Title

Climate Change Signature on Millions of Lakes

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Climate Change Signature on Millions of Lakes

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Geography

by

Solomon Vimal

2022

ABSTRACT OF THE DISSERTATION

Climate Change Signature on Millions of Lakes

by

Solomon Vimal
Doctor of Philosophy in Geography
University of California, Los Angeles, 2022
Professor Steven Adam Margulis, Co-Chair
Professor Yongwei Sheng, Co-Chair

Lakes are unique in the land surface due to their well-known anomalous intrinsic properties – unusually large heat capacity, stark albedo contrast with water's phase change and sun's position. They also exhibit a wide spectrum of extrinsic properties – related to their occurrence, distribution and abundance. That they are ubiquitously besprinkled over most land surfaces with such intrinsic (extrinsic) anomalous (spectrum of) properties makes them a low-hanging fruit to observe from space and tease out in-land climate change signatures from local to global scales. In this dissertation, I explore four aspects in our current understanding of lakes and their connection to climate change, and I show that: 1) Long-term lake changes are multi-directional in nature as a rule and not exception; 2) Lake evaporation calculations using global data can be improved by ~5% at seasonal scales and ~50% (i.e. 5-10X better) in the energy gap to turbulence scales (i.e. ~30 minutes), compared to 5 other state-of-the-*art* mass-transfer methods, by virtue of a century-old misunderstood body of work by Robert E. Horton that is based on kinetic theory of gasses; 3) Long-term trends can be separated from correlation noise up to 1-sigma better than current practice in terms of both statistical power and confidence by combining a portfolio of 16 methods from two families of trend detection tools from Econometrics (parametric) and Hydrology (non-parametric); 4) Building upon the results of 1-3, a quasi-analytical water albedo model, and derived lake and climate variables from many sources (including Google Earth Engine datasets) can help us characterize lake changes up to sub-daily and sub-meter (micro-topography) scale, under the assumption of regional hydro-climate homogeneity at 0.25 degree spatial resolution (an unavoidable caveat governed by rain gauge density) for millions of Arctic Boreal Zone (ABZ) lakes. Collectively, these results I demonstrate at continental scale spanning whole of Canada and Alaska, ~10 million lakes, carve a pathway for a high-fidelity understanding of local-to-global scale climate change signatures on ~100 million lakes, which are, due to their intrinsic and extrinsic characteristics, our best in-land sentinels of climate change.

The dissertation of Solomon Vimal is approved.

Rong Fu

Glen M. MacDonald

Yongkang Xue

Steven Adam Margulis, Committee Co-Chair

Yongwei Sheng, Committee Co-Chair

University of California, Los Angeles

2022

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DEDICATION

I dedicate this dissertation to my wife Anna Bonazzi; my little cutie daughter, Marina; and the person who was most helpful to make this dissertation work possible, Marian Olivas.

I also dedicate this work to the late Robert Horton and late George Polya whose ideas and spirit of not mixing heuristic reasoning (guesses) from first principles (facts) laid the foundation for my thinking.

And finally, my work is dedicated to my family in India and Italy, who have been an integral part of my journey.

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Vita - Biographical Sketch - Solomon Vimal

Education

University of California, Los Angeles (UCLA)
C. Phil in Geography | Sept 2018 – Ph.D. exp. June 2022

- Staff Research Associate III & Graduate Student Researcher, 2017-2019
- Taught 12 courses at UCLA-Geography, 2018-2022
- Designed & delivered a course on Geospatial Data Science in Water & Climate
- Invented 1 patent-pending geospatial trend detection algorithm
- Received 6 UCLA fellowships (~$35K), 2 NASA data visualization competition prizes ($2K), and a gift from Google AI, Israel ($3K)

Erasmus Mundus Flood Risk Management, European Commission
Joint Triple Master of Science Degree | Sept 2013 – Aug 2015

- M.Sc. in Hydro-science & Engineering, Technical Uni. of Dresden, Germany
- M.Sc. in Water-science (Hydro-informatics), UNESCO-IHE, the Netherlands
- M.Sc. in Flood Risk Management, Barcelona Tech, Spain
- Studied/worked in 4 EU countries & 5 U.S. states (FL, NC, AL, TX, UT).
- National Flood Interoperability Experiment to test IBM's hydraulic model and HAND algorithm, later operationalized at NOAA National Water Center via CyberGIS to 2.7M rivers (~700X increase in forecast density).
- Scholarship (100% tuition, €6K travel, €24K stipend) & 1 NSF grant ($3K).

St. Peter's University, India
Bachelor in Civil Engineering | Aug 2008 – Apr 2012

- Capstone on surface water modeling using Remote Sensing, GIS and (Differential) GPS data with MATLAB.
- Received gold medal for securing 1st rank in all semesters in the civil engineering program and 1st rank among all departments in two semesters.

Positions

Risk Management Solutions (rms.com)
Hydrology Modeler | 2016-2017

Indian Institute of Science, Bangalore
Project Assistant | 2012-2013

Common definitions and abbreviations

GCM: Global Climate Model

LSM: Land Surface Model

MC: Monte-Carlo

MK: Mann-Kendall - a rank based (non-parametric) trend detection method

DGP (SDG): Data Generation Process (Synthetic Data Generation)

EOS: Earth Observation Satellite

ARMA: Auto-Regressive Moving Average

OUCH: Observability, Ubiquity, Contiguity and Homogeneity of lakes

PIP: Principal Interaction Processes

SIP: Suspected Interaction Processes

1
Introduction

Arctic Boreal Zone (ABZ) lakes' response to climate change is among the most important, as well as easiest to quantify, local in-land climate change signatures for numerous reasons. This chapter fleshes out these reasons and describes the connection to the ensuing work (chapters 2-4) as a summary of chapters: 1) understanding the physics of evaporation, a first-order lake process; 2) understanding the mathematics of separating signal from noise in long-term trends applied here to hydro-climatic variables; 3) applying (1) and (2) for modeling long-term changes in ABZ lakes in a warming climate.

Motivation

Lakes are critically important in the wake of global climate change due to their local and global relevance. Particularly lakes in the so-called Arctic-Boreal Zone (ABZ) of North America including all of Canada and Alaska are of great interest – the domain of interest in the present study. Most climate models predict that the ABZ will experience a level of warming twice as high as the global average by the end of the century (Hassol, 2004; Parker et al, 2009). The analysis in this dissertation is limited to the most recent three decades (1984-present) of observed (satellite and gauge) and model reconstructed data to analyze the impact of climate change on lakes.

Study domain and definition of lakes

ABZ: Arctic Boreal Zone. Here we refer to ABZ as the region that spans all of Canada and Alaska, though a more precise definition for the area considered in this dissertation would be about 80% of Northern Canada and all of Alaska. ABZ globally also spans Eurasia in the same latitudinal belt as that of North America. The zones of the ABZ were drawn from Environment Canada (1998), and extended to include Alaska.

Definition of lakes: all in-land surface water is called "lakes" here, and to be more precise, they are the permanent and ephemeral in-land surface water bodies as indicated by the monthly and annual scale Landast imagery derived from Pekel et al (2016) dataset. By count and surface area, a majority of the area are indeed lakes while some are rivers. For the resolution of analysis performed in this dissertation (0.25 degree), this definition is reasonable though it is imprecise.

Significance

Local relevance: Lakes are critically important to understand global warming, especially lakes in the rapidly warming Arctic. They provide a strong basis for a hyper-local scale climate change risk assessment, reduction, response, adaptation, mitigation, sequestration, and risk transfer. A convenient abbreviation to remember why ABZ lakes are critically important is OUCH: it stands for four features that are particular to lakes, **O**bservability, **U**biquity, **C**ontiguity, and **H**omogeneity. "OUCH" features make ABZ lakes an attractive low-hanging fruit to scientists to understand climate change impacts locally and globally.

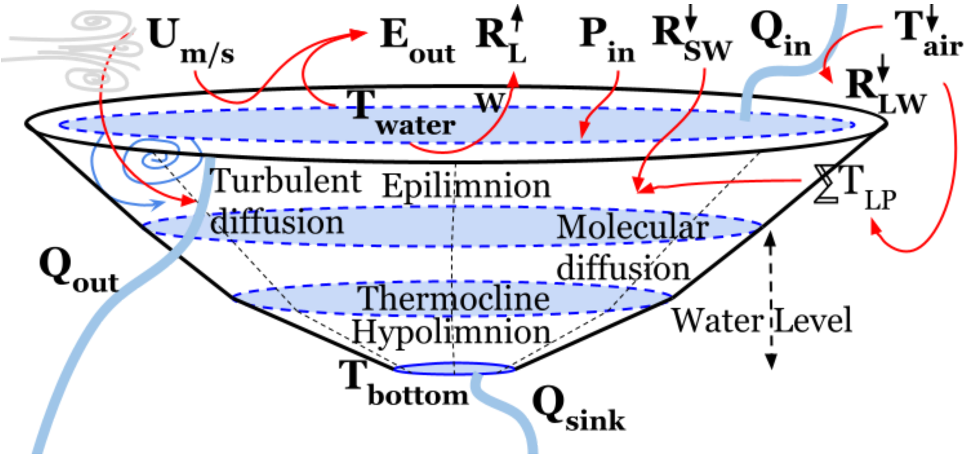
Global relevance: Arctic lakes may be regarded as sentinels of climate change as their local responses to climate, if understood correctly, forebode future planetary-scale climate change risks as manifested through water, the primary way in which heat and moisture are redistributed globally. The most important of global scale implications that should concern scientists has to do with a dramatic hazard posed by Arctic lakes: they are perched atop a layer of permafrost, which has been dubbed a ticking bomb for global warming because of its high content of methane, a potent greenhouse gas (10X more CH4 than non-Arctic regions), and it contains 2X carbon as that in the atmosphere. Furthermore, the region is known to have accelerated regional warming (up to >7X) in Arctic fringes compared to global average, due to the well-documented Arctic amplification phenomenon by which an initial increase in warming leads to an increasingly faster and more intense loop of warming.

Summary of chapters and summary figures

In the context of the importance of lakes sketched above, this dissertation is articulated in 4 core chapters (2-5) followed by a conclusion (chapter 6). A summary of these chapters is provided below as a map of the dissertation. The same blocks of text are provided at the beginning of each chapter to aid the flow of reading. A centerpiece figure of each chapter is provided here for a visual summary of the contribution of each chapter (figure labels and annotations are provided later in the chapters).

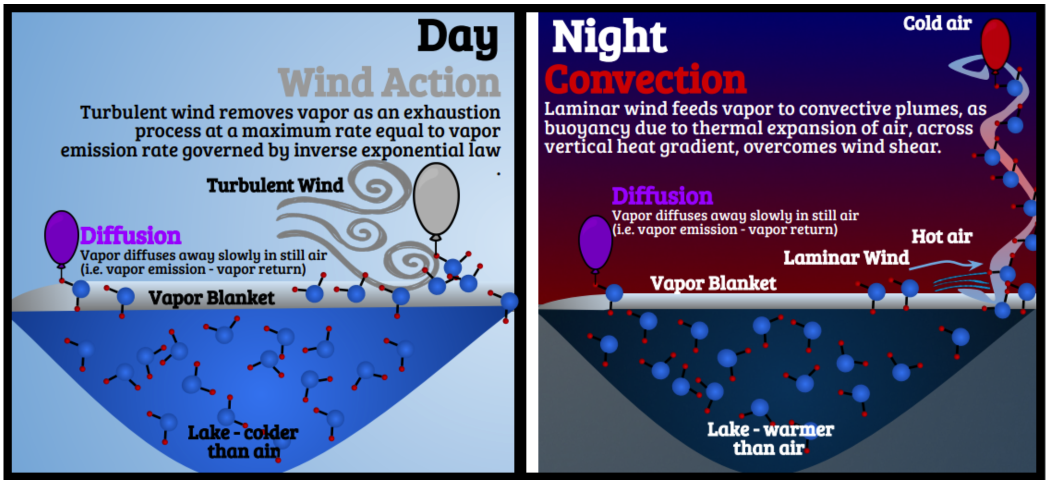
Chapter 2: Review of Arctic lake changes, causes and consequences

Contradictory observed lake trends, their causal explanations and consequences as reported in literature are juxtaposed. About 120 papers are reviewed and synthesized, highlighting competing hypotheses in explaining lake changes, causes and consequences. It is shown that basically all hydro-climate variables have bi-directional changes. Ten lessons learnt from the review are enlisted and modeling priorities are identified and a conceptual model design is proposed.



Chapter 3: Physics of evaporation

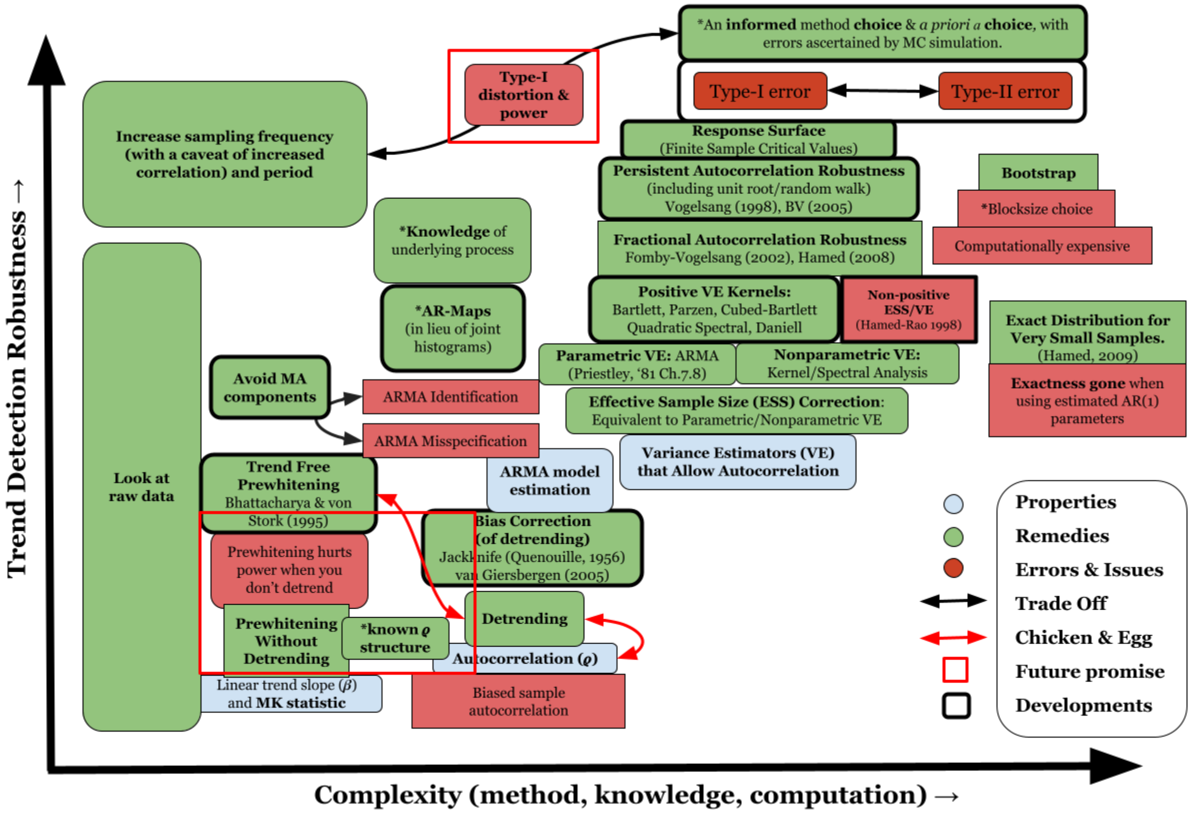
This chapter, from which a paper has recently been published (Vimal and Singh, 2022), discusses the question of how to estimate *lake evaporation, a process that allows us to understand the response of Arctic lakes to changing climate conditions. The work focuses on a century-old overlooked open water evaporation formula credited to Robert E. Horton. We show that this method improves evaporation estimation by 5-50% (seasonal to sub-daily). The improved method allows us to assess the changing character of Arctic lakes over the pan-ABZ domain (as done in Chapter 5) using widely available meteorological data.*



Chapter 4: Robust trend detection

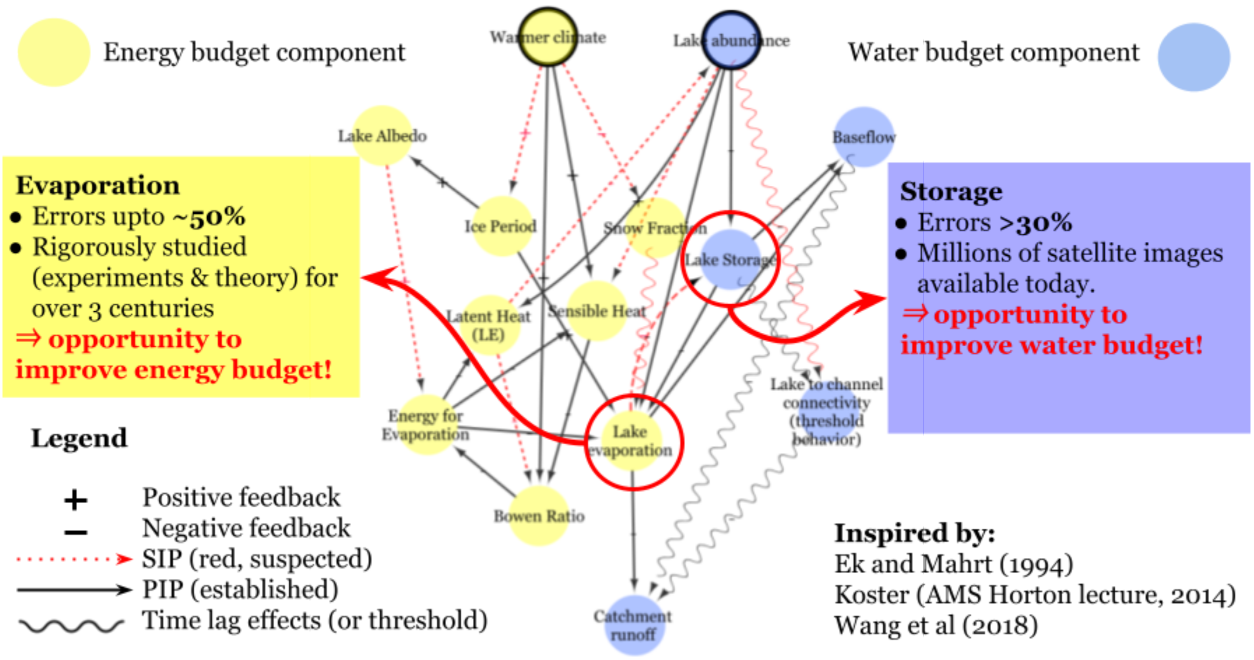
This chapter discusses the mathematical aspect of change (e.g. climate change or Arctic lake change), that is the question of how to reliably distinguish signal from noise in long-term trends. This chapter shows that detectable hydro-climatic trend signals can be separated from correlation noise at a 2-sigma level, nearly a ~1-sigma improvement from current practice. This is made possible by a marriage of trend detection methods from Hydrology (non-parametric family of tests: Mann-Kendall and its variants) and Econometrics (parametric tests) that together represent a portfolio of 16 individual candidate methods. Combining these methods, trend detection robustness (i.e. both statistical confidence and power) improves by ~1 sigma compared to current hydrology standards. This approach also allows us to detect climate change signals from lakes and hydro-climate variables without any a priori assumptions about the data.

Intellectual Property (IP) protection: *the work in this chapter has led to a set of potential patents. A part of this chapter has been* *excluded for IP protection reasons. To bridge the gap between chapters 1-3 and 5, as well as to address the title of the dissertation, the work on trend detection is presented in this chapter with sufficient details to appreciate the background and conclusions without revealing the core IP details.*



Chapter 5: High-Fidelity Detection of Climate Change Signature from Lakes

We identify first-order priorities to conduct a high-fidelity detection of climate signature from lakes. The priorities include closing two measurement gaps with better observations (open water albedo, sinkholes), improving modeling of critical energy and water budget processes, evaporation and microtopography respectively, and identifying (spatial) principal and suspected interaction processes (PIPs and SIPs) and conducting robust trend detection to detect long-term climate change impacts on Arctic-Boreal lakes: our best inland local scale sentinels of climate change.



Evaporation
- Errors upto ~**50%**
- Rigorously studied (experiments & theory) for over 3 centuries

⇒ opportunity to improve energy budget!

Storage
- Errors >**30%**
- Millions of satellite images available today.

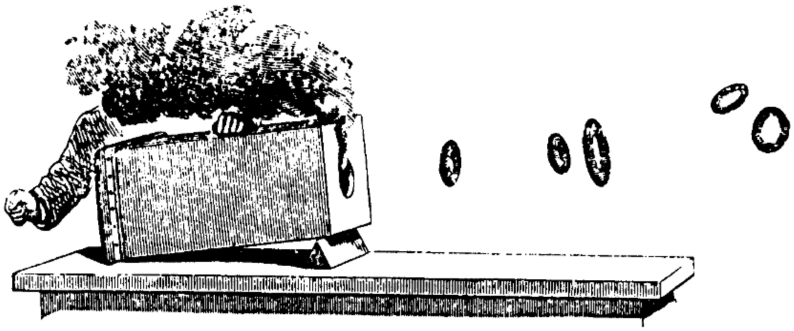
⇒ opportunity to improve water budget!

Inspired by:

Ek and Mahrt (1994)
Koster (AMS Horton lecture, 2014)
Wang et al (2018)

Chapter 6: Conclusion and Reflections

> *The unprecedented scale of satellite and ground observation data available today and advancements in trend detection enables us to understand climate-related changes in Arctic lakes in a robust way with high fidelity. The analyses conducted in chapters 1-5 suggest that some of the scientific priorities to improve our ability to model their unique physical signatures are: 1) improved model design including updated and more accurate evaporation estimates; 2) increased direct observations of open water albedo via field or remote sensing observations. I conclude the dissertation with a personal reflection on going from climate signature to fingerprint using lab experiments.*



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2

Arctic Lake Changes: Causes, Consequences and Modeling Priorities

Contradictory observed lake trends, their causal explanations and consequences as reported in literature are juxtaposed. About 120 papers are reviewed and synthesized, highlighting competing hypotheses in explaining lake changes, causes and consequences. It is shown that basically all hydro-climate variables have bi-directional changes. Ten lessons learnt from the review are enlisted and modeling priorities are identified and a conceptual model design is proposed.

Abstract

The Arctic Boreal Zone (ABZ) lakes have been rapidly changing in recent decades, a phenomenon of critical importance in global climate change studies. Numerous studies in the last five decades in Russia, Canada and Alaska have observed widespread lake expansions and contractions, as well as instances of rapid disappearance. The number of lakes analyzed in each of these studies has exponentially increased (by six orders of magnitude) since the 1950s, starting from individual lake studies to 100 million in-land water bodies using Google Earth Engine in the most recent years of the satellite earth observation era (1970s to present). Over these years, the fluctuations of lakes are increasingly believed to be accelerating due to global warming. First, this review summarizes the lake dynamics reported in regional studies (over the last 30-50 years),

trends in various lake-related factors (physical quantities like occurrence, heat storage and ice phenology). Second, drawing from literature, we delineate dozens of mechanisms associated with warming induced lake changes in the land-atmosphere system, including their positive or negative feedbacks, and time lag effects. Third, we analyze their agreements with theoretical expectations in a rapidly warming climate, among other things, considering scale issues and Simpson's paradox. Fourth, using several objective site selection criteria and observed data from stations (7,832 stream gauges and ~2,800 rain gauges in Canada), we reformulate open questions, and urgent priorities, to understand the changing character of lakes of the North American ABZ. Finally, we highlight 10 lessons learned that may inform better modeling practice.

Introduction

In the North American Arctic Boreal Zone (ABZ), numerous studies of the recent decades have reported that lakes of this region have dramatically changed over the recent decades (Smith et al, 2005; Plug et al, 2008; Marsh et al, 2008; Pekel et al, 2016; Pickens et al, 2020). The lake change trends observed in these studies are bi-direcctional in nature, although rapid disappearance has stronger absolute magnitude in trend than lake expansion (Olthof, 2015). According to the lake change mechanism reported in Yoshikawa and Hinzman (2003), Smith et al (2005) observed that "the spatial pattern of lake disappearance suggests (i) that thaw and "breaching" of permafrost is driving the observed losses, by enabling rapid lake draining into the subsurface; and (ii) a conceptual model in which high-latitude warming of permafrost triggers an initial but transitory phase of lake and wetland expansion, followed by their widespread disappearance”. Accelerated Arctic warming due to climate change (Hassol, 2004) is heavily implicated in these lake change dynamics, especially by increasing the Active Layer Thickness (ALT) and formation of Taliks (Yoshikawa and Hinzman, 2003). While several studies have corroborated the conceptual model aforementioned, numerous alternative mechanisms are also reported in literature (see a chronological summary presented in Table 1 for some such works over the last decade). It is clear that the reasons for heterogeneous changes of lakes and the causal mechanisms are ambiguous, especially concerning the role of long-term climate change impacts on lakes and vice versa.

Arctic lakes: why are they sentinels of climate change?

Most climate models predict that the ABZ will experience a level of warming twice as high as the global average by the end of the century (Hassol, 2004; Parker et al, 2009). Climate change impacts on the terrestrial system are arguably way more complex to model than those in the ocean, and this is mainly due to the heterogeneity of terrestrial surfaces. However, lakes are good proxies for local terrestrial impacts of climate change as water’s anomalous but well-known properties (e.g. freezing, evaporation rates, etc.) can be well bounded (for the most part in its natural occurrence as surface water) unlike other terrestrial surfaces which are heterogeneous in composition and prone to more sources of errors in their known (i.e. measured) physical properties. Therefore, understanding the impacts of climate change on lakes, though difficult, *is the* low hanging fruit in terms of quantifying the terrestrial impacts of global warming. Furthermore, impacts of climate on lakes constitute an important part of the freshwater system, which is intricately connected with ecological services to the freshwater biota. Even more important is the fact that lakes are *sentinels of climate change*: they constitute an early warning signal owing to their unique sensitivities (due to the high thermal inertia and contrasting energy reflective properties of water), and are hence a foreboding of many future changes to come in the terrestrial land system, which is, as noted earlier, way more heterogeneous than the oceans. These facts underscore the importance of climate change impact studies on lakes, as well as their associated causal pathways and consequences.

Arctic lakes: collective **research initiatives**

Scientists from a wide range of geo-science disciplines are interested in the impacts of climate change on the ABZ and its carbon feedback, which are intricately connected with lake changes. Multiple national agencies and multi-national bodies have increasingly prioritized the study of the Arctic Boreal Zone in recent years: among US Agencies are the Department of Energy's Next-Generation Ecosystem Experiments (NGEE-Arctic) project in Alaska (Wullschleger et al, 2011), see http://ngee.ornl.gov/; the National Science Foundation's Navigating the New Arctic projects (Strawhacker, 2019); and NASA's Arctic Boreal Vulnerability Experiment (ABoVE) (designed as a decade-long project to quantify the changing carbon dynamics and disturbance regimes of the North American Arctic). Numerous studies of lakes of Canada and Alaska have emerged from these projects, and as many as ~250 data products since the beginning of the ABoVE project alone which started in 2015. Similarly, scientists from eleven European countries participated in a European Union project called "Climate and Lake Impacts in Europe (CLIME)". CLIME was a project funded by the Environment and Sustainable Development research subprogramme of the European Union and was one of the first EU projects to develop tools and models that could be used to simulate the responses of lakes to both the historical and projected changes in the climate. The project resulted in over 100 journal articles and also a book (George, 2010). Broader Eurasian initiatives of similar scope began in 2004, with the Northern Eurasia Earth Science partnership Initiative (NEESPI) and its follow-on project, the Northern Eurasia Future Initiative (NEFI), which have led to over 1000 journal articles (see Groisman, 2017). These (mostly) decadal scale initiatives highlight the importance of climate impacts of the ABZ for the earth science community as well as government agencies. It is of interest in the present review to summarize and build on these numerous works.

Lake change studies of the p*re-satellite* era

Before the 1970s, scientists already began observing lake changes as a signal of climate change in boreal climates, e.g. in USSR, Finland (Eurasia), and North America (US and Canada), as exemplified by the lake measurements and changes since the 1850s reported in Williams (1970). Subsequent works in the 1980s and 1990s, most notably Robertson's PhD dissertation in the 1980s, eventually published in 1992 (Robertson et al, 1992), used lake ice breakup as a proxy for climate change impacts, similar to what was attempted earlier by Williams (1970). In the following decades, many researchers followed suit to examine the role of lake ice (Smith, 2000). A similar trend of climate change research can be seen not only in Arctic lakes, but also other lakes worldwide (Robertson, 1992). While the signal of climate change was clear in these decades of research, in the pre-satellite era, lake studies were limited to individual or a few lakes at most in nearly all investigations.

Lake change studies of the s*atellite* era

In the satellite era, studies from more recent decades have examined lake changes over a large spatial domain, and a step change in the number of lakes simultaneously considered. E.g. 'Disappearing Arctic Lakes' by Smith et al (2005) in West Siberia investigated ~10,000 lakes, a similar study by Caroll et al (2011) investigated 2800 Tundra ponds of Alaska (Andresen and Lougheed, 2015) which are particularly of interest for this review. Although satellite observations are prone to large errors (as they miss small water bodies and may have misclassification errors), they are a promising area and a great alternative to lake studies based on individual lake observations to assess regional scale impacts of climate change. Field campaigns of comparable scale would be cost prohibitive and unwieldy to carry out. The aforementioned studies utilized satellite images of about 30x30 meter resolution and kite-borne aerial imagery of 1 hectare resolution (100m x 100m), which capture much of the spatial heterogeneity of lakes, even if not entirely.

In the early part of the lake study explorations with satellite data, studies were fraught with difficulties due to image registry complications as well as computational processing and data quality issues. This was a primary driver for the direction of research and a host of studies were focussed on addressing remote sensing data registry issues: for example, Sheng et al (2008) proposed innovative solutions for accurate geo-registration of thousands of satellite images using stable centroid points of lakes. Shen et al (2015) proposed a similar algorithm for the deepest point of lakes (not the centroid) by representing the deepest point as the largest inner circle that can be drawn within the lake polygon, using Voronoi diagrams and an algorithm based on medial axis simplification (MAS). Shah et al (2008) proposed a solution that considers scale invariance and preserves pseudo-invariant features (PIFs), i.e. stable and persistent shapes in rapidly changing lakes, using which a geo-registration accuracy of 0.66 pixels was achieved.

In recent years, these issues have been corrected near perfectly, and have given rise to a new generation of high quality archives of long-term and global surface water records from space observations. Such methods for lake geo-location and numerous other advances in processing remote sensing (e.g. Gorelick et al, 2016; Alsdorf et al, 2007) have enabled lake studies over large scales and high resolutions. Cretaux et al

(2011) and Sheng et al (2016) have proposed methods to carry out representative lake extent mapping at up to continental scales. Not only the spatial extents, but also the height variations of lakes are now routinely analyzed, e.g. using Altimetry datasets (Song et al, 2015). With these advancements, today it is possible to examine numerous lakes at once in a single study.

Finally, NASA's major decision to make its Landsat data public in 2008, and with subsequent development of tools like Google Earth Engine (Gorelick et al, 2016) that support rapid processing of the entire archive, we now have the capability to revisit their analyses and hypotheses using millions of satellite images that are all freely available at the same resolution, but with larger temporal and spatial coverage. For example, Pekel et al (2016) and Yamazaki et al (2018) have developed highly useful datasets that can be leveraged for lake studies which collate over 10 million images and are available in the public domain. With these developments, it is possible to assess millions of lakes in a single study, to revisit some of the observations and conclusions made in previous studies from the 1970s to early 21st century.

While our ability to monitor lakes and track lake change in a single study has dramatically improved in the last few decades (by ~1000 folds in early ~2000s and by a million folds since 2010s), our understanding of the system is lacking by far for the amount of data we now possess. In particular, the various causal pathways of lake changes and their impacts are hitherto poorly quantified and understood. This presents a large gap, and a need for scientific research to match the data volume, motivating our study to approach continental scale evaluation of lake changes. Furthermore, lake changes are particularly dramatic in the Northern latitudes where the rate of regional warming is greater than twice the global warming average (*IPCC. in Climate Change 2013: The Physical Science Basis)*. It is hence of great interest to examine the lake changes from the 1970s to present over the domain of the global arctic and non-Arctic regions. In line with recent research interest in Northern Latitudes, it is of particular interest to examine lakes of the Arctic-Boreal Zone that span latitudes 50 to 70 separately, so we tabulate our review into 3 categories for natural lakes: North American Arctic, Eurasian Arctic, Rest of the World and a 4th category for man-made reservoirs.

Trends observed in lake quantities

Lake **occurrence changes (area and count)**

Global evaluations of lake changes in the Arctic latitudes show several mixed signals, whereby lake properties are observed to be increasing in some areas and decreasing in other areas, and increasing and decreasing, accelerating and decelerating (with or without statistical significance), aligning or contradicting with theory. These observations and notable contradictions are analyzed and summarized in the tables below for the studies that emerged from the United States, Canada and Eurasia separately.

Table 2.1: Lake change studies in Alaska, United States

Regions of lake changes	**Key agreements and contradictions in literature**	**Methods and findings**	**Primary citation(s)**
Regions in **Council, Alaska**	**Pond shrinkage** observed in **discontinuous** permafrost near Council Alaska.	**24 ponds** were observed in 1950 and 19801 from aerial photography and satellite images (IKONOS) for the year 2000, to assess shrinkage over the last 20 years. The mechanism of drainage is talik formation due to expanding thermokarst ponds that drain in a warming climate during similar precipitation conditions (572, 416 and 432 mm).	Yoshikawa and Hinzman (2003)
Alaska	**Unanimous lake contraction** occurred over the entire time period for all regions of discontinuous permafrost. **No change** in coastal continuous permafrost.	Remotely sensed datasets for **10,000 closed basin ponds.** The change percentages were 4-31% in surface area, and 5-54% in count of ponds. It was accompanied by temperature trends. **Causes:** ET or permafrost drainage.	Riordan, Verbyla, and McGuire (2006)
Alaskan Boreal Forest	**14/15** lake pairs **increased in area** from 1950 in the last 50 years.	**Causes:** The one lake that drained had shallow thaw depth, and shoreline slope, among other characteristics.	Roach et al (2011)
Yukon Flat, Alaska	Of **2280** lakes, **350 lakes shrank**, and **103 lakes expanded.**	"80.7% of lake area variability was attributed to intra-annual and inter-annual variability in local water balance and mean temperature"	Chen et al (2012)

Northern Seward Peninsula, **Alaska**	Small water bodies **increased** and **large water bodies decreased**.	Remote sensing data of high spatial resolution was used for years 1950/51, 1978 and 2006/07 to observe thermokarst lakes. Water Bodies of size greater than 0.1 Ha **increased** from **666 to 737**. Analysis of larger lakes shows (>40 Ha) shows a decrease of 24% and 26% in number and area. *This is explained by formation of remnant ponds following partial drainage of larger water bodies. Lateral breaching, and not subterranean infiltration, is the dominant mechanism.*	Jones et al (2013)
Alaska (over a 1000 km latitude and longitude gradient)	**Statistically significant increase and decrease** of lakes was observed among **2300 lakes**.	Lake drainage was found to be dominant in lakes far from rivers, and in areas of forest fire and coarse soil, and there is evidence for subsurface drainage. Proposed a method to identify at-risk lakes.	Roach et al (2013)
Barrow Peninsula, Alaska	Of 2800 ponds analyzed in 22 drained thaw lake basins. **Net decrease of 30.3%** in area and 17.1% (479 lakes) in number of ponds over 62-year period. **Linear downward trend (from obs).**	Historical imagery of 1948 compared with sub-meter resolution imagery from 2002, 2008 and 2010, and photogrammetry of 2010-2013 from kite-borne imagery and field observations. **Causes: increased evaporation due to warmer and longer summers**, **permafrost degradation**, and **transpiration** from encroaching aquatic emergent macrophytes.	Andersen and Lougheed (2015)
Yukon Flats, Alaska	**Decadal scale lake level fluctuations** due to climate fluctuations are typical features of the region, with sporadic wet spells.	Sediment core data was used to estimate 5500 years of hydrological changes. Most of the last 800 years had dry periods with brief wet spells.	Anderson et al (2018)

Yukon Flats, North Central Alaskan lakes	**Lake reductions** were observed predominantly.	Isotope studies were conducted in **175 lakes**. 26 of 175 may potentially be due to the thawing mechanism, but the climate trend explains most lake changes, i.e. 95% lake contributions are due to river water, groundwater and precipitation due to multidecadal climate trends (greater moisture deficit since the mid-1990s).	Anderson et al (2013)
Yukon Flats, Alaska	Lake changes are **predominantly intra-annual.**	Variability in closed basins were smaller than connected basins. Intra-annual variability is as large as 42% within summer (June to Aug). Lakes of similar transitions were spatially clustered.	Chen et al (2013)
Yukon Flats, Alaska	**Bidirectional change occurred, but lakes were clustered: 350 lakes shrank** and 103 lakes expanded.	Intra-annual variability accounts for 80.7% of total lake variability in closed basins.	Chen et al (2016)

Table 2.2: Lake change studies in Canada

Regions of lake changes	**Key agreements and contradictions in literature**	**Methods and findings**	**Primary citation(s)**
Western Canada	Rate of lake **disappearance decreased** from 1950-2000. Climate, geomorphology, and hydrology are responsible for this change.	**41 thaw lake basins** in Western Canada were examined between 1950-2000 using aerial photographs and topographic maps. Their rate of drainage decreased significantly over the periods 1950–1973, 1973–1985, 1985–2000, from over 1 lake/year to approximately 0·3 lake/year	Marsh et al (2008)

Old Crow Basin, **Northern Yukon, Canada**	Lake area **increased** initially and then **decreased.**	Aerial photographs, satellite images, and numerical lake models were used for the period 1951-2001. Lake trend patterns are associated with pacific decadal oscillations. Until 1971 lakes (~70% of lakes) increased, and then decreased (~45% lakes). **Causes:** Reductions are due to warmer and drier climates (in 1977).	Labrecque et al. (2009)
Coastal Plain, Northwest Territories (NWT), Canada	**Negative trend magnitudes are greater**, but the **total area of lake expansion** was significantly **greater than contraction.**	Using Landsat infrared validated with 0.5 m orthophoto imagery to evaluate Landsat mapping algorithms. Lakes that drained, were quick, and lakes that expanded were overall more pervasive.	Olthof, Fraser, and Schmitt (2015)
Continental Canada	**No long term net variations over Canada:** this has been noted in many global regions, and less than **0.001% net expansion** is observed in terms of permanent water bodies in Canada between 1984 and 2015.	Landsat archive from 1984 to 2015 was used to assess transitions (increase, decrease, etc.). Net variations (increase - decrease) was mostly positive, though the magnitudes are quite small.	Pekel et al (2016)

Table 2.3: Lake change studies in Eurasian Arctic

Regions of lake changes	**Key agreements and contradictions in literature**	**Methods and findings**	**Primary citation(s)**
Latitudes ~62 to ~68 of Siberia	**Lake expansion** was found in **continuous permafrost** (12%) and between 1973 and 1998, 11% of the **~10,000 large lakes shrunk** below 40 Ha (6% decline in area), and numerous lakes had **permanently disappeared** (did not reappear in the period 1998-2003) in **sporadic**	Remotely sensed images from multiple sources were used (Russian MSS for 1973 and Landsat for 1997-8). **Causes:** permafrost thawing mechanism.	Smith et al (2005)

	permafrost regions.		
North Western Siberia	**No statistical evidence of long term trend in lake size distribution.**	Lake changes co-occur with increase and decrease. Based on satellite data from 1973, 1987-88, 2007-09, in **3 basins**. Local permafrost conditions impact individual lakes.	Karlsson et al (2014)

Table 2.4: Lake change studies in the rest of the world

Regions of lake changes	**Key agreements and contradictions in literature**	**Methods and findings**	**Primary citation(s)**
Canada domain (global study)	**Mixed transitions dominate**: the total area of multiple water or land transitions far exceeds the area where unidirectional increase or decrease is observed.	The entire Landsat dataset was used to show that unidirectional change in surface water is far outnumbered by mixed changes (multi-directional).	Pickens et al (2020).
Swiss lakes	Lakes are **increasing** in deglaciated alpine regions	1000 new lakes have formed in deglaciated regions	Mölg et al (2021)

Most studies report simultaneous lake expansion and lake contraction over widespread areas. Pickens et al (2020) addressed an important point related to the directionality of change, and they suggested that unidirectional change isn't the dominant characteristic of most in-water bodies, and that the *area of multiple transitions far exceeds areas of unidirectional change*, though their work refers to all inland water bodies and not just lakes (similar to Pekel et al, 2016). This doesn't preclude the possibility of unidirectional change observed in several lakes (Smith et al, 2005; Anderson et al, 2013; Riordan et al, 2006), which seems to be mostly driven by the type of permafrost substrate due to complex local processes. Chen et al (2016) showed that often unidirectional change is seen in a cluster of lakes. These observations suggest that modelers should adopt a framework of understanding lake changes that accounts for bi-directional trends within the same study domain. Some of the contradictions noted in Table 1 are evidently a result of sampling issues. It is of interest to understand the statistical characteristics of such changes, and also, more importantly, to understand the competing physical behaviors and mechanisms that may result in opposite feedback. Some of the key variables that relate to lake trend changes (lake physical quantities) as well as causal factors are reviewed in the following section.

Climate signatures on lakes

Table 2.5: Trends in lake temperature attributes: agreements and contradictions

Factors related to lake thermal and ice phenology changes in scientific literature	**Key agreements and contradictions found in literature**	**Primary citation, methods used, spatio-temporal extent**
Ice phenology trends, in terms of statistical significance of change observed.	**Delay of freeze-up date**, **not always statistically significant**: Studies have reported statistically significant trends for the North Hemisphere as a whole and **no statistically significant trends** in Russian Arctic rivers.	Smith (2000) used observation records of numerous Russian Arctic rivers. Palecki and Barry (1986) found the same in Finland, and Magnuson (2000) in the Northern Hemisphere. Data records of 39 lakes over the last ~150 years (1846-1995) show an average delay in freeze date by 5.8 days per 100 days.
	Ice break date is unanimously observed to **occur sooner**: Contradictions do not exist as to the statistical significance of trends in Arctic ice break up date. Break up **(melt) date is earlier** than before and statistically significant in the	All studies reviewed agree on this shift in ice break date, and an average advance in breakup dates by about **5-6.5 days per 100 years** (Smith, 2000; Palecki and Barry, 1986; Magnuson (2000).

