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► To cite this version:

Muriel Bergé-Nguyen, Jean-François Cretaux, Stéphane Calmant, Sarah Fleury, Rysbek Satylkanov, et al.. Mapping mean lake surface from satellite altimetry and GPS kinematic surveys. *Advances in Space Research*, 2021, 67, pp.985-1001. 10.1016/j.asr.2020.11.001 . insu-03671352

HAL Id: insu-03671352

<https://insu.hal.science/insu-03671352>

Submitted on 3 Feb 2023

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Mapping Mean Lake Surface from satellite altimetry and GPS kinematic surveys

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Abstract

Lake water height is a key variable in water cycle and climate change studies, which is achievable using satellite altimetry constellation. A method based on data processing of altimetry from several satellites has been developed to interpolate mean lake surface (MLS) over a set of 22 big lakes distributed on the Earth. It has been applied on nadir radar altimeters in Low Resolution Mode (LRM: Jason-3, Saral/AltiKa, CryoSat-2) in Synthetic Aperture Radar (SAR) mode (Sentinel-3A), and in SAR interferometric (SARin) mode (CryoSat-2), and on laser altimetry (ICESat). Validation of the method has been performed using a set of kinematic GPS height profiles from 18 field campaigns over the lake Issykkul, by comparison of altimetry's height at crossover points for the other lakes and using the laser altimetry on ICESat-2 mission. The precision reached ranges from 3 to 7 cm RMS (Root Mean Square) depending on the lakes. Currently, lake water level inferred from satellite altimetry is provided with respect to an ellipsoid. Ellipsoidal heights are converted into orthométric heights using geoid models interpolated along the satellite tracks. These global geoid models were inferred from geodetic satellite missions coupled with absolute and regional anomaly gravity data sets spread over the Earth. However, the spatial resolution of the current geoid models does not allow capturing short wavelength undulations that may reach decimeters in mountaineering regions or for rift lakes (Baikal, Issykkul, Malawi, Tanganika). We interpolate in this work the geoid height anomalies with three recent geoid models, the EGM2008, XGM2016 and EIGEN-6C4d, and compare them with the Mean Surface of 22 lakes calculated using satellite altimetry. Assuming that MLS mimics the local undulations of the geoid, our study shows that over a large set of lakes (in East Africa, Andean mountain and Central Asia), short wavelength undulations of the geoid in poorly sampled areas can be derived using satellite altimetry. The models used in this study present very similar geographical patterns when compared to MLS. The precision of the models largely depends on the location of the lakes and is about 18 cm, in average over the Earth. MLS can serve as a validation dataset for any future geoid model. It will also be useful for validation of the future mission SWOT (Surface Water and Ocean Topography) which will measure and map water heights over the lakes with a high horizontal resolution of 250 by 250 meters.

Keywords

Satellite altimetry, GPS survey, mean lake surface, geoid.

1. Introduction

Water level inferred from satellite altimetry over lakes is provided with respect to an ellipsoid. However, ellipsoidal height is not spatially constant because the surface at rest (i.e. in hydrostatic equilibrium) of a lake mimics the local equipotential surface of the gravity field. It is then practically difficult to give a single value of the height of the lake with respect to ellipsoid. Assuming that the equipotential at the location of a lake is not significantly different from the reference one, the geoid, since the height of the lake is negligible with respect to the Mean Earth radius, the varying ellipsoidal heights can be converted into a single value, the orthometric height of the surface, simply by subtracting the geoidal undulation from the ellipsoidal heights. This is the reason why; an accurate geoid model is essential when measuring water height over a lake.

The geoid is defined as the equipotential surface of the gravity field, which best fits with the global mean sea level in the least square sense (National Geodetic Survey, 1986). For lakes, it is assumed to be parallel to the so-called mean lake surface (MLS in the following). Geoid at global scale are represented by models, inferred from geodetic satellite data together with in situ gravity field measurements. The geoid undulations are therefore defined as *‘the distance, taken along a perpendicular to the ellipsoid of reference, from that ellipsoid to the geoid’* (National Geodetic Survey, 1986; Jiang et al., 2019)

However, even the most recent models EIGEN-6C4d (Förste et al., 2014), XGM2016 (Pail et al., 2018) or EGM2008 (Kingdon et al., 2008; Pavlis et al., 2012) do not provide geoid undulations at a spatial resolution which would allow correcting precisely water level measured by the altimeters above a reference ellipsoid. These geoid undulations depend on the variations in gravity anomalies related to the crustal density near the surface. They are generally not known, and may be affected by high frequency densities anomalies (Kingdon et al., 2008). Indeed, the degree-order of the geoid model that are achieved using gravity satellite missions (GRACE and GOCE principally) are limited to large spatial variations that cannot capture smaller scales of MSL spatial undulations (Kingdon et al., 2008; Jiang et al., 2019). Consequently, removal of geoid undulations fails to provide a single constant height value over large lakes and an alternative method must be developed. Satellite altimetry has been used already for the calculation of gravity anomalies over the ocean surface (Sandwell and Smith, 1997, 2005; Hwang et al., 2002) and over large lake surfaces (Kingdon et al., 2008). A method to correct altimetry measurement for geoid undulations has been developed using the fact that they are temporally constant and observed along the tracks from one cycle to the following ones for satellites flying on Exact Repeat Mission (ERM) orbits (Jiang et al., 2019). In the case where a lake is covered by several tracks without any cross-over points, it is moreover possible to correct for any geoid gradient between two distinct tracks by averaging water level time series calculated using the track individually on overlapping period (Birkett

et al., 1995; Cretaux and Birkett, 2006; Cretaux et al., 2016). This approach, namely ‘the repeat track technique’, allows calculating the surface undulation along a mean track position, and it serves as height correction for altimetry over lakes. Therefore, we can correct the geoid errors using the repeat track technique without a priori accurate MLS when using the ERM, but accurate MLS is essential for missions like Saral/AltiKa or Jason-2 when they were placed in drifting orbits.

However, knowledge of gravity field at high resolution can be locally improved using satellite altimetry considering the high accuracy of these data along their tracks over lakes. Therefore, if we can derive the MLS from altimeters on a set of some large lakes on the Earth, these MLS could also be used for validation of current geoid model. We know from recent studies that the commissioning error of the current geoid models is of the order of 18 cm (Pavlis et al., 2012), and that from satellite altimetry this uncertainty can easily be reduced locally (Jiang et al., 2019). Jiang et al. (2019) have used CryoSat-2, Saral/AltiKa (in the drifting phase), Sentinel-3A and ICESat data over lake Nam-Co on the Tibetan Plateau. They have demonstrated the capabilities of these missions to estimate MLS for large lake. We have extended the approach using the Jason-1/2/3 family. Our results have been validated using field work over the lake Issykkul located in Kyrgyzstan using GPS surveys along the track of these satellites, along the coast of the lake, and on the region not covered by the altimeters. Using this method, we have calculated the MLS over 22 large lakes distributed on the Earth. It will also serve as data set for calibration of the SWOT’s mission. SWOT will carry an interferometer in Ka (36 Ghz) band named KaRin. One of the challenging issues in term of instrumental error of KaRin is the phase screen error which requires to be fully corrected using a precise geoid over a large area. Moreover, the validation of the KaRin interferometer over continental surface will also be challenging, especially due to unknown geoid, since errors are linearly correlated to the distance to the nadir across the swath. MLS that are produced using our method will therefore serve as database for calibration / validation of SWOT for at least these both effects: phase screen and cross track errors.

In section 2 of this paper we present the datasets used for this study. In section 3 we present the methodology developed to determine the MLS. In Section 4 we present the validation experiment performed over the Issykkul lake, the resulting MLS and the error budget estimated. In section 5 we present the different MLS obtained for each of the 22 selected lakes (Figure 1a-f) together with the RMS of the calculation. In section 6 the results of the comparison with the three geoids tested are presented before we conclude on future uses of this work and perspective of evolution.

2. Altimetry data sets

The Jason-3, Saral/AltiKa, Sentinel-3A and CryoSat-2 nadir radar altimeters have been selected to calculate the MLS. ICESat laser altimetry has also been used due to their high accuracy. This choice is a trade-off between data accuracy and number of passes accumulated over each track; we have kept Cryosat-2 and ICESat data although the number of passes on each track were low because the spatial coverage over each lake was very dense. The data of

Jason-1 during the interleaved phase were much noisier than for other altimeters and we prefer not using them in the calculation of the MLS.

Radar altimeters have been used to compute time series of water level change over the large lakes since 1992 when Topex / Poseidon (CNES/NASA mission) was launched (Cretaux et al., 2016; Schwatke et al., 2015). Jason-1 (2001-2008), Jason-2 (2008-2016) and Jason-3 enable to perform long term monitoring using the same orbit at 66° of inclination and a repeat cycle of approximately 10 days. These satellites carry altimeters in Ku band (13.76 GHz) all operating in LRM (Low Resolution Mode). Due to their short time repeat cycle, these missions are well adapted for studying water height variability over lakes and rivers.

The series of ERS-2 (1994-2003), Envisat (2001-2010) and Saral/AltiKa (2013-2016) were put in another orbit, inclined at 98.55° with a repeat cycle of 35 days. With such orbital parameters, the spatial density of measurements over each of the lakes is consequently much higher than with the Jason family. Moreover, Saral/AltiKa was the first altimeter in orbit operating in Ka band (35.75GHz). It allowed achieving a reduction of the footprint's size by a factor 2-3 and to drastically diminish the ionospheric effects (Verron et al. 2018). It also has a higher pulse repetition frequency (40 Hz) compared to the other previous missions (20 Hz). After 2016, Saral/AltiKa was moved into a geodetic drifting orbit. We did not use the data after 2016 since our method is based on the repeat track technique.

On April 8, 2010, ESA (European Space Agency) launched CryoSat-2, a mission dedicated to the study of the sea ice and the continental polar caps and glaciers. Its orbit has an inclination of 92° and a repeat cycle of 369 days. A such long-time repeat cycle is a strong limitation to study the hydrodynamic of small lakes, but for determination of MLS this is an advantage with very high-density continental coverage, allowing to fill the inter-track gaps of aforementioned missions. Indeed, the inter-track distance at equator is 7.5 km and about 6 km at mid latitude where most of the large lakes are located. The CryoSat-2 Synthetic aperture Interferometric Radar Altimeter (named SIRAL) was the first one to operate in SAR (Synthetic Aperture Radar) mode which allows reducing the footprint to about 300 m along-track (Jiang et al., 2017). Its pair of antennas allow also activating a second mode: The SARin (Synthetic Aperture Interferometric mode). This mode permits to determine the lateral position of the main surface reflector, possibly aside the satellite track, and to reduce again the footprint. CryoSat-2 data in the three modes (LRM, SAR and SARin) are released by ESA in the shape of GDRs (Global Data Records). Because of problems with the baseline-C processing over land (problems corrected for the baseline-D which should be distributed by the end of 2020), we use the L2 baseline-B for this study that spans almost 5 years from end of 2010 to the beginning of 2015.

More recently, ESA launched the Sentinel-3 series in two interleaved orbits inclined at 98.65° with a repeat cycle of 27 days. The Sentinel-3A satellite was launched in 2016 and the Sentinel-3B in 2018. The altimeters onboard these two satellites operate fully in SAR mode on Ku-band. It has several advantages for small water bodies, but also for determination of the geoid slope on large lakes when approaching to shoreline. This characteristic result from the size of the footprint which is reduced by a factor ranging from 10 to 50 compared to LRM

altimetry mode. It allows a much better selection of the reflecting point and drastically reduces the pollution from the ground when the satellite is close to the lake's shoreline. It is however valid only when the orbital track is almost perpendicular to the shoreline. We did not use Sentinel-3B data in this study since few cycles were available at the time of the data processing and we need to accumulate many cycles for each track over a lake in order to estimate accurately the mean lake profiles.

Altogether, these missions constitute a constellation scanning the Earth with high spatial resolution. The radar ranges at 20 Hz and 40 Hz were processed in order to calculate the water height above ellipsoid with a sampling of the measurements along track ranging from 150 meters for Saral/AltiKa to 350 m for the Ku altimeters. For this study we have used the altimetric range and their corrections from the Geophysical Data Records (GDRs) released in the Centre de Topographie de l'Océan et de l'Hydrosphère (CTOH) database which is maintained at LEGOS laboratory. CTOH gathers all the available GDRs from the different space agencies, converts them into a common NetCDF format and include additional corrections. These data are finally made available for the international scientific community on its web site (ctoh.legos.pbs-mip.fr) with identical corrections for all missions. For this study, the added corrections are the various geoid solutions and some atmospheric corrections.

In addition, data from the first laser-ranging instrument GLAS on board ICESat (2003-2009) were also processed (Zwally et al., 2003 and <http://search.earthdata.nasa.gov/search?q=icesat>). ICESat was flying in an orbit inclined at 86° with a repeat cycle of 91 days. GLA06 v34 global elevation products were used. These products include surface elevation determined with specific algorithm for tides and atmospheric effects (Brenner et al., 2012). ICESat has a laser footprint of ~ 70 m and a data spacing of ~ 150 m. Within the footprint, the precision of the range measurements is 2 cm (Zwally et al., 2003). Due to the long repeat cycle, the inter-track distance is about 20 to 30 km allowing to provide dense coverage on large lakes. It has been used in several studies for lake water level change determination over the Tibetan Plateau (Zhang et al., 2011, and many others).

Table 1: list of altimeters used for the calculation of MLS.

Mission	Space Agency	Band	Altimetric modes	Period Coverage (years)	Period Cycle (days)	Spatial coverage
Jason-3	NASA/CNES/EUMETSAT/NOAA	Ku	LRM	2016-2019	10	$\pm 66^\circ$
SARAL	CNES/ISRO	Ka	LRM	2013- 2016	35	$\pm 81.5^\circ$
Sentinel-3A	ESA	Ku	SAR	2016-2019	27	$\pm 81.5^\circ$
CryoSat-2	ESA	Ku	LRM/SAR/SARin	2010- 2015	369	$\pm 88^\circ$
ICESat	NASA	Laser	laser	2003-2009	91	$\pm 88^\circ$

The high density of measurements was used to calculate the MLS (Figure 2). However, we also may observe that many tracks have been removed from the calculation. Thanks to the high number of potential tracks and dense coverage of each lake, we have decided to be very strict in the outlier elimination and the selection of valid measurements.

3. Methodology

We have used the algorithm developed at LEGOS for the determination of water height along track which is detailed in Cretaux and Birkett (2006) and Cretaux et al. (2016), with the exception that we didn't correct the range measurements for geoid undulation using the repeat track technique since our purpose is to use water level above the ellipsoid to determine the MLS.

The first step is to compute a mean vertical profile along the track of the satellite¹. We define for each track, a box of 1 km² along the ground-track. For each individual box, we correct each measurement from the average water level changes of the lakes (extracted from Hydroweb site: <http://hydroweb.theia-land.fr/>), in order to remove average water height changes of the lake, and to determine the mean ellipsoidal profile along the track. A reference date, common to all missions is set to the 1/1/2010. The reference date is arbitrary but by doing so, all measurements used for the calculation of the MLS are corrected for any hydrological height changes. Indeed, we assume that the dynamic of the lake level is equal everywhere on the lake and that the lake surface is in hydrostatic equilibrium. We also considered that temporal variation of the gravity field over the lakes is negligible in amplitude compared to the magnitude of the static geoid undulation along each track. The same assumptions have been used in the similar study of Jiang et al. (2019). The outliers are eliminated using a filter applied on each individual box. On each box, the measurements that deviated from the median by a value higher than 2 sigma (in the sense of standard deviations) are removed and the median is then calculated. A final step consists in a moving average filtering every 5 adjacent boxes along the track. Doing that along each satellite track we build a data set of ellipsoid height measurements of the lake surface (Figure 3), then used to determine the MLS.

Since each of these mean profiles are calculated satellite by satellite, and since there remains errors of few centimeters magnitude in water level time series used to correct for hydrological variability of the lake surface, there are residual inter-satellite biases that must be adjusted. It is calculated lake by lake. In order to do this, we considered the ICESat mean profiles as the reference and used a crossover point adjustment in order to determine the bias with other satellites. We started with CryoSat-2 and select each track of this satellite crossing at least one of the ICESat track. Using the median of the height difference between each CryoSat-2 and ICESat pair we adjust an inter-mission bias and apply it to each CryoSat-2 mean track profile. Then we do the same processing for the other missions considering the crossover point with

¹ Altitude of the satellites in the GDRs were calculated using different reference frames in the precise orbit determination: some are expressed in ITRF2014, other in ITRF2018. The CTOH service at LEGOS, before releasing the altimetry data to the users, homogenised altitude of all satellites in WGS84 ellipsoid. These were the data used in this study.

the ICESat + CryoSat-2 dataset. Tracks that deviate significantly from the reference height at the crossing with the network of reference tracks (2 sigma criteria has been applied) were filtered out during this process. The coherency of the data and the robustness of the calculation were reached with this method. At the end of this step in the data processing, we obtain, for each lake, a spatial distribution of orthometric heights representing a realization of the MLS. This realization is provided with a reference date common to all which is 2010/01/01 by construction.

