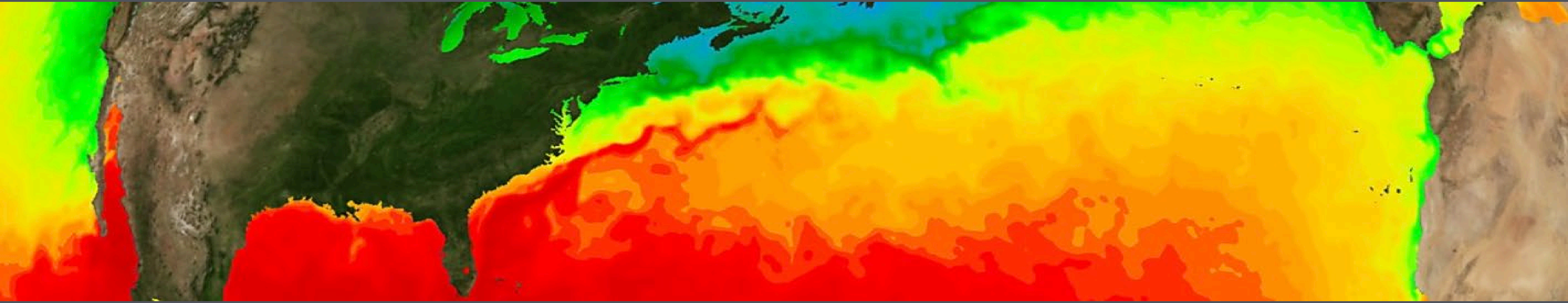
National Centre for Earth Observation
Department of Meteorology

Thermal remote sensing for hydrology and the cryosphere



Chris Merchant (Reading) and Abigail Waring (Leicester)

Outline

- Thermal radiative and physical properties of water bodies
- Case study – Lakes and how they are changing with climate
- Case study – Industrial thermal plumes
- Case study – Sudd flooding
- Case study – Remote sensing as exploration – Greenland
- Thermal radiative and physical properties of snow and ice
- Case study – AW 1
- (Case study – AW 2?)
- Wrap up and questions

Thermal remote sensing of water

Photo: DavidRippin, University of York.
West Greenland, 2024.

Surface water temperatures are the most accurately measured temperatures from space.

Open ocean sea ST <0.3 K
Inland waters, coastal <0.6 K
Relative uncertainties smaller

Why?

Water-air interface

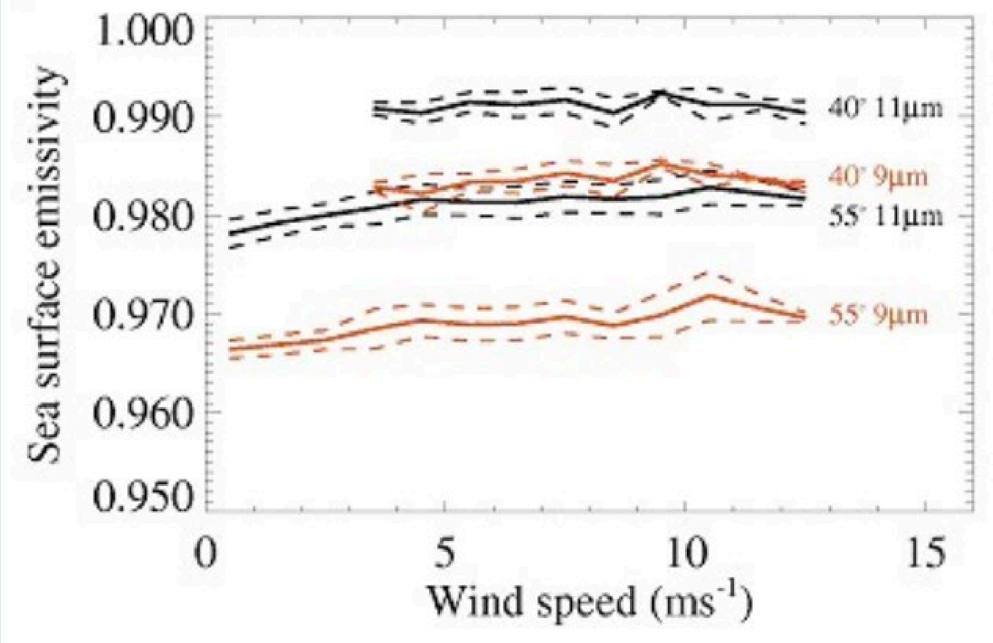
Emissivity dominated by intrinsic properties of water

Roughening of surface by wind changes the effective emissivity

Water surface emissivity

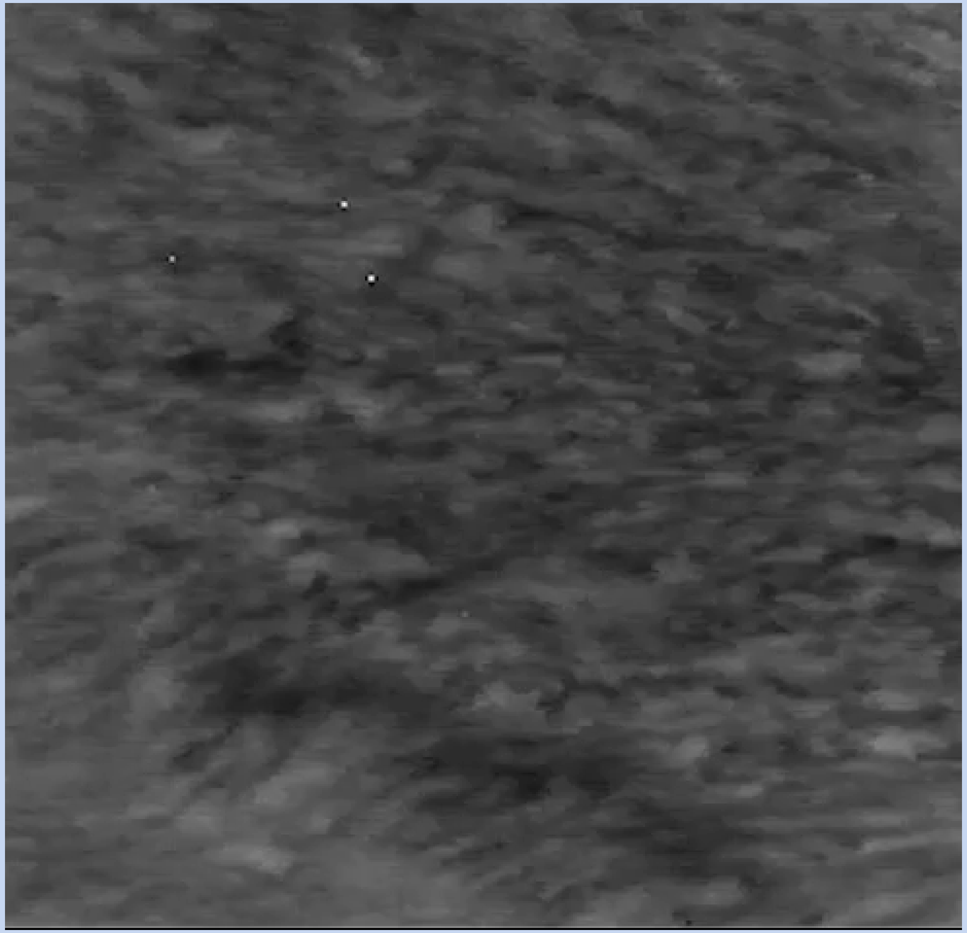
- 0.97 to 0.99

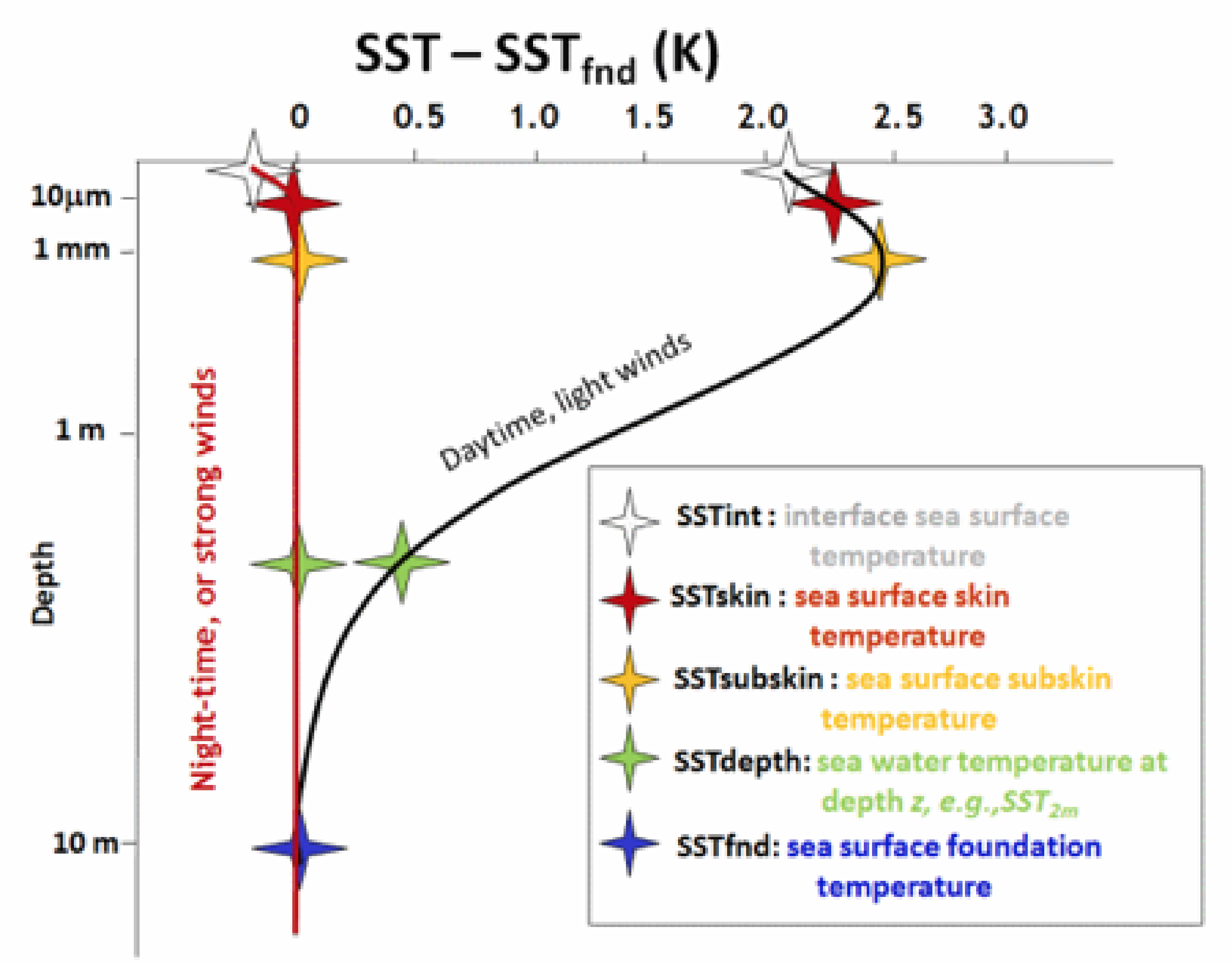
- **Satellite view angle**
- **Surface state (wind roughening)**
- **Salinity**
- **Temperature**
- Slicks



https:// modis.gsfc.nasa.gov/ sci_team/meetings/200503/posters/ocean/minnett1.pdf

What is observed?



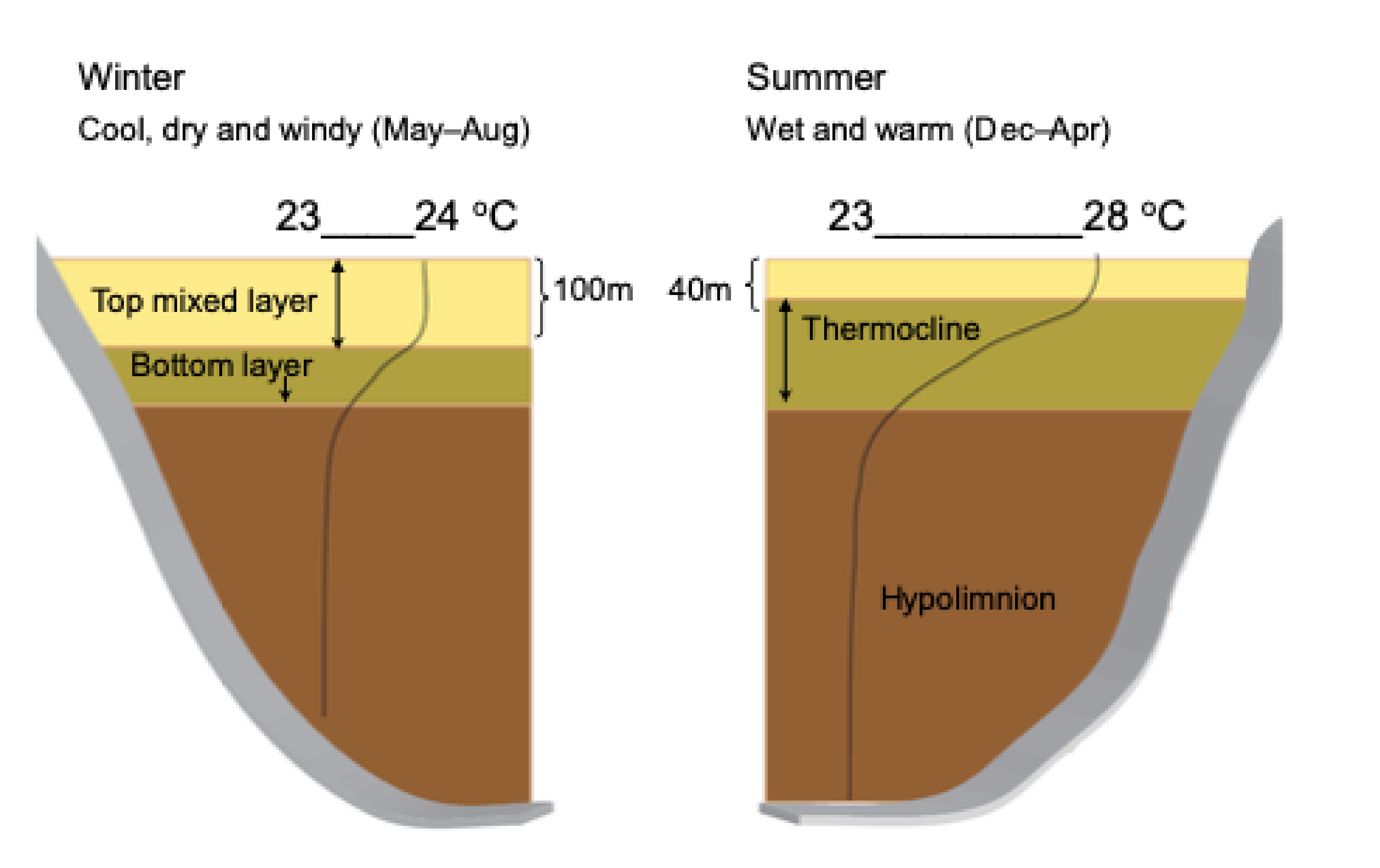


Skin vs. depth surface water temperature

- The skin SWT measured by IR is key to some of the physical interactions of the water body and atmosphere
  - energy balance
  - evaporation rates
  - impact on atmospheric boundary layer

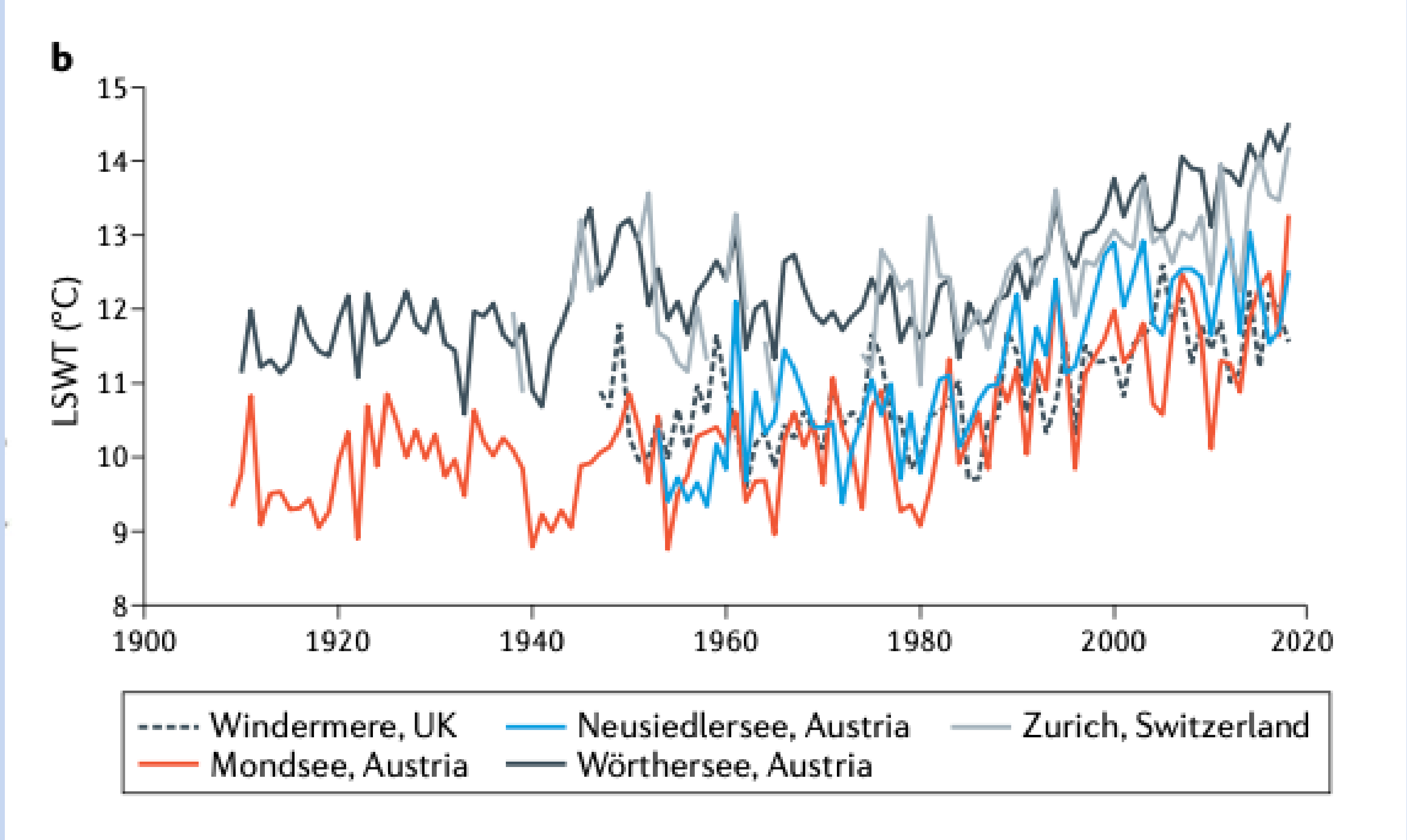
- The temperatures at depth are more relevant to ecosystem and water quality impacts
  - temperature sensitive species
  - mixing regime of lakes, oxygenation

