Algorithm Theoretical Basis Document for "Cloud Products" (CMa-PGE01 v3.2, CT-PGE02 v2.2 & CTTH-PGE03 v2.2)

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Prepared by Météo-France / Centre de Météorologie Spatiale

REPORT SIGNATURE TABLE

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DOCUMENT CHANGE RECORD

Version	Date	Pages	CHANGE(S)
1.4	7 November 2007	67	Initial version (content derived from "User Manual for PGE01-02-03 v1.3 (Cloud Products) of the SAFNWC/MSG: scientific part")
2.0	23 August 2008	75	Content adapted to version v2.0
3.0	17 May 2010	87	Content adapted to version v3.0
3.1	24 March 2011	87	Content adapted to v3.1
3.2	15February 2012	88	Content adapted to version v3.2
3.2.1	15 July 2013	87	Content adapted to NWP management change

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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://www.nwcsaf.org. This document is applicable to the SAFNWC processing package for Meteosat Second Generation satellites meteorological satellites, SAFNWC/MSG.

1.1 Scope of the document

This document is the Algorithm Theoretical Basis Document for the cloud products PGE01 (CMa, Cloud Mask), PGE02 (CT, Cloud Type) and PGE03 (CTTH, Cloud Top Temperature and Height) of the SAFNWC/MSG software package.

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

1.2 Software Version Identification

This documents describes the algorithms implemented in the release2013 of the SAFNWC/MSG software package (CMa-PGE01 v3.1, CT-PGE02 v2.1, CTTH-PGE03 v2.2).

1.3 Improvement from previous version

CMa, CT and CTTH algorithms remain unchanged since previous release (v2012).

1.4 Definitions, Acronyms and Abbreviations

6S	Second Simulation of Satellite Signal in the Solar Spectrum
BRDF	Bi-directional Reflectance Functions
CMa	Cloud Mask (also PGE01)
CMS	Centre de Meteorologie Spatiales (Météo-France, satellite reception centre in Lannion)
CTTH	Cloud Top Temperature and Height
CT	Cloud Type
ECMWF	European Centre for Medium range Weather Forecast
EUMETSAT	European Meteorological Satellite Agency
FOV	Field Of View
HDF	Hierarchical data Format
HRIT	High Rate Information Transmission
IR	Infrared
K	Kelvin
MODIS	Moderate-Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
NIR	Near Infra-Red
NOAA	National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
PGE	Product Generation Element

R0.6µm	0.6 visible reflectance
RTMOM	Radiative Transfer based on Matrix Operator Method
RTTOV	Rapid Transmissions for TOVs
SAF	Satellite Application Facility
SAF NWC	SAF to support NoWCasting and VSRF
SAF OSI	Ocean and Sea Ice SAF
SEVIRI	Spinning Enhanced Visible & Infrared Imager
SST	Sea Surface Temperature
SUM	Software User Manual
SW	Software
T11µm	11 micrometer infrared brightness temperature
TIGR	Tovs Initial Guess Retrieval
TOA	Top Of Atmosphere
VIS	Visible

1.5 REFERENCES

1.5.1 Applicable Documents

Reference	Title	Code	Vers	Date
[AD. 1]	Validation Report for "Cloud Products" (CMa-PGE01 v3.2, CT-PGE02 v2.2 & CTTH-PGE03 v2.2)	SAF/NWC/CDOP/MFL/SCI/VR/06	1.0	15/02/12
[AD. 2]	Software User Manual for the SAFNWC/MSG application	SAF/NWC/CDOP/INM/SW/SUM/2		

Table 1: List of Applicable Documents

1.5.2 Reference Documents

Reference	Title	Code	Vers	Date
[RD.1]				
[RD.2]				

Table 2: List of Referenced Documents

2. DESCRIPTION OF CLOUD MASK (CMA) PRODUCT

2.1 CLOUD MASK (CMA) OVERVIEW

The cloud mask (CMa), developed within the SAF NWC context, aims to support nowcasting applications, and additionally the remote-sensing of continental and oceanic surfaces. The CMa allows identifying cloud free areas where other products (total or layer precipitable water, land or sea surface temperatures, snow/ice cover delineation) may be computed. It also allows identifying cloudy areas where other products (cloud types and cloud top temperature/height) may be derived.

The central aim of the CMa is therefore to delineate all cloud-free pixels in a satellite scene with a high confidence. In addition, the product provides information on the presence of snow/sea ice, dust clouds and volcanic plumes.

CMa cloud detection is performed by a multi-spectral threshold method: the image is compared with thresholds which delimit brightness temperatures/reflectance of cloud free pixels from those of pixels containing clouds, dust or snow/sea ice. The critical point is the thresholds tuning. This process is complemented by an analysis of the temporal variation (on a short period of time: 15 minutes) of some spectral combination of channels (to detect rapidly moving clouds), a specific treatment combining temporal coherency analysis and region growing technique (to improve the detection of low clouds) and a temporal analysis of the HRV channel to detect sub-pixel low clouds.

2.2 CLOUD MASK (CMA) ALGORITHM DESCRIPTION

2.2.1 Theoretical description

2.2.1.1 Physics of the problem

Brightness temperatures and reflectances of a cloud free area depend on its type, on the atmospheric conditions, on the sun and satellite respective positions. They are more or less modified by clouds, aerosols or snow/sea ice. Indeed, cloudy pixels can be often identified, because they appear colder (at 10.8 micron) and/or brighter (at 0.6 or 0.8 micron) than cloud free areas. A fine analysis of their respective spectral behaviour is nevertheless needed to perform a full cloud detection. For example, low clouds identification at nighttime relies on their low emissivities at 3.7 micron, whereas thin cirrus clouds can be identified, due to their different emissivities at 10.8 micron and 12 micron. Cloud free areas covered by snow or ice are identified at daytime with their very low reflectivity at 3.7 micron and high reflectivity at 0.6 micron, whereas oceanic cloud free areas affected by sun glint are identified with their very high reflectivity at 3.7 micron...

The CMa identifies pixels that are contaminated by either clouds, dust or snow/sea ice. The problem to be solved is to automatically predict, with sufficient accuracy, brightness temperatures and reflectance of cloud free areas, so that any discrepancy between the measured and predicted values can be used to detect contaminated pixels.

2.2.1.2 Mathematical Description of the algorithm

2.2.1.2.1 Algorithm outline

The algorithm is based on multispectral threshold technique applied to each pixel of the image. A first process allows the identification of cloudy pixels. It consists in a first set of multispectral threshold tests (summed up below) which is complemented by an analysis of the temporal variation (on a short period of time: 15 minutes) of some spectral combination of channels (to detect rapidly moving clouds), a specific treatment combining temporal coherency analysis and region growing technique (to improve the detection of low clouds) and a temporal analysis of the HRV channel (to detect sub-pixel clouds). These complementary tests are optional and described in specific sections 2.2.1.2.2.15 to 2.2.1.2.2.18.

The first series of tests allows the identification of pixels contaminated by clouds or snow/ice; this process is stopped if one test is really successful (i.e., if the threshold is not too close to the measured value). The characteristics of this set of tests are summed up below:

- The tests, applied to land or sea pixels, depend on the solar illumination and on the viewing angles (daytime, night-time, twilight, sunglint, as defined in Table 3) and are presented in Table 4 and Table 5.
- Most thresholds are determined from satellite-dependent look-up tables (available in coefficients' files) using as input the viewing geometry (sun and satellite viewing angles), NWP forecast fields (surface temperature and total atmospheric water vapour content) and ancillary data (elevation and climatological data). The thresholds are computed at a spatial resolution (called "segment size") defined by the user as a number of SEVIRI infra-red pixels. Some thresholds are empirical constant or satellite-dependent values (available in coefficients' files).
- The quality of the cloud detection process is assessed.
- A spatial filtering is applied, allowing to reclassify pixels having a class type different from their neighbours and to reduce known defaults as cloud false alarms in coastal area and in edges of snowy areas.
- A test is applied to cloud contaminated pixels to check whether the cloud cover is opaque and completely fills the FOV.

This first series of tests allows to determine the cloud cover category of each pixel (cloud-free, cloud contaminated, cloud filled, snow/ice contaminated or undefined/non processed) and compute a quality flag on the processing itself. Moreover, the tests that have allowed the cloud detection (more that one test are possible, if some tests were not really successful) are stored.

A second process, allowing the identification of dust clouds and volcanic ash clouds, is applied to all pixels (even already classified as cloud-free or contaminated by clouds). The result is stored in the dust cloud and volcanic ash cloud flags.

Details on the tests are given in section 2.2.1.2.2.

Nighttime	Twilight	Daytime	Sunglint
Solar elevation < -3	-3<Solar elevation<10	10 < Solar elevation	Cox & Munck > 10% Solar elevation > 15

Table 3: Definition of illumination conditions

Cox & Munck stands for the reflectance computed using Cox & Munck theory (see Cox and Munck, 1954) ; the solar elevation is expressed in degrees.

Daytime	Twilight	Nighttime
Snow detection	Snow detection	T10.8µm
T10.8µm	T10.8µm	T10.8µm-T12.0µm
R0.6µm	R0.6µm	T8.7µm-T10.8µm
T10.8µm-T12.0µm	T10.8µm-T12.0µm	T10.8µm-T8.7µm
T8.7µm-T10.8µm	T8.7µm-T10.8µm	T10.8µm-T3.9µm
T10.8µm-T3.9µm	T10.8µm-T8.7µm	T3.9µm-T10.8µm
T3.9µm-T10.8µm	T10.8µm-T3.9µm	Local Spatial Texture
Local Spatial Texture	T3.9µm-T10.8µm	T8.7µm-T3.9µm
	Local Spatial Texture	
	T8.7µm-T3.9µm	

Table 4: Test sequence over land

Daytime	**Sunglint**	**Twilight**	**Nighttime**
Ice detection	Ice detection	Ice detection	SST
SST	SST	SST	T10.8µm-T12.0µm
R0.8µm (R0.6µm)	T10.8µm-T12.0µm	R0.8µm (R0.6µm)	T8.7µm-T10.8µm
R1.6µm	T8.7µm-T10.8µm	R1.6µm	T10.8µm-T3.9µm
T10.8µm-T12.0µm	Local Spatial Texture	T10.8µm-T12.0µm	T12.0µm-T3.9µm
T8.7µm-T10.8µm	R0.8µm (R0.6µm)	T8.7µm-T10.8µm	T3.9µm-T10.8µm
T10.8µm-T3.9µm	T10.8µm-T3.9µm	T10.8µm-T3.9µm	Local Spatial Texture
T3.9µm-T10.8µm	Low Clouds in Sunglint	T12.0µm-T3.9µm	
Local Spatial Texture		T3.9µm-T10.8µm	
		Local Spatial Texture	

Table 5: Test sequence over sea

[T3.9µm, T8.7µm , T10.8µm and T12.0µm stand for brightness temperatures at 3.9, 8.7, 10.8 and 12.0 micrometer ; R0.6µm,R0.8µm and R1.6µm stand for VIS/NIR bi-directional top of atmosphere reflectances at 0.6, 0.8 and 1.6 micrometer normalised for solar illumination ; SST is the split-window (used for SST calculation) computed from T10.8µm and T12.0µm measurements. Low Clouds in Sunglint is a specific module for low clouds identification in sunglint areas.]

2.2.1.2.2 Individual cloud detection tests description

2.2.1.2.2.1 Test on SST

The test is the following :

Over sea, a pixel is classified as cloud contaminated if :

- SST(T10.8µm, T12.0µm) < SSTthreshold and
- sstclim > 270.15 K

where (for MSG1/SEVIRI)

SST(T10.8µm, T12.0µm)=0.977*(T10.8-273.15)

+ (0.075*(sstclim-273.15)+1.127*(sec-1))*(T10.8-T12.0)
+ 1.156 +273.15 (in K)

sec is the secant of the satellite zenith angle,
sstclim is the climatological SST (in K)

This test allows to detect most of the clouds over the ocean for any solar illumination. This test is not applied if the climatological SST is too low, which indicates that the ocean could be frozen.

A split window algorithm, using T10.8µm and T12.0µm brightness temperatures to compute Sea Surface Temperature, is applied to all pixels over the ocean. A pixel is then classified as cloudy if its split window value is lower that the estimated Sea Surface Temperature.

The threshold is computed from a monthly climatological minimum SST by substracting an offset (linear function of the secant of the satellite zenith angle ranging from 1.5K (for satellite zenith angle lower than 60 degrees) up to 2.5K (satellite zenith angles larger than 78.5), an additional 0.5K being added in coastal areas). This offset is needed to account for the imperfections of the climatology, especially in areas with persistent cloudiness, and in areas where the oceanic SST varies rapidly in space and time.

If T12.0µm is missing, the test is replaced by T10.8µm < sstclim – 9K.

2.2.1.2.2.2 Test on T10.8µm

The test is the following :

A pixel is classified as cloud contaminated if :

- T10.8µm < T10.8threshold.

This test is applied over land and over sea (only if the climatological SST is lower than 270.15 K which indicates that the ocean may be frozen). It allows the detection of the clouds having a 10.8µm brightness temperature lower than the surface brightness temperature.

The T10.8µm threshold is computed from surface temperatures forecast by NWP model, by accounting for atmospheric absorption and small scale height effects (over land only) as described below [the different physical meaning of brightness temperature and NWP surface temperature (dependent on the NWP model) is not accounted for] :

- The surface temperature for a given slot is then interpolated from the two nearest NWP fields (spatially interpolated at the segment's spatial resolution) according to rules related to the relative position of the scene and the two NWP terms in a diurnal cycle assumed to be driven by sun rise and sun set local times.
- The atmospheric absorption is accounted for through an offset computed as a function of satellite zenith angle, integrated atmospheric water vapour content and solar zenith angle. Two tables (for night-time and daytime conditions) have been pre-computed by applying RTTOV to radio-soundings from a data set provided by ECMWF (F.Chevalier, 1999). The satellite zenith angle and the water vapour content are used to interpolate in these tables, whereas the solar zenith angle is used to interpolate between the night-time and the daytime values.
- A dry adiabatic law is used to account for the height difference between the elevation of the NWP grid and of the pixel; this simple process, only applied over land, allows to roughly simulate small scale height effects in mountainous regions.

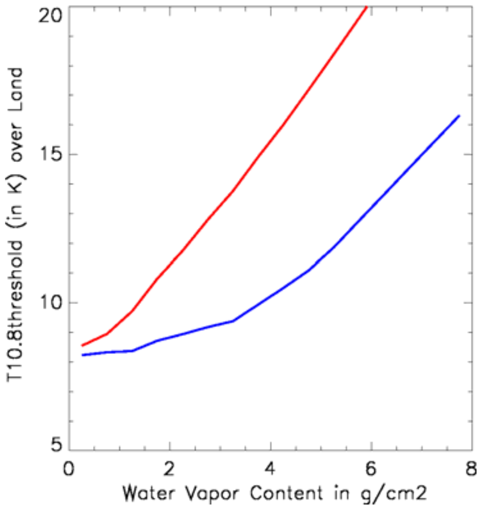

Figure 1: Illustration of the offset accounting for atmospheric absorption over vegetated surface for a satellite zenith angle of 48 degrees. Blue and red curves correspond to nighttime and daytime conditions

An offset of -3K is added in nighttime conditions over Africa to limit the confusion of cloud free areas with clouds.

A SEVIRI pixel is diagnosed favourable to extreme cooling over land in nighttime and twilight conditions when:

- altitude < 1500m and (FSKT < 263K or FSKT < 268K and SNOC > 5)

Where FSKT is the forecasted skin temperature and SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day for any daytime duration). A box size of 16 pixels has been used when prototyping.
When these conditions are met T10.8threshold is modified as follows:

- If T108threshold > = 255K
  - o T108threshold=T108threshold – 5.0K
- If T108threshold <255K
  - o T108threshold=T108threshold – 5.0K -0.4*(255K-T108threshold)

2.2.1.2.2.3 Test on T10.8µm-T12.0µm

The test is the following :

A pixel is classified as cloud contaminated if :

- T10.8µm -T12.0µm > T10.8T12.0threshold and
- (over land only) T10.8µm < 303.15 K

This test, which can be applied over all surfaces in any solar illumination, allows the detection of thin cirrus clouds and cloud edges characterised by a higher T10.8µm-T12.0µm than cloud-free surfaces.

The difficulty is to estimate the cloud free surfaces T10.8µm-T12.0µm difference which depends on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths. This test will be useless if the estimated clear-sky T10.8µm-T12.0µm difference is too high, which may be the case at daytime. The rough check applied over land to T10.8µm allows to minimize the confusion of very warm moist areas with clouds.

Over sea, two look-up tables (for cold and warm seas) have been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset (F.Chevalier, 1999), using Masuda emissivities (Masuda et al., 1988). The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these tables using the climatological SST.

Over land, two look-up tables (for night-time and daytime conditions) have been calculated by applying RTTOV to radio-soundings from an ECMWF dataset, using a constant emissivity of 0.98 in both channels (Salisbury et al., 1992). The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these two tables using the solar zenith angle.

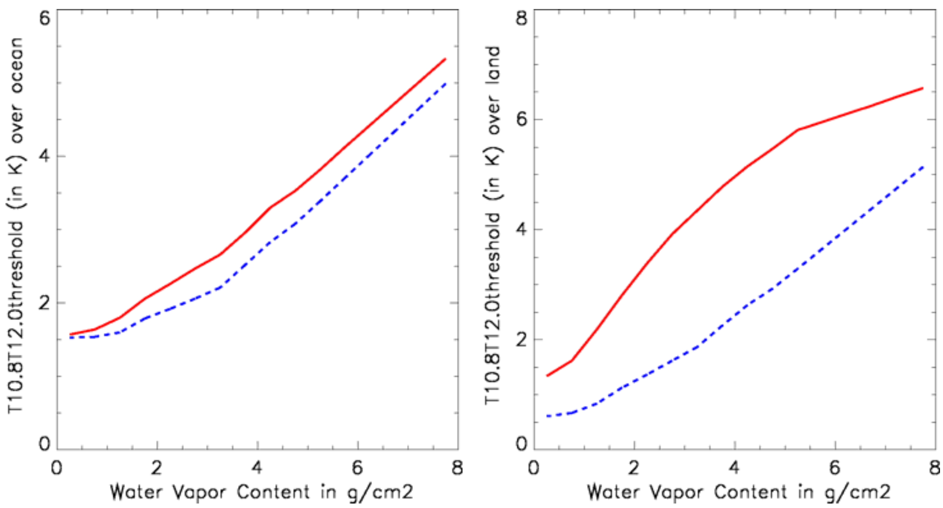

Figure 2: Illustration of T10.8T12.0threshold for a satellite zenith angle of 48 degrees. Over Ocean, blue and red curve correspond to cold and warm seas. Over Land, blue and red curves correspond to nighttime and daytime conditions

An offset of 1K has been added over Africa to limit the confusion of very moist cloud free areas with clouds.

2.2.1.2.2.4 Test on T8.7µm-T10.8µm

The test is the following :

A pixel is classified as cloud contaminated if :

- T8.7µm -T10.8µm > T8.7T10.8threshold.

This test aims to detect thin cirrus clouds over all surfaces in any solar illumination.

It is based on the fact that high semi-transparent clouds are characterised by relatively high T8.7µm-T10.8µm difference as compared to surface values. The difficulty is to estimate the cloud free surfaces T8.7µm-T10.8µm difference which depends on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths.

Over sea, one look-up table has been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset (F.Chevalier, 1999), using Masuda emissivities (Masuda et al., 1988). The threshold is interpolated into this table using satellite zenith angle and water vapour content.

Over land, two look-up tables (in daytime and nighttime conditions) have been established by applying RTTOV to radio-soundings from an ECMWF dataset. Only one set of emissivities (Salisbury et al., 1992) has been used, corresponding to vegetated areas (0.98 in both channel). The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these two tables using the solar zenith angle.

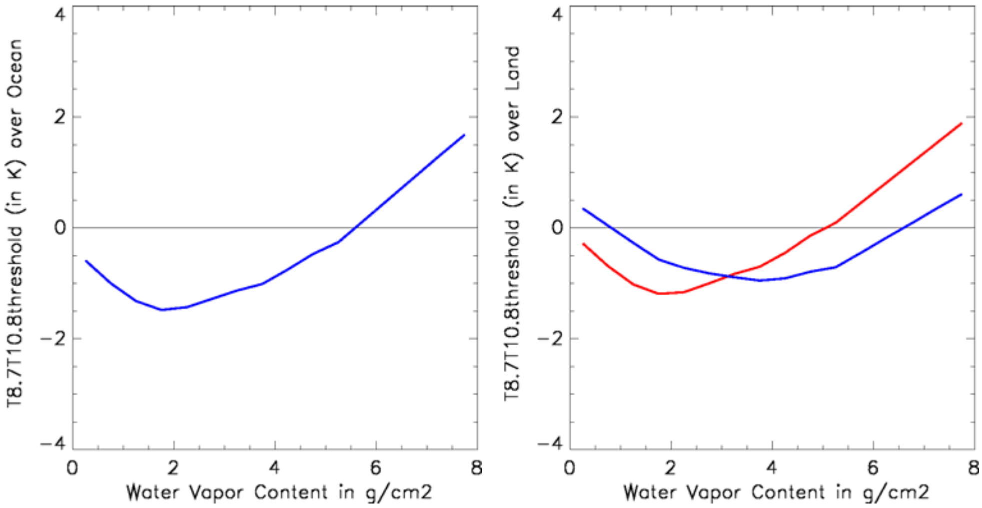

Figure 3: Illustration of T8.7T10.8threshold for a satellite zenith angle of 48 degrees. Over Land, blue and red curve correspond to night and daytime conditions.

