ASTER cloud coverage reassessment using MODIS cloud mask products

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ABSTRACT

In the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) Project, two kinds of algorithms are used for cloud assessment in Level-1 processing. The first algorithm based on the LANDSAT-5 TM Automatic Cloud Cover Assessment (ACCA) algorithm is used for a part of daytime scenes observed with only VNIR bands and all nighttime scenes, and the second algorithm based on the LANDSAT-7 ETM+ ACCA algorithm is used for most of daytime scenes observed with all spectral bands. However, the first algorithm does not work well for lack of some spectral bands sensitive to cloud detection, and the two algorithms have been less accurate over snow/ice covered areas since April 2008 when the SWIR subsystem developed troubles. In addition, they perform less well for some combinations of surface type and sun elevation angle. We, therefore, have developed the ASTER cloud coverage reassessment system using MODIS cloud mask (MOD35) products, and have reassessed cloud coverage for all ASTER archived scenes (>1.7 million scenes). All of the new cloud coverage data are included in Image Management System (IMS) databases of the ASTER Ground Data System (GDS) and NASA's Land Process Data Active Archive Center (LP DAAC) and used for ASTER product search by users, and cloud mask images are distributed to users through Internet. Daily upcoming scenes (about 400 scenes per day) are reassessed and inserted into the IMS databases in 5 to 7 days after each scene observation date. Some validation studies for the new cloud coverage data and some mission-related analyses using those data are also demonstrated in the present paper.

Keywords: ASTER, MODIS, MOD35, cloud mask, cloud coverage, ASTER GDS, LP DAAC, metadata

1. INTRODUCTION

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) [1] developed by the Japanese Government is a high spatial resolution multispectral imager on the Terra satellite—the first platform of the National Aeronautics and Space Administration's (NASA) Earth Observing System (EOS)—launched in December 1999. The ASTER instrument has three, six, and five spectral bands with spatial resolutions of 15, 30, and 90 m in the visible and near-infrared (VNIR), the shortwave infrared (SWIR), and the thermal infrared (TIR) spectral regions, respectively. The ASTER instrument has some observation modes—the Full Mode is an observation mode with all spectral bands and is applied to most of daytime observations, the VNIR-Only Mode is occasionally used in emergent daytime observations, and the SWIR+TIR Mode and the TIR-Only Mode are used in nighttime observations.

Cloud assessment in Level-1 processing is performed by either of two algorithms. The first algorithm based on the LANDSAT-5 TM Automatic Cloud Cover Assessment (ACCA) algorithm [2] has been used for limited daytime scenes observed under the VNIR-Only Mode and all nighttime scenes. This algorithm was used for all scenes before 28 October 2000, called the ASTER Cloud Coverage Assessment Algorithm (ACCAA) [3][4]. The second algorithm based on the LANDSAT-7 ETM+ ACCA algorithm has been used for daytime scenes observed under the Full Mode since 28 October 2000. However, the first algorithm does not work well for lack of some spectral bands sensitive to cloud detection, and the two algorithms have been less accurate over snow/ice covered areas since April 2008 when the SWIR subsystem developed troubles in the detector temperature control. In addition, they perform less well for some combinations of

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surface type and sun elevation angle such a desert observation under a low sun elevation.

We, therefore, have developed the ASTER cloud coverage reassessment system using Terra/MODIS cloud mask (MOD35) products. Since the MODIS instrument has a duty cycle of 100%, MOD35 products are available for almost all ASTER scenes. The ASTER archived scenes (>1.73 million scenes) have been reassessed for cloud coverage using the developed system, and daily upcoming scenes (about 400 scenes per day) are reassessed every day. All the reassessed results are transferred to ASTER Ground Data System (GDS) and NASA's Land Process Data Active Archive Center (LP DAAC), and used in ASTER product search by users. In the present paper, we introduce this system in detail. The present paper also involves some validation results of the new cloud coverage data and some ASTER's mission analysis results using those data.

2. CLOUD ASSESSMENT ALGORITHMS

2.1 ASTER cloud assessment algorithm

In the ASTER Project, two kinds of algorithms are used for cloud assessment in Level-1 processing [4]. Both algorithms are based on the ACCA algorithm of the LANDSAT Project [2].

The first algorithm, ACCAA, is the modified version of the LANDSAT-5 TM ACCA algorithm [3][4]. The algorithm is a single pass process that employs thresholds for bands 2 (VNIR), 4 (SWIR), and 11 (TIR) as follows:

[Filter 1] $B2 \leq TH_2$ = not cloud

[Filter 2] $B11 \geq TH_{11}$ = not cloud

[Filter 3] $\{B4 > TH_4\}$ or $\{TH_4 \geq B4 > TH_4'$ and $B2 > TH_2'\}$ = cloud

where Bx is the reflectance for bands 2 and 4, and the temperature for band 11, and TH_x is an empirical threshold for band x which are defined as a function of sun elevation, latitude zone, and month. Filters 1 and 2 express that clouds have high reflectance and low temperature. Filter 3 can separate cloud and snow/ice.

The second algorithm with higher accuracy is the modified version of the LANDSAT-7 ETM+ ACCA algorithm [2]. The algorithm has two passes. The pass one consists of eight filters.

