Evaporation from a temperate closed-basin lake and its impact on present, past, and future water level

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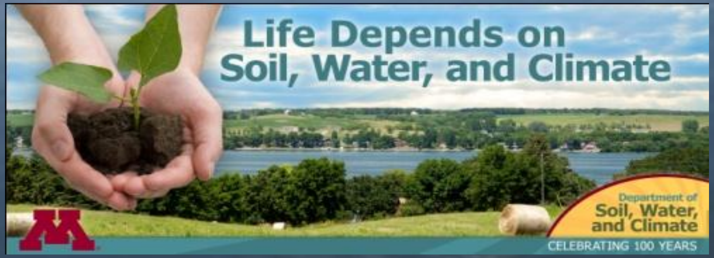
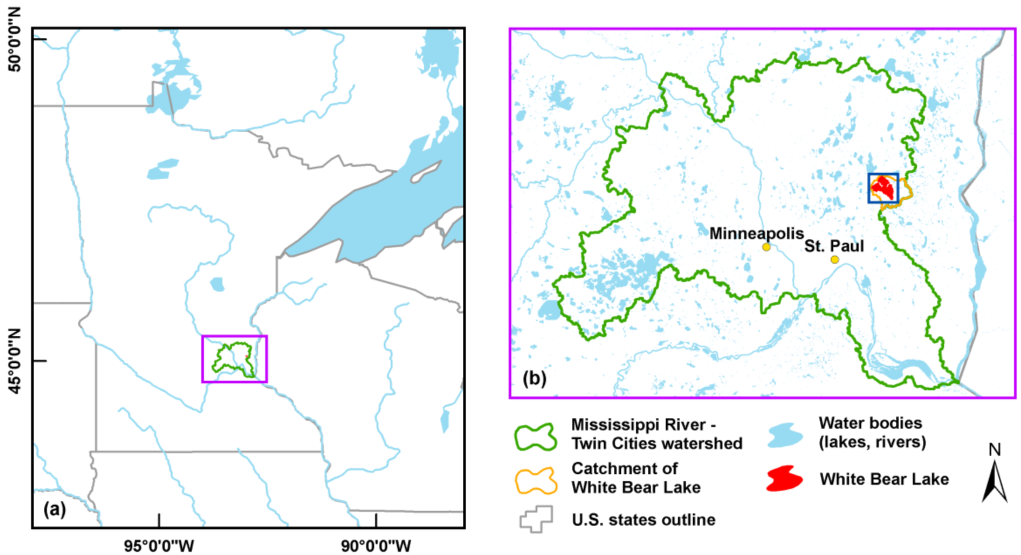
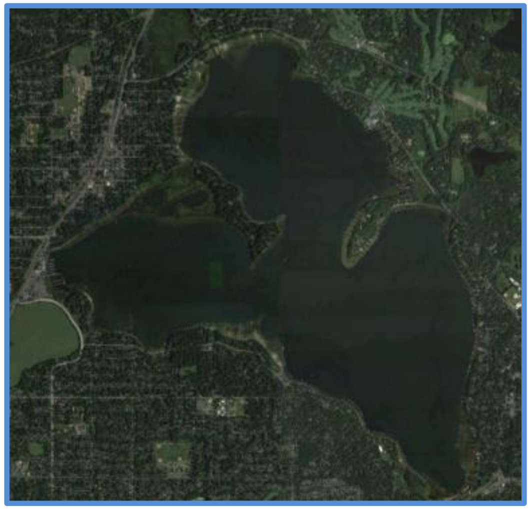


Yale-NUIST Center on Atmospheric Environment
June 22, 2017

White Bear Lake (WBL)





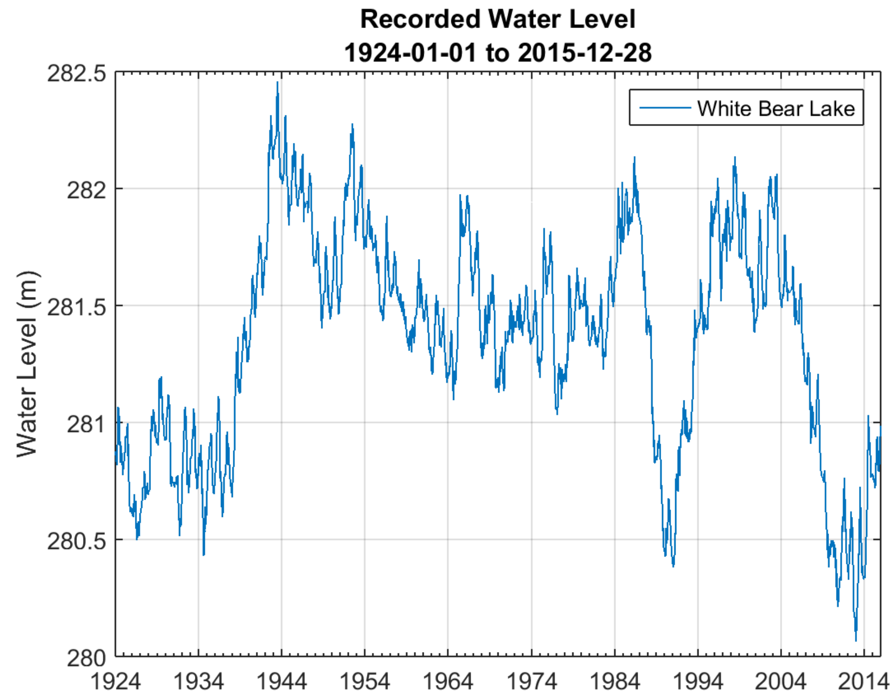
"White-bear Lake … is a lovely sheet of water, and is being utilized as a summer resort by the wealth and fashion of the State. It has … its fine summer residences; and plenty of fishing, hunting, and pleasant drives… White-bear Lake is *the* resort."

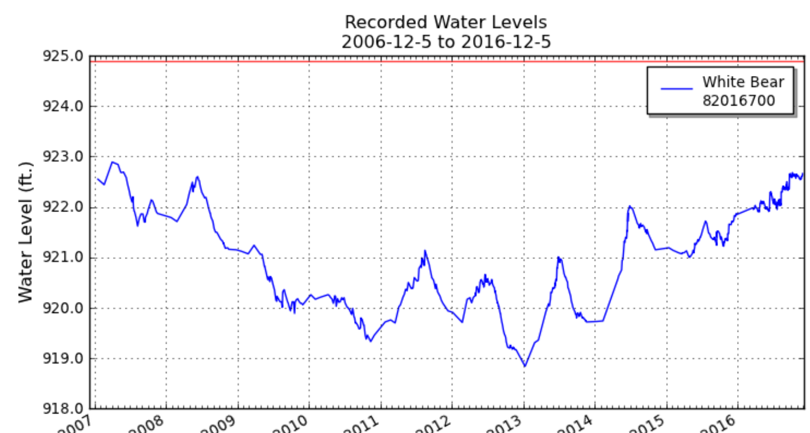
Life on the Mississippi By Mark Twain

Historical Perspective

(mprnews.org, 2014)

(fmr.org, 2012)





(MN DNR)

Public Concerns

MINNESOTA PUBLIC RADIO

Land of 9,999 "shrinking" lakes? Is White Bear Lake MN's "climate change canary in coal mine?"

Paul Huttner October 1, 2012, 7:04 PM 2 Comments

MINNESOTA PUBLIC RADIO

Why not just fill up White Bear Lake from one of the rivers?

Dave Peters March 26, 2014, 9:32 AM 10 Comments

MINNESOTA PUBLIC RADIO

Water

$50M pipe might not restore White Bear Lake levels

Elizabeth Dunbar July 23, 2014, 4:54 PM 0 Comments

TwinCities.com PIONEER PRESS

How to fix White Bear Lake? Many facts still unknown

By DEBRA O'CONNOR | doconnor@pioneerpress.com

PUBLISHED: July 24, 2014 at 11:01 pm | UPDATED: November 3, 2015 at 10:39 am

MPRnews

Water rising again in White Bear Lake, but will it stay?

Matt Sepic · White Bear Lake, Minn. · Sep 3, 2015 Environment

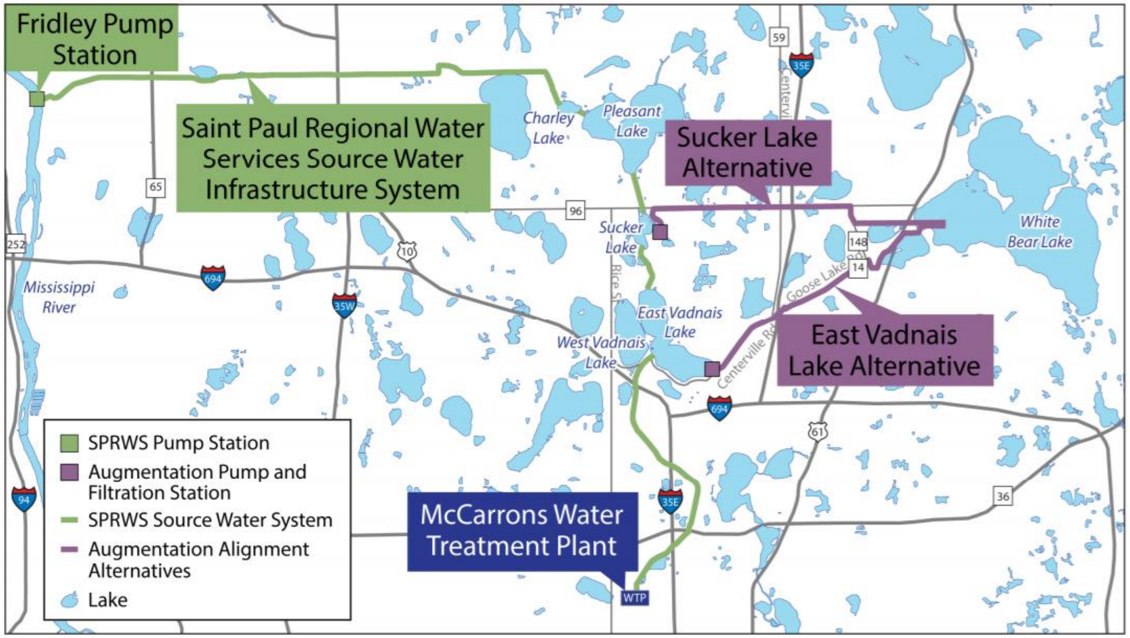
TwinCities.com PIONEER PRESS

White Bear Lake wants answers about low water level, despite recent rise

By HALEY HANSEN | hhansen@pioneerpress.com

PUBLISHED: December 8, 2016 at 7:01 am | UPDATED: December 8, 2016 at 7:06 am

Proposed water augmentation



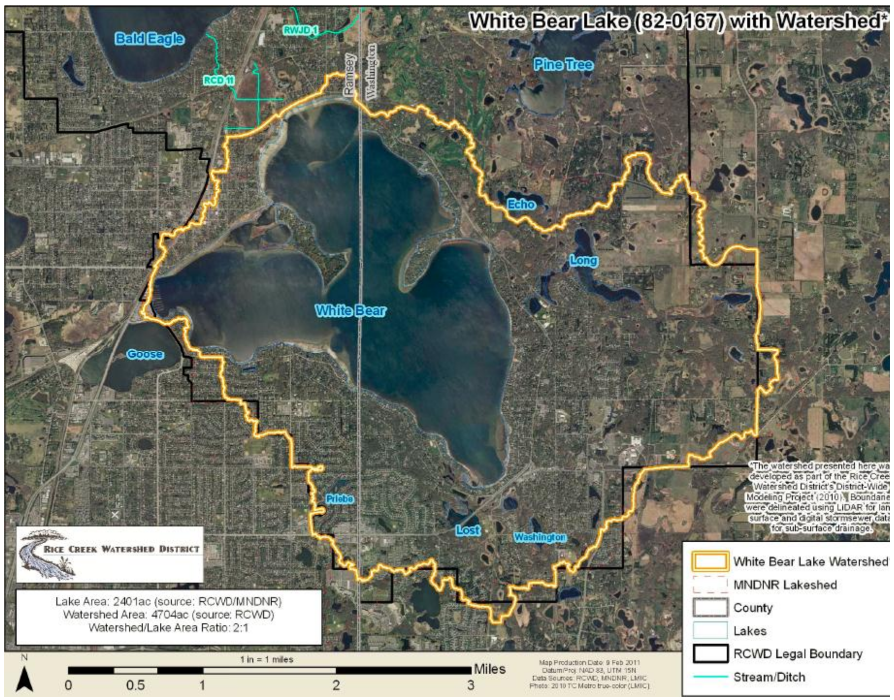
(MN DNR)

