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合成開口レーダーで捉えた西クンルン山脈の 山岳氷河表面速度場の多様性

Diversity of Glacier Surface Velocity in the West Kunlun Shan, NW Tibet, Detected by Synthetic Aperture Radar

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要旨.

合成開口レーダー(SAR)は天候に左右されず広範囲かつ定期的に観測が可能
なため、氷河表面流速の検出に幅広く用いられている。本研究ではチベット高原
北部西クンルン山脈の山岳氷河を対象に衛星搭載型合成開口レーダーが取得し
たデータを使用しピクセルオフセットによる解析を行った。地形によるSAR 画像
のずれの補正はSRTM4 Digital Elevation Model を使用した。氷河は地表勾配
に沿って流れる平行流を仮定しピクセルオフセット法で得られた結果から氷河表
面速度場を最小二乗法的に推定した。

SAR データの解析により、西クンルン山脈の山岳氷河の表面速度場とその多
様性が明らかになった(図1)。北斜面のDuofeng氷河では上流から下流まで連続
的に流動し、下流域において明確な季節変動を検出した。West Kunlun氷河, N2
氷河では表面速度の経年的な加速、末端の前進や散乱強度の増加を検出した。
南斜面のZhongfeng氷河の最西の支流では表面速度の経年的な減少、速度分
布の変化、下流域における流動の停滞、散乱強度の減少を検出した(図2)。下流
域の停滞が存在する氷河は他にも観測された。表面速度が季節的に増加する時
期は気温や降水量が増加する時期と一致するため、融解した水が氷河の底面滑
りに影響を与えていると考えられる。また表面速度の経年的な加速や減速、末端

の前進や散乱強度の増加や減少は氷河サージ(Glacier Surge) と呼ばれる現象と
一致している。そのため、西クンルン山脈の山岳氷河の多様性は夏季の降水や
気温の上昇に加え氷河サージがその一因である可能性がある。

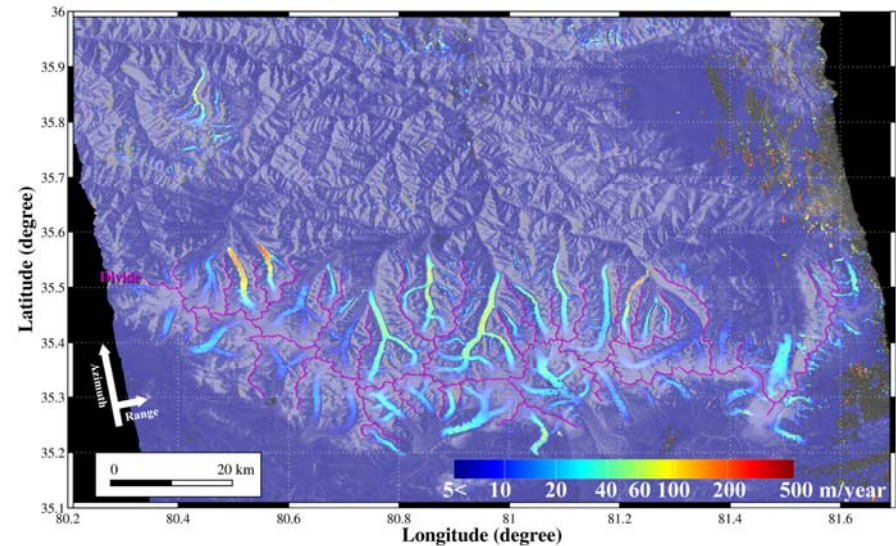


図 1. ALOS/PALSAR から求めた西クンルン山脈山岳氷河の表面速度場の一例。
5-500m/day を対数スケールで表示。背景は SAR 強度画像。紫線は山脈の分水
嶺を示す。

SARで捉えたチベット高原北部西クンルン山脈 山岳氷河表面速度場の多様性

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1 Graduate School of Science, Hokkaido University,

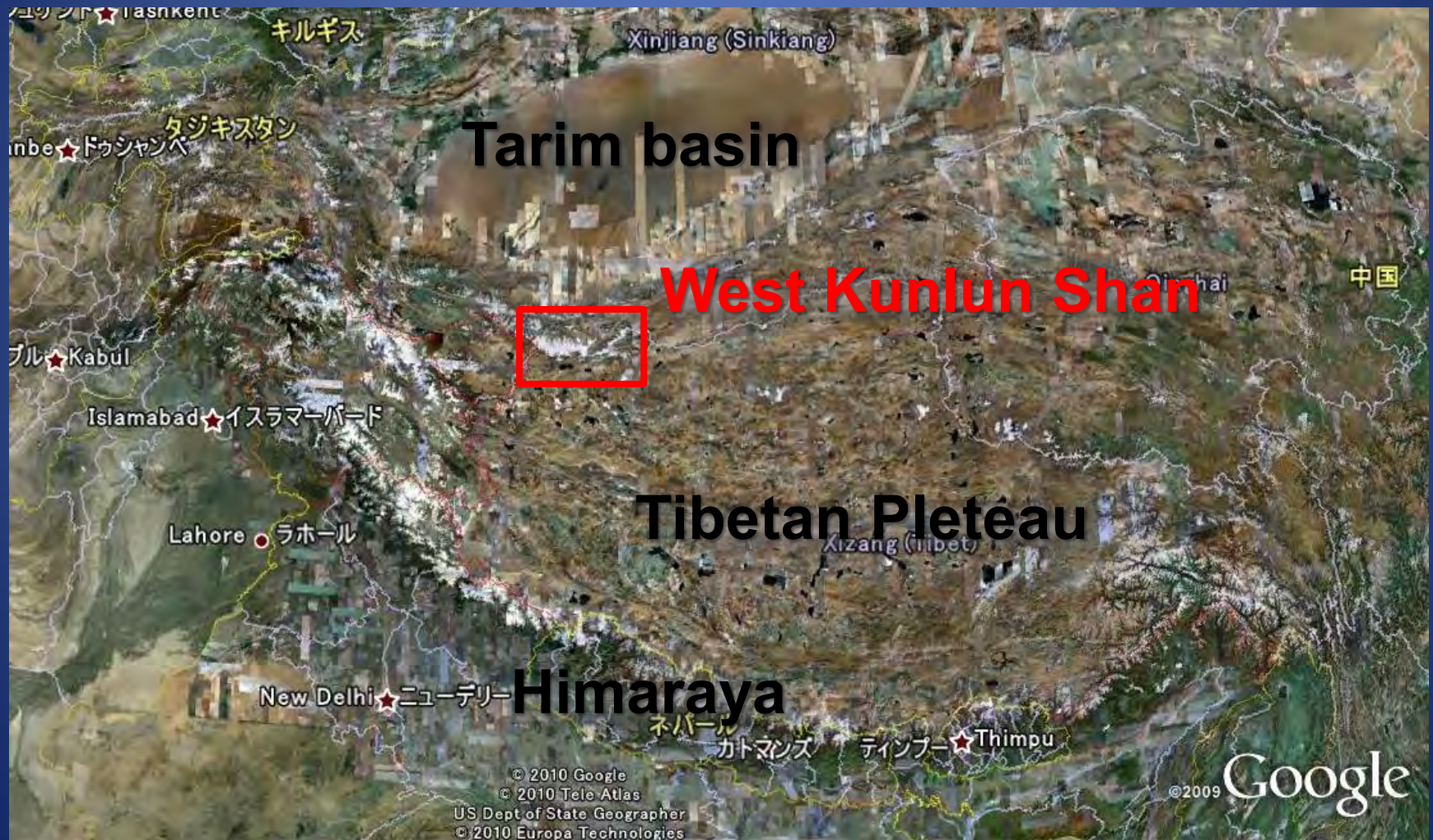
2 Department of Natural History Sciences, Hokkaido University



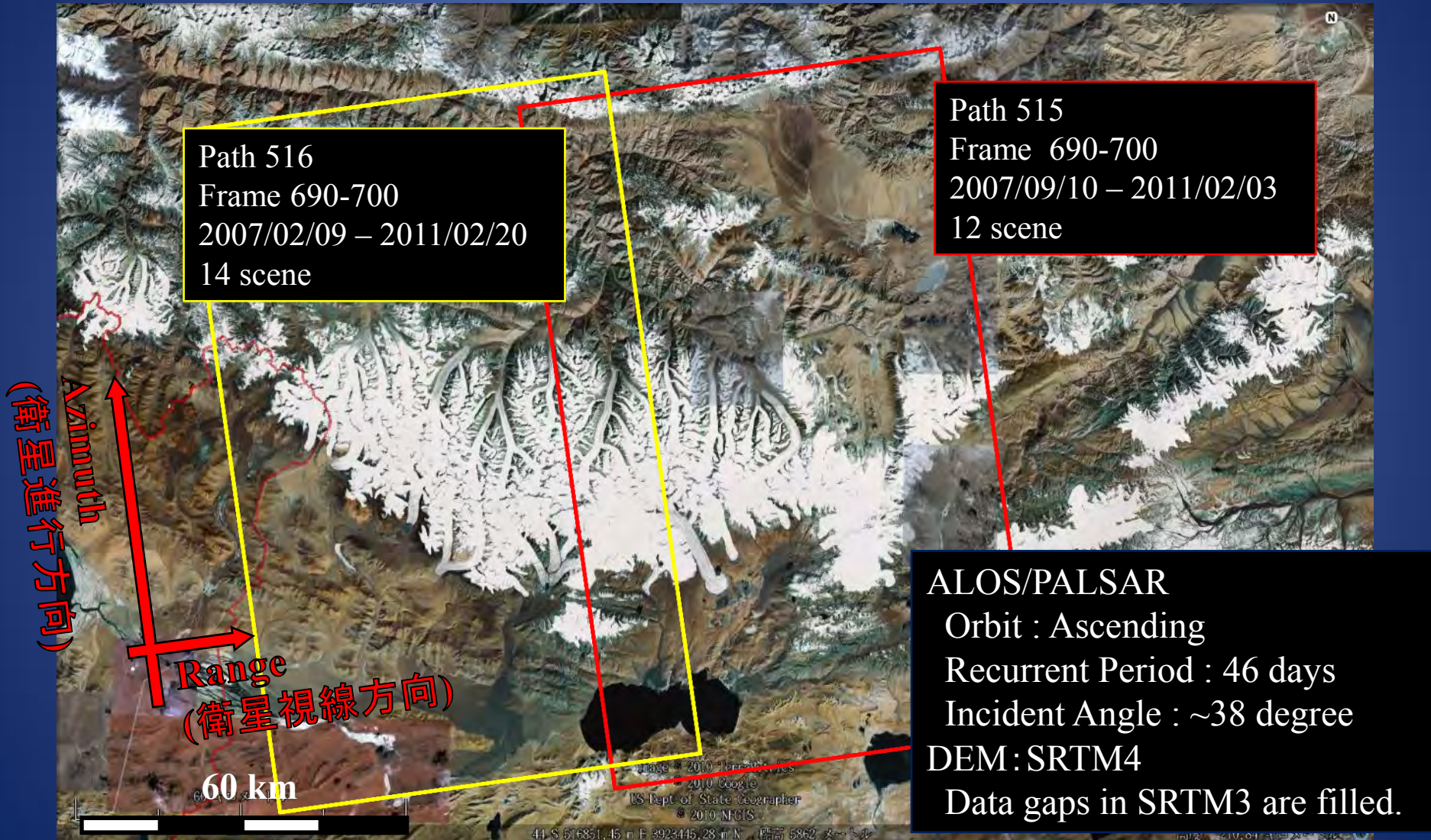
Hokkaido University
SPACE GEODESY



Where is West Kunlun Shan?

