EUMETSAT NWC SAF

SUPPORT TO NOWCASTING AND VERY SHORT RANGE FORECASTING

Algorithm Theoretical Basis Document for Cloud Type of the NWC/PPS

NWC/CDOP3/PPS/SMHI/SCI/ATBD/CloudType, Issue 2, Rev. 1

13 December 2018

Applicable to SAFNWC/PPS version 2018

Applicable to the following PGEs:

Acronym	**Product ID**	**Product name**	**Version number**
CT	NWC-066	Cloud Type	3.0

Prepared by Swedish Meteorological and Hydrological Institute (SMHI)

REPORT SIGNATURE TABLE

Function	Name	Signature	Date
Prepared by	SMHI		13 December 2018 2018
Reviewed by	SAFNWC Project Team EUMETSAT		3 February 2017
Authorised by	Anke Thoss, SMHI *SAFNWC PPS Manager*		13 December 2018

DOCUMENT CHANGE RECORD

Version	Date	Pages	Changes
1.0d	22 January 2014	39	Replacing CDOP-document: SAF/NWC/CDOP/SMHI-PPS/SCI/ATBD/2 First version for SAFNWC/PPS v2014 Changes since v2012: Updated the output description, and some smaller general improvements.
1.0	15 September 2014	40	Implemented RIDs from PCR-v2014: -LSc1 (formal issues) -LSc2 (summary of requirements) -LSc3, PW21-PW22 (editorials and clarifications) -PW23 (removing unnecessary status flags) General changes: -Added a description of the new dataset: multi-layer. -Replaced validation with results from v2014.
1.1	13 March 2015	41	Added a missing description of multi-layer flag in pps_config_common.cfg
2.0d	23 December 2016	33	Changes for PPS v2018: -Changed the algorithm description (now highly dependent on CTTH-pressure) -Describe channels needed for using VIIRS I-bands. -Describe channels needed for MERSI-2. -Added the status flag: suspected heavy aerosol. -Updated images and preliminary validation tables to version 2018.
2.0	20 February 2017	35	Implemented RIDs from PCR-v2018: -Heinemann-017: For I-band resampling, make a reference to SW/UM/2. -Heinemann-020, Lutz-042: Made clarifications before and in table10. -Lutz-041: Added a missing offset in table10. -Heinemann-021, -018: Describe flagging when CTTH data is missing. -Hienemann-018: Added a sub-section about processing time.
2.1beta	9 May 2018	34	Document code changed from NWC/CDOP2/PPS/SMHI/SCI/ATBD/4 to NWC/CDOP3/PPS/SMHI/SCI/ATBD/4. Changes for v2018: -Updated algorithm description with an additional cirrus test, using CTTH-temperature. -Updated the validation section to use VIIRS data instead of GAC data. This is possible with CALIPSO version 4. -Some changes for the configuration.
2.1d	17 October 2018	34	Changes for v2018 ORR: - Added TBD01, about MERSI-2 usage.
2.1	13 December 2018	34	Updates after v2018 ORR: OBJ2_VR_C_Peregrin_064: Clarifying that the class fractional is only used for low clouds. OBJ2_UM_SCI_Heinemann_039: Removed most PGE-<*number*> notations in this document. OBJ2_UM_SCI_Heinemann_041: editorial Other changes: -A small clarification on the need of CMa.

Table of Contents

List of Tables and Figures

1. INTRODUCTION

The EUMETSAT "Satellite Application Facilities" (SAF) are dedicated centres of excellence for processing satellite data, and form an integral part of the distributed EUMETSAT Application Ground Segment (http://www.eumetsat.int). This documentation is provided by the SAF on Support to Nowcasting and Very Short Range Forecasting, SAFNWC. The main objective of SAFNWC is to provide, further develop and maintain software packages to be used for Nowcasting applications of operational meteorological satellite data by National Meteorological Services. More information can be found at the SAFNWC webpage, http://nwc-saf.eumetsat.int . This document is applicable to the SAFNWC processing package for polar orbiting meteorological satellites, SAFNWC/PPS, developed and maintained by SMHI (http://nwcsaf.smhi.se).

1.1 PURPOSE

This document is the Algorithm theoretical Basis Document for the Cloud Type (CT) of the SAFNWC/PPS software package.

This document contains a description of the algorithm, including scientific aspects and practical considerations.

1.2 SCOPE

This document describes the algorithms implemented in the CT version 3.0 of the 2018 SAFNWC/PPS software package delivery.

1.3 DEFINITIONS AND ACRONYMS

Acronym	**Explanation**
ACPG	AVHRR/AMSU Cloud Product Generation software (A major part of the SAFNWC/PPS s.w., including the PGEs.)
AEMET	Agencia Estatal de Meteorología (Spain)
AHAMAP	AMSU-HIRS-AVHRR Mapping Library (A part of the SAFNWC/PPS s.w.)
AMSU	Advance Microwave Sounding Unit
AVHRR	Advanced Very High Resolution Radiometer
CDOP	Continuous Development and Operational Phase
CDOP-2	Second Continuous Development and Operational Phase
CMa	Cloud Mask (also PGE01)
CMa-Prob	Cloud Probability (also PGE01c)
CM-SAF	Climate Monitoring SAF
CPP	Cloud Physical Products (also PGE05)
CT	Cloud Type (also PGE02)
CTTH	Cloud Top Temperature, Height and Pressure (also PGE03)
EPS	EUMETSAT Polar System
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GEO	Geosynchronous equatorial orbit
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
LEO	Low earth orbit
MHS	Microwave Humidity Sounding Unit
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
OSISAF	Ocean and Sea Ice SAF
PC	Precipitating Cloud (also PGE04)
PGE	Process Generating Element
PPS	Polar Platform System
RGB	Red Green Blue
SAF	Satellite Application Facility
SAFNWC	Satellite Application Facility for support to NoWcasting
SMHI	Swedish Meteorological and Hydrological Institute
TBC	To Be Confirmed
TBD	To Be Defined
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS	Visible

See [RD.1.] for a complete list of acronyms for the SAFNWC project.

1.4 REFERENCES

1.4.1 Applicable documents

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]

For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the current edition of the document referred applies.

Current documentation can be found at SAFNWC Helpdesk web: http://www.nwcsaf.org

Ref	Title	Code	Vers	Date
[AD.1.]	NWCSAF Project Plan	NWC/CDOP3/SAF/AEMET/MGT/PP	1.2	10/10/18
[AD.2.]	NWCSAF Product Requirements Document	NWC/CDOP3/SAF/AEMET/MGT/PRD	1.1	17/12/18
[AD.3.]	System and Components Requirements Document for the SAFNWC/PPS	NWC/CDOP3/PPS/SMHI/SW/SCRD	2.1	13/12/18

Table 1: List of Applicable Documents

1.4.2 Reference documents

The reference documents contain useful information related to the subject of the project. These reference documents complement the applicable ones, and can be looked up to enhance the information included in this document if it is desired. They are referenced in this document in the form [RD.X]

For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. For undated references, the current edition of the document referred applies