[Filter 1] $B4 \leq TH_2$ = not cloud

[Filter 2] $NDSI = (B1–B4)/(B1+B4) \geq TH_{NDSI}$ = not cloud

[Filter 3] $B13 \geq TH_{13}$ = not cloud

[Filter 4] $(1–B4)*B13 \geq TH_{4,13}$ and $B4 < TH_4$ = not cloud, $(1–B4)*B13 \geq TH_{4,13}$ and $B4 \geq TH_4$ = ambiguous

[Filter 5] $B3/B2 \geq TH_{3/2}$ = ambiguous

[Filter 6] $B3/B1 \geq TH_{3/1}$ = ambiguous

[Filter 7] $B3/B4 \leq TH_{3/4}$ = ambiguous

[Filter 8] $(1–B4)*B13 < TH'_{4,13}$ = cold cloud, $(1–B4)*B13 \geq TH'_{4,13}$ = warm cloud

where Bx is the reflectance except for band 13, and the temperature for band 13, and TH_x is an empirical threshold for band x. Pixels classified as "ambiguous" or "warm clouds" are applied to the pass two that refines the pass one result based on statistical features in band 13 (TIR) and spatial distribution.

In the early mission period, the first algorithm (ACCAA) was applied to all daytime and nighttime products. Since 28 October 2000, the second algorithm has been used for all daytime products observed by the Full Mode, but the ACCAA has been still used for all nighttime products and some daytime products observed by the VNIR-Only Mode because some spectral bands necessary for the second algorithm are not available [4][5]. Since April 2008, cloud assessment over snow/ice covered areas have been less reliable, because band 4 (1.6-μm) which is effective for cloud and snow/ice separation has been not available due to a problem of the SWIR detector temperature control.

2.2 MODIS cloud assessment algorithm

The MOD35 product is the Terra/MODIS Level-2 cloud mask product with spatial resolutions of 1 km and 250 m. In the ASTER cloud reassessment system, the 1-km products are used because the 250-m products are not available for nighttime observations.

The MOD35 algorithm is divided into seven conceptual domains according to surface types and solar illumination [6]: (1) daytime land, (2) daytime water, (3) nighttime land, (4) nighttime water, (5) daytime desert, (6) daytime snow/ice covered regions, and (7) nighttime snow/ice covered regions. Then, appropriate single field-of-view (FOV) spectral tests are applied for the given domain. The results of the single FOV tests are grouped as follows:

Group I (Simple IR threshold test)

[BT_{11}] daytime water, and nighttime water

[$BT_{13.9}$] all daytime and nighttime domains

[$BT_{6.7}$ & BT_{11}–$BT_{6.7}$] all daytime and nighttime domains

Group II (Brightness temperature difference)

[$BT_{8.6}$ –BT_{11} & BT_{11}–BT_{12}] daytime and nighttime domains except for snow/ice

[$BT_{7.3}$ –BT_{11}] nighttime land, coastline, and desert

[BT_{11} –$BT_{3.9}$] all daytime and nighttime domains

Group III (Solar reflectance tests)

[$R_{0.66}$ or $R_{0.87}$] all daytime domains

[$R_{0.87}$/$R_{0.66}$] daytime water, land, and coastline

Group IV (NIR thin cirrus)

[$R_{1.38}$] all daytime domains

Group V (IR thin cirrus)

[$BT_{3.7}$ –BT_{12}] nighttime land, snow/ice, and desert

where BTx is the brightness temperature of band x, and Rx is the reflectance of band x. For nighttime observations, Groups I, II, and V are applicable.

The minimum of the confidence flags of tests in each group is defined as the confidence flag of that group. The final cloud mask confidence is given by calculating the *N*th root of the product of *N* groups' confidence flags, where *N* is the number of groups applied. In some cases, spatial uniformity on 3 x 3 pixel regions and/or temporal consistency is also checked. Thus, the final cloud mask is expressed by four levels of confidence: cloudy, uncertain, probably clear, and confident clear.

MODIS cloud mask products have been validated using aircraft observations, surface remote sensing, and Terra/Aqua platform instruments [6].

3. ASTER CLOUD REASSESSMENT SYSTEM

3.1 Availability of MOD35 products in ASTER cloud assessment

The MODIS instrument has a duty cycle of 100%, while the ASTER instrument has the maximum duty cycle of 8%. Therefore, all ASTER observations are accompanied by Terra/MODIS observations, so that MOD35 products are available for almost all ASTER scenes except for a few cases that MODIS data were lost due to some reasons such as a Science Formatting Equipment (SFE) anomaly and a data transmission failure [7]. The swath width of MODIS is 2,330 km in cross track while that of ASTER is 60 km, and ASTER scenes are located near the central line (nadir line) on the corresponding MODIS scene.

Since MODIS Level-2 products including a MOD35 product are divided at a 5-minute interval in the observation time, the MOD35 product corresponding to each ASTER scene can be identified by the ASTER observation time. The MOD35-based cloud mask of each ASTER scene can be generated by crop and interpolation for the identified MOD35 product. Thus, each ASTER product is not necessary for generation of its MOD35-based mask―only observation time and scene location, included in the metadata, are necessary for this processing.

3.2 ASTER cloud reassessment system using MOD35 products

The ASTER cloud reassessment system using MOD35 products was originally developed for cloud reassessment of ASTER nighttime scenes [8]. For improvement of cloud assessment not only for nighttime but also for daytime, this system was updated as to be applicable to daytime scenes as well as nighttime scenes, but it was not combined with the ASTER Ground Data System (ASTER/GDS) because of the minimum modifications to ASTER/GDS which had been stably operated. Thus, the cloud reassessment system is placed out of ASTER/GDS, and only metadata and cloud reassessment results are exchanged between the cloud reassessment system and ASTER/GDS. The detailed descriptions on the cloud reassessment system are given below:

1. The ASTER cloud reassessment system using MOD35 products is operated by Ibaraki University.
2. ASTER/GDS provides the metadata (scene ID, location, etc.) of ASTER scenes for Ibaraki University.
3. In Ibaraki University, MOD35 products corresponding to the ASTER scenes listed are determined, and downloaded from the Level 1 and Atmosphere Archive and Distribution System (LAADS) Web (http://ladsweb.nascom.nasa.gov/) operated by NASA Godard Space Flight Center (GSFC). Next, the cloud mask image of each ASTER scene is generated, and distributed through a web site. Then, the cloud coverages (scene cloud coverage, and quadratic cloud coverages) of the ASTER scenes are calculated from the generated cloud masks.
4. ASTER/GDS obtains the cloud coverage data from Ibaraki University, and send them to LP DAAC.
5. ASTER/GDS and LP DAAC rewrite a related database in each Image Management System (IMS), thus users can search ASTER products based on the new cloud coverage information.