A SEVIRI pixel is diagnosed favourable to extreme cooling over land in nighttime and twilight conditions when:

- altitude < 1500m and (FSKT < 263K or FSKT < 268K and SNOC > 5)

Where FSKT is the forecasted skin temperature and SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day for any daytime duration). A box size of 16 pixels has been used when prototyping.

When these conditions are met T8.7T10.8threshold is modified as follows:

- if T108threshold <250K T8.7T10.8threshold = T8.7T10.8threshold + 0.4K

2.2.1.2.2.5 Test on T3.9µm-T10.8µm in nighttime conditions

The test is the following :

A pixel is classified as cloud contaminated if :

- T3.9µm - T10.8µm > T39T10.8threshold_night and
- T10.8µm > 240 K

A SEVIRI pixel is diagnosed favourable to extreme cooling over land in nighttime condition when:

- altitude < 1500m and (FSKT < 263K or FSKT < 268K and SNOC > 5)

Where FSKT is the forecasted skin temperature and SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day for any daytime duration). A box size of 16 pixels has been used when prototyping.

When these conditions are met T39T10.8threshold_night is modified as follows:

- If 250K <= T108threshold <= 255K
  - T39T10.8threshold = MAX(T39T10.8threshold, -0.5x T108threshold +129.0)
- If T108threshold <250K
  - T39T10.8threshold = -0.15x T108threshold +41.5

Where FSKT is the forecasted skin temperature, SNOC is the snow occurrence in any pixel of the segment box surrounding the considered pixel (counted during any of the four previous or the current day), and T108threshold is the primary threshold on T10.8 as computed for the considered vegetated surface.

This test allows the detection of high semi-transparent clouds only in night-time conditions.

It is based on the fact that the contribution of the relatively warm grounds to the brightness temperature is higher at 3.9µm than at 10.8µm, due to a lower ice cloud transmittance (Hunt, 1973), and to the high non-linearity of the Planck function at 3.9µm. This test is usable only at night-time, when solar irradiance does not act upon the 3.9µm channel radiance. The cloud free surfaces T10.8µm-T3.9µm difference (depending on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths) has to be accurately estimated to allow this test to detect most semi-transparent clouds. An additional difficulty is the high radiometric noise (enhanced for low temperatures) that affects the 3.9µm channel: this is the reason why the use of this test is limited to pixels warmer than 240K. The non linearity effect makes this test much more efficient than the T10.8µm-T12.0µm test to detect high semi-transparent clouds over rather warm grounds at night-time.

Two look-up tables (for cold and warm seas) and four look-up tables (for cold and warm vegetated or arid surfaces) have been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset (F.Chevalier, 1999), using Masuda emissivities (Masuda et al., 1988) for oceanic conditions and using a constant emissivity of 0.98 in both channels (Salisbury et al., 1992) for vegetation (an offset of 1 Kelvin is added to simulate arid conditions). The threshold is interpolated into these tables using satellite zenith angle and water vapour content, together with the climatological SST (sea) or forecast surface temperature and climatological visible reflectance (land).

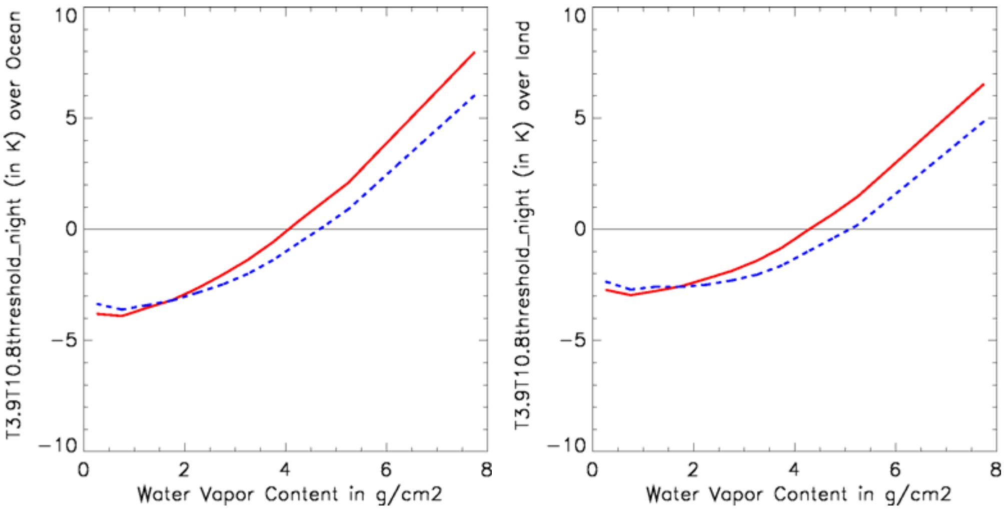

Figure 4: Illustration of T3.9T10.8threshold_night for a satellite zenith angle of 48 degrees. Blue and red curve correspond to cold and warm vegetated surfaces.

2.2.1.2.2.6 Test on T10.8µm-T3.9µm

The test is the following :

A pixel is classified as cloud contaminated if :

- T10.8µm - T3.9µm > T10.8T3.9threshold and
- T10.8µm > 240 K and
- (over land only) T8.7µm – T10.8µm > (-4.5-1.5*(1./cos(θ_{sat})-1)) (in K)

where θ_{sat} is the satellite zenith angle

This test allows the detection of low water clouds at night-time, but also low clouds shadowed by higher clouds.

It is based on the fact that the water cloud emissivity is lower at 3.9µm than at 10.8µm (Hunt, 1973), which is not the case for cloud free surfaces (except sandy desertic areas). A basic assumption is that the 3.9µm channel is not affected by the solar irradiance, which is the case at night-time and in shadows. The cloud free surfaces T10.8µm-T3.9µm difference (depending on the difference of atmospheric absorption (mainly due to water vapour) and surface emissivity in the two infrared wavelengths) has to be accurately estimated to allow this test to detect most low water clouds. An additional difficulty is the high radiometric noise (enhanced for low temperatures) that affects the 3.9µm channel: this is the reason why the use of this test is limited to pixels warmer than 240K. The rough check applied to T8.7µm-T10.8µm allows to minimize the confusion of sandy arid areas with low clouds.

Over sea, one look-up table has been elaborated by applying RTTOV to radio-soundings from an ECMWF dataset (F.Chevalier, 1999), using Masuda emissivities (Masuda et al., 1988). The satellite zenith angle and the water vapour content are used to interpolate in this table.

Over land, two look-up tables (for vegetated and arid surfaces) have been established by applying RTTOV to radio-soundings from an ECMWF dataset. A set of emissivities (Salisbury et al., 1992 and 1994) corresponding to vegetated areas (0.98 in both channels) has been used, the table corresponding to arid areas being obtained from the one for vegetated areas by adding an offset of 4K. The threshold is interpolated into these two tables using satellite zenith angle and water vapour content, and between these two tables using the climatological visible reflectance.

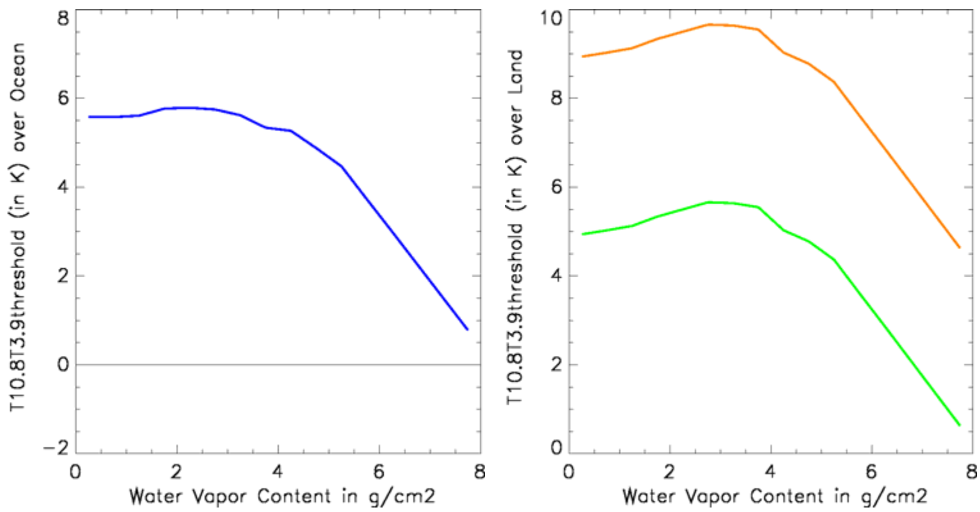

Figure 5: Illustration of T10.8T3.9threshold for a satellite zenith angle of 48 degrees. Over Land, green and brown curves correspond to vegetation and desert.

To increase the T10.8µm-T3.9µm test efficiency over Europe, two correction factors, empirically developed from SEVIRI measurements to better account for satellite zenith angle effect and CO_2 absorption, are added to the threshold computed from RTTOV simulations only over European regions (defined by their latitude between 36 and 90 degrees north, and their longitude between 30 degrees west and 60 degrees east):

-The correction factor to account for satellite zenith angle effect is tabulated below as a function of satellite secant $1/\cos(\theta_{sat})$):

$1/\cos(\theta_{sat})$	1	1.5	2.0	3.0	3.8	4.25	8
T10.8T3.9threshold correction factor (in K)	0.0	0.0	-0.6	-1.1	-1.1	0.5	0.5

-The correction factor to better account for CO_2 absorption is tabulated below as a function of (T10.8µm-T13.4µm) brightness temperatures difference:

T10.8µm-T13.4µm (in Kelvin)	0.0	11	13.0	15.0	17.0	20.0
T10.8T3.9threshold correction factor (in K)	-1.5	-1.5	-1.0	-0.5	0.0	0.0

Finally, an offset of 1K has been added to the threshold over Africa to decrease the confusion of arid areas with low clouds.

2.2.1.2.2.7 Test on T12.0µm-T3.9µm over ocean

The test is the following :

A pixel is classified as cloud contaminated if :
- T12.0µm - T3.9µm > T12.0T3.9thresholdand
- T10.8µm > 240 K

This test intends to detect low water clouds over the ocean in night-time conditions.

This test is very similar to the one applied to the T10.8µm - T3.9µm (see 2.2.1.2.2.6), but is usually more efficient over ocean due to a higher contrast between cloud free and low clouds T10.8µm-T3.9µm values. An example of the threshold used is displayed in Figure 6

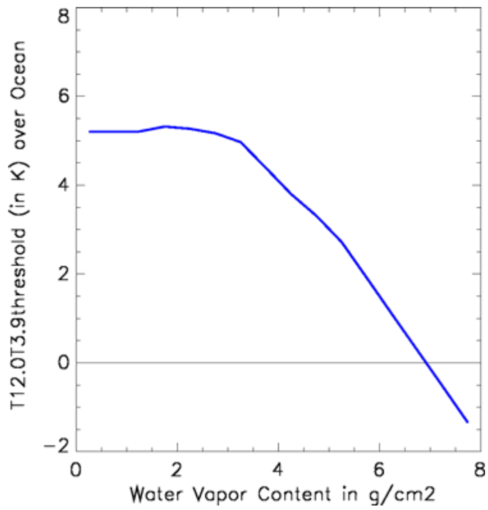

Figure 6: Illustration of T12.0T3.9threshold over the Ocean for a satellite zenith angle of 48 degrees.

2.2.1.2.2.8 Test on T8.7µm-T3.9µm over desert

The test is the following :

A pixel is classified as cloud contaminated if :
- T8.7µm - T3.9µm > T8.7T3.9threshold and
- T10.8µm - T3.9µm > T10.8T3.9veget_threshold and
- T10.8µm > 240 K

where T10.8T3.9veget_threshold is computed assuming vegetated surface

This test allows the detection over the desert of low water clouds at night-time. It is only applied over Africa.

Low clouds are usually detected at night-time thanks to their T10.8µm-T3.9µm brightness temperatures differences as explained in 2.2.1.2.2.6. This is practically never the case over desert because there is no contrast in this feature between low clouds and desert.

The T8.7µm-T3.9µm test is based on the fact that desertic areas have low emissivities at 3.9µm and 8.7µm, whereas low water clouds have low emissivities at 3.9µm, but not at 8.7µm. A consequence is that low clouds are characterized by higher T8.7µm-T3.9µm differences as compared to values over desert. This test is limited to pixels warmer than 240K to insure that the 3.9µm channel is not too much affected by radiometric noise (enhanced for low temperatures) and to pixels having not too low T10.8µm-T3.9µm brightness temperature differences to limit confusion of savannah with low clouds.

One look-up table has been established by applying RTTOV to radio-soundings from an ECMWF dataset. A set of emissivities (0.98 in both channels) has been used. The threshold is interpolated into this tables using satellite zenith angle and water vapour content.

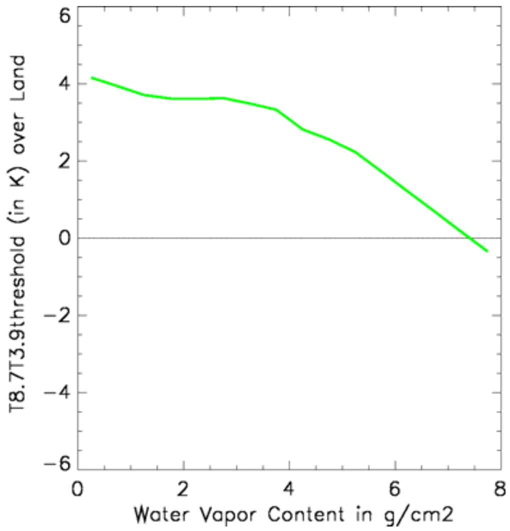

Figure 7: Illustration of T8.7T3.9 threshold over desertic area for a satellite zenith angle of 48 degrees.

2.2.1.2.2.9 Test on T10.8µm-T8.7µm over land

The test is the following :

A pixel is classified as cloud contaminated if :

- T10.8µm – T8.7µm > T10.8T8.7threshold and
- Climatological albedo < 20 % and
- $1/\cos(\theta_{sat}) > 1.5$

where θ_{sat} is the satellite zenith angle

This test intends to detect low clouds over vegetated areas at high satellite zenith angle at night-time or at low solar elevation. It is only applied over European areas (defined by their latitude between 36 and 90 degrees north, and their longitude between 30 degrees west and 60 degrees east).

Usually, low clouds are characterized at night-time by high T10.8µm-T3.9µm brightness temperatures differences, which allow their identification over land (see 2.2.1.2.2.6). This detection may be less efficient at large viewing angles as cloud free T10.8µm-T3.9µm values may become rather high. To increase low clouds detection efficiency in night-time conditions at high satellite zenith angle, an empirical test has been developed, based on the observation that the decrease of T8.7µm–T10.8µm with satellite zenith angle is much stronger for low clouds than for vegetated areas. This empirical test is also very useful in case low solar elevation to detect low clouds (at large viewing angles only).

The T10.8T8.7threshold has been empirically derived from SEVIRI measurements as a function of the satellite secant: T10.8T8.7threshold (in K) $=3.7+0.3*(1/\cos(\theta_{sat}))$

2.2.1.2.2.10 Test on R0.6µm, R0.8µm or R1.6 µm

These tests are the following :

Over land and over sea (only if R0.8µm unavailable), a pixel is classified as cloud contaminated if :

- R0.6µm > R0.6threshold

Over sea, a pixel is classified as cloud contaminated if :

- R0.8µm > R0.8threshold

Over sea, a pixel is classified as cloud contaminated if :

- R1.6µm > R1.6threshold

These tests, applied to the visible (0.6µm) or near-infrared (0.8µm and 1.6µm) TOA reflectances, aim to detect at daytime clouds having a reflectance higher than the underlying surfaces.

The visible or near-infrared reflectance measured over the cloud-free oceans mainly corresponds to Rayleigh and aerosol scattering (weaker in the near-infrared band) and to the solar reflection over the ocean, which is very low apart from sunglint conditions, and in turbid areas (for the visible channel only). Therefore near-infrared bands (0.8µm and 1.6µm) are used over the ocean, the visible band (0.6µm) being used only in case 0.8µm is not available.

As the cloud-free land reflectance is usually much higher in the near-infrared wavelengths than in the visible (due to the vegetation spectral radiative behaviour at these wavelengths), the test is therefore only applied to the visible channel.

The threshold is computed from the simulation of the surface (ocean or land) TOA reflectance by adding an offset:

- The TOA reflectance is simulated as: TOA Reflectance = (a0 + a1*surface/(1-a2*max(surface,200%))) + offset + corrective_factor where :
  - a0, a1 and a2 are coefficients computed from satellite and solar angles, water vapour and ozone content using look-up tables. These look-up tables have been pre-computed for a great variety of angles and water vapour and ozone content using a very fast model based on 6S (Tanre et al., 1990), using a maritime or continental aerosol of 30km or 70km horizontal visibility for sea and land respectively.
  - surface is the land or ocean surface reflectance. The Ocean surface reflectance is given by the maximum reflectance computed by the Cox & Munck model (Cox & Munck, 1954), for the satellite and solar angles and for wind speed between 0 and 20 m/s: this approach overestimates the reflectance in sunglint conditions. The Land surface reflectance is computed from a monthly climatological visible reflectance atlas, bi-directional effects being simulated using a model developed by Roujean (Roujean et al., 1992) with 2 sets of coefficients empirically derived [(k0=1.4, k1=0.15*k0, k2=1.0*k0) for low reflectance and (k0=1.3, k1=0.05*k0, k2=0.5*k0) for highly reflective areas].
- Offsets (7% over sea (9% for R0.6µm), 8% over land) are added; an additional offset (3%) is added over sea in coastal areas to account for possible misregistration.
- The following corrective factor is added over land to allow high reflectance in the forward scattering direction: corrective_factor (in %) = $4.0 + 29 * (\cos(\text{scattering angle}) - 0.68)^2$ where scattering_angle is the scattering angle ([0.,π] from backward to forward direction).

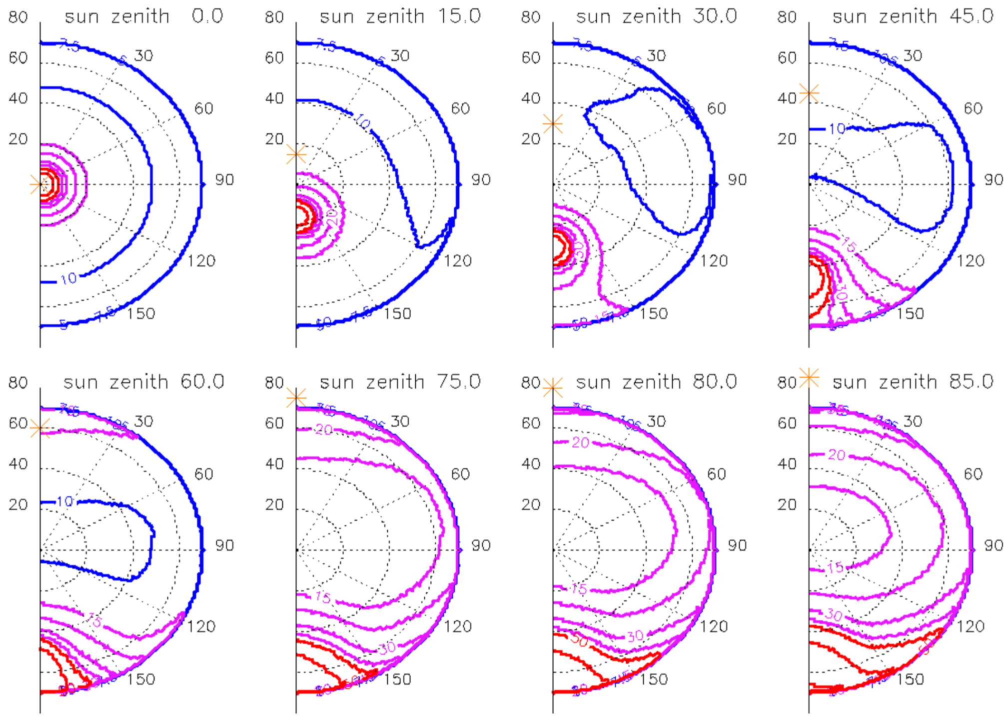

Figure 8: Polar representation of R0.8threshold over Ocean for eight sun zenith angles.

