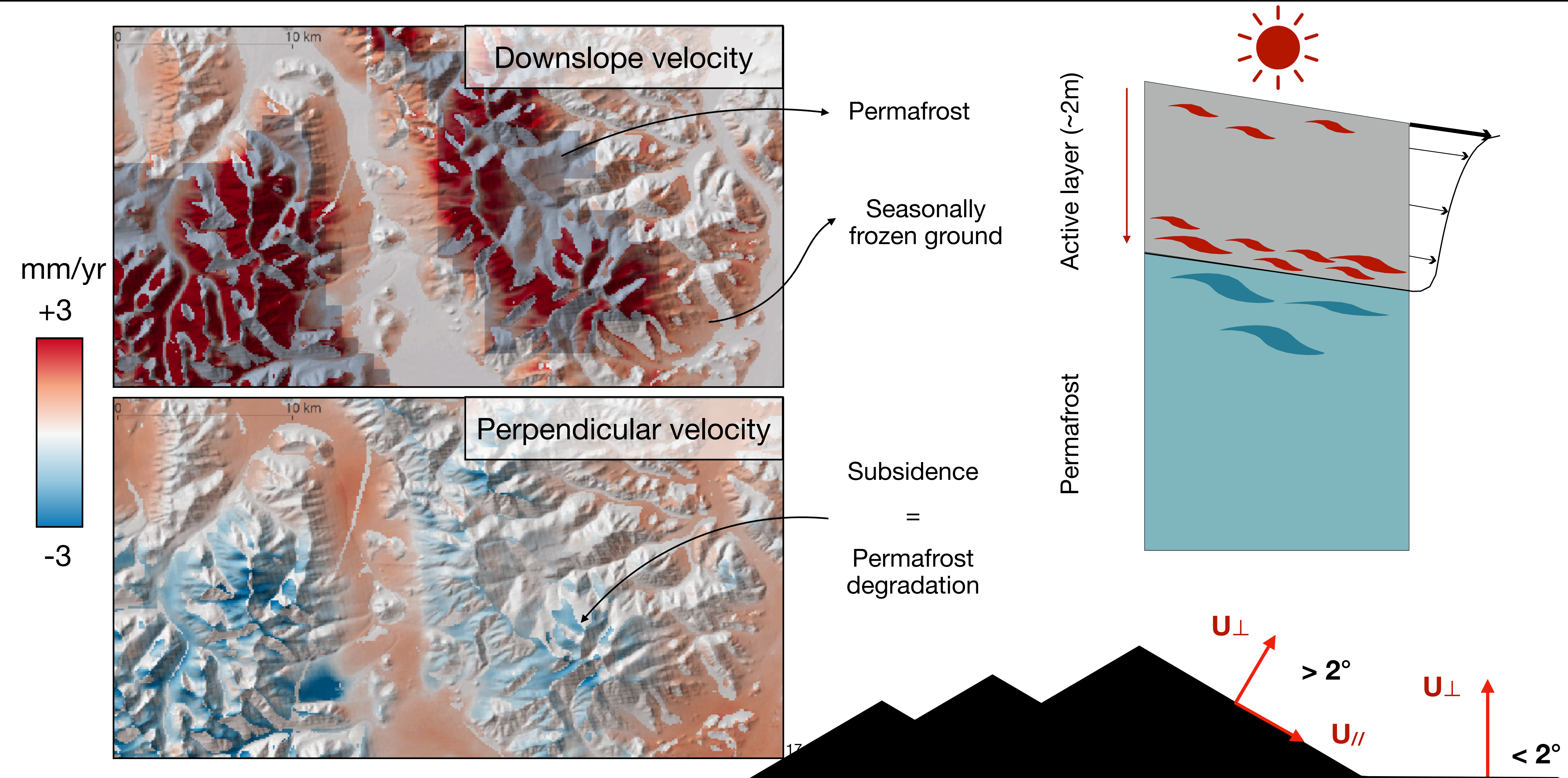
Widespread hillslope processes across the Tibetan Plateau: MAAT (°C)



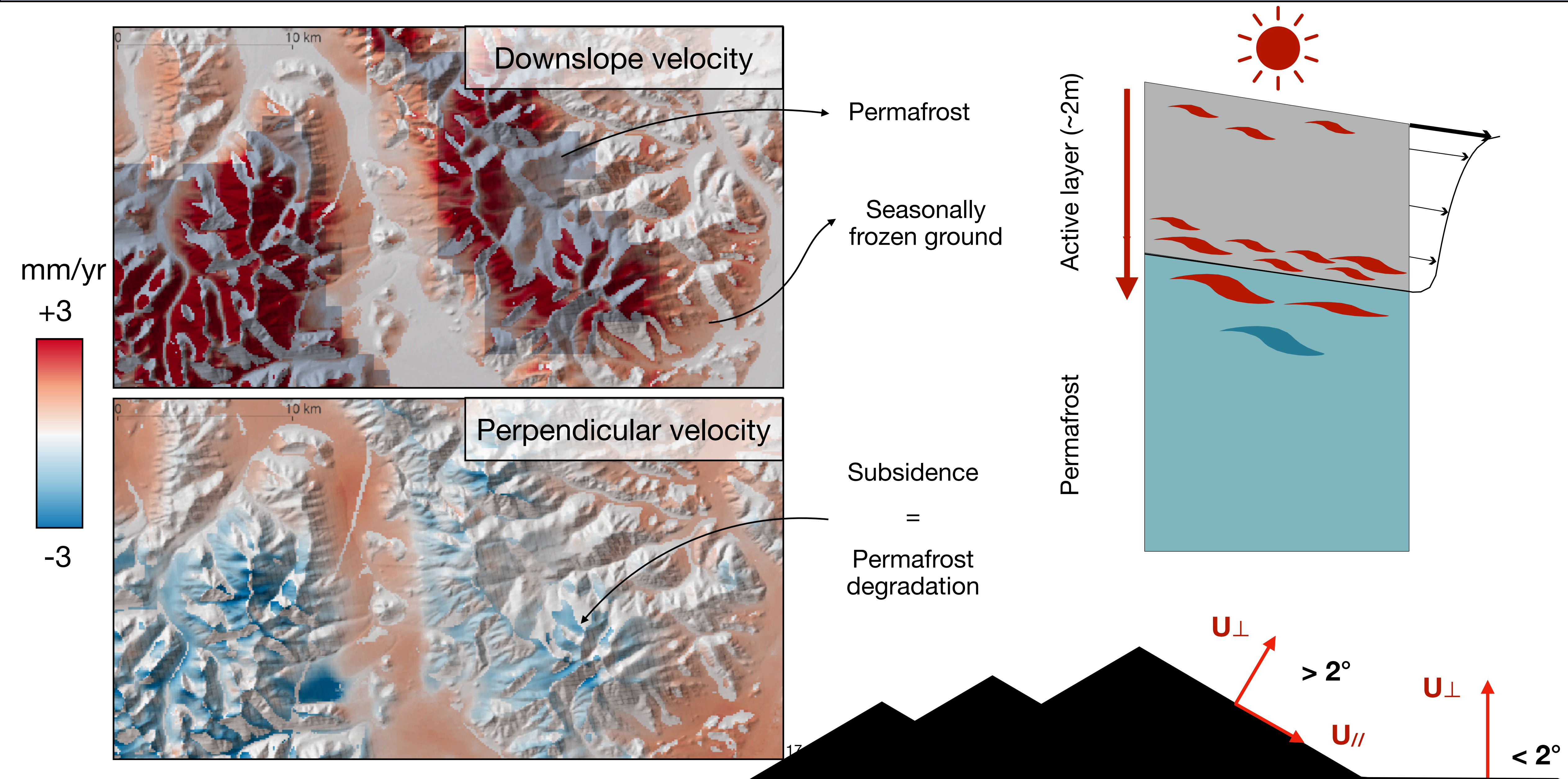
Widespread hillslope processes across the Tibetan Plateau: MAAT (°C)



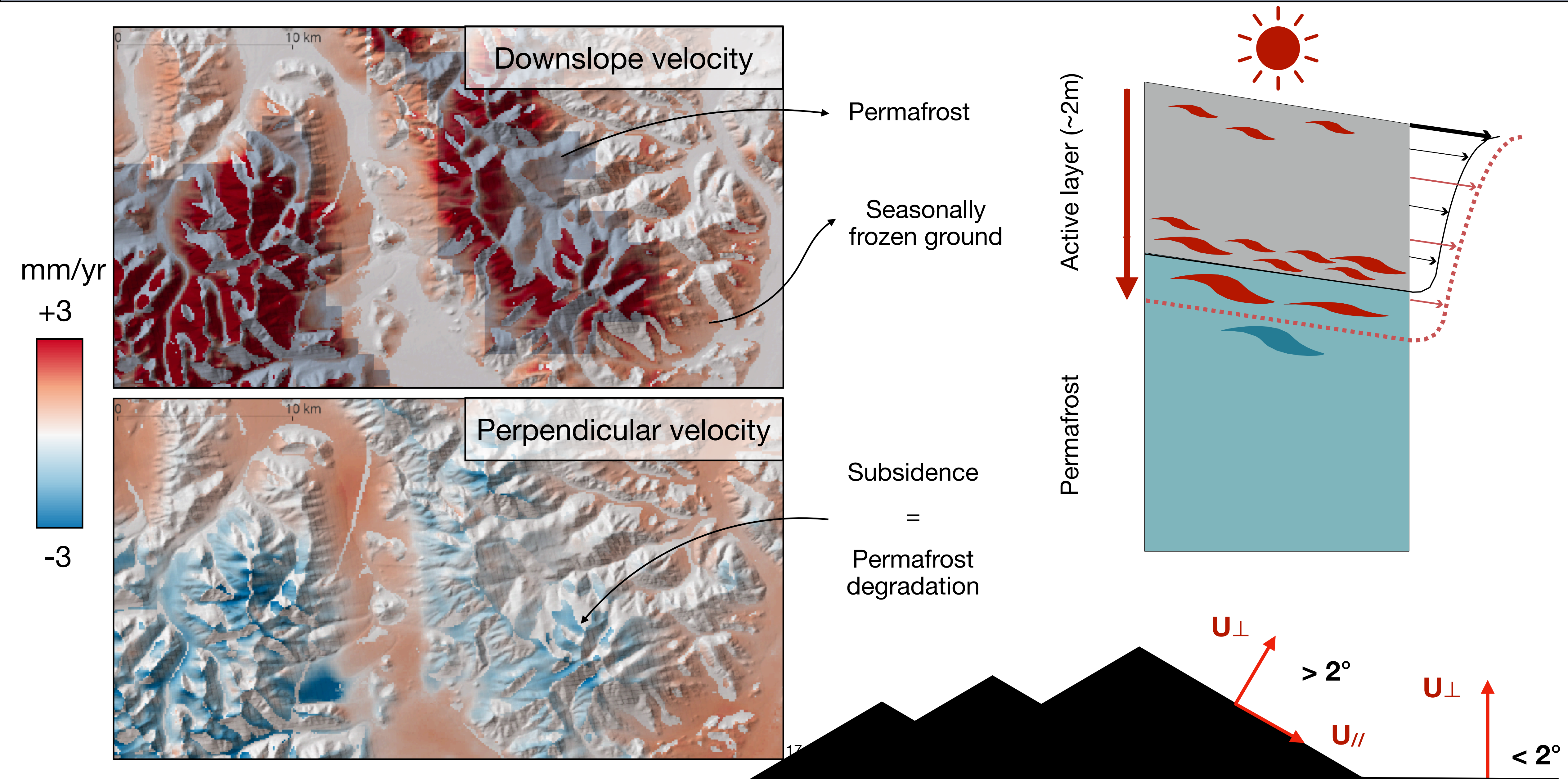
Impact of permafrost degradation on solifluction ?



