Fernerkundung von Gletschern und Eiskappen in Hochgebirgen und Polargebieten im Kontext des globalen Klimawandels

Matthias Braun

Perito Moreno Glacier, Argentina
Structure & introduction

• Relevance of glaciers & ice sheets
  - Polar ice sheets => sea level rise, fresh water & ocean circulation, process understanding
  - High mountains => sea level, water balance and discharge regimes, daily amplitudes & extreme events, irrigation, hydro power, drinking water, tourism => process understanding, glacier volume estimates, cal/val of scenarios computations

• Climate scenarios and polar amplification

• Glaciers, ice caps and ice sheets as ECVs & example products

• Methods to determine glacier/ice sheet mass changes and their difficulties
  - Gravimetric measurements
  - Geodetic mass balances
  - Input-Output / Flux gate approach

• Mass changes of the polar ice sheets
• Impacts in high mountain regions (ex. from South America)
Global sea level rise

Ground data

Satellite data

Currently 3.2 mm a⁻¹

https://climate.nasa.gov/vital-signs/ice-sheets/
22 June 2018
Sea level change and contribution of different drivers (2002-2014)

Rietbrock et al. (2016), PNAS

Glacier & ice sheets contribute similarly as steric expansion

Greenland

Glaciers

Antarctica

1.37 mm /yr
Global surface temperature trend and scenarios

Global average surface temperature change

(a)
Polar amplification

(a) Change in average surface temperature (1986–2005 to 2081–2100)

RCP 2.6

RCP 8.5

IPCC AR5 (2013)
An ECV is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth’s climate.

**Relevance**: The variable is critical for characterizing the climate system and its changes.

**Feasibility**: Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.

**Cost effectiveness**: Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.
ECV for Glaciers & Ice caps

Product Requirements:

- **Glacier Area**:
  - Frequency: Annual (at end of ablation season)
  - Resolution: Horizontal 15-30 m; Vertical 1 m
  - Required Measurement uncertainty: 5 %
  - Standards/References: IGOS (2009); Paul et al. (2009)
  - Entity (Satellite): WGClimate (link is external)
  - Entity (in situ): GCW (link is external)

- **Glacier Elevation Change**:
  - Frequency: Decadal
  - Resolution: Horizontal 30 m-100 mx; Vertical 1 m
  - Required Measurement uncertainty: 2 m/decade
  - Stability (per decade unless otherwise specified): 1 m/decade
  - Standards/References: Zemp et al. (2013)
  - Entity (Satellite): WGClimate (link is external)
  - Entity (in situ): GCW (link is external)

- **Glacier Mass Change**:
  - Frequency: Seasonal to annual (the latter at end of ablation period)
  - Resolution: Vertical: 0.01 m or 10 kg/m2 (at point location)
  - Required Measurement uncertainty: Better than 200 kg/m2/year (glacier-wide)
  - Entity (Satellite): WGClimate (link is external)
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- **Surface Elevation Change**:
  - Frequency: 30 days
  - Resolution: Horizontal 100 m
  - Required Measurement uncertainty: 0.1 m/year
  - Stability (per decade unless otherwise specified): 0.1 m/year
  - Entity (Satellite): WGClimate (link is external)
  - Entity (in situ): GCW (link is external)

- **Ice Velocity**:
  - Frequency: 30 days
  - Resolution: Horizontal 100 m
  - Required Measurement uncertainty: 0.1 m/year
  - Stability (per decade unless otherwise specified): 0.1 m/year
  - Entity (Satellite): WGClimate (link is external)
  - Entity (in situ): GCW (link is external)

- **Ice Mass Change**:
  - Frequency: 30 days Resolution: Horizontal 50 km
  - Required Measurement uncertainty: 10 km³/year
  - Stability (per decade unless otherwise specified): 10 km³/year
  - Entity (Satellite): WGClimate (link is external)
  - Entity (in situ): GCW (link is external)

- **Grounding Line Location and Thickness**:
  - Frequency: Yearly
  - Resolution: Horizontal 100 m; Vertical 10 m
  - Required Measurement uncertainty: 1 m
  - Stability (per decade unless otherwise specified): 10 m
  - Entity (Satellite): WGClimate (link is external)
  - Entity (in situ): GCW (link is external)
Glaciers & ice caps

- ICSU
- IUGG
- UNEP
- UNESCO
- WMO
- IPCC
- WGMS
- NSIDC
- GLIMS

Global Terrestrial Network for Glaciers

under the auspices of: ICSU (WDS), IUGG (IACS), UNEP, UNESCO, WMO

welcome

The Global Terrestrial Network for Glaciers (GTN-G) is the framework for the internationally coordinated monitoring of glaciers and ice caps in support of the United Nations Framework Convention on Climate Change (UNFCCC). The network, authorized under the Global Climate/Terrestrial Observing Systems (GCOS, GTOS), is jointly run by the World Glacier Monitoring Service (WGMS), the U.S. National Snow and Ice Data Center (NSIDC), and the Global Land Ice Measurements from Space Initiative (GLIMS). More...

