GEODETIC SCIENCE
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Monitoring Water Level Variations over the Great Lakes Using Contemporary Satellite Geodetic Observations

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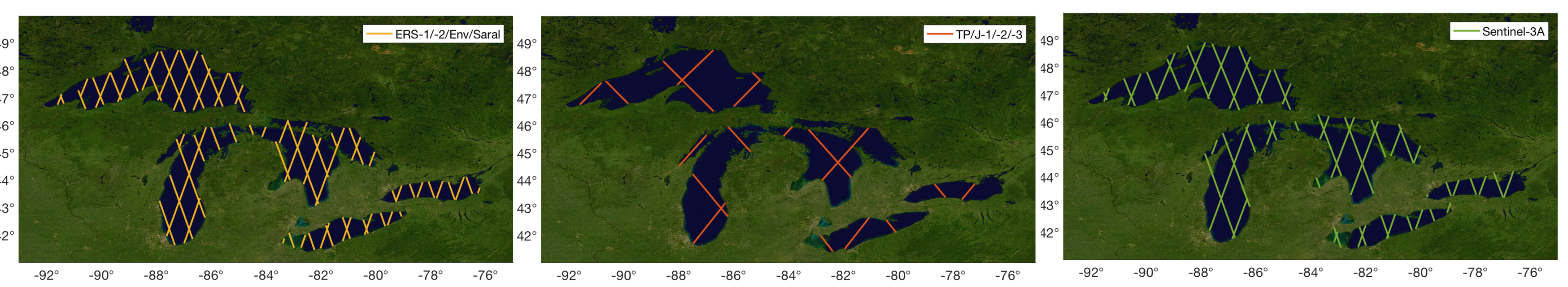
Introduction

A constellation of multiple-platforms, multi-band active remote sensing satellites including all-weather sensors dedicated for scientific research are already operational or to be launched. The sensors include multi-platform radar/laser altimetry, radiometry, NOAA/NOS/CO-OPS/NGS/NRCAN and OSU GPS network around the Great Lakes, and GRACE/GRACE-Followon satellite gravimetry. Among these observations, notably spanning more than two and half decades, 1985–2018, are the multi-mission satellite radar altimetry, including ERS-1/-2, Envisat, Geosat, GFO, TOPEX/Poseidon, Jason-1/-2/-3, SARAL/Altika, CryoSat-2, Sentinel-3A. Satellite altimetry have been continuously measuring synoptic water level, wind, wave heights and potentially snow/lake ice extent series over the entire Great Lakes. These measurements could complement *existing* CoastWatch products and data sets, to improve Great Lakes environmental monitoring, refine the Great Lakes height datum for safe navigation, and enhance Lake forecasting skills via assimilative near real-time data sets into hydrodynamic forecast models.



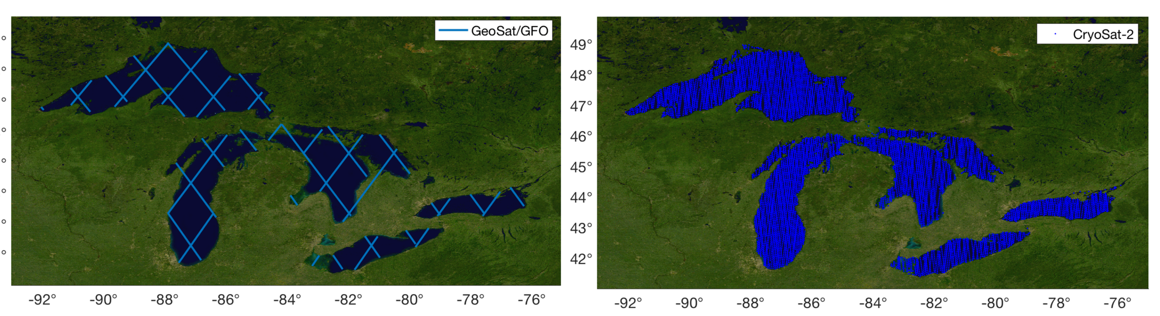


Fig. 1 shows the spatial coverage of **multi-mission satellite radar altimetry** tracks over the Great Lakes, measuring water level since 1985 to present. These figures show ground tracks of ERS-1/-2/Envisat/Altika, yellow, TOPEX/Jason-1/-2/-3, **red**; Sentinel-3A, **green** and Geosat/GFO-1, **blue**, and ground tracks of a complete Cryosat orbit repetition cycle (369 days).