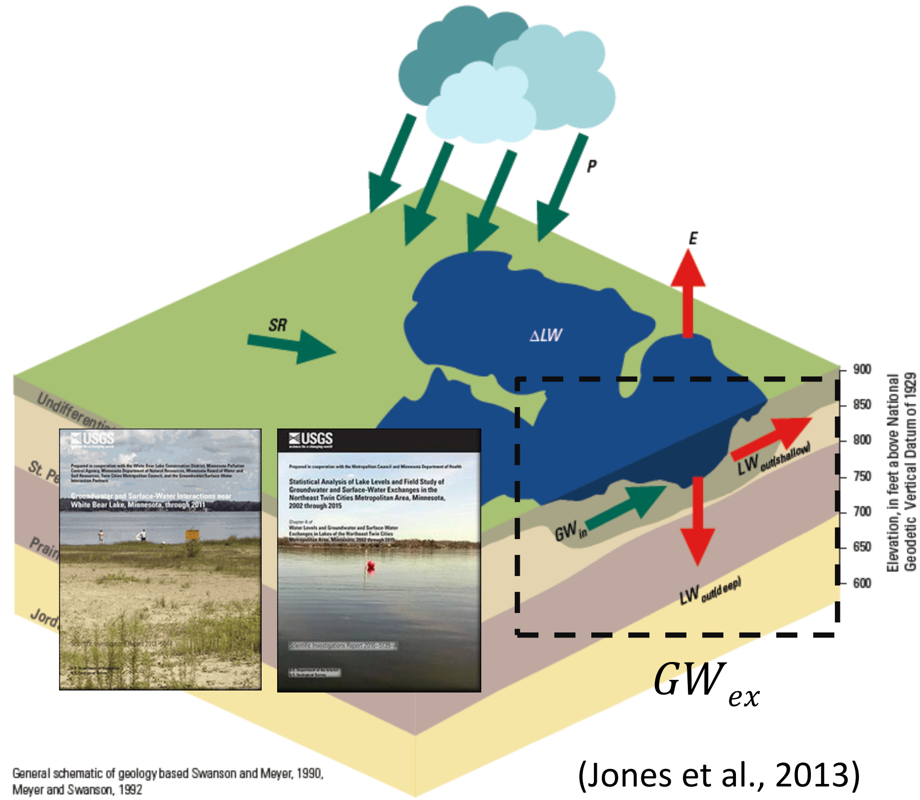
Water quality?
Ecology?
Hydrology?

Estimated Cost	Sucker Lake Alternative	East Vadnais Lake Alternative
Construction Cost (2018-19 dollars)	$67 million	$55 million
Operations and Maintenance Cost*	$570,000 / year	$570,000 / year

*Assuming annual pumping of two billion gallons (7.6×10^6 m^3) per year.

Hydrology of WBL





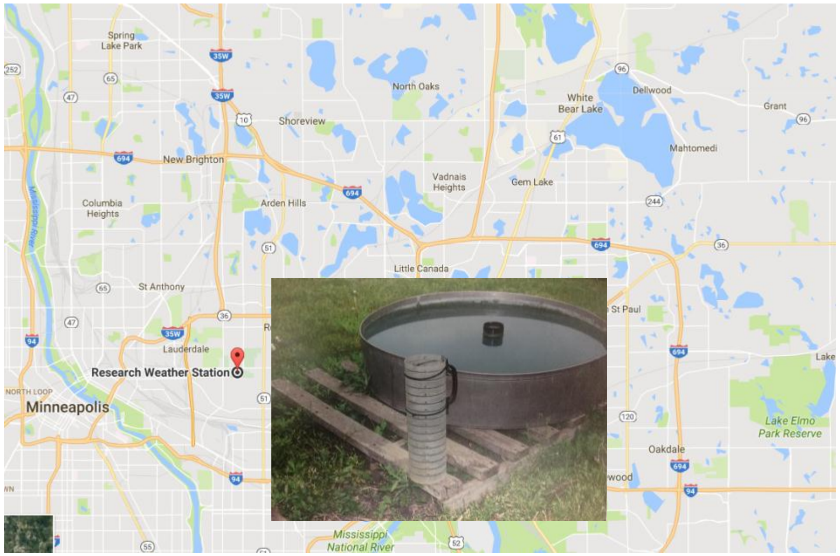
(Jones et al., 2013)

Watershed area : Lake area = 2:1

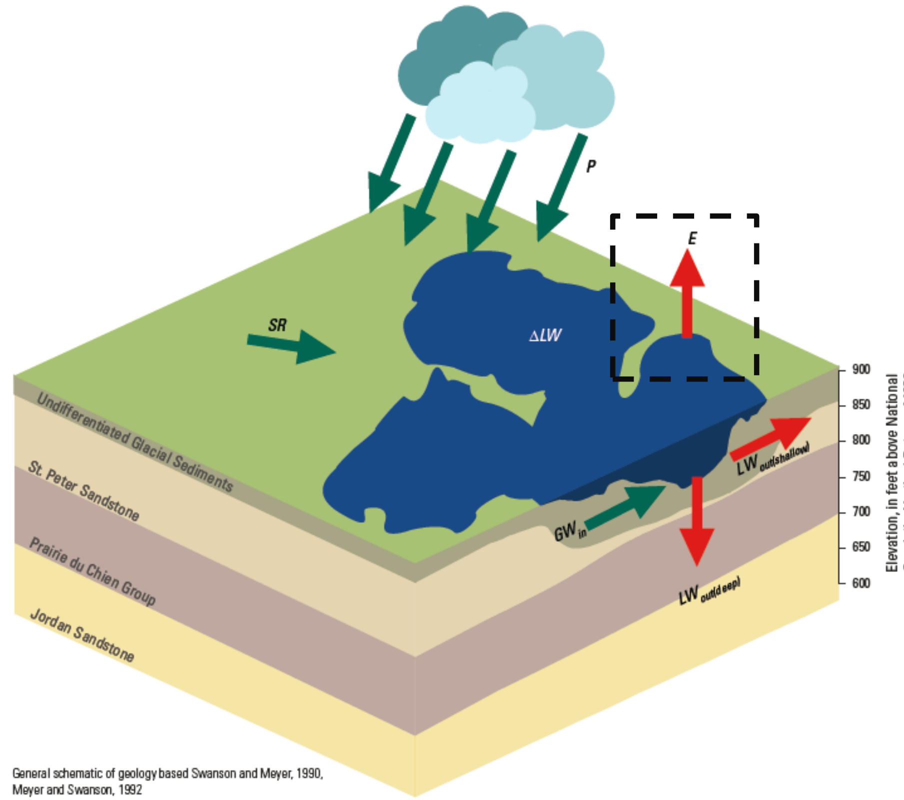
Closed-basin lake

$$\Delta L = P - E + GW_{ex}$$

Pan vs. Lake



(Minnesota State Climatology Office)



Heat capacity?
Dynamic feature?
Ice phenology?

"It is easy to understand their intuitive appeal, because they model the evaporation from a free water surface in a visible way… it is still very difficult, if not impossible, to make a general and practical use of pan data except special situations."

Evaporation into the Atmosphere By Wilfried Brutsaert

Scientific Questions

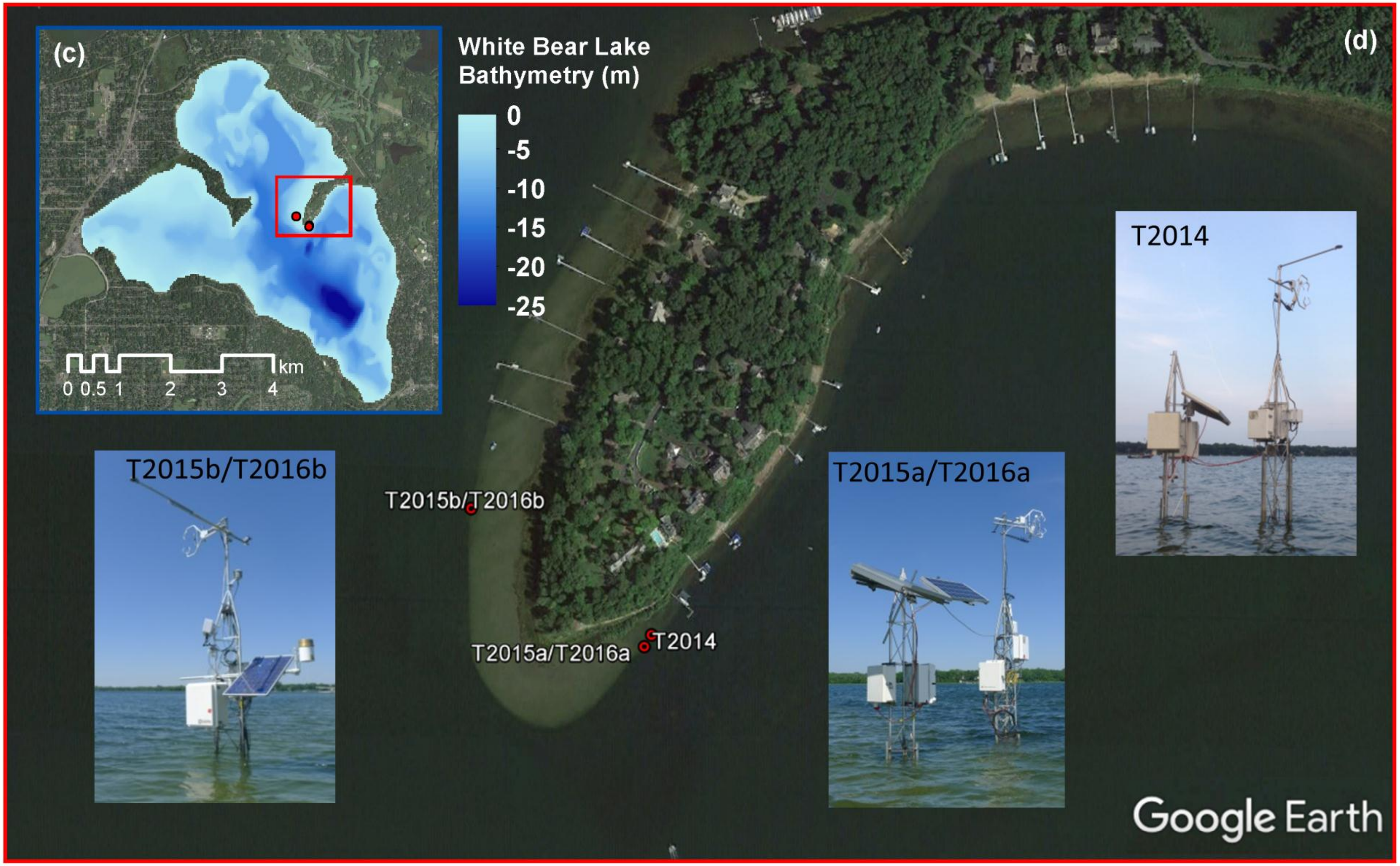
- What is the magnitude of evaporation from WBL and how much does it vary seasonally and inter-annually?
- How sensitive is annual evaporation to meteorology and climate and to what extent has evaporation from the lake changed over the past 30 years?
- How are changes in climate going to impact evaporation and WBL lake water level through the 21st Century?
- What are the potential implications for other lakes within the Mississippi River - Twin Cities watershed?