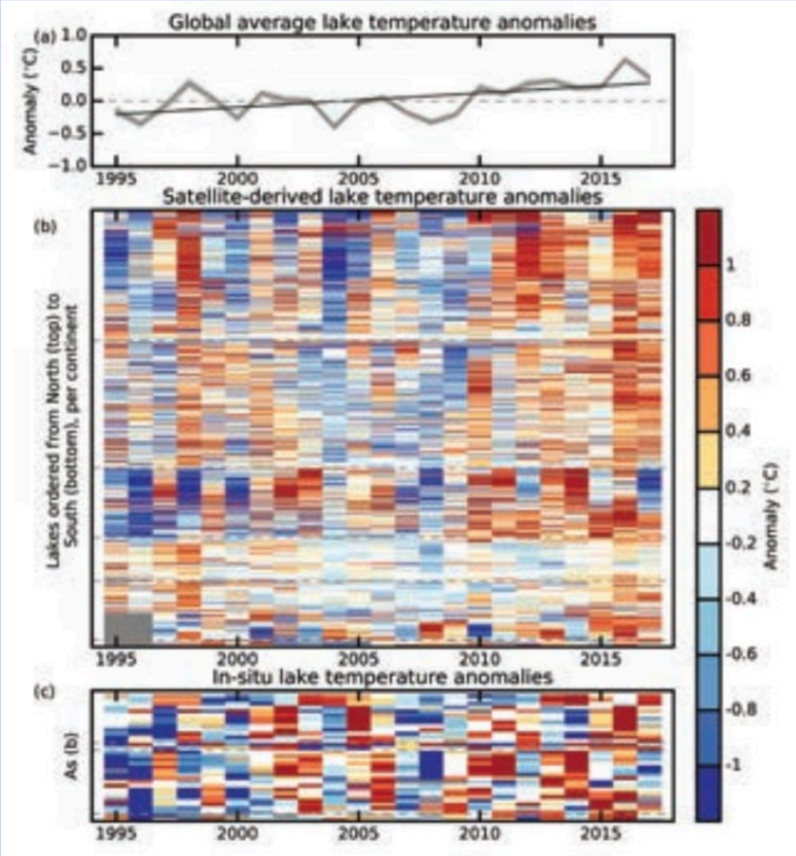
Lake Malawi



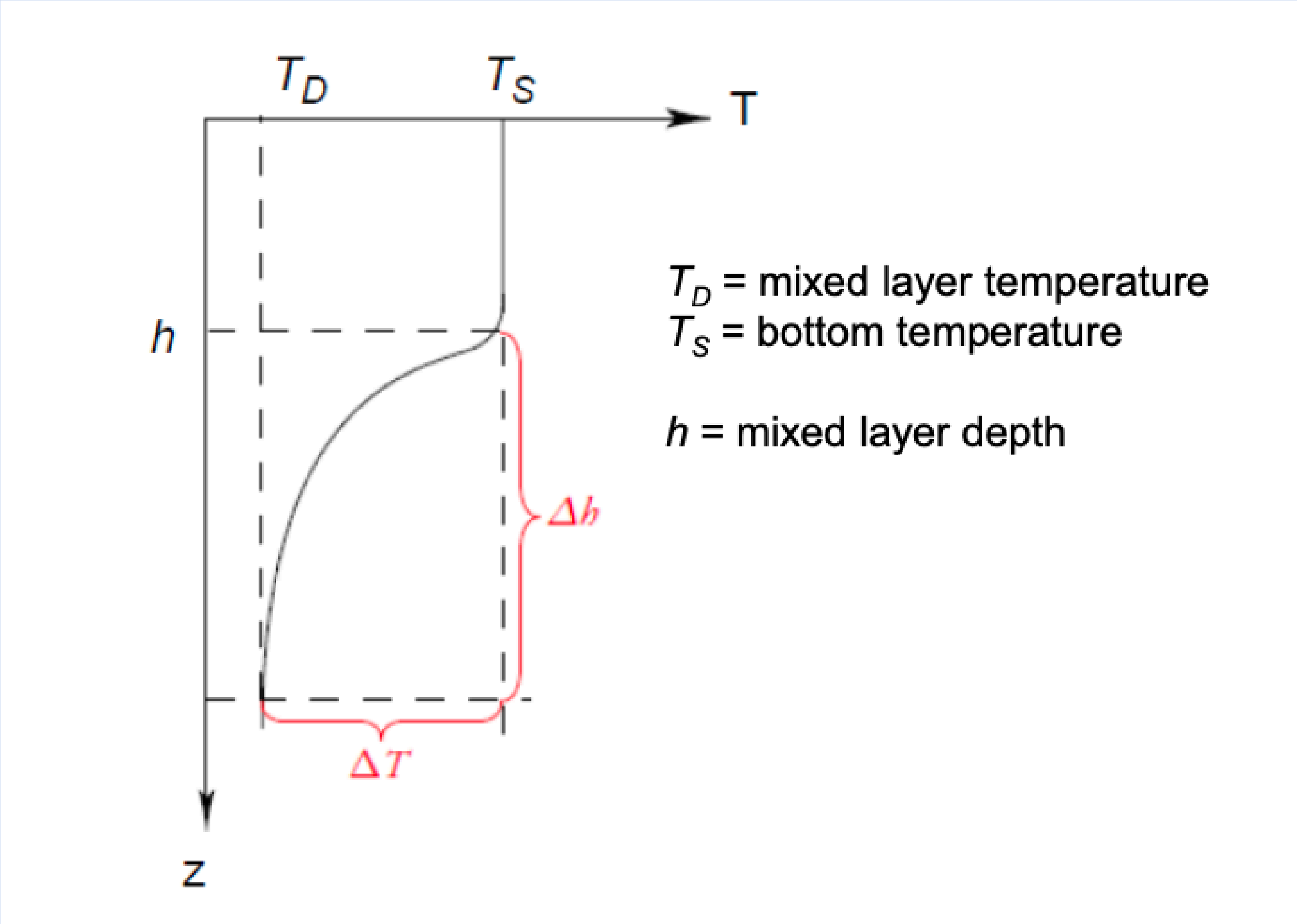
Winter
Cool, dry and windy (May–Aug)
23
24 °C
Top mixed layer
Bottom layer
100m
Summer
Wet and warm (Dec–Apr)
23
28 °C
40m
Thermocline
Hypolimnion

Lake in-situ observations are rare





LSWT as a modelling constraint



FLakemodel (others are available)

Drive from numerical weather prediction fields.

Tuning parameters:

- opacity
- wind scaling (fetch),
- effective depth
- ice-albedo for seasonally ice covered

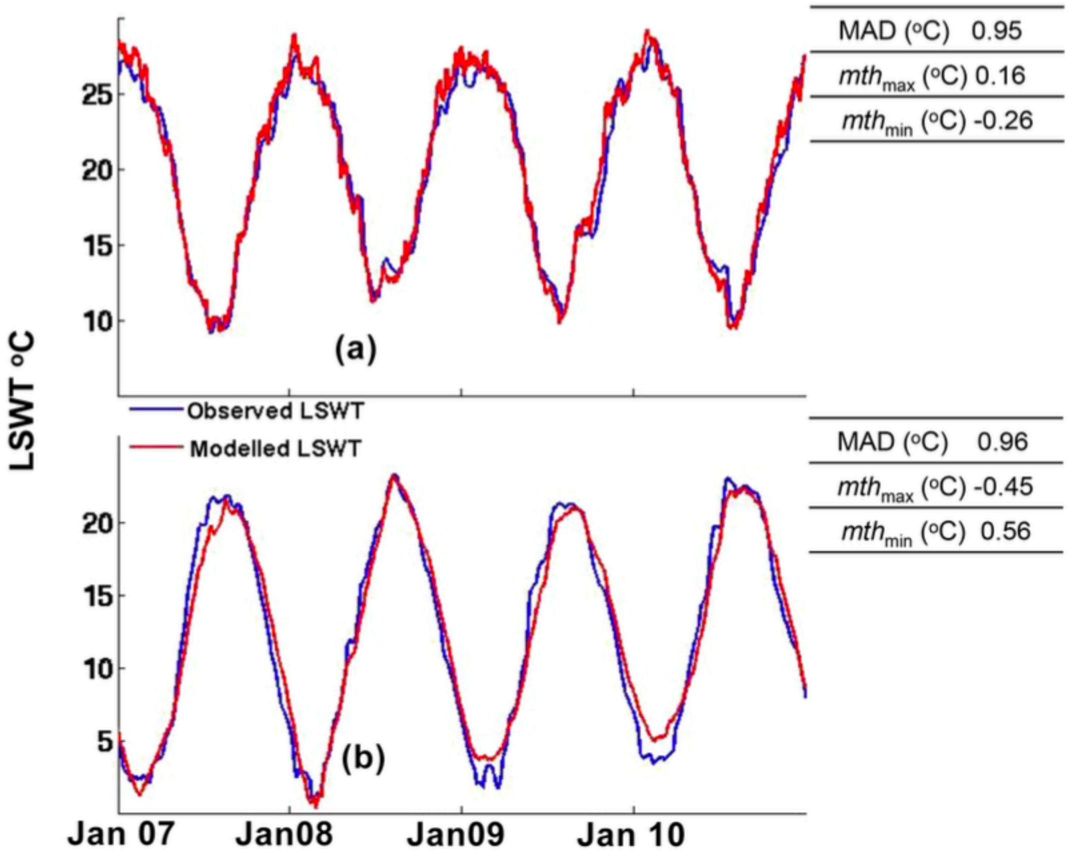


Figure 14. Observed LSWT versus tuned model LSWT for saline and high altitude lakes **(a)** Lake Chiquita, Argentina (31° S 63° W, salinity 145 g L^{-1}); **(b)** Lake Van, Turkey (39° N 43° E, 1638 m a.s.l., salinity 22 g L^{-1}).

Geosci. Model Dev., 9, 2167–2189, 2016
www.geosci-model-dev.net/9/2167/2016/
doi:10.5194/gmd-9-2167-2016

Geoscientific Model Development
Open Access
EGU

Determining lake surface water temperatures worldwide using a tuned one-dimensional lake model (*FLake*, v1)

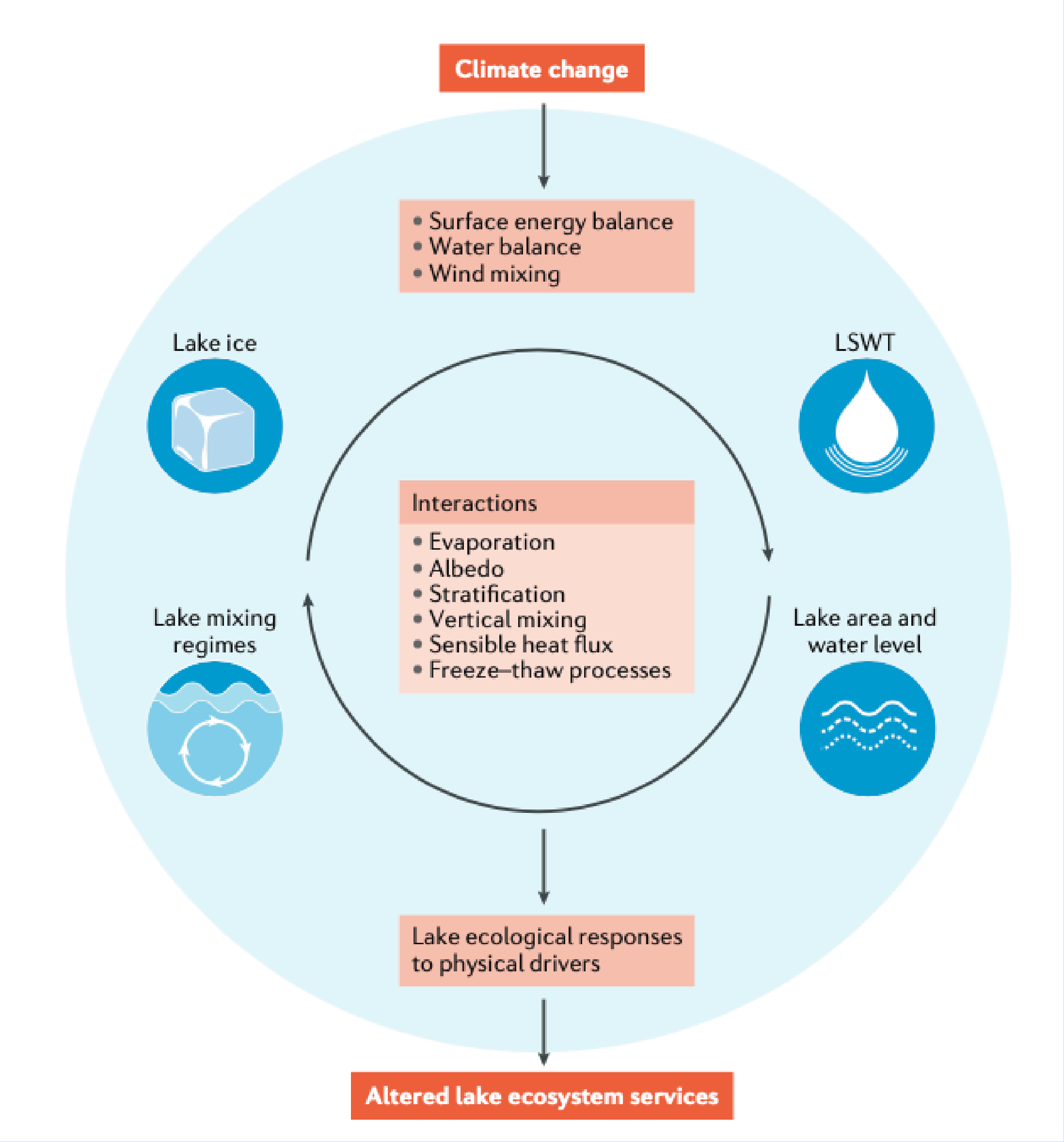
Aisling Layden[1,a], Stuart N. MacCallum[2], and Christopher J. Merchant[3]

[1]4 Rose Hill, Sligo, Ireland
[2]School of Geosciences, University of Edinburgh, Grant Institute, The King's Buildings, West Mains Road, Edinburgh, EH9 3FE, UK
[3]Dept. of Meteorology, University of Reading, Harry Pitt Building, 3 Earley Gate, P.O. Box 238, Whiteknights, Reading, RG6 6AL, UK
[a]formerly at: University of Edinburgh, School of Geosciences, Crew Building, Kings Buildings, West Main Rd, Edinburgh EH9 3JN, UK

- www.geosci-model-dev.net/9/2167/2016/
- Concept: if LSWT annual cycle and inter-annual variability are well simulated, model outputs are also informative about variability through the lake depth

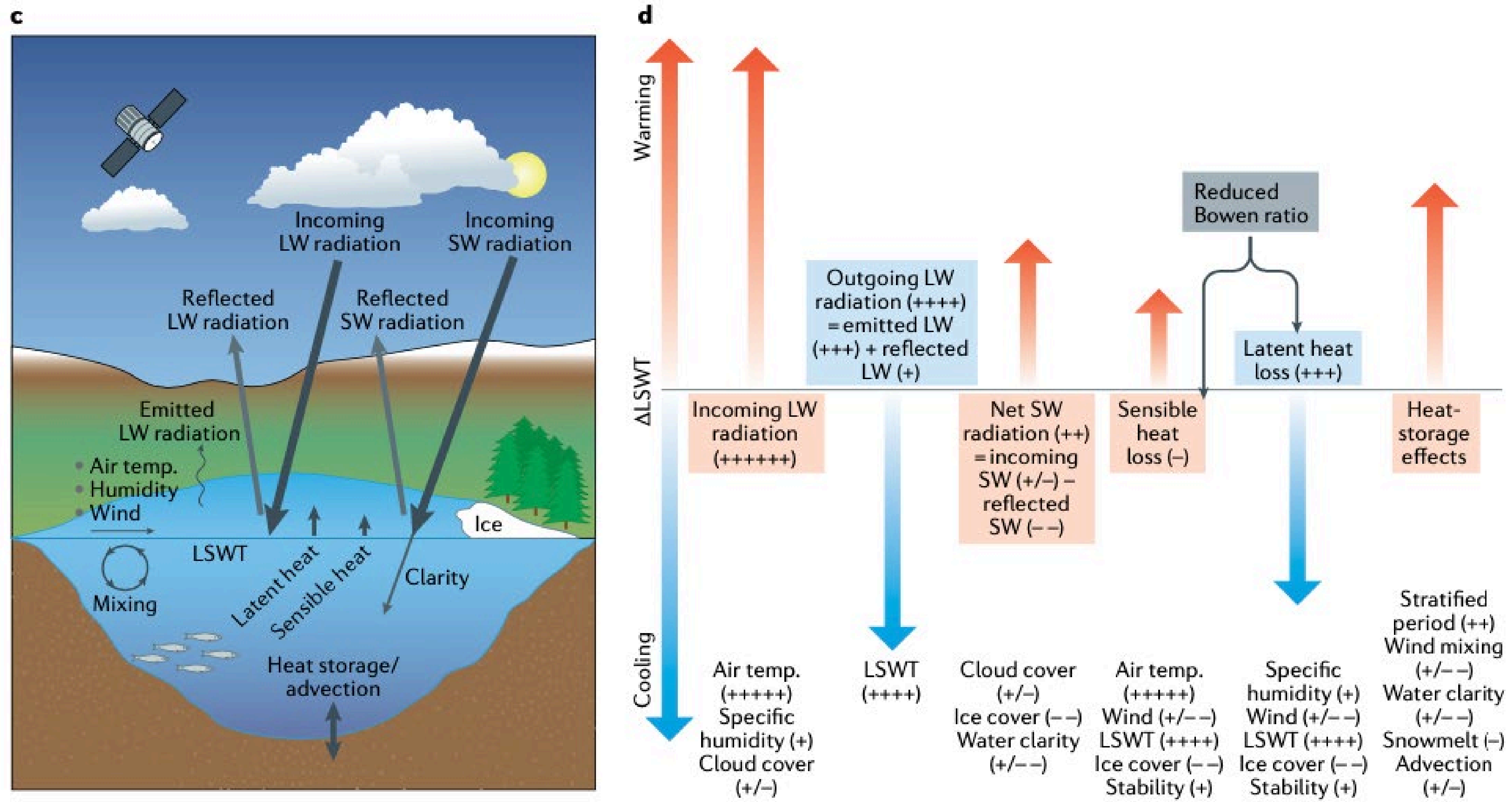
Case-study 1 : Worldwide changes in lakes in interaction with climate

- Examples of insights gained from using TIR LSWT timeseries to constrain 1-d physical lake models

