NASA/ DFO MODIS Near Real-Time (NRT) Global Flood Mapping Product Evaluation of Flood and Permanent Water Detection

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Introduction

The purpose of this evaluation is to better understand how well the MODIS Near Real-Time (NRT) Global Flood Mapping 3-Day Product (http://oas.gsfc.nasa.gov/floodmap/) is performing and to identify any shortcomings or issues so that the underlying detection algorithm can be improved. Both flood event and non-flood (permanent water) sites were selected and evaluated. The criteria for flood event site selection was straightforward: incorporate 1) as many areas spread across the globe as possible, paying attention to varying latitudes, 2) different times of the year, 3) areas of high (i.e. central Africa) and low percentage cloud cover (i.e. Australia), 4) areas in which NASA Goddard Space Flight Center's Office of Applied Sciences has active projects (i.e. Caribbean, southern Africa, North Africa), and 5) flooded areas that coincide with various land cover, represented by the NASA MODIS 500m IGBP Land Cover Type product, in order to determine if there is a relationship between product performance and land cover type. These criteria were honored whenever possible but obvious limitations exist as our site selection for flood mapping was ultimately dictated by where flood events occurred in 2013 and 2014. NRT mapping products from these most recent years were used in order to evaluate the latest iteration of the NRT product, with sites selected based on the Dartmouth Flood Observatory (DFO) flood listing (http://floodobservatory.colorado.edu/Archives/ Master Listrev.htm). The evaluation focuses on the 3-day product (3D3OT; v4.9), with a few 2-day (2D2OT; v4.1) and 14-day (14x3D3OT; v4.9) product examples. Brief introductions to the NASA MODIS NRT Global Flood Mapping system and products are provided below. This project was developed in collaboration with Bob Brakenridge at the Dartmouth Flood Observatory (DFO): http://floodobservatory.colorado.edu

System Description

The MODIS instrument, onboard NASA's Terra and Aqua satellites, provides twice daily near-global coverage at 250-m resolution in two optical bands; these are the key data sources for the MODIS NRT flood products. The LANCE processing system at NASA GSFC (lance-modis.eosdis.nasa.gov) provides the products that are ingested within a few hours of satellite overpass. The Terra equatorial overpass is at ~10:30 AM local solar time, and Aqua at 1:30 PM. Data are mosaicked from all orbits falling within a 10x10 degree tile for each satellite, each day. Although other instruments provide higher resolution data, none provide global daily coverage. Currently, the water detection algorithm uses a ratio of MODIS 250-m reflectance Band 1 and Band 2, and a threshold on Band 7 to provisionally identify pixels as water. The algorithm development team is looking into the future incorporation of targeted radar data in order to avoid cloud cover interference; please refer to http://oas.gsfc.nasa.gov/floodmap/home.html

System Products

The MODIS NRT system produces global daily surface and flood water products at approximately 250-m resolution, in 10x10 degree tiles. Most products are multi-day composites to minimize cloud cover issues. Currently, three standard products are produced: 2-day (2D2OT), 3-day (3D3OT), and 14-day (14x3D3OT). The product date is the last day of the

composite period. Thus, a 3-day product (3D3OT) product dated 2012015 would include data from 2012013, 2012014, and 2012015. A single-day product (1D1OS) is turned on for specific events of current interest, but is not (as of yet) run routinely. Table 1 lists each composite with a brief description. The core product is distributed in geotiff format and includes both flood and non-flood surface water (Table 2).

2D2OT	2 Days imagery, 2 Observations required, Terrain shadow masking applied
3D3ON	3 Days imagery, 3 Observations required, Terrain shadow masking applied
1D1OS	1 Day imagery, 1 Observation required, terrain & cloud shadow masking applied
14x3D3OT	Composite (simple addition) of the previous 14 days' 3-day product

Table 1. Product composites.

MWP (MODIS Water Product)	Both flood and non-flood surface water in geotiff format Four classes are represented: 0: Insufficient data to make water determination (cloudy, missing images, swath gaps swaths, or bad data values). 1: No water detected. 2: Water detected AND coinciding with reference water (e.g., not flood). 3: Water detected, beyond reference water, is likely flood.

Table 2. NASA MODIS NRT Global Flood Mapping core product description.

Water detections are composited over the product window. If a pixel is identified as water over several (2 or more for the 2D2OT product and 3 or more for the 3D30T product using 4 image and 6 image set (Terra and Aqua) respectively), it is then definitively marked as water, and output in the MWP (MODIS Water Product). Multiple water detections are required because cloud shadow can appear quite spectrally similar to water. In cases where cloud shadow occurs in the same spot in multiple observations, the products may incorrectly flag such areas as water, but commonly cloud shadows move and are not (falsely) identified as water. Higher numbers of required water detections (moving from 2 day, 4 image data sets to 3 day, 6 image sets) helps further remove cloud shadow noise, but also increases the latency of the product. As of product version 4.7, a draft version of cloud shadow masking is applied, but only to single-day products: it can also remove areas of true flood near clouds.

Shadows may also occur from topography, but these are largely stationary (most variation is from seasonal sun angle changes). As of product version 4.4, a draft version of terrain shadow masking is now routinely applied. This eliminates much, but not all, issues of terrain shadow getting tagged as water due to its spectral similarity.

The detected water is compared to a reference surface water layer (NASA MODIS MOD 44W product) that shows "normal" water extent, and any pixels found outside the normal water extent are marked as flood, and output in the MWP. The MOD 44W product is derived from 16-day composites of MODIS reflective and emissive bands at their nominal resolutions and is one of

several reference water data sets available. It is not optimal because it is seasonally static and in places out of date (some indicated lakes no longer exist while others have formed), and thus does not reflect normal seasonal lake and river water height variations. Initial work is underway to provide an updated reference water layer which will also include non-flood ephemeral water. DFO uses, instead, the Shuttle Water Boundary data (SWDB) which is at a much higher spatial resolution of 90 m and was obtained during February, 2000 by NASA's SRTM mission.

For more detailed information regarding these products, please refer to
http://oas.gsfc.nasa.gov/floodmap/README_MODISFloodMapProducts_17Jun13.txt

Higher-Resolution Satellite Data

In addition to the 250-m MODIS reflectance data, both Landsat and EO-1 satellite data were used to assist in the evaluation. Each of the following were downloaded when available to confirm the presence or absence of flood water.

Landsat 7 Enhanced Thematic Mapper Plus (ETM+):

A sensor onboard the Landsat 7 satellite that has been operational since July 1999 with a 16-day repeat cycle. The approximate scene size is 170 km north-south by 183 km east-west. The sensor's six 30-m spectral bands were used for flood water confirmation.

Landsat 8 Operational Land Imager (OLI):

A sensor onboard the Landsat 8 satellite that has been operational since February 2013 with a 16-day repeat cycle and an 8-day acquisition offset to Landsat 7. The approximate scene size is 170 km north-south by 183 km east-west. 30-m spectral bands were used for flood water confirmation.

Earth Observing 1 Advance Land Imager (EO-1 ALI):

A sensor onboard the EO-1 spacecraft that has been operational since November 2000 and was initially part of a 1-year validation/ demonstration mission. An Extended Mission is in effect and data are now collected based on customer tasking request. The approximate scene size is 42 km north-south by 37 km east-west. 30-m spectral bands were used for flood water confirmation.

The descriptions above were compiled from the following websites. Please refer to them for more detailed information.
http://pubs.usgs.gov/fs/2012/3072/fs2012-3072.pdf
http://landsat.usgs.gov/
https://lta.cr.usgs.gov/ALI
http://eo1.gsfc.nasa.gov/

Flood Event Site Selection

The starting point for flood event selection was the DFO 'Current Event' website (http://floodobservatory.colorado.edu/Archives/MasterListrev.htm). Other floods were chosen by searching through the NRT flood map tiles or based on other recommendations. A total of 53 flood events were selected (Fig. 1 & Table 3).

Fig. 1. Flood event locations (red) used in the NRT 3D3OT product evaluation.
(Note: a few floods may be difficult to see on the map due to their close proximity to other floods. See full list below.)

LOCATION	YEAR	LAT	LON	LOCATION	YEAR	LAT	LON
Argentina	2013	-34.913	-57.845	Norway	2013	66.695	14.200
Australia	2014	-17.579	139.462	Oman	2013	22.920	58.584
Bosnia	2014	44.863	18.932	Palestine/Syria	2013	33.031	37.223
Botswana	2014	-20.508	22.754	Peru	2014	-12.419	-71.523
Brazil	2014	-19.380	-40.095	Peru	2013	-8.574	-76.187
Burundi	2014	-4.140	29.650	Philippines	2013	9.886	118.626
Cambodia	2013	12.789	104.584	Philippines	2013	7.257	125.308
Cambodia	2014	12.860	104.260	Romania	2014	44.062	24.494
Cameroon	2013	12.861	14.180	Russia	2013	68.569	134.679
Canada	2013	51.899	-104.530	Russia	2013	44.256	39.103
China	2013	30.015	121.215	Russia	2013	46.072	38.598
China	2014	29.686	113.250	Saint Vincent	2014	13.378	-61.171
Cuba	2013	22.904	-81.396	Saudi Arabia	2013	22.762	52.394
Cuba	2013	22.113	-81.316	Solomon Islands	2014	-9.678	160.342
England	2014	51.729	-1.406	South Sudan	2013	7.578	30.671
France	2014	43.351	4.860	Spain	2013	36.974	-6.367
France	2014	43.469	4.554	Sri Lanka	2013	7.920	81.069
India	2013	25.335	85.966	Tanzania	2014	-8.176	36.695
Indonesia	2013-2014	4.480	97.289	Thailand	2013	7.816	100.172
Indonesia	2013	-3.867	121.883	Tunisia	2013	33.964	8.542
Indonesia	2013	-2.628	120.919	USA-Alabama	2014	31.859	-87.619

Ireland	2013-2014	52.878	-9.394	USA-Arizona	2013	35.408	-111.300
Namibia	2013	-17.612	24.702	USA-Colorado	2013	39.898	-105.980
Nepal	2013	28.691	84.062	USA-Georgia	2014	31.297	-84.947
New Zealand	2013	-44.359	170.669	USA-Kentucky	2014	37.801	-88.039
New Zealand	2014	-43.454	172.613	USA-Hawaii	2013	19.492	-155.580
Norway	2013	61.283	10.478				

Table 3. Flood event location listing used in the NRT 3D3OT product evaluation.

<u>Permanent Water Site Selection</u>

The following permanent surface water sites were selected. If permanent water, besides ocean, was found in the same tile as the flood event, it was evaluated along with flooded areas. A few additional cases were also chosen, resulting in a total of 56 permanent water evaluation sites (Fig. 2 & Table 4).