	Siberian Arctic rivers.	
Theory vs. observation in lake temperature trends.	Lake **temperature should decrease:** Under increased CO2, **lakes will be colder** due to absorption of IR range energy by CO_2.	Chowdhary and Kukla (1979)
	Lake **temperature increases are observed**: Lake temperature trends are reported to be increasing at a faster pace than the atmosphere.	Austin and Colman (2007) reported this in the case of Lake Superior, attributing it to declining ice cover.

A study of Wisconsin lakes, which is based on the longest ice break data record of 135 years, showed that by relating climate and ice break changes, we can infer that the days of lake ice cover are expected to drop by about ***11 days for every 1 degree C increase*** in temperature (Robertson et al, 1992). Similarly, a study on 63 lakes in Finland showed that a 1.1 C of temperature change in November temperature signifies a 5 day change in freeze-up date of the same sign (Palecki and Barry 1986). The role of ice phenology is of particular importance because it has been recognized since the 1970s as an indicator of climate change, and it is relatively easy to capture from remote sensing studies. In sum, lake temperature and ice phenology characteristics unanimously indicate climate warming as the culprit. However, the observations do not show a consistent agreement across regions in terms of lake occurrence. Eventually, our interest is to examine how these feedbacks (and mixed signals) propagate into the larger climate system of the ABZ, which is a critical question to be addressed. Even a partial progress in this direction to untie some of these mixed signals may be regarded as an important scientific contribution. So one question that may be posed is related to how the lake ice-albedo effect takes shape in a warming climate with spatially explicit representation of lakes of the ABZ domain, to examine their signatures in streamflow. This question can be conceptualized with a simplified schematic (Figure 2 shown below) drawing from Figure 1 for clarity.

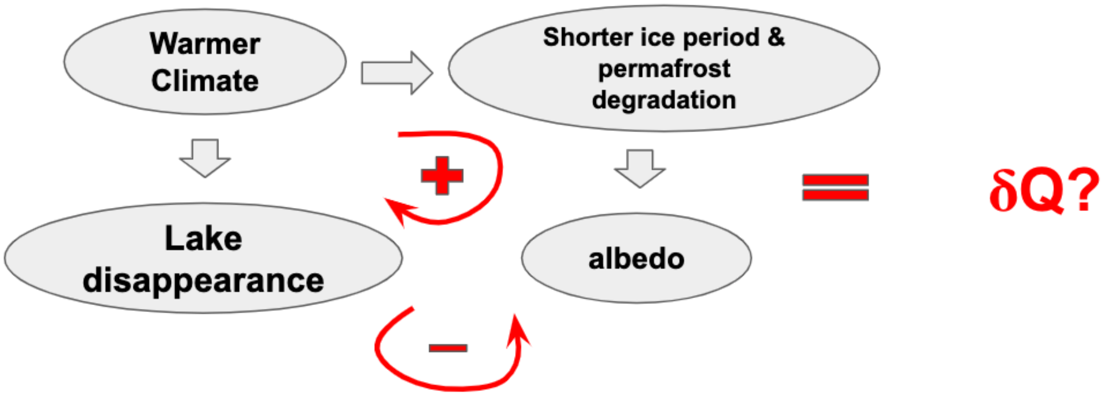


Figure 2.1: Positive and negative feedback of lake and ground ice

Trends in lake change drivers

There are gaps in our understanding of lake induced consequences to the climate. The table below examines a few contradictions seen in literature related to lake change causes, from intensification of the water cycle, attribution to temperature vs precipitation, observed changes in snow depth and soil temperature, as well as theoretical expectations from radiative transfer mechanisms.

Table 2.6: Changes in lake trend perturbations: agreements and contradictions

Factors related to lake change causes	Key agreements and contradictions found in literature	Primary citation, methods and spatio-temporal extent
Precipitation intensification is expected, though there is insufficient reconciliation between theory and observations as to the source of moisture (i.e. polarward transport vs local evaporation source).	**Unanimous increase: Precipitation** is expected to **increase** by up to **50%** in the Arctic due to local evaporation change mainly by the end of the 21st century due to **increased** relative contribution **evaporation** and **reduced polar moisture transport**.	Bintanja and Selten (2014) used CMIP5 GCMs to examine projected climate change impacts for RCP4.5 and 8.5. Routson et al (2019) arrived at a similar conclusion.
	Source of moisture is not the pole: The Arctic is expected to have a weaker equator-pole temperature gradient which will **reduce** the moisture transport from poles, making the local evaporation contribution to precipitation more significant, leading to a **positive ice-albedo feedback** loop.	Finnish researchers found a 1.7% increase per decade in the recent decades using observed data (Førland, and Hanssen-Bauer, 2000).
	Precipitation is the dominant driver: Heterogenous 12-month precipitation is the dominant driver of lake changes. Cumulative 12 month precipitation preceding scene acquisition ($r^2 = 0.82$) is the dominant control and not summer or mean annual air temperature.	Plug et al (2008) examined Landsat scenes from 1978-2001 to classify thermokarst lakes in NorthWestern Canada.
	Precipitation is not the dominant driver: significant trends did not co-occur with lake trends in Alaska, rather **temperature is the dominant driver.**	Riordan et al (2008) examined meteorological data and remotely sensed images for 10,000 closed-basins from the 1950s to 2002 in Alaska.
Lake temperature: Contradictions exist in attribution to temperature changes. Lake change intensification by CO_2 based warming has	**Increases:** Temperature is one of the most dominant processes in large lakes and it has been shown that lake evaporation changes are largely controlled by temperature parameterization, which is impacted by the size of the lake.	(Anderson et al, 2013) used remotely sensed images from multiple sources to examine changes in lake occurrence. They showed that water dynamics contribute 95% to lake trends.

competing factors and contradictions: radiative transfer theory contradicts observations.	**Decreases:** Increased inter-annual variability was observed, contrary to theory, in both freeze and breakup dates since 1950, as CO_2 absorption of terrestrial longwave energy is in the far IR (>5μm), and water is impervious to longwave. Shortwave is absorbed by CO_2 in the 05-5 μm range which competes with water as water's absorption is very high in the near IR range (high penetration depth). Near IR is also responsible for warming of snow and dissipation of snowpack. However, near IR is absorbed by atmospheric CO_2, and this has been shown to lead to a net cooling effect of open water.	Chowdhary and Kukla (1979) examined radiative transfer equations to absorptive properties of water and CO_2 to understand the role of global warming. Magnuson et al (2000) examined lake observational records. The temperature contribution noted by Subin (2012) is in contradiction with this study
Deep lake temperature	μDeep lake temperatures are **increasing** in the Great Lakes	Anderson et al (2021) examined 3-hourly 30-year records of lake temperature
Soil temperature shows contradictory signals over large regions of Canada.	**Increases:** overall in Canada, soil temperature increased by 0.07 degree per decade and in another study by 0.28 degree per decade.	Beltrami et al (2003) used temperature versus depth profiles measured at 246 sites, and Qian et al (2011) used 30 climate stations across Canada during 1958–2008.
	Decreases: in Eastern Canada soil temperature decreased substantially over a large spatial domain.	Zhang et al (2005) used model simulations to show that temperature increased in Canada overall, but for a substantial part of eastern Canada, it decreased by up to 2 degrees.
Regional Albedo	Satellite products of regional albedo are **400% off** in an inter-comparison of 9 products in January.	He et al (2014) compared 9 global albedo data products and reported.
	Surface water albedo explains 25% of the regional albedo variation	Webb et al (2021) showed that variance in albedo decline is explained upto 50-70% (mostly due to snow and open water).

Active Layer Thickness	**Increases: in North Eastern Greenland**	Since 1996, ground surface temperatures have increased by 1.5 °C on average, and the active layer thickness has increased by 1 cm yr−1 (Elberling et al., 2010, Hollesen et al., 2011).
Permafrost degradation has **positive** and **negative** feedback from surface water and vegetation succession.	Permafrost **persists in mean annual temperature of 2C** and **degrades in -20C!**	Jorgenson (2010): "Analyses show that vegetation succession provides strong negative feedbacks that make permafrost resilient to even large increases in air temperatures. Surface water, which is affected by topography and ground ice, provides even stronger negative feedbacks that make permafrost vulnerable to thawing even under cold temperatures."
Snow depth change shows **contradictory** signals (see Aygün et al, 2020)	**Increases:** Snow cover depth increased in Eurasia (0.4 cm per decade), Northern Russia (1.9 cm per decade) and Russia (0.64 cm per decade)	Zong et al (2018) examined 1814 Eurasian station observations from 1966-2012, Ye et al (1998) examined Russia and Northern Russia.
	Decreases: Snow depth decreased by 0.65 cm per decade in Canada	Vincent et al (2015) used climate synoptic station measurements from 1955.
Streamflow	From 1964-2016, substantial decrease for first half, and greater increase in second half: overall winter flows **increasing** and overall summer flows **decreasing** (with the exception of the most recent decade) partly **due to flow regulation**	Dery et al (2016) used observed station data from 42 rivers in Northern Canada. See also Koster et al (2017).
	Long-term increase in all NA and Eurasian rivers.	Moon et al (2021)'s Arctic report card.

Role of heat storage in lakes: one of the first order controls on heat storage in lakes is snow cover thickness, as it acts as an insulation (Solomon et al, 2007). Temperature-driven processes have starkly different time scales, especially in large lakes. Lakes store heat and the temperature varies by depth of water, so much so that in large lakes the temporal lag in air temperature to water surface temperature can be in the order of multiple months, while the ice response of lakes is nearly instantaneous when the temperature is above zero (Leopold, 2000). Austin and Coleman (2006) noted that summer water temperatures in Lake Superior are increasing at a higher rate than air temperature, signifying a positive ice-albedo effect. In a previous generation of works (Horton, 1927), water surface temperature was directly used to calculate evaporation, but in more recent methods, lake evaporation in large lakes such as the Great Lakes has been modeled with air temperature and a different structure that simulates the lake's thermal profile (Croley, 2012). Accordingly, the response of lakes to a changing climate may be largely dependent on the size of the lake (Croley and Lewis, 2006). The recent studies show that lake depth is inversely related to surface temperature in the warming phase of summer (early summer), and it is reciprocal in the cooling phase. This property of lakes is related to their thermal inertia, which is significantly higher than the surrounding ground masses and air. This is the reason why lakes exert a dampening effect on the climate.

Role of wind: in large lakes, evaporation is disproportionately high in the cold season, which is dominated by high winds and forced convection (Oswald and Rouse 2004).

Role of baseflow: baseflow from the lake happens when the ground heat flux between the lake and its bottom surface increases hydraulic conductivity. This depends to a great extent on the heat storage properties of the lake, and surface energy distribution (and ice phenology) mainly controlled by the depth of the lake, as well as the radiation budget at the surface of the lake. Smith et al (2007) and Jacques and Sauchyn (2009) have reported a growing importance of groundwater, i.e. an increase in Winter Baseflow from permafrost thawing.

Implications of lake changes

Lakes are well regarded as sentinels of climate change (Adrian et al 2009), since lake changes represent an early signal of larger future climate change impacts. Their implications for climate change are quite clear, as there is a potential for severe ramifications: a decrease in surface water bodies and permafrost, which leads to methane release, could trigger a feedback loop leading to even higher warming in the area and even higher methane emissions (Schuur et al, 2015; Schuur and Abbott, 2011). Local scale studies using field surveys have shown that lake expansion of 14.7% can cause as much as 58% of increased methane emissions in high latitude lakes of Siberia (Walter et al, 2006). But the exact mechanism of lake changes is still not quite clear in the existing literature, especially concerning the mutual influences and contradictions noted in the factors delineated above.

Permafrost and methane implications

Lake expansion from thawing of permafrost is concurrent with warming-increased methane emissions. Freshwater methane emissions are estimated to be 122 ± 60 Tg yr−1 (~20% of the total emission to the atmosphere, see Gunthel et al, 2019)

Most methane from lakes is emitted from thawing of lake margins, and between the 1970s and 2000, the methane emissions in certain Siberian regions have increased by as much as 58% (Walter et al, 2006), though such estimations may be relevant locally but not regionally due to poorly understood causal factors of methane production. This is evident in that estimates of methane in recent studies have been found to vary by a large magnitude. For example, studies reported that there are 1300 Pg of carbon in the permafrost region (800 is permanently frozen), which is estimated to be 300 Pg lower than previously thought in the Yedoma region of Siberia and Alaska (Hugelius et al 2014). The permafrost and peat soils of the ABZ are known to release methane when they thaw, and they are the largest global reservoir of terrestrial carbon, containing twice as much carbon as the Earth's atmosphere (Zimov et al, 2006; Schuur et al, 2008). But here again, there are contradictions in literature when we examine the reports of studies from Alaskan and Siberian studies with respect to the role of lakes in methane release.

Table 2.7: Lake change consequences: agreements and contradictions

Factors related to consequences of lake changes	Key agreements and contradictions found in literature	Primary citation, methods and spatio-temporal extent
Methane emissions: Lake-density related contradictions exist in	**High limnicity leads to large methane emissions:** In the fringes of lakes, cryoturbation is known to cause methane release, and estimates can be **5 folds higher** than previously estimated.	Walter et al (2006) used remote sensing, aerial surveys and year-round, continuous measurements of CH4 flux in North Siberian lakes. Katey et al (2007) show that methane bubbling from lakes is

estimations of methane emissions from lakes.		a **key contributor to global methane budget, as a source**.
	Low limnicity leads to large methane emissions: The largest emissions happen in dry regions (<5% limnicity) in Alaskan Tundra. **Cold season dominates methane emissions.**	Zona et al (2016) used eddy covariance flux towers and aircraft data from five eddy covariance (EC) towers along a 300-km latitudinal transect on the North Slope of Alaska.
	High lake area leads to higher oxic methane release (>50% from surface areas >1 km^2).	Gunthel et al (2019) studied one lake with mass balance. **Thermal stratification and littoral sediment area contribute** to methane emissions.
Lake benthos biomass	**Decreases** in the subarctic taiga [...] and **decreases** in the High Arctic.	Chertoprud et al (2021)
	Increases in the hypoarctic tundra	

The contradiction pointed out in Table 4 suggests a lack of fundamental understanding of how lakes contribute to methane release. The scientific significance of this is evident in soil-carbon feedback (whether positive or negative), which is closely connected with lakes. This carbon feedback is highly temperature sensitive and is one of the most important variables to be accurately represented to understand terrestrial carbon dynamics (Davidson and Janssens, 2006). Estimated magnitudes are off by large factors: Anthony et al (2010) conducted ice bubble surveys and accounted for ebullition seeps in Siberia and Alaska lakes. According to their study, lake methane is estimated to be 5-to 8-fold higher than previously thought. Despite such large fluctuations in recent estimates of methane, and numerous studies, the role of lakes in methane release in various permafrost conditions is still not well understood. However, due to the temperature sensitivity of carbon fluxes, it seems to be that heat storage estimations in lake models are of first order importance for its CO_2 and methane emission implications.

Approaches to understanding lakes

After understanding the evolution of climate change impact studies of lakes, it may help to gain a general overview of the ways in which lake change studies have been approached by scientists from diverse geo-science domains.

Hydrological perspective: Hydrologists and land surface modelers who have attempted to develop models of lake physics (Hostetler and Bartlein, 1999; Bowling et al, 2003, 209; Bohn et al, 2018; Subin et al, 2012; Goyette et al, 2010), and applied them to lake rich regions (Gao et al, 2010; Mishra et al, 2010a, 2010b, 2011a, 2011b), have resorted to process-based models that simulate lake energy and mass balance to represent lake processes.

Glaciological perspective: Lakes are intimately connected with the substrates on which they occur in the ABZ, most often permafrost (gelisols) in the Northern ABZ. Permafrost scientists, soil carbon researchers, cryosphere researchers, and glaciologists recognize the importance of lakes in the scientific questions they address. The primary of such questions in the ABZ is the role of cryoturbation in releasing carbon when lakes change. Cryoturbation essentially means frost churning, and refers to the mixing of materials from various layers of the soil down to the bedrock due to freezing and thawing processes. In the fringes of lakes, such processes are known to contribute to most of the methane release (Walter et al, 2006). It occurs to varying degrees in most gelisols, but has also been documented in the discontinuous permafrost region, and this is a primary mechanism by which methane is released into the atmosphere. It is a major concern due to the increasing dynamics of lakes in the Arctic, though the mechanisms are poorly understood and recent estimates suggest 5-8 fold higher quantities of methane than previously thought. It is hence of interest to understand the changing nature of lake occurence and other physical properties (heat storage, ice phenology, etc.) reviewed in this article, as such processes are poorly quantified in existing climate models (Subin et al, 2012).

Lakes of the domain considered here are primarily developed due to deglaciation. Remote sensing experts, geomorphologists, landscape and landform researchers have approached questions of lake changes from a perspective of terrain analysis considering hypsometry and bathymetry of lakes, which are fundamental in making lakes integrators of land surface signatures. Therefore, understanding these interconnections is important due to the requirements of lake bathymetry estimation which are needed for physical lake quantity estimations (volume, temperature, ice break, etc.).

Climatological perspective: Efforts have been made by climate researchers to utilize remote sensing approaches to back-calculate bathymetry by matching model-simulated lake temperature with remotely sensed observations, which seems to be a promising direction (Balsamo et al, 2009; Li et al, 2019). It is hence of interest to scholars from such a wide variety of fields to understand lake changes. Understanding the complex network of processes around lakes as reviewed in this article helps develop a holistic understanding of the physical processes that contribute to lake changes of varying time scales. The following sections will review how lake changes have been approached by different researchers to get a sense of how to develop a comprehensive understanding of Arctic lake changes. Visualizing the system in a graphical model will aid our comprehension of the lake hydrology system. A graphical model of the land surface processes that impact lake changes is presented below (Figure 1), drawing from the mechanisms of lake changes, causes and consequences examined from literature

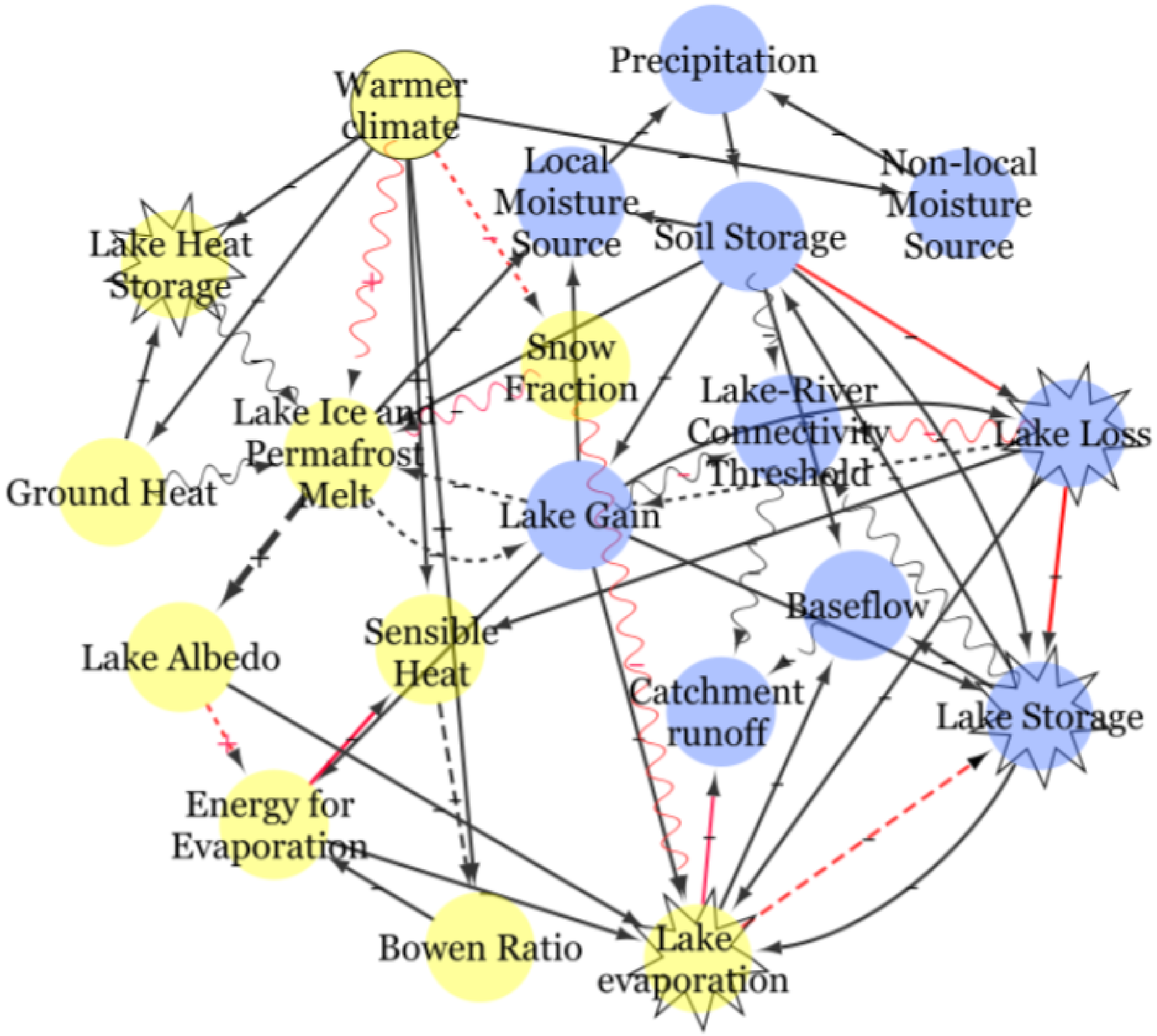


Figure 2.2: Lake-land-climate system

Red arrows show inverse relationship, black solid lines direct proportionality, sinusoidal lines are time lag effects. Yellow nodes are predominantly related to energy balance, and blue are related to water balance.

A warmer climate leads to reduction in ice cover and snow fraction (more precipitation would fall as rainfall). This reduces snow insulation effects of ice, leading to an increase in the penetration depth of shortwave radiation and to higher energy absorption by lakes (due to lower albedo). Ultimately, this causes a lowering of bowen ratio (increase of latent heat, i.e. evaporation). More evaporation may lead to shrinkage of the lake, and thereby reduction in lake area, which stabilizes the evaporation rate by reaching a new equilibrium. Lake storage non-linearly interacts with overall runoff by a threshold behavior (either by a fill and spill behavior or lateral breaching behavior), and also sub-surface flow paths (baseflow). This network of complexities, as one can appreciate from Figure 1, is impacted by both positive and negative changes to multiple intermediary variables which are quite complex to track. Hence a framework is needed to track the state of each of these variables simultaneously.

Evaluating competing hypotheses of long-term lake change

There are various climate fingerprints on lakes, especially in pristine lakes which can cause appearance, disappearance, increase, decrease, acceleration, and deceleration of lake area. The signatures that may underpin the role of climate change may be: local temperature trends (MAAT, DMAAT); local teleconnections with atmospheric processes known to be changing; ice break and formation date change - integrated signal; changes in periodicities of climate extremes (reservoirs); radiation budget change; correlations with warm and cold years and wet and dry years (predictable sign switching); albedo change. However, there are several factors that smudge the climate fingerprints on lakes, and they include the following: Simpson's paradox in time: sub-daily to seasonal to decadal scale changes; the equivalent of Simpson's paradox in space: spatial heterogeneity. Spatial heterogeneity of hydrological processes (evaporation, runoff, and soil storage) which led to unpredictable changes (McDonnel et al, 2007) or lack of understanding of organizing principles of lakes? An example of (1) and (2) is the two-stage process of lake expansion followed by contraction due to sub-surface leakage (Smith et al, 2005) is observed and verified locally, but does not generalize pan-domain; uncertainty in albedo from data products (upto 400%); ENSO and NAO, i.e. natural expected cycles of known periodicities; unknown source of moisture: perhaps accelerated or intensified water cycle (Yao et al, 2019). Is the poleward moisture transport responsible more than local evaporation (Britanja and Selten, 2014)? Is local moisture a contributor? Is the spatial heterogeneity of rainfall a dominant factor in the observed lake changes? Cloud phenology changes and its long-term trends. It will become clear to the reader that each of these questions is quite complicated to answer, and a search of literature would reveal contradictory claims which simply confounds our understanding of the causes and effects of lake changes. To make these questions tractable over a large domain, such as the one chosen here (Arctic Boreal Zone of North America), which may be different from the Eurasian Arctic, we should start with remote sensing observations of lake changes over a large continental domain. It is also beneficial to start with an assessment of remote sensing data to fully comprehend the various observed processes, before adopting models that can simulate such lake processes. In cases where the change direction is more persistent, what are the possible causes of disappearance? In cases of reappearance, what are the dominant causes? Are there tipping points in lake changes due to permafrost pathway (sub-surface leakage)? Can we see the signature of such tipping points in some lakes? How do we know that the lakes that disappeared are permanently drained (Smith et al, 2005)? Is it possible to ascertain their permanence (see the Padova river time series reference in Horton, 1927)? How do we attribute the change to possible causes to compare their relative significance? These questions require an approach to evaluate competing hypotheses starting from simple models and building up to complex ones, but a complex simple model would be one where the lake is isolated from the rest of the land surface. There are two pathways with this approach, either to soft-couple a lake model with a land surface model or to integrate it into the land surface model, but in either case, the first starting point where a lot of progress can be made is by isolating the lake from the rest of the land surface.

Isolation of lakes from the surrounding land surface

When utilizing models, it may be advantageous to treat the lake energy and mass balance without considering the rest of catchment hydrology as lakes are easily observable from space, and the catchment characteristics and heterogeneities are often too complex to be observed with similar accuracies. Therefore, the local land surface interactions should be deliberately omitted, except the inflow and outflow into the lake for what concerns external influence to the lake hydrological system. The advantage of doing so is evident in the fact that lakes possess well-known physical properties and constitute a homogeneous part of the land surface (Penman, 1948). These characteristics not only facilitate the characterization of lakes and tying them to observable data over a large spatial domain, but they also serve as a good proxy for inland climate impacts, as lakes are good proxies to detect climate signals. It may be beneficial for the purpose of clearing the contradictions found in literature to redefine our overarching questions into more specific questions that are easier to address: what are the quantitative changes in lakes and their regional distribution? What is the statistical significance of their long-term change? What are the key physical components of the hydrologic system that impact and are impacted by lake changes, i.e. what are the dominant mechanisms? What is the spatial and temporal scale at which the long term climate signal on lakes is truly reflected, e.g. can we observe evidence for water cycle intensification at regional scale or is the dominant moisture source poleward moisture transport? Can we see the signals of long term changes of mean in physical quantities with regards to lake changes?

The system should be representative of a large domain (e.g. continental scale) in order to distinguish the local scale changes in lakes from mesoscale processes. Any model that describes part of the system should reproduce trends that are statistically significant. To aid such confidence, the timescale of records should be long enough to warrant statistically sound conclusions. Moreover, the statistical power and confidence of the trend detection method, and how they change with signal to noise ratio change should be well known before diagnosing the causes of lake changes further. Regionalization of parameters needs to be considered in a scale that is commensurate with the spatial scale of the process modeled. Even if the entire system is not described, we need to whittle down and retain the critical parts of the system, which after being identified should be thoroughly analyzed and their uncertainties quantified. A natural question related to catchment characteristic is whether the trend is a result of local processes or more large-scale processes, i.e. do the trends hold far upstream. Another question is whether surface advection across the lake is more significant than vertical transport via evaporation. A lake classification system that separates lakes with and without network connectivity seems warranted as most dynamic lakes (>60%) have been reported to be connected to surface water features (Rey et al, 2019). If these specific questions can all be addressed, then we can conclusively test for climate change signatures in lakes.

Spatial scale to examine lake change processes

State-space representation and limitations of this approach: To address questions related to lake changes in a warming climate, one may take advantage of the framework of water and energy balance or budget, and a closed-system approach to understand the interactions of the various parts of the lake system. The main limitation of this approach to understanding lakes over a large domain is that the inputs and outputs are what define the scale at which the process can be conceptualized. While it is still possible to model smaller scale processes within, validation of internal processes is fraught with difficulties and is not easy to test over wide ranging conditions. In our case, the limiting resolution is about 0.25 degree (~500 sq.km and varies by latitude), as rainfall spatial heterogeneity over continental scales is generally only barely known down to this detail. Another problem is related to parameter estimation for the processes considered. Without accepting these limitations, it would be infeasible to diagnose the causes of lake changes over the domain we are considering here. While the scale of modeling should ideally be at the same scale at which the system can be considered to be closed (i.e. input minus output is zero), the spatial detail can still still be represented with much higher resolution (e.g. down to 30 m with landsat derived surface water data, see Pekel et al, 2016).

It has been shown that sub-grid topographic heterogeneity is lacking in current climate modeling efforts, even at km scale, so incorporation of hectare scale surface heterogeneity (if lakes can be used as proxy and the climate impacts of lakes can be quantified using the proposed remote sensing resolutions) significantly improves such models. Bohn et al, (2014) showed that methane emission estimates improved by over 30% by such considerations. There is a lot of room for scale considerations in modeling lakes within the context of land surface modeling. Especially in high latitudes, where there are numerous small lakes, the right modeling architecture to simulate their processes is still inadequately developed. In order to make progress in this direction, the appropriate scale for conceptualizing a lake model can be identified by considering the system limitations (noted earlier), and using a downward search to represent various features of lake changes suggested by Klemes (1983). There have been numerous studies and also a special issue dedicated to this topic in the hydrology literature (Sivapalan et al, 2003).

The same also applies for temporal scale, where one could start from annual variations and understand and explain observations well before moving onto seasonal, monthly, daily and diurnal variations of lake states and fluxes.

Data selection strategy to address confounding factors

To answer conclusively how lakes contribute to climate change impacts and vice versa (i.e. the causes and consequences of lake changes), we can take a few steps to make the problem more approachable. First and foremost, the goal is to gain a sufficient description of the lake hydrological system. Such a description should have the essential components, but details unnecessary for the spatial scale considered still need to be whittled down to isolate parts of the system that can be correctly examined to see signatures of climate change impacts. Second, the system should be identified as a closed one, such that the input and output is known to as great an accuracy as possible. Such identification is possible with careful selection of catchments where detailed gauges are available.

In order to identify the catchments that are best suited for the lake-catchment channel conveyance experiment, several additional attributes were computed (see Table 2.8) using three databases: Rain gauge data (AHCCD from ECCC), stream gauge data (HYDAT from ECCC), ABoVE hydrological fluxes (Vimal et al, 2019). We have demonstrated such selection in my recent work (Vimal et al, 2017) using objective criteria (see the two tables below for data and criteria for selection):

Table 2.8: Datasets identified for examining lakes changes over Canadian ABZ

	Variable *& purpose*	**Data source and primary citation**	**Derived** Yes/No
INPUT	**Meteorological model forcing:** *derived from CFSRv2 and validated with CRU and rain gauges from AHCCD*	ORNL-ABoVE monthly fluxes dataset; Vimal et al, 2019 (ORNL); Coccia and Wood (in revision)	Yes
	Permafrost: *used for overlay analysis.* Permafrost Region Pond and Lake database (PeRL, Muster et al, 2017)	Circumpolar Active Layer Monitoring (CALM) field data; Brown et al, (1997 & 2000);	No
METHODS	**Lake surface extents:** *used for lake min and max lake extent (bathymetry) & storage time series*	Pekel et al (2016): monthly history time series extracted from Google Earth Engine.	Yes
	Lake shoreline elevation: *derivative used for bathymetry.*	MERIT-DEM (Yamazaki et al, 2016)	Yes
	Lake area and size distribution: *vector dataset used to derive lake size distribution.*	Lakes Inventories: Sheng et al (2016); Verpoorter et al (2014); Downing et al (2006); also derived from Pekel et al dataset	Yes
	River network topology: *to identify lakes that span multiple grids and for selecting catchments.*	Canadian National Hydro Network (NHN, Coulibaly et al, 2013)	No
VALIDATION	**Rain gauge data:** *Data from ~2800 gauges were extracted. used to select catchments where error is negligible.*	Adjusted & Homogenized Canadian Climate Data (AHCCD), Mekis et al (2018) and CRU (Harris et al, 2014)	No
	Stream gauge data: *Data from ~6000 gauges were extracted in this study and used for model evaluation.*	HYDAT sqlite database from Environment and Climate Change Canada (ECCC).	Yes*
	Ice cover: *used for model evaluation.*	ICEsat, ICEsat-2, Cryosat, Song et al (2015)	No
	BERMS flux towers: *used for model evaluation.*	Chun et al (2014)	No

Selection criteria for identifying suitable sites: From the original ECCC stream gauge database, which contained 7832 stream gauges, the following criteria were used to select 150 ideal gauged catchments for lake studies in our study domain:

1. Only gauges that had published ECCC catchment shapefiles were considered. This reduced the number of candidate gauges significantly from 7832 down to 1565.
2. Of these gauges, the ones that had an unrealistic annual runoff ratio value (more than 1 or equal to 0 for any given year for which there is an overlapping data record of nearby gauged precipitation and streamflow) were removed. This happens when the shapefile delineated by ECCC is imprecise: 584 gauges had this problem. Most of these 584 catchments with incorrect area provided by ECCC were smaller than the true catchment area. After applying this criterion, the number of candidate gauges was reduced to 981.
3. Gauges that did not have even one year of overlapping precipitation and streamflow data recorded from rain and streamflow gauges were removed. This reduced the number of candidates to 959 gauges.
4. The next condition was to limit the gauges to locations where the precipitation forcing is as accurate as possible in the gridded dataset. In order to select such catchments, the percentage bias in the precipitation forcing was constrained to be less than 10%. This reduced the number of candidate gauges to 741 locations. Furthermore, the

correlation with the precipitation gauge was set to be above 0.8. This, together with other data quality issues, significantly reduced the candidate gauges from 997 to 150 gauges.

From this set of gauges, several physical features related to lakes and conveyance properties were derived. The range of catchment areas considered here seemingly does not impact the analysis: this was confirmed by examining the correlation matrix of the 18 climate and morphological attributes, where catchment area is not correlated with any of the other variables (it is unclear why this is so, where some correlation could have been expected, e.g. pbias vs correlation between gauges).

Table 2.9 (below) summarizes the attributes that were computed for all the ECCC gauges where detailed information was available, and from these, the aforesaid approach was used to select the most suitable catchments.

Table 2.9: Attributes considered to select catchments for lake change analysis

Attribute name	**Attribute definition**
Near_RainGage_ID	Gauge ID of the nearest rain gauge
Precip_Gauge_Distance	Distance to the nearest rain gauge
Correlation	Correlation between CFSv2 gridded data and the nearest rain gauge of AHCCD database
Precip_overlap_years	Number of years of overlap while computing correlation
Precip_overlap_start	Start year of when precipitation records overlap
Precip_overlap_end	End year of when precipitation records overlap
Catch_area	Catchment area (or effective catchment area if available) in sq.km.
Flow_overlap	Whether or not streamflow data overlaps with precip data (binary)

Flow_overlap_start	Year when flow data record overlap begins
Flow_overlap_end	Year when flow overlap ends
RR_mean	Mean Runoff Ratio
RR_min	Min Runoff Ratio
RR_max	Max Runoff Ratio
RR_std	Standard deviation of Runoff Ratio
mean_P	Mean annual precipitation (mm)
pbias	Percentage bias between rain gauge and gridded data
selected	Whether or not the catchment location is selected for lake change experiments (binary 1 or 0)

The modeling framework is essentially a system that decomposes widely available data of meteorological forcing (precipitation, daily min and max temperature, and wind speed) to create the various system components using semi-empirical formulae, physical equations of known land system processes, water and energy budget calculations, considering exchanges between the lake and its surrounding land-atmosphere components. Such modeling has two essential components of formulations: runoff and evaporation. Understanding the joint evaporation and runoff behavior is one of the primary goals of the land surface system modelers use to assess the impacts of climate change on hydrology. Several models exist to model lake fluxes, e.g. Community Land Model Lakes algorithm (Subin et al, 2012), NOAA's lumped-parameter Great Lakes continuous evaporation model (Croley, 2012), the Variable Infiltration Capacity macroscale hydrological model (VIC; Bowling and Lettenmaier, 2010). See Martynov et al (2010) for a lake model intercomparison project

(Lake-MIP). Evaporation formulation in models has received a disproportionate attention in model design (Koster et al, 2015), and yet the evaporation estimates of lakes are largely imprecise in such models (Mishra et al, 2010) when applied over large domains. However, when individual lakes are considered, most lake fluxes are well simulated (see Bowling and Lettenmaier, 2010). Vimal et al (2017) showed that using the VIC model, depth change of lakes can be simulated at daily time scale to within 10 cm lake depth accuracy over a 30-year period by considering various lake parameters and prescribed lake geometry. This was demonstrated in a few lakes, among which the results of Redberry Lake, Saskatchewan, Canada are shown below (see Figure 2). Modeling is often accurate if the lake geometry is known. A predominant issue is that over large domains, the storage capacity and bathymetry curve of the lake contains large errors (as much as 30% of volume for large lakes; Mishra et al, 2010). Despite decades of development of lake schemes within land surface and climate models (Bowling et al, 2010; Bohn et al, 2013; Subin et al, 2012), when applied to large regions, models have large errors and uncertainties (Koster et al, 2015). One of the main reasons why lake fluxes and model parameters are difficult to estimate is because the models do not account for the surface connectivity of lakes, advection and so on, nor lake size distributions, although it is well known that lake temperature storage properties change drastically with lake size (Subin et al, 2012). Ignoring such features, especially where there are numerous lakes, can lead to large errors.

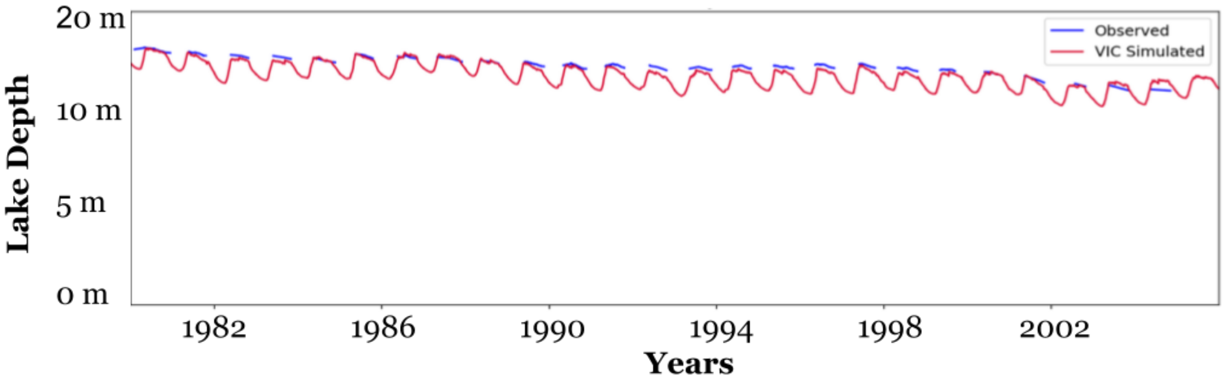


Figure 2.3: Model simulated lake depth at Redberry Lake, Saskatchewan, Canada

In Figure 2.3, the part of lake depth that is not observed is due to lake freezing in winter months. The graph shows only liquid water. Ice mass is saved as a separate variable (not shown here in this graph). One can see that the long term variations and the seasonal variations are reasonably captured by the model. Various model calibration techniques exist and have been demonstrated in cases of lake models (Bohn et al, 2018), but in practice, for models that include many parameters as the one used above, calibration should be avoided where possible in favor of observed data, ideally from remote sensing sources. While such level of lake modeling accuracy as shown above can be achieved in individual lakes, the same cannot be expected over the pan-ABZ domain, so once parameters are derived over the selected catchments, parameter transfer approaches can be used to transfer them to catchments with similar climate (precip, temperature), soil, and vegetation.

Uncertainties in lake parameters can be improved by model calibration. For instance, to achieve decimeter scale accuracy, in the specific case of Redberry lake

(Vimal et al, 2017), Shuffled Complex Evolutionary Algorithm (SCE-UA, Duan et al, 1992) was used with 1000 iterations. The same accuracy wasn't achieved with a new simulation of the same number of iterations, which shows that convergence of the lake model is not guaranteed (signifying existence of local maxima), so global optimization is quite intractable for the scale at which the lake process is modeled currently. This is an inherent limitation in the scale of modeling that we have used, which necessitates a change in scale. The high sensitivity of lake models to lake geometry parameters can be explained by the threshold behavior of lake overflow which is very hard to measure from space, and fill and spill mechanisms for large lakes can vary by large orders of magnitude. One can think of a lake with a large surface area which will suddenly overtop for a millimeter over the threshold for initiating channel runoff. Once that threshold is reached, the entire lake area contributes to flow instantly. One can imagine that estimating the threshold is a non-trivial problem for millions of lakes. These challenges imply that isolating the lake water balance from the catchment water balance could yield more generalizable results and quicker convergence.

As summarized in Table 1, most studies report bi-directional trends for their study domain. While the spatial distance between lakes that have opposite signs of change were not reported, there seems to be a necessity to estimate this quantity which might provide clues as to the nature of clustering of lake changes, which can help with understanding their mechanisms.

The work of Vulis et al (2019) seems to be an early attempt at quantifying lake changes by distance from channel network. An inherent disadvantage of land surface modeling framework is that it does not have explicit representation of individual lakes or even distribution of lake sizes. So alternate modeling frameworks that account for channel connectivity and distributed hydrology may perhaps be more appropriate for lake modeling, especially in places where seasonal impacts of channel connectivity becomes important like Arctic deltaic basins (see Vulis et al, 2019).