Outline

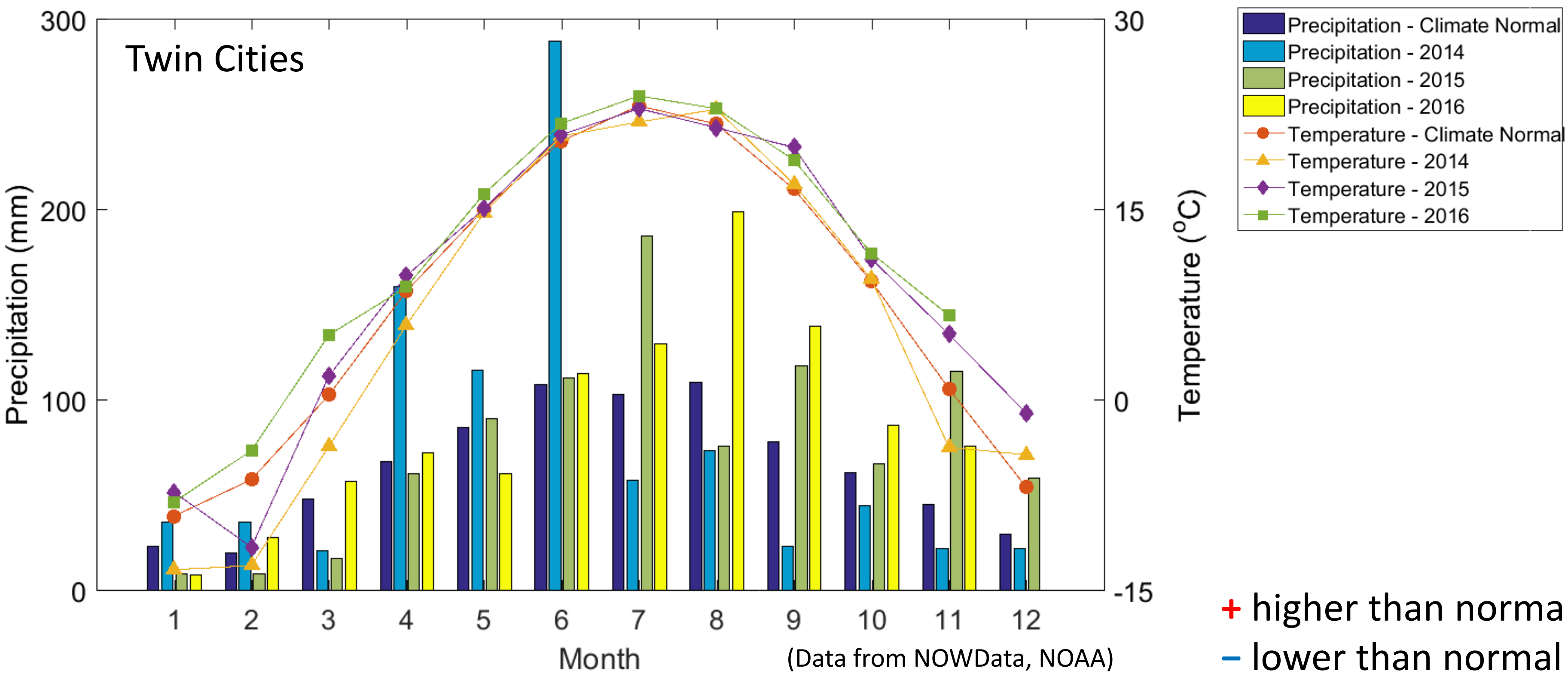
- Eddy Covariance Observations
- Ice phenology
- Numerical Modeling
- Evaporation and Water Level

Part 1: Eddy Covariance Observations

Micrometeorological Towers



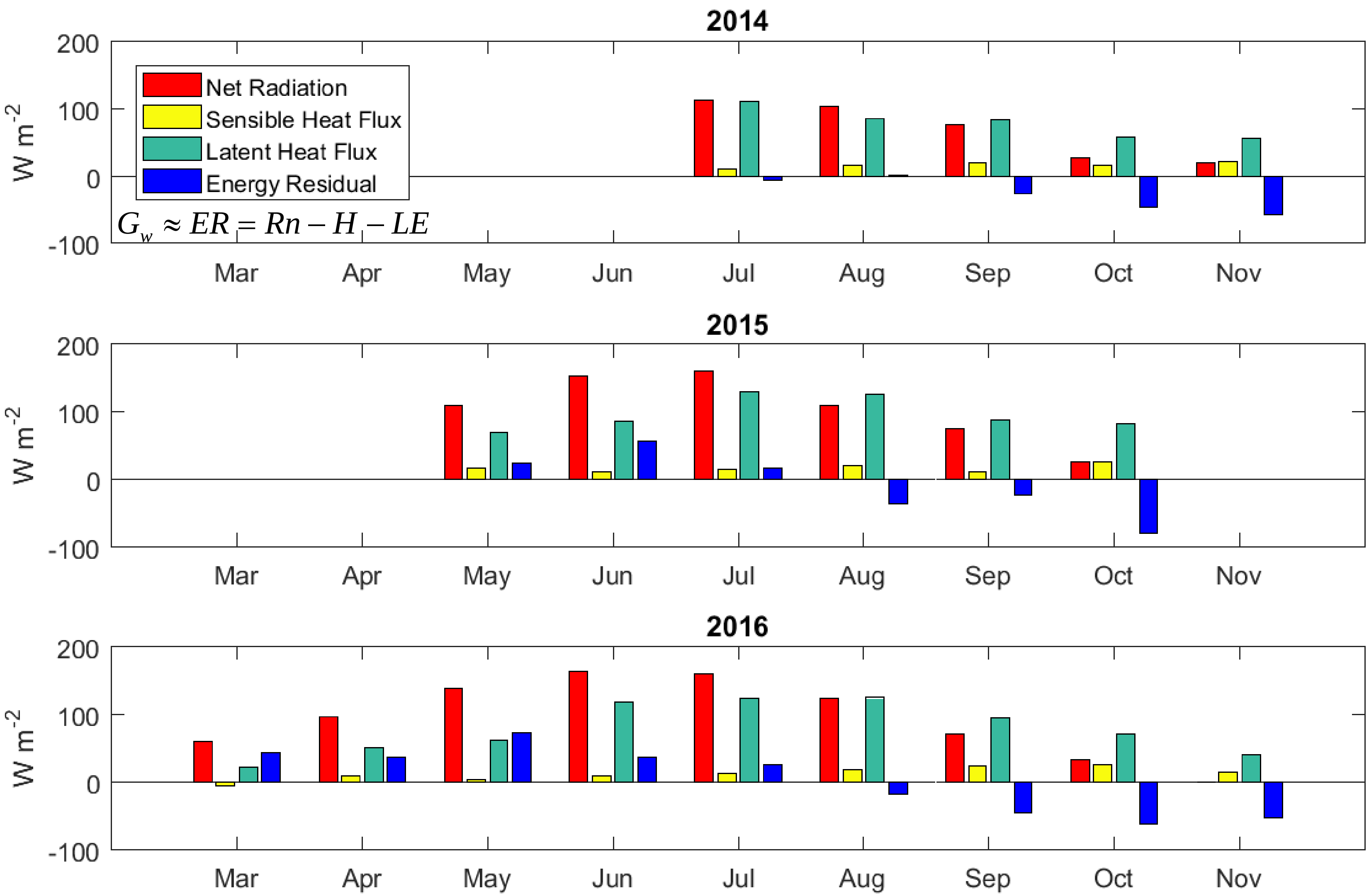
Climatology



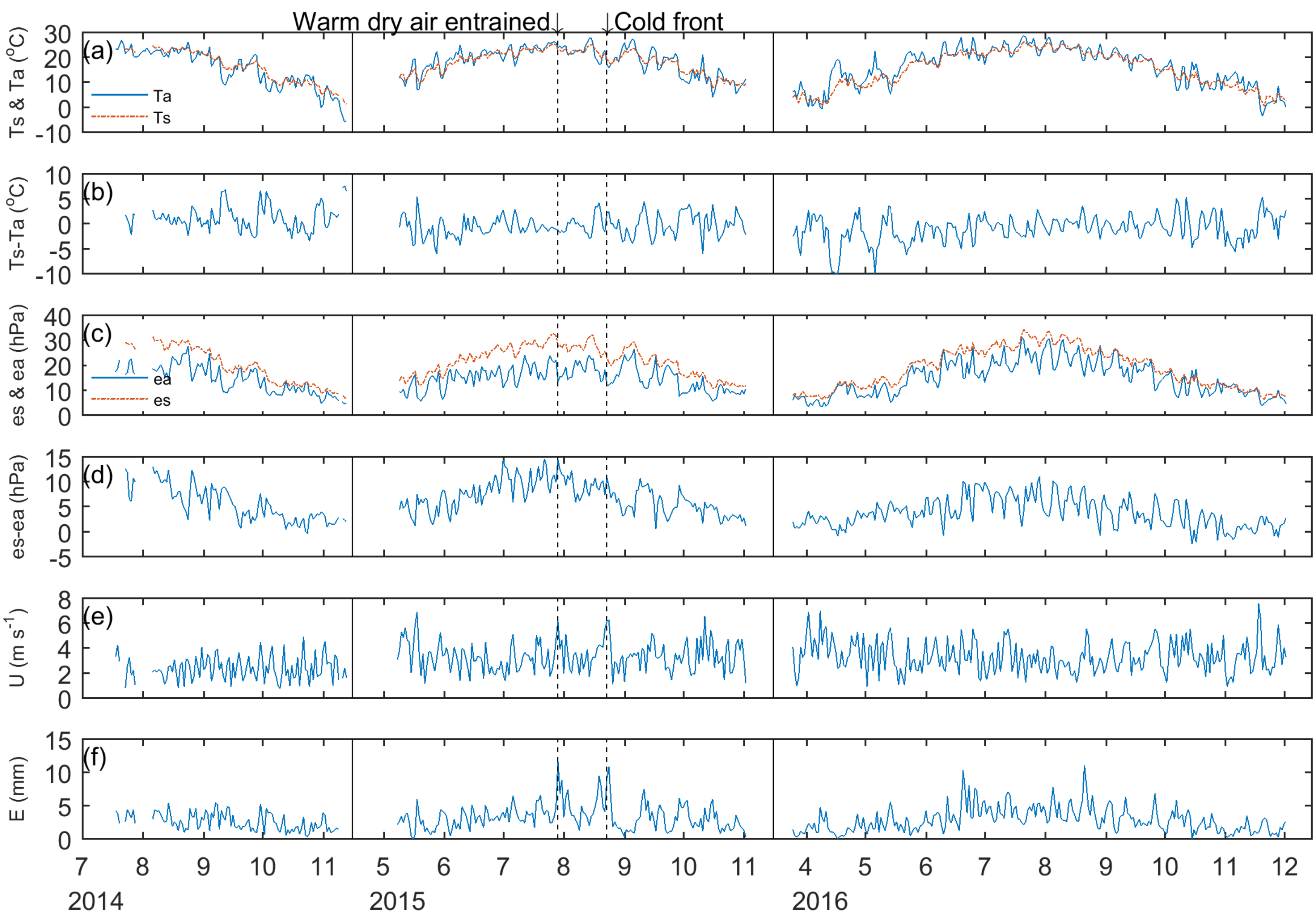
+ higher than normal
– lower than normal
~ about the same

	2014												2015												2016										
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
P	+	+	–	+	+	+	–	–	–	–	–	–	–	–	–	–	+	+	+	–	+	+	+	+	–	+	+	+	–	+	+	+	+	+	+
T	–	–	–	–	~	~	–	+	~	~	–	–	+	–	+	+	~	~	~	~	+	+	+	+	+	+	+	~	+	+	+	+	+	+	+

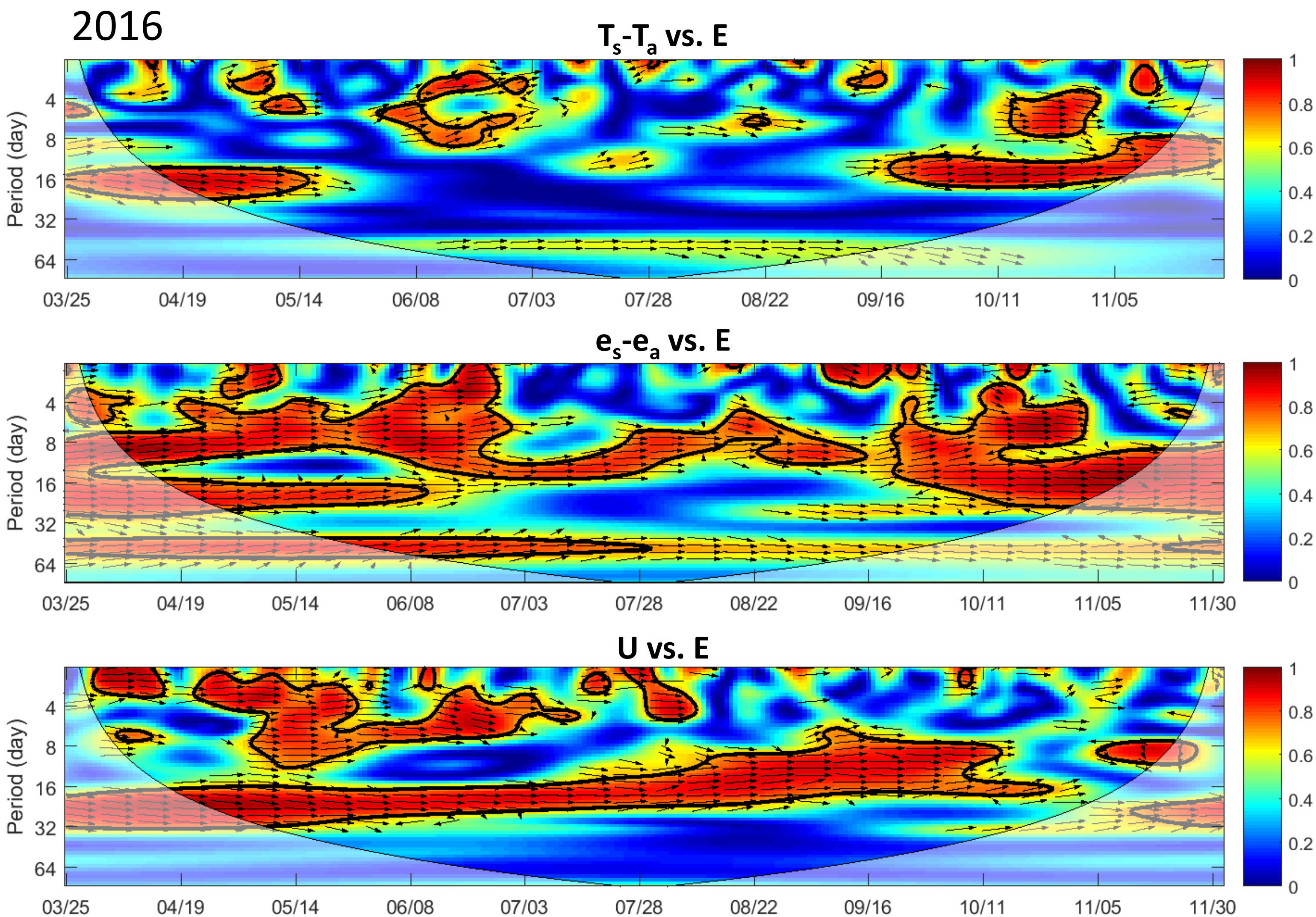
The heat released from the lake was the main energy source for evaporation in the fall