Fig. 1 displays data flows among organizations. Typically, the metadata are transferred from ASTER/GDS to Ibaraki University within 4―6 days after each scene observation date, and then the reassessed cloud coverage data are transferred from Ibaraki University to ASTER/GDS in one day. Thus, the new cloud information will be available on the web sites 5―7 days after each scene observation date.

Fig. 2 shows an example of cloud coverage data transferred from Ibaraki University to ASTER/GDS, including scene ID (granule ID), day/night flag, total cloud coverage, quadratic cloud coverages (for upper left, upper right, lower left, lower right subscenes), and uncertainly. The uncertainty is the ratio (%) of "uncertain" pixels to all pixels, where "uncertain" means one of the four confidence levels in a MOD35 product. The uncertainty itself is not inserted into the IMS databases.

Fig. 3 shows an example of a generated cloud mask image with its ASTER browse image.

For all ASTER archived scenes, cloud masks and cloud coverages were generated by August 2009, and transferred from Ibaraki University to ASTER/GDS and LP DAAC. As for daily upcoming scenes (about 400 scenes per day), their metadata are transferred from ASTER/GDS to Ibaraki University every day, and their cloud coverage data are transferred from Ibaraki University to ASTER/GDS and then inserted into each IMS database. As of 12 September 2010, the number of ASTER scenes processed by the cloud reassessment system is about 1.73 million (1.51 million in daytime, and 0.22 million in nighttime). The number of the MOD35 products used is about 168,700, which means that about ten ASTER scenes are included in one MOD35 scene in average.

All ASTER cloud masks are distributed to general users at http://tonolab.cis.ibaraki.ac.jp/ASTER/cloud/ which is linked from the ASTER Science Web (http://www.science.aster.ersdac.or.jp/en/project/other.html). On the cloud mask web site, a user needs to input the observation date and time of an ASTER scene of interest and can optionally select either a heading up mask or a north up mask for a nighttime scene (Fig. 4 left), so that, if the requested cloud mask exists, it is displayed as a JPEG image and its raw files are also provided (Fig. 4 right). Raw cloud mask files are 700×700 images in two formats: 8-bit format and 32-bit format. The 32-bit format is the first 32-bits of the 48-bit MOD35 cloud mask (the last 16-bits excluded contain 250-m resolution flags available in only daytime). The specification of the 32-bit format is shown in Table 1. The 8-bit format contains only the confidence levels in a character type (0: cloudy, 1: uncertain, 2: probably clear, 3: confident clear).

4. EVALUATION AND APPLICATION OF NEW CLOUD MASKS

4.1 Evaluation of new cloud masks

Fig. 5 shows four examples with inconsistency between the original and the new cloud coverages. Case 1 is a scene from Sahara Desert under a clear condition. The original cloud coverage shows perfectly cloudy, while the new one shows perfectly clear. The original cloud assessment performs less well for some combinations of surface type and sun elevation angle such as a desert observation under a low sun elevation. Case 2 is the opposite case of Case 1. Case 3 is a scene from a vegetated area partly covered by snow―the original cloud assessment seems to have misjudged snow-covered pixels as cloudy pixels. In Case 3, the original cloud assessment underestimated cloudy pixels, while the new cloud assessment shows a reasonable result.

Fig. 6 compares histograms of the original and the new cloud coverages for daytime (left) and nighttime (right). As shown, the original cloud assessment overestimates cloudy pixels for cloud coverages of 0 to 10% (mostly clear), particularly for nighttime. Fig. 7 shows scatter diagrams between the original and the new cloud coverages for 8,000 scenes randomly sampled from daytime and nighttime scenes. As shown, the correlation between the original and the new cloud coverages is low, particularly for nighttime.

The left of Fig. 8 shows a composite image of 210 ASTER band-3N images observed from March 2000 to June 2008 for an area of N36–37 and E140–141 in Japan. The right of Fig. 8 shows the mean cloud coverage map (white: high clear rate) generated from MOD35 cloud mask images for these ASTER images, where for each cloud mask image, clear and probably clear pixels were counted as 1, cloudy pixels were counted as 0, and uncertain pixels were not counted [9]. The mean cloud coverage map indicates an unnatural boundary over the ocean about 3 km away from the coastline, probably because the coastal region test in the MOD35 algorithm failed to notice some clouds. It also has an unnatural boundary over the ocean about 20 km from the coastline. Though the right side of this boundary seems to be often covered by clouds actually, the cause of the boundary is still under investigation.

Additionally, the new cloud masks for 16,500 scenes including 1,201 nighttime scenes―about 1% of the total scenes―were selected at random, and visually evaluated using ASTER browse images. As the results, 23 scenes (0.14%) were judged as "bad". About 80% of these "bad" scenes are located in lithosphere, and a half of them are from Antarctic. Though visual evaluation using browse images may not be so accurate, the results indicate that the MOD35 products are mostly reliable.

4.2 ASTER mission analysis using generated cloud masks

In the ASTER project, the mission achievement has been periodically analyzed since the early mission period, but the cloud coverage information used in these analyses was not accurate because the original cloud coverage information was used. Since the cloud coverage information has been updated by the present study, these mission-related analyses will be improved in the future. In the present study, we show some examples of mission-related analyses using the new cloud coverage information.

