



Istituto di Ricerca per la Protezione Idrogeologica



Consiglio Nazionale delle Ricerche



IPROMO
28 SEP – 9 OCT 2020

GLACIER MONITORING USING TIME-LAPSE IMAGERY THE CASE STUDY OF THE PLANPINCIEUX GLACIER

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NATIONAL RESEARCH COUNCIL OF ITALY
RESEARCH INSTITUTE OF THE GEO-HYDROLOGICAL PROTECTION
GEOHAZARD MONITORING GROUP

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VALUABLE TOOL FOR GLACIER
MONITORING

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KINEMATICS AND INSTABILITIES



DIGITAL IMAGE CORRELATION (DIC)

DIC DEVELOPED IN THE 80s FOR LABORATORY EXPERIMENTS

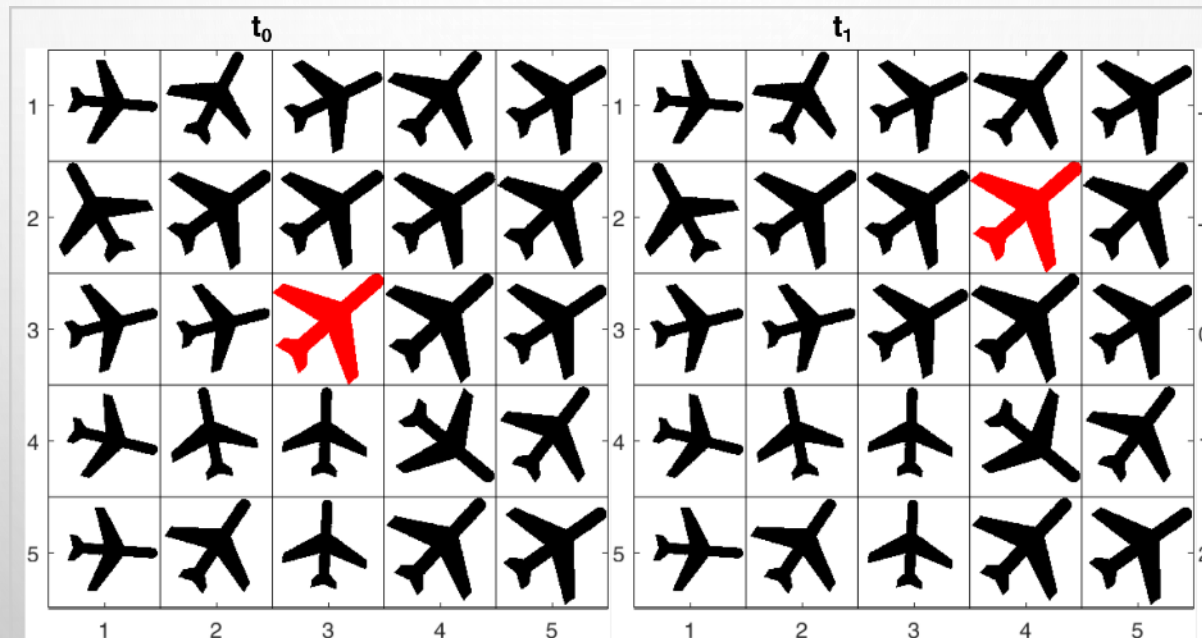
IN EARTH SCIENCES, DIC WAS APPLIED MOSTLY ON AEROSPACE IMAGES
DURING THE 90s

THE FIRST STUDY OF TERRESTRIAL DIC ON GLACIER WAS IN 2000 TO
MEASURE THE SURFACE VELOCITY OF THE GODELY GLACIER (NZ)^[1]

HOWEVER, CONTINUOUS DIC MONITORING PLANS ARE RARE

DIC - FUNDAMENTALS

THE PRINCIPLE OF DIC IS TO SEARCH FOR THE DISPLACEMENT OF AN IMAGE TILE BETWEEN TWO ACQUISITIONS OF THE SAME SCENE.

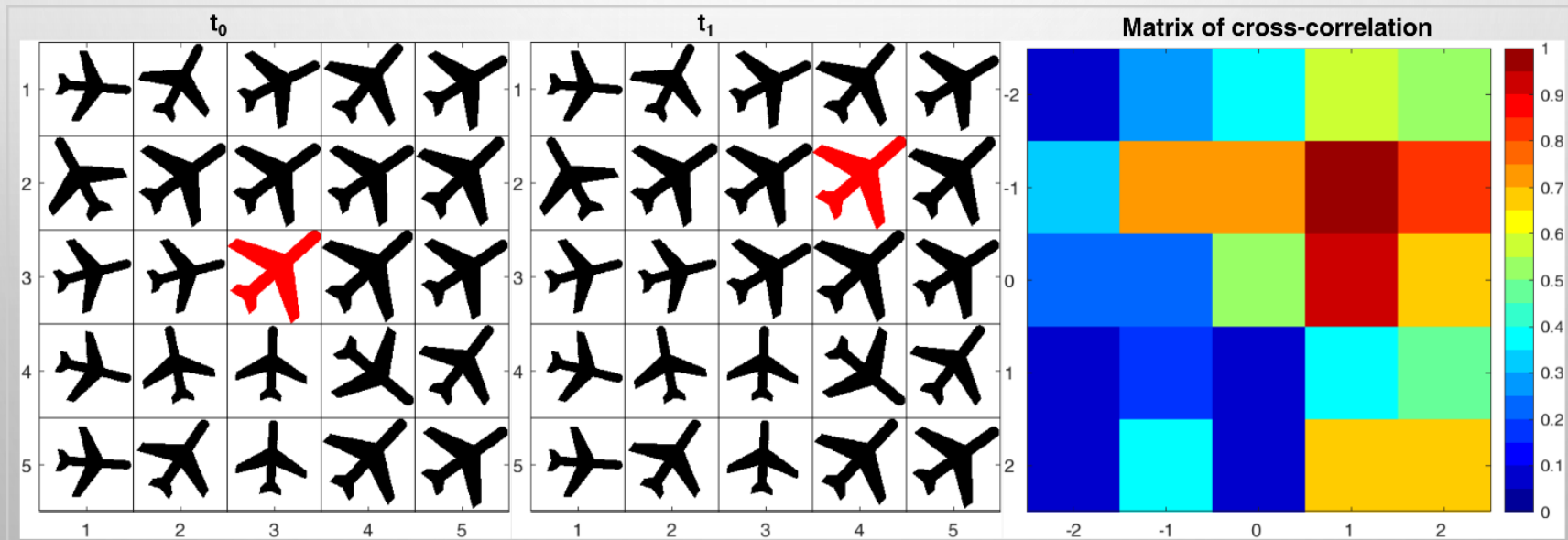


DIC - FUNDAMENTALS

THIS IS DONE WITH THE CALCULUS OF THE SPATIAL CROSS-CORRELATION (**CC**)

CC IS A SIMILARITY INDEX CALCULATED BETWEEN THE REFERENCE TEMPLATE AND MULTIPLE CANDIDATES OF SEARCHING TEMPLATES.

THE POSITION WHERE THE BEST SIMILARITY IS FOUND CORREPONDS TO THE DISPLACEMENT OF THE REFERENCE TEMPLATES.

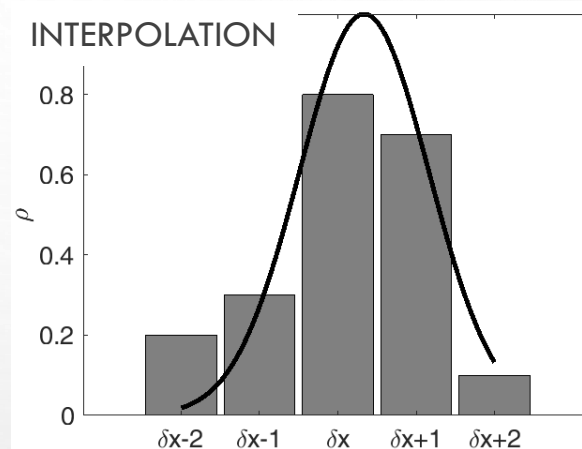


DIC ACCURACY AND PRECISION

SUBPIXEL SENSITIVITY

ADOPTING AN INTERPOLATION OF THE CROSS-CORRELATION MATRIX IT IS POSSIBLE TO OBTAIN A SUB-PIXEL MEASUREMENT

ADOPTING AN INTERPOLATION OF THE CROSS-CORRELATION MATRIX IT IS POSSIBLE TO OBTAIN A SUB-PIXEL MEASUREMENT



UNCERTAINTY

TIPYCAL UNCERTAINTY IN
GLACIOLOGICAL SURVEYS IS 0.5 – 1 PX

DIC - MONITORING APPLICATION



TYPICAL DIC APPLICATION FOR GLACIER
MONITORING IS TO ACQUIRE AN **IMAGE
SEQUENCE** USING A DSLR CAMERA

DIC PROCESSING PRODUCES **DAILY RESULTS**

DIC - PROCESSING

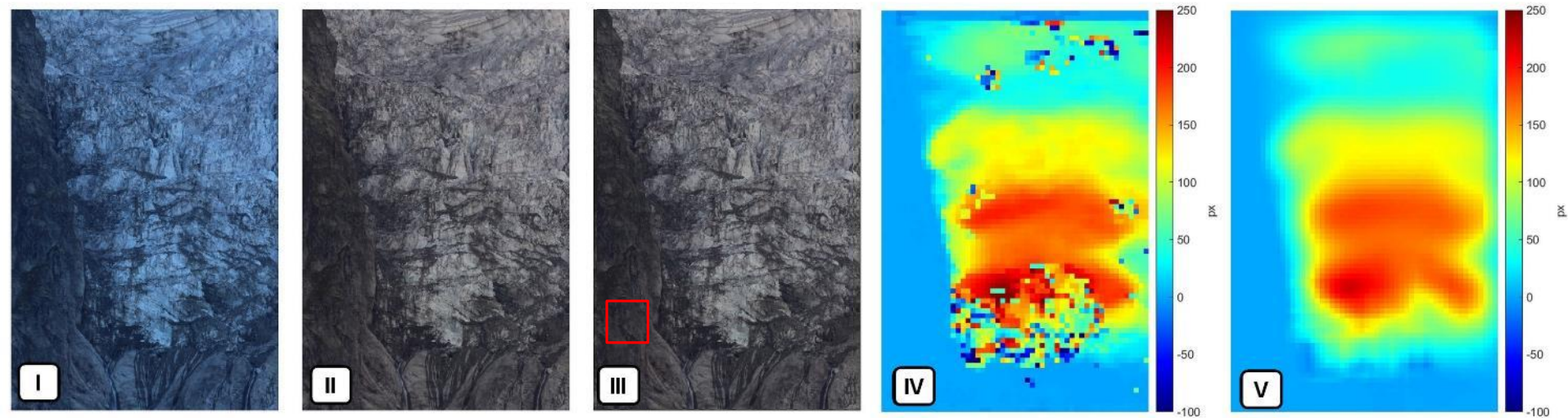


IMAGE
SELECTION

IMAGE
PROCESSING

COREGISTRATION

CROSS-
CORRELATION

RESULT
REFINEMENT

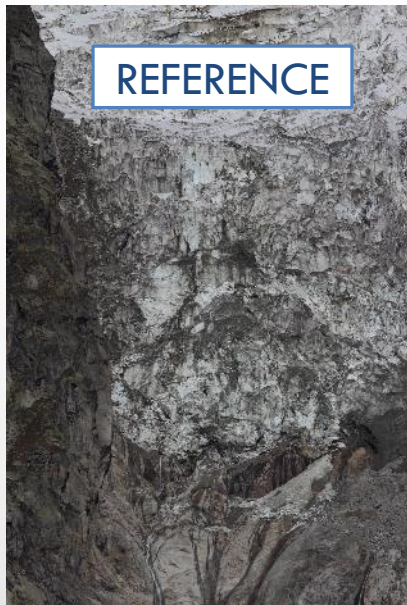


IMAGE SELECTION ^[2]