Current documentation can be found at SAFNWC Helpdesk web: http://www.nwcsaf.org

Ref	Title	Code	Vers	Date
[RD.1.]	The Nowcasting SAF Glossary	NWC/CDOP2/SAF/AEMET/MGT/GLO	2.1	03/02/17
[RD.2]	Validation of CM-SAF cloud products derived from AVHRR data in the Arctic region"	SAF/CM/SMHI/SR/CLOUDS-ORR/B	1.0	19/01/09
[RD.3]	Output Data Format of the SAFNWC/PPS	NWC/CDOP3/PPS/SMHI/SW/DOF	2.0d	13/12/18
[RD.4]	Algorithm Theoretical Basis Document for the Cloud Mask of the NWC/PPS	NWC/CDOP3/PPS/SMHI/SCI/ATBD/CloudMask	2.1	13/12/18
[RD.5]	Algorithm Theoretical Basis Document for Cloud Top Temperature, Pressure and Height of the NWC/PPS	NWC/CDOP3/PPS/SMHI/SCI/ATBD/CTTH	2.1	13/12/18
[RD.6]	Algorithm Theoretical Basis Document for Precipitating Clouds of the NWC/PPS	NWC/CDOP3/PPS/SMHI/SCI/ATBD/PC	2.1	13/12/18
[RD.7.]	User manual for the SAFNWC/PPS Application: Software Part, 2.Operation	NWC/CDOP3/PPS/SMHI/SW/UM/OPER	2.0	13/12/18
[RD.8]	Scientific and Validation Report for the Cloud Product Processors of the NWC/PPS	NWC/CDOP2/PPS/SMHI/SCI/VR/Cloud	2.0	13/12/18

Table 2: List of Referenced Documents

1.4.3 Scientific References

Since the algorithm design for cloud type follows same physical principles and to large extend the same logic as for cloud mask, the references for cloud mask also apply to cloud type classification:

Allen, R. C., Durkee, P. A., and Wash, C. H., 1990. Snow/cloud discrimination with multispectral satellite measurements. *Journal of Applied Meteorology* ***29***, 994-1004.

Anderson, J., Hardy, E., Roach, J., and Witmer, R., 1976. A land use and land cover classification system for use with remote sensor data. Technical report, U.S. Geological Survey.

Berendes, T., Kuo, K., Logar, A., Corwin, E., Welch, R., Baum, B., Petre, A., and Weger, R., 1999. A comparison of paired histogram, maximum likelihood, class elimination, and neural network approaches for daylight global cloud classi_cation using AVHRR imagery. *Journal of Geophysical Research* ***104*****(D6)**, 6199-6213.

Cox, C. and Munk, W., 1954. Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter. *Journal of the Optical Society of America* ***44*****(11)**, 838-850.

Derrien, M., Farki, B., Harang, L., Gléau, H. L., Noyalet, A., Pochic, D., and Sairouni, A., 1993. Automatic cloud detection applied to NOAA-11/AVHRR imagery. *Remote Sensing of Environment* ***46***, 246-267.

Dybbroe, A., Karlsson, K.-G., and Thoss, A., 2005a. AVHRR cloud detection and analysis using dynamic thresholds and radiative transfer modelling - part one: Algorithm description. *Journal of Applied Meteorology* ***41*****(1)**, 39-54.

Dybbroe, A., Karlsson, K.-G., and Thoss, A., 2005b. AVHRR cloud detection and analysis using dynamic thresholds and radiative transfer modelling - part two: Tuning and Validation. *Journal of Applied Meteorology* ***41*****(1)**, 55-71.

Eidenshink, J. and Faundeen, J., 1994. The 1 km AVHRR global land data set-first stages in implementation. International Journal of Remote Sensing **15(17)**, 3443-3462.

Eyre, J. R., Brownscombe, J. L., and Allam, R. J., 1984. Detection of fog at night using Advanced Very High Resolution Radiometer (AVHRR) imagery. *Meteorological Magazine* ***113***, 266-271.

Hunt, G. E., 1973. Radiative properties of terrestrial clouds at visible and infra-red thermal wavelengths. *Quarterly Journal of the Royal Meteorological Society* ***99***, 346-369.

Inoue, T., 1985. On the temperature and effective emissivity determination of semi-transparent cirrus clouds by bi-spectral measurements in the 10 µm window region. Journal of the Meteorological Society of Japan **63(1)**, 88-98.

Karlsson, K.-G., 1989. Development of an operational cloud classification model. *Int. J. Remote Sens.*, **10**, 687-693.

Karlsson, K.-G., 1996. Cloud Classification with the SCANDIA model. Reports Meteorology and Climatology **67**, SMHI.

Karlsson, K.-G. and Dybbroe, A., 2009. Evaluation of Arctic cloud products from the EUMETSAT Climate Monitoring Satellite Application Facility based on CALIPSO-CALIOP observations. *Atmos. Chem. Phys. Discuss.*, ***9****, 16755-16810, 2009.*

Karlsson, K.-G. and Liljas, E., 1990. The SMHI model for cloud and precipitation analysis from multispectral AVHRR data. PROMIS reports **10**, SMHI. 74pp.

Kriebel, K. T., G. Gesell, M. Kästner, and H. Mannstein, 2003. The cloud analysis tool APOLLO: Improvements and validations. *Int., J. Remote Sens*., **24**, 313-329.

Salisbury, J. W. and d'Aria, D., 1994. Emissivity of terrestrial materials in the 3 - 5µm atmospheric window. *Remote Sensing of Environment* ***47***, 345-361.

Saunders, R. and Kriebel, T., 1988. An improved method for detecting clear sky and cloudy radiances from AVHRR data. *Int. J. Rem. Sens.* ***9***, 123-150.

Stowe, L., McClain, E. P., Carey, R., Pellegrino, P., and Gutman, G. G., 1991. Global distribution of cloud cover derived from NOAA/AVHRR operational satellite data. *Adv. Space Res.* ***11***, 51-54.

Stowe, L. L., Davis, P. A., and McClain, E. P., 1999. Scientific Basis and Initial Evaluation of the CLAVR-1 Global Clear/Cloud Classification Algorithm for the Advanced Very High Resolution Radiometer. *Journal of Atmospheric and Oceanic Technology* ***16***, 656-681.

Warren, D., 1989. AVHRR channel-3 noise and methods for its removal. *Int. J. Remote Sens*., **10**, 645-651.

1.5 Document Overview

This document contains a theoretical description of the algorithms for cloud type derivations. The document has been structured in the following sections:

- Section 1 contains the current introduction along with the list of used acronyms and applicable and reference documents.
- Section 2 A short introduction to the cloud type product
- Section 3 A short overview of the cloud type algorithm
- Section 4 Algorithm description in more detail

1.6 Scientific Updates since PPS Version 2014

The CT product in PPS-v2018 is now made after CTTH, and it uses information from CTTH (pressure, temperature and height) to better predict the type of clouds. This means that now the CTTH and the CT products agree better. Previous versions of CT used combination of temperature difference between surface and cloud as well as the atmospheric temperature profile to get rough height estimations.

Because more info is taken from the height and pressure of CTTH, there are no longer special offsets for different illumination condition in the CT-product, instead all pixels use the same offsets and the same tests.

The fractional clouds class is now only used for low-level fractional clouds.

The cloud phase flag is removed from the CT product; it is recommended that the phase from the CPP product is used instead.

PPS-v2018 can process CT on VIIRS I-band resolution. It requires imager data in a level 1c file as input. In the level 1c file the M15 and M16 should be resampled to the I-band resolution. (See description in [RD.7.].) This is done to not lose the M15-M16 information from the M-band resolution.

