Algorithm Theoretical Basis Document for Cloud Top Height Product

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Abstract

The cloud top height product is an element of the fundamental cloud product, which incorporates cloud mask, cloud type/phase and cloud top height. The Meteorological Satellite Center (MSC) of Japan Meteorological Agency (JMA) separated cloud mask, cloud type/phase and cloud top height, which were contained in miscellaneous level 2 products in the Himawari-7 era, and put them together as a fundamental cloud product. The cloud top height product incorporates the three elements of cloud top height, temperature and pressure, and its algorithm is based on EUMETSAT's NoWCasting Satellite Application Facility (NWCSAF). The inputs are satellite data from Advanced Himawari Imager (AHI) observations, vertical profile data from a radiative transfer model and cloud type data from a cloud type/phase product. Evaluation conducted over a period of two weeks from 20 July to 2 August 2015 showed that cloud top height was underestimated in comparison to corresponding values from MODIS (the Moderate Resolution Imaging Spectroradiometer) and Calipso (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation).

1. Introduction

The cloud top height product provides some of the basic information for level-2 products, and some cloud products of the Meteorological Satellite Center (MSC) of Japan Meteorological Agency (JMA) has their own individual cloud top height retrieval procedure. Since Himawari-8 was launched in 2014 and began operation on 7 July 2015, MSC has separated cloud mask, cloud type/phase and cloud top height from miscellaneous cloud products and put them together into a single output called the fundamental cloud product. It is rational to create level-2 products using existing cloud mask, cloud type/phase and cloud top height information. The fundamental cloud product is also used for High Resolution Cloud Analysis Information (Suzue et al. 2016), which is a level-2 product. With 16 bands, Himawari-8 additionally has better observation performance than Himawari-7 (MTSAT-2). As a result, previous cloud top height estimation data from Himawari-7 can no longer be put to practical use by MSC. Multi-band observation data from geostationary meteorological satellites (e.g., Cloud Top Temperature and Height (Meteo France 2012) and the ABI Cloud Height Algorithm (Heidinger 2012)) were used in previous studies. MSC uses the algorithm adopted for Cloud Top Temperature and Height (Meteo France 2012) because it is well established and relatively easy to understand.

This document outlines the cloud top height product and its algorithm. The product includes information on cloud top height, cloud top temperature and cloud top pressure. The document also describes the required input data, practical considerations and related evaluation. The procedure for the product's derivation is based on the NWCSAF algorithm (Meteo France 2012).

1.1. Content

This is the Algorithm Theoretical Basis Document for cloud top height, temperature and pressure. It describes scientific considerations, limitations and other aspects of the algorithm used.

1.2. Definitions, acronyms and abbreviations

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ABI: Advanced Baseline Imager (mounted on the GOES-R satellite).

AHI: Advanced Himawari Imager (mounted on Himawari-8 for observation with 16 bands; central wavelengths: 0.47, 0.51, 0.64, 0.86, 1.6, 2.3, 3.9, 6.2, 6.9, 7.3, 8.6, 9.6, 10.4, 11.2, 12.4, 13.3 microns) .

Calipso: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation.

CT: JMA's Cloud Type product, which includes information on cloud type and cloud phase. The cloud top height product requires CT information in order to switch methods for cloud top height calculation.

$\varepsilon(\lambda)$: Cloud emissivity of wavelength. Cloud emissivity is the ratio of radiation to black body in a temperature.

GOES-R: Geostationary Operational Environmental Satellite -R Series.

GSM: Global Spectral Model (JMA's NWP model).

JMA: Japan Meteorological Agency.

MODIS: Moderate Resolution Imaging Spectroradiometer (mounted on NASA's Aqua and Terra satellites).

MSC: Meteorological Satellite Center.

NWP: Numerical Weather Prediction.

NASA: National Aeronautics and Space Administration.

λ(lambda): Center wavelength of AHI bands.

LRC: Local radiative center. This is the maximum $\varepsilon(\lambda)$ pixel accessed via a large adjacent $\varepsilon(\lambda)$ pixel from the target pixel. In this cloud top height product, λ is set as 11.2 microns for LRC calculation. When a target pixel is cloudy, the LRC is a thick part in the cloud area. This concept is utilized to judge the cloud drop phase at the edge of a cloud area, and is incorporated into the GOES-R ABI algorithm (Heidinger 2012).

