

# A new satellite-derived glacier inventory for Western Alaska

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## ABSTRACT

Glacier inventories provide the baseline data to perform climate change impact assessment on a regional scale in a consistent and spatially representative manner. In particular, a more accurate calculation of the current and future contribution to global sea-level rise from heavily glacierized regions such as Alaska is a major demand in this regard. Here we present a new glacier inventory for a large part of Western Alaska (incl. Kenai Peninsula, Tordrillo, Chigmit and Chugach Mts.) as derived from nine Landsat TM scenes by using well established automated glacier mapping techniques (band ratio). Because many glaciers are covered by optically thick debris or volcanic ash and partly calve into water, outlines were manually edited during post-processing. The scenes were acquired between 2005 and 2009 and cover c. 8830 glaciers ( $>0.02 \text{ km}^2$ ) with a total area of c.  $16,250 \text{ km}^2$ . Also in this region large parts of the area (47%) are covered by only few (31) but large ( $>100 \text{ km}^2$ ) glaciers, while glaciers  $<1 \text{ km}^2$  contribute only 7.5% to the total area, but 86% to the total number of analysed glaciers. We found a strong dependence of mean glacier elevation on distance from the ocean and only a weak one on aspect sector. Glacier area changes were calculated for a subset of 347 glaciers by comparison with the Digital Line Graph outlines from USGS. The overall shrinkage was 23% between the 1948-1957 and the 2005-2009 epochs.

## 1. INTRODUCTION

In context of global warming, glaciers located in Alaska have shown, like in almost every region around the world, a strong retreat since their Little Ice Age maximum extent with a more pronounced acceleration during the last decades of the twentieth century (WGMS, 2008). To better understand and model the glacier response to climate change, global inventories in a digital format are required (e.g. Beedle and others, 2008; Radić and Hock, 2010). In the case of Alaska, the most important purpose of an inventory is a better quantification of the glacier melt contribution to global sea-level rise (e.g. Kaser and others, 2006; Berthier and others, 2010) as well as the modeling of future changes in the water resources (Zhang and others, 2007).

As a part of the ESA project GlobGlacier (Paul and others, 2009), this study focuses on the generation of accurate glacier inventory data from the Landsat TM and ETM+ satellites (acquired between 2002 and 2009) for a region with poor coverage (from the Chugach to the Chigmit Mts.) in both the World Glacier Inventory (WGMS, 1989) and the Global Land Ice Measurements from Space (GLIMS) glacier database (Raup and others, 2007). In a previous study, Manley (2008) also stressed the importance to put some effort in creating a glacier inventory from former data compiled by the USGS in the 1950's for the Eastern part of the Alaska Range. We have thus decided to use the digitally available version of these former glacier outlines survey to assess mean decadal changes in glacier size for a subset of selected glaciers. The complete dataset will be available through the GLIMS website ([www.glims.org](http://www.glims.org)).

## 2. STUDY REGION AND INPUT DATA

### 2.1 Study region

The region under consideration for this study is situated around the Gulf of Alaska (Fig. 1) with glaciers ranging in altitude from sea level up to 4000 m a.s.l. For the purpose of a more regionalized assessment of glacier inventory data, the region has been divided into seven sub-regions ((1) Tordrillo, (2) Chigmit, (3) Fourpeaked Mts., (4 and 5) South and North Kenai Mts., (6) Chugach and (7) Talkeetna Mts.) . While the Tordrillo Mts. are situated on the Southern part of the Alaska Range, the Chigmit and Fourpeak Mts. are also considered to belong to the Aleutian Range and extend right on the South of Tordrillo Mts. to the Kamishak Bay. There are several thousand glaciers in these mountain ranges ranging from numerous small cirque glaciers to large valley glaciers with multiple basins (Denton, and Field, 1975). Several of them are classified as surge type glaciers like the Hayes or the Harpoon Glaciers and some represent glaciers covering volcanoes like for example the Crater Glacier on Mt Spurr (3,374 m).

