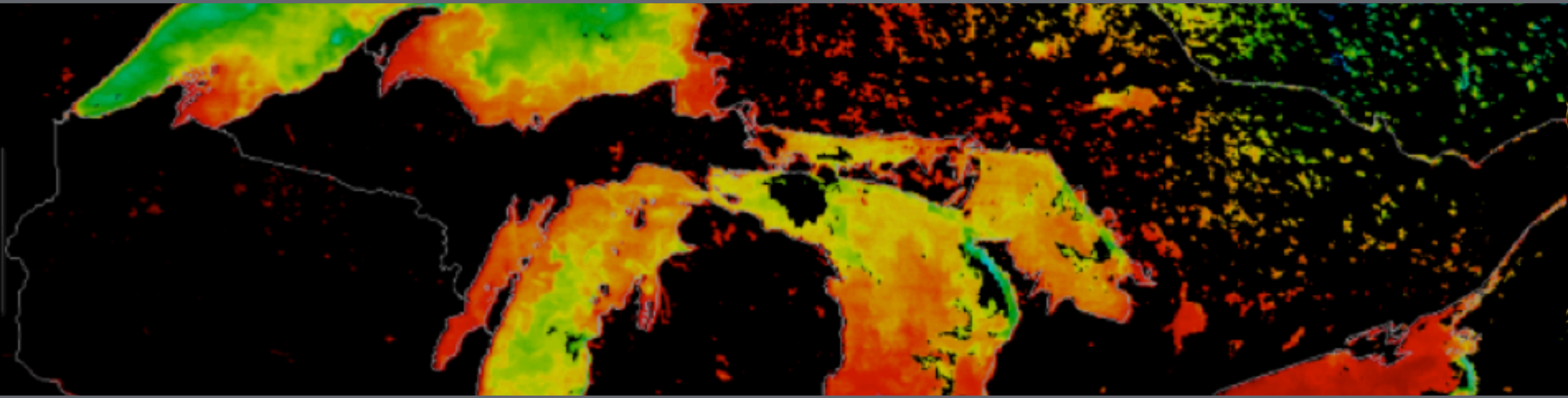
Earth Observation and Space
Department of Meteorology

University of Reading

THERMAL OBSERVATION OF INLAND WATERS



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ACKNOWLEDGEMENTS

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OUTLINE

- Need for thermal remote sensing of lake surface water temperature (LSWT)
- Sensors of LSWT, past and present
- Requirements for LSWT remote sensing
- Global lake temperature variability
- State of the climate regarding LSWT

THERMAL REGIMES OF LAKES …

- … are driven by dynamic interaction with the surface radiation environment and the atmospheric boundary layer
- ... profoundly influence lake ecosystems and biogeochemical cycling, for example through seasonal stratification and mixing
- ... are often poorly quantified via in situ observations, if measured at all
- ... are sensitive to climatic change, including amplified responses to air temperature change in particular circumstance
- ... and therefore need to be systematically observed and understood

- Across a global scale, thermal remote sensing can provide highly relevant observations

LSWT SENSORS

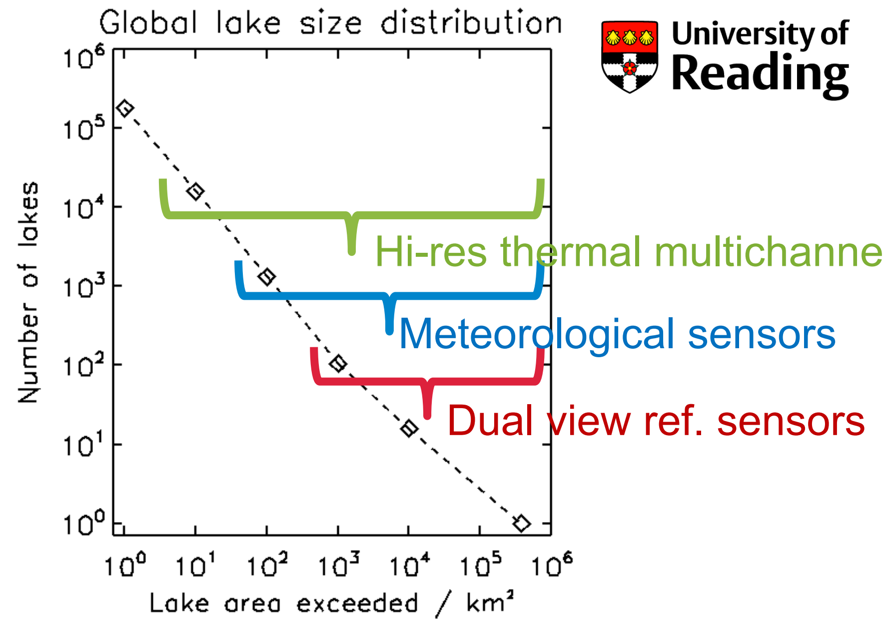
- For quantitative temperatures at global scale and reasonable repeat, meteorological-resolution IR sensors (~1 km resolution)
  - ATSRs (1991 to 2012)
  - AVHRRs (potentially early 1980s to present, but need an archive of local direct-broadcast to get full resolution data 1 km)
  - MODIS and VIIRS (current)
  - SLSTR (current)
- ~1 km applies only at nadir
  - Limitation*: O(30 km^2) lakes
- Dual-view (ATSRs and SLSTR):
  - Practical for O(300 km^2) lakes