Fig. 9 shows global maps of the number of cloud-free observations in a 0.1 degree by 0.1 degree grid for daytime (upper) and nighttime (lower), where "cloud-free" means a cloud coverage of 20% or less. Almost half areas in global have been observed 6 or less times under clear sky conditions for the past 10 years, while some areas such as USA, the Middle-East Asia, and Japan have been observed 13 or more times. The average number of cloud-free observations in daytime is 9.0, and that in nighttime is 3.9.

Fig. 10 shows global maps of the success rate in the same grid for daytime (upper) and nighttime (lower), where the success rate is the ratio of the number of cloud-free observations to that of total observations. The average of the success rate is 33.3% for daytime, and 40.4% for nighttime. A possible reason that the success rate is higher in nighttime than in daytime is because t ASTER nighttime observations have been focused on geological areas (exposed rocks and soils), volcanoes, and some large cities, not on vegetation areas typically located in humid areas

5. CONCLUSIONS

The ASTER cloud reassessment system has been developed, and all ASTER scenes have been reassessed (about 1.73 million scenes as of September 2010). Daily upcoming scenes (about 400 scenes per day) are reassessed every day. The new cloud coverages are input to the IMS databases of ASTER/GDS and LP DAAC in 5 to 7 days after each scene observation date, and general users can search ASTER products based on the updated cloud information. The new cloud mask images are distributed to general users through the web site.

The new cloud coverages and cloud mask images have been compared with the original ones, and about 1% of all scenes were visually evaluated using ASTER browse images. All the results indicate that the new ones are surely more reliable than the original ones, although a further investigation is necessary particularly for snow/ice covered regions and offshore regions.

The new cloud coverages generated in the present study are useful also for mission-related analyses. The numbers of cloud-free observations and the success rates have been globally mapped for daytime and nighttime using the new cloud coverages, which show that the average number of cloud-free observations is 9.0 for daytime, and 3.9 for nighttime, and the mean success rate is 33.3% for daytime, and is 40.4% for nighttime.

Currently the new cloud coverage information is applied to the IMS databases but not to each ASTER product distributed to a general user. In the future, we want to apply it to each product for improvement of usability.

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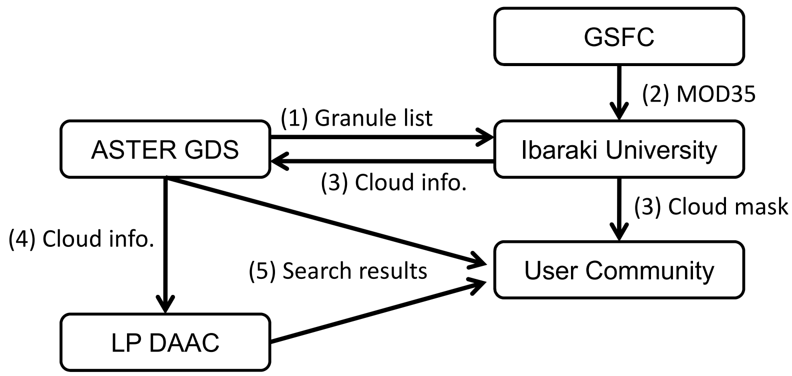

Fig. 1: Data flows among organizations.

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granule_id,day_night,total_cloud,lu_cloud,ll_cloud,ru_cloud,rl_cloud,uncertainty
ASTL1A 1008061919231008110001,1,92,100,80,93,95,3
ASTL1A 1008061919321008110002,1,90,93,93,76,97,4
ASTL1A 1008061919401008110003,1,69,56,62,84,74,5
ASTL1A 1008061919491008110004,1,45,76,1,95,9,2
ASTL1A 1008061919581008110005,1,2,0,1,0,8,2
ASTL1A 1008061920071008110006,1,31,19,45,14,46,8
ASTL1A 1008061920161008110007,1,48,41,39,41,72,9
ASTL1A 1008062002421008110008,2,44,52,46,61,17,25
ASTL1A 1008062013191008110009,2,0,0,0,0,0,0
ASTL1A 1008062013281008110010,2,1,0,1,0,0,1
ASTL1A 1008062057401008110011,1,18,54,3,10,4,6
ASTL1A 1008062057491008110012,1,1,1,1,1,1,1
ASTL1A 1008062057581008110013,1,8,1,25,0,7,5
ASTL1A 1008062058071008110014,1,11,4,1,21,19,6
ASTL1A 1008062058161008110015,1,6,0,20,1,1,1
ASTL1A 1008062058241008110016,1,36,75,23,30,16,8
ASTL1A 1008062058331008110017,1,5,3,12,2,3,2
ASTL1A 1008062122221008110018,2,21,26,28,11,18,25
ASTL1A 1008062122311008110019,2,14,35,17,4,1,12
ASTL1A 1008062122401008110020,2,12,6,26,0,14,12
ASTL1A 1008062153401008110021,2,2,1,6,1,1,3
ASTL1A 1008062258351008110022,2,0,0,0,0,0,0
ASTL1A 1008062328261008110024,2,14,23,18,16,1,6
ASTL1A 1008062328341008110025,2,6,10,1,12,2,4
ASTL1A 1008062328431008110026,2,8,7,11,12,1,4
ASTL1A 1008062351241008110027,1,100,100,100,100,100,0
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Fig. 2: Example of cloud coverage data transferred from Ibaraki University to ASTER/GDS (total_cloud is the total cloud coverage, and lu_cloud, ll_cloud, ru_cloud, rl_cloud are the quadratic cloud coverages for upper-left, lower-left, upper-right, and lower-right, respectively)