This website provides general information on GTN-G and a map-based browser for available glacier data.
Glaciers & ice caps

- ICSU
- IUGG
- UNEP
- UNESCO
- WMO
- IPCC
- WGMS
- NSIDC
- GLIMS
Remote sensing products for glacier research and monitoring

- Glacier & ice sheet extent
- Glacier & ice sheet volume and mass changes
  - Ice dynamics
- Grounding line
- Melt status
- Surface properties & albedo
- Supra-glacial lakes
- Pre-glacial lake extent
- Internal structures
- Snow density & water equivalent
- Glacier thickness (airborne/groundbased GPR)
- …
Due to a consolidated remote sensing effort, we now know that there are more than 200’000 glacier worldwide. Inventory is continuously updated, all scientist can submit their data sets. Standardized methodology and documentation Used by modellers (future scenarios) and for e.g. ice thickness reconstruction
Methods to determine glacier & ice sheet mass changes

Gravimetry

Input – output

Geodetic

(c) USGS
Methods to determine glacier & ice sheet mass changes

Gravimetry

+ Direct measurement
+ Time series

- Only regions resolved
- GIA
- Size of the region
- Leakage

Input – output

+ Glacier resolving
+ Process information
+ Time series

- Error assessment
- Uncertainties of input data
- Amount of input data

Geodetic

+ Glacier resolving
+ Different data sources
+ Integrated measurement
+ Time series

- Error assessment
- Structure / phase unwrapping
- Gap filling & spatial interpolation

- Firn compaction
  (Trend assumption)
- (Radar penetration)

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Methods to determine glacier & ice sheet mass changes

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**Input – output**
- Glacier resolving
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**Geodetic**
- Different data sources
- Integrated measurement
- Time series
- Error assessment
- Uncertainties of input data
- Amount of input data

Methods and mission are highly complementary and reliability

Analysis of data from different missions increase confidence and reliability

Remote sensing is often the only change to provide regional assessments since access is limited or systems to large

Field-based studies using the glaciological or hydrological approach link very nicely, but often restricted to smaller systems and safe access
Consolidated Antarctic mass changes

IMBIE team (2018), NGEO
Consolidated Antarctic mass changes

IMBIE team (2018), NGEO
Global glacier mass change estimates

Gardner et al. (2013), Science
## Global glacier mass change assessment from different methods

<table>
<thead>
<tr>
<th>Region</th>
<th>Mass Change (km², Gt a⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antarctic &amp; Subantarctic</td>
<td>-29.400 km², -29 Gt a⁻¹</td>
</tr>
<tr>
<td>High Mountain Asia</td>
<td></td>
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<tr>
<td>Arctic Canada North</td>
<td></td>
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<tr>
<td>Alaska</td>
<td></td>
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<tr>
<td>Greenland</td>
<td></td>
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<tr>
<td>Russian Arctic</td>
<td></td>
</tr>
<tr>
<td>Arctic Canada South</td>
<td></td>
</tr>
<tr>
<td>Svalbard</td>
<td></td>
</tr>
<tr>
<td>Southern Andes</td>
<td>4.100 km², -4 Gt a⁻¹</td>
</tr>
<tr>
<td>Western Canada /US</td>
<td></td>
</tr>
<tr>
<td>Iceland</td>
<td></td>
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<tr>
<td>Low Latitudes</td>
<td></td>
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<tr>
<td>Scandinavia</td>
<td></td>
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<tr>
<td>North Asia</td>
<td></td>
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<tr>
<td>Central Europe</td>
<td></td>
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<tr>
<td>New Zealand</td>
<td></td>
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<tr>
<td>Caucasus &amp; Middle East</td>
<td></td>
</tr>
</tbody>
</table>

Gardner et al. (2013), Science
Elevation & mass changes HMA

Elevation change $\frac{dh}{dt}$ (m a$^{-1}$) Volume change $\frac{dV}{dt}$ (km$^3$ a$^{-1}$) Mass change $\frac{dm}{dt}$ (Gt a$^{-1}$)

-0.15 ± 0.05 -3.925 ± 0.59 -3.336 ± 0.55

Missions: SRTM – TanDEM-X
Time period: 2000-2012/13
Area measured: 26'172 ± 1'570 km$^2$
Impacts of glacier changes in high mountains

Peru:

- 54% of the energy production from hydropower with 5.4% increasing energy demand per year (Vuille et al., 2018)
- Agricultural production in the Cordillera Blanca is strongly relying on irrigation
- Mining claims in Peru cover 11% of the country surface => water amount, quality and suspended matter concentration
- Production of one ounce of gold requires 25 m³ water in 2008
- Glacier hazard & risk: GLOFs and ice avalanches
- Downstream ecological impacts
- Social and political conflicts resulting from water allocation

=> At which state are we currently (peak water) and what is glacier volume and mass loss?