$R_{\{m,opaque,clear\}}(\lambda)$: R_m represents measured radiance, R_{opaque} represents opaque cloud radiance at an arbitrary level as calculated using a radiative transfer model, and R_{clear} represents surface radiance via clear air as calculated using a radiative transfer model.

RTTOV: Radiative transfer code developed by EUMETSAT (Eyre 1991).

SST: Sea surface temperature.

$T(\lambda)$: Brightness temperature at the center wavelength λ. The brightness temperature of other bands is expressed in the same way.

2. Cloud top height product outline

The cloud top height product provides data on cloud top height, cloud top temperature and cloud top pressure as calculated using the algorithm adopted for NWCSAF cloud top height. The cloud type from the Cloud Type/Phase product (Mouri et al. 2016) is important because it is used to determine one of three height retrieval methods (see Subsection 2.2).

2.1. Input data

i. AHI observation data (6.2, 7.3, 11.2 and 13.3 microns)

Radiance data are required for the cloud top height product. The spatial resolution is 2 km at the sub-satellite point, and normalized geostationary projection (Japan Meteorological Agency 2013) is used. The output rate is one product per hour.

ii. Radiative transfer data calculated from GSM output

RTTOV is utilized for radiative transfer calculation. The variables acquired from RTTOV are radiances observed by the AHI for individual wavelengths based on the conditions of a black body held in equilibrium with air temperature at the altitudes of mandatory levels. The wavelengths are 6.2, 7.3, 11.2 and 13.3 microns. The vertical levels are 32 mandatory ones and the surface, but radiances up to the tropopause level are used in most cases for height estimation.

iii. Cloud type data

CT data are utilized for the cloud top height product. Only cloudy pixels and those for which the satellite zenith angle is smaller than 84 degrees are processed in the product. For satellite zenith angle limitation, an angle slightly smaller than the limitation of 85 degrees for RTTOV is set.

iv. Altitude and temperature of mandatory levels and surface

The relevant altitudes and temperatures are acquired from NWP data.

2.2. Process flow of the cloud top height product

Cloud top height estimation involves one of the following:

i. The interpolation method
ii. The radiance ratioing method
iii. The intercept method

These methods are described in the next chapter (see Fig. 1 for the process flow), and their selection depends on the CT cloud type. For semi-transparent cloud, the intercept method is used. Such cloud is optically thin, and radiation from the lower layer is also observed by the AHI with this type. Under such conditions, application of the intercept method results in correction of lower-layer radiation, and is suitable for single-layered semi-transparent cloud like cirrus.If the intercept method does not produce suitable results, the radiance ratioing method is applied; if this also fails to produce suitable results, the interpolation method is utilized. When the radiance ratioing method or the interpolation method is applied after the intercept method, LRC is utilized for radiance estimation. This is also used for fractional cloud. For opaque and fractional cloud, the interpolation method is utilized. Such cloud is optically thick, and only radiation from the cloud top is observed by the AHI.

When an inversion layer is present, cloud is set at its upper side. This procedure is also applied for opaque cloud below the middle level as discriminated by CT.