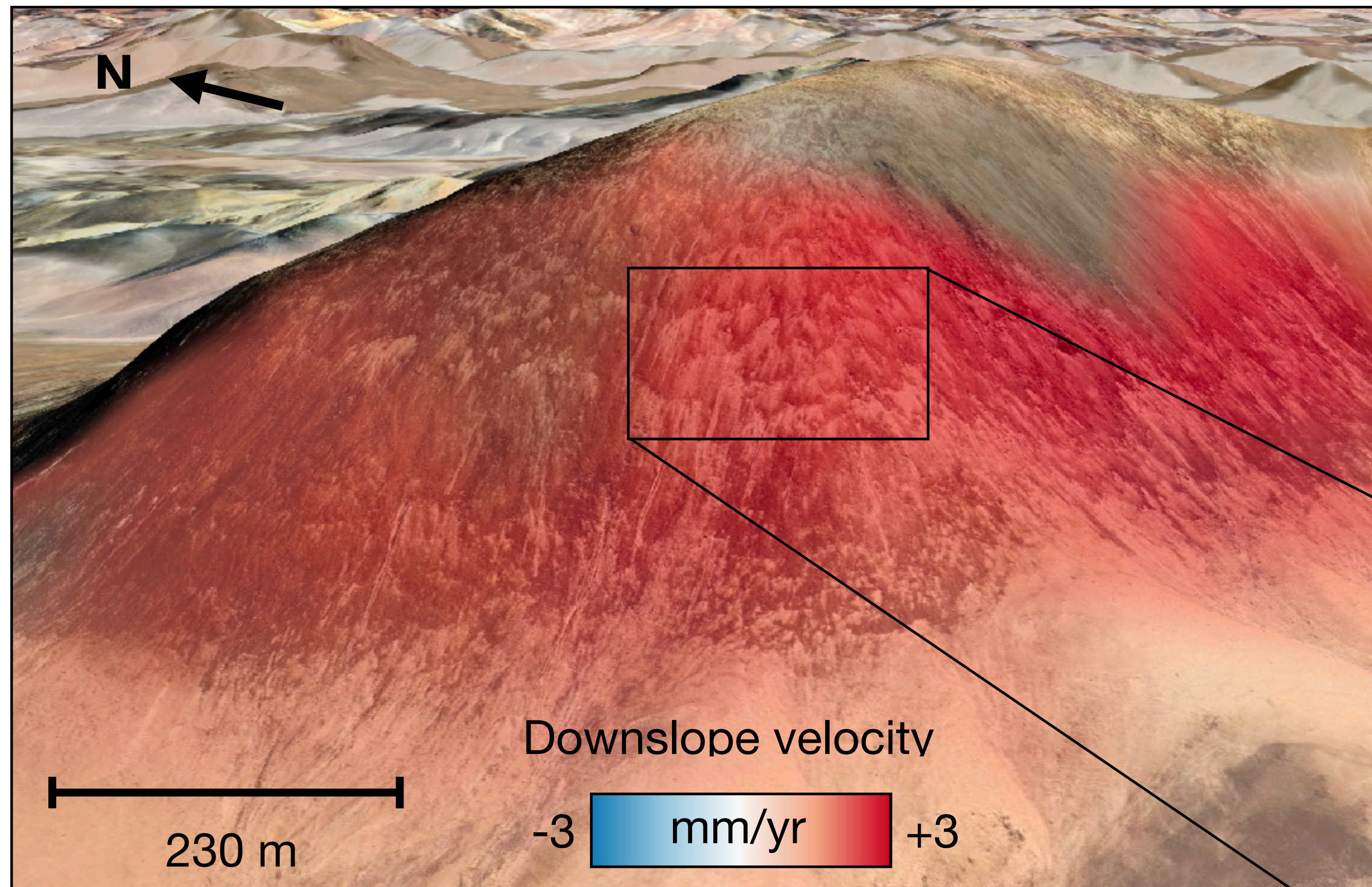
Impact of permafrost degradation on solifluction ?



Impact of permafrost degradation on solifluction ?



Conclusion



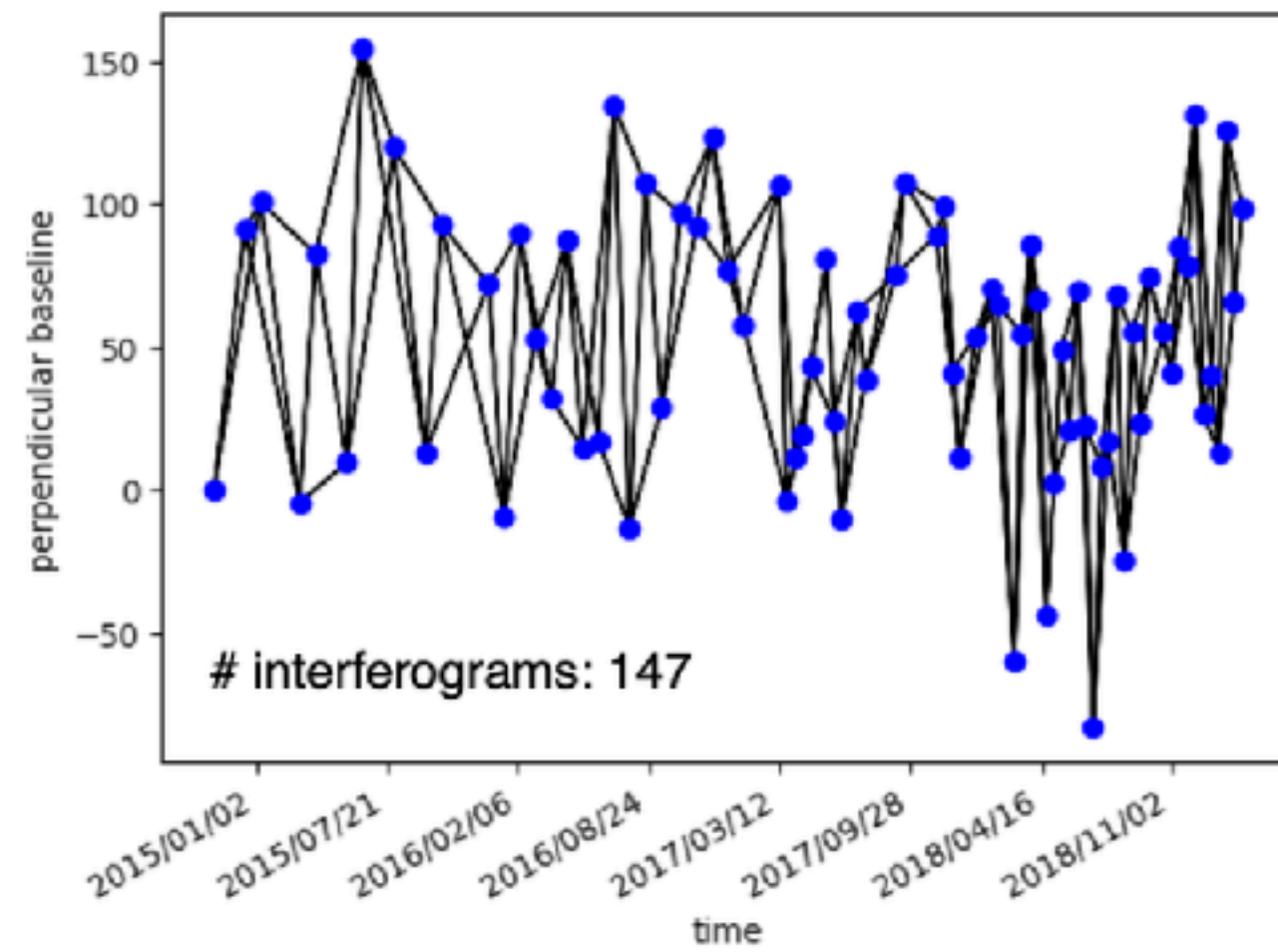
- Widespread hillslope deformation observed across the Tibetan Plateau using InSAR data
- Associated with mm-cm/yr solifluction processes primarily controlled by slope angle and ground thermal regime.
- Mainly driven by seasonal basal shearing.
- Is this a long-term behavior or a transient response to recent warming ?