The Kenai Mts. are located on the Kenai Peninsula in the Southern part of Alaska between the Cook Inlet and the Gulf of Alaska. The maximum elevation of glaciers here is 2,000 m a.s.l. and the three main ice masses are the Sargent, the Harding and an unnamed icecap. The part of the Chugach Mts. considered here is bounded on the East by the Cooper River and on the West by the Knik Arm. Together, these mountain ranges contain about one-third of the glacierized areas of Alaska (Post and Meier, 1980). Many large glaciers are of tidewater type and drain into the Northern Prince William Sound like the Harvard, Yale, Columbia, Shoup and Valdez glaciers. In the West, until 1966 Knik glacier dammed the outflow from the Lake Georges, resulting in annual glacier-outburst floods (Post and Mayo, 1971). The Talkeetna Mts. are the final region surveyed in this study. They are located North of the Matanuska River in the North of Chugach Mountains. Many peaks are higher than 2,000 m with a maximum of 2,550 m. As the entire study region includes glaciers of all types (e.g. valley, mountain, cirque, icecap, calving) with highly variable elevation ranges and glaciers located from the coast to the interior of the land, different climatic regimes and responses to climate change can be expected.

In general, the study region experiences a predominant maritime climate close to the coast and a more continental climate further away from it (e.g. <http://climate.gi.alaska.edu>). In the maritime region, mountain ranges act as a barrier for the Westerlies resulting in high amounts of annual precipitation along the coast of the Gulf of Alaska and frequent cloud cover. Both clouds and frequent seasonal snow fields considerably decreased the number of appropriate satellite scenes in this region so that the inventory data finally refer to a five-year period.

*Fig. 1*

### 2.2 Input data

We analyzed all Landsat scenes from 1999 to 2009 that are freely available in the [glovis.usgs.gov](http://glovis.usgs.gov) archive and processed to the standard terrain correction (Level 1T). We finally selected ten of them covering our study region (see Fig. 1). In Table 1 all scenes are listed with path-row and date identification.

Scene B (ETM+ from 2002) was processed in the beginning of the study though it had considerable amounts of seasonal snow hiding several glacier boundaries. When two scenes from 2009 (A and C) with much better snow condition became available we decided to use these for the inventory of the Chugach Mts.

For Western Alaska Range (scenes 72-17) we finally combined two scenes. The scene from 2005 (I)

had much better snow condition (in particular in the accumulation region), but the lower part of most low lying glacier tongues were barely visible due to a dense layer of fog and/or smog from fire. The lower glacier parts were hence derived from the 2007 scene (J), to a large part by manual digitization of the debris-covered tongues.

### *Table 1*

To calculate topographic glaciers parameters (e.g. minimum, mean and maximum elevation, mean slope and mean aspect) and to perform hydrological analysis (watersheds) for the determination of drainage divides to separate contiguous ice masses into individual glaciers (e.g. Bolch and others, 2010; Schiefer and others, 2008), a digital elevation model (DEM) is required. For the study region we have used the ASTER GDEM and the USGS National Elevation Dataset (NED), both with a spatial resolution of 30 m, and for a part of the region (south of 60° N) the SRTM C-Band DEM with resolutions of 1" (~30 m, SRTM-1) and 3" (~90 m, SRTM-3). The SRTM DEM is known for its good accuracy with a mean deviation from a reference data set of about  $3 \pm 15$  m (Berry and others, 2007). However, the accuracy is worse in the rough terrain of high mountains with typical problems of SAR derived DEMs (radar shadow, layover, foreshortening), which cause data voids. We thus use the seamless SRTM DEM from CGIAR, Vers. 4 where these voids were filled with additional elevation information (<http://srtm.csi.cgiar.org>). A comparative study between the SRTM-1 and the NED data in the US revealed slightly higher accuracy of the SRTM-1 DEM both in horizontal and in vertical direction (Smith and Sandwell, 2003).

The GDEM can be of good accuracy (Hayakawa and others, 2008) but has inaccuracies mainly in regions of steep slopes and snow due to low contrast (Frey and Paul, *subm.*) and contains artificial bumps, pits (local depressions) and holes which are typically for ASTER derived DEMs (Kääb and others, 2002; Toutin, 2008). Due to its northern limitation (60° N), the SRTM DEM was available only for the southern part of the Kenai Peninsula while the NED and the GDEM cover the entire region. Several tiles of both DEMs were downloaded, mosaiced and re-projected to UTM Zone 5 and bilinearly interpolated to 30 m cell size. Hillshades were created for all three DEMs to better recognize artifacts. While the NED refers to the contour lines of the related topographic maps from the 1950s, the GDEM was created from all available scenes in the ASTER archive acquired between 1999 and 2007. Hence, the topography in the GDEM does much better fit to the acquisition period of the Landsat data (Table 1) and was therefore used to calculate minimum glacier elevation.