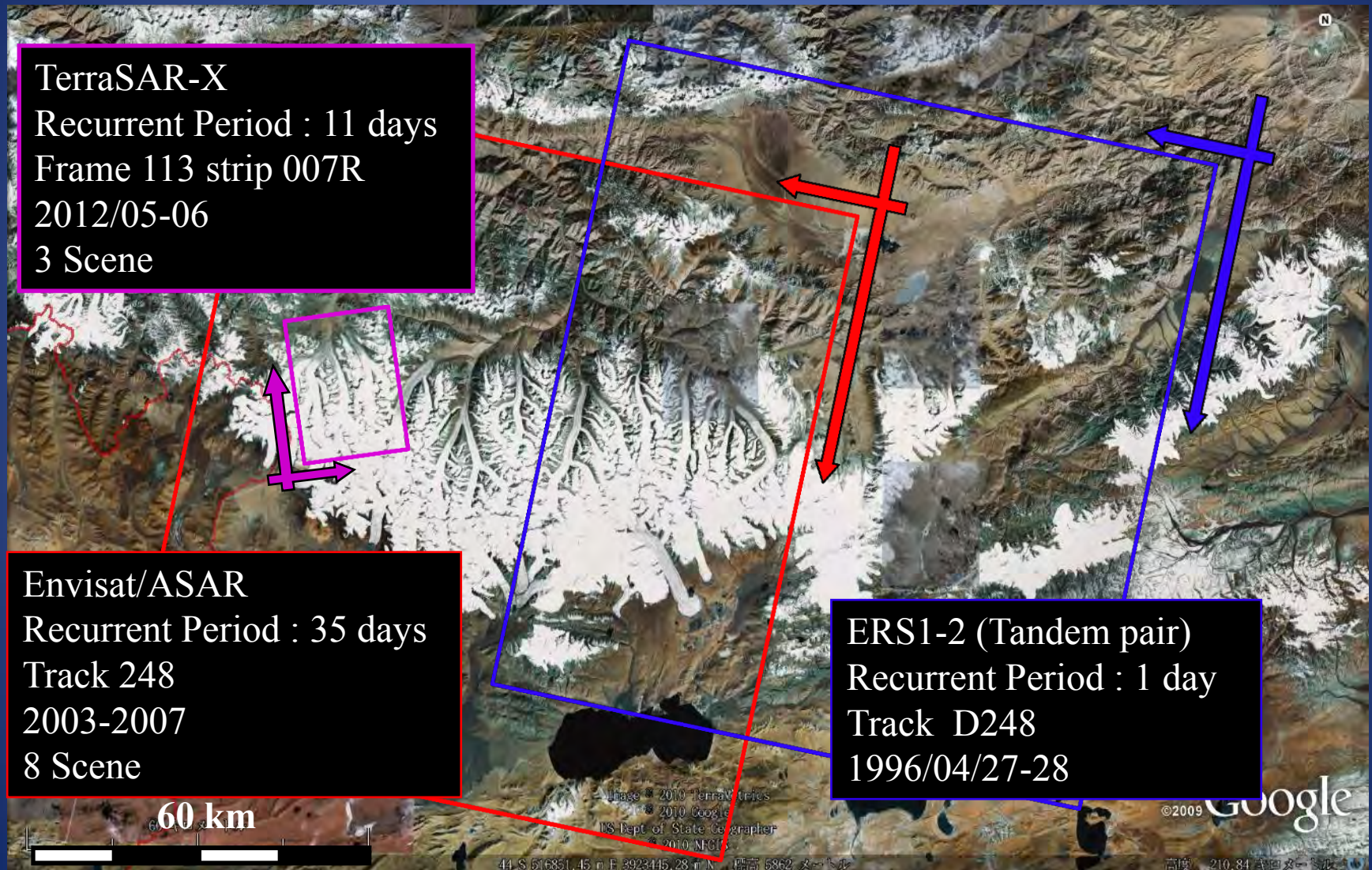


Datasets: ALOS/PALSAR (Feb 2007-Feb 2011)



The PALSAR data belongs to METI and JAXA
SRTM4 available from CGIAR-CSI (<http://srtm.csi.cgiar.org>)

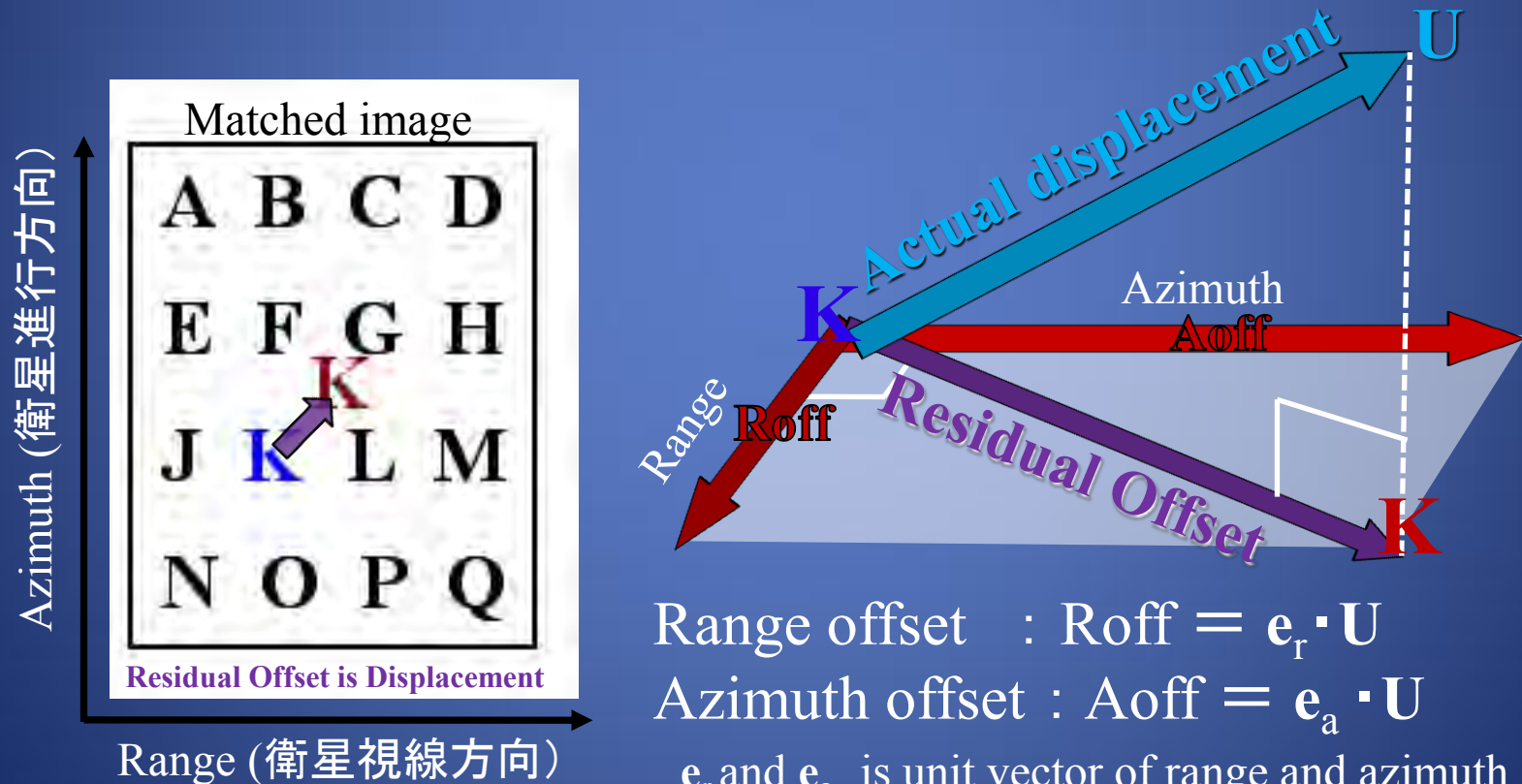
Datasets: ERS1-2, ASAR, TSX



The ASAR data belongs to ESA
SRTM4 available from CGIAR-CSI (<http://srtm.csi.cgiar.org>)

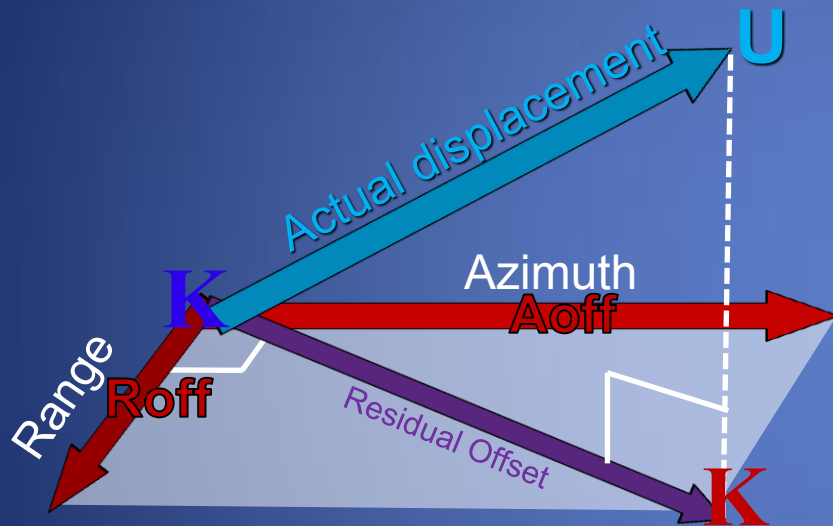
Pixel Offset (Feature tracking)

- Residual offset of image matching two SAR image.
- Effective to detect displacement **greater than ~ 1 meter**
- We can detect **2 component (range and azimuth)**.



(小林・飛田・村上, 測地学会誌, 第57巻, 第2号, 2011)

Convert to surface velocity



Range offset : $R_{off} = \mathbf{e}_{ran} \cdot \mathbf{U}$
 Azimuth offset : $A_{off} = \mathbf{e}_{azi} \cdot \mathbf{U}$
 Actual displacement : $\mathbf{U} = (U_x, U_y, U_z)^T$
 U_x : west-east component
 U_y : south-north component
 U_z : vertical component

Actual displacement and range-azimuth offset

$$\mathbf{U} = (U_x, U_y, U_z)^T$$

$$\begin{pmatrix} R_{off} \\ A_{off} \end{pmatrix} = \begin{pmatrix} \mathbf{e}_{ran} \\ \mathbf{e}_{azi} \end{pmatrix} \cdot \mathbf{U}$$