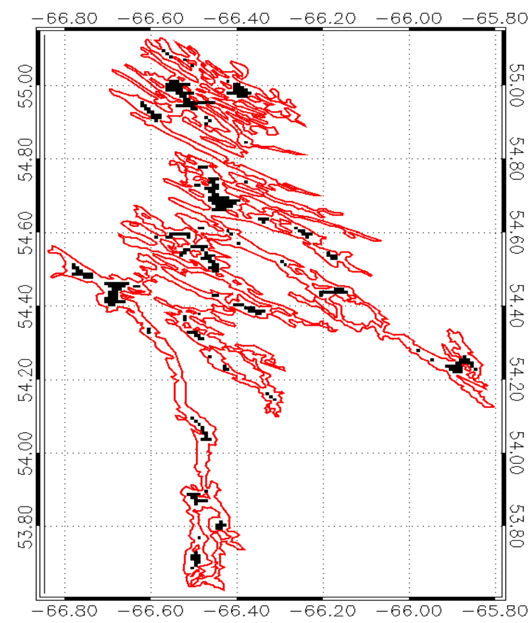
Oblique view

SLSTR

LSWT SENSORS

- For small lakes and lakes with complex shapes, the dual-view and meteorological sensors are limited
- In principle ~1000+ lakes are accessible to meteorological sensors, although not yet achieved in practice by a global dataset
- A hi-res (~100 m) multichannel sensor could open up many more lakes to observation
  - Although repeat frequency is a challenge if sensor is narrow swath





Subset of area of Lake Astray able to be sensed by ATSR

GCOS REQUIREMENTS FOR LSWT

ECV	Products	Frequency	Resolution	Uncertainty	Stability
Lake	Surface Water Temperature	Weekly	300m	1 K*	0.01 K/yr**
		Achieved by VIIR/ SLSTR sensors, but not by LandSat8/ASTER	Achieved by LandSat8/ ASTER, but not by VIIRS/ SLSTR	Achievable by VIIRS/SLSTR; challenging for LandSat8 (calibration problems and noise)	Potentially from ATSRs, TBC for SLSTR series

*This uncertainty is rather large for climate science, and inconsistent with the stability requirement – perhaps it is driven more by technology/retrieval capabilities

**Stability is an aspect that is extremely difficult to prove directly for lakes, because there is no reference known to have the required stability. The best knowledge of LSWT stability comes from the limited stability assessments possible for sea surface temperature, which uses related (but distinct) retrieval algorithms.

LSWT ESTIMATION

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- Two steps:
  - Cloud screening / water detection
  - Inversion of IR-window channel radiances to surface temperature
- Because of the variable altitudes and prevailing atmospheric conditions across lakes, a global approach is best based on "dynamic" methods involving exploitation of numerical weather prediction
  - Water detection (day only), Bayesian cloud detection at night
  - Optimal estimation or similar for LSWT estimation

- The inverse process tends to amplify noise by a factor between 2 and 5, so the GCOS uncertainty target of 1 K implies brightness temperature noise ~0.3 K in TIR channels
  - Better than this is available at 1 km resolution
  - Future hi-res TIR sensors may be able to beat this noise

LAKE-CENTRE & IN SITU ANALYSES

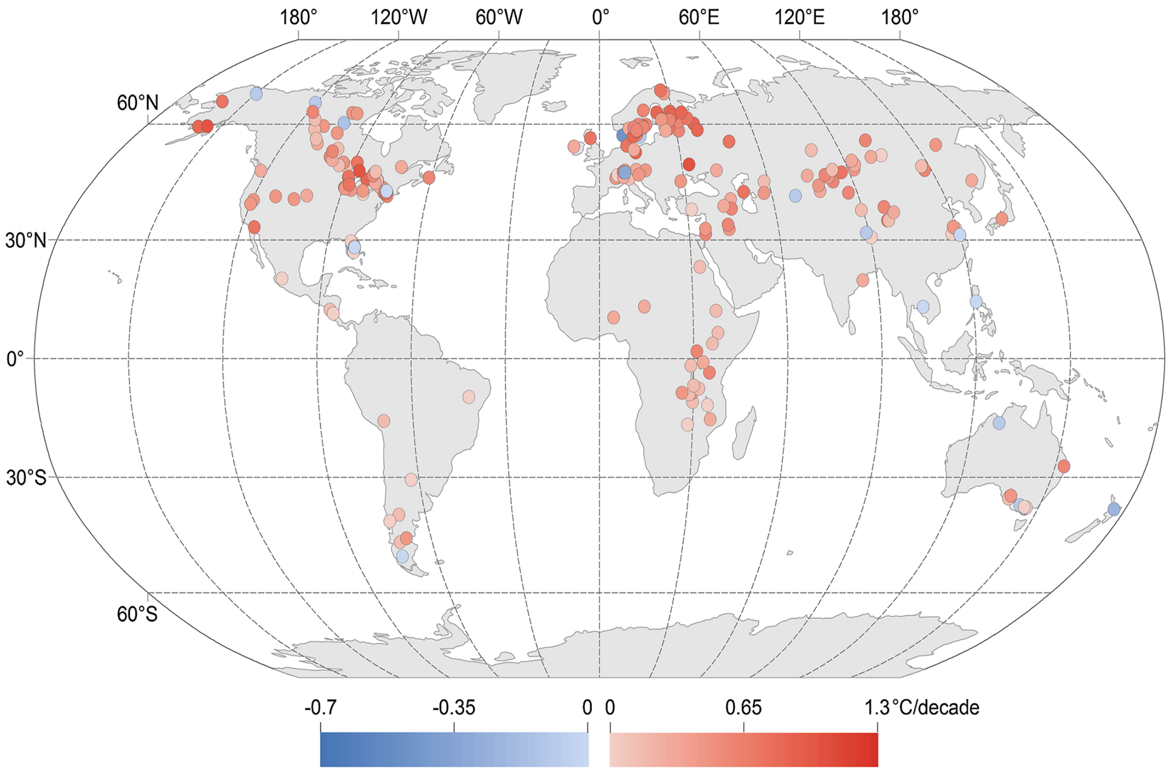
- Riffler et al. (2015), Alpine lakes, AVHRR 1 km