FUNDAMENTAL TO OBTAIN HIGH-QUALITY RESULTS

MOSTLY DONE MANUALLY → HUMAN EFFORT REQUIRED

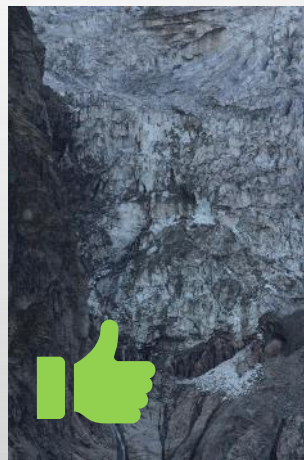
SHADOWS



SIMILAR
ILLUMINATION



DIFFUSE
ILLUMINATION



NO VISIBILITY

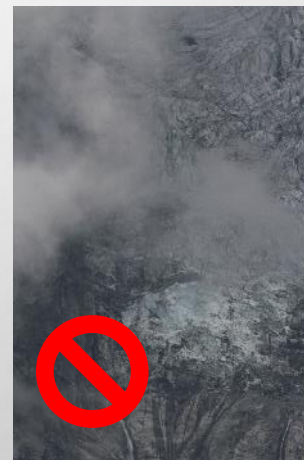
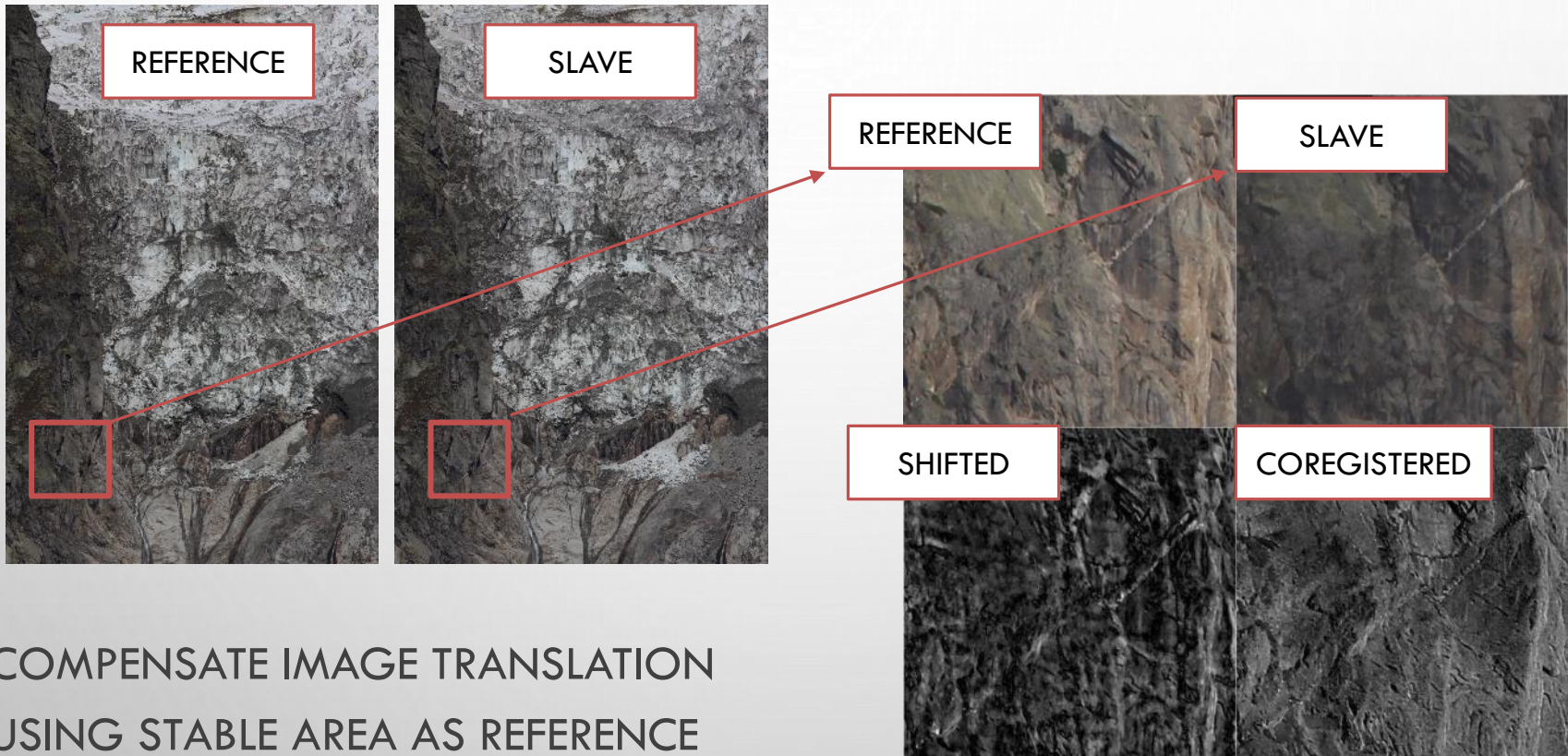


IMAGE PROCESSING

DIC WORKS WITH MONOCHROMATIC IMAGES



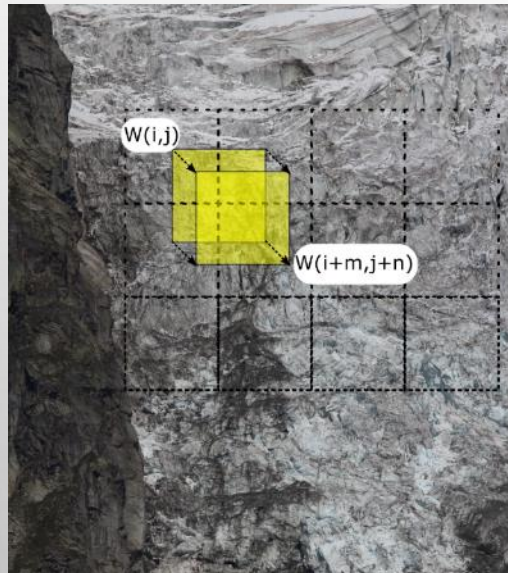
COREGISTRATION



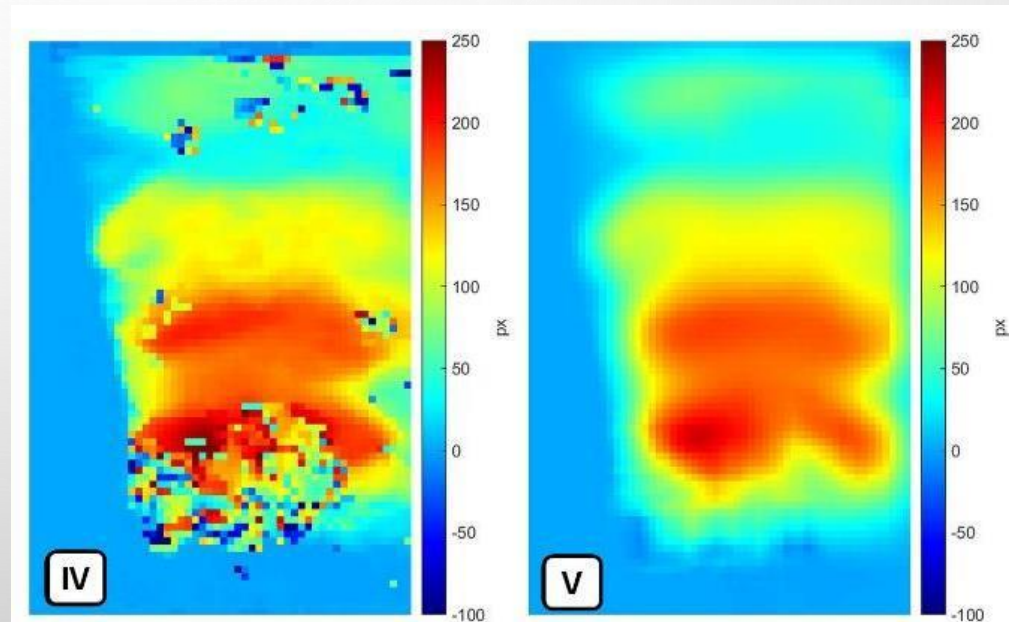
COMPENSATE IMAGE TRANSLATION
USING STABLE AREA AS REFERENCE

CALCULATING SURFACE DISPLACEMENTS

SLIDING WINDOW WHERE TO
CALCULATE CROSS-CORRELATION



RAW RESULT

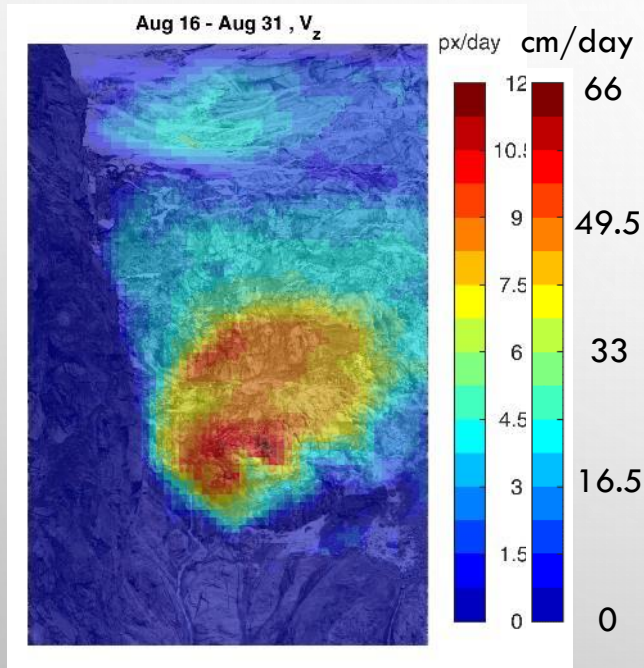


RESULT REFINEMENT

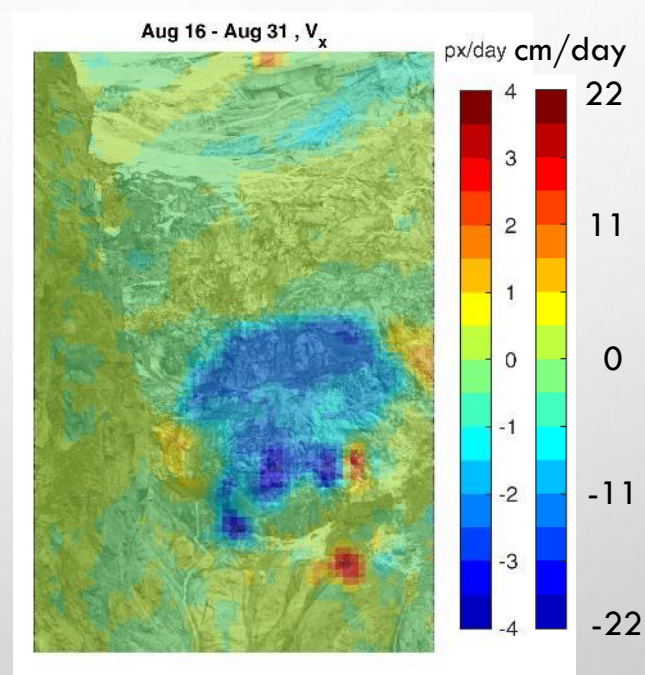
DIC - OUTPUT

MAPS OF DISPLACEMENT COMPONENTS ORTHOGONAL TO THE LINE OF SIGHT

VERTICAL COMPONENT



HORIZONTAL COMPONENT



METRIC CONVERSION

$$1 \text{ px} = 2D \tan\left(\frac{\text{atan}\left(\frac{S}{2f}\right)}{R}\right)$$