The polar angle corresponds to the satellite azimuth angle (sun azimuth is taken equal to 0); the radius represents the satellite zenith angle; iso-reflectance curves are displayed in different colours according to their reflectance value (blue if lower than 10%, purple if lower than 40%, red if higher than 40%)

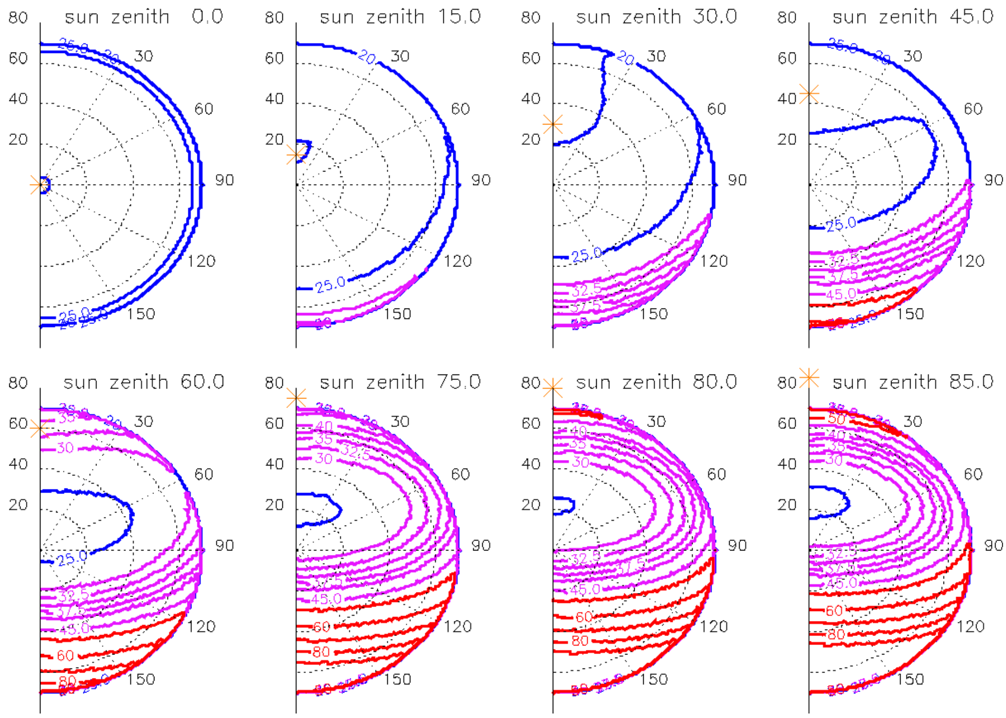

Figure 9: Polar representation of R0.6threshold over Land (surface reflectance of 10%) for eight sun zenith angles.

The polar angle corresponds to the satellite azimuth angle (sun azimuth is taken equal to 0); the radius represents the satellite zenith angle; iso-reflectance curves are displayed in different colours according to their reflectance value (blue if lower than 25%, purple if lower than 45%, red if higher than 45%)

2.2.1.2.2.11 Low Cloud Test in Sunglint

The following test is applied if the sun elevation is higher than 15 degrees:

A pixel is classified as cloud contaminated if :

- T3.9µm < 320 K (to make sure 3.9µm is not saturated) and
- R0.6µm > 60% and
- (T3.9µm-T10.8µm)/cos(θ_{sol}) > 0 K and
- R0.6µm > (1./0.15)*(T3.9µm-T10.8µm)/cos(θ_{sol}) (θ_{sol} is the solar zenith angle)

This test aims to detect low clouds in sunglint conditions.

Low clouds can easily be detected at daytime over the ocean by their high visible or near-infrared reflectances. This is not possible in case of sunglint, because the sea reflectance at these wavelengths may then be higher than that of clouds. The use of both 0.6µm and 3.9µm channels allows to detect low clouds even in areas affected by sunglint. Indeed, oceanic areas with high 0.6µm reflectances have also very high 3.9µm reflectances, which is usually not the case for low clouds. The solar contribution in the 3.9µm channel in case of sunglint is approximated by (T3.9µm-T10.8µm)/cos(θ_{sol}). The rapid saturation of the 3.9µm radiance limits the use of this test in case of strong sunglint.

2.2.1.2.2.12 Test on T3.9µm-T10.8µm in daytime or twilight conditions

The following test is applied in daytime or twilight conditions (except in sunglint areas):

A pixel is classified as cloud contaminated if :

- T3.9µm - T10.8µm > T3.9T10.8threshold_day and
- T10.8µm > 240 K and
- (over Africa only) T8.7µm – T10.8µm > (-4.5-1.5*(1./cos(θ_{sat})-1)) (in K)

where θ_{sat} is the satellite zenith angle

This test allows the detection of low clouds at day-time (except sunglint areas over the ocean) and twilight conditions.

It is based on the fact that solar reflection at 3.9µm may be high for clouds (especially low clouds), which is not the case for cloud free areas (except sunglint). The rough check applied to T8.7µm-T10.8µm allows to minimize the confusion of sandy arid areas with low clouds.

The threshold T3.9T10.8threshold_day is computed from T3.9T10.8threshold_night (see section 2.2.1.2.2.3) by adding the solar contribution:

Over ocean: T39.T10.8threshold_day (in K)=T3.9T10.8threshold_night
+ 0.7*Cox_munck*cos(θ_{sol}) +7

Over land: T3.9T10.8threshold_day (in K)= T3.9T10.8threshold_night
+ 0.4*Clim_alb*cos(θ_{sol}) +2.0 + corrective_factor

T3.9T10.8threshold_night is computed as explained in section 2.2.1.2.2.3, Cox_munck is the maximum ocean surface reflectance computed using Cox&Munck theory, Clim_alb is the continental climatological visible reflectance, corrective_factor, added to account for contribution of the solar illumination in backward and forward scattering direction, is defined as:

Corrective_factor=36*cos(θ_{sol})*(cos(scattering angle)-0.41)^2

θ_{sol} is the solar zenith angle and scattering_angle is the scattering angle ([0.,π] from backward to forward direction).

2.2.1.2.2.13 Snow or Ice detection Test

The following snow and ice detection test is applied if the sun elevation is larger than 5 degrees:

A pixel is classified as contaminated by snow if :

- (R1.6µm) < R1.6threshold and
- (R0.6µm -R1.6µm)/ (R0.6µm +R1.6µm) > (0.30+0.15*(cos(scattering angle)-1)^2) and
- (T3.9µm-T10.8µm)/cos(θsol) < 10K and

- (T10.8threshold – 5.0) < T10.8µm < 286.15 (in K) and
- T10.8µm-T12.0µm < 2K and
- Min(R0.6threshold, (20+45*(cos(scattering angle)-0.55)^2)%) < R0.6µm and
- 20% < R0.8µm

-where R1.6thrshold is the threshold displayed on Figure 10, T10.8threshold and R0.6threshold are thresholds used in cloud masking with infrared and visible channels, θsol is the solar zenith angle, and scattering angle is the scattering angle ([0,π] from backward to forward direction).

A pixel is classified as contaminated by ice if :

- Climatological SST < 277.15 K and
- (R1.6µm) < R1.6threshold and
- R0.6µm -R1.6µm)/ (R0.6µm +R1.6µm) > (0.30+0.15*(cos(scattering angle)-1)^2) and
- (T3.9µm-T10.8µm)/cos(θsol) < 10K and
- (T10.8threshold – 5.0) < T10.8µm < 277.15 (in K) and
- T10.8µm-T12.0µm < 2K and
- R0.6threshold < R0.6µm and
- 20% < R0.8µm

-where R1.6thrshold is the threshold displayed on Figure 10, T10.8threshold and R0.6threshold are thresholds used in cloud masking with infrared and visible channels, θsol is the solar zenith angle, and scattering angle is the scattering angle ([0,π] from backward to forward direction).

Ice and snow appear rather cold and bright, and may therefore be confused with clouds (especially with low clouds) during the cloud detection process. Ice and snow must therefore be identified first, prior to the application of any cloud detection test. This test aims to detects pixels contaminated by snow or ice: if this test is satisfied, the pixel is classified as snow or ice and no further cloud detection is attempted.

The basis of this test, restricted to daytime conditions, is the following :

- Snow & ice are separated from water clouds by their low reflectance at 1.6 µm or at 3.9 µm.
- Snow & ice are separated from cloud free oceanic or continental surfaces by their higher R0.6µm visible reflectance and slightly colder T10.8µm brightness temperature.
- T10.8µm-T12.0µm brightness temperature difference helps to discern cirrus from snow & ice.
- R0.8µm is useful to separate shadows from snow & ice.

Surface snow reflectances have been tabulated for various viewing geometries and for hexagonal particle shape (3 different sizes) with the radiative transfer model developed by C.Le Roux (see Le Roux et al, 1996). Top of Atmosphere snow reflectance at 1.6µm are then computed using these look-up tables (both 250µm and 70µm hexagonal particles have been retained) together with a module (based on 6S (Tanre et al., 1990)) to simulate the atmospheric effects. The R1.6threshold threshold applied to the 1.6µm channel is derived from these simulated snow reflectances by adding an offset (10%).

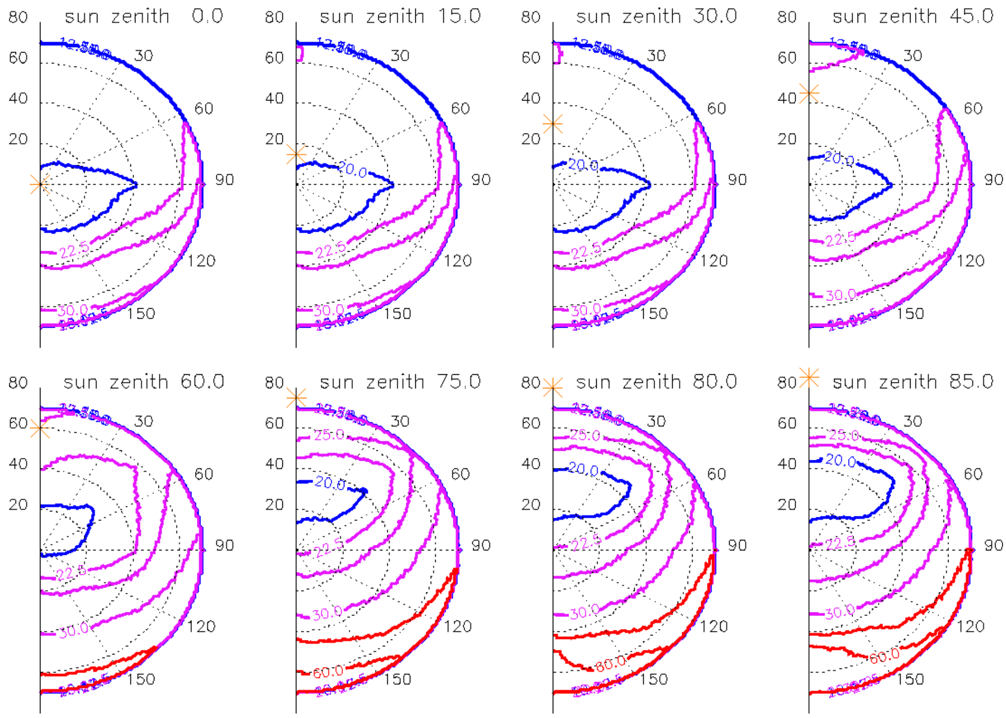

Figure 10: Polar representation of R1.6threshold over snow for eight sun zenith angles.

The polar angle corresponds to the satellite azimuth angle (sun azimuth is taken equal to 0); the radius represents the satellite zenith angle; iso-reflectance curves are displayed in different colours according to their reflectance value (blue if lower than 20%, purple if lower than 30%, red if higher than 30%)

2.2.1.2.2.14 Local Spatial Texture Tests

The following tests are applied:

Over Sea, a pixel is classified as cloudy if :

- [SD(T10.8µm) > 0.6K and SD(T10.8µm-T3.9µm) > 0.2K (0.4K at daytime) and T10.8µm < MAX(T10.8µm) – 2*noise(T10.8µm)]

or

- [SD(R0.8µm) > (0.8%+0.03* R0.8threshold) and R0.8µm > MIN(R0.8µm) + 2./SNR(R0.8µm) at daytime only]

T10.8µm-T3.9µm is not used in too cold areas (due to noise effects).

Over Land, a pixel is classified as cloudy if :

- [SD(T10.8µm) > 1.0K (2.0K at daytime) and SD(T10.8µm-T3.9µm) > 1.0K (2.0K at daytime] or
- [DR0.6µm > f(DT10.8µm) / (DR0.6µm)) at daytime only]

This process is not applied in very mountainous regions ; moreover T10.8µm-T3.9µm is not used in too cold areas (due to noise effects).

-SD, MIN, MAX, stand for local standard deviation, minimum, maximum, computed using the 8 surrounding pixels, provided they correspond to the same surface type (i.e., sea or land)
-R0.8threshold is the visible threshold (in %) defined previously
-DR0.6µm stands for the maximum difference between the visible reflectance of a pixel and its eight neighbours; DT10.8µm is the corresponding brightness temperature difference and R= DT10.8µm/ DR0.6µm is the ratio.
Noise stands for the instrumental noise in Kelvin of the feature at the given SEVIRI brightness temperature
SNR stands for the signal to noise ratio of the feature for the given SEVIRI visible band

-The f(R) function is tabulated below:

R=(DT10.8µm) / (DR0.6µm)	-5	-3	0	0.25	0.5	1
Threshold applied to (DR0.6µm)	2%	2%	5%	10%	15%	15%

These tests detect small broken clouds, thin cirrus or cloud edges, by using their high spatial variations in the visible, near infrared or infrared channels. The difficulty comes from the natural heterogeneity of the surface background : Oceanic areas are rather homogeneous, with the exception of strong thermal fronts (large T10.8µm variation), turbid coastal areas (large R0.6µm variation), sunglint areas (large R0.6µm and R0.8µm variation) ; Land surfaces are generally much more inhomogeneous, especially in mountainous or desertic regions. The simultaneous analysis of spatial coherency in two spectral bands allows to overcome the difficulty:

- Over Ocean, the combined use of T10.8µm & T10.8µm-T3.9µm for all illumination conditions is efficient for detecting clouds, and avoids misclassification of thermal front.
- Over land, the combined use of T10.8µm & T10.8µm-T3.9µm for all illumination conditions allows to minimise misclassification, except in very mountainous or in arid areas.
- Continental areas at daytime may present as large R0.6µm, R0.8µm and T10.8µm horizontal differences as clouds do. But, a cloud-free surface having higher R0.6µm than the neighbourhood is less vegetated and therefore warmer, whereas a pixel contaminated by clouds and having higher R0.6µm than its neighbours should be more cloud contaminated, and therefore colder. This property, not observed in arid areas, is used at daytime over land in the Local Spatial Texture Test.

2.2.1.2.2.15 <u>Temporal test to detect rapidly moving or developing clouds</u>

This time-differencing test is applied to the whole image. It is designed to catch high thin clouds moving rapidly and appearing colder than their underlying surface that are not detected by spectral or textural tests. It is similar to the technique described by d'Entremont and Gustafson, 2003. A time-interval of 15 minutes is used.

- Over sea a pixel whose Δ_{15mn}(T10.8) is lower than -0.6K is declared as cloudy.
- Over land a pixel whose Δ_{15mn}(T10.8) is lower than DT10.8 is declared as cloudy.

where DT10.8 varies from –3.0K to -0.6K according to time related to local sunset and sunrise. For deserts near sunset DT10.8 has been set to –4K. This temporal test is also applied to snow contaminated pixels.

The threshold DT10.8 used over land is computed so that a maximum cooling in the diurnal cycle near the sunset does not generate a false alarm. Therefore the test may be more efficient over arid surfaces around sunset than at noon during the warming period before the observed maximum temperature. Its computation is illustrated in Figure 11 below.

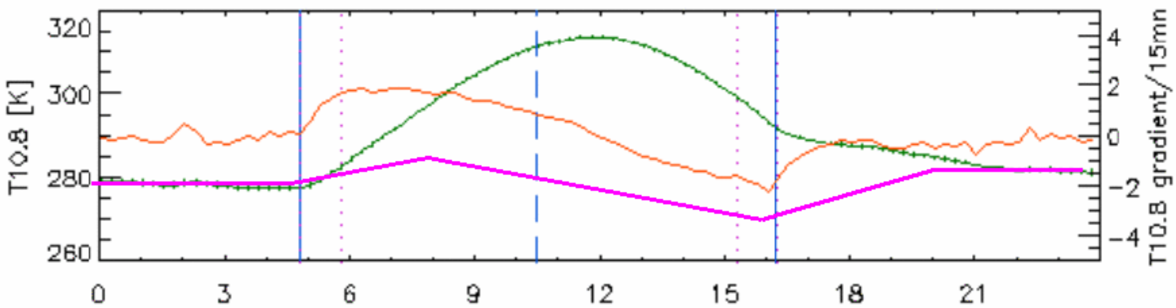

Figure 11 graphical illustration of DT10.8 threshold over land (pink) for a 24h period labelled in UTC time, sunrise and sunset are vertical solid blue line, compared with a real T10.8 cycle(green) and its gradient (orange) for a 15 minute interval

2.2.1.2.2.16 Temporal test to restore stationary low or mid-level clouds in twilight conditions

The day-night terminator separates sunlit from dark regions and its line is apparent near local sunrise and sunset. It crosses the earth's disk with a speed about 1600 km/h in equatorial regions. Its orientation varies with the season, showing a larger sunlit area in the higher latitudes during summer. If defining the day-night transition as the area where sun zenith angle θ is between 80° and 93°, about one hour is necessary to get separated zones near the equator, for high latitude regions it may be longer. Therefore a one-hour time interval between images is a minimum if one wants to get a given "twilight" pixel previously analysed by the day or night algorithm.

In the current image the day-night transition portion is delimited according to sun zenith angle, and temporal differences of features that are known to be nearly insensitive to solar illumination change for a low cloud target are computed: $|\Delta_{1h}(T10.8)|$, $|\Delta_{1h}(T10.8-T12.0)|$, $|\Delta_{1h}(T10.8-T8.7)|$ where $|\Delta_{1h}|$ is the absolute value of temporal difference with a time interval of one hour. The CMa_{1h} and CT_{1h} of the previous image are used to identify pixels of the current image that were previously classified as low or mid-level clouds one hour earlier and detected by a high confidence test. Those pixels are restored as cloudy in the current transition area if the absolute values of temporal features, noted Δ_{1h},satisfy the following conditions:

- over land $|\Delta_{1h}(T10.8)| < 1.0K$ and $|\Delta_{1h}(T10.8-T8.7)| < 0.5K$
- over water $|\Delta_{1h}(T10.8)| < 1.0K$ and $|\Delta_{1h}(T10.8-T12.0)| < 0.6K$

When analysing the results obtained by this first step during testing, we were not fully satisfied because cloud parts remained undetected, but still discernible in enhanced VIS image. In general the inner part of low cloud decks were caught while their optically thinner part or new portions appearing with the cloud development or its forward motion may have passed through the temporal differencing procedure and kept as clear. Moreover pixels that are not detected one hour sooner can't be restored by this technique. An example of the efficiency of this technique is illustrated in Figure 12, where one can see that it is efficient for a part of the image, where clouds were previously detected, and that it does not work over a wide area over Spain where clouds were not detected one hour sooner.

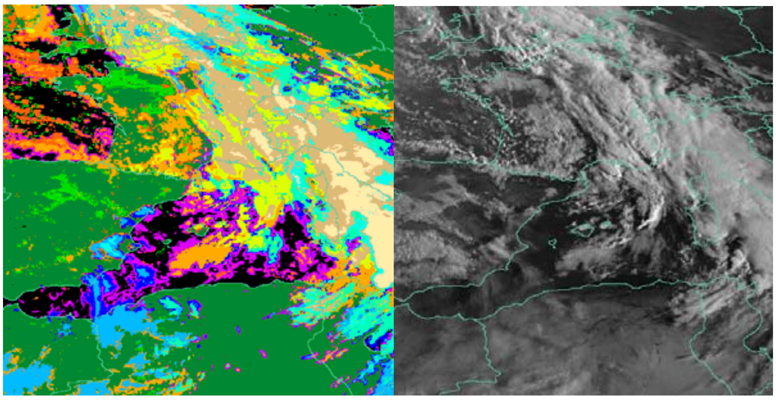

Figure 12 Illustration of stationary clouds restoration displayed in light green in CT picture (right) compared with BRF 0.6 (left) MSG2 on 25 September 2006, 06h30 UTC

2.2.1.2.2.17 Spatial expansion of stationary clouds in twilight conditions

To improve the detection of the outer part of the cloud we decided to use the radiometric statistical attributes of the newly detected pixels as constraints of a region-growing technique applied to the initial stationary cloudy pixels identified by the first step. The goal of this second step is to spatially extend the initial cloud "seeds" to their connected pixels presenting similar characteristics.