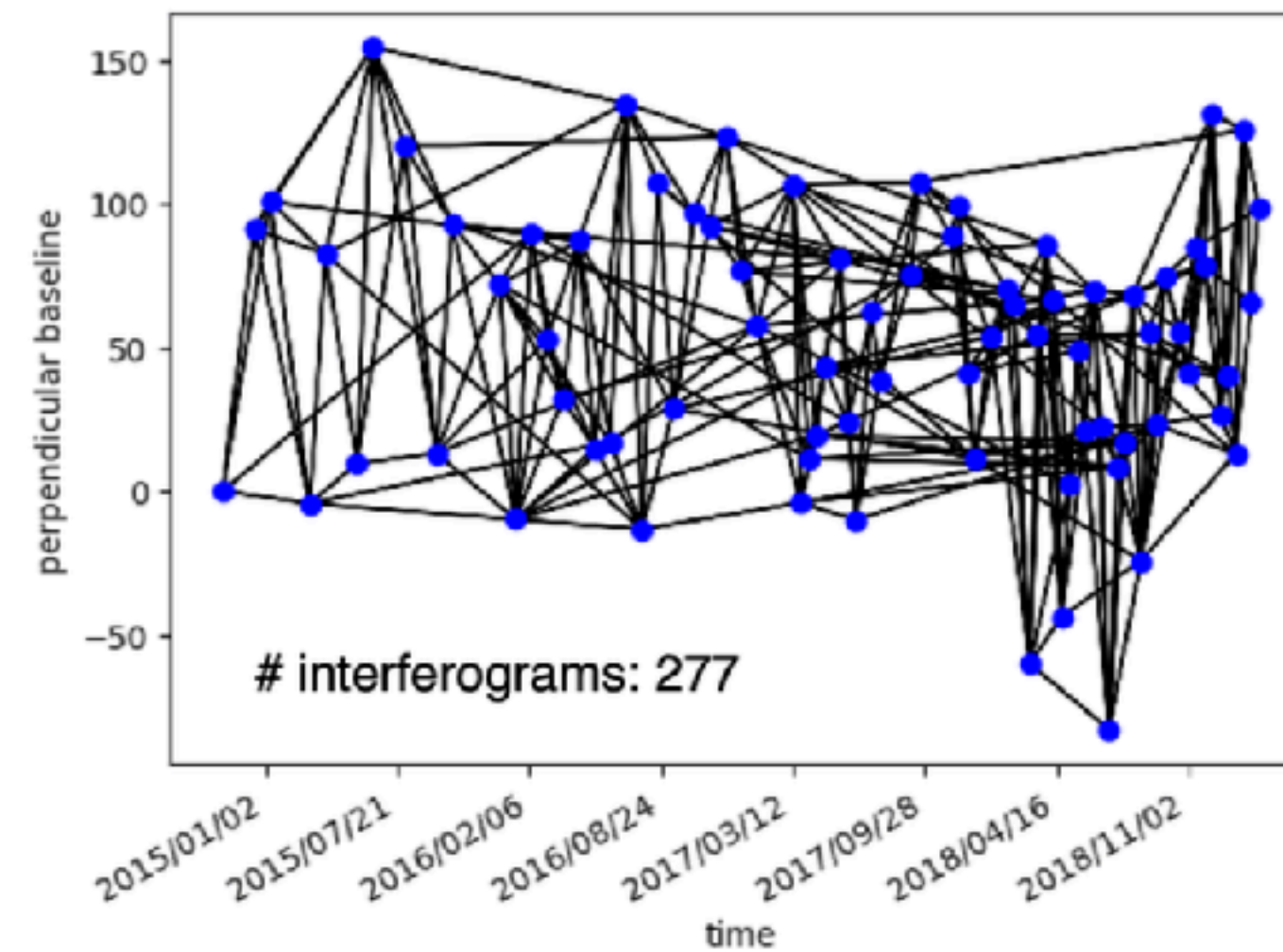
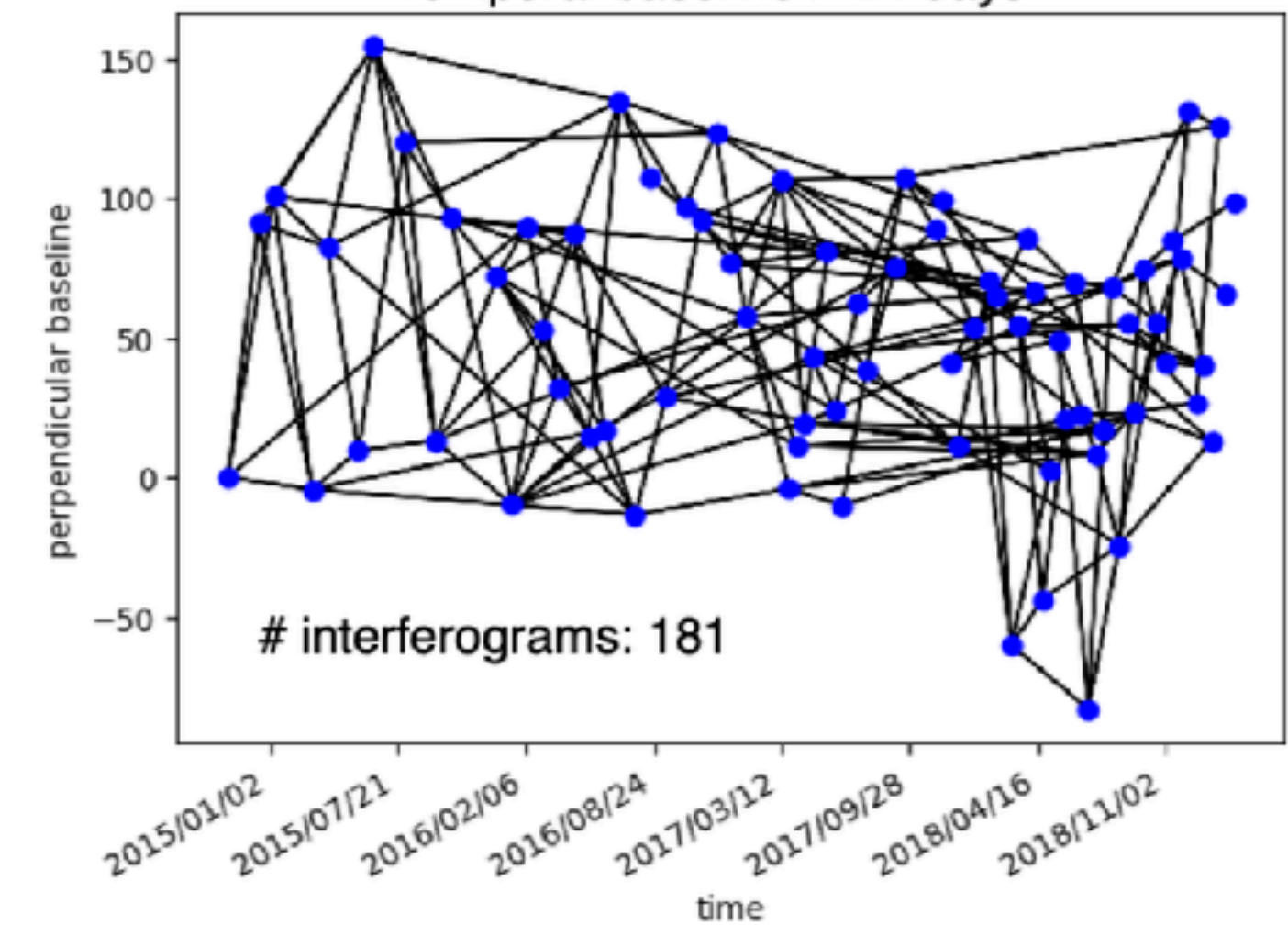
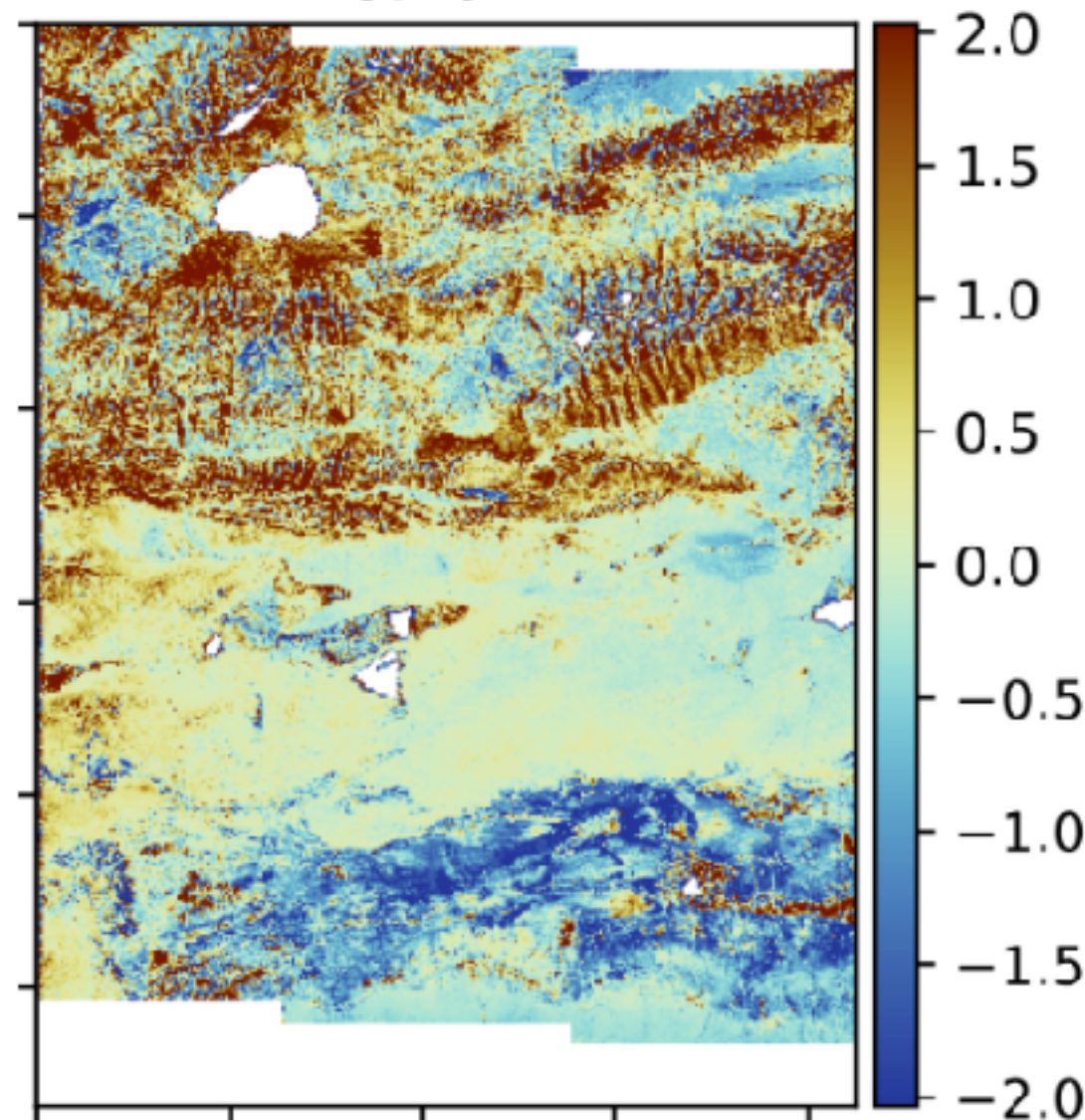
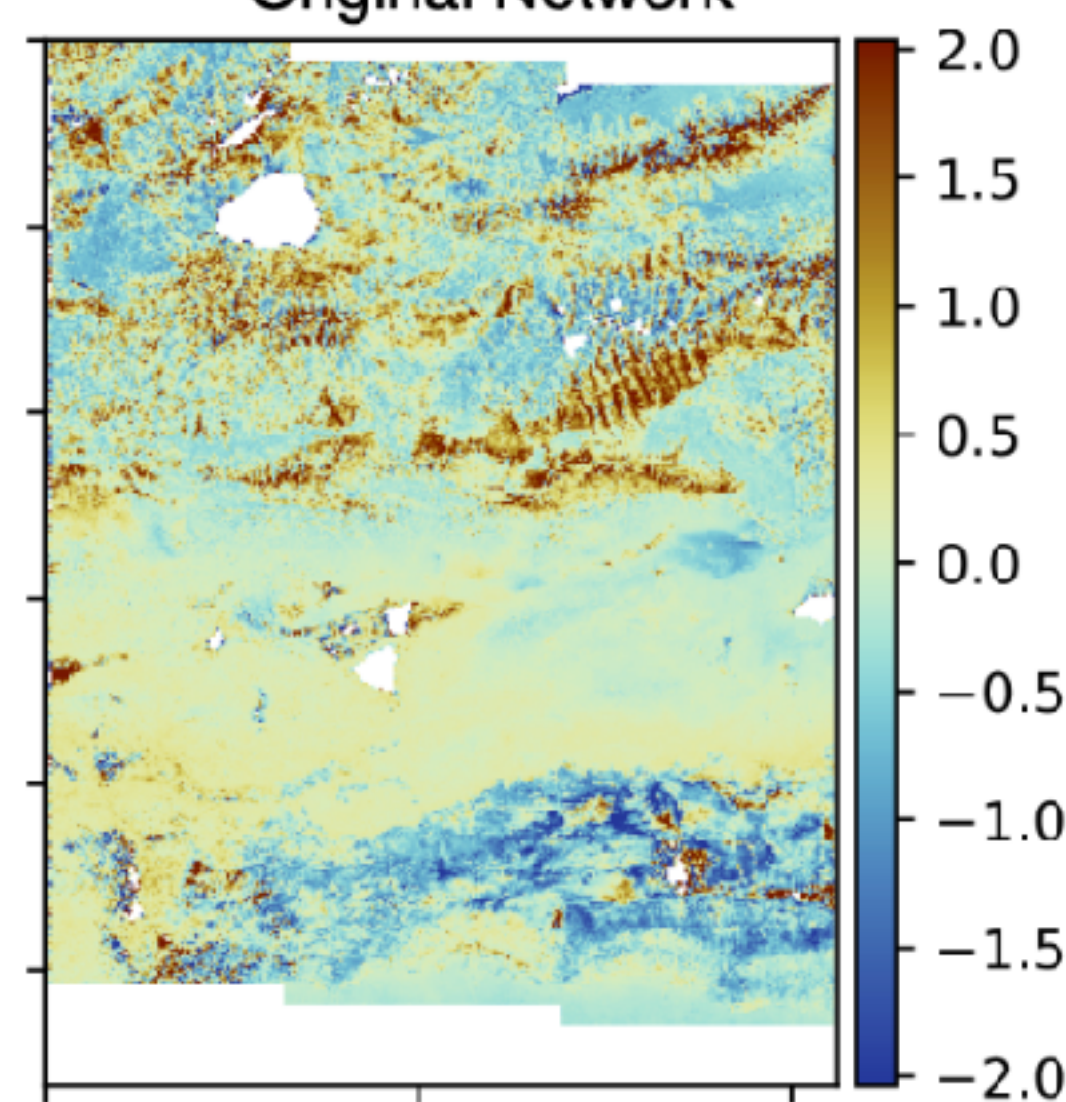