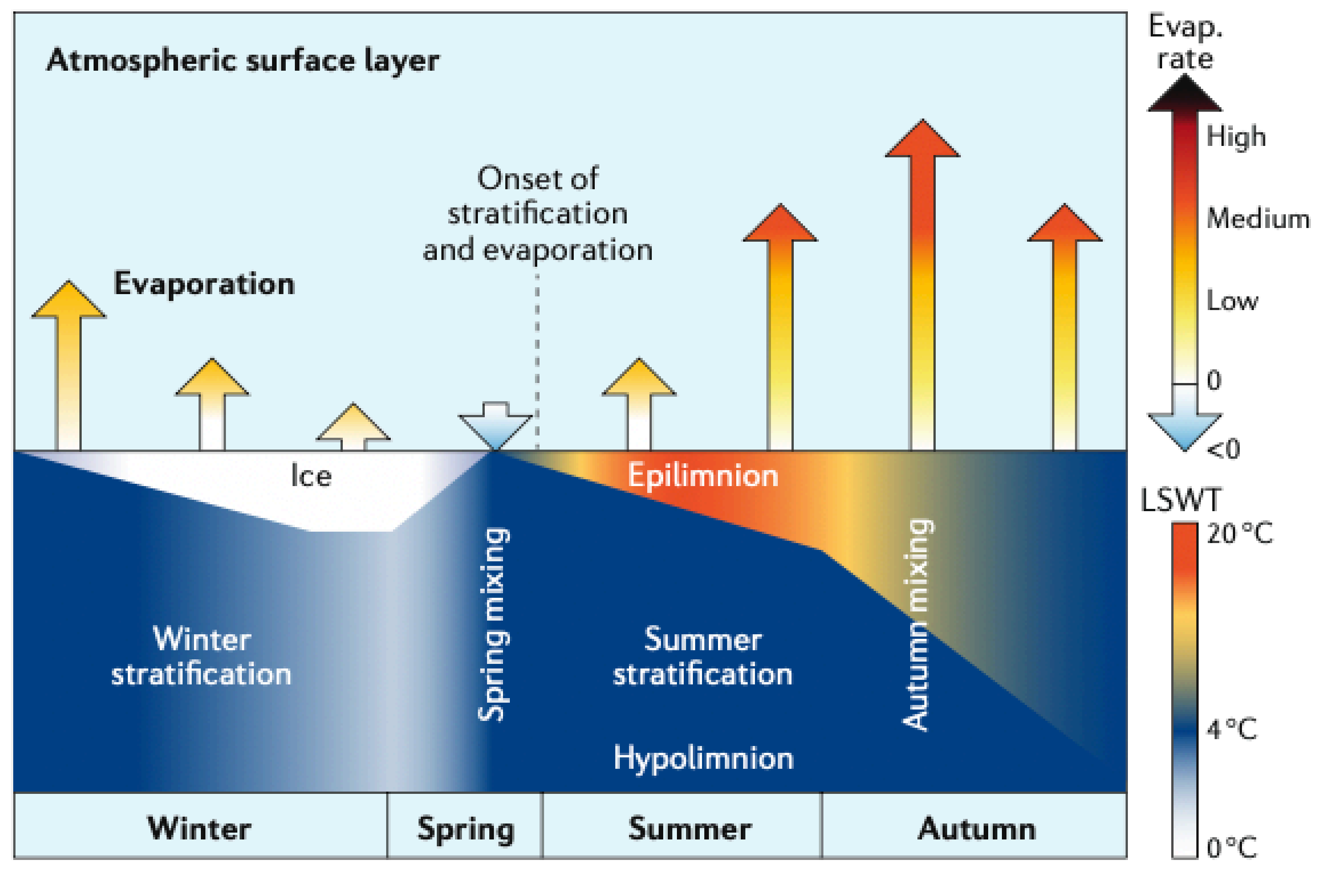


doi.org/10.1038/ s43017-020-0067-5

doi.org/10.1038/ s43017-020-0067-5



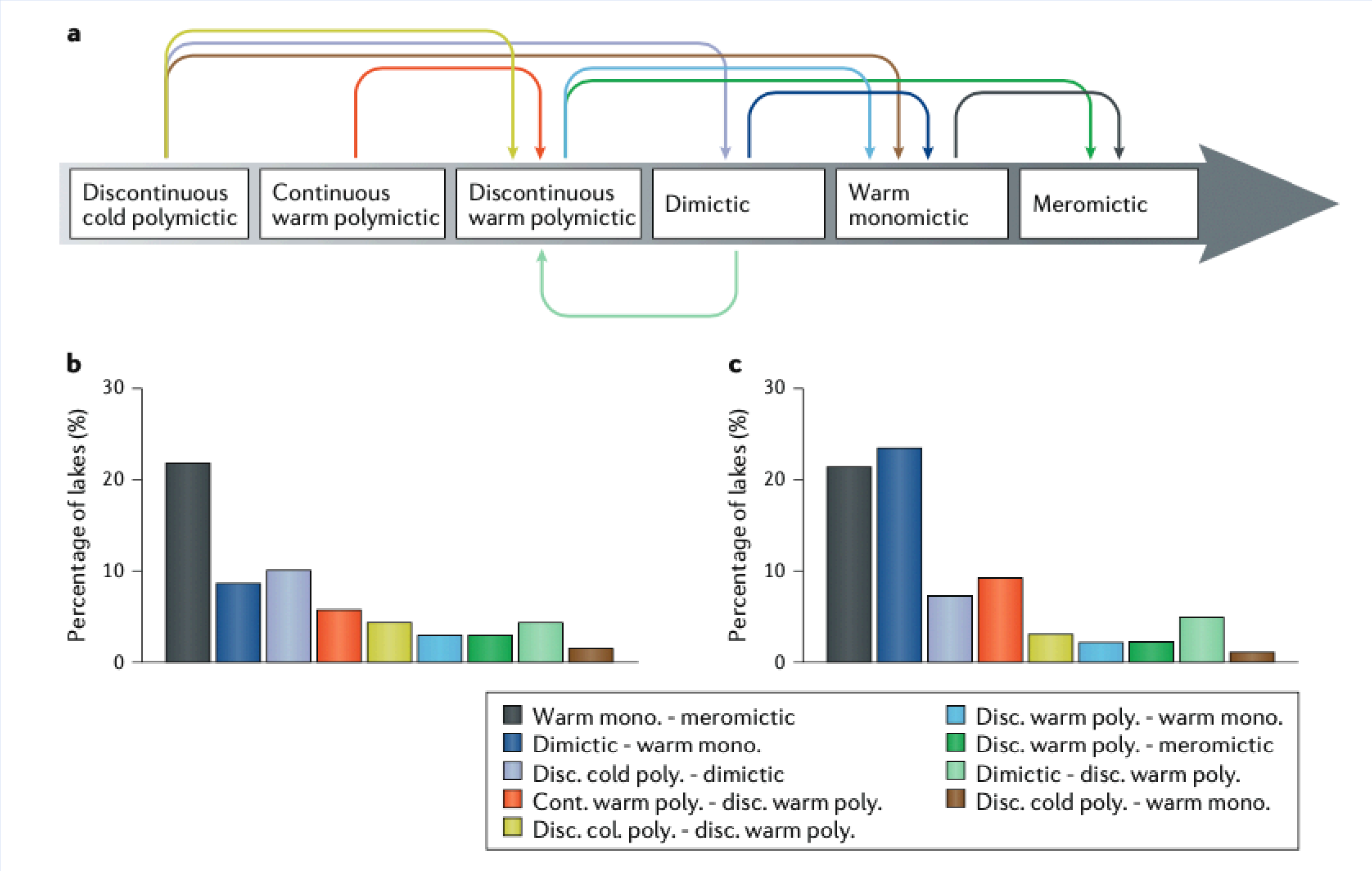
Key lake characteristic is mixing regime



Lake Malawi : rarely and irregularly mixed

Many temperate lakes are **dimictic** (mix during two seasons)

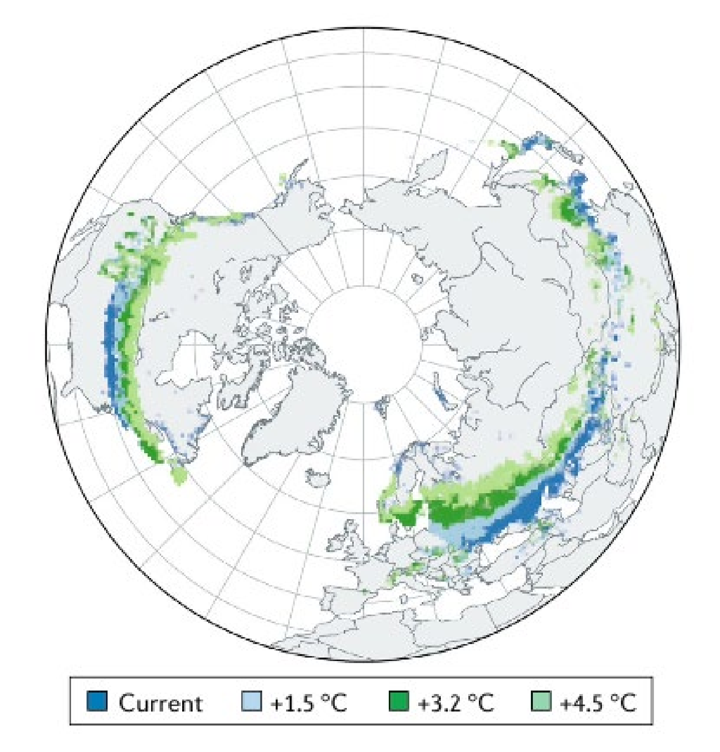
Mixing regimes change



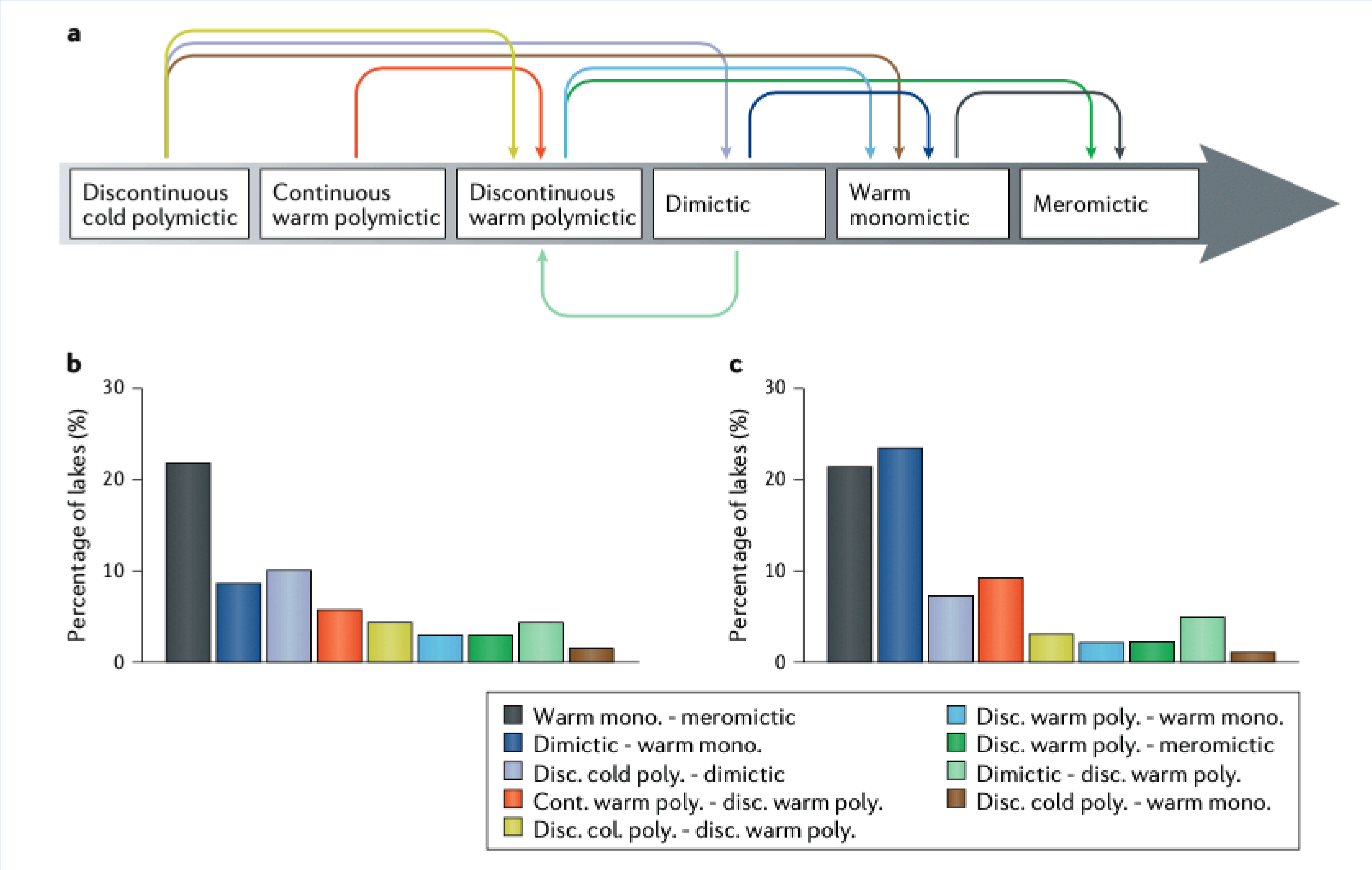
Worldwide alteration of lake mixing regimes in response to climate change

R. Iestyn Woolway & Christopher J. Merchant

Nature Geoscience 12, 271–276 (2019) | Cite this article



Mixing regimes change



Worldwide alteration of lake mixing regimes in response to climate change

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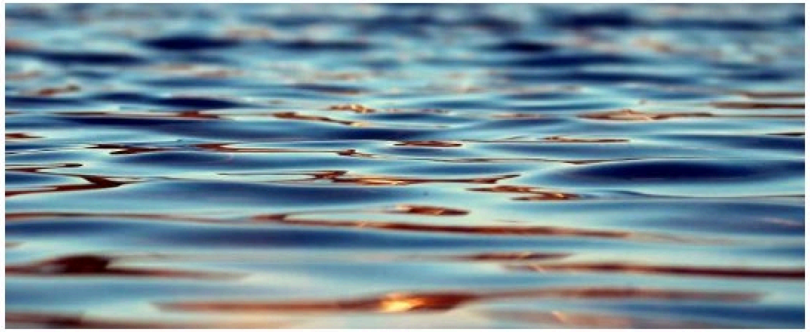
Nature Geoscience **12**, 271–276 (2019) | Cite this article

10k Accesses | **353** Citations | **136** Altmetric | Metrics

Lake 'dead zones' could kill fish and poison drinking water

by University of Reading

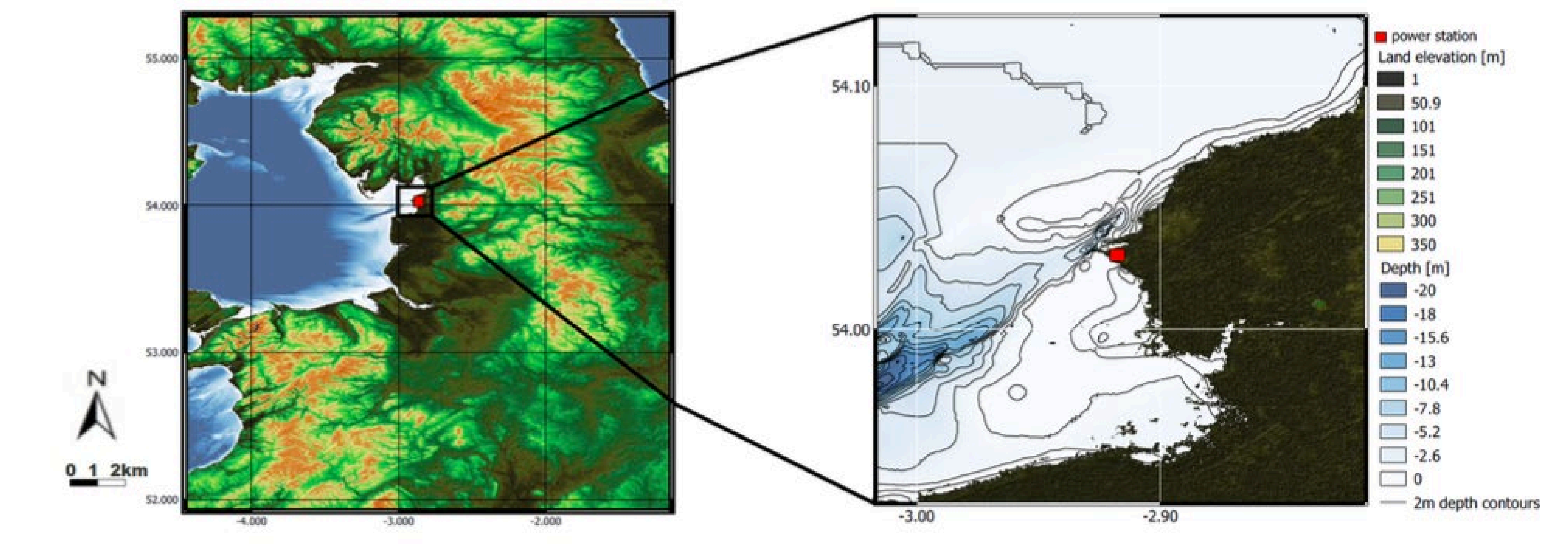


Credit: CC0 Public Domain

'Dead zones' could become increasingly common in lakes in future due to climate change, reducing fish numbers and releasing toxic substances into drinking water.