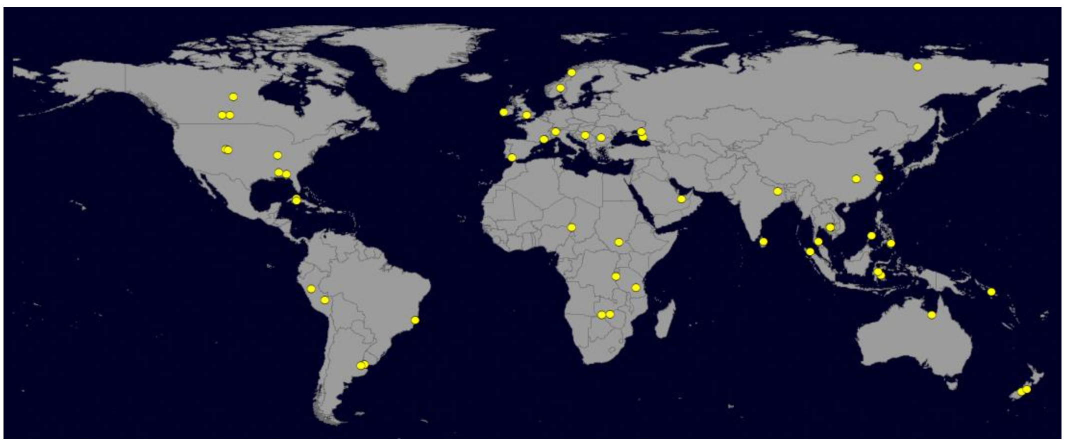

Fig. 2. Permanent water locations (yellow) used in the NRT 3D3OT product evaluation.
(Note: a few sites may be difficult to see on the map due to its close proximity to another site. See full list below.)

LOCATION	YEAR	LAT	LON	LOCATION	YEAR	LAT	LON
Argentina	2013	-34.913	-57.845	Ireland	2013-2014	52.878	-9.394
Argentina	2013	-35.345	-58.986	Namibia	2013	-17.612	24.702
Australia	2014	-17.579	139.462	New Zealand	2013	-44.359	170.669
Bosnia	2014	44.863	18.932	New Zealand	2014	-43.454	172.613
Brazil	2014	-19.380	-40.095	Norway	2013	61.283	10.478
Brazil	2013	-19.343	-40.099	Norway	2013	66.695	14.200
Burundi	2014	-4.140	29.650	Oman	2013	22.920	58.584
Cambodia	2013	12.789	104.584	Peru	2014	-12.419	-711.523
Cambodia	2014	12.860	104.260	Peru	2013	-8.574	-76.187
Cambodia	2013	12.860	104.260	Philippines	2013	9.886	118.626
Cambodia	2014	12.860	104.260	Philippines	2013	7.257	125.308
Cameroon	2013	12.861	14.180	Romania	2014	44.062	24.494

Canada	2013	51.899	-104.527	Russia	2013	68.569	134.679
Canada	2013	51.754	-107.341	Russia	2013	44.256	39.103
Canada	2013	58.224	-103.420	Russia	2013	46.072	38.598
China	2014	29.686	113.250	Saudi Arabia	2013	22.762	52.394
China	2013	30.015	121.215	Solomon Islands	2014	-9.678	160.342
Cuba	2013	22.904	-81.399	South Sudan	2013	7.578	30.671
Cuba	2013	22.113	-81.316	Spain	2013	36.974	-6.367
England	2014	51.729	-1.406	Sri Lanka	2013	7.920	81.069
England	2013	51.755	-1.353	Tanzania	2014	-8.176	36.695
France	2014	43.351	4.860	Thailand	2013	7.816	100.172
France	2014	43.469	4.554	USA-Alabama	2014	31.856	-87.619
France	2013	45.980	8.703	USA-Colorado	2013	39.898	-105.982
India	2013	25.335	85.966	USA-Colorado	2013	39.773	-105.229
Indonesia	2013-2014	4.480	97.289	USA-Georgia	2014	31.297	-84.947
Indonesia	2013	-3.867	121.883	USA-Kentucky	2014	37.801	-88.039
Indonesia	2013	-2.628	120.919	Zambia	2013	-17.344	27.527

Table 4. Permanent water location listing used in the NRT 3D3OT product evaluation.

Base maps (National Geographic, Google) were frequently used when selecting areas of permanent water. It was discovered that some of the areas in the National Geographic base map depict seasonal wetlands while Google Maps had a more accurate representation of permanent water (Fig. 3).

Fig. 3. Comparison between National Geographic and Google base maps. (Burketown, Queensland, Australia)

Flood Detection Method and Results

A rating system was developed to assess the performance of the 3D3OT NRT product. The product was downloaded and compared to the Lance-processed MODIS MOD09/MYD09 250-meter surface reflectance band composites (bands 1, 2, 7) to visually assess the presence of water in the image. Using the MODIS Terra/Aqua surface reflectance products to evaluate our MODIS-based flood maps may seem somewhat circular; however this was an important step to provide a visual evaluation of the automated procedure, and to ensure there were no inherent errors in the MODIS imagery itself (i.e. saturated bands). It also helped to verify terrain shadow issues and was helpful in some cases to understand why some water was not being detected (eg larger pixels present at the edge of a MODIS scan).

When higher-resolution imagery was available (i.e. Landsat, EO-1) it was also used to confirm the presence/ absence of flood water and to compare pre-flood imagery in order to better understand flood extent and to identify flood misdetections caused by terrain shadow. The MODIS imagery was downloaded from the OAS production server while the higher resolution imagery, along with MODIS imagery that was no longer available locally, was downloaded from USGS EarthExplorer (http://earthexplorer.usgs.gov/). The qualitative rating scores are as follows:

1 - poor = water not detected or water erroneously detected
2 - fair = less than half of the water is detected
3 - good = about half of the water is detected
4 - excellent = most of the water is detected
5 - almost perfect = just about all of the water is detected
TMC - Too Many Clouds = no flood or permanent water detected

For the most part, the product was successful in capturing the flooded areas (Fig. 4 & Table 5). 44% of the flood events were classed as either *good*, *excellent* or *almost perfect*, 23% were either classed as *poor* or *fair*, and 33% could not be evaluated due to too many clouds (*TMC*). These percentages represent product performance given real-world limitations of the data, such as cloud cover.

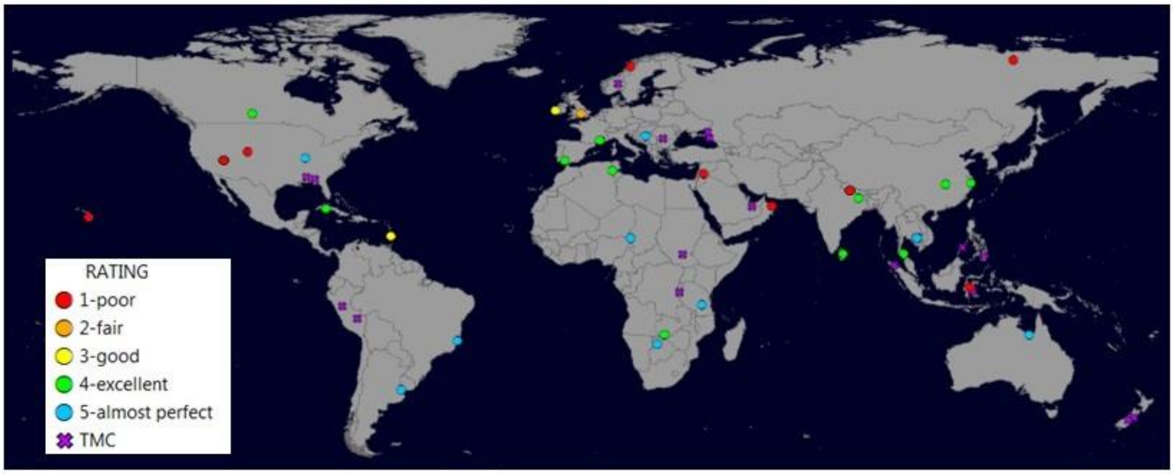

Fig. 4. Flood detection rating at each flood event location.
(Note: a few floods may be hard to see on the map due to their close proximity to other floods.)

RATING	Count	%
5-almost perfect	11	21
4-excellent	10	19
3-good	2	4
2-fair	1	2
1-poor	11	21
TMC - too many clouds	17	33
Outside product coverage area*	1	Eliminated from equation
TOTALS	53	100

Table 5. Flood detection rating breakdown. (*Note: 'Outside product coverage area" represents a flood event in the Solomon Islands that was initially selected before it was discovered to be within a tile that has no product availability.)

If the *TMC* cases are excluded from the equation, the total case results reflect the performance of the algorithm/compositing itself and where the product could have been successful. The flood events that were classed as either *good*, *excellent* or *almost perfect* increase to 66% while the events classed as either *poor* or *fair* increase to 34% (Table 6).

EVENT TYPE	No clouds	Overall
Flood (good, excellent, almost perfect)	66%	40%
Flood (poor, fair)	34%	23%

Table 6. Flood detection rating summary.

Successful Flood Detection Examples by the 3D3OT NRT Product

The examples below (Figs. 5-10) represent flood events that were successfully detected and conform to the flood waters present in both the Landsat/EO-1 and MODIS imagery. Note that, although in some cases the MODIS product is overlaid on the higher resolution imagery, it does not represent a classification based on the higher resolution imagery; it is the MODIS flood product. Thus the 250-m flood product pixels appear ‘blocky’ compared to higher resolution Landsat/EO-1 imagery. In addition, higher resolution imagery was not always available for the same date of the NRT flood product displayed. If the flood occurred for more than 1 day, then an attempt was made to choose higher resolution images from sometime within the time period of the flood. Because the 3D3OT NRT product incorporates three days of MODIS data, the MODIS reflectance data that coincided with the same three dates were examined, even if all of the imagery is not depicted in the following examples. Only the clearest example is provided.

Figure 5 shows a flood event that took place in Brazil from Dec 23, 2013 through Jan 4, 2014 due to heavy rain, affecting 314,285 km^2, displacing 60,000 people and killing 45. The flooded area to the west of Linhares can be seen. The same area is dry in the pre-flood Landsat scene.