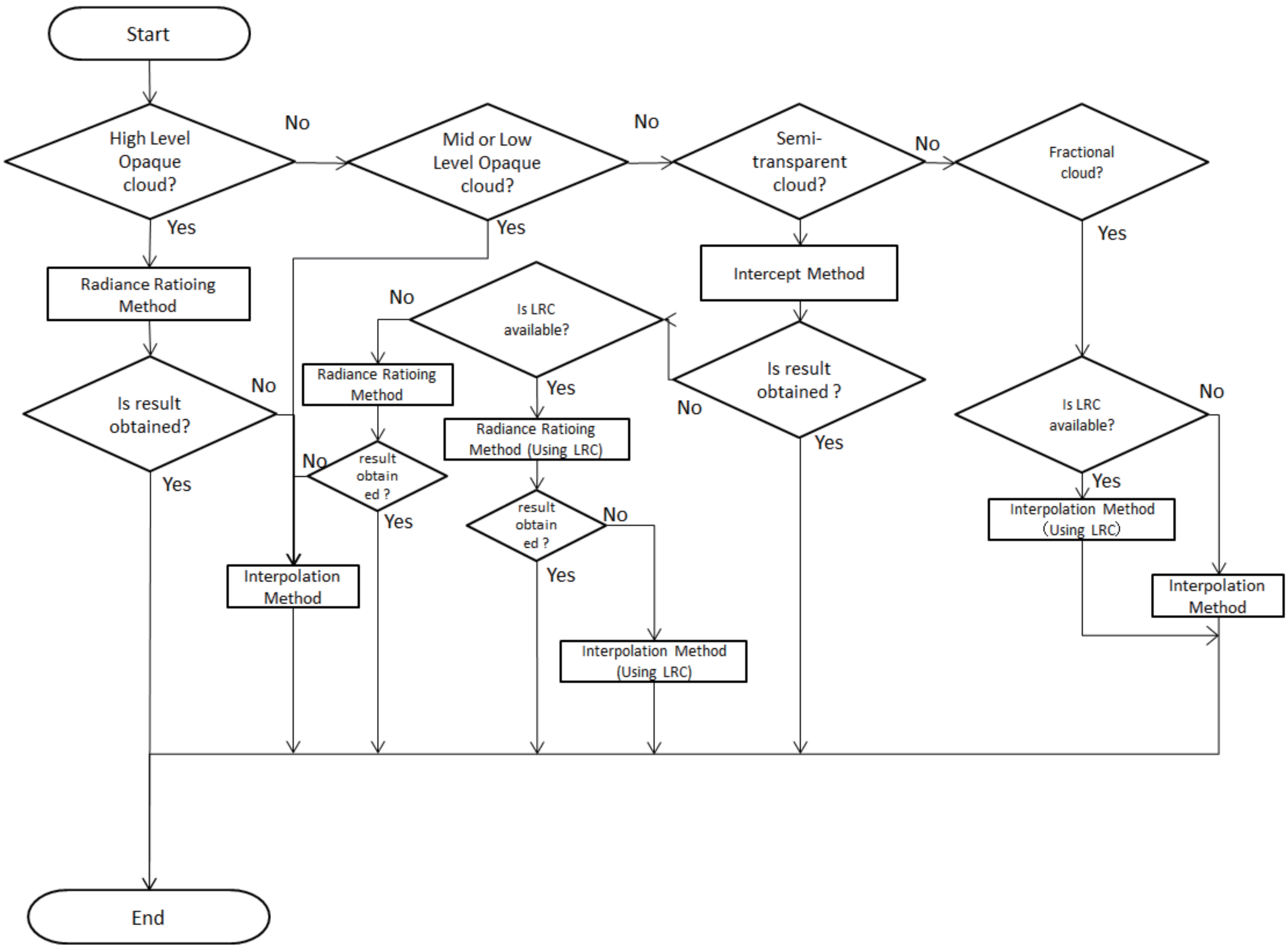

Fig. 1 Process flow of the cloud top height product
Information on opaque or semi-transparent cloud is derived from the cloud type product.

2.3. Output data

i. Cloud top height (m)
ii. Cloud top temperature (K)
iii. Cloud top pressure (hPa)
iv. Quality flags

Chapter 4 provides information on the format of these data, which all have a spatial resolution of 2 km at the sub-satellite point. The output rate is one product per hour. Cloudy pixels contain valid data and fine pixels contain invalid (-9999) data. Pixels with a satellite zenith angle smaller than 84 degrees are contained.

3. Cloud top height product algorithm

3.1. Interpolation method

Radiance observed by the AHI and the vertical profile of black body radiance as calculated using the RTTOV radiative transfer model are compared in this approach, and the two mandatory levels sandwiching the observed radiance are determined. The ration of interpolation between the radiances of these levels is linearly derived based on the observed radiance. For pressure interpolation, a pressure logarithm is utilized. Height, pressure and temperature are determined from the interpolation ratio and the two mandatory levels. This method is applicable for levels below the tropopause layer. When an inversion layer is present, cloud is set at its upper side in the MSC algorithm. A wavelength of 11.2 microns is adopted, as this represents a window region for water vapor. This approach is similar to window channel estimation (Neiman et al 1993) and radiance fitting (Hamman et al 2014). Figure 2 shows an example of pressure determination using this method. The vertical profile of radiance at 11.2 microns is calculated using radiative transfer model. The interpolation ratio of radiance between the two levels sandwiching the observed radiance reflects the interpolated pressure between the two levels. This example shows an observed radiance of 85.2 mW converted to 591.4 hPa.