A number of papers have explored lake-climate interactions using "point" data: lake centre pixels from satellite and/or in situ monitoring locations

1990 to 2010 trends in seasonal LSWT for Lake Constance in satellite and in situ measurements

LAKE-CENTRE & IN SITU ANALYSES

- O'Reilly et al. (2015), Global lakes analysis, mixed in situ and satellite data used



A number of papers have explored lake-climate interactions using "point" data: lake centre pixels from satellite and/or in situ monitoring locations

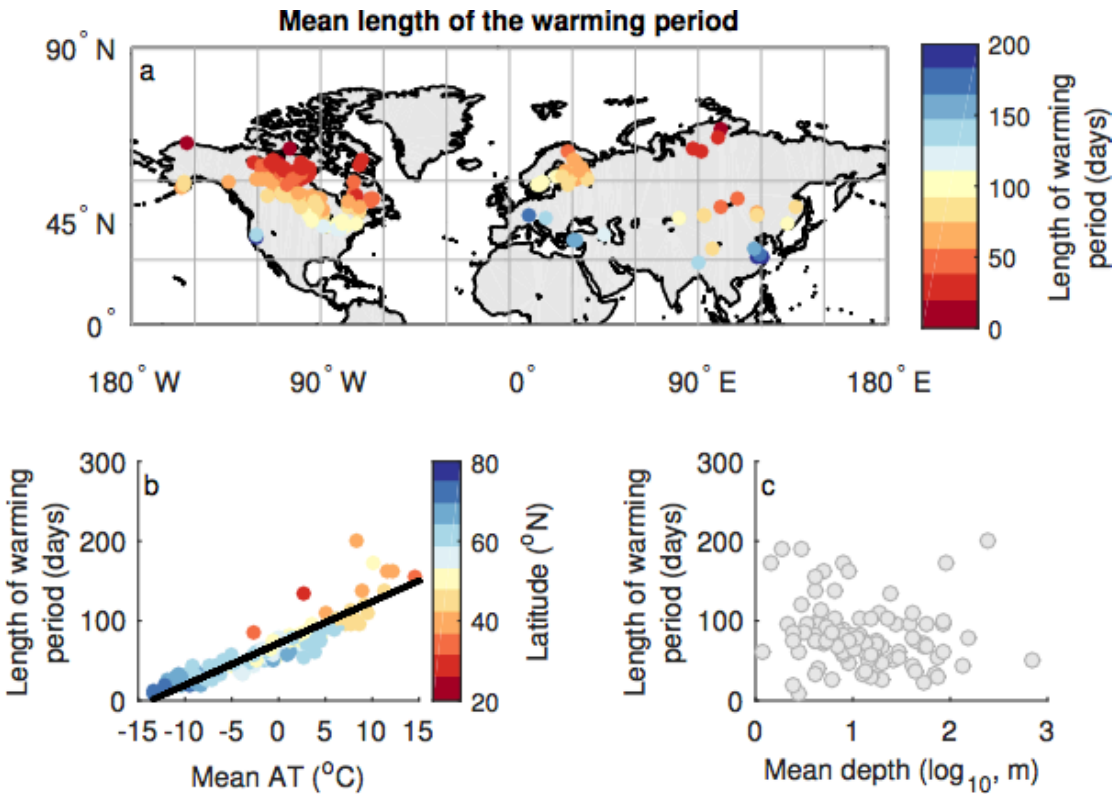
1985 to 2009 trends in summer LSWT

Ice-season lakes warming faster than ambient air

No-ice lakes warming at same or slower rate than air

LAKE-MEAN ANALYSIS

- Woolway and Merchant (2017), global analysis using ATSR-series lake-mean data



We recently examined the reasons for the O'Reilly observation about LSWT relative to air temperature using lake-mean data from satellite

Quantified the dependencies of the length of the warming period (LSWT >4 degC until summer peak), t_{warm}

Also (not shown) quantified the persistence of thermal anomalies (anomaly correl. timescale), t_{corr}