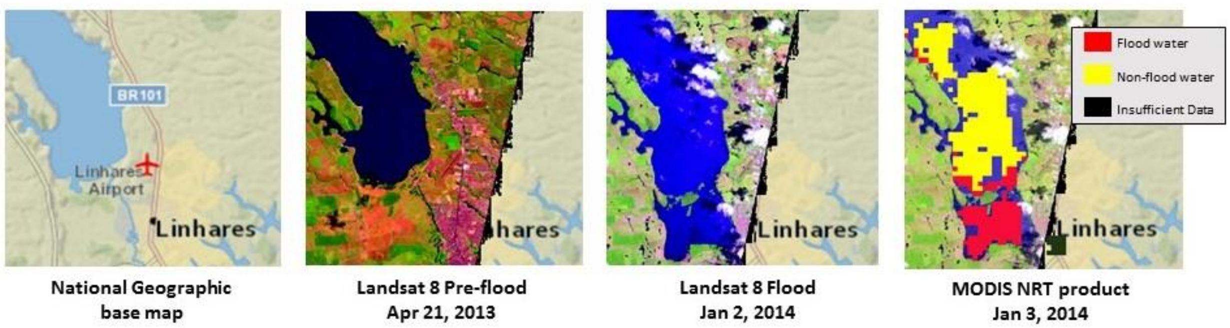

Fig. 5. MODIS NRT 3D3OT flood water detection in Brazil.

Figure 6 shows a (seasonal) flood event in northwestern Queensland, Australia that occurred on January 31, 2014. The evaluation site was selected by browsing through the NRT tiles so no associated information (flood cause and effects) is provided. The flooded areas are very apparent in the bottom row of images, while the absence of flooding is equally apparent in the top row.

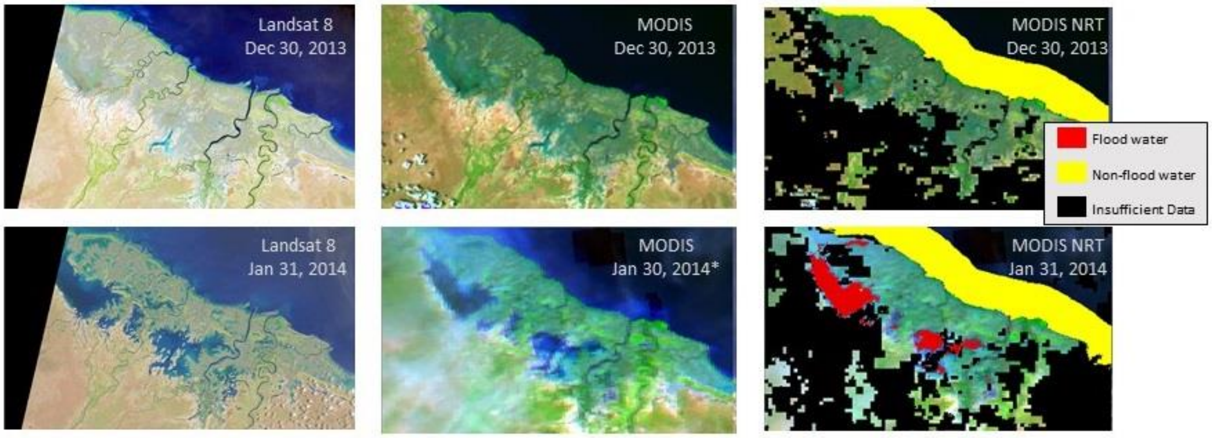

Fig. 6. MODIS NRT 3D3OT flood water detection in Australia.

Figure 7 shows flood water detection results for a flood that occurred in the Lake Chad region of Cameroon in November 2013 probably due to heavy rain. The evaluation site was selected by browsing through the NRT tiles so no associated information (flood cause and effects) is provided. The flooded area was detected without issue.

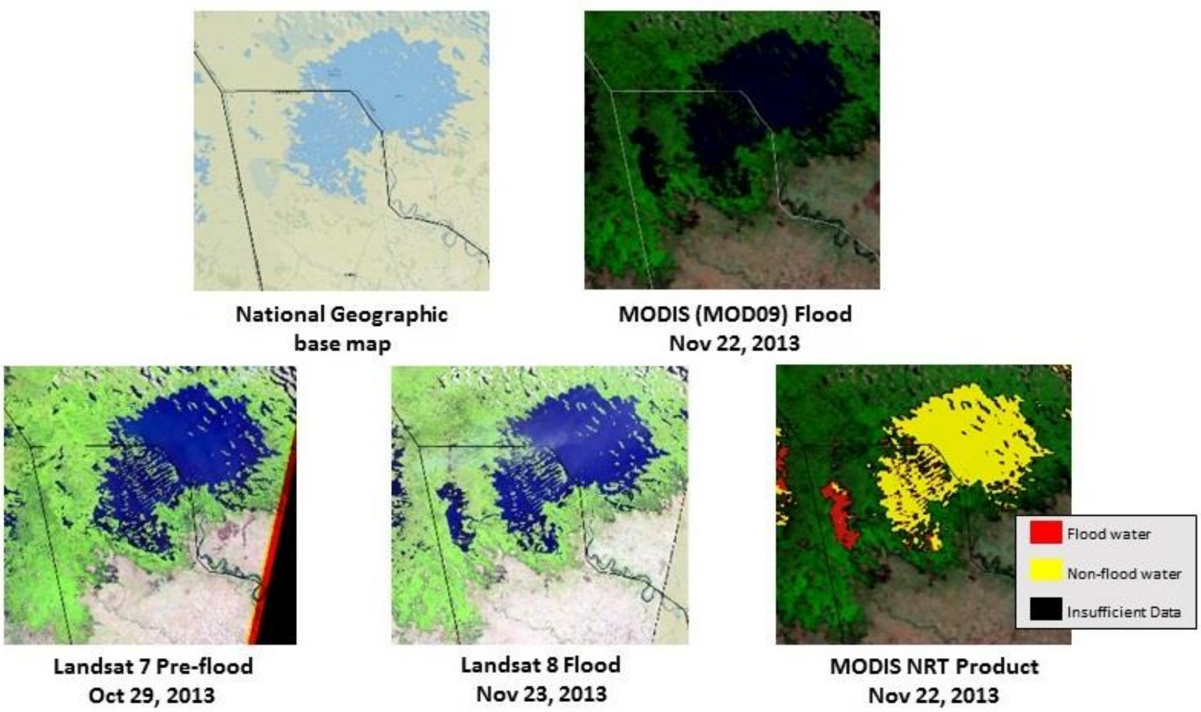

Fig. 7. MODIS NRT 3D3OT flood water detection in Cameroon.

Figure 8 shows flood water detection results for a flood that occurred in Bosnia-Herzegovina (and Serbia and Croatia) in May 2014 due to heavy rain. These floods affected 115,748 km^2 and

displaced 4,000 people, leaving 3 dead. The flood extent can clearly be delineated when comparing to a Landsat 8 scene of the same area from 7 months earlier.

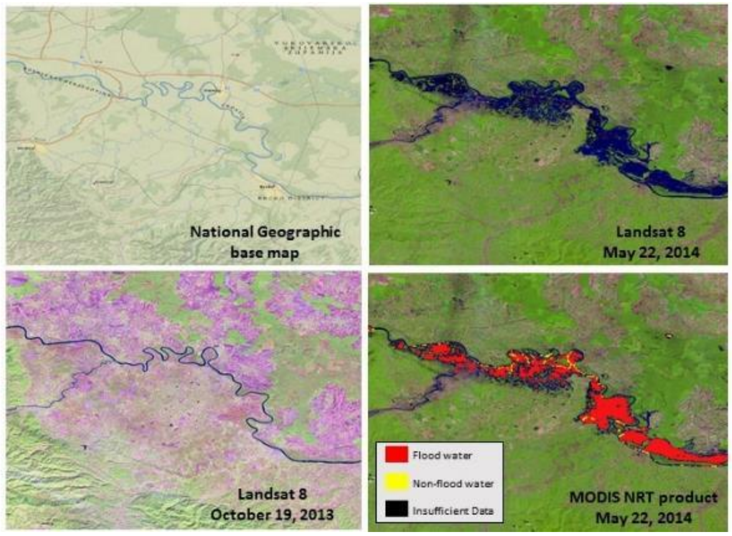

Fig. 8. MODIS NRT 3D3OT flood water detection in Bosnia-Herzegovina.

Figure 9 shows flood water detection results for a flood event that occurred in Cambodia in September and October 2013 due to monsoonal rains. These floods affected 52,283 km^2 and displaced 60,000 people, leaving 122 dead. The flooded areas around Lake Tonle Sap are clearly identifiable.

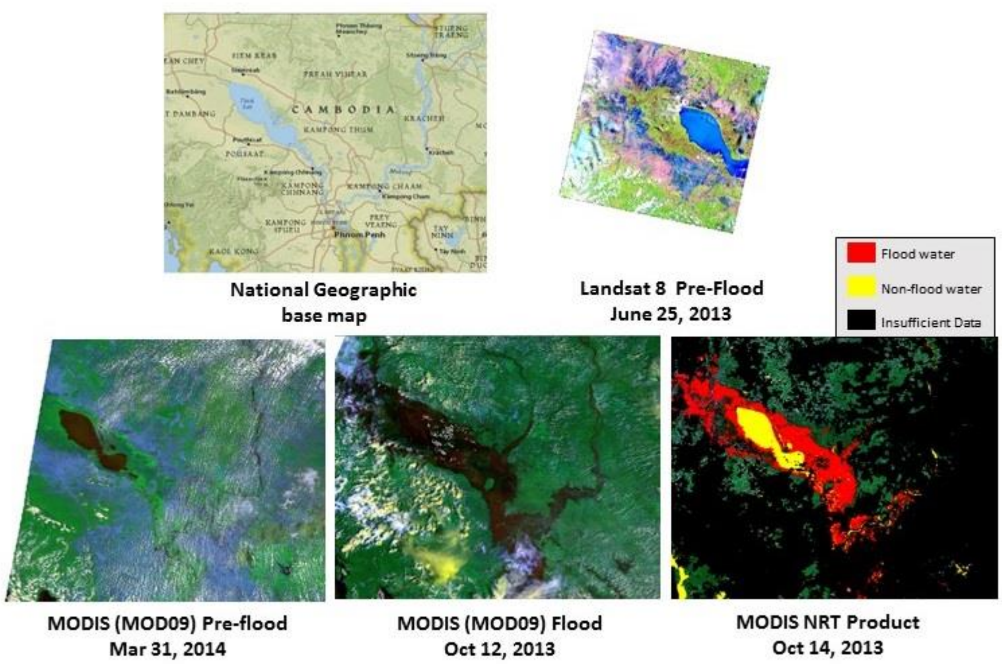

Fig. 9. MODIS NRT 3D3OT flood water detection in Cambodia.

One final example of successful flood mapping is shown in Figure 10 and represents a flood in Kentucky due to heavy rain in January 2014, affecting 16,070 km^2 and leaving 5 dead.