2. INTRODUCTION TO THE SAFNWC/PPS CLOUD TYPE

The Cloud Type is first of all aimed at nowcasting applications.. It also provides an essential first step in the derivation of radiative fluxes over sea within the Ocean & Sea Ice SAF OSISAF). The main objective is to provide a detailed cloud scene analysis, which for all cloudy pixels in the scene distinguishes between the following generic cloud classes: fractional clouds, semi-transparent clouds, high, medium, and low clouds (including fog). The CT product is input to the SAFNWC polar satellite based retrievals for Precipitating Clouds, PC, described in **[RD.6]**.

The SAFNWC/PPS was developed for the Advanced Very High Resolution Radiometer (AVHRR) onboard the polar-orbiting weather satellites NOAA and Metop. It is implemented so that it automatically handles both AVHRR/2 data, with channel 3B during both day and night, and AVHRR/3 data, which has the possibility to activate channel 3B during night and switch to channel 3A during day. The instrument measures outgoing reflected solar energy and radiated thermal energy from land, sea, clouds and the atmosphere in 6 channels.

By now the algorithm has been generalized. It can process data from the MODIS and VIIRS instruments. It will also be prepared for using data from the MERSI-2 instrument.

2.1 Satellite channels

Satellite channels used by the SAFNWC/PPS are from the Metop and NOAA imager instrument AVHRR/3 as well as from MODIS and VIIRS, and planned for MERSI-2. See Table 3 -Table 7 for more details about the different channels.

Table 3 The AVHRR/3 channels and their approximate spectral positions on NOAA 15, 16 and 17 (small deviations in the spectral response do occur between different NOAA satellites).

	Ch 1	**Ch 2**	**Ch 3A**	**Ch 3B**	**Ch 4**	**Ch 5**
λ (µm)	**0.58-0.68**	**0.725-1.0**	**1.58-1.64**	**3.55-3.93**	**10.3-11.3**	**11.5-12.5**

Table 4: Names and spectral specifications of MODIS channels, used so far. A new spectral range (compared to the previously used AVHRR channels) is introduced by the use of channel 29.

	Ch 1	**Ch 2**	**Ch 6**	**Ch 20**	**Ch 29**	**Ch 31**	**Ch 32**
λ (µm)	**0.62-0.67**	**0.841-0.876**	**1.628-1.652**	**3.66-3.84**	**8.4-8.7**	**10.78-11.28**	**11.77-12.27**

Table 5: Names and spectral specifications of MERSI-2 channels, as planned to use (TBD01)

λ (µm)	**0.650**	**0.865**	**1.640**	**3.80**	**8.55**	**10.8**	**12.0**

Table 6: Names and spectral specifications of VIIRS channels, used so far. A new spectral range (compared to the previously used AVHRR channels) is introduced by the use of channel M14, but the VIIRS channels are similar to those used for MODIS..

	Ch M5	**Ch M7**	**Ch M10**	**Ch M12**	**Ch M14**	**Ch M15**	**Ch M16**
λ (µm)	**0.672**	**0.865**	**1.61**	**3.7**	**8.55**	**10.763**	**12.013**

Table 7 Names and spectral specifications of VIIRS channels, when using a combination of I-band and M-band channels

	Ch I1	**Ch I2**	**Ch M9**	**Ch I3**	**Ch I4**	**Ch M14**	**Ch M15**	**Ch M16**
λ (µm)	**0.64**	**0.865**	**1.378**	**1.61**	**3.74**	**8.55**	**10.763**	**12.013**

2.1.1 Solar channels

Because of their different names that come with different instruments, channels are determined by their spectral position rather than by their name. Exceptions are made in case of referencing to instrument specific issues.

In the 0.6µm channel, clouds appear bright because of the high reflectance while the signal from land and sea is generally poor (exception: sunglint areas over sea). Snow and ice on ground also appear bright. For the 0.8µm channel, the contrast between clouds and land is high and reflectance from sea surface is low, too (except for sunglint areas). However the signal from vegetated land is more intense compared to the 0.6µm channel.

The 1.6µm channel is a so called near IR-channel. It allows to distinguish between snow/ice covered land and signal from other sources. The reflectance from snow and ice decreases with increasing wavelength in the Visible to NIR spectral range, and the reflectance over snow/ice is thus much smaller than in the 0.6µm or 0.8µm channels, providing a means to detect snow cover on the ground during daytime. Similarly this channel is also sensitive to the cloud phase; water clouds reflect more energy in this spectral range than ice clouds.

2.1.2 Thermal channels

The 3.7µm channel lies in the spectrum where the outgoing energy comes from two sources: solar reflectance and thermally emitted radiation. This channel is sensitive to cloud phase and is particularly useful for the detection of night-time water clouds. The detection of thin cirrus can be done by analysing differences of the 3.7µm channel to the 11µm or the 12µm channel. Snow-covered ground has almost no contribution to the signal, received within this spectral range.

In the region around 8.5µm, there is a channel (unfortunately not on AVHRR instruments) close to one ozone-line but still in the window region. This channel in combination with the 11µm channel might enhance the contrast in the night cirrus test if used instead of one of the 11 or 12 micron channels. This channel is not active in the CT product yet.

The channel, located round 11 µm, is what is often referred to as the "IR window channel", i.e. radiation from the Earth's surface or cloud tops is little effected by extinction in the atmosphere. This channel responds to the temperature of clouds and surfaces and returns a signal close to what is called the thermodynamic temperature. The characteristic of the 12µm channel is very similar to its neighbour at 11µm. However, there are some differences, for example the detection of cirrus (the atmosphere seems denser with increasing wavelength).

2.2 Requirements

The requirements for the SAFNWC/PPS products are described in the Product Requirements Document [AD.2.]. In Table 8 is given a summary of the requirement specific for the cloud type product. These requirements are valid for central Europe

Table 8 Accuracy requirements for Cloud Type

	POD	**FAR**
Threshold accuracy	50%	60%
Target accuracy	70%	40%
Optimal accuracy	80%	20%

3. ALGORITHM OVERVIEW

The main objective for the CT is to give a detailed cloud analysis after the CMA and CTTH are done. For every cloud filled or cloud contaminated pixel in the CMA, the CT algorithm sub-divide each cloudy pixel into different cloud categories. The CT algorithm uses a threshold technique which works using one or several tests. Spectral information from the satellite channels, brightness temperature and reflectance depending on light condition and pressure and height from the CTTH product, are compared with thresholds which mark the border between the different cloud categories. Together with the threshold test there are also so called threshold offsets. The threshold offsets are empirically derived, using the database of interactive training targets and from visual inspection. When deriving the offsets, they may vary with the underlying surface (land, sea or coast), the sun-satellite viewing geometry and illumination (night, twilight, day) or sunglint, and presence of low-level inversion or topography (low or high terrain). Those offsets work as a tuning parameter to adapt the algorithm to the training targets (compare Dybbroe et al., 2005a; Dybbroe et al., 2005b).

The CT algorithm is a multi-spectral threshold retrieval applied to each pixel of the satellite scene. The multi-spectral retrieval technique is widely used in operational cloud typing using AVHRR data. The SCANDIA, APOLLO, and the LUX schemes on which the PPS system inherits are good examples. See Karlsson (1989), Derrien et al. (1993) and Kriebel et al. (2003). The retrieval utilise that different cloud types leave varying marks in the visible and thermal spectrum. Carefully derived thresholds help to discriminate single features. In the best case the sum of spectral signs, the fingerprint leads univocally to a certain cloud type.

