MOD44W: Global MODIS water maps user guide

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    a. Carroll, M. L., DiMiceli, C.M., Townshend, J.R.G., Sohlberg, R.A., Elders, A.I., Devadiga, S., Sayer, A.M., & Levy, R.C. 2016. "Development of an operational land water mask for MODIS Collection 6, and influence on downstream data

products." *International Journal of Digital Earth*, **10 (2):** 207-218 [10.1080/17538947.2016.1232756]

Introduction

In the past decade significant advances have been made in the characterization and quantification of water on the surface of the Earth (Carroll et al. 2009; Feng et al. 2015; Klein et al. 2015; Pekel et al. 2016; Salomon et al. 2004; Verpoorter et al. 2012). The human imprint on the extent of surface water is apparent in the construction of dams to create reservoirs, the diversion of river water for agriculture resulting in the desiccation of the Aral Sea, and changes in surface water extent due to our changing climate. Since the initial development of MOD44W in 2009, MODIS data have been used to monitor flooding (Ahamed and Bolten 2017; Policelli et al. 2016) and surface water change (Carroll et al. 2011b; Klein et al. 2015; Pekel et al. 2014; Sun et al. 2011). With the MODIS data record exceeding 17 years it was determined that updating MOD44W from circa 2000 to current would be a valuable contribution to the global remote sensing world. MODIS data have continually been collected from daily observations of Earth, with a binary classification (each observation labeled as land, water, or undetermined) stored in the intermediate 16-day composite maintained at the University of Maryland for the MODIS Vegetation Continuous Fields product (Carroll et al. 2011a; Carroll et al. 2009). Below we detail the updated methods and file formats for the new annual global MODIS surface water extent maps.

The original MOD44W collection 5 is the static dataset created from MODIS data 2000 – 2002 and the SRTM Water Body Dataset. This dataset was updated with bathymetry data to differentiate ocean from inland water as well as deep inland water (such as Laurentian Great Lakes), coarsened to 500 m spatial resolution, and provided to the MODIS science team for use in collection 6 MODIS reprocessing. A detailed description of this "collection 6" dataset is given below. The original user guide is included as an appendix here for continuity in documentation.

MODIS surface reflectance data are not calculated for areas south of 60° south, hence no annual updates are possible for this region using the MOD44W inputs. The static MOD44W for this region was determined from the Mosaic of Antarctica (Scambos et al. 2007) and remains the best companion data to complete the global map of water for any year of MOD44W collection 6.

MOD44W Collection 6

The original methodology used the SRTM Water Body Dataset as a base, averaged up from 90 m to 250 m spatial resolution and gridded into the MODIS sinusoidal tile grid (Carroll et al. 2009). For collection 6, the original MOD44W collection 5 was used as the base and annual summaries of the water observations are created. Presence of water is determined daily, per pixel and accumulated in summary layers every 16 days for both Aqua and Terra. The algorithm for this was a decision tree classifier trained with MODIS data and was validated for the original MOD44W C5 (Carroll et al. 2009). From these 16-day summaries an annual summary was calculated based on the probability of water calculated from daily observations of water using equation 1:

$$P_w=((\Sigma O_w)/(\Sigma O_w+ \Sigma O_L)) \qquad 1$$

where P_w = probability of water; O_w = observations of water from daily classification; O_L = observations of land from daily classification. The probability of water is calculated for each year from 2000 to 2015. Pixels are considered water if $P_w \geq 50\%$. A series of masks are applied to address known issues caused by terrain shadow, burn scars, and cloudiness or ice cover in oceans. These masks are described in the following sections.

Terrain shadow mask

Terrain shadow is a significant issue in many areas of the world. For collection 5, a mask was created using slope, elevation and hand delineation of problem areas. For the current collection (C6) we endeavored to automate this process while still addressing terrain issues. The 7.5 arc second (nominally 250 m spatial resolution) Global Multi-resolution Terrain Elevation Data 2010 (GMTED) was used to calculate slope globally (Danielson and Gesch 2011). A threshold of 5° was implemented to identify potential terrain shadow areas, as this threshold has been found to be effective in previous studies (Carroll et al. 2016a; Klein et al. 2015). Slope derived from the 1 arc second SRTM DEM was used in areas of complex and very steep terrain with narrow water bodies such as British Columbia, Canada, and the Fjords of Scandinavia. This helped to resolve some terrain issues that remained after implementing the GMTED. To accomplish this, slope was calculated at 30 m spatial resolution (approximately 1 arc second) in the MODIS tile grid. This was aggregated to 250 m spatial resolution by selecting the median value to represent any given pixel. Median is used instead of average because it was found that a few high slope pixels could skew the average limiting the utility of this metric. From the median slope at 250 m spatial resolution a threshold of 5° was implemented to maintain consistency with the GMTED threshold used in other places. The slope derived from finer resolution SRTM was used to mask terrain shadow in problematic areas, as mentioned above.