The normalization used when handling VIS values is an inverse cosine function of satellite zenith angle θ. This purely geometric normalization is an air-mass correction of the solar beam pathlength assuming a plane-parallel atmosphere. In the day-night terminator area this assumption is no longer correct, and two effects become important: curvature of atmosphere and refraction. When sun zenith angle approaches 90°, because of curvature of atmosphere the solar beam pathlength is significantly shorter than the plane parallel one. This explains why for VIS pictures normalized using this inverse cosine function, values displayed near day-night terminator appear too high.

Twilight whose exact definition is the diffused light in the sky when the sun is just below the horizon, just after sunset or just before sunrise, is an effect of atmospheric refraction. The refractive index of air decreases when wavelength increases, in other words, blue light, which comprises the shortest wavelength region in visible light, is refracted at significantly greater angles than is red light. Refraction may be neglected even for θ near 85°, but not when caring about features in rather low atmosphere for higher sun zenith angle.

For these two reasons we have replaced the inverse cosine BRF normalization function by an analytical formulation valid for a standard atmosphere proposed by Li and Shibata, 2006. Their parameterization accounts for spherical atmosphere and refraction. Aware that this parameterization should be adapted to the narrowband spectral characteristics of each VIS band of SEVIRI and to the current state of atmosphere, we keep it as a first order correction for a better handling of VIS BRF in twilight area. Figure 13 compares it with inverse cosine normalization.

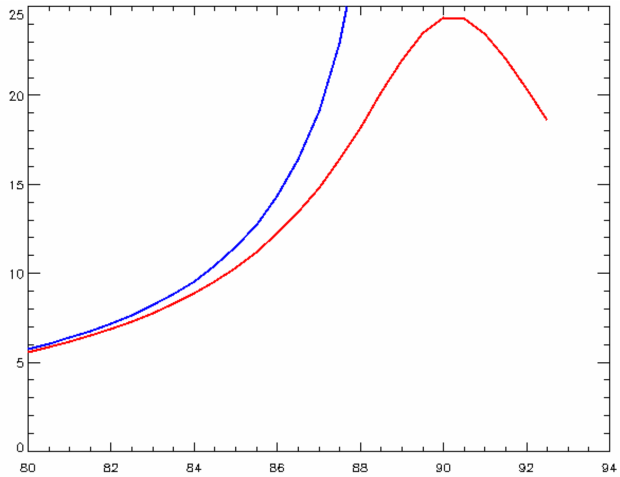

Figure 13 VIS normalization factor variation with sun zenith angle, inverse cosine (blue) and parameterization given by Li et al 2006 (red)

Because BRF of pixels in day-night terminator portion becomes very sensitive to noise when approaching the terminator line, we allow region-growing for 75°<θ<89°. Groups of connected pixels restored by the first temporal-differencing method form initial seeds for the region-growing are identified. Any group comprising more than eight elements is taken into account. For each significant group two mean values are computed: normalized BRF0.6 (AVG0.6) and T108 (AVG10.8). A group is expanded while a 8-connectivity neighbour pixel x belonging to the day-night transition area satisfies simultaneously the following conditions:

$SCAT_x < 150°$

$BRF0.6_x > MAX(1.05*AVG0.6, THR_{exp})$

$AVG10.8 + 0.5K < T10.8_x < AVG10.8 - 5.0K$

Where THR_{exp} is 40% over Africa to avoid false alarms over arid areas and 30% elsewhere

$SCAT_x$ is the scattering angle [0°,180°], 0° for backward scattering

$BRF0.6_x$ is the normalized BRF in VIS06 SEVIRI at location x

$T10.8_x$ is the brightness temperature of SEVIRI 10.8 µm at location x

The main risk of the method is to add cloud false alarms and it is maximal when the radiometer is looking in the sun direction because measured clear-sky BRF0.6 increase dramatically. That is why we forbid region growing at locations where scattering angle is greater than 150°. Moreover we reject region-growing restoring more than 10000 elements for the same seed assuming that a too wide region-growing is suspect. The strategy employed in the region-growing technique may produce small differences in presence of blurry low cloud edges resulting in small jumps in cloud features animations.

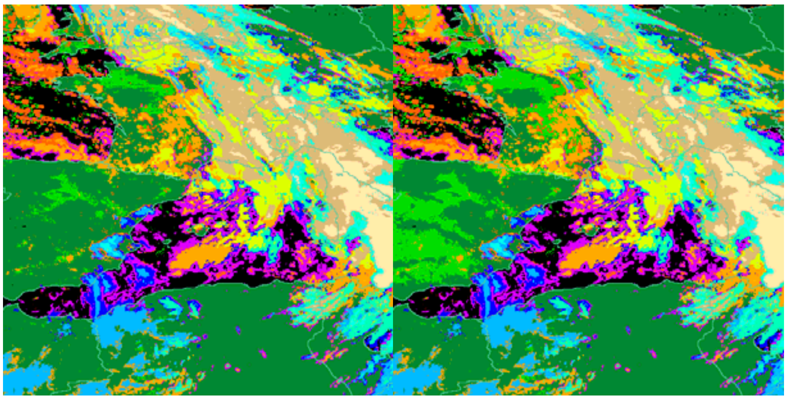

Figure 14 Illustration of spatial expansion restoration and stationary cloud restoration displayed in light green in CT picture (right) compared with stationary clouds restoration only (left), MSG2 on 25 September 2006, 06h30 UTC

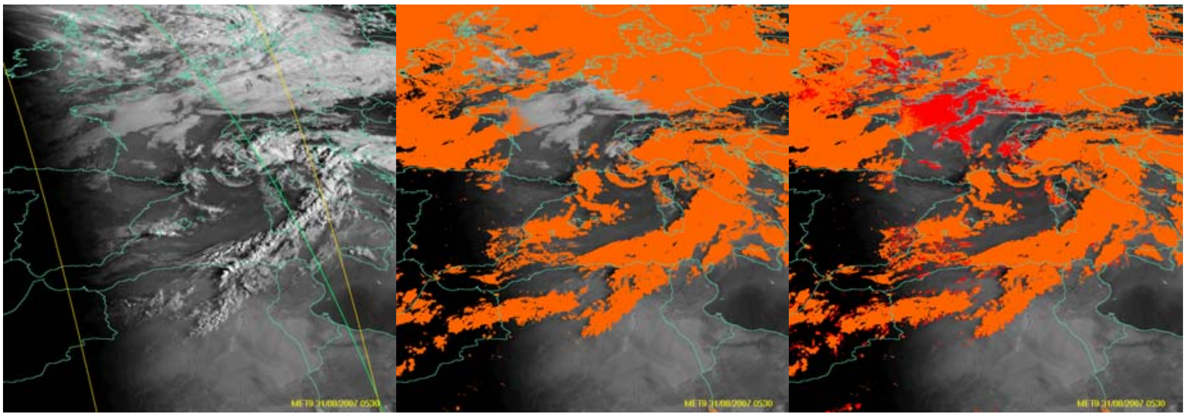

Figure 15 31 August 2007, 05h30 UTC METEOSAT 9 left: Normalized SEVIRI 0.6 with limits of transition area (yellow) and 1h sooner (green) centre: SAFNWC/MSG v2.0 cloud mask (orange) superimposed with SEVIRI 0.6 right: same as centre with new twilight detection (red)

2.2.1.2.2.18 <u>Temporal analysis of HRV channel to detect sub-pixel clouds</u>

A better detection of small scale low clouds at daytime was requested by users during the SAFNWC users workshop held at Madrid in 2005. Therefore the use of HRV for its better spatial resolution (1km x 1km at satellite sub-point) was one of the improvement tasks planned during CDOP. The algorithm described in this section is an output of this task. Computing a cloud mask at the HRV resolution has been tested but not retained in the final algorithm.

We designed this improvement as an add-on option of the cloud mask, as some users may be restricted by hardware considerations or would like to avoid changes in cloud detection efficiency that is the the main drawback of using HRV as it does not always cover the same regions of the earth disk all the day long. The optional HRV-based algorithm is applied only to SEVIRI pixels remained as clear after the two previous steps of the cloud mask algorithm (SEVIRI spectral and textural thresholding and temporal-differencing and region-growing). It requires not only the HRV data of the current scene, but also the scene observed and analysed 15 minutes sooner.

2.2.1.2.2.18.1 HRV reflectance test over land

The assumption is that any low cloud exhibits higher HRV reflectance than underlying clear-sky surface. This test is designed to catch static small scale low clouds that are not detected by change detection technique.
A SEVIRI pixel is classified as cloud contaminated if not already classified as cloud by previous tests and if:

- solar elevation > 5° and Max(R_{hrv} 3x3) > R_{hrv}threshold
  Where Max(R_{hrv} 3x3) is the maximum HRV normalized reflectance in the 3x3 HRV array covered by the corresponding SEVIRI low resolution pixel.

The threshold is a crude estimate of clear-sky broadband reflectances derived from maps of monthly values and an angular empirical correction. The monthly maps are obtained from a combination of black sky albedo for 3 MODIS narrow bands (0.55µm, 0. 67µm and 0.86µm) available from a NASA website dedicated to MODIS atmosphere (http://modis-atmos.gsfc.nasa.gov/ALBEDO/index.html). Black-sky albedo is the directional hemispherical reflectance computed at local solar noon estimated from MODIS Terra and Aqua measurements. The following black-sky albedo combination is used:

- $Rmap=0.265xBSA_{0.55}+0.222xBSA_{0.67}+0.513xBSA_{0.86}$

And the threshold is derived from this combination according to

- $R_{hrv}threshold = 1.0xRmap +60.0 +29*(\cos(scattering\_angle)-0.68)^2$

where scattering_angle is the scattering angle ([0.,π] from backward to forward direction).

The parameterization of this test has been designed using a period of collocations of SYNOP and satellite data including HRV. When applied to full disk data during summer 2009 false alarms that were too difficult to remove (not clearly depending on Rmap or scattering angle) appeared in some places. To avoid them, the threshold has been increased lately before the software delivery to the integrator. The consequence is that some rather static topographically induced clouds such as for instance valley fog not directly detected by other SEVIRI visible channels still remain not detected by this test.

2.2.1.2.2.18.2 Local spatial HRV texture test over sea

A SEVIRI pixel is classified as cloud contaminated if:

- solar elevation > 10° and SD(R_{hrv} 3x3)/Mean(R_{hrv} 3x3) > .08 or SD(R_{hrv} 3x3) > 0.8%
- solar elevation < 10° and solar elevation > 5° and SD(R_{hrv} 3x3)/Mean(R_{hrv} 3x3) > .16 or SD(R_{hrv} 3x3) > 0.4%

- Mean(R_{hrv} 3x3) and SD(R_{hrv} 3x3) stand respectively for the mean and standard deviation computed using the 9 reflectances of HRV pixels covered by the SEVIRI low resolution pixel

This test based only on HRV local texture inside SEVIRI low resolution pixel detects heterogeneities over sea, one feature detects small clouds when background is rather dark whereas the other one is more efficient for heterogeneities inside clouds or sunglint, that were not detected by previous test based on other SEVIRI visible channels.

2.2.1.2.2.18.3 Local spatial texture and temporal test over land

This test is a mixture of texture tests, change detection tests and image processing technique.

2.2.1.2.2.18.3.1 Change detection test over land

A SEVIRI pixel is classified as cloud contaminated if:

- clear (and not snowy)

and

- $SD(R_{hrv}\ 3x3) > 5\%$ and $MIN(RN_{hrv}\ 3x3)_{cur} > 10\%$
  and $abs(1.0- MAX_{cur}(RN_{hrv}3x3)/ MAX_{prev}(RN_{hrv}3x3) > 0.03$
  and $abs(1.0- MIN_{cur}(RN_{hrv}3x3)/ MIN_{prev}(RN_{hrv}3x3) > 0.03$
  or
- $SD(R_{hrv}\ 3x3) > 1.5\%$ and $MIN(RN_{hrv}\ 3x3)_{cur} > 10\%$
  and $SD_{cur}(R_{hrv}\ 3x3)/MEAN_{cur}(R_{hrv}\ 3x3) - SD_{prev}(R_{hrv}\ 3x3)/MEAN_{prev}(R_{hrv}\ 3x3) > 0.03$
  and $MAX_{cur}(RN_{hrv}\ 3x3)) > 1.03* MAX_{prev}(RN_{hrv}\ 3x3))$

-SD MIN MAX MEAN stand respectively for the spatial standard deviation, minimum value, maximum value and mean of the feature.
-R_{hrv} is the HRV reflectance
-RN_{hrv} is the HRV reflectance normalized by the analytical formulation of solar pahthlength valid for a standard atmosphere proposed by Li and Shibata, 2006. (in place of classical inverse cosine function).
-indices $_{cur}$ and $_{prev}$ stands for pixels from the current image or the one 15 minutes sooner.

The assumption behind this test is that a mobile or evolving bright target inside a 3x3 HRV array is a cloud. False alarms that have been problematic are clear sides of cloud shadow limits moving over bright grounds. This is why he pixels detected by this test are further processed by a neighbourhood analysis described below.

2.2.1.2.2.18.3.2 Clear restoral test over land

This test is designed to remove some false alarms passing through the previous test, and is applied only to pixels detected by the previous test
A SEVIRI pixel at low resolution scale is restored as clear

- Its $MEAN(R_{hrv}3x3)$ is minimum among other land pixels in its SEV_{3x3} low resolution neighbourhood

2.2.1.2.2.18.3.3 Cloud restoral test over land

Obviously during visual inspection of the results some clouds remained missed after the change detection test. Brighter pixels in the neighbourhood of pixels detected as clouds by the HRV change detection algorithm described in the previous sections should also be detected as cloudy. This test is designed to this purpose.
A SEVIRI pixel on land at low resolution scale in the 11x11 neighbourhood of a HRV change detection is restored as cloud if at least 5 pixels inside 11x11 neighbourhood are detected by HRV change detection tests

- $MIN(RN_{hrv}\ 3x3)_{cur} > 10\%$

and

- $MAX(R_{hrv}\ 3x3) > MEAN_{11x11}(Max(R_{hrv}\ 3x3)$ of the pixels detected by HRV if nb > 5)

and

- $SD(R_{hrv}\ 3x3) > 1.5\%$
  or
  $MAX(R_{hrv}\ 3x3)-MIN(R_{hrv}\ 3x3) >$
  $MEAN_{11x11}(MAX(R_{hrv}\ 3x3)- MIN(R_{hrv}\ 3x3))$ of the pixels detected by HRV if nb > 5)

2.2.1.2.2.18.4 Examples of HRV-based algorithm impact

2.2.1.2.2.18.4.1 Maritime cloud patterns

As the algorithms are different over water, 2 cases illustrate typical difficult cloud patterns. The figures show how HRV resolves the cloud field when compared with the low resolution SEVIRI visible band and how the HRV-based detections are transposed at the SEVIRI low spatial resolution. One can also note that generally these detections correspond to either fractional or low clouds in the CT cloud type product.

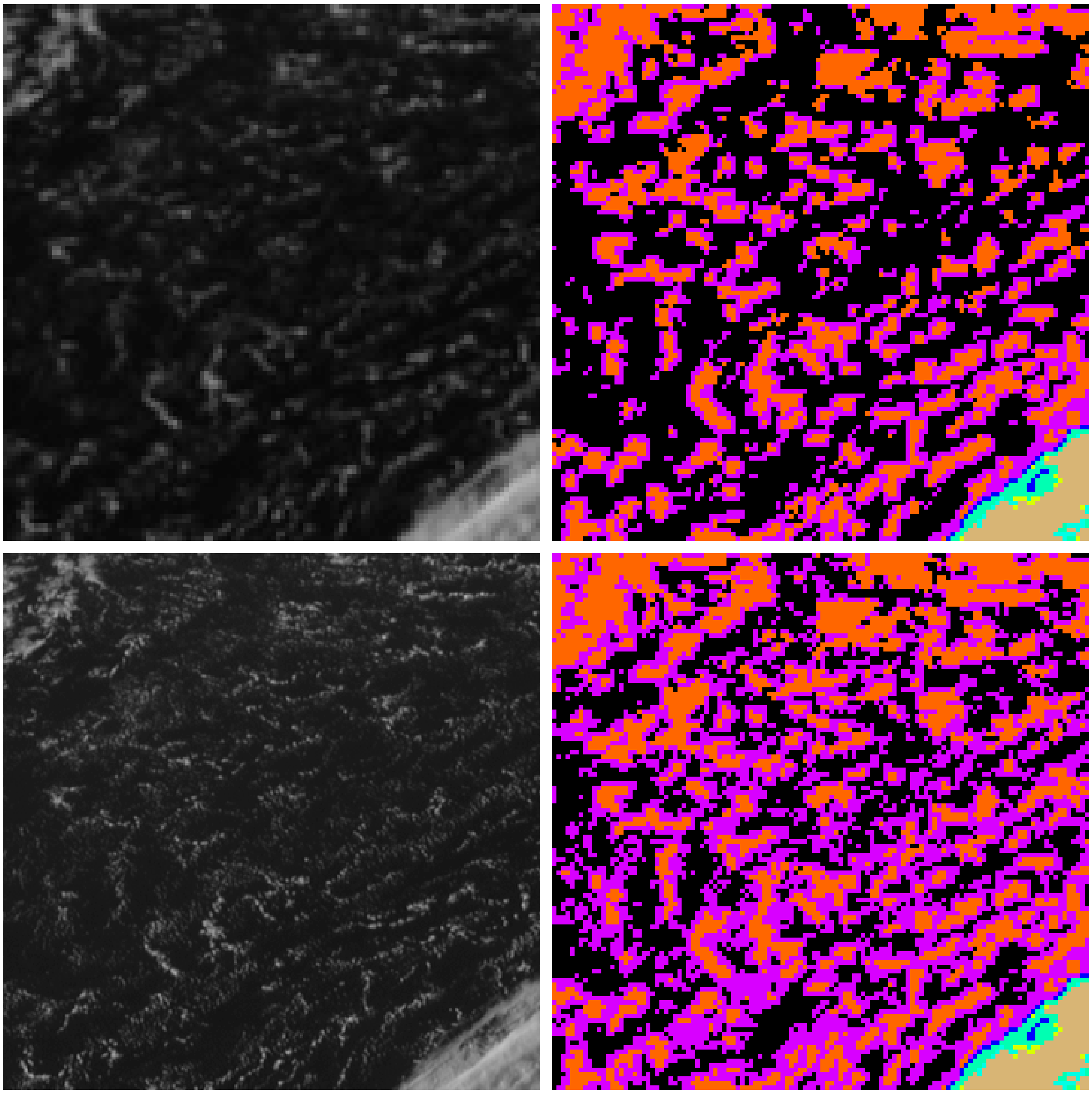

Figure 16 Shallow convection maritime clouds over Northern Atlantic, 8 September 2009. 17h00UTC, (120x120 at low resolution SEVIRI scale). Top left: 0.8 μm visible reflectance; top right: v2009 cloud type; bottom left: HRV reflectance; bottom right: v2010 cloud mask

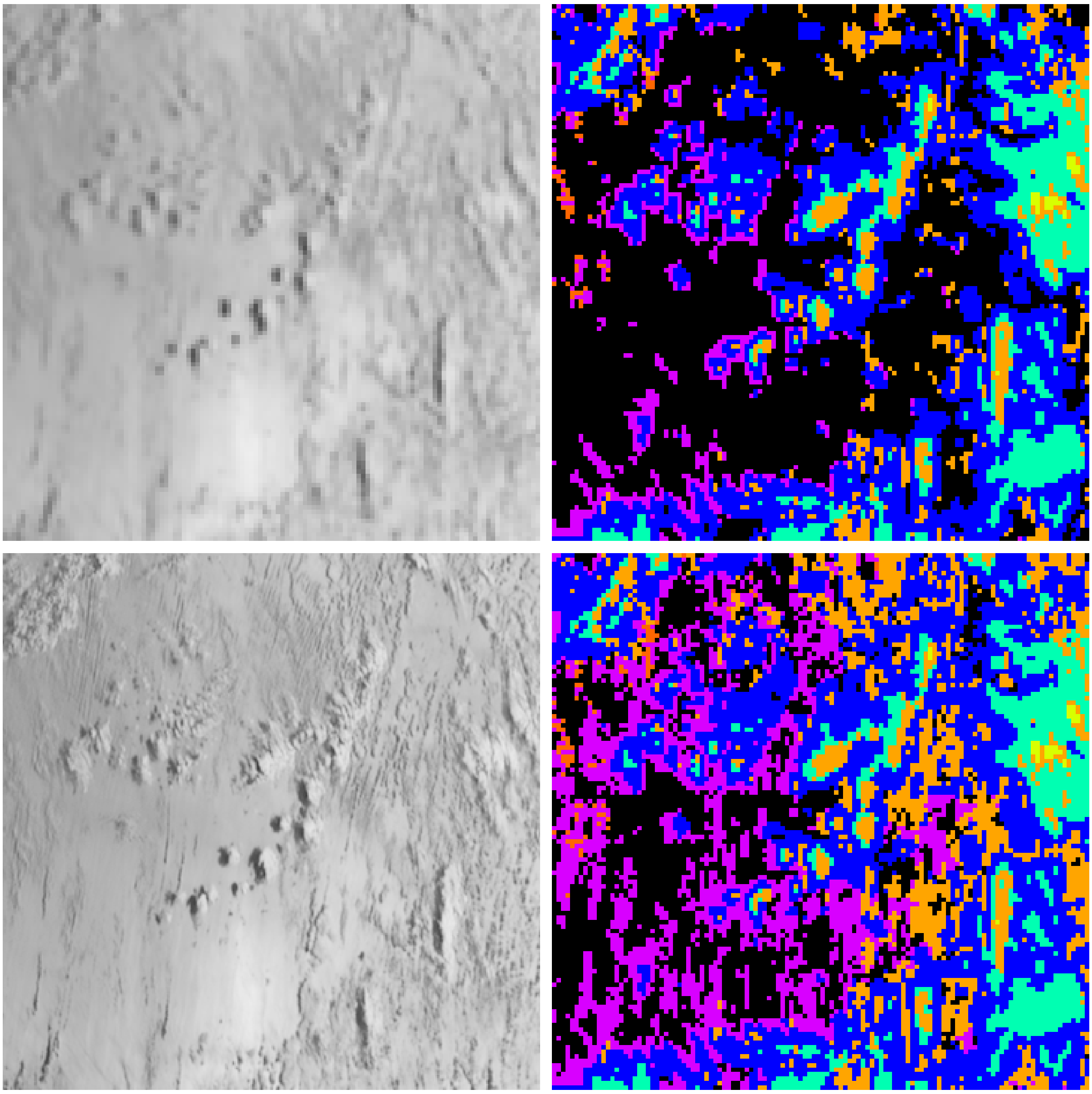

Figure 17 Sunglint with trade-wind convective low clouds over Indian Ocean, 8 September 2009, 04h00UTC, (120x120 at low resolution SEVIRI scale). Top left: 0.8 µm visible reflectance; top right: v2009 cloud type; bottom left: HRV reflectance; bottom right: v2010 cloud type

2.2.1.2.2.18.4.2 Continental cloud patterns

Four cases are displayed to illustrate situations with various backgrounds where the algorithm applied to HRV data improves the cloud detection, one over Europe, two over Africa, and one over South America.