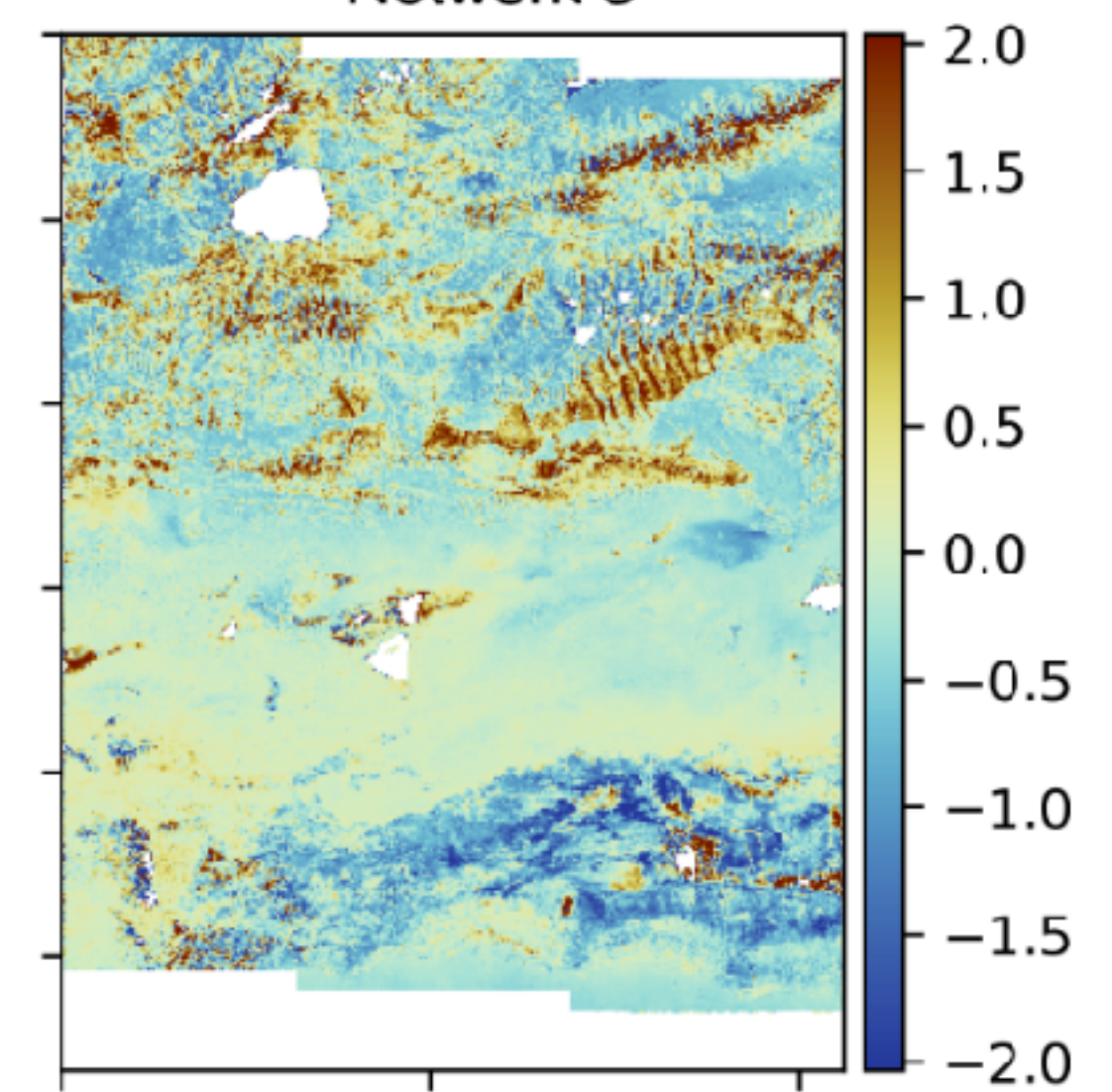
[Google Earth image of a mountain affected by active solifluction processes, with InSAR-derived downslope velocities superimposed.](#)