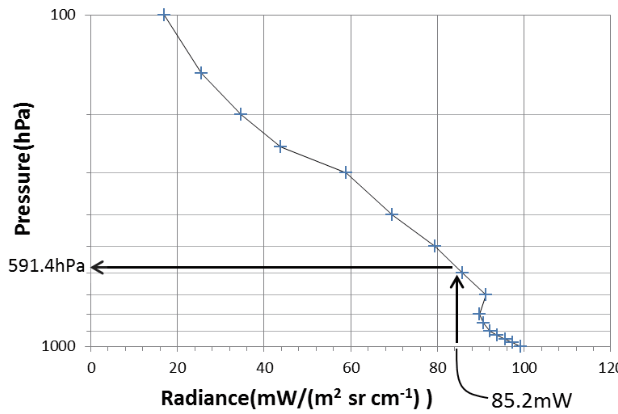

Fig. 2 Outline of the interpolation method

3.2. Radiance ratioing method

This approach is also known as the CO_2 absorption method (Menzel et al 1983) and the CO_2-slicing method. If cloud is assumed to be a single layer, radiance as determined by the AHI is formulated as

$$R_m(\lambda) = N\varepsilon R_{opaque}(\lambda) + (1 - N\varepsilon)R_{clear}(\lambda) \quad (1)$$

where N is the cloud amount. If R_{opaque} is known, height can be estimated using the approach of the interpolation method. Equation (1) is transformed to Equation (2).

$$R_m(\lambda) - R_{clear}(\lambda) = N\varepsilon\left(R_{opaque}(\lambda) - R_{clear}(\lambda)\right) \quad (2)$$

Cloud top pressure is estimated from the ratio of radiance between two wavelengths (Chahine 1974, Smith and Platt 1978).

$$\frac{R_m(\lambda_1)-R_{clear}(\lambda_1)}{R_m(\lambda_2)-R_{clear}(\lambda_2)} = \frac{N\varepsilon_1\left(R_{opaque}(\lambda_1)-R_{clear}(\lambda_1)\right)}{N\varepsilon_2\left(R_{opaque}(\lambda_2)-R_{clear}(\lambda_2)\right)} \quad (3)$$

The value of the left-hand side is derived once $R_m(\lambda_1)$, $R_m(\lambda_2)$, $R_{clear}(\lambda_1)$ and $R_{clear}(\lambda_2)$ are determined. The value of $R_{opaque}(\lambda_1)$ and $R_{opaque}(\lambda_2)$ on the right-hand side depend on the vertical profile. As $N\varepsilon_1$ and $N\varepsilon_2$ are almost equal:

$$\frac{N\varepsilon_1}{N\varepsilon_2} \approx 1 \quad (4)$$

Equation (3) can be written as

$$\frac{R_m(\lambda_1)-R_{clear}(\lambda_1)}{R_m(\lambda_2)-R_{clear}(\lambda_2)} = \frac{R_{opaque}(\lambda_1)-R_{clear}(\lambda_1)}{R_{opaque}(\lambda_2)-R_{clear}(\lambda_2)} \quad (5)$$

Values of $R_{opaque}(\lambda_1)$ and $R_{opaque}(\lambda_2)$ satisfying Equation (5) are then derived from the vertical profile of radiance. R_{clear} is essentially surface radiance calculated using the radiative transfer model, but its accuracy may be limited in association with that of water vapor estimation in NWP. Accordingly, measured clear sky radiance is adopted if clear pixels are present in the 3 x 3 pixel array centered on the target pixel. MSC uses three band pairs (11.2(B14)/6.2(B08)-micron pair, 11.2(B14)/7.3(B10)-micron pair and 11.2(B14)/13.3(B16)-micron pair) in the related algorithm. Figure 3 shows an example of pressure retrieval using this method. The horizontal axis represents pressure (hPa), and the vertical axis shows the value of the left-hand side (measured ratio) minus the right hand side (simulated ratio) of Equation (5).