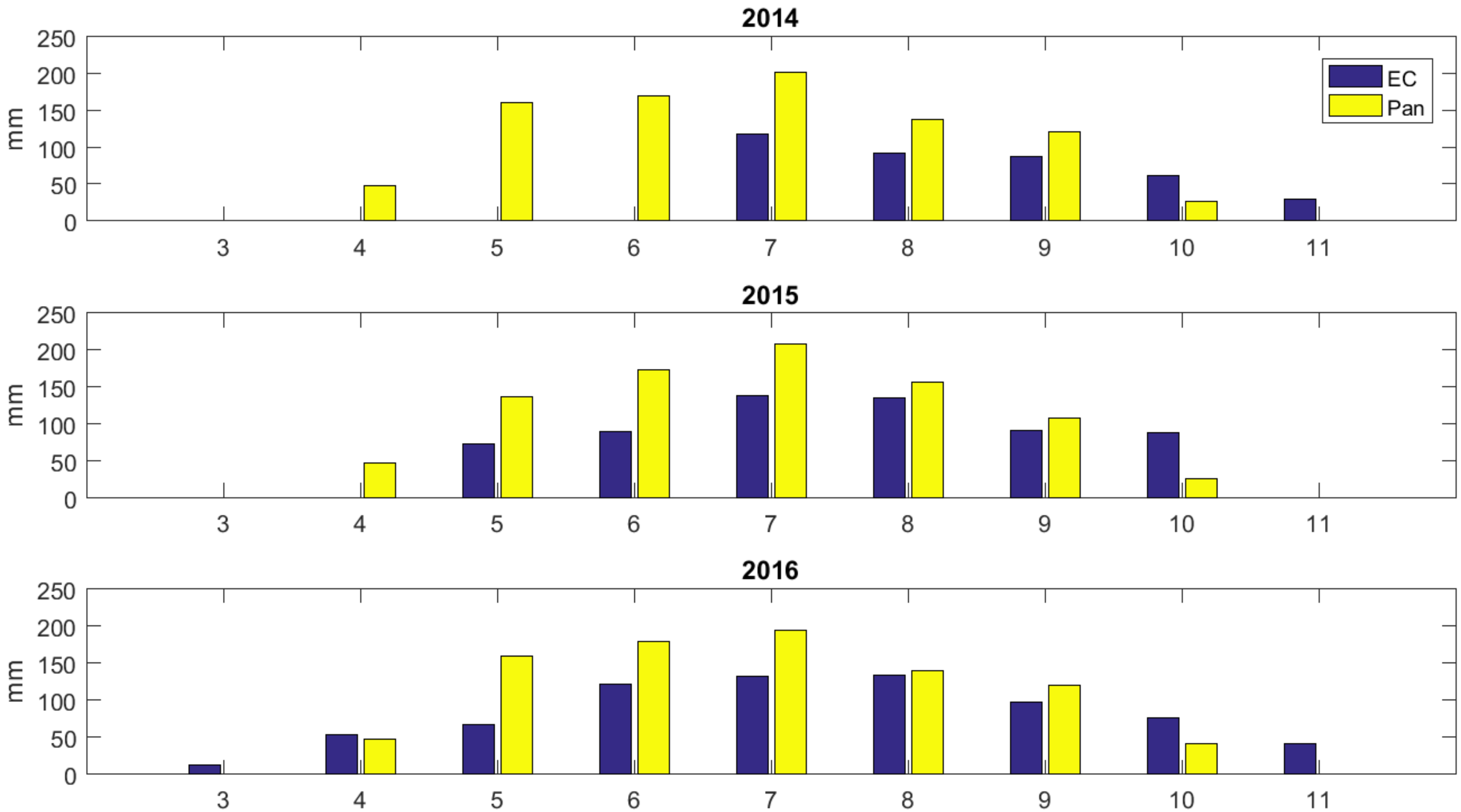
Daily evaporation at WBL was strongly influenced by synoptic-scale variability



A pronounced two-week cycle of evaporation in the fall coincided with synoptic scale systems as identified from wavelet analyses



Pan vs. Lake

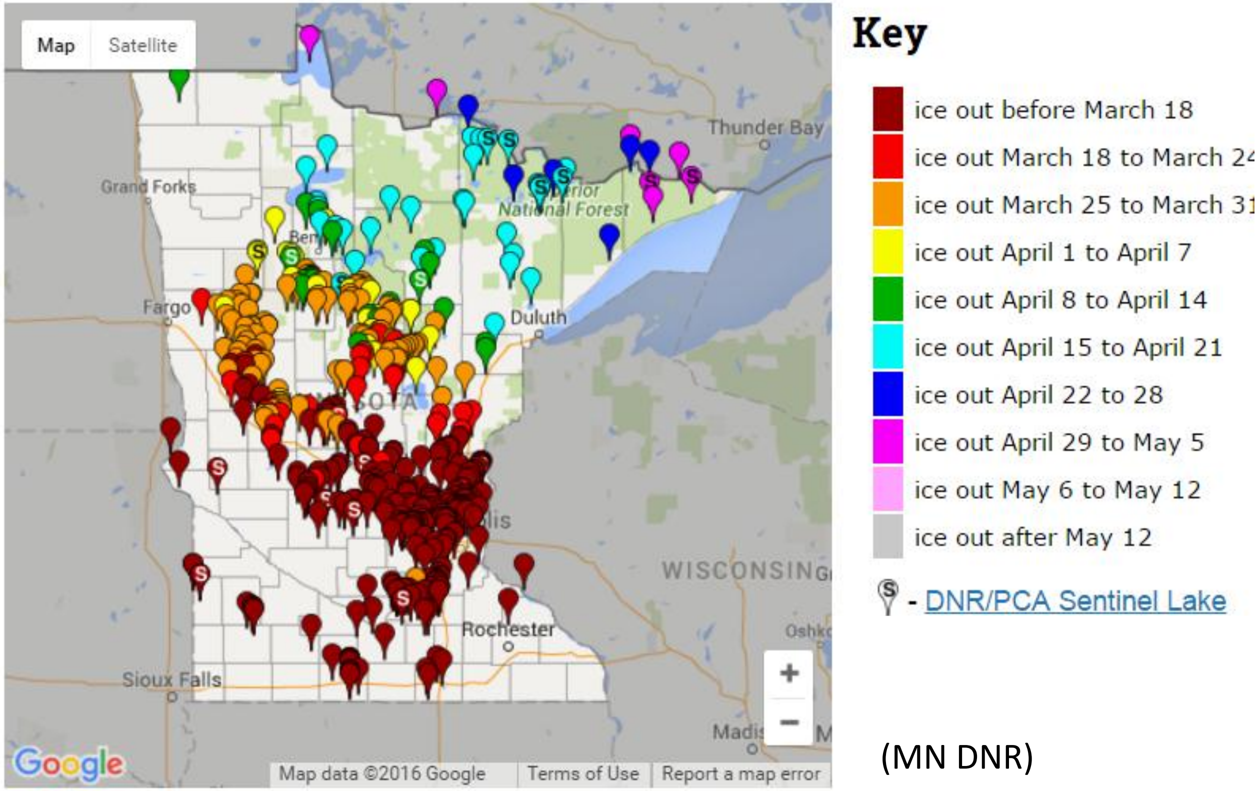


The lake-to-pan evaporation ratio showed large monthly and inter-annual variability. In particular, the variability in the length of ice-free periods can have a large influence on these ratios making it impractical to obtain a representative annual value.

Part 2: Ice Phenology - The Challenge of Estimating Annual Evaporation

The length of Ice-free period is an important factor to estimate evaporation in temperate lakes.

2016 Lake Ice Out Dates



(MN DNR)

Mar 16th, 2016 - Recorded earliest ice-out date at WBL

Lack of ice-in data at WBL

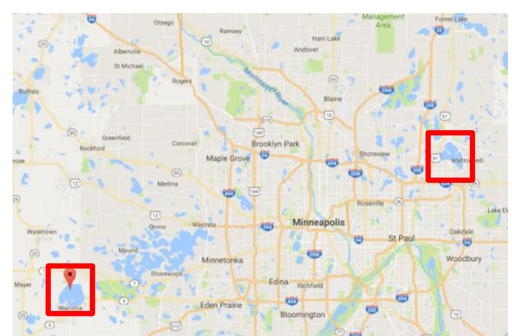
Remote Sensing – MODIS data

- 500-m daily reflectance
- Normalized Difference Snow Index

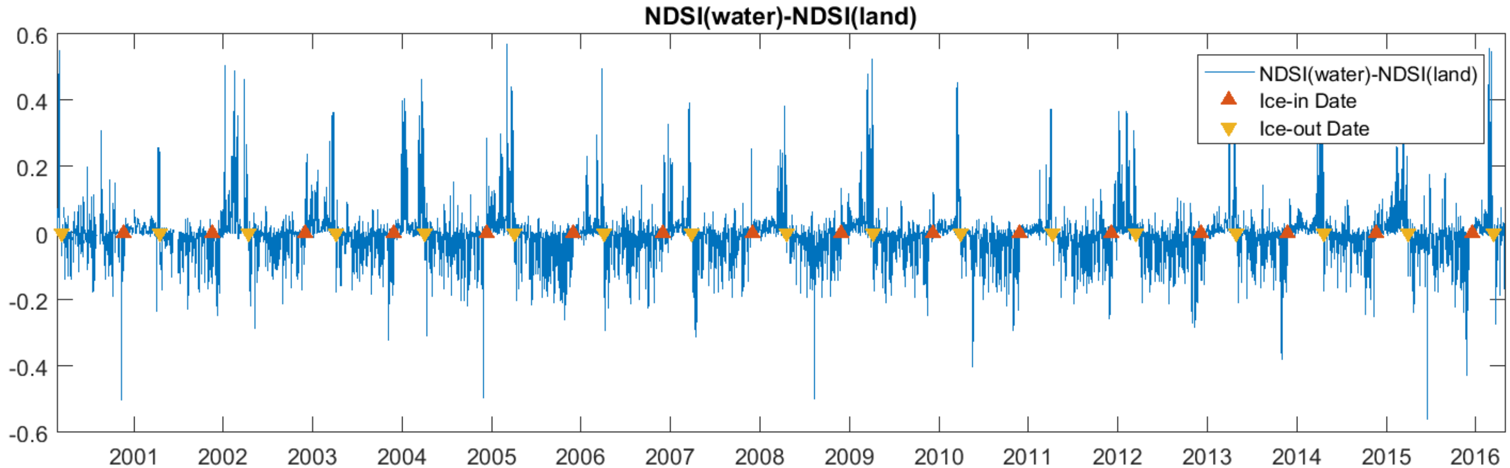
$$NDSI = \frac{Band2 - Band5}{Band2 + Band5}$$ (Irish, 2000)