The cloud type classification employs a sequence of threshold tests in an `if-else-if`-structure. Contrary to the CMA algorithm, where testing is continued if one of the features tested is close in value to its corresponding threshold, the CT algorithm stops if a threshold test is successful. Also where almost all of the threshold tests of the CMA algorithm are grouped (using several threshold tests concurrently), the threshold tests in the CT algorithm often use a few or even a single feature (e.g. the T11T12). The sequence of testing (from version 2018) is independent of the time of day.

In short first the clouds with height below 500m are classed as Very Low. Then pixels with pressure below 680 hPa, and with an increased T11-T12 as compared to the cloud free case, are classed as thin cirrus. The thin cirrus cloud category is then divided in the four classes: *very thin cirrus*, *thin cirrus*, *thick cirrus* and *cirrus above low or mid level clouds*, according to the 11µm brightness temperature and to the distance of T11-T12 from the cloud free case. Then clouds with pressure below 680hPa that have a cloud temperature (from CTTH product) more than 35K colder than T11 are also classed as thin cirrus. These are not divided further. Remaining clouds with pressure below 440 hPa will be high or very high. Remaining clouds with pressure between 680 and 440 hPa will be medium level clouds. Pixels with pressure higher than 680 hPa, that have both a high local texture in the 11µm brightness temperature and a small deviation in 11 µm brightness from surface temperature, will be classed fractional clouds. All remaining clouds with pressure higher than 680hPa will be Low clouds.

The activities carried out in the main processing stage are described in Figure 1. Prior to performing CT classification, necessary satellite input imageries must be prepared.

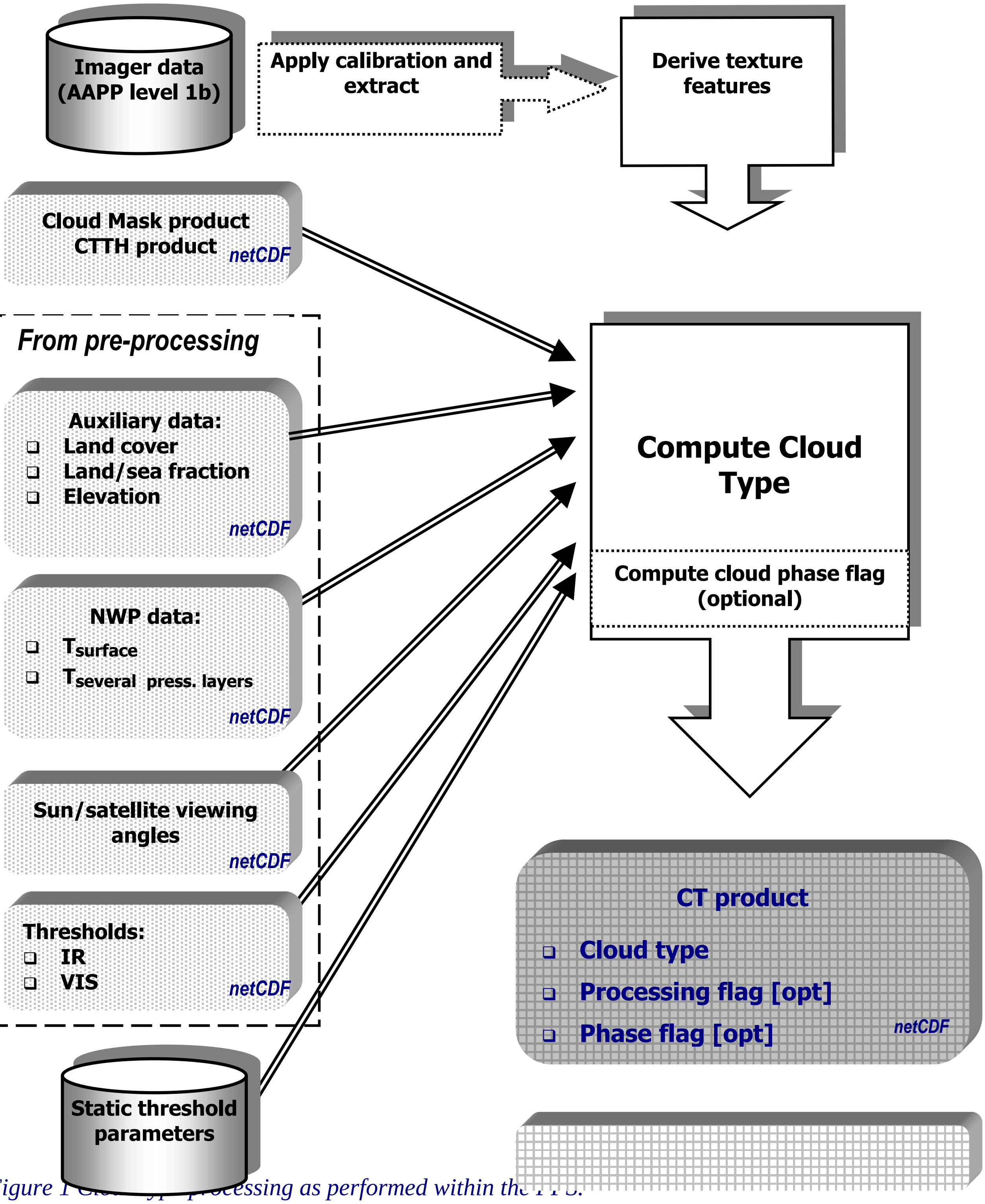

Figure 1 Cloud type processing as performed within the PPS.

The output file comes in netcdf.

4. ALGORITHM DESCRIPTION

4.1 THEORETICAL DESCRIPTION

4.1.1 Physics of the Problem

As described already in [RD.4], the light emitted or reflected by the earths surface or atmospheric constituents carries information on the matter within its path. The spectral composition of the instruments observations allows (under good conditions, explained later in this document) to distinguish not only between cloud-free and cloudy but also between certain cloud types.

Similar to the cloud-mask algorithm a threshold technique is applied to tackle this task. In case of having adequate temperature differences between surface and the cloud itself, it is possible to categorise a cloudy pixel in semi-transparent, fractional and opaque. Semi-transparent clouds means clouds optically thin enough for the signal to be influenced by underlying clouds or surface. In principle semi-transparent clouds have an optical thickness of 1 to 2, for example thin cirrus.

The pressure from the CTTH products is used to predict the vertical position of the cloud in the atmosphere, as it gives valuable information on the cloud type (fractional water clouds are low, and thin cirrus are often high).

4.1.2 Mathematical Description of the Problem

In the following we present a detailed description of the numerical cloud type identification. The cloud type algorithm use threshold tests which are made by some different features. The features are a single channel or a combination of two channels, i.e. brightness temperature difference. Also pressure and height from the Cloud Top Temperature and Height products is used.

Table 9 Description of the features used for threshold tests.

Feature	Description
R06	**Reflectance at 0.6 µm**
CTTH-height	**Height from CTTH product**
CTTH-pressure	**Pressure from CTTH product**
T11T12	**Brightness temperature difference T11 – T12 µm**
T37T12	**Brightness temperature difference T37 – T12 µm**
T11T37	**Brightness temperature difference T11 – T37 µm**
$T11-T_{sur}$	**Difference between T11 and surface skin temperature (from NWP)**
$T11-0.5*T_{500}-0.5*T_{ttro}$	**Difference between T11 and mean of temperature at 500hPa and at tropopause (from NWP)**
$T11-T_{500}$	**Difference between T11 and temperature at 500hPa (from NWP)**
$T11-T_{700}$	**Difference between T11 and temperature at 700hPa (from NWP)**
$T11-T_{850}$	**Difference between T11 and temperature at 850hPa (from NWP)**
$T11-T_{950}$	**Difference between T11 and temperature at 950hPa (from NWP)**

$T11_{text}$	**Local T11 µm standard deviation. (texture)**

Texture is defined as spatial variability where the standard deviation is calculated over 5 by 5 pixels, and over 3 by 3 pixels when using GAC-settings. High local texture means large variance.