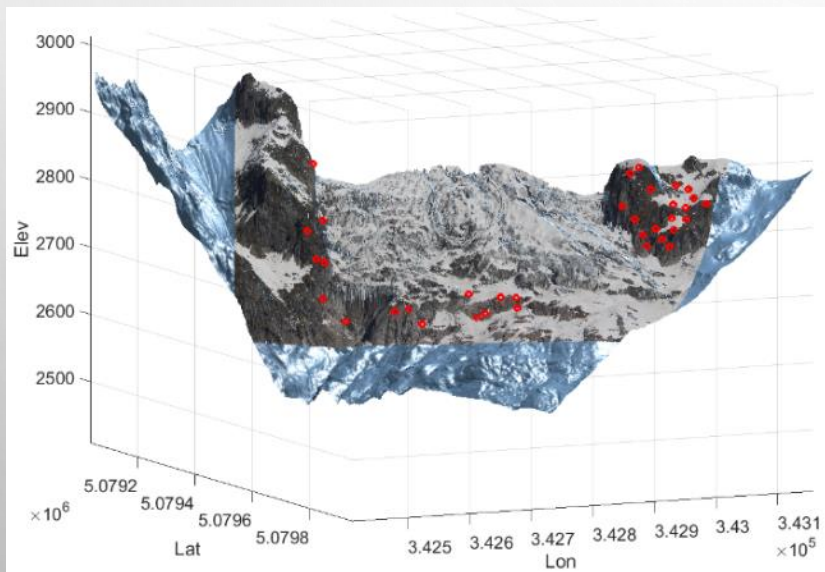
**IN THE PLANINCIEUX
GLACIER**

1 PX = 5.5 CM

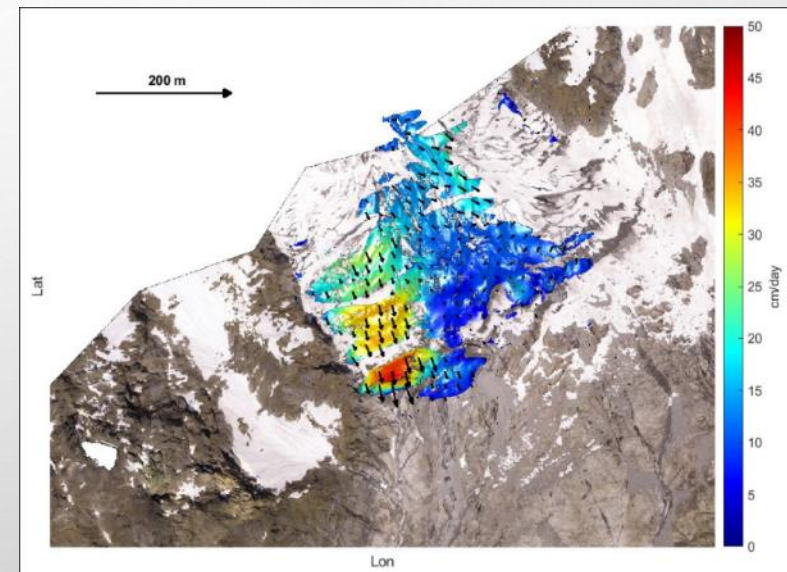
DIC - OUTPUT

RESULTS REPRESENTATION IN THE REAL-WORLD COORDINATES ALLOWS
COMPARISON AND COUPLING WITH OTHER MONITORING SYSTEMS

ORTHORECTIFICATION



GEOREFERENCING



DIC: A VALUABLE TOOL FOR GLACIER MONITORING

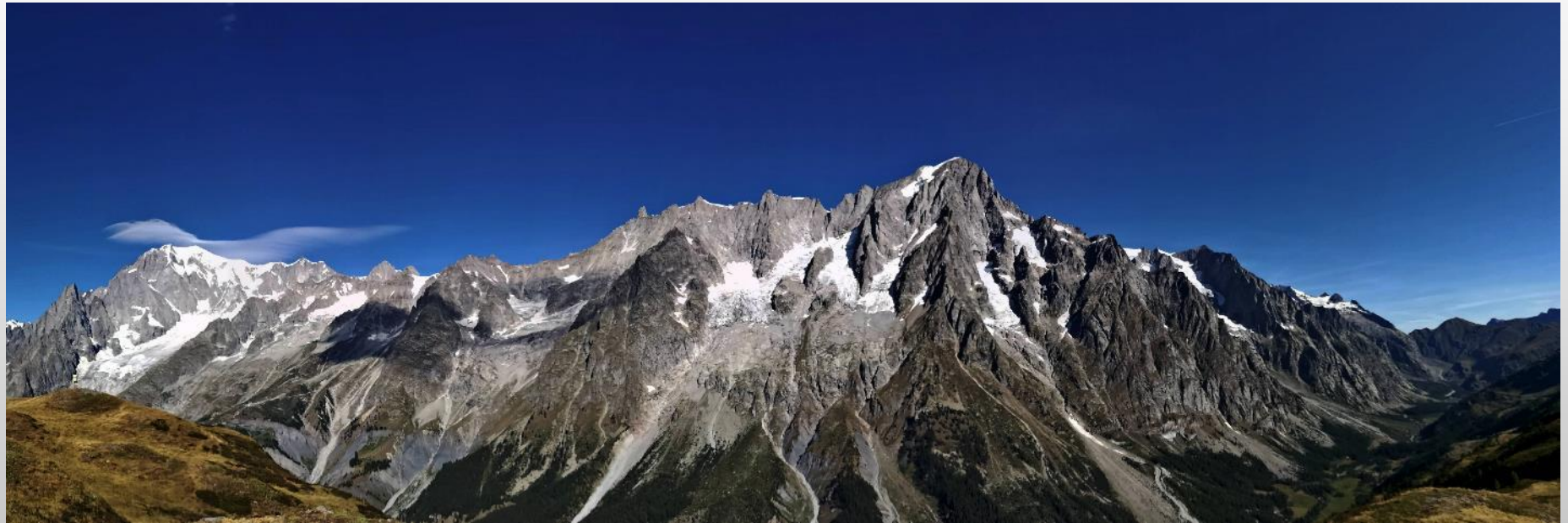
PROS

- 2D SPATIALLY-DISTRIBUTED RESULTS
- REMOTE SENSING
- LOW COST AND PORTABLE HARDWARE
- OBSERVATION OF COMPLEX GEOMETRIES
- SIMPLE PROCESSING AND RESULT INTERPRETATION

CONS

- IMPOSSIBLE DURING NIGHT AND BAD WEATHER
- SUFFERS SHADOW EFFECTS
- MANUAL IMAGE SELECTION
- NO 3D INFORMATION
- LOW SENSIBILITY OF THE MEASUREMENT (IRRELEVANT FOR FAST GLACIERS)

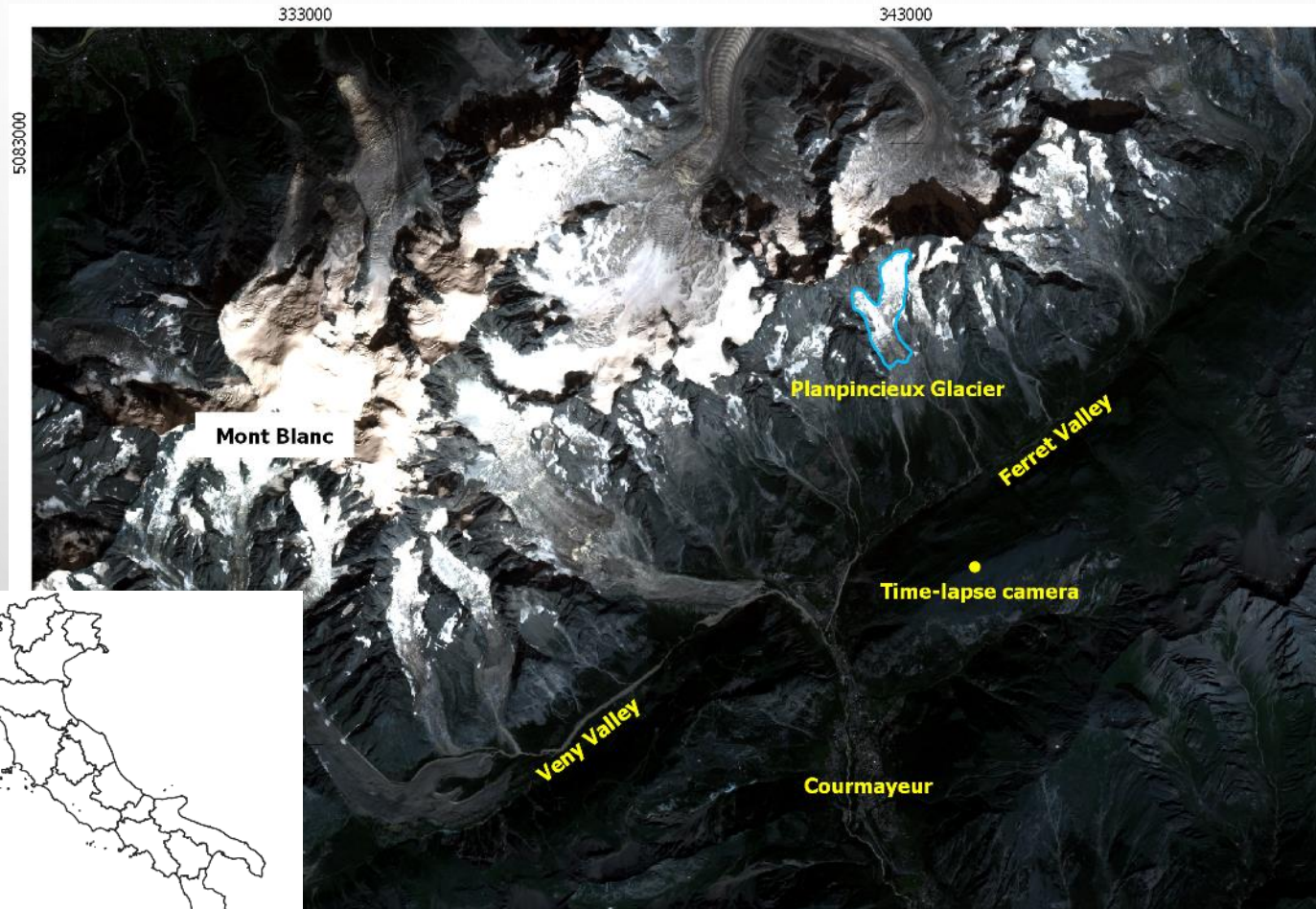
CASE STUDY: PLANPINCIEUX GLACIER ^[3]