LAKE-MEAN ANALYSIS

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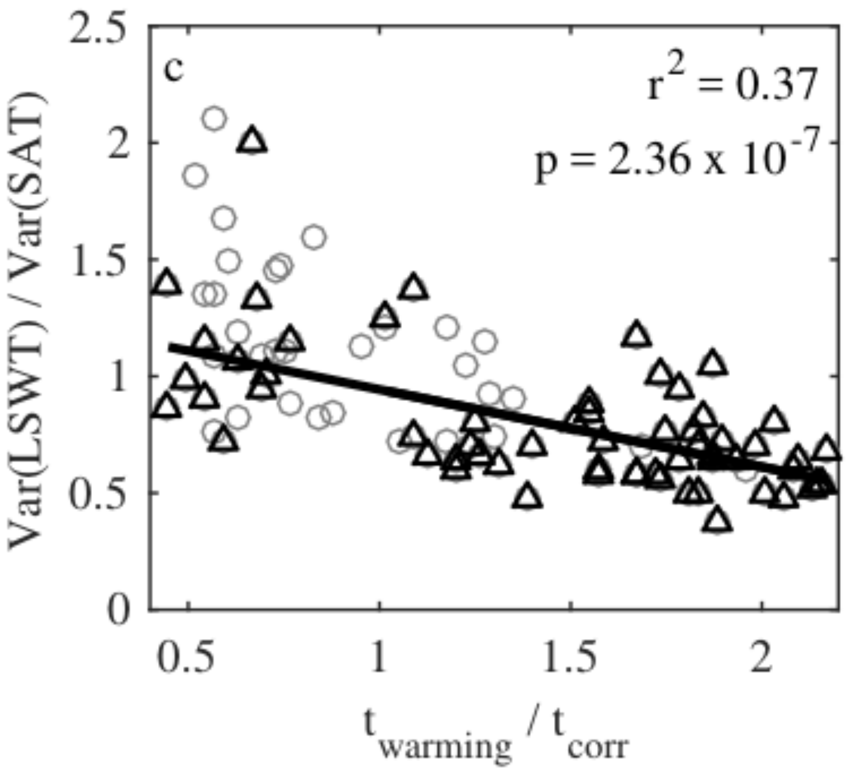
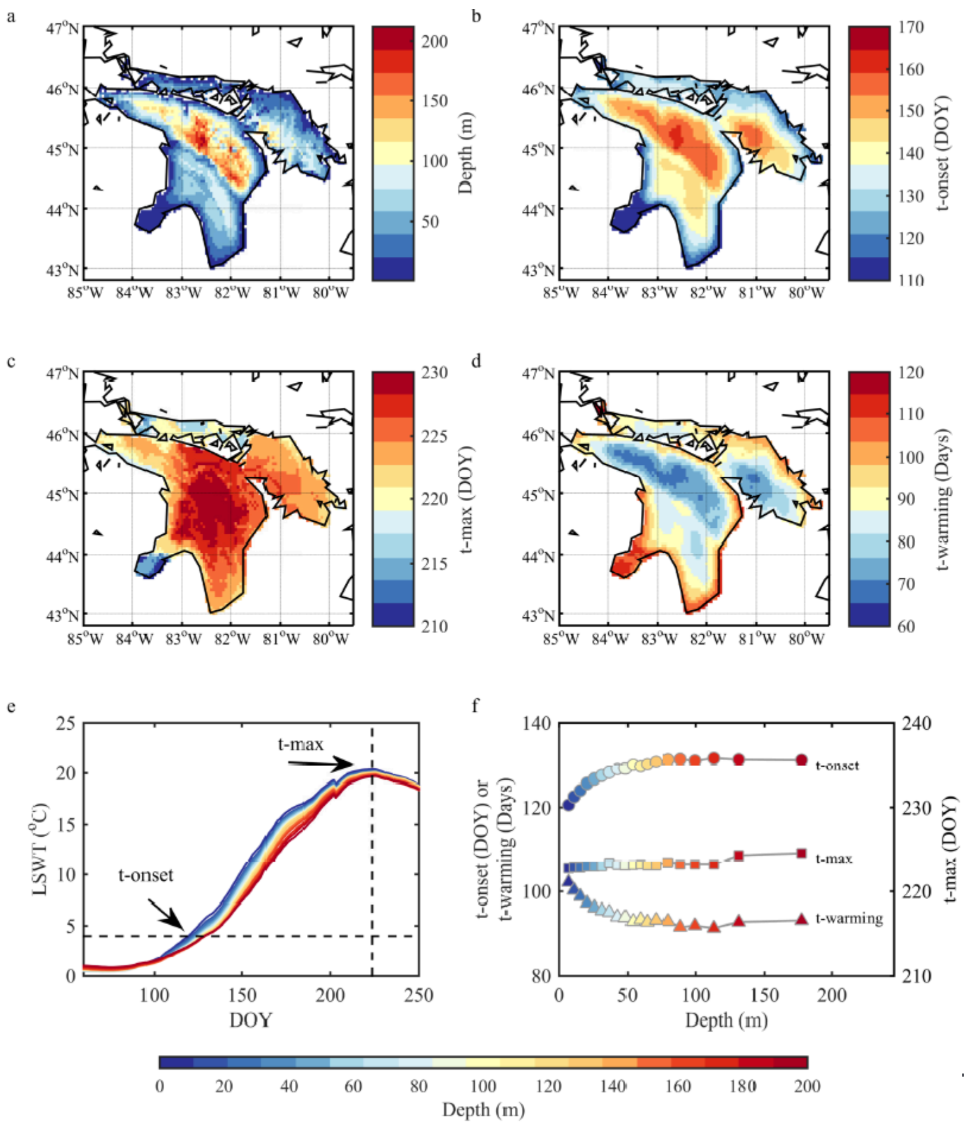


We recently examined the reasons for the O'Reilly observation about LSWT relative to air temperature using lake-mean data from satellite

The shorter the warming season relative to the thermal anomaly correlation time scale, the more likely LSWT variability is to exceed air temperature variability.