Ocean mask

To derive the ocean mask for collection 6 we used the MOD44W C5 to define the boundaries of the continents. The coastline was buffered by 4 pixels (~1 km) into the water bodies. This buffered water was intersected with the ocean (all 3 ocean classes merged to one class) from MOD44WA1 to isolate ocean from inland water. This mask was applied to all annual collection 6 water maps to account for ocean water that is routinely obscured by clouds, ice, or other visual impediments. For pixels in which the ocean mask was applied, a QA value was set in the accompanying QA layer, described later in this text.

Burn scar

The MODIS burn scar product (MCD64A1) (Giglio 2015; Giglio et al. 2009) was used to create a mask of past burn scars which can, at times, be confused with water. The monthly burn scar product was combined to produce annual max extent of burn scars. Three of these masks were combined to produce a 3 year rolling max extent of burn scar after it was determined that burn scars, especially in northern latitudes, can still be confused with water for several years after the initial burn scar was detected. The MOD44W collection 5 water mask was applied to the burn scar maps to address the mismatch in resolution (burn scar is a 500 m product) and to avoid confusion in the burn product with known water. The annual burn mask was applied globally to the associated annual water map and a QA value was set to indicate where burn scars are located relative to water bodies.

Urban/impervious surface

As the spatial resolution of water masks has improved it has become apparent that urban shadowing and some urban building materials (i.e. asphalt roads and shingles) can sometimes be confused with water. This typically only occurs in centers of large cities with very tall buildings but nevertheless is a source of error. A global impervious surface map at 30 m spatial resolution (Brown de Colstoun et al. 2017) was employed to address this issue. This map was converted from UTM projection to MODIS sinusoidal and averaged up to 250 m spatial resolution. A threshold of 75% impervious was determined empirically and used to identify core areas of urban regions. This final mask was applied globally and a QA value was set to indicate where water values were converted to land based on this mask.

Static Small Water Bodies from MOD44W

During final evaluation of the annual products it was observed that a number of small water bodies (lakes and narrow rivers) that were represented in MOD44W C5 were not represented in any year of C6. Extensive evaluation using high resolution data through Google Earth demonstrated that the water bodies in question were valid but below detectable levels with the current method. These water bodies were then added back in to each year of C6 and a value "8" was set in the QA layer so that users can decide whether and how to use these water bodies.

Final output maps

The final maps are a binary (land = 0, water = 1, Fill = 250 (outside of projected area), No Data = 253) representation of the surface water on Earth for each year from 2000 through 2015. Each annual map has an associated per pixel quality assurance (QA) layer that provides the user with information on the determination of water. Below is a description of the values in the QA layer for collection 6

QA description

- 1 = high confidence observation
    - For high confidence observations no distinction is made in the QA between land or water because this is already described in the data layer
- 2 = lower confidence water
    - Few observations of water but MOD44W collection 5 indicated water; this helps maintain continuity of narrow rivers that were represented by the SWBD in MOD44W collection 5
- 3 = lower confidence land
    - Few observations of water or land
- 4 = ocean mask
    - Buffered out from coast by ~1 km (i.e. 4 pixels)
- 5 = ocean mask but no water observations recorded
    - Probable continuous sea ice, or land expansion through deltas or urban reclamation
- 6 = burned area
    - That would have been confused with water
- 7 = urban or impervious surface
    - Water detected but converted to land due to mask
- 8 = No water detected but MOD44W shows inland water

    - Mostly small lakes and some narrow parts of rivers. These were put back in after extensive evaluation for continuity with MOD44W C5
- 10 = Fill (outside of projected area)
- 253 = No data

The QA value of 8 can be used to back out areas that are labeled as permanent water if the user deems them erroneous for their application. These are areas that were labeled as water in MOD44W C5 probably because of the finer spatial resolution of the SWBD but they don't necessarily show up in "MODIS-only" maps because they are mixed water and land pixels. In most cases these are narrow rivers or narrow reaches of larger rivers, but can also show up on the edges of lakes.

Validation

The classification method was previously validated in Carroll et al. (2009). No additional validation is performed here.

Results and discussion

The primary improvement in MOD44W between collection 5 (C5) and collection 6 (C6) is the generation of a time series rather than a simple static representation of water. Water bodies fluctuate in size and location over time through both natural and anthropogenic influence. To evaluate the difference between the static C5 and annual C6 products we first converted the annual C6 into a single maximum extent over the 16 years. The resulting difference (figure 1) shows differences primarily on coastlines and areas with wetlands that have varying amounts of surface water each year depending on how much precipitation they receive. In most cases the difference is quite small, a few pixels, but large changes such as along the coast of Greenland and in Southeast Asia can be seen. Australia also stands out as they were in a prolonged drought in the early 2000's when MOD44W C5 was created and have seen more rain in the 2010's which filled shallow lakes again.