Altimetry data from RADS and GDR

Satellite Mission	Data Products	Repeat Cycle	Data rate	Time Period
TOPEX/ Poseidon	CASH from LEGOS	10 days	10 Hz	1992-2002
Jason-1	GDR from AVISO	10 days	20 Hz	2002-2009
Jason-2	GDR from AVISO	10 days	20 Hz	2008-2018
Jason-3	CalVal phase, GDR from AVISO	10 days	20 Hz	2016-2018
ERS-1	Phase c, g, REAPER from ESA	35 days	20 Hz	1992-1993(c) 1995-1996(g)
ERS-2	CTOH V2 from LEGOS	35 days	20 Hz	1995-2007
ENVISAT	GDR V3 from ESA	35 days	18 Hz	2002-2010
SARAL/Altika	GDR from AVISO	35 days	40 Hz	2013-2018
Geosat	RADS	17 days	1 Hz	1985-1989
Geosat Follow-On	RADS	17 days	1 Hz	2000-2008
CryoSat-2	RADS	369 days	1 Hz	2010-2018
Sentinel-3A	RADS	27 days	1 Hz	2016-2018

In this study radar altimetry data of TOPEX/Poseidon, Jason-1/-2/-3, ERS-1/-2, ENVISAT, and SARAL/Altika from Geophysical Data Records (GDR) radar altimetry data sets and Geosat, GFO, Sentinel-3A and CryoSat-2 from Radar Altimeter Data System (RADS) data products are used for water level estimation. GDR altimeter products are used to provide high-frequency retracked measurements from OCEAN, ICE-1, ICE-2, and SEA ICE retrackers. In this study, we used ICE-1 retracked measurements, which have been demonstrated to be a suitable retracker for inland water bodies.

Table 1. List of all satellite altimetry missions used in this study together with their main characteristics.

In order to convert the range measurements to water levels serving as input for CoastWatch, numerous preprocessing steps are necessary.

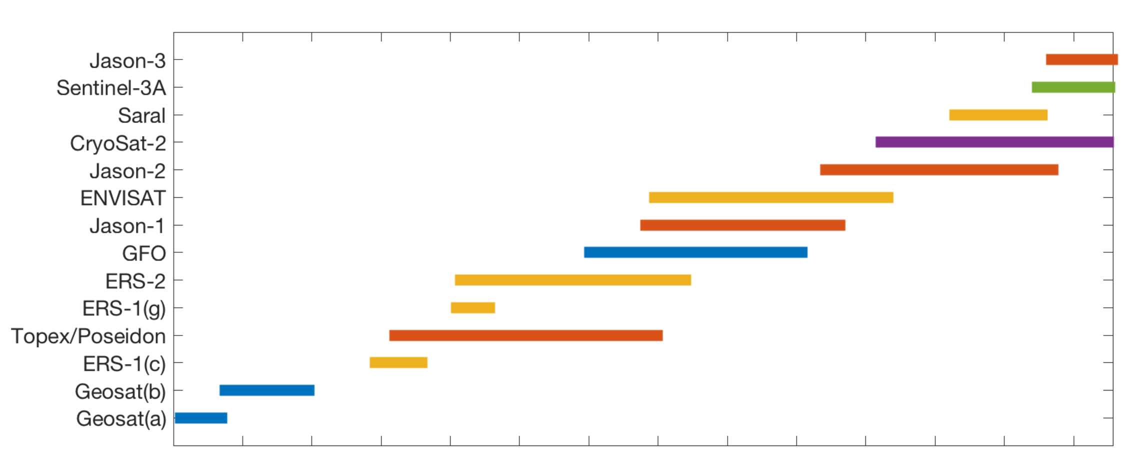


Fig. 2 Shows time span of all the altimetry data products used in this study. It covers from 1985 to 2018 (present) with about two year data gap from 1990 to 1992.