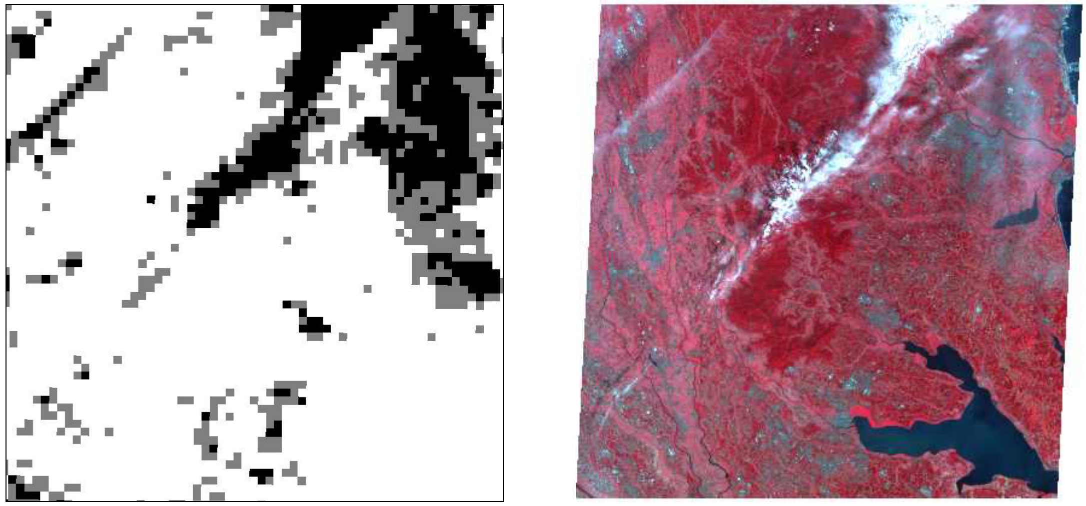


Fig. 3: Example of a new cloud mask image (left) with its ASTER browse image (right). The cloud mask image shows cloud, probably clear, and confident clear in black, gray, and white, respectively. No uncertain pixel exists in this example.

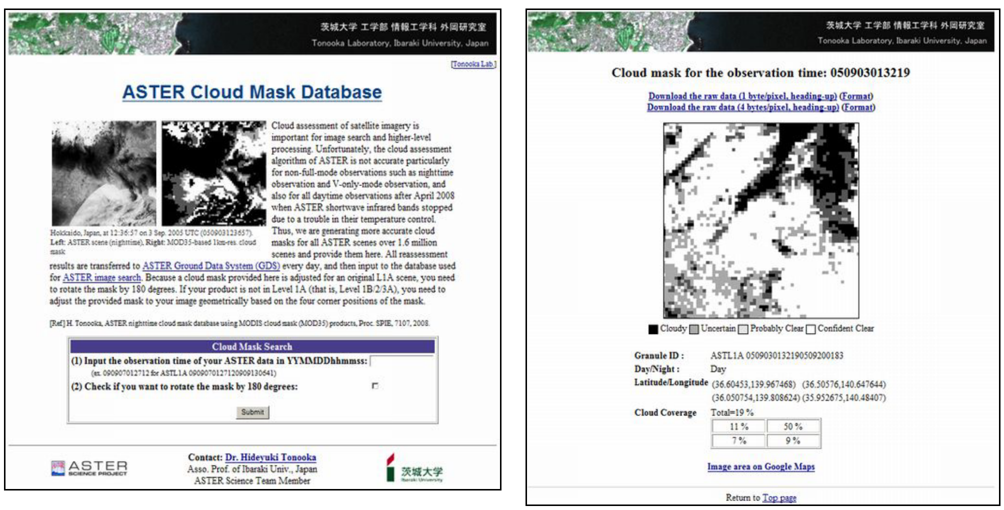


Fig. 4: Top page distributing ASTER cloud masks (left), and an example of a search result (right).

Table 1: Specification of the 32-bit cloud mask format (the first 32-bits of the original 48-bit MOD35 cloud mask [6]).

Bit field	Description	Bit field	Description
0	Cloud Mask Flag (0=not determined, 1=determined)	16	High Cloud Flag-1.38μm Test (0=Yes/1=No)
1-2	Unobstructed FOV Confidence Flag (00=cloudy,01=uncertain,10=probably clear,11=confident clear)	17	High Cloud Flag-3.7-12μm Test (0=Yes/1=No)
3	Day/Night Flag (0=Night/1=Day)	18	Cloud Flag-IR Temperature Difference (0=Yes/1=No)
4	Sun glint Flag (0=Yes/1=No)	19	Cloud Flag-3.9-11μm Test (0=Yes/1=No)
5	Snow/Ice Background Flag (0=Yes/1=No)	20	Cloud Flag-Visible Reflectance Test (0=Yes/1=No)
6-7	Land/Water Flag (00=Water,01=Coastal,10=Desert,11=Land)	21	Cloud Flag-Visible Ratio Test (0=Yes/1=No)
8	Non-cloud obstruction Flag (heavy aerosol) (0=Yes/1=No)	22	Clear-sky Restoral Test- NDVI in Coastal Areas (0=Yes/1=No)
9	Thin Cirrus Detected (solar) (0=Yes/1=No)	23	Cloud Flag-7.3-11μm Test (0=Yes/1=No)
10	Shadow Found (0=Yes/1=No)	24	Cloud Flag-Temporal Consistency (0=Yes/1=No)
11	Thin Cirrus Detected (infrared) (0=Yes/1=No)	25	Cloud Flag-Spatial Consistency (0=Yes/1=No)
12	Spare (Cloud adjacency) (post launch)	26	Clear-sky Restoral Tests (0=Yes/1=No)
13	Cloud Flag-simple IR Threshold Test (0=Yes/1=No)	27	Cloud Test-Night Ocean Variability Test (0=Yes/1=No)
14	High Cloud Flag-CO2 Threshold Test (0=Yes/1=No)	28	Suspended Dust Flag (0=Yes/1=No)
15	High Cloud Flag-6.7μm Test (0=Yes/1=No)	29-31	Spares