Parallel flow assumption

$$\mathbf{U} = \mathbf{e}_{grad} U$$

$$\begin{pmatrix} R_{off} \\ A_{off} \end{pmatrix} = \begin{pmatrix} \mathbf{e}_{ran} \cdot \mathbf{e}_{grad} \\ \mathbf{e}_{azi} \cdot \mathbf{e}_{grad} \end{pmatrix} U$$

$$\mathbf{d} = \mathbf{G} \mathbf{U}$$

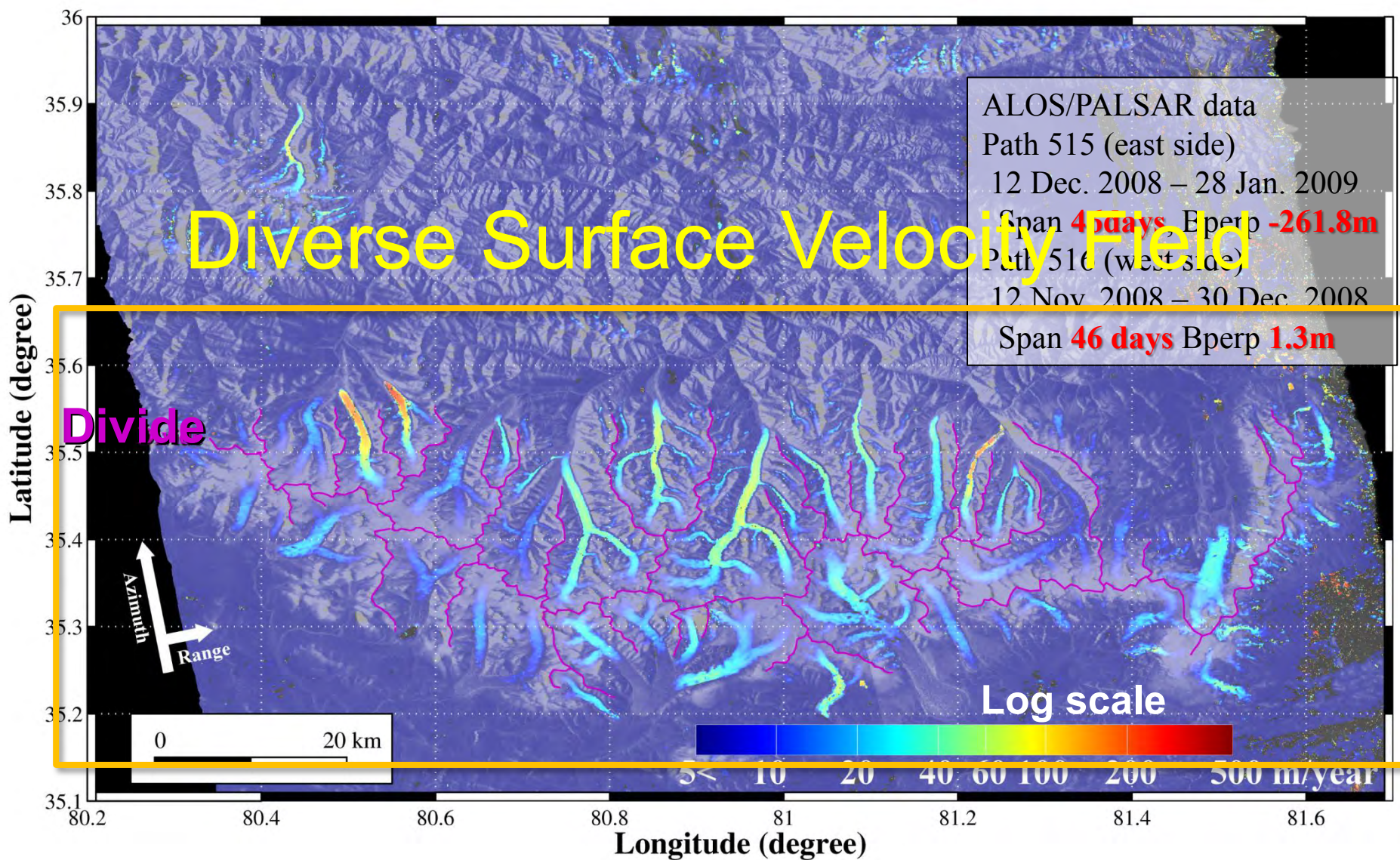
Least square method

$$\mathbf{U} = (\mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T \mathbf{d}$$

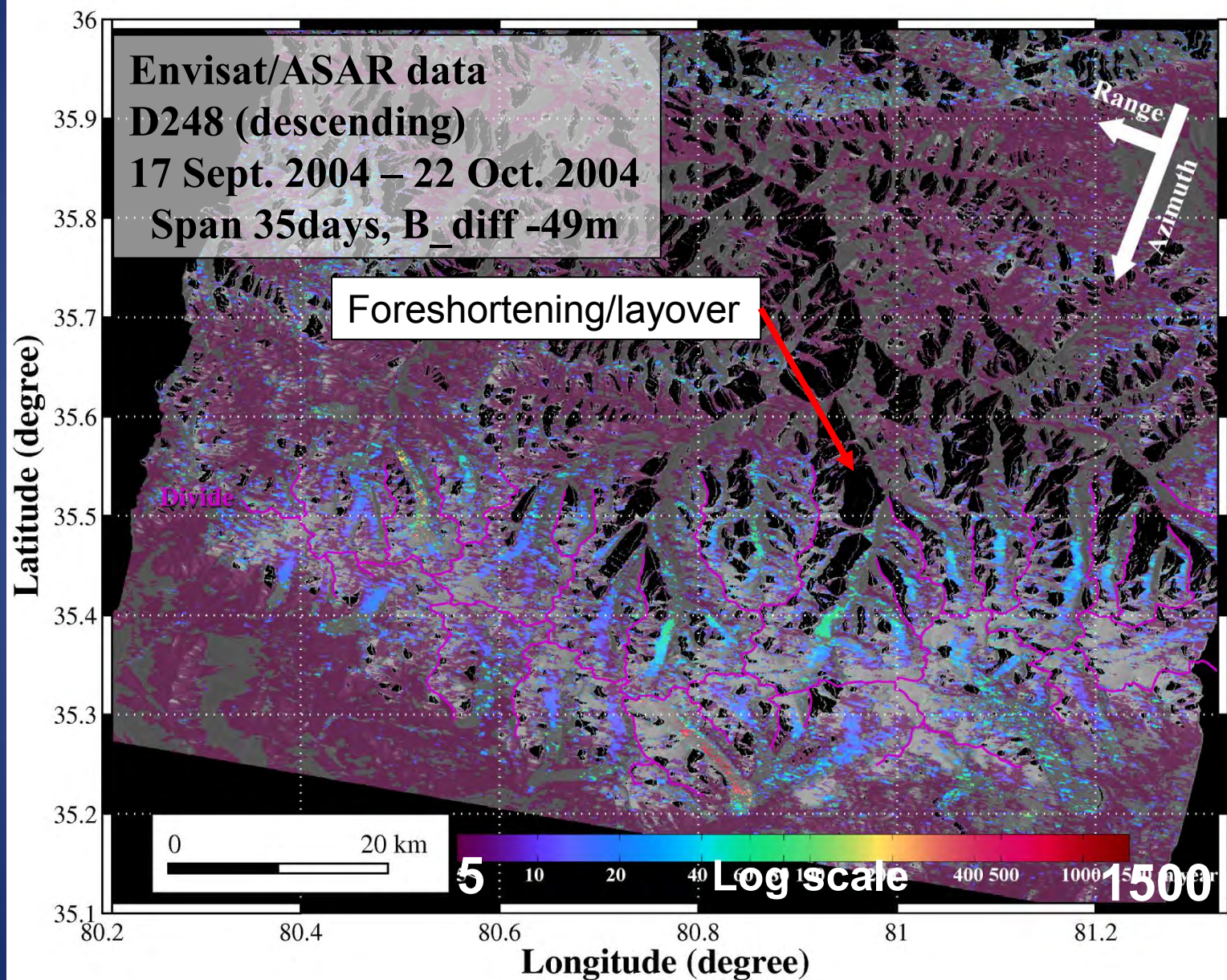
$$\mathbf{U} = \mathbf{e}_{grad} U \quad (\text{m/year})$$