VIEW FROM THE MONITORING STATION

PLANPINCIEUX GLACIER

AREA OF STUDY



PLANPINCIEUX GLACIER

GLACIER ELEVATION 2500-3500 M

ACCUMULATION AREA COMPOSED OF TWO CIRQUES

ABLATION AREA COMPOSED OF TWO LOBES
IN TEMPERATE THERMAL REGIME

MONTITAZ LOBE $\sim 30^\circ$ STEEP WITH MANY
CREVASSES

GLACIER TERMINUS IS IN CORRESPONDENCE
OF A MORPHOLOGICAL STEP THAT CAUSES
FREQUENT CALVING



PLANPINCIEUX GLACIER

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PLANPINCIEUX GLACIER

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ABLATION AREA COMPOSED OF TWO LOBES
IN TEMPERATE THERMAL REGIME

**MONTITAZ LOBE ~30° STEEP WITH MANY
CREVASSES**

GLACIER TERMINUS IS IN CORRESPONDENCE
OF A MORPHOLOGICAL STEP THAT CAUSES
FREQUENT CALVING



PLANPINCIEUX GLACIER

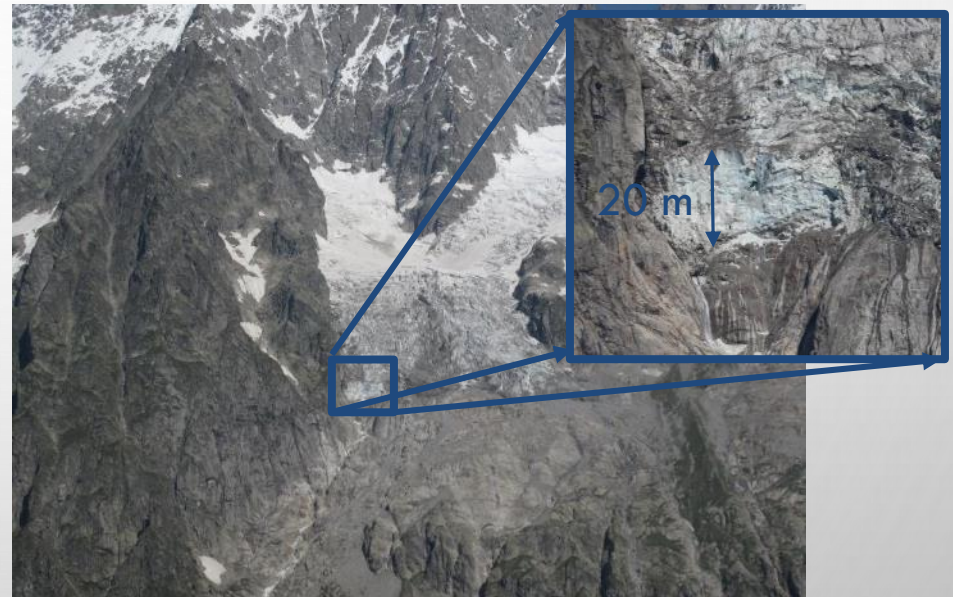
GLACIER ELEVATION 2500-3500 M

ACCUMULATION AREA COMPOSED OF TWO CIRQUES

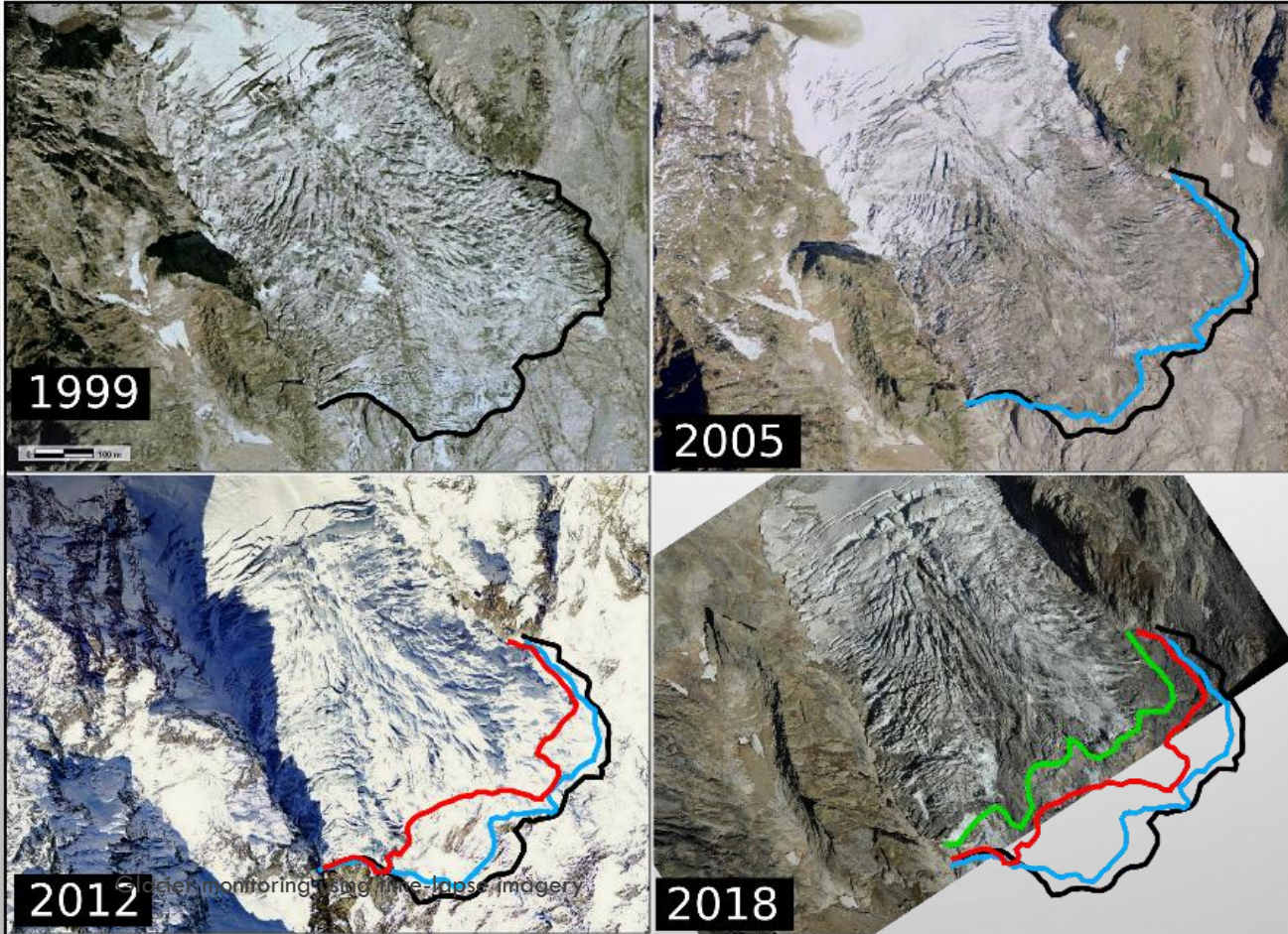
ABLATION AREA COMPOSED OF TWO LOBES
IN TEMPERATE THERMAL REGIME

MONTITAZ LOBE $\sim 30^\circ$ STEEP WITH MANY
CREVASSES

**GLACIER TERMINUS IS IN CORRESPONDENCE
OF A MORPHOLOGICAL STEP THAT CAUSES
FREQUENT CALVING**



GLACIER SHRINKAGE



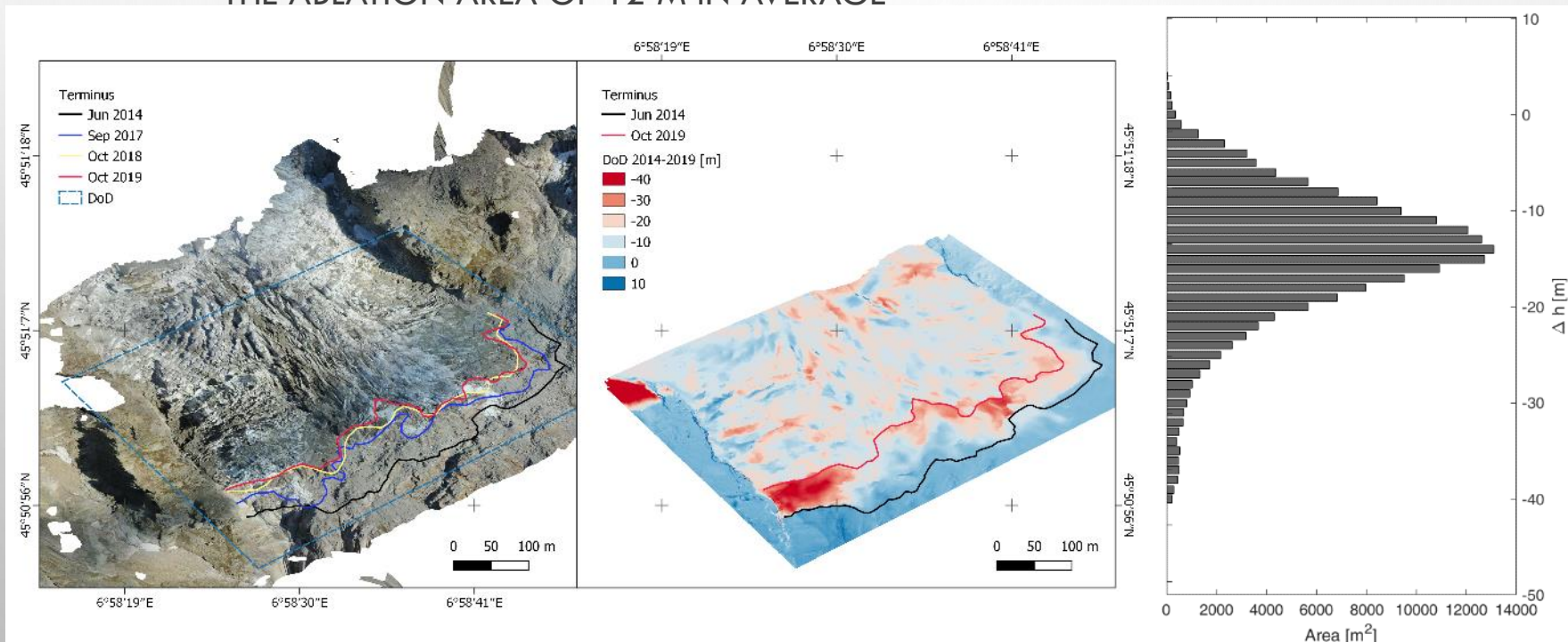
IN 20 YEARS THE GLACIER
RETREATED A FEW HUNDRED
METERS

GLACIER SHRINKAGE

DEM OF DIFFERENCE

BETWEEN 2014 AND 2019, THE GLACIER THICKNESS DECREASED IN THE ABLATION AREA OF 12 M IN AVERAGE

VOLUME LOST
 $2.5 \cdot 10^6 \text{ m}^3$



PLANPINCIEUX GLACIER MONITORING

IN THE PAST SEVERE ICE BREAK-OFFS OCCURRED FROM THE MONTITAZ LOBE (IN OROGRAPHIC RIGHT)

THE PLANPINCIEUX GLACIER IS CONTINUOUSLY MONITORED SINCE 2013 WITH A TIME-LAPSE CAMERA WHICH MEASURES THE SURFACE DAILY VELOCITY

THE VISUAL INVESTIGATION OF THE IMAGES ALLOWS TO IDENTIFY THE BREAK-OFFS AND TO ANALYSE THE DEVELOPMENT OF INSTABILITY PROCESSES