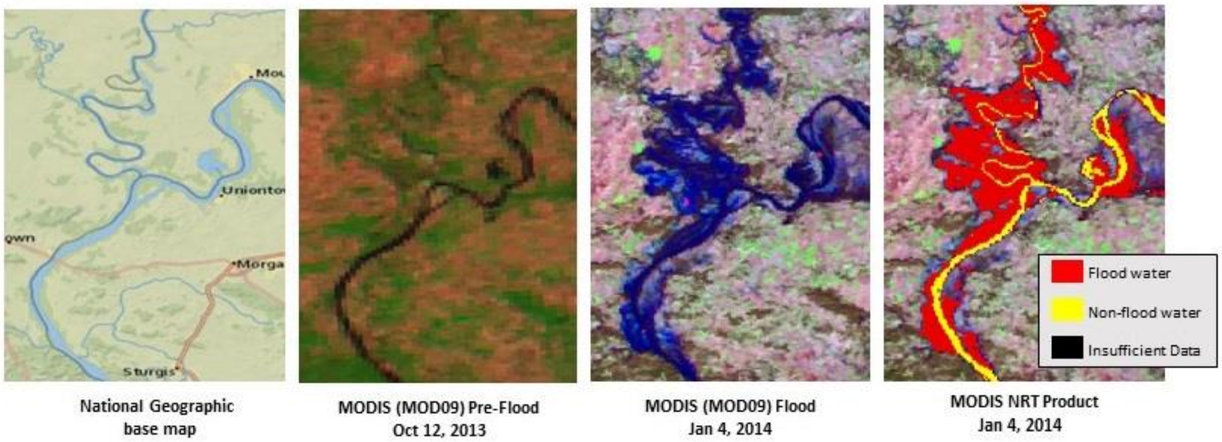

Fig. 10. MODIS NRT 3D3OT flood water detection in Kentucky, USA.

Unsuccessful Flood Detection Examples by the 3D3OT NRT Product: False Negatives

Based on the evaluation, it was found that the most frequent causes for poor flood detection by the 3D3OT NRT product are cloud cover (Fig. 11) and terrain shadow (Figs. 12 & 13), both already known to be limitations prior to evaluation. See http://oas.gsfc.nasa.gov/floodmap/productDescription.htm (Section F.) for more information.

Figure 11 represents a flood event in Peru that occurred from January 1-4, 2014 due to heavy rains, affecting 300 people over an area of 74,144 km^2. Flood water was not detected due to persistent cloud cover (middle panel, Fig. 11). Note that while one or more clear images were obtained during the 3-day compositing period, because of the “3 clear image” requirement, the 3D3OT NRT product labeled the area as ‘insufficient data’ (right panel, Fig. 11)._This is a “cost” for decreasing the cloud shadow errors, and can be considered an error of omission, or false negative. In circumstances when a flood event is not detected due to cloud cover, the NRT 14-day flood product may prove more useful. The 14-day option will be discussed briefly below.

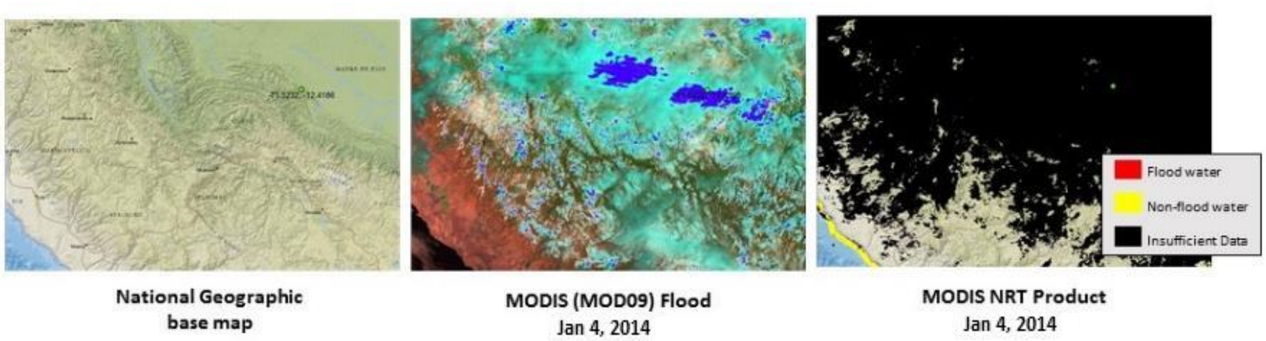

Fig. 11. Cloud cover obstructing MODIS NRT 3D3OT flood water detection in Peru.

Another phenomenon that lead to flood omission is inundated vegetation. Figure 12 shows flood water detection results for a monsoonal rain flood event that occurred in Namibia in March 2013. These floods affected 100,905 km^2 and displaced 10,000 people. Note this example includes a Radarsat-2 dataset, which is not incorporated into the detection algorithm, but was available in this case, and helps evaluate the product in this example. Although the flood detection algorithm did an excellent job at mapping the majority of the flood, when reviewing a combination of EO-1 ALI, MODIS, and Radarsat-2 data it seems as though a portion of the flood was not detected. This is probably due to the inundated vegetation in the northern part of the flooded area, resulting in a false negative. These flooded vegetated areas appear green in the reflectance data and white in the radar data (Fig. 13). However, it is also possible that the area not detected is a recently flooded areas that is still wet but with no substantial standing water. This could be the reason that the area looks dark optically while the Radarsat shows it as dry.

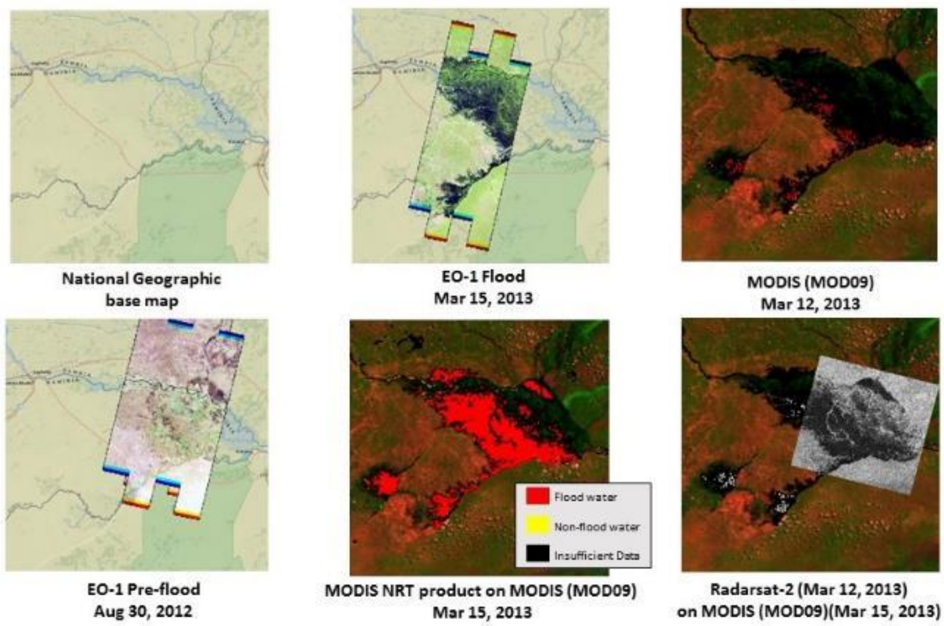

Fig. 12. MODIS 3D3OT NRT flood water detection in Namibia.

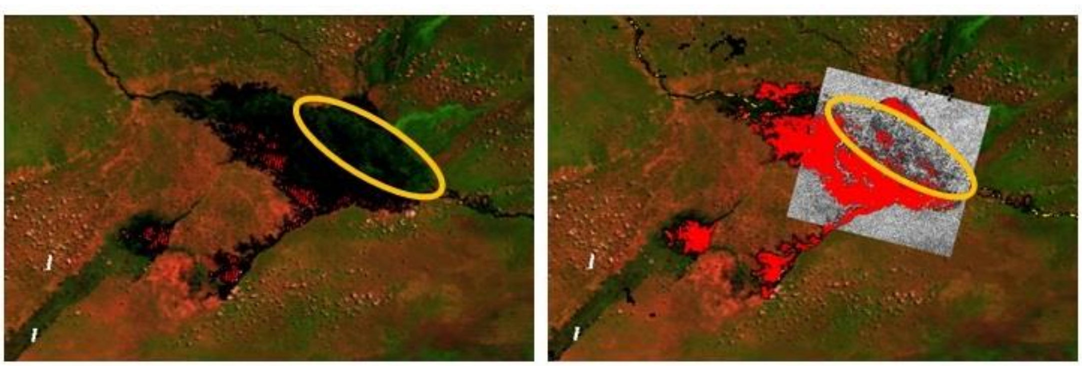

Fig. 13. Flooded vegetated areas (orange ellipse).

Unsuccessful Flood Detection Examples by the 3D3OT NRT Product: False Positives

In Figure 14, terrain shadow created false positives, or errors of commission, for flooding throughout the Al Hajar Mountains of Oman. Products and imagery for both June and November were reviewed since, if these are indeed terrain shadows appearing in November, they should disappear when the sun is higher, at mid-year. This is the case, as seen in the June example and so the review provided strong evidence that the January flood indications were false positives likely to be an artifact of terrain shadow. Note that it is possible that land that falls within a shadow (terrain or cloud) may in fact be flooded, but in these cases it is difficult to confirm the existence of flood.

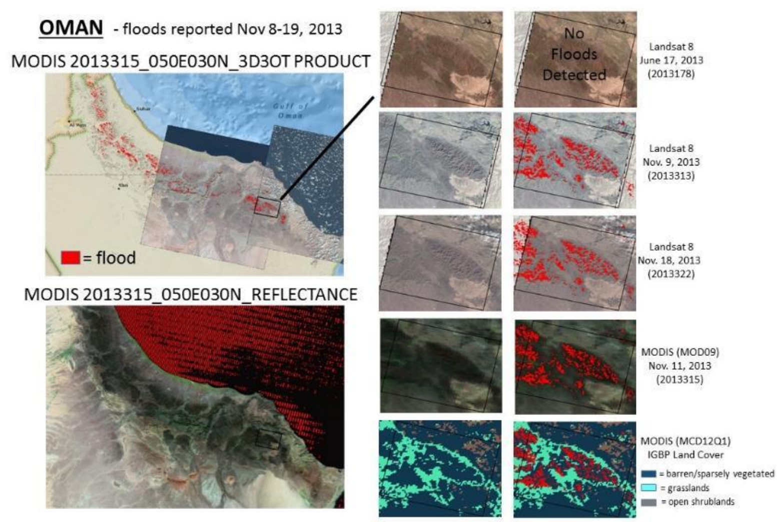

Fig. 14. Terrain shadow causing erroneous flood detection in Al Hajar Mountains, Oman.