Summary of 10 insights drawn from this review

Due to the dramatic changes to ABZ lakes observed since the 1970s, understanding the causes and consequences of lakes is important to evaluate the terrestrial impacts of climate change in the Arctic. Before the satellite earth observation era, approaching lake studies was not tractable over numerous lakes and large spatial domains at the scales relevant for analyzing global climate impacts spanning many latitudes, while also accounting for local heterogeneities. However, since lakes have been well monitored from space since the 1970s, it is now possible to analyze numerous lakes in a single study. In this review, we have provided a synthesis of literature on lake changes in the ABZ by examining the trend magnitudes and uncertainties, as well as their causes and consequences. Our literature survey on lake change trends included several studies conducted in Alaska (sub-regions and latitudinal transects), sub-regions of Canada, Siberia, and continental Canada and Russia, over varying permafrost conditions. A substantial part of the review was dedicated to developing a good understanding of the lake's physical system components. Taken together, 10 key insights derived from this review can be summarized as follows:

1. **Bi-directional change is the rule and not the exception, and necessary but not sufficient, and uni-directional change is overused:** Lakes in nearly all places are both increasing and decreasing (see Table 1), and as such, one of the important recommendations suggested from this review is to choose a modeling architecture that allows representation of both these changes at the same time for any given region of analysis over the ABZ domain, such that unidirectional change is not attributed to lake changes. Examining bi-directional change is a good starting point to extend the current practice of viewing change as linear trends, though multi-directional change detection is needed, and robust change detection is needed.
2. **Hydrologic wet and dry periods are seldom considered and knowledge of periodicities of well-known phenomena are largely missing:** The idea of hydrologic wet and dry periods are not accounted for in most trend studies as this needs more careful consideration, and is partly the reason why the basic hypothesis in long-term change of lakes is still viewed in a unidirectional manner in individual studies, and explains the observations of (1).

This pattern of scientific reporting and investigation needs to change as it is not too helpful to understand climate change signatures of lakes.

3. **Simultaneous consideration of multiple hypotheses is needed to explain the change observations:** Under a certain time and spatial scale, when regionally unidirectional trends may be expected due to global warming, multiple hypotheses may co-exist for the same observation, and they have to be simultaneously evaluated. For example, the lake change mechanism reported by Jones et al (2013), previously discussed in Shah (2010) is a critical mechanism to examine further in all regions, i.e. when lake count increases together with simultaneous (co-occurring) but larger area of lake contraction, as it suggests that lakes may be drying and dividing into smaller ponds. This explanation seems equally plausible as the hypotheses of Yoshikawa and Hinzman (2003) (applied over a larger spatial scale in Smith et al, 2005) regarding subsurface drainage, though there isn't sufficient evidence to our knowledge in literature that weighed out these two alternative explanations for the same observation of expansion and contraction of lakes. Evidence that the Jones et al (2013) hypothesis corresponds to a smaller base rate (~5% of total lakes) than the predominant changes has been presented in other independent research in terms of the number of lakes involved, but still the water balance impact of such lakes was found to be dominant at ~60%. Umbanhowar et al (2013) write "Coalescence of water bodies could cause a decrease in number but not area, but we observed

only 80 water bodies that coalesced, versus 27 that split, representing <5% of the 1471 total recorded in 1956 for the eight sites". Another hypothesis for long-term change is evaporation driven desiccation of Arctic lakes and ponds, which has also been put forth as a mechanism that explains permanent lake change in the Arctic (Smol and Douglas, 2007).

4. **Systems approach is necessary, considering all feedbacks (positive, negative), coupling (weak and strong) and time-lag effects:** we need to diagnose the causes of lake change in a warming climate with an understanding of the lake physical system (Figure 1) in its entirety, as it includes several competing factors (positive and negative feedbacks to the same physical component) that can explain the direction of the potential multi-directional changes. Similar to the complex lake occurrence changes noted, we also identified contradictions in literature in observations related to physical quantities of lakes (lake temperature change and ice phenology change), as well as causal factors for lake changes. We then examined contradictions in observation vs theory in some of these factors. Most noteworthy among these is the observation that precipitation increased in the ABZ, though the source of moisture is still unclear: it could be polar moisture transport due to global atmospheric circulation, or due to local moisture sources caused by increased local evaporation. Some studies also report that precipitation trends are negligible and not statistically significant as temperature or lake change trends.

Therefore, understanding the precise climatological causes of lake change (e.g. regional precipitation or evaporation changes) in a warming climate seems to be a promising area of investigation.

5. **Data selection procedure is important (especially reporting the distance to rain gauge):** The data selection procedures and modeling resolution limitations noted in this review could help identify a set of sites for conducting robust scientific experiments before translating to a larger domain over millions of lakes at Landsat resolution. Such selection of sites and data can help conclusively eradicate some of the confounding factors observed in literature, especially for what concerns catchment hydrological aspects of interpreting lake changes.
6. **Modeling and parameter transfer:** From the model results demonstrated in our previous work, we have suggested changes to conceptualization of lake modeling, moving from catchment scale to a smaller scale of lake water and energy balance scale to help identify lake parameters that can be estimated more directly. Once parameters are derived for carefully chosen catchments, they can be transferred to other regions with similar physiological properties where gauge observations are lacking.
7. **Scale of hydrologic analysis should be chosen non-arbitrarily and assumptions about the scale choice should be stated explicitly:** Some limitations and scale considerations were discussed, and 0.25 degree was

suggested as a reasonable scale limit based on accuracy of gridded rainfall products (Vimal et al, 2019) to run land surface models. This is essential to achieve a closure in water balance, where the inputs are known (and assumed to be uniform at the governing scale).

8. **Simple modeling frameworks can be examined:** In addition to the systems modeling approach suggested, one other framework which we suggest involves concepts of demand and supply of energy and water, which are interrelated, and they each have bounds which can be estimated with existing climate data at the suggested scale. Literature is lacking in this area with regards to lake studies, though there are numerous catchment scale hydrological studies in the hydrology literature, so to fill this gap, the widely used budyko framework (see Budyko, 1971 and Choudhury, 1999) could be considered.
9. **Modeling complexity should increase in stages from low to high:** Once some basic understanding is developed at a coarse climatological scale, we can move on to finer and finer scales, from climatological to decadal to annual to seasonal, following a downward search approach as suggested by Klemes (1983). The same goes for modeling: one can start with a simple graphical model of the system (one based on literature on lakes was presented here in this review, before moving on to data driven assessments, climatological scale assessments with Budyko framework, and eventually land surface modeling or distributed modeling framework (MODWET, Margulis, 2000). Doing so would force one to

rethink structural issues in models and bear in mind to design as simple a model as possible to examine the system of interest and fully simulate critical interactions. A well-constructed lake model would have the following factors that are well-characterized and at the appropriate scale where information is available.

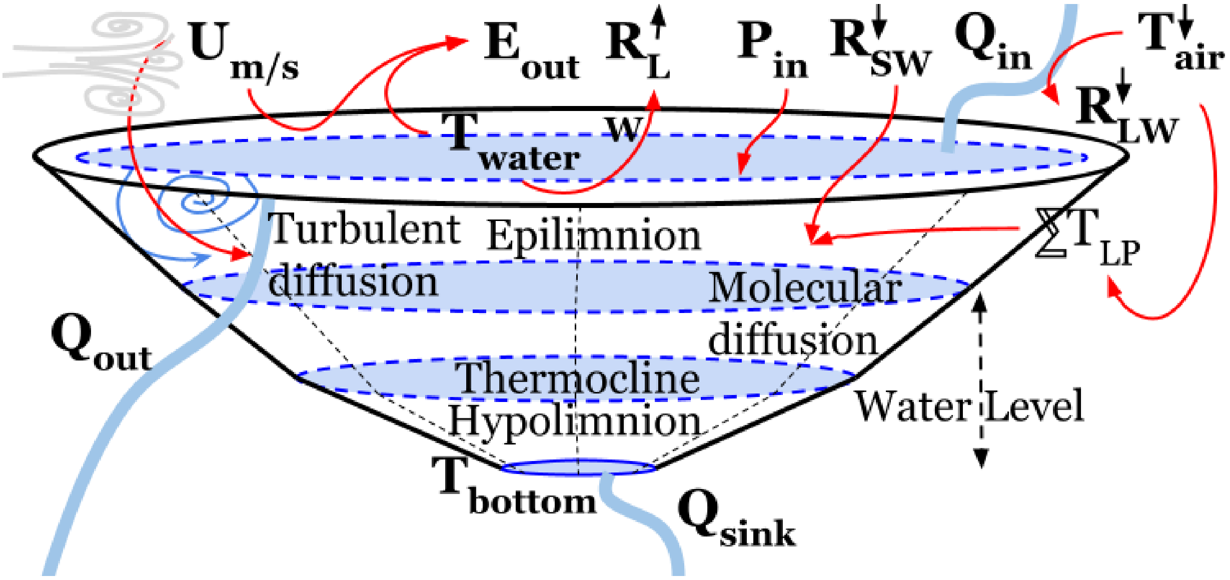
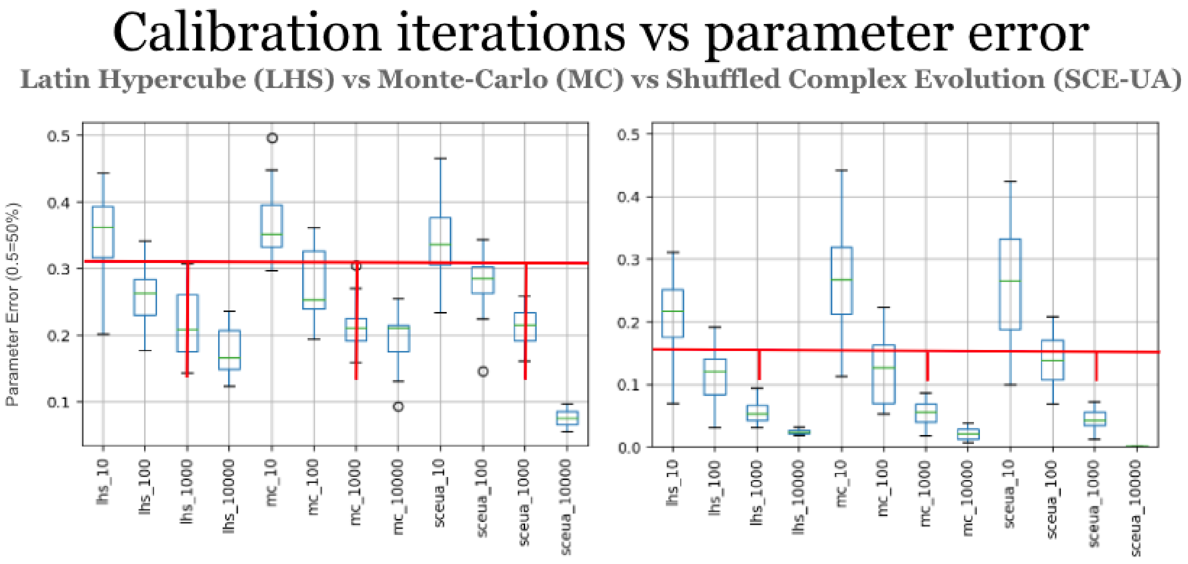


Figure 2.4. Lake Model for evaluation of long-term climate impacts of Arctic lakes.

Heat exchange in lakes, R_{LP}, due to T_{LP} (temperature exchange at the perimeter of the lake) for all lakes within a chosen domain area can be written as: $R_{LP=}\sum_{lake=1}^{n} P_{lake}\,\delta_{lake}\,R_{ground}$, where, δ-lake is a dirac function {1,0} term of lake connectivity within the grid cell (e.g. a 0.25 grid can have 1000 lakes within) and can be approximated with NASA's 10-day AMSRE data (Kawanishi et al,

2003) with calibration to represent connectivity as a function of aggregated wet and dry periods. P_{lake} is the perimeter of each individual lake; R_{ground} is the energy exchange in the lake-land interface. Heat exchange in this interface is responsible for frost churning (cryoturbation) which leads to methane release, and this is an important process to characterize accurately.

Calibration experiments with models show that among Latin Hypercube (LHS), Monte-Carlo (MC) and Shuffle Complex Evolution (SCE-UA), SCE-UA does disproportionately better if the number of iterations is very large (order 10,000), but is not appreciably better than simpler methods for smaller iterations in a 9-parameter model.



9-parameter model

3-parameter model

Figure 2.5. Calibration and number of iterations

Over parameterized models suffer from this calibration problem and do not scale well to large numbers of locations. To achieve a 0.05% accuracy such a large number of iterations is needed, but lake parameter sensitivity is often in the range of 0.0001 due to scale effects, if the lake is not isolated from the rest of the land surface. This is why isolating the lake is recommended.

10. **Threshold processes are aplenty in water balance but seldom modeled correctly:** Two key threshold processes are sub-surface sinkholes (Martinez et al, 1998), an abrupt process that develops in the order of days, and network connectivity for its control on seasonal dynamics, and river connectivity, which seems to exhibit a strong control on ABZ lake changes (Rey et al, 2019). This can be addressed by adopting a distributed modeling approach which enables explicit characterization of fill and spill mechanisms (Coles and McDonnell, 2018) in individual lakes, lake connectivity (Woo et al, 2007) and network control on seasonal dynamics (Vulis et al, 2019).

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3
Physics of lake evaporation

This chapter, from which a paper has recently been published (Vimal and Singh, 2022), discusses the question of how to correctly estimate lake evaporation, a critical process that allows us to understand the response of Arctic lakes to changing climate conditions. The work focuses on a century-old overlooked open water evaporation formula credited to Robert E. Horton. We show that this method improves evaporation estimation by 5-50% (seasonal to sub-daily). The improved method allows us to assess the changing character of Arctic lakes over the pan-ABZ domain (as done in Chapter 3) using widely available meteorological data.

Abstract

Evaporation from open water is among the most rigorously studied problems in hydrology. Robert E. Horton, unbeknownst to most investigators on the subject, studied it in great detail by conducting experiments and heuristically relating his observations to physical laws. His work furthered known theories of lake evaporation, but it appears that it got dismissed as simply empirical. This is unfortunate, because Horton's century-old insights on the topic, which we summarize here, seem relevant for contemporary climate change-era problems. In re-discovering his overlooked lake evaporation works, in this paper we: 1) examine his several publications in the period 1915-1944 and identify his theory sources for evaporation physics among scientists of the late 1800s; 2) illustrate his lake evaporation formulae which require several equations, tables, thresholds, and conditions based on physical factors and

assumptions; and 3) assess his evaporation results over continental U.S., and analyse the performance of his formula in a subarctic Canadian catchment by comparing it with five other calibrated (aerodynamic and mass transfer) evaporation formulae of varying complexity. We find that Horton’s method, due to its unique variable vapor pressure deficit (VVPD) term, outperforms all other methods by ~3-15% of R^2 consistently across timescales (days to months), and an order of magnitude higher at sub-daily scales (we assessed up to 30 mins). Surprisingly, when his method uses input vapor pressure disaggregated from reanalysis data, it still outperforms other methods which use local measurements. This indicates that the vapor pressure deficit (VPD) term currently used in all other evaporation methods is not as good an independent control for lake evaporation as Horton’s VVPD. Therefore, Horton’s evaporation formula is held to be a major improvement in lake evaporation theory which, in part, may: A) supplant or improve existing evaporation formulae including the aerodynamic part of the combination (Penman) method; B) point to new directions in lake evaporation physics as it leads to a “constant” and a non-dimensional ratio - the former is due to him, John Dalton (1802), and Gustav Schübler (1831), and the latter to him and Josef Stefan (1881); C) offer better insights behind the physics of the evaporation paradox (i.e. globally, decreasing trends in pan evaporation are unanimously observed, while the opposite is expected due to global warming). Curiously, his rare observations of convective vapor plumes from lakes may also help explain the mythical origins of Greek deity Venus and the dancing Nereids.

Introduction

The problem of accurate lake or open water evaporation estimation has been a subject of scientific inquiry, in the modern sense of combined experimental and theoretical study, for the past four centuries. Factors that control evaporation have been investigated since the time of Edmund Halley (1687) with rapid progress in theories of thermodynamics, aerodynamics (turbulence theory), and molecular kinetics (kinetic theory of gasses) that led to better understanding of evaporation due to wind's influence, convection, and diffusion. Brutsaert's treatise on "Evaporation Into the Air" provides an overview of concepts that evolved from antiquity (Brutsaert, 1982, Chapter 2). From the 1700s, key contributions have included those of Johann and Daniel Bernoulli (1700s); John Dalton, Rudolf Clausius, Osborne Reynolds (1800s); the celebrated voyage through turbulence theory (Davidson et al., 2011) from European, American, and Russian schools, among others, especially as data of field experiments on surface winds and diffusion became increasingly crucial for chemical warfare efforts over the course of the 20th century (Sutton, 1953). More recent developments include the recognition of the complementary principle of evaporation in the late 1900s (Bouchet, 1963; Morton, 1994; Brutsaert, 1982) and the evaporation paradox (Roderick and Farquhar, 2004) which have large implications in climate change debates.

Robert E. Horton, a pioneer in hydrology, well-regarded for his contributions to areas of hydrology like infiltration, overland flow, and river geomorphology, is not usually considered a fundamental contributor to the field of evaporation. However, unbeknownst to most in mainstream evaporation theory, tucked away in his home-based experimental catchment beside a pond, Horton conducted rigorous experiments and theoretical work on open water evaporation from the 1910s until the end of his career, circa 1945. In particular, in 1917 he published a set of formulae for estimating evaporation (including within lake variations of evaporation) based on physical laws which he believed were more robust than the then existing methods. The sub-text to the title of his first 1917 paper claims:

> "Empirical Statement Based on Physical Law Agrees with Observed Facts and Is Held To Be an Improvement Over Existing Formulas" – Horton (1917a)

He held the view that his equation was superior to other known methods for the following decades, even in the face of rapid developments in evaporation theory in that period (e.g. see Horton, 1934). After we examined several of Horton's papers and reports related to evaporation from lakes and pan evaporimeters (or simply, pans) from 1917 to 1944 (the year before his death), we noted that he derived his formula theoretically, but since the values of the coefficient in his formula were not easily available, and his formula resembles other empirically derived formulae, several investigators may have dubbed it as simply empirical (see Rohwer, 1931). However, Horton's nuanced understanding of the boundary layer physics of his time (turbulence theory, horizontal vapor transport via laminar flow, convective transfer of vapor, wind and vapor blanket characteristics), and the sound premise of his work based on molecular kinetics, reveal the potential of his work to offer new insights for an improved formulation of evaporation. The theory behind his work is illustrated in Sect. 2. After evaluating Horton's evaporation formulae (in Sect. 3), we find that his claim of having developed an improved method not only stands to be true in his time, but also holds great contemporary value, and it is unfortunate that it has been largely overlooked or forgotten. Therefore, in this paper we examine his evaporation work from the perspective of contemporary theories as well as those of his time to highlight his ingenious perceptual, experimental, and theoretical insights into the subject. We revisit his claims, replot his figures with recent data, simplify the use of his experimental tables (by converting them to parametric forms), assess his method's ability to generalize across wide-ranging conditions, and show the relevance of his method for contemporary large-scale evaporation problems.

Horton's broader contributions and bibliography

Hydrologists need no introduction to some of Horton's contributions like infiltration theory, overland flow, geomorphological laws, etc. What may not be widely known is that he published an estimated 200 papers and reports, mostly single authored (~90%), but of these, only about 80 works are available from readily accessible sources (Hall, 1987). Horton's unpublished works are held at the U.S. National Archives in College Park, Maryland (cataloging and organization was done by Walter Langbein). A subset of his archive is also held at his alma mater Albion College (Accavitti, 2019). In the last few decades, Dr. Keith Beven from Lancaster University and Dr. Jim Smith from Princeton University examined a portion of the archive contents and presented their findings via publications (Beven, 2004 a, b, c) and an AMS Horton lecture (Smith, 2010).

About 80 of Horton's contributions were provided by Hall (1987) and curated by the AGU Virtual Hydrology Project (see Foufoula-Georgiou, accessed 2021-05-19). A more complete list of Horton's works was collated by Dr. Elizabeth Clark, which includes ~135 works, for an American Meteorological Society (AMS) Horton Lecture delivered by Dr. Dennis Lettenmaier (Lettenmaier, 2008). Combining these lists and conducting additional searches, the first author collated 168 works, the most comprehensive list of Horton's works available to our knowledge. Years and titles are shared in Supplementary.

Horton's lake evaporation method and related projects

About a dozen of Horton's papers and reports are related to his evaporation method and supporting ideas, but one can get a full understanding of his published contributions on lake evaporation from four key publications: Horton (1917a, 1927, 1934 and 1943b). Horton's evaporation method was first introduced in Horton (1917a), as part of a three-paper series (Horton 1917a, b and c) in *Engineering News-Record* for the purpose of improving waterpower, water-supply and irrigation projects. The larger goal of the three papers was to reduce errors in estimates of stream yield, especially to get accurate estimates of low flows to ensure the success of hydraulic (water supply) projects. This goal necessitated reliable evaporation estimates, leading Horton to developing his own method to calculate it. The tables needed to implement his method were not published in entirety in Horton (1917a), but only in a later report on Great Lakes a decade later (Horton, 1927) which was a major project in his career involving a rigorous procedure for lake evaporation estimation among a broader hydrological study of the Great Lakes. This work was conducted in collaboration with C.E. Grunsky, and was an extensive 432-page report. The central innovation of this contribution is that prior to this work, it was not possible to achieve correlations between discharge and lake levels which are impacted by a variety of natural and artificial causes. A substantial portion of the report is a presentation of available data related to the hydrology of the Great Lakes and the remaining is an analysis of various aspects of the water balance (precipitation, runoff, evaporation) including 142 tables and 73 figures. In another paper 7 years later, Horton (1934) provided more theoretical insights into his evaporation method with some explanation of its physical basis. Besides these major works on the evaporation method itself, projects where he discussed or estimated lake evaporation spanned earlier and later times in his career: e.g. in Horton (1905), he discusses evaporation and water balance in the context of small kettle ponds, and in Horton (1944), he did so in the context of a dam design for the Hemlock lake system. As a final point to contextualize his lake projects, it is worth noting here that Horton's experimental catchment beside his house included a pond about 200 meter long and 60 meter wide (a figure is provided in Horton, 1919a) where he conducted some key evaporation experiments and interesting observations (we revisit this in Sec. 7, Closing Note).

Previous examinations of Horton’s lake evaporation method

The various above-mentioned works related to lake evaporation have been cited sparingly which shows that they were largely overlooked. They have not been collectively examined in any previous work to our knowledge, and in the few citations to them, the value and sophistication of the method was not recognized. Horton’s lake evaporation equation received some attention in Chow’s Handbook (in Sect. 11 on evaporation written by F. J. Veihmeyer; Chow, 1964). Horton’s formula is surprisingly not included in Brutsaert’s treatise (Brutsaert, 1982) which has ~650 citations of evaporation-related works, though his work on evaporation pans has been cited, referencing standardized class-A pans. The equation was cursorily reviewed in a few recent studies. McMahon et al (2016) cite the equation (presumably taken from Chow, 1964) as part of a larger review together with other evaporation equations. Singh and Xu (1997) evaluated Horton’s evaporation equation in comparison with 12 other (mostly) empirical equations that resemble it, but incorrectly, in the sense that the vapor pressure deficit (VPD) was multiplied with the wind factor, whereas for correct use of Horton’s equation the wind factor is to be multiplied with vapor pressure of water, and not the total deficit - a fundamental difference between his method and other methods (as will be explained in Sections 2 & 3 in more detail). As inferred from citations to his key evaporation paper (Horton, 1917a) via Google Scholar (accessed, April 29, 2021), few investigators from Russia and Portugal have examined his evaporation work, and one particular work from Japan (Siomi and Yosida, 1940) seems to have examined Horton's equation in some detail, but not as comprehensively as we undertake here. All these works do not account for the full complexity of his approach: for comprehensive use of Horton's lake evaporation method, about 20 equations and two tables are needed (Sections 2 & 3). One of these tables was not very accessible, as it was published in a report (Horton, 1927) which presumably was not so widely circulated as an academic journal, which we believe may have led to the limited use of his method.

Mainstream evaporation works in Horton's time

For the context of works preceding Horton's time, interested readers are ushered to an excellent contribution by Grace Livingston published as 8 pieces in *Monthly Weather Review* between 1908 and 1909 and later compiled into a book (see Livingstone, 1910). This annotated bibliography includes ~850 works on evaporation from late 1600s up to the early 1900s, lists 155 publication outlets, and was translated from multiple world languages (Japanese, French, Italian, German, Russian, among others). It is possible that Horton considered his equation as an improvement over other evaporation formulae presented in this review. Horton did not cite this bibliography in any of his evaporation papers, but there are multiple reasons to speculate why he might have examined it: 1) many of Horton's works were published in the same journal (*Monthly Weather Review*); 2) he followed an unconventional citation style and often included no reference lists in his papers (e.g. see Horton, 1917a); 3) Mrs. Grace Livingstone was the ex-wife of a plant physiologist, Burton E. Livingston, whose work on evaporation Horton certainly followed (Horton, 1927); 4) the compiled book format of the annotated bibliography (Livingstone, 1910) was available at the Weather Bureau Library in Washington and John Crerar Library in Chicago, places that Horton presumably frequented due to their proximity to the work he did in Chicago and his engagements with members and initiatives of the Weather Bureau (Horton, 1927); and finally, 5) most, if not all, of the theoretical sources that Horton's evaporation method relied on (discussed later in see Sec. 1.5) appear in one place in Livingstone (1910).

Horton's evaporation method was apparently developed and used in New York, Michigan and Chicago (see Horton, 1927), but in the same time period many similar efforts were underway throughout the United States (presumably in other countries too). Three such works are worth highlighting: 1) The thermodynamic approach using Le Chatelier's principle applied to energetics was undertaken in California at the *Scripps Institute of Oceanography* and *California Institute of Technology*, which led to the energy balance solution of lake evaporation, and the Bowen ratio (Bowen, 1926). Subsequent works by others that picked up on this work are summarized in a succinct compendium by McEwens (1930) and a historical summary by Lewis (1995). 2) A review of mass transfer and energy balance based evaporation studies on Lake Hefner resulting from collaboration between several *U.S. agencies: Geological Survey*, *Department of Navy*, *Bureau of Ships*, *Navy Electronics Laboratory*, *Department of Interior*, *Bureau of Reclamation*, *Department of Commerce*, and *Weather Bureau* (USGS, 1954). 3) A statistical attack on the problem led by geophysicist J. F. Hayford, who notably spent over 2000 hours developing a superior method, including a mammoth effort by 41 persons who collectively spent some 32,000 man hours on this work (Folse, 1929, p. 7). The method uses temperature and humidity of the preceding day to calculate the following day's evaporation, and includes a large system of equations with many free parameters, which is optimized to minimize error (for more details see Folse, 1929). It was developed for the Great Lakes, and did perform reasonably well there, but generalized poorly in other lakes, and did not gain wider attention (see critical review by Bernard, 1936). These highlight some of the various independent efforts dedicated to calculating evaporation around the time when Horton's method was developed.

Horton's main sources for theories and experiments of lake evaporation physics

Citations provided in Horton's work show that he relied on the works of several European scientists for concepts related to the physics of evaporation. He did examine several empirical equations developed in the US (see Horton, 1934), but he does not appear to have followed the works conducted by Bowen and Cummings (Bowen, 1926).

Perhaps this is because Bowen's works appeared in *Physical Review*, while Horton published his works in *Monthly Weather Review*. Moreover, Horton's approach differed in that it was premised on aero-hydrodynamics and kinetic theory approaches which were developed mainly by European scientists.

A molecular kinetics view of evaporation is fundamental to his approach, and he developed this view mainly from John Dalton's theories and experiments on evaporation of water and other chemicals (Dalton, 1802). Dalton's work was in fact the only work that he directly cited when he first published his evaporation paper (Horton, 1917a), though with a closer look through his later papers (Horton, 1927 and 1933), it does appear that he developed his method by building upon multiple works. It appears that he studied: Thomas Stevenson's (1882) work on wind speed variation by height, while conducting his own experiments on the role of wind on evaporation (see Horton, 1927); Geoffrey I. Taylor (1918) for the role of turbulence and vapor blanket (Horton, 1934); Napier Shaw's *Manual of Meteorology* (Shaw, 1932) and Julius von Hann's *Lehrbuch Der Meteorologie* (von Hann, 1926) for work on Psychrometry (see Horton, 1934, and also Horton, 1921, though no citations are provided in the latter); Thomas Tate (1862) for laws of evaporation; Josef Stefan (1881) for water surface's geometric controls on evaporation and also perhaps the role of vapor blanket in turbulent and convective transfer of vapor from large and small water bodies. Stefan is cited in Horton (1934), but Stefan's work may have also inspired his equations in Horton (1917a) due to their resemblance. A reference to a Chemistry book he read in his youth (from his short story collection, see Horton, 1938) can be traced to *"A Dictionary of Chemistry"* by James Watts (Watts, 1882) wherefrom Horton learned about a sampling method to collect combustible marsh gasses from shallow ponds and lakes. In a posthumous work on convectional vortex rings (Horton and van Vliet, 1949), he uses P. G. Tait's acid experiment to understand convection (Tait lecture, 1878, referenced in Dolbear, 1894 and Risteen, 1896) which gives one a mental picture of how he viewed convective evaporation from lakes. From these references, we can see how his Physical Chemistry knowledge developed over the course of his life.

His references also included American textbooks, two in particular: Allen Risteen's *Molecules and Molecular Theory* (Risteen, 1896) and Amos Emerson Dolbear's *"Matter, Ether and Motion"* (1892). Risteen's work is cited in Horton (1934) where his evaporation formula is discussed in more detail than in previous papers. It appears that Horton's collaborator van Vliet, who published Horton's work on convectional vortex rings posthumously (Horton, 1949), misspelled his reference to Dolbear as Dalhaer (perhaps a transcription error). These American textbooks referred to theories developed in Europe by Rudolf Clausius and a treatise on Kinetic Theory of Gases (Watson, 1876). Watson's work on kinetic theory, in turn, credits the origin of these theories to Johann Bernoulli, James Clerk Maxwell, Rudolf Clausius and Ludwig Boltzmann. Most of these scientists were aerodynamicists, physicists, and chemists. Notably, Dolbear was not only a physicist but also a pioneering inventor who competed with Alexander Graham Bell at the Supreme Court of the U.S. for priority on the patent of the telephone (his claim was that he invented it 10 years earlier, but he lost the case). Nearly all of these books are available for free from Google Books (full reference and hyperlinks are provided in the reference list).

Premise of Horton's evaporation formula

Before we delve into the details of the evaporation equation, a quote from Horton contextualizes how he supposedly viewed his evaporation formula:

> "A rational equation may be defined as one which can be derived directly from fundamental principles, which fits all the experimental data and which represents the physical conditions correctly throughout the entire range of their occurrence and hence is valid outside the range of experimental observation" – Horton (1941).

Some fundamental principles he alluded to in his evaporation formula are related to thermodynamics (i.e. work done in phase changes, latent heat), and they include references to geometric proofs of the same from the perspective of kinetic theory drawn from Risteen (1896), discussed in Horton (1934). More importantly, the premise of Horton's fundamental principles in his evaporation method is the kinetic theory of gasses (Loeb, 1934) which he explicitly stated in Horton (1917a). His molecular kinetics view of evaporation is best captured in the following quote:

> "In a mixture of air and water-vapor there is a certain number of vapor molecules per unit volume. When there is wind the air and vapor are swept along together at a rate depending on the pressure-gradient. This, as in case of hydraulic flow, is independent of the total pressure. At a given vapor-pressure the same amount of vapor is carried by

> the wind per unit of time and per unit of volume of air, whether the number of air molecules per unit volume is large or small." – Horton (1934).

Horton considered the movement of molecules and their behavior at the surface of the lake as three key processes: 1) vapor emission, 2) vapor removal (by diffusion, convection, and wind action), and 3) vapor return. These processes are discussed in multiple papers (Horton 1917a and 1934). It may benefit the reader to review these three processes in some detail before introducing the evaporation equations.

Vapor emission and vapor return

Horton's first paper on evaporation (Horton, 1917a) does not discuss the thermodynamic perspective, but his derivation of the various parts of the evaporation equation does use the underlying principles, as exemplified in the following quote:

> "[Latent heat] comprises of two elements: (1) Internal work in overcoming molecular attractive forces which, in general, including viscosity and surface-tension, increase as the temperature decreases, and the latent heat of internal work also increases as the temperature decreases; (2) the external latent heat, which measures the work done by the emitted vapor in expanding against the external pressure, decreases slightly as the pressure on the liquid surface decreases with decreased boiling temperature, but the total latent heat increases slowly as the temperature decreases." – Horton (1934)

He examined these thermodynamic factors to identify the role of pressure in impacting vapor emission and vapor removal. While pressure does affect vapor emission rates due to external latent heat, it is negligible, so the impact of pressure on evaporation can be attributed to vapor removal (somewhat like a proof by elimination).

Vapor return is controlled by wind action (which is non-linear) and the vapor pressure of the overlying air or the *vapor blanket*, i.e. a thin layer of vapor just above the water surface analogous to viscous sub-layer in open channel flow. The characteristics and role of vapor blanket is discussed separately in more detail in the following sections.

Vapor removal

Vapor removal, as previously stated, happens due to diffusion, wind action and convection.

Diffusion

Horton's conception of evaporation via diffusion is perhaps drawn from Dalton's (1802) original work which is the only reference he cites when he first published his lake evaporation formula in Horton (1917a). Dalton posited:

> "Evaporation [...] is caused by *vis inertiae* of the particles of air; and is similar to that which a stream of water meets with in descending amongst pebbles [...]. From a great variety of experiments [on evaporation,] I have found the results entirely conformable with the above theory [...] – Dalton (1802, pp. 581-584).

The rate of diffusion is governed by water temperature (for vapor emission rate) and barometric pressure and vapor pressure of air (vapor return rate), and is not explicitly affected by wind action or convection (Horton, 1934).

Wind action

According to contemporary evaporation literature (see Brutsaert, 1982), wind can have two effects: 1) turbulence transfer of vapor away from surface; and 2) advective (bulk fluid mass) transport due to mean horizontal wind. In Horton's work, wind action is considered separately as a bulk exhaustion process that removes vapor at a maximum rate equal to the rate of vapor emission. The rate of wind action in Horton's work is based on Dalton's observation:

> "[Dalton] found that a strong wind made the amount of evaporation double that taking place in still air. He concluded that the increase in evaporation rate was proportional to the wind velocity" – Horton (1917a)

Evaporation by horizontal advection seems to be included in Horton's conceptualization of wind action (it is considered indirectly), where for a given elemental area, the vapor pressure of water is amplified by the wind up to a limiting value, which indirectly accounts for the rate of vapor removal by advection and turbulent transfer: they are not differentiated.

Convection

It may help the reader to first disambiguate the term convection as it is sometimes used interchangeably with advection (e.g. convection-dispersion equation/advection-dispersion equation). Convection normally refers to heat transport via vertical plumes in fluids when wind shear is overcome by thermally driven buoyant production of kinetic energy, while advection normally refers to transport of quantities (heat or matter) due to mean horizontal flow of wind (see Hess, 1979; Stull, 1988; and Eagleson, 1990). Horton's usage of the term convection does share similarities with the common parlance in turbulence theory pertaining to heat transport, i.e. convection happens due to expansion from surface air heating as well as vapor addition which causes a reduction in density (as the bulk air is heavier than moist air) which result in instability. Convective plumes are fed and sustained by laminar wind that feeds moisture horizontally into it, and continues until the buoyant force overcomes the shear force due to horizontal wind. It is sustained until the moisture available to feed the plume is depleted. This conceptualization of convection is not clearly described in Horton's evaporation papers, but we inferred it from the following quote in his paper (Horton, 1933) on columnar vapor drift (a mechanism of evaporation):

> "In the eerie morning hours [...] vapor columns present a spectral appearance as they travel slowly over the water surface, resembling sheeted ghosts or white-robed whirling Dervishes walking on the water. [...] Obviously columnar vapor drift [also amorphous vapor drift] is a visualization of convective vapor removal from a water surface during evaporation. [...] A vapor column forms wherever a sufficient degree of instability develops through the warming of a layer of air close to the water surface and through the accumulation of water vapor (which is lighter than air) therein. A vapor column is fed by horizontal flow of air and vapor toward it close to the water surface. Apparently it grows until its feeding area encounters another area from which the vapor has already been exhausted or until the frictional resistance of horizontal flow balances the vertical convective forces" – Horton (1933)

Horton regarded convection as a *rheologic* system, i.e. a flow process with solid and fluid characteristics, typically in response to forces (in the case of evaporation, as pressure over a unit elemental area). In the following quote, his view of convection as a rheologic system is clearly stated:

> "The ordinary, vertically convective system [...] may be considered hydrodynamically as a rheologic or flow system, resembling the flow through a vertical pipe connecting two reservoirs, with lower pressure in the upper reservoir. This may be called the tubular type of vertical convection." – Horton (1949)

While numerous physical factors were taken into consideration in his understanding of evaporation, to get a mental picture of Horton's conceptualization of processes that govern evaporation, the schematic below (Fig. 1) may serve as a graphical summary of the key processes related to evaporation.

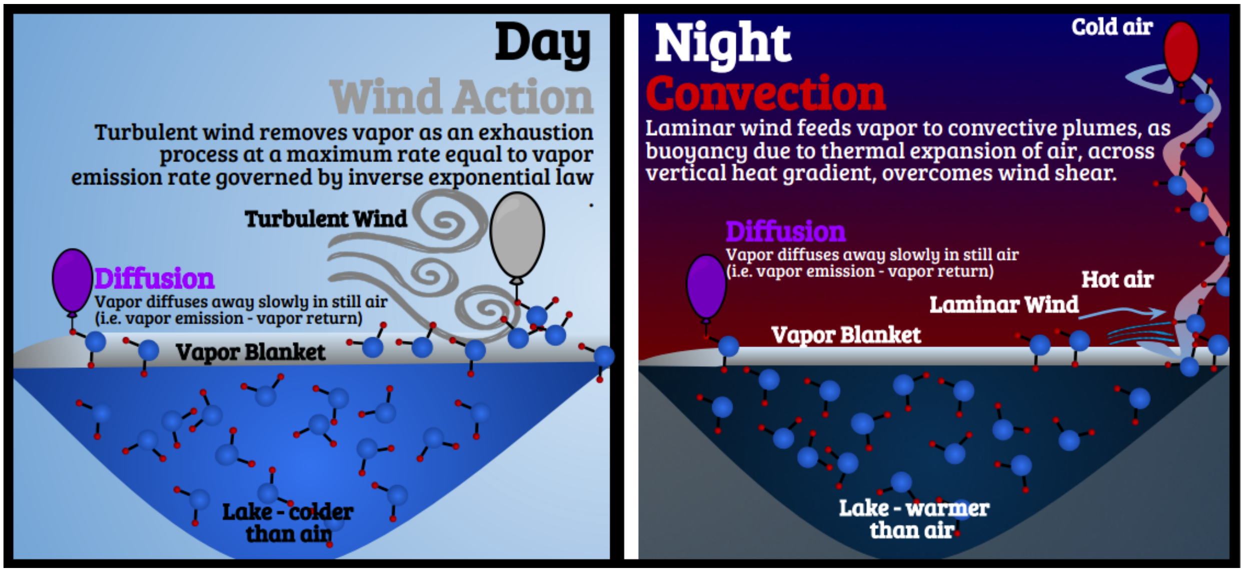


Figure 3.1: Horton's understanding of primary processes that control evaporation.

Here, the colored balloons represent evaporation aided by vapor removal due to diffusion (purple), wind action (gray) and convection (red). Diffusion can be upward or downward in direction: upward (positive) is evaporation and downward (negative) is condensation (see Sec. 3.5). Gray balloon (wind action) depends on wind speed about 1 foot away from the surface of the water, it is governed by an inverse exponential law, and can happen during day or night, though it is accentuated during the day when wind speed is higher. Red balloon (convection) depends on temperature deficit across a vertical gradient and laminar wind that accompanies vapor removal, and it occurs predominantly during the night (Horton, 1917a) when water is warmer than air due to its higher heat memory (i.e. specific heat capacity).

Illustration of Horton's evaporation method

In what follows, we illustrate Horton's evaporation equations, their theoretical basis (where possible using direct quotes), correction factors and tables (as parametric equations) and provisional values of coefficients with appropriate units.

Evaporation equations: pan evaporation, evaporative capacity and lake evaporation

If V_w is the saturated vapor pressure at surface water temperature (θ_w) and v_a is the actual vapor pressure of overlying air a small distance above the water surface at air temperature (θ_a), the Dalton Factor (more commonly called the vapor pressure deficit, VPD) is *[*$V_w - v_a$*]*. All evaporation equations use VPD, but in Horton's equation for evaporation, the VPD term is replaced with a variable VPD term (**VVPD**), $\left[\Psi V_w - v_a\right]$, where the variable Ψ is called the *wind factor* (elaborated in the following section). Ψ is not to be confused with a constant factor: it varies with meteorological conditions and has no units. Its values range from 1-2 ($1 \leq \Psi \leq 2$) depending on near-ground wind speed (w_0), to account for vapor removal by wind action and convection from the vapor blanket. There are multiple reasons behind the position of Ψ in VVPD which can be inferred from Horton's papers (1917a, 1927 and 1934). We discuss these reasons in the following section with direct quotes to Horton, where appropriate, to convey his thinking.

Pan evaporation (E_P), which is the same as *evaporative capacity from lake (*E_{Cw}*)*, is assumed by Horton as

$$E_P = C\left[\Psi V_w - v_a\right] \qquad (1a)$$

C is a constant related to time and elemental area over which evaporation happens and the units of measurement of evaporation and vapor pressure. He measured vapor pressure in inches of mercury and wind speed in miles per hour. The provisional values he prescribed for C (in inch per time units) are: 0.4 for a small elemental area, 0.36 for a 12 square inch pan over daily scale, 12.2 for an average month of 30.42 days, 73.2 for 6 months. Some of these provisional values for C are given in Horton (1917a) and others in Horton (1927). According to Horton (1917a), these values are not standardized and are subject to revision. We provide revised values in Sec. 3 (Table 3).

Evaporation capacity (E_C) relative to air is calculated w.r.t. saturated vapor pressure of air (V_a) as

$$E_C = C\left[\Psi V_a - v_a\right] \tag{1b}$$

He defined E_C as:

> "The maximum rate of evaporation which can be produced by a given atmospheric environment from a unit area of wet surface exposed parallel with the wind, the surface having at all times a temperature exactly equal to that of the surrounding air." – Horton (1919a)

For small water bodies, particularly those with shallow depth, in the absence of water surface temperature data, when the lag between water and air temperature is negligible, Eqn. (1b) can be used. Over pans, an area factor and the variability of vapor blanket thickness should be taken into account (see sections below), but can be ignored over large lakes.