The last step is the final interpolation of the MLS using all selected tracks with their individual measurements that, at this stage of the calculation, are all assumed to be corrected from all inter-mission biases. These measurements represent an irregular distribution of the MSL at the reference date. Our final objective is to calculate a regular gridded MSL, with a grid step of 1 km^2 . In order to achieve this objective, we have performed spatial interpolation of the irregular set of data using in a first step a Delauney's triangulation followed by a surface interpolation. Over an irregular gridded data set of discrete point, the Delaunay triangulations transform the datasets into triangles, which have the properties that any of the circumscribed circle of any of the triangles contains no other points inside it. The Delaunay's triangulation is a useful step to interpolate irregular datasets to a regular one. We used pre-coded subroutines TRIANGULATE and TRIGRID from IDL programming language in order to perform the interpolation of the MLS onto a regular grid (1 km^2) from irregular mean track profiles.

For each MLS, we also have calculated the RMS of the biases at the crossover points from each profile used to interpolate the MSL in order to provide an order of magnitude of the uncertainty.

4. validation

4.1 GPS height levelling over the Lake Issykkul

The lake Issykkul ($42^{\circ}10' - 42^{\circ}40'$ North, $76 - 78^{\circ}$ East, Republic of Kyrgyzstan (Figure 1) was chosen in 2004 to serve as calibration / validation (C/V) of radar altimeters. Lake Issykkul (6236 km^2) is the second largest mountain lake on the Earth (after Lake Titicaca, 8372 km^2) and is located in the Tien Shan and Ala Too Mountains. It has a length of 178 km and a width of 58 km. It is therefore large enough to be overflowed by all past and current satellites. Between 2004 and 2019, a total of 18 campaigns were performed for the C/V of several satellite altimeters. Many details on the experimental design are given on Cretaux et al. (2009, 2011, 2013, 2018) and Bonnefond et al. (2018).

A boat cruising along the altimeter tracks carries a GNSS receiver at the bow coupled with microwave radar measuring continuously the distance between the GPS antenna and the lake surface. The radar and the GNSS receiver provide their measurements every 30 seconds. During each campaign, the ellipsoid water height of the lake is calculated by the processing of the GNSS data using the GINS software in the Precise Point Positioning (PPP) kinematic mode (Loyer et al., 2012; Marty et al., 2011). The accuracy reached by this system is at the level of 2-3 cm RMS (see Cretaux et al. (2018) and Bonnefond et al. (2018) for all details on

accuracy assessments and field work design). During each campaign the boat cruised along satellite tracks since the main purpose was the determination of altimeter biases. However, the accumulation of measurements since 2004 all across the lakes has given a dense distribution of GPS height measurements. The resulting dataset has allowed us to validate the MLS calculated using only satellite altimetry (Figure 5a shows the tracks followed by the boat over the 18 campaigns). For each campaign we have built daily data sets of the GNSS vertical profiles and applied a moving average filter and visual elimination of evidently erroneous GPS measurements.

Then, each GNSS dataset has been corrected from water level changes of the lakes using Hydroweb (the reference date is first of January 2010 in order to remain consistent with the calculation of the MLS from altimetry data) and we have adjusted final residual biases for each set of GNSS data at crossover points. It has allowed us to calculate MLS using only the GNSS measurements, and to compare the GNSS derived surface to the MLS using only satellite altimeter mean profile. Finally, a MLS combining all types of data (GPS and altimeters) was computed.

The principal differences between the GNSS surface and altimetry surface are concentrated near the shoreline (Figure 5d). It is due to the strict selection of altimetry measurements that were eliminated during the data processing. In general, for lakes in mountain areas, significant errors in altimetry measurements are observed. This is due to inhomogeneous surface illuminated in the radar footprint, and to the inability for the onboard tracker failing to adapt the position of the listening window gates to abrupt changes in the topography in the close loop mode which is generally used for past missions (Arsen et al., 2015; Biancamaria et al., 2017). Indeed, the onboard tracker calculates the average range of waveform in advance based on previous registered echoes, in order to adjust the signal reception's window. If the surrounding topography is steep, likely the case in mountainous regions, the data may be lost due to signal attenuation, or erroneous due to contamination from the ground surface within the waveform. In contrast, during most of the GPS campaigns, we have sampled water height closed to the shoreline in order to cover the whole lake surface. The RMS of difference between the GPS and the MLS inferred from satellite altimetry is approximately 6 cm, with over most part of the surface of the lake, absolute values of the differences less than 8 cm, apart from some narrow bands near the coast.

Lake Issykkul is a deep-water body in a mountainous environment. It is 700 m deep at its deepest point. Such a significant volume of water constitutes a significant deficit of mass below the surface of the lake compared to surroundings. It has been demonstrated in other studies, that gravity anomalies in such type of environment are amplified compared to other regions (Li et al., 2015; She et al., 2016). Mountain ranges higher than 4000 m run more or less parallel to the North and South coasts of the lake. The mass of these ranges exerts gravitational attraction outward of the lake. Hence, both the mass deficiency below the surface of the lake and the mass excess all around combine to produce the deflections of the vertical as large as 20 cm/km which are evidenced by the curvature of surface at the rims of the Lake.

4.2 Comparison with ICESat-2 heights

We have used the first year's data on the lidar altimeter from ICESat-2 satellite for validation of the method over four lakes: Issykkul, Baikal, Nam Co and Tanganika. The ICESat-2 data used in this study have been collected on the <https://nsidc.org/data/ATL08> (Neuman et al., 2019). For each of the passes collected between November 2018 and August 2019 we have plotted the water height elevation above the ellipsoid on the four lakes. We have then interpolated the MLS using the coordinates along the tracks presenting enough valid data (we have observed many gaps in the ICESat-2 data for some passes probably due to cloud cover). The results are illustrated by Figure 6a-j. Not all comparisons done are presented but the ones in the Figure 6 are representative of what has been measured. When compared to the ICESat-2 tracks (which we recall were not used to calculate the MLS, so can be considered as external validation data), the results show a very high agreement. The RMS of differences between the interpolation along the MLS and the ICESat-2 ellipsoid heights is often at the order of magnitude of 2-5 cm. However, as we see on Figures 6a, 6d, 6g, 6h, 6i, the questions on the uncertainty of the MLS near the shoreline can be still significant. Some other comparisons not shown here also present these discrepancies at the decimetre level when we approach the coast. These results provide further very instructive information on the impact of interpolation across the lake surface. The presence of bays, for example over the Lake Baikal or Tanganika, even amplifies the sensitivity of results to the distance of the shoreline. Figure 6d is an illustration of this shoreline effect and has been met in several other passes. The positions of ICESat-2 tracks used here did not coincide to any other datasets (GPS or other altimeters) so the differences observed include the errors induced by the data and errors induced by the interpolation process. This is particularly true along the lakeshore since many tracks used for the calculation of the MLS has been truncated a few kilometres away from the coast.

Table 2 gives for the 4 lakes chosen for this validation process the RMS of the differences between the ICESat-2 passes and the MLS interpolated along these passes. We see that the RMS ranges from approximately 5 to 9 cm, which is consistent with the results of internal validation (RMS at cross over points: Table 3). This result also gives an overview of the precision of the MLS with good indication on the current limitation principally along the lakeshores.

Another conclusion from this comparison is that the ICESat-2 mission, when data from several cycles would be acquired, will be strongly helpful for the calculation of new MLS for each of the large lakes from this study. We even may expect large improvement near the coast, in particular for lakes in mountain areas like the Lakes Issykkul or the Titicaca.

	RMS (cm)	Number of ICESat passes
Issykkul	5.1	24
Baikal	8.6	73
Tanganika	6.8	29
Nam Co	4.9	5

Table 2: Summary of the comparison along the ICESat-2 tracks with the MLS on four selected lakes.

4.3 Error budget

We can distinguish two main sources of uncertainty in the calculation of the MLS. The measurements and the geophysical errors.

Measurements errors are due to altimetry data processing with an error budget depending on many parameters. It was documented in several publications. For large lakes, range measurements have the same quality than over the ocean: it is at the centimetre level (Cretaux et al., 2009, 2018; Quartly et al. 2020). The corrections due to the propagation of the radio-signal in the atmosphere, including wet and dry troposphere, and ionosphere also contribute to the final uncertainty. Since for lakes, the radiometer which over the ocean measures precisely the wet tropospheric correction, cannot be used due to its very large footprint (dozen of km), we must use meteorological models. Precision is generally on the order of 1-2 cm when it is not raining. When climate conditions are too wet, it may reach few cm (Cretaux et al., 2009). Finally, the Sea State Bias (SSB) which is a consequence of wind speed and wave height, is not well modelled over lakes and is not considered in the calculation. In most of the case, the effect is in theory very negligible (less than 1 cm) but in some extreme conditions it can reach several centimeters. In such situation the measurements will deviate enough from the mean profile, and since we filtered out the passes that present high deviation, we believe this effect is eliminated. Several studies have used in situ measurements in order to evaluate the precision of satellite altimeters over lakes. For large lakes, it is at the level of 2-5 cm (Cretaux et al., 2009; Quartly et al., 2020; Schwatke et al., 2015 and many others).

Geophysical sources of errors are of two types: the seiche effect and the elastic deformation of the Earth Crust due to water mass loading effect.

Seiche are resulting from wind forcing and atmospheric pressure gradient across a lake. It is impossible to model them without good wind data and without a bathymetry of the lake. It can reach several cm of spatial variability of the lake surface when it occurs due to permanent wind regime. For example, over the Lake Issykkul, it generates East-West oscillation of the lake's surface (Cretaux et al., 2009, 2011). Over the Great Lakes of North America, it even can reach decimetres (Birkett 1995). If it happens when the satellite is passing over the lakes, it will generate a corresponding deviation of the lake profile under the situation that the pass is parallel to the direction of the wind. It occurs very rarely, and it is well observed since the lake profile along the track deviates significantly from the mean lake profile for such pass and is eliminated from the calculation.

The second source of error is due to the crustal deformation of the lake's bed in response to the increased or decreased mass load. In Argus et al. (2020) a study over the Great Lakes of North America, based on model and on analysis of GRACE, GPS levelling and altimetry data, it was shown that the resulting effect is a fall of the lake floor of 8-23 mm for the period 2013

to 2019, when water level of the Great lakes have increased by several decimeters. The consequence on our MLS calculation is however reduced since each lake profile calculated cycle by cycle are corrected from water level changes using Hydroweb time series. All data are referred by this way to the common date of 1/1/2010. The subsidence of Great Lakes of North America due to loading effect only causes an error of water level time series in Hydroweb, since it attributes to hydrological phenomena what is in fact a crustal deformation. However, it remains an error due to the spatial gradient of this elastic deformation: from 23 mm in the center of the lake to 8 mm near the lakeshore. It contributes however to a very low additional error of few mm in the MLS.

5. MLS datasets

In order to calculate the MLS for some of the largest lakes in the world, we have applied the methodology described above on a set of 22 lakes spread over the continents (Figures 1a-f). For each of them we have extracted the Sentinel-3A, Saral/AltiKa, Jason-3, CryoSat-2 and ICESat whenever data were present. We have consequently produced 22 gridded datasets at 1 km² of the MLS of these 22 lakes. They are present over five continents (Europe, Asia, Africa, North and South America). There are five mountain lakes (Nam Co, Issykkul, Argentino, General Carrera and Titicaca) where we may expect some errors near the shore. There are three lakes in rift valleys (Tanganika, Malawi, Baikal), where the slope of the geoid is expected to be high. When lakes are covered by ice in winter the range measurements can present higher errors. We have therefore decided to keep only free ice data for lakes Ladoga, Onega, Athabasca, Baikal, Winnipeg, Winnipegosis, Vanerm, Nam-Co and the 5 Great Lakes. For lakes covered by ice, we decided not to use the data in winter time, since altimetry may be noisy over ice surfaces.

In order to assess uncertainty of the different MLS, we have a very limited possibility. The general data processing has been validated using the Issykkul lake with additional data (GPS), and the comparison with ICESat-2 data was shown above. Another option is to compare for each lake the RMS of the differences between the data used at the crossover point before doing the MLS interpolation. This does not allow to quantify the impact of the distribution of the measurements across the whole lake surface on the resulting MLS. However, it provides an overview of the quality of the data used when outliers has been removed. We recall that, once the datasets are completed, the last step only consists of triangulation and interpolation of the irregular grid in order to achieve a regular one at a resolution of 1 km² (by choice considering a balance between the goal to provide high resolution and the spatial dispersion of the data: we tested other resolutions, 500 m² to 5 km² and 1 km² was the best compromise). The Figure 7 presents some of the resulting MLS for four lakes, Lake Superior, Baikal, Ladoga and Victoria. The tracks used for the calculation are also represented. We see that depending on the lake the distribution of data is different. This is due to the process of outlier elimination, based on crossover point analysis before constituting the final datasets for each lake. We also see for some lakes like for the Victoria in the north side, or Superior in the south one, that many measurements along the coast were not presented in the database used for the calculation. For most of the lakes we have observed that except with Sentinel-3A, the data close to the lakeshores (within a distance of 3 to 5 km) were partially or totally removed

during the data processing. Same conclusions were obtained Jiang et al. (2019) came up with the same conclusion with their study on the lake Nam-Co. Table 3 summarizes the RMS of the differences of height above ellipsoid at the crossover points for each of the lake. It ranges between 2.5 cm for the best (lakes Argentino and Titicaca) to 8.6 cm for the worse (lake Michigan). The 6.3 cm of RMS observed with the lake Issykkul is coherent with the comparisons done with the MLS inferred from GNSS data alone (section 4).

Lake	Latitude (°)	Longitude (°)	Number of tracks	RMS at crossover points (cm)	Lake extent (km ²)
Argentino	-50.3	287.1	24	2.5	1466
Athabasca	59.2	251.2	80	6.6	7900
Baikal	53.4	107.6	79	5.7	31500
Balkhash	46.3	75.9	108	4.5	18200
Erie	42.2	278.7	88	4.8	25800
G. Carrera	-46.6	287.8	15	3.6	20000
Huron	45.2	277.8	95	5.3	59570
Issykkul	42.5	77.4	40	6.3	6236
Ladoga	61.0	31.3	41	6.4	18135
Malawi	-12.2	34.6	24	4.8	29600
Michigan	44.5	273.3	70	8.6	58000
Nam Co	30.8	90.6	15	5.5	2020
Nicaragua	11.6	274.6	24	4.6	8150
Onega	62.0	35.2	31	6.6	18200
Ontario	43.8	282.5	72	6.3	19009
Superior	47.7	271.9	151	5.9	82200
Tanganika	-6.5	30.0	27	4.8	32000
Titicaca	-15.9	290.7	14	2.5	8372
Vanerm	58.9	13.2	17	6.5	5650
Victoria	-1.5	33.1	64	7.3	68800
Winnipeg	52.1	262.4	39	6.7	23750
Winnipegosis	52.5	259.8	23	4.8	5150

Table 3: Datasets used for each of the selected lakes and RMS of the differences of mean lake profiles at cross over point.

6. Validation of geoid models

Ellipsoidal heights over lake surfaces show lateral variations. Assuming that no unmodeled hydrodynamic or atmospheric effects act on these surfaces, one can make the hypothesis that these surfaces of fluid bodies remain perpendicular to the only force that remains acting on them: gravity. In a first approximation, we thus consider that the curvature of lake surfaces reproduces the spatial variations of the inclination of the gravity acceleration within the lake area, the so called deflection of the vertical, hence the undulation of the local geoid.

Consequently, we have mapped the unbiased differences between the MSL on each lake with undulations derived from different geoid models projected on the respective lakes. We used three recent models: EGM2008, EIGEN6c4d and XGM2016. For each model we first of all interpolate the available geoid gridded datasets (that are inferred from the spherical harmonic coefficients) to the resolution of the MLS (1 km²). Then we have generated maps of the differences and associated statistics.

Since such direct comparison does not allow to determine which part from the differences is due to the interpolated MLS and which one is due to the geoid model, we also compared the geoid models along each of the satellite tracks used for the calculation of the MSL. In such comparison done on data before they are used to calculate the MLS, it allows to assess more accurately the geoid undulations errors at high frequency, considering the altimetry data as truth.