The Digital Line Graph (DLG) dataset was utilized to calculate changes in glacier size (see 3.4). This former glacier mapping has been compiled by the USGS from the 1:63,360-scale 15-minute topographic quadrangle maps. For glacier identification we used the digital topographic maps (Digital Raster Graph) from the USGS that were created from vertical aerial photographs (1948-1957) by stereo-photogrammetric techniques, the Geographic Names Information Service (GNIS) which is also available in a digital format (<http://geonames.usgs.gov/>), the Alaska Atlas and Gazetteer book, and the recently published Alaska volume (1386-F) of the Satellite Image Atlas of Glaciers of the World (Williams and Ferrigno, 2008) from USGS.

### 3. METHODS

#### 3.1 Glacier mapping

While mapping an individual glacier or a small region with several glaciers can be done manually, this is hardly feasible for a large region like Western Alaska encompassing several thousand glaciers. The glacier mapping technique used in this work is the well-established semi-automatic band ratio method (TM3/TM5) with manual threshold selection (e.g. Paul and Kääb, 2005). This method is based on the specific spectral reflectance properties of snow and ice compared to other terrain. While reflectance of glacier ice and snow in band TM3 (red) is comparably high (with possible sensor saturation over fresh snow), it is very low in band TM5 (shortwave infrared, SWIR). These spectral differences make the ratio TM3/TM5 very efficient to discriminate glaciers from other terrain. Further advantages of the technique are the efficiency in mapping glaciers in cast shadow, its reproducibility and consistency for an entire region, as well as its accuracy for clean to slightly dirty glacier ice (e.g. Albert, 2002; Paul, 2002; Andreassen and others, 2008). However, manual corrections are still needed in particular for debris-covered ice, calving glacier termini and water surfaces. By applying an additional threshold in band TM1 (blue), the classification in cast shadow is much improved (Paul, and Kääb, 2005). Before outlines are edited, a noise filter is applied to remove isolated snow patches and to close gaps. The classified map is then converted in vector format and imported by the GIS software. In a post-processing step, the necessary corrections for clouds, shadow, debris cover, and water bodies are applied. To facilitate the interpretation, false color composite images (e.g. with bands 543 as RGB) are used in the background. Higher spatial resolution data (e.g. aerial photographs, Google Earth) are also utilized for interpretation of selected glaciers when they are available. In Fig. 2 we visualize the automatically derived and the corrected glacier outlines for a subset of the Chugach Mts. region. Some critical regions (e.g. debris-cover or water surfaces) are highlighted by circles. All steps of the processing were performed with standard software for image processing and a geographic information system (GIS) for post-processing.

*Fig. 2*

#### 3.2 DEM comparison

To find the most suitable DEM for calculation of drainage divides, we compared the performance of all four DEMs with each other. In all DEMs the sinks were removed and they were smoothed with a 3 by 3 median filter to minimize the effect of possible outliers. The resulting drainage divides are very similar for distinct mountain ridges, although the coarser resolution of the SRTM-3 DEM is recognizable (Fig. 3). Some differences can be observed in the flat terrain of the accumulation areas. The divides derived by SRTM seem to be more realistic when visually comparing them with the satellite data. Larger deviations of the basins as calculated from the GDEM can be attributed to unnatural peaks and sinks which commonly occur in the GDEM. However, in most cases the ice divides did not vary significantly in the accumulation regions and all DEMs are suitable for the intended task. We have finally chosen the NED DEM because it covered the whole study region and performed slightly better than the GDEM.

#### 3.3 Drainage divides

One of the main outcomes of a glacier inventory is a comprehensive set of parameters for each glacier entity (Paul and others, 2009). A DEM allows us to create the required drainage divides to clip the contiguous ice masses into individual glaciers (e.g. Manley, 2008). We here apply the approach by Bolch and others (2010) to calculate the divides from the USGS NED DEM. For this purpose, a 1 km buffer is created around all glaciers to constrain the hydrological calculations to this buffer. As this

method generates a high number of artificial and very small polygons in the ablation area, these are selected with a spatial query tool and removed. In a second step, visual inspection was used to further improve the result, especially in the accumulation area where anomalies in the DEM often introduce errors (e.g. Svoboda and Paul, 2009; Frey and Paul, *subm.*). A hillshade raster, a flow direction grid, topographic maps and false color composites are also used to manually correct the basins. After intersection of the drainage divides with the glacier outlines, topographic glacier inventory parameters were calculated for each glacier entity following Paul and others (2009) from the NED DEM and in the case of minimum elevation from the GDEM.