Figure 15 shows false positives due to terrain shadow in the Nepalese Himalayas.

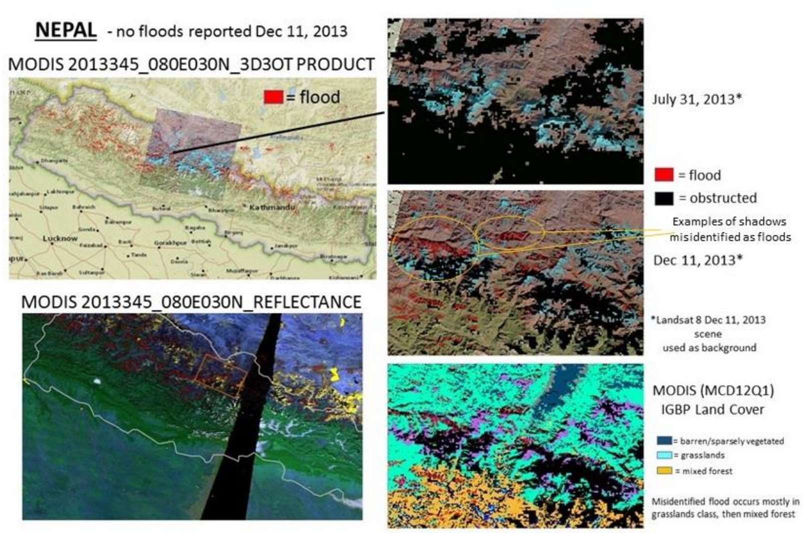

Fig. 15. Terrain shadow causing erroneous flood detection in Nepalese Himalayas.

It was discovered that false positives also occurred in areas characterized by volcanic material, as seen in Hawaii (Fig. 16), Syria (Fig. 17), and Arizona (Fig. 18). These misdetections persist throughout the year.

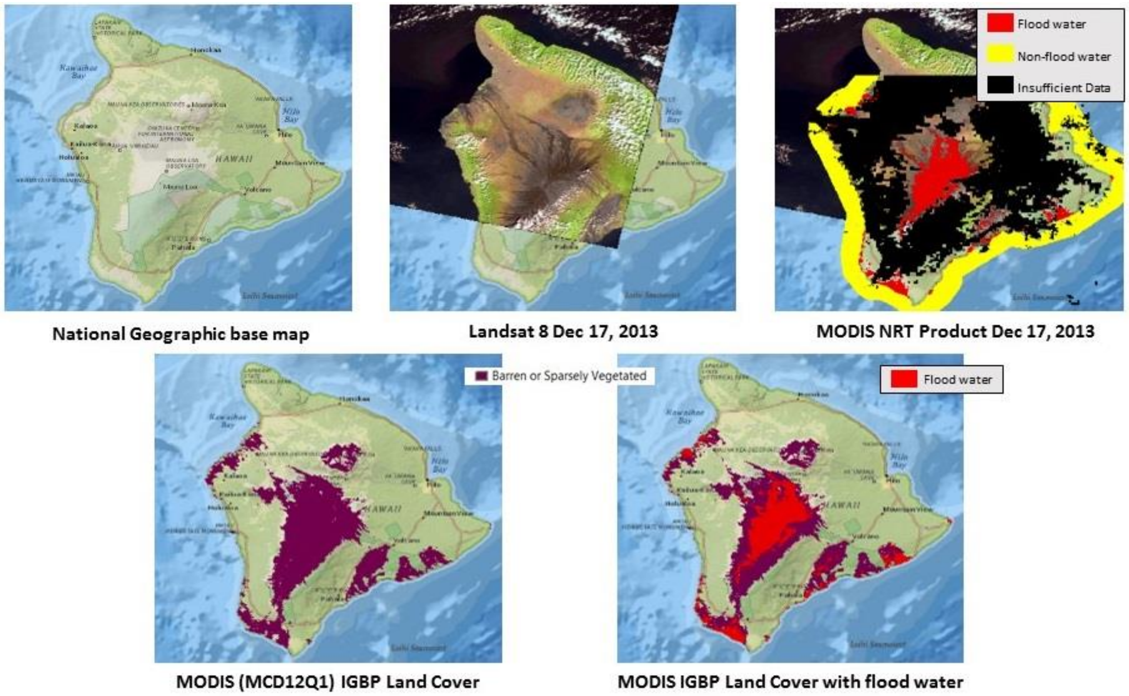

Fig. 16. Volcanic material causing false positives on exposed volcanic material, Mauna Loa, Hawaii.

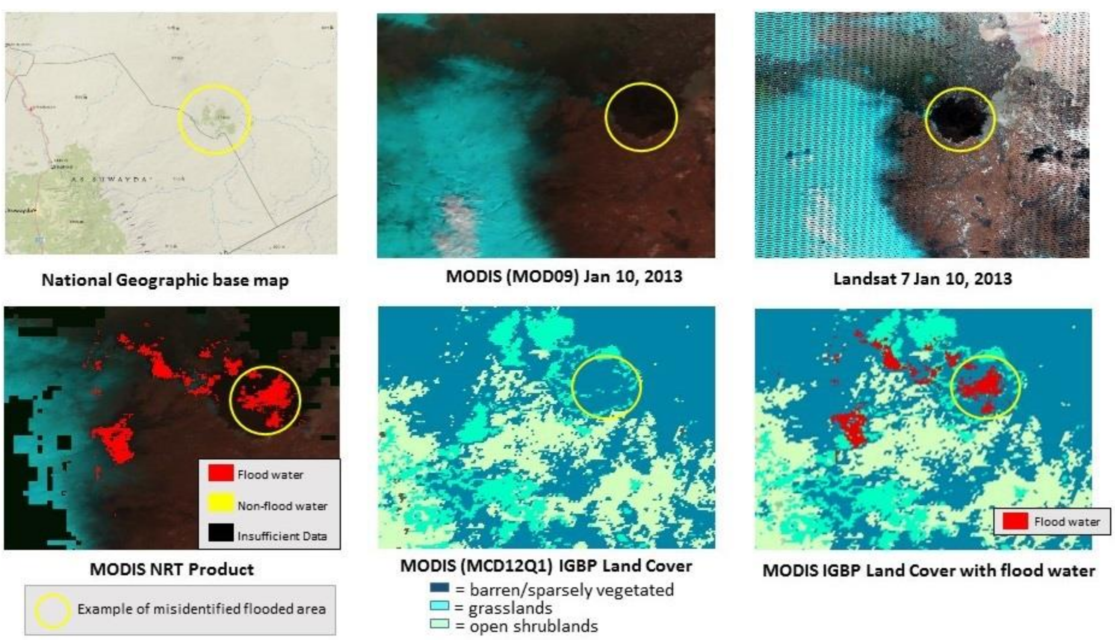

Fig. 17. Volcanic material causing false positives in Tulul al-Safa volcanic field, Syria.

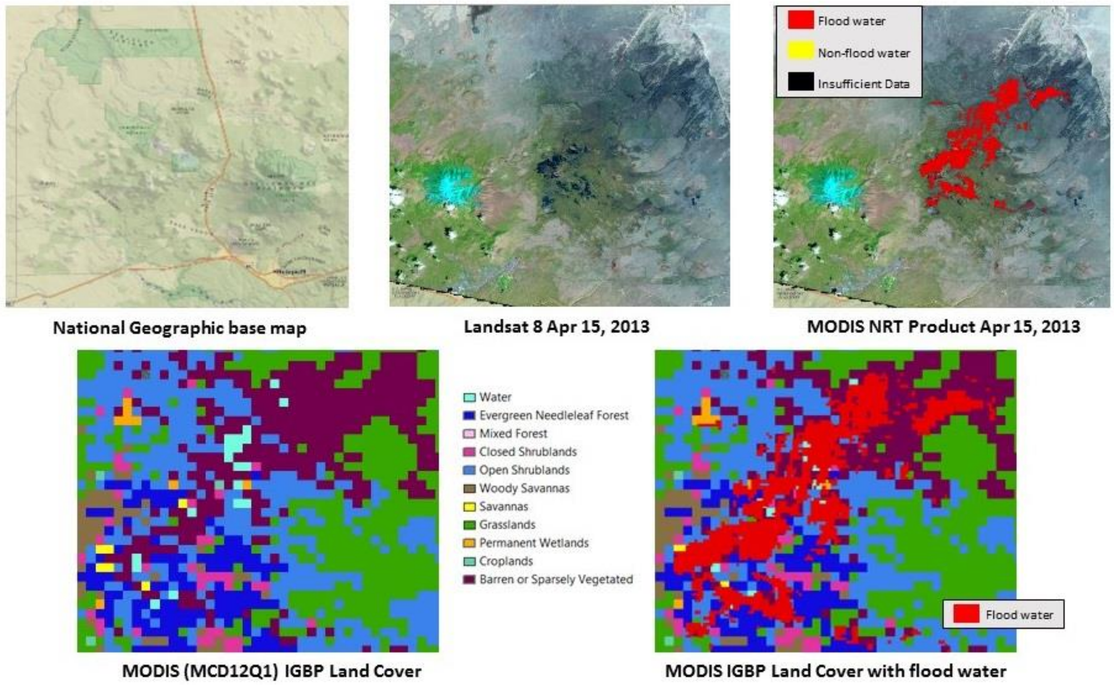

Fig. 18. Volcanic material causing false positives in Sunset Crater, Arizona.

In these three examples, the volcanic material coincides mostly with the barren and sparsely vegetated MODIS IGBP class. This can be seen best in the Hawaii example (Fig. 16) where all of the false positives lie within this class.

Another phenomenon that sometimes results in flood commission error is cloud shadow (Fig.19).