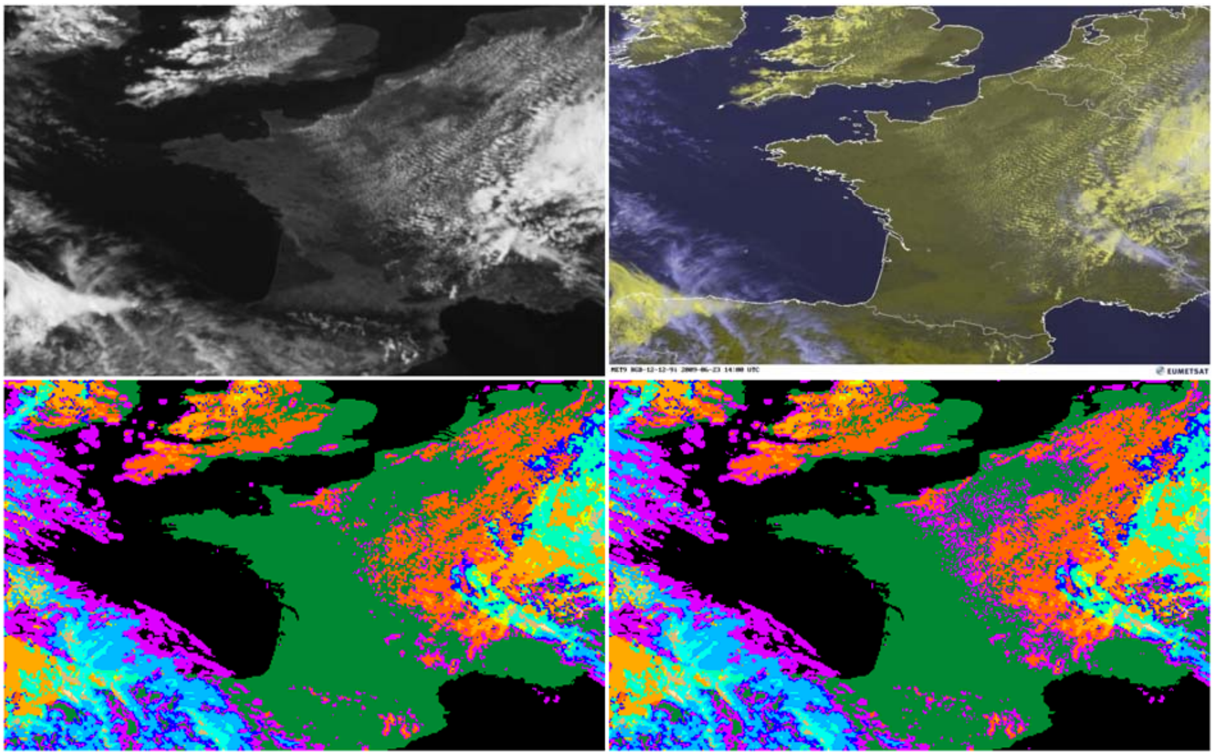

Figure 18 Fair-weather cumulus in subsident air over western Europe, 23 June 2009, 14h00UTC, (1270x770 at SEVIRI low resolution scale). Top left: enhanced 0.6 μm visible reflectance; top right: EUMETSAT RGB (12-12-9); bottom left: v2009 cloud type; bottom right: v2010 cloud type

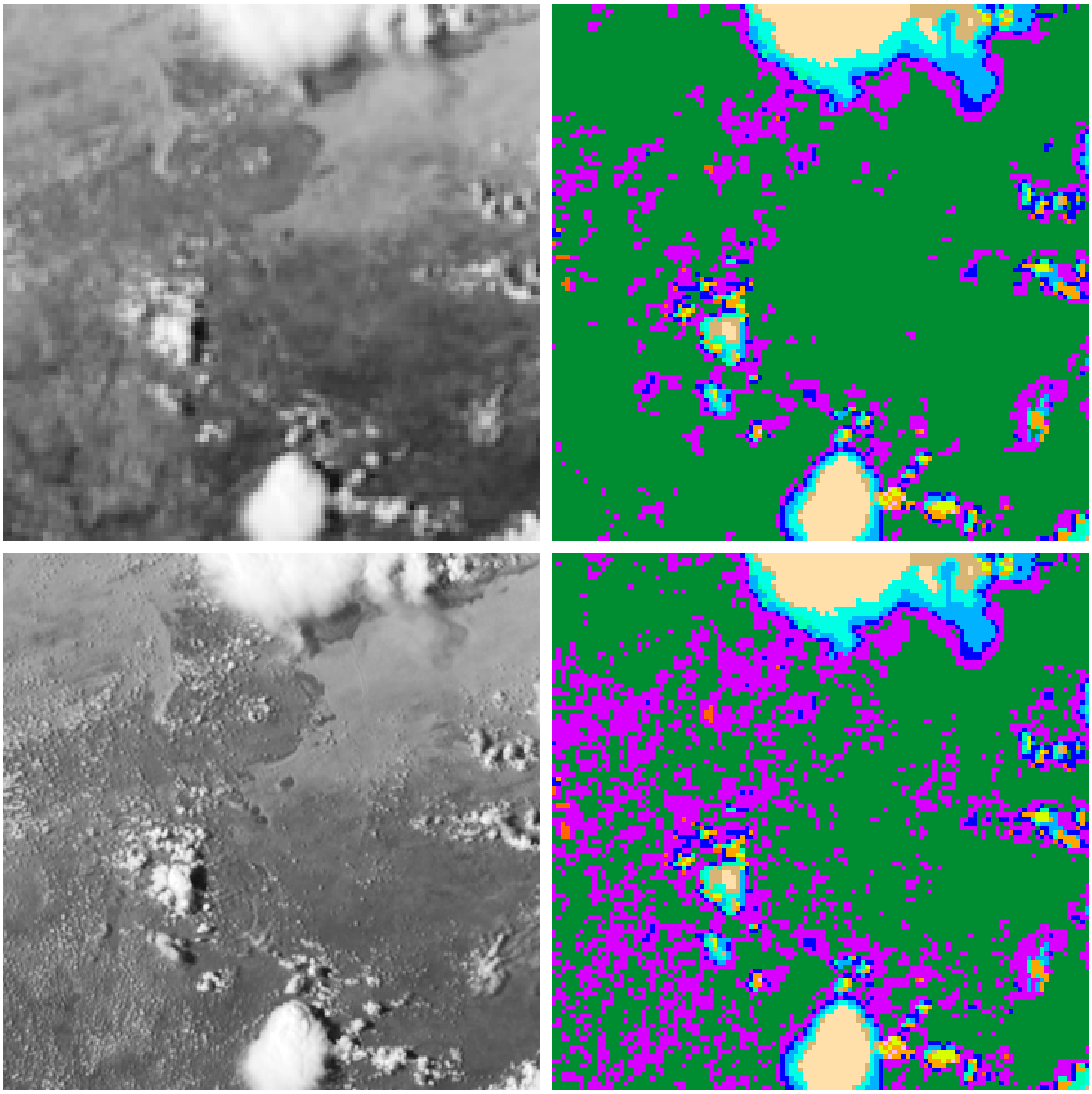

Figure 19 Heterogeneous convection over complex terrain in Mauritania, 8 September 2009, 15h00UTC, (120x120 at low resolution SEVIRI scale). Top left: 0.6 µm visible reflectance; top right: v2009 cloud type; bottom left: HRV reflectance; bottom right: v2010 cloud type

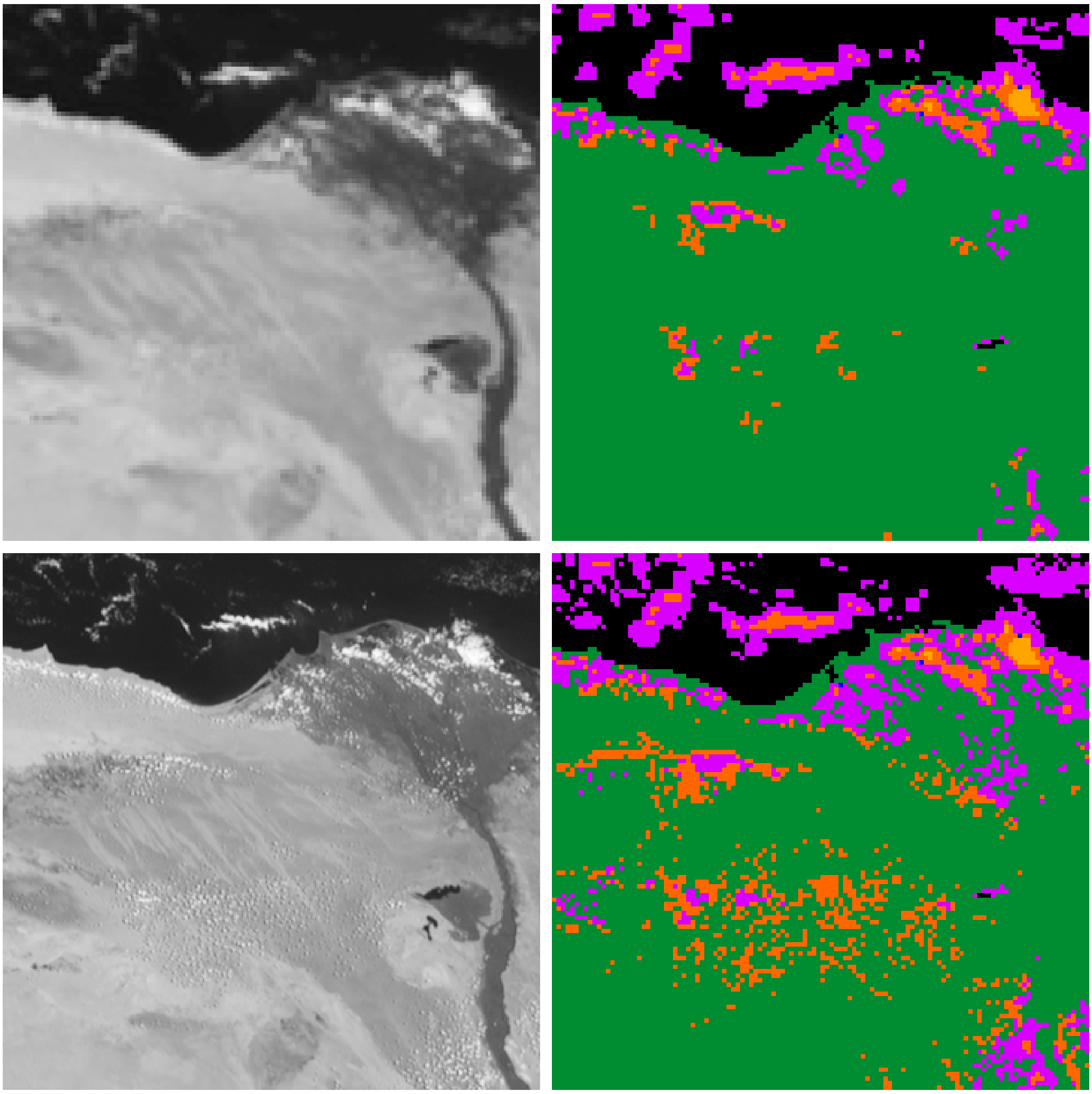

Figure 20 Fair-weather cumulus over Egypt near Nile delta, 9 September 2009, 10h00UTC, (120x120 at low resolution SEVIRI scale). Top left: 0.6 μm visible reflectance; top right: v2009 cloud type; bottom left: HRV reflectance; bottom right: v2010 cloud type

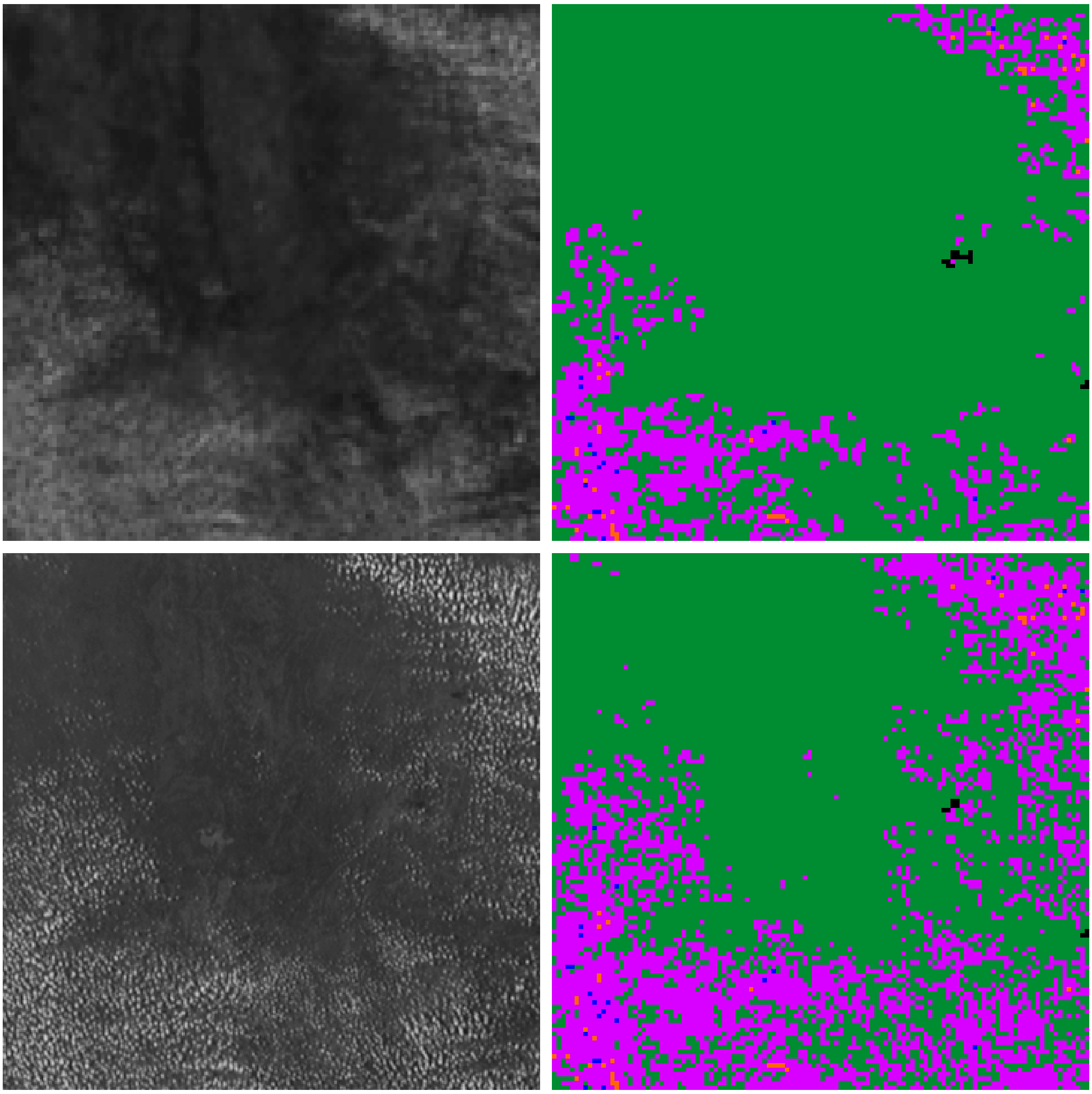

Figure 21 Shallow convection over Brazil, 7 September 2009, 17h00UTC, (120x120 at low resolution SEVIRI scale). Top left: 0.6 μm visible reflectance; top right: v2009 cloud type; bottom left: HRV reflectance; bottom right: v2010 cloud type

2.2.1.2.2.19 Clear restoral test for cold scenes

This test is designed to remove some remaining false alarms in the coldest scenes. It exploits the fact that for some extremely cold ground surfaces, in presence of strong nocturnal clear-sky inversion, the T7.3 brightness temperature, sensitive to atmosphere temperature is warmer than the one observed in the 10.8µm atmospheric window.

A pixel is restored as clear when detected by T108thr test at any illumination, or Visible test or T39T108thr test at daytime or twilight under the following conditions:

- If t108thr < 250K and T7.3-T10.8> 0.5K

2.2.1.2.2.20 Spatial filtering

The spatial filtering is applied at the final stage of cloud detection after the sequence of all tests.

The use of local spatial texture test, even relaxed, in the vicinity of coast line may induce false alarms in the sea side of the coastal zone. This spatial filtering dedicated only to coastal pixels is designed to reduce this default. It is not applied around a water group smaller than 50 elements

The coastal seaside pixels are identified by subtracting the result of 2 morphological dilatations of land pixels eroded twice by a 3x3 structuring element.

The following filtering is applied to coastal pixels:

- Over sea a pixel detected cloudy by a local spatial texture test is restored clear when belonging to a 3x3 box clear at 10% and to a 7x7 box clear at 50%.
- Over land a pixel detected as cloudy is restored clear when belonging to a 3x3 box clear at 10% and to a 7x7 box clear at 50%.