*Fig. 3*

### 3.4 Change assessment

To use the glacier outlines from the Digital Line Graph for calculation of size changes, we first adjusted the drainage divides created for the glacier inventory to the DLG outlines and then used it to separate the contiguous ice masses. We then manually selected a subset of 347 glaciers suitable to assess area changes that occurred in the seven sub-regions. For this subset, the glaciers in both datasets must be clearly identifiable, which is often not the case (see 5.2). Because the large glaciers are often calving (in lakes) or are of tidewater type, the resulting selection contains mostly “smaller” glaciers, with the largest one being 68 km<sup>2</sup> in size. The dates of individual glaciers to which the DLG outlines refer to were obtained from Berthier and others (2010) for most of them or directly from the USGS 1:63,000 topographic maps.

## 4. RESULTS

### 4.1 Glacier inventory data

The glacier inventory of Western Alaska includes 8827 glaciers larger than 0.02 km<sup>2</sup> and covers a total area of 16.250 km<sup>2</sup> (Table 2). While the 31 (0,4%) glaciers larger than 100 km<sup>2</sup> account for 47% of the total area, the 7627 glaciers (86%) <1 km<sup>2</sup> account for only 7.5% of the area. These percentages vary with the specific mountain range analysed, but the general picture is rather similar in all regions. The strong contrast in the number and size contribution is visualized for the Chugach Mts. in Fig. 4. The largest glaciers are also located in this region, but some are found in the Kenai Peninsula and the Tordrillo Mts. (Table 3). This table also provides selected parameters from the inventory for the ten largest glaciers. Three of these huge glaciers are land terminating while seven are calving into lakes or the ocean. In Table 4 the number and area covered for the seven sub-regions is listed along with the mean size in each region. While four regions have an ice cover between 1900 and 2700 km<sup>2</sup>, the Chugach Mountain region has nearly 6500 km<sup>2</sup> and two have an ice covered area close to 340 km<sup>2</sup> (Fourpeaked Mountain and Talkeetna Mountains). On the other hand, the mean size of the glaciers in each region is rather similar for five regions (from 1.1 to 1.8 km<sup>2</sup>) and only slightly larger for South Kenai Peninsula and Chugach Mountains (2.3 and 2.6 km<sup>2</sup>). This indicates that a region with comparably large glaciers is always accompanied by a proportionally higher number of small glaciers.

*Table 2-4*

*Fig. 4*

In Fig. 5 the area-elevation distribution for the seven sub-regions in 100 m binning is shown. While most of the ice (84%) is located between 600 and 2000 m of altitude, the glaciers in the Chugach Mts. have an elevation range from sea-level to almost 4000 m. The much higher mean elevation of the glaciers in the more continental regions Tordrillo and Talkeetna is clearly visible. The different curves do thus also reflect the disparity in the topo-climatic conditions.

*Fig. 5*

The spatial analysis of mean glacier elevation (that can be used as a proxy for the steady-state ELA, (e.g. Braithwaite and Raper, 2009)) revealed a strong increase from glaciers close to the coast towards the interior of the country from about 100 to 3000 m a.s.l. (Fig. 6). To give this visual interpretation more weight, we have defined an arbitrary point in the Gulf of Alaska and calculated the distance of each glacier to this point. A linear regression yields a high correlation ( $R^2 = 0.9059$ ) between this distance (from 100 to 500 km) and the mean elevation (from 1000 m to nearly 2000 m). This regional trend has of course a high local variability, indicating that changes in temperature and/or precipitation will affect each glacier differently. We have also analysed the variation of mean elevation with aspect sector for each sub-region (Fig 7). Apart from the already described increase of mean elevation with distance from the coast, the graph reveals only a small variability with aspect sector (in the mean) in each region indicating no dependency on this factor. This suggests that the precipitation regime has a much higher influence on mean elevation than radiation receipts.

*Fig. 6*

*Fig. 7*

## 4.2 Glacier changes

In Fig. 8 the relative change in glacier area per decade versus glacier size is illustrated for the subsample of 347 glaciers. As for several other regions where such analysis has been performed, a large variability of the changes is found with an increase in scatter and an increasing relative area loss towards the smallest glaciers. All glaciers in this subsample lost area, in total, the loss represents about 23% of the initial area (1948 -1957) which is in good agreement with the changes found by Barrand and Sharp (2010) for Yukon glaciers.