Case-study 2 : Industrial thermal plumes

- Mapping of industrial / power-station discharges can save money while ensuring environmental compliance (Faulkner et al., https://doi.org/10.3390/rs11182132)



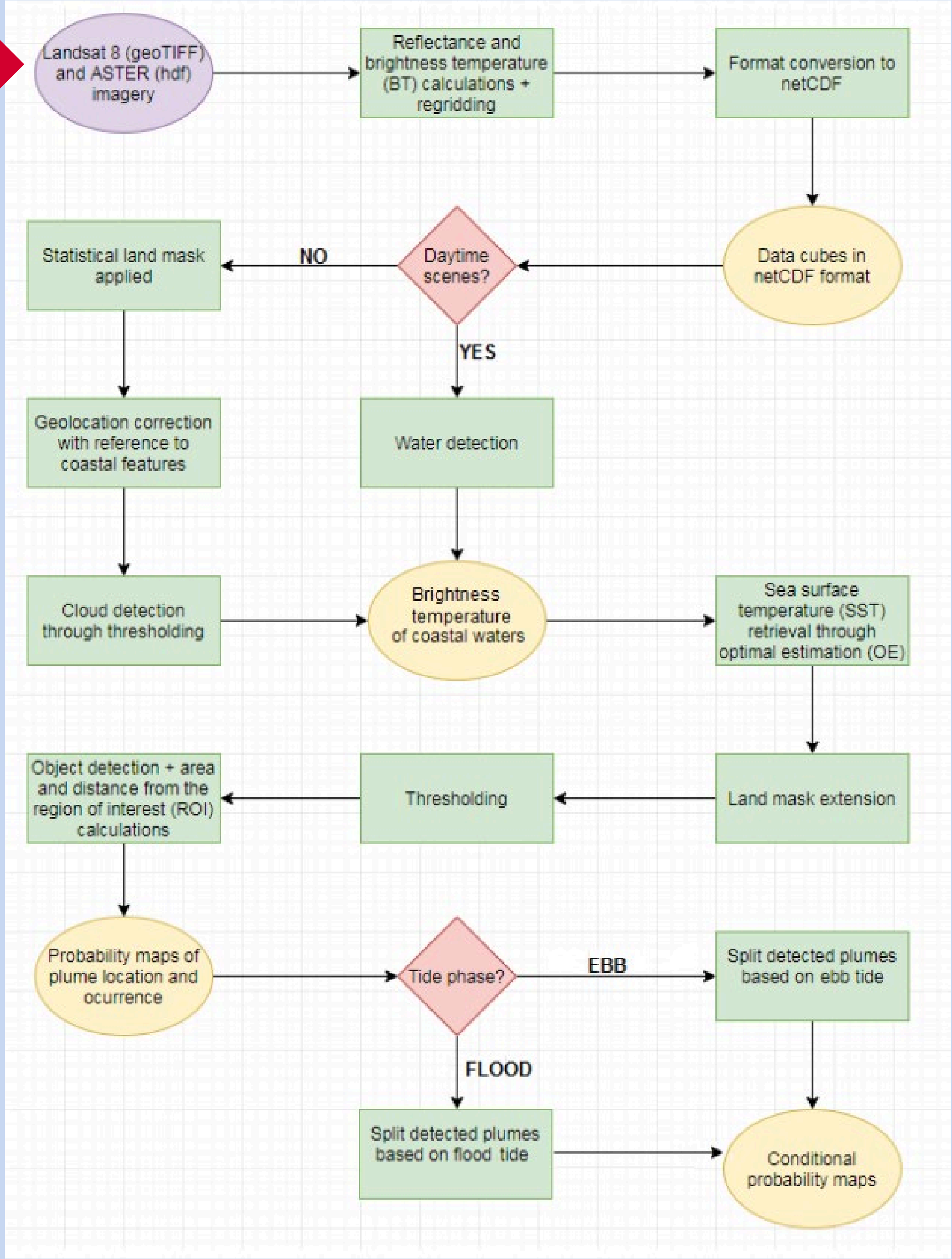
Google Earth

https://www.geograph.org.uk/photo/2391185

https://www.geograph.org.uk/photo/533184

Empirical mapping of thermal plume beyond outflow

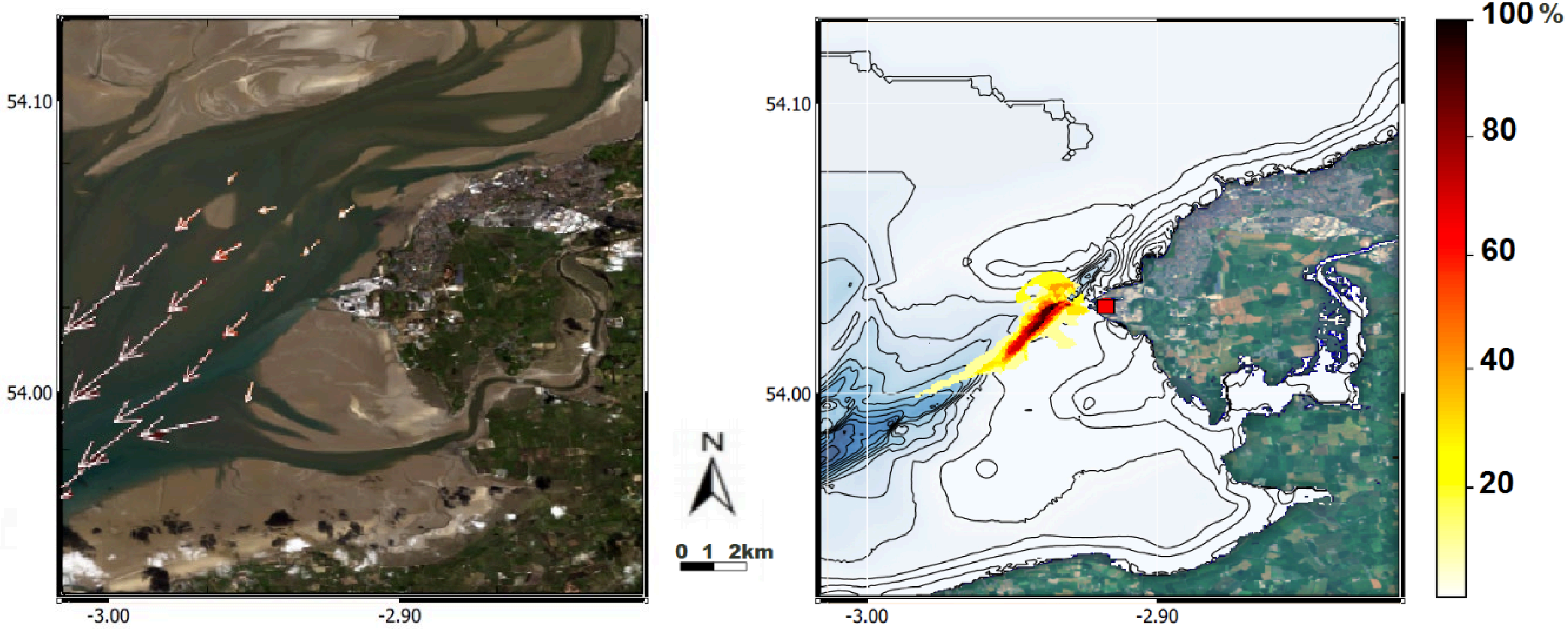
LandSat8 and ATSER



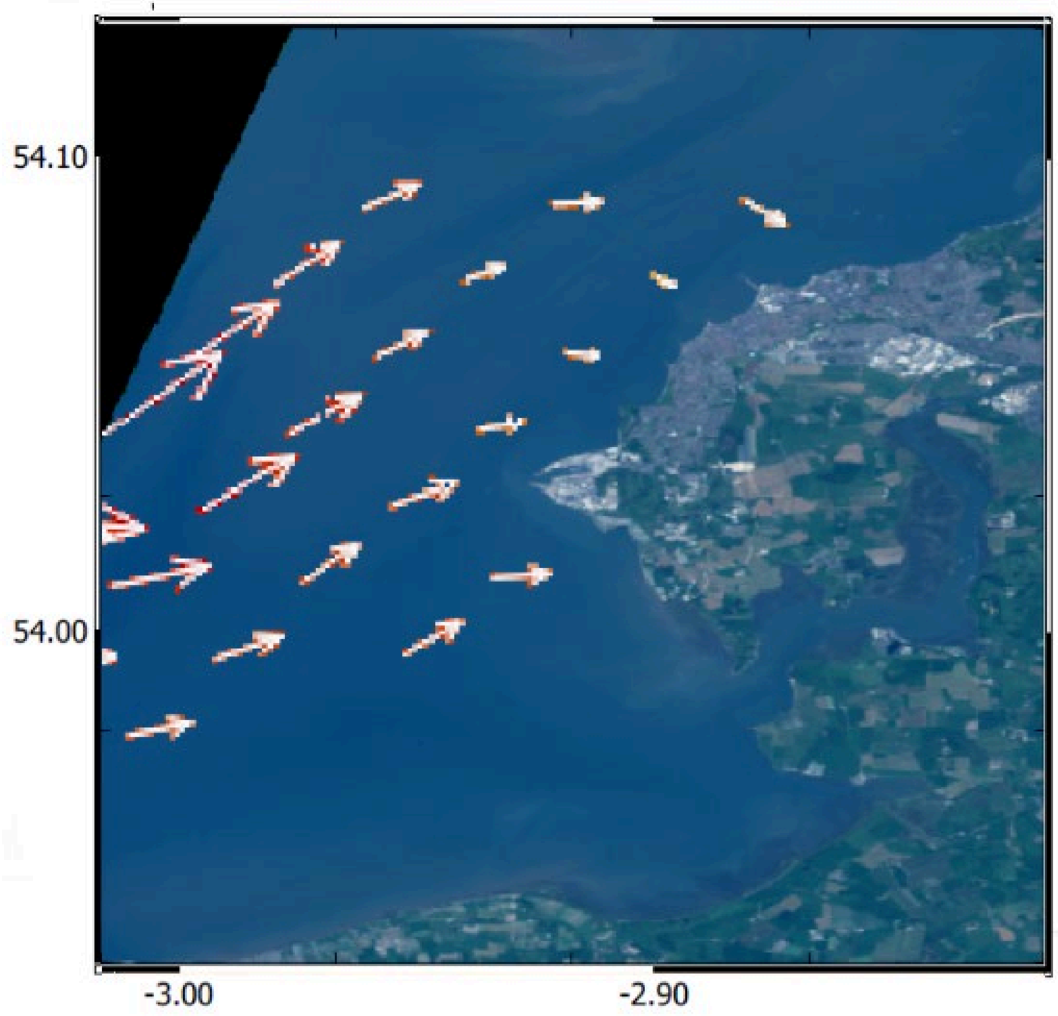
Steps to identify water (varies with tide) and retrieve water temperature

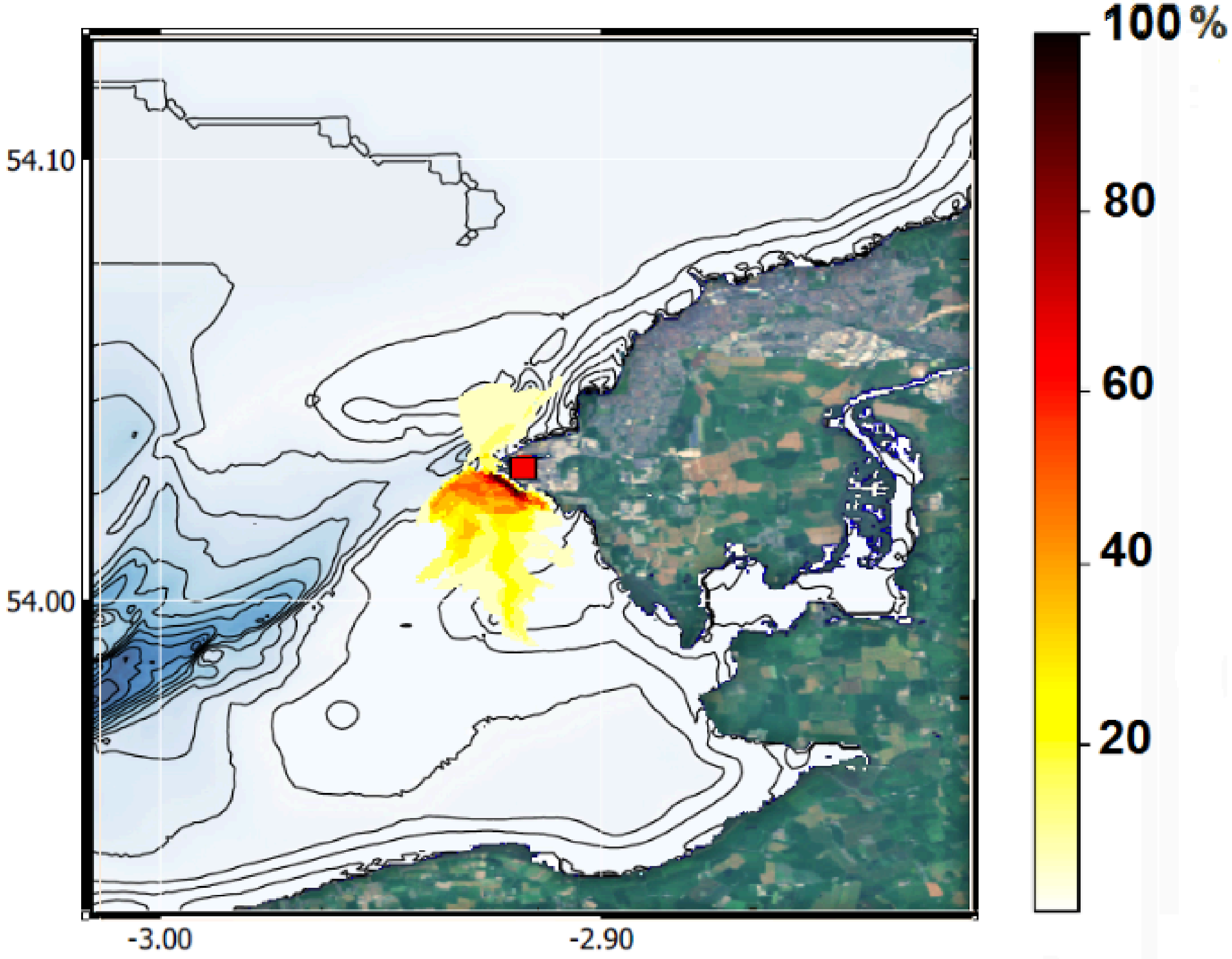
Compositing conditional on tidal phase

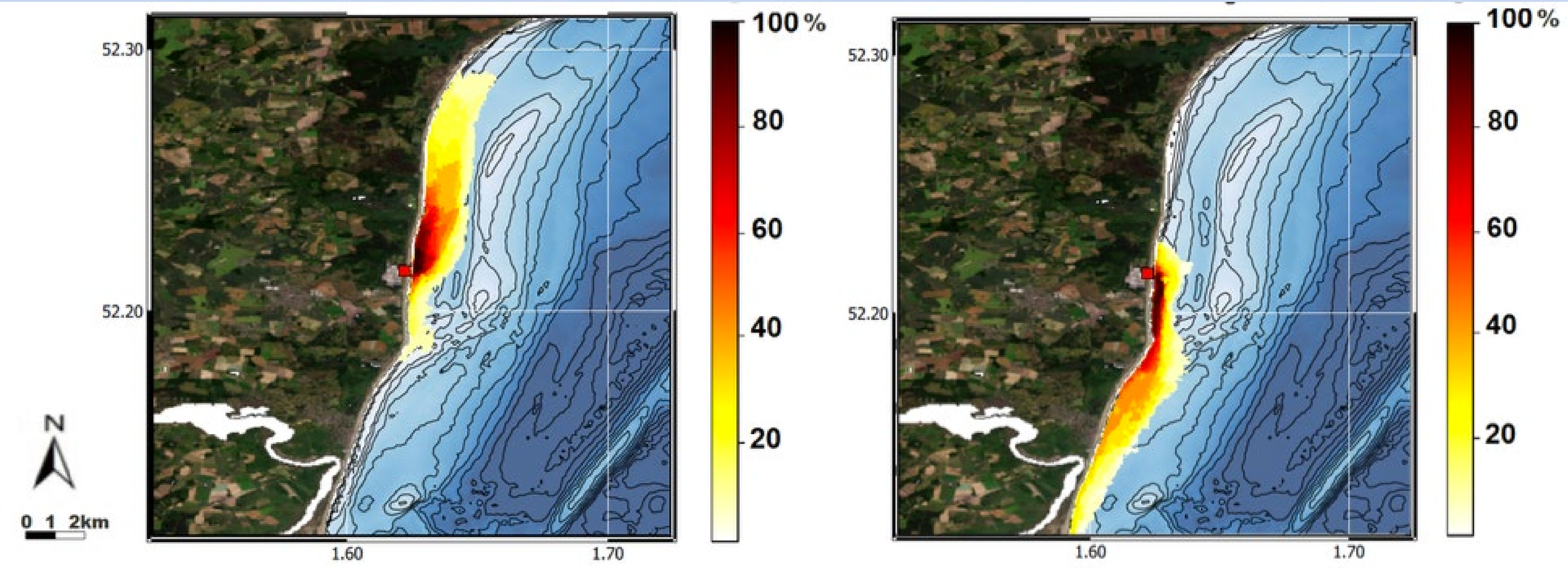
EBB



FLOOD







SIZEWELL NUCLEAR POWER STATION

Case study 3 – Sudd Wetland Floods

University of Reading

Home | All posts | Events | Awards & Prizes

South Sudan floods: the first example of a mass population permanently displaced by climate change?

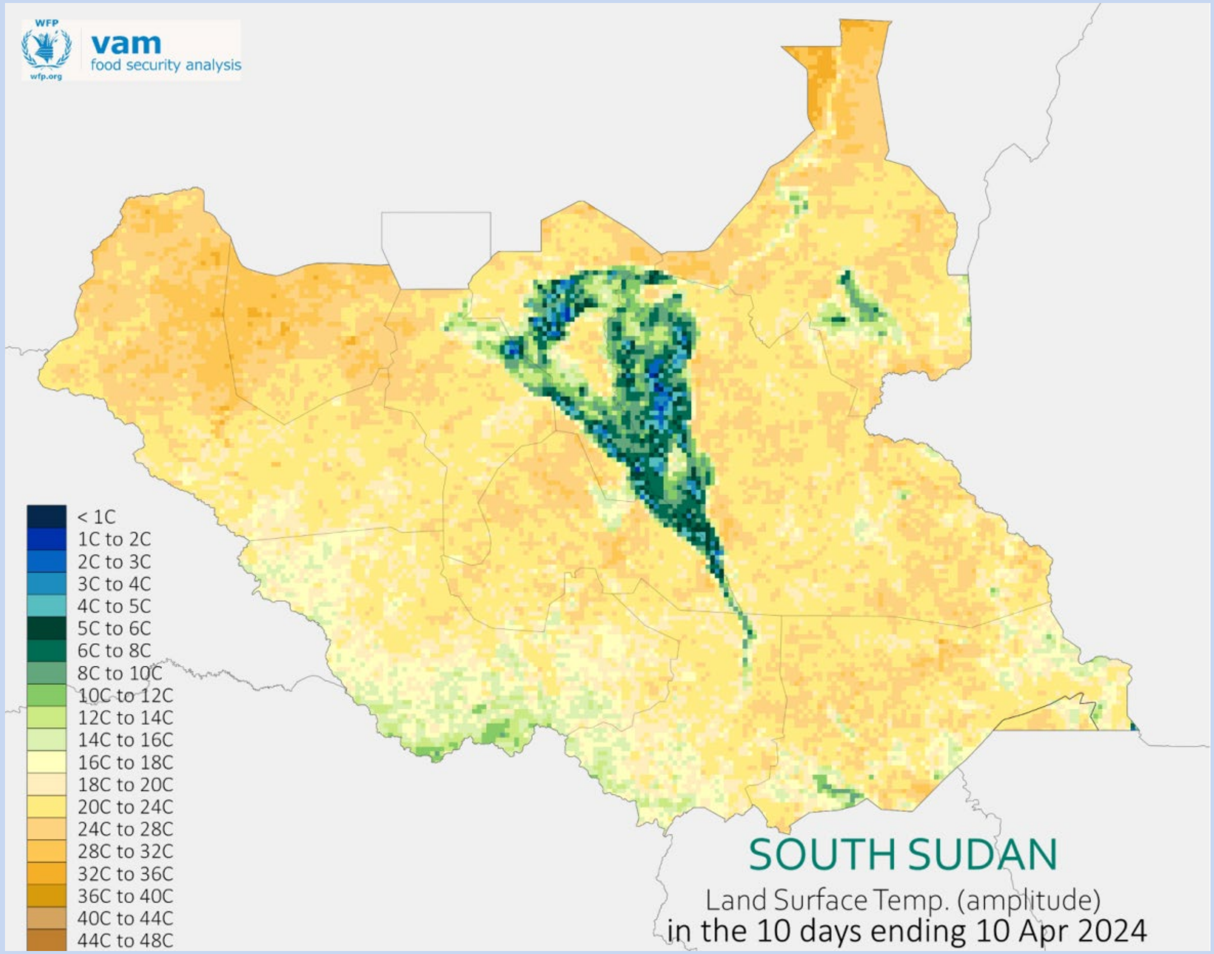
Posted on
19 September 2024

Enormous floods have once again engulfed much of South Sudan, as record water-levels in Lake Victoria flow downstream through the Nile. More than 700,000 people have been affected. Hundreds of thousands of people there were already forced from their homes by huge floods a few years ago and were yet to return before this new threat emerged.