Lake evaporation (E_L) is calculated w.r.t. vapor pressure of overlying vapor blanket (V_b) as

$$E_L = C\left[\Psi V_w - V_b\right] \tag{1c}$$

Vapor pressure of vapor blanket (V_b) is calculated from the corresponding vapor blanket temperature, θ_b (Horton, 1927, pp.161) using what is now called the Clausius-Clapeyron relationship, but in Horton's time this was calculated using graphical Psychrometric charts (see Horton, 1921). Vapor blanket temperature is approximated by a simple relationship, $\theta_b = \theta_w + (\Psi - 1)\Delta$, where Δ represents the difference between surface water and air temperature regardless of sign, i.e.: $\Delta = \left|\theta_w - \theta_a\right|$, where θ_a is air temperature. The expression for θ_b appears to be only a heuristic (i.e. an approximation with no theoretical basis) that may be applicable only in monthly time scales. Furthermore, Horton (1927, pp. 161-162) noted that it works for small variations of θ_w from θ_a, but suggested that if the air temperature is much higher than water, when relative humidity approaches 100%, then the relationship may not hold, because under such a condition, the distance over which vapor blanket becomes fully formed approaches infinity.

Wind Factor (Ψ)

The inclusion of Ψ in the VVPD terms is what leads Horton's equation to generalize across a variety of physical conditions and perform better that several other equations (see Sect. 4), and what makes us consider Horton's evaporation formulae semi-empirical or quasi-physical (or "rational" in Horton's terms, see Horton, 1941).

The wind factor, Ψ, depends on the wind velocity close to the water surface (w_0) which, when convection is ignored, is assumed to be of the form of an inverse exponential law

$$\Psi = H - e^{-kw_0} \tag{2a}$$

In this paper, H is designated as the Horton lake evaporation constant. Horton assigned it a constant value of 2 but it could be a little lower (discussed below). For the value of k, a constant called the *wind coefficient*, Horton prescribes values of 0.2 or 0.3 depending on the exposure of the evaporation pan (Horton, 1917a), but our experiments (as will be shown later, see Table 3) show it can be as low as 0.13. Apparently, Ψ values change depending on the values assumed for k and the Ψ tables Horton published (provided later as parametric equations in Sec. 3.2.4) are for k=0.3 (Horton, 1943b).

Adjustment of Ψ for convective vapor removal in light (or absent) wind: In the case where warm days are followed by cool nights, convective vapor removal may be important. Convective vapor removal happens more readily in the night times than in the day times. When surface winds are suppressed by inversion, and when water temperature is higher than that of air, evaporation may be dominated by convection, so an alteration of the formula for Ψ given by Eqn. (2a) is required. Horton's observations suggest that for ordinary natural temperatures, the w_o in exponent can be replaced by the $w_0 + \sqrt{\theta - \theta_a}$, which would then include the effect of convective transport in the absence of strong winds (given below as Eqn. 2b). To calculate the combined convection and wind action when wind speed is low, conditions where convection prevails can be related to a Beaufort force scale for light or calm. Horton does not specify a threshold, but he prescribes 2 mph in an example problem. Therefore, when convection is not ignored, under mild winds, when $\theta > \theta_a$, Ψ under these conditions is given by

$$\Psi = H - e^{-k(w_0 + \sqrt{\theta - \theta_a})} \qquad (2b)$$

where θ *and* θ_a are temperatures of water and air measured in Fahrenheit.

Theoretical basis of Ψ in relation to physically-based methods: One familiar with the combined equation of Penman may recognize that Horton's approach to adjust the wind term with a convective term bears some resemblance to the physics represented in the combined equation which uses a harmonic mean-like weighting, wherein the psychrometric constant accounts for the role of pressure (the aerodynamic term) and slope of the saturation vapor pressure curve accounts for the role of temperature (the energetics term) together forming the combination method. Similarly, Horton's assumption that convection is caused by a combined effect of calm wind and temperature gradient appears to be logically related to part of the physics represented by the *Flux Richardson Number* ($R_{if} = -B/P$), i.e. the ratio of buoyancy production (B), which represents buoyant force from vertical temperature gradient (turbulent heat flux), to that of shear production (P), an aerodynamic term (momentum flux times wind velocity gradient). Refer to Stull (1988) and Hess (1979) for their derivations. Understanding these relationships may lead to improved formulations of Ψ.

Assumptions behind Ψ and rationale for its position in VVPD

Though the rationale behind Ψ is not discussed in his first paper where the evaporation method was introduced (Horton, 1917a), in the context of applying his equation under varying conditions of pressure (elevation), in a paper 17 years later (Horton,1934), Horton clarifies the main assumptions behind the usage of Ψ and the rationale for its position in VVPD, which can be summarized as four key points: A) non-linear control of wind; B) wind as an exhaustion process; C) upper limit of wind's influence; and D) wind's influence on condensation. As these are the main reasons for the superior performance of his method, we discuss them briefly with direct quotes where applicable.

A) **Nonlinear control of wind:** This assumption is motivated by a simple physical reason, apparently not considered elsewhere by the numerous other investigators who studied evaporation by the mass transfer mechanism:

> "Most existing evaporation formulas are in error in that they involve a linear factor for wind correction such that wind effect apparently increases indefinitely as the wind velocity increases. It has been proved experimentally, and is indicated by physical considerations, that since the wind can do no more than to remove the water vapor as fast as it is emitted from the liquid surface, there is a maximum or limiting value of the wind factor corresponding to each water surface temperature." – Horton (1917a)

Other investigators followed Dalton's suggestion and included a wind correction factor that assumes the form $f(u) = (1 + Kw)$ where the wind velocity w is multiplied by a factor K. Further, equations of this type do not account for Dalton's important observation that evaporation doubles with strong wind:

> "with the same evaporating force, a strong wind will double the effect produced in a still atmosphere." – Dalton (1802, see pp. 581-584).

The value of 2 for H in Ψ can therefore be credited to Dalton's experiments on evaporation, but it was also verified by Horton's own experiments with wind under varied conditions (Horton, 1917a).

B) **Wind as an exhaustion process:** To our knowledge, wind's role on vapor removal as an exhaustion process has not been studied by other investigators.

> "The removal of vapor by wind corresponds to a condition of natural exhaustion to which the inverse exponential law commonly applies." – Horton (1917a)

The theoretical basis for such a view appears in some detail in Horton (1934):

> "Ψ [is] a wind-factor, based on the assumption that mechanical removal of vapor by the wind is of the nature of an exhaustion process and hence follows the inverse exponential or inverse compound interest law. It is also based on the assumption that the maximum possible effect of wind-action is to remove the newly emitted vapor from contiguity with the water-surface as fast as it is emitted." – Horton (1934)

"Natural exhaustion" mentioned in this quote is analogous to Horton's use of natural exhaustion in his paper on the physical interpretation of infiltration excess (see Horton, 1941), where he explains that its physical basis can in part be justified from first principles, and such use of inverse exponential law is at least "semi-rational" (quasi-physical), as it gives a complete picture of the physical characteristics (in this case evaporation) under natural conditions. Based on the physics described by Horton, we infer that natural exhaustion happens from the reservoir (vapor blanket) of saturated vapor that is replenished by the vapor pressure of the water surface, which is then depleted by wind action and convection. Multiplying Ψ with the total vapor pressure deficit (or the vapor pressure of air) would not represent the same. This point will become clearer in Sec 3.5 where the constituents of the evaporation formula are discussed.

C) Upper limit of wind's influence: Horton provides a rational basis for the upper limit of Ψ in the following quote:

> "In accordance with the Dalton formula, with the form of wind factor hitherto commonly used, the rate of evaporation increases indefinitely as the wind velocity is increased. This is obviously incorrect, since the rate of evaporation cannot in any event exceed the rate of vapor emission, and the latter is not affected by wind velocity in the absence of waves and spray. These must be for each water-surface temperature a maximum rate of evaporation, which rate cannot be increased by further increase in the wind velocity" – Horton (1917a)

The rationale for the wind factor can be understood by considering the extremes: when evaporation is at its maximum rate, when wind speed is high (i.e. evaporation happens at double the rate as compared to still air, as Dalton observed), i.e. $\Psi = 2$, the formula for evaporation reduces to $2CV$, assuming $v=0$ (i.e. the air is fully dry) since we are interested in the extreme case. In the other extreme, if wind speed is 0 and humidity is high, $\Psi = 1$, so Horton's equation reduces to free diffusion in still air, similar to Dalton's equation, $C(V-v)$.

The limitations of Dalton's evaporation work were well-known before Horton's time. For example, it has been noted that Dalton's observations were for the month of August only, and evaporation estimated using his equation were found to be imprecise in other Summer months (Soldner 1807). Also, Dalton's observation of doubling of evaporation rate in strong winds has had further refinements in other studies of Dalton's time, one of which is mentioned in Brutsaert (1982):

> "[Soldner's] perceptive remarks notwithstanding, during the next half century, apparently little progress was made as regards the effect of the air stream. [...] Schübler's [1831] data obtained during 1826 at Tübingen [...] showed that evaporation of a water surface exposed to wind was 1.7 times larger than that of a sheltered surface in summer, and 4 times larger in winter." – Brutsaert (1982)

Other studies in Horton's time independently allude to similar results from experimental observations (e.g. see Kennedy, 1933). Some insightful observations by these various works by Dalton, Schübler, Soldner have not been taken into consideration in modern mass-transfer formulations of evaporation. Going by cited references, it appears that Horton's work happened independently from Schübler's, Soldner's, and Kennedy's, while it did build upon Dalton's observations.

D) Wind's influence on condensation: Besides evaporation, diffusion and convection, and pressure effects (discussed further below), Horton's equation is robust to condensation. His equation's ability to generalize for condensation is another distinct and physically meaningful feature that differentiates it from other Dalton-type empirical equations, and also motivates the position of wind factor Ψ. Horton (1917a) writes,

> "Condensation or dew rarely occurs on windy nights [...] experiments were made to determine the effect of wind on the condensation of moisture on the surface of cans containing ice and water, and mixtures of ice and salt"

In a paper 17 years later, Horton (1934) revisits the role of condensation, revisiting experimental results in conjunction with the properties of his equation, and he writes,

> "It is evident that wind—except a slight wind—does not affect the rate of vapor-emission and return by diffusion but it does increase the rate of mechanical removal of newly emitted vapor. Consequently it appears that wind tends to decrease condensation instead of increasing it."

These observations agree with Rohwer's (1931) experiments which Horton (1934) verified. Kennedy (1933) observed that when water is cooler than air, and for humidity above 77 per cent, condensation occurs under such sub-adiabatic conditions, but Horton (1917a) nuances this further, adding that condensation happens only under low wind speeds, and decreases with increasing wind speed, which apparently is captured with the formulation of VVPD.

Adjustment of Ψ for pan geometry

Lake evaporation calculation is not contingent on the availability of pan evaporation data, but pan evaporation (as shown in Sec. 2.7) can be used to cross-check actual lake evaporation. The wind speed at ground has to be corrected considering the pan diameter (D) and depth (d) below the rim and a factor $\rho = \frac{10d}{D}$. Pan evaporation is calculated as

$$\Psi = H - e^{-k(w-\rho)} \qquad (2c)$$

The use of pan data as a proxy for lake evaporation is justified after due consideration of various factors that cause lake and pan evaporation to differ from each other, namely: 1) humidity corrections, 2) rim height and depth effects, and 3) vapor blanket formation and exhaustion characteristics governed by meteorological factors (wind speed); 4) temperature difference between pan and lake surface.

Horton felt quite strongly about improper usage of pan data, especially when they are land-exposed as it appears from this quote:

> "The land-exposed evaporation pan appears to be about the poorest device humanly contrivable for the purpose of determining the evaporation losses from broad water surfaces." - Horton (1917a)

Values of Ψ and ground wind velocity

Horton (1927) conducted ingenious experiments on wind that circumvented the need for wind tunnels:

> "For the purpose of determining the effect of wind on evaporation, experiments were carried out at the author's laboratory, using pails filled close to the rim, and suspended so as to swing freely from a rotating frame.[...] These experiments and studies served to determine the coefficients in the formula." – Horton (1927)

Wind factor (Ψ) changes based on wind speed measured near the ground (w_0). He calculated w_0 based on his and Stevenson's experiments for velocity variation by height (see Stevenson, 1882), but he only published the data in a report ten years after the publication of his equation. The table provided by Horton (1927) for Ψ can be converted into a cubic polynomial with coefficients that have 5 decimal places for values of wind speed ranging from 0-15 miles per hour (mph), or equivalently 0-6.7 meter per second (mps). For wind speeds beyond this limit, the value of Ψ can be linearly interpolated between 1.95 and 2 as a reasonable approximation. However, at near ground level (at about 1 foot height from the water surface), such speeds are quite unlikely. As we believe this was the main barrier in using Horton's equation more widely, we converted the values of his tables from his lesser-known report (Horton, 1927) into the following expressions for convenience:

$$\Psi\left(w_0^{mps}\right) = 0.00372 w_0^3 - 0.0641 w_0^2 + 0.40396 w_0 + 1 \tag{2d}$$

$$\Psi\left(w_0^{mph}\right) = 0.00033 w_0^3 - 0.01281 w_0^2 + 0.18059 w_0 + 1 \tag{2e}$$

We also converted another table he provided in a much later work (Horton, 1943b) where the values for Ψ varied slightly:

$$\Psi\left(w^{mph}\right) = 0.00027 w^3 - 0.01162 w^2 + 0.17493 w + 1 \tag{2f}$$

The table values for Ψ might possibly be an error in Horton (1943b), but it seems worth pointing out the difference, however slight. To develop Eqns. 2d-f, we first extracted the values from Horton's table using online scanning software (https://extracttable.com/), then we fitted it as a two-parameter function with 6 unknowns (see Supplement). We assessed several methods to develop parametric equations from Horton's tables, such as monkey saddle, logarithmic, and power law relationships, shifted divergence, rooting behaviors, etc., and were able to obtain a coefficient of determination of 0.99. However, the functions that provided this fit did not capture the high velocity variations satisfactorily. We were fortunate to obtain an improved solution with the assistance of Dr. Mikuszeit through Stack Overflow (see Vimal and Mikuszeit, 2021). The coefficient of determination (R^2) of the best formulation was 0.999. Wind velocity, w_0, is given by

$$w_0 = f\left(H, w_H\right) \tag{3a}$$

$$w_0 \ = \ 14.555\, w_H^{1.617}(0.05 + \left(H - 16.614 w_H + 68.614\right)^{-0.65})) \tag{3b}$$

where w_H is the wind velocity, as measured by an anemometer at some height H above the ground or above the water surface. The equation holds for values of height of wind measurement and velocities, $5 \leq H \leq 200\ feet$ and $1 \leq w_H \leq 30$ miles per hour respectively. These values do not exceed typical conditions. To calculate wind measurements at heights other than w_0, since algebraic manipulations cannot be easily used on Eqn. (3b), a bisection search method was used to calculate wind velocities at various heights. This approach was later used for the other equations that relied on wind measurements at different heights. The bisection method converges to within two decimal places with 10 iterations and takes a fraction of a second, so it can be adopted for simulations over long time periods and over large domains with many grid cells.

Area factor for pan evaporation depending on turbulence and humidity

While using pan evaporation to calculate lake evaporation, an area factor is required. The area factor, F, for pan evaporation uses the concept of *evaporative capacity* (E_{cw}) w.r.t. water (note that evaporative capacity in Eqn. 1b is the same but w.r.t. air temperature, and E_{cw} is the same as E_P given in Eqn.1a). It is obtained as the ratio of evaporation from lake E_L to the evaporative capacity (E_{cw}):

$$F = \frac{E_L}{E_{cw}} = \frac{C\left[\Psi V_w - V_b\right]}{C\left[\Psi V_w - v_a\right]} \qquad (4a)$$

When the water and air temperatures are identical (this would apply more for small lakes, where the temporal lag in water temperature is negligible), then, $V_w = V_b$ and $v_a = hV_w$, where h is relative humidity given by v_a/V_a.

If air and water temperature are equal, then the correction factor F reduces to

$$F = \frac{\Psi - 1}{\Psi - h} \qquad (4b)$$

Horton (1943b) deduced that when air and water temperature are not equal, the area correction factor to be related to two ratios (r and h') is similar to relative humidity, where $r = \frac{V_b}{V_w}$, and $h' = \frac{v_a}{V_w}$, as

$$F = \frac{\Psi - r}{\Psi - h'} \tag{4c}$$

These relationships are provided in Horton (1927, p. 162). The influence of turbulence on F is discussed in Horton (1943). If p is the fraction of time during which turbulent flow prevails up to some considerable height above the ground, under turbulent conditions, correction factor F is given by

$$F = (1 - p) + p\frac{[\Psi - 1]}{[\Psi - h]} \tag{4d}$$

The derivation of Eqn. (4d) is not shown step-by-step in Horton (1943), but it appears that it follows directly from the following equation (Eqn. 5) presented in Sec. 3.4, as indicated by the following quote from Horton:

> "[The author] deduced a rational expression for area-factor based on the assumption that near the windward edge of a broad water-surface an unknown fraction m of the emitted vapor is carried to leeward [...]" - Horton (1943)

Contemporary atmospheric boundary layer (ABL) theory helps approximate p, which can be determined to a fair degree of accuracy by estimating diurnal variations of boundary layer height (see Stull, 1988).

Vapor blanket characteristics

The vapor blanket is conceptually similar to a viscous sub-layer in open channel flow and is formed due to the existence of a laminar flow layer which horizontally transports moisture in the downwind direction, which leads to its growth in height. The horizontal variation of vapor blanket height, which is in the order of a few meters, is critical when estimating pan evaporation. Pans have a poorly formed vapor blanket because of their small size, as even weak winds can remove the laminar layer before it is fully formed. Once pan evaporation is corrected for the formation and disturbance of the vapor blanket layer, their use for lake evaporation can be readily justified (Horton, 1927). In the case of both pans and lakes, the vapor blanket characteristics are the same (both are governed by meteorological factors), but over pans the variation of evaporation over the variable thickness of vapor blanket is more important, while over large lakes, for most of the area concerned, evaporation rate is constant (except in cases of very high humidity and temperature gradients). So the impact of variable vapor blanket thickness, though present, can be ignored as negligible. It is important to account for the effect of vapor blanket during both daytime (when it's slightly larger) and night-time conditions (see example problem in Horton, 1917a).

Horizontal variation of vapor blanket: Understanding the process of vapor blanket formation and accurately quantifying its development and disturbance from the windward fringe of the lake to the leeward side can be considered as one of the main theoretical breakthroughs in Horton's evaporation work. Horton derived an expression (see Eq. 5 below) to capture where, when and how much the evaporation rate varies across the lake (or pan) surface. Assuming a strip of unit width, the horizontal distance of the vapor blanket before its thickness becomes constant is given by

$$x_c = \frac{1}{mC} log_e \frac{\psi V - \upsilon_0}{\psi V - \upsilon_c} = \frac{1}{mC} log_e \frac{E_0}{E_c} \qquad (5)$$

where x_c is the distance from the windward edge of the water surface where the vapor blanket thickness becomes constant. The horizontal scale of x_c is typically in the order of a few yards. Our calculations show that it can be in the order of a few meters. υ_0: vapor pressure at the shore on the windward side; υ_c: vapor pressure at a distance x downwind; E_0: evaporation at the windward shore of the lake; E_c: evaporation at x; m: the fraction of moisture carried by wind action from the shore towards the leeward side of the lake, where vapor blanket thickness quickly approaches a constant value. Typical values of m are given as: 0: water surfaces broken by waves and over rough land surfaces; 0.3-0.4: gusty winds; 0.6-0.7: steady winds; 1: perfectly horizontal uniform wind (Horton, 1917a).

Though Horton does not provide the steps to derive Eqn. (5), derivations for analogous problems which resemble this equation solved by Horton and others may provide some insight. For convenience of reference, one such derivation by Horton (1927, p. 63) and how it can be interpreted for the derivation of Eqn. (5) is given in the Supplement. Some examples of viscous sub-layer problems in open channel flow are given in Horton et al (1936).

Another useful formula Horton provides is one for calculating evaporation (E_x) at any point x along the lake or pan. Assuming a strip with unit width and length (x) downwind along the direction of mean wind, evaporation at the point x is

$$E_x = E_0 e^{-mCx} \tag{6}$$

Average evaporation (E_{av}) over the strip from shoreline to the location x over the developing vapor blanket is then

$$E_{av} = \frac{E_0}{mCx}\left(1 - e^{-mCx}\right) \tag{7}$$

Vapor blanket height: In most cases, vapor blanket thickness is only a few mm, and it is related to wind velocity. Horton (1943b) presents an equation given by G. I. Taylor (1918). Though Horton's reference has the same title as that provided in reference, the year specified by him (1934) could have been a typo, and the correct reference is likely to be the one given here. After inspecting Taylor's papers from 1934 and conducting a cursory search of his bibliography for similar titles, we did not find the equation Horton provided. From Horton (1943b), vapor blanket thickness (T_g, in feet) given by Taylor is apparently $T_g = 0.0293w$, where w is the wind speed at a height of 1 foot in miles per hour.

Horton is among the few hydrologists to rigorously examine the role of the vapor blanket in lake evaporation. So, to conclude this section, a brief synopsis of some of the other studies conducted by other investigators may aid the readers in pursuing further research in this direction. Horton's source for the idea of vapor blanket and its contributions to evaporation rates could perhaps be the Slovenian scientist Josef Stefan (1882):

> "The fact that the amount of evaporation from a basin is proportional not to the surface content but rather to the square root of this surface content leads to the result that evaporation from large water basins is proportionally smaller compared to the evaporation from a small basin. Let us also add that this is true not only for diffusion-driven evaporation

> but also for convection-driven evaporation. *When an air current moves across a water surface, it will initially lift up large amounts of water vapor as soon as it crosses the boundary of the basin, but then it will not cause much evaporation as it progresses.*"
>
> - Stefan 1882, p560, emphasis added (own translation)

A derivation similar to that of Eqn. (5) is provided in an analogous problem of diffusion and evaporation by Stefan (1882) who may have inspired Horton's derivation. Stefan, in turn, relates the derivation to two other analogous problems in heat conduction and electricity. These analogous problems give the germ of the solution for Eqn. (5). Mitrovic (2012) translated an important work conducted by Stefan related to diffusion that has been long forgotten.

The characteristics of the vapor blanket have been studied in only a few other works to our knowledge. Sutton (1934) and Vercauteeren (2011) have considered the shape of the vapor blanket in the windward edge, but its properties with respect to evaporation (and with regards to turbulence, convection, etc.) over lakes were not unexplored. Millar's (1937) apparently rigorous study of the vapor blanket was not accessible to us (we were unable to obtain a copy of the paper), but a summary is provided in a USGS report (1954; see chapter on Mass Transfer Studies by Marciano and Harbeck) which shows Millar's equations. They indeed seem to resemble Stefan's work on diffusion. Finally, there is an indirect reference to vapor blanket in Peter Eagleson's textbook on *Dynamic Hydrology* which supposedly includes a description of the vapor blanket as a conceptual thin layer, and it is described with a schematic, but no sources were given (Eagleson, 1990, Fig. 12-1, p. 213).

Separable physical factors in the evaporation equation

Role of pressure (evaporation change with altitude): To understand the role of vapor removal and diffusion, for convenience we can consider a general form of equations (1) and (2). Ignoring convection, inserting Ψ from Eqn. (2a), into Eqns. (1a) and ignoring the suffixes of water and air for simplicity, the general evaporation equation is given by

$$E = C\left[(H - e^{-kw_0})V - v\right] \tag{8a}$$

If H, as given by Horton (drawn from Dalton), can be taken as a constant 2, then Eqn. (8a) can be factored into

$$E = C(V - v)_{Diffusion} + C\left(1 - e^{-kw_0}\right)V_{Vapor\ removal} \tag{8b}$$

By separating Eqn. (8a) into its physically meaningful parts as shown in Eqn. (8b), one can account for the role of barometric pressure which impacts only one of the terms (free diffusion, which is the first part here). When pressure changes with altitude, the first term here is adjusted for pressure drop which solely impacts free diffusion. Horton's rationale is as follows:

> "It is evident that in order to determine the effect of change in barometric pressure on evaporation, other things equal, its effect on vapor removal by diffusion, which is always present, and its effect on

> vapor removal by wind-action, must be considered separately. This may readily be accomplished by the use of an evaporation formula published some years ago" – Horton (1934)

An inverse relationship between diffusion and pressure was first proposed by Thomas Tate (1862) and later derived by Stefan (1881). If B_0 and B are barometric pressures at datum (sea level) and pressure at a given elevation respectively, the evaporation equation, according to Horton (1934), becomes

$$E = C\left(\frac{B_0}{B}\right)(V - v) + C\left(1 - e^{-kw_0}\right)V \qquad (8c)$$

The second part represents enhanced vapor emission facilitated by vapor removal from the vapor blanket, which can be by wind or convection: wind's influence is independent of barometric pressure (Horton, 1934). The relationship between convection and barometric pressure was not known to him, and he had an argument to not investigate further:

> "The relation of barometric pressure to convective vapor removal has apparently not been studied. Since convection is, in general, not present when there is strong wind-action, it will not be considered here." – Horton (1934)

Under humid conditions, Horton (1934) suggested that the role of wind-induced vapor removal may be several times higher than that of still air, but it does not appear that this effect is explicitly accounted for in his equation.

Experimental precision

The precision that went into Horton's experimental measurements is quite remarkable. He performed detailed experiments on the melting of snow considering dozens of physical variables measured at 10-20-minute intervals (Horton, 1915). These experiments, together with his earlier study on evaporation from snow (see Horton, 1914) seem to have contributed to his later experiments on condensation (see Horton, 1917a). He developed instruments to measure minimum and maximum daily temperatures of water surface and a geometrical approach for snow temperature (Horton, 1919b). To cross-check his daily snow measurements, he made additional measurements at an accuracy of 1/5th of a degree at hourly intervals to cross check the diurnal (min and max) daily snow temperature readings (Horton and Leach, 1934). He used graphical methods to calculate vapor pressure and humidity which give values to within 1-2% accuracy (Horton, 1921). Some evaporation measurements to cross-check his evaporation calculation (see Horton, 1927, pp. 150-155) were made to ~1/1000th of an inch precision.

Evaluation of Horton's evaporation method

Evaluating on an Arctic lake with observed and disaggregated vapor pressure

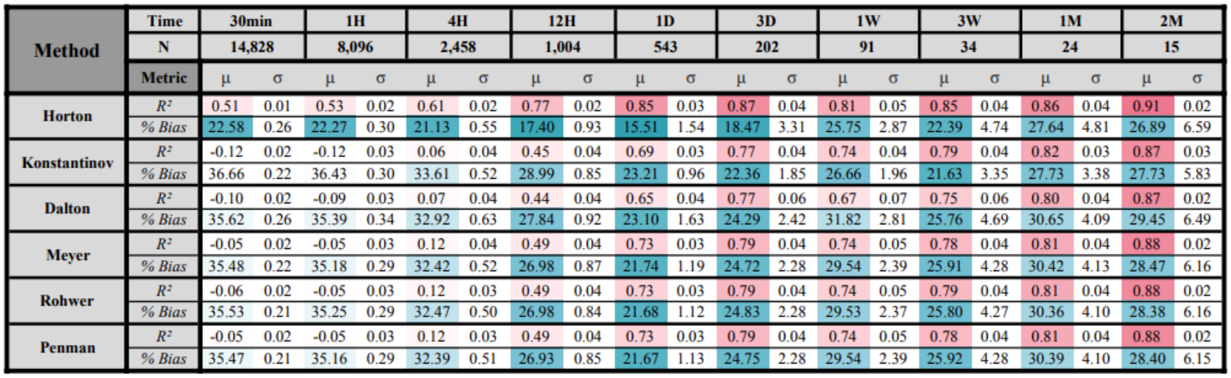
High latitude lakes are quite important in the context of accelerated Arctic warming (Smith et al, 2005), as the region is besprinkled with numerous tiny lakes. The mean evaporation for each lake may vary appreciably due to the variability of vapor blanket thickness (Eqns. 5-8), which means that the role of the vapor blanket cannot be ignored. In the domain of Canada and Alaska alone, there are over 13 million lakes measured at Landsat resolution (approximately ~0.1 hectares, but varies by latitude), and perhaps many more at finer scales. Horton (1934) noted that high latitude evaporation processes may be quite different from mid latitudes, because available water at the surface may be altered by condensation processes, and the predominant evaporation surface is snow, especially above the snow line (Horton, 1934). So it follows that the methods of midlatitudes cannot be directly applied, though Horton believed that his evaporation method is generalizable for sub-zero conditions and condensation (unlike the other empirical equations for evaporation).

We tested Horton's evaporation equation on Baker Creek in subarctic Canada where 30-minute meteorological data were available as measured over the lake as well as near the lake (see Spence and Hedstrom, 2018 for data description and measurement heights). For vapor pressures of air measured in either location, the difference in evaporation was slight. To evaluate the performance of Horton's equation, following Singh and Xu (1997), we selected five other equations that resemble Horton's equation and calibrated them by treating all the coefficients as free parameters, preserving only the shape of the equation. We selected 5 equations (see Table 3) with various shapes: Konstantinov, Dalton, Meyer, Rohwer, Penman. Note that Penman referred to here is not the combined equation, but only a part of the combined equation (aerodynamic) provided in Penman's original work (Penman, 1948). Most empirical Dalton-type formulas do not include a temperature deficit term, except few that are of the type of Konstantinov (1968). The general forms of the equations are given in Table 3.

Actual vapor pressure of the air is one of the most important variables which is difficult to obtain. So, to understand the robustness of the various methods to errors in this variable, in addition to using observed measurements available for the test site, we calculated actual vapor pressure as a function of solar geometry, diurnal temperature range and seasonal precipitation (see Bennet et al, 2020 and Bohn et al, 2013). The data for this were drawn from our previous work (Vimal et al, 2019).

We used a bootstrap approach to get the mean (μ) and standard deviation (σ) for coefficient of determination (R^2) and percentage bias (% of mean absolute percentage error), where we sampled 50%, 75% and 100% of the record length and 50 random samples with replacement for each length, and 11 time scales (30 minutes to 2 months), in total 1650 random bootstrap samples. For all these combinations, the time period of analysis was 8 April, 2009 to 20 September, 2016. Missing values were ignored, and data coverage mostly represents Summer months (further details are in Spence and Hedstrom, 2018).

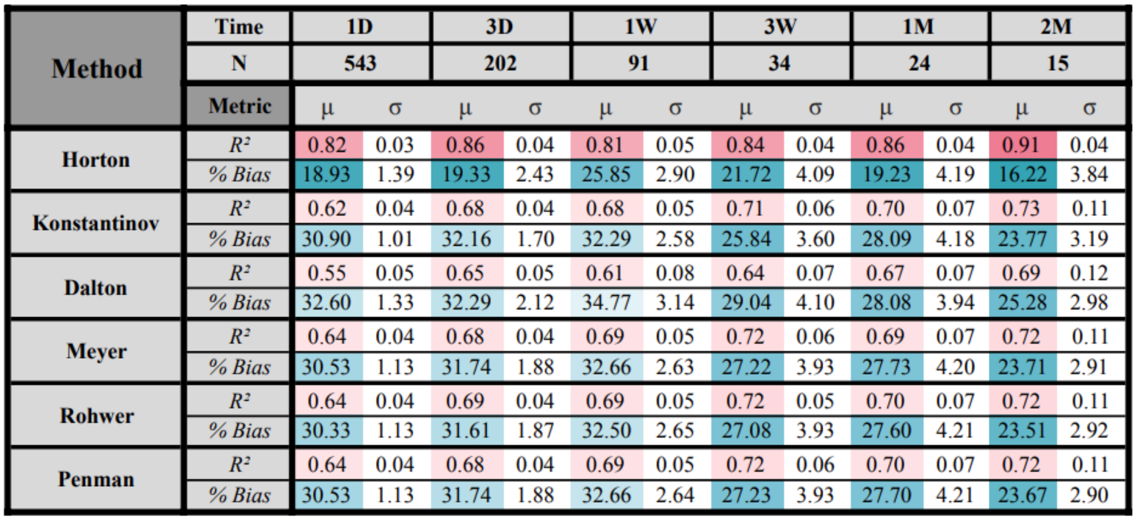
Table 3.1: Performance metrics (R² and % bias) for evaporation methods using observed data inputs. Darker shades of teal and pink highlight the good results.



Method	Time	30min		1H		4H		12H		1D		3D		1W		3W		1M		2M	
	N	14,828		8,096		2,458		1,004		543		202		91		34		24		15	
	Metric	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Horton	*R²*	0.51	0.01	0.53	0.02	0.61	0.02	0.77	0.02	0.85	0.03	0.87	0.04	0.81	0.05	0.85	0.04	0.86	0.04	0.91	0.02
	% Bias	22.58	0.26	22.27	0.30	21.13	0.55	17.40	0.93	15.51	1.54	18.47	3.31	25.75	2.87	22.39	4.74	27.64	4.81	26.89	6.59
Konstantinov	*R²*	-0.12	0.02	-0.12	0.03	0.06	0.04	0.45	0.04	0.69	0.03	0.77	0.04	0.74	0.04	0.79	0.04	0.82	0.03	0.87	0.03
	% Bias	36.66	0.22	36.43	0.30	33.61	0.52	28.99	0.85	23.21	0.96	22.36	1.85	26.66	1.96	21.63	3.35	27.73	3.38	27.73	5.83
Dalton	*R²*	-0.10	0.02	-0.09	0.03	0.07	0.04	0.44	0.04	0.65	0.04	0.77	0.06	0.67	0.07	0.75	0.06	0.80	0.04	0.87	0.02
	% Bias	35.62	0.26	35.39	0.34	32.92	0.63	27.84	0.92	23.10	1.63	24.29	2.42	31.82	2.81	25.76	4.69	30.65	4.09	29.45	6.49
Meyer	*R²*	-0.05	0.02	-0.05	0.03	0.12	0.04	0.49	0.04	0.73	0.03	0.79	0.04	0.74	0.05	0.78	0.04	0.81	0.04	0.88	0.02
	% Bias	35.48	0.22	35.18	0.29	32.42	0.52	26.98	0.87	21.74	1.19	24.72	2.28	29.54	2.39	25.91	4.28	30.42	4.13	28.47	6.16
Rohwer	*R²*	-0.06	0.02	-0.05	0.03	0.12	0.03	0.49	0.04	0.73	0.03	0.79	0.04	0.74	0.05	0.79	0.04	0.81	0.04	0.88	0.02
	% Bias	35.53	0.21	35.25	0.29	32.47	0.50	26.98	0.84	21.68	1.12	24.83	2.28	29.53	2.37	25.80	4.27	30.36	4.10	28.38	6.16
Penman	*R²*	-0.05	0.02	-0.05	0.03	0.12	0.03	0.49	0.04	0.73	0.03	0.79	0.04	0.74	0.05	0.78	0.04	0.81	0.04	0.88	0.02
	% Bias	35.47	0.21	35.16	0.29	32.39	0.51	26.93	0.85	21.67	1.13	24.75	2.28	29.54	2.39	25.92	4.28	30.39	4.10	28.40	6.15

Table 1 shows that Horton's method is substantially more accurate than the other five methods of varying complexity consistently across timescales and sample sizes.

Table 3.2: Performance metrics (R² and % bias) for evaporation methods using reanalysis-based disaggregated actual vapor pressure.



Method	Time	1D		3D		1W		3W		1M		2M	
	N	543		202		91		34		24		15	
	Metric	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Horton	*R²*	0.82	0.03	0.86	0.04	0.81	0.05	0.84	0.04	0.86	0.04	0.91	0.04
	% Bias	18.93	1.39	19.33	2.43	25.85	2.90	21.72	4.09	19.23	4.19	16.22	3.84
Konstantinov	*R²*	0.62	0.04	0.68	0.04	0.68	0.05	0.71	0.06	0.70	0.07	0.73	0.11
	% Bias	30.90	1.01	32.16	1.70	32.29	2.58	25.84	3.60	28.09	4.18	23.77	3.19
Dalton	*R²*	0.55	0.05	0.65	0.05	0.61	0.08	0.64	0.07	0.67	0.07	0.69	0.12
	% Bias	32.60	1.33	32.29	2.12	34.77	3.14	29.04	4.10	28.08	3.94	25.28	2.98
Meyer	*R²*	0.64	0.04	0.68	0.04	0.69	0.05	0.72	0.06	0.69	0.07	0.72	0.11
	% Bias	30.53	1.13	31.74	1.88	32.66	2.63	27.22	3.93	27.73	4.20	23.71	2.91
Rohwer	*R²*	0.64	0.04	0.69	0.04	0.69	0.05	0.72	0.05	0.70	0.07	0.72	0.11
	% Bias	30.33	1.13	31.61	1.87	32.50	2.65	27.08	3.93	27.60	4.21	23.51	2.92
Penman	*R²*	0.64	0.04	0.68	0.04	0.69	0.05	0.72	0.06	0.70	0.07	0.72	0.11
	% Bias	30.53	1.13	31.74	1.88	32.66	2.64	27.23	3.93	27.70	4.21	23.67	2.90

Darker shades of teal and pink highlight good results. Surprisingly, Horton's method outperforms other methods even when using estimated input vapor pressure (Table 2) while the other 5 methods use local measurements (Table 1). It must be noted that previous studies have shown that vapor pressure near water bodies (e.g. coastal regions) has a large bias and uncertainty (see Bohn et al, 2013), which makes the result even more surprising. A reason for the poorer performance of other methods could be that we estimated wind velocity at various heights by back-calculating using Eqn. (3b) and the bisection method previously mentioned. Another reason could be the dependence of vapor pressure measurement on observation height for some, even if not all, of the other methods. Konstantinov's equation depends on wind speed at ground height (same as Horton's method), and uses more input variables related to temperature, and yet does not perform better. We do not draw bald conclusions directly from Tables 1 and 2, before testing under multiple catchments and lakes of wide-ranging meteorological conditions. However, if this result holds across various locations and regions, as we will show below more generally, then we can arrive at a few conclusions: 1) that Horton's formula is robust against overfitting of errors making it more physically based; and 2) the variable vapor pressure deficit (VVPD) term, unique to Horton's evaporation formula, is a better control on evaporation than VPD.

Generality of the method

We use the term generality in the following connotations: 1) Parameter certainty: i.e. how relatively unchanging the parameters in the calibrated equations are across wide ranging conditions, time averages (mean of evaporation is considered when time averaging, so effect of time in parameters is ignore), and record lengths; 2) how well it performs in wide ranging conditions across various meteorological conditions and altitudes; 3) How well it performs across continental which follows from both (1) and (2). The ability for a method to generalize across such conditions shows that the method is not an empirical fit, but has a rational or physical basis.

Parameter certainty

If the parameter values are unchanging or have only a slight variability, they can be assumed to possess a physical meaning which does not need site-specific tuning (or calibration). Such unchanging values are termed constants and identifying such constants is common in Physics. Of the three connotations of generality we are interested in, parameter certainty is the most important. In all the six methods we compared, there were 17 parameters, and each one was tuned for each of the 1,650 bootstrap samples using a vectorized approach (see Sec. 4.1 for breakdown of sample size and record lengths). In total, this represents 1,68,300 tuned parameters which are summarized in Table 3 (shown below). To make their comparison straightforward, the time unit of reference observation was kept identical to the native resolution, e.g. daily or monthly evaporation values were averaged into units of mm per 30 minutes, which allows us to compare values of parameters across methods and time scales. Some outliers in parameter values were found (possibly due to errors in data) but were removed using the same criteria (10th percentile) for all 6 methods each considered independently. The last column here shows normalized values of variability (σ/μ) as a percentage, which can be compared across methods.

Table 3.3: Parameter uncertainty comparison between six evaporation formulas (mean μ and σ/μ)

Evaporation method	Equation	Parameter	Mean (μ)	σ/μ (%)
Horton	$C\left[\left(H - e^{-kw_0}\right)V - v\right]$	H	1.71	1.3%
		K	0.13	4.3%
		C	0.18	12.9%
Meyer	$C\,(V - v)(A - u_9/B)u_9$: *wind at 9m height*	C	-0.06	1.6%
		A	-2.39	4.3%
		B	4.70	7.2%
Penman	$A(V - v)\left(B + Cu_2\right)u_2$: *wind at 2m height*	A	0.16	10.5%
		B	-0.33	5.1%
		C	-0.06	5.6%
Rohwer	$A\,(B - CPa)(D + E * u_0)(V - v)$ Pa: pressure u_0: *ground wind*	A	1.03	3.8%
		B	1.03	20.3%
		C	0.98	20.3%
		D	0.56	6.1%
		E	0.92	5.1%
Konstantinov	$\left[A\,\frac{(\theta-\theta_a)}{u_0} + Bu_0\right] * (V - v)$	A	0.09	20.2%
		B	0.03	9.8%
Dalton	$C\,(V - v)$	C	0.39	18.4%

Among all parameters, the parameter H has the most unchanging value (1.71) and the smallest (1.3%) relative variability (σ/μ **%)**, while average of all other parameters is 9.5%, which shows that it is the most generalizable and requires the least site-specific tuning among the 17 parameters considered across all 6 methods. The value for H that Horton originally prescribed was 2, drawing from Dalton's experiments (see quote in Sec. 2.2.2). The other two parameters of Horton's equation are not particularly more certain than the parameters of other equations. Meyer's equation, which relies on wind speed at 9m height, has one of the parameters (C) that performs nearly as well as

Horton's H, with 1.6% variability, but it has no physical meaning as it has a negative value.

Previous investigations on H: To our knowledge, there is no other evaporation formulation that captures the role of H, though aspects of its role have been observed previously. Horton's source for H could be regarded as Dalton (1802). Dalton conducted his experiments in a single site in high and low evaporation conditions and high and low temperatures, so our result (1.71) can be said to be more robust than Dalton's, as our bootstrap sampling strategy accounts for more wide-ranging conditions. Even so, the value of 1.71 may need confirmation from several lakes across latitudes to ascertain its value. This value, interestingly, agrees very closely with Schübler's (1831) experimental observations that evaporation accentuated by wind during Summer was 1.7 times greater (Brutsaert, 1982). The parameter H appears to be a significant development in lake evaporation physics, and can be designated as *Horton constant,* sharing credit with Dalton and Schübler.