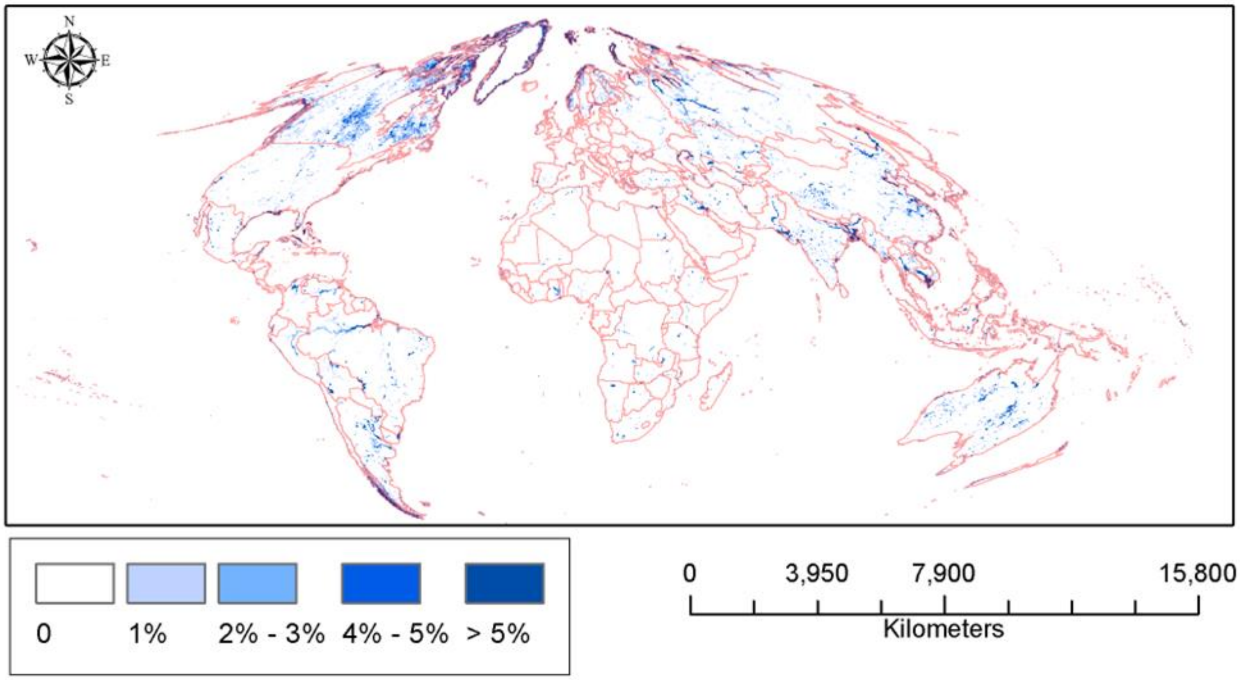

Figure 1 Global map showing the areas where differences between Collection 5 MOD44W and the new Collection 6 MOD44W are most prevalent.

In addition we produced a global summary of number of occurrences of water per pixel for the full 16 year record (figure 2). The areas that are water in all years are shown in light gray while areas that are water in at least one year but less than 16 years are shown in gradations of blue, areas where no MODIS tiles were available are in dark gray. As seen in the table embedded in figure 2, 68% of pixels that are identified as inland water appear in every year and only 12% occur in 1 to 3 years. The pixels that do not show up in all years are either surface water gained, surface water lost, or errors of commission caused by poor reflectance values that were not filtered by the surface reflectance QA.

Years Water Detected	Percent of Pixels
always water	68%
13 to 15	8%
10 to 12	4%
7 to 9	4%
4 to 6	5%
1 to 3	12%