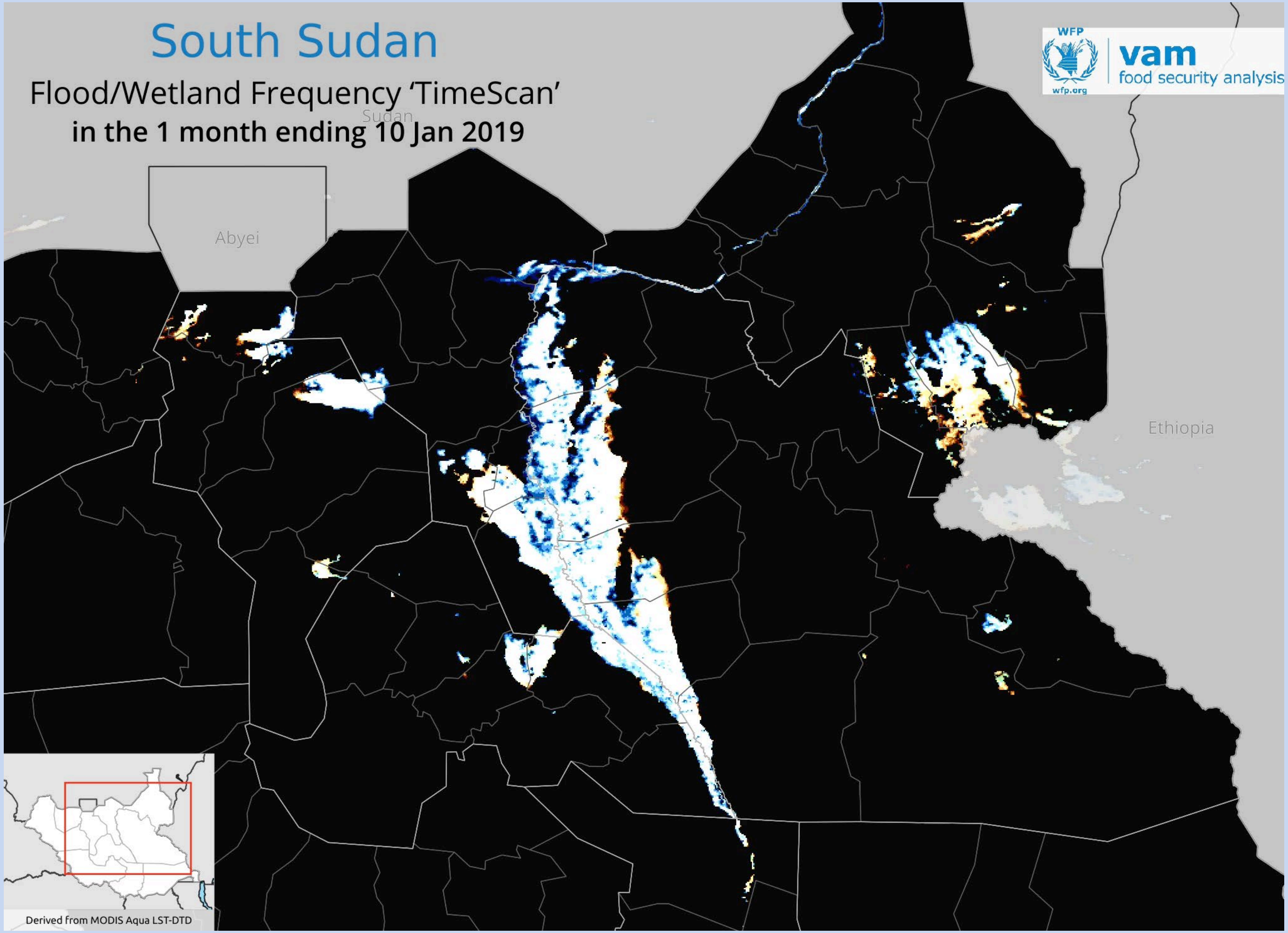
Now, there are concerns that these displaced communities may never be able to return to their lands. While weather extremes regularly displace whole communities in other parts of the world, this could be the first permanent mass displacement due to climate change.

Normal water detection doesn't work

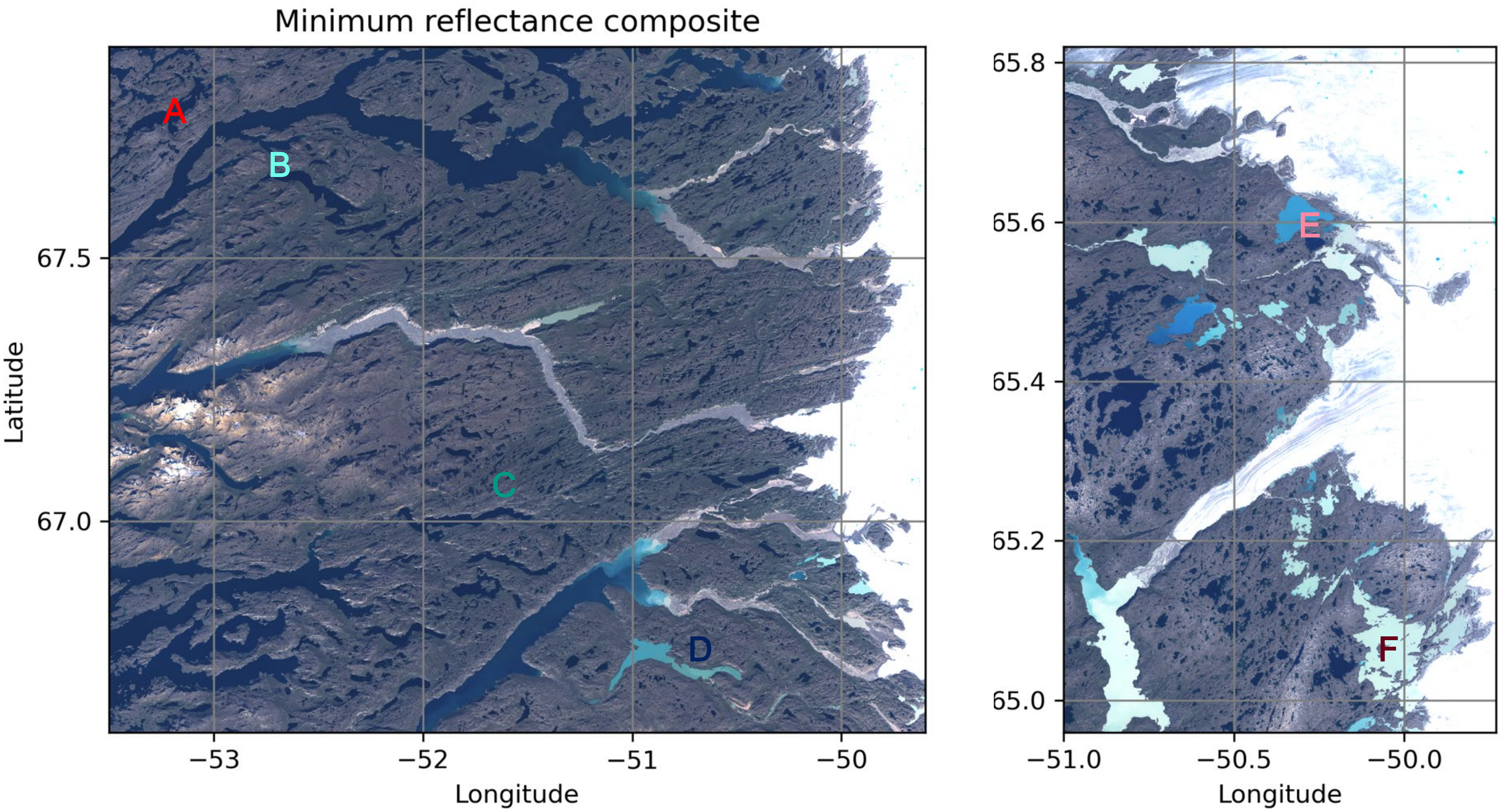
World food programme approach - DTR

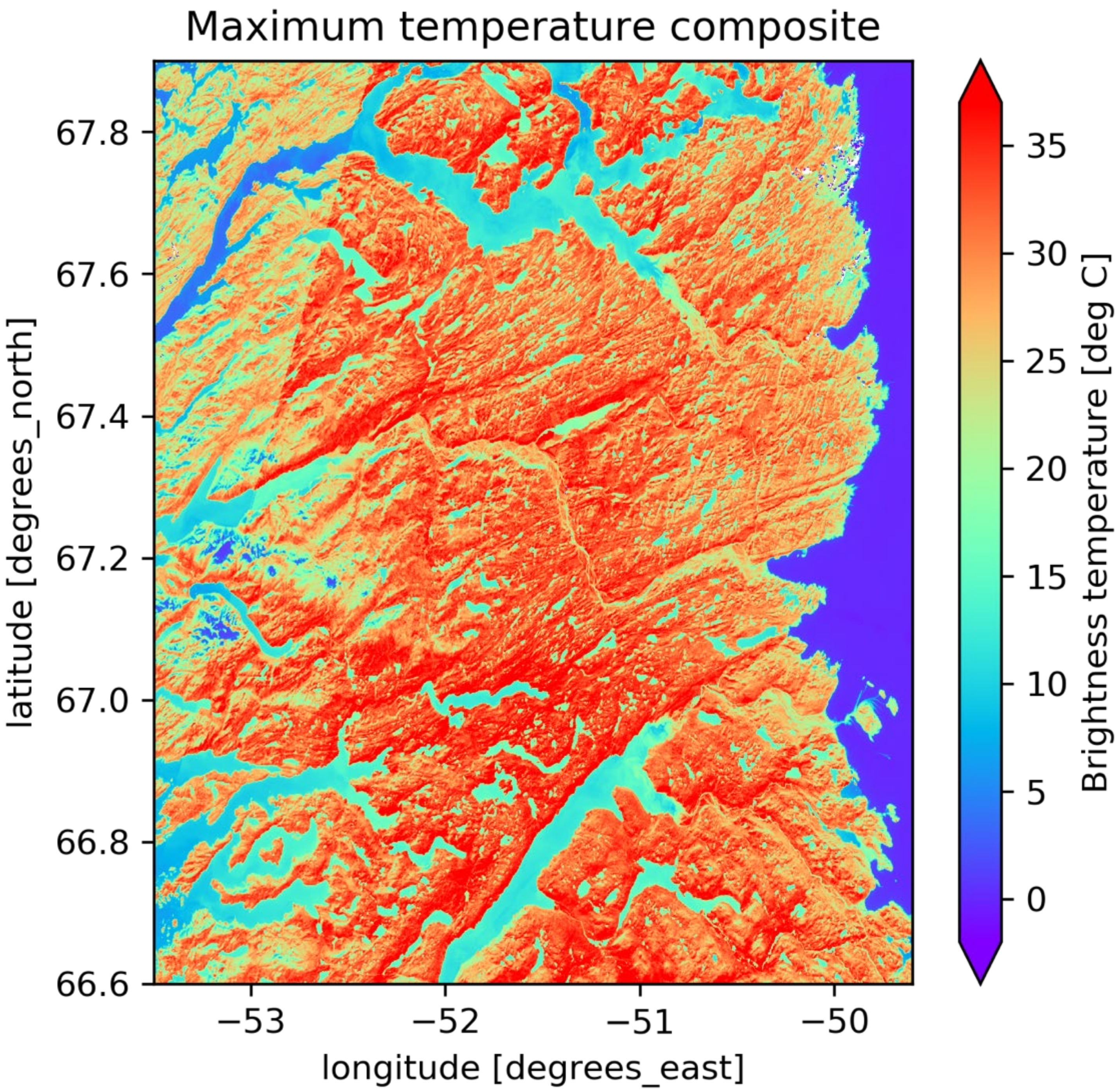


Over a 10 day period, the flooded extent is assessed from the diurnal temperature range: ie, the contrast of daytime and nighttime LST (from MODIS)

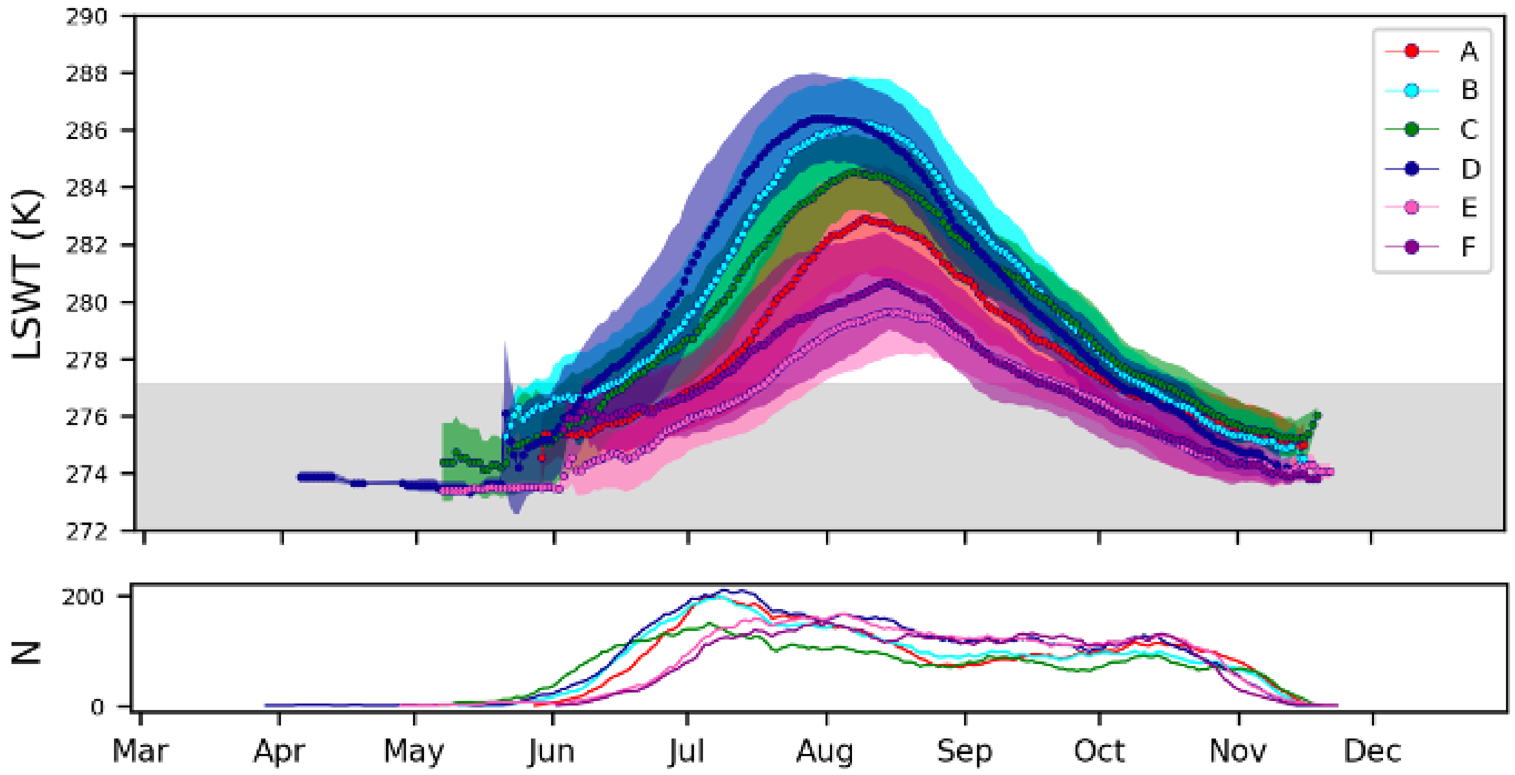

South Sudan
Flood/Wetland Frequency 'TimeScan'
in the 1 month ending 10 Jan 2019
Sudan
Abyei
Ethiopia
WFP
wfp.org
vam
food security analysis
Derived from MODIS Aqua LST-DTD

Case study 4 –Remote sensing as exploration

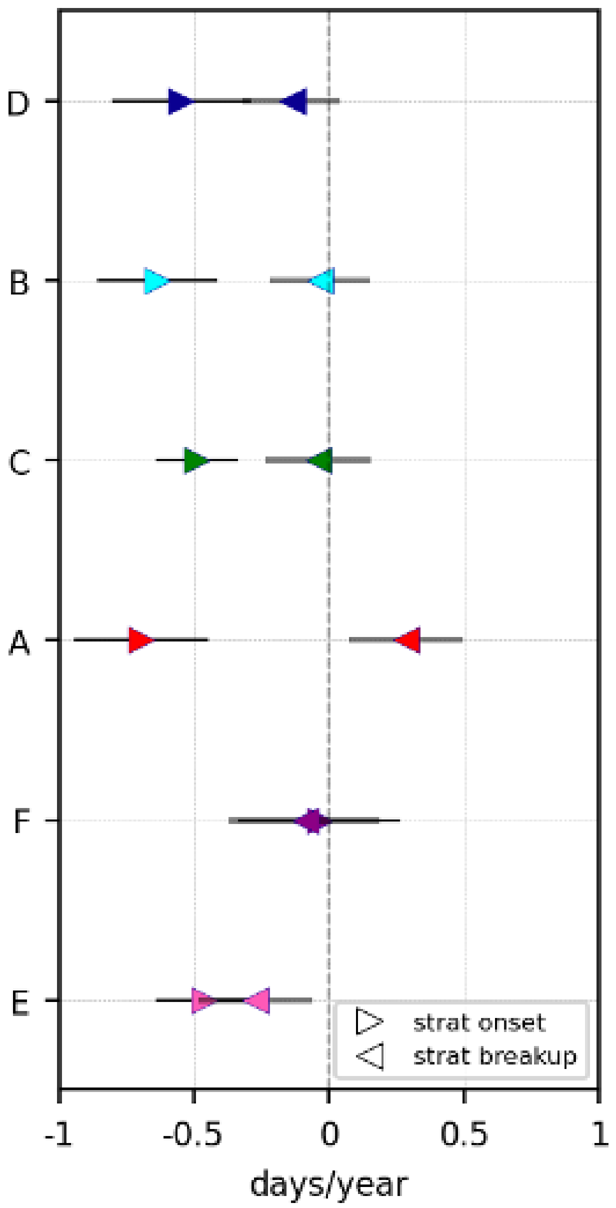

Minimum reflectance composite
A
B
C
D
E
F
67.5
67.0
Latitude
−53
−52
−51
−50
Longitude
65.8
65.6
65.4
65.2
65.0
−51.0
−50.5
−50.0
Longitude