Estimates across altitudes and sub-zero temperature conditions

Horton claimed that his method was rational (physical) in that it is robust to conditions outside for which it was used (Horton, 1927; p159), which the other empirical methods of his time were not (e.g. that by Carpenter and Fitzgerald, see Fitzgerald, 1886), as most were tuned for local conditions. He investigated the role of condensation rates, evaporation from snow surfaces (Horton, 1914), temperature deficits and wind speed in high altitude and polar regions (Horton, 1934). In a Snow Conference paper (Horton, 1943) he comments on the processes involved in evaporation from snow that includes independent variables that depend on latitude and altitude, which were not known with certainty. When lake surfaces are partially covered with ice, he recommends using a weighted average of lake water and ice temperatures, for partially frozen lakes. The role of thickness of ice on air-water temperature relationship was observed, i.e. thicker ice brings air and ice temperature closer. Additional factors that influence evaporation under such conditions could be the percentage, intensity, and duration of laminar and turbulent air flow, which depend on latitude and elevation (Horton, 1934), and also other physical factors due to snow and ice, that is A) area exposed to air (vs projected area from snow surface) due to influence of snow porosity may increase evaporation; and B) the disproportionate departure of air temperature much above ice temperatures compared to water temperature. Horton suggested that these factors may require a separate treatment (Horton, 1934).

Evaluating Horton's evaporation results over Continental U.S.

Horton used 112 pan evaporimeters' data over the continental US and plotted precipitation, evaporation and runoff into one figure sliced by longitudes (see figure in Horton, 1943). We re-plotted his chart together with a land surface model results simulated at over 200,000 model grid locations over the continental US by Livneh et al (2013). We aggregated the model results the same way as Horton did by 2-degree grid boxes. Surprisingly, the curves for P, E, and Q are remarkably similar (see Fig. 2). We further aggregated data into three climate normals, i.e. three 30-year averages from 1921 to 2010 to see whether there exist long term climate change influences, but found none - this could possibly be an inherent issue with the Livneh et al, 2013 dataset, which possibly is detrended. The record lengths of Horton's data were variable, so they are not shown, but they are in the order of magnitude to be regarded as climate normals, i.e. long-term climate average.

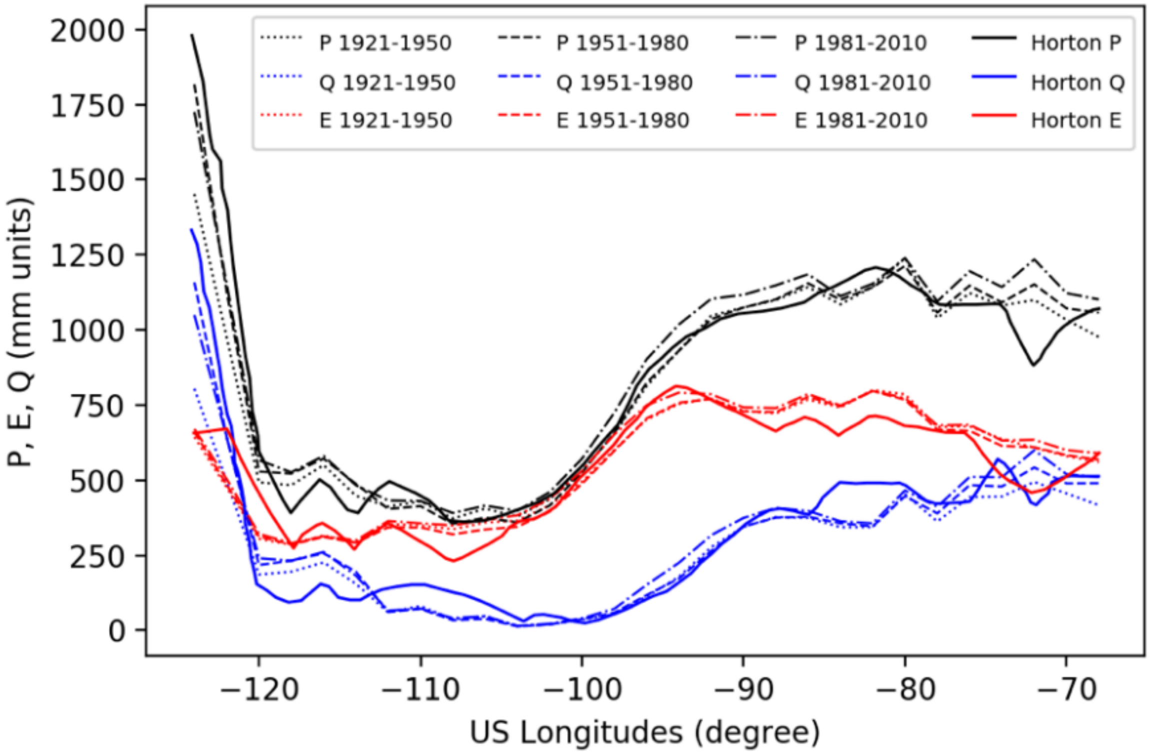


Figure 3.2: Comparison of con-US 2-degree average values of precipitation (P), Evapotranspiration (E), and runoff (Q) estimates: replotting the chart from Horton (1943b) together with Livneh et al (2013) over three climate normals.

The difference in evaporation is substantial in the Great Lakes region (between longitudes -90 and -80), though precipitation seems to be similar, and this may be explained as follows: Cleveland and Chicago, which are on different sides of the Great Lakes, may have a similar temperature (except in Winter), but the number of sunshine hours (and cloud cover) may change significantly between the two places (see Jenson and Haise, 1963). Some of these factors were directly and indirectly accounted for in Horton's estimation of evaporation from the Great Lakes. For example, he considered wind data from multiple locations and performed some interpolation-based corrections. Also, the land surface model results were masked out for the Great Lakes pixels, so it is possible that the evapotranspiration of that longitude band on average is greater than the evaporation from Great Lakes which may explain the difference. Larger lakes, as noted by Stefan (1882) and suggested by Horton's formula (Eqn. 5), may possibly yield a lower total evaporation than the rest of the land surface, which is quite unintuitive, but for the scale of the Great Lakes, this cannot be ascertained as there may be numerous other factors that come into play. However, we can conclude that the evaporation formula does generalize over continental scales owing to the remarkable similarity seen in Fig. 2.

Discussion

Horton's contribution to lake evaporation physics

While this paper highlights a century-old method, we do not fail to recognize that advancements in evaporation theories of the last century have been stellar: one needs to only look at the number of numbers (mostly dimensionless) that are used to represent the physics that control evaporation - Dalton, Reynold, Prandtl, Taylor, Karman, Stanton, Schmidt, (Flux) Richardson, Peclet, Nusselt, Sherwood, Raleigh to name some (see Pasquill, 1942; Hess, 1979, and Brutsaert, 1982 for an introduction to many of these developments). Besides the fields of aero-, thermo- and hydrodynamics where most of these numbers emerged, there have also been great strides forward in the kinetic theories of evaporation (see Gerasimov and Yurin, 2018). One can argue that progress would lead to unification of these numbers into a smaller set. Nevertheless, in the quest for the smaller set, among the candidate numbers, we believe two of Horton's core contributions discussed in this paper could be considered for their fundamental relevance to lake evaporation estimation: 1) the ratio E_o/E_c in Eqn. (5) which represents the ratio of evaporation at the fringe of the lake to evaporation where the vapor blanket acquires a constant thickness; 2) H, the seemingly constant coefficient (see Table 3), the value of which was prescribed by Horton as 2 (or a little lower as we find, 1.7), which is arguably what makes the VVPD term a better independent control on evaporation than VPD. These two, we suggest, could be called the *Horton ratio* and the *Horton constant for lake evaporation*, respectively. The former could also be credited to Stefan (1881); see also Mitrovic (2012) who re-discovered another century-old problem credited to Stefan, and the latter to John Dalton (1802) and Gustav Schübler (1831). It appears that Horton provided the first quantitative treatment highlighting the importance of these two values for lakes.

Can Horton's evaporation formula replace other methods?

Among the 5 equations we evaluated, Meyer's, Rohwer and Penman's equation shapes and results differ but slightly. Expectedly, Konstantinov's (1963) method, which draws additional information from a temperature deficit term, in addition to VPD and wind (as done in other methods), has the second highest complexity and performs the second best, while Dalton's method (the simplest one) is the poorest. What we have shown here suggests that Horton's equation can indeed replace these other methods. A question that begs to be answered here is: should Horton's evaporation equation for lakes be preferred over the Penman (combination) equation, especially in the context of continental scale land surface modeling? Before answering this question, it is worth noting that Penman's formula is indeed adapted from Rohwer's (1931) formula, who in turn in his work commented on Horton's evaporation formula, saying that,

> "From a theoretical standpoint [Horton's] formula is worthy of consideration, but, as the values of the constants in the formula have not been definitely determined, the practical value of the formula is small"

Our answer to this question from this study is that it could be for the following reasons:

1) Horton's VVPD can replace VPD: the aerodynamic part of the Penman equation invariably depends on the VPD term which, as we showed above, will indeed be less accurate than Horton's VVPD.

2) Separability of barometric pressure: the Penman aerodynamic component is weighted by psychrometric constant (essentially a barometric pressure term), which plays a role in diffusion but not aerodynamic action. As shown in Eqn. 8c, an inverse barometric pressure term may be added to only the diffusion term, which is separable from wind action, which is possible with Horton's equation but not the other aerodynamic formulas hitherto used in various combination methods (Penman and others).

3) Error in energy variables: the energy balance approach relies on variables such as surface radiation and ground heat flux (which depend on cloud cover, ground heat exchange, etc.), which are prone to errors. Furthermore, there exist first-order issues with energy budgets because of errors in a crucial variable, open water albedo, which varies as a function of sun's angle (see field experiments by Sivkov, 1971). Seasonal variability can be up to a factor of 7, but most lake schemes do not account for this variability: for example, the lakes energy scheme of Bowling and Lettenmaier (2009) uses a constant albedo value for open water (similarly in Hostetler and Bartlein, 1990; and Croley, 2012).

4) Horton's method depends on water temperature data and not radiation: using water surface temperature data for evaporation has the crucial advantage that it can be directly measured from space (see Sharma et al., 2015), especially for large water bodies, with a fair degree of accuracy (~1.15 °C for small lakes and 0.45 °C for large lakes). Rapid mixing of surface water due to wind, and vertical density gradients (see experiments on stratification by Gregory, 2012) together favor surface water temperature to equalize quickly across the surface. This is especially true in small lakes where surface temperature can be considered as uniform. Over large lakes, temperature varies with bathymetry due to variable rates of vertical mixing in large lakes - however, this variability only depends on lake bathymetry which can be treated as a static parameter, and heat exchange can be modeled or observed with better accuracy in larger lakes from space observations (as noted before). On the other hand, in a study by Rahaghi et al. (2019), it was shown that radiation at the surface of a large Swiss lake (Lake Geneva) varied on the order greater than 40 Wm^{-2} in different parts of the same lake, which is quite a significant error for a large lake and was attributed to shading effect by clouds, a dynamic error. In terrestrial hydrology, where radiation budget is calculated from temperature (e.g. Bohn et al, 2013), Horton's method has a particular advantage. These arguments make a strong case for favoring Horton's equation over the combination method, for both large and small lakes.

Should we revisit the evaporation paradox?

The relationship between pan and actual evaporation is a topic of great importance today in the wake of accelerated climate warming. There is unanimous consensus that pan evaporation is reducing globally, while in a warming climate the opposite is generally expected, which is known as the *evaporation paradox* (Roderick and Farquhar, 2002). A friendly introduction to the topic is given in Singh (2016, Chapter 42.2.3). This paradox is explained by evaporation observations in larger scales across sites of variable moisture availability, considering how energy is redistributed between latent and sensible heat based on moisture availability. This paradox is considered resolved by Bouchet's (1963) principle of complementarity, which shows the relationship between pan, actual and theoretical evaporation. Morton (1994), Szilagyi et al. (2017), Brutsaert and Yeh (1970) and Brutsaert (1982, 2015) further extended the work by Bouchet (1962). In studies that involve pans, including several that are related to the evaporation paradox, pan evaporation calculations are often done with a static pan correction parameter, but as Horton shows very clearly, it would be quite wrong to use a static parameter (Horton, 1917a). The explicit role of vapor blanket has been ignored in these studies except perhaps indirectly (as moisture availability is related to atmospheric humidity, which influences vapor blanket characteristics). A table in Maidment (1992; Table 4.3.1., Chapter 4 on Evaporation by Shuttleworth) taken from Doorenbos and Pruitt (1977) provides a quasi-quantitative guidance on pan correction as a function of humidity values and a scale similar to Beaufort wind force scale (i.e. light, moderate, strong winds). However, Horton's quantitative treatment and physical explanations for the differences in evaporation rates from pan to lake precedes Doorenbos and Pruitt (1977) by half a century. Furthermore, Horton's insights on vapor blanket's physical properties and the area factor F shed a new light on the evaporation paradox and generalizes it beyond standard pan sizes. Considering these, it seems that a revisit to explain the evaporation paradox is warranted.

Conclusions

Horton's century-long forgotten works on lake evaporation seem to have great contemporary value for the theoretical insights they offer and for their relevance in modeling lakes of all sizes. The fine-scale precision afforded by Horton's *"law of the wall"*-type equation (Eqn. 5) and Eqns. 6 & 7 for vapor blanket characteristics credited to Josef Stefan and him appears to be essential to estimate evaporation in small lakes and pans, and using pan evaporation as a proxy for large lakes. From these equations, and considering the importance of the *Horton ratio* (E_o/E_c), taken together with the area factor F (Eqns. 4a-d) for pan evaporimeter measurements, an opportunity arises to revisit the complementarity relationship between pan and lake evaporation and the so-called evaporation paradox. More generally, Horton's improved formulation that relies on the Horton Constant H and VVPD (credited to John Dalton, Gustav Schübler and him), due to the dynamic wind factor Ψ (Eqns. 2 a-c), may partially or fully supplant other evaporation equations that rely on VPD, owing to its better generalizability (local to continental, across time scales and latitudes). We believe that Horton's evaporation method was largely overlooked and forgotten because the tables needed for their proper use were unavailable widely. Therefore, in this paper we present the parametric forms of his ground wind velocity experimental results (Eqns. 2d-f and Eqn. 3b), which may serve as a ground reference for wider use of his method. Considering all this, our main conclusion is that Horton's (1917a) claim of having developed a superior evaporation method (Eqns. 1a-c) seems to hold even today: we believe that his method, which was heuristically related to physical laws, is an improvement over other known lake evaporation formulae.

Closing note

As a closing note, to entertain the *History of Hydrology Special issue* readers, we would like to highlight an amusing historical anecdote that came out of Horton's detailed evaporation study. In the early morning, over warm lakes in a cold climate, when the wind is calm and laminar flow of wind on the surface of the lake feeds moisture into convective plumes of vapor, they appear as columns of about 10 inches in diameter and over 4 feet in height. Horton got the rare chance to witness these apparitions in his early morning observations – he calls them the dancing columnar vapor drift (Horton, 1933). He notes that this phenomenon, as also previously noted by a German scientist (Dr. Johannes Walther), may be a curious explanation of the myth of the Greek deity Venus' origin and that of the dancing Nereids upon Greek waters.

We hope the various observations and conclusions drawn here to highlight the value of Horton's lake evaporation works will be developed further. We also hope this serves to rekindle the interest of readers to (re-)discover Horton's contributions to lake evaporation in addition to his broader published and unpublished works.

Data availability. Data sets used in this article are publicly available (see citations in text), and codes are available upon request. The updated bibliography of Horton is available upon request.

Competing interests. The authors declare that they have no conflict of interest.

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Author contributions. SV conceptualized the study, performed simulations, and prepared the manuscript. VPS conducted literature search, design of simulations, interpretations of Horton's derivations, and edited the manuscript.

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Appendix

A. A useful derivation of lake equilibrium levels drawn from Horton (1927) to interpret vapor blanket derivation

The derivation presented below compliments Eqn. (5) of the main text. Though it does not represent the same physical problem, it does provide an analogous solution of the same shape, from which the derivation steps of Horton for Eqn. (5) can be inferred. Our inference of the same is provided below the derivation.

Time taken for lake levels to stabilize after channel has been modified resembles the formulation of the x_c

Stage-discharge relationships for inflow and outflow of the lake are given by

$$Q = c + kh\#(A1)$$

Inflow, outflow and storage are related by,

$$Idt – Adh = Qdt\#(A2)$$

where

$$I = c + kh2\#(A3)$$

Rearranging

$$(I - Q)dt = Adh\#(A4)$$

$$(c + kh2 - c - kh)dt = Adh\#(A5)$$

Reducing

$$k(h2 - h1)dt = Adh\#(A6)$$

$$dt = \frac{A}{k}\frac{dh}{h_2 - h}\#(A7)$$

The time it takes for lake level to reach a new mean equilibrium level from the time the change to the channel is made ($h = h_1,\ when\ t = 0$) is given by integrating the above,

$$\int dt = \int \frac{A}{k}\ \frac{dh}{h_2 - h} \Rightarrow t = - \frac{A}{k} log_e \frac{h_2 - h_1}{h_2 - h}\#(A8)$$

where h_1: water surface height at original mean stage (above improved channel bottom); h_2: water surface height at original stage (above original channel bottom); A: lake surface area. Q: mean outflow rate; h: depth at time t refers to new control sill elevation; t: time taken for lake level to reach a new mean equilibrium level, time of change of channel t_0=0.

Inference of derivation vapor blanket horizontal distance considering Eqns. (A1-8): Analogous to the above derivation, Horton's derivation of Eqn. (5) must have been as follows: change of distance (dx) of vapor blanket disturbance is directly related to horizontal rate of change of vapor pressure and inversely related to the amount of vapor transported horizontally (m), and a constant related to elemental area (C) from which vapor is transported, as well as the VVPD. Rearranging and integrating by parts, and taking limits from x=0 to x_c, we get a ratio of evaporation from windward to leeward sides, i.e. fringe of the lake where it is maximum to where it approaches a constant value at a distance x_c.

B. Fitting a function to Horton's wind velocity correction factor (w_o)

Several methods were tested in order to estimate the wind height at ground level as a function of measurement height and velocity at the given height, including: 1) Monkey Saddle; 2) shifted divergence in measurement height and root like behavior in velocity at that height; 3) multi-linear regression; and 4) polynomial regression (with and without log).

Monkey Saddle is given by,

$$z = ax^{3} - bxy^{2} + c \qquad (B1)$$

Root and shifted divergence is given by the shape,

$$z = ax^{p}(b + (y - cx - d)^{-q} \qquad (B2)$$

where, x: velocity measured at height H $w_{H;}$ y: Height H; z: velocity at ground (at 1 foot height from surface, $w_{h=0}$); values of a, b, c, p, and q are 14.555, 0.05, 16.644, -68.614, 1.617, 0.65.

Substituting, the values of coefficients, the final equation is given by

$$w_{0} = 14.555\, w_{H}^{1.617}(0.05 + \left(H - 16.614w_{H} + 68.614\right)^{-0.65} \qquad (B3)$$

Dr. Nikolai Mikuszeit, on Stack Overflow, provided a solution with an R^2 value of 0.999, which is given by

$$w_{0} = \frac{1.874}{(H+13.83)^{0.162}}\, w_{H}^{\left(\frac{0.949}{(H+1.228)^{0.052}}\right)} \qquad (B4)$$

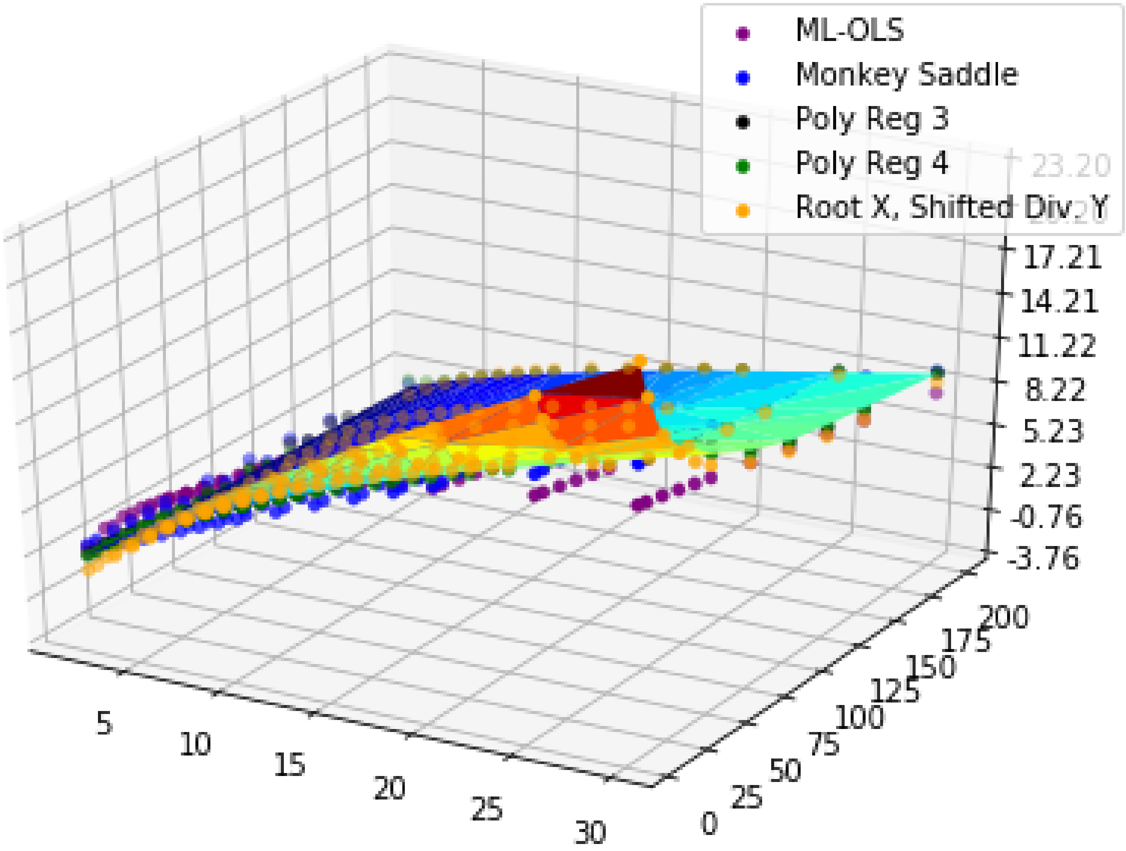

Figure S3.1: Visual validation of the wind-function fit for various functional forms

Where, x: velocity measured at height H $w_{H;}$ y: Height H; z: velocity at ground (at 1 foot height from surface, $w_{h=0}$)

Table S3.1 Horton's updated bibliography – most comprehensive to our knowledge: titles include those of papers, reports, books, and technical discussions

S.No.	Year	Title
1	1896	A report for the New York State Engineer and Surveyor
2	1900	Computational works connected with hydraulic tests
3	1900	Report on the measurement of the volume of streams and the flow of water in the State of New York
4	1901	Available water power of Michigan and its economical development
5	1901	American canal problems with special reference to the state of New York
6	1902	The law of water as applied to paper mills
7	1903	Annual Report of the State Engineer and Surveyor of New York
8	1905	The drainage of ponds into drilled wells
9	1905	Snowfalls, freshets, and the winter flow of streams in the state of New York
10	1905	Progress of Stream Measurements for the Calendar Year 1904, Part 2, Hudson, Passaic, Raritan and Delaware River Drainages
11	1905	Report of progress of stream measurements for the calendar year 1904; Part VI, Great Lakes and St. Lawrence River drainage
12	1906	Surface drainage of land by tile
13	1906	Weir experiments, coefficients, and formulas
14	1906	Turbine water-wheel tests and power tables
15	1906	Underground water resources of Long Island, New York
16	1906	Report of progress of stream measurements for the calendar year 1905, Part II, Hudson, Passaic, Raritan, and Delaware River drainages
17	1906	Report of progress of stream measurements for the calendar year 1905; Part VI, Great Lakes and St. Lawrence River drainages
18	1906	Hudson, Passaic, Raritan, and Delaware River Drainages
19	1906	Great Lakes and St. Lawrence River drainages
20	1907	The Adirondack rainfall summit
21	1907	Weir experiments, coefficients, and formulas
22	1907	Determination of stream flow during the frozen season
23	1908	Deforestation, drainage and tillage with special reference to their effect on Michigan streams

24	1910	The Turbine Water Wheel as a Prime Mover
25	1911	Ebermayer's experiments on forest meteorology
26	1913	Effects of recent flood on New York streams; study of rainfall and stream discharge, with hydrographs for fourteen rivers
27	1913	Flood frequency and flood control
28	1914	Evaporation from snow and errors of rain gage when used to catch snowfall
29	1914	Discussion of Report of Committee on Yield of Drainage Areas
30	1914	Derivation of runoff from rainfall data. Discussion
31	1915	Idiosyncrasies of Underground Water
32	1915	The melting of snow
33	1915	Discussion of paper by A. F. Meyer on Computing Runoff from Rainfall and other Physical data
34	1915	Discussion: Yield of Underground Reservoirs
35	1916	Standing-wave experiment
36	1916	Some better Kutter's formula coefficients
37	1916	Diagram for full comparison of hydraulic turbines
38	1916	A study of the depth of annual evaporation from Lake Conchos, Mexico. . Discussion hy M. Hegly, Robert E. Horton, and J. W. Ledoux. p.
39	1917	A new evaporation formula
40	1917	A new evaporation formula developed
41	1917	Rational study of rainfall data makes possible better estimates of water yield
42	1917	Failure of hydraulic projects from lack of water prevented by better hydrology
43	1917	Determining the regulating effect of a storage reservoir
44	1917	Drainage Basin and Crop Studies Aid Water-Supply Estimates
45	1918	Air chimneys of ice below a waterfall
46	1918	Additional data needed by engineers
47	1918	Discussion on "obstruction to flow by bridge piers"
48	1919	Watershed Leakage in Relation to Gravity Water Supplies
49	1919	Additional meteorological data needed by engineers
50	1919	Evaporative capacity
51	1919	Device for obtaining maximum and minimum water surface temperatures
52	1919	Rainfall interception
53	1919	Some broader aspects of rain intensities in relation to storm-sewer design
54	1919	The measurement of rainfall and snow

55	1919	Discussion on The Duty of Water In the Pacific Northwest
56	1920	From the Committees: Hydrological Meteorology
57	1920	Modern hydraulic turbine design
58	1920	Comparison of snow-board and raingage-can measurements of snowfall
59	1920	Weather and literature
60	1921	Vapor pressure and humidity diagram
61	1921	Results of Evaporation Observations
62	1921	Correlation of maximum rain intensities for long and short time-intervals
63	1921	Discussion of the probable variation in yearly precipitation
64	1921	Cloudburst rainfall at Tarborton
65	1921	Unusual lightning
66	1921	Thunderstorm-breading spots
67	1921	The beginning of a thunderstorm
68	1921	The depletion of ground-water supplies
69	1922	Discussion of “The American Mixed-Flow Turbine”
70	1922	Discussion of "Siphon Spillways"
71	1923	Group distribution and periodicity of annual rainfall amounts
72	1923	Transpiration by forest trees
73	1923	Rainfall interpolation
74	1923	Accuracy of areal rainfall estimates
75	1923	Rainfall duration and intensity in India
76	1923	Discussion
77	1923	Engineering Meteorology and Hydrology
78	1924	Determining mean precipitation on a drainage basin
79	1924	Discussion on Distribution of Intense Rainfall
80	1924	The Distribution of intense Rainfall and some other Factors in the Design of Storm Water Drains
81	1924	Flood reduction by reservoirs
82	1924	Discussion of paper by C. S. Jarvis on flood flow characteristics
83	1927	Hydrology of the Great Lakes
84	1927	Report on the lake lowering controversy and a program of remedial measures
85	1928	Report on proposed tri-state compact [to] Board of Commissioners
86	1931	The field, scope and status of the science of hydrology
87	1931	Field, scope and status of hydrology, Water and Water Engineering

88	1931	New gravity water-supply system of Albany, N. Y.
89	1931	Discussion of "Horton on Regulation of Niagara River"
90	1932	Water diversion between drainage basins
91	1932	Drainage basin characteristics
92	1932	Discussion of the report of the committee on floods
93	1933	Slope table for fully controlled hydraulic experiments in open channels
94	1933	The relation of hydrology to the botanical sciences
95	1933	The role of infiltration in the hydrologic cycle
96	1933	Separate roughness coefficients for channel bottom and sides
97	1933	Storm-flow prediction
98	1933	Columnar Vapor Drift
99	1933	Primary Rainfall Types
100	1934	Water-losses in high latitudes and at high elevations
101	1934	Compilation and summary of the evaporation records of the Bureau of Plant Industry, U.S. Department of Agriculture, 1921-32
102	1934	Snow-surface temperature
103	1934	Laminar sheet flow
104	1934	Recent tendencies in relation to valuation of water rights
105	1934	Discharge coefficients for tainter gates
106	1934	Composite roughness in channels
107	1935	Surface runoff phenomena : Part I, Analysis of the hydrograph
108	1936	Natural stream-channel storage
109	1936	Maximum groundwater levels
110	1936	Surface-runoff control, Headwaters Control and Use, Chapter II
111	1936	Historical development of ideas regarding the origin of springs and ground water
112	1936	Relation of Hydraulic and Laboratory Resaerch to Physical and Economic Geography
113	1937	Hydrologic Interrelations of Water and Soils
114	1937	Determination of infiltration capacity for large drainage basins
115	1937	Hydrologic aspects of stream-flow stabilization
116	1937	Natural stream channel-storage (Second paper)
117	1937	Hydrologic aspects of stream-flow stabilization
118	1937	Hydrologic research

119	1938	Analysis of simulated rainfall experiments
120	1938	Channel waves subject chiefly to momentum control
121	1938	Phenomena of the contact zone between the ground surface and a layer of melting snow
122	1938	Rain wave-trains
123	1938	Seddon's and Forchheimer's formulas for crest velocity of flood-waves subject to channel-friction control
124	1938	Report on Soil Conservation Service special advisory committee, 1937-1938
125	1938	Definitions and classification of flood waves
126	1938	The interpretation and application of runoff experiments with reference to soil erosion problems
127	1938	Apples from Eden and other short stories
128	1939	Memorandum regarding purpose and procedure for research project on infiltration [in Delaware River]
129	1939	Analysis of runoff-plat experiments with varying infiltration capacity
130	1939	Hydrologic advisory committee to the Research Division of the United States Soil Conservation Service, 1938-1939
131	1939	What Can We Do About the Weather?
132	1940	Hydrologic advisory committee to the Research Division of the United States Soil Conservation Service, 1939-1940
133	1940	The infiltration-theory of surface-runoff
134	1940	Hydrophysical approach to quantitative morphology of drainage basins
135	1940	An approach toward a physical interpretation of infiltration capacity
136	1940	Suggestion for a comprehensive research program on runoff phenomena
137	1940	Delaware River Basin Flood Volumes, n. 1
138	1940	Determination of areal average infiltration-capacity from rainfall and runoff data
139	1940	Sprinkled Plat Runoff and Infiltration Experiments on Arizona Desert Soils
140	1940	Sprinkled Plat Runoff and Infiltration Experiments on Arizona Desert Soils
141	1941	The Role of Snow, Ice and Frost in the Hydrologic Cycle
142	1941	Flood-crest reduction by channel storage
143	1941	Sheet erosion: past and present
144	1941	Virtual channel-inflow graphs
145	1941	Hydrologic advisory committee to the Research Division of the United States Soil Conservation Service

146	1941	Discussion (in response to N. E. Edlefsens, Report of the committee on the physics of soil-moisture, 1940-1941, pp. 917-926)
147	1941	Discussion (in response to M. R. Huberty and A. F. Pillsbury, Factors influencing infiltration-rates into some California soils, pp. 686-693)
148	1942	Discussion (in response to A. B. C. Anderson, J. E. Fletcher, and N. E. Edlefsen, Soil-moisture conditions and phenomena in frozen soils, pp. 356-364)
149	1942	Derivation of infiltration-capacity curve from infiltrometer experiments
150	1942	Hydrologic advisory committee to the Research Division of the United States Soil Conservation Service, 1941-1942
151	1942	Remarks on hydrologic terminology
152	1942	An experiment on flow through a capillary tube
153	1942	Closure to discussion (in response to Horton, R. E., An experiment on flow through a capillary tube, pp. 534-538)
154	1942	Simplified method of determining an infiltration-capacity curve from an infiltrometer-experiment
155	1942	A simplified method of determining the constants of the infiltration-capacity equation
156	1942	Some effects of rain erosion and sedimentation on infiltration-capacity
157	1943	Evaporation—Maps of the United States
158	1943	Hydrologic interrelations between lands and oceans
159	1943	On the relation of soil conservation to air and ground-water pollution
160	1943	A discussion of the relation of soil conservation to air and ground-water pollution
161	1944	Report on proposed improvement and extension of Hemlock Lake water supply system, Rochester, N.Y
162	1944	Some Hydrologic Characteristics of the United States, Part 1
163	1945	Infiltration and runoff during the snow-melting season, with forest-cover
164	1945	Erosional development of streams and their drainage basins, hydrophysical approach to quantitative morphology
165	1947	Preliminary outline for a comprehensive research on runoff phenomena
166	1948	The physics of thunderstorms
167	1948	Statistical distribution of drop sizes and the occurrence of dominant drop sizes in rain
168	1949	Convectional vortex rings – hail

4

Robust Trend Detection

This chapter discusses the mathematical aspect of change (e.g. climate change or Arctic lake change), that is the question of how to reliably distinguish signal from noise in long-term trends. This chapter shows that detectable hydro-climatic trend signals can be separated from correlation noise at a 2-sigma level, nearly a ~1-sigma improvement from current practice. This is made possible by a marriage of trend detection methods from Hydrology (non-parametric family of tests: Mann-Kendall and its variants) and Econometrics (parametric tests) that together represent a portfolio of 16 individual candidate methods. Combining these methods, trend detection robustness (i.e. both statistical confidence and power) improves by ~1 sigma compared to current hydrology standards. This approach also allows us to detect climate change signals from lakes and hydro-climate variables without any a priori assumptions about the data.

Intellectual Property (IP) protection: *the work in this chapter has led to a set of potential patents. A part of this chapter has been excluded for IP protection reasons. To bridge the gap between chapters 1-3 and 5, as well as to address the title of the dissertation, the work on trend detection is presented in this chapter with sufficient details to appreciate the background and conclusions without revealing the core IP details.*

Introduction

"Sky-rocketing" earth observation satellites, data and tools

One earth observation satellite (EOS) image from NASA's most successful satellite program (Landsat) was ~$3500 in 1998, and it was ~$600 in 2006. In a landmark decision that same year, NASA made its entire Landsat archive of millions of satellite images public and free at once. With this explosion of data availability, scientists now have a global coverage of earth observations and an annual (or sub-annual) time series that can be constructed for ~35 years. In response to these developments, Google developed Google Earth Engine (Gorelick et al, 2016) which now provides scientists with near instant access to the entire Landsat archive among 1000s of additional satellite and other geospatial datasets.

Motivation for robust trend detection

Though the instruments, data and tools have “sky-rocketted”, some aspects of statistical techniques available to analyze and gain insights from the time series data in the geosciences are still in the 1940s. A predominant question that is the subject of most geoscience problems is how do observations at a location in space change in the long-term as opposed to near-term oscillations. How does one estimate such changes in a statistically robust way? In this question lies the purpose of trend detection. A working definition of *time series trend detection* is the notion of checking whether a variable is “systematically” increasing or decreasing “on average” over time. It can be done at various levels from simple to complex methods.

Looking at the data

In very simple cases, especially when working with individual time series, one might simply use eye-balling or a scatter or line plot to examine the trend and no statistical tools are needed. A method of slightly more complexity is innovative trend analysis (ITA, Güçlü, 2020) which uses a straight line to separate points of up-trends and down-trends visually by eye-balling. When working with a large number of time series, eye-balling becomes unwieldy, for example when we are interested in trends at various spatial locations, and in such cases, a statistically robust approach to trend detection becomes inevitable.

Mixed model

When working with multiple time series trends simultaneously, a mixed model (i.e. with slope as the random variable) can be used to examine the slope of linear fit of the form for multiple spatial locations (i,j):

$$Y_{i,j,t} = \beta_{1i,j} + \beta_{2i,j}t + \varepsilon$$

Histograms of slope β_2 may serve as a simple visual method to view trend magnitudes for multiple locations at once. While this allows us to view the magnitude of trends at multiple locations simultaneously, it is still not robust to oscillations, especially if the trend magnitude is small and cyclic oscillations around the mean are large.

The need for robust trend detection

A mathematical definition of *linear trend estimation* is that of computing the slope of a straight line fit to a time series with time in *abscissa* (X-axis) and any given variable in the *ordinate (Y-axis)*. One cannot be content with fitting a line as it might be due to a spurious regression fit, so a way of ensuring statistical "goodness of fit" is desired. Due to serial dependence in time series data, with eye-balling, if the dependence is high, we sometimes will see a trend but there isn't one, so a more systematic way to examine trends is needed, which the statistical approach affords. There are also cases when there is noise (due to serial dependence of data or measurement errors) in the data and you cannot see the trend, but a statistical approach allows you to see it.

A dictionary of concepts for robust trend detection

It may be helpful to start with some basic definitions to understand how trend detection can be performed with robustness. The concepts covered in the dictionary below include those of statistics typically taught via multiple courses in upper division level mathematics, engineering or economics education. While many of these concepts are covered in applied science education, a refresher may help the reader who is expected to be a practitioner in applied sciences.

Statistical tests

The most important question irrespective of the choice of trend test is whether the trend magnitude or trend direction (or say just its presence) can be ascertained, i.e. is it really the signal of a long-term trend or some noise due to oscillations around the mean? To answer this question, we need what are called *statistical trend tests*, which are used to perform *robust trend detection*, the topic of this paper. A number of *parametric* and *non-parametric* methods are available for this purpose to achieve *robustness* with *hypothesis testing*.

Robustness

Statistical robustness becomes possible when the sample sizes are of order ~30 or more (by virtue of a thumb rule related to Central Limit Theorem). It allows one to set trend estimation on a probabilistic footing. Though not universally valid by any means, typically, time series that have sample sizes smaller than 30 samples are not regarded as fit to detect long-term change. In climate change studies, this period is called the “climate normal”. This heuristic has to do with the geometric properties of the normal distribution, which is the property that 95% of the “normal” magnitudes and frequencies of observations of “natural” variables happens within 2 standard deviations (of the variable) from the mean, or in other words, 30 samples are representative to construct a sample “normal” distribution of the true population and tell with ~95%

certainty whether any random value selected from the real population of the distribution is indistinguishable from the sample mean. This concept is exploited to assign statistical robustness in trend detection.

Hypothesis testing

Building on the simple working definitions, a more accurate definition for the presence of a trend comes from the notion of hypothesis testing, which may be defined as a conditional test that assumes a distribution of the test statistic which differentiates the null (i.e. null hypothesis, H0, or no trend or trend=0) from the alternative hypothesis (non-zero positive or negative trend) if the statistic is sufficiently large or small (i.e. typically ~2 standard deviations away from the mean of 0, i.e. α=0.05).

Rejection probability (p)

A rejection probability is the probability of rejecting a null hypothesis.

Critical value and finite sample critical value

Critical value references the prescribed level that is used to compare the p value or the t(or J)-statistic test for the hypothesis test at a prescribed level of α. It can be derived analytically in the case of tests that depend on a defined distribution or the distribution can be constructed using what are called finite sample critical values (using an Monte-Carlo simulation, defined below).

Trend detectability

It is important to pause and ponder here that there are two parts to the detection problem: 1) Can a trend be detected when it does exist? (an ability that is called "power"); 2) When a trend does not exist, can we be "confident" it is not a trend?

Statistical significance or probabilities of rejection or "confidence" (1-α)

The ability to report a trend only when it does exist is called statistical confidence. Lack of confidence leads to what is called, "Type-I" error, due to Pearson (1930). In other words, when the slope of the trend is zero (i.e. $\hat{\beta}=0$), the probability of null rejection is called the type-I error. Typically, scientific experiments assume $\alpha=0.05$, i.e. if the experiment is repeated 20 times (i.e. 100/(0.05 x 100), statistically, 1 in 20 of those times it is not going to make a mistake, i.e. reject the null incorrectly. As we will later see with some controlled experiment results, the error in this is often as high as being 1 in 2 or 1 in 3 when we believe (or report) it to be 1 in 20 in 1000s of scientific studies in applied science (specifically hydrology), using methods which are being used in 1000s of papers every year. A test is configured *a priori* with a significance level, alpha, such that a test statistic falsely rejects the null hypothesis with probability α. The quantity, $1-\alpha$, is the probability of not rejecting the null hypothesis and is sometimes called the 'confidence level' of the test.

Statistical power (1-β)

The ability of a trend test to correctly detect trends that do exist is dubbed statistical power. Simply put, power is the probability of not making a Type II error (Weiss, 2008). Statistical power ranges from 0 to 1, i.e. high power is equivalent to low probability β of wrongly failing to reject the null hypothesis decreases. Lack of "power" leads to what is called Type-II error.

Mathematically, power is 1 – β. In other words, when slope of the trend is non-zero (e.g. $\widehat{\beta}>0$) the probability of not rejecting the null hypothesis of no trend when there is a trend is called the power (i.e. 1 minus type II error). Note that $\widehat{\beta}$ (slope) and β (type-II error) are entirely different variables. It is computed for a given level of significance (often assumed to be at 0.05). Power of a test varies with record length, trend magnitude, and the marginal probability distribution of the data of independent time series. For dependent time series, power will also vary with the form of the dependence of the observation (Lettenmaier, 1976). Powers lower than 0.8, while not impossible, would typically be considered too low for most areas of research. If the power is close to 1, the hypothesis test is good at detecting a trend when it does exist. Power is equivalent to the sum of true positive and false negative in terms of the confusion matrix, which suggests that high power does not necessarily mean it is good as the goal of a test is to have a high true positive and a low false negative (α). Therefore, power without confidence is not too useful.