Figure 8 presents maps of difference between MLS and the three different geoids. It includes three sources of errors: altimetry errors, geoid model errors, and interpolation errors. It shows geographical patterns with maximum of difference that can exceed one meter in the case of rift valley lakes. We see the high slope of geoid undulations (particularly for lake Baikal and Tanganika) reaching several decimeters per kilometer (an order of magnitude higher than usual geoid undulation over the Great Lake of North America). For the lake Baikal (Figures 8a-c) we note that the three models miss a structure in the central part of the lake, although this is less pronounced with EIGEN6c4d. For lake Tanganika (Figure 8d-f) EGM2008 presents significant differences over the whole surface, with a big depression present in the MSL in the center and the north parts of the lake and absent in the geoid model. The differences along the coast are also very high. This is much less visible for EIGEN6c4d and quite absent for XMG2016, which in this case fits well with the MSL even near the coast. This result is confirmed in Figure 8.

Figure 9 gives RMS of the differences between the MLS and the geoid models, for all lakes, but only along the altimeter tracks used in the MLS calculation. Considering that altimetry errors are lower than the geoid models' uncertainty, this type of comparison gives an order of magnitude of uncertainties of each geoid model. It indeed does not incorporate the error budget the contribution of the MLS interpolation process, which varies depending on the distribution of selected altimeter measurements.

The results presented in Figure 9 show that the three models are quite coherent in terms of accuracy. Such an agreement reveals that the errors at the corresponding –short- wavelengths are in some part independent of the procedure used to derive the harmonic coefficients of the models. Yet, the dataset of ground measurements of gravity anomalies is largely common to all the models, with similar limitations. Therefore, we can assess that these errors have two sources. In areas such as Africa and central Asia, the data available for the calculations are rare and often ancient, hence possibly of limited accuracy. In addition, they were not collected on the lake themselves, only on the shore. Consequently, these measurements see poorly the anomalies in the center of the lakes. In the mountain or rift lakes like Baikal, Issykkul, Malawi or Tanganika, the height anomalies are particularly large (several meters in a few tens

of kilometers), because of the depth of the lake (several hundreds of meters). It produces a large mass deficit and the surrounding high relief also contribute to deflect the gravity vector outward from the lake. There, the commission error of the global geoid model is likely to be much larger than for the lakes in Northern America, comparatively much shallower because they lie in the middle of a tectonically inactive continental core of gentle topography, and are actually sampled offshore. Hence the reduced variations in the geoid anomaly is likely to be much better sampled in the dataset available for the latter area.

This calculation also shows that the precision of the MLS (from altimetry RMS at crossover points: see also Table 2) is very stable at approximately 6 cm for each of the lakes. It is hard to conclude on the respective uncertainty of each of the models, but these results clearly indicate that thanks to satellite altimetry the finer scale of the rapidly varying geoid spatially is visible at high resolution. We can see it also more clearly on Figure 9 as shown with a track of ICESat over the lake Tanganika.

Figure 10 represents the differences between an ICESat selected track to the three geoid models. We see that these differences are different between each geoid and not randomly distributed. We also see that locally the differences between the geoid and the MLS can reach several decimeters.

7. Perspectives and conclusions

The purpose of this work is to use satellite radar and laser altimetry from past and current missions (Jason-3, Saral/AltiKa nominal phase, Cryosat-2, Sentinel-3A and ICESat) in order to calculate the MLS over large lakes. A set of 22 lakes spread over 5 continents were selected for this study. A method based on the repeat cycle technique already used in the production of lake water height in Hydroweb database has been developed in order to extend this technique for the interpolation of MLS. It is based on adjustment of the water height along each track to a common reference and by reduction of the RMS at the crossover points of the satellite tracks. The method has been validated using the Lake Issykkul in Central Asia where several GNSS levelling campaigns were performed. 18 campaigns have been done since 2004 allowing to map the lake surface with a high density of water height measurements fully independent from satellite altimetry. It has allowed to quantify the uncertainty by comparing MLS inferred from the GPS and the one using multi-satellite altimetry. An uncertainty of 6 cm has been obtained. Comparisons between the MLS and the first year of passes of the Lidar altimeter on ICESat-2 also confirmed the high precision of the MLS. Moreover, we have seen that due to the footprint size and some issues on the onboard trackers, many data are missing along the coastline of lakes or have been removed from the calculation. For each lake, we have also observed that the Sentinel-3A measurements presented better results close to the coast, allowing a better mapping of the MLS although this is still insufficient data to fully cover the coastal areas (in general within 3-5 km of the shoreline) of large lakes. We have also compared the MLS produced in this study to three geoid models: EGM2008, EIGEN6c4d and WGM2016. Due to the high resolution of altimetry data and validation on Lake Issykkul, the MLS calculated have been considered as reference surfaces to determine the limitation of geoid models over large lakes. We have seen

that the MLS is able to determine high slope of the geoid over short distances which was not the case with the models. From this study, it is impossible to determine which models fits better with MLS over the 22 lakes, since their score varies from one lake to another. However, we have observed that over lakes located in rift valleys (Tanganika, Malawi, Baikal) the low resolution of the model causes an erroneous estimation of height surface of several decimeters at high resolution. Some large depressions on the MLS are fully absent in the models. In conclusion, satellite altimetry highlights that even the most up to date geoid models lack resolution at the scale of the lakes, even the largest ones. This limitation prevents the full use of altimetry from non ER orbits in the computation of water level series over a large number of lake since a MLS is required in this case.

The perspective and future work on this subject are numerous and promising with the new missions. We distinguish the perspective considering two aspects: the first concerns the potential improvements of the MLS using new data. The second aspect concerns the use of the MLS as a set of new data for geoid model calculation and validation and lastly for the validation of the SWOT missions.

- 1) First of all, the data of Sentinel-3B were not included in this study since we didn't have enough information on the data quality. Moreover, at the time of the study, the sentinel-3B was still under evaluation by different groups and not enough cycles were acquired at CTOH with enough degree of confidence. However, we have observed that the SAR data on Sentinel-3A are very precise over large lakes (Cretaux et al., 2018). For the MLS studies, they were accurate enough even close to the lakeshores, which was often not the case with the other missions. Sentinel-3B will be included in future work.

ICESat also often provides precise measurements along the lakeshore but, unfortunately, the high number of gaps in the datasets limits the use of these data. However, when ICESat track were acquired (which means also under clear skies), they were very accurate. This leads us to believe that with the ICESat-2 mission launched in 2018, when enough passes will be acquired, it will lead us to calculate refined MLS particularly close to the lakeshores.

In 2022, the wide swath interferometer on the SWOT mission will offer a new set of data to map the MLS over large lakes. The spatial resolution even in the low-resolution mode of the instrument (500 m), with onboard data processing, will offer an unprecedented view on the lake surface.

With the work currently done on the onboard a priori data base, which is conducted at CNES and LEGOS with the Ocean-next company, we will upload a large number of reference height of lakes worldwide. Linked to the onboard navigator named DIODE, it has already demonstrated on Jason-3 mission that it allows reducing by a high factor the number of missing data on lakes and rivers, in particular in the lakeshore vicinity. Future and current missions like Sentinel-3A/3B and Sentinel-6/Jason-CS will benefit also from this evolution.

- 2) It has been pointed out by Kingdon et al. (2008) that altimetry has the potential to correct the *model to high frequency component of the gravity field*. However, they also noted that satellite altimetry is not *accurate enough to distinguish density formation*. Since this study was done (in 2008) new technical characteristics of the current altimeters may solve this question. Until now, no measurements of the deflection of the vertical have been incorporated into the determination of geopotential models. Nevertheless, the altimetry data contain precise information to extend towards higher coefficients the harmonic decompositions of the geopotential. On another hand, a set of MLS can serve for future validation of the models.

3)

In 2022 the interferometer onboard SWOT will provide measurements on lakes and river worldwide. It will measure lake height, lake extent, river height, slope and width. It will also measure ocean mesoscale and sub-mesoscale ocean surface. A program of calibration / validation of the instrument onboard SWOT is under development and will contain a large set of a priori database for this purpose. The sources of errors and biases with SWOT are numerous and will all need a particular attention. MLS can serve for this purpose. It will allow calibrating the roll error, the phase screen bias and establish the error budget of SWOT across the swath. We indeed know that the random error of the Karin instrument is correlated to the distance to the nadir (minimum of error close to equidistance of near and far edge of the swath). The roll error is linearly dependent on the distance to the near range. Therefore, comparing the lake surface heights measured by SWOT across the swath for each of these lakes will allow quantifying these different sources of errors. During the lifetime of the SWOT mission, comparison between the MLS and the height surfaces on large lakes will also allow quantifying the long wavelength surface oscillations of the lakes due to barometric and wind effects: the seiches effect which may reach several decimeters on large lakes, (Cretaux et al., 2009; Birkett 1995).

In the present study, we limited our dataset to the exact repeat missions. Actually, past or current non-exact repeat missions provide a much denser coverage that could be used to improve MLS. The problem to solve is the reduction of the noise that could not be achieved by averaging cycles as done with the repeat orbits. In a next step, we foresee to include these data after filtering them with filters defined from the spectra of the difference between the mean profile and the individual profiles, for each satellite that flew an Exact Repeat Mission before it is posted on another orbit.

Acknowledgments: We acknowledge the data producers (NASA, ESA, CNES, CTOH/LEGOS) for providing all datasets used in this study. We thank the CNES for funding our work through the TOSCA program. We dedicate this article to the crews of the Multur in Cholpon Ata and the team of Kyrgyz colleagues from Bishkek and Kyzyl Suu who host and maintain our instrumentation. We also dedicate this article to Gulya, with whom we now work for about 16 years in Cholpon Ata, for her hospitality, and to Vladimir and Dushen our first, regretted, mentors when we started the work in Kyrgyzstan.

Availability of the MLS

The MLS calculated will be made freely available to potential users and other scientists by simple request by email to the corresponding author in a first step. Before the launch of the SWOT mission, the MLS will be recalculated using few years of additional data on new tracks not included in this work (Sentinel-3B and ICESat-2). It will then be made available through the CTOH/LEGOS and AVISO web sites.

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Figure captions

Figure 1: The 22 lakes selected to the calculation of the MLS over (a) Africa, (b) Europe, (c) Central Asia, (d) Patagonia, (e) South America, and (f) North America. 1: Argentino, 2: General Carerra, 3: Titicaca, 4: Nicaragua, 5: Ontario, 6: Erie, 7: Huron, 8: Michigan, 9: Superior, 10: Winnipeg, 11: Winnipegosis, 12: Athabasca, 13: Malawi, 14: Tanganika, 15: Victoria, 16: Vanerm, 17: Ladoga, 18: Onega, 19: Balkhash, 20: Issykkul, 21: Namco, 22: Baikal.

Figure 2: satellite tracks used for the MLS calculation of the Lake Michigan in North America. Colour code of dots is as follows: Red for CryoSat-2, black for ICESat, green for Saral, yellow for sentinel-3A, and grey for Jason3.

Figure 3: After processing the measurements as described above, the geoidal undulations inferred from satellite altimetry are represented along the four altimeters' tracks over the lake Issykkul.

Figure 4. Map of the MLS of lake Tanganika. The RMS at crossover points for this lake is 4.7 cm. See Figure 2 for colour code of dots.

Figure 5: Lake Issykkul: (a) the MLS using GNSS data only from the 18 field campaigns, (b) with satellite altimetry (Saral/AltiKa, Jason-3, Sentinel-3A, CryoSat-2 and ICESat), (c) using all data (GNSS and altimetry), and (d) the difference between GNSS and altimetry inferred MLS.

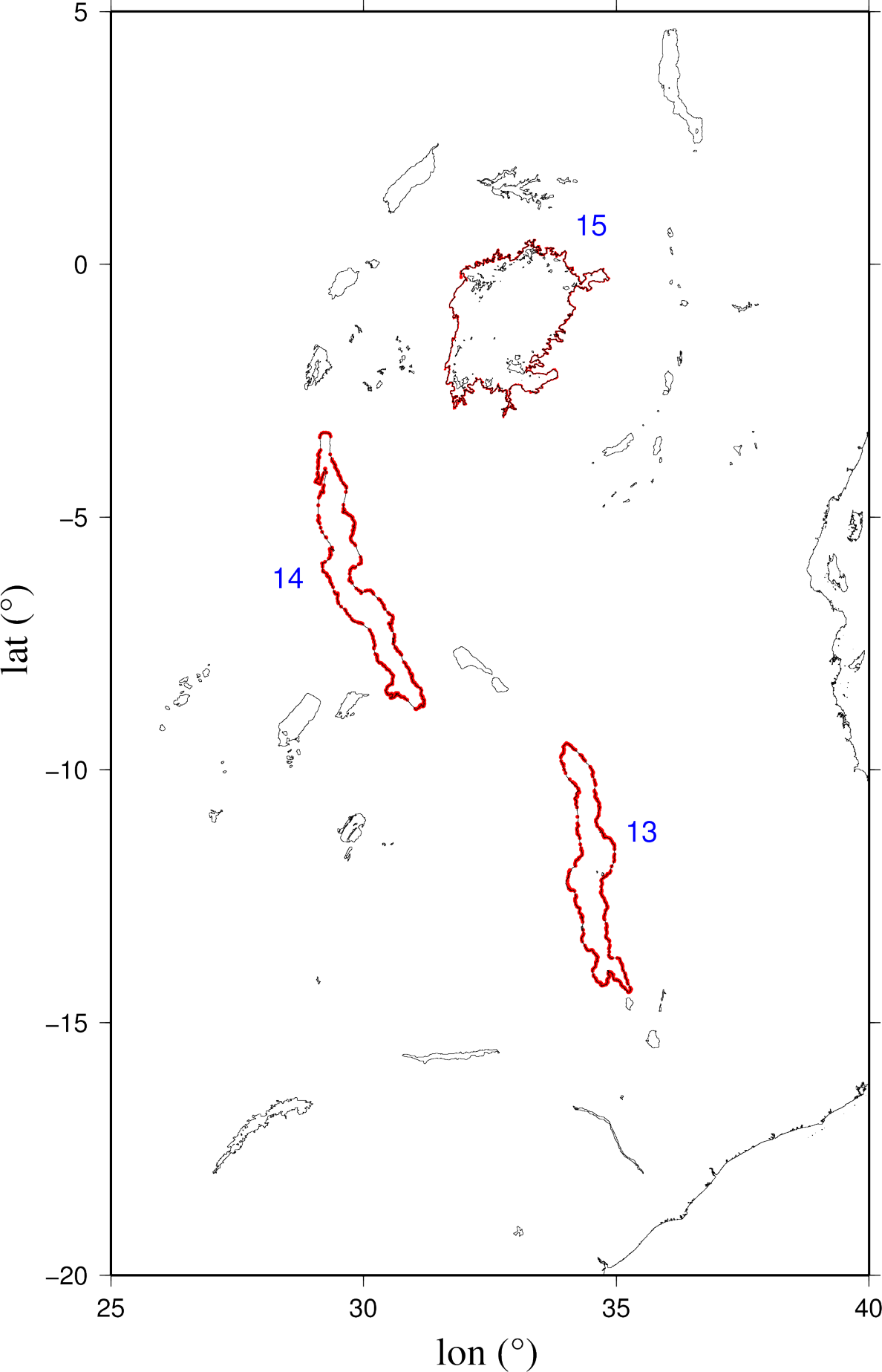
Figure 6: ICESat-2 ten selected tracks compared to MLS over the lake Issykkul (a-d), the Baikal (e-h) and the Tanganika (i-j). Position of the individual tracks are represented in the box of the top left corner of each figure. The MLS and the ellipsoid height along ICESat-2 have been level to zero for better visualization of the differences.