Results

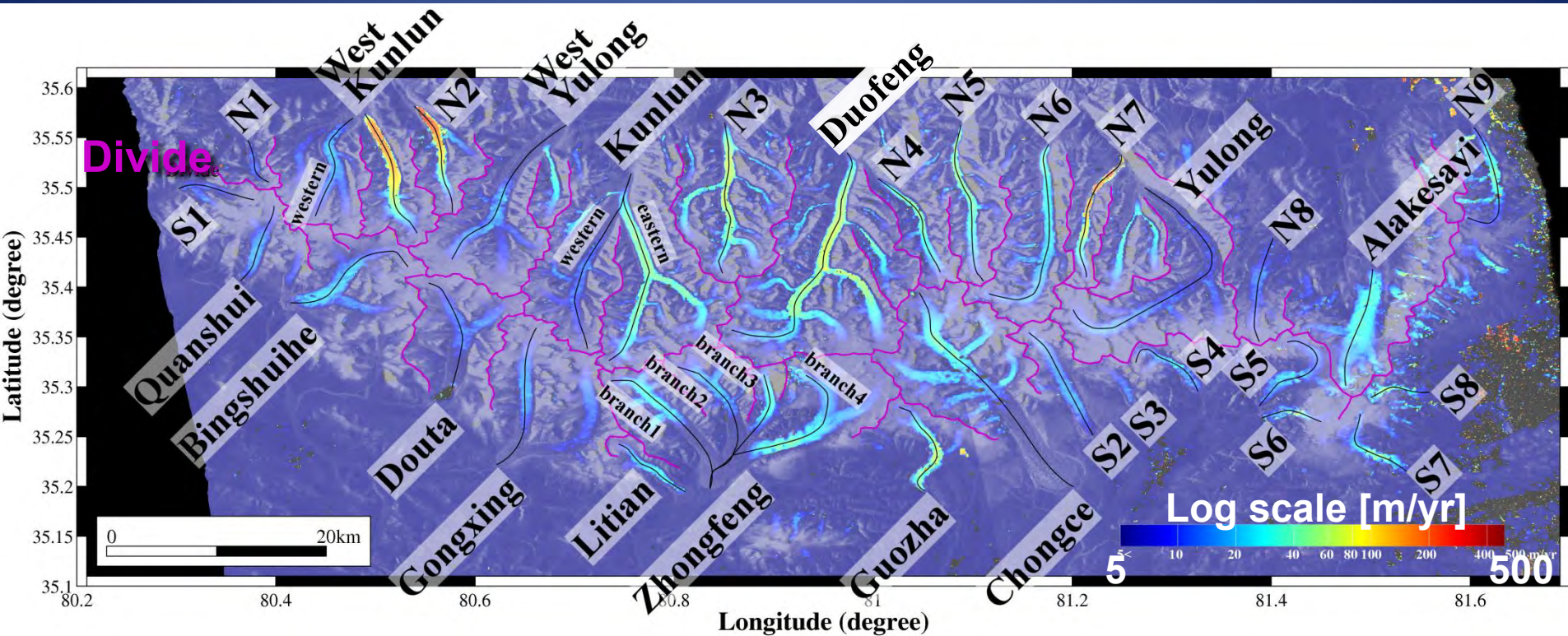
Surface Velocity in WKS



Envisat/ASAR result

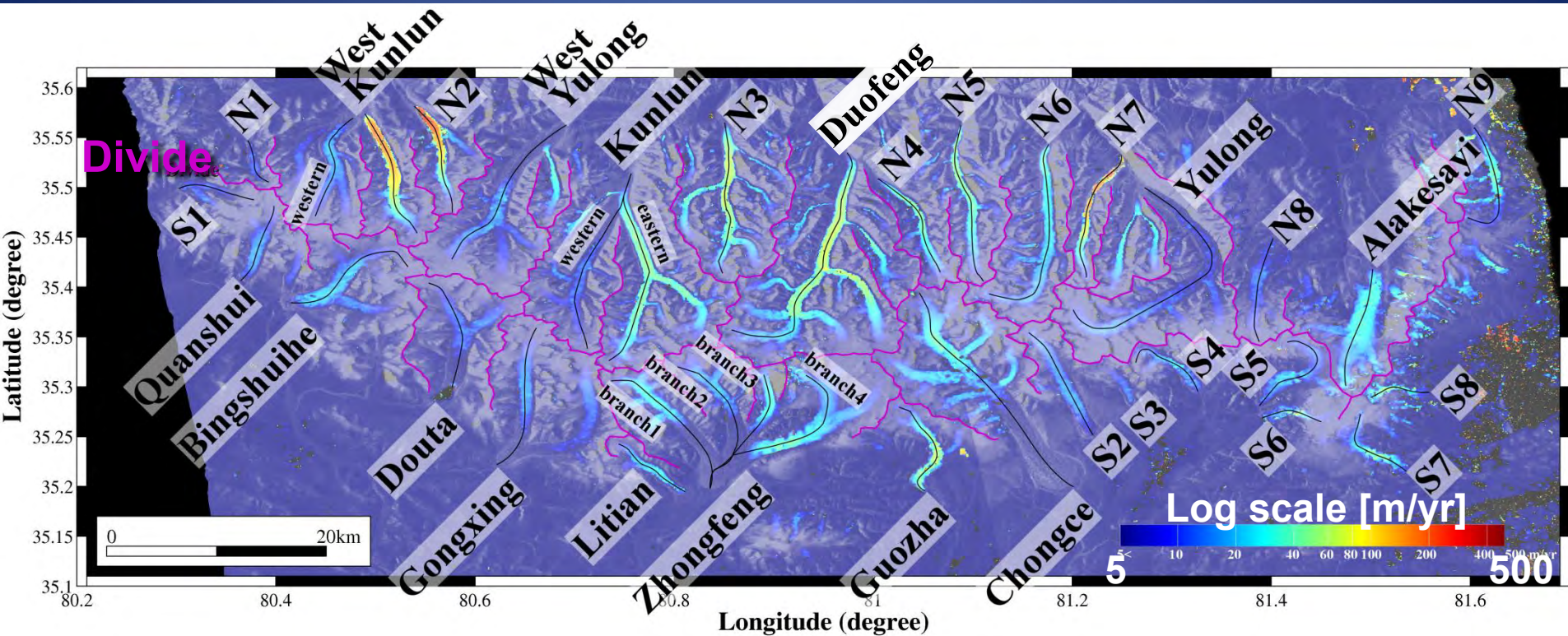


Diverse velocity in WKS



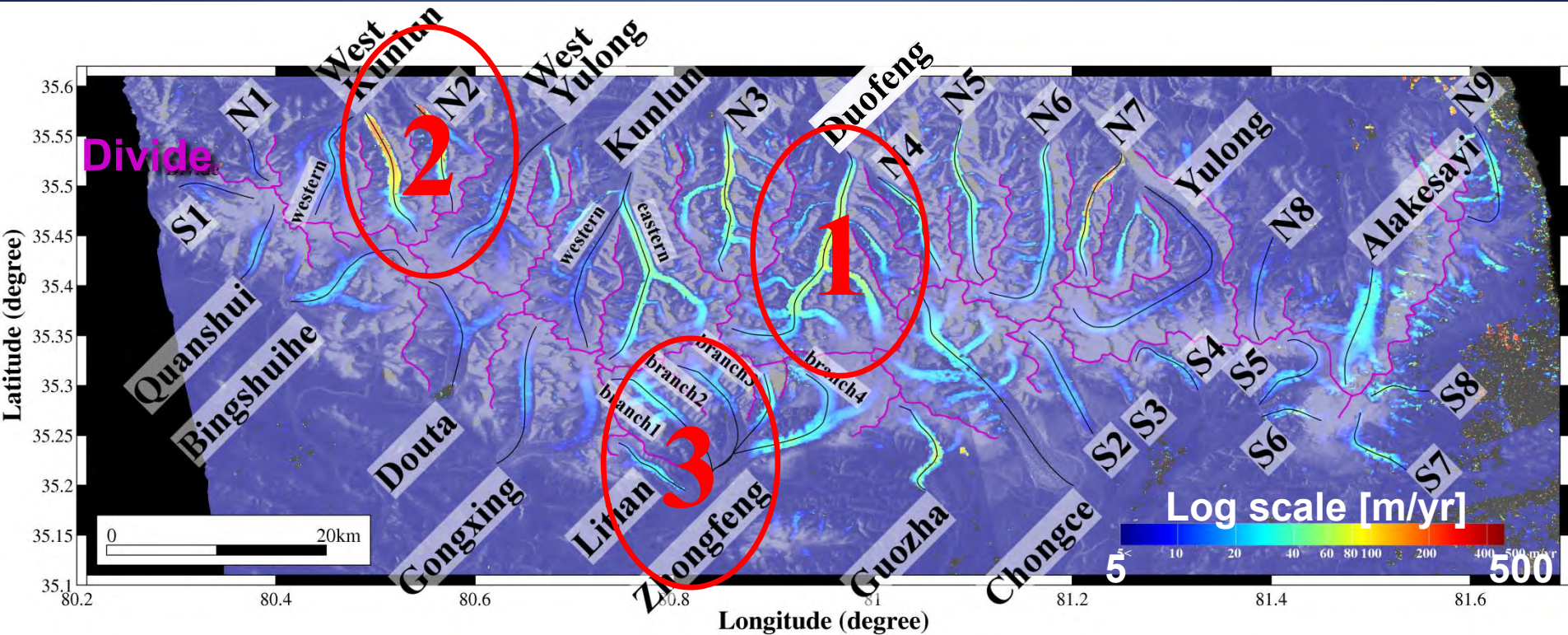
- We examined 36 glaciers in WKS.
 - 25 glaciers **flow continuously** (Duofeng, N3-6, S1-8, etc).
 - 3 glaciers are **extremely rapid** (N2, West Kunlun, N7).
 - 8 glaciers are **stagnant** (Zhongfeng, Chongce, etc).

Flow line and error estimation



- ① We set **flow line center of glacier** (North 17, South 19).
- ② **Average surface velocity** with 10×10 pixels (i.e. $500\text{m} \times 500\text{m}$) along flow line and estimated **standard deviation as error**.
- ③ We excluded if sample number ≤ 50 pixels or standard deviation $> 30\text{m/year}$. Only surge type, we excluded if sample number ≤ 25 pixels.

Diverse velocity in WKS



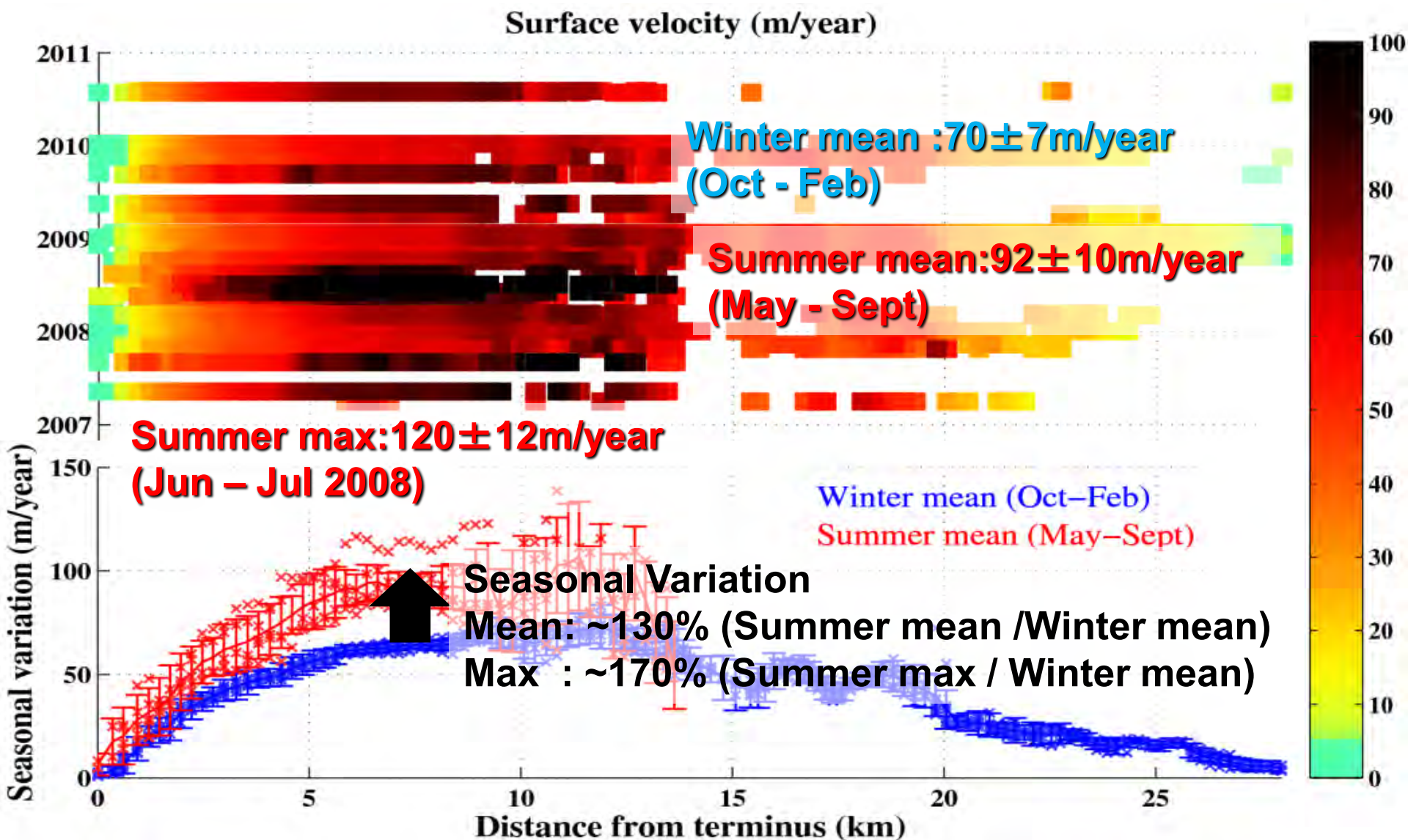
- Topics

- 1 : Seasonal variation
- 2 : Active phase of glacier surge
- 3 : Quiescent phase of glacier surge

Seasonal variation

Case : Duofeng glacier

Velocity profile of Duofeng glacier

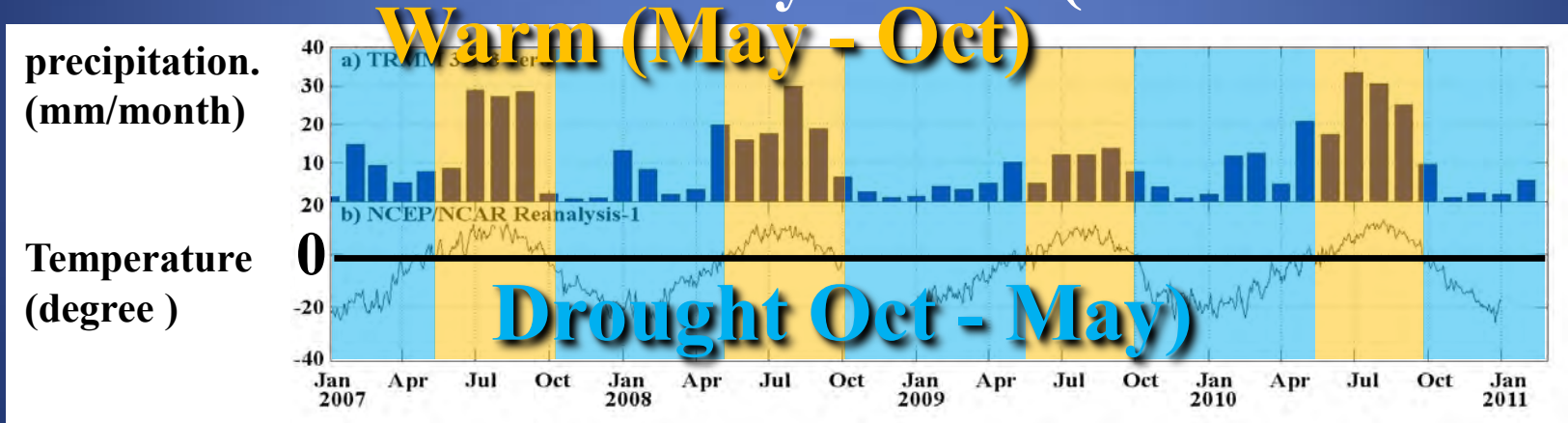


Precipitation and Temperature at WKS

- **From field research** (No station in WKS).