4.1.2.1.1 Introduction

High semi-transparent (cirrus) clouds can be distinguished from opaque clouds using the T11T12 or T3.7T12 features. The method builds on the facts that the transmissivity decreases with increasing wavelength in the IR for ice clouds, that the atmospheric temperature decrease with height, and that the surface temperature is usually much higher than the cloud temperature. Those facts often work well but one should be aware of the following which can lead to misinterpretation; The colder the surface the more ambiguous the separation of opaque and semi-transparent high clouds gets.

Due to the larger difference in transmissivity and the higher non-linearity of the Planck function at 3.7µm the T3.7T12 feature is most efficient provided the ground is relatively warm. It can, however, only be used during night as the solar reflection contaminates the feature in daylight. At lower surface skin temperatures this feature gets less useful due to the increased noise stemming from a high digitisation error. At around and below 230-240 K the signal to noise level is so low that the benefit of this feature in cloud discrimination gets insignificant. For AVHRR instruments where channel 1.6 is activated during day there is no 3.7 channel available. For other instruments than the AVHRR, the use of the 8.5µm channel is pronounced to provide valuable benefit in the future.

Unfortunately fractional low clouds may also give rise to the same increase in the T11T12 and T3.7T12 features as observed for thin cirrus clouds. This is due to the non-linearity of these features with temperature and an often observed difference in temperature between the surface and the cloud. This leads to an inherent ambiguity in the attempt to distinguish between fractional water clouds and thin cirrus clouds. However, at least a partial separability seems possible as thin cirrus clouds may appear colder (as observed by T11 for instance) than fractional water clouds. But the variabilities in cirrus and fractional water cloud temperatures are very large, and often the overlap is considerable if at all separable.

The presence of low or medium level cloud cover beneath the semi-transparent cirrus has the effect of reducing the T11T12 and T3.7T12 due to a lowered background temperature, further complicating the cloud separation.

4.1.2.1.2 Implementation

The pressure and height from the CTTH is used to better predict the cloud type. First of all clouds lower than 500m will be set to class Very Low. Only clouds with lower pressure than 680 hPa can be classed as cirrus, and this only if they have a large difference in T11-T12. Only clouds with pressure below 440 hPa can be classed as High or Very High opaque. Only clouds with higher pressure than 680 hPa can be classified as fractional water clouds or Low clouds. For more details on the tests see *Table 10*.

For pixels that have nodata in the CTTH product (this is very few pixels!), simplified tests using only t11 and temperatures at 500 hPa, 700 hPa, 850 hPa and tropopause are used. I.e. this is a sub-set of the tests described in Table 10. These pixels will be flagged by two flags: in condition flag: 'useful input product is missing', in quality flag 'Retrieval quality: Bad'

The tests for cloud type classes are performed in the order described by Table 10. Thus if a test fails, the next test in the sequence will be done. While if a test succeeds, that class will be used, and the testing stops there (unless there are second tests for that tests). The main test sequence is all the first tests, in the order described (line by line).

There is also a secondary test sequence: If the first test for cirrus succeeds the test sequence continues with the second tests for cirrus. The logic for second tests is the same as for first tests: if it fails then make the next test, if it succeeds then use that class and stop. Once a sequence of second tests has been entered, one of the second tests has to succeed (i.e. the last is an else-statement), and the test sequence will never return to the first tests again.

Table 10 The thresholding of semi-transparent cirrus, opaque and fractional clouds over all surfaces. "O" stands for offset, and is either a true constant offset or linearly varying in the secant of the satellite zenith angle.Each table row corresponds to an `elseif` clause, so that in addition to the test requirements listed in one row the previous tests should have failed if the classification should even be considered.

Cloud Type Class	First Test	Second Test
Very low	CTTH-height < 500 m	
Cirrus See second test to determine which cirrus class	CTTH-pressure < 680 hPa AND $T11 - T12 > T11T12_{threshold} + O_{t11t12}$	
Cirrus on lower clouds		$T11 < T_{500hPa}$ AND $T11 - T12 > T11T12_{threshold} + O_{t11t12(verythin)}$
Very thin cirrus		$T11 - T12 > T11T12_{threshold} + O_{t11t12(verythin)}$
Cirrus on lower clouds		$T11 < 0.5T_{500hPa} + 0.5T_{tropopause}$ AND $T11 - T12 > T11T12_{threshold} + O_{t11t12(thin)}$
Thin cirrus		$T11 < T_{700hPa}$ AND

Cloud Type Class	First Test	Second Test
		$T11 - T12 < T11T12_{threshold} + O_{t11t12(thin)}$
Thick cirrus		*If no other cirrus type was successful cirrus will be thick cirrus.*
Thin cirrus	CTTH-pressure < 680hPa AND T11 – CTTH-temperature > 35	
Very High Opaque	CTTH-pressure < 440 hPa AND $T11 < 0.5T_{500hPa} + 0.5T_{tropopause}$	
High Opaque	CTTH-pressure < 440 hPa	
Medium Clouds	CTTH-pressure < 680 hPa	
Fractional clouds	$T11_{text} > O_{t11text(subpixel)}$ AND $\lVert (T11 - T_{sur}) - T11Tsur_{threshold} \rVert < O_{t11tsur(subpixel)}$ AND CTTH-pressure >=680	
Low clouds	CTTH-pressure >=680 AND CTTH-height>=0	
	Normally no pixels left by now!	
Very High Opaque	$T11 < 0.5T_{500hPa} + 0.5T_{tropopause}$	
High Opaque	$T11 < T_{500hPa}$	
Medium Clouds	$T11 < 7_{700hPa}$	
Low clouds	$T11 < T_{850hPa}$	
Very low clouds	*All remaining pixels*	

4.1.2.1.3 Possible future improvements

The cloud type is much improved now in version 2018 with the use of pressure from CTTH.

Additionally, the use of complement information from different channels (provided by new instruments) might help to improve the CT product further.

Table 11 The threshold offsets used in detection of semi-transparent cirrus and fractional water clouds over land and sea. sec stands for the secant of the satellite zenith angle: 1/cos(θ_{sat} *)*

Threshold Offsets	
T11T12	
$O_{t11t12(opaque)}$	$0.0K$
$O_{t11t12(verythin)}$	$O_{t11t12(opaque)} + 1.6K - 0.2 \times (\sec - 1)$
$O_{t11t12(thin)}$	$O_{t11t12(opaque)} + 0.8K - 0.2 \times (\sec - 1)$
T37T12	
T11-T$_{sur}$	
$O_{t11tsur(subpixel)}$	$12K$
T11$_{text}$	
$O_{t11text(subpixel)}$	$1.0K$ (4.0K GAC-settings)

Some offsets differ between GAC settings and not-GAC settings.