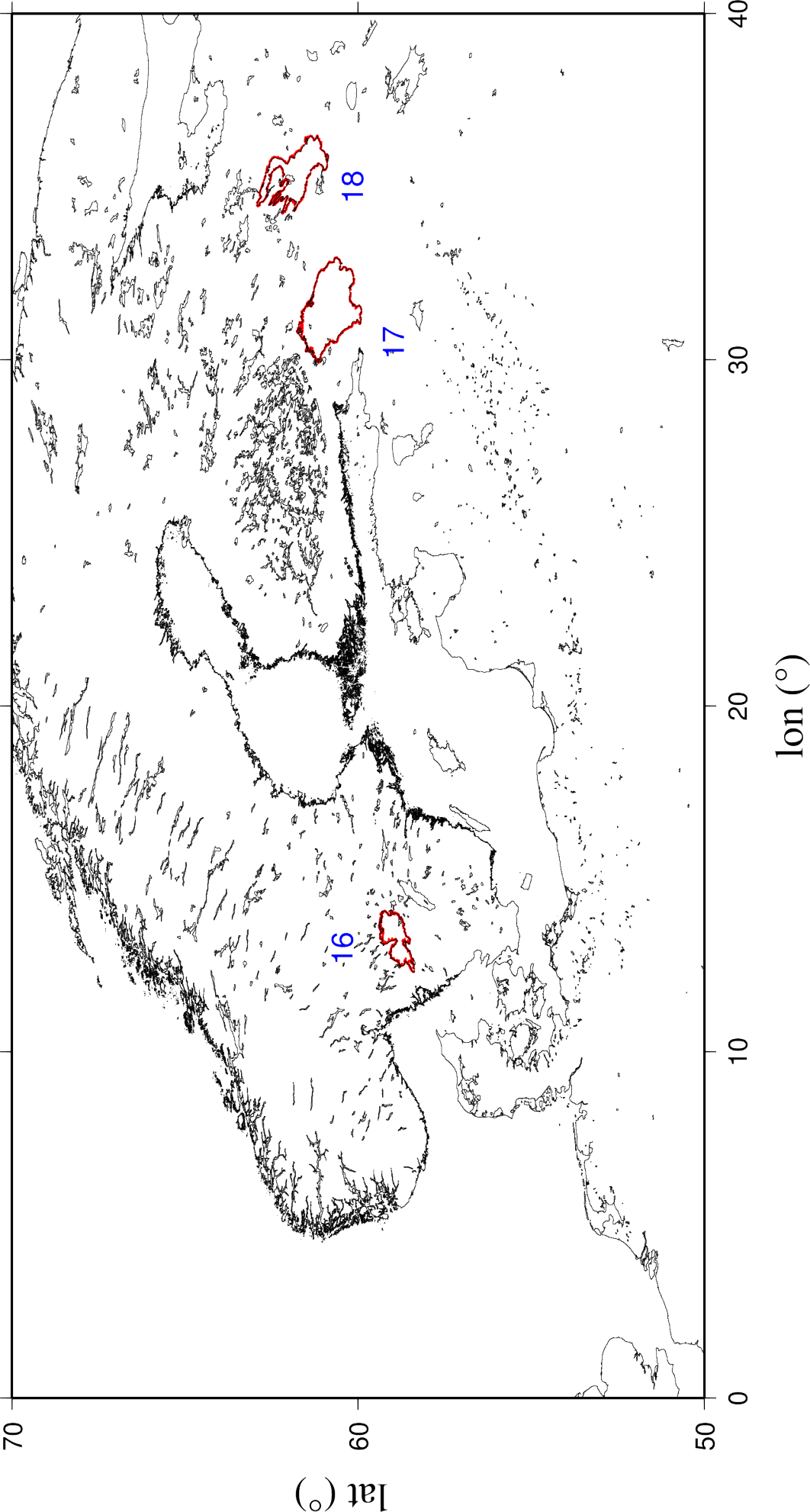
Figure 7: MLS of 4 large lakes, belonging to 4 different continents, (a) Europe (Ladoga), (b) North America (Superior), c) Africa (Victoria) and (d) Asia (Baikal). The green line corresponds to the Saral/AltiKa tracks, the red line to the CryoSat-2 tracks, the grey to the Jason-3, the black to ICESat tracks, and the yellow to the Sentinel-3A Satellite tracks

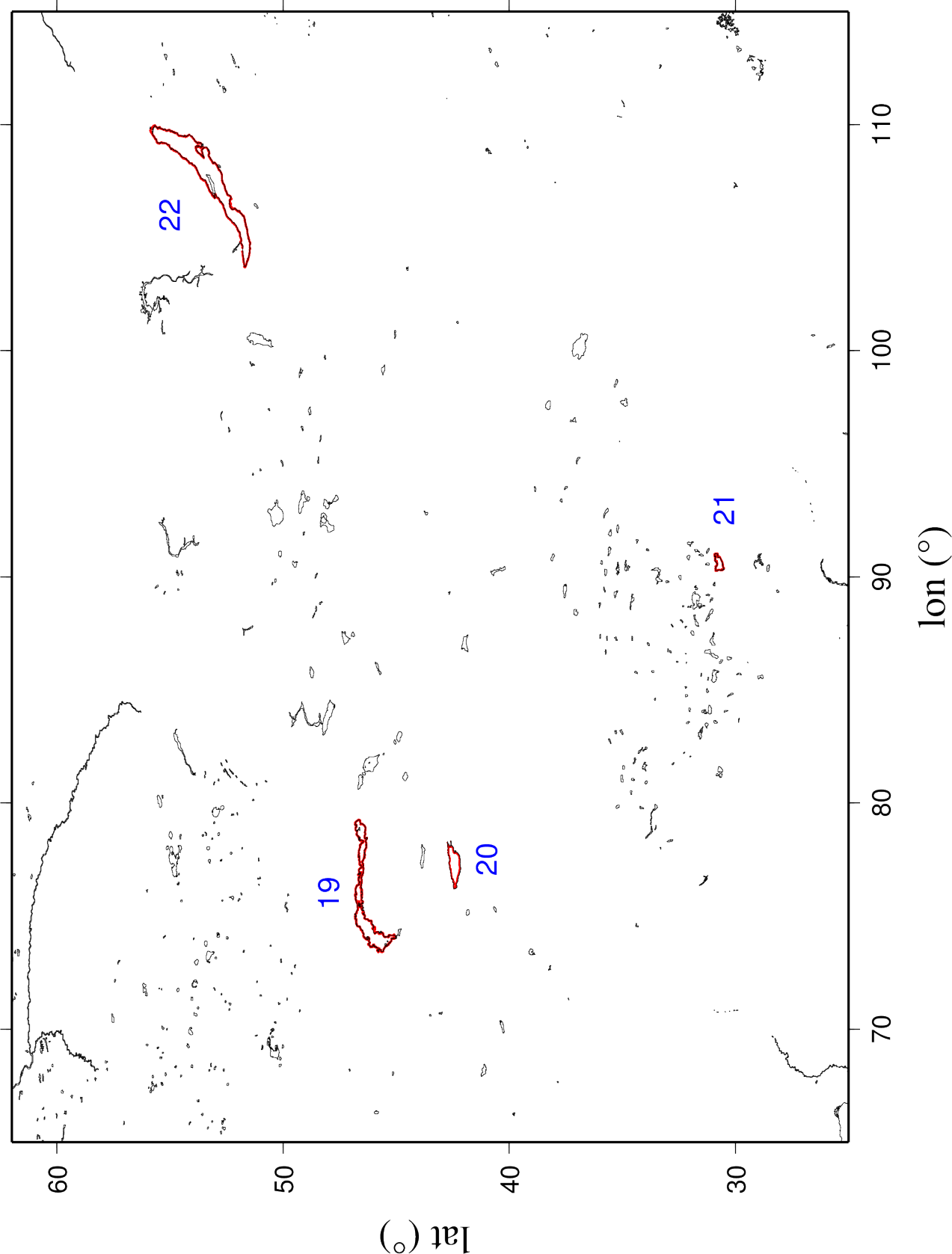
Figure 8: MLS minus Geoid models for lake Baikal (a) with EGM2008, (b) with EIGEN6-c4d, (c) with XGM2016, and for lake Tanganika (d) with EGM2008, (e) with EIGEN6-c4d, (f) with XGM2016

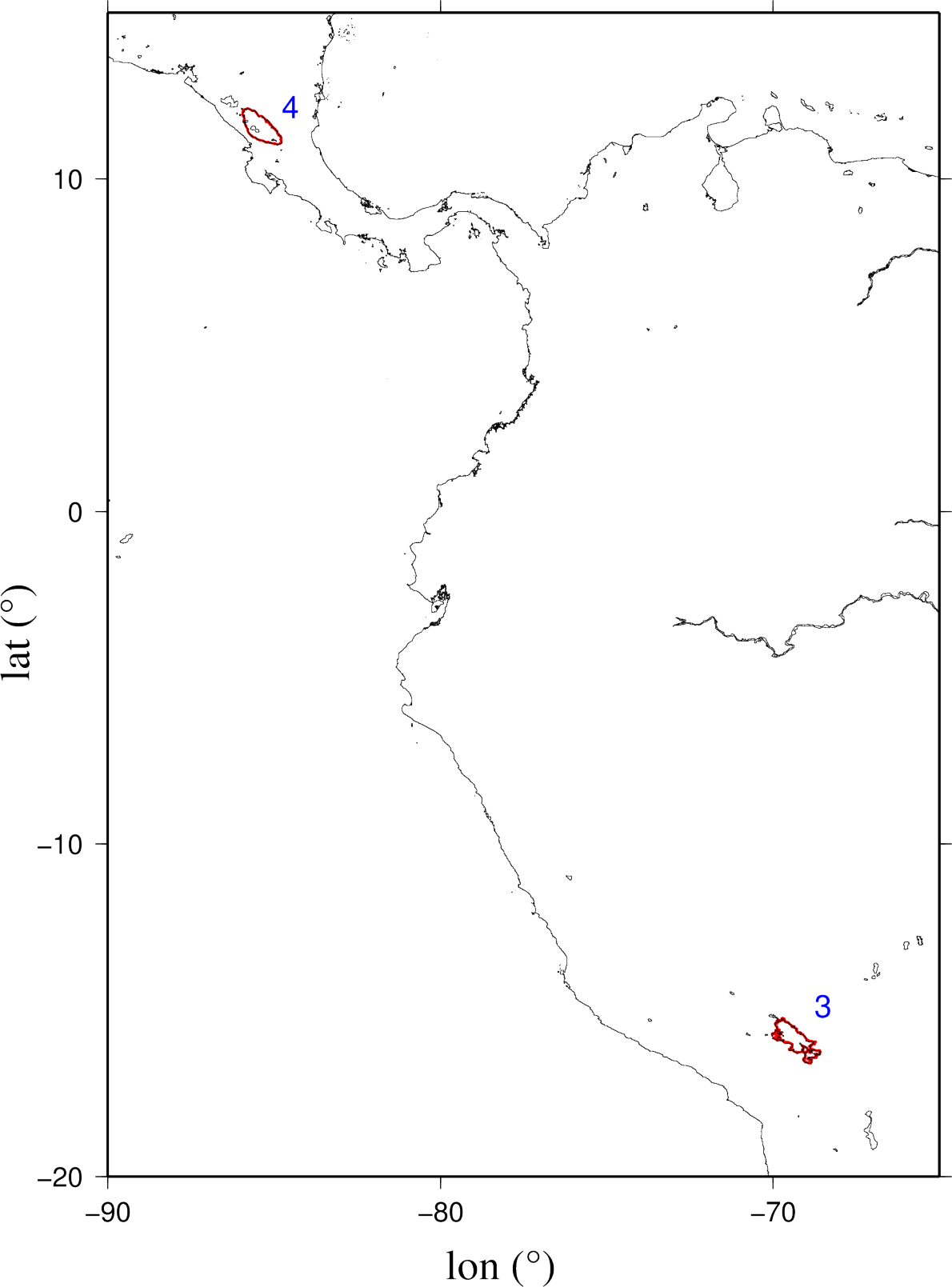
Figure 9: RMS of the differences between altimetry data along each track used to calculated the MSL and the corresponding geoid heights from models (in meters). The comparison in yellow corresponds to the RMS of the remaining differences at crossover points for each lake (values are given in Table 2)

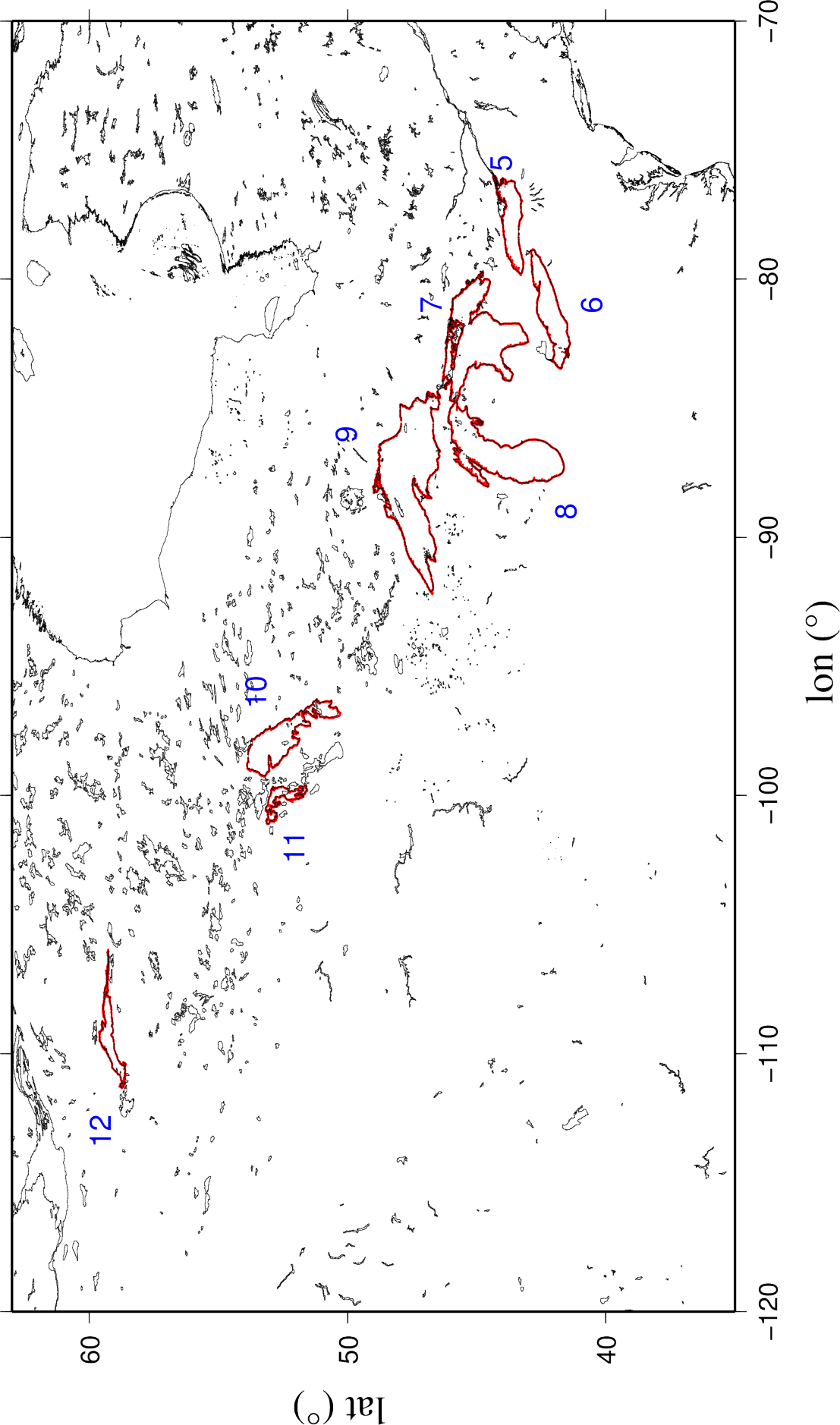
Figure 10: Unbiased difference between along-track ICESAT data over Lake Issykkul and collocated geoidal undulations interpolated from 3 global models