*Fig. 8*

## 5. DISCUSSION

### 5.1 Glacier inventory data

Due to the importance of glaciers in Alaska for global sea-level rise (e.g. Kaser and others, 2006), most of the recent studies on glacier change in Alaska focus on changes in glacier volume, either for selected glaciers (e.g. Arendt and others, 2006; Muskett and others, 2009) or entire mountain ranges (e.g. VanLooy and others, 2006; Berthier and others, 2010). Several of these studies lack the possibility to exclude certain types of glaciers (e.g. calving or surging) from the analysis to better assess the impact of climate change on mass balance, as outlines of individual glaciers in this region have not been available so far. Moreover, the study of Kaser and others (2006) highlighted the importance of determining the mass balance for an entire mountain range from the direct measurements of a few selected and often comparably small glaciers. This is indeed only possible when the representativeness of the measurements for the entire region is clear (e.g. Fountain and others, 2009; Paul and

Haeberli, 2008). With the here presented new glacier inventory for a larger part of western Alaska, we think that the research issues mentioned above can be addressed adequately in the future. The topographic parameters calculated for each glacier from a DEM might also facilitate large-scale modeling applications (e.g. Raper and Braithwaite, 2005).

Though we had preferred to have all satellite scenes used for the inventory acquired within one (at best) or a few years, we decided to use only the scenes with the best snow conditions (Table 1) to minimize the workload and error for manual corrections due to seasonal snow. In the resulting five-year period some glaciers like Columbia have shown considerable changes in their extent, but as we know for each glacier outline the exact date of acquisition, a proper reference for change assessment is provided nevertheless. As mention above, in the case of the eastern part of the Chugach Mountains, we have first processed the Landsat ETM+ scene from 2002, but later two scenes from 2009 with much better snow conditions became available. As a simple update of the previously mapped extent by digital combination of the 2002 and 2009 outlines was not practical, we completely re-processed the outlines for this region.

Apart from some small glaciers under heavy debris-cover or with an unclear transition to creeping permafrost bodies, the manual correction of the outlines was straightforward. However, we are aware that the manually corrected outlines of individual (in particular small) glaciers might have large errors, but we are rather sure that for about 95% of all glaciers the accuracy of the outlines is better than 3% and will thus meet GCOS requirements (IGOS, 2007). In several cases we might have included perennial snow fields in the inventory as no bare ice was visible on the satellite images, but this is a common problem (e.g. DeBeer and Sharp, 2009; Paul and Andreassen, 2009) and these elements can be marked in the attribute table (Paul and others, 2009).

From the observed count and size distribution in each sub-region we conclude that the application of automated glacier mapping techniques is highly preferable over manual digitization; on the one hand to cover the entire sample of glaciers in a region within a short period of time and on the other hand to reduce the workload and create a consistent and reproducible data set. The strong dependence of glacier mean elevation on distance from an arbitrarily chosen point in the ocean is very promising for establishing simple parameterizations of either ELA or precipitation in high mountain regions. There is virtually no influence of mean glacier aspect sector on mean elevation within a mountain range (Fig. 7), so unlike in other regions the influence of global radiation on this parameter is strongly reduced (Evans, 2006). We assume that this observation can be explained with the influence of the high annual precipitation amounts on glacier location as well as with the multi-basin origin of many glaciers which often cause differences between the mean aspect of the entire glacier compare to the ablation region.

## 5.2 Area changes

The calculation of area changes is based on a manually selected sample of 347 glaciers as we found several ambiguities between the DLG outlines and our new inventory (Fig. 9). The example in this figure shows that the DLG outlines do in some cases not match to the glacier covered area on the topographic maps, which implies that they must have been updated somehow. Apart from normal retreat with separation of tributaries, we see glaciers that have been mapped in the DLG but not in our inventory (and vice versa in other regions). This could mean that (a) the glacier has disappeared, (b) we failed to map the glacier due to complete debris cover, or (c) that in the DLG seasonal snow was mapped. Hence, despite the changes are clearly visible, the outlines of the DLG are rarely usable for automatic change assessment. But also for the manual selection performed here, the error bounds are likely large as cartographers and glaciologists can have different perceptions on what a glacier is and the 'truth' can be a matter of debate, even in the field. For the manual selection these cases have been

excluded so that our estimate of the relative area loss is probably a lower bound. In a future study we will try to assess changes in glacier length or area also from a comparison with earlier Landsat images.