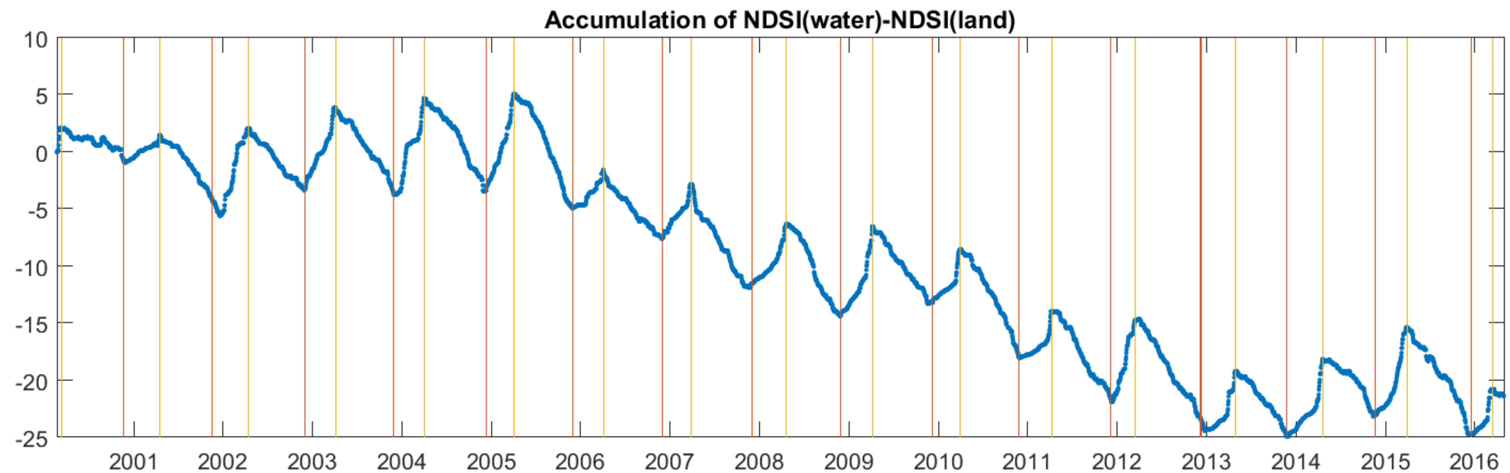
  - Band 2 (NIR: 841-876 nm)
  - Band 5 (SWIR: 1230-1250 nm)

- Accumulation of NDSI(water)-NDSI(land)
- Example: Lake Waconia

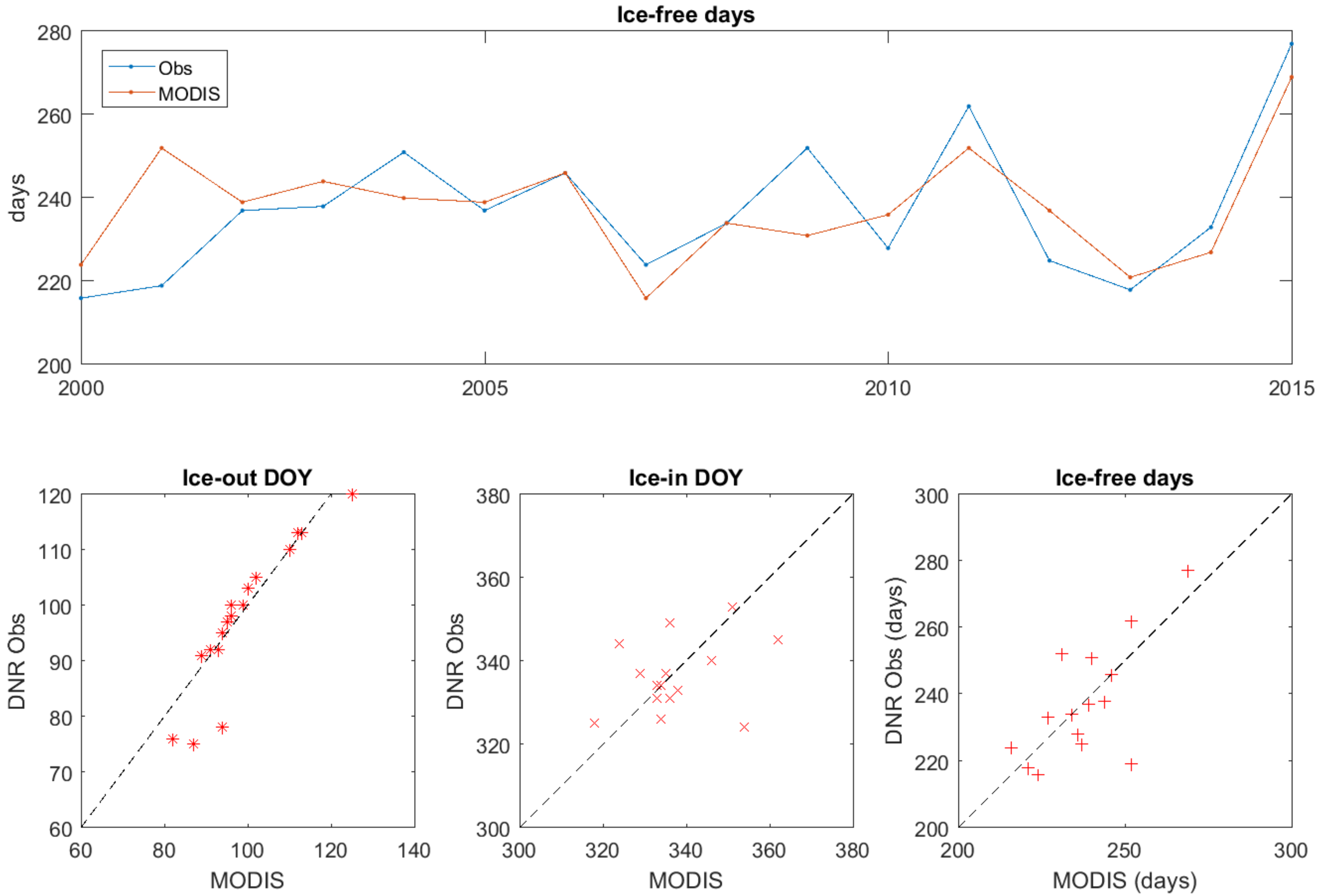


NDSI(water)-NDSI(land)

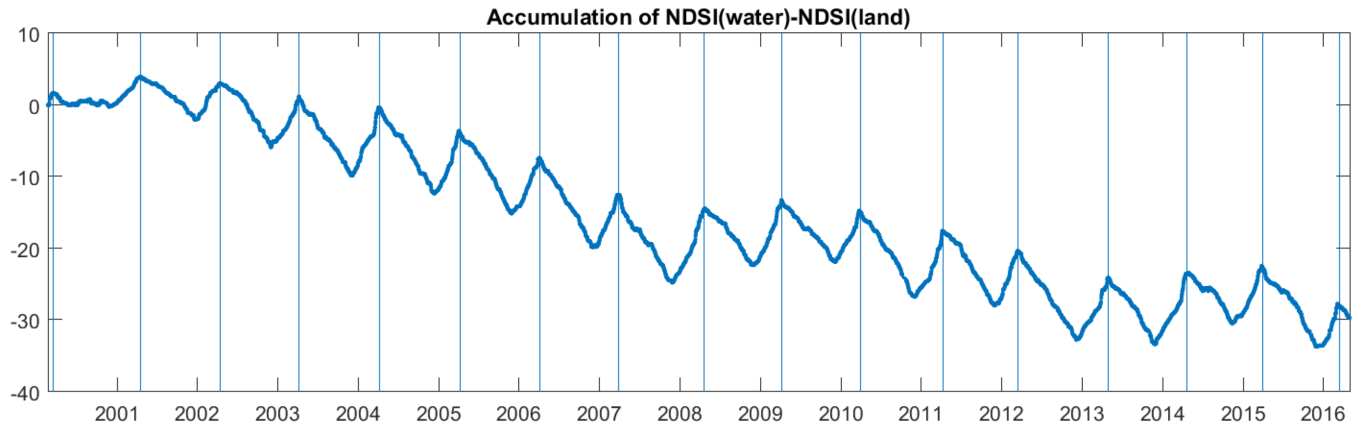


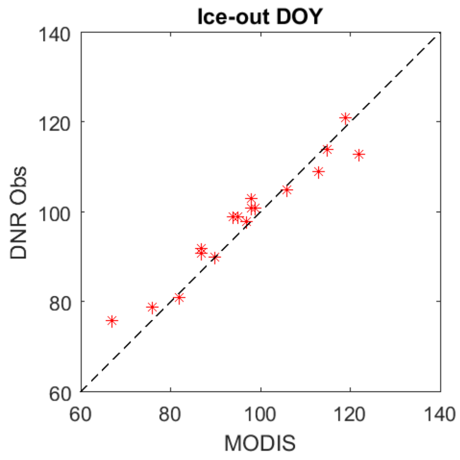


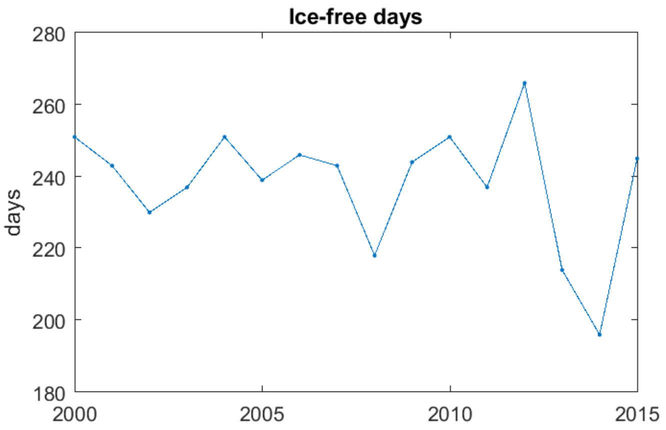
Ice-free days



WBL ice phenology



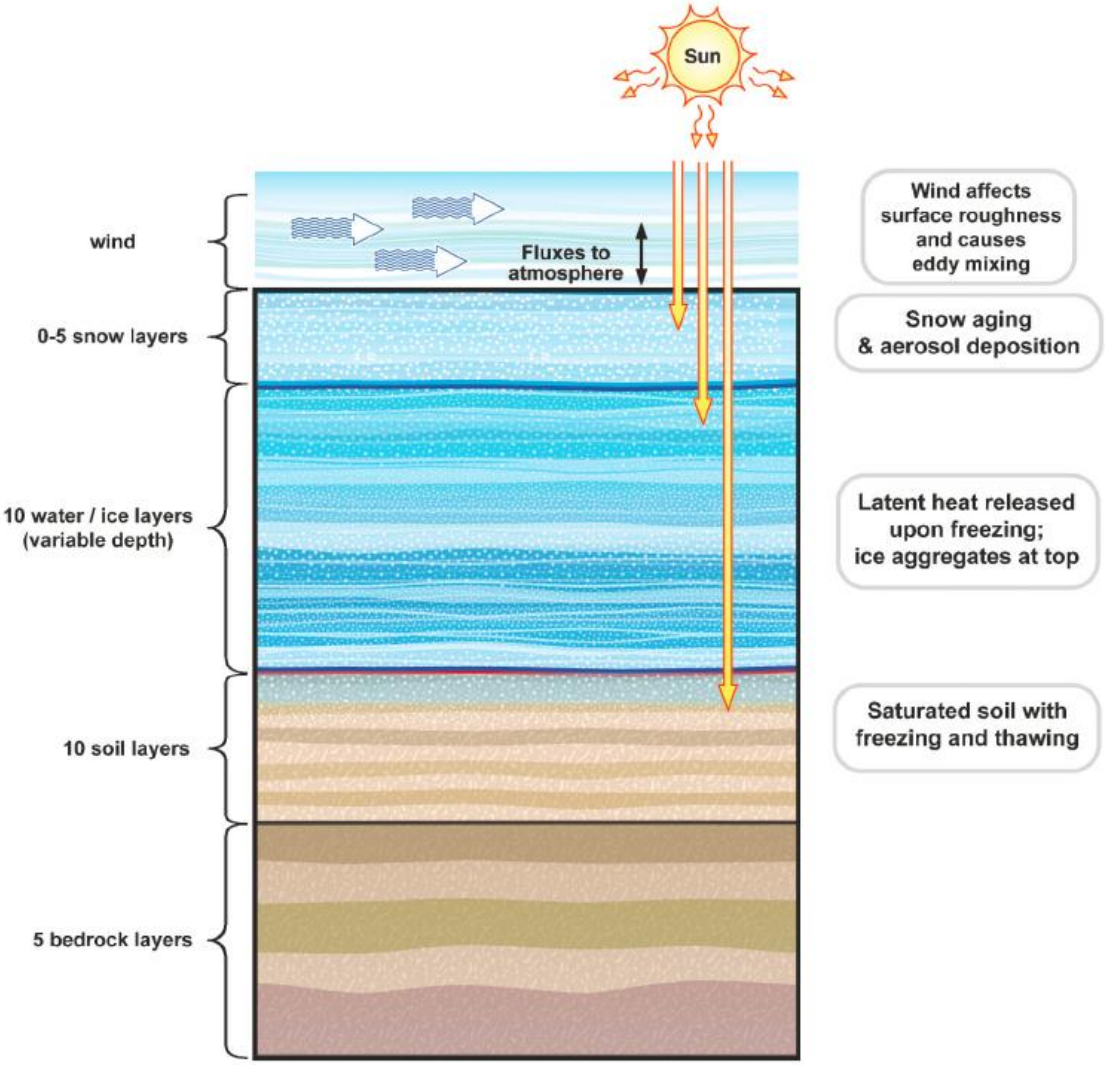




Part 3: Numerical Modeling

CLM4-LISSS

- Community Land Model – Lake, Ice, Snow and Sediment Simulator
- 1D thermal diffusion equation (no horizontal flux exchanges)
- Adequate to simulate lake water temperature and surface energy fluxes