Annual mean precipitation and temperature : **~460mm, -13.4 °C.**
(Zheng et al., *Bull. Glacier Res.*, 1988)

- **From satellite and reanalysis data (from 2007 to 2011).**



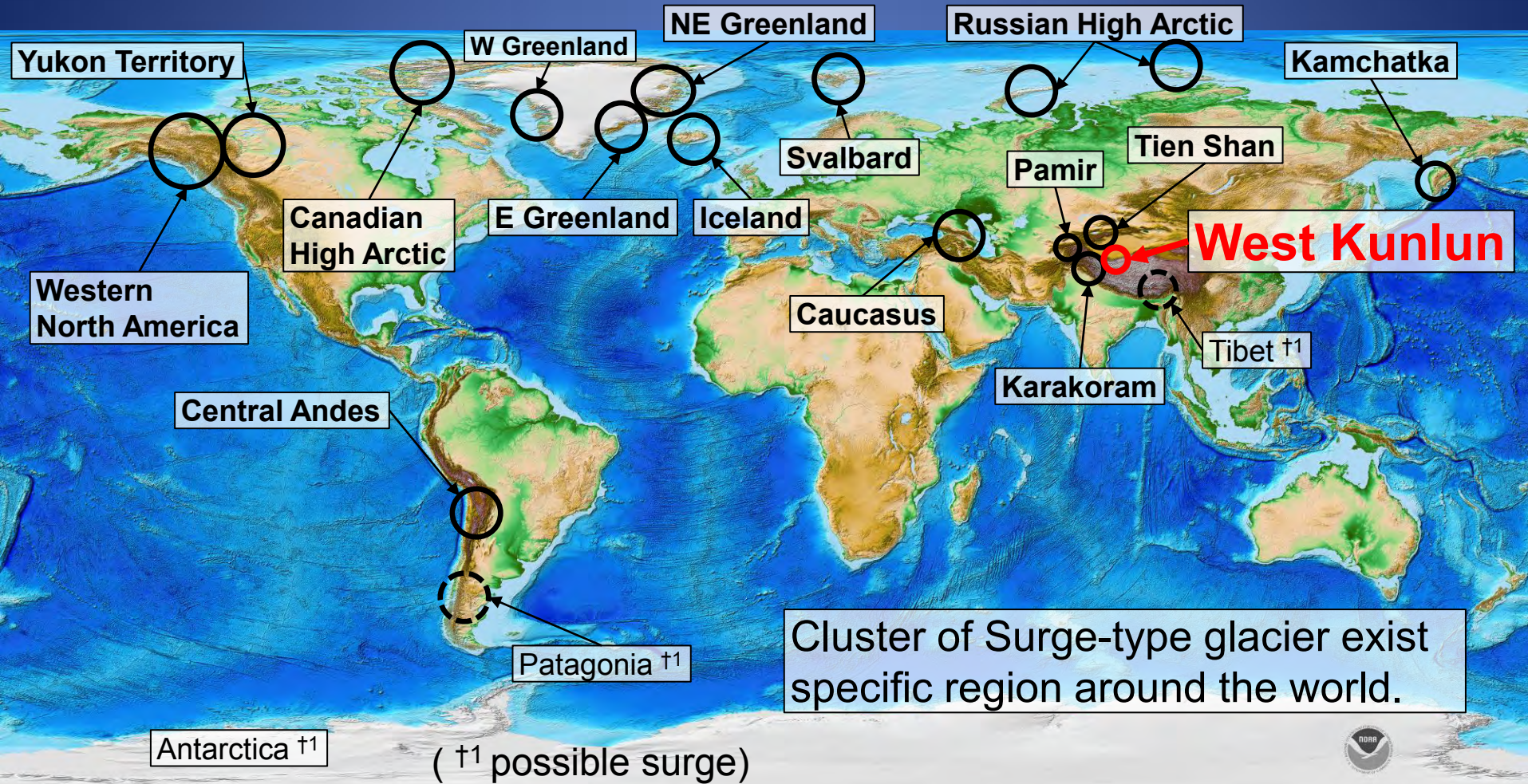
TRMM 3B43 ver6 : Average of Lat. 34.625 – 35.625, Lon. 80.125 – 82.125. NCEP/NCAR Reanalysis-1

Summer speed up is coincident with **warm season.**

Glacier surge

• Glacier Surge

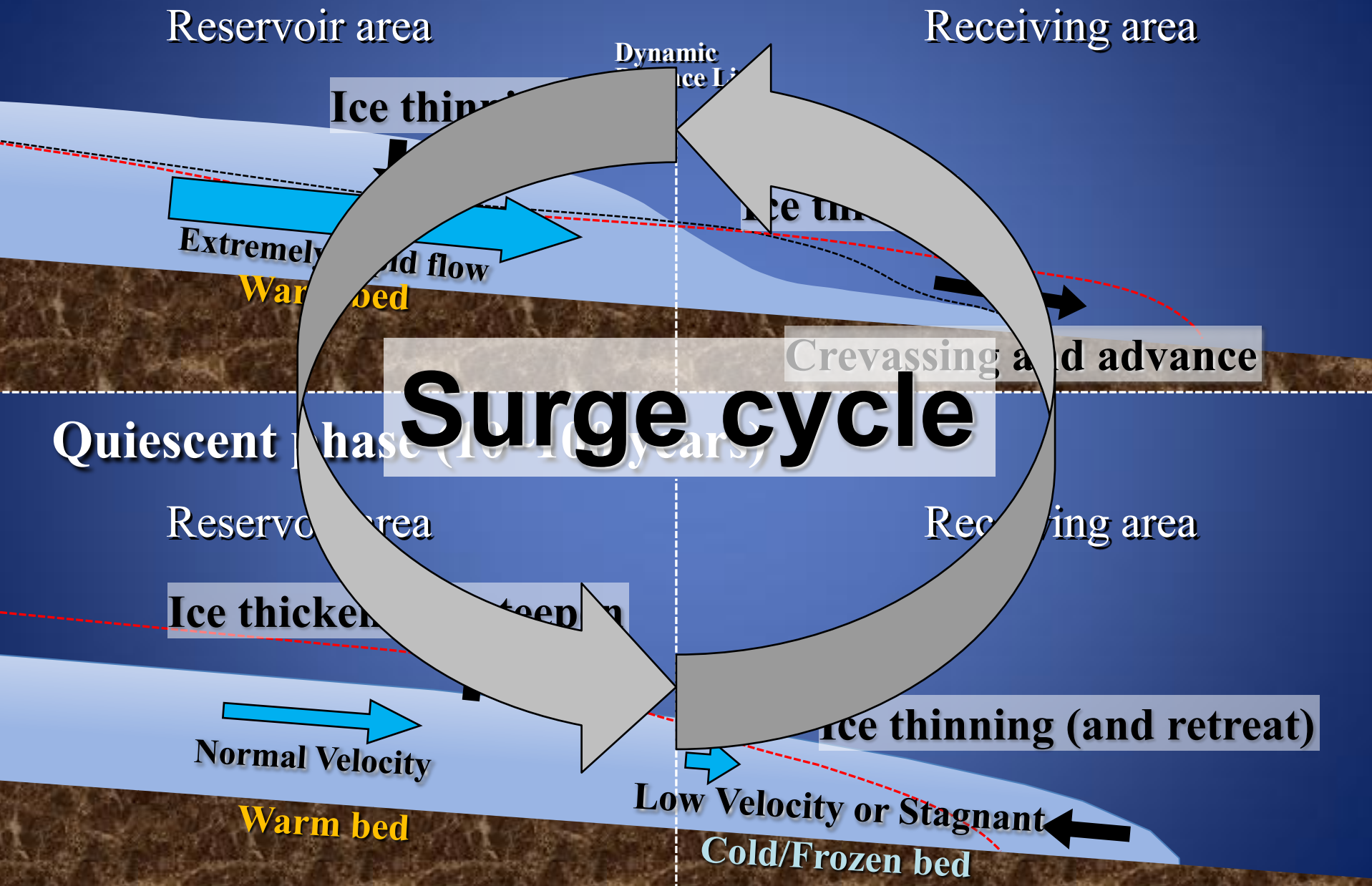
Unusually **rapid flow** and **advancing of glacier terminus** in short term.



Map data ;NOAA ETOP1 (<http://www.ngdc.noaa.gov/mgg/global/global.html>)

Surge distribution (Jiskoot, H., 1999. Characteristics of surge-type glaciers. Unpublished Ph.D. Thesis, University of Leeds, UK)

Active phase (= Surge) (several months ~ 10 years)