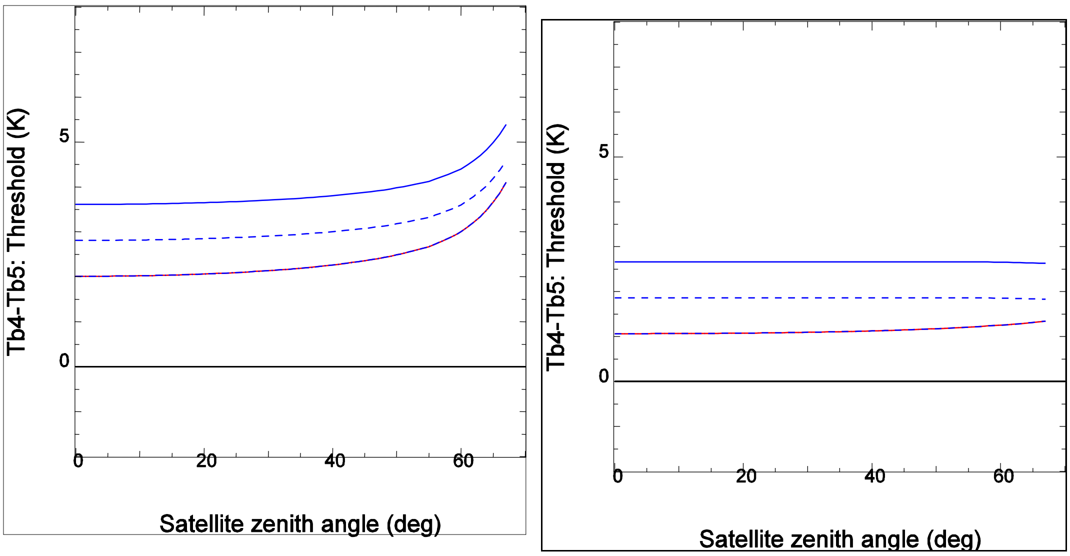

Figure 2 Examples of the T11T12 thresholds used for semi-transparent clouds distinction. The thresholds are displayed as a function of satellite zenith angle. The panel to the left shows the thresholds used for an integrated water vapour content of 25 kg/m^2 and surface temperature of 290K, and the thresholds to the right are valid for 10 kg/m^2 and 270K. The red curves (difficult to see as they are almost exactly coinciding with the blue ones for this example) are the cloud free thresholds ($O_{t11t12(opaque)}$), and the blue ones are for the thin cirrus separation. The dash-dotted is for the thick cirrus ($O_{t11t12(thick)}$) and is equal to the cloud free threshold. The dashed curves are for the thin cirrus ($O_{t11t12(thin)}$), and the full blue curves are for the very thin cirrus clouds ($O_{t11t12(verythin)}$).

4.2 PRACTICAL CONSIDERATION

4.2.1 Validation

Validation of the PPS cloud type product can be carried out against CALIOP data, making use of the vertical feature mask classification. CALIOP cloud layers are subdivided according to height using the ISCCP method and according to transparency (low level clouds > 680hPa, medium level 680-440hPa, high level <440hPa). PPS cloud "cirrus" categories can however not be fully validated using this method, since the existing CALIOP "thin" category selects much thinner clouds than imager used for this CT and CALIOP generally is sensitive to clouds too thin to detect with instruments, used here. Also the PPS cloud type does not differentiate between high- and medium-level semi-transparent cirrus. The PPS cirrus class is therefore considered a success both for CALIOP altocumulus and cirrus see Table 12 for information of which cloud combinations are treated as successes. To treat CALIOP transparent altocumulus as a correct match with PPS cirrus can be questioned; however there are thin altocumulus and this is a fair way to treat those. Not also that some convective clouds can have a thin cirrus layer on top. This means that some considered miss classified clouds that are classified as cirrus by PPS and as deep convective by CALIOP are actually correctly classified. Table 13 presents the results from a comparison of PPS and CALIOP cloud types for one orbit of Suomi-NPP VIIRS data for PPS v2018 and PPS v2014. See Table 15 for a more detailed analysis. In Table 13 we can see that POD and FAR for all classes are within threshold accuracy both for PPS-v2014 and PPS-v2018 and that PPS-v2018 have better scores.

Table 12 Overview of PPS and CALIOP cloud type matches that are considered to be correct (marked with X).

		PPS cloud types				
CALIOP cloud types		*Low*	*Low (frac)*	*Medium*	*High*	*Cirrus*
CALIOP low	*low overcast (tp)*	*X*	*X*			
	low overcast (oq)	*X*	*X*			
	transition	*X*	*X*			

	stratocumulus					
	low broken cumulus	*X*	*X*			
CALIOP medium	*altocumulus (tp)*			*X*		*X*
	altostratus (oq)			*X*		
CALIOP high	*cirrus (tp)*				*X*	*X*
	convective (op)				*X*	

Table 13 POD and FAR scores for the three different cloud categories, from validation of one S-NPP orbit from 2015.

Time of day	**POD Low (%)**	**POD Medium (%)**	**POD High (%)**	**FAR Low (%)**	**FAR Medium (%)**	**FAR High (%)**	**FAR Cirrus (%)**
PPS-v2018	89.4	72.0	76.3	3.9	39.1	8.8	32.3
PPS-v2014	76.3	56.7	71.6	18.1	59.3	9.9	38.8

. In Table 13 green numbers means that target accuracy is fulfilled (or sometimes even optimal accuracy), while red numbers means that threshold accuracy is not fulfilled.

Table 14 Accuracy requirements for Cloud Type

	POD	**FAR**
Threshold accuracy	50%	60%
Target accuracy	70%	40%

Optimal accuracy	80%	20%

Table 15Comparison of PPS version 2014 and version 2018. Notice that less medium and high clouds (especially transparent ones) are misclassified as low or fractional in version 2018. Notice also that less low clouds are classed as cirrus. Low clouds are generally now better classed as low. But for the CALIOP type **low broken cumulus** *some more clouds are now classed as medium or high level clouds. The difference in number of pixels (N) is because of the higher POD cloudy of the v2018 cloudmask.*

CALIOP type	N	Low	Frac	Medium	High	Cirrus	PPS
Low Clouds							
low overcast (tp)	1330	59.9	16.4	15.8	0.5	7.4	2018
	1300	43.4	15.2	26.6	0.2	14.6	2014
low overcast (oq)	1516	90.9	5.9	1.6	0.0	1.6	2018
	1525	75.5	10.1	12.7	0.0	1.8	2014
transition stratocumulus	5032	44.6	48.4	4.2	0.1	2.6	2018
	4511	47.2	31.1	12.0	0.6	9.1	2014
low broken cumulus	677	35.0	35.9	14.0	1.3	13.0	2018
	719	42.1	34.2	10.2	0.8	12.7	2014
Medium Clouds:							
altocumulus (tp)	1220	2.8	1.5	36.9	7.4	51.5	2018
	1233	15.7	14.2	24.9	2.3	42.9	2014
altostratus (oq)	2196	1.3	0.1	62.9	12.3	23.4	2018
	2199	4.3	4.4	50.5	20.1	20.7	2014
High Clouds:							
cirrus (tp)	7554	1.1	1.8	7.6	15.7	73.7	2018
	7326	7.1	3.5	11.3	21.8	56.2	2014
deep convective (op)	4888	0.0	0.0	1.2	56.1	42.7	2018
	4889	0.2	0.1	1.7	*61.8*	*36.2*	2014

Another PPS cloud type validation for older versions has been performed in CMSAF for arctic areas ([RD.2]). For details of that study see also Karlsson et al., 2009.