This largely accounts for the O'Reilly observation

WITHIN-LAKE VARIABILITY

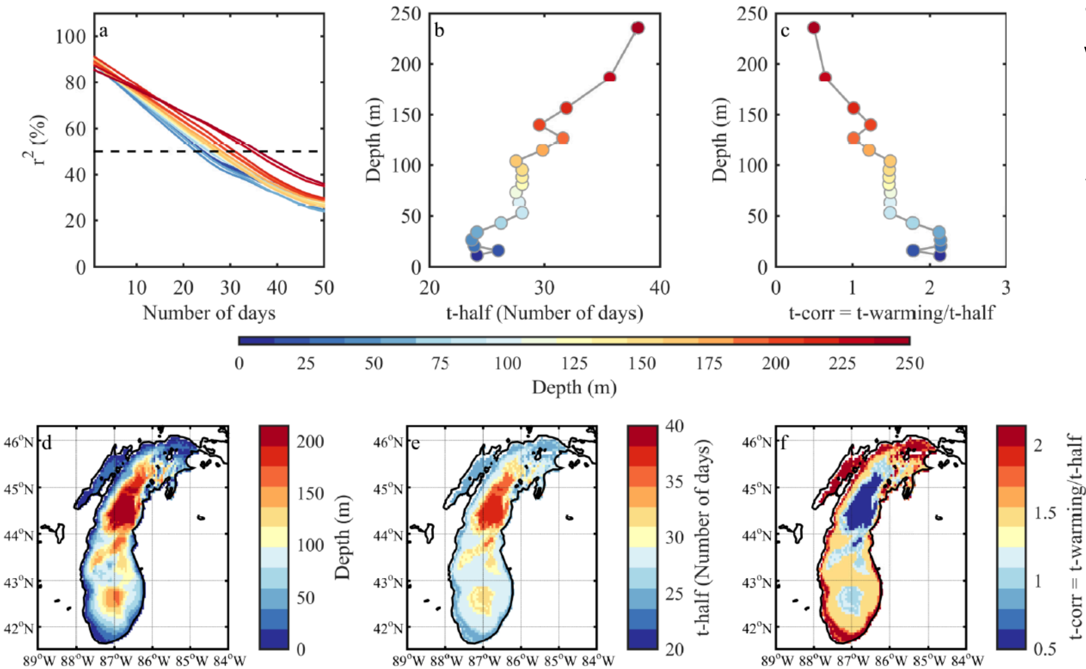


- Real power of satellite LSWT arises from the ability to analyse and explain the complexity of within-lake temperature variability. Not practically accessible via in situ data.

Woolway and Merchant (In Review)

Length of warming period varies within lakes significantly

WITHIN-LAKE VARIABILITY



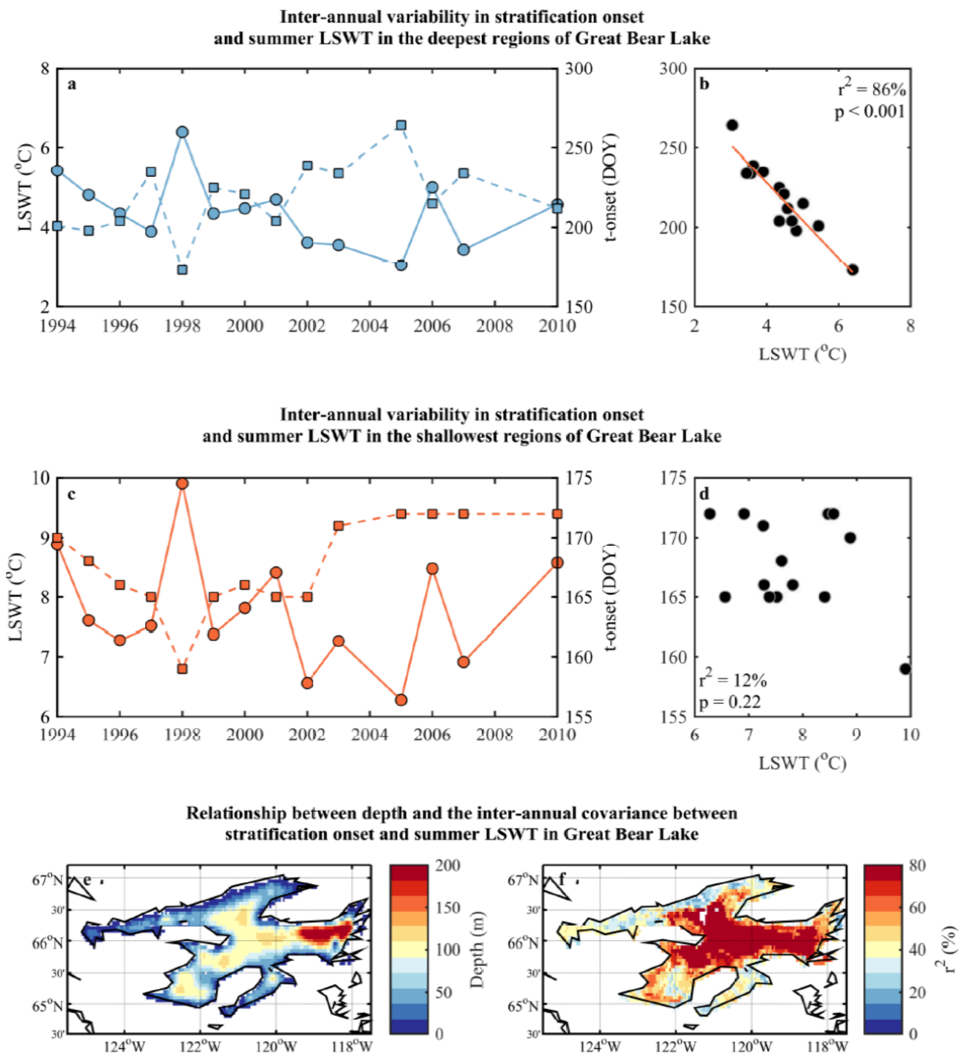
- Real power of satellite LSWT arises from the ability to analyse and explain the complexity of within-lake temperature variability. Not practically accessible via in situ data.