An analogy for power and confidence

Power is the ability to convict a criminal for a crime, and confidence is the ability to avoid convicting an innocent. Just like how confidence is always preferred in jurisprudence, in robust statistics and climate change trend detection (and broadly in scientific experiments), having high power at the expense of confidence is not very useful as it leads to wasteful expenditure of time and effort and convicting the innocents (which is costly to undo, and often never done, as the search for evidence often stops at that point, and guilt takes over and leads to even more wasteful expenditure of time/effort to cover up or justify the mistakes). But with this analogy, it is amply clear that one does not guarantee the other. Often power is gained at the expense of confidence and vice versa, but balancing the two in a reasonable and acceptable manner is the goal of robust trend detection. In doing so, confidence is often fixed at an *a priori* level of $\alpha=0.05$ or at a confidence level of 95% ($1-\alpha$) or at the rate of convicting 1 innocent person for every 20 criminals. In other words, for a death penalty for extreme criminals, you want a tiny α (say 0.01) which will decrease the chances of catching all the criminals, but only 1 in every 100 convict will be an innocent.

Correlation

Correlation is the property that relates two quantities in terms of a linear relationship. Two time series are said to be positively (negatively) correlated if systematically (in some instances) when values are observed to be above (below) its mean, the other also is above (above) the mean, but there may be no causal relationship between them.

Serial Correlation

Serial correlation is also known as autocorrelation, and in simpler terms it represents correlation in time, i.e. the value of one variable in time has some dependence on the previous value (across the time series, though this may not be true for all samples, but is generally true of the underlying true deterministic process). This property can be viewed also as predictable oscillations in the time series that are different from the average trending behavior. Serial correlation often interferes with detection of trends. Similarly the correlation of the noise can be considered separately (as will be discussed in the *ARMA model* definition below)

Bias Corrected Autocorrelation

Grenander and Rosenblatt (1953) showed that if you know the true autocorrelation and the time series is stationary, when estimating trend parameters least squares is the best solution, ignoring correlation structure. *A priori* knowledge of correlation structure of the time series would be ideal, but this is not possible in most time series. Bias correction is the process for removing biases from the estimated autocorrelation. Sample derived autocorrelation is prone to sampling bias, and such biases are pronounced especially in small samples. A solution for this problem is to perform bias-correction for autocorrelation using the results of van Giesenbergen (2005), Bao and Ullah (2007), and Quenouille (Jackknife, 1956) with respect to some properties of the time series.

Long-run variance or zero frequency spectral density

The long-run variance is the (large sample) variance of the sample average of an autocorrelated mean zero time series that is covariance stationary. The long-run variance is an infinite sum of autocovariances and is a component of the variance of an estimated trend slope. The long-run variance is distinct and different from the variance of a stationary time series. When the time series has no autocorrelation (i.e. white noise), the long-run variance and the variance are equal.

Prewhitening

A procedure to eliminate or reduce short-term persistence to improve the ability of detecting long term trends. It has been shown that for large samples ($n \geqslant 50$), and high slopes of trend ($\beta \geqslant 0.01$), prewhitening can lead to loss of power, because serial correlation has a negligible effect in these cases (Bayazit and Önöz, 2007). On the other hand, when pre-whitening involves high correlation (more than $|0.95|$), it can be handled by setting a threshold. It can be shown that prewhitening has no effect on power. If the AR1 parameter is known, then you don't lose or gain power as opposed to not prewhitening. When prewhitening is done with time series that do not have auto-correlation, it kills power.

Trend free prewhitening

Trend free prewhitening refers to removing the trending behavior before applying the prewhitening procedure.

Non-parametric methods

Non-parametric methods are those where the hypothesis test is not performed against the slope for which the test is performed. There are several such methods (few are discussed below), which have interesting advantages (e.g. robustness to outliers), but also big disadvantages (e.g. lack of adaptability to tests of various slopes).

Rank based trend method

The presence or absence of trend can be identified with rank-based methods, e.g. Mann Kendall test (MK) i.e. by checking whether the frequency of higher values that appears later in time is more than those earlier in time. In this case we cannot say anything about the trend magnitude, but only the direction (or that it exists or is different from 0) under certain conditions (assumptions) of the time series data. We will discuss these methods in more detail in the Methods section.

Permutation based trend method

Theil-Sen slope (Thiel, 1950; Sen, 1968) approach, though called non-parametric, is actually a semi-parametric estimator also known as a quantile median estimator. It is an approach to assess all permutations of pairs of points in the time series. It assumes that the trend is linear in time, so it has more variation in terms of estimating the trend than least squares. If the data is normally distributed, then least squares estimation has a smaller error, but if the tail is fatter, then sen's slope estimator has a smaller variance than least squared. This method is more robust to outliers and widely used, but suffers from the disadvantages of the rank based tests.

Parametric methods

Ordinary Least Squares (OLS)

OLS is the most common way to estimate a linear trend. It is the preferred way to calculate the trend magnitude. The statistical robustness of the trend is guaranteed by using a test statistic using the standard error. Though this is widely used, it does not handle serial correlation at all and often can be misleading in small slopes and/or large oscillations (serial dependence).

Vogelsang trend test

Vogelsang (1998) method is a parametric trend test applied to data that has been pre-processed by a partial sum procedure. This allows hypothesis testing about trend slopes without having to directly estimate a long-run variance. The method also has a scaling factor that controls over-rejections caused by very strong autocorrelation including the case of a unit root (generalized random walk) in the autocorrelation. With its usage, the possibility that the statistical significance is being spuriously generated by strong serial correlation or a unit root in the data can be effectively ruled out (Fomby and Vogelsang, 2002).

Bunzel-Vogelsang trend test

The Bunzel and Vogelsang (2005) trend test is a parametric trend test based on the original data that uses a nonparametric kernel estimator of the long-run variance of the random component to construct a test statistic. This test can be configured with a similar scaling factor as the Vogelsang test that controls over-rejections caused by strong serial correlation including a unit root. The Bunzel-Vogelsang test typically has higher power than the Vogelsang test because it is based on a more precise estimator of the trend slope. Because the Bunzel-Vogelsang test uses a kernel estimator of the long-run variance, a bandwidth and kernel need to be chosen in practice. This choice is avoided by the Vogelsang test.

Kernel and bandwidth

A kernel is a weighting function of a symmetric geometric shape that for the purpose of long-run variance estimation, downweights sample autocovariances (or autocorrelations) as a function of the autocovariance lag. For a given kernel, a bandwidth parameter controls how fast or slow the downweighting is applied. Nonparametric kernels estimators of the long-run variance are when testing hypotheses about the trend parameters of a time series with serial-correlation in the random component (details are discussed in the Appendix). The variance of a trend slope estimated by OLS is proportional to the long-run variance based on a central limit theorem (CLT) result. If the usual OLS variance estimator is used to construct a t-statistic for the trend slope, it can be shown that the t-statistic will have tails that are fatter or thinner than a standard normal random variable (for positive or negative serial-correlations respectively) giving an invalid test. A valid test is constructed using a t-statistics based on an estimator of the long-run variance. The long-run variance can be estimated parametrically by assuming an ARMA structure for the errors or nonparameterically using a kernel weighting sum of sample autocovariance. The ratio of the sample variance of the random component to an estimator of the long-run variance is sometimes called the ***Effective Sample Size (ESS)*** that accounts for serial correlation. The ESS approach is typically implemented under the assumption the autocorrelation is of AR(1) form. The nonparametric kernel approach does not take stand on the ARMA structure.

The choice of kernel and bandwidth for the nonparametric kernel long-run variance estimator was analyzed by Andrews (1991) building on well known results from the time series spectral analysis literature. For a given kernel Andrews (1991) derived data dependent formulas for the bandwidth that minimize the approximate mean-square error of the long-run variance estimator.

ARMA model

ARMA stands for auto-regressive moving average model. It is a statistical model that can construct or represent a time series as a sum of its constituents which are the AR (auto-regressive) and MA (moving average) components. ARMA models are used to generate synthetic (i.e. made up) data which can be induced with a trend (of any arbitrary magnitude) and noise of any type (correlated or uncorrelated) to test whether a given *trend test* does indeed detect a real trend.

AR

“Auto-regressive” is a component (parameter) of the ARMA model which captures the strength of the serial correlation (or correlation in time) in the actual physical variable (e.g. actual rainfall amount which, in monthly scale, is related to the amounts of the preceding months, e.g. winter months that have much of the year’s precipitation at a location are followed by winter months of high precipitation). It can be defined for various autocorrelation lags.

MA

Moving average is the same as AR, but over what is considered correlated or uncorrelated error (or noise, e.g. measurement error from satellites or other sources of errors) as opposed to the underlying process signal (AR component).

Interoperability of AR and MA

AR and MA are interoperable, i.e. MA can be written in the form of a sum of linear AR components of T (length of time series) minus AR lags.

Randomized Trials

Bernoulli trial

A Bernoulli trial or binomial trial is a random experiment, in this case a trend test (parametric or non-parametric) at an *a priori* fixed null-rejection or significance level) with exactly two possible outcomes, "trend" and "no trend", in which the probability of success is the same every time the experiment is conducted. An ARMA model with a randomly generated error term can be used to create a synthetic time series with known properties, on which a trend test is performed at a desired (or prescribed) significance level, which can be considered a Bernoulli trial. Bernoulli trials follow *binomial law* which allows us to assign a straight-forward deterministic (closed-form) confidence interval.

Monte-Carlo (MC) simulation

Monte-Carlo simulations may be used to quantify the power and confidence using numerous Bernoulli trials of the trend test. The underlying concept in MC is to use randomness (via random number generators) to conduct a large number of trials such that the aggregate properties (confidence and power) of a trend test may be determined for an *a priori* desired confidence interval.

Replicates (n)

An instance of a random Bernoulli trial using a pseudo-random number generator done in Monte-Carlo simulations, in this case using an ARMA model of a particular specification (i.e. for a chosen range of AR and MA orders, p and q, respectively).

Confidence interval (CI)

Confidence interval is the average number of rejections you get (over n replicates of ARMA time series or bernoulli trials) and it can be calculated with a formula as CI = $2\sqrt{\frac{p(1-p)}{n}}$

For rejection probability (alpha), p=0.05 and number of replicates (n) = 1000.

CI = 0.01. MC simulation of 1000 replicates would give us a confidence of 0.01 on “power” and “confidence”.

Bootstrap (resampling) methods

A random sampling technique to construct a smooth distribution from using Monte Carlo sampling. It is a convenient way to construct any distribution (in the present context: distribution of the test statistic) directly from a finite sample of data without making any assumptions about the underlying distribution.

Response Surface

An established relationship between explanatory (dependent) variables and one or more response (independent) variables. The method was introduced by George E. P. Box and K. B. Wilson in 1951.

Negative variance problem

The possibility, in practice, of a nonparametric kernel long-run variance estimator being negative was re-discovered in the econometrics literature in the 1980s. An observed time series that generates a negative estimated variance makes it impossible to compute a t-statistic. There is a direct link to long-run variance estimation and spectral density estimation. The spectral density estimation literature goes back to the 1940s and 1950s and is well summarized in the textbook by Priestley (1981).

1. Bartlett and Parzen (1961) knew in the 1940s and 1950s that non-parametric kernel spectral density estimators could give negative values for some kernel and

bandwidth combinations. They proposed kernel functions that guarantee positive estimators for any bandwidth choice.

2. Using the fact that long-run variance estimators are proportional to spectral density estimators at frequency zero, Newey and West (1987) leveraged the Bartlett kernel to provide a long-run variance estimator guaranteed to be positive. They proved the validity of the Bartlett kernel estimator in settings much more general than in Bartlett's original work.
3. Hamed and Rao (1998) (HR98) essentially use a nonparametric kernel estimator of a long-run variance to modify Mann-Kendall trend tests to make them valid when a time series has autocorrelation. HR98 used a kernel that is approximately equal to the cube of the Bartlett kernel with bandwidth equal to sample size. HR98 put zero weight on statistically insignificant autocorrelations which is equivalent to putting holes in the kernel. The cubed Bartlett kernel with holes does not guarantee a positive variance estimator in practice.

Effective sample size correction

The ratio of the sample variance to the long-run variance of the random component of a potentially trending series is sometimes called the Effective Sample Size (ESS) that accounts for serial correlation. The ESS approach is typically implemented using a parametric estimator of the long-run variance under the assumption that the autocorrelation is of AR(1) form.

Trade offs or chicken and egg problems

There are at least four trade offs when dealing with robust trend detection.

Trade-off 1: identification problem vs misspecification

When an ARMA model is fit to a time series, there is often a trade-off between the desire to identify the correct model and misspecification of the model to achieve parsimony (*occam's razor*). It is analogous to balancing the number of unknowns and the number of equations in simultaneous equations, a well-known issue. In George Polya's (1945) heuristics of problem solving, in the planning phase of problem solving, he suggests asking three questions: is the data sufficient to determine the unknown? Or insufficient or redundant? Identification problem has to do with redundancy. Often when the number of AR and MA parameters are large and the length of the time series is small, there may be multiple optimal (redundant) fits for the same data, which leads to what is called the *identification* problem. The same issue is often called *equifinality* in the context of hydrology modeling in an overdetermined system (relative to the information) and may be called other things in other fields. This is a common issue in model fitting when large numbers of parameters are involved. However, if the time series is large and the number of parameters is small, the unique value of the roots can be determined. When an identification problem exists, it can be dealt with by using, what we call, ARMaps, and reducing the (p,q) order of the ARMA model, even if the model does not fully represent the true structure of the data, to avoid unwieldiness. There are obvious trade-offs between accepting a misspecified ARMA model (owing to desired simplicity) and errors due to the identification problem. The identification problem can also be resolved by having knowledge of the underlying process, at least for some (if not all) of the ARMA (p, q) parameters.

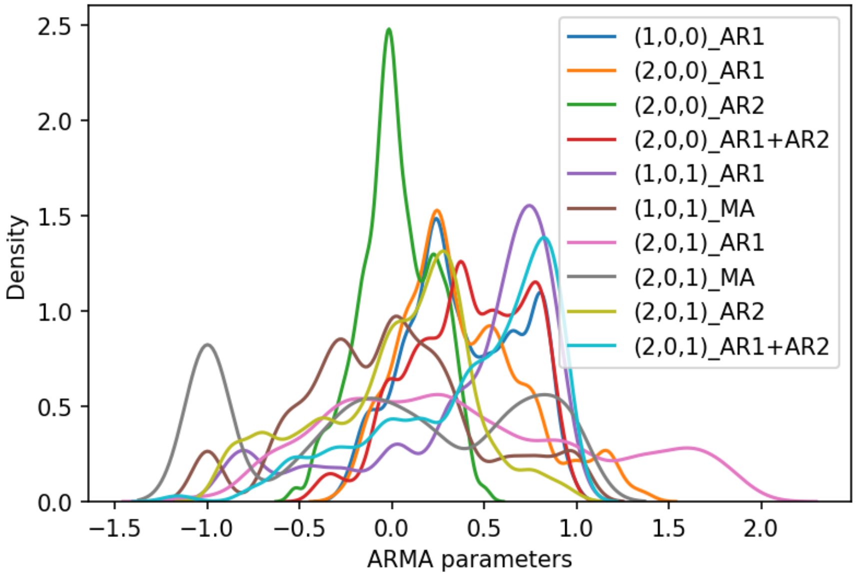

Figure 4.1: Parameter ranges for various ARMA model specifications fit to the same selected empirical data.

Note that the centroids of the ARMA(1, 21, 2) models are stable in most cases, but there is a wide range due to misspecification of the model.

Trade-off 2: power vs confidence or errors of omission vs commission

When the true trend is very close to zero, statistical confidence and power diminish significantly, as even a little bit of noise (in the form of serial correlation, error or otherwise) in the opposite direction could make the trend indistinguishable from a non-trend. Conversely, if the slope is really large and the serial correlation is small, both "power" and "confidence" increase. While the former *curse from being too close to zero* is always guaranteed, the latter is not always guaranteed, and requires some careful work to ensure it is (at best, almost) guaranteed. Among the two desired features of high power and confidence, to simplify the problem of trend detection, often confidence is fixed at 95% (i.e. 5% of imperfection in null-rejection probability is widely accepted), and then a test that has the highest power (ability to detect trends when they do exist) is widely considered the best tool at hand to conduct robust trend detection. Other than the constraint of having to fix one or the other, a practical reason for fixing null-rejection rate *a priori* is that often scientific effort should not be misdirected as a low alpha level is considered an error of *commission* while low power is an error of *omission*. As with the analogy in jurisprudence given earlier, *committing* a mistake is worse than *omitting* (in this case, the presence of a trend).

Trade-off 3: detectability of trend vs magnitude of trend

Obviously, when the slope of the linear trend fit is large, one would imagine that it is easier to tell whether the trend really exists, and *vice versa*. What's convenient is that this tradeoff can be quantified with a quasi-analytical expression and this is a widely recognized result in econometrics but in hydrology literature this is largely not known, discussed or used:

If the AR1 parameter is plus or minus 1, $\sigma = |1 + \theta||$ and $\beta_{max} = 26\sigma T^{\frac{1}{2}}$

If $\phi_1 + \phi_2 = 1$, i.e. unit root case, detected trend should be larger for maximizing power, $\sigma = \frac{|1+\theta|}{|1+\phi_2|}$ and $\beta_{max} = \frac{25\sigma}{T^{\frac{3}{2}}}$

Else, $\sigma = \frac{|1+\theta|}{|1-\phi_1-\phi_2|}$ and $\beta_{max} = \frac{25\sigma}{T^{\frac{3}{2}}}$

Trade-off 4: uncertainty of autocorrelation vs inference of the trend

Detrending increases the certainty of estimated auto-correlation, but when no auto-correlation is present, detrending will lead to spurious auto-correlation, and it is not possible to have simultaneous knowledge of the two. This is the most common chicken and egg problem of trend detection. The path forward when confronted with this problem is to consider the range of trends in a given context and the range of auto-correlations and the uncertainties in ARMA model specifications for a wide range of slopes to understand what the trade offs may be in terms of actual power and confidence. This is beyond the scope of the present study, but can be dealt with a similar simulation framework as that used here.

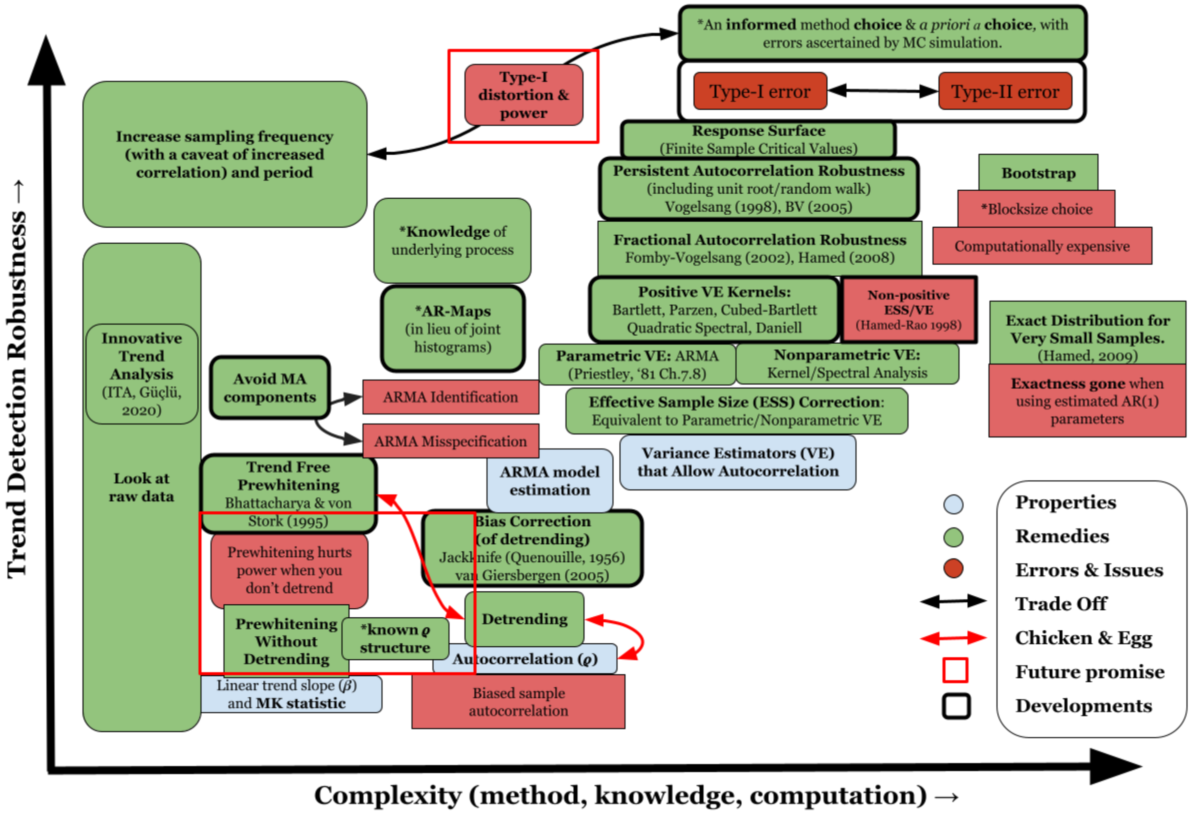

Figure 4.2: complexity of trend detection method vs robustness

*methods developed in this work

Figure 4.2 brings together the various operations involved in robust trend detection considering complexity of the method, expert knowledge and computation, in relation to the gain in robustness in terms of detecting the trend with certainty (numerical or visual).

Developments in sister domains: Hydrology and Econometrics

Jargon differences

A large body of literature exists in time series trend detection in the fields of Hydrology and Econometrics but the developments in these fields have not diffused into each other and they seem to have evolved independently. This is evidenced by jargon differences in referring to the same concept in the two sister fields. What is called *Synthetic Data Generation* (SDG) in Hydrology is called *Data Generation Process* (DGP) in Econometrics. The term statistical *confidence* is not preferred by econometricians when referring to statistical *significance*. What is called an *identification problem* for estimation of ARMA parameters is often called *equifinality* in the context of parameter estimation problems in hydrology – both referring to finding a *pareto* (optimal) set of parameters that lead to the same outcome. In econometrics, *burn in* refers to initiating a model and running it for a period of time for the values that depend on initial conditions to regress to mean, while in Hydrology, in the context of model building, the same may be called *warm up*. What is *trial and error* to a hydrologist would be *successive approximations* for an econometrician. Such jargon differences show that the collaboration across these fields is linguistically challenging, but the same ideas have been examined from different angles. While this is not necessarily undesirable, it serves to show that some problems solved in one field may not be solved by the other field. In the remainder of this paper, we show that it turns out that this is the case for robust trend detection where a family of non-parametric trend detection tests in Hydrology and a family of parametric tests in Econometrics mutually benefit from each other. Jargon differences are not a problem per se – one or the other can be adopted to mean the same thing.

Can one accept a null-hypothesis?

With the framework of robust trend detection, the notion of *accepting* a null-hypothesis does not in theory exist, as one only *rejects* the null hypothesis, and *failing* to reject does not mean that one *accepts* it, which follows from the fact that alpha levels are fixed *a priori* at the desired level and power levels are not necessarily fixed at a high level (though it might be high in some cases due to the strength of the slope or the weakness of the correlation), but it is not uncommon to see "acceptance" besprinkled in the hypothesis testing context. This is more true in hydrology than in econometrics.

Problem statement and science question

Trend detection scientific literature within the domain of Hydrology (where non-parametric tests have been preferred for their advantageous properties) developed without mathematical proofs, while in Econometrics, trend detection tools (parametric tests) developed with accompanying proofs. Doing proofs improves one's understanding of why a method works, but it does not guarantee better results in all circumstances. This leads us to the science questions of the present paper. The science question can be divided into three simple sub-questions:

1) **Confidence:** how well can the desired *a priori* value of statistical confidence be achieved in trend detection without bootstrap?
2) **Power:** what is the maximum power one can obtain in detecting time series data from the families of parametric and non-parametric tests?
3) **Marriage:** How can the best of both worlds of parametric and non-parametric tests be combined to improve (1. Confidence) and (2. Power) and how can we approximate a bootstrap?

Combining the two families of trend tests, i.e. the parametric tests from the econometrics literature and the non-parametric trend tests from the non-parametric trend detection tests, a superior solution for trend detection may be found. The ensuing work has been filed into a provisional patent and is not disclosed via this dissertation. However, the results derived and their key conclusions are highlighted briefly in what follows.

Conclusion

The marriage of Hydrology (non-parametric) and Econometrics (parametric) methods leads to a portfolio of methods that can be combined into a computationally efficient, pseudo-bootstrap parametric cum non-parametric trend detection system that can be used for empirical data with no a priori knowledge about the time series, which is arguably better than the existing methods in the fields of econometrics and hydrology independently. This hybrid trend detection system can be applied to numerous real-world time series (with only a small caveat: we need to fix a priori the time period of the response surfaces, which can be done based on the typical record lengths in Earth Observation Satellite data). The advantage is that with no *a priori* information about the properties of the series, we can apply this tool.

Caveat of the study and further developments

The present study shows the range of considerations for the simplest case of robust trend detection of the a priori hypothesis that the trend is linear which may aid correlative studies. This is directly extensible to step-changes and non-linear trends. However, this does not help with causality questions and some assumptions here do not extend well to some related problems of trend detection that help with causal diagnoses such as products or ratios of trends of two or more variables in evaluating competing hypotheses for causal mechanisms. The econometrics literature provides a large body of work for these questions.

This robust trend detection framework allows practitioners to conduct a robust multi-scale analysis in various spatial and temporal aggregations, enabling an analysis of Simpson's Paradox considering spatial and temporal scales of analysis. However, elements of this framework can be helpful to quickly identify the optimal scale of aggregation to tease out long-term trends and avoid spurious interpretations of long-term trends. Some of these issues have been identified in Libertino et al (2019) who allude to a widely observed phenomenon in trend studies in regional hydro-climate studies. To handle Simpson's paradox, one can adopt simultaneous heterogeneous robust trend detection in sub-grid scales while constraining the scale of analysis to a more coarse scale, e.g. one that is dictated by homogeneity of climate (say precipitation).

Acknowledgements

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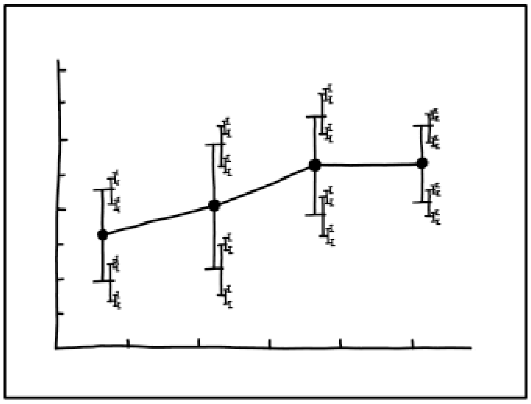
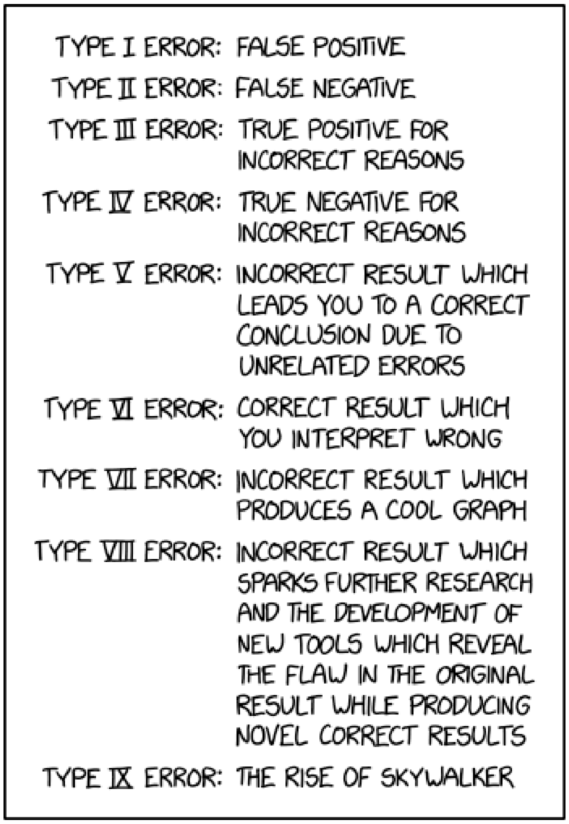
Appendix A: Relevant web-comics (XKCD)



I DON'T KNOW HOW TO PROPAGATE ERROR CORRECTLY, SO I JUST PUT ERROR BARS ON ALL MY ERROR BARS.



TYPE I ERROR:	FALSE POSITIVE
TYPE II ERROR:	FALSE NEGATIVE
TYPE III ERROR:	TRUE POSITIVE FOR INCORRECT REASONS
TYPE IV ERROR:	TRUE NEGATIVE FOR INCORRECT REASONS
TYPE V ERROR:	INCORRECT RESULT WHICH LEADS YOU TO A CORRECT CONCLUSION DUE TO UNRELATED ERRORS
TYPE VI ERROR:	CORRECT RESULT WHICH YOU INTERPRET WRONG
TYPE VII ERROR:	INCORRECT RESULT WHICH PRODUCES A COOL GRAPH
TYPE VIII ERROR:	INCORRECT RESULT WHICH SPARKS FURTHER RESEARCH AND THE DEVELOPMENT OF NEW TOOLS WHICH REVEAL THE FLAW IN THE ORIGINAL RESULT WHILE PRODUCING NOVEL CORRECT RESULTS
TYPE IX ERROR:	THE RISE OF SKYWALKER

5

High-Fidelity Detection of Climate Change Signature from Lakes

We identify first-order priorities to conduct a high-fidelity analysis of inland climate signature from lakes. The priorities include closing two measurement gaps with better observations (open water albedo, sinkholes), improving modeling of critical energy and water budget processes, evaporation and microtopography respectively, and identifying (spatial) principal and suspected interaction processes and conducting robust trend detection to detect long-term climate change impacts on Arctic-Boreal lakes: our best inland local scale sentinels of climate change.

Abstract

Pinning down the role of climate change in the long-term changes undergone by Arctic-Boreal Zone (ABZ) lakes (disappearance, reappearance, shrinking, expansion) is critically important to understand future climate impacts, especially considering the relevance of ABZ lakes to the global methane budget in the context of Arctic amplification. We conducted a retrospective (1984-2018) analysis on millions of lakes of the North American ABZ using ground and satellite observations of a wide range of geophysical variables. We analyzed them in multi-scale representations, i.e. spatial scales of ~25 kilometer grid (climatology) upto fine sub-meter scale (microtopography), and in sub-daily to climatological time scales. Our analysis suggests that we must: (1)

close two major observation gaps (open water albedo and sinkholes); and (2) inform model design by known limits of detecting trends, separating long-term change trends from correlation noise, in principal and suspected interactions processes (PIPs and SIPs) using a Hortonian *rational* and *correlative* study, especially those processes that are suspected to be levers of non-linear feedback. Doing so can enable high-fidelity detection of local to global scale in-land climate change signatures from Arctic lakes, our best sentinels for climate change.

Arctic amplification

The global Arctic has been on the edge of climate change research for decades due to the so-called Arctic amplification process, i.e. disproportionate warming in the high latitudes caused by the ice-albedo feedback: high temperature causes ice melting, which causes a decrease in albedo (as ice turns into water), which causes an even stronger increase in temperature and ice melting, and so on. Joint research efforts by American, Russian, and European scientists (among others) have led to the creation of a large body of knowledge on the conditions of the Arctic Boreal Zone, or ABZ. One example is the contribution of the Northern Eurasia Earth Science Partnership Initiative (NEESPI), which started nearly two decades ago and resulted in over 1500 journal articles with a total funding of ~$150 million. A follow-on project of similar scale and scope is the Northern Eurasia Future Initiative (NEFI, Groisman et al, 2017). Similarly, on the North American Arctic side, the NASA-ABoVE project generated ~366 field surveys and remote sensing data products since its inception in 2015 to understand the dynamics of the ABZ (https://above.nasa.gov/profiles/above_products.html, accessed: March 14, 2022). These projects have resulted in significant new knowledge, which highlights the Earth Science community's unanimous recognition of the critical importance of understanding the ongoing changes of the ABZ in a warming climate.

ABZ lakes as climate change sentinels

Lakes are generally considered a low-hanging fruit in climate change studies due to their unique local scale contiguity in space, homogeneity in surface properties, well-known anomalousness in intrinsic (heat capacity, albedo, density) and extrinsic properties (distribution, occurrence, abundance), space-born observability and in-land ubiquity. Arctic lakes in particular are even more unique and critically important as climate change sentinels amongst all other land features of the Arctic due to multiple reasons. They experience Arctic amplification, i.e. a disproportionate warming impact found in high latitudes due to water's unique and anomalous properties of high heat capacity and disproportionate albedo change during phases changes between ice and liquid. Unlike the rest of the land surface (e.g. soil and vegetation), lakes are contiguous and homogenous across their area (at the surface seen from an aerial view), making them the easiest to observe from space, and they are ubiquitously besprinked over the global Arctic.

These reasons collectively make ABZ lakes most vulnerable to climate change and at the same time make them great access points for a straight-forward assessment of local in-land climate impacts. Furthermore, accurate knowledge of Arctic lakes' dynamics in a warming climate is essential because they are perched on a substrate of permafrost, which is critical for the global methane budget. Collectively, these factors make ABZ lakes our best sentinels to predict and understand a warming climate, and indeed, one of the most visible features of the ABZ region's vulnerability to climate change is the strong change dynamics of its lakes. ABZ lakes have been reported to shrink, expand, disappear, reappear at an unprecedented rate in the recent decades. A predominant interpretation is that they are disappearing (Smith et al, 2005), but the present study shows that the change in lake dynamics is not only limited to disappearance, and that the causes for their complex transformations still need to be clearly investigated.

The challenge in understanding Arctic lakes' response to climate change

That climate change is among the culprits in the dynamics of Arctic lakes is presumed and widely-accepted, but despite the recognized importance of this factor, there are still first-order issues in lake change studies due to methodological gaps, hydrologic process knowledge gaps (e.g. abrupt thaw, disappearance, albedo, etc.) and observation gaps (open water albedo and sinkholes mainly). This complicates the challenge of correctly understanding Arctic lake change, which to put it plainly, as Henderson-Sellers and co-authors did in the 1980s, is "disturbing" (Henderson-Sellers and Hughes, 1982; Henderson-Sellers and Wilson, 1983). In this paper, we conduct a large sample analysis that explores some of these issues, to enable teasing out accurate in-land local climate change signals from sentinel lakes.

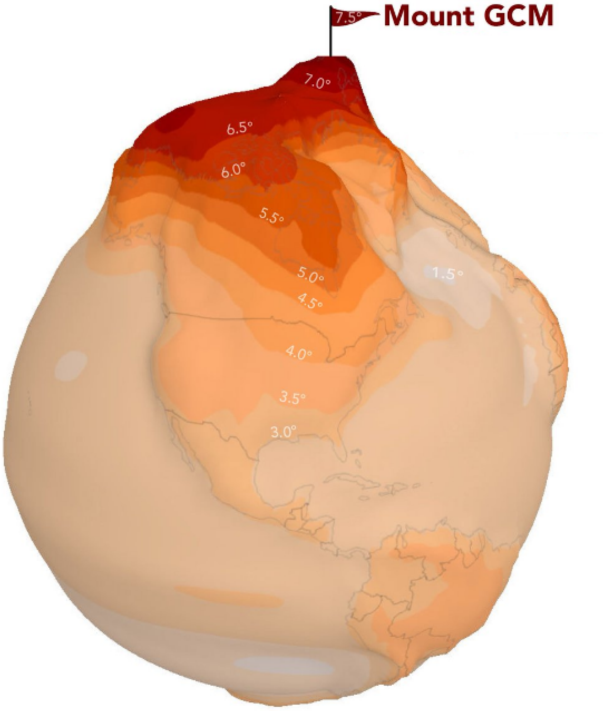


Figure 5.1: Arctic amplification effect of future warming for Representative Concentration Pathway (RCP) 8.5 Wm^{-2} adapted from Greg Fiske (with permission)

Main Text

We computed surface water change magnitudes and directions, their geophysical controls (processes) from among 100s of quantities (see table provided in Appendix). We analyzed their principal and suspected interactions using a conceptual systems diagram that highlights feedback and time lag effects. We also identified two target variables that represent the most important energy and water budget components, which are evaporation and storage respectively, where substantial improvement in terms of modeling accuracy can be achieved due to the scale of data available today.

Surface Water Change

We began our analysis with an assessment of the overall surface water changes in the North American Arctic over the past three decades, to better understand the scale of lake increases/decreases. Surface water change intensity (loss and gain) was calculated as change between two epochs: 16 March 1984 to 31 December 1999, and 1 January 2000 to 10 October 2015, as epoch1-epoch2 /epoch1+epoch2. Global loss of permanent water is 3.22%, while in Canada it is 1.01%, while the gain percentages for the World and Canada are 6.61% and 2.49% respectively (Pekel et al, 2016; see supplementary material). The net gain in Canada is 1.48%. While the net change globally and regionally in Canada is gain, there are regions in the ABZ where the net change is loss, by a small margin.

Among these, as shown in the Appendix, the percentage of regional gain in Prairies region of Canada is the most intense increase, relative to loss, and in this region human induced change in the land surface is disproportionately greater than in other areas of Canada, due to increased agricultural activity in the region. On a regional scale, direct human influence is the dominant pattern of surface water change as compared to climate change related increase or decrease.

Water change was also computed specifically for Canada and Alaska (dubbed NA - North-American - Arctic) using the Pekel et al (2016) dataset. Net lake area changes were categorized based on different permafrost conditions, as the state of permafrost (frozen soil) underlying or surrounding Arctic lakes influences the actual availability of freshwater and can complicate the relationship between increasing temperatures and changing lake sizes.

We examined changes by permafrost regions as well as hydro-climatically similar regions grouped as follows: Arctic Mountains and Fjords, Arctic Tundra, Northeastern Forest, Atlantic Canada, Great Lakes and St. Lawrence, Prairies, Northwestern Forest, Mackenzie District, Pacific Coast, Alaska, South British Columbia Mountains, Yukon and Northern British Columbia Mountains. The results are shared in the Appendix.

Identification of Suspected Interaction Processes (SIPs) and Principal (Established) Interaction Processes (PIPs)

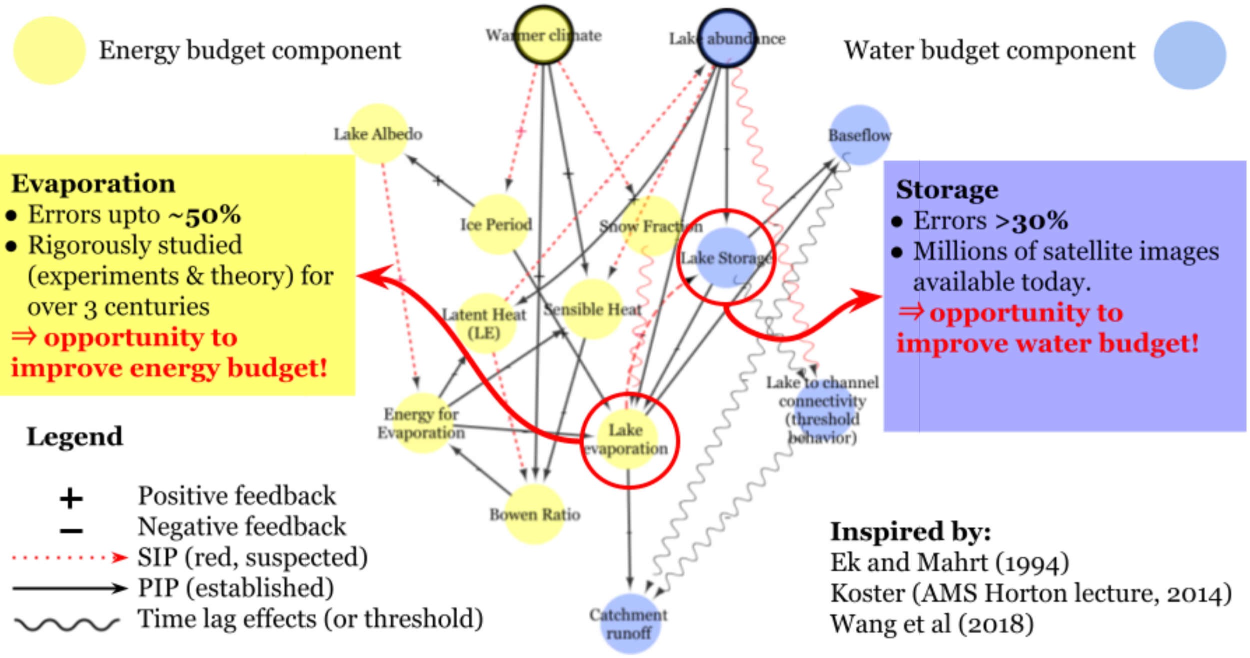


Figure 5.2: PIPs and SIPs with positive and negative feedback and time lag effects

As shown in Figure 5.2, multiple factors related to energy and water budgets interact in non-linear ways in the process governing lake changes, posing the question of how to correctly understand the relative weight of each factor and the overall effect of a complex system of this kind. In a thus far largely under-appreciated paper, Hasselman (1988) provided a framework for an analysis to reduce model complexity without compromising on ability to conduct sensitivity analyses in terms of non-linear process interaction and time dependency called Principal Interaction Processes (PIP). PIP is based on the notion that despite a large number of interactions in nonlinear systems, most of the interactions can be reduced to a few principal interactions and simplified expansion coefficients that can be used to conduct sensitivity analyses. Though generalizable to time series data of models or observations, this framework is typically applied in the context of decomposing non-linear model results that have time dependence. In the same vein as PIPs, we conducted a data-based analysis that captures the non-linear spatial variations and their underlying processes which we call spatial PIPs. An extension of this framework is the Suspected Interaction Processes (SIPs) inspired by a suspected system interaction diagram credited to Ek and Mahrt (1994). Spatial PIPs and SIPs are important to separate and isolate spatially distinct signatures of climate change impacts on lakes. Using this approach, we can capture multi-scale spatial variability in ~13 million North American Arctic lakes under the assumption of homogeneity in climate at a resolution fixed by the density of rain gauges and reliable reanalysis products (Vimal et al, 2020). Such an analysis may also be dubbed a correlative research, of the kind promoted by Robert Horton (Horton, 1933). Following Horton's definition of a correlative research study (Vimal, forthcoming), we examined a large body of literature to identify reported sensitivities, long-term trends, contradictions seen in literature reports. A correlative study may be defined as:

> "Scientific research may be broadly classified as (a) correlative, (b) laboratory, (c) field. Before any field or laboratory research is undertaken on an important topic, a thorough correlative research should be carried out to determine just what has been done on the subject and what most needs to be done. The correlative research corresponds to the making of a map of existing highways before undertaking to complete the highway system of a region. Its importance can not be overstressed." - Horton (1937)

To this end, we examined over 100 geophysical variables (enlisted in appendix A) and a subset of covariates at the daily, monthly, seasonal, and annual scales, and in multiple spatial resolutions (0.25 to 2 degrees) to pin-point the cause of their observed changes. Though correlations and principal component analyses do not imply causality, our analysis is a good starting point to inform model design choices. A preliminary correlative research study of a large number of papers supported our data-informed interpretation of SIPs and PIPs. We performed independent validations on these variables where pertinent (details are in Appendix). We used these datasets to assess causal relationships with lake trends and climatic trends based on first-principles approaching it from the perspective of a Hortonian rational method (Horton, 1937). The variables we analyzed include states, fluxes, trends and derivatives of surface water change (ephemeral and permanent changes), permafrost, peat fraction, and geologic factors, among others. Analyzing these data allowed us to evaluate whether measured lake size changes could be attributed to long-term climate trends, what percentage of variance can be attributed to natural (daily to seasonal to long-term) variability, and whether there are variables with particularly strong explanatory power among the variables we considered.