4.2.2 Quality control

The processing/quality flags appended to the CMA are copied to the CT output. Thus e.g. a pixel having low confidence according to the CMA processing flags will be assigned a low confidence also in the CT. See section *Quality control and validation* in ATBD-01 [RD.4] for details.

If CTTH data is missing for a certain pixel, it will be assigned the quality bad.

If there is CTTH-pressure data, but no CTTH-height data for a certain pixel, it will be assigned the quality questionable.

4.2.3 Processing time

The cloud type product needs the CTTH product as input (from v2018 onwards). The CTTH take some processing time. If you are in a hurry to get your cloud type product, and not being so interested in the CTTH product, you can configure CTTH for faster processing, i.e. producing only cloud top pressure, not height or temperature. (See [RD.5]). But keep in mind that the quality of the cloud type product will be a bit reduced under this configuration.

4.2.4 Assumptions and limitations

A known problem is the misclassification of semi-transparent cirrus as fractional water clouds. Cloud edges on the other hand are frequently interpreted as high semi-transparent clouds. These mentioned situations provide an ambivalent spectral signature. In the v2018 version of the cloud type, these problems have significantly decreased. Note that the fractional class is only used for low-level fractional clouds in PPS version v2018.

The cloud type now much benefits from the PPS CTTH product. The quality of the cloud type is therefore dependent of the quality of the CTTH.

4.2.5 List of inputs

4.2.5.1 Satellite data

The same spectral information as needed by the CMa is input to the CT and as the CMa is mandatory input to the CT, though only the 11µm and 12µm channel are mandatory for the CT.

The algorithm has been developed specifically for the AVHRR instrument on board the current and future polar orbiting NOAA and EUMETSAT Metop satellites. It has been implemented so that it automatically handles both AVHRR/2 data, with channel 3B during both day and night, and AVHRR/3 data, with channel 3B during night and 3A during day.

Recent efforts have been made to widen the applicability of the PPS to other instruments on polar platforms. Up to now it is possible to process data from MODIS and from VIIRS on the Suomi-

NPP platform and future JPSS satellites. See Table 16 for a complete list of channels and requirements.

Table 16 The channels and their approximate spectral positions. Mandatory channels and those which are not yet used are specified.

λ (µm)	**0.6**	**0.9**	**1.6**	**3.7**	**8.5**	**11**	**12**
	Optional (not used)	**Optional (not used)**	**Optional (not used)**		**Optional (not used yet)**	**Mandatory**	**Manda-tory**

4.2.5.2 Cloud Mask

The cloud mask product as provided by the CMa is mandatory input for the CT. The CT is not processed for pixels that are classified as cloud free in the CMa, but the cloud free class already assigned in the CMa is filled in. The sea/ice class of CMa is used as a basis for the CT sea/ice classes. Also the CMa processing flags are used within the CT algorithm, and some flags are even copied without modification from CMa to CT.

4.2.5.3 CTTH

The Cloud Top Temperature, Pressure and Height product as provided by CTTH is input for the CT. The Cloud Top Pressure is mandatory as input, while the Cloud Top Temperature and Cloud Top Height are optional as input -but recommended.

4.2.5.4 Sun and satellite angles

Similar to the CMa, the CT needs information on the sun- satellite viewing geometry in pixel resolution.

The instantaneous sun-satellite viewing geometry is stored for every satellite FOV. The angles are the sun zenith angle (θ_{sun}), the satellite zenith angle (θ_{sat}) and the sun-satellite azimuth difference angle. The satellite zenith angle is always positive and increases from 0° at the sub-satellite point to about 68° at the edges of the swath. The azimuth difference is defined as

$$\delta\phi = \begin{cases} 360° - \delta\phi' : \delta\phi' > 180° \\ \delta\phi' \quad : \delta\phi' \leq 180° \end{cases}$$

Where $\delta\Phi' = |\Phi_{sun} - \Phi_{sat}|$. Here Φ_{sun} is the sun azimuth (counted clockwise from the local north) and Φ_{sat} is the satellite azimuth. Surface specular reflection on a perfect mirror will be observed by the satellite when $\delta\Phi = 180°$ provided the sun zenith angle equals the satellite zenith angle.

The sun-satellite angles are mandatory for the CMa and CT. The angles are be derived from the AAPP level 1b file (or the corresponding NOAA LAC data) by using interpolation and extrapolation (see [RD.7.]). For VIIRS angles are derived from the str data file, prepared by CSPP. For MODIS angles are derived from the level 1b data file.

4.2.5.5 Land cover characterisation and elevation

The same land-use and elevation data needed by the CMa is required by the CT.

We use the 1km global land cover characterisation database available from the Unites States Geological Survey (USGS) (see Anderson et al., 1976 and Eidenshink and Faundeen, 1994), mainly for separating land and water surfaces, but also to identify barren and desert areas where shortwave IR emissivities are significantly below 1 (Salisbury and d'Aria, 1994). Digital elevation model (DEM) data is derived from the *Global 30 arc seconds topography database*, GTOPO30, (http://edcdaac.usgs.gov/gtopo30/) and used to separate low and gentle terrain from high and rough mountaneous terrain.

The native elevation and land-use data are being processed and mapped onto the swath by the PPS software to produce land-use, elevation, and fraction of land maps valid for the current scene. See [RD.7.] for a description of how to generate physiography data for a swath. The physiography data are mandatory for the CMA and CT.

4.2.5.6 NWP data

Like the CMa, the CT uses NWP parameters as either provided by a short range forecast (lead times between 6 and 24 hours) in case of nowcasting, or as provided by a valid analysis in case of off line processing (as e.g. in re-processing for climate applications).

The CT requires the temperature at the 950hPa, 850hPa, 700hPa, 500hPa, and tropopause levels, and also the surface (skin) temperature. Like for the CMA these parameters are needed in full (map-projected) pixel resolution.

4.2.5.7 Parameter files and algorithm configuration files

The CT only has a few configuration parameters, one environment variable about the input, and the rest related to how much is wanted in the final output. These can be found in the file `pps_config_common.cfg` and are listed here:

- SM_CT_CTTH_HEIGHT_MANDATORY (default False): Environment variable. Whether CTTH-height and CTTH-temperature is mandatory or optional input. (CTTH-pressure is always mandatory.)
- `GENERATE_CLOUDTYPE` (default True): Whether the cloud type main output is wanted.
- `GENERATE_PROCESSING_FLAG` (default True): Whether the processing flags are wanted.
- `GENERATE_MULTILAYER_FLAG` (default False): Whether the multi-layer flag is wanted.

At least GENERATE_CLOUDTYPE must be yes for being able to use CT as an input to PC. It is also a benefit for PC if GENERATE_PROCESSING_FLAG is yes.

The CT uses a number of static thresholds and threshold offsets, defined in the file threshold_offsets.cfg, and threshold_offsets_gac.cfg when GAC-settings are used. Altering these parameters, which have been determined during algorithm tuning and validation, will strongly affect the quality of the CT output. It is **not** recommended to modify those.

4.2.6 Description of output

The content of the CT consist of six datasets, as described below.