Lake level estimation

For the application of satellite altimeter data over lakes, there are numerous corrections for altimeter measurements to determine water level estimates. For radar altimetry data, the instrument corrections, media corrections (dry and wet troposphere corrections, and the ionosphere correction based on global ionosphere maps), and geophysical corrections (solid Earth and pole tides) are applied:

$$h = h_{lake} - h_{geoid} = h_A - (h_R + h_C) - h_{EGM} + \varepsilon \qquad \text{Eq. 1}$$

$$h_C = h_i + h_{wet} + h_{dry} + h_{iono} + h_{se} + h_{pol} \qquad \text{Eq. 2}$$

where h is water level over lake; h_{lake} is lake surface height; h_{geoid} is EGM2008 geoid height; h_A is orbital height; h_R is altimeter range measurement; h_C are altimeter range corrections. These range corrections include instrument corrections h_i, media corrections (wet troposphere correction h_{wet}, dry troposphere correctionh_{dry}, ionosphere correction h_{iono}) and geophysical corrections (solid Earth tide h_{se} and pole tide h_{pol}). Then we got lake level height of the ice1 retracker above the EGM2008 geoid in the WGS84 height system in meters which will be used as input data for next filtering step.

Filter outliers from altimetry data

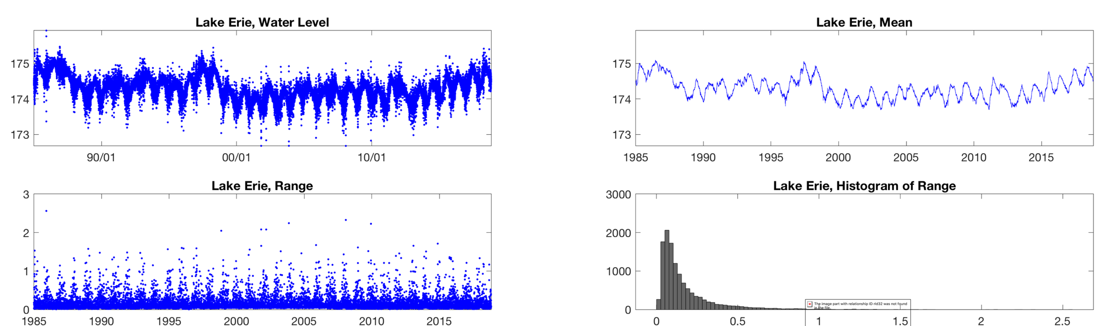


Fig. 3 Daily water level over Lake Erie from 9 gauge stations (in situ). For each day the range of lake level from 9 stations could be more than 1 m and most of water level ranges are less than 0.3 m.

Because of different reflections within the large footprint of radar altimeter (water, land and ice), the data quality over inland water targets is not as good as over open ocean. Therefore, in order to get precise and reliable dataset without many outliers for computation of water level time series, a careful data pre-processing is required. Especially observations effected by land should be excluded from computations. We studied available in situ water level observations to understand the local lake level variations which will help us to set thresholds for altimetry data filtering. **Fig.3** shows an example for Lake Erie. The pre-processing includes various user-defined outlier rejections: i) lake outline polygons; ii) wave height threshold; iii) ice threshold; iv) median absolute deviation (MAD) threshold; v) along time series gaussian kernel regression (GKR) outliers.