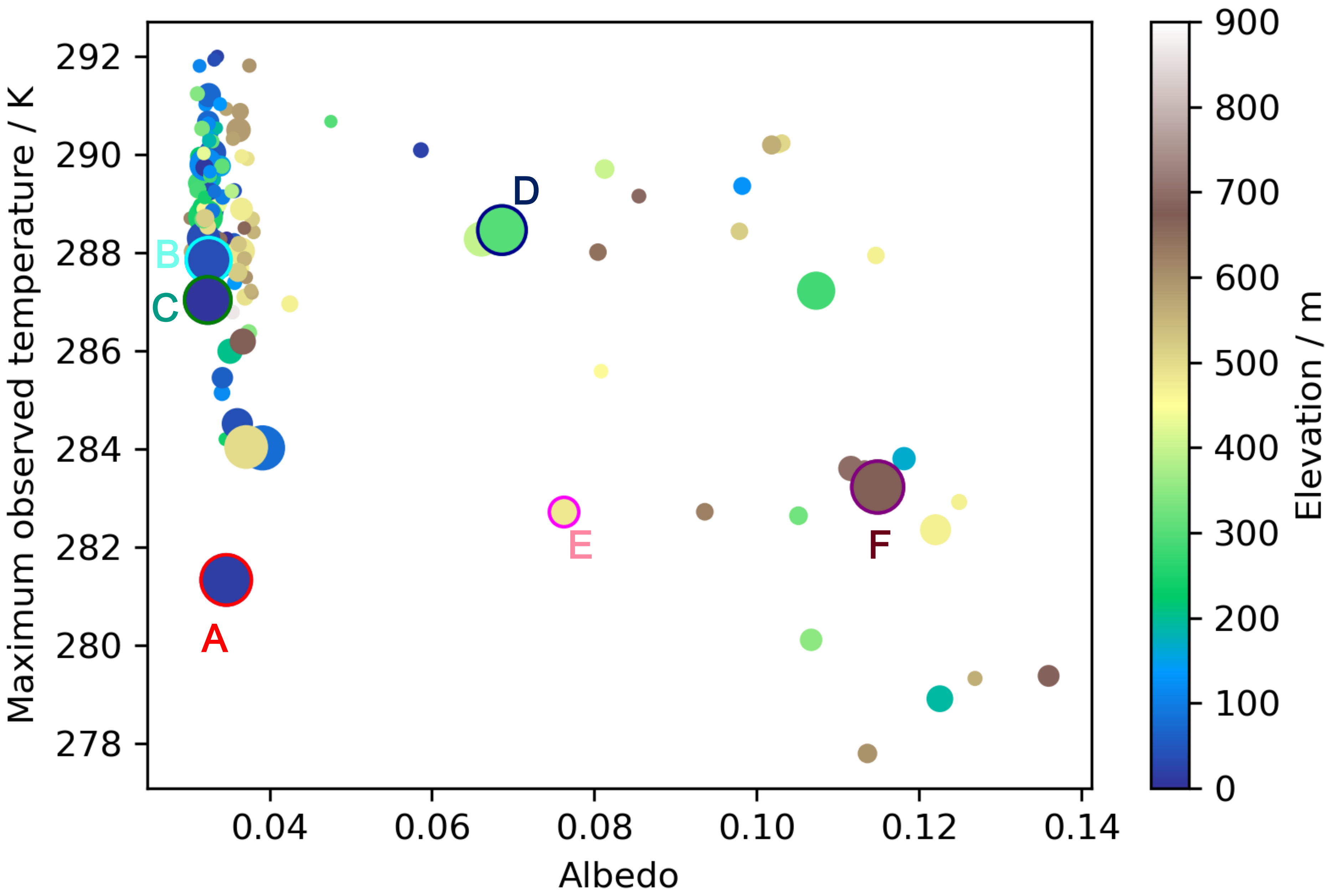


Maximum temperature composite
latitude [degrees_north]
67.8
67.6
67.4
67.2
67.0
66.8
66.6
longitude [degrees_east]
−53
−52
−51
−50
Brightness temperature [deg C]
35
30
25
20
15
10
5
0



Stratified (>4 deg C) season is changing mainly by delay of autumn stratification by ~5 days per decade

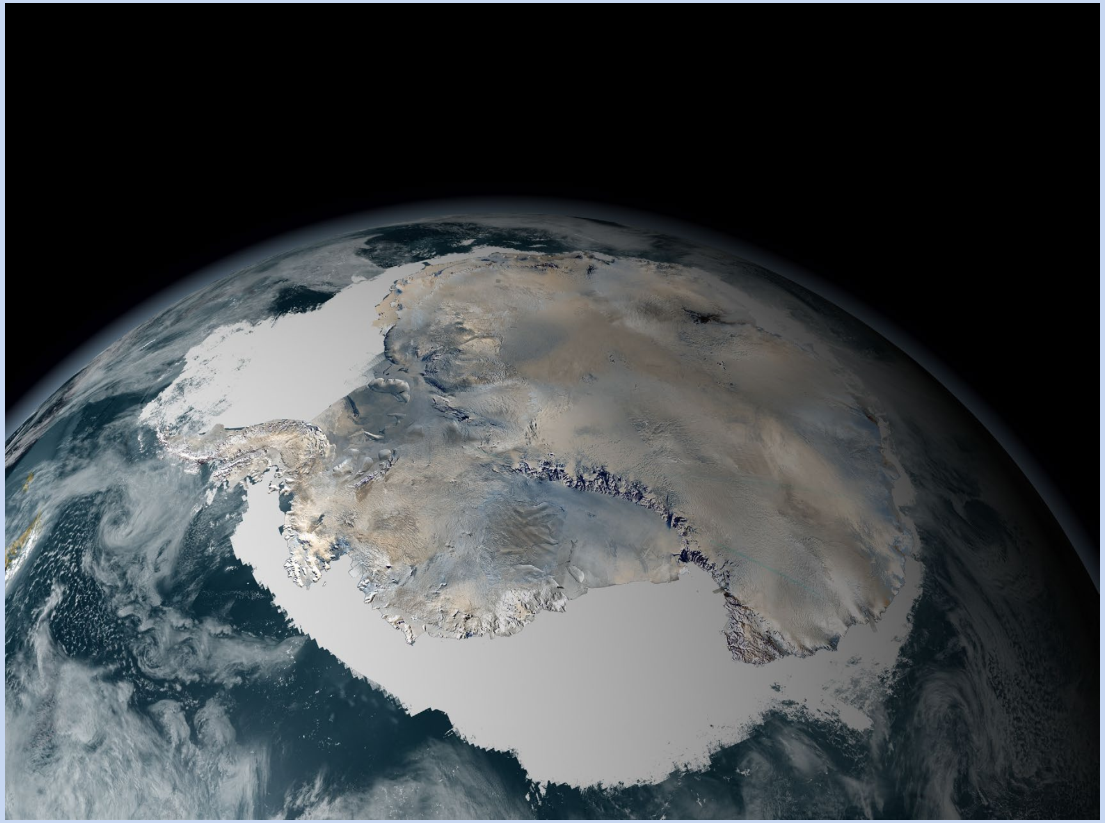



Maximum observed temperature / K
292
290
288
286
284
282
280
278
0.04
0.06
0.08
0.10
0.12
0.14
Albedo
A
B
C
D
E
F
Elevation / m
900
800
700
600
500
400
300
200
100
0

Thermal Remote Sensing of the Cryosphere

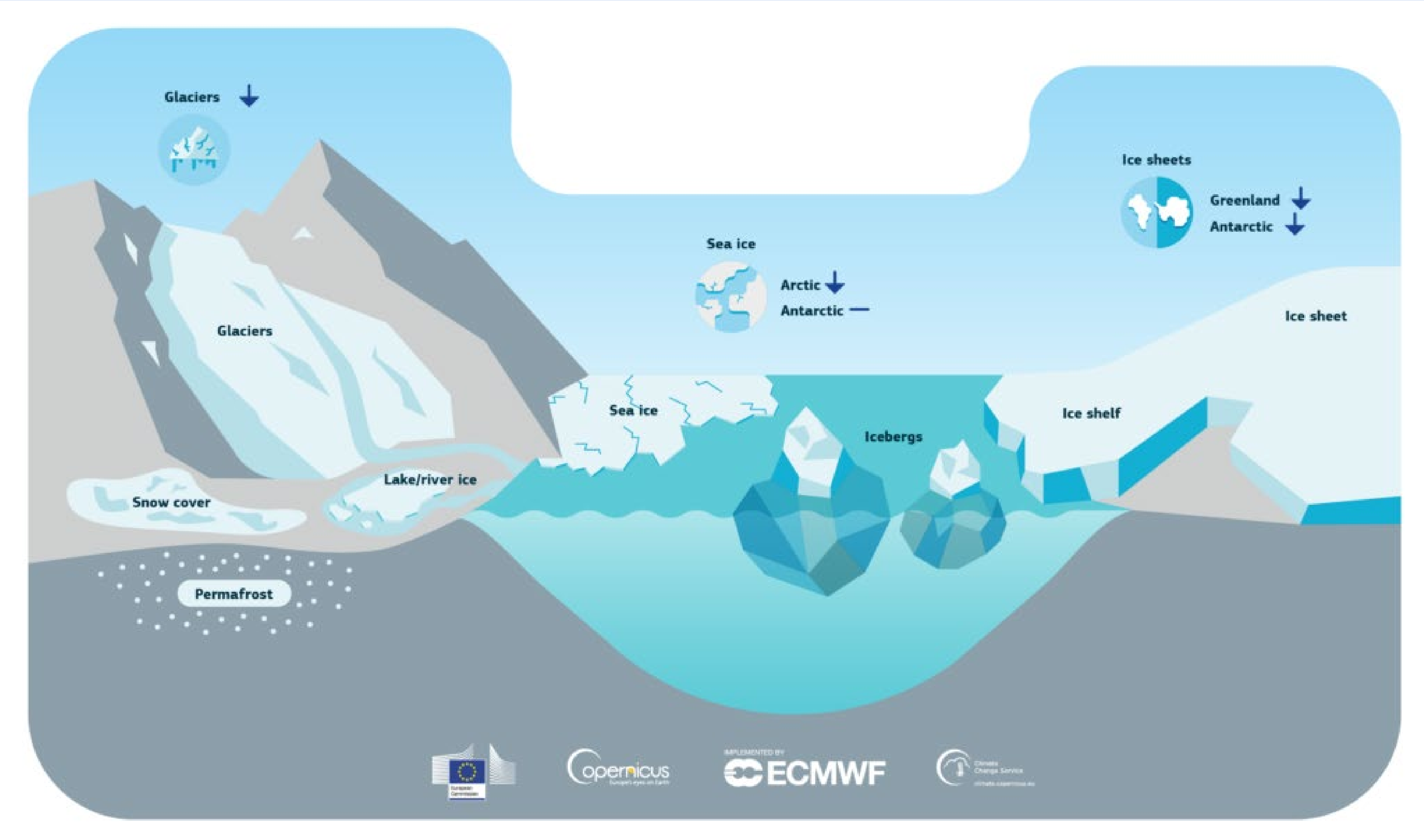
Outline:

- Significance of ice and snow analysis
- How is the Cryosphere changing?
- Thermal signatures of ice and snow
- Petermann Glacier Ice Shelf case study



Significance of Ice and Snow Analysis

- Landscapes on Earth covered in ice and snow are collectively known as the cryosphere
  - a word derived from the Greek *krios* meaning ’cold’ .
- The polar regions, encompassing the Arctic and Antarctic, mark the extremities of the cryosphere
- The constituents include:
  - snow cover, sea ice, freshwater ice, large land ice masses (such as glaciers, ice sheets and ice shelves), and permafrost (permanent sub–surface ice).



How is the cryosphere changing?

Albedo Effect

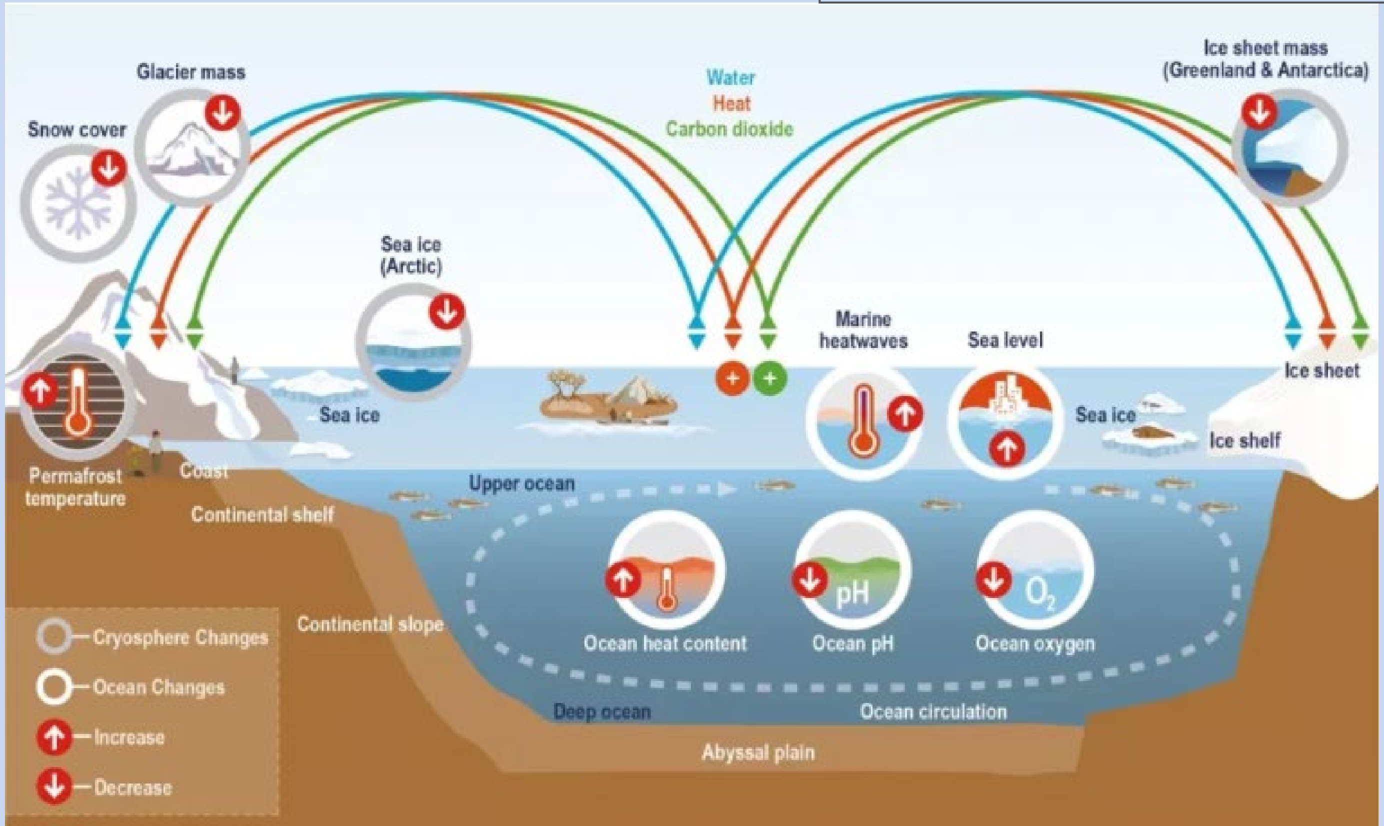
Ice and snow's high reflectivity (albedo) reflects solar radiation, cooling polar regions and regulating Earth's temperature.

- Help maintain global Temperature Regulation
- Reduced Ice Cover
- Ice Storage & Sea Level

Human Influence

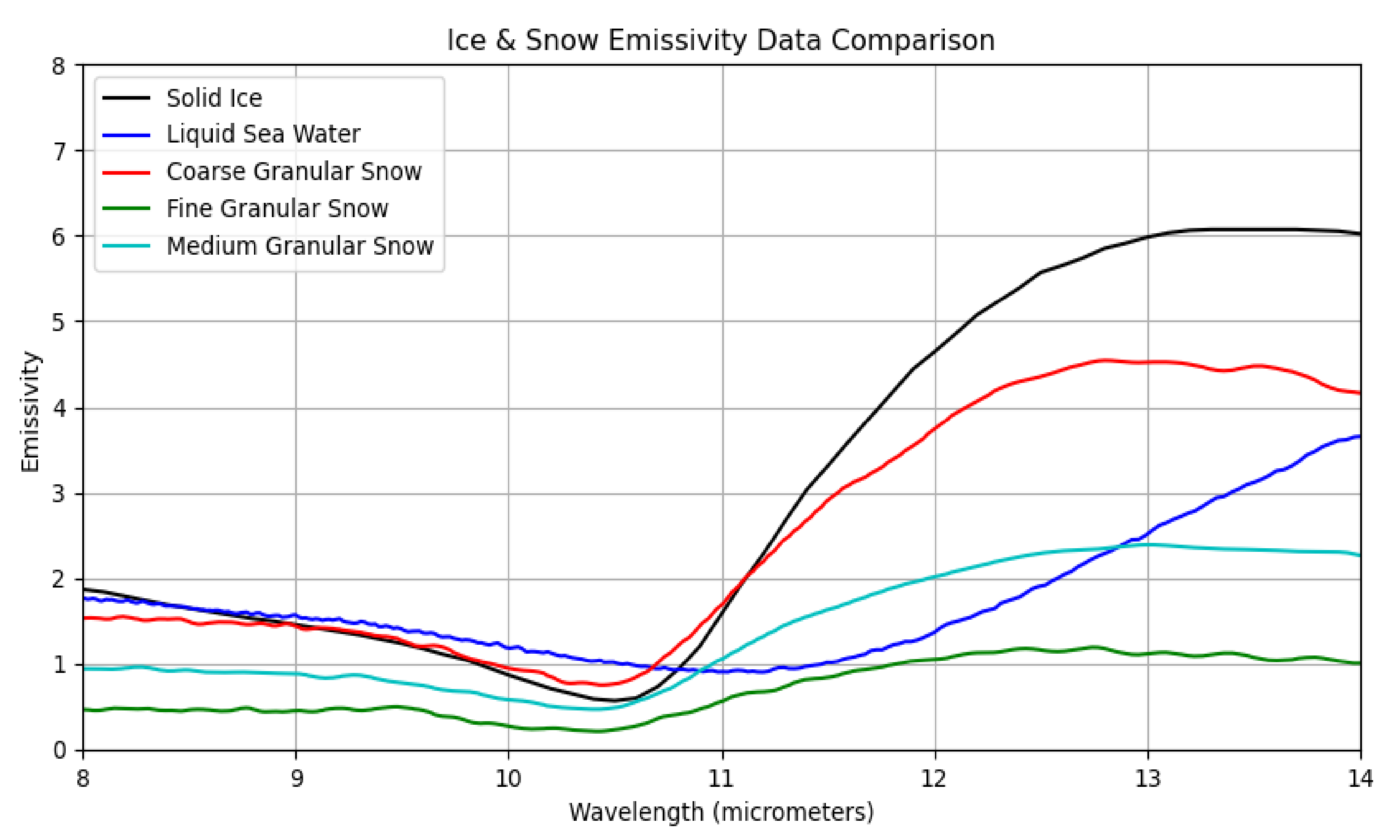
Greenhouse gas emissions accelerate ice melt, disrupting natural cycles and enhancing climate change through positive feedback.

- Greenland Ice Sheet (GrIS) and Ross Ice Shelf are experiencing intensified melting.
- Darkening surfaces and rising temperatures accelerate ice loss.