Supplementary data

Network 2: 2 successive dates

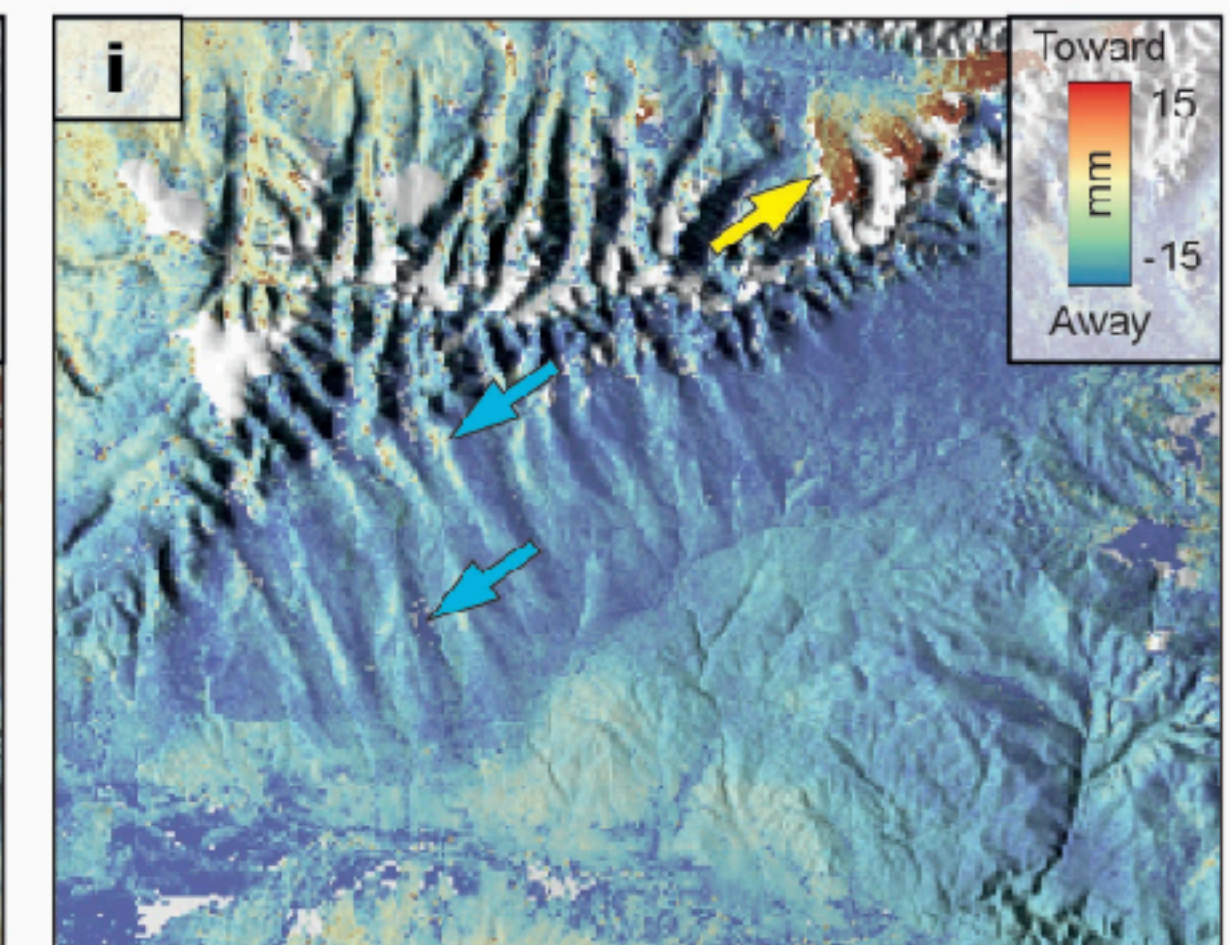
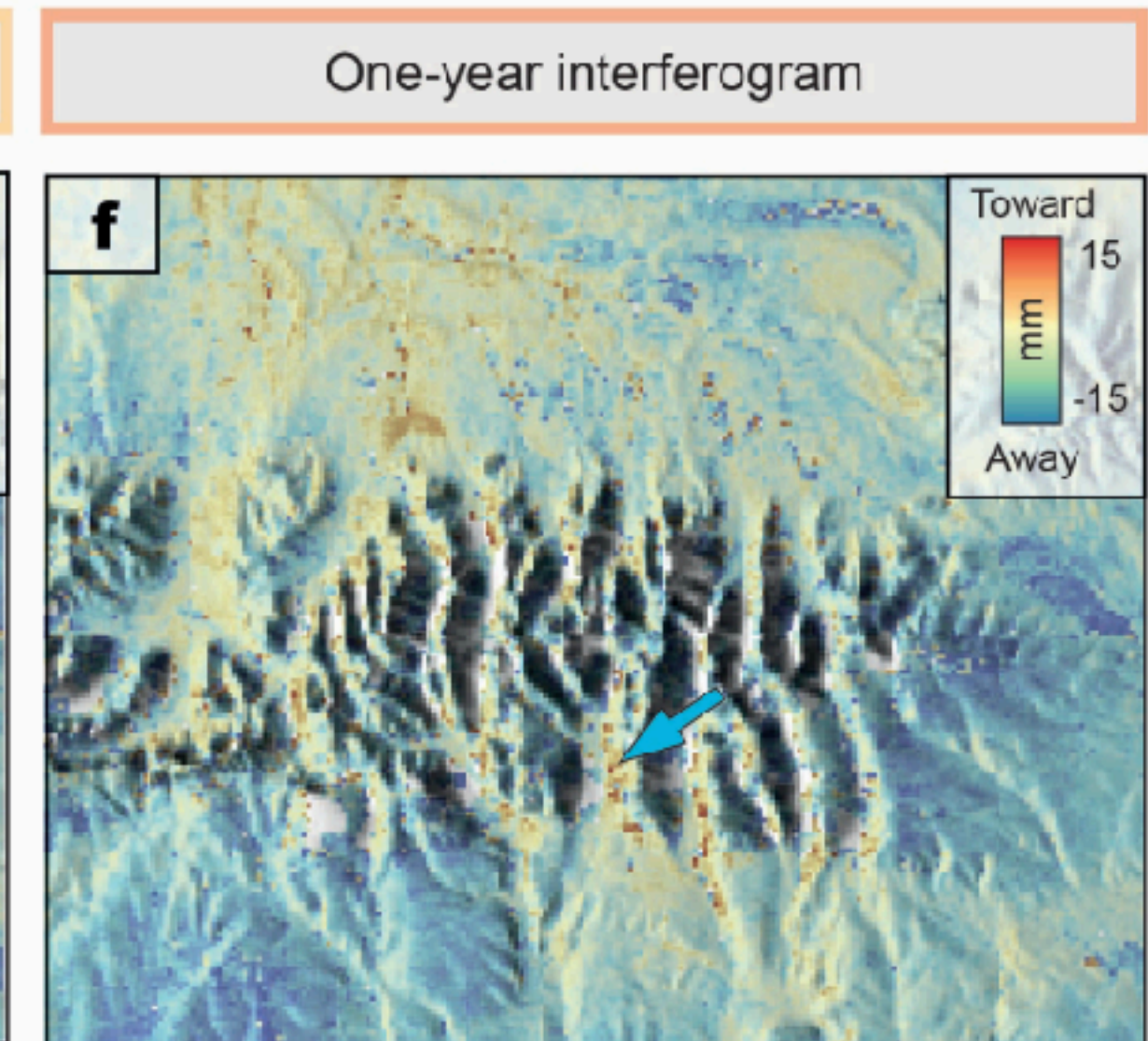