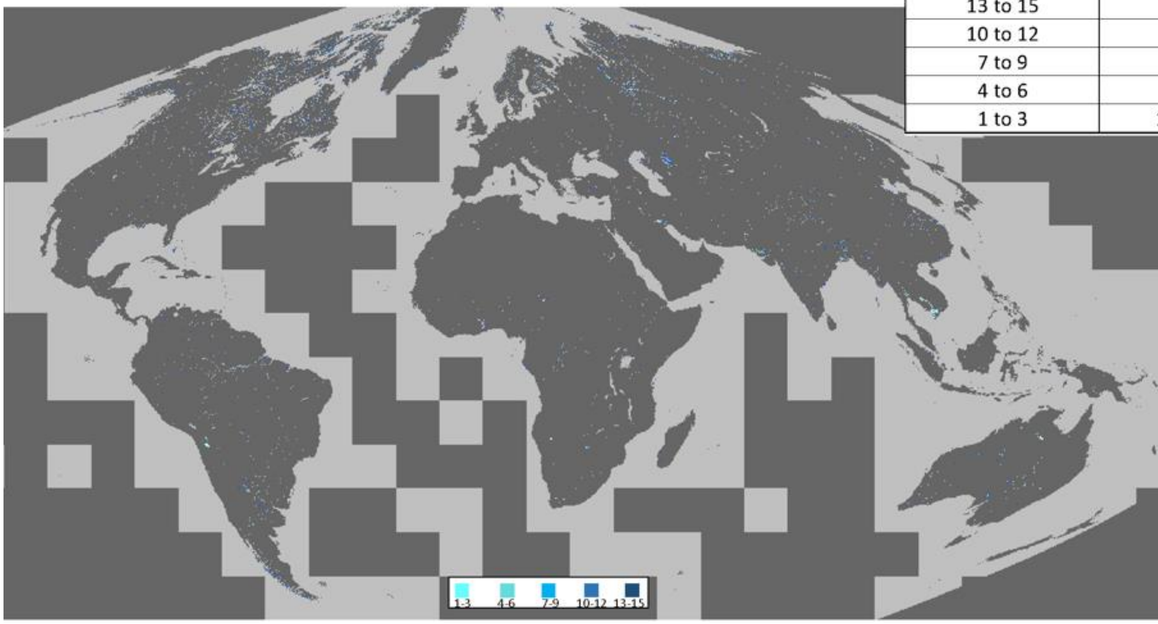

Figure 2 Global map showing the frequency of occurrence of water from all 16 years of MODIS surface water extent. Dark gray is land or no data; light gray is always water; and light blue to dark blue shows an increasing number of years where water was detected.

A unique feature of this dataset is the ability to perform time series analysis both regionally and on a per water body basis. The user can quantify total number of pixels of water over a region or the globe and compare that to the same region over any number of years. **However we strongly discourage the practice of simple subtraction of any two years to define "change in surface water".** Differencing any two images will identify differences between the datasets but may encourage erroneous conclusions because of the transient nature of surface water. A method for object based analysis of surface water change based on the area of the water body has been described in (Carroll and Loboda 2017) and is encouraged for performing time series analysis with this dataset. An example using this methodology was performed for 20 water bodies selected to represent different geographic regions and size classes, results in table 2.

Table 1 Area (km^2) for sample of lakes over 16 year data record. Simple linear regression (Ordinary Least Squares) performed on area for each lake. Slope and P-value shown in last two columns. Area for each year between 2000 and 2015 were used, only even years shown in table to make the table easier to read.

Water Body	2000	2002	2004	2006	2008	2010	2012	2014	Average Area	Slope	P-value
Aral Sea	27,975	26,148	24,739	22,342	15,796	18,214	16,177	8,630	19,556	-1097.86	0.00003
Sarygamysh Lake	3,794	3,747	3,833	3,902	3,906	3,892	3,882	3,900	3,860	9.51	0.00022
Lake Baikal	32,035	32,005	32,041	32,025	32,016	32,017	32,038	32,007	32,021	-1.32	0.26439
Khovsgal	2,791	2,784	2,794	2,791	2,794	2,790	2,786	2,792	2,790	-0.08	0.71923
Dead Sea	916	913	905	909	906	897	890	895	903	-1.71	0.00000
Lake Urmia	4,953	4,789	4,834	4,653	4,310	3,871	3,671	3,497	4,273	-116.11	0.00000
Tharthar Lake	1,656	1,667	1,925	1,829	1,704	1,664	1,621	1,679	1,718	-6.89	0.18881

Cachuma Lake	9.07	9.18	8.59	9.44	9.39	9.12	9.23	7.19	8.88	-0.07	0.08541
Razazza Lake	1,330	1,142	948	935	806	533	396	667	822	-58.10	0.00000
Hulun Lake	2,317	2,255	2,155	1,998	1,923	1,859	1,823	2,073	2,047	-23.72	0.00280
Bei'er Lake	615	613	613	609	608	608	614	619	612	0.20	0.43352
UID 1421	116	101	95	9	73	44	104	94	78	-1.29	0.49275
Lesser Slave Lake	1,156	1,155	1,162	1,155	1,169	1,157	1,159	1,169	1,163	0.58	0.03938
Dauphin Lake	517	517	516	517	516	517	517	535	521	0.98	0.14649
Hay Lake	166	149	121	162	427	260	164	170	212	3.29	0.55883
Salton Sea	961	967	958	957	962	942	935	931	948	-2.84	0.00000
Lake Tahoe	500	501	499	500	500	499	499	500	500	0.00	0.90171
Lake Van	3,582	3,584	3,584	3,581	3,582	3,586	3,582	3,585	3,583	-0.02	0.81784
Poopó Lake	1,646	2,137	1,930	1,926	1,570	1,489	2,043	1,851	1,800	-22.22	0.11214
Lake Titicaca	7,797	8,067	8,107	7,995	7,939	7,857	7,930	7,879	7,952	-11.57	0.03611

Examples of the time series for Aral Sea, Bei'er Lake and Hay Lake are shown in figure 3 – 5 respectively. These figures show inter-annual variability in each of the water bodies and the large scale decline of the Aral Sea.