PHOTOGRAPHIC MONITORING SYSTEM



TWO TIME-LAPSE CAMERAS WITH DIFFERENT OPTICAL LENGTH OBSERVE DIFFERENT GLACIER PORTIONS

SCHEDULED HOURLY ACQUISITION

REMOTE CONTROL WITH GPRS CONNECTION

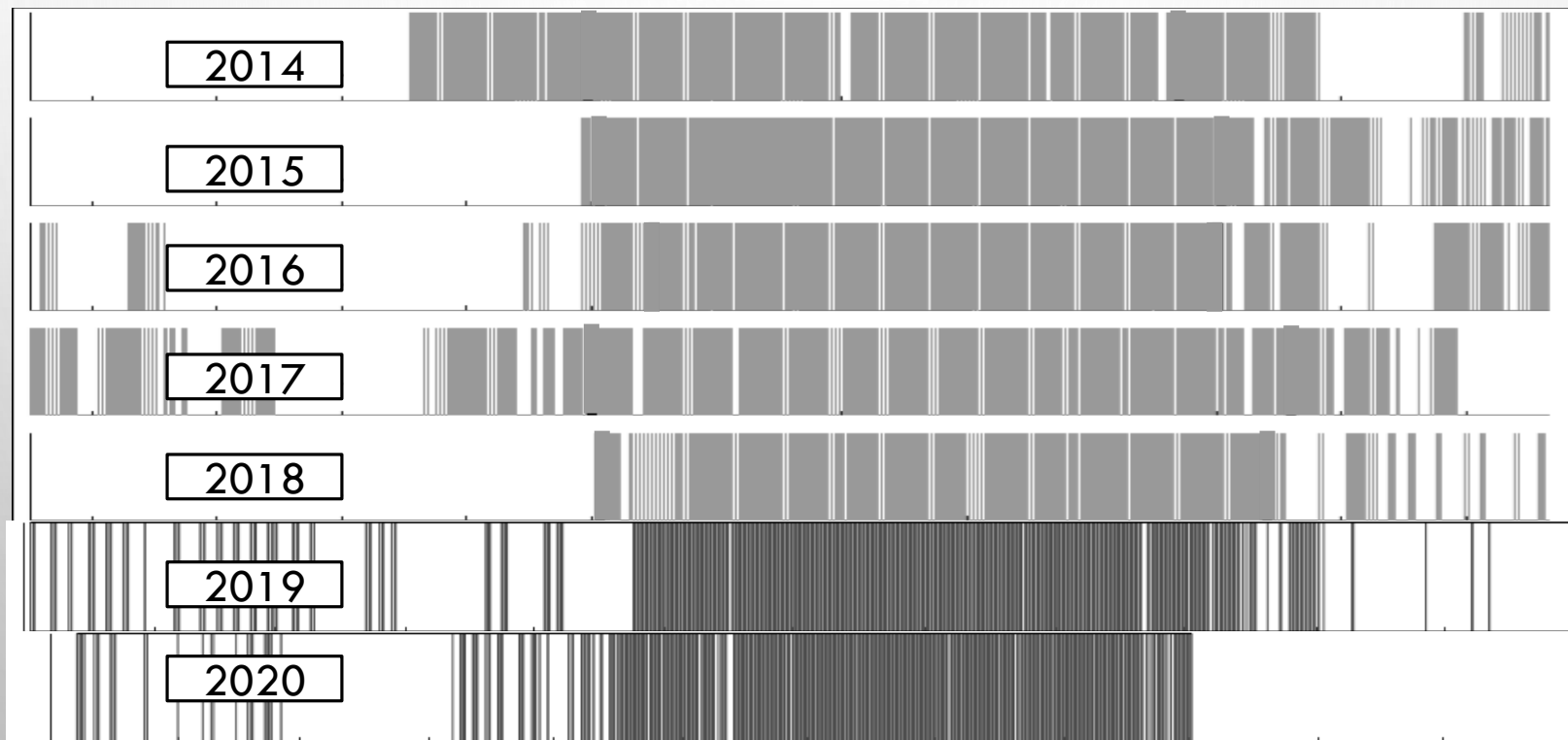
AUTONOMOUS ENERGY SUPPLY WITH SOLAR PANELS

GLACIER DISTANCE IS 3800 M

HARDWARE GLOBAL COST APPROXIMATIVELY €10000

PHOTOGRAPHIC DATASET

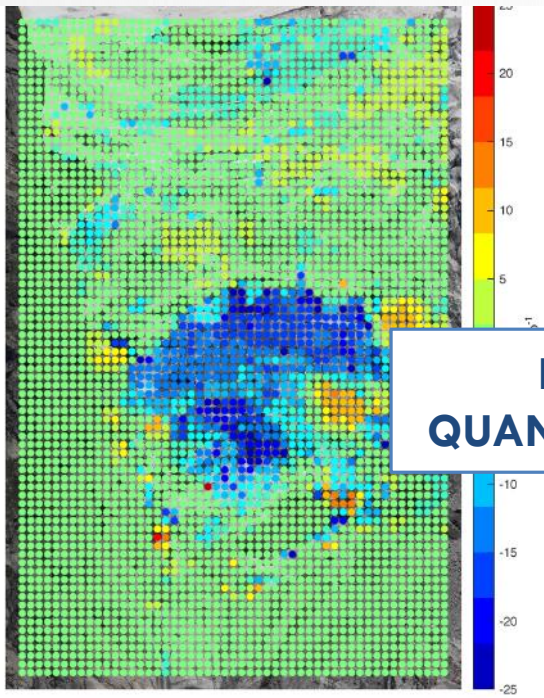
MORE THAN **35000** IMAGES ACQUIRED IN 7 YEARS OF MONITORING
→ HIGH TEMPORAL RESOLUTION



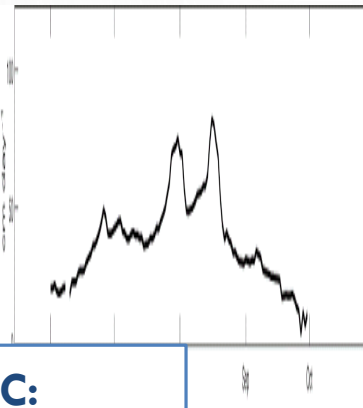
PRODUCTS OF THE MONITORING

MAPS OF DAILY MOTION

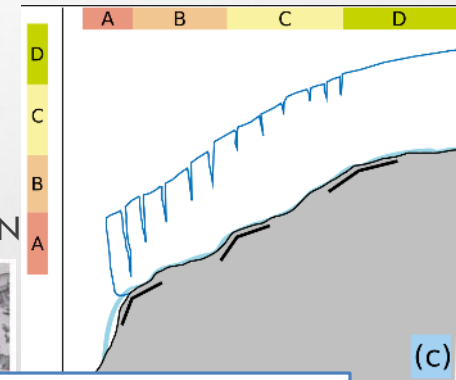
TIME SERIES OF VELOCITY



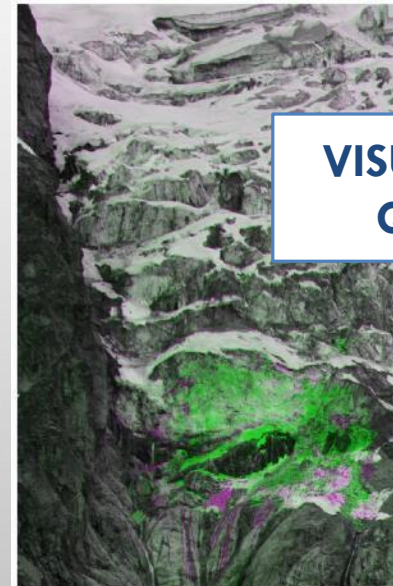
**DIC:
QUANTITATIVE**



INSTABILITY PROCESSES



BREAK-OFF IDENTIFICATION



**VISUAL ANALYSIS:
QUALITATIVE**

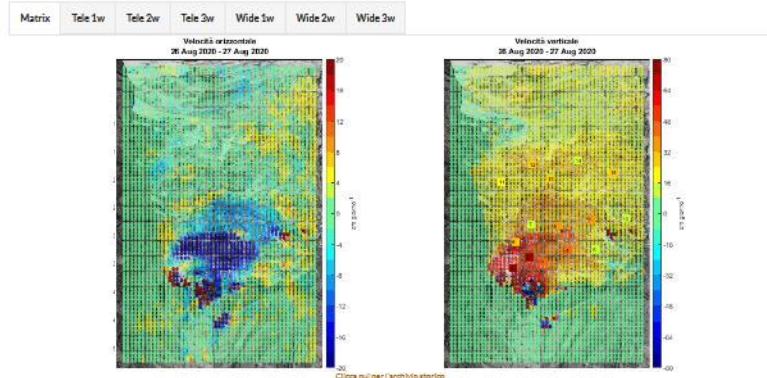
DAILY UPDATE WEB PAGE



Postazione sperimentale per il monitoraggio del Ghiacciaio di Planpincieux (AO)

Ambedue i dati vengono caricati automaticamente sul sito web e non sono stati approvati definitivamente dal personale GMG. Possono essere presenti alcune inconsistenze dovute al temporaneo malfunzionamento degli strumenti di monitoraggio o a variazioni delle condizioni ambientali del sito monitorato. La revisione dei risultati da parte del personale del GMG può portare a variazioni. Gli utenti sono pregati di considerare con attenzione la natura preliminare delle informazioni contenute in queste pagine prima di utilizzarle tali dati per interpretare delle decisioni che riguardano la propria o la pubblica sicurezza.

Progetto di ricerca per lo sviluppo di un sistema di monitoraggio sperimentale della fronte glaciale del Ghiacciaio di Planpincieux in collaborazione con Fondazione Montagna Sicura e Regione Autonoma Valle d'Aosta



MONITORING RESULTS ARE AUTOMATICALLY COMMUNICATED EVERY DAY TO THE AUTHORITIES ON A RESTRICTED-ACCESS WEB PAGE

PERIODICAL BULLETINS DESCRIBE DETAILED INVESTIGATION OF THE GLACIER STATE AND REPORT THE VALIDATED RESULTS

PERIODICAL BULLETINS

Figure 1. Componenti orizzontali della velocità

Figure 2. Componenti verticali della velocità

l'incremento di entrambe le componenti della velocità è dovuta all'allargamento di una fratturazione a corona che interessa il margine del settore centrale del ghiacciaio. Questo ha portato ad una elevata attività, fino al verificarsi di un importante crollo della porzione destra della fronte, ed allo spostamento verso destra della parte centrale del ghiacciaio.

In seguito all'osservazione della forte accelerazione verificatasi nei giorni tra il 15 e il 20 di agosto, unitamente all'allargamento della frattura a monte del settore centrale, si è ritenuto necessario un approfondimento circa l'evoluzione giornaliera della velocità, anche allo scopo di effettuare un confronto con il comportamento del ghiacciaio nella scorsa estate.

Sono stati individuati tre settori caratterizzati da una cinematica uniforme (Figura 4) per i quali è stata calcolata la velocità media giornaliera della quale è stata analizzata la serie temporale durante il corso dell'anno. In Figura 5 si riporta la serie della velocità verticale giornaliera, mediata su un periodo di 7 giorni, per gli anni 2016-2017.

Riguardo all'evoluzione del settore 3, è evidente durante la stagione estiva un andamento oscillatorio, caratterizzato da forti accelerazioni seguite da periodi di decelerazione. Tale andamento è solitamente in fase in tutti i settori. Come si vede in Figura 5, i picchi di velocità corrispondono a eventi di crollo della parete frontale, che provocano una diminuzione del carico del sistema e quindi un rallentamento per effetto di una minore spinta verso valle.

In seguito al vulcanismo crollò del 29 agosto, il settore centrale non ha registrato diminuzioni della velocità nei giorni successivi all'evento. Tale anomalo comportamento ha richiesto un'analisi più frequente dei dati per rilevare possibili segnali precursori di ulteriore attività del ghiacciaio. I dati sono stati inviati a FMS in report dedicati. Come si vede dal grafico in Figura 6, la velocità del settore centrale è effettivamente diminuita in seguito al crollo, anche se con un ritardo di alcuni giorni rispetto al settore frontale.

Figure 4. Settori analizzati nel report.

Figure 5. Serie temporali di velocità giornaliera (mediata su sette giorni) per i tre settori analizzati negli anni 2016 e 2017. Vengono riportati anche i crolli registrati sui vari settori durante la stagione estiva.