Our analyses of a large number of lakes and lake-related variables reveals first-order physical factors that do not seem to be incorporated correctly in nearly all lake studies that assess water and energy budget and long-term trends of lakes, which points us towards a critical measurement gap: dynamic open water albedo and sub-surface sinkholes. Furthermore, we found that evaporation and storage both have errors of the order of 30%, and the errors increase as the liminicity increases, while the opposite should be true given the scale of data. We improved the accuracy of evaporation calculations using a century-old method credited to Robert E. Horton (Vimal and Singh, 2022) and we improved storage estimate accuracy using an algorithm that, by virtue of Central Limit Theorem, reduces vertical error in digital topography down to sub-meter accuracy for lakes under the assumption of climate homogeneity at the scale of 0.25 degree (a non-optional limit imposed by the density of rain gauges). Apart from these two critical variables, we found that three first-order processes (PIPs and/or SIPs) are entirely missed in current generation of land surface models (LSMs), which suggest that feedback and causal chains of lake change are as yet not understood. In this situation, LSMs which are used as boundary conditions for Global Climate Models (GCMs) are incorrect at the sub-daily time scale at which GCMs are solved.

1. Measurement gaps

a. Clear water albedo: an overlooked, critical variable

In our analysis, we noted open (clear) water albedo is seldom considered as a dynamic variable in land models, and we identified an analytical solution based on Fresnel's equation. We plugged in the values of Russian field experiments over Arctic lakes from the 1960s. These field measurements, which were a result of an important recognition of the wide range of clear water albedo values, have been largely ignored in the GCM and LSM communities to our understanding. A copy of an English translation of a Russian text on the subject, translated by Israel's scientific translation program (Sivkov, 1971), was held at the National Library of Israel (NLI). The table of values was originally published by Sivkov (1952) in Russian. We obtained a copy of Sivkov (1971) from the NLI after obtaining their copy-rights permission for research purposes. We adopted the coefficients from their table to correct the analytical Fresnel's equation which varies with latitude. The correction needed here is related to lake turbidity, depth, diffraction, etc. which varies as a function of these properties together with the parameters of Fresnel's equation (Henderson-Sellers, 1983). While Sivkov's work was examined and extended by Cogley (1979) and utilized by Henderson-Sellers (1983), these developments have been forgotten and are not included in contemporary land surface model lake schemes that are used to set the boundary condition for Global Climate Models (GCMs). Clear water albedo can be calculated using a derivative of Fresnel's equation (see Henderson-Sellers and Hughes, 1982).

$$a_F = 50\left[\frac{\sin^2(Z-r)}{\sin^2(Z+r)} + \frac{\tan^2(Z-r)}{\tan^2(Z+r)}\right] \qquad (1)$$

The value for Z requires a correction factor provided in Sivkov (1971).

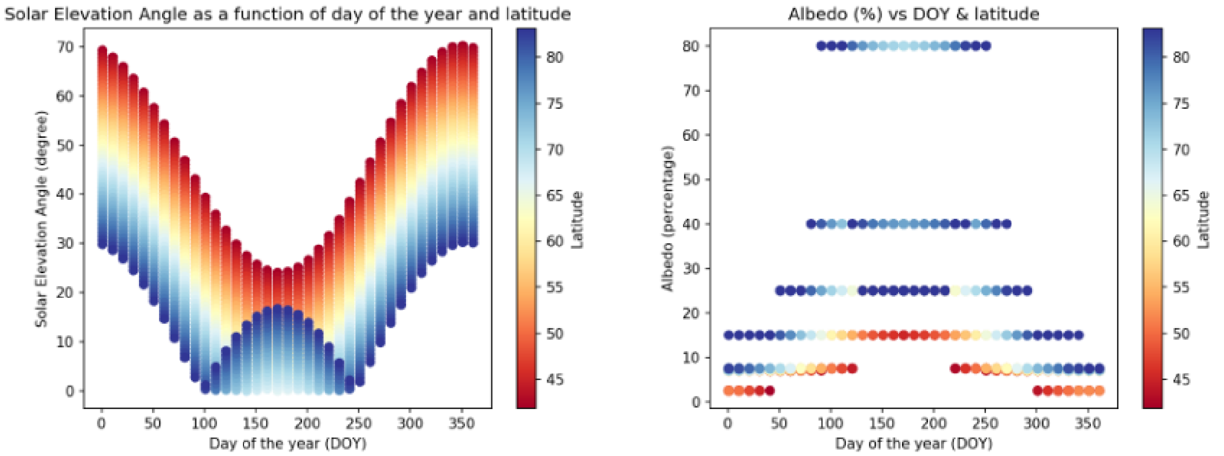


Figure 5.3: Clear water albedo variation over the pan-ABoVE domain as a function of Day of Year (DOY), latitude and sun's elevation angle.

Using Fresnel's equation figure together with values of the curves of the Russian measurements shows albedo dependence on zenith angle. When we contrast the range of values with the constant value of 0.03 for open water used in current models, we can expect an error of ~700% at the sub-daily time scale, which is the time scale at which lake energy balance is resolved, which then serves as a boundary condition for GCMs.

Alarm bells of the 1980s

Henderson-Sellers and co-authors alerted the GCM scientific community about the importance of surface albedo three decades ago. For example, they said: "We suggest that the monitoring of local, zonal and global albedo variability is of fundamental importance." (Henderson-Sellers and Hughes, 1982); "[...] the diversity among the methods of assigning surface albedos to locations which come under the influence of the **cryosphere** is disturbing" (bold-face emphasis was added to highlight the relevance for Arctic Amplification); “The proposed accuracy is ±0.05 or an equivalent percentage value for all land surfaces.”; “[...] lack of coherence among climate models [...] as measured by the differing degrees of accuracy and complexity of specification of surface albedos is disturbing.” (Henderson-Sellers and Wilson, 1983). Despite the problem being pointed out as early as the 80’s, , models used for the northern latitudes (above latitude 50) today are still known to have errors of up to 0.4 in albedo (i.e. 400% absolute error, and 800% relative to the prescribed measurement goal considering GCM model sensitivity) across satellite products (He et al, 2014). Additionally, the current class of lake schemes in land surface models which simulate lake energy balance at sub-daily scale seem to have a static parameter of 0.03 for the water albedo, which does not account for at least ~700% of the diurnal to seasonal variability.

Demand and supply of energy

Lake changes driven by temperature depend on the lake’s ability to be impacted by the temperature (thermal conductivity), which varies significantly between solid ice and liquid water. So it is important to examine the demand and supply of lake change drivers. This effect can be quantified in terms of open water albedo, which varies by latitude and solar geometry (solar elevation angle and the refractive index of water which further varies by zenith angle). Our analysis revealed that, on the lake energy demand side, lake loss is most controlled by Summer albedo (r=-0.65). Autumn albedo (r=0.6), and minimum temperature Vogelsang trend (with statistical significance, r=-0.52) seem to suggest that lake loss is not occurring where the temperature increase is highest, which is surprising. For lake gain, however, Summer Albedo (r=-0.7: PC1, var=22.3% & loading 0.90) is the strongest co-variate, while Winter Albedo is the strongest PC (loading of 0.95 in PC1), and mean annual albedo is negligible. The Albedo of the Autumn season (r=-0.64) appeared to be strongly negatively correlated. Similarly, clear water albedo (a seasonally varying quantity that can be computed with an analytical formula) is the strongest predictor (>0.7) of both the Tmin and Tmax trends, and seasonal albedo performs better than aggregated annual albedo.

Causal pathway

The pathway of this influence via changes is the ice phenology which is well-documented in literature (Robertson et al., 1992). Overall, among the 100 geophysical variables we analyzed, albedo pops out as the most significant in explaining long-term lake trends as well as temperature (min and max) trends in the Arctic. So closing the measurement gap in open water albedo (and perhaps also largely ABZ land albedo) is among the highest priorities in Arctic lake studies. In the long term, collection of field data for this variable will be fundamental as it will improve energy budget calculations significantly. Though EOS data availability has exploded in recent years, robust methods to extract information from them are largely lagging behind, and observation goals set nearly 40 years ago as a 5-year goal, are still not met, and continue to have ~800% errors than the prescribed level of accuracy considering GCM sensitivities. However, using the field experiment results from Russian ABZ studies, in conjunction with analytical models for open water albedo can serve as a temporary provisional solution.

b. Sinkholes

The permafrost thawing mechanism suggested by Yohsikawa and Hinzman (2003), and sub-surface sinkholes that develop abruptly in the order of days suggested by Martinez et al (1998) could essentially be the same thing. Sinkholes have been well-studied in Florida's karst substrates (LeRoy Evans III, 2021), where measurement devices exist to monitor them, and mass balance approaches can be used to detect the existence of sinkholes from monitoring rates of change. Such engineering approaches are lacking in Arctic lake studies, especially those undertaken by the larger community wide efforts like that of NASA-ABoVE and NEESPI. Measuring sinkholes could turn out to be an important measurement goal, though our analysis did not reveal their importance. Threshold processes like sinkholes are generally difficult to model, and pose a major challenge to closing the water budget.

2. Process knowledge gaps

a. Evaporation

Evaporation is a critical variable that connects the water and energy budgets of lakes. Land-surface models that serve as boundary conditions to GCMs rely on what is called the Penman-Monteith combination equation which is based on radiation budget for calculation of evaporation. Though this equation is widely recognized as a “physically-based” equation, in reality, aspects of its physical basis are questionable, especially when models tend to use a static albedo to assess the energy budget of the lakes (Vimal and Singh, 2022). There are alternatives to this approach that can leverage satellite-borne data to achieve higher accuracy. In our previous work (Vimal and Singh, 2022), we found an equation for evaporation developed by Robert E. Horton in 1917 (Horton, 1917) and described in a rare report held at the University of California library (Horton and Grunsky, 1927) turns out to provide a superior way to calculate open water evaporation which does not rely on the radiation budget, but on temperature only. Using Horton’s approach also makes it possible to better explain the “evaporation paradox” and better quantify methane ebullition from cryoturbation in the fringes of the lakes, a process that is hitherto not well understood.

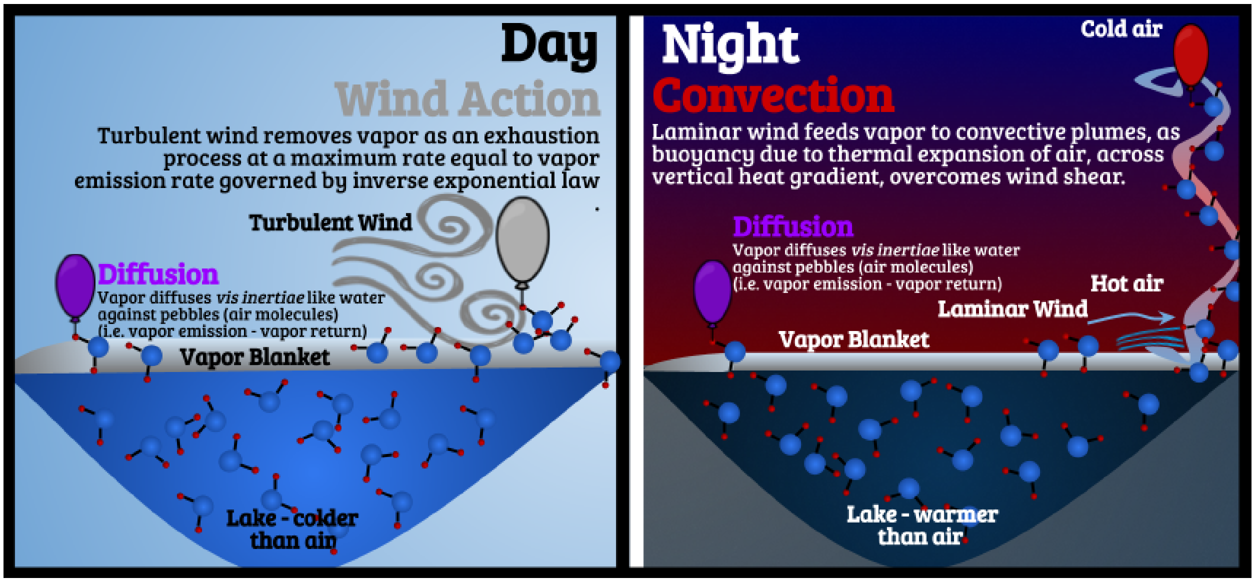


Figure 5.4: Lake processes and sub-lake variability (from Chapter 3)

Sublake variability of lakes provided in Vimal and Singh (2022) is a critically important factor in lake evaporation estimation as it affects the rate of evaporation by up to a factor of 2.

$$x_c = \frac{1}{mC} log_e \frac{\psi V - \upsilon_0}{\psi V - \upsilon_c} = \frac{1}{mC} log_e \frac{E_0}{E_c} \qquad (2)$$

where x_c is the distance from the windward edge of the water surface where the vapor blanket thickness becomes constant. The horizontal scale of x_c is typically in the order of a few yards. Our calculations show that it can be in the order of a few meters. υ_0: vapor pressure at the shore on the windward side; υ_c: vapor pressure at a distance x downwind; E_0: evaporation at the windward shore of the lake; E_c: evaporation at x; m: the fraction of moisture carried by wind action from the shore towards the leeward side of the lake, where vapor blanket thickness quickly approaches a constant value. Typical values of m are given as: 0: water surfaces broken by waves and over rough land surfaces; 0.3-0.4: gusty winds; 0.6-0.7: steady winds; 1: perfectly horizontal uniform wind (Horton, 1917).

b. Micro-topography

Micro-topography refers to features that are on the meter to sub-meter scale. An algorithm that leverages Central Limit Theorem to extract microtopography features from globally available digital terrain and surface water change data is provided in Appendix. The algorithm provides sub-meter scale accuracy in 80% of the continental domain, with the caveat of one assumption, the long-term change in lakes is assumed to be homogenous over a climatology grid scale of 0.25 degree. This assumption is inevitable as rain gauge densities dictate this limit for global scale applications, as afforded by presently available reanalysis datasets (Vimal et al, 2019).

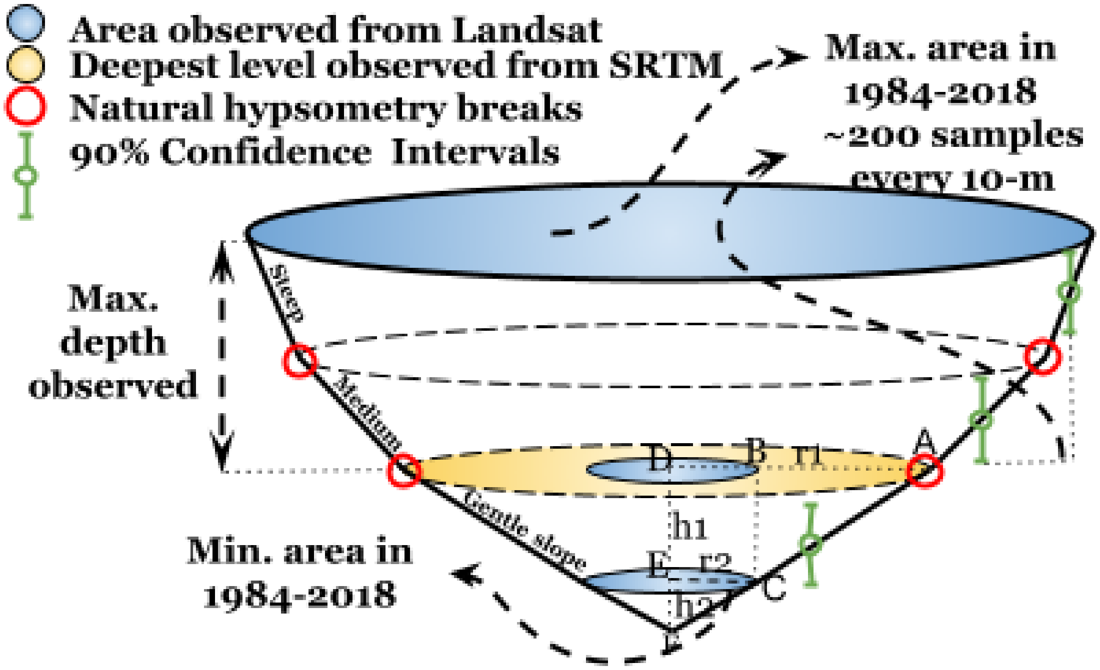


Figure 5.5: Sub-meter scale microtopography estimation combining Pekel et al (2016) and Yamazaki et al (2018) datasets

Bohn (2013) showed that incorporating micro-topography effects leads to improvement of up to 30% errors in methane emission studies. This is corroborated in our study of lakes: we found that the three micro-topographic gradients (in the order of their distance from the lake) derived from data appear to have a dominant role in explaining long-term lake change. That this can be extracted from data directly is very encouraging, so we suggest that lake models incorporate this information directly using the proposed algorithm rather than relying on statistical relationships of lake area and depth, which is the current modeling practice. Also, the order of importance of the 3 micro-topographic features we considered (steep, mild, gentle slopes) suggest ground heat exchange with lakes may be of first-order importance. Lake microtopographic slopes furthest away from the lake have the highest strength in explaining long-term variance of lake change, and the slopes closest to the lake have the least, but they are regularly arranged within the same principal component and in order.

c. Other variables of first-order importance

Similar improvements in the physical understanding of lake hydrology are needed for subsurface flows. Correlative and rational studies (per Horton's definition in his 1933 article in Science) as explored here provide some choice of additional variables to design such a perceptual model. This can help the development of perceptual models or reduced order models i.e. SIPs and PIPs to assess first-order relationships between ABZ surface hydrology (including lakes) and the GCM variables that rely on the boundary conditions. Horizontal surface water fluxes in high latitudes are quite large to justify column-type LSMs to serve as boundary conditions to GCMs, as evidenced in isotope studies (Gibson and Edwards, 2002). However, understanding first-order processes in a systematic way and including the first-order variables suggested here is of critical importance for global climate modeling, especially as it relates to inter-operation with

Cryosphere processes, which was described in the 1980s as “disturbing” and can be viewed today as “alarming”.

3. Signal to noise gap in long-term trends

A survey of literature (~120 papers reviewed in Vimal, 2022, forthcoming) shows dozens of variables (lake/soil temperature, area/frequency) region-to-region have opposite sides of change, suggesting that Simpson’s paradox may be at play. While some of the processes related to arctic lakes are abrupt (e.g. abrupt thawing of permafrost), others are more gradual. Pan-domain to local data for hundreds of geophysical variables do not show permafrost leakage as dominant, i.e. Arctic lakes aren’t only disappearing. What this suggests is that co-occurring increases and decreases of lakes need to be viewed together as a cyclic process where more stable, long-term trends of lake change may be visible. To adequately address this issue, adopting an econometrics or engineering lens may help interpret signals vs noise in long-term trends to complement the gaps of current trend detection methods used in hydrology, as explained below.

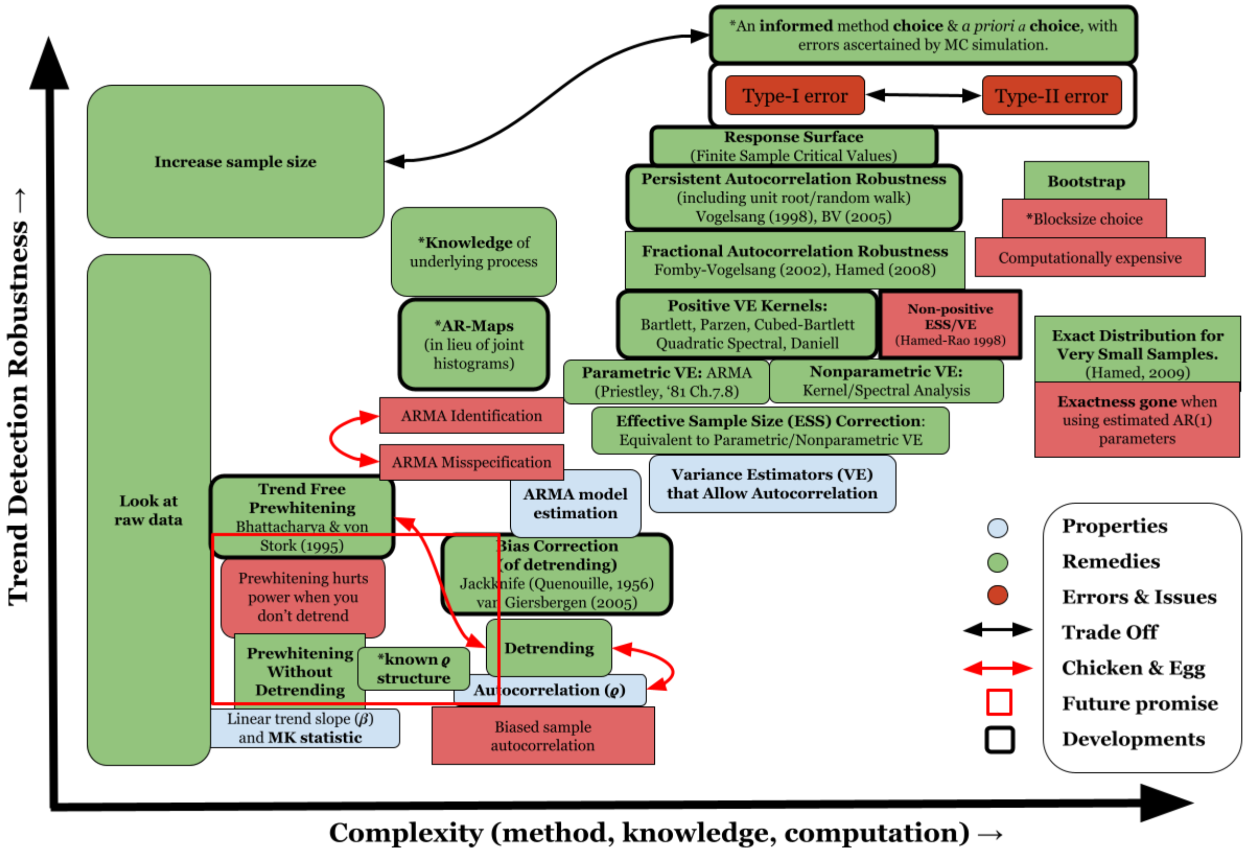


Figure 5.6: Robust Trend Detection (from Chapter 4)

In the engineering hydrology approach, the issue of long-term changes considering periodicities has been well-studied for decades using Intensity-Duration-Frequency (IDF) curves. Similarly, in the field of econometrics, long-term changes have been very rigorously studied for decades using spectral analysis and robust trend detection. Adopting the analysis frameworks of these domains is a fertile direction for climate change assessments, especially Arctic change. Besides recognizing that scale matters in space (heterogeneity) and time (periodicity), various hypotheses (scaling, non-linear change, etc.) need to be considered in addition to linear-trend detection, though the linear case may well be a reasonable starting point to identify first-order SIPs and PIPs.

Traditional trend detection adopted in applied sciences like hydrology and geosciences is often reported with statistical “confidence”. Though statistical confidence is reported at a 95% significance, in hydrologic change, this “confidence” is often guaranteed only at a 50-60% level due to correlation in time that complicates the assessment of lake trends which leads to large Type-I errors. The trade-offs between Type-I and Type-II errors need to be universally reported in Arctic change detection, but this metric is seldom reported.

A shift in perspective towards engineering design, i.e. recognizing the relative roles of intensity, duration and frequency while assessing hydrologic change and robust trend detection could facilitate statistical confidence in long-term change studies and reduce the instances of Simpson’s paradox in reporting of hydrological trends in the Arctic. Absence of this may explain why local-scale reasons behind Arctic lake change are still elusive. However, the increase in the time period of analysis, inevitable due to ongoing long-term space-borne imaging efforts, would lead to much higher certainty in the future, as both Type-I and Type-II errors reduce with increased sample size.

Closing Note

Our study has shown that evaporation, lake microtopography, clear water albedo, and trend detection are crucial factors to be considered when studying the change dynamics of Arctic lakes and most of these factors are poorly characterized at the scales possible today with the explosion of data. Our analysis of lake area changes in the Arctic Boreal Zone of Canada and Alaska points to three directions to improve our understanding and correct calculation of these factors, suggesting both short-term solutions and long-term improvements in lake modeling. If we poorly deal with these first-order factors, lakes' water and energy budget elements at diurnal (to climatological) scales, their retrospective estimates and projections could be off by orders (to factors) of magnitude. Furthermore, methane budgeting, a high priority climate risk mitigation agenda for the coming years, will be disproportionately impacted as lakes represent a sizable portion of the budget. Arctic lakes' space-borne **o**bservability due to their anomalousness, their in-land **u**biquity, spatial **c**ontiguousness of occurrence, and spatial **h**omogeneity of physical property (OUCH) makes them a low-hanging fruit to juice out local to global scale in-land climate change signatures. The developments in the present work improve the fidelity of isolating climate change signatures.

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Appendix

Variables used in our analysis

Here we provide a summary of the various variables we analyzed and some limited exploratory analysis and validation we (or previous works) performed, where pertinent.

Landsat surface water change: We used data on occurrence, recurrence, change intensity, loss/gain, seasonality, and transitions between ephemeral, seasonal, & permanent classes from Pekel et al (2016). We computed mean and standard deviations of these characteristics at 0.25 degree resolution over the domain which represents seasonal, annual, decadal, and multi-decadal scale lake dynamics. Quality assessment for the surface water dataset we used was conducted extensively in the work by Pekel et al. (2016). They performed a thorough validation study and reported that their water classifier produced less than 1% of false water detections, and missed less than 5% of water. However, it should be noted that there are large gaps (NaN values) in the historical monthly Landsat dataset due to cloud cover, which is why we did not perform a monthly scale analysis.

For the purpose of this study, we ignored the difference between lakes and rivers and referred to all the in-land water pixels as lakes (as lakes have a significantly larger surface area), and we believe this will not affect our interpretation of the larger lake dynamics, as natural river dynamics themselves are a part of the lake dynamics.

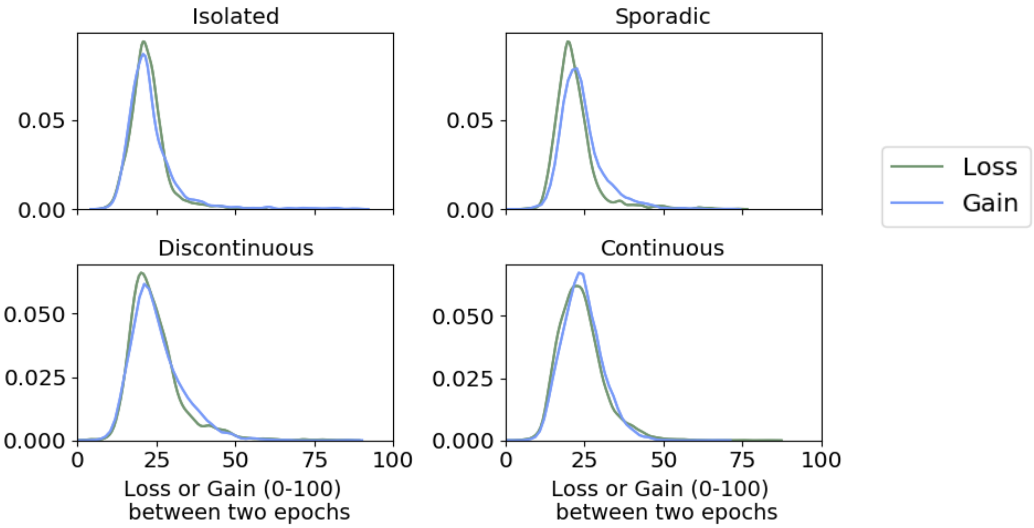


Figure S5.1: KDE plot panel of lake changes (loss and gain) by permafrost regions

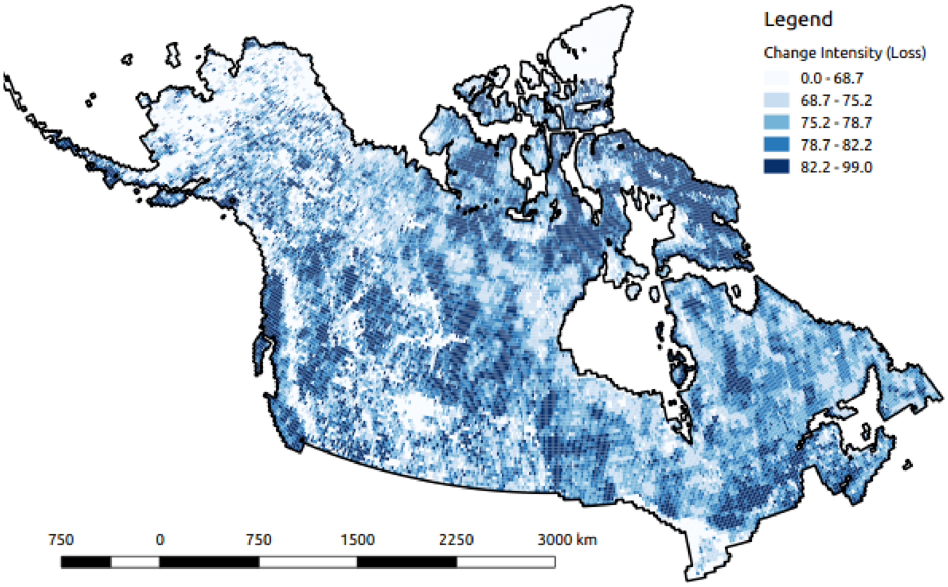


Figure S5.2: Spatial distribution of surface water changes intensity (loss).

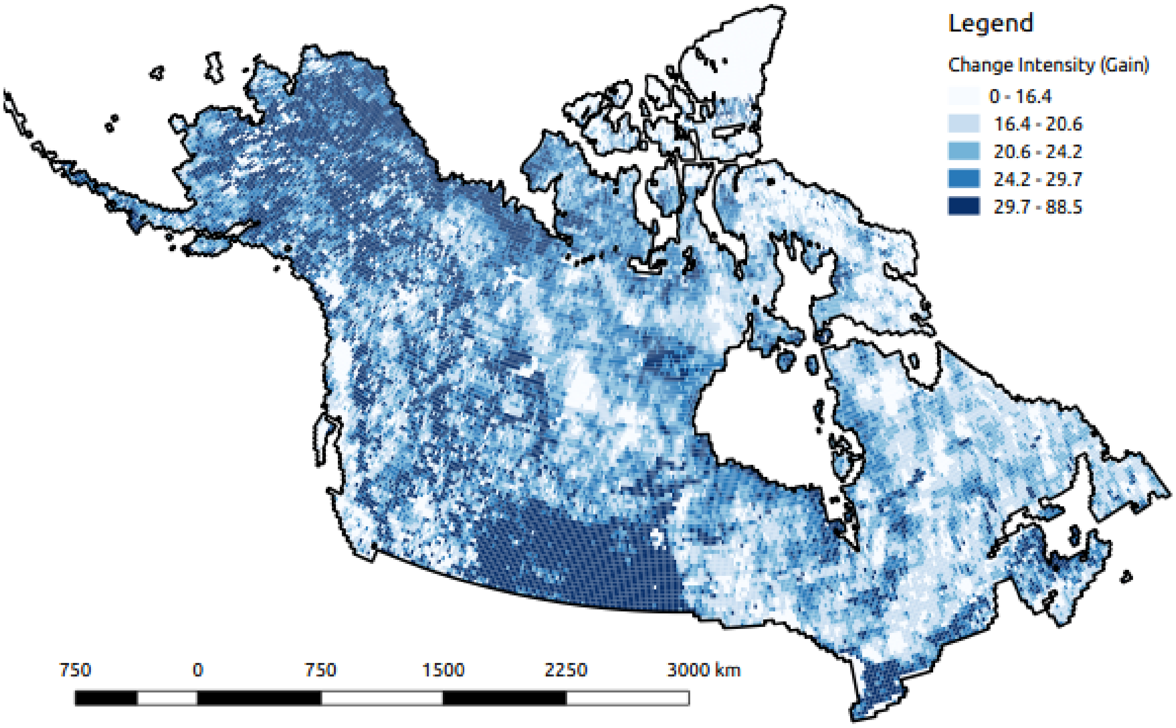


Figure S5.3: Spatial distribution of surface water changes intensity (gain).

The spatial patterns in S5.2 and S5.3 are due to a combination of local meteorological factors and ground interaction factors, and river flow patterns in the horizontal dimension which are in turn moderated by non-local vertical and horizontal factors. The prairie (Southern) region's higher gain is due to increased agricultural activity. The white blotches in the center of the maps show no gain as they represent areas of large lakes where water is always present. The striated patterns seen in the maps are due to projection changes from WGS to Equal Area projection.

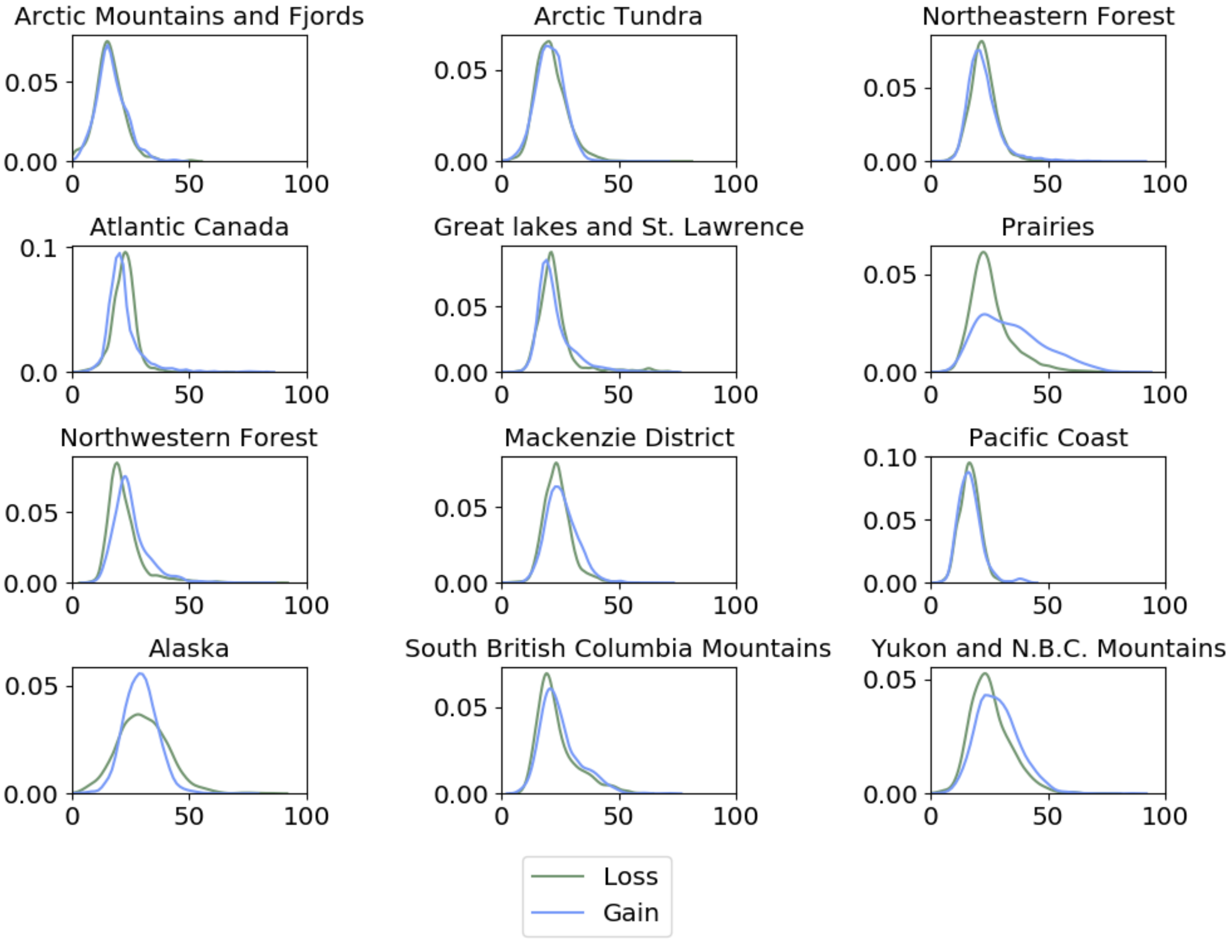


Figure S5.4a: Spatial distribution of surface water changes (loss and gain) reported by regions: Arctic Mountains and Fjords, Arctic Tundra, Northeastern Forest, Atlantic Canada, Great Lakes and St. Lawrence, Prairies, Northwestern Forest, Mackenzie District, Pacific Coast, Alaska, South British Columbia Mountains, Yukon and Northern British Columbia Mountains. Values range from 0-100.

Climate trends: Climate Change influence on lakes evidently is mediated through climate variables such as temperature **(**min, max) at the diurnal scale, precipitation, runoff, wind, etc. We biased-corrected and verified (Vimal et al., 2019) these variables with respect to station data using CRU TS3.10 dataset (Harris et al., 2014). Evaluation of regional precipitation errors was done as follows.

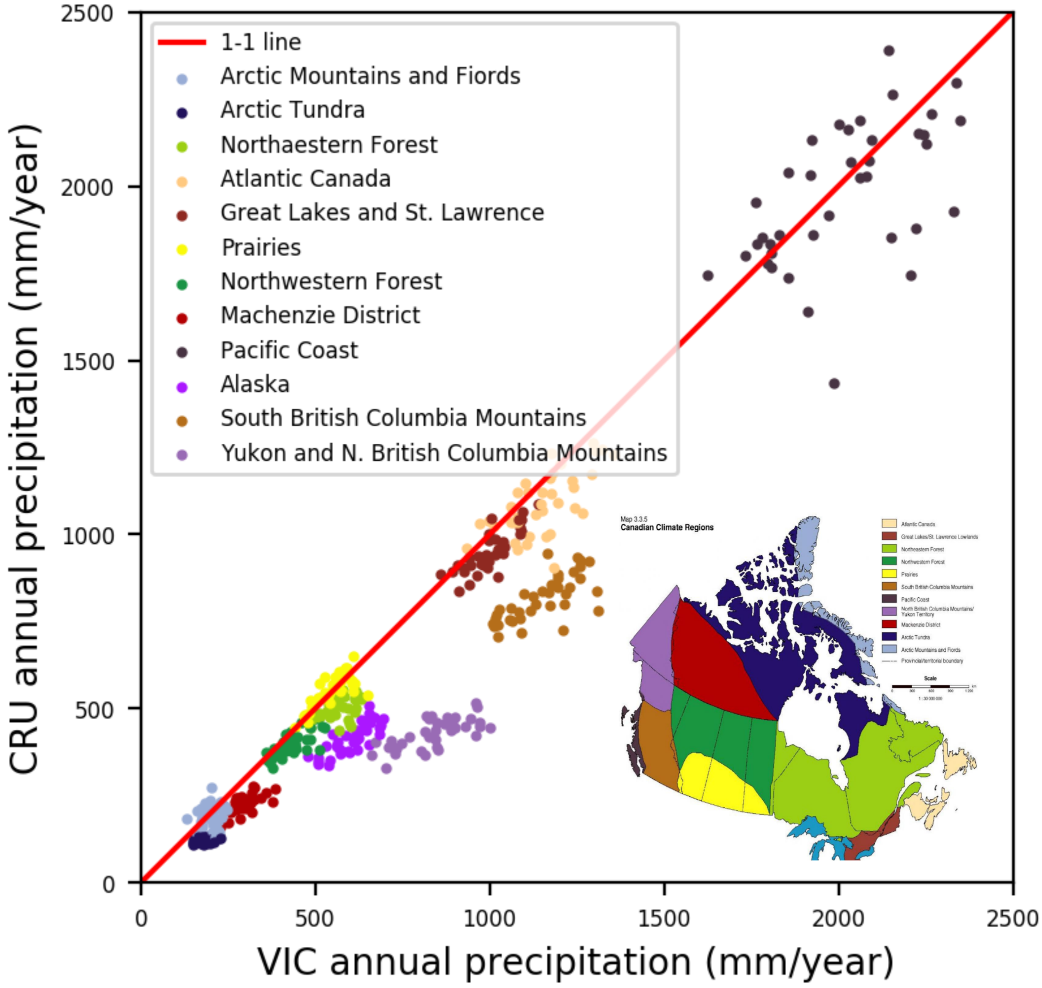


Figure 5.4b: Regional evaluation of Vimal et al (2019) precipitation dataset

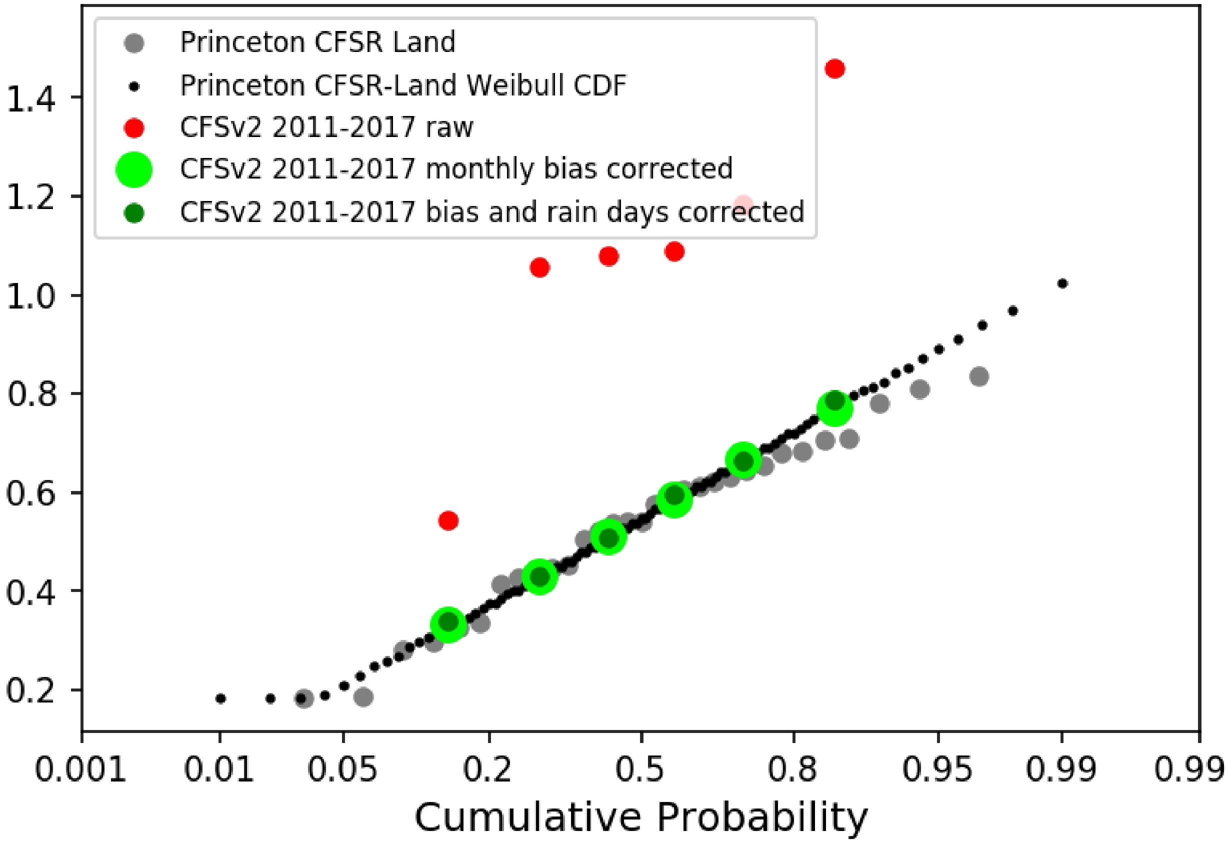


Figure S5.5: Probability plot of Vimal et al (2019) compared with Princeton Reanalysis dataset (Coccia and Wood, unpublished, personal communications)

We calculated the trends in these variables at significance levels of 0.05 using a novel method for trend detection. Further, for this study, we individually examined the ground station data for a few regions where significant (0.05 and 0.01) trends were found and verified that the trend seen from the gridded product is in fact also reflected in the point station measurements. The trends were computed for two decadal epochs separately within them and between them, and over the climate normal scale (i.e. entire period 1984-2018).