(Subin et al., 2012)

Important features

- The model includes
  - improved calculations of surface fluxes and lake temperature
  - improved parameterizations of lake properties such as roughness, albedo and opacity
  - processes of freezing and melting
  - a comprehensive treatment of snow

Flux Calculations

Energy Balance: $S + L = H + \lambda E + G$

$$S = \beta S_a,$$

$$L = -\epsilon\left(\sigma T_g^4 - L_{atm}\right),$$

$$H = \rho_{atm} c_p \frac{T_g - \theta_{atm}}{r_{ah}},$$

$$\lambda E = \lambda \rho_{atm} \frac{q_g - q_{atm}}{r_{aw}},$$

$$G = k \frac{T_g - T_T}{\Delta z_T / 2},$$

- $\boldsymbol{S_a}$ Net shortwave radiation
- **β** fraction of S_a absorbed by the lake surface
- $\boldsymbol{L_{atm}}$ downward longwave radiation flux
- $\boldsymbol{T_g}$ water surface temperature Critical variable
- q_g saturated specific humidity at T_g
- $\mathbf{r_{ah}}$ aerodynamic resistance with respect to sensible heat
- $\mathbf{r_{aw}}$ aerodynamic resistance with respect to latent heat
- $\boldsymbol{k}$ thermal diffusivity

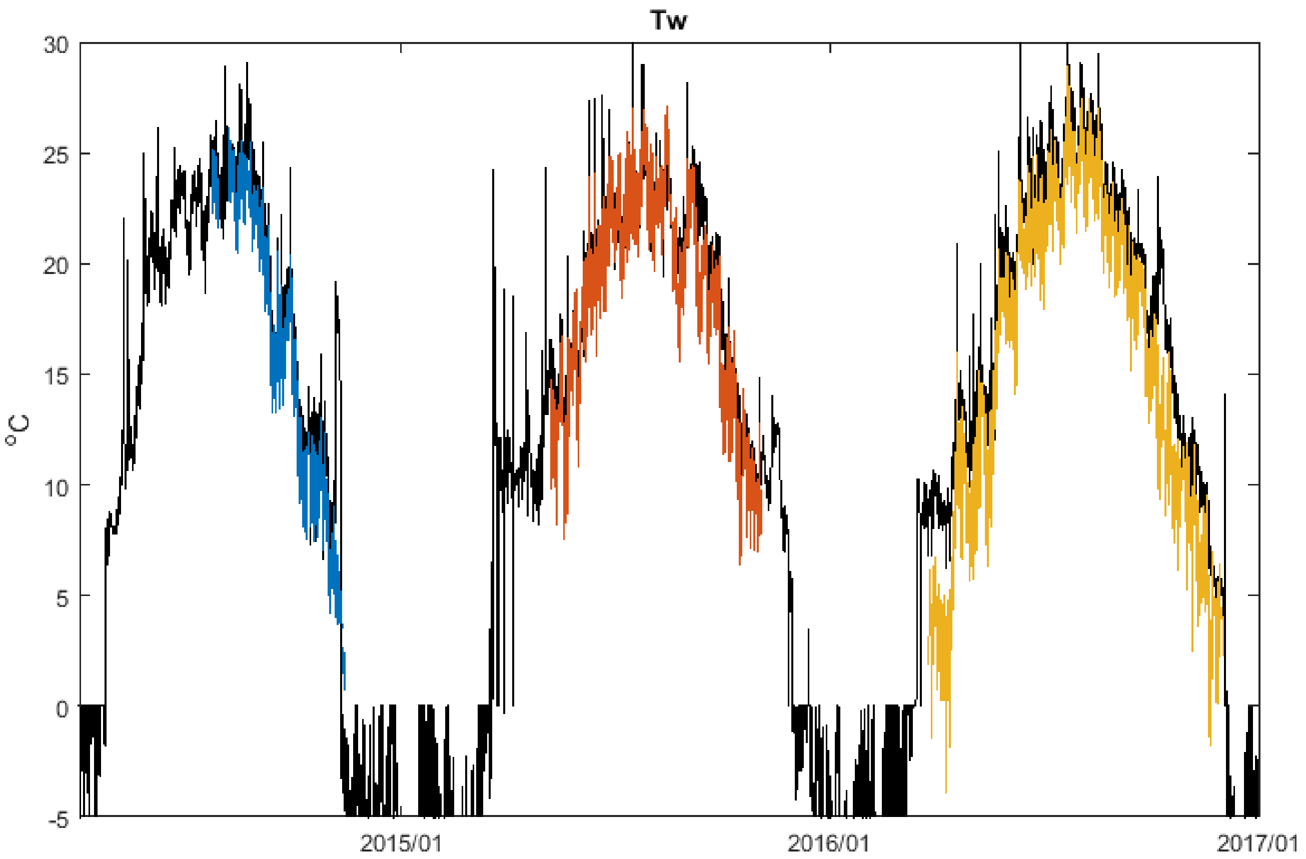
Critical parameters

- T_T temperature of the top lake model layer
- Δz_T top lake model layer thickness

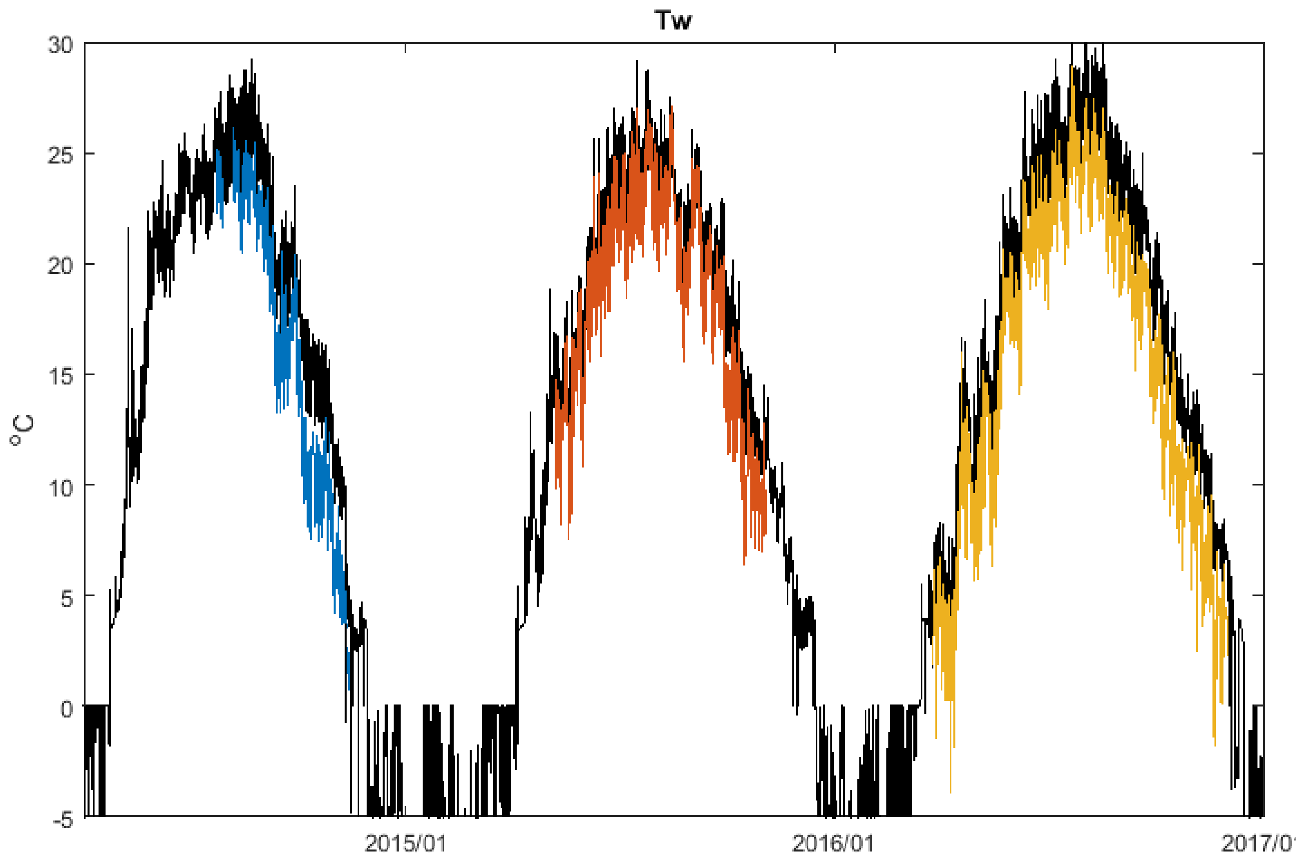
Model Tuning

	WBL	Lake Taihu (Deng et al, 2013; Hu et al., 2016)
Depth of lake	25 m	2 m
Convective mixing	On	Off
Albedo	Original scheme in CLM4-LISSS	Observed
Thickness of the lake surface layer (z_a)	0.6 m	0.2 m
Light extinction coefficient (η)	Observed (0.57 m^{-1})	Observed (5 m^{-1})
Wind-driven eddy diffusivity (K_e)	0.005 of the original scheme in CLM4-LISSS 0.1×10^{-5} ~1.8×10^{-5} $m^2\,s^{-1}$	0.02 of the original scheme in CLM4-LISSS 0.1×10^{-5} ~ 4×10^{-5} $m^2\,s^{-1}$
Enhanced eddy diffusivity	On	Off
Roughness length of momentum (z_{0m})	$10\times f(u^*)$, 10^{-4} ~ 10^{-5} m	3.3×10^{-4} m
Roughness length of heat (z_{0h})	$\ln(z_{0m}/z_{0h})=7.36$, 10^{-7} ~ 10^{-8} m	1.9×10^{-6} m
Roughness length of moisture (z_{0q})	$\ln(z_{0m}/z_{0q})=7.48$, 10^{-7} ~ 10^{-8} m	3.9×10^{-8} m