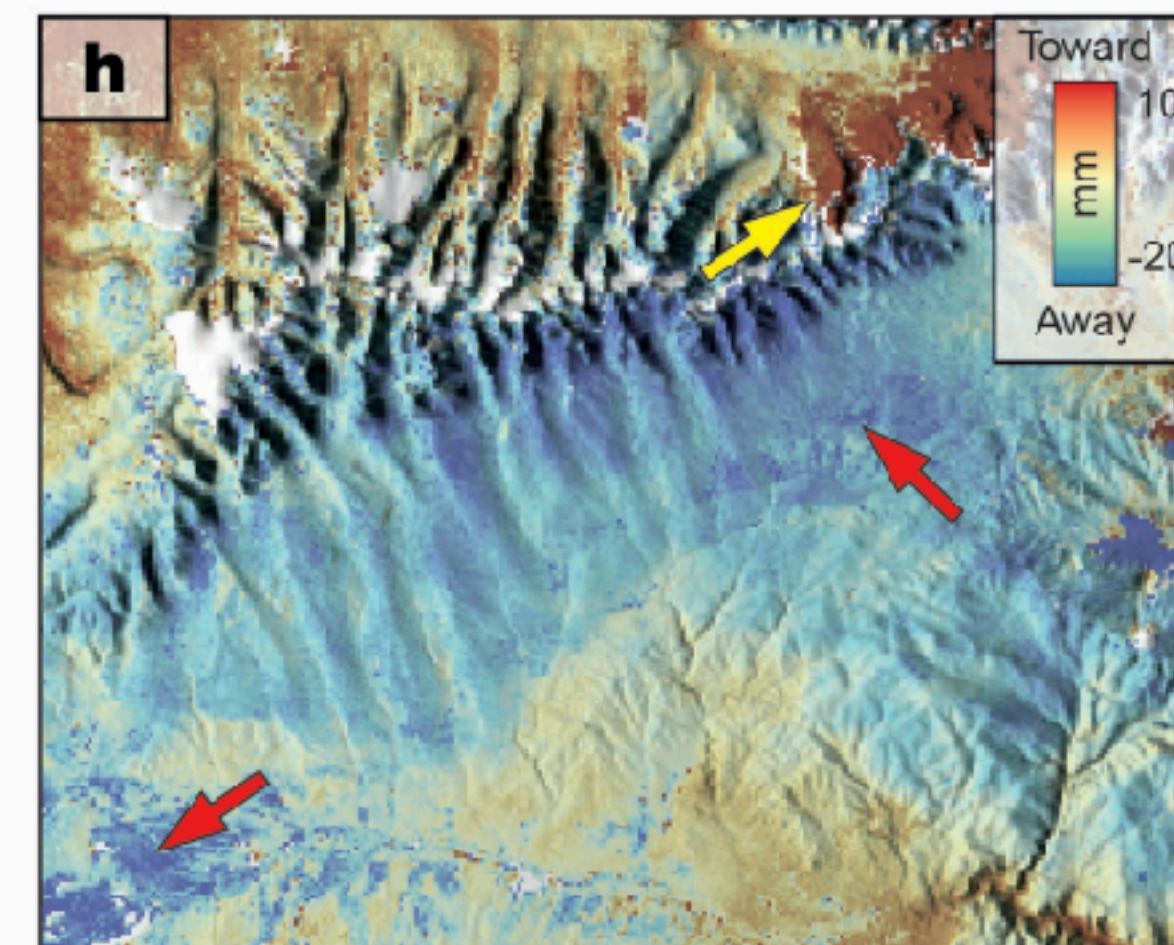
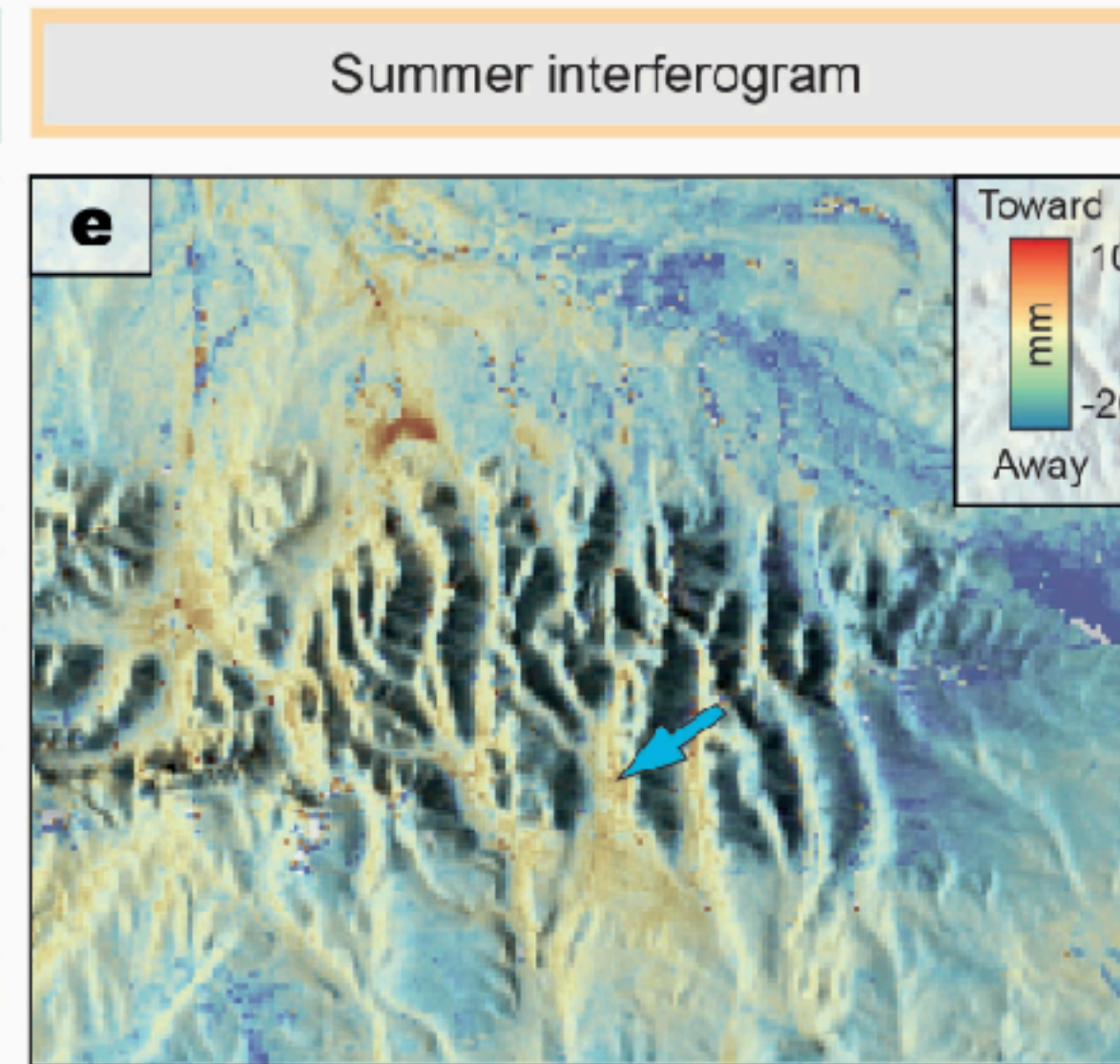
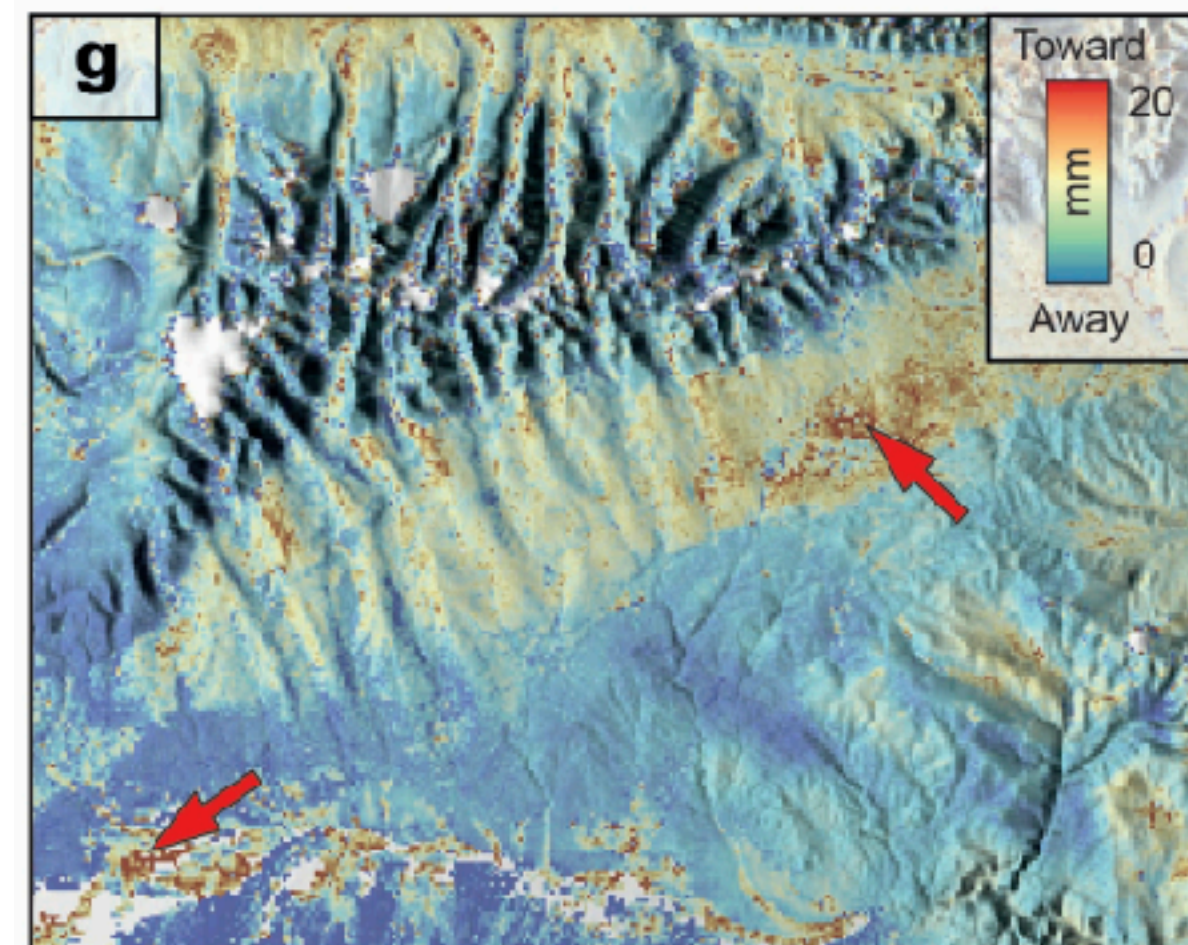