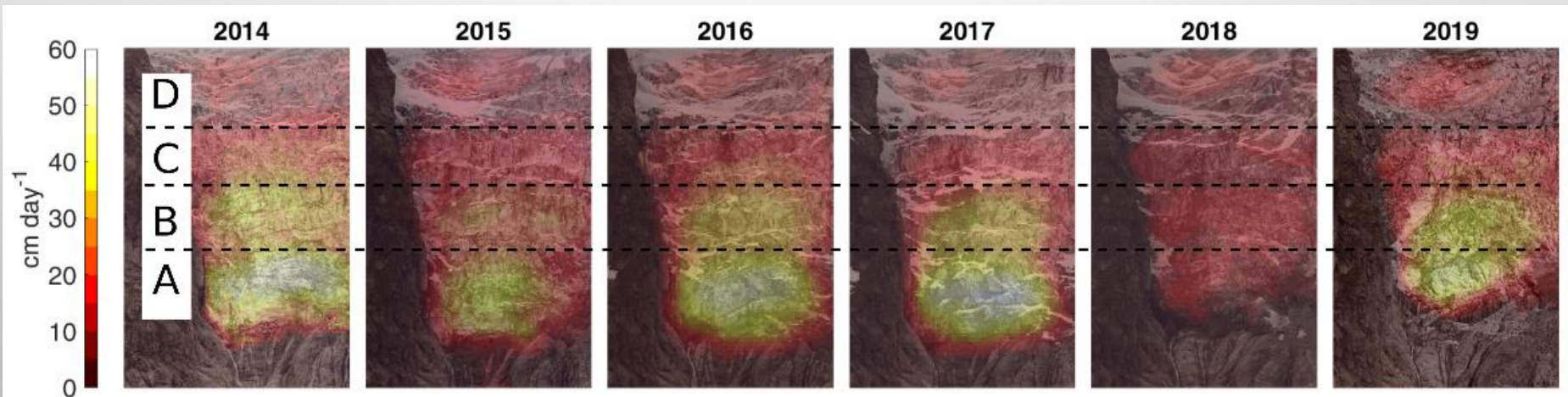
KINEMATIC DOMAINS OF THE MONTITAZ LOBE

THE SURFACE VELOCITY PATTERN IS TYPICALLY FORMED OF 4 DISTINCT KINEMATIC DOMAINS

THE LIMITS OF THE KINEMATIC DOMAINS CORRESPOND TO THE CREVASSES WHICH DELIMITATE THE MORPHOLOGICAL SECTORS

THE POSITION OF THE CREVASSES INDICATE WHERE THE STRONGEST TENSILE STRESSES ACT

THE PORTION BELOW CAN BECOME UNSTABLE AND COLLAPSE



MORPHOLOGICAL SECTORS OF THE MONTITAZ LOBE



A SERIES OF CREVASSES DEVELOPS EVERY YEAR APPROXIMATELY IN THE SAME POSITION

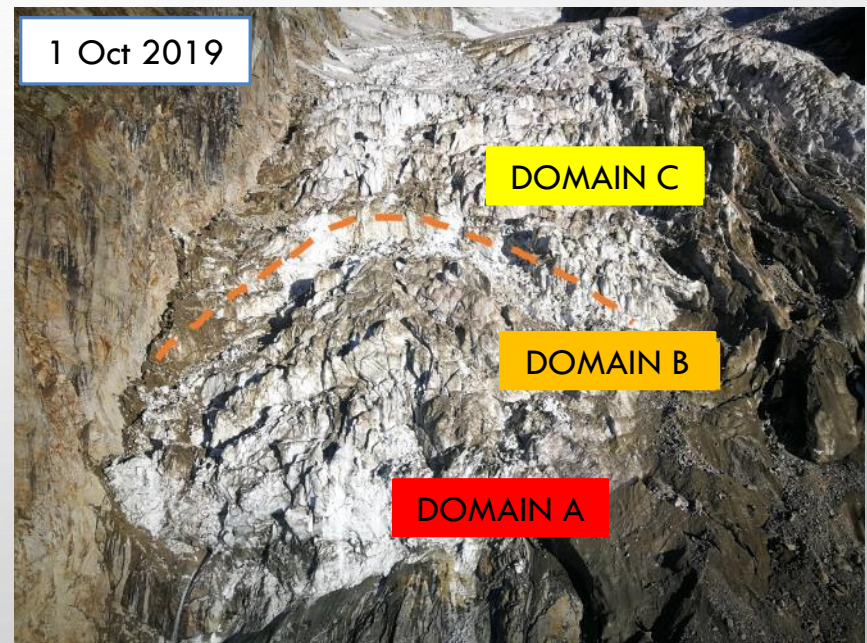
THE MONTITAZ LOBE IS COMPOSED OF DISTINCT MORPHOLOGICAL SECTORS WHICH SHOW DIFFERENT BEHAVIOURS

CRISIS OF 2019 AND 2020

IN 2019 AND 2020, THE TWO LOWER
SECTORS MERGED → A LARGER VOLUME
BECAME UNSTABLE (250000-500000 m³)



16 Aug -12 Oct 2019



1 Oct 2019

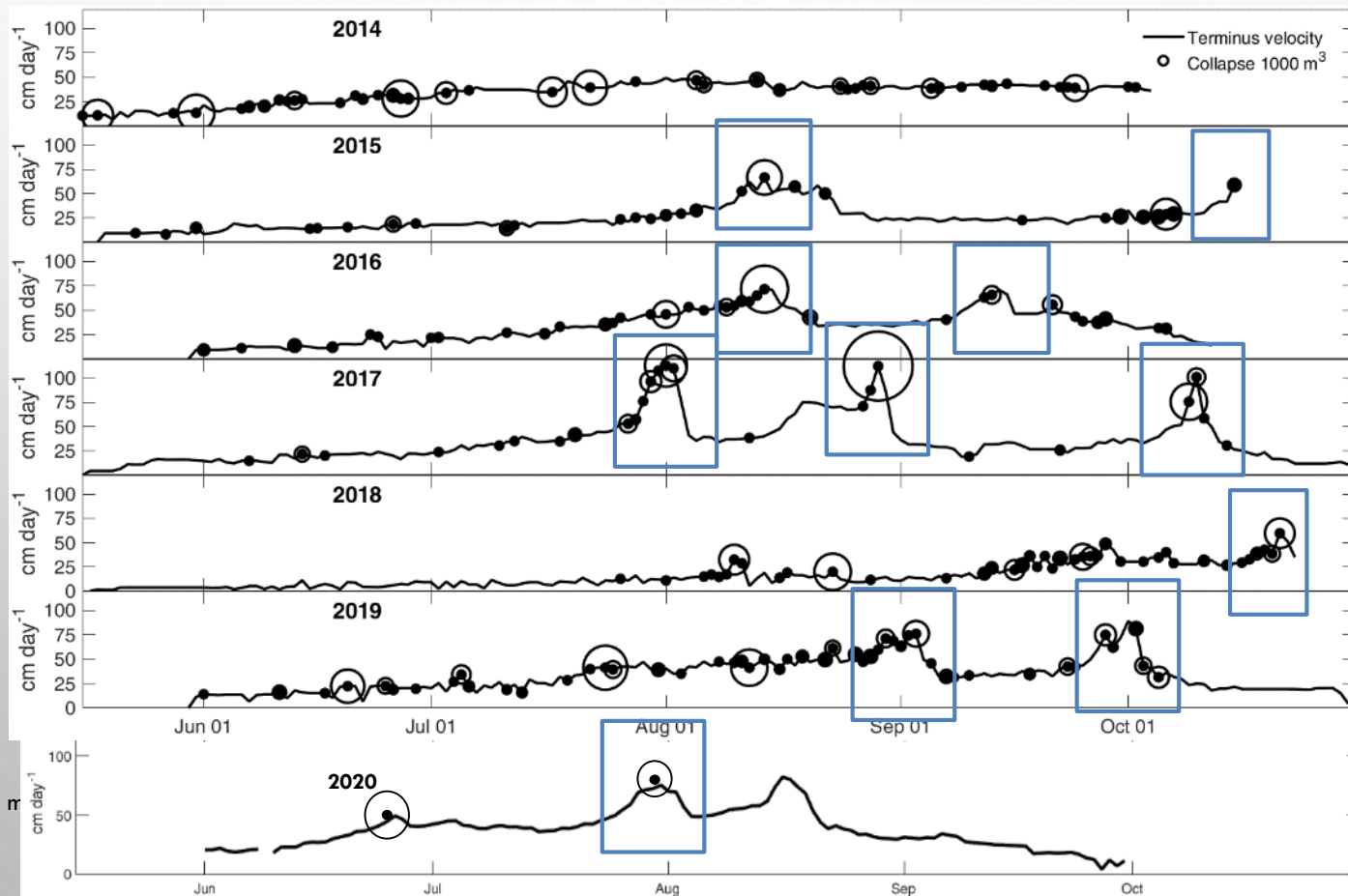
DOMAIN C

DOMAIN B

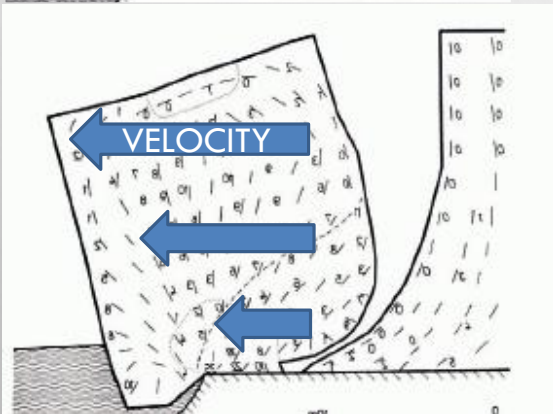
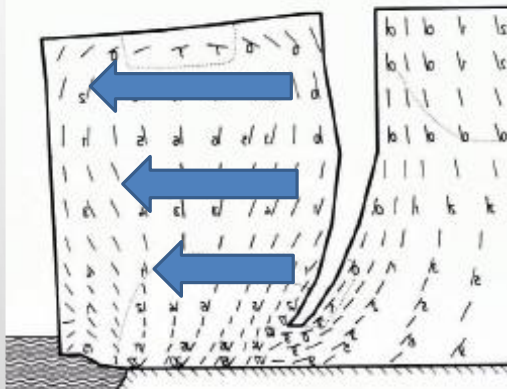
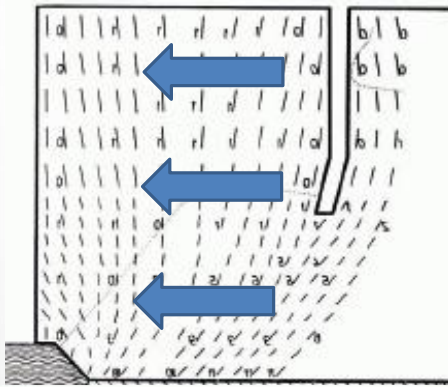
DOMAIN A

TIME SERIES OF DAILY VELOCITY

EVERY YEAR A FEW SPEED-UP PERIODS OCCUR
AND CULMINATE WITH LARGE BREAK-OFFS



Glacier m



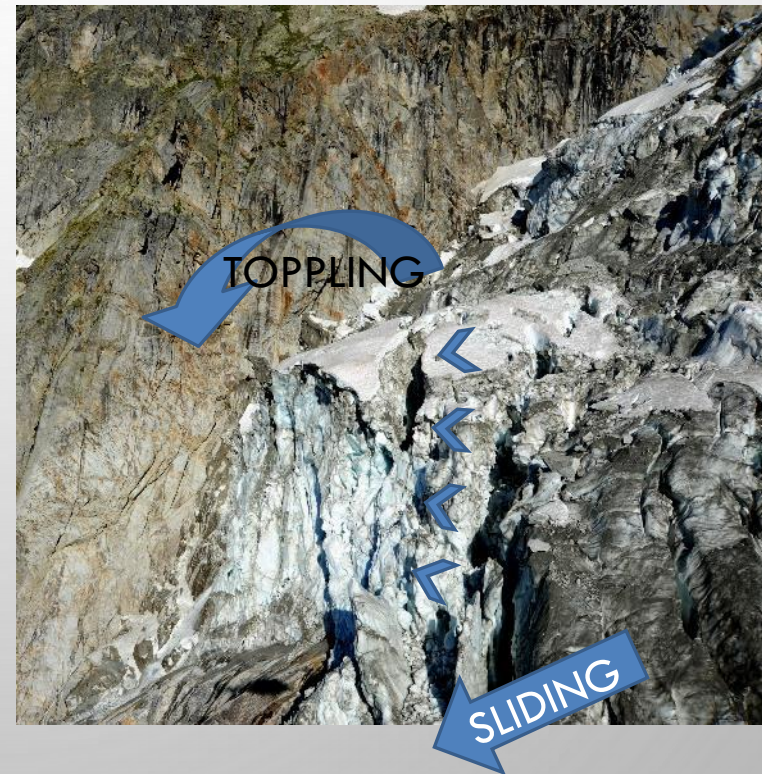
MODIFIED FROM IKEN, 1977 [4]