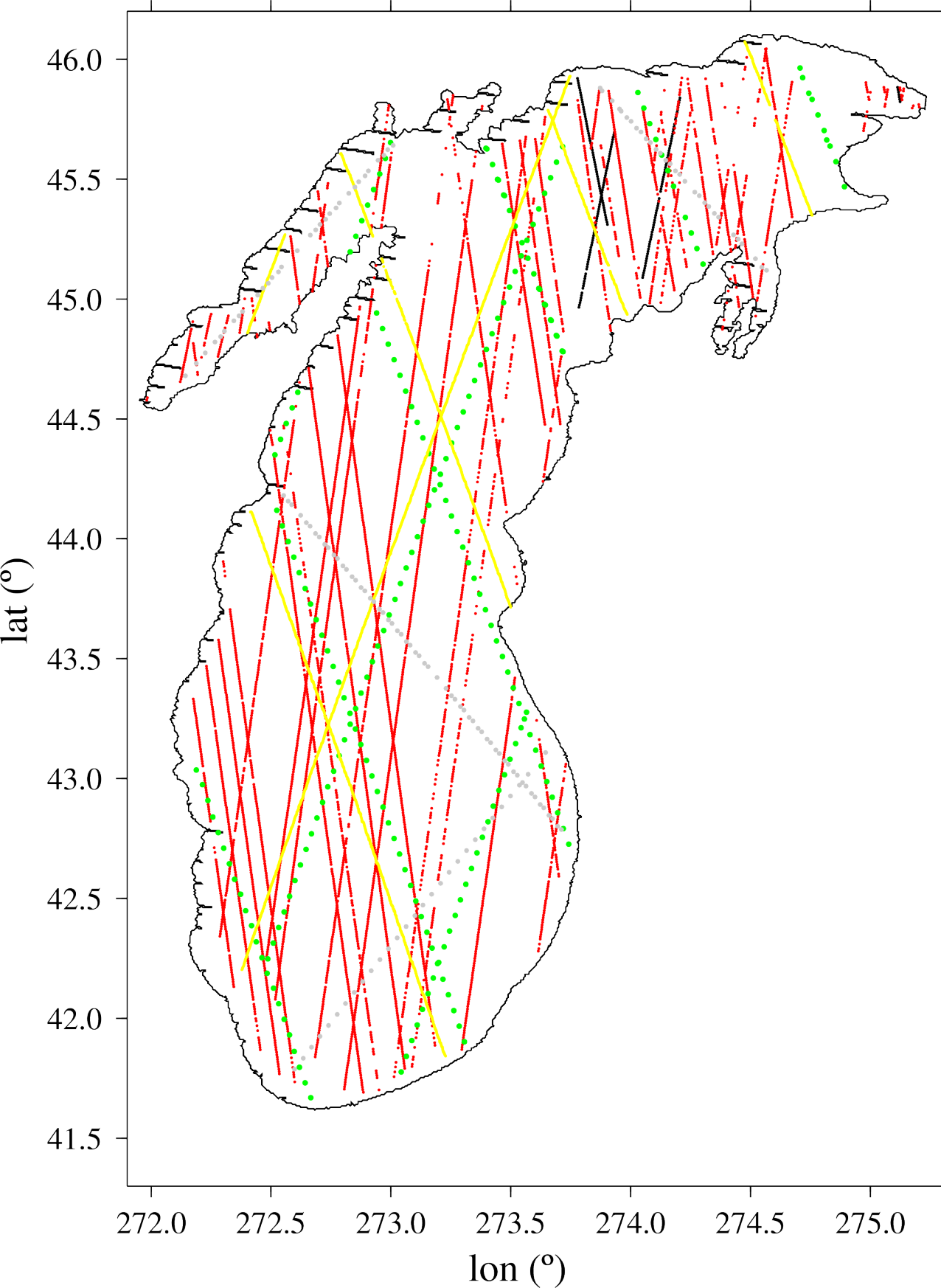




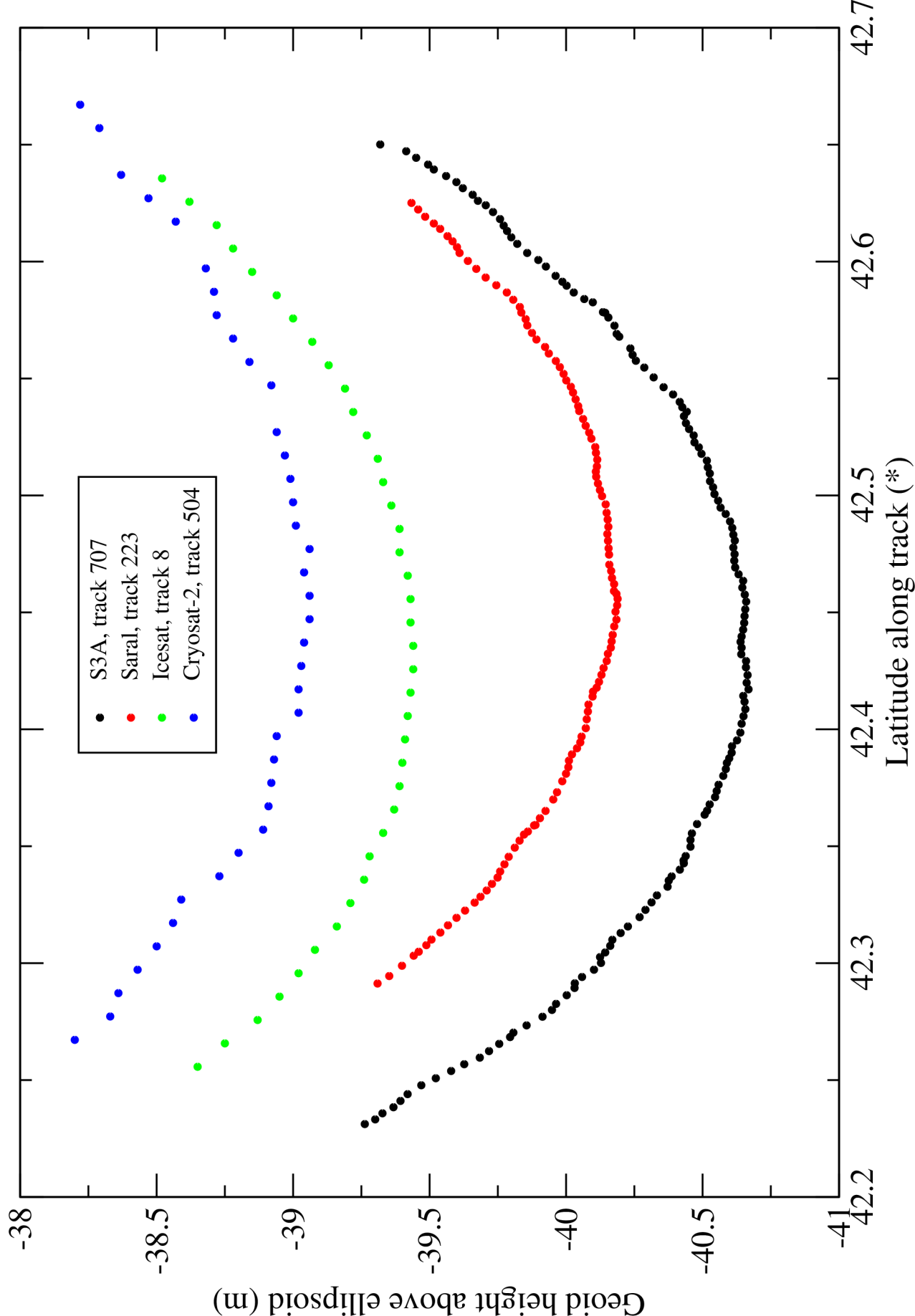


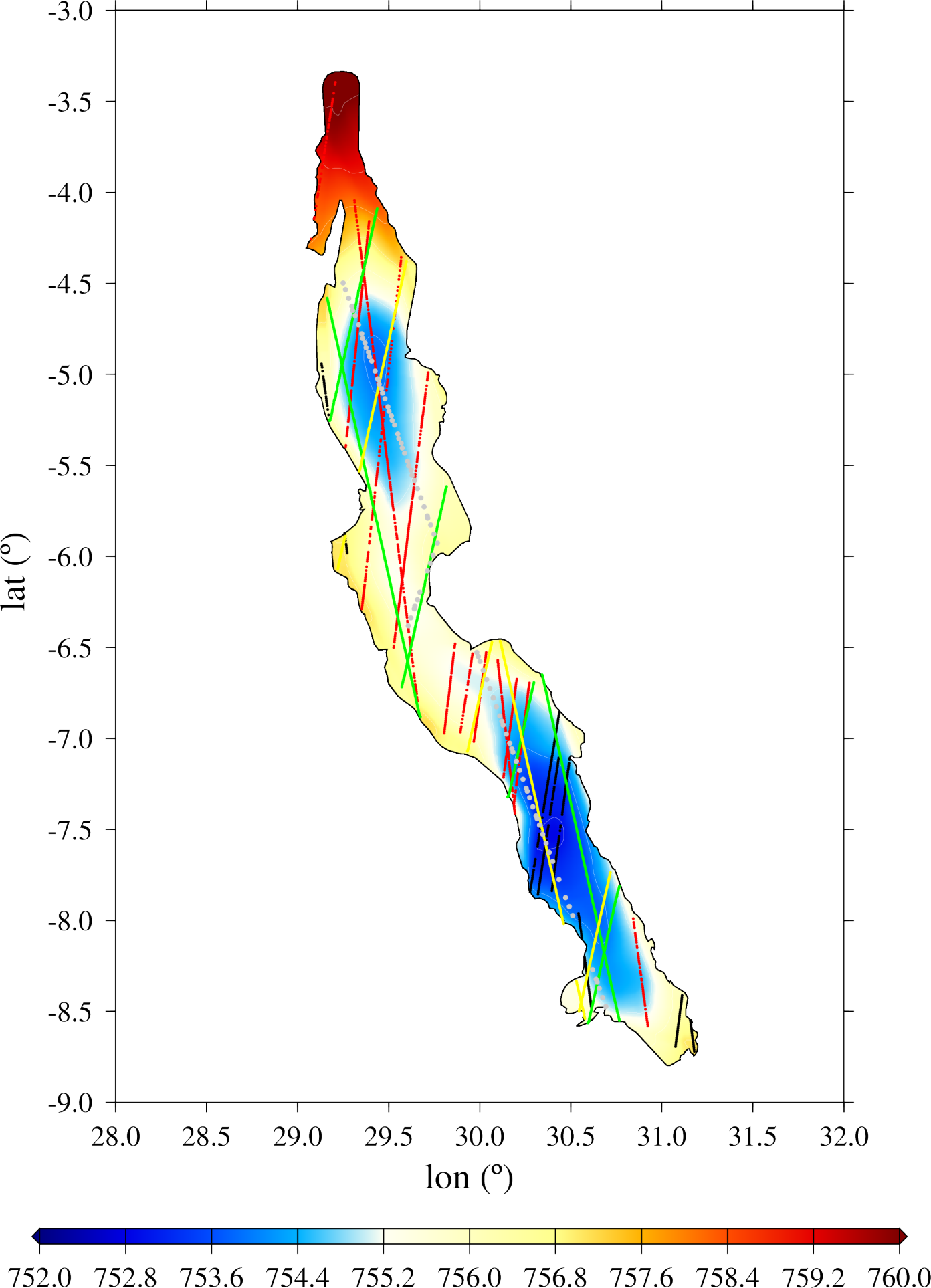


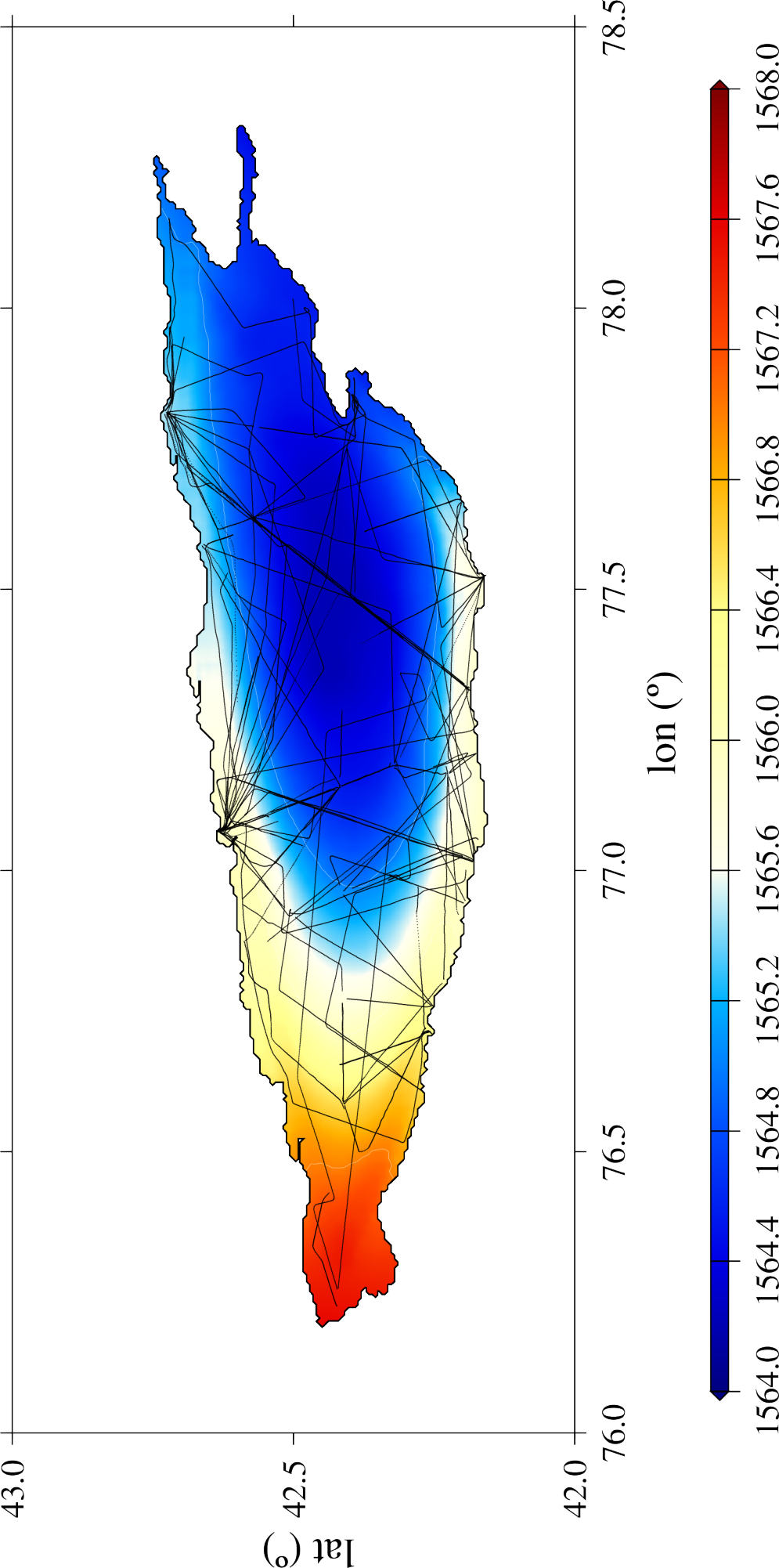


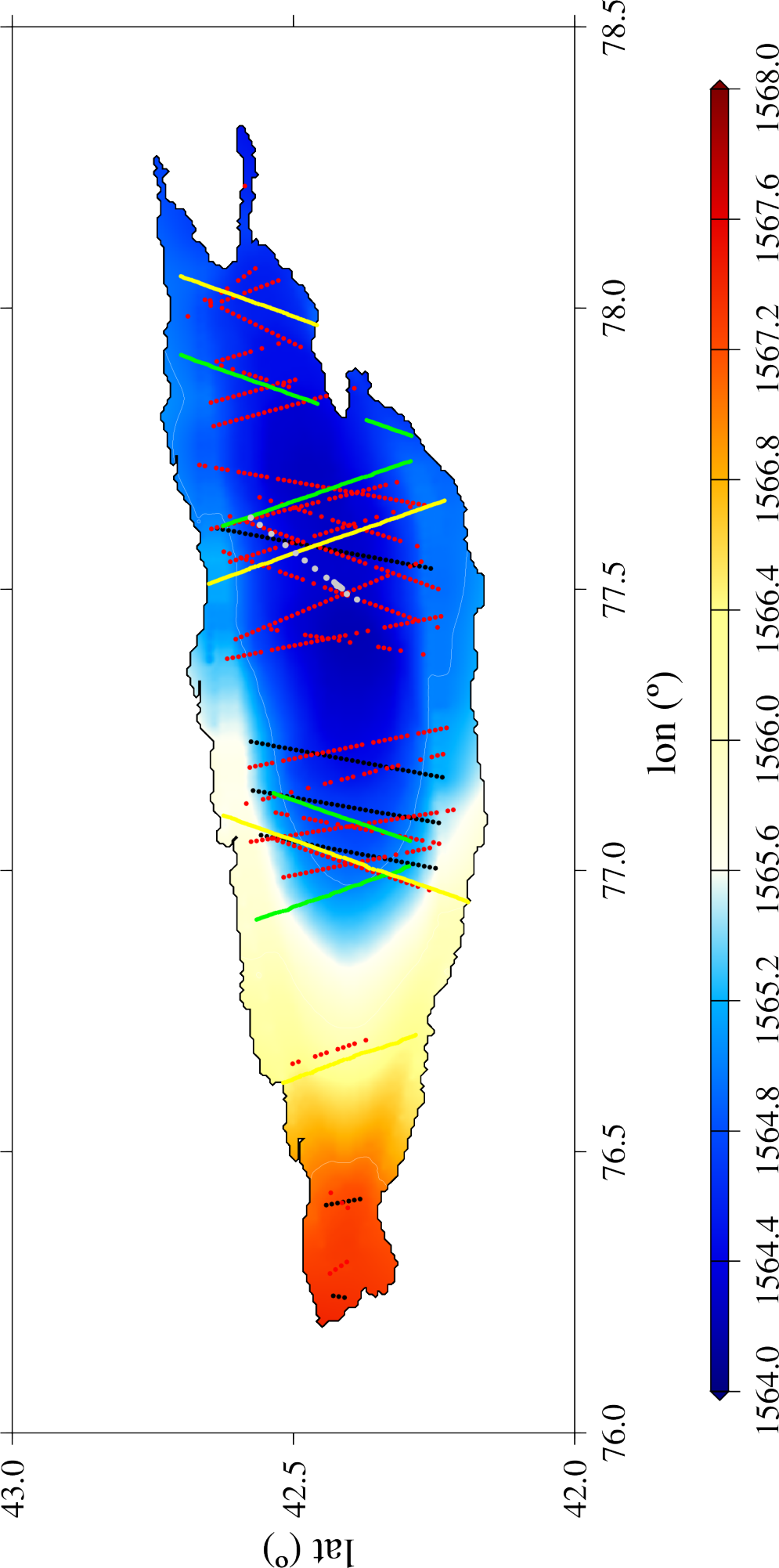