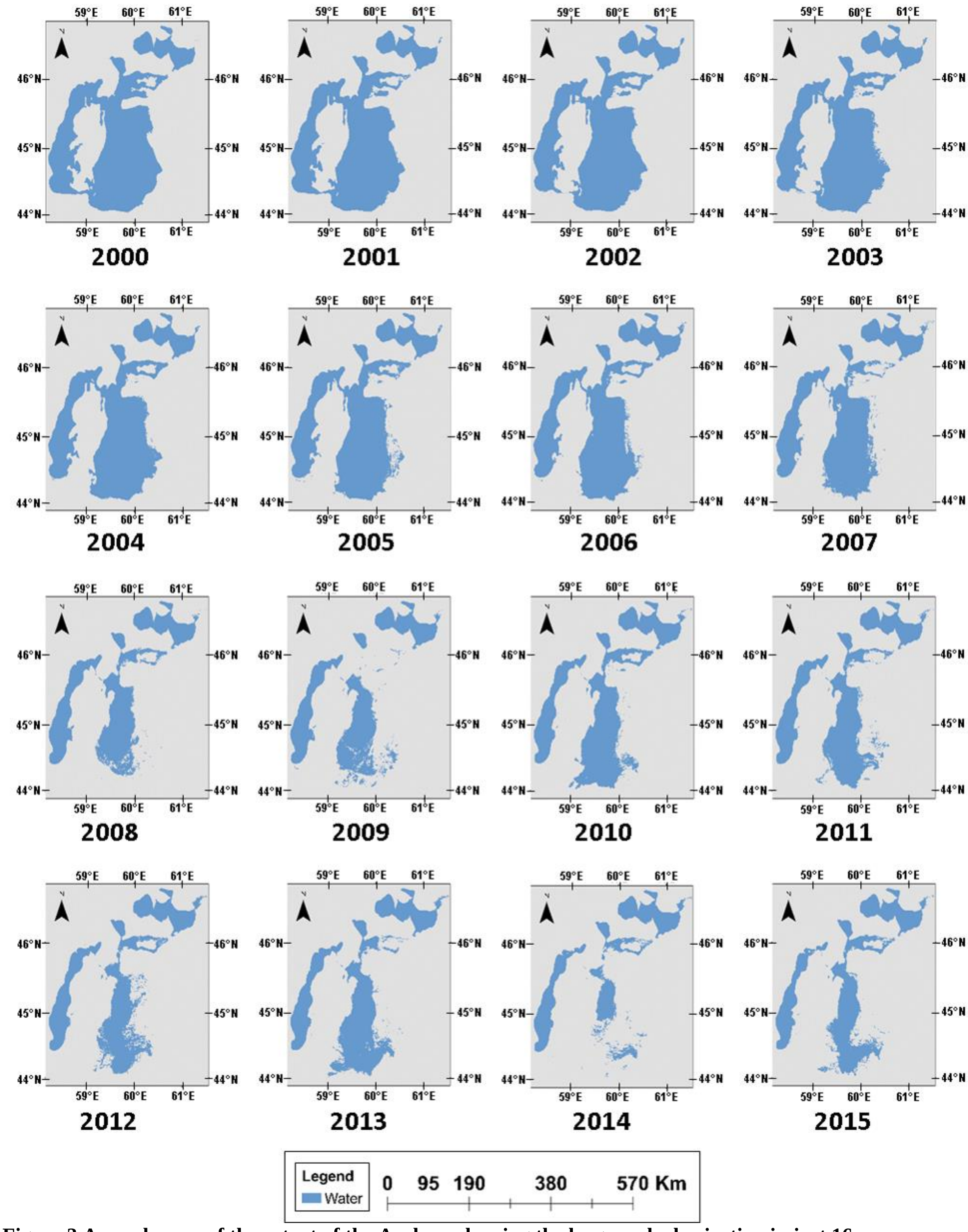

Figure 3 Annual maps of the extent of the Aral sea showing the large scale dessication in just 16 years.