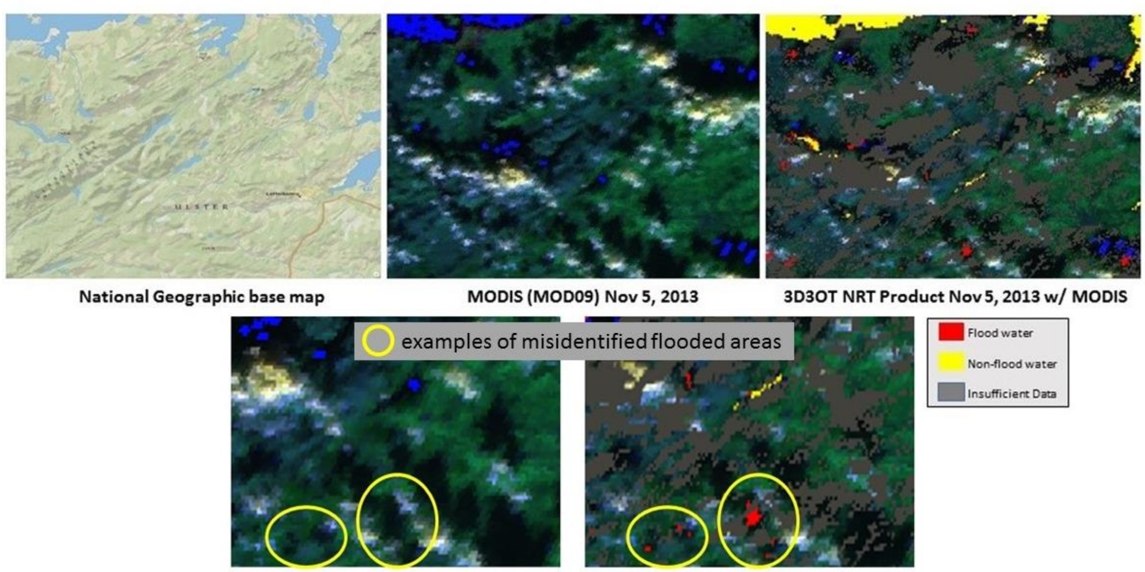

Fig. 19. Cloud shadow causing false positives in Ireland.

Land Cover and Flood Detection Results

The MODIS 500m Yearly IGBP Land Cover Type product (https://lpdaac.usgs.gov/products/modis_products_table/mcd12q1) was used to assess whether or not there is a relationship between flood detection performance and land cover type by manually determining the majority land cover type for each flood event (Fig. 20). 12 of 15 of the IGBP land cover types, excluding the 'water' class, were represented (Table 7).

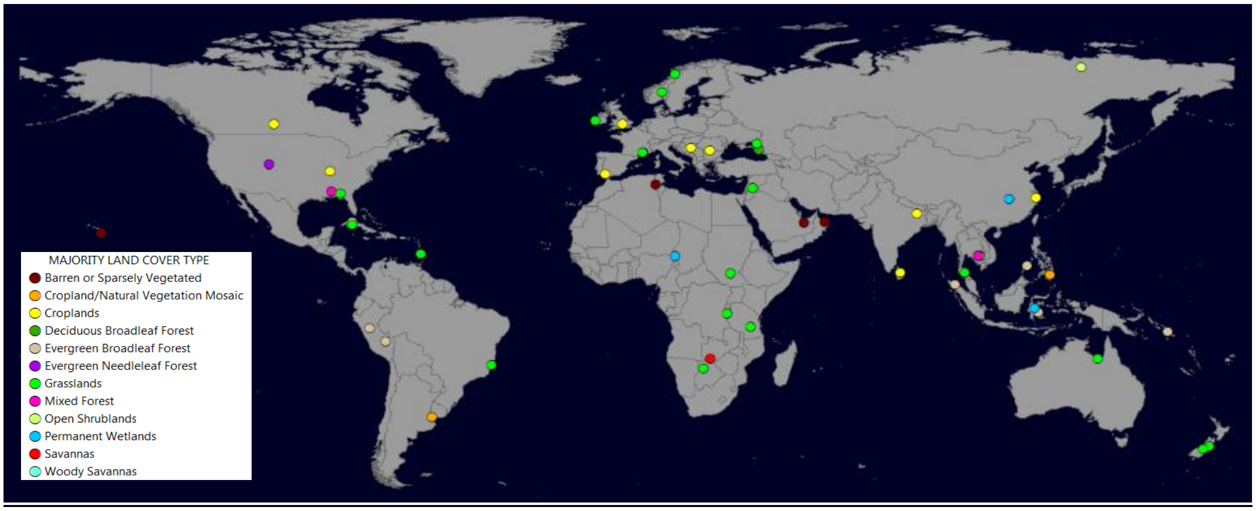

Fig. 20. MODIS IGBP land cover class at each flood event location.
(Note: a few sites may be hard to see on the map due to their close proximity to other sites.)

Land Cover Type	TMC	1-poor	2-fair	3-good	4-excellent	5-almost perfect	Outside product coverage area	TOTAL
Barren/Sparsely Veg.	1	3	0	0	1	0	0	5
Cropland/Natural Veg. Mosaic	3	0	0	0	0	1	0	4
Croplands	1	0	1	0	6	2	0	10
Deciduous Broadlf Forest	1	0	0	0	0	0	0	1
Evergreen Broadlf Forest	6	0	0	1	0	0	1	8
Evergreen Needlelf Forest	1	2	0	0	0	0	0	3
Grasslands	2	3	0	1	1	0	0	7
Mixed Forest	1	1	0	0	0	2	0	4
Open Shrublands	0	1	0	0	0	1	0	2
Permanent Wetlands	0	1	0	0	2	1	0	4
Savannas	1	0	0	0	0	3	0	4
Woody Savannas	0	0	0	0	0	1	0	1
TOTAL	17	11	1	2	10	11	1	53

Table 7. Flood detection rating by land cover.

The majority of floods that occurred in *barren and sparsely vegetated* areas were poorly detected, due to either volcanic material or terrain shadow, as discussed previously. The poor detections that occurred in *evergreen needleleaf forested* areas were found in Colorado and France. In Colorado, cloud shadow was the cause of the misdetection while in France, it seems that some area of permanent water (although classified as forest in the MODIS product) is being misclassified as flood. The poor detections that occurred in *grassland* areas were due to volcanic material, terrain shadow, and permanent water misidentification. It would appear that, in this category, the IGBP class may be misclassified since the volcanic material should coincide with the *barren and sparsely vegetated* class and not *grasslands*. The product generally worked very well in the *cropland* and *savanna* landcovers.

Time of Year and Flood Detection Results

Upon quick inspection of the ratings and the months in which the floods occurred, there doesn't seem to be any correlation. The black numbers in the Table 8 represent the total number for flood events in each rating category for a given month. The orange values in parentheses represent the number of flood events of the total that occurred in the southern hemisphere.

FLOOD RATING	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Poor	3 (1)	1		1	2				1	1	2		11
Fair	1												1
Good	2												2
Excellent	2		2(1)		1	1				2	1	1	10
Almost Perfect	3(2)	1	1(1)	2(1)	2(1)					1	1		11
TMC	4(2)	2(1)	2(1)	4	1	1(1)				1(1)		2	17

Table 8. Flood detection rating by month.

Permanent Water Detection Method and Results

The evaluation of permanent water detection by the 3D3OT NRT product was completed in the same manner as described in the previous flood detection method section (p. 8) using MODIS surface reflectance and higher resolution imagery, when available, to evaluate the product. For the most part, the product was successful in capturing permanent water bodies (Fig. 21 and Table 9). 58% were classed as either *good*, *excellent* or *almost perfect*, 11% were either classed as *poor* or *fair* and 31% could not be evaluated due to too many clouds (*TMC*).

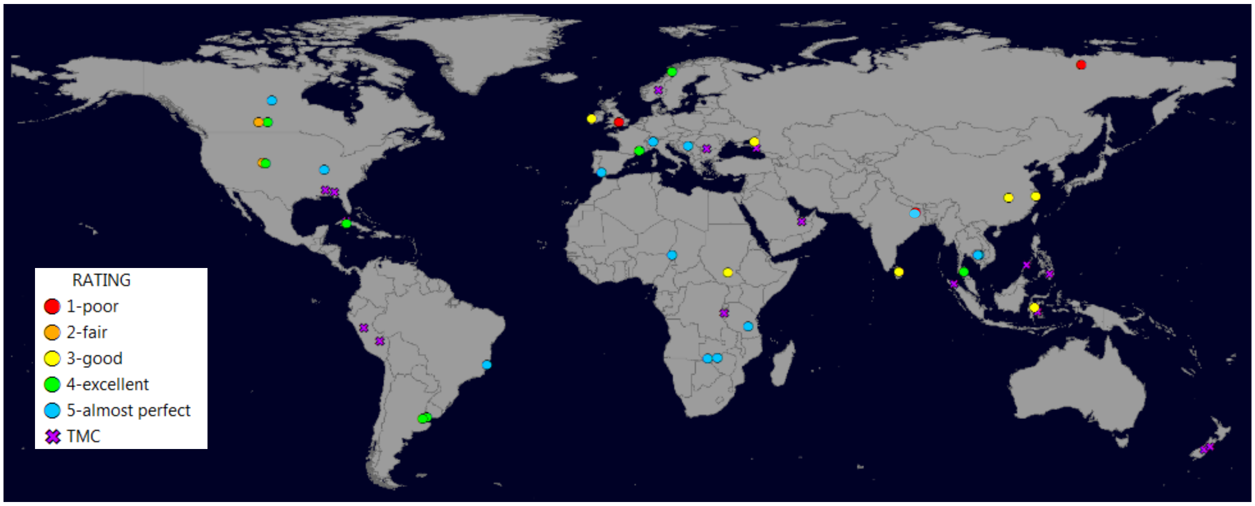

Fig. 21. Permanent water detection rating at each location.
(Note: a few sites may be hard to see on the map due to their close proximity to other sites.)

RATING	Count	%
5-almost perfect	16	29
4-excellent	9	16
3-good	7	13
2-fair	2	4
1-poor	4	7
TMC - too many clouds	17	31
Outside product coverage area*	1	Eliminated from equation
TOTALS	56	100

Table 9. Permanent water detection rating breakdown. (*Note: 'Outside product coverage area" represents a flood event in the Solomon Islands that was initially selected before it was discovered to be within a tile that has no product availability.)

As mentioned previously, these percentages represent product performance given real-world limitations of the data, such as cloud cover. If the *TMC* cases are excluded from the equation, the total case results reflect the performance of the algorithm/compositing itself and where the product could have been successful. Areas of permanent water that were classed as either *good*, *excellent* or *almost perfect* increase to 84% while the events classed as either *poor* or *fair* increase to 16% (Table 10).

EVENT TYPE	**No clouds**	**Overall**
Permanent water (good, excellent, almost perfect)	**84%**	**58%**
Permanent water (poor, fair)	**16%**	**11%**

Table 10. Permanent water detection rating summary.

Successful Permanent Water Detection Examples by the 3D3OT NRT Product

The successful capture by the 3D3OT NRT product of permanent water, classed as 'Non-flood water', can been seen in the figures of Cameroon/Chad, Cambodia, and Kentucky (Figs. 7, 9, and 10 respectively). Additional successful permanent water detection examples are shown below (Figs. 22-23).

Fig. 22. Permanent water detection, Lake Kariba on the border of Zambia and Zimbabwe.

Fig. 23. Permanent water detection on the southern coast of France.