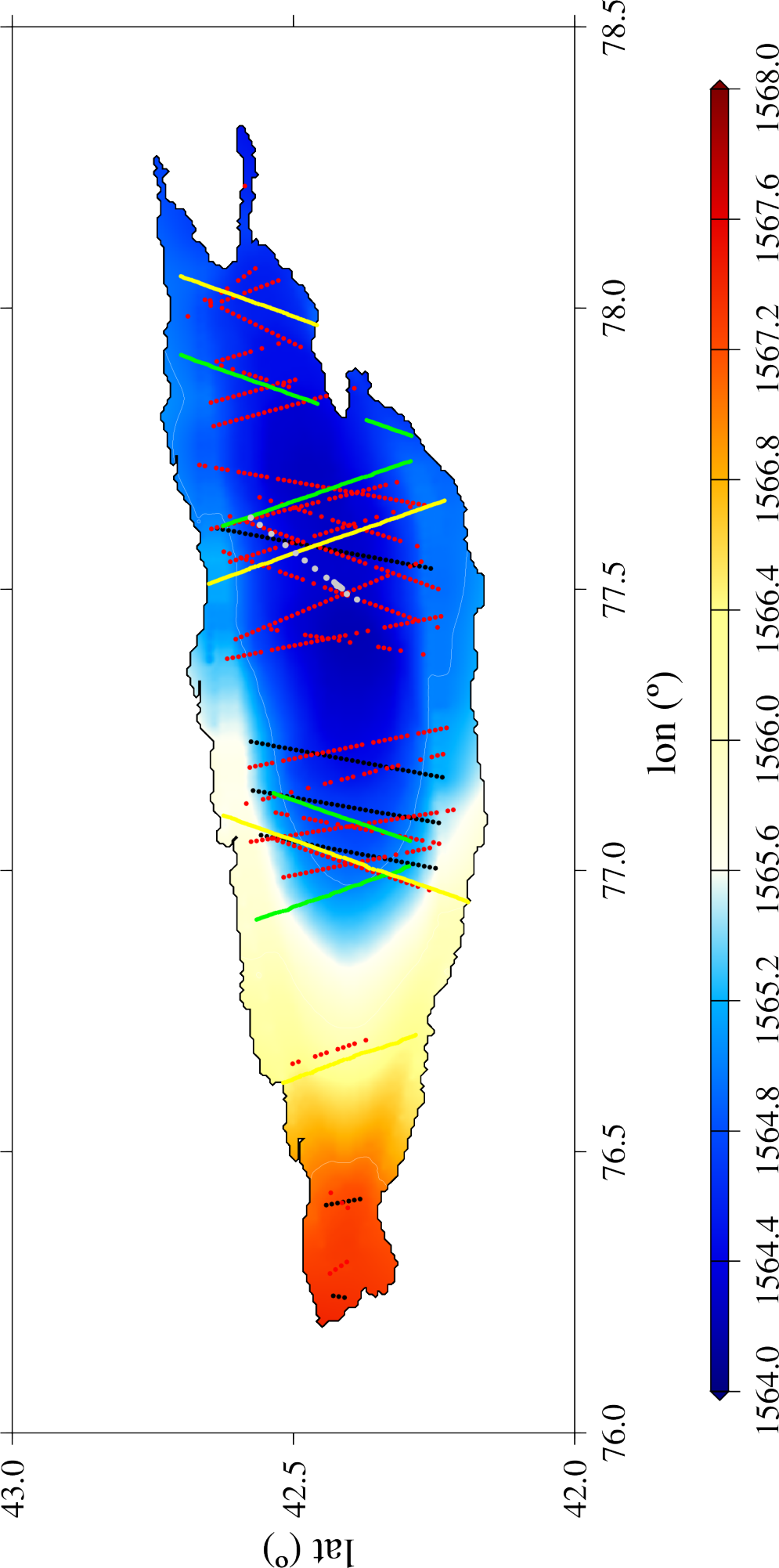
Lake Issykkul

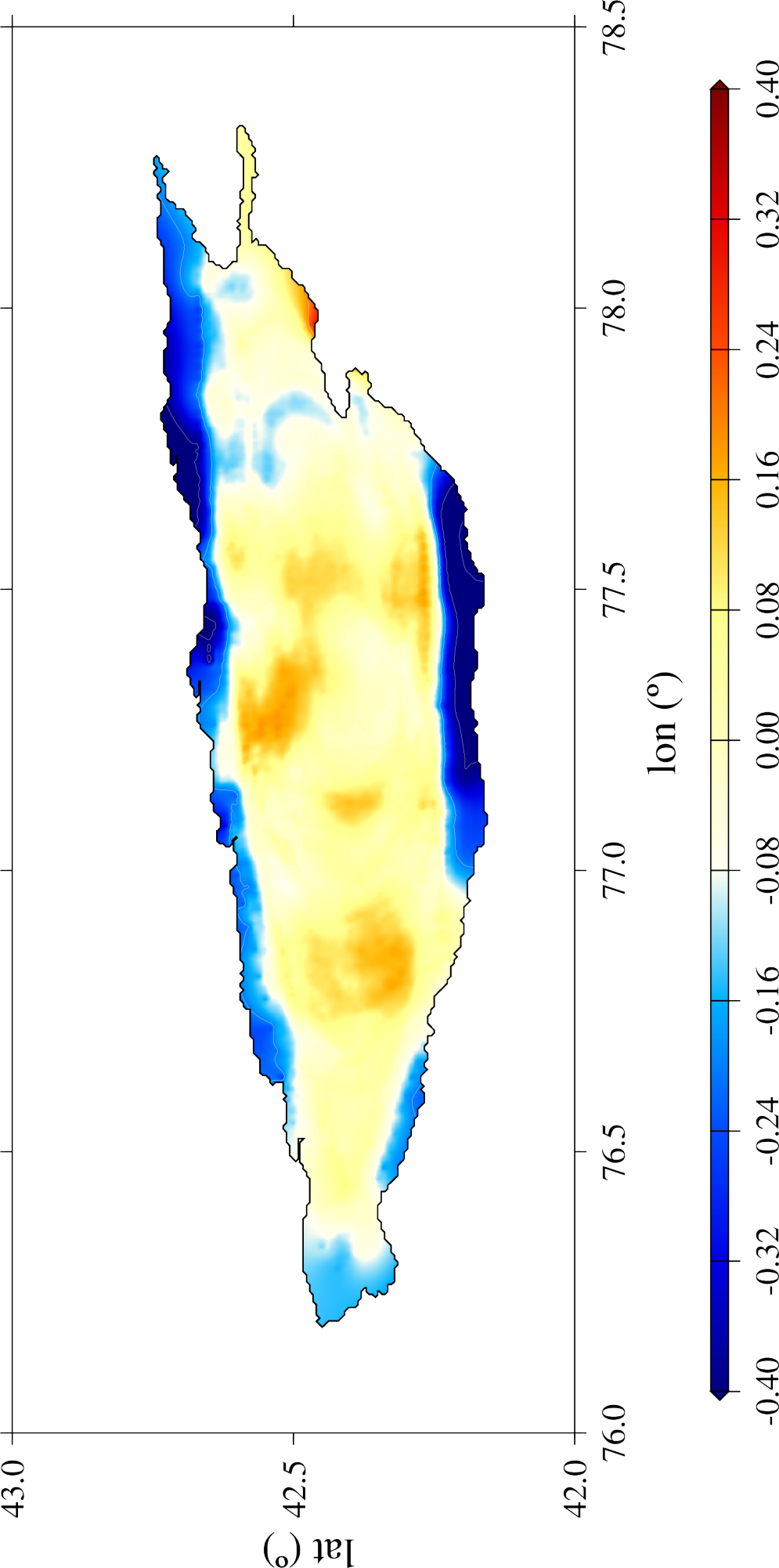


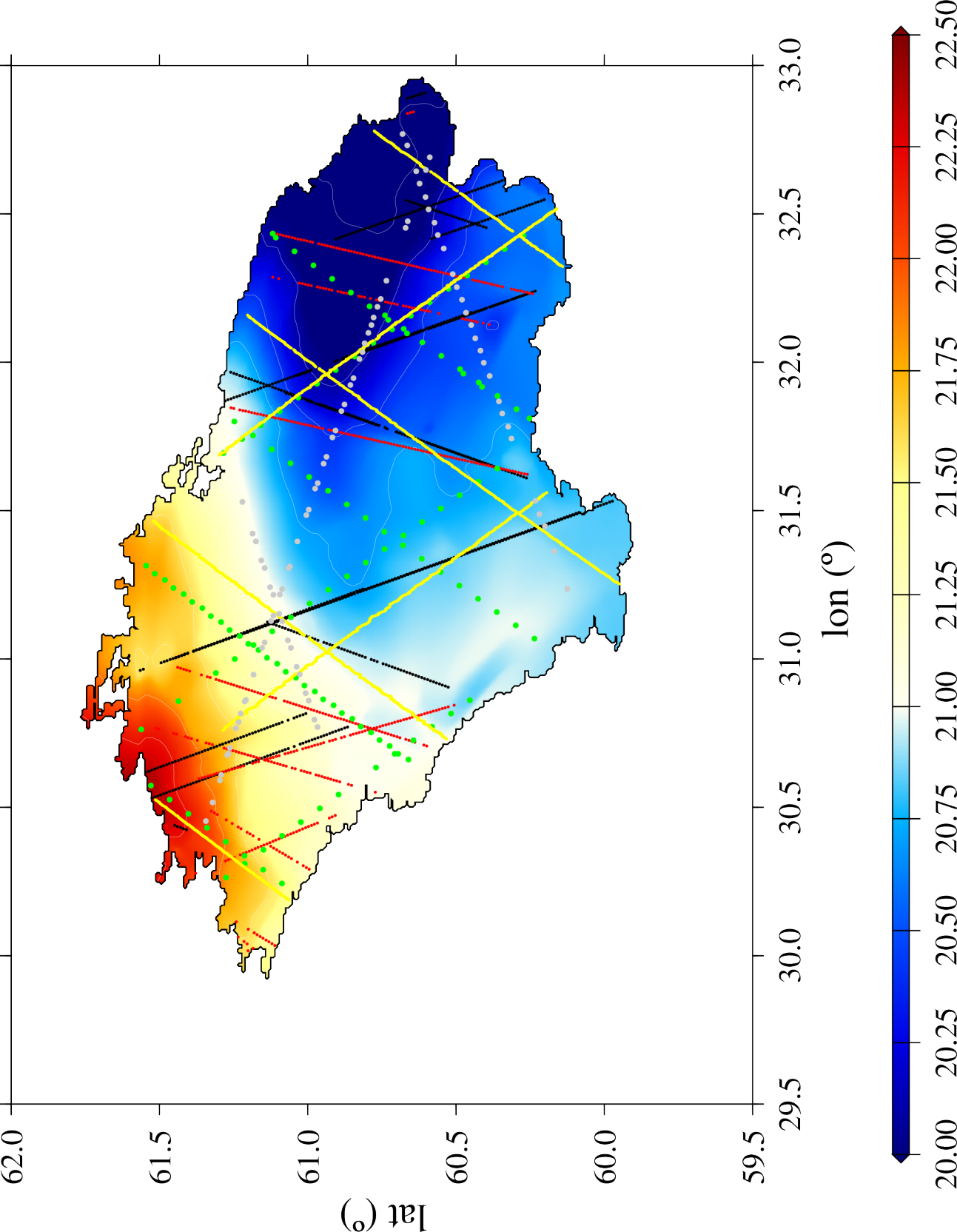


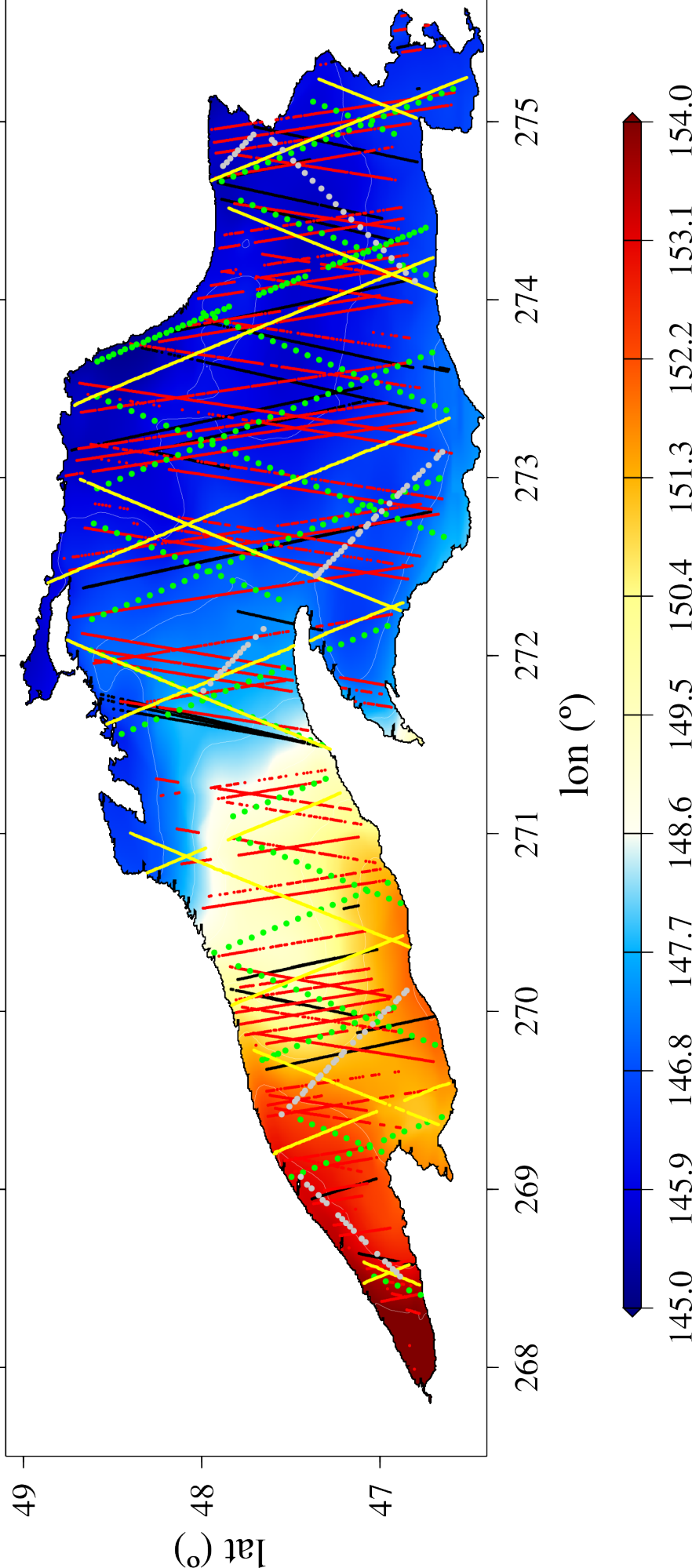