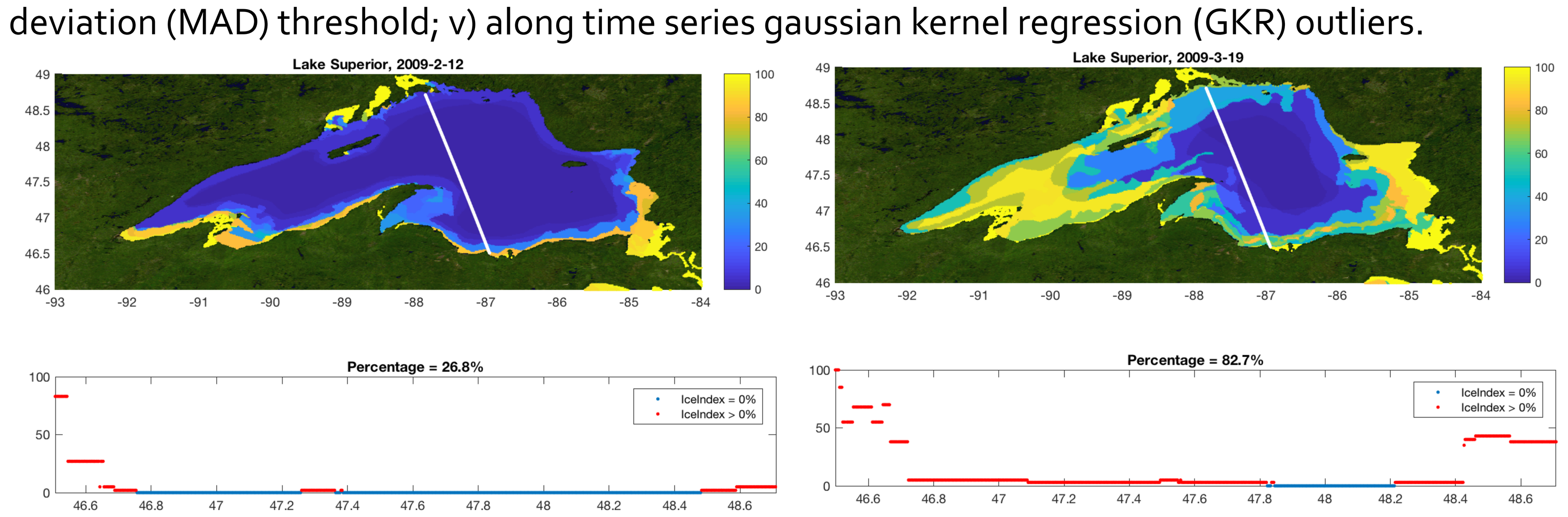


Fig. 4 Example of ice threshold applied over Lake Superior for Envisat Pass 465 Cycle 76 (left) and 77 (right). We used daily interpolated ice coverage data over Great Lakes (downloaded from the website: www.glerl.noaa.gov/data/ice) to estimate ice index for altimetry observations. Because of the spatial resolution of ice data and the foot print size of altimetry, all altimetry observations points with ice index larger than **0%** will be classified as ice.

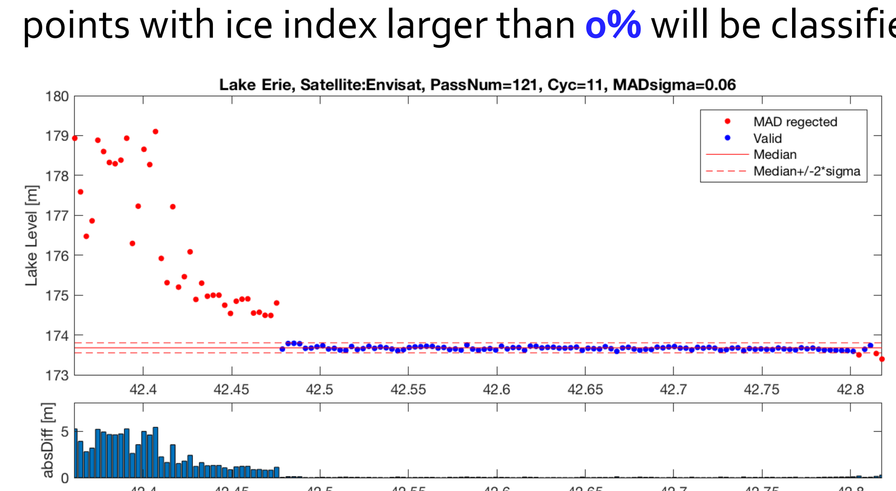


Fig. 5 Example of MAD (Median Absolute Deviation) sigma threshold applied over Lake Erie for Envisat Pass 121 Cycle 11. Comparing with mean with standard deviation method which is particularly sensitive to outliers, median with MAD is an alternative approach offering the advantage of being very insensitive to the presence of outliers. Here we used median plus/minus 2*MAD to filter outliers.