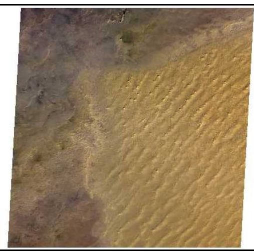
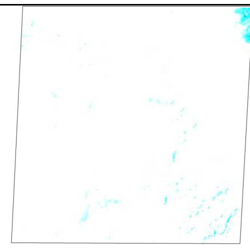
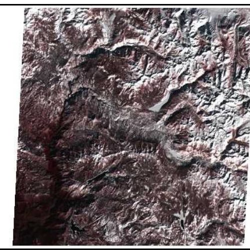
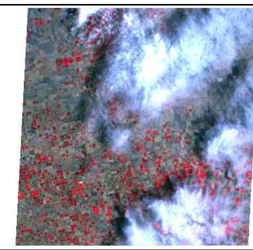
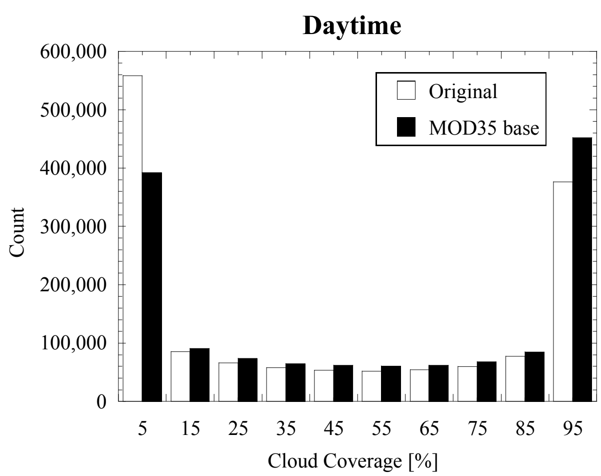
Case	Case 1		Case 2		Case 3		Case 4	
Browse								
Scene ID	ASTL1A 0812301002580901010667		ASTL1A 0808260133420808280285		ASTL1A 0801071851170801100123		ASTL1A 0805011744070805050438	
Location	Sahara Desert		Tokyo		California		Texas	
Condition	Clear		Cloudy		Clear, snow covered		Partly cloudy	
Cloud coverage (quadratic and total)	Original	Original	Original	New	Original	New	Original	New
	100 100 100 100	0 0 0 0	0 0 0 0	100 100 100 100	100 100 90 100	1 3 1 1	1 10 0 13	42 81 12 67
	total=100	total=0	total=0	total=100	total=97	total=1	total=6	total=50

Fig. 5: Four examples with inconsistency between the original and the new cloud coverages.



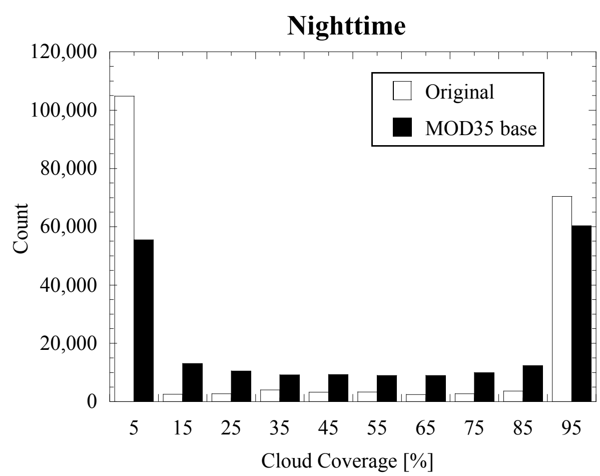


Fig. 6: Histograms of the original cloud coverage (white) and the new cloud coverage (black) for daytime (left) and nighttime (right).