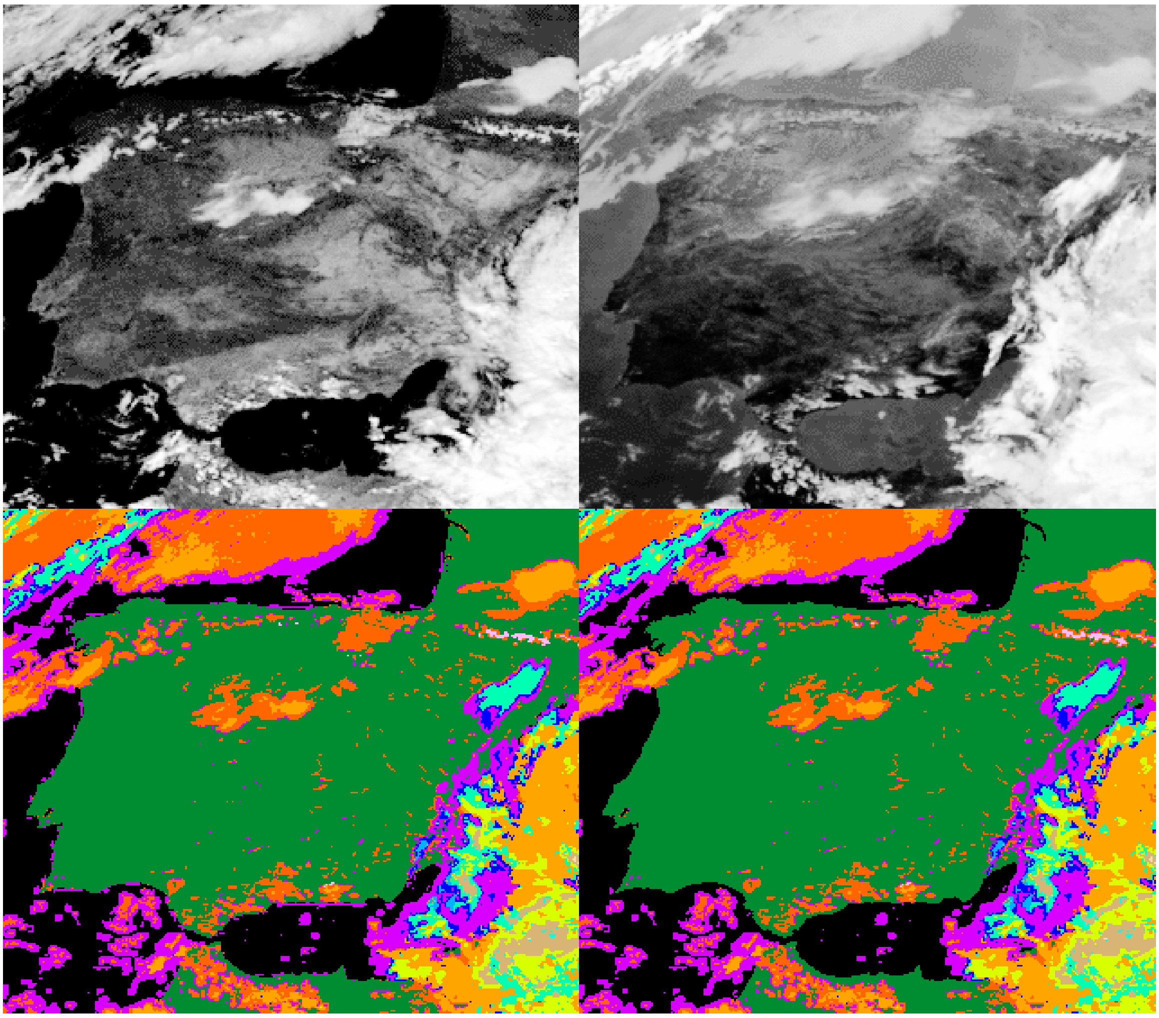

Figure 22 Illustration of spatial filtering effect in coastal area, 28 November 2007 12h00UTC top left VIS 0.6, top right IR T10.8; bottom left, CT without coastal filtering; bottom right CT with coastal filtering

In CT pictures it is very frequent to observe snowy areas surrounded by a band of low clouds. In general such pixels are in fact partially covered by snow and wrongly detected as cloud because insufficiently covered by snow. When examining in details this default we have found that in general such pixels are detected cloudy by a local spatial texture test.

The outer limits of snowy areas are identified by subtracting the result of 2 morphological dilatations of snowy pixels by a 3x3 structuring element eroded twice by the same structuring element.

The following filtering is applied to outer edge band of a snowy area:

- A pixel detected cloudy by local spatial texture test is restored clear if belonging to a 3x3 box with at least a clear pixel and without cloudy pixels detected by another test

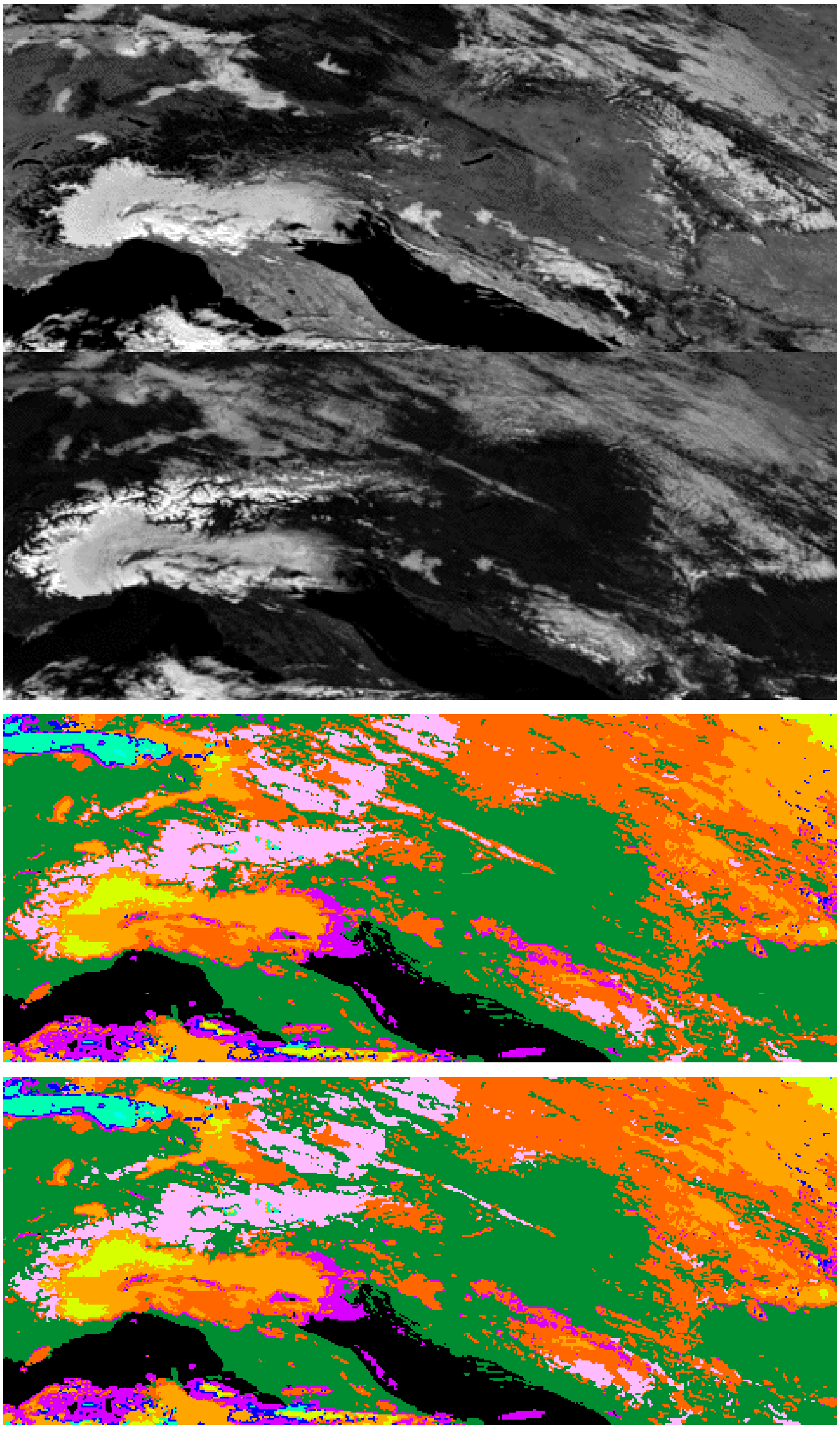

Figure 23 Illustration of spatial filtering effect in snowy area edges, 28 November 2007 12h00UTC, from top to bottom; NIR 1.6,VIS 0.6; CT without snow edge filtering; CT with snow edge filtering

The following spatial filtering process is finally applied:

- all the isolated cloudy pixels that have been detected by a test using the 3.9µm are reclassified as cloud-free.
- all the isolated cloud free pixels are reclassified as cloudy.

All the reclassified pixel are flagged as of very low confidence.

2.2.1.2.2.21 Opaque clouds detection Test

This test has been implemented to identify opaque clouds :

A cloud contaminated pixel is classified as opaque cloud if :

- T10.8µm -T12.0µm < 2K

The aim is to identify pixels fully covered by a single cloud layer whose infrared emissivity is close to unity, and are therefore not contaminated in the infrared wavelength by the surface. The calculation of the cloud top temperature and height of these pixels would then have only required a correction for atmospheric attenuation above the cloud.

The opaque cloud identification is applied to pixels previously detected as cloud contaminated. It relies on the analysis of the T10.8µm -T12.0µm brightness temperature difference : this difference is higher for semi-transparent ice clouds (due to their higher transmitivity at 10.8µm) and broken clouds, than for opaque clouds.

Nota Bene: if the user is interested in getting information on whether the pixel is partly or fully covered by clouds, it is thought that the CT product should be used instead the CMa product, because the CT algorithm is much more sophisticated. Nevertheless, the opaque cloud identification remains implemented in CMa not to force the user to change their applications.

2.2.1.2.3 Quality assessment

A quality flag is appended to the CMa. It allows the identification of cloud-free, cloudy and snowy pixels that may have been misclassified:

- a pixel classified as cloudy is flagged as of low confidence if no cloud detection test has been really successful. A threshold test is said really successful if the difference between the threshold and the measurement is larger than a security margin depending on the test itself:

Cloud Tests	**SST**	**T10.8µm**	**T10.8µm-T12.0µm**	**T10.8µm-T3.9µm T12.0µm-T3.9µm T8.7µm-T3.9µm**	**T3.9µm-T10.8µm**
Security margin for quality assessment	2 K	3 K	0.5 K	0.5 K	0.5 K
Cloud Tests	**R0.6µm**	**R0.6µm**	**R0.6µm**	**Local Spatial Texture**	
Security margin for quality assessment	0.2*threshold	0.2*threshold	0.2*threshold	0.2*threshold	

- a pixel classified as cloud free is flagged as of low confidence if the difference between the threshold and the measurement is lower than an security margin (see above table) for at least one cloud detection test.

- a pixel classified as snow/ice is flagged as of low confidence if the difference between its observed R1.6µm and the corresponding threshold of this feature used in the snow/ice detection test is lower than 0.2*threshold.

Such a quality flag should allow to identify high confidence cloud free areas for surface parameters computation. On the other hand, the identification of extended cloudy or cloud free area flagged as low confidence should help in identifying areas where the algorithm may be not accurate enough [note that it is understandable that cloud edges or cloud free areas bordering clouds are flagged as of low confidence].

2.2.1.2.4 Dust cloud identification

The following algorithm has been empirically derived to detect and classify dust clouds at daytime and also at night-time over sea:

Over the ocean at daytime, a pixel is classified as contaminated by dust cloud if :

- Separation from cloud free surfaces:
- {
    - [(R1.6µm / R0.6µm) > 0.4 and
      (R1.6µm > R1.6threshold - 5%) and
      (T12.0µm-T10.8µm) > T120T108threshold)] or
    - [(R1.6µm / R0.6µm) > 0.6 and
      (R1.6µm > R1.6threshold - 5%)] or
    - [(R1.6µm / R0.6µm) > 0.4 and
      (R1.6µm > R1.6threshold - 7%) and
      SD(T10.8µm-T3.9µm) <0.3°C and
      (T12.0µm-T10.8µm) > -1K)] or
    - [R0.6µm > R0.6threshold - 5% and
      (T12.0µm-T10.8µm) > T120T108threshold] } and
- Separation from clouds:
- {
    - -5°C - 5*(1/cos(θsat) -1) < T10.8µm – SSTclim and
    - (T8.7µm-T10.8µm) >-(2.5-0.17*(1-1/cos(θsat))) and
    - SD(T10.8µm)<0.4°C and
    - { [R0.6µm < R0.6threshold +20% and
      SD(R0.6µm)<0.6 % and SD(R0.8µm)<0.6 % and
      SD(R1.6µm) <0.3%+0.01*R0.6µm or SD(R0.6µm)<0.1% and
      SD(T10.8µm-T3.9µm) <0.4°C] or
      [R0.6threshold+10%<R0.6µm and
      (T8.7µm-T10.8µm) > -1.0 and
      SD(R0.6µm)<1.0 %] or
      [R0.6threshold+20%<R0.6µm<R0.6threshold +40% and
      (T8.7µm-T10.8µm) > -1.5 and
      SD(R0.6µm)<0.6 % and SD(R0.8µm)<0.6 % and
      SD(T10.8µm-T3.9µm) <0.4°C] }
- Sun elevation larger than 20 degrees, including sunglint areas):

[where R0.6threshold and R1.6threshold are used in the cloud masking scheme, θsat is the satellite zenith angle, T120T108threshold defined in text, SD is the standard deviation,]

Over the ocean at nightime, a pixel is classified as contaminated by dust cloud if :

- {[(Saharan_dust_index > 0.6 and -5°C - 5*(1/cos(θsat) -1) < T10.8µm – SSTclim) or
  (Saharan_dust_index > 1.0 and -10°C - 5*(1/cos(θsat) -1) < T10.8µm – SSTclim)] and
- SD(T10.8µm) < 0.4°C and SD(T10.8µm-T3.9µm) <0.4°C and
- (T108µm-T120µm)<1.2 and
- (T87µm-T108µm)>-(2.5-0.17*(1-1/cos(θsat)) }
- Sun elevation lower than –3 degrees:

[where θsat is the satellite zenith angle and SD is the standard deviation and
Saharan Dust Index (SDI)= 0.53476*(T39µm-T87µm)-0.838710*(T108µm-T120µm)+1.28362 (for MSG1)]

Over continental surfaces at daytime, a pixel is classified as contaminated by dust cloud if :

- Sun elevation larger than 20 degrees and
- 273.15K < T10.8µm < 315.15K and
- R0.6µm < R0.6threshold +15% and
- SD(T10.8µm) < 3.0 K and SD(R0.6µm) < 3.0 % and
- [[((T3.9µm - T10.8µm) > -10 K and (T12.0µm-T10.8µm) > 2.5 K or
  ((T3.9µm - T10.8µm) > 12 K and (T12.0µm-T10.8µm) > 0.6 K] or
  [(T12.0µm-T10.8µm) > -1 K and
  { (T8.7µm-T10.8µm) > -1.0 K and R0.6µm /R1.6µm <0.8 } or
  (T8.7µm-T10.8µm) > min(-1.0,2.5-0.18* R0.6µm) K and R0.6µm /R1.6µm <0.7}]]

[where R0.6threshold used in cloud masking, R0.6threshold used in cloud masking]

The aim is to identify dust that is transported out of deserts over both continental and oceanic surfaces. These events are rather frequent over North Africa and adjacent seas (Atlantic Ocean and Mediterranean sea). The difficulty is to separate dust clouds from cloud free areas without confusing them with water clouds. Techniques proposed in literature are based on brightness temperature differences [10.8 and 3.9µm (Ackerman, 1989), or 10.8 and 12.0µm (used by NOAA to map dust clouds); a thermal contrast between the ground and the dust cloud is needed to make these techniques efficient], or on visible reflectances spatial homogeneity (Jankowiak and Tanre, 1992). The result of this detection process is stored in a separate flag.

The threshold applied over the ocean to the T12.0µm-T10.8µm brightness temperature difference is, as most IR thresholds, calculated from pre-computed tables defined by applying RTTOV to an atmospheric profiles database provided by ECMWF (F.Chevalier, 1999). It is illustrated on Figure 24.

The nightime detection of dust over sea is based on the thresholding of the Saharn Dust Index (SDI, see Merchant et al., 2006) computed from T3.9µm, T8.7µm, T10.8µm and T12.0µm.

2.2.1.2.5 Volcanic ash cloud identification

The following algorithm has been empirically derived to detect and classify volcanic ash clouds:

At nightime or twilight, a pixel is classified as contaminated by volcanic ash if:

- T12.0µm -T10.8µm > T12.0T10.8threshold_volcan_night and
- T3.9µm -T10.8µm > T3.9T10.8threshold

[T12.0T10.8threshold_volcan_night is a finely tuned threshold explained below in the text, T3.9T10.8threshold is a threshold used in the cloud detection process].

At daytime over sea, a pixel is classified as contaminated by volcanic ash if:

- T12.0µm -T10.8µm > T12.0T10.8threshold_volcan_day and
- |R0.6µm - R1.6µm| < 10%

At daytime over land, a pixel is classified as contaminated by volcanic ash if:

- T12.0µm -T10.8µm > T12.0T10.8threshold_volcan_day and
- T10.8µm < (T10.8threshold + 20K) and
- |R0.6µm -R1.6µm| < 10% and T3.9µm -T10.8µm > 5K or
  |R0.6µm -R1.6µm| < 20% and T3.9µm -T10.8µm > 13K

[T12.0T10.8threshold_volcan_day is a finely tuned threshold explained below in the text, T10.8threshold is the threshold used in the T10.8µm infrared test during the cloud detection process].

Most volcanic ash clouds events (but not all!) are characterized by highly positive T12.0µm-T10.8µm brightness temperature difference. The aim of this test is to detect these volcanic events, and minimize false alerts. The result of this detection process is stored in a separate flag.

The threshold applied to the T12.0µm -T10.8µm is finely tuned to limit at the maximum the false alert rate:

- at daytime, T12.0T10.8threshold_volcan_day varies linearly with R0.6µm from 0.7K (at R0.6µm equal 0%) up to 1.7K (at R0.6µm larger than 60%); an additional offset, which is a linear function of the satellite secant (from 0K up to 1K for a satellite secant of 5) is finally added to T12.0T10.8threshold_volcan_day to account for the higher T12.0µm-T10.8µm of clouds at large satellite zenith angle.
- at nighttime, T12.0T10.8threshold_volcan_night decreases with T10.8µm from 1.2K (at T10.8µm lower than 223.15K) down to T12.0T10.8threshold (at T10.8µm larger than T10.8threshold+20K); an additional offset, which is a linear function of the satellite secant (from 0K up to 1K for a satellite secant of 5) is finally added to T12.0T10.8threshold_volcan_day to account for the higher T12.0µm -T10.8µm of clouds at large satellite zenith angle. T10.8threshold is the threshold used in the T10.8µm infrared test during the cloud detection process, whereas T12.0T10.8threshold, illustrated on Figure 24, is calculated as explained in 2.2.1.2.4.

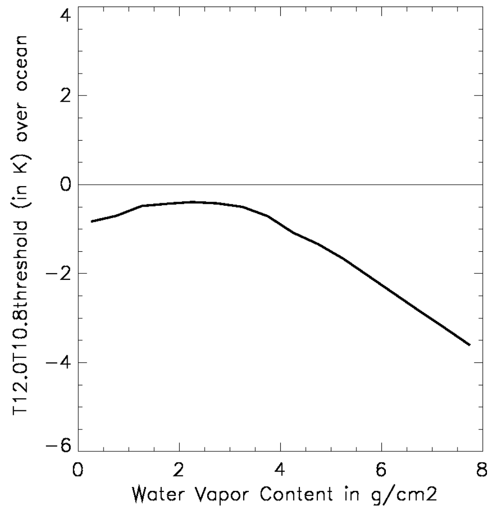

Figure 24: Illustration of T12.0T10.8threshold used in the dust and volcanic cloud detection over the ocean for a satellite zenith angle of 48 degrees

2.2.2 Practical considerations

2.2.2.1 Validation

Table 6 summarises the validation results of the current version. More details can be obtained from the validation report for cloud products ([AD. 1]).

PGE01 flags	Validated accuracy
PGE01 cloud detection If validated over European areas using SYNOP observations	POD: 96.5%
PGE01 dust flag If validated over sea and Africa for solar elevation larger than 20 degrees using interactive targets	POD: 55.5% over sea 58.5% over land

Table 6: Summary of validation results of the current PGE01 version (POD stands for Probability Of Detection)

2.2.2.2 Quality control and diagnostics

A quality assessment, detailed in 2.2.1.2.3, is performed by the CMa itself through a comparison between thresholds and measurements, low confidence corresponding to thresholds and measurements close to each other.

Nine bits in the CMa output are dedicated to quality description (see in 2.2.2.4). They include a quality flag based on the quality assessment performed by the CMa (see above paragraph), but also information on the lack of NWP fields or SEVIRI non mandatory channels which leads to a decrease of CMa quality.

2.2.2.3 List of inputs for Cloud Mask (CMa)

The input data to the CMa algorithm are described in this section. Mandatory inputs are flagged, whereas the impact of missing non-mandatory data on the processing are indicated.

- **Satellite imagery:**

The following SEVIRI bi-directional reflectances or brightness temperatures of the scene to be analysed are needed at full IR spatial resolution (at HRV spatial resolution for HRV):

HRV	R0.6µm	R0.8µm	R1.6µm	T3.9µm	T7.3µm	T8.7µm	T10.8µm	T12.0µm	T13.4µm
Optional	Mandatory	Optional	Optional	Mandatory	Optional	Optional	Mandatory	Mandatory	Optional

The CMa software checks the availability of SEVIRI channels for each pixel. If non mandatory channels are missing for one pixel, the tests using these channels are not applied, or applied differently (for example, snow detection uses either R1.6µm or T3.9µm; visible channel test over the ocean uses either R0.8µm or R0.6µm) and a result is available for this pixel. No results are provided for pixels where at least one mandatory channel is missing.

The following SEVIRI bi-directional reflectances or brightness temperatures or CMa or CT of the scene analysed one hour sooner are optionally needed to improve the cloud detection in day-night transition. If one of them misses this improvement is not performed.

$R0.6\mu m_{1h}$	$T8.7\mu m_{1h}$	$T10.8\mu m_{1h}$	$T12.0\mu m_{1h}$	CMa_{1h}	CT_{1h}
Optional	Optional	Optional	Optional	Optional	Optional

The following SEVIRI brightness temperatures or CMa or CT of the scene analysed 15 minutes sooner are optionally needed to improve the cloud detection of fast moving clouds. If one of them misses this improvement is not performed.