BREAK-OFF DYNAMICS

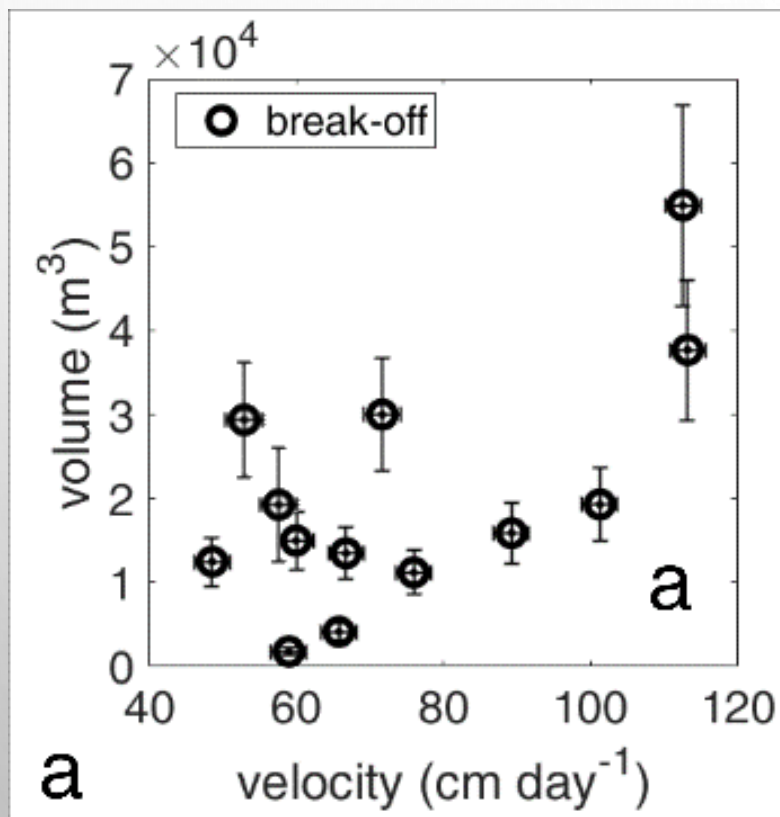
THE CREVASSE DEVELOPMENT CAUSES THE TOPPLING OF THE ICE CHUNK

THE GLACIER SLIDING SUM WITH THE ROTATIONAL MOVEMENT AND YIELDS THE ACCELERATION

WHEN THE CREVASSE REACHES THE BEDROCK, THE ICE CHUNK COLLAPSES



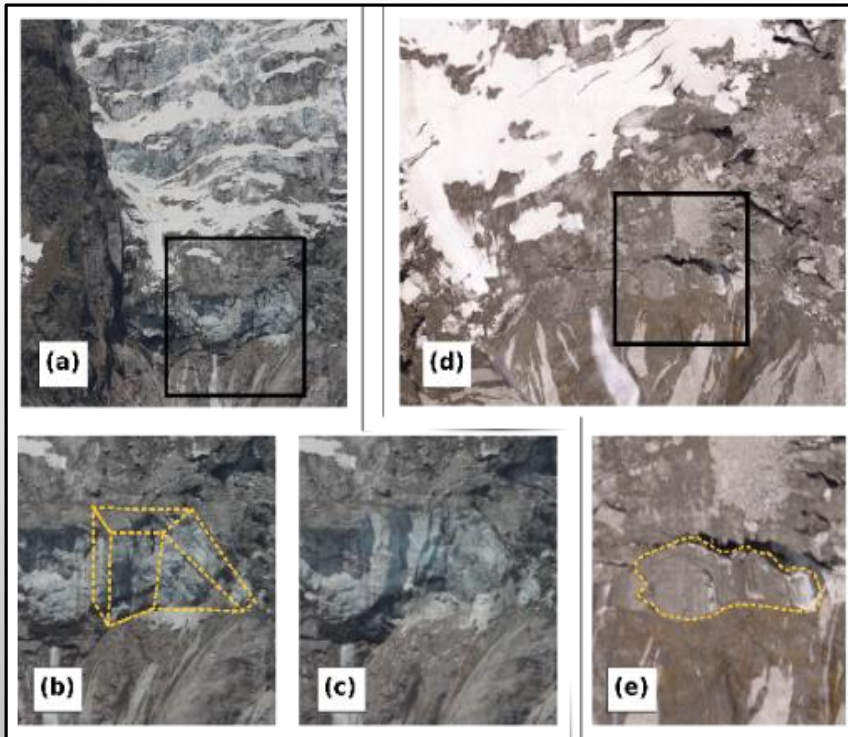
VELOCITY vs VOLUME



IT HAS BEEN IDENTIFIED A MONOTONICAL RELATIONSHIP BETWEEN MAXIMUM GLACIER VELOCITY AND BREAK-OFF VOLUME DURING THE SPEED-UP PERIODS

A-PRIORI ESTIMATE OF THE VOLUME

BREAK-OFF VOLUME ESTIMATE



VOLUME IS ESTIMATED WITH 2D IMAGES
ADOPTING ASSUMPTIONS OF ICE AND
BEDROCK GEOMETRY

GOOD AGREEMENT WITH LIDAR DATA

BREAK-OFF IDENTIFICATION

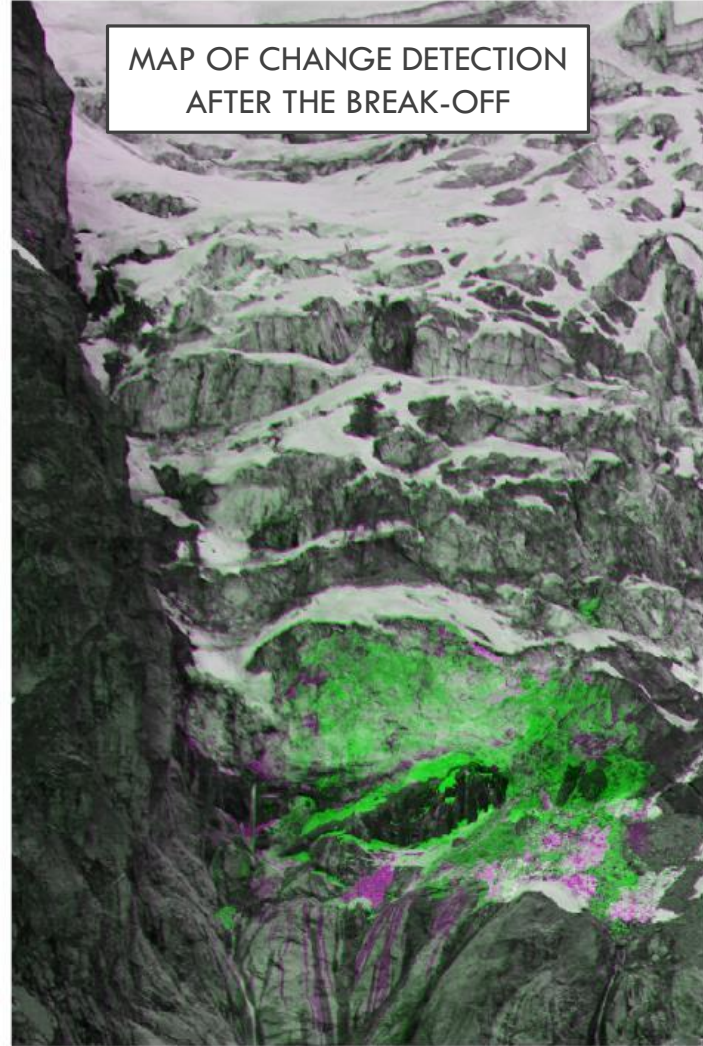
PRE-EVENT



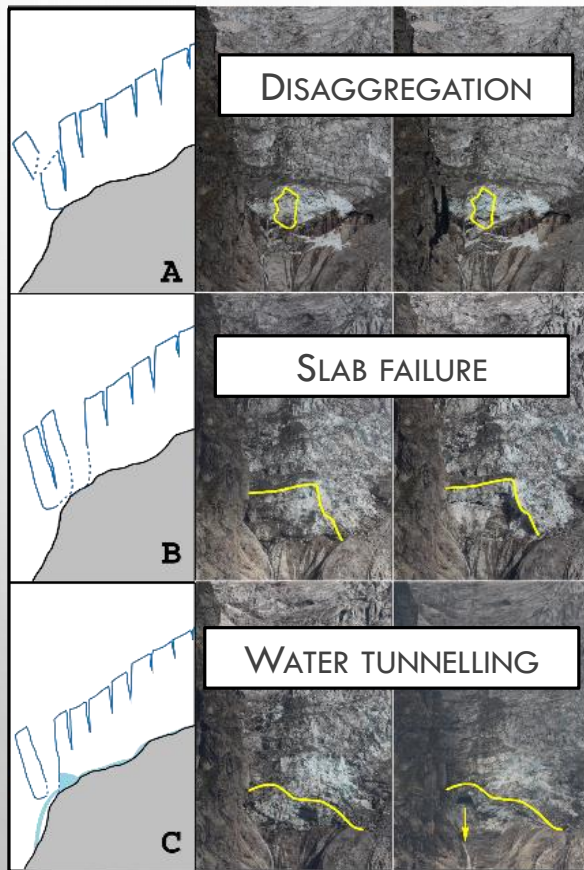
POST-EVENT



MAP OF CHANGE DETECTION
AFTER THE BREAK-OFF



BREAK-OFF CLASSIFICATION

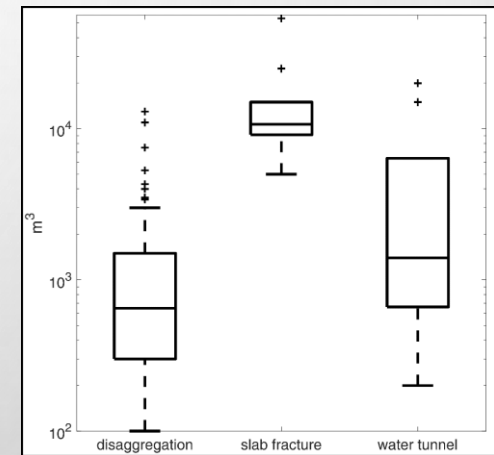


DISAGGREGATION: TOPPLING OF SMALL FRAGMENTS (10^3 m^3) DUE TO THE MOTION BEYOND THE BEDROCK CLIFF

SLAB FAILURE: DETACHMENTS OF LARGE ICE LAMELLA (10^4 - 10^5 m^3) DELIMITED BY LARGE CREVASSES OFTEN PRECEDED BY ACCELERATION

WATER TUNNELLING: DEVELOPMENT AND COLLAPSE OF ENDOGLACIAL TUNNELS

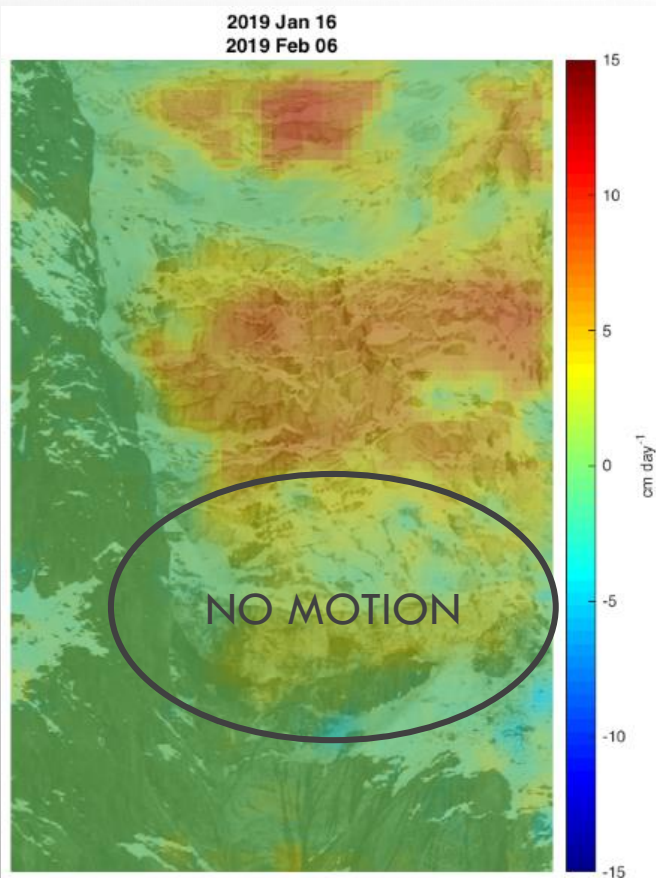
BREAK-OFF VOLUME FOR EVERY BREAK-OFF PROCESS



WHAT MAKES THE GLACIER MOVE?