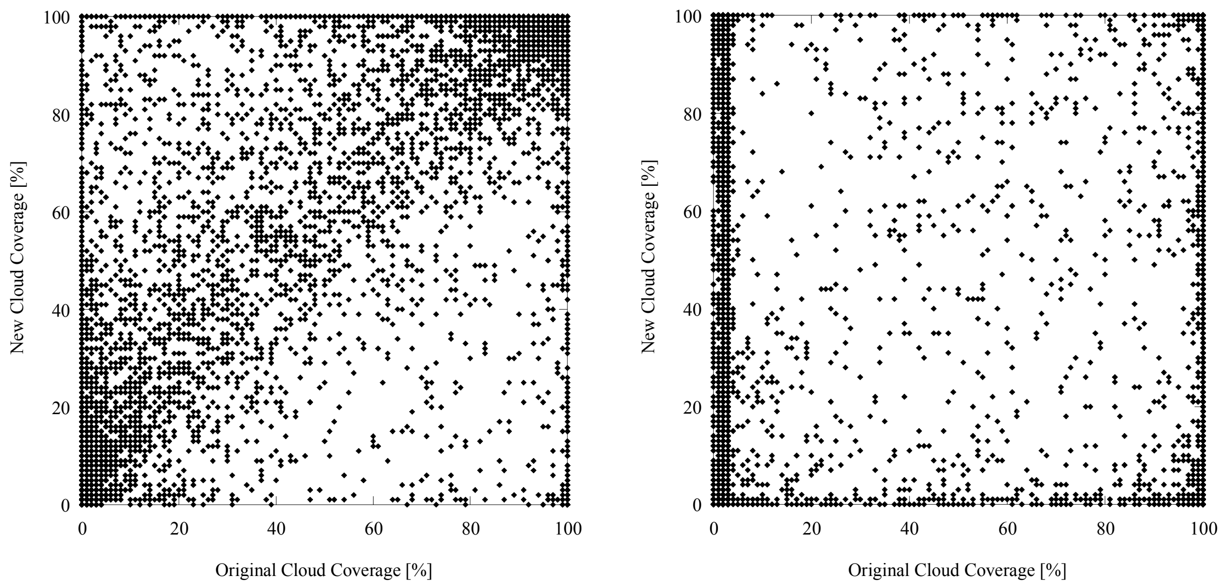


Fig. 7: Scatter diagrams of the original and the new cloud coverages for 8,000 scenes randomly sampled for daytime (left) and nighttime (right).

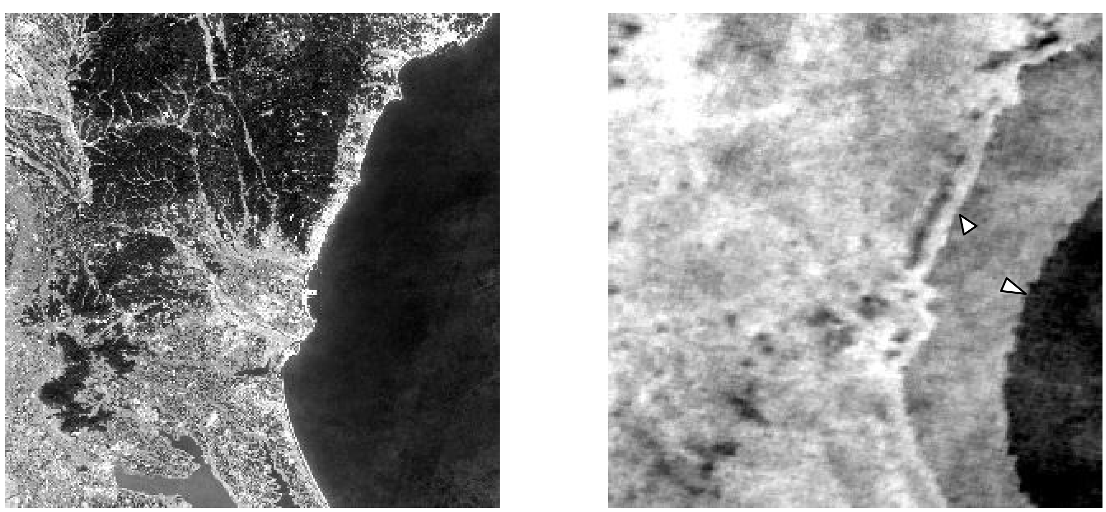


Fig. 8: Composite image of 210 ASTER band-3N images observed from March 2000 to June 2008 for an area of N36–37 and E140–141 in Japan (left), and the mean cloud coverage map (white: high clear rate) generated from MOD35 cloud mask images for these ASTER images (right), showing unnatural boundaries over the ocean about 3 km and 20 km away from the coastline (indicated by triangles) [9].