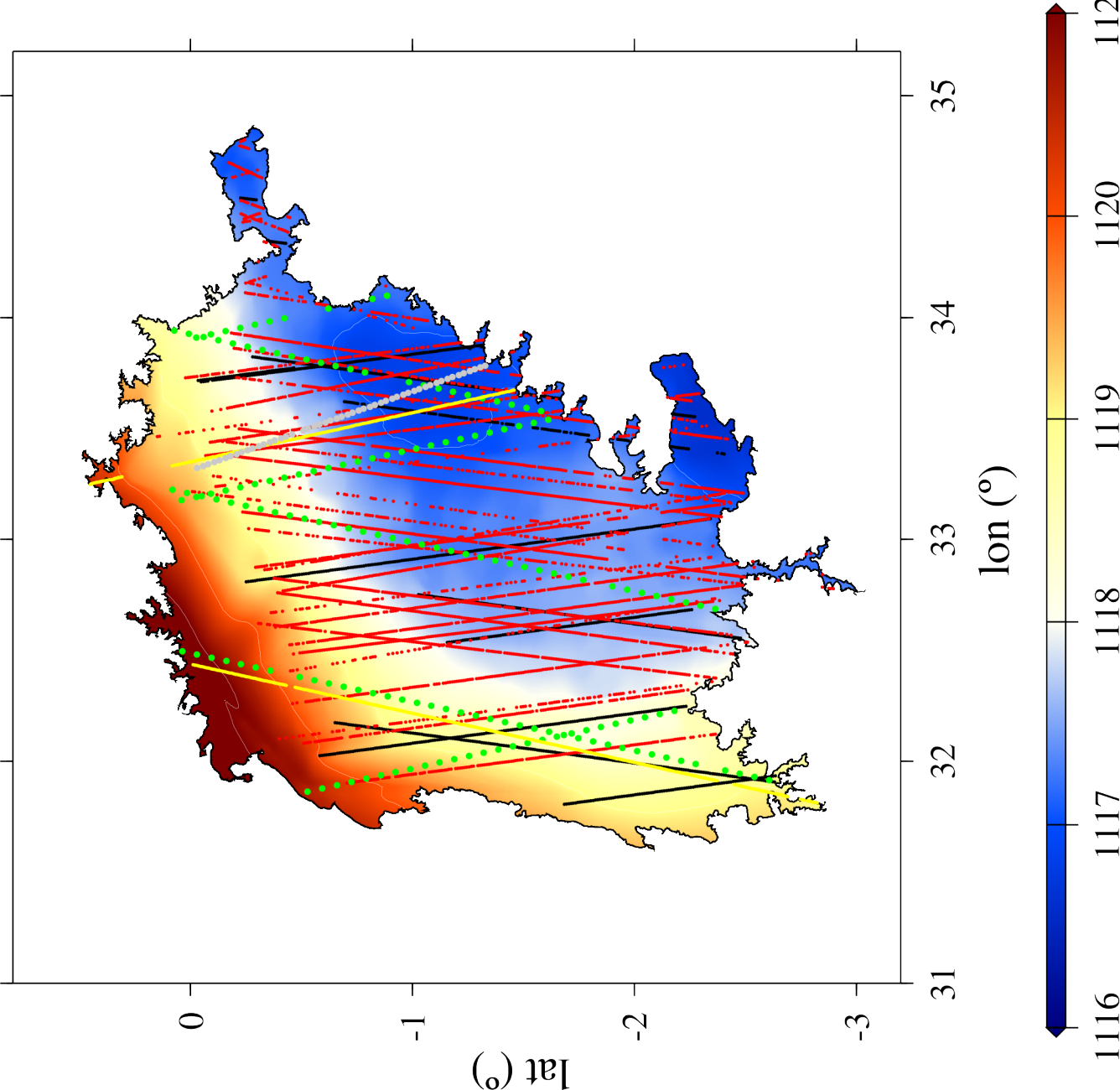


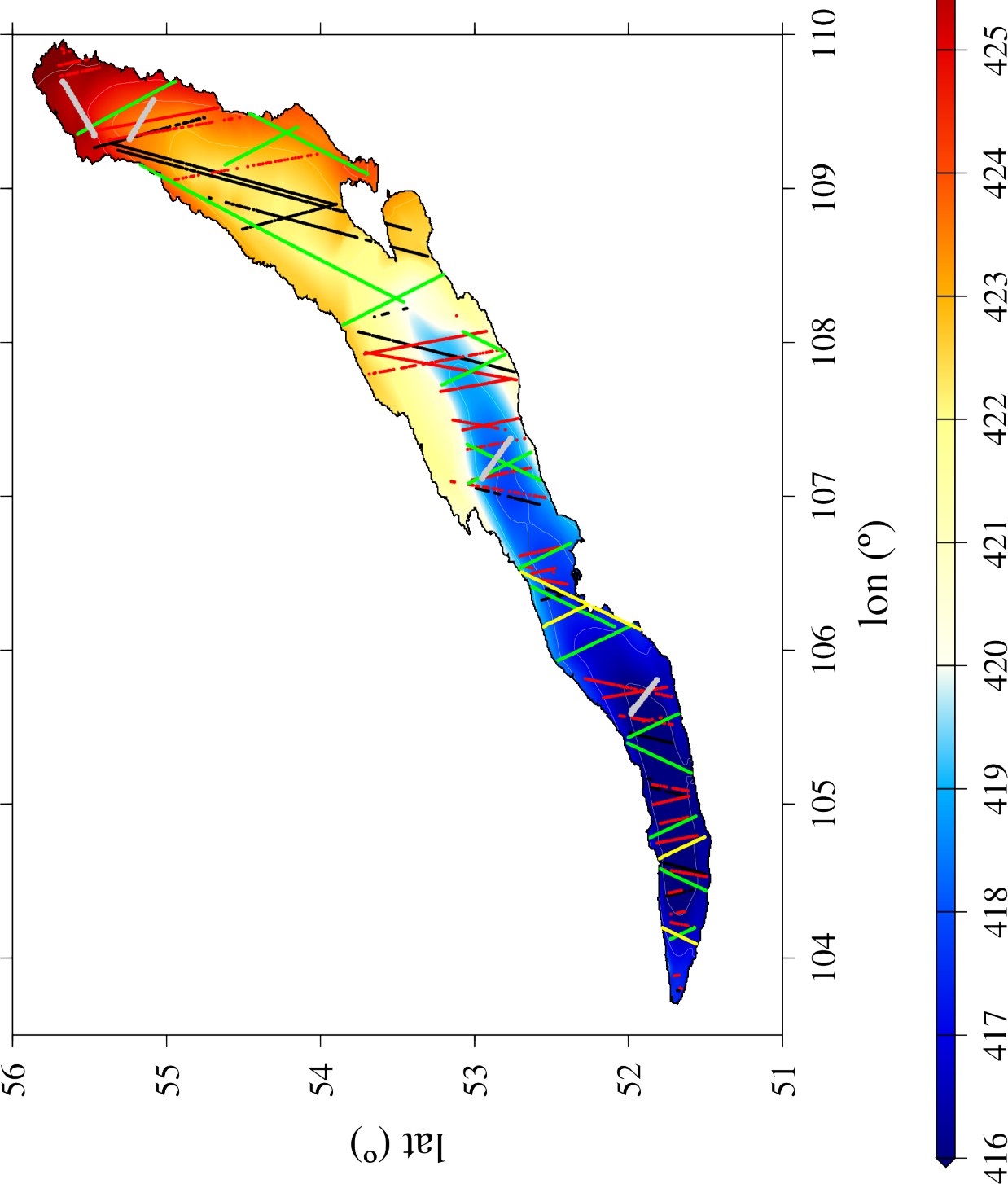


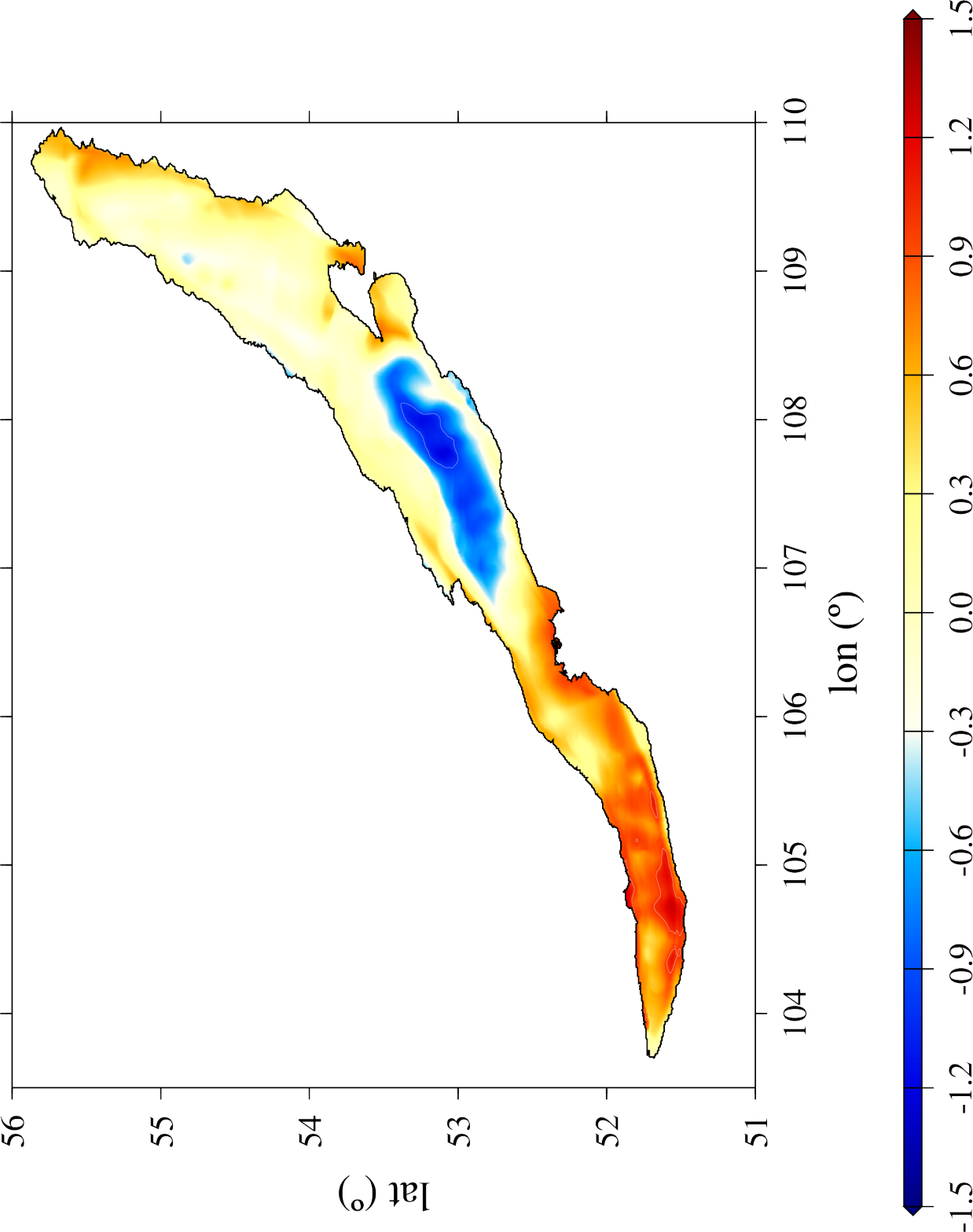


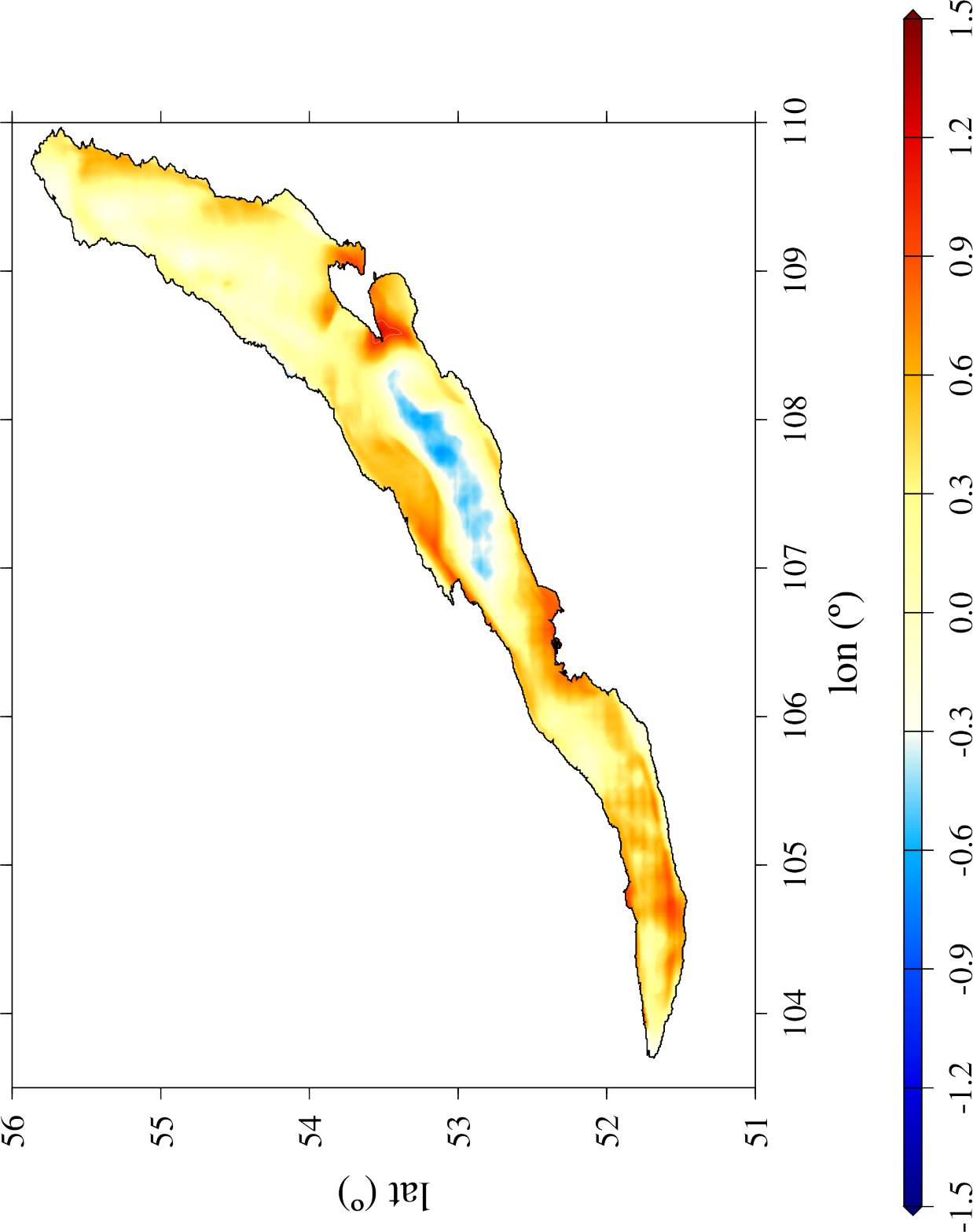


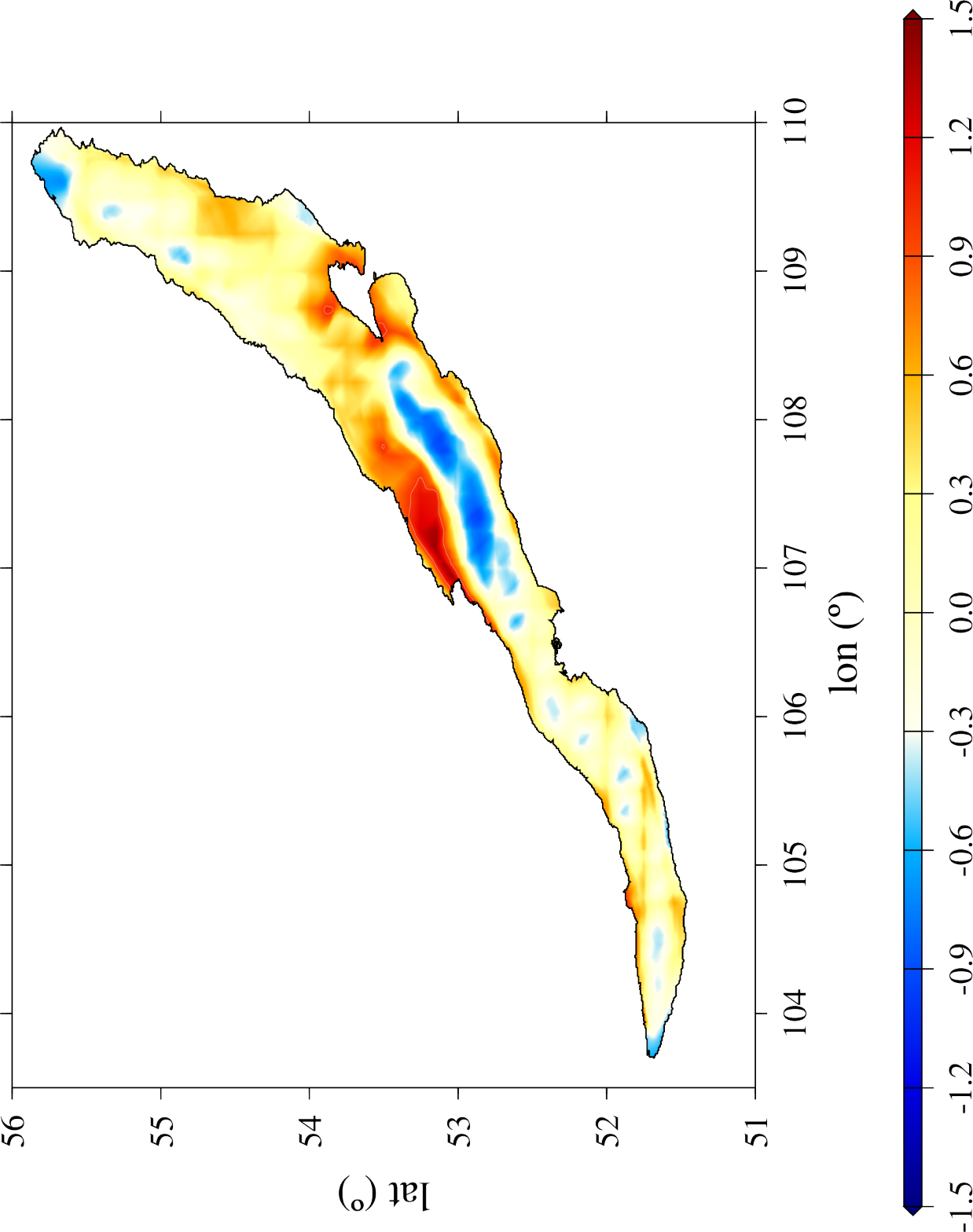