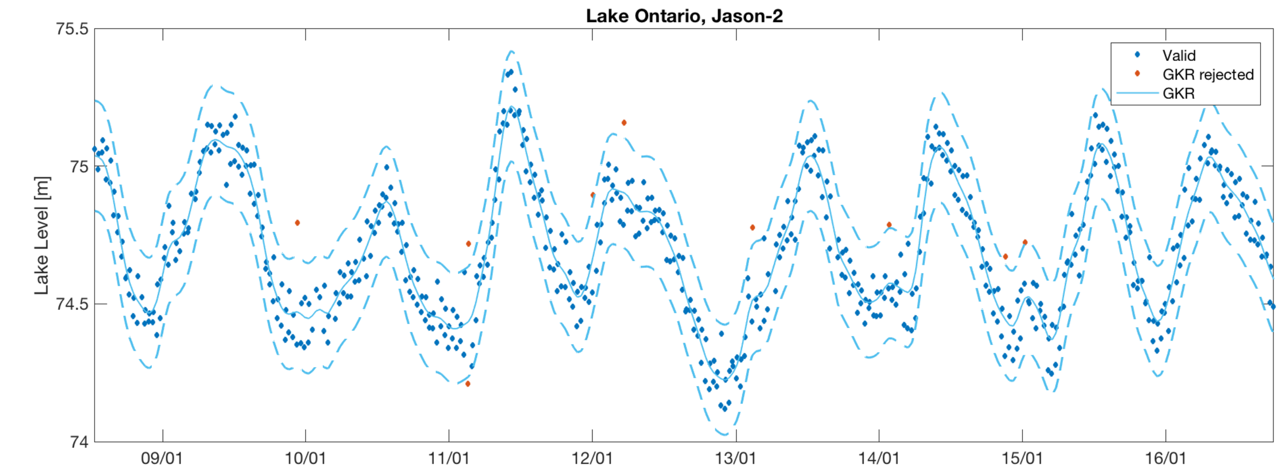


Fig. 6 Example of GKR threshold applied over Lake Ontario for Jason-2. We used GKR±0.2 m as threshold to filter outliers from radar altimetry observations. Each dot represents mean value of one cycle of a pass over Lake Ontario.