Thermal Signatures

The thermal emissivity of snow and ice is fundamental to the energy balance and interaction of the polar and cryosphere regions with the atmosphere



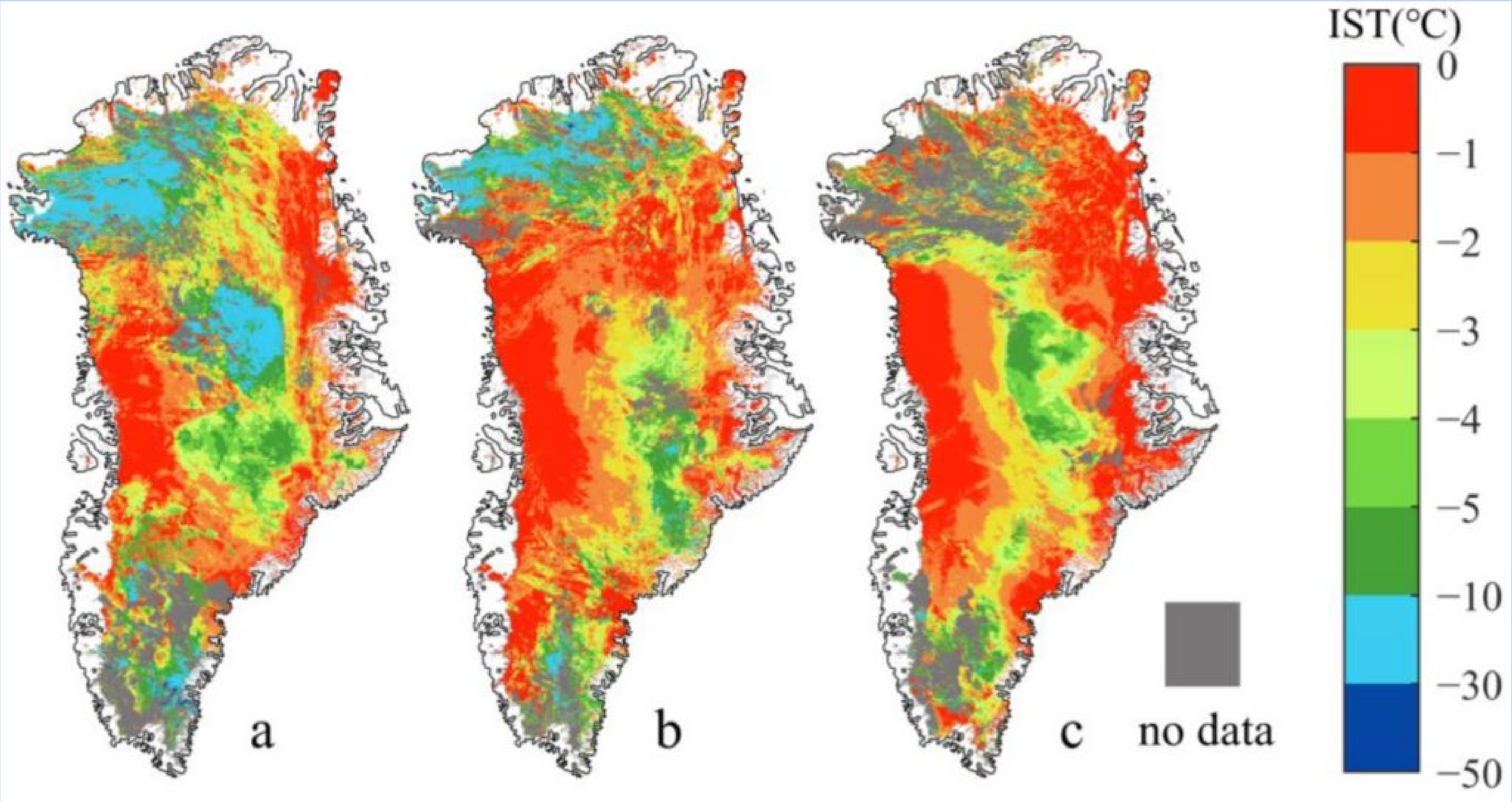
- **Emissivity and Climate Impact**:
  - Snow and ice emissivity, influenced by factors like grain size and surface roughness, affects thermal radiation, energy exchange, and surface temperatures, playing a key role in climate modeling and polar climate dynamics.
- **Albedo and Infrared Interaction**:
  - While snow and ice reflect solar radiation due to high albedo, they also emit thermal radiation, with variations in emissivity based on snow compaction and ice characteristics.

These reveal can important information about glaciological processes, ice surface physics, and their interactions with weather, climate, and oceanic circulations.

Thermal Signatures: Surface Temperature

The theory of land surface temperatures (LST) states that all objects emit thermal radiation based on their temperature, with surface features like ice, snow, and melt ponds radiating heat in specific infrared wavelengths, which can be measured to determine their temperature.

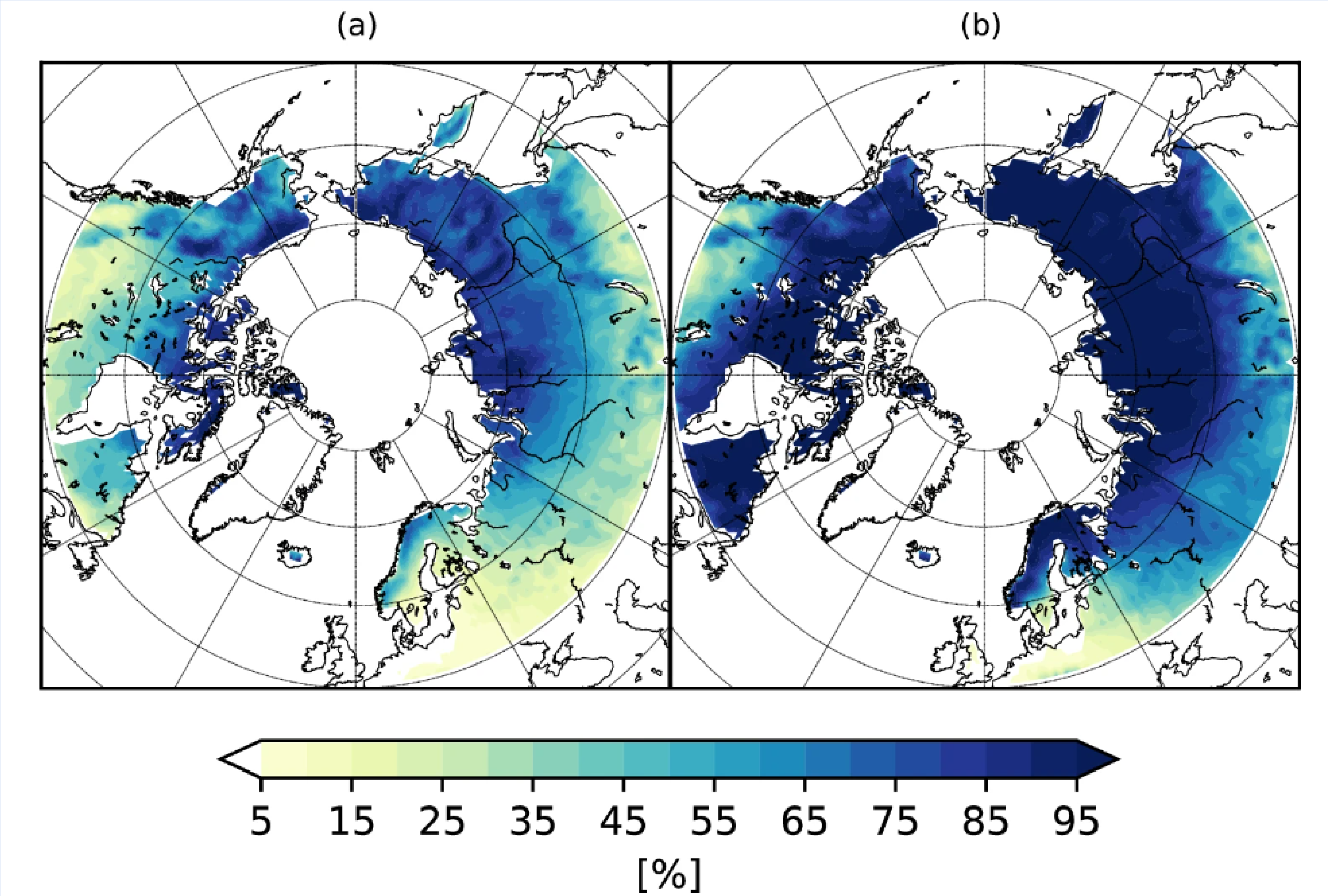
- **Ice Surface Radiation and Satellite Monitoring**:
  - Ice surfaces emit thermal radiation in the mid-wave and thermal infrared ranges, and satellites consistently measure ice surface temperatures, though cloud cover may affect accuracy.
- **Climate Impact and Thermal Mapping**:
  - Melting ice exposes low-albedo surfaces, amplifying warming, particularly in the Arctic, while thermal sensors provide critical data for monitoring temperature variations and ice loss trends.



IST retrieval from the polar orbiting MODIS satellite. It serves as a key indicator of the energy balance occurring at the surface of the ice.

Thermal Signatures: Snow Cover

Satellite imaging has advanced in accurately measuring snow accumulation, depth, water equivalent, and albedo, producing highly precise snow cover maps that outperform traditional methods like ground surveys or aerial photography.

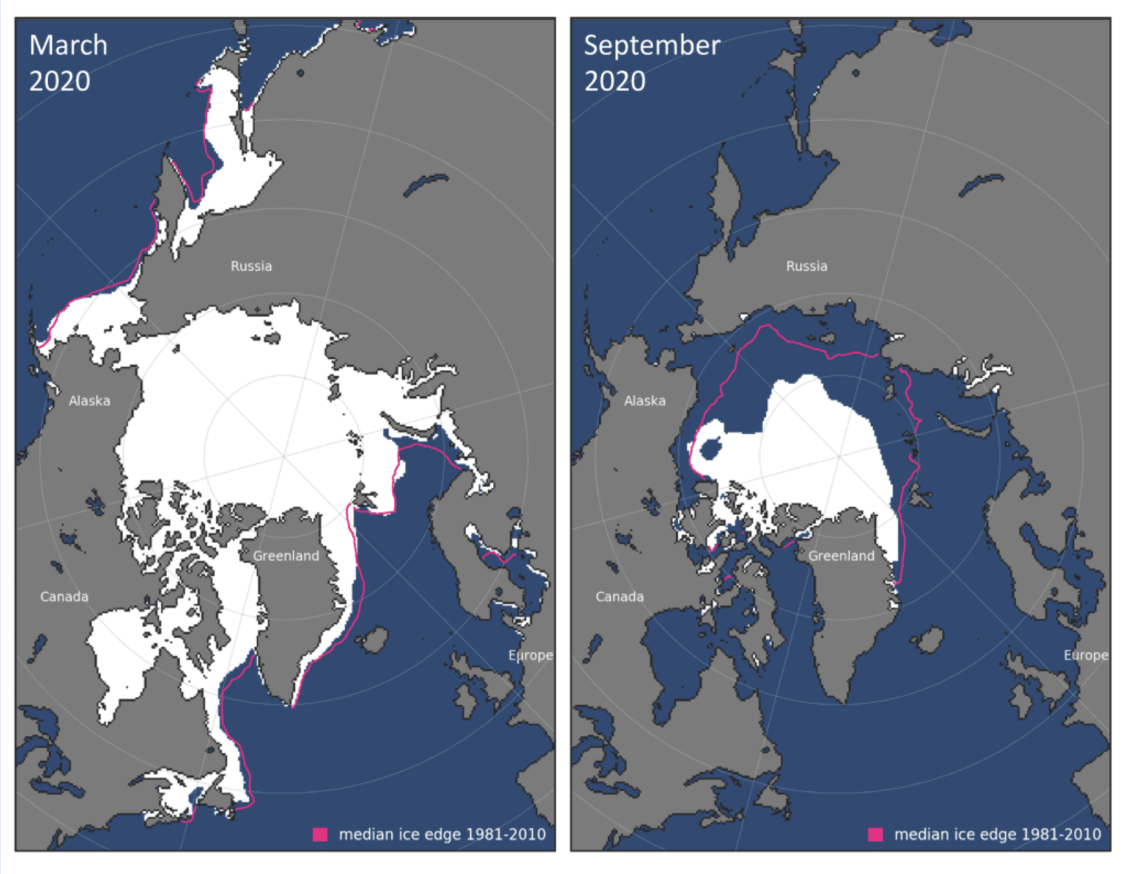


- **Snow Cover and Thermal Properties**:
  - Snow types (wet, dry, ice) vary in thermal properties due to composition and density, with thermal remote sensing capturing these differences to analyze radiation and snow characteristics.
- **Applications and Climate Relevance**:
  - Snow cover data supports climate studies, hydrology, hazard monitoring, and resource management, while thermal data complements snow cover maps by linking snow cover to surface temperatures and seasonal changes.

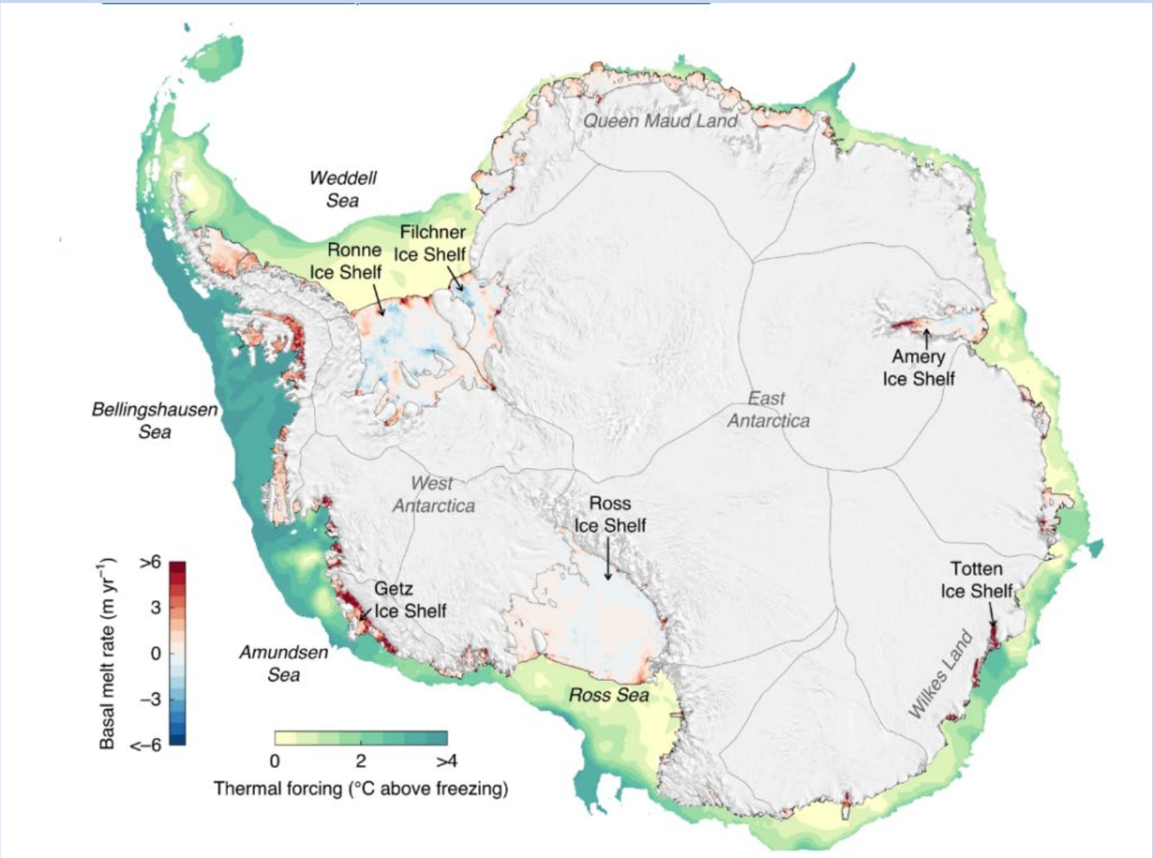
Climatology of snow cover extent in October–November (a) and March
April (b) from the NCEP/CFSR reanalysis over the period 1979–2005[23]

Thermal Signatures: Ice Melt Detection

- **Thermal Remote Sensing**: Tracks temperature changes in ice and snow, providing critical data on melt extent, ice mass loss, and dynamics in polar regions.
- **Melt Impacts and Sea Level Rise**: Surface snowmelt reduces reflectivity, while basal melting causes significant ice shelf mass loss, accelerating sea level rise and requiring detailed monitoring.
- **Melt Ponds and Sea Ice Decline**: Melt ponds reduce albedo, amplifying Arctic warming, while thermal data tracks declining sea ice extent, aiding climate change analysis.