$T8.7\mu m_{15mn}$	$T10.8\mu m_{15mn}$	$T12.0\mu m_{15mn}$	CMa_{15mn}	CT_{15mn}
Optional	Optional	Optional	Optional	Optional

The HRV bi-directional reflectance of the scene analysed 15 minutes sooner are optionally needed to improve the sub-pixel cumulus cloud detection. If not available this improvement is not performed.

HRV_{15mn}
Optional

The SEVIRI channels are input by the user in HRIT format, and extracted on the processed region by SAFNWC software package.

- **Sun and satellite angles associated to SEVIRI imagery**

This information is mandatory. It is computed by the CMa software itself, using the definition of the region and the satellite characteristics.

- **NWP parameters:**

The forecast fields of the following parameters, remapped onto satellite images, are used as input :

- surface temperatures (required to get good quality results over land ; but not mandatory)
- air temperature at 950hPa (alternatively 925hPa). Used to check low level inversion.
- total water vapour content of the atmosphere,
- altitude of the NWP model grid (alternatively surface geopotential on the NWP model grid). Required if NWP fields are used as input.

These remapped fields are elaborated by the SAFNWC software package from the NWP fields input by the user in GRIB format.

The NWP fields are not mandatory: the CMa software replaces missing NWP surface temperatures or total water vapour content of the atmosphere by climatological values extracted from ancillary dataset, but the quality of CMa is then lower.

- **Ancillary data sets:**

The following ancillary data, remapped onto satellite images, are mandatory :

- Land/sea atlas
- Land/sea/coast atlas
- Elevation atlas
- Monthly minimum SST climatology
- Monthly mean 0.6µm atmospheric-corrected reflectance climatology (land)
- Monthly mean large band visible surface reflectance climatology (land, for HRV processing)
- Monthly integrated atmospheric water vapor content climatology
- Monthly climatology of mean air temperature at 1000 hPa

These ancillary data are available in the SAFNWC software package on MSG full disk in the default satellite projection at full IR resolution; They are extracted on the processed region by the CMa software itself.

Coefficients's file (also called threshold tables), containing satellite-dependent values and look-up tables for IR thresholds and for solar channels' thresholds, are available in the SAFNWC software package, and are needed by the CMa software.

- **Configurable parameters:**

Three configurables parameters are available in the default CMa model configuration file:

- CMA_SZSEG: The size of the segment is configurable (see its definition in section 2.2.2.6.1). Its default value is 4. Information on how to change the size of the segment can be found in section 2.2.2.6.1 and in the software user manual ([AD. 2]).
- TEMPORAL_USE: The flag defining if temporal information is to be used (to allow a better detection of fast moving clouds and low clouds in twilight conditions) is configurable (see its definition in section 2.2.2.6.1). Its default value is TRUE. Information on how to change this value can be found in section 2.2.2.6.1 and in the software user manual ([AD. 2]).
- HRVNEED: The flag indicating if HRV data have to be used (to allow enhanced sub-pixel cumulus detection) is configurable (see its definition in section 2.2.2.6.1). Its default value is TRUE. Information on how to change this value can be found in section 2.2.2.6.1 and in the software user manual ([AD. 2]).

2.2.2.4 Description of Cloud Mask (CMa) output

The content of the CMa is the following:

- **The main product output consists in the following six categories coded on 3 bits**

0	Non-processed	containing no data or corrupted data
1	cloud-free	no contamination by snow/ice covered surface, no contamination by clouds ; but contamination by thin dust/volcanic clouds not checked
2	Cloud contaminated	partly cloudy or semitransparent. May also include dust clouds or volcanic plumes.
3	Cloud filled	opaque clouds completely filling the FOV. May also include thick dust clouds or volcanic plumes.
4	Snow/Ice contaminated	
5	Undefined	has been processed but not classified due to known separability problems

- **16 bits to describe which test was successful**

For each cloudy pixel, the bits corresponding to the successful tests are activated. More than one bit may be activated, if tests were not really successful (measurement too close to thresholds)).

0 T10.8µm or SST
1 R0.6µm (land) or R0.8µm (sea)
2 Sunglint test using 3.9µm
3 Local Spatial Texture
4 T10.8µm - T12.0µm
5 T10.8µm - T3.9µm or T12.0µm - T3.9µm
6 T3.9µm - T10.8µm
7 Spatial smoothing (reclassify isolated cloud-free pixels)
8 T8.7µm - T3.9µm
9 R1.6µm (sea)
10 T8.7µm –T10.8µm or T10.8µm –T8.7µm
11 Snow using R1.6µm or T3.9µm
12 HRV-based test
13 Stationary cloud in twilight
14 Spatial expansion of stationary cloud in twilight
15 Temporal-differencing

- **11bits for quality**

3 bits to define illumination and viewing conditions:
0 Undefined (space)
1 Night
2 Twilight
3 Day
4 Sunglint

2 bits to describe NWP input data
0 Undefined (space)
1 All NWP parameters available (no low level inversion)
2 All NWP parameters available (low level inversion)
3 At least one NWP parameter missing

2 bits to describe SEVIRI input data
0 Undefined (space)
1 All useful SEVIRI channels available ;
2 At least one useful SEVIRI channel missing
3 A least one mandatory SEVIRI channel missing

2 bits to describe the quality of the processing itself:
0 Non processed (containing no data or corrupted data)
1 Good quality (high confidence)
2 Poor quality (low confidence)
3 Reclassified after spatial smoothing (very low confidence)

1 bit for temporal processing indicator (significant for cloud-free pixels)
0 Not performed
1 Performed

1 bit for HRV processing indicator (significant for cloud-free pixels)
0 Not performed
1 Performed

- **2 bits for dust detection**

0 Non processed (containing no data or corrupted data)
1 dust
2 non dust
3 undefined (due to known separability problems)

- **2 bits for volcanic plume detection**

0 Non processed (containing no data or corrupted data)
1 volcanic plume
2 non volcanic plume
3 undefined (due to known separability problems)

2.2.2.5 Example of Cloud Mask (CMa) visualisation

It is important to note that the CMa product is not just images, but numerical data. At first hand, the CMa is rather thought to be used digitally (together with the appended flags (quality, dust detection, volcanic ash detection)) as input to mesoscale analysis models, objective Nowcasting schemes, but also during the extraction of other SAFNWC products (CT for example).

Colour palettes are included in CMa HDF files, allowing an easy visualisation of CMa main categories, dust and volcanic ash clouds flags.

No example of CMa main categories's visualisation are given, as it is thought that the user will be more interested to visualize the CT product which can be seen as a refinement.

Example of visualisation of the dust cloud and the volcanic ash cloud flags superimposed on infrared images are given in Figure 25 and Figure 26 , using SEVIRI and MODIS imagery.

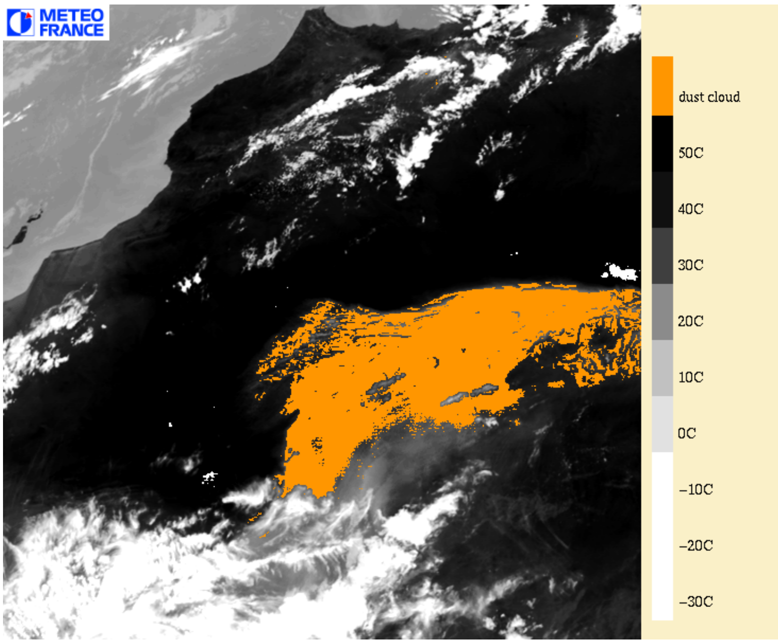

Figure 25: Example of SEVIRI dust cloud flag superimposed on a 10.8µm infrared image: dust cloud over North Africa on 14th July 2003 at 13h00 UTC.

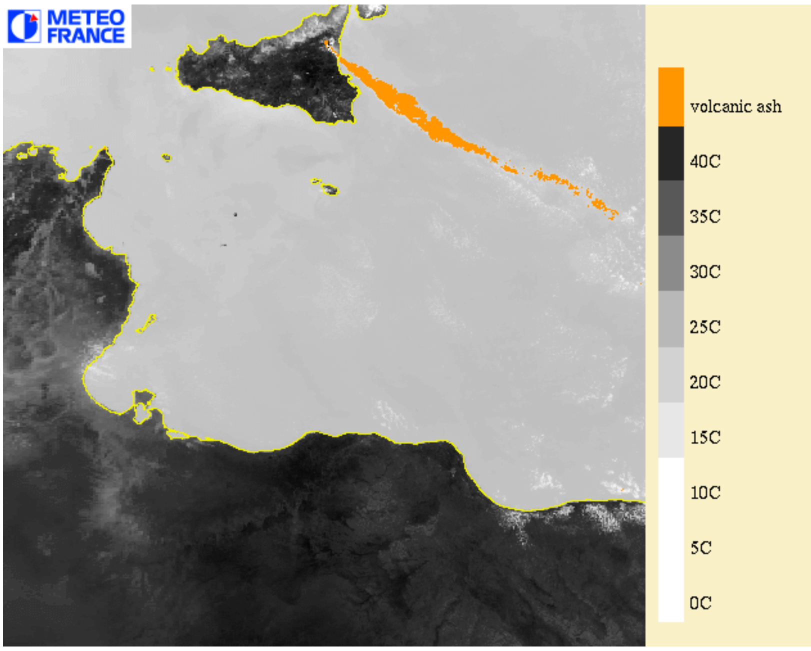

Figure 26: Example of MODIS volcanic ash cloud superimposed on a 10.8µm infrared image: Etna eruption on 22th July 2001 at 9h55 UTC.

2.2.2.6 Implementation of Cloud Mask (CMa)

CMa is extracted by PGE01 of the SAFNWC/MSG software package. Detailed information on how to run this software package is available in the software user manual ([AD. 2]).

The software architecture of PGE01 has been strongly modified in version v2010 (to make the life easier for the user). It is now very similar to the other PGEs.

When a new region is defined the user has now to manually prepare the CMa model configuration files for this new region using a default CMa model configuration file provided in the SAFNWC/MSG software package. As the content of NWP_CONF_FILE is dependent on the local installation, the user must make the NWP_PARAMXX consistent with the local NWP_CONF_FILE when the standard one is not used.

There is an option for the user to monitor the so-called CMa preparation step before SEVIRI images are available (to speed up the process). By default, this preparation step is performed during the CMa execution step.

The CMa execution step (which includes the CMa preparation step in case it has not been launched before) is automatically launched by the Task Manager (if real-time environment is selected).

2.2.2.6.1 Manual preparation of Cloud Mask (Cma) model configuration file for each region

When a new region is defined and added in system and run configuration files, the user must manually prepare the CMa model configuration files by adapting the CMa default model configuration file available in the SAFNWC software package. Three parameters are configurable in the default CMa model configuration file:

- CMA_SZSEG (default value: 4): the size of the segment for CMa. The new segment size must also be updated in the lines NWP_PARAMxx [Segments are square boxes in the satellite projection, whose size is expressed as the number of IR pixels of one edge of the square box. The size of the processed regions must be a multiple of the segment size. All the solar and satellite angles, the NWP model forecast values, the atlas values and the thresholds will be derived over all the processed regions at the horizontal resolution of the segment. Note also that the land/sea atlas will be available at the full IR resolution, allowing the identification of the surface type (land or sea) of all IR pixels, whatever the segment size. The quality is not very much dependent of the segment size (if lower than 4). A segment size of 4 allows the preparation step to be 9 times faster than if a segment size of 1 was used]
- TEMPORAL_USE (default value: TRUE): a flag defining if the temporal analysis should be done. [TEMPORAL_USE flag is checked at the execution step. PGE01 applies the temporal analysis if its value is TRUE. This flag has been made configurable to allow users being blocked by hardware resources to still run the PGE01 by assigning it to FALSE in the configuration file.]
- HRV_NEED (default value: TRUE): a flag indicating whether the HRV analysis should be done. [HRV_NEED flag is checked at the execution step. PGE01 applies the HRV analysis if its value is TRUE. This flag has been made configurable to allow users being blocked by hardware resources to still run the PGE01 by assigning it to FALSE in the configuration file.]

Moreover as the content of NWP_CONF_FILE is dependent on the local installation, the user must make the NWP_PARAMXX consistent with the local NWP_CONF_FILE when the standard one is not used (for details see section dedicated to NWP data files in SAF/NWC/CDOP/INM/SW/SUM/2 [AD. 2]) .

2.2.2.6.2 The Cloud Mask (Cma) preparation step

By default, this CMa preparation step is performed during the CMa execution step (see section 2.2.2.6.3).

But to speed up the CMa processing, this preparation step can performed by the command mfcms_next_pge01 which can be launched in advance of satellite data reception according to a pre-defined time scheduling to be manually set by the user.

This preparation step includes the computation on the region at the segment spatial resolution of:

- the solar & satellite angles,
- the monthly climatological & atlas maps,
- the thresholds for the CMa algorithm

2.2.2.6.3 The Cloud Mask (Cma) execution step

The CMa execution step (which by default includes the CMa preparation step see 2.2.2.6.2) is the real-time processing of the SEVIRI images itself over the region. This process consists in the launch of the command: PGE01 by the Task manager. The cloud masking is then performed, using the thresholds prepared during the preparation step.

2.3 ASSUMPTIONS AND LIMITATIONS

The following problems may be encountered:

- Low clouds may be not detected in case low solar elevation, over both sea and land.
- It may happen that large areas of low clouds are not detected in night-time conditions over land. This can be the case in "warm sectors", but also in areas viewed with high satellite zenith angles or if the low clouds are surmounted by very thin cirrus.
- Snowy grounds are not detected at night-time and are therefore confused either with low clouds or cloud free surface.
- False detection of volcanic ash clouds happens especially in daytime conditions (over low clouds and desertic surfaces), but also in night-time (over cold clouds). The volcanic ash clouds detection is not performed in case low solar elevation.
- Over land, dust cloud detection is performed only at daytime. Over land, dust clouds are not well detected when the sun is low or if they are too thin. Over sea, some dust areas may not be detected(especially the thinnest parts). Moreover, some wrong detection may be observed in oceanic regions, especially at nighttime near Namibie coast and occasionally over the South Atlantic (at latitude larger than 50 degrees).

The CMa product may be used to identify cloud-free surfaces for oceanic or continental surface parameters retrieval. Nevertheless, as some clouds remains undetected and to account for artefacts such as shadows or aerosols, the user should apply a post-processing which could include:

- the spreading of the cloud mask that should allow to detect cloud edges and mask shadows or moist areas near cloud edges
- the use of the cloud mask quality flag not to compute surface parameters in bad quality cloud free areas
- the implementation of an additional filtering based on the temporal variation around the current slot

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3. DESCRIPTION OF CLOUD TYPE (CT)PRODUCT

3.1 CLOUD TYPE (CT) OVERVIEW

The cloud type (CT), developed within the SAF NWC context, mainly aims to support nowcasting applications. The main objective of this product is to provide a detailed cloud analysis. It may be used as input to an objective meso-scale analysis (which in turn may feed a simple nowcasting scheme), as an intermediate product input to other products, or as a final image product for display at a forecaster's desk. The CT product is essential for the generation of the cloud top temperature and height product and for the identification of precipitation clouds. Finally, it is also essential for the computation of radiative fluxes over sea or land, which are SAF Ocean & Sea Ice products.

The CT product therefore contains information on the major cloud classes : fractional clouds, semitransparent clouds, high, medium and low clouds (including fog) for all the pixels identified as cloudy in a scene. A second priority is the distinction between convective and stratiform clouds (implementation not planned before 2012), and the identification of clouds for which the top mainly consists of water droplets.

CT is performed by a multi-spectral threshold method: pixels previously detected as cloudy by CMa are classified by a threshold procedure which is applied to the channels combinations that allow the discrimination of all cloud types. The critical points are the choice of the channels combinations and the threshold tuning.

3.2 CLOUD TYPE (CT) ALGORITHM DESCRIPTION

3.2.1 Theoretical description

3.2.1.1 Physics of the problem

Brightness temperatures and reflectance of clouds very much depend on their characteristics: - height (low, medium or high level clouds); - amount (semi-transparent or opaque; sub-pixel or filling the pixel) and texture; - phase (water or ice clouds). They are also affected by the atmospheric conditions and by the sun and satellite respective positions.

The pixels contaminated by clouds are supposed to have been identified by the CMa product. The problem to be solved is then, to determine the adequate combinations of SEVIRI channels that will allow the separation of clouds presenting different characteristics, and how these combinations of channels will be affected by atmospheric conditions and sun/satellite geometry.

3.2.1.2 Mathematical Description of the algorithm

3.2.1.2.1 Algorithm outline :

The CT algorithm is a threshold algorithm applied at the pixel scale, based on the use of CMa and spectral & textural features computed from the multispectral satellite images and compared with a set of thresholds.

The set of thresholds to be applied depends mainly on the illumination conditions (defined in Table 3), whereas the values of the thresholds themselves may depend on the illumination, the viewing geometry, the geographical location and NWP data describing the water vapour content and a coarse vertical structure of the atmosphere.

The CT classification algorithm is based on a sequence of thresholds tests which are detailed in the following sections. A separate processing described in section 3.2.1.2.3 is applied to compute the cloud phase. In addition, it should be noted that in the current version of CT, no separation between cumuliform and stratiform clouds is performed.

3.2.1.2.2 Main cloud type identification

3.2.1.2.2.1 Fractional and high semitransparent clouds identification at nighttime

The high semitransparent clouds are distinguished from opaque clouds using the T10.8µm-T12.0µm, T8.7µm-T10.8µm or T3.9µm-T10.8µm features.

- T10.8µm-T12.0µm is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface. This brightness temperature difference decreases if the semitransparent cloud is too thick or too thin.
- T8.7µm-T10.8µm is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface.
- The T3.9µm-T10.8µm feature is also very efficient to distinguish high semitransparent clouds from the opaque clouds. It is based on the fact that the contribution of the relatively warm grounds to the brightness temperature of semitransparent cloud is higher at 3.9µm than at 10.8µm, due to a lower ice cloud transmittance, and to the high non-linearity of the Planck function at 3.9µm. This feature is more efficient if the thermal contrast between cloud top and surface is large. Due to noise problem, this feature cannot be used in case of too cold T3.9µm.

The fractional low clouds have also T10.8µm-T12.0µm and T3.9µm-T10.8µm higher than opaque clouds, which therefore may lead to confusion with very thin cirrus. But usually cirrus clouds have larger T8.7µm-T10.8µm than fractional low clouds .

The presence of a lower level under the cirrus cloud leads to reduce T10.8µm-T10.2µm and T3.9µm-T10.8µm when compared to those of single level cirrus. T10.8µm-T12.0µm is more reduced than T3.9µm-T10.8µm, making this last feature more efficient to detect cirrus overlaying low water clouds. But it seems impossible to detect overlapping clouds with only spectral features such as T10.8µm-T12.0µm or T3.9µm-T10.8µm at the pixel resolution, neither with local textural features ; the CT algorithm therefore does not separate cirrus overlaying low clouds from fractional cover or mid-level clouds at nighttime.