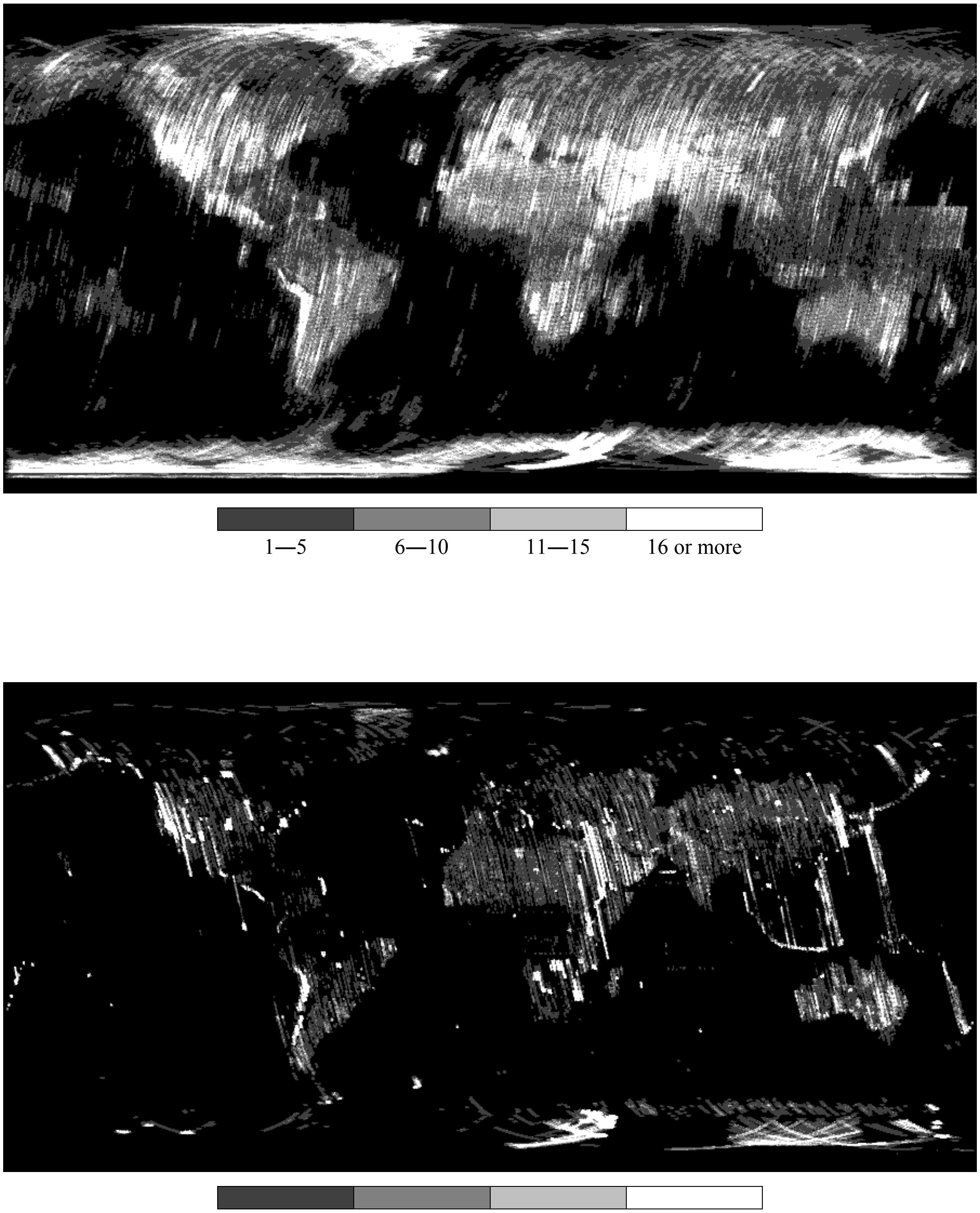


Fig. 9: Global maps of the number of cloud-free observations in a 0.1 degree by 0.1 degree grid for daytime (upper) and nighttime (lower), where "clear" means a cloud coverage of 20% or less.

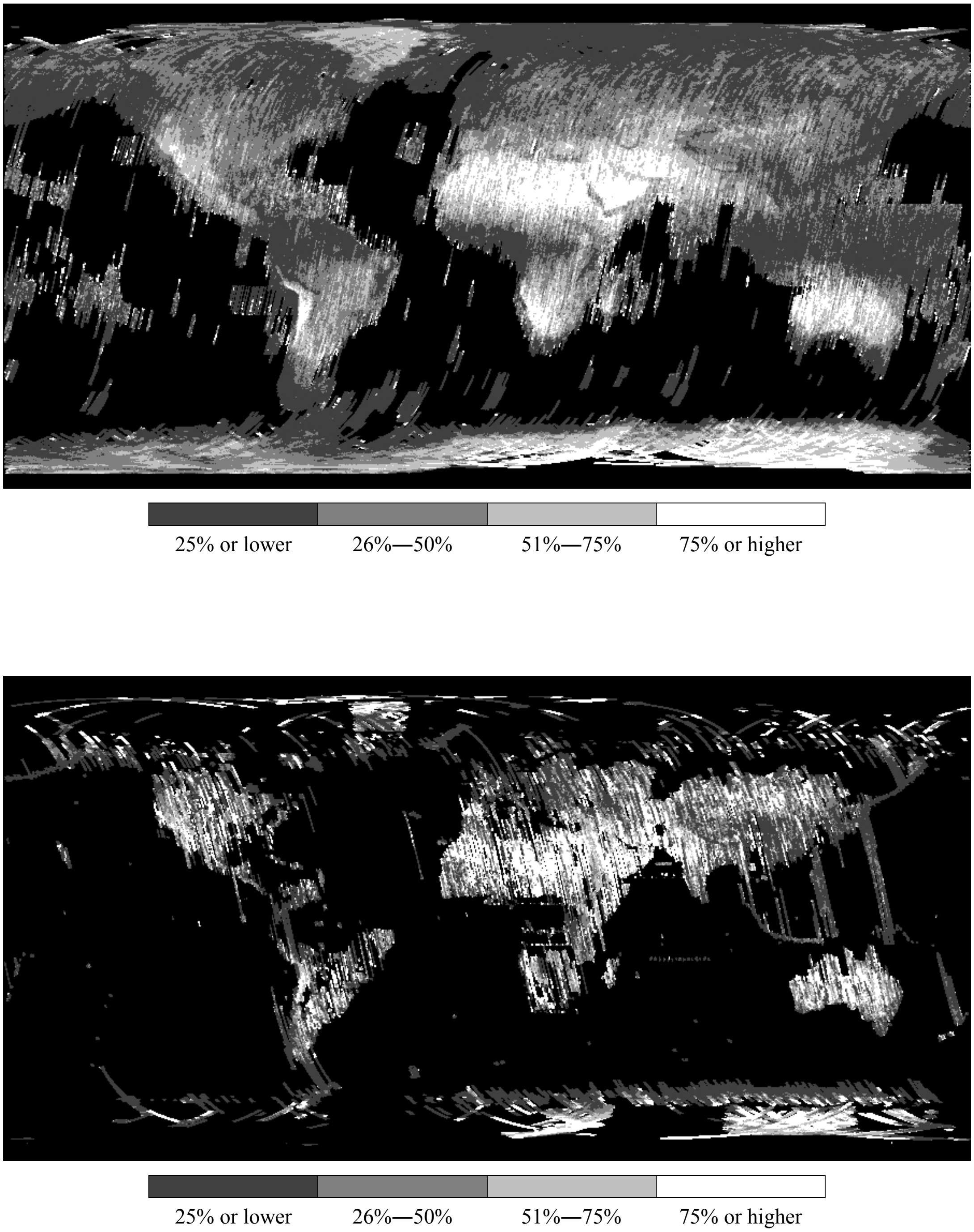


Fig. 10: Global maps of the success rate in a 0.1 degree by 0.1 degree grid for daytime (upper) and nighttime (lower), where the success rate is the ratio of the number of cloud-free observations to that of total observations