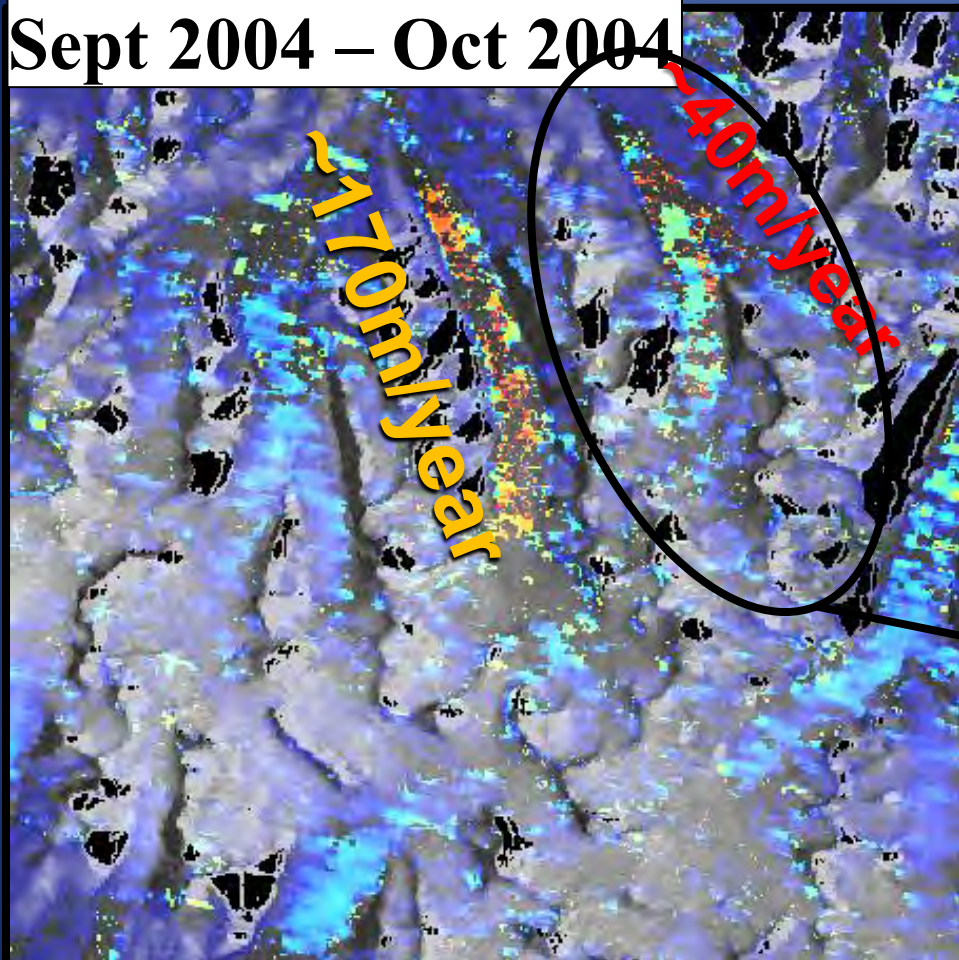


Active phase of glacier surge

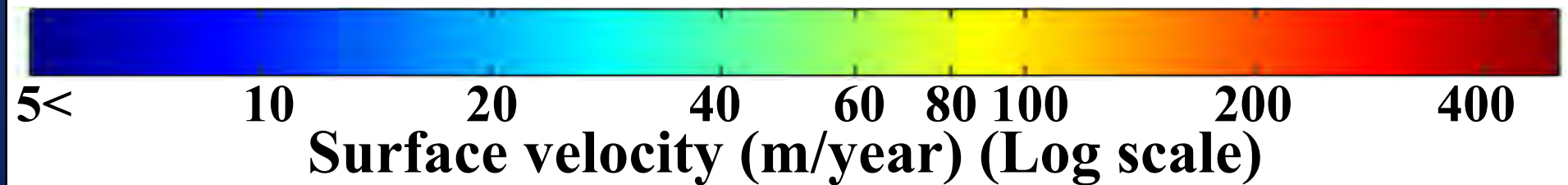
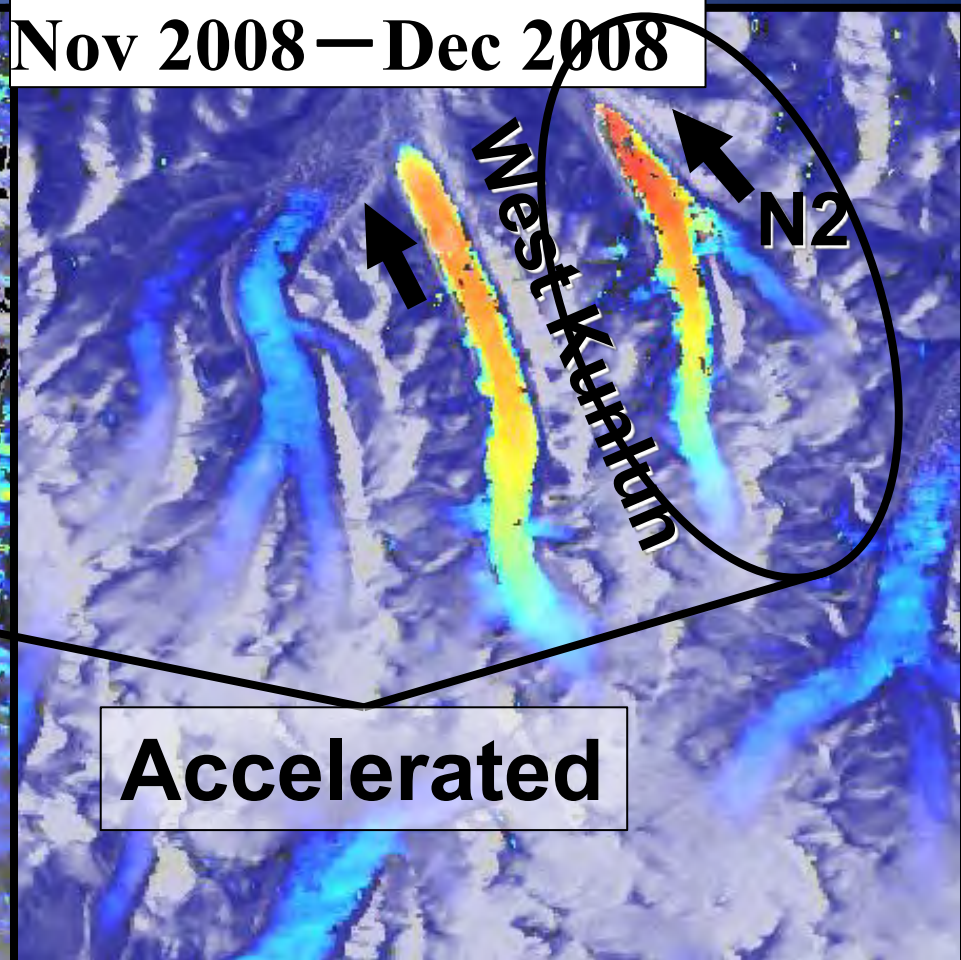
Case : N2 and West Kunlun glacier

Glacier Surge : N2 and West Kunlun

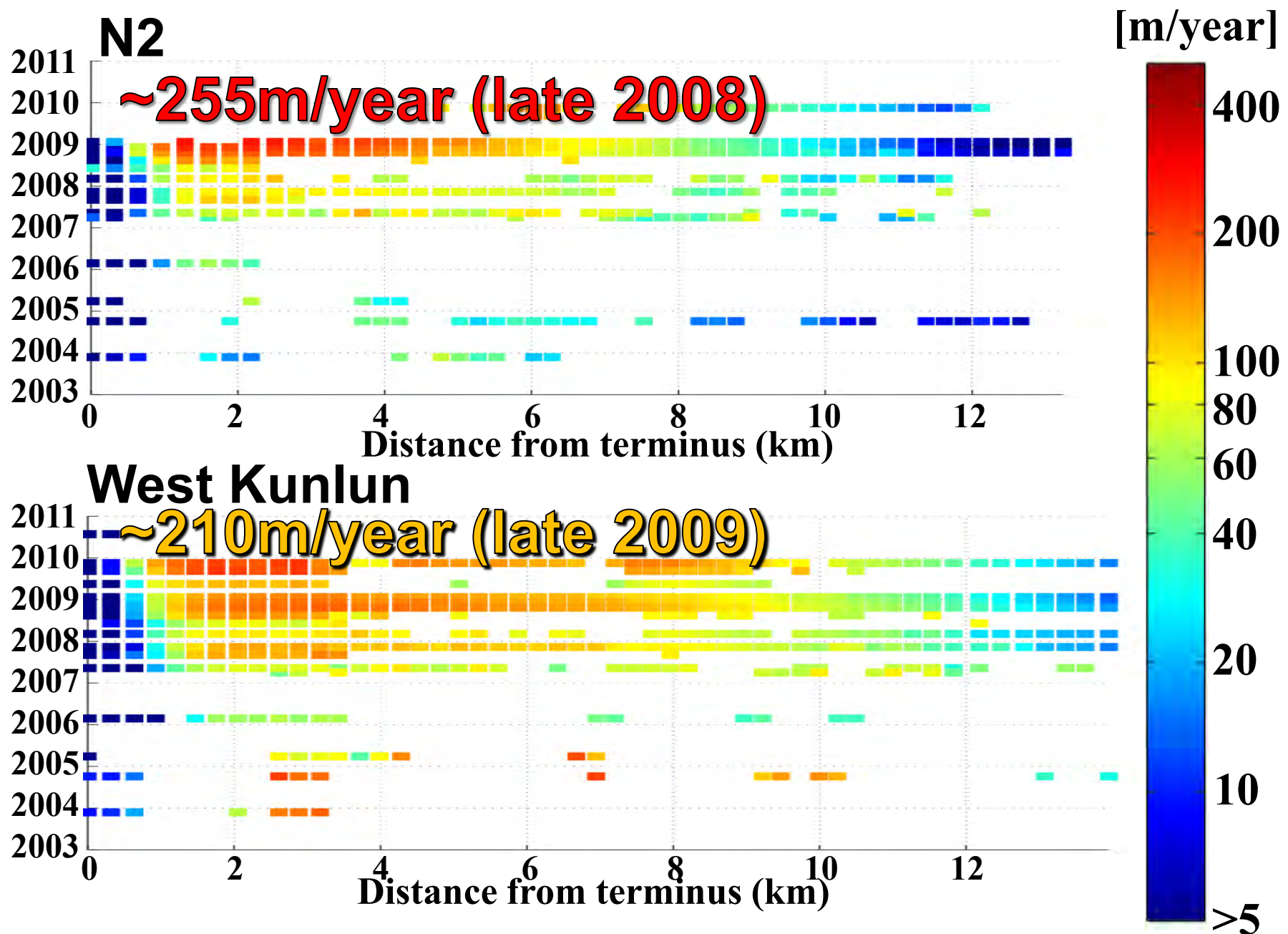
Sept 2004 – Oct 2004



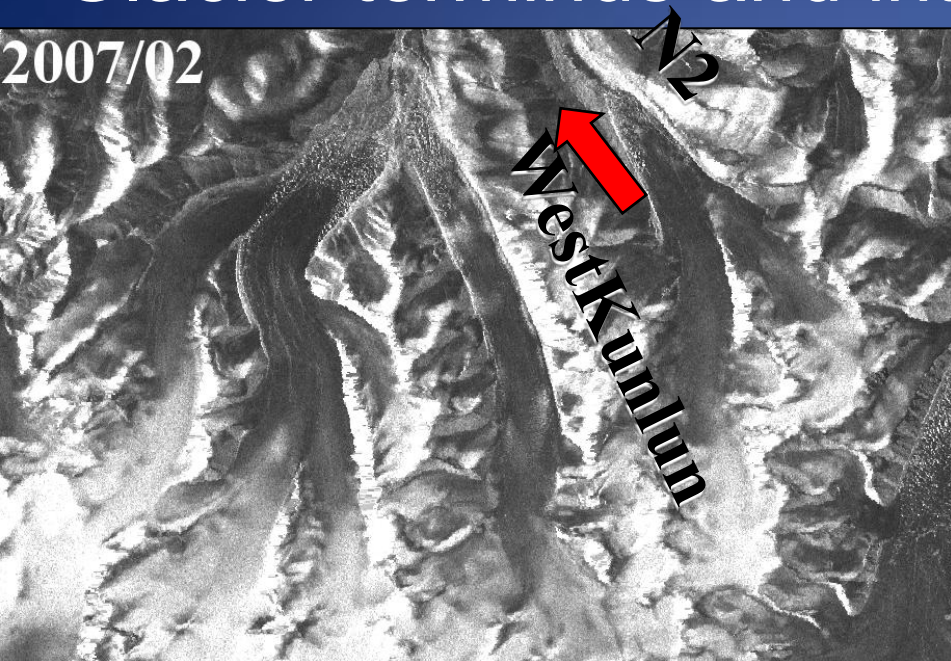
Nov 2008 – Dec 2008



Profiles of N2 and West Kunlun



Glacier terminus and intensity change



N2 Glacier

Terminus advancing **from 2008/11.**

Total advance

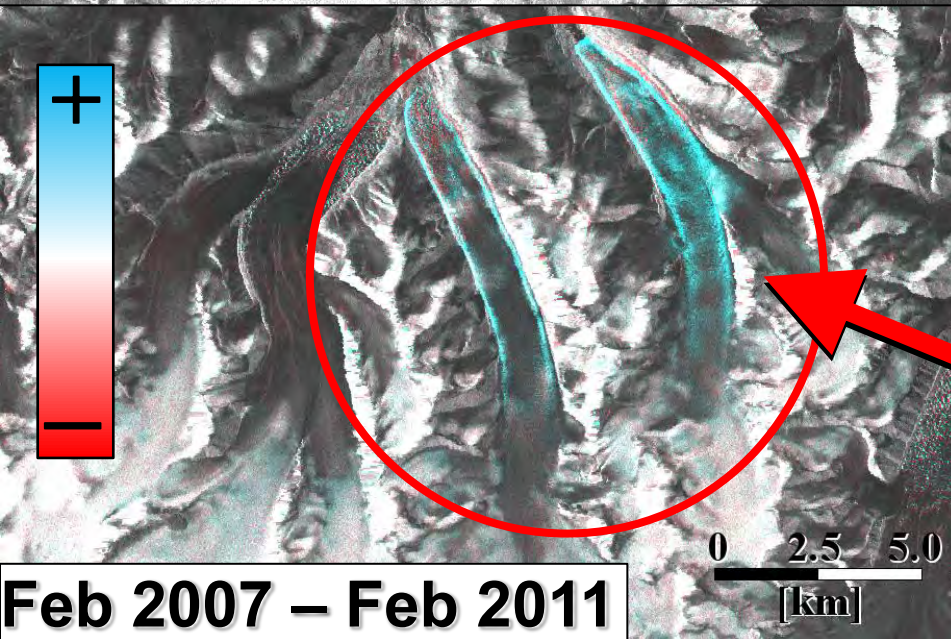
2008/11/14-2011/02/20 (828days)

916m (403m/year)

West Kunlun Glacier

Glacier terminus was unclear.