Example: Convective mixing off



Example: Convective mixing on

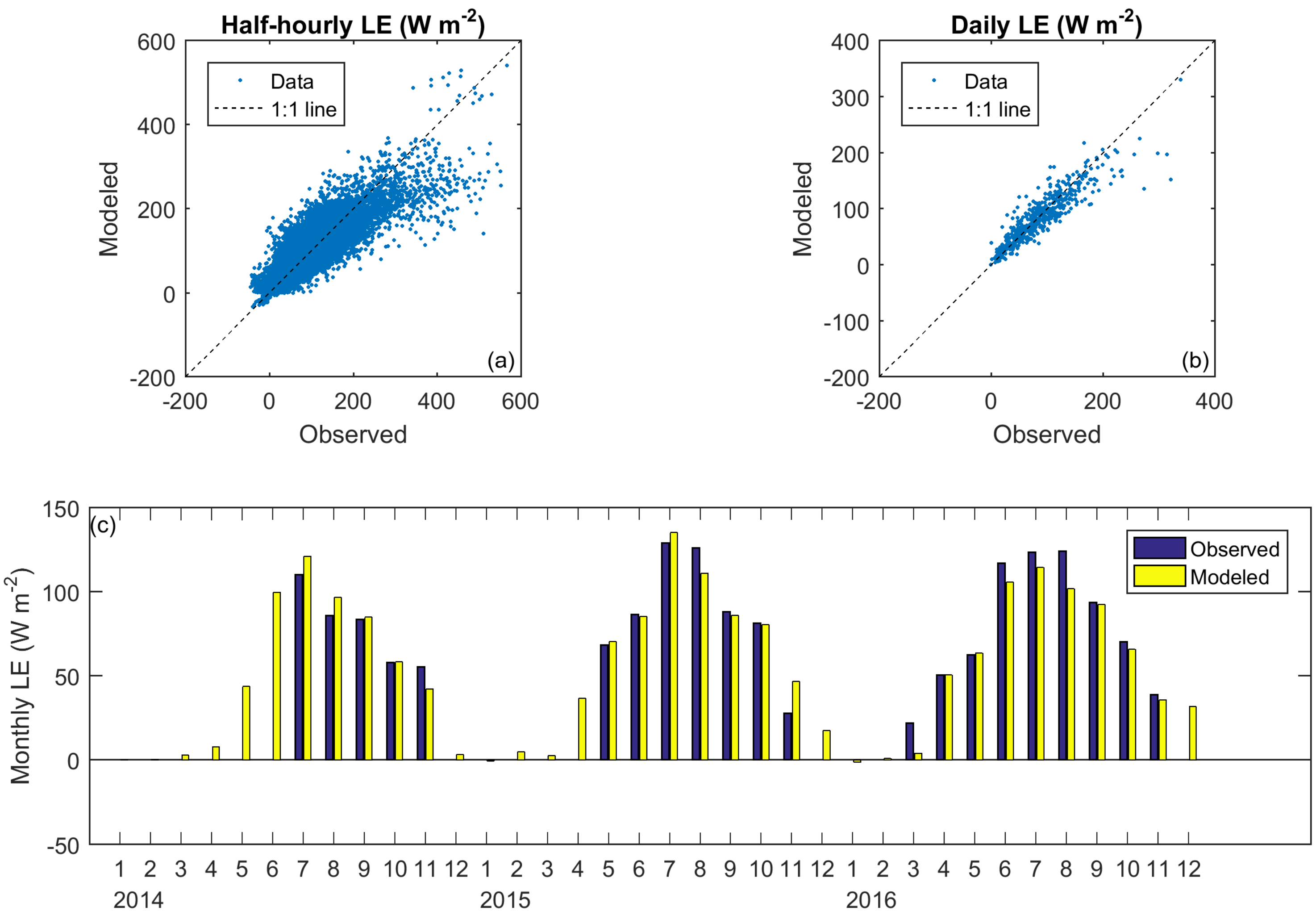


Modeling Cases

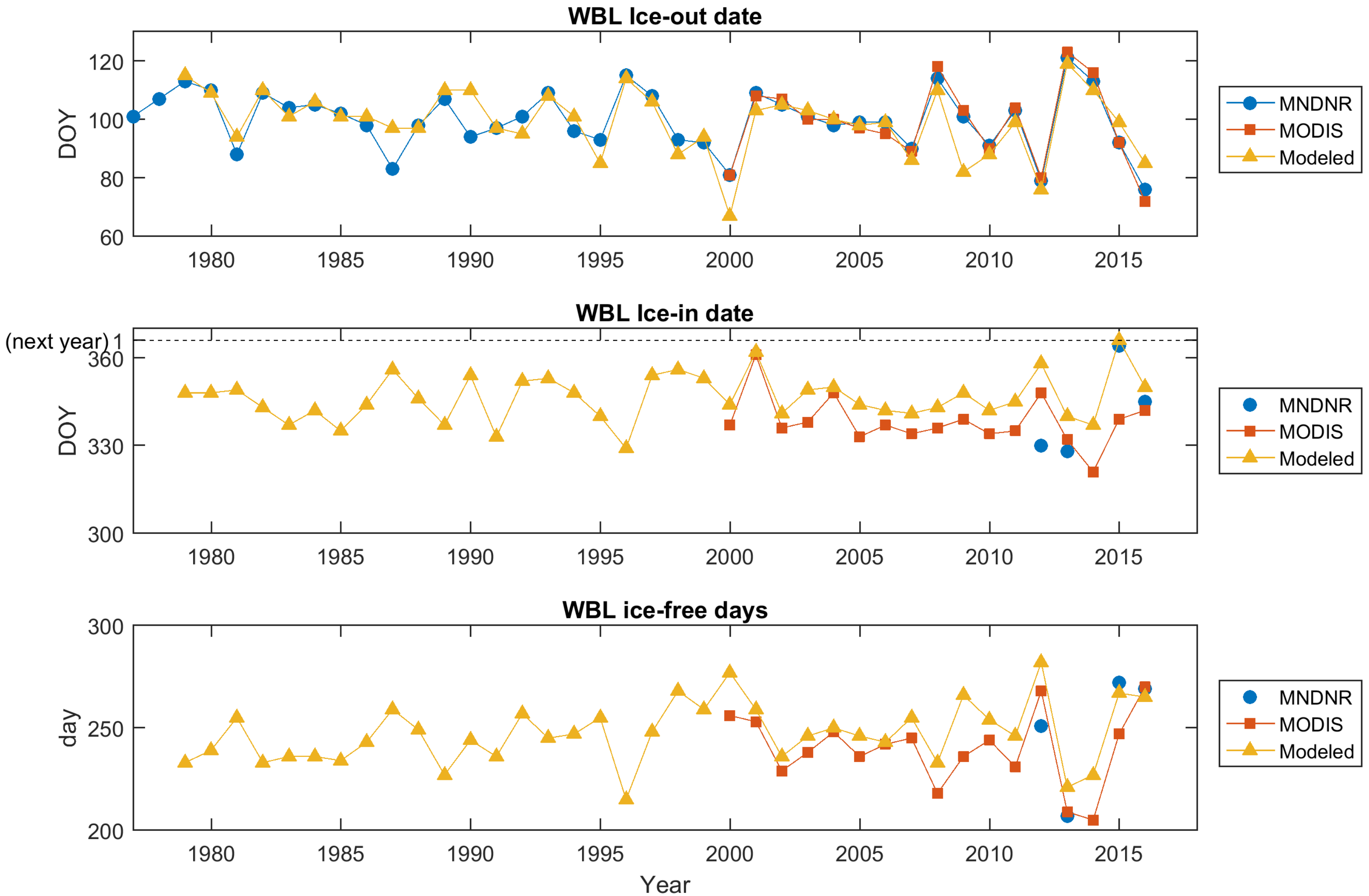
	Validation	Retrospection	Forecast
Period	2014-2016	1979-2016	2017-2100
Forcing data	Obs and NLDAS	NLDAS	GFDL-ESM2G under RCP8.5
Spin-up data	2004-2013 of NLDAS	10x 1980 of NLDAS	2006-2016 of GFDL-ESM2G

- NLDAS: North American Land Data Assimilation System project phase 2(NLDAS-2) Primary Forcing Data L4 (Xia et al., 2012)
  - Hourly, 0.125 x 0.125 degree
- GFDL-ESM2G: one of the climate models in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Dunne et al., 2012)
  - 3-hourly, 2.0 x 2.5 degree