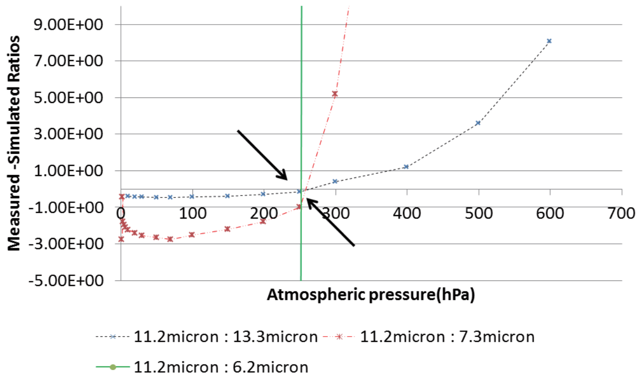

Fig. 3 Outline of the radiance ratioing method
B14:B16 is 11.2/13.3-micron pair, B14:B10 is 11.2/7.3-micron pair, and B14:B08 is 11.2/6.2-micron pair.

The dashed line indicates the 11.2(B14)/13.3(B16)-micron pair, the chain line represents the 11.2(B14)/7.3(B10)-micron pair, and the solid line represents the 11.2(B14)/6.2(B08)-micron pair. The arrows show the point of intersection with the zero line of the measured-simulated ratio and each pair line (251.6 hPa for the 11.2(B14)/6.2(B08)-micron pair, 257.5 hPa for the 11.2(B14)/7.3(B10)-micron pair, and 261.8 hPa for the 11.2(B14)/13.3(B16)-micron pair. The final retrieved cloud top height is the minimum pressure (at the highest altitude) determined from one of the three band pairs. This follows the intercept approach of NWCSAF.

3.3. Intercept method

The Intercept method (Schmetz et al. 1993) is adopted for semi-transparent clouds. In the NWCSAF procedure, a linear expression is first set up via the least square approach in a scatter diagram of observed radiances for two bands. The data contained in the diagram are radiances of 16 or so pixels around the target pixel, and a 33 x 33-pixel template is formed. There are no limitations on surface type when the template is made. Next, the intersection of the black body radiance curve for each level is derived, along with the relevant linear expression. The window channel's radiance at the intersection indicates the height of semi-transparent cloud in the troposphere. The cloud top height is then retrieved as in the interpolation method. There are three band pairs in this algorithm (11.2/6.2 microns, 11.2/7.3 microns and 11.2/13.3 microns). The minimum pressure (at the highest altitude) is selected from among the three pairs. Figure 4 shows an example of how pressure is retrieved using this method. The retrieved radiance of 11.2 microns for the 11.2/6.2-micron pair, for example, is 17 mW (Fig. 4 (a)), that for the 11.2/7.3-micron pair is 23.9 mW (Fig. 4 (b)), and that for the 11.2/13.3-micron pair is 16.0 mW (Fig. 4 (c)). Figure 4 (d) shows that cloud top pressure is determined from the retrieved radiance of 11.2 microns. The radiance profile for 11.2 microns is calculated using RTTOV. The retrieved radiances of the three pairs indicate individual pressure levels in the vertical profile. In this case, 17 mW marks 95.16 hPa for the 11.2/6.2-micron pair. In the same way, the 11.2/7.3-micron pair indicates 139.5 hPa and the 11.2/13.3-micron pair indicates 95.11 hPa. The value of 95.11 hPa from the 11.2/13.3-micron pair is adopted as the cloud top pressure, as it is the lowest level.