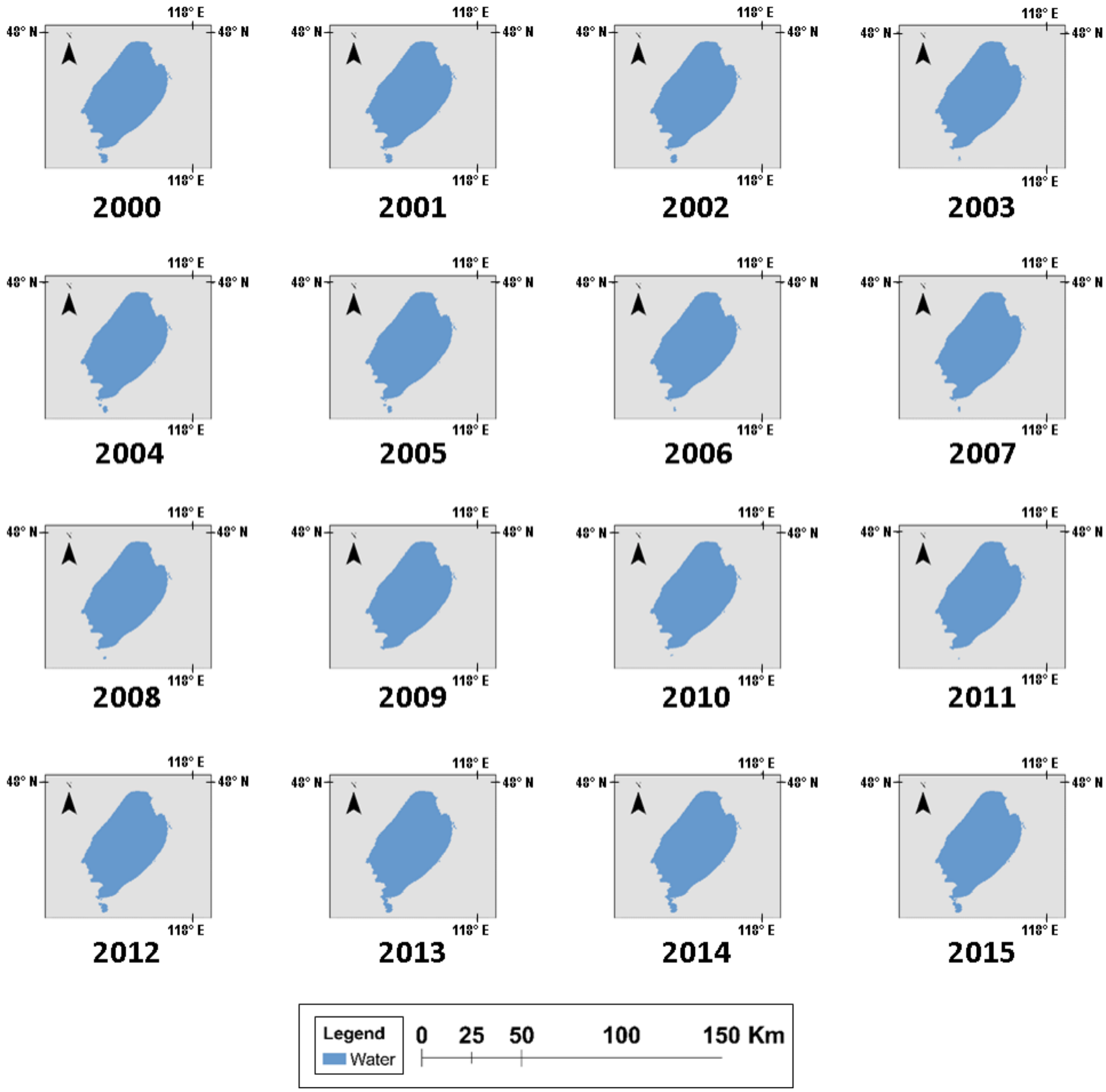

Figure 4 Annual maps of the extent of Lake Bei'er showing it is generally stable through time.