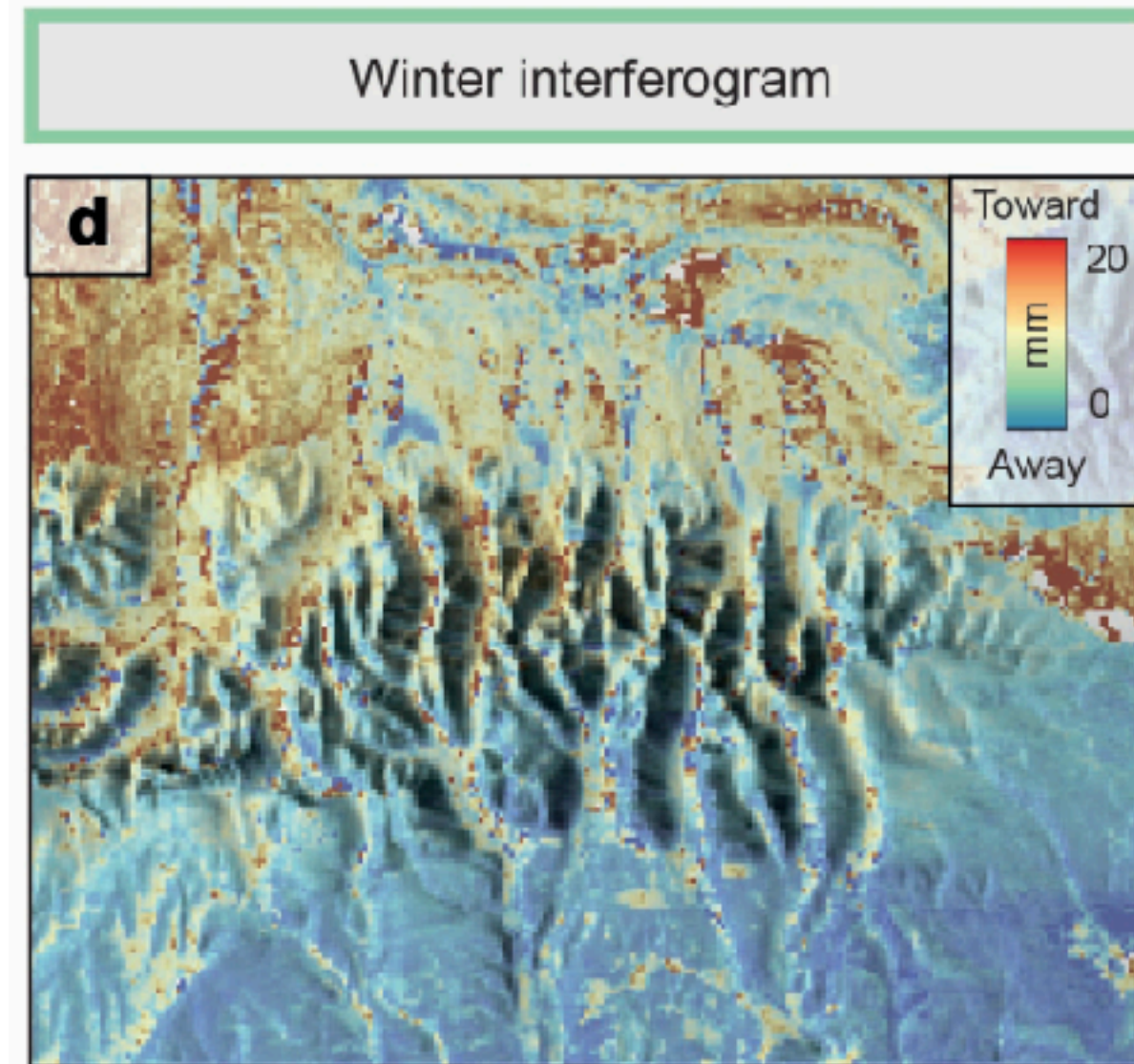
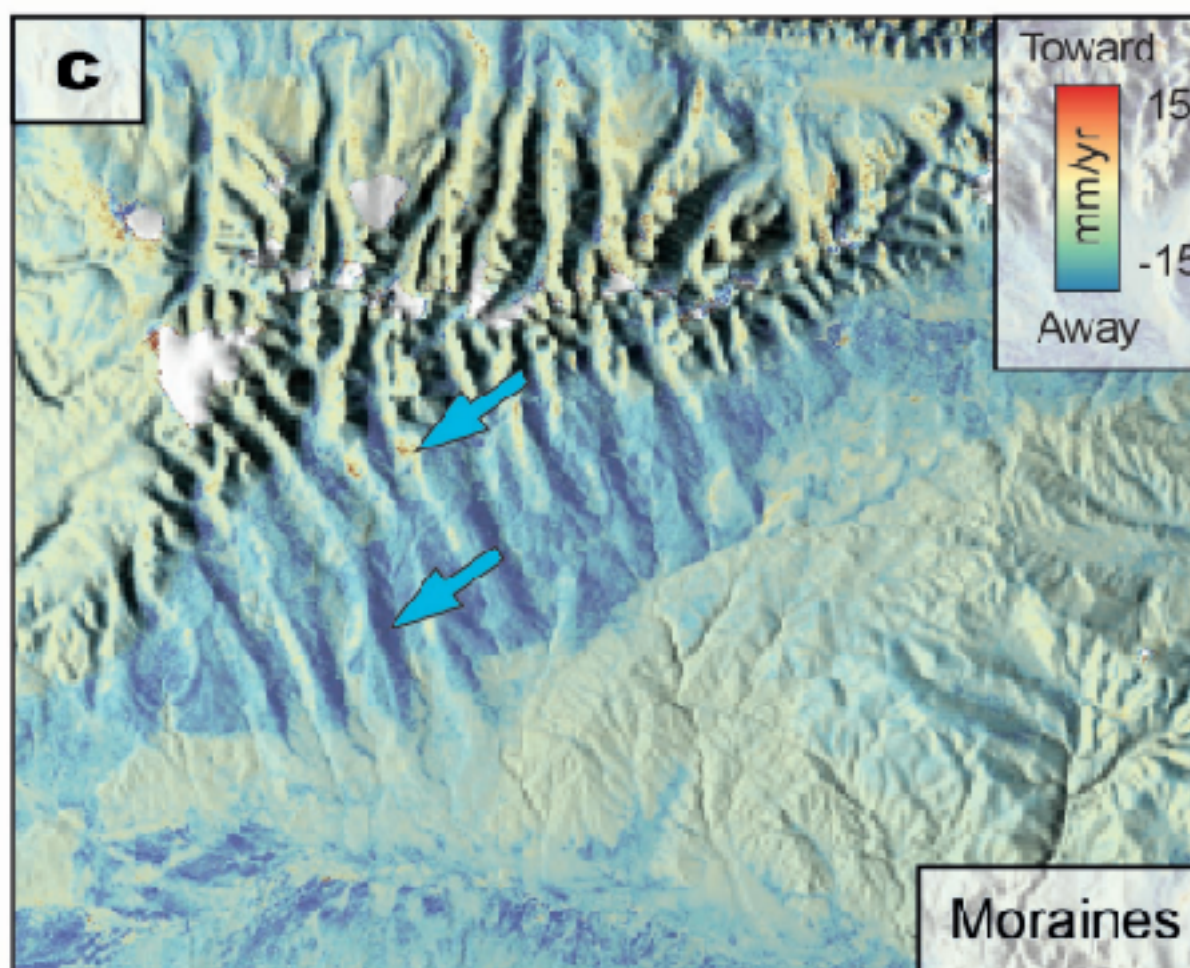
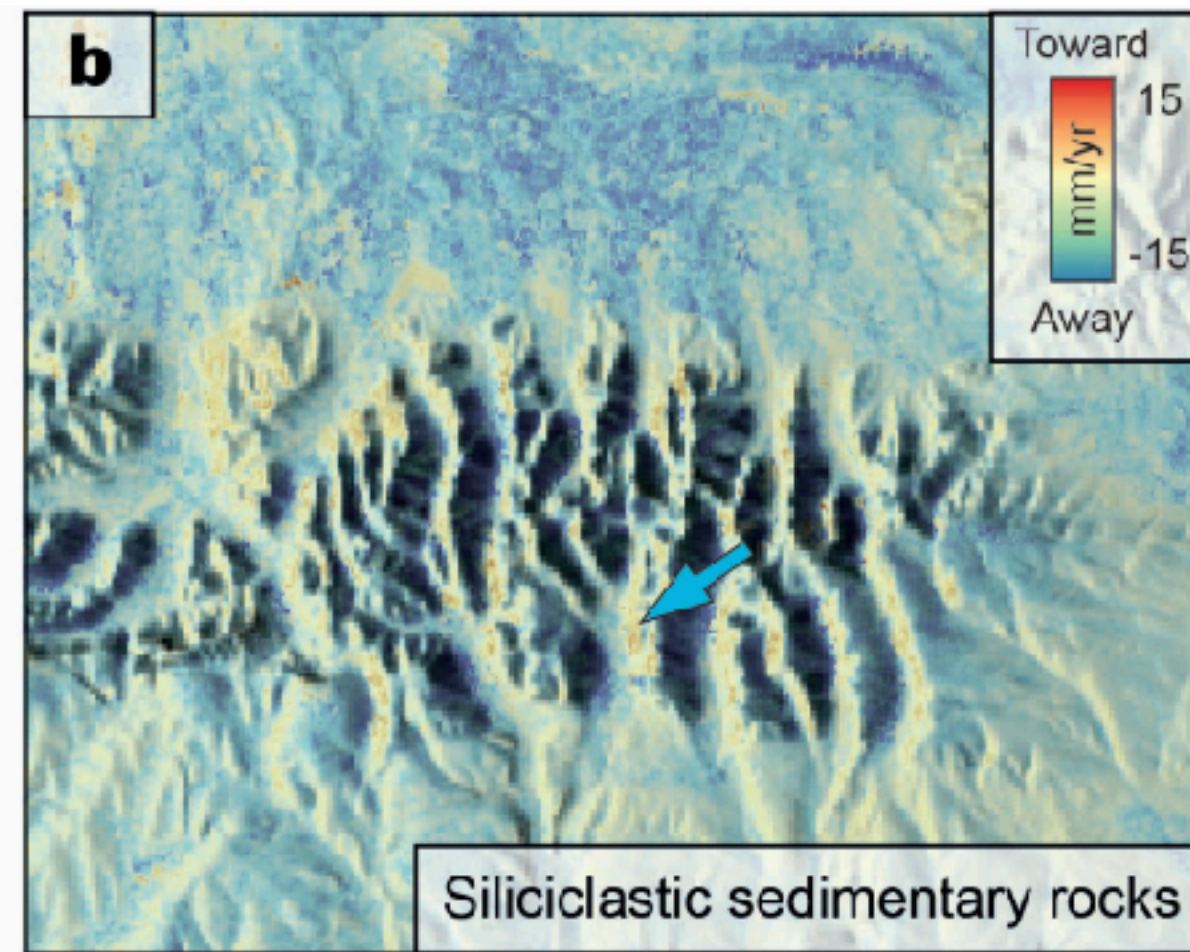