*Fig. 9*

## **6. CONCLUSIONS**

In this contribution we presented a new satellite-derived glacier inventory of Western Alaska that is finally based on nine scenes from Landsat TM acquired between 2005 and 2009. This five years period is required due to frequent clouds and seasonal snow on most scenes in the USGS archive. The mapped 8,827 glaciers larger than 0.02 km<sup>2</sup> cover an area of 16,250 km<sup>2</sup> with only few of them (31) are larger than 100 km<sup>2</sup> and most glaciers (86% by number) smaller than 1 km<sup>2</sup>. We found a strong relationship between glacier mean elevation and the distance from the ocean, which corroborates with a decreasing amount of precipitation toward the interior country.

We used the band ratio method (TM3/TM5) with a threshold to automatically map all glaciers in the region. The needed corrections for misclassified lakes or water bodies and the omitted debris-covered parts of glaciers were manually edited. Drainage divides derived from the national DEM (NED) allowed us to obtain individual glacier entities and topographic inventory parameters. Because of strong changes in the ablation zones, the parameter minimum elevation was calculated from the more recent ASTER GDEM. For a selection of 347 glaciers we found an overall recession of 23% (by area) between the 1948-1957 (DLG) and 2005-2009 (Landsat) epochs. Due to several omission or commission errors between the two data sets, a more detailed analysis of the DLG data is required before it can be used for further change analyses. In forthcoming studies, we will use the here derived glacier inventory data set for assessment of glacier specific changes.

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## Tables

Table 1. List of the Landsat scenes used in the glacier inventory of Western Alaska. (source: <http://glovis.usgs.gov>). See Fig. 1 for location of footprints.

| <b>Id</b> | <b>Type</b>    | <b>Path</b> | <b>Row</b> | <b>Date</b> |
|-----------|----------------|-------------|------------|-------------|
| <b>A</b>  | Landsat 5 TM   | 66          | 17         | 06.09.2009  |
| <b>B</b>  | Landsat 7 ETM+ | 67          | 17         | 01.08.2002  |
| <b>C</b>  | Landsat 5 TM   | 68          | 17         | 03.08.2009  |
| <b>D</b>  | Landsat 5 TM   | 68          | 18         | 12.09.2006  |
| <b>E</b>  | Landsat 5 TM   | 69          | 18         | 09.07.2009  |
| <b>F</b>  | Landsat 5 TM   | 70          | 17         | 28.08.2007  |
| <b>G</b>  | Landsat 5 TM   | 70          | 18         | 28.08.2007  |
| <b>H</b>  | Landsat 5 TM   | 71          | 19         | 14.09.2005  |
| <b>I</b>  | Landsat 5 TM   | 72          | 17         | 20.08.2005  |
| <b>J</b>  | Landsat 5 TM   | 72          | 17         | 26.08.2007  |

Table 2. Summary of glacier count and area value per size class for the entire dataset.

| <b>Size Class</b>         | <b>Count</b> | <b>Percent</b> | <b>Area (km<sup>2</sup>)</b> | <b>Percent</b> |
|---------------------------|--------------|----------------|------------------------------|----------------|
| < 0.1 km <sup>2</sup>     | 4701         | 53.3           | 211.12                       | 1.3            |
| 0.1 - 0.5 km <sup>2</sup> | 2240         | 25.4           | 520.13                       | 3.2            |
| 0.5 - 1 km <sup>2</sup>   | 686          | 7.8            | 487.72                       | 3.0            |
| 1 - 5 km <sup>2</sup>     | 856          | 9.7            | 1874.02                      | 11.5           |
| 5 - 10 km <sup>2</sup>    | 132          | 1.5            | 875.99                       | 5.4            |
| 10 - 50 km <sup>2</sup>   | 160          | 1.8            | 3236.03                      | 19.9           |
| 50 - 100 km <sup>2</sup>  | 21           | 0.2            | 1444.01                      | 8.9            |
| > 100 km <sup>2</sup>     | 31           | 0.4            | 7601.08                      | 46.8           |
| <b>Total</b>              | <b>8827</b>  | <b>100.0</b>   | <b>16250.1</b>               | <b>100.0</b>   |

Table 3. The ten largest glaciers in the study region (sorted by size) with some topographic parameters.