Unsuccessful Permanent Water Detection Examples by the 3D3OT NRT product: False Negatives

Permanent water omission errors frequently resulted from cloud cover and small water body size. If the water body is too small, the resolution of the MODIS product may be too coarse to identify it. There are also a few instances when only a small amount of the permanent water is detected (red circles in Fig. 24), possibly due to cloud cover, but maybe due to other factors, such as scan angle. The product results (middle and right panels, Fig. 24) are surprising since the water pixels are clearly identifiable in 5 of the 6 Terra/Aqua images that comprise the 3-day products. The only image fully obscured by cloud cover is the Aqua image from July 5 (middle-left panel, Fig. 24). The same water bodies are clear in the 5 other images.

The same problem is found in the poor product results shown in Figure 25, which is strangely pixelated. Upon inspection of other products from different dates for the same location, the permanent water is sometimes represented, revealing that the scan angle may in fact be the cause. In any case, detection of the river at this location is at the limit or resolution of the sensor: most pixels along the river will be mixed water/land. Further investigations need to be conducted to better understand the nature of the omission, and to test the spatial limit of detection of permanent water.

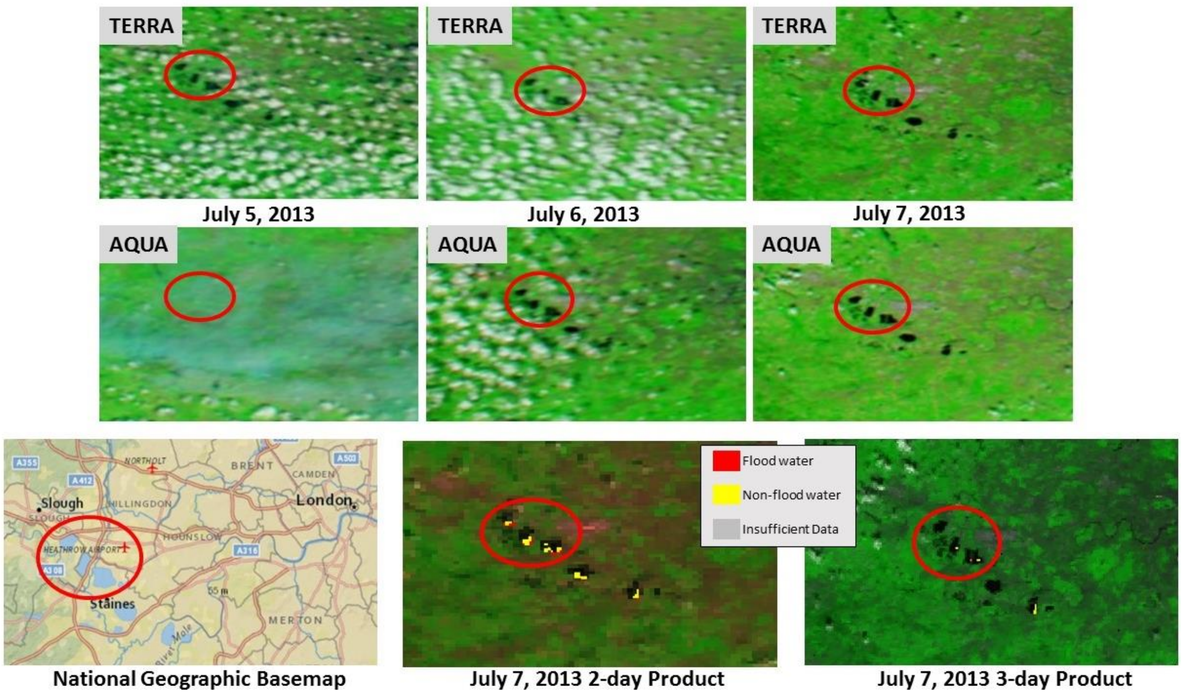

Fig. 24. Permanent water omission near London, England.

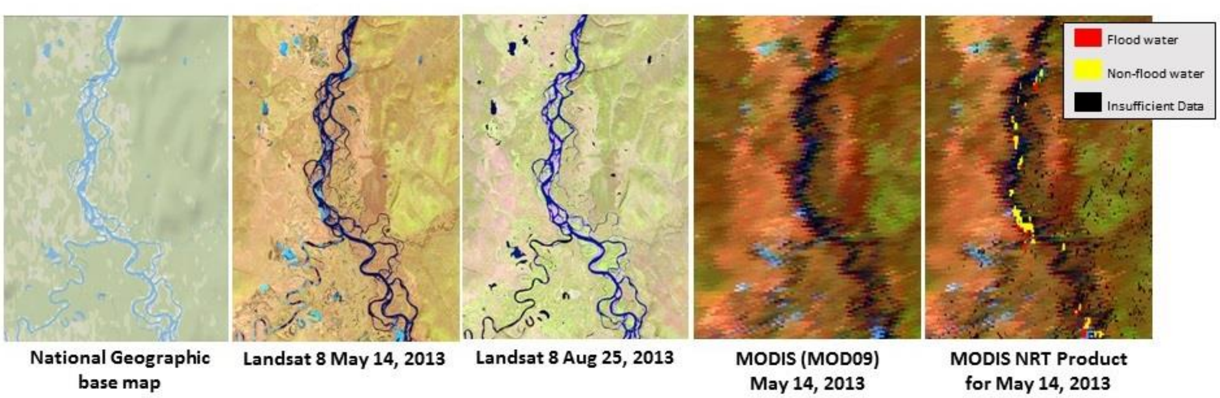

Fig. 25. Permanent water omission near Saydy, Russia.

Unsuccessful Permanent Water Detection Examples by the 3D3OT NRT product: False positives

No major examples of commission errors were discovered in the evaluation of permanent water bodies.

3D3OT vs 2D2OT Product

Although the focus of the evaluation was on the 3-day (3D3OT) NRT product, at times the 2-day (2D2OT) product was assessed for comparative reasons. In a few cases, the 2-day product results were better than those of the 3-day product in terms of how cloud cover was handled (Figs. 26, 27 & 28). In Figure 26, the flood water representation is more complete in the 2-day product than in the 3-day product due to less cloud cover over the area of interest in the first two days, than in the third day. This is because the 2-day product requires less cloud free acquisitions than the 3-day product for any given water pixel.

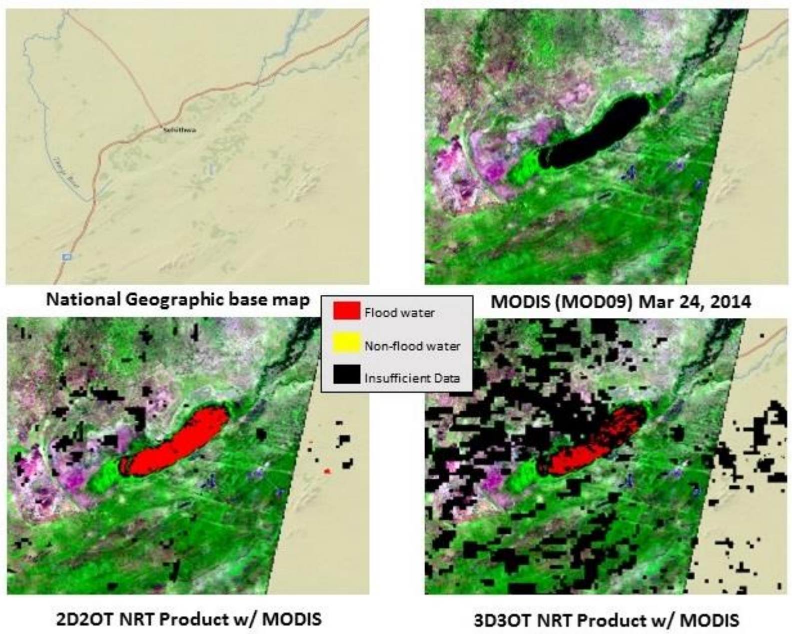

Fig. 26. 2-day (2D2OT) vs. 3-day (3D3OT) product results in Botswana.

In terms of permanent water detection, Figure 27 shows, for Cambodia on June 25, 2013, there was one clear MODIS Aqua image available (middle-left panel, Fig. 27), but with Terra there was a gap between swaths (left panel, Fig. 27). June 24th (top-right panel, Fig. 28) had partly cloudy images of the lake for both sensors. June 23rd was useless for both as the images were totally cloud covered (top-middle panel, Fig. 28). So in this case, the 3-day product for June 25th (bottom-middle panel, Fig. 28) didn't have the 3 cloud free acquisitions required to indicate water and so the composited cloud cover over the 3 days produced worse results that the 2-day product (middle-right panel, Fig. 27). The 2-day product is better since there were clear data from Aqua on the 25th (bottom-left, Fig. 28) with the two partly clear/partly cloudy images on the 24th. The omission of some of the permanent water pixels is shown for the 3-day product

(Figs. 27 & 28). Compare the middle-right panel of Fig 27 (yellow represents permanent water) to the bottom middle/right panel of Fig. 28 to see the difference between the 2-day and 3-day product results.

This is the downside of the 3-day product, with the upside being the elimination of most cloud shadow issues (Fig. 29). A 1-day product is available that requires a single water detection on a single day (nominally two data acquisitions) to classify a pixel as water, however as previously mentioned, it is only turned on for specific events of current interest, and is not yet run routinely.

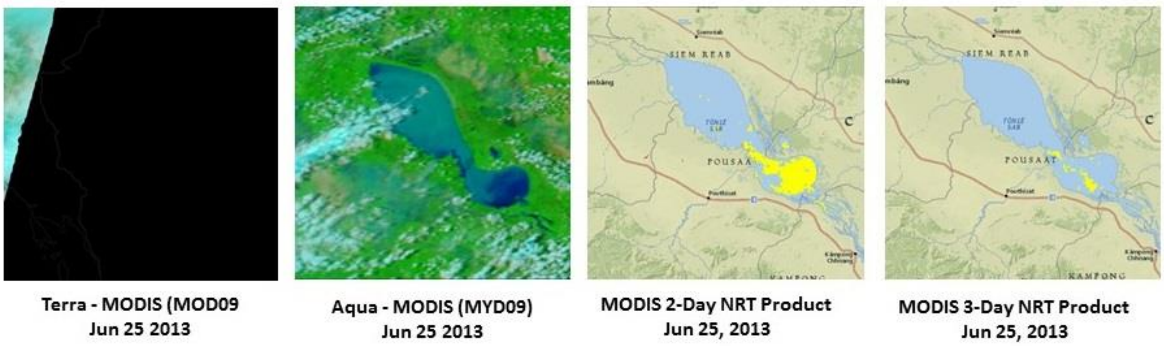

Fig. 27. MODIS Terra and Aqua images and 2-day vs 3-day permanent water product representation (yellow) for Cambodia, June 25, 2013.