Main Output

Table 17 Main output key

Number of the Class	Name of the Class	Description/ Comments
1	Cloudfree land	No contamination by clouds or snow covered surface.
2	Cloud free sea	No contamination by clouds or snow/ice covered surface.
3	Land contaminated by snow	
4	Sea contaminated by snow/ice	
5	Very low clouds	Include fog, used for all very low clouds
6	Low clouds	used for all low clouds
7	Medium level clouds	used for all very medium level clouds
8	High opaque clouds	used for all high opaque clouds
9	Very high opaque clouds	Used for all very high opaque clouds
10	Fractional	Sub-pixel water clouds (including cloud edges); only used when the clouds at the same time are low.
11	High semi-transparent very thin cirrus	
12	High semi-transparent thin cirrus	
13	High semi-transparent thick cirrus	
14	High semi-transparent cirrus above low or medium level clouds	
15	Not used value	For GEO: High semi-transparent above snow/ice
Fill Value	No/corrupted data	

Status flags

Table 18 Statusflags

Meaning of individual status flags (i.e. if according bit is set to 1).

Bit Number	Description
0	Low level thermal inversion in NWP field
1	NWP data suspected low quality
2	Sea ice map is available
3	Sea ice, according to external map
4	*dummy*
5	Suspected heavy aerosol

Conditions flags

Bit Number	Description
0	Pixel is out of swath or points to space
1 and 2	Defines the illumination condition: 0: N/A 1: Night 2: Day 3: Twilight
3	Sunglint
4 and 5	Defines whether it is land or sea: 0: N/A 1: Land 2: Sea 3: Coast

Bit Number	Description
6	High terrain
7	Rough terrain
8 and 9	Satellite input data status: 0: N/A 1: All satellite data are available 2: At least one useful channel is missing 3: At least one mandatory channel is missing
10 and 11	NWP input data status: 0: N/A (not classified pixel or NWP data not used) 1: All NWP data are available 2: At least one useful NWP field is missing 3: At least one mandatory NWP field is missing
12 and 13	Product input data status: 0: N/A (not classified pixel or input product data not used) 1: All product input data are available 2: At least one useful input product is missing 3: At least one mandatory input product is missing
14 and 15	Auxiliary data status: 0: N/A (not classified pixel or auxiliary data not used) 1: All auxiliary data are available 2: At least one useful auxiliary field is missing 3: At least one mandatory auxiliary is missing

Quality flags

Bit Number	Description
0	Pixel is NODATA
1	This bit is not used in PPS. It is a left over to keep the same bit numbers as GEO.
2	This bit is not used in PPS. It is a left over to keep the same bit numbers as GEO.
3 to 5	Retrieval quality: 0: N/A (no data) 1: Good 2: Questionable 3: Bad 4: Interpolated/Reclassified

Multi-layer flag

Table 19 Multi-layer flag

Bit Number	Flag Name	Description
0	Not multi-layer	Cloudy, but not multi-layer. (i.e. single layer)
1	Multi-layer	Cloudy, in two or more layers.
_FillValue	nodata	Either cloud free, or missing information.

4.2.7 Visualisation

It is important to note that the PPS CT product first of all provide a digital analysis of the cloud field, and the cloud classification should be used together with the appended quality flag and the PPS CPP Cloud Phase as input to automatic mesoscale analysis or nowcasting schemes.

Images may be derived and displayed to the forecaster but the products are not just images. Even when used for image display the additional flags should be presented or made easily available to the forecaster as is the case using the SMHI PPS tool for visualisation, Image Viewer (see Figure 3). The user may also with advantage choose to highlight certain cloud categories as is done on the SMHI web site (http://www.smhi.se/saf).

The cloud type product can also be opened and visualized using hdfview (works for netCDF-files, as well)..

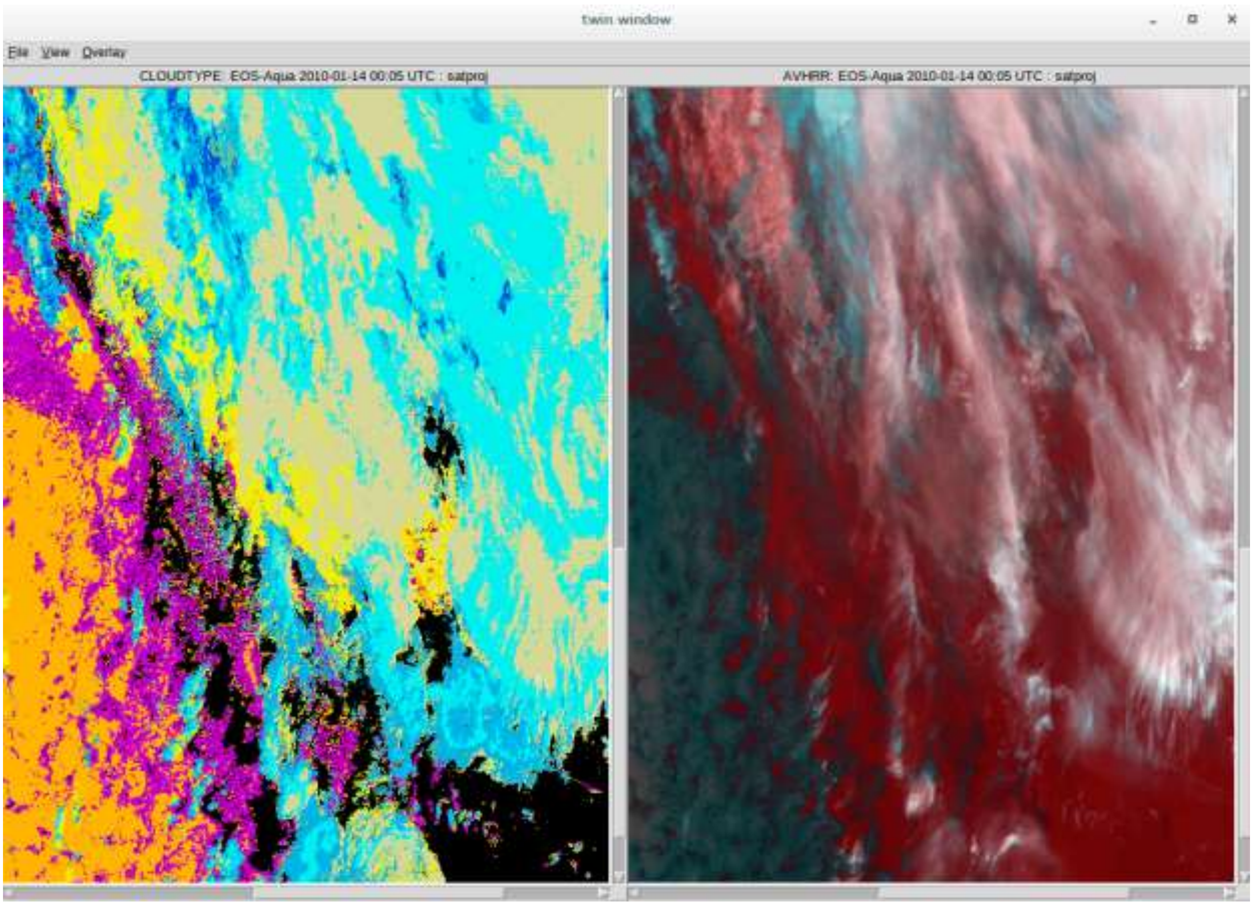

Figure 3 Example of cloud type image display using a dedicated PPS image viewer developed at SMHI. To the right a close up RGB image using channels 11um 12um and 3.7um. To the left the corresponding cloud type. Instrument MODIS on sattelite EOS-Aqua 2010-01-14 00:05UTC.

ANNEX A. List of TBC, TBD, Open Points and Comments

TBD/TBC	Section	Resp.	Comment
TBD01	2.1	SMHI	MERSI-2 capabilities will be provided later as a patch to v2018, if and when, necessary info and data are available