Remove bias from satellite altimetry and validation

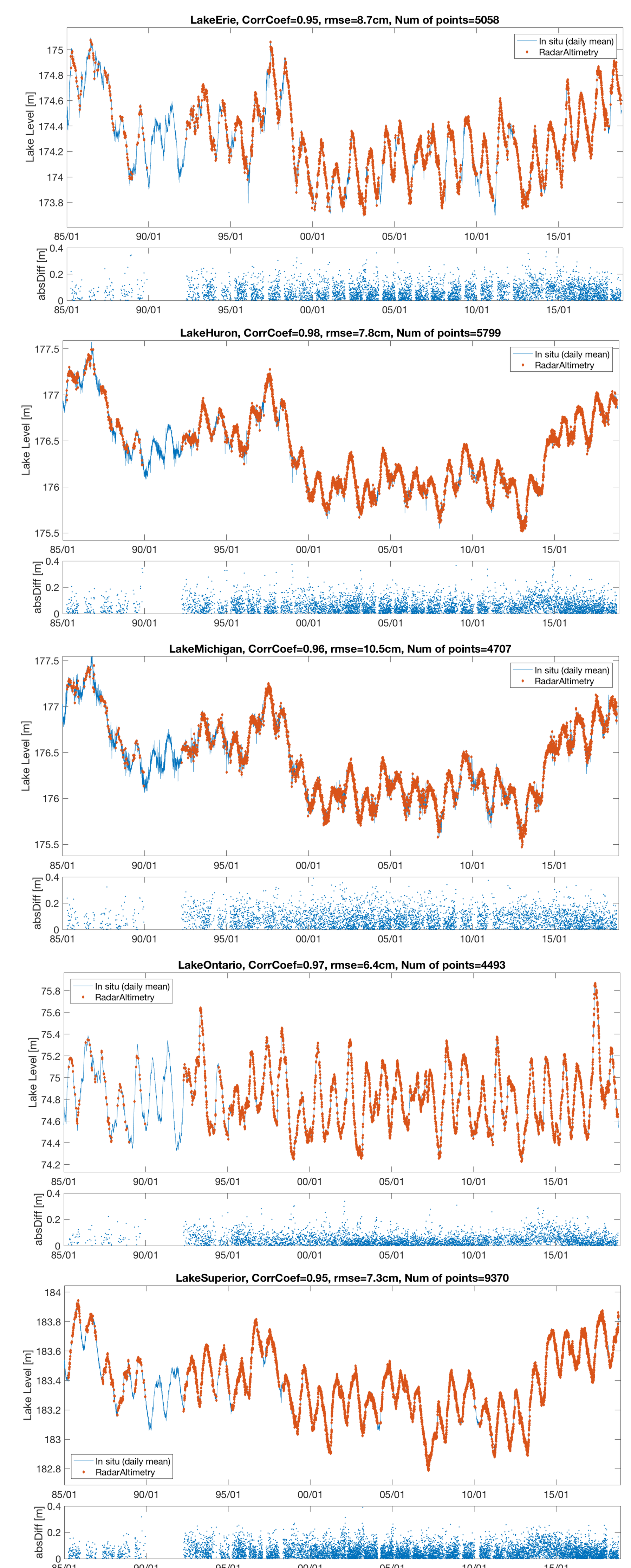


Fig. 7 Water level time series of Lake Erie, Huron, Michigan, Ontario, and Superior from radar altimetry data (1985-2018) compared with in situ data (daily mean, 1985-2018) and shifted to the water level height of in situ data. The differences between water level from altimetry and in situ data are plotted during the time period both datasets are available. The correlation coefficient, rmse and number of available points are shown in the title of each figure. Each point represents mean value of radar altimetry data of each pass and cycle.

Table 2 Water level time series of Great Lakes from altimetry compared with in situ data from gauge stations.

Lake Name	Station ID	CorrCoef	rmse	Num of points
Erie	9063020	0.89	12.7	5057
	9063028	0.91	11.7	5034
	9063038	0.93	9.6	4431
	9063053	0.95	8.9	4953
	9063063	0.94	9.4	5057
	9063079	0.91	12.1	4939
	9063085	0.85	16.2	5051
	9063090	0.89	13.7	4940
Huron	9075002	0.97	8.9	5659
	9075014	0.98	8	5795
	9075035	0.95	12.1	5794
	9075065	0.98	7.5	2924
	9075080	0.98	8.2	5681
	9075099	0.98	8	5669
Michigan	9087023	0.96	10.3	4584
	9087031	0.96	10.5	4378
	9087044	0.95	12.1	4655
	9087057	0.96	10.9	4707
	9087068	0.96	10.5	4295
	9087072	0.96	10.4	4197
	9087079	0.95	12.5	4577
	9087088	0.96	10.6	2330
	9087096	0.96	10.8	4477
Ontario	9052000	0.97	6.9	4473
	9052030	0.97	6.6	4492
	9052058	0.97	6.5	4493
	9052076	0.97	6.7	4259
Superior	9099004	0.93	8.9	9365
	9099018	0.95	7.5	9370
	9099044	0.95	7.4	9297
	9099064	0.93	8.8	9370
	9099090	0.95	7.5	9368

Acknowledgement. This research is supported by a CIGLR Postdoctoral Fellowship Award, and by OSU's Global Water Institute (http://globalwater.osu.edu), and the School of Earth Sciences.