Network 1: Original

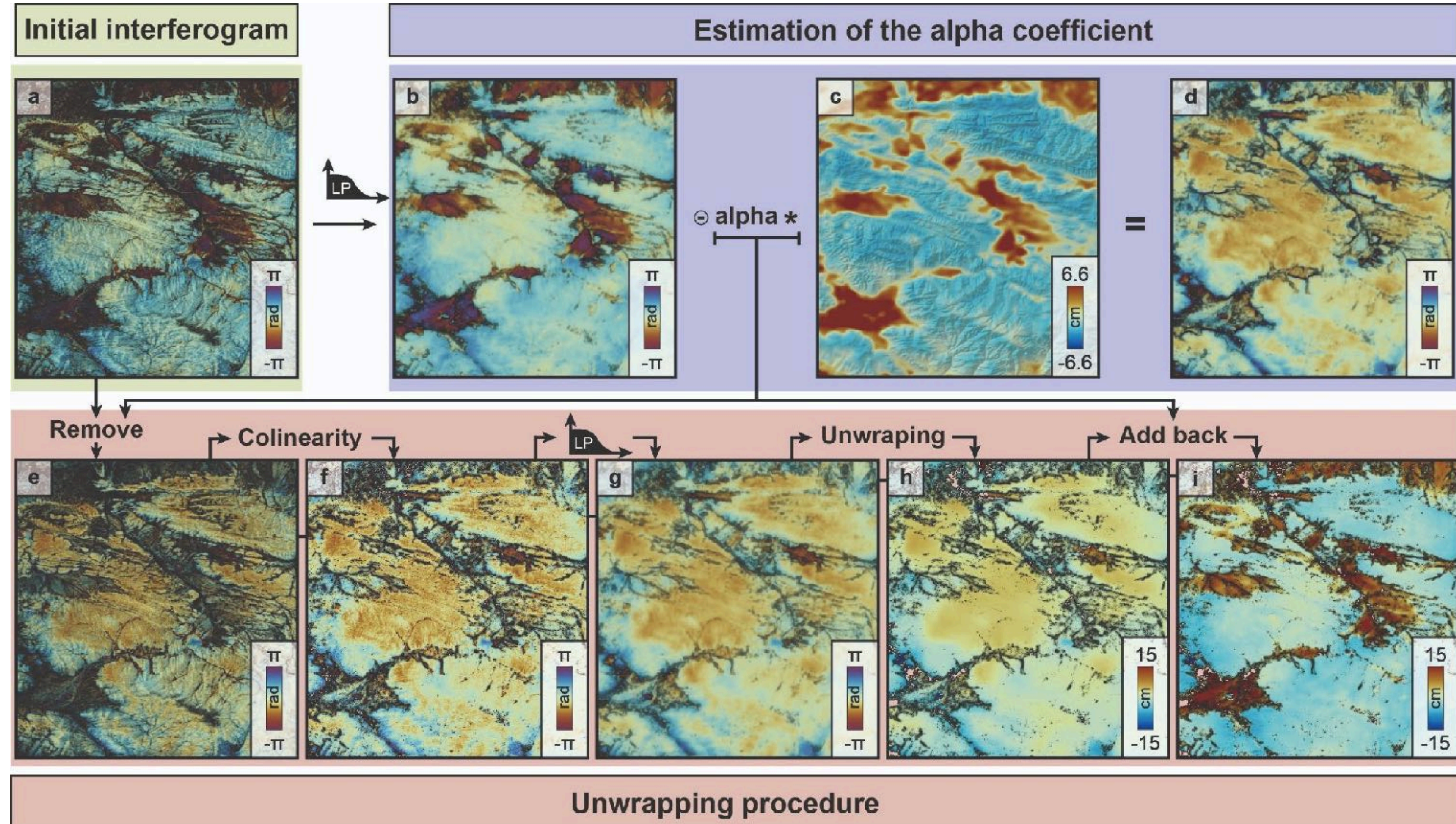
Network 3:
Temporal baseline > 24 daysLOS velocity (rad/yr)
Network 1LOS velocity (rad/yr)
Original NetworkLOS velocity (rad/yr)
Network 3

Supplementary data

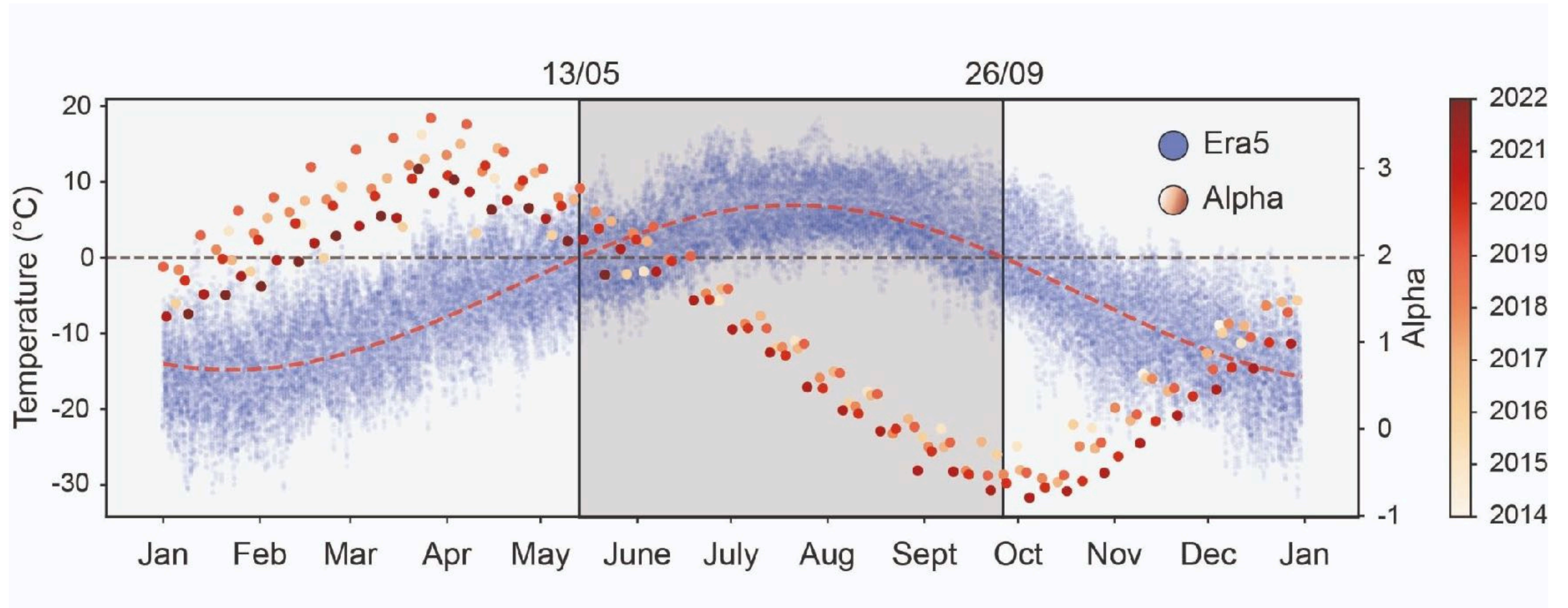
Los velocity

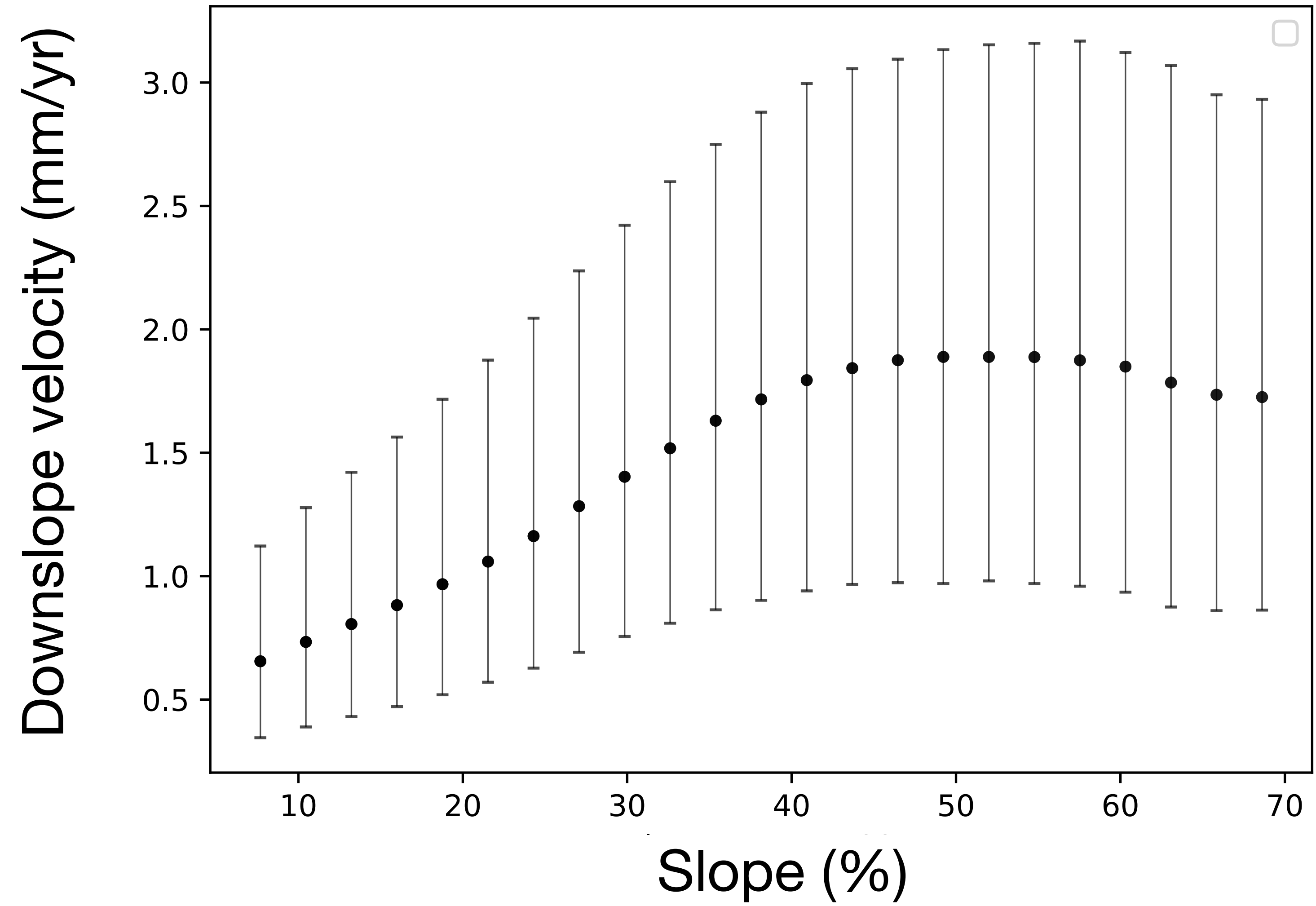


Supplementary data



Supplementary data





Supplementary data