  Woolway and Merchant (In Review)

  Length of warming period varies within lakes significantly

  Deeper portions have shorter warming seasons and longer correlation time scales …

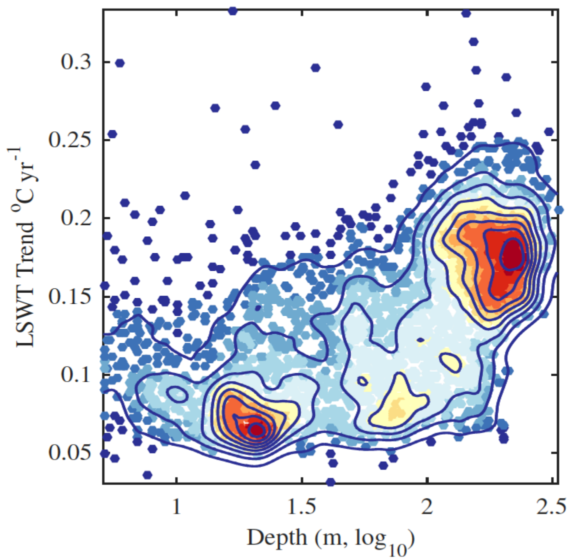
WITHIN-LAKE VARIABILITY



- Real power of satellite LSWT arises from the ability to analyse and explain the complexity of within-lake temperature variability. Not practically accessible via in situ data.

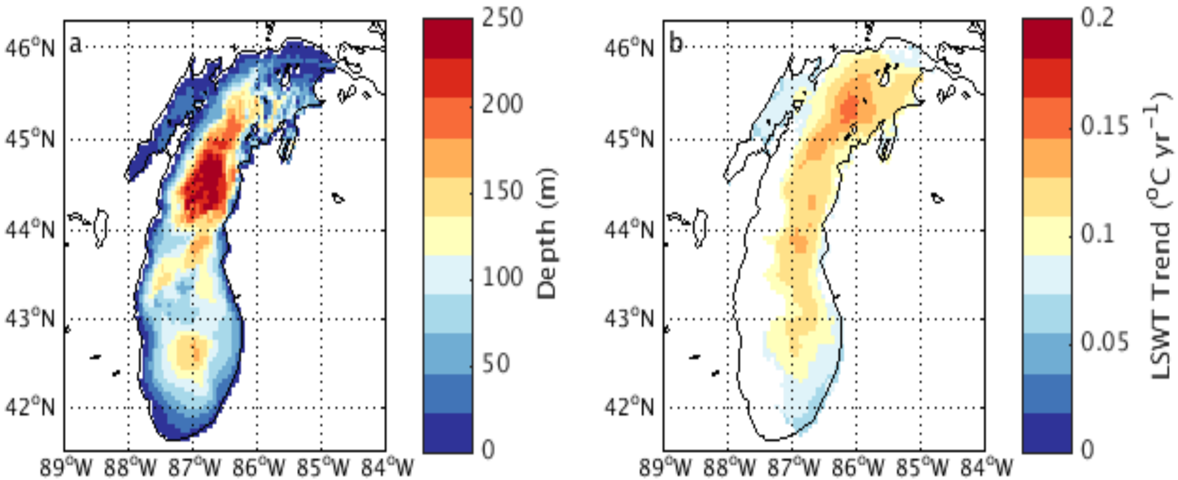
… and therefore are influenced most by early season thermal anomalies (e.g., earlier stratification onset – which is the main driver of amplified lake warming)

WITHIN-LAKE VARIABILITY



- Real power of satellite LSWT arises from the ability to analyse and explain the complexity of within-lake temperature variability. Not practically accessible via in situ data.