GRAVITY

MORE RELEVANT DURING WINTER



WINTER BEHAVIOUR

DURING THE WARM SEASON, THE FRONTAL PORTION PARTIALLY DETACHES FROM THE MAIN GLACIER BODY

IN THE COLD SEASON, THE LOWER PART FREEZES AGAINST THE BEDROCK

THE GLACIER BODY MOVES FOR GRAVITY

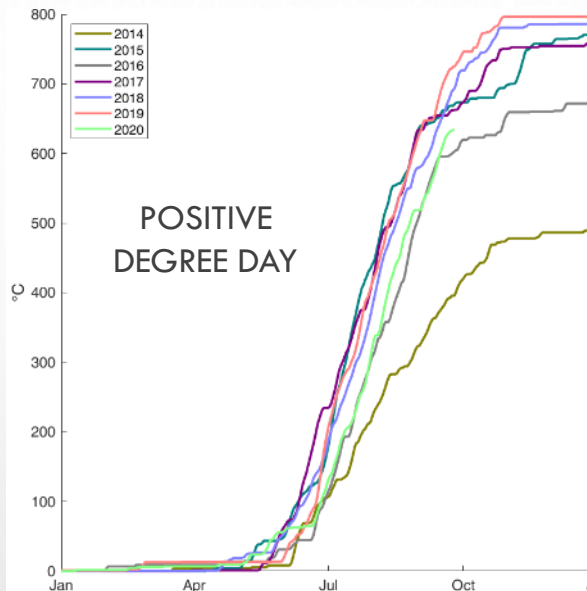
WHAT MAKES THE GLACIER MOVE?

LIQUID WATER

FACILITATES SLIDING

- **ICE MELTING** → HIGH TEMPERATURE CAN INCREASE GLACIER VELOCITY (?)
- **WATER PERCOLATION** → THE PRESENCE OF SNOW/THE ABSENCE OF CREVASSES ON THE GLACIER SURFACE CAN REDUCE SLIDING (?)

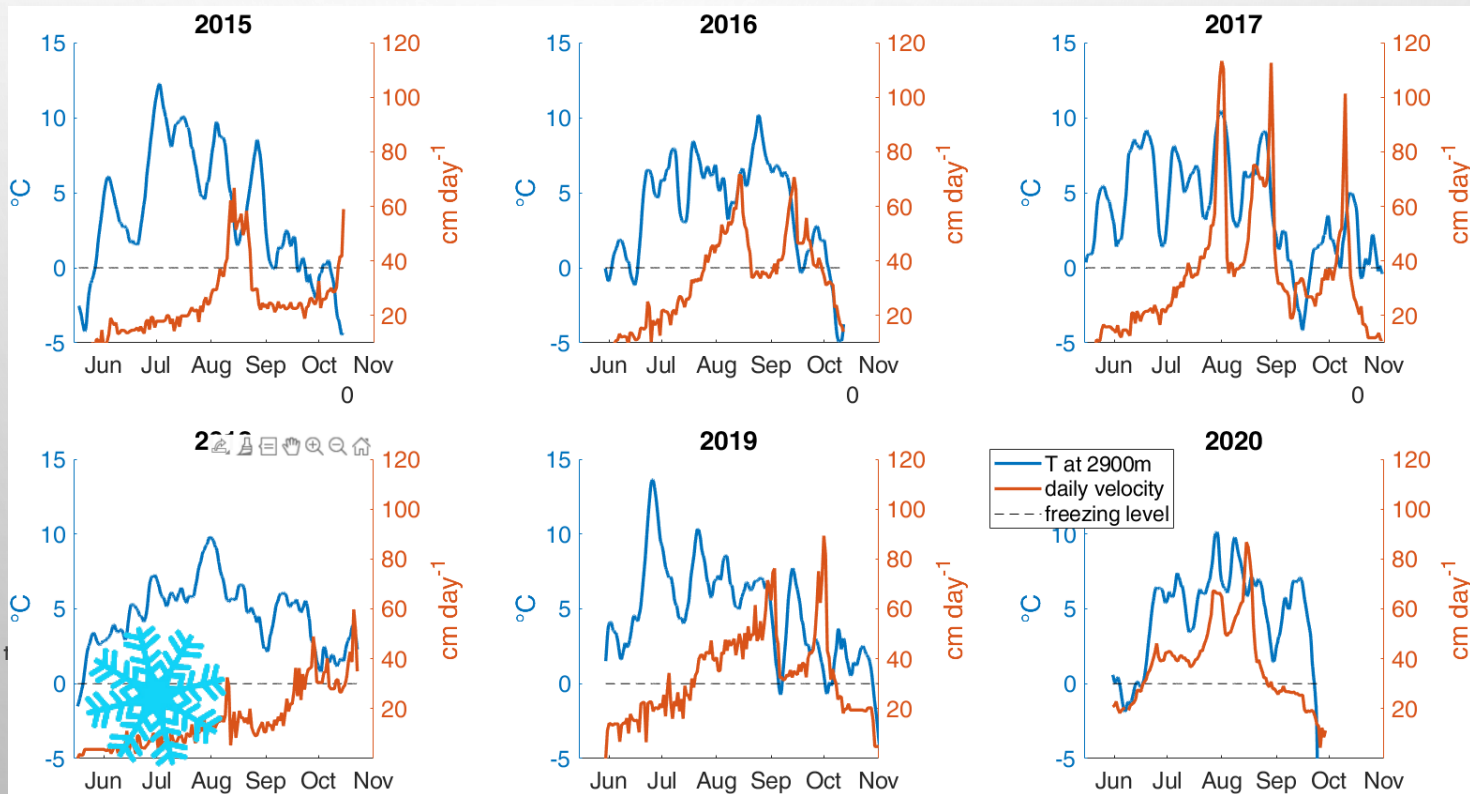




VELOCITY vs TEMPERATURE

SUMMER 2014 WAS MUCH COOLER THAN USUAL → IN 2014 SPEED-UP PERIODS DID NOT OCCUR

A CLEAR RELATION BETWEEN VELOCITY AND TEMPERATURE DOES NOT APPEAR



TEMPERATURE AT 2900 M
FRONTAL VELOCITY

Glacier monitoring using t

HYDRAULIC SYSTEM^[5]

WELL-DEVELOPED HYDRAULIC SYSTEM FACILITATES THE WATER DRAINAGE AND **DECREASES THE GLACIER SLIDING**

DIFFUSE SMALL CHANNELS, FILM AND WATER POCKETS INCREASE THE BASAL PRESSURE AND **CAUSE THE GLACIER SLIDING**

HYDRAULIC SYSTEM CAN CHANGE FOR THE GLACIER MOTION



EFFICIENT WATER
DRAINAGE

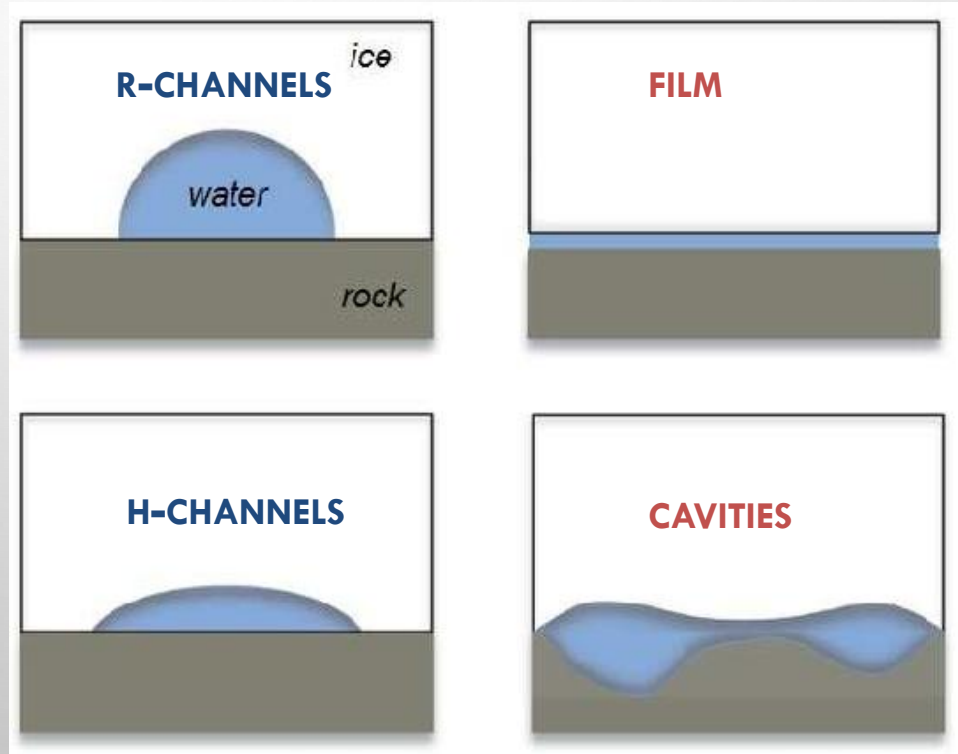


LIMITED WATER
DISCHARGE



CAVITY

EFFICIENT DRAINAGE



INEFFICIENT DRAINAGE

CONCLUSIONS

DIC PROVIDES MAPS OF SURFACE KINEMATICS. THE DISPLACEMENT PATTERN INDICATE WHERE THE STRONGEST STRESSES ACT. THIS IS IN ACCORDANCE WITH THE FORMATION AND POSITION OF CREVASSES.

THEREFORE, THE ANALYSIS OF THE KINEMATIC MAPS CAN BE A FIRST EVALUATION TO IDENTIFY POSSIBLE UNSTABLE BODIES AND TO ESTIMATE THEIR VOLUME.

THE VELOCITY-VOLUME RELATIONSHIP CAN PROVIDE AN A-PRIORI ESTIMATE OF THE BREAK-OFF.

A STRONG VELOCITY INCREASE CAN BE A PRECURSOR OF A LARGE COLLAPSE

DIC PROVIDES RESULTS WITH DAILY TEMPORAL RESOLUTION AND CANNOT BE APPLIED DURING NIGHT AND BAD WEATHER

PRESENTLY, IT IS NOT POSSIBLE TO PREDICT THE INSTANT OF THE BREAK-OFF

**TIME-LAPSE IMAGERY CAN
BE A VALUABLE TOOL FOR
RISK ASSESSMENT**

**DIC CAN NOT BE USED
FOR EARLY WARNING
ACTIVITIES**

THANK YOU



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