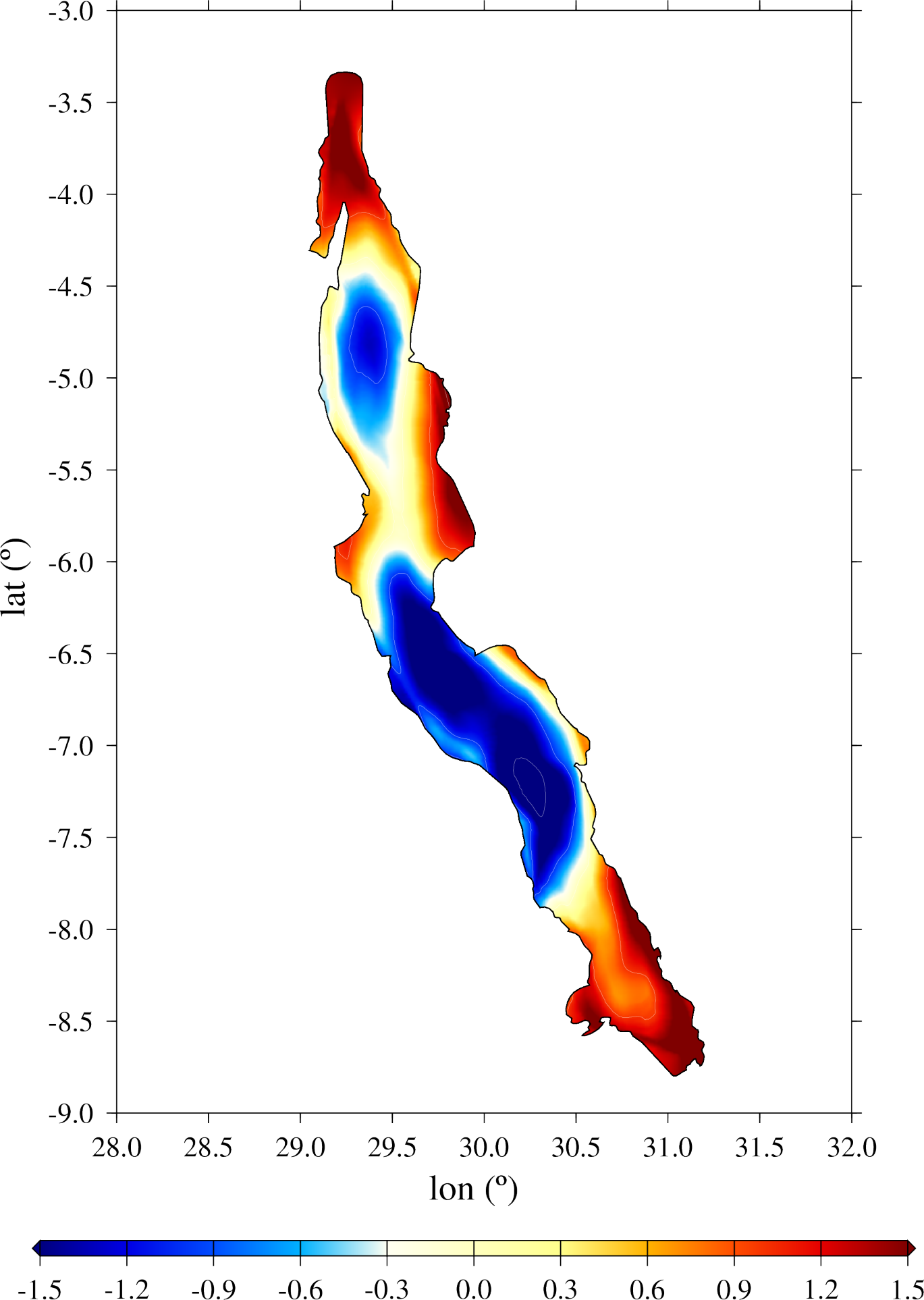


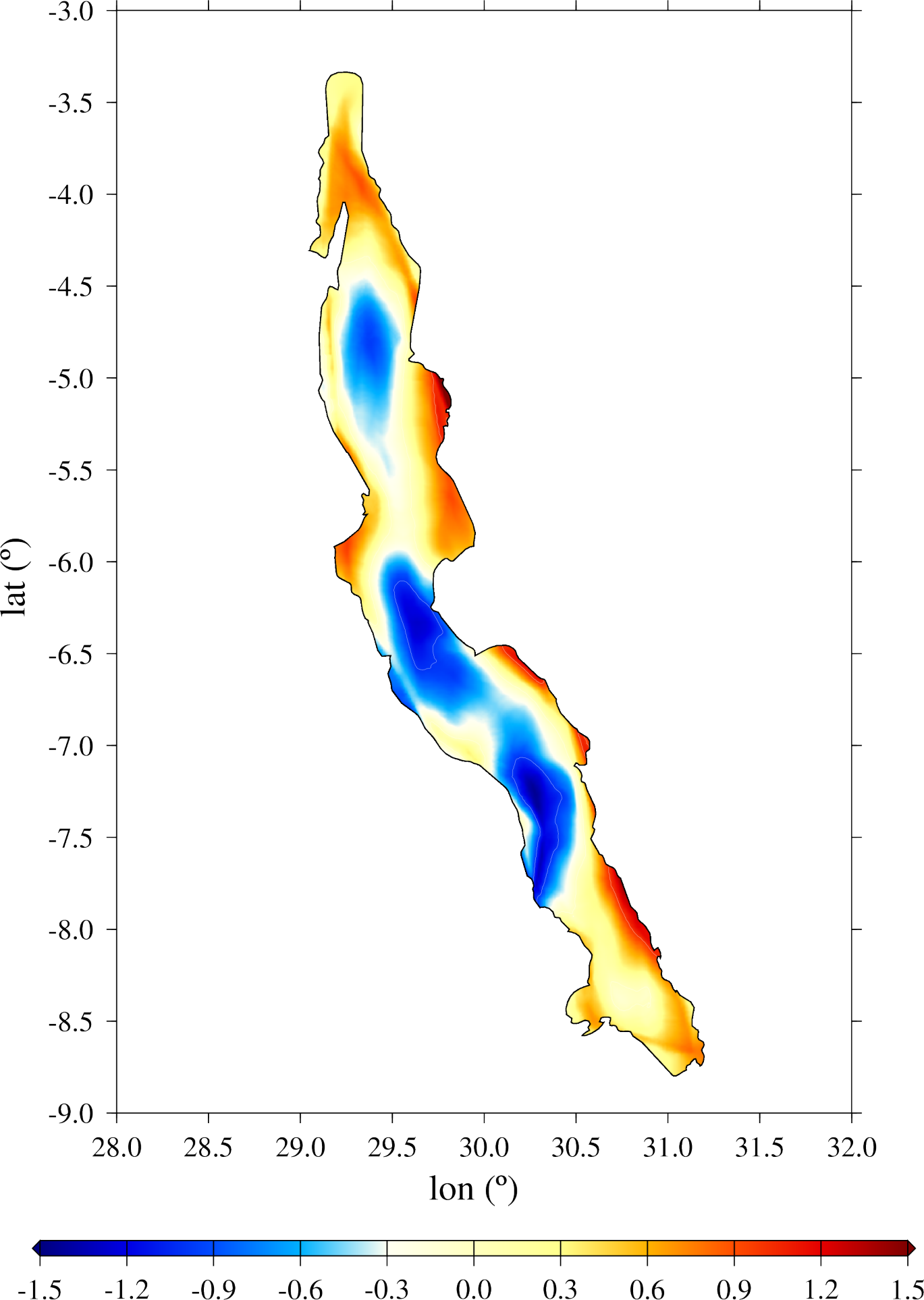


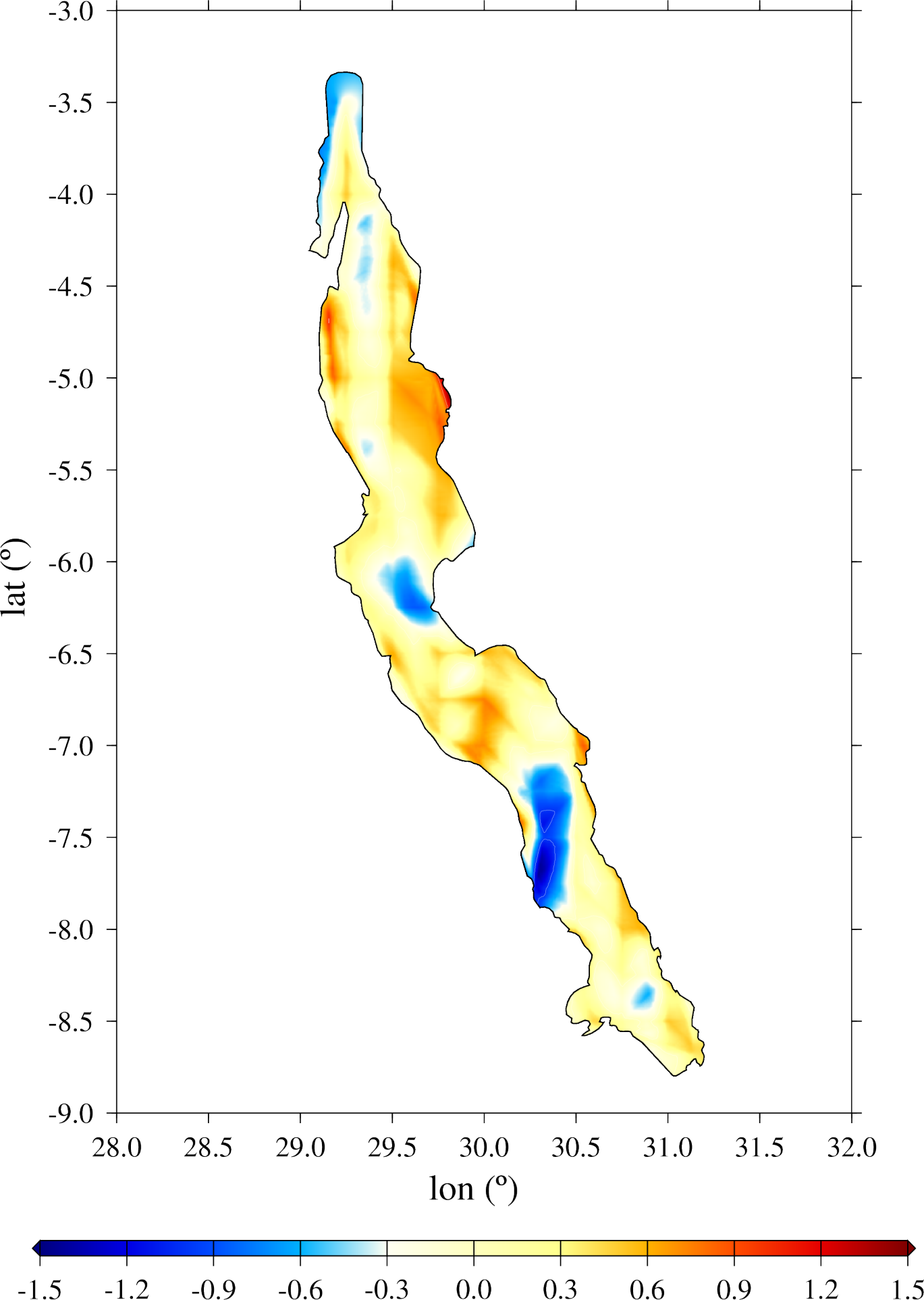


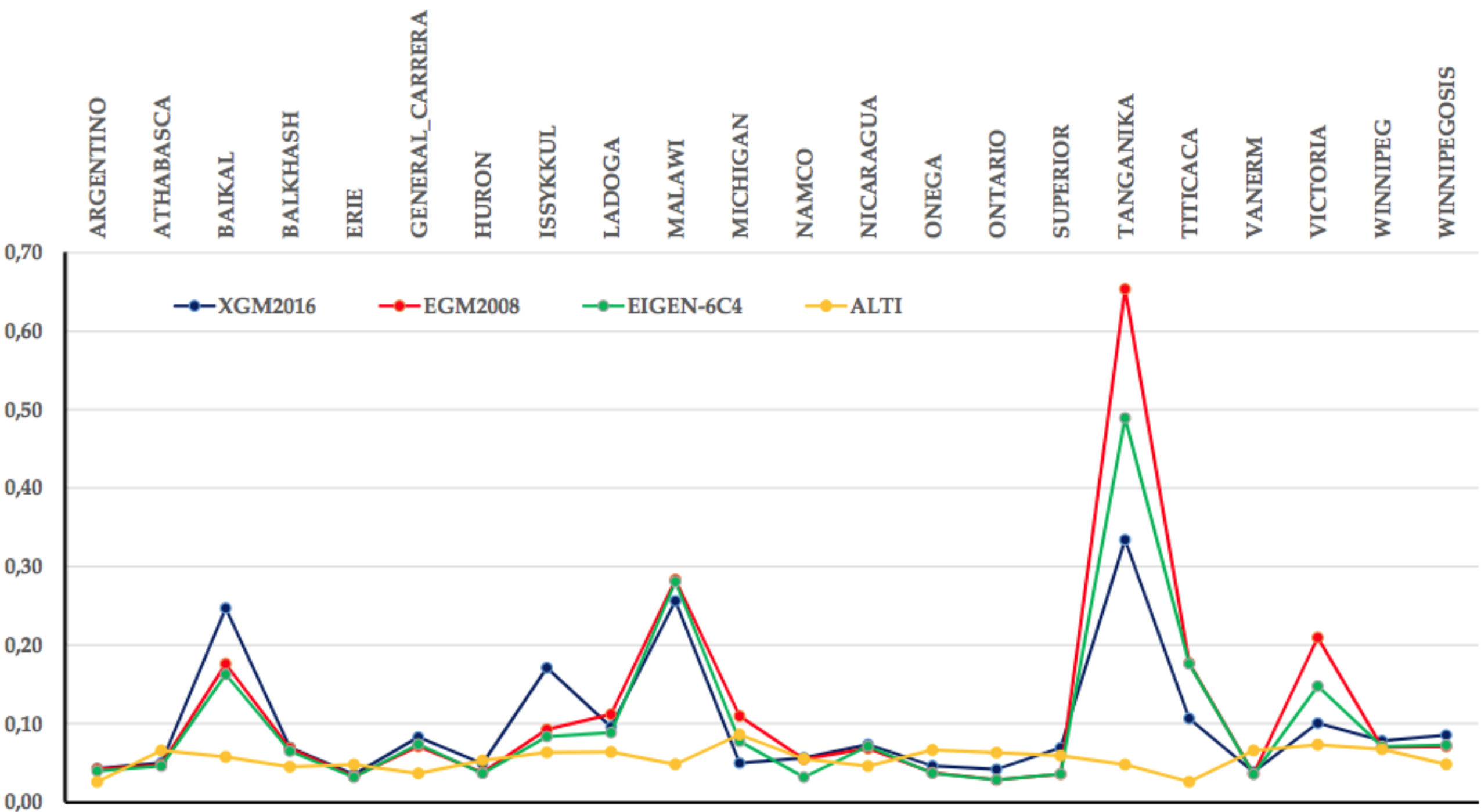












ICESAT, Track 14