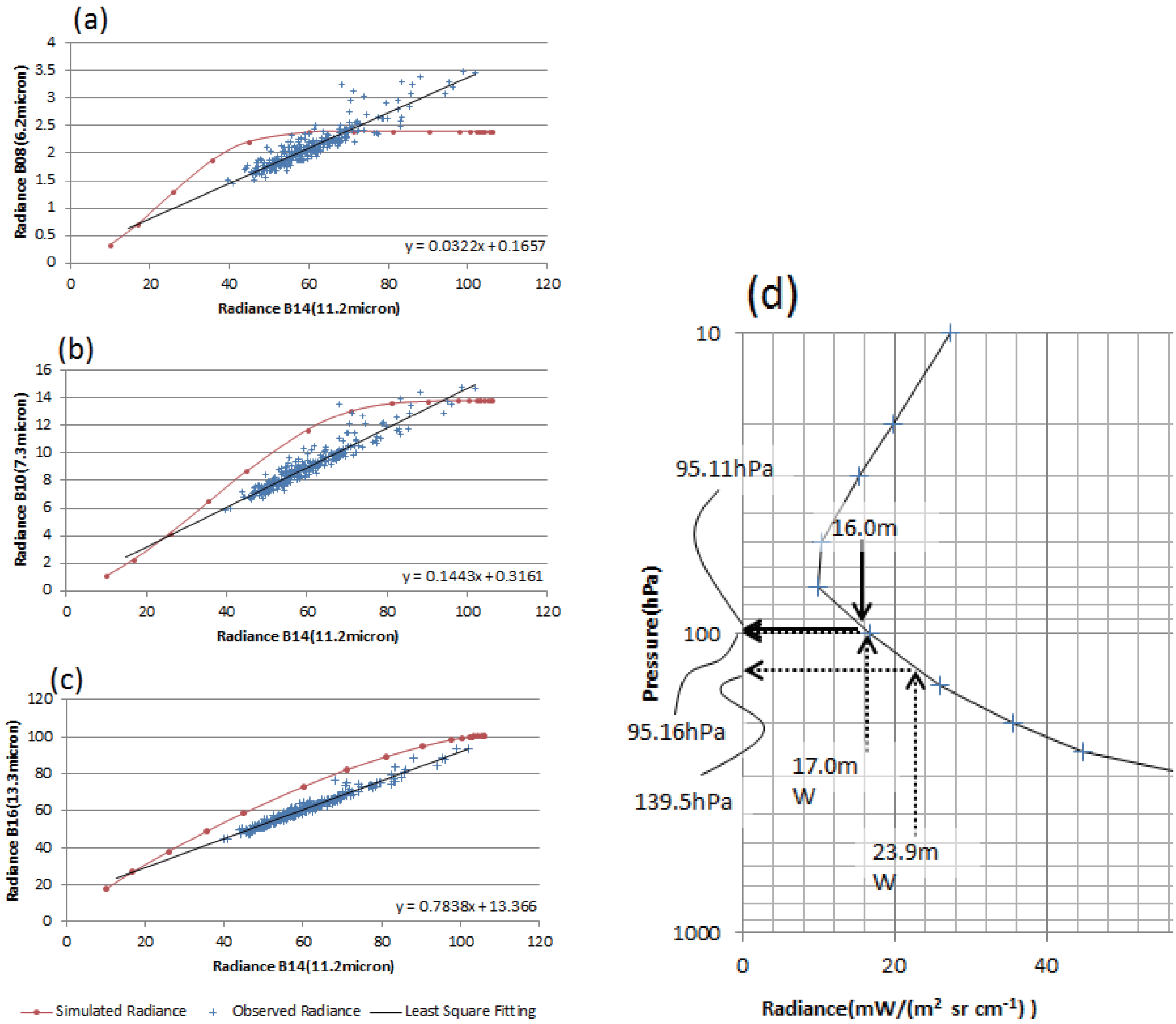

Fig. 4 Outline of the intercept method

The horizontal axis shows the observed radiance for 11.2 microns, and the vertical axis represents the observed radiance of band pairs. The unit is mW m^{-2} sr^{-1} $(cm^{-1})^{-1}$.

(a) Scatter diagram of 11.2 and 6.2 micron observed radiances.

The curve (the solid red line) of radiative transfer calculation for 11.2 and 6.2 microns is also shown.