… and, in turn, show higher trends in summer LSWT



STATE OF LAKE CLIMATES

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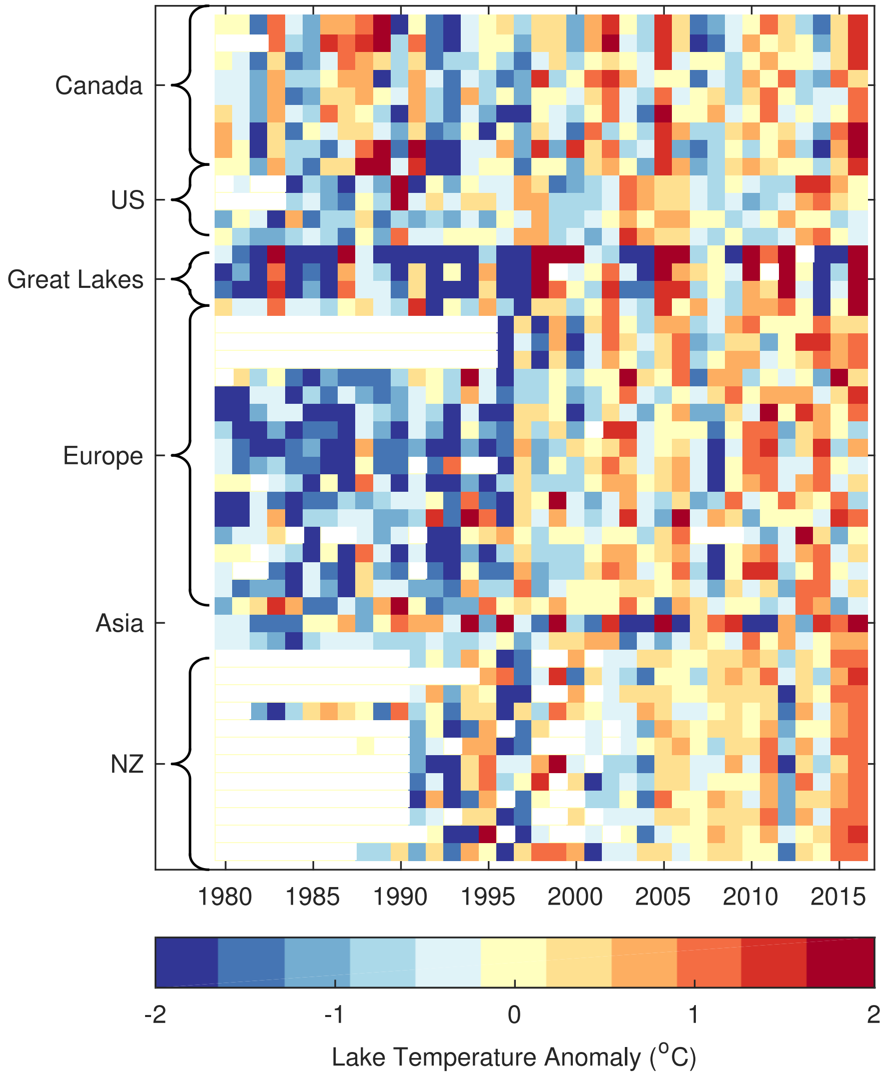

In situ summer LSWT anomalies collected for 48 lakes

STATE OF LAKE CLIMATES

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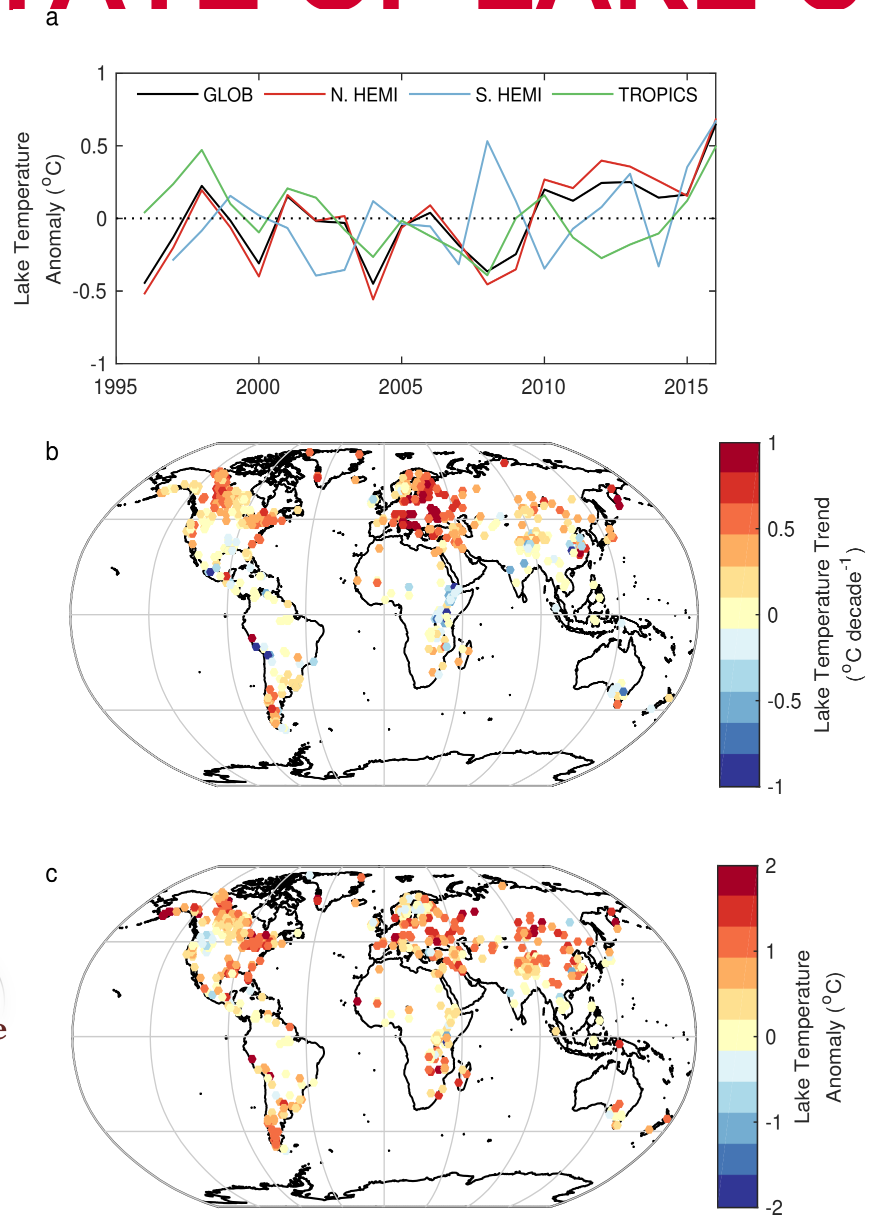