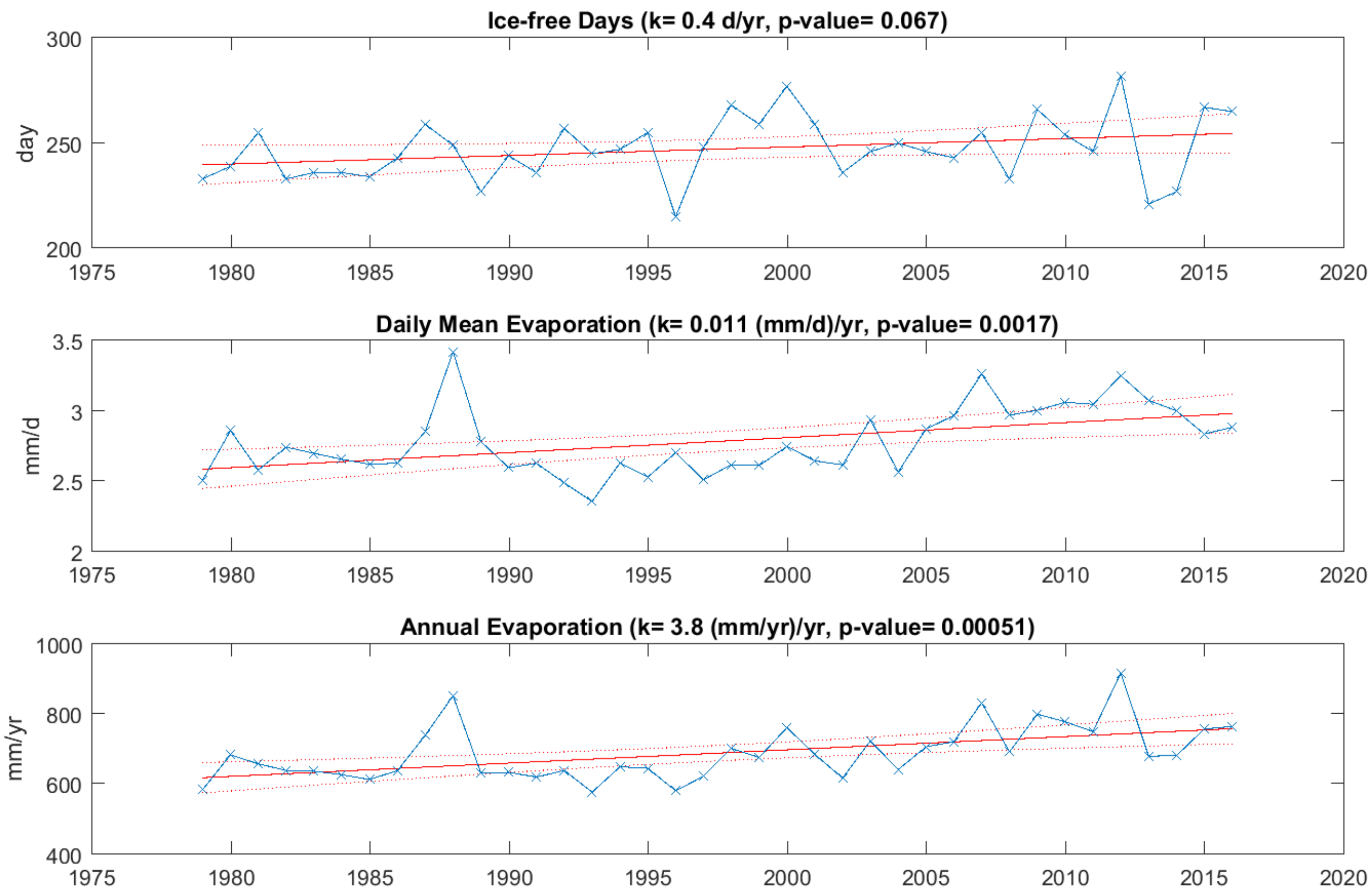
Validation Outputs



Ice Phenology



Retrospective Evaporation



Annual Evaporation from 2014 to 2016

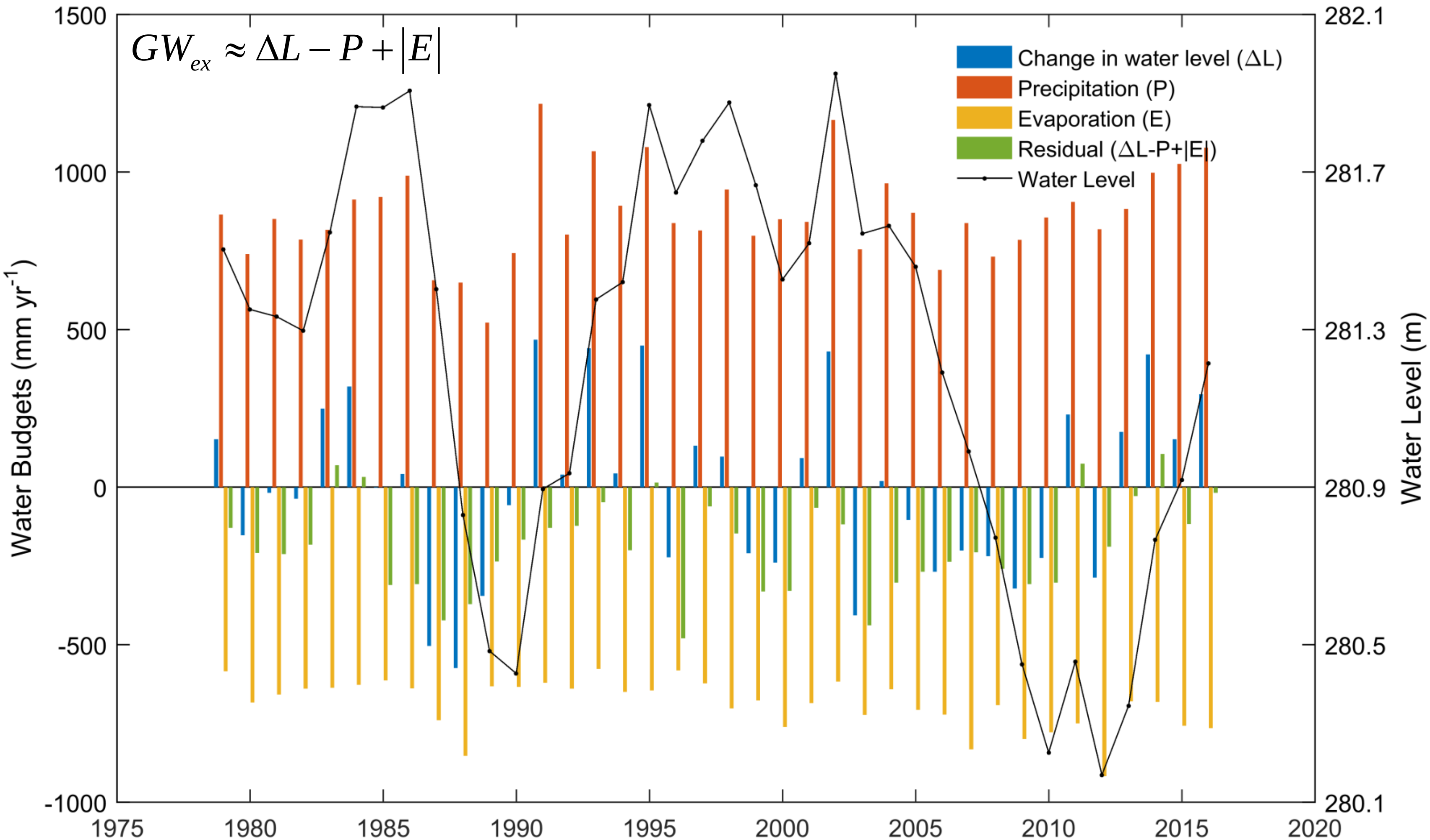
Year & Observation Period (days[×])	**Sources of Evaporation and ice phenology data**	**Ice-out date**	**Ice-in date**	**Ice-free days**	**Daily E (mm)**	**Annual E (mm)**	**Averaged Annual E (mm)**
2014	EC, MNDNR	Apr 23	*Nov 17	209	2.60	543	559±22
Jul 18	Weighted EC, MNDNR	Apr 23	*Nov 17	209	2.56	535	
to Nov 14	Validation modeling	Apr 22	Nov 28	221	2.57	567	
(102)	Retrospective modeling	Apr 20	Dec 3	228	2.59	590	
2015	EC, MNDNR	Apr 2	Dec 30	273	3.35	915	779±81
May 8	Weighted EC, MNDNR	Apr 2	Dec 30	273	2.79	763	
to Oct 31	Validation modeling	Apr 3	Dec 16	258	2.75	709	
(177)	Retrospective modeling	Apr 9	(2016) Jan 1	268	2.73	731	
2016	EC, MNDNR	Mar 16	Dec 10	270	2.88	778	766±11
Mar 25	Weighted EC, MNDNR	Mar 16	Dec 10	270	2.77	748	
to Nov 30	Validation modeling	Mar 13	Dec 15	278	2.78	773	
(251)	Retrospective modeling	Mar 25	Dec 15	266	2.87	764	

× The integrated days does not include the missing days within observation period.

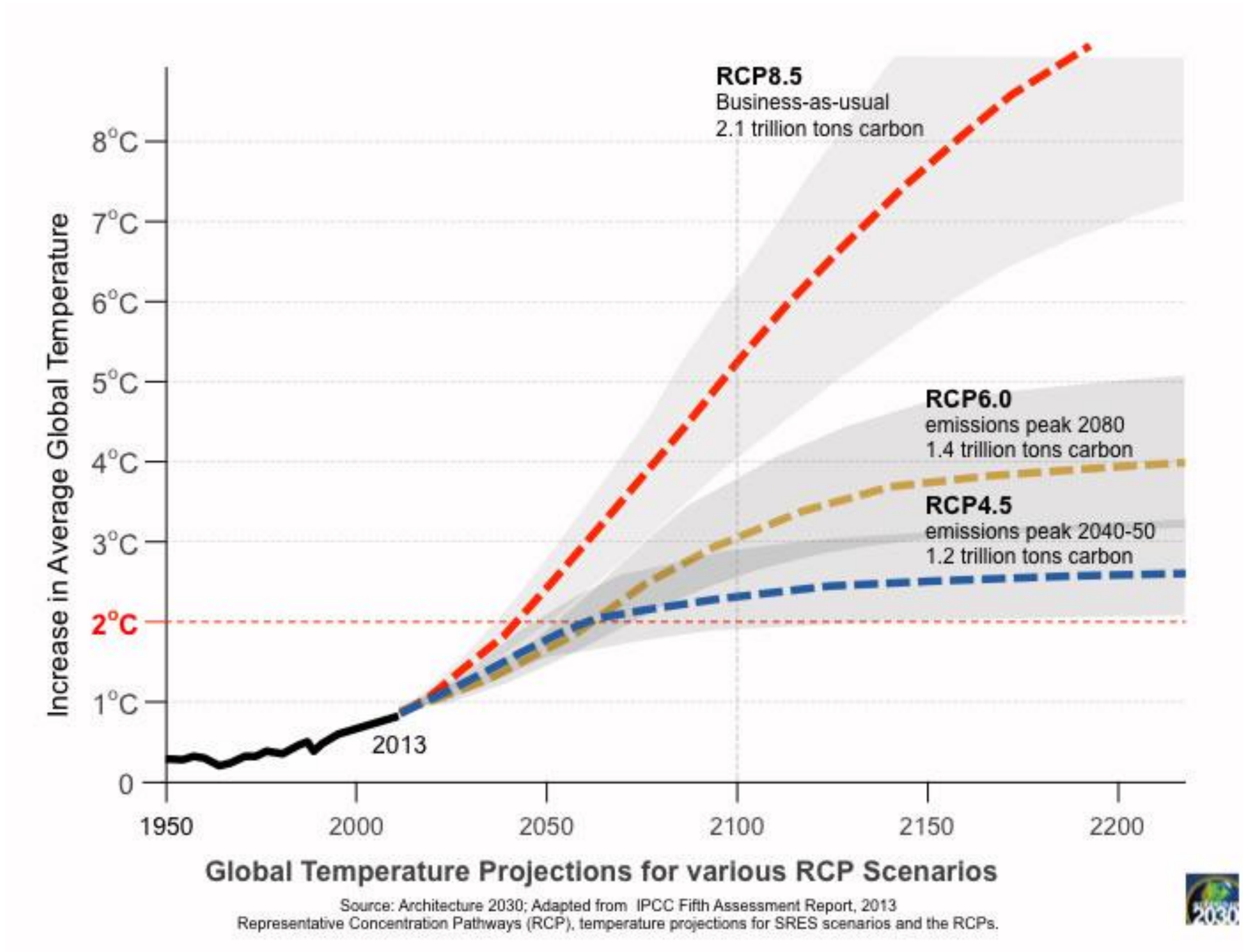
* No record from MNDNR, filled by the MODIS data.

Part 4: Evaporation and Water Level

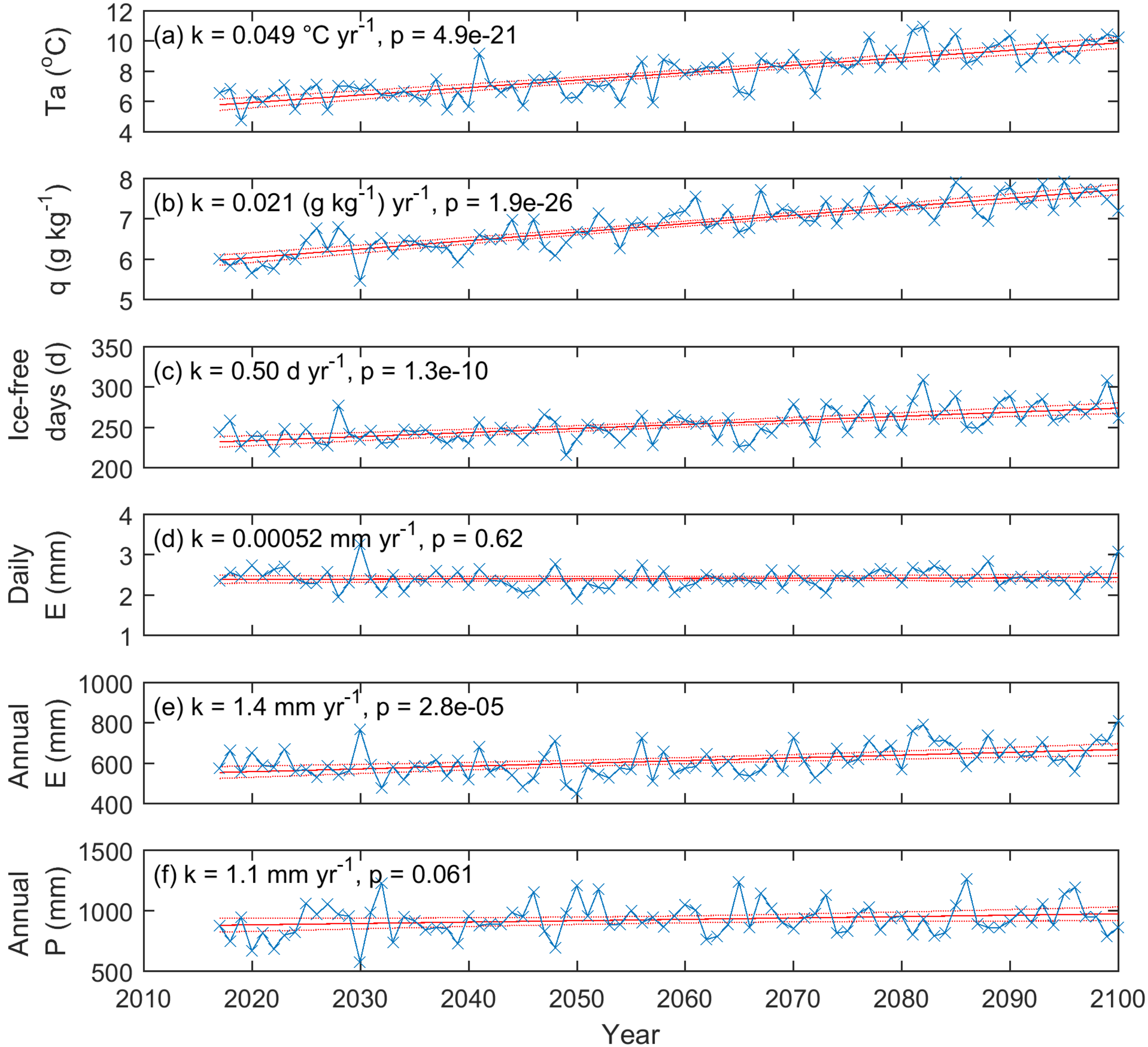
A regional drought and potential intensified groundwater use can have a dramatic impact on water level at a closed-basin lake



Future Climate Change Scenarios



Evaporation under RCP8.5 Scenario



Conclusions

- The annual evaporation at WBL from 2014 to 2016 was 559±22, 779±81, and 766±11 mm, respectively. The annual evaporation in 2014 was least among the three years, due to its relatively short ice-free period and its relatively lower daily evaporation rate.
- The retrospective analyses indicated that WBL evaporation increased by about 3.8 mm yr^{-1} from 1979 to 2016, which was attributed to both increased daily mean evaporation and the extended ice-free period.
- Annual evaporation at WBL will increase 1.4 mm yr^{-1} over this century under the RCP 8.5 scenario, which is largely driven by the extended ice-free periods.

Regional Implications for Lake Water Levels

- **Lake levels within the region are closely coupled to evaporation**
  - The lake level declines at WBL during 1986–1990 and 2003–2012 were caused by the coupled low precipitation and high evaporation
- **Small changes in the evaporation rate or ice phenology can have significant impacts on available water for the communities**
  - For WBL, a typical evaporation rate of 5 mm per day during the summer is equivalent to 4.9×10^4 m^3 of water or roughly 0.5 m^3 s^{-1} of continuous 24-hour pumping
  - Given an advanced ice-out date or postponed ice-in date of just one day is likely to result in an additional water loss of 2×10^4 m^3

Regional Implications for Lake Water Levels

- **A tendency for increased likelihood of lower water levels and greater fluctuations in water level for WBL and other lakes within the region are expected**
  - Lake evaporation is expected to increase due to the extended ice-free period as climate continues to warm

- **Proposed water augmentation strategies within the region must be aware of the potential changes in supply and demand as climate continues to warm**
  - Per capita water use in Minnesota is about 0.23 m^3 d^{-1} per person (Maupin et al., 2014). The additional 100 mm of evaporation at WBL resulting from the long-term change in climate is equivalent to the annual water use of over 11,000 people

Acknowledgements

- **Advisor**: Timothy Griffis [a]
- **Co-authors**: John M. Baker [a,b], Paul V. Bolstad [c], Matt D. Erickson [a], Xuhui Lee [d,e], Jeffrey D. Wood [a,f], and Cheng Hu [e]
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  - [f] School of Natural Resources, University of Missouri, Columbia, Missouri, USA

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Thank you!