(b) Scatter diagram and curve for 11.2 and 7.3 microns (as per Fig. 4 (a))

(c) Scatter diagram for 11.2 and 13.3 microns (as per Fig. 4 (a))

(d) Simulated radiance profile for 11.2 microns as calculated using RTTOV

4. Input/output data

4.1. Input data

i. AHI data

Brightness temperatures and radiances at 6.2, 7.3, 11.2 and 13.3 microns are observed by the AHI.

ii. Vertical profiles calculated using the RTTOV radiative transfer code

The vertical profiles of brightness temperatures and radiances are calculated using RTTOV. The wavelengths are the same as those of AHI data.

iii. Cloud type product results

Cloud type information is required.

4.2. Output data

i. Cloud top pressure, cloud top altitude and cloud top temperature

These data are output in flat binary form at 1 byte per pixel. Figure 5 shows the pixel order, and Table 1 shows the specifications for cloud top pressure, altitude and temperature. The start count is minus 127 in all cases, and the physical quantity is determined using

$$\text{Physical quantity} = \text{slope} \times (\mathit{count\ value} + 127)$$

ii. Quality flag data

These data are also output in flat binary form at 1 byte per pixel. Table 2 details quality information per pixel.

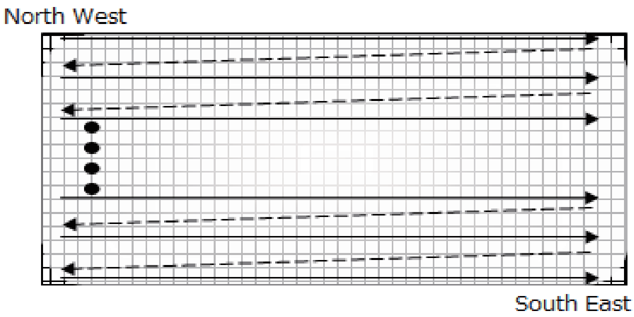

Fig. 5 File format and pixel order
Data are written in flat binary format.

5. Data provision for general users

The cloud top height product is used exclusively by MSC and is not provided to external users.

6. Cloud top height product evaluation

Evaluation was carried out over a period of two weeks from 20 July to 2 August 2015. The cloud top height product was compared to its MODIS counterpart (Baum et al. 2012) and Calipso (Winker et al. 2006). In the match-up process, pixels within 2 km and within 5 minutes of the scanning time between cloud top height product data and MODIS or Calipso data were picked up. Table 3 shows the results of evaluation for the cloud top height product of MODIS and Calipso during this period. Figure 6 shows a time-series representation of mean errors and root mean square errors for cloud top height. In the cloud top height product, cloud top height was underestimated in comparison to corresponding values from MODIS and Calipso throughout the period.

Table 1 Output specifications for cloud top pressure, altitude and temperature

Pressure				
digit	Slope	Start count	End Count	Specail Count(no pressure available)
8bit	5hPa/count	-127	+127	-128

Altitude				
digit	Slope	Start count	End Count	Specail Count(no pressure available)
8bit	100m/count	-127	+127	-128

Temperature				
digit	Slope	Start count	End Count	Specail Count(no pressure available)
8bit	1K/count	-127	+127	-128

Table 2 Pixel quality information

★Quality flag. 1byte per 1pixel. Bit 0 stands for least significant bit.

*Bit 0–1(Category 1). The 2bits are processing status
0:non processed. encompasses – Pixel mainly looking at space.
1:non processed FOV is Clear
2:Good Quality
3:Poor Quality

* Bit 2–4(Category 2). The 3bits are describing the thermal inversion layer from RTTOV vertical profile Data.
0:RTTOV is unavailable(out of range) or not adopted.
1:No thermal inversion and no subsident layer
2:No thermal inversion and subsident layer exists.
3:Thermal Inversion layer exists and No Subsident layer exists.
4:Thermal Inversion layer exists and Subsident layer also exists.

* Bit 5–7(Category 3). The 3 bits are adopted method for cloud top height estimation.
0: non processed
1: Opaque cloud, using RTTOV.
2: Intercept 11.2/6.2
3: Intercept 11.2/7.3
4: Intercept 11.2/13.3
5: Radiance ratioing 11.2/6.2
6: Radiance ratioing 11.2/7.3
7: Radiance ratioing 11.2/13.3

The quality flags are constructed by the order of categories below.