Probably advancing from 2009-2010.



Surface scattering properties

Clearly increased.

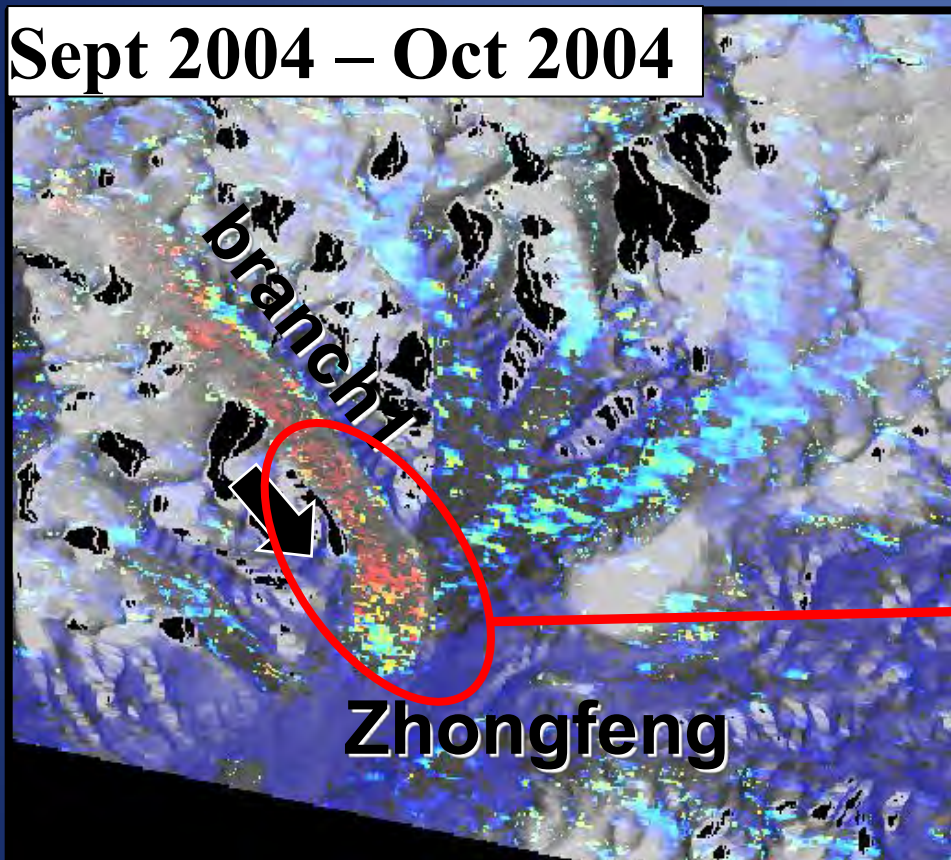
(especially border of glacier)

Shift to Quiescent phase

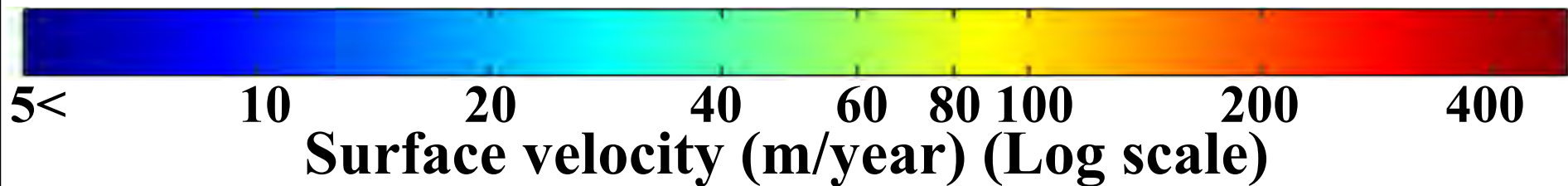
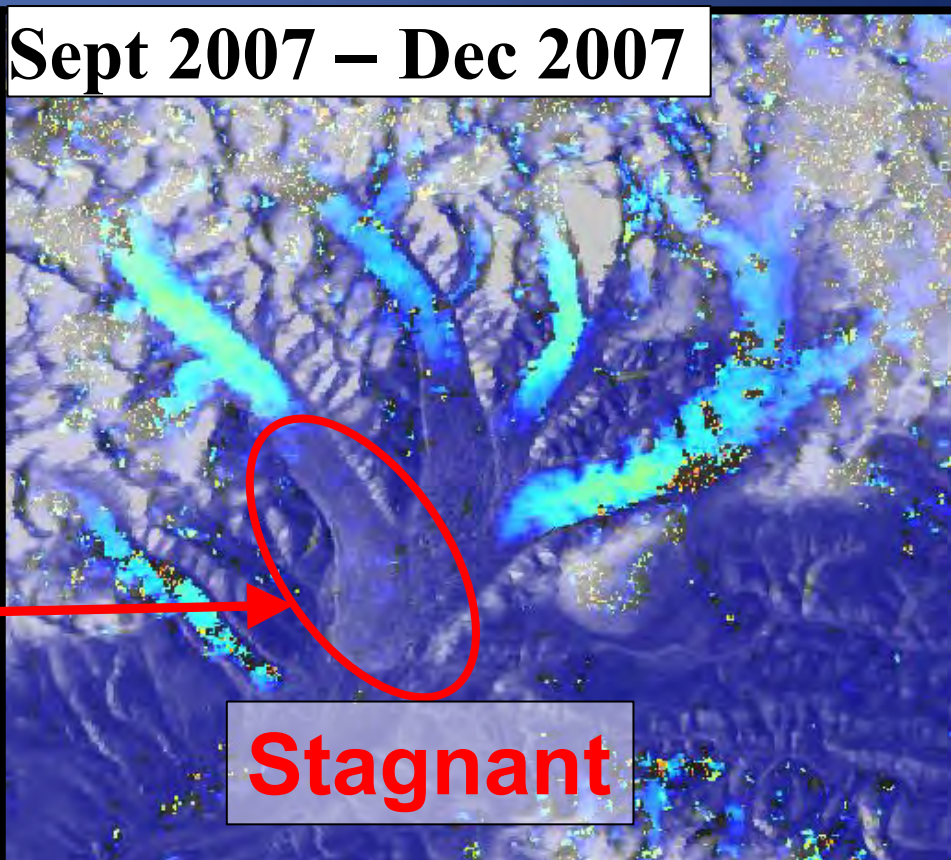
Case : Zhongfeng glacier (branch 1)

Extremely rapid : Zhongfeng (branch1)