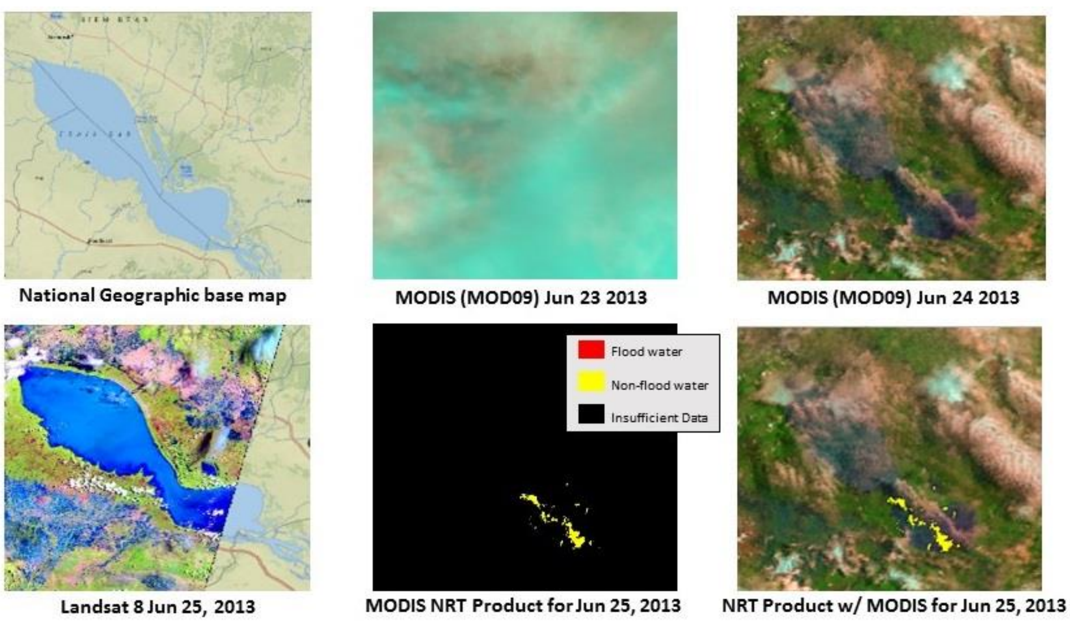

Fig. 28. 3-day product results in Cambodia. Most of the permanent water is obscured due to 3-day composite of cloudy imagery.

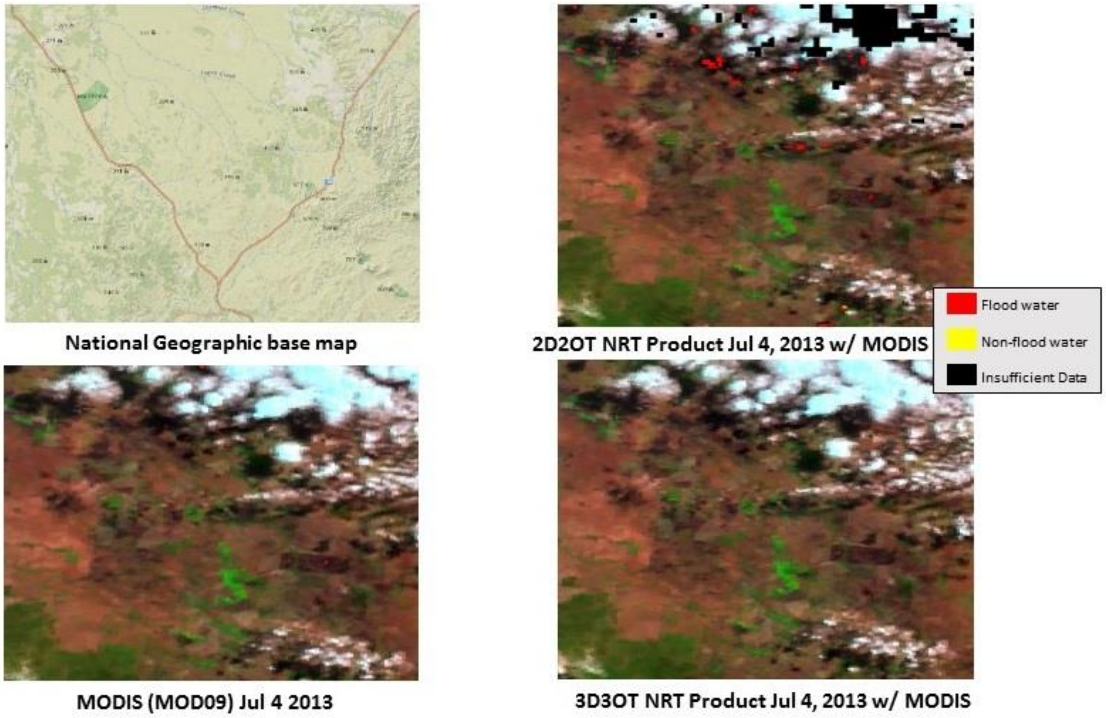

Fig. 29. Elimination of cloud shadow false positives in Australia (red areas in top right image are misidentified as floods) when going from the 2-day to the 3-day NRT product.

<u>14-Day Product</u>

As mentioned earlier, in circumstances when a flood event is not detected due to cloud cover, the NRT 14-day flood product (14x3D3OT) may prove more useful than a single 3-day product. The 14-day flood product is a 2nd order product; it is a composite of the previous 14 days' 3-day products, and thus provides a recent-historical view of flooding and surface water extent. The 14-day product helps to overcome patchiness in 2 and 3 day products due to clouds that might otherwise suggest a flood is no longer present. For more information on this product please refer to http://oas.gsfc.nasa.gov/floodmap/productDescription.htm.

Below (Fig. 30) is a comparison between the 3-day and the 14-day product. What one should note is that the 14-day product (right panel) shows flood event activity in areas that are clouded over in the 3-day product (left panel). A full evaluation of the 14-day product is beyond the scope of this initial product evaluation.

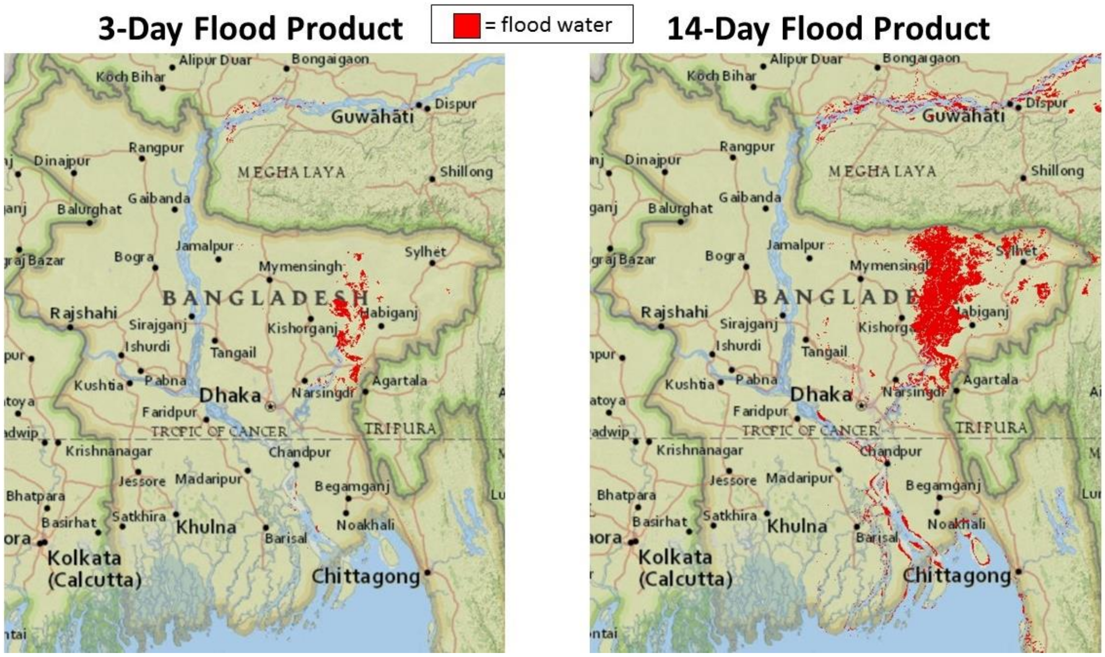

Fig. 30. NRT 3-day vs. 14-day product results for Sept 25, 2014, Bangladesh

Landsat Incorporation

As shown in this paper, Landsat has been very valuable in the evaluation of the NASA/ DFO MODIS NRT flood mapping products. It is possible to produce water classifications from Landsat 8 images as outlined on http://floodobservatory.colorado.edu/Version3/2014Paraguay4150.html. Further evaluation and validation of the MODIS NRT product results could proceed by comparing these to a Landsat 8 classification, with the assumption that Landsat 8 will be more accurate due to its 30-m spatial resolution rather than 250-m. However, the MODIS NRT date(s) to use will need to be chosen carefully in order to match with Landsat 8, because of the three day coverage of the NRT files.

Conclusion

The flood event and permanent water detection capabilities of the NASA/ DFO Global MODIS Flood Mapping Product performed very well overall on both accounts. Performance patterns did not seem to be influenced by latitude or time of the year, although IGBP land cover type may be a factor.

In some circumstances the product did not perform very well. Areas of cloud cover and possible inundated vegetation lead to errors of omission while areas of extreme terrain, volcanic material, and cloud shadows lead to errors of commission. These causes, along with the examples provided in this document, are listed in the Table 11.

Causes of Commission	Causes of Omission
Terrain Variation (Oman, Nepal) – terrain shadow leading to false flood water positives	**Cloud Cover** (Peru, Cambodia) – obscuring spectral response of flood water
Volcanic Material (Hawaii, Syria, Arizona) – spectral characteristics of volcanic materials leading to false flood positives	**Inundated Vegetation** (Namibia) – obscures surface water
Cloud Shadow (Ireland, Australia) – shadow leading to false flood positives	**Short-lived floods, small floods,** and **sediment-rich areas of water** (not encountered in the evaluation locations)

Table 11. Causes of erroneous flood commission/omission.

Other factors not encountered in this evaluation that may lead to errors of omission are 1) if the flood is too short-lived to be seen given that three days of reasonably clear skies are needed to capture it, 2) floods too small to be detected by the 250m MODIS pixels used by the system, and 3) sediment-rich areas of water that camouflage the flood event as land. Scan angle may contribute to poor detection also, but we have only preliminary evidence for this.

Some opportunities for improvement lie in the possibility to adjust the band math portion of the algorithm for different map sheets and use validation images or maps to fine tune the water detection math. Filtering out terrain shadow, setting thresholds for water/land at different values for different times of the year, and change detection will also be of use. Overall, this evaluation does not reveal any particular deficiency in the water detection algorithm as most of the errors appear to be due to shadows, clouds, and volcanic material.