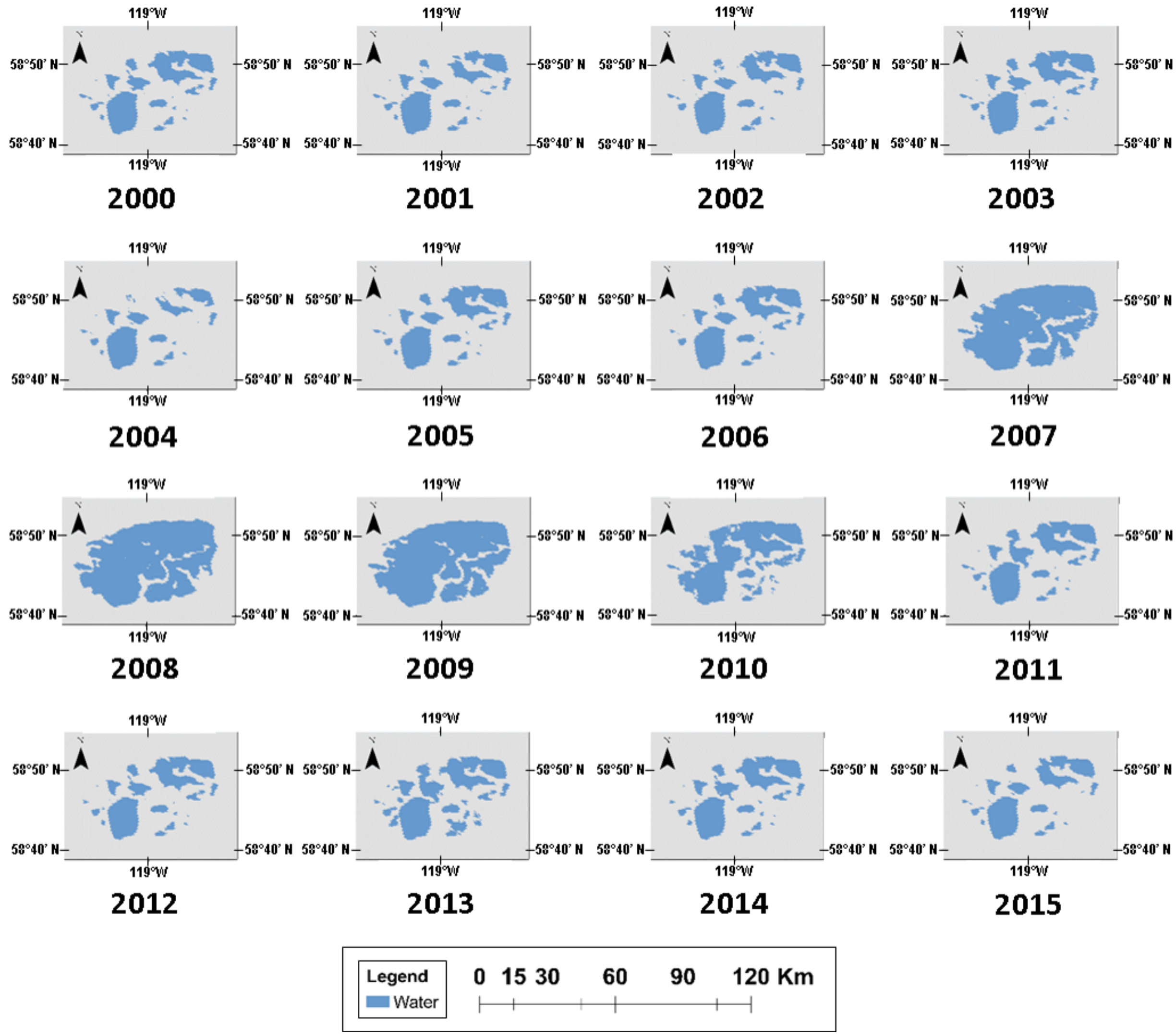

Figure 5 Annual maps of the extent of Hay Lake showing significant inter-annual variability in the lake complex over time.

As demonstrated in Carroll et al. 2009, the best results from the annual time series will be for water bodies that are greater than 3 MODIS pixels in size or ~0.16 km^2 due to limitations in detections in areas smaller than this. We anticipate that the annual time series of water maps can be used to mask water in other MODIS products, as a regional to global measure of total water, or for studies of individual medium to large water bodies. Please cite the data as:

Carroll, M.L., DiMiceli, C.M., Hubbard, A.B., Wooten, M.R., Sohlberg, R.A., Townshend, J.R.G. 2017. Global Raster Water Mask at 250 Meter Resolution Derived from MODIS for Collection 6. (accessed mm/dd/yyyy)

Future Work

The annual maps of surface water extent show how the nominal extent of water changes from year to year. Additional work is being done to capture seasonal or ephemeral water that is present on the landscape for several weeks to several months but is not there for at least 50% of the total observations. An example of this is the area around Tonle Sap in Cambodia which floods every year for a few weeks depending on the strength of monsoon rains in a given year. This work takes full advantage of the daily observations that are possible with MODIS, is ongoing work that requires significant testing and will be released once it has been fully validated.

As of this writing, (October, 2017) the data required to create a map for Antarctica (and all areas south of 60° S) have not been produced by the MODIS production system. This was due to an oversight in the processing script for the daily MODIS 250 m surface reflectance product which is necessary to perform the daily water classification. The issue is being corrected and data for Antarctica should be available by Summer, 2018.