Example:
Chavimochic project in the La Libertad coastal region:
- US$ 0.5 Mia agricultural export production by irrigation
- Drinking water of 800,000 people in Trujillo
- Jobs for >60,000 people
- and energy production

All from the Santa river originating from the Cordillera Blanca
Impacts of glacier changes in high mountains

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United Nations Office for Disaster Risk Reduction
Glacier discharge & irrigation Peru

The New York Times

The New York Times

http://www3.imperial.ac.uk
Discharge from glaciers – the “Peak water” effect

Huss & Hock (2018), NGEO
Discharge from glaciers – the “Peak water” effect

Huss & Hock (2018), NGEO
Daily and response to extreme events

- snow
- firn
- glacier ice

\[ Q_{\text{daily}} \]

- glacier ice

\[ Q_{\text{daily}} \]
Global glacier equilibrium mass

Marzeion et al (2018), NGEO
Natural hazards: Glacier Lake Outburst Floods and avalanches


http://glacierhub.org/
Natural hazards: Glacier Lake Outburst Floods and avalanches

Huaraz city covered by the 1941 flood after failure of the end moraine causing 5000 casualties.

In 2010 a tsunami of 23m was induced by a large glacier calving event destroying 50 homes and a water processing plant.

In 1970 the Ancash earthquake induced an ice avalanche whipping out the towns of Yungay and Ranrahirca. A volume of 80 million m³ of water, mud, rocks and snow was estimated.

http://www.ce.utexas.edu/
Conclusion & Outlook

With current satellite mission we have fantastic possibilities to determine various variables (not only ECVs!), however, we need:

- global, reliable and glacier specific mass change estimates
- regular assessments of glacier status
- multi-mission approaches
- missions that can continue current measurements (Cryosat FO, TanDEM-L, TanDEM-X FO, ASTER FO)
- to be prepared for big data
- a common methodology for error assessment
- links to climatological and hydrological studies => hydrological scenarios
- more remote sensing integration into ice dynamic modelling and ice thickness reconstruction => ice volume and scenarios
- socio-economic and political links => awareness and mitigation
- fast, cost-free and continuous access to archives
Thanks for attending and listening
Hydrological impacts in the Tropical Andes

Mark et al. (2017)
Seasonal runoff change (Santa river, Peru)

Juen et al. (2007)
Grounding line mapping with remote sensing

Friedl et al. (in prep.)
Changes of glaciers & ice caps
CMIP5 predictions under different emission scenarios

- RCP2.6 (annual)
- RCP2.6 (summer)
- RCP2.6 (autumn)
- RCP2.6 (winter)
- RCP2.6 (spring)

- RCP4.5 (annual)
- RCP4.5 (summer)
- RCP4.5 (autumn)
- RCP4.5 (winter)
- RCP4.5 (spring)

- RCP8.5 (annual)
- RCP8.5 (summer)
- RCP8.5 (autumn)
- RCP8.5 (winter)
- RCP8.5 (spring)

SCAR AntClim21

Matthias.h.braun@fau.de
Mass change estimates of the Patagonian ice fields

Foresta et al. (2018), RSE
Ice thickness reconstruction

- 2D physically based bedrock map
- Input: DGM, outlines, SMB, \( \frac{dh}{dt} \), measured thickness, surface velocity
- Based on mass conservation & solves for ice flux
- Cost functions for optimization
- Robust under different glacier geometries (ice cap, land- or marine-terminated glaciers, …)
- High degree of automation
- Provides uncertainty estimate
- Embedded in Elmer Ice ice flow model on FAU High Performance Computing Center
Ice thickness reconstruction – NPI

Ice flux

Ice thickness

San Rafael

San Quintin

Nef

Colonia
Watershed

Biophysical and hydrologic processes (glacier recession, "peak water", ecological change)

Impacts on water availability and quality

Water Access and Use

Impacts on water allocation and control

Social arrangements and engineered systems (land use, laws, institutions, infrastructure)

Social impacts on natural systems (development pathways, water quality standards)

Uncertain impacts and partial constraints on resource use strategies (global warming, ENSO)
Mass change of the Antarctic ice sheet from GRACE

https://data1.geo.tu-dresden.de/ais_gmb/index.html
Mass change of the Greenland ice sheet from GRACE

https://data1.geo.tu-dresden.de/ais_gmb/index.html
Sea level finger prints (2003-2014)

Rietbröck et al. (2016), PNAS