Trends and temperatures obtained for 681 lakes globally (1996 – 2016) from ATSR/AVHRR

Only possible by thermal remote sensing

SLSTR (and VIIRS) can maintain this capability

More comprehensive picture including smaller inland waters
will require hi-res, low noise, well-calibrated TIR missions.

ARC Lake

GloboLakes

STATE OF LAKE CLIMATES

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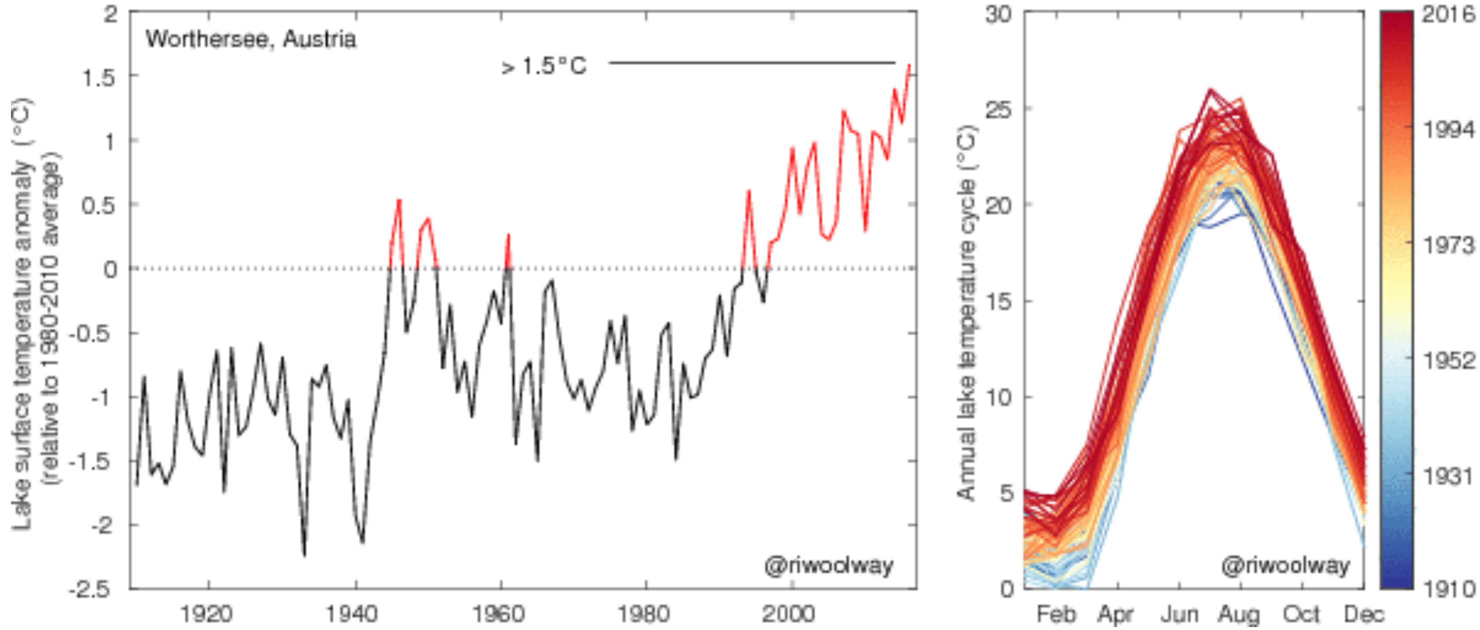

Current warming unprecedented in past 100 years