| <b>#</b> | <b>Glacier name</b> | <b>Sub-region</b>     | <b>Area [km<sup>2</sup>]</b> | <b>Date</b> | <b>Mean elevation</b> | <b>Mean slope</b> | <b>Mean aspect</b> |
|----------|---------------------|-----------------------|------------------------------|-------------|-----------------------|-------------------|--------------------|
| 1        | Columbia Glacier    | Chugach Mts           | 945.371                      | 2009        | 1426.26               | 10.4286           | 279.80414          |
| 2        | Harvard Glacier     | Chugach Mts           | 528.167                      | 2009        | 1821.25               | 18.8855           | 290.25292          |
| 3        | Knik Glacier        | Chugach Mts           | 441.485                      | 2009        | 1599.36               | 8.79849           | 1.52134            |
| 4        | Chenega Glacier     | North Kenai Peninsula | 392.243                      | 2006        | 1004.71               | 7.35956           | 94.12848           |
| 5        | Tazlina Glacier     | Chugach Mts           | 384.654                      | 2009        | 1509.81               | 6.32898           | 23.75717           |
| 6        | Nelchina Glacier    | Chugach Mts           | 337.6                        | 2009        | 1780.85               | 9.69825           | 30.53897           |
| 7        | Tustumena Glacier   | South Kenai Peninsula | 336.514                      | 2006        | 1201.76               | 5.30722           | 10.35724           |
| 8        | Triumvirate Glacier | Tordrillo Mts         | 333.226                      | 2007        | 1532.59               | 11.1837           | 147.63535          |
| 9        | Matanuska Glacier   | Chugach Mts           | 319.072                      | 2009        | 1961.16               | 11.9711           | 29.40691           |
| 10       | Blockade Glacier    | Chugach Mts           | 256.018                      | 2007        | 1291.24               | 8.20193           | 86.35861           |

Table 4. Summarize of glacier value per sub-regions. Region names come from the Alaska Atlas and Gazetteer book (DeLORME edition).

| Region ID | Region name           | Count | Area [km <sup>2</sup> ] | Mean size [km <sup>2</sup> ] |
|-----------|-----------------------|-------|-------------------------|------------------------------|
| 1         | Tordrillo Mountains   | 1672  | 1998.4                  | 1.2                          |
| 2         | Chigmit Mountains     | 1971  | 2778.0                  | 1.4                          |
| 3         | Fourpeaked Mountain   | 280   | 329.4                   | 1.2                          |
| 4         | South Kenai Peninsula | 1051  | 2408.3                  | 2.3                          |
| 5         | North Kenai Peninsula | 1079  | 1900.9                  | 1.8                          |
| 6         | Chugach Mountains     | 2466  | 6491.8                  | 2.6                          |
| 7         | Talkeetna Mountains   | 308   | 343.1                   | 1.1                          |

## Figure captions

Fig. 1. Location map showing the footprint of the ten Landsat scenes analyzed for this study (red squares, where the red letters refer to the scenes IDs). The sub-regions are delimited by dashed squares with the numbers referring to the IDs (see Tables 1 and 3) and glaciers are in light blue. The location of the study region is shown in the inset.

Fig. 2. Raw classification result from the algorithm (black) and appended manual corrections (yellow) for a small region in the Chugach Mts (scene A). Circles denote examples for misclassification of water bodies and non-classification of the debris-cover glaciers. A false-color composite (bands 432 as RGB) of Landsat scene is displayed in the background.

Fig. 3. Comparison of drainage divides derived from the four different DEMs where the background is a shaded relief from the USGS NED.

Fig 4. Color-coded illustration of the glacier size distribution in the Chugach Mts. Thick lines represent the basins.

Fig. 5. Glacier area-elevation distribution (hypsoigraphy) for the seven sub-regions (see Fig. 1 for location) in 100 m binning.

Fig. 6. Spatial variability of mean elevation for glaciers larger than 5 km<sup>2</sup> over the entire study region. Glaciers are in light grey and in the background is a shaded relief from the USGS NED.

Fig. 7. Mean value of the mean elevation per aspect sector for each sub-region.

Fig 8. Scatter plot of glacier shrinkage in percent per decade as a function of initial glacier area (1951-1957).

Fig 9. Illustration of glacier recession in the Valdez district (south of Chugach Mts). Thick black lines show the DLG glacier outlines and light grey shading represent the new glacier inventory within the DLG extent while the dark grey shading depict the new glacier inventory outside the DLG extent. An example of the DRG (sheet # c61144a1) is displayed in the background.