MSB		LSB
Cat3	Cat2	Cat1
3bit	3bit	2bit

Table 3 Mean errors and root mean square errors for the period from 20 July to 2 August

	JMA cloud height to MODIS cloud height	JMA cloud height to Calipso cloud height
Mean Error (m)	-541.4	-1834.5
Root Mean Square Error (m)	3313.2	4457.4

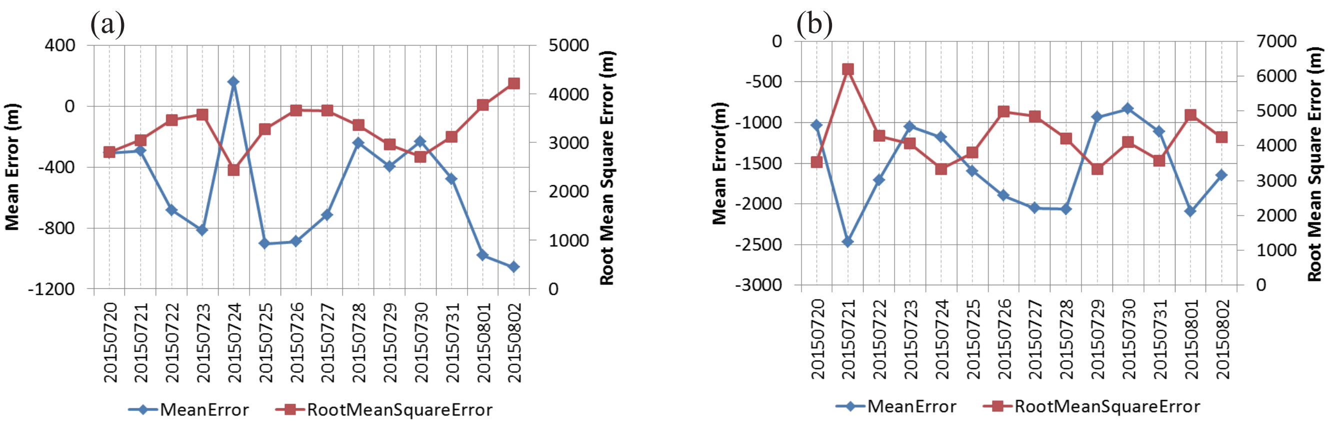

Fig. 6 Time-series representation of mean errors and root mean square errors

The horizontal axis represents the date, the left vertical axis represents mean error, and the right vertical axis represents root mean square error.

The fig (a) and the fig (b) show evaluation for MODIS and Calipso cloud top height, respectively.

7. Assumptions and limitations

i. The semi-transparent cloud top height algorithms are assumed for single-layer cloud rather than multi-layered cloud. The accuracy of semi-transparent cloud top height estimation is lower for multi-layered cloud.

ii. The accuracy of cloud top height estimation is lower if the cloud type is not properly classified. Cloud top height for semi-transparent cloud classified as opaque in the cloud type product is underestimated, while that for opaque cloud correctly classified as opaque is overestimated.

iii. Accuracy for fractional cloud is lower if the cloud does not fully cover the target pixel.

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雲頂高度アルゴリズム記述書

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要旨

雲頂高度プロダクトは、基本雲プロダクトの一要素である。基本雲プロダクトは雲マスク、雲タイプ、雲頂高度プロダクトからなる。気象庁気象衛星センターでは、ひまわり８号を機に、様々な２次プロダクトが取り扱う雲マスク、雲タイプ・相、雲頂高度を独立させ、基本雲プロダクトとしてまとめ上げた。高分解能雲情報が現在基本雲プロダクトを使用している。

雲頂高度プロダクトは、雲頂高度、雲頂温度、雲頂気圧の３つの要素から成り、アルゴリズムは欧州気象衛星機関の NWCSAF という枠組みで開発されたものを使用している。入力データはひまわり 8 号に搭載されている AHI（Advanced Himawari Imager）によって観測されたデータ、放射伝達計算済みの鉛直プロファイルデータ、および雲タイププロダクトによって出力された雲タイプデータである。2015 年 7 月 20 日から 8 月 2 日の 2 週間における雲頂高度の評価では、MODIS 雲頂高度および Calipso 雲頂高度に対して、本プロダクトの雲頂高度はやや低い傾向であった。

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