Data Access

The following tools offer options to search the LP DAAC data holdings and provide access to the data:

- Bulk download: LP DAAC Data Pool and DAAC2Disk
- Search and browse: USGS EarthExplorer and NASA Earthdata Search
- Subset and explore: AppEEARS

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Appendix

For completeness the basic descriptions of the two collection 5 water masks (MOD44WA1, MOD44W) are included here. Full description of the MOD44W Collection 5 water mask is available in Carroll et al, 2009.

MOD44WA1 Collection 5

For collection 6 MODIS processing, the MODIS science team requested an update to the existing 1 km water mask (Salomon et al. 2004) that had been used for collection 5. The MOD44W 250 m binary mask was already available but lacked the distinction between inland water and oceans that was required for some MODIS data products. The MOD44W 250 m spatial resolution was combined with the ETOPO1 global bathymetry dataset (Amante and Eakins 2009) to distinguish between binary (land/water) representation and the three ocean classes (shallow, moderate, and deep) as well as identify deep inland water. The data were then aggregated to 500 m spatial resolution by majority rule. This 500 m version of the data is called MOD44WA1, full description in (Carroll et al. 2016b), was created for consistency with previous MODIS production land/water masks and contains the following classes:

Table 2 Pixel value definitions for MOD44WA1.

Value	Class	Definition
0	Shallow Ocean	Ocean pixel with depth < 160 ft
1	Land	Land detected
2	Shoreline	Last land pixel before water
3	Inland Water	Open surface water on continent
4	Ephemeral Water	Not populated in this version
5	Deep Inland Water	Inland water > 160 ft
6	Moderate Ocean	Ocean pixel with depth > 160 ft but <400 ft
7	Deep Ocean	Ocean pixel with depth > 400 ft

The thresholds for defining shallow, moderate and deep were chosen for the pre-launch MODIS water mask and have been maintained with previous versions and thus have been maintained in this version as well. The implementation of ETOPO1 results in some differences in the delineation of moderate and deep ocean as well as deep inland water. These differences are quantified and described in detail in (Carroll et al. 2016b).

MOD44W Collection 5

The original MOD44W collection 5 dataset was created from MODIS and Shuttle Radar Topography Mission Water Body Dataset (SWBD) to fulfill the MODIS science team's need for a 250 m resolution operational water mask. The data layer has three values:

- 0 Land
- 1 Water
- 253 Fill (outside the projection)

And the QA layer has seven values:

- 1 SRTM Water Body Dataset (SWBD) water
- 2 MODIS 250 m Water-hits water
- 3 MODIS 250 m Decision-tree water
- 4 Digitized water
- 5 Mosaic of Antarctica (MOA) water
- 10 Digitized land
- 253 Area outside of projection
- 255 Fill value

The SWBD was used because of its fine spatial resolution and because of its consistent representation of the land surface. Since the SRTM data were collected over a short time period of only 11 days, it should provide a spatially coherent representation of surface water. Additionally, the cloud penetrating properties of the Radar offers superior performance over optical data alone, particularly in cloudy areas such as the humid tropics. Using this remotely sensed data product has the advantage of a single source of information, unlike the typical vector data sets which are dependent on disparate sets of information to create a single data set.

A global 250m data set in 16 day composites for the entire 8+ years of Terra data and 6+ years of Aqua data, Collection 5, is online at the University of Maryland. This data set (MOD44C) was originally created as the input to the MOD44A (Vegetative Cover Conversion) and MOD44B (Vegetation Continuous Fields VCF) products. For a full description of these products see Carroll et al (2006). During the compositing process the daily surface reflectance data (Vermote and Kotchenova, 2008) was interrogated using a decision tree algorithm to distinguish between water and land. This daily depiction of water was stored in the 16-day composite data as a sum of “hits” labeled as water in the process. These “hits” were then interrogated and used where ever gaps exist in the SWBD.

The MODIS mosaic of Antarctica (MOA), available from the National Snow and Ice Data Center (NSIDC) DAAC, is a mosaic of MODIS 250m level 1b (L1B) data for the continent of Antarctica (Haran et al, 2005). This was generated using the Radarsat Antarctic Mapping Project Antarctic Mapping Mission 1 (RAMP AMM1) data (Haran et al, 2005) as a reference to overlapping MODIS observations to create a fine resolution (125m) image for the continent of Antarctica. This vector shoreline product is available from the National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (DAAC).

The MOD44W Collection 5 is a global raster data set in the Sinusoidal projection, subset into tiles matching the MODIS tile grid. This dataset is intended to replace the old EOS 1km Land/Water mask originally created in the mid-1990’s and updated in 2002. The 2002 update was global except for 80° to 90° N (where no data were available at that time) and was performed by Boston University (Salomon et al, 2004). This update solved numerous errors including many misplaced rivers in South America but was limited by the 1km spatial resolution and the inability to solve problems in the far north due to lack of data.