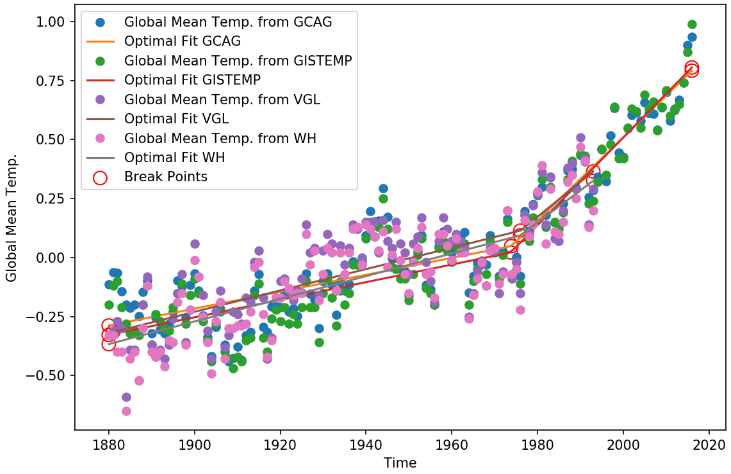


Figure S5.6: Global average temperature anomaly time series from 4 sources (CGAG, GISTEMP, VGL, and WH)

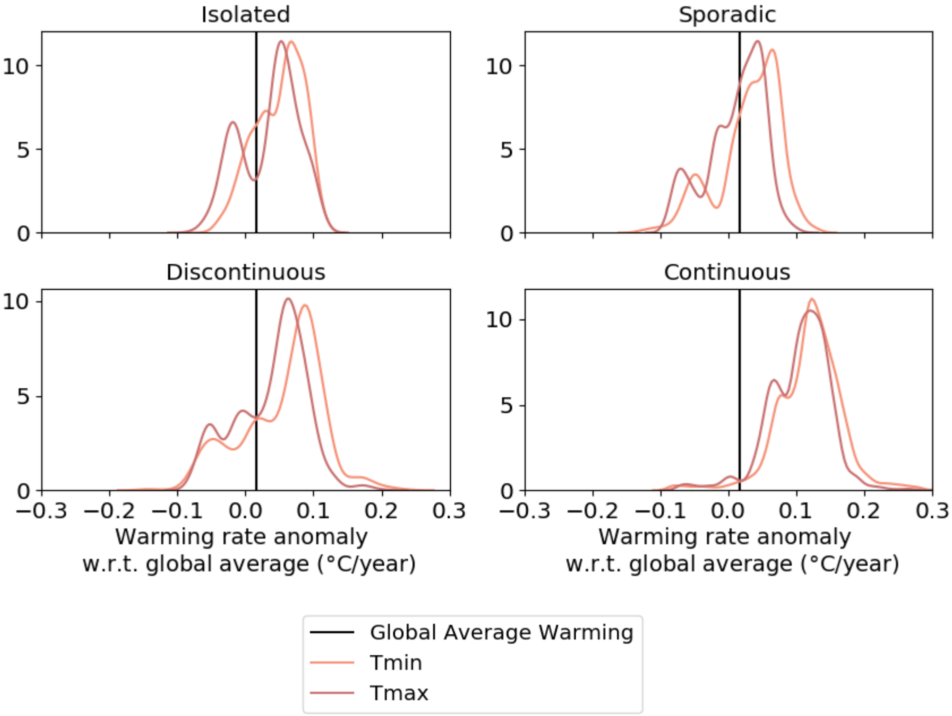


Figure S5.7: Warming by permafrost regions

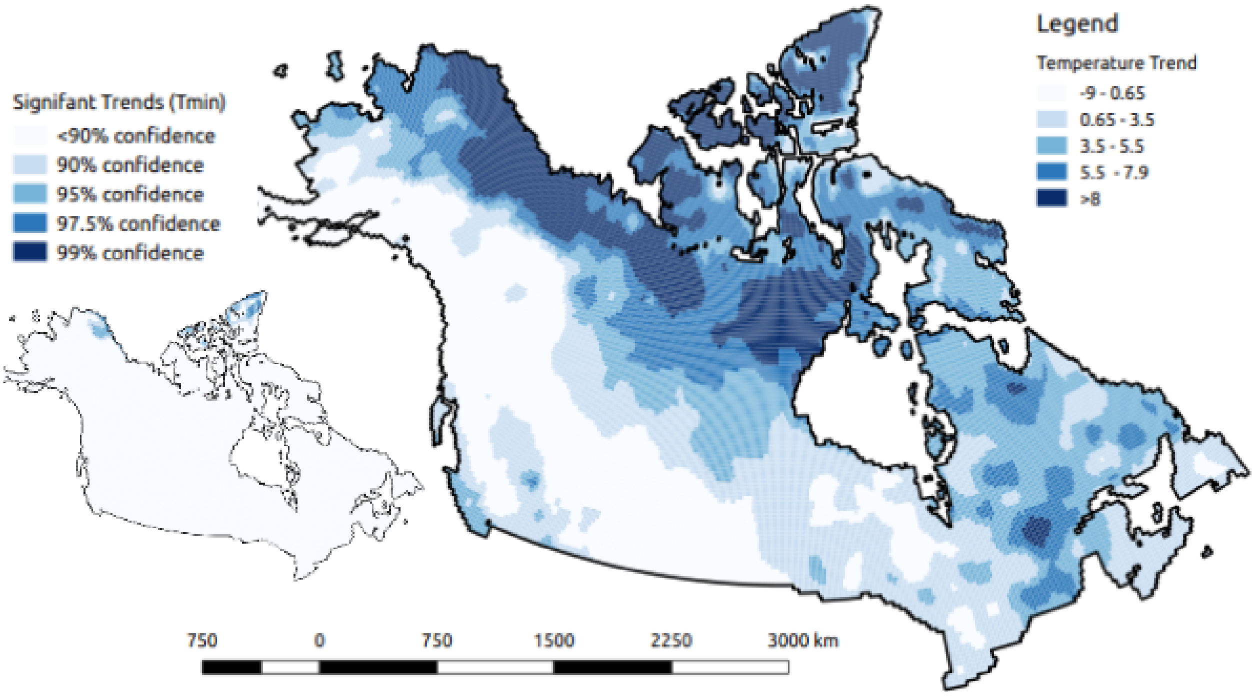


Figure S5.8: Temperature trends for Tmin and their statistical significance at the highest confidence permitted by the Vogelsang test (1998)

Permafrost conditions: permafrost conditions continuous, discontinuous, sporadic and isolated were derived from Brown et al (2002), a widely used dataset and also the same dataset used in previous studies on disappearing lakes (e.g. Smith et al., 2005) which we revisit here.

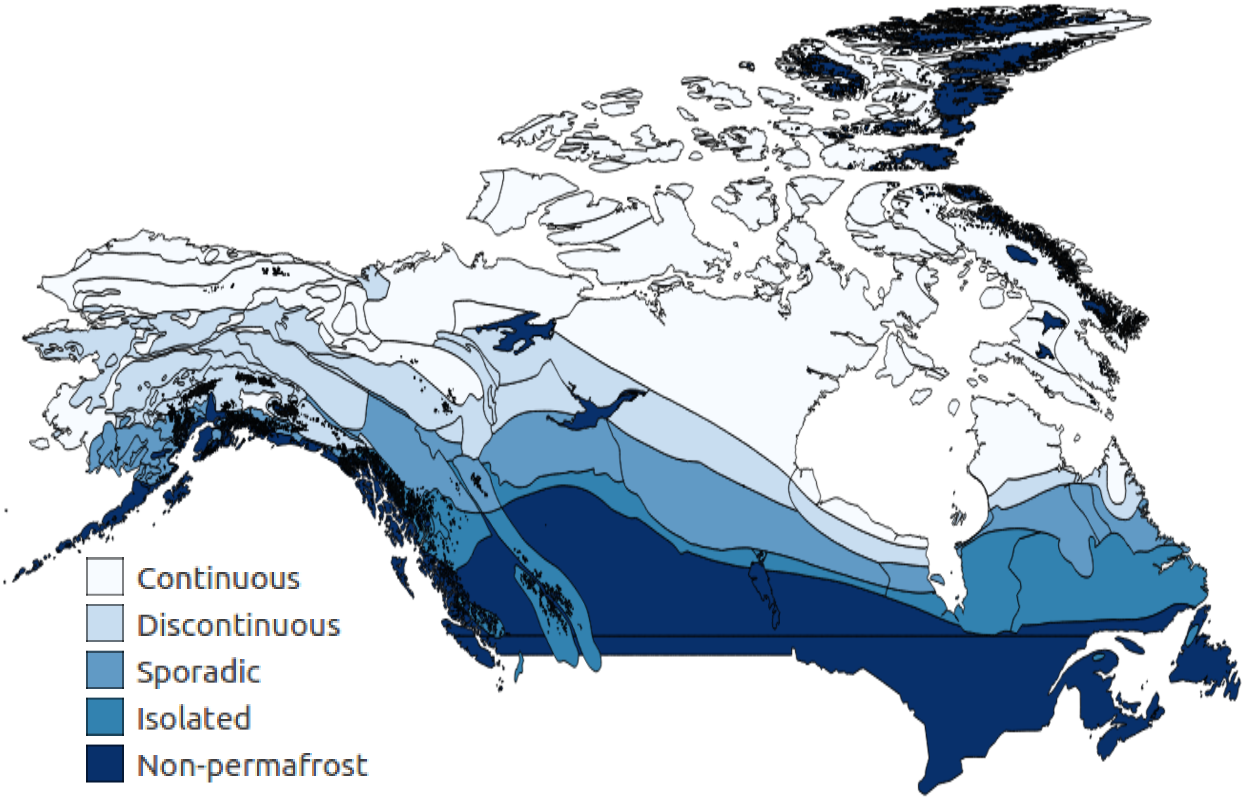


Figure S5.9: Permafrost conditions of the domain

Eco-climate-regions: Canada's Environment and Climate Change Canada (ECCC) provides a map of climate regions. The region is classified into 12 categories, see Figure 9.

Source:
Environment Canada, Atmospheric Environment Service, Climate Research Branch, 1998. *Climate Trends and Variations Bulletin for Canada*. Ottawa.

Figure S5.10: Ecoregions of Canada

Peatland fraction: The peatland fraction data, which was developed using machine learning, has an RMSE of 4% and a coefficient of determination of 0.91. The peat maps show a value of zero where topsoil organic carbon content is below a threshold value of 13 kg/m2 (see Wu et al, 2017 for further details on validation).

Digital elevation data: MERIT-DEM (see Yamazaki et al., 2017 and 2019). MERIT-DEM is composed of two different satellite products 1) Shuttle Radar Topography Mission (SRTM); does not have coverage over latitude 60, and its native resolution is 30 m, and aggregated to 90m. It was an 11 day shuttle mission in 2002 February. 2) Advanced Land Observing Satellite "DAICHI" (ALOS). It was a 5-year mission by JAXA from 2006 and 2011 that observed 6.5 million images and aggregated as a terrain dataset in 2014.

Lake geometry: In a companion paper (in preparation), we present an algorithm to calculate lake bathymetry in millions of lakes in the ABZ domain which essentially used DEM and surface water products previously described. As by-products of this algorithm we computed several variables. Some variables we derived from this algorithm include lake counts (area distribution), lake perimeter, lake volume, lake depth (definitions mentioned in the data dictionary). To represent lake geometry, we considered maximum lake area variation over the Landsat period to calculate the maximum potential change in volume and the corresponding shoreline hypsometry (bathymetry) as linear slopes for 3 sections. The 3 sections were defined by natural break points identified by optimization (piecewise linear fit). The algorithm enabled us to compute these properties in over 13 million lakes. The algorithm is described in the appendix section and illustrated below (S. Figure 3).

Steps involved in the algorithm:

Step 1: select shoreline pixels of ephemeral (seasonal) water using minimum and maximum inland water extents from Landsat data.

Step 2: sample the shoreline elevations of DEM at those selected pixels.

Step 3: identify and label contiguous regions using a centro-symmetric matrix window.

Step 4: normalize each labeled region w.r.t. base elevation depth.

Step 5: construct an equivalent shoreline bathymetry curve using normalized depths.

Step 6: identify natural breaks in local hypsometry using optimization, i.e. break points of piecewise linear fit. We used lines for simplicity.

Step 7: Using the nearest (in most cases gentlest) slope, extrapolate the slant of the cone further underwater and calculate the hidden volume using triangle similarity.

Using the depth-area relationship developed in the 7-step process, we broke the bathymetry curve (of depth to lake-radius) into 3 sections by a piecewise linear fit using optimization. Assuming the shape of the equivalent lake to be slices of a as many cones as there are depth-area pairs (figure 3), we extended the lowest (gentle) slope (slant of the cone) downward into the lake, and computed the volume that is exposed and the volume that is hidden using triangle similarity. ABAC=ADAF AF = AD x ACAB; DF =CBAC x AF; DF=CB x ADAB.With DE (i.e. h1+h2), subtracting the volume of the larger cone (r1, h1) from the smaller cone (r2, h2), storage volume for a given depth area pair of the lake was calculated. For the part of lake shoreline bathymetry that is above the water level at the time of DEM data acquisition, the lake storage for each of the 100s of depth area pairs was calculated. The ratio of visible storage to the hidden storage was also computed.

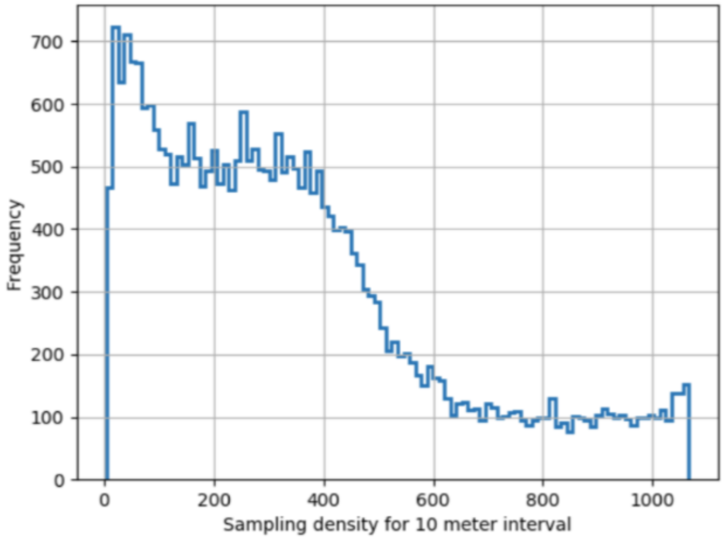


Figure S5.11: Samples per 10 m shoreline distance over the ABZ domain

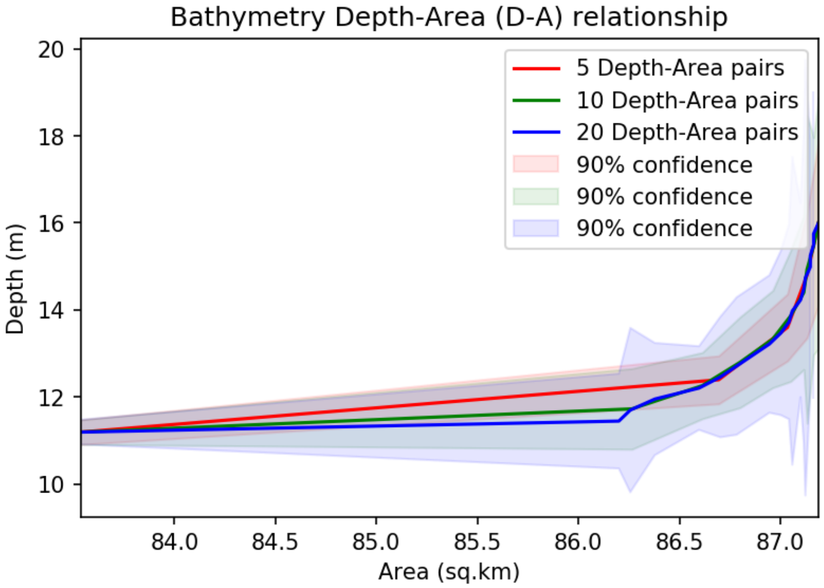
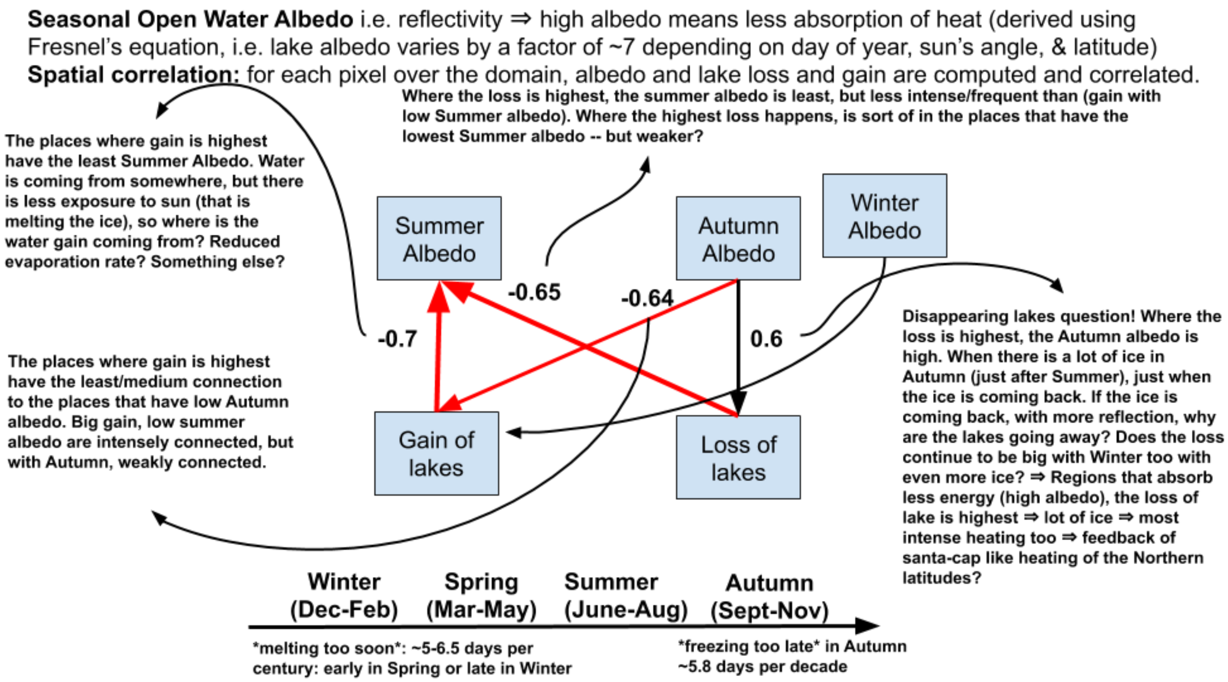


Figure S5.12: Vertical accuracy based on no. of depth-area pairs

Figure S5.12 is based on the bathymetry data of Redberry Lake, Saskatchewan Canada.

Albedo



Seasonal Open Water Albedo i.e. reflectivity ⇒ high albedo means less absorption of heat (derived using Fresnel's equation, i.e. lake albedo varies by a factor of ~7 depending on day of year, sun's angle, & latitude)
Spatial correlation: for each pixel over the domain, albedo and lake loss and gain are computed and correlated.

Where the loss is highest, the summer albedo is least, but less intense/frequent than (gain with low Summer albedo). Where the highest loss happens, is sort of in the places that have the lowest Summer albedo -- but weaker?

The places where gain is highest have the least Summer Albedo. Water is coming from somewhere, but there is less exposure to sun (that is melting the ice), so where is the water gain coming from? Reduced evaporation rate? Something else?

The places where gain is highest have the least/medium connection to the places that have low Autumn albedo. Big gain, low summer albedo are intensely connected, but with Autumn, weakly connected.

Disappearing lakes question! Where the loss is highest, the Autumn albedo is high. When there is a lot of ice in Autumn (just after Summer), just when the ice is coming back. If the ice is coming back, with more reflection, why are the lakes going away? Does the loss continue to be big with Winter too with even more ice? ⇒ Regions that absorb less energy (high albedo), the loss of lake is highest ⇒ lot of ice ⇒ most intense heating too ⇒ feedback of santa-cap like heating of the Northern latitudes?

melting too soon: ~5-6.5 days per century: early in Spring or late in Winter

freezing too late in Autumn ~5.8 days per decade

Figure S5.13: Role of ice-phenology: seasonal albedo and its influence on lake gain and loss

Table S5.1. Dictionary of 120 variables used in the study

S. No	Short Name	Variable Name (Long name) and definition
1	albAutumn	Albedo in the autumn
2	Albedo	Albedo average over the year

3	albSpring	Albedo in Spring (Fresnel's equation)
4	albSummer	Albedo in Summer (Fresnel's equation)
5	albWinter	Albedo in Winter (Fresnel's equation)
6	Area	Area of the grid cell accounting for WGS projection distortion by latitude.
7	brkp1	Break point of the lowest (gentlest) slope
8	brkp2	Break point of the in-between (intermediate) slope
9	brkp3	Break point of the highest (steepest) slope
10	chngGnMn	Change in water gained (mean)
11	chngGnStd	Change in water gained (standard deviation)
12	chngLosMn	Change in water lost (mean)
13	chngLosStd	Change in water lost (standard deviation)
14	ClimZone	Climate Zone ID (see table 1) as defined by ECCC.
15	delSlpMd	median change in slope of the slant of cone
16	delSlpMn	mean change in slope of the slant of the cone
17	delSlpStd	standard deviation change in slope of the slant of the cone
18	depthDelMn	Depth change mean
19	downSlope	Lowest slope
20	dpthDelStd	Depth change standard deviation
21	FlatArea	Area of the bathymetry that was measured as flat from DEM pixels
22	geometry	polygon box of the grid cell
23	hidVol	Hidden volume under the lowest DEM pixel observed from SRTM and ALOS 3D
24	hidVolFrac	Fraction of hidden volume to total volume
25	lakeCount	Total lake count
26	LakeDstrb	Lake distribution, size and count pairs for all sizes of lakes measured within the lake
27	Lat	Latitude
28	Lat_Lon	Latitude and Longitude together
29	Lon	Longitude
30	LossFrac	Loss fraction (mean loss over mean gain)
31	maxDepth	Max. depth of the lake
32	maxLakeRad	Max lake radius of the equivalent lake
33	midSlope	Max slope of the cone
34	minLakArea	Min lake area
35	minLakeRad	Min lake radius
36	mxLakeArea	Max lake area

37	mxLakPChng	Max lake percentage change
38	occMean	Occurrence mean and standard deviation, captures both the intra and inter-annual variability and changes. SWOmonth = ∑WD month / ∑VO month; WD=water detection; VO=valid obs.
39	occStd	Occurrence standard deviation
40	P2002	Precipitation of the year 2002 to check if there is any signal from SRTM derived bathymetry w.r.t to precipitation
41	PE1KenS	Sen's Slope for epoch 1 for precipitation
42	PE1KenT	Kendall tau for epoch 1 for precipitation
43	PE1KnSl	P Epoch 1 Sen's Slope
44	PE1VogS	P Epoch 1 Vogelsang Significance level
45	PE1VT	Vogelsang trend for epoch 1 for precipitation; 0 signifies not significant at 90% confidence
46	PE2KenS	P epoch 2 kendall significance level
47	PE2KenT	P epoch 3, kendall tau
48	PE2KnSl	P epoch 2 Sen's slope
49	PE2VogS	P epoch 2 Vogelsang significance
50	PE2VogT	P epoch 2 Vogelsang Trend
51	Peatland	Peatland fraction map derived from machine learning
52	Permafrost	Permafrost map with 5 categories (1-5)
53	PFVogS	P full data record, Vogelsang significance
54	PFVogT	P full data record, Vogelsang trend
55	PminusE	Precipitation minus evaporation over climate normal time period (19709-2017)
56	Precip	30 year precipitation normal and precipitation for the year 2002.
57	radDelMn	Radius change mean
58	radDelStd	Radius change standard deviation
59	recMean	The frequency with which water returns from years to year is expressed as a percentage. Recurrence mean: inter-annual behavior of water surfaces and captures the frequency with which water returns from year to year. A ‘water year’ is a year with at least one water observation, while an ‘observation year’ is a year with at least one valid observation within the water season. Water recurrence is then calculated as the ratio of the number of water years to observation years.
60	recStd	Recurrence standard deviation: inter-annual behavior of water surfaces and captures the frequency with which water returns from year to year. A ‘water year’ is a year with at least one water observation, while an ‘observation year’ is a year with at least one valid observation within the water season. Water recurrence is then calculated as the ratio of the number of water years to

		observation years.
61	saAutumn	Solar elevation angle in Autumn
62	saSpring	Solar elevation angle in Spring
63	saSummer	Solar elevation angle in Summer
64	saWinter	Solar elevation angle in Winter
65	seasMean	Seasonal mean
66	seasStd	Seasonal standard deviation
67	SolarAngle	Solar elevation angle averaged over the year
68	TmaxE1KenS	T max epoch 1 kendall significance
69	TmaxE1KenT	T max epoch 1 kendall Tau
70	TmaxE1KnSl	T max epoch 1 Sen's slope
71	TmaxE1VS	T max epoch 1 Vogelsang significance
72	TmaxE1VT	T max epoch 1 V trend
73	TmaxE2KenS	T max epoch 2 Ken Significance
74	TmaxE2KenT	T max epoch 2 ken trend
75	TmaxE2KnSl	T max epoch 2 Sen's slope
76	TmaxE2VS	T max epoch 2 Vogelsang significance
77	TmaxE2VT	T max epoch 2 Vogelsang Trend
78	TmaxFVS	T max full Vogelsang significance
79	TmaxFVT	T max full vogelsang trend
80	TminE1KenS	T min epoch 1 kendall significance
81	TminE1KenT	T min Epoch 1 kendall tau
82	TminE1KnSl	T min Epoch 1 Sen's slope
83	TminE1VS	Vogelsang trend significance level for epoch 1
84	TminE1VT	Vogelsang trend for epoch 1
85	TminE2KenS	T min epoch 2 Kendall significance
86	TminE2KenT	T min epoch 2 Kendall trend
87	TminE2KnSl	T min epoch 2 Sen's slope
88	TminE2VS	T min epoch 2 Vsignificance
89	TminE2VT	T min epoch 2 V trend
90	TminFVS	T min F V significance
91	TminFVT	T min full V trend
92	totVol	Total volume

93	trEP	Transitions between 3 states (Epehmeral, Seasonal and Permanent)
94	trES	Transitions between 3 states (Epehmeral, Seasonal and Permanent)
95	trLostPerm	Transition lost permanent
96	trLostSeas	Transition lost seasonal
97	trNewPerm	Transition new permanent
98	trNewSeas	Transition new seasonal
99	trNotWater	Transition not water
100	trPerm	Transition permanent water
101	trPS	Transition permanent to sesonal
102	trSeas	The errors of omission for seasonal water were reflected in accuracies of 74.9% (TM), 73.8% (ETM+) and 77.4% (OLI), see Pekel et al (2016)
103	trSP	Seasonal to permanent
104	upSlope	Uppermost slope of lake bathymetry
105	visVol	Visible volume of lake from space
106	Volume	Total volume
107	WindE1KenS	Wind epoch 1 kendall significance
108	WindE1KenT	Wind epoch 1 kendall Tau
109	WindE1KnSl	Wind epoch 1 Sen's slope
110	WindE1VS	Wind epoch 1 Vogelsang significance
111	WindE1VT	Wind epoch 1 Vogelsang trend
112	WindE2KenS	Wind epoch 2 kendall significance
113	WindE2KenT	Wind epoch 2 kendall Tau
114	WindE2KnSl	Wind epoch 2 Sen's slope
115	WindE2VS	Wind epoch 2 Vogelsang significance
116	WindE2VT	Wind epoch 2 Vogelsang trend
117	WindFVS	Wind full Vogelsang trend significance
118	WindFVT	Wind full Vogelsang trend

6

Conclusions and Reflections

The unprecedented scale of satellite and ground observation data available today and current advancements in trend detection enables us to understand climate-related changes in Arctic lakes in a robust way with high fidelity. In particular, these advancements allow us to better distinguish climate signals from correlation noise in disappearance/reappearance dynamics in Arctic lakes, the best sentinels of climate change. The analyses conducted in chapters 1-3 suggest that some of the scientific priorities to improve our ability to model their unique physical signatures are: 1) improved model design including updated and more accurate evaporation estimates; 2) increased direct observations of open water albedo and sinkholes via field or remote sensing observations. In conclusion, some inspiring lab experiments are highlighted to complement and extend the study, as a personal reflection to go from climate signature to fingerprint.

With the explosion of data access and tools to work with continental scale lake and meteorological data, methodological innovations have not yet caught up with the scale and resolution of the data at hand today. This dissertation is an attempt to focus on some of the most important variables that enable hyper-resolution land surface modeling of Arctic lakes and their response to climate change, considering how these lakes serve as sentinels of climate change. In particular, that includes characterization of the available information in sub-daily to sub-meter scales, under the limits of assumptions of hydro-meteorological homogeneity at 0.25 degree scale (a non-optional limit set by the density of rain gauges), and limits of detectability of change from time series of observations or model results – a non-optional limit set by the earth observation satellite observation record length available today. With these limits in mind, this dissertation makes three significant advances in the domain of hydro-meteorology: 1) sub-daily scale lake evaporation physical modeling advances that can account for sub-lake variation in lakes (especially important in small lakes); 2) sub-meter scale characterization of lake micro-topography which is known to influence methane emissions estimates up to 30%; 3) a 1-σ improvement in ability to detect trends (with known limits of detectability). Utilizing these three advances, in conjunction with numerous other variables, I revisit a widely known problem of the disappearance of Arctic lakes. By using new data and analytical tools, this dissertation identifies various challenges and opportunities connected to this problem and broadens the lens of hydrologic change by exploring various features in lake changes, including disappearance, reappearance, shrinking, and expansion.

The conclusions and future directions can be broken down by chapter:

1. **Introduction:** The broader importance of Arctic lakes in the climate change era (connected to their location, number, distribution, and unique thermal and reflective properties) makes them among the most attractive low hanging fruits to tackle the study of climate change in-land. This may lead to better planning and hedging against the risks of the climate crisis from local to global scale in-land climate signature.

2. **Arctic lake change, causes and consequences:** A large number of studies show that basically every major variable such as soil temperature, lake area, lake counts, lake temperature, methane estimates and their dependence on limnicity, and lake water and energy budget, shows changes in both directions and varies from one site to another. This suggests that the lens to study lakes as sentinels of climate change should be one where Simpson's paradox is handled well, i.e. scale of domain of analysis, time scale and signal vs noise should be carefully considered in order to assess which of the numerous causal pathways (hypotheses) of lake change are in fact at play.

3. **Lake physics knowledge (evaporation):** Open water evaporation, a primary lake process, has been studied for centuries. Nevertheless, fundamental problems in evaporation estimation exist. My analysis shows that a significant improvement in its estimation is possible from Robert Horton's century-old work on lake evaporation formulae, which I build on in the present work (Vimal and Singh, 2022). His work, as adapted by the present study, is applicable for global lake studies as it does 5-50% (seasonal to sub-daily) better than other methods. The improvement of ~50% at 30-min scale is quite remarkable as it is in the time scale that falls between the energy gap and turbulence scales (i.e. ~30 minutes), and it is nearly 1-sigma (5-10X) better in terms of the large-scale kinetic energy detected by the method compared to 5 other state-of-the-*art* mass-transfer methods. Considering the value of Horton's method and his deep understanding of applied physics, which was largely overlooked, it is my strong

belief that revisiting and disintering his larger body of his work (see Appendix of Chapter 3) by spending at least $30M funding in stages in the next decade will likely maximize our collective benefits in understanding how climate risks are manifested through water. Several of his results have been incorrectly interpreted not only with respect to evaporation theory, but broadly in geomorphology, meteorology and applied statistics. My results suggest it will be extremely fruitful to focus on Horton's "rational" (quasi-physical) approach to applied physics before complex model building exercises, which sets hydrology on an applied physics and quantitative footing and is truly reproducible from lab experiments to reanalysis estimations (i.e. continental to global scale simulations of lake change).

> "A rational equation may be defined as one which can be derived directly from fundamental principles, which fits all the experimental data and which represents the physical conditions correctly throughout the entire range of their occurrence and hence is valid outside the range of experimental observation" – Horton (1941).

4. **Separating long-term climate change signals from noise:** Though there is a great excitement for machine learning in applied sciences (hydrology, climate science and geosciences broadly), classical statistics and literature on robust trend detection have much to offer too. Classical trend detection methods used in Hydrology (Mann-Kendall and variants) have been heavily studied and used in hydrologic research, but hydrologists' understanding or use of trend detection falls behind other fields like econometrics or biometrics. The main lesson learnt is that trends need to be robust to correlation in time (a ubiquitous property of hydrometeorological time series). Hence, I

recommend 1) that the Mann-Kendall method and its variants be used more cautiously, considering the limitations of its statistical "confidence" and "power" and 2) that hybrid methods (drawing from the econometrician's toolkit) be adopted more widely, not only for understanding climate signatures on lakes, but more broadly in geoscience change or general time series trend detection problems. As the analysis of chapter 4 was able to show, using a combination of the Mann-Kendall method (non-parametric) and the Vogelsang method (parametric), i.e. a combined portfolio of 16 methods, allows us to increase statistical confidence and power in trend detection from approximately 50-60% (actual current standard in hydrology) to approximately 95% - the often desired statistical significance level.

5. **First-order scientific priorities in Arctic lake science were identified using a correlative research study:**

> "Scientific research may be broadly classified as (a) correlative, (b) laboratory, (c) field. Before any field or laboratory research is undertaken on an important topic, a thorough correlative research should be carried out to determine just what has been done on the subject and what most needs to be done. The correlative research corresponds to the making of a map of existing highways before undertaking to complete the highway system of a region. Its importance can not be overstressed." - Horton (1937)

It is important to note that the conceptual systems diagram of the lake-climate system is akin to the highway map, and the progress made in Chapters 2-5 represent critical first-order PIPs and SIPs that offer us a starting point to then assess the speed of moving of levers (via robust trend detection) of a complex non-linear feedback systems. From this study, it has become clear that Arctic lake studies require further research in two principal directions, 1) application of robust trend detection to precisely trace climate-related lake changes and that of all system variables (states and fluxes) concerned; 2) field measurement of open water albedo and sinkholes are among the crucial factors (and missing pieces) to explain lake disappearance/reappearance cycles. To expand on these points: a hydrologic engineering lens, i.e. considering frequency and periodicities, is needed in Arctic lake studies to perform robust trend detection in order to ascertain the permanence of long-term change in lakes, and Arctic lakes cannot be said to be disappearing without the lens of robust trend detection as described in Chapter 4. With regards to open water albedo, alarm bells concerning the need for better observation of these variables were rung as early as in 1986 by Henderson-Sellers. In the same vein, there is a strong need to measure subsurface sinkholes, perhaps via space-borne observations using inverse modeling methods, or direct measurements from the field. Without an accurate understanding of these variables, lake change assessments from an energy or water balance perspective are subject to large errors at the resolution (sub-daily scale) pertinent for GCMs as done within LSMs.

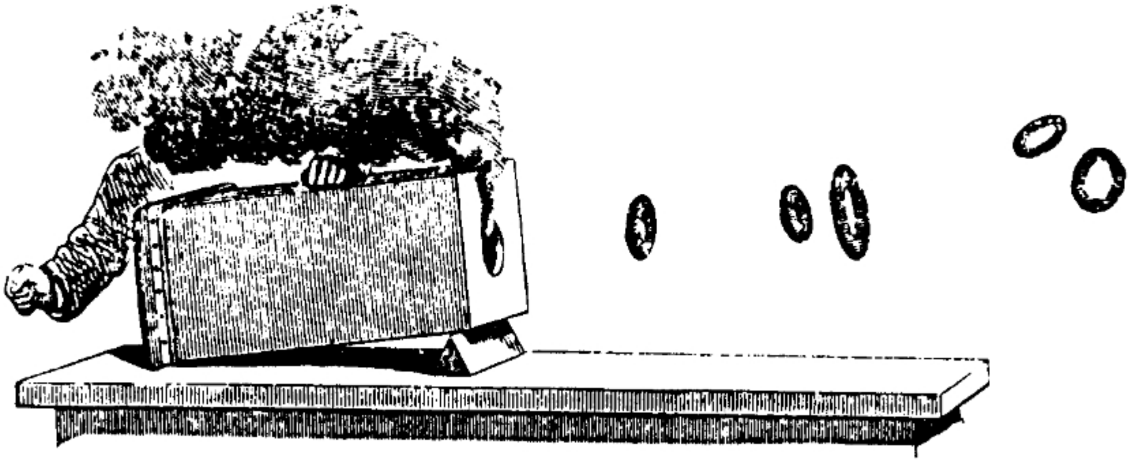
Collectively, these results I demonstrate at continental scale spanning whole of Canada and Alaska, ~10 million lakes, carve a pathway for a high-fidelity understanding of local-to-global scale climate change signatures on ~100 million lakes, which are, due to their intrinsic and extrinsic characteristics, our best sentinels of climate change.

Need for laboratory work – going from signature to fingerprint

While most of this dissertation was concerned with interpretation of retrospective data, with insights for modeling, an area not touched in this dissertation, but nevertheless, the most important for Arctic lake science to pass for science, is the need for laboratory work. I will provide three examples that may be inspiring starting points, which I chanced upon in the course of my dissertation research:

1. **Experiment for correction of wind speed measured at the surface of water.** Horton (1927) used an ingenious method with a pail of water filled to the brim and suspended and rotated to simulate surface wind velocity at the angular velocity of the swing. This experiment allowed him to derive a reliable table of values for wind velocity correction necessary to estimate evaporation. At the time he devised this experiment and derived the tables, and to this day, mechanical devices such as wind tunnels are used to conduct such experiments, but such expensive devices are not needed to conduct relevant experiments. What is needed though is a first principles and experimental approach that can bring about concrete knowledge in physical processes. Extending from this inspiration, one can imagine how a pressure cooker or a freezer with ice cubes and kitchen trays can be used to understand the mechanisms that underlie lake change in the cryosphere.

2. **Lake thermal stratification:** A lab experiment on Youtube (*Lake Stratification with Stan Gregory*, https://www.youtube.com/watch?v=XExQ6uaDEJQ; accessed May 16, 2022) on stability and thermal stratification of lakes helped me better comprehend the scales involved in terms of diffusion and turbulence in lakes. Arctic lake studies should include such experiments to understand dominant processes.
3. **Convection in the boundary layer and in lakes:** P. G. Tait's famous acid experiment which Horton used to study convective vapor plumes and convective precipitation in the atmospheric boundary layer allowed me to appreciate how they are all intimately tied together across scales in terms of the underlying mechanisms of advection vs diffusion. This concept can be best understood in the lab, and should be studied in detail to make progress on the work in Chapter 3. Similar lab experiments are needed for understanding hydro-meteorological processes.



Tait's smoke ring apparatus (source: P. G. Tait 1876, p.292)

This dissertation develops some tools and insights to tease out climate signatures from lakes using noisy gauge and earth observation data, imperfect models, and computers. Any signature thus identified should conform to lab experiments, which may be regarded as better evidence, i.e. fingerprints of the culprit, climate change, in millions of lakes that are undergoing an unprecedented change today.