Monthly average sea ice extent map for (left) March 2020 and (right) September 2020

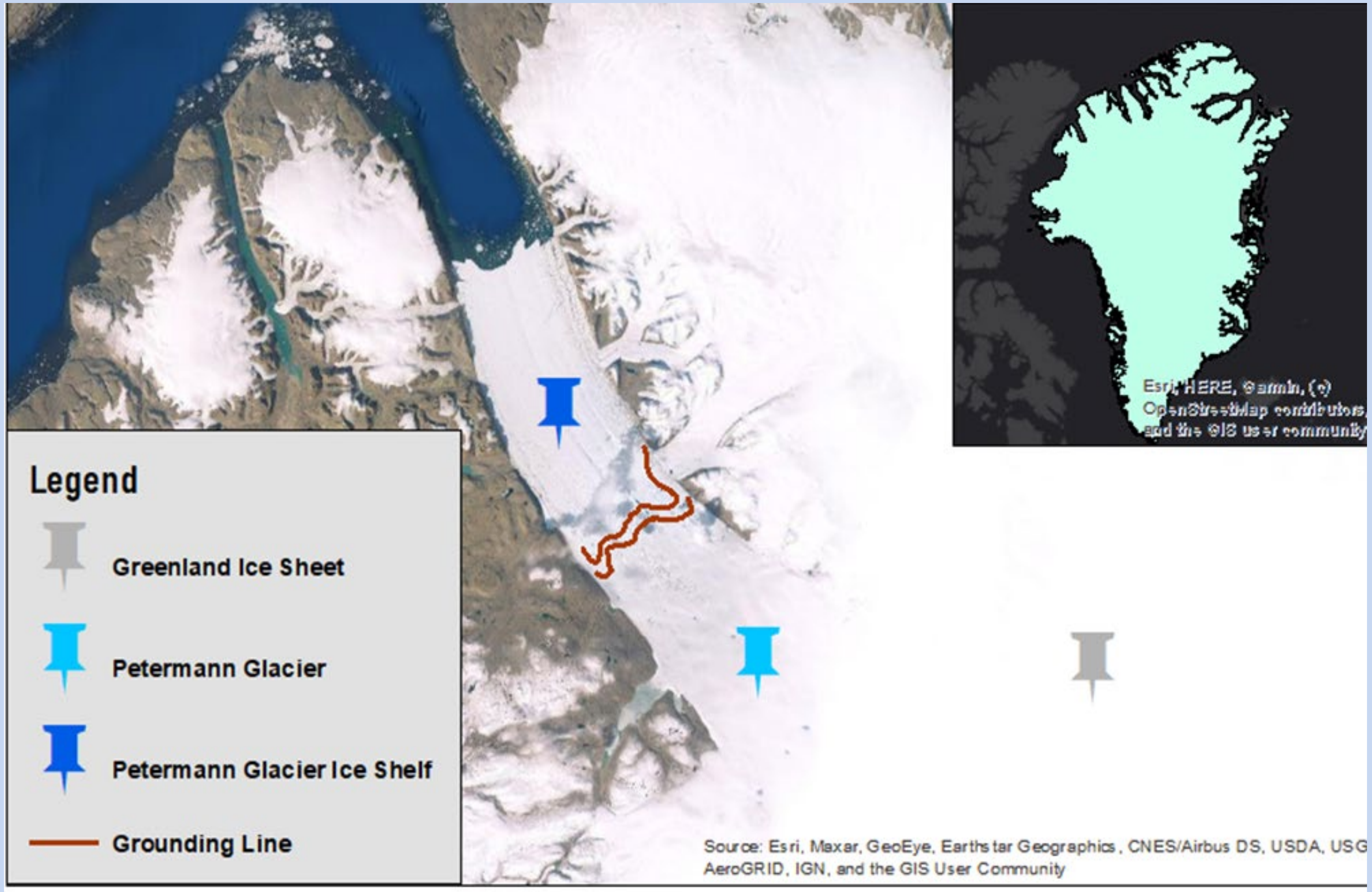


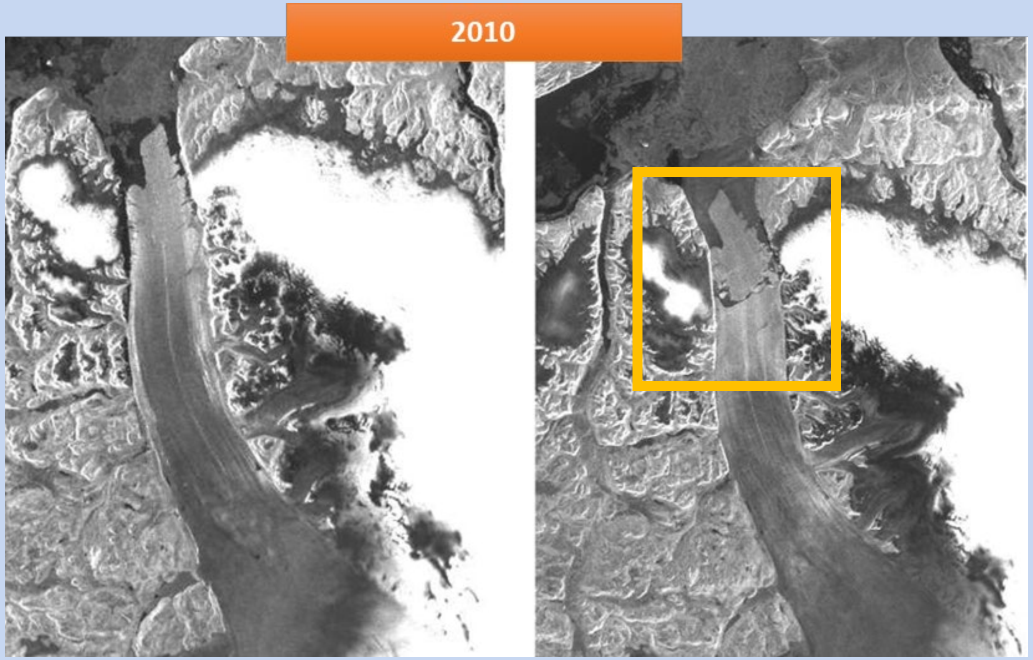
Basal melt rates of Antarctic Ice Shelves averaged between 2010-2018 using Cryosat-2 Altimetry with mapped thermal forcing

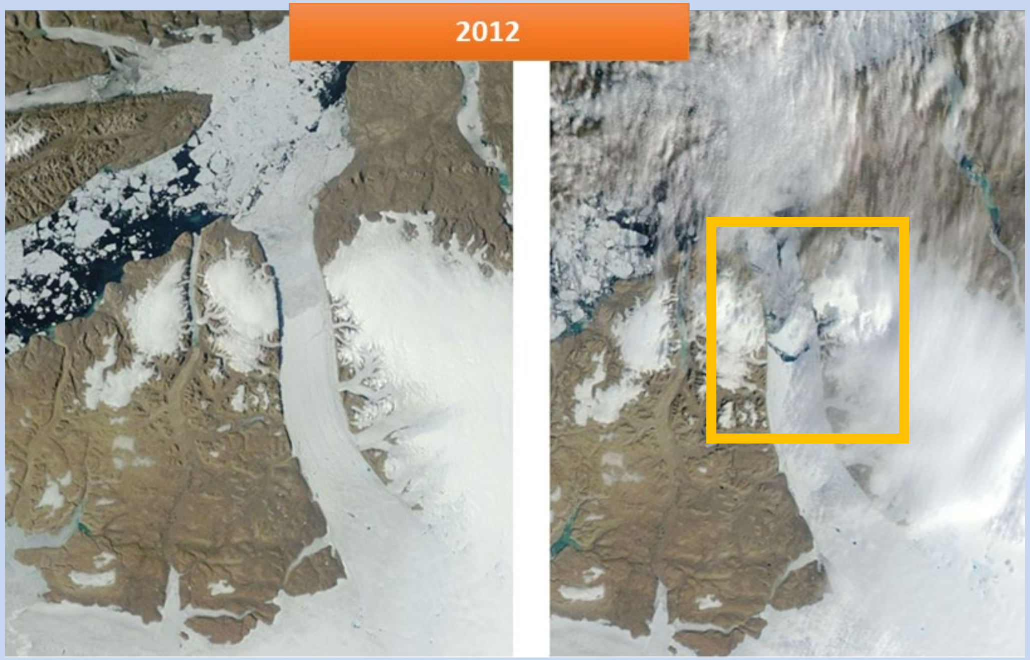
Case Study:
Petermann Glacier Ice Shelf, Greenland

Impacts on the PGIS

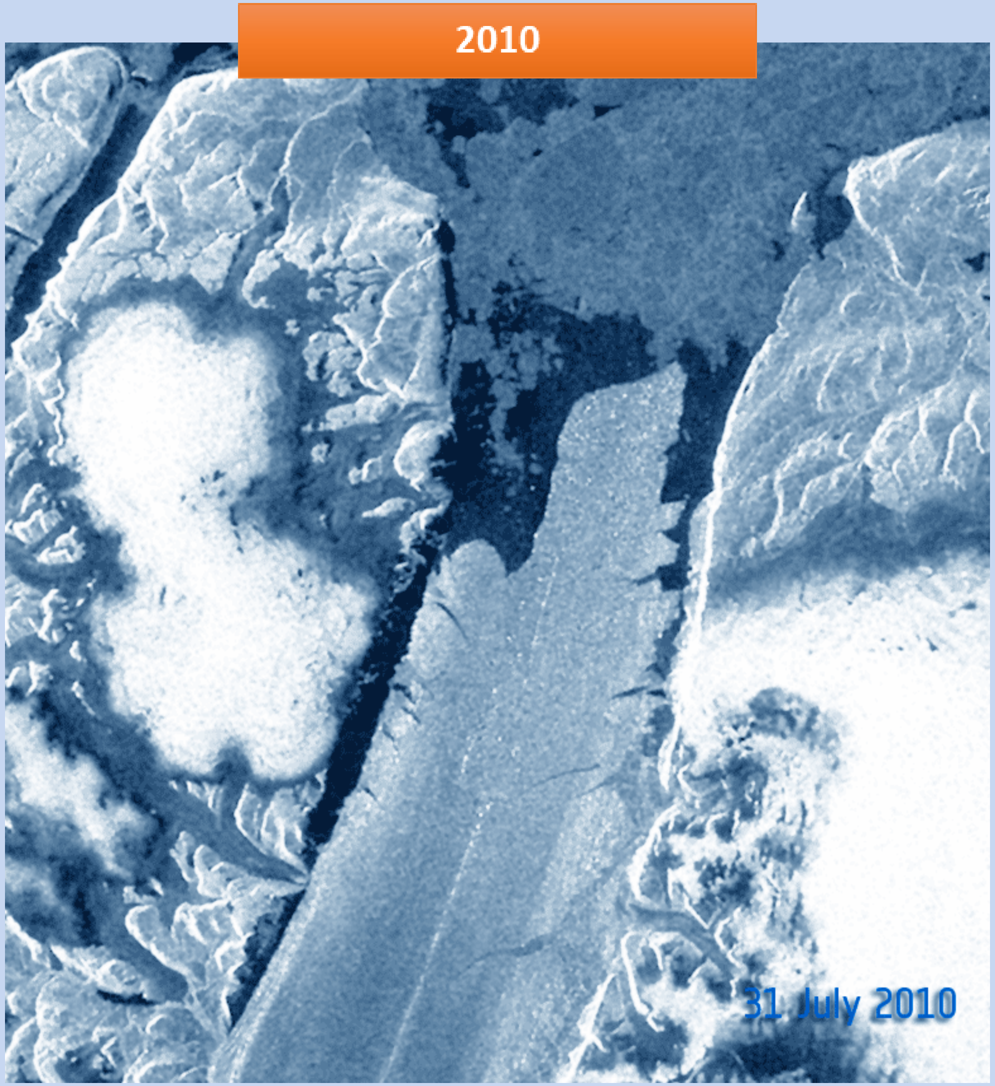
•An **ice shelf** is a large floating platform (tongue) of ice that forms where a tidewater glacier or ice sheet flows past the grounding line onto the ocean surface.







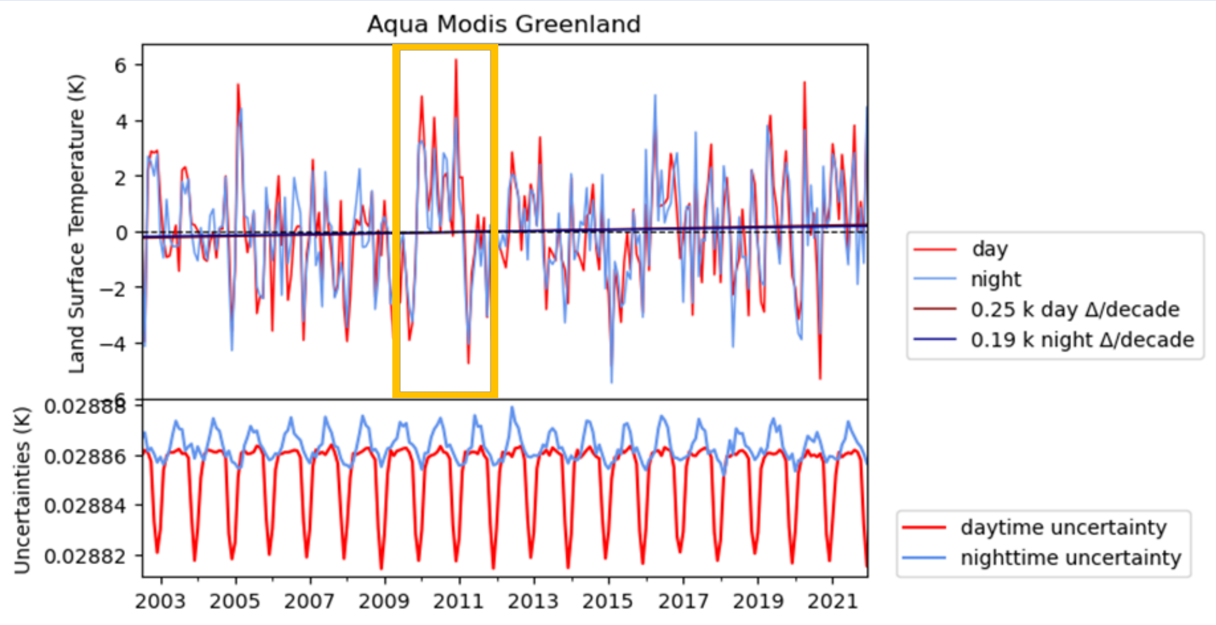
Major Calving Events

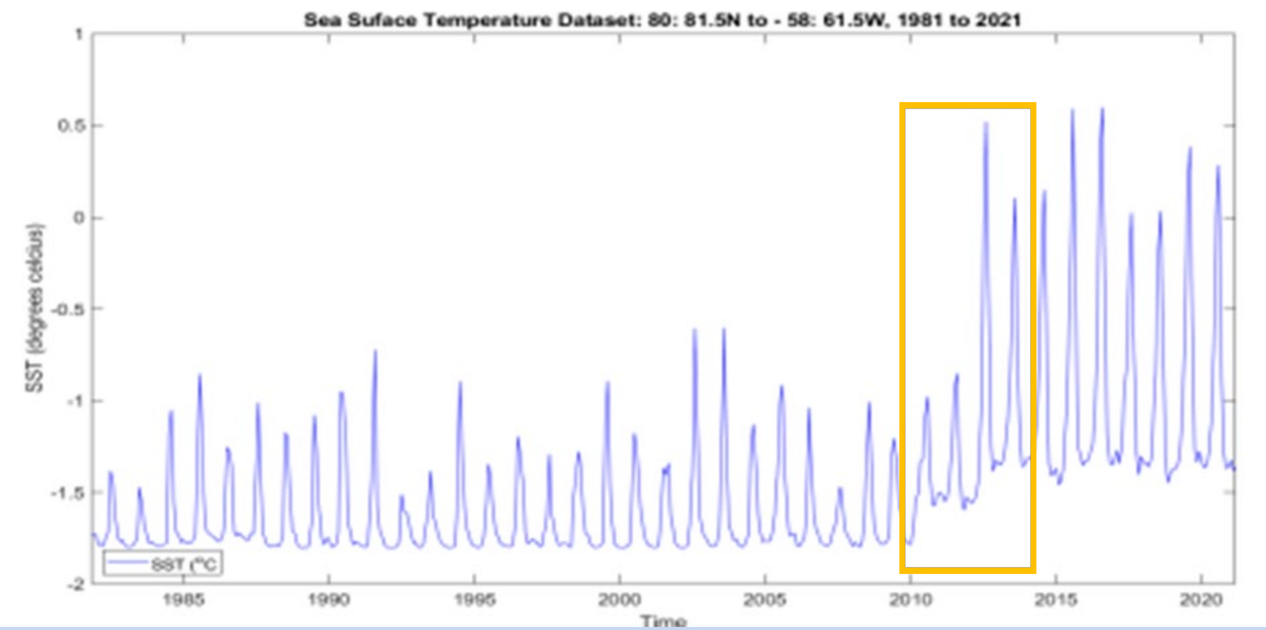


In 2010 the ice shelf reduced by 16,580 m and the ice speed increased by 282 m y-1
In 2012 the shelf reduced a further 8,430 m and the ice speed increased by 267 m y-1
1988 the ice speed was 148.8 m y-1

Climate Drivers

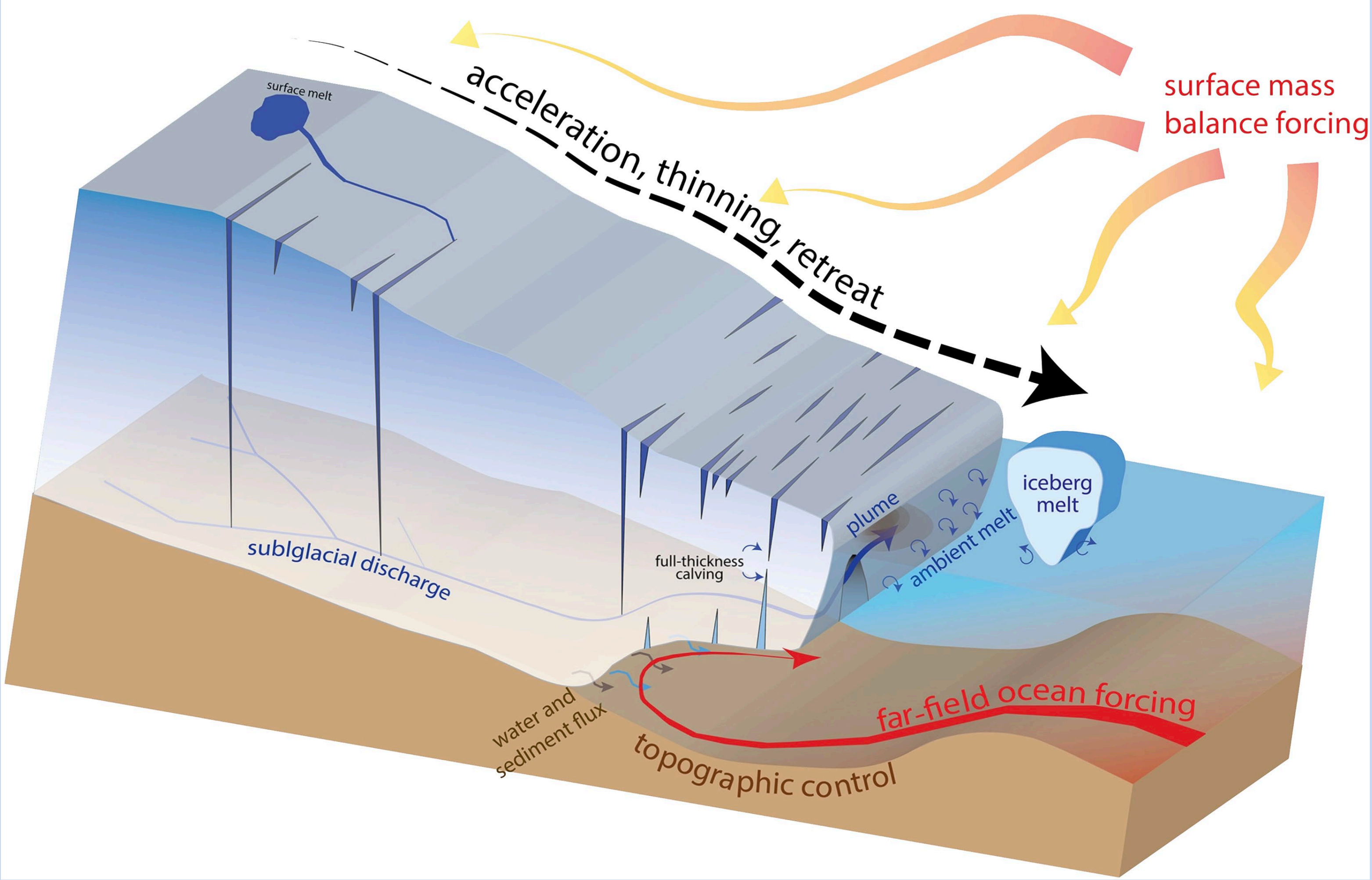
- **Arctic Amplification**
  - Heating up 3x faster than the rest of the world
- **Rising Temperatures**
  - Air, ocean and surface temperatures all increased between 2010-2012
- **Natural Drivers**
  - Natural atmospheric circulation patterns was found to influence rising air and surface temperatures
    - Greenland Blocking Index
    - North Atlantic Oscillation
    - Arctic Oscillation





Impacts

- **Sensitivity**
  - Ice shelves are highly sensitive to temperature changes
  - They are affected by both air and ocean
- **Induced Ice Flow Speed-up**
  - Floating terminus acts as a plug to the 'parent' glacier (buttressing)
    - Calving = less resistance = increased ice speed and discharge and more mass loss
- **Rising Sea Levels**
  - Increased glacier meltwater discharge is adding freshwater into the ocean
    - This is causing rapid SLR
    - Also results in desalination – which affects global circulation and heat transport



Wrap up and questions