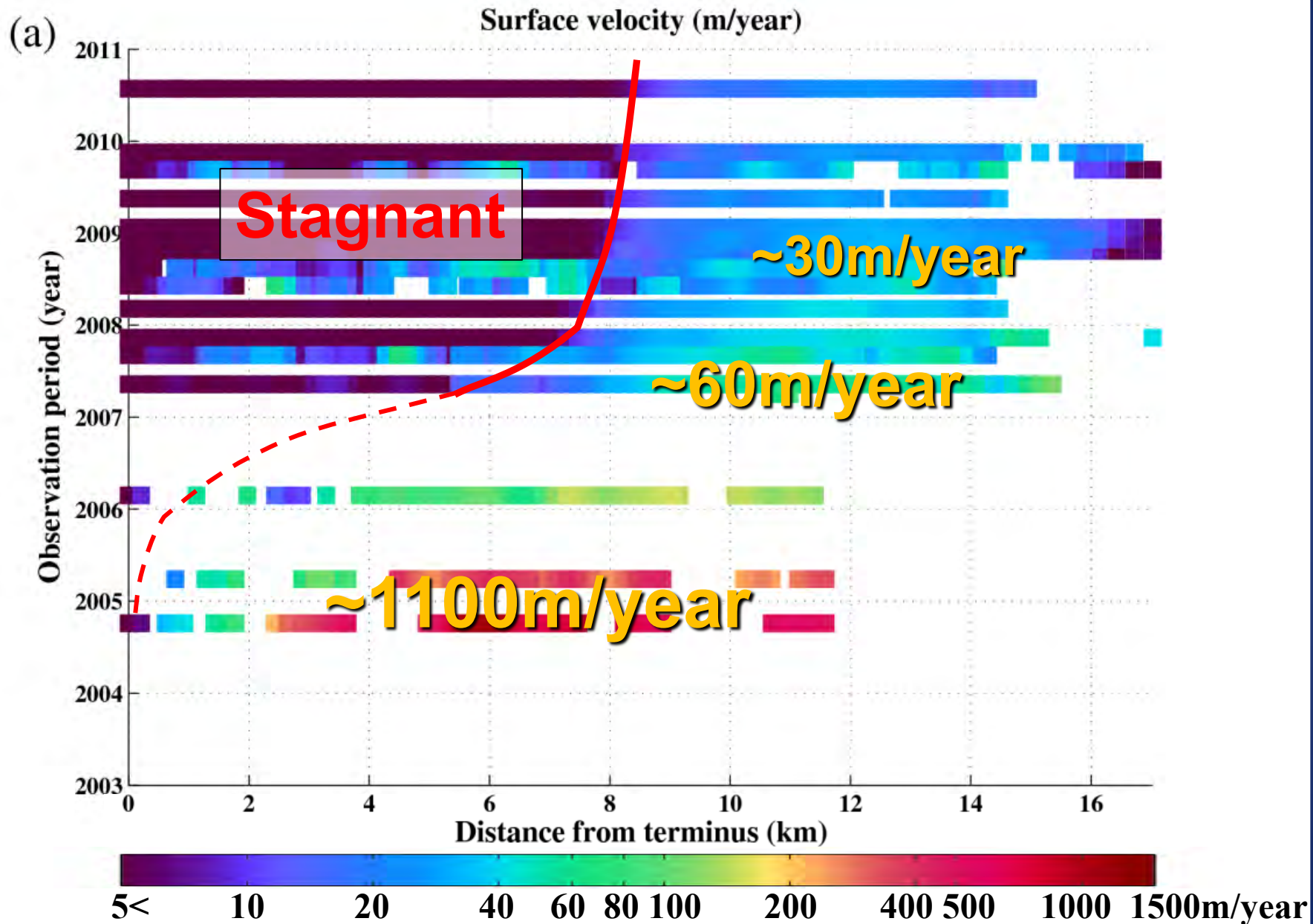
Sept 2004 – Oct 2004



Sept 2007 – Dec 2007

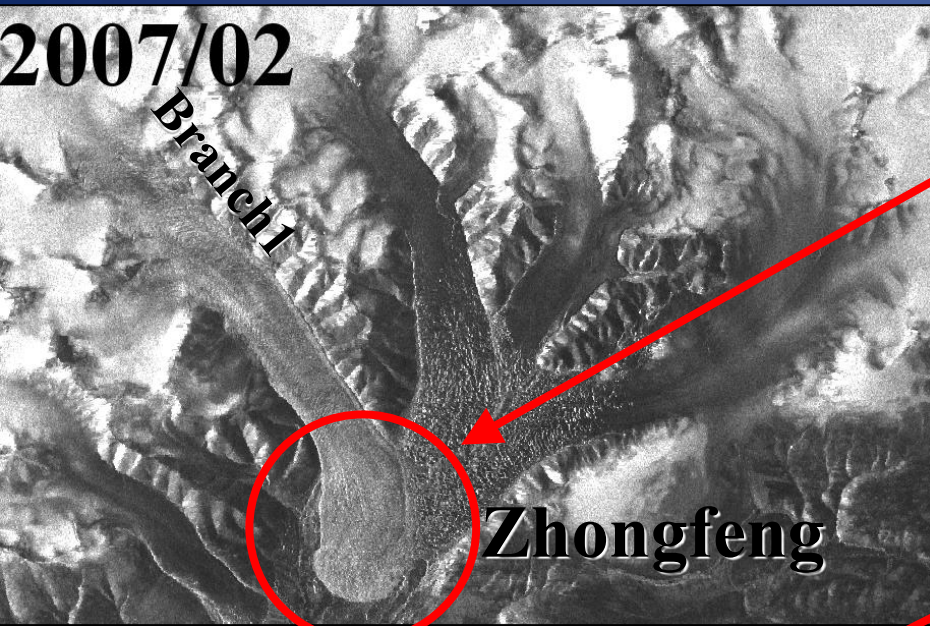


Profiles of Zhongfeng (branch1)



Glacier terminus and intensity change

2007/02

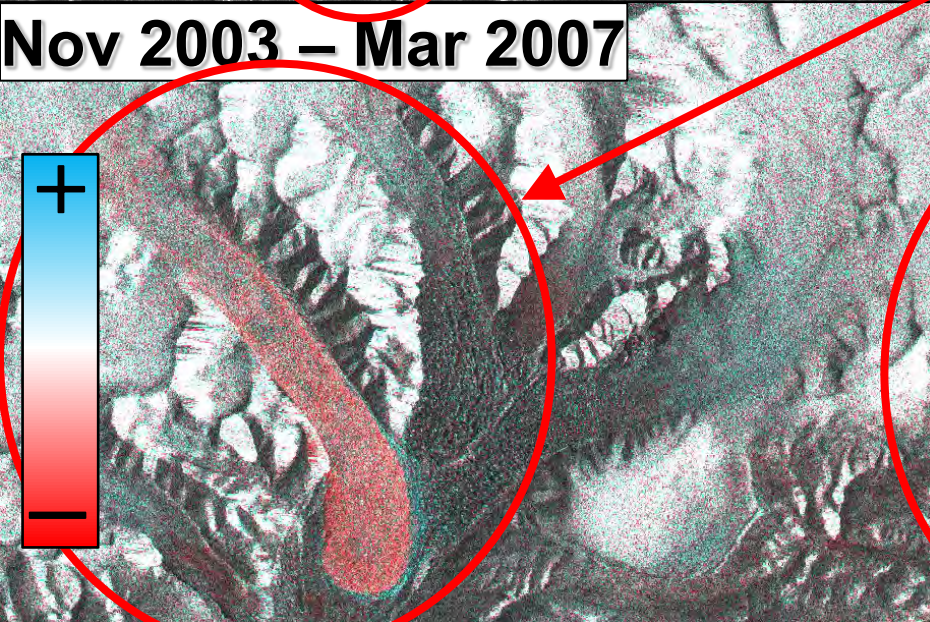


Zhongfeng (branch1)

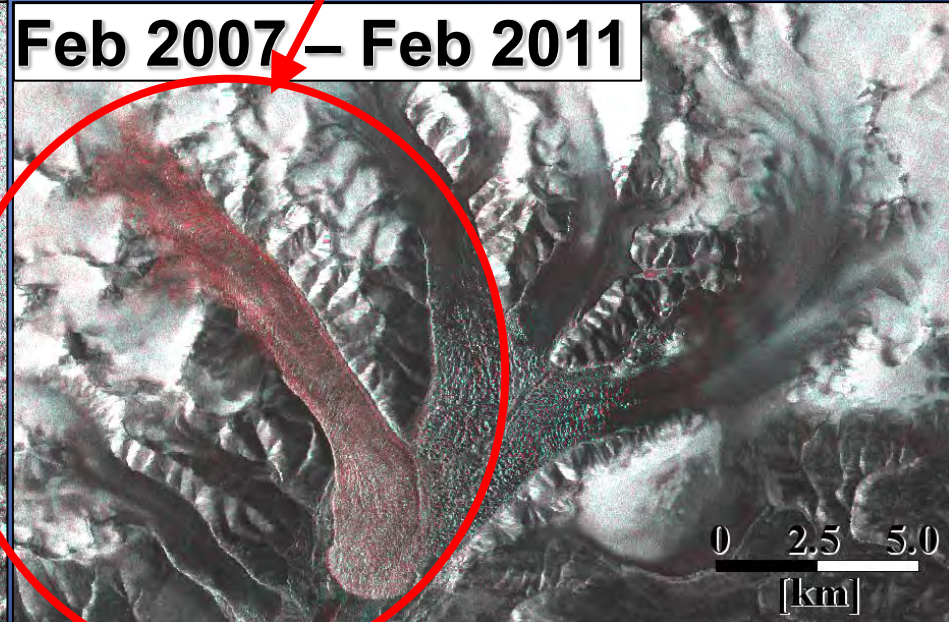
No terminus change (2007-2011)

Surface scattering properties
Clearly **decreasing**.

Nov 2003 – Mar 2007

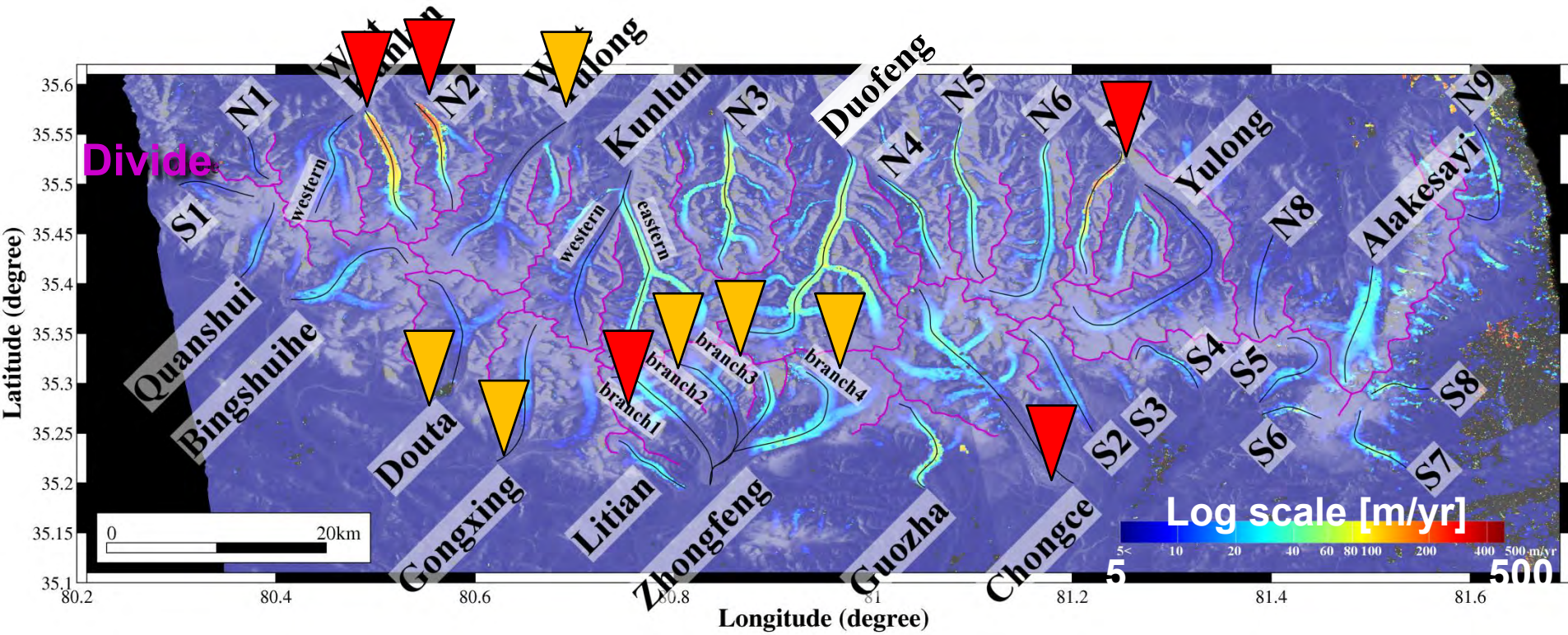


Feb 2007 – Feb 2011



RGB composed image (left) Envisat/ASAR (right) ALOS/PALSAR

Surge-type glacier in WKS



- **5 glacier** is confirmed surge-type
- **6 glacier** is possible surge-type

Active phase (= Surge) (several months ~ 10 years)

Reservoir area

Active phase

Receiving area

Surface velocity

~200-1000m/year

Duration: ~5-10 year

Ice th

Extremely

Ice flow

Warm bed

Zhongfeng (b1), Chongce

- Deceleration
- Shift to stagnant flow
- Close crevasse

N2, West Kunlun, N3

- Acceleration
- Advance of glacier terminus
- Crevassing

Reservoir area

Receiving area

Ice th

Quiescent phase

Stagnant flow

Surface velocity

~0-5m/year (lower), ~20-30m/year

Duration: Unknown

Normal Velocity

Warm bed

Ice thinning (and retreat)

Low velocity or Stagnant

Cold/Frozen bed

Summary

- We detected **glacier surface velocity and its diversity** in WKS
Seasonal variation / Glacier Surge
- We examined 36 glaciers in WKS.
- At least 11 glaciers are **surge-type glacier**.

Active phase (= Surge)

Maximum velocity : ~250 – 1000m/year

Duration : 5-10 years

Intensity change: Opening / closing of crevasse.

Quiescent phase (stagnant flow)

Maximum velocity : ~20-30m/year (upper part)
: ~0-5m/year (lower part)

Duration : Unknown



Thank you for listening

Acknowledgement

- PALSAR level 1.0 data were provided partly from the PIXEL (PALSAR Interferometry Consortium to Study our Evolving Land surface) and partly from ALOS 3rd PI (#538) under a cooperative research contract with JAXA.
- The PALSAR data belongs to METI and JAXA, Envisat and ERS 1/2 data is copyrighted by ESA, TerraSAR-X /Tandem-X data is copyrighted by DLR.
- This study is assisted by ESPEC Foundation for Global Environment Research and Technology (Charitable Trust) (ESPEC Prize for the Encouragement of Environmental Studies).
- Amante, C. and B. W. Eakins, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp, March 2009 (<http://www.ngdc.noaa.gov/mgg/global/global.html>) .
- Jarvis A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from <http://srtm.csi.cgiar.org>.