The scheme used at nighttime is the following:

<table>
<tr><th colspan="3">High semitransparent clouds</th></tr>
<tr><td>high semitransparent thick clouds:</td><td>T10.8µm < maxT108hi</td><td>T10.8µm -T12.0µm > T108T120thick</td></tr>
<tr><td rowspan="2">high semitransparent meanly thick clouds:</td><td>maxT108hi < T10.8µm < T108interthr</td><td>[T3.9µm –T10.8µm > T39T108thin_high or T10.8µm -T12.0µm > T108T120thick]</td></tr>
<tr><td>T108interthr < T10.8µm < maxT108med</td><td>[T3.9µm –T10.8µm > T39T108thin_low or T10.8µm -T12.0µm > T108T120thick]</td></tr>
<tr><td></td><td>maxT108med < T10.8µm < maxT108low</td><td>[T3.9µm –T10.8µm > T39T108t_low or T10.8µm -T12.0µm > T108T120thick]
and
[T8.7µm -T10.8µm > T87T108opaque or T3.9µm –T10.8µm > T39T108thin_low]</td></tr>
</table>

high semitransparent thin clouds:	maxT108low < T10.8µm<maxT108low+delta	[T3.9µm –T10.8µm > T39T108_vlow or T10.8µm -T12.0µm > T108T120thick] and [T8.7µm -T10.8µm > T87T108opaque or T3.9µm –T10.8µm > T39T108thin _low]

Fractional low clouds		
Fractional clouds:	maxT108med < T10.8µm < maxT108low	[T3.9µm –T10.8µm > T39T108_low or T10.8µm -T12.0µm > T108T120thick] and [T8.7µm -T10.8µm < T87T108opaque] and [T3.9µm –T10.8µm < T39T108thin _low]
	maxt108low<T10.8µm<maxT108low+delta	[T10.8µm -T12.0µm > T108T120thick or T3.9µm -T10.8µm > T39T108_vlow] and [T8.7µm -T10.8µm < T87T108opaque] and [T3.9µm -T10.8µm < T39T108thin _low]
	maxT108low+delta < T10.8µm	[T10.8µm -T12.0µm > T108T120thick or T3.9µm -T10.8µm > T39T108_vlow]

The thresholds used in this scheme are the following:

- MaxT11low, maxT11med, maxT11hi and maxT11vh thresholds are explained in section 3.2.1.2.2.4.
- An intermediate T10.8µm threshold has been defined:
  T108interthr = maxT108low+(maxT108hi- maxT108low)/2
  If T108interthr > maxT108med T108interthr= maxT108med+(maxT108hi- maxT108med)/2.
- T108T120opaque, T39T108opaque, T87T108opaque and Delta are computed by interpolating in look-up tables using satellite zenith angle and total integrated atmospheric water vapour content. These look-up tables have been elaborated by applying RTTOV to radiosoundings from an ECMWF dataset (F.Chevalier, 1999) for surface having an emissivity of one.
- New T39T108 thresholds according to observed T10.8µm have been defined as:
  T39T108thin_high = T39T108opaque +5.*(maxT108low-T108)/(maxT108low- maxT108hi)
  T39T108thin_low = T39T108opaque+2.*(maxT108low-T108)/(maxT108low- maxT108hi)
  T39T108_low = T39T108opaque+1 (in K)
  T39T108_vlow = T39T108opaque-1 (in K)
- T108T120thick has been defined as : MAX (T108T120opaque-0.2 , 1.5) (in K)

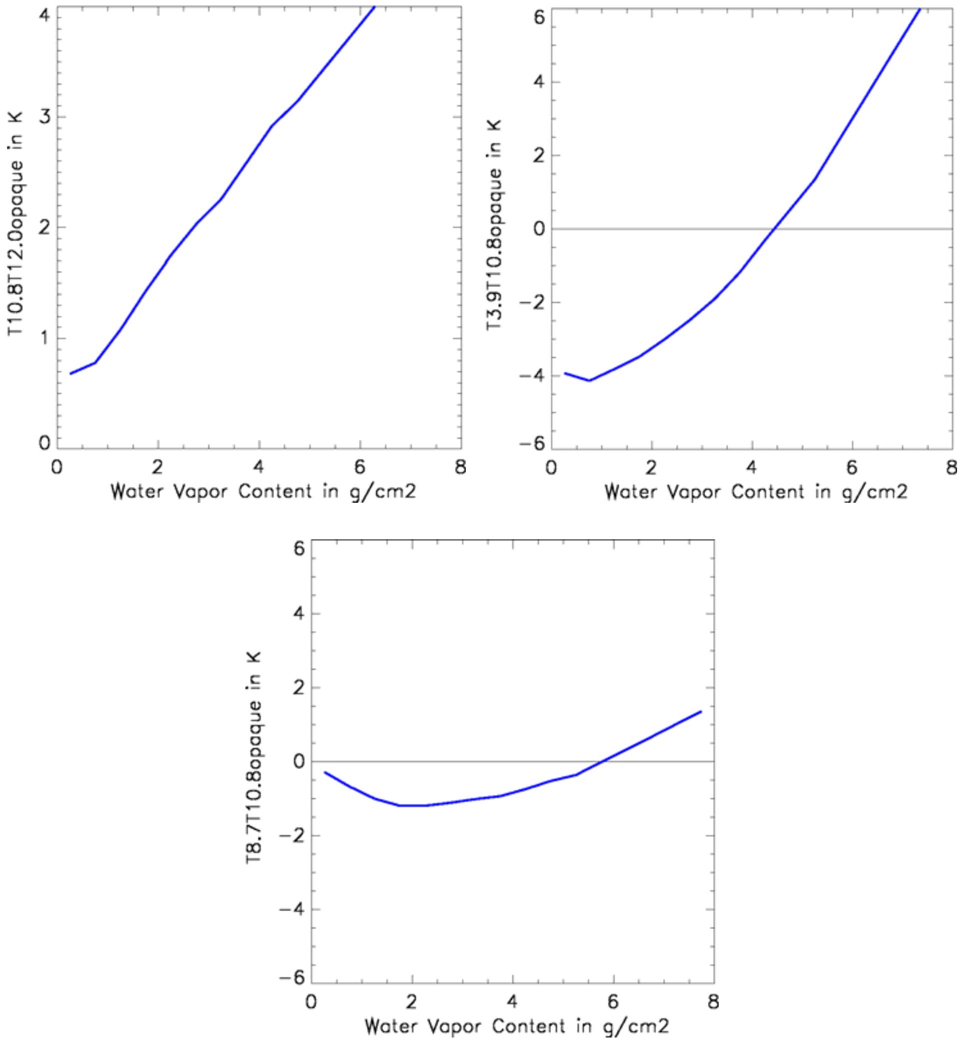

Figure 27: Illustration of T108T120opaque,T39T108opaque and T87T108opaque for a satellite zenith angle of 48 degrees

3.2.1.2.2.2 Fractional and semitransparent clouds identification in twilight conditions

T3.9µm cannot be used in twilight conditions as in nighttime conditions, due to solar contamination. High semitransparent or fractional low clouds can still be separated from opaque clouds by their relatively high T10.8µm-T12.0µm value. As in nightime conditions, cirrus clouds have much higher T8.7µm-T10.8µm values than fractional low clouds.

The scheme used in twilight conditions is the following:

High semitransparent clouds		
high semitransparent thick clouds:	T10.8µm < maxT108hi	T10.8µm -T12.0µm > T108T120opaque
high semitransparent meanly thick clouds:	maxT108hi < T10.8µm < maxT108med	T10.8µm -T12.0µm > T108T120opaque
high semitransparent thin clouds:	maxT108med<T10.8µm<maxT108low+delta	T10.8µm -T12.0µm > T108T120opaque and T8.7µm -T10.8µm > T87T108opaque

Fractional low clouds

Fractional clouds:	maxt108med<T10.8µm<maxT108low+delta	T10.8µm -T12.0µm > T108T120opaque and T8.7µm -T10.8µm < T87T108opaque
	maxT108low+delta < T10.8µm	T10.8µm -T12.0µm > T108T120opaque

The meaning of the thresholds is the same as in the nighttime scheme.

3.2.1.2.2.3 Fractional and high semitransparent clouds identification at daytime

The high semitransparent clouds are distinguished from opaque clouds using spectral features (T10.8µm-T12.0µm, T8.7µm-T10.8µm, R0.6µm) and textural features (variance T10.8µm coupled to variance R0.6µm in daytime conditions):

- T10.8µm-T12.0µm is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface. This brightness temperature difference decreases if the cloud is too thick or too thin.
- T8.7µm-T10.8µm is usually higher for cirrus clouds than for thick clouds, especially in case of large thermal contrast between the cloud top and the surface.
- Cirrus clouds present lower R0.6µm reflectances than opaque clouds having the same radiative temperature.
- Cirrus clouds are much more spatially variable in temperature than in visible reflectance.

The fractional low clouds have also T10.8µm-T12.0µm higher than opaque clouds, but usually lower than thin cirrus. Fractional low clouds usually appears warmer and brighter than thin cirrus clouds; moreover cirrus clouds have larger T8.7µm-T10.8µm than fractional low clouds

High semitransparent over low or medium clouds appear rather bright and cold, but are characterised by rather high T10.8µm-T12.0µm and T8.7µm-T10.8µm (if the thermal contrast between cirrus and lower cloud layer top temperature is large enough).

The scheme used at daytime is the following:

High semitransparent clouds		
high semitransparent thick clouds:	T10.8µm < maxT108hi	T10.8µm -T12.0µm > T108T120opaque
high semitransparent meanly thick clouds:	maxT108hi < T10.8µm < maxT108med	R0.6µm < maxCiR06 and T10.8µm -T12.0µm > T108T120opaque
high semitransparent above low or medium clouds:		R0.6µm > maxCiR06 and T10.8µm -T12.0µm > T108T120opaque
	maxT108med < T10.8µm < maxT108low	[R0.6µm > maxCiR06 and T10.8µm-T12.0µm > T108T120opaque and varilogT10.8/varilogR06 > varilogthr] or [R0.6µm < maxCiR06 and T8.7µm -T10.8µm > T87T108opaque]

high semitransparent thin clouds:	maxt108low< T10.8µm < maxT108low+delta	[R0.6µm < maxCiR06 and T8.7µm -T10.8µm > T87T108opaque] or [R0.6µm > maxCiR06 and T10.8µm-T12.0µm > (T108T120Threshold+ T108T120opaque)/2 and T8.7µm -T10.8µm > T87T108opaque]

Fractional low clouds		
Fractional clouds:	maxT108med < T10.8µm < maxT108low	R0.6µm < maxCiR06 and T8.7µm -T10.8µm < T87T108opaque
	maxt108low<T10.8µm<maxT108low+delta	[R0.6µm > maxCiR06 and T10.8µm -T12.0µm > (T108T120threshold+ T108T120opaque)/2 and T8.7µm -T10.8µm < T87T108opaque] or [R0.6µm < maxCiR06 and T8.7µm -T10.8µm < T87T108opaque]
	maxT108low+delta < T10.8µm	[R0.6µm > minLowR06 and T10.8µm -T12.0µm > (T108T120threshold+ T108T120opaque)/2] or [R0.6µm < minLowR06]

The IR thresholds used in this scheme are the following:

- MaxT11low, maxT11med, maxT11hi and maxT11vh thresholds are explained in section3.2.1.2.2.4.
- T108T120Threshold is the threshold used to separate cloudy from cloud-free pixels (see section 2.2.1.2.2.3).
- T87T120opaque, T108T120opaque and Delta have already been defined in the night-time scheme.

The textural features used are defined as:

- VarilogT10.8=log(1+ var(T10.8µm)) and
- VarilogR0.6=log(1+var(R0.6µm)/13.)

where var stands for the standard deviation in a bin of 9 pixels centred on the pixel to classify. The threshold applied to the ratio varilogT10.8/varilogR0.6 (varilogthr) is a constant value: 2.2

MaxCiR06 mainly aims to separate opaque from semi-transparent clouds. Its computation is based on the assumption that semitransparent and opaque clouds can be roughly separated in the R0.6µm/T10.8µm space by a straight line defined by two reference points:

- The coldest and brighter one is determined by: (T10.8µm=223.15K, R0.6µm=35%).
- The warmest and darker one is depending surface effects and atmospheric effects :
    - Its reflectance depends on the surface reflectance, for which we have an indication from a sea reflectance when over sea or the monthly mean 0.6µm value from climatology when over ground.
    - Its temperature is estimated from the SST climatology file over sea or from NWP surface forecast temperature over land.

Two sets (sea and land) of thresholds (slope and intercept of the straight line) are then computed by accounting for cloud bidirectional effects (using coefficients proposed by Manalo & Smith, 1996, overcast model, and with a weighting factor of 0.4 for Rayleigh part), for the visible calibration variation with time, and for the variation of earth-sun distance.

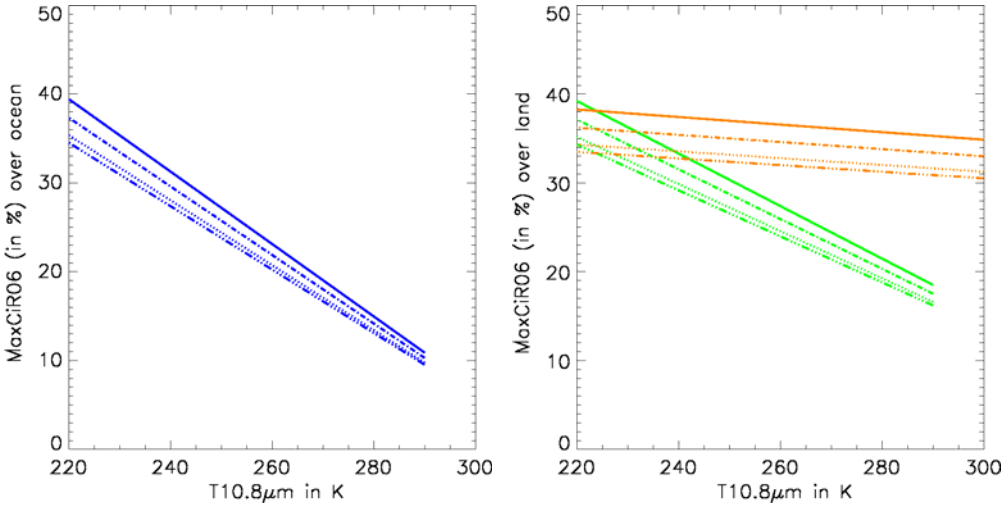

Figure 28: Illustration of MaxCiR06 over Ocean and over Land. Solar zenith angles (30 and 70 degrees), azimuth difference (0 and 90 degrees). In green over vegetated areas, in brown over desert

MinLowR06 is aimed to put a minimum value to an acceptable reflectance of a low cloud, mainly to separate fractional and low clouds. It is derived from a constant value (13% over sea and 20% over land) accounted for bidirectional effects (using coefficients proposed by Manalo & Smith, 1996, overcast model, and with a weighting factor of 0.4 for Rayleigh part).

3.2.1.2.2.4 Low/medium/high clouds separation

Once the semitransparent or fractional clouds have been identified, the classification of the remaining cloudy pixels between low, mid-level and high clouds is performed through a simple thresholding on the T10.8µm brightness temperature which is related to their height. In order to account for atmospheric variability, NWP forecast temperatures at several pressure levels are used to compute the thresholds that allows to separate very low from low clouds (maxT11low), low from medium clouds (maxT11med), medium from high clouds (maxT11hi), and high from very high clouds (maxT11vh).

To decrease the wrong classification of low clouds as medium clouds (in case strong atmospheric thermal inversion), medium clouds are not allowed to present too large T10.8µm-T7.3µm brightness temperature differences. In fact, for a field of view obstructed by a low or mean opaque cloud, T7.3µm is sensitive to water vapour content above the cloud and to cloud top temperature. Therefore for a same atmospheric profile and identical microphysical properties of opaque clouds, T10.8µm-T7.3µm decreases with cloud top pressure.

The separation between cumuliform and stratiform clouds is not performed in the current version of CT. Hence, the clouds are labelled as stratiform and a flag indicates that the separation between stratiform and cumuliform clouds has not been attempted.

Opaque clouds		
Very high opaque and stratiform clouds:	T10.8µm < maxT108vh	Not semitransparent or fractional
high opaque and stratiform clouds:	maxT108vh < T10.8µm < maxT108hi	Not semitransparent or fractional
Medium and stratiform clouds:	maxT108hi < T10.8µm < maxT108me and T10.8µm – T7.3µm < T108T73thrlow	Not semitransparent or fractional

Low and stratiform clouds:	maxt108me < T10.8µm < maxT108low or [maxT108hi < T10.8µm < maxT108me and T10.8µm – T7.3µm > T108T73thrlow]	Not semitransparent or fractional
Very low and stratiform clouds:	maxT108low < T10.8µm	Not semitransparent or fractional

These five thresholds are the following :

- maxT10.8vh = 0.4 * T_{500hPa} +0.6 * T_{tropo} - 5 K
- maxT10.8h = 0.5 * T_{500hPa} -0.2 * T_{700hPa} + 178 K
- maxT10.8me = 0.8 * T_{850hPa} +0.2 * T_{700hPa} - 8 K
- maxT10.8low = 1.2 * T_{850hPa} -0.2 * T_{700hPa} - 5 K
- T108T73thrlow = 4.0*sec + 8.5 K (sec is the secante of the satellite zenith angle)

If the air temperature at tropopause level is not available, maxT10.8vh = maxT10.8h – 25K.

In case a thermal inversion has been detected in the NWP fields input by the user, a additional process is applied that allows to reclassify medium clouds as low clouds if their T8.7µm-T10.8µm is lower than a specific thresholds depending of the satellite viewing secant and if their T10.8µm is warmer than maxT11med minus an offset (up to 10°K depending on the T8.7µm-T10.8µm value). The basis of this test is that low T8.7µm-T10.8µm values characterizes low clouds rather than medium clouds. The test on T10.8µm is a security to avoid too cold clouds to be classified as low clouds. This "reclassification test" is applied only in case of the presence of a thermal inversion which is characterized by NWP air temperature differences between two vertical levels (950/925hPa and surface, 850hPa and surface, 850hPa and 950/925hPa) larger than 3°K. This test is not applied over arid areas. To summarize, a mid-level clouds is therefore reclassified as low level clouds if:

- A thermal inversion is present in the NWP fields input by the user
- Visclim < 30% (to exclude arid areas)
- T8.7µm-T10.8µm < -1.2-(1./cos(θ_{sat})-1) (in K) and T10.8µm > maxT108me –5.0 (K) or
  T8.7µm-T10.8µm < -1.7-(1./cos(θ_{sat})-1) (in K) and T10.8µm > maxT108me –8.0 (K) or
  T8.7µm-T10.8µm < -2.2-(1./cos(θ_{sat})-1) (in K) and T10.8µm > maxT108me –10.0 (K)

Where visclim is the climatological 0.6µm reflectance value, maxT108me is the threshold normally applied to T10.8µm to distinguish low from mid-level clouds, θ_{sat} is the satellite zenith angle

A rough insight of the range of low/medium/high clouds top pressures has been obtained by analysing statistics of retrieved (using PGE03) cloud top pressure for each of these cloud types. The following rough top pressure ranges have been obtained (no dependency with latitude or season was observed):

Very low opaque cloud	pressure larger than 800hPa
Low opaque cloud	pressure between 650hPa and 800hPa
Medium opaque clouds	pressure between 450hPa and 650hPa
High opaque clouds	pressure between 300hPa and 450hpa
Very high opaque clouds	pressure lower than 300hPa

3.2.1.2.3 Cloud phase flag computation

The cloud phase retrieval algorithm makes a pragmatic use of T8.7µm-T10.8µm, T10.8µm and the CT cloud type itself to complement a fine analysis of the measured and simulated 0.6µm and 1.6µm reflectances, as summarized below:

- Ice clouds are usually characterized by weaker absorption at 1.6µm than water clouds and should therefore have lower 1.6µm reflectances for given 0.6µm reflectances. Radiative transfer calculations nevertheless shows that it may be difficult to distinguish clouds made of small ice crystal from those made of large water particles. During the phase retrieval, the observed 0.6µm and 1.6µm reflectances for cloudy pixels are compared to the appropriate pre-calculated cloud reflectances (available in LUT (Look Up table)), ambiguous situations are identified.

- Warm (respectively cold) opaque clouds are supposed to be constituted of water (respectively ice) particles, whereas the temperature range between 0°C and –40°C may correspond to both (or a mixture) of water or ice clouds.
- Cloud classified as semi-transparent in CT cloud type are supposed be constituted of ice particles. Cloud classified as fractional may correspond to thin cirrus or sub-pixel low clouds; their retrieved cloud phase is therefore set "undefined".
- Water clouds usually have low T8.7µm-T10.8µm and ice clouds rather high values. Simple viewing angle-dependant thresholds subjectively defined from SEVIRI observations is used to identify obviously water or ice clouds.

Some details on the content of the LUTs and on the origin of the 0.6µm/1.6µm surface reflectances climatologies used during the process are first given. The algorithm logic is then detailed together with the thresholds computation. The content of the cloud phase flag is also recalled.

LUT computation:

The radiative transfer model RTMOM developed by Eumetsat (see Govaerts, 2008) is used to perform a set of radiative transfer calculations for four water cloud models (characterized by their droplet size) and four ice cloud models (characterized by their crystal size diameter), as described in Table 7, to prepare the LUTs. An example of LUT for the four water and four ice cloud models at a given location (fixed viewing angles and surface cloud-free reflectances) is displayed in Figure 29. The blue (respectively orange) solid curves corresponds to the four ice (respectively water) cloud models; the dotted line corresponds to equal optical thickness; large droplet (ice crystal) corresponds to the lower curves.

Wavelengths	VIS0.6 and NIR1.6 (MSG filters)
Illumination and Viewing Angles	
Cosine Solar Zenith Angle (μ_0):	1.0 to 0.0 in steps of 0.05
Cosine Viewing Zenith Angle (μ):	1.0 to 0.0 in steps of 0.05
Relative Azimuth Angle (ψ):	0, 2.5, 5, 10, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115, 125, 135, 145, 155, 165, 170, 175, 177.5, 180
Cloud Properties	
Water Droplets:	Mie theory r_e = 4, 8, 16, 30 µm
Ice Particles:	Obtained from Baum. D_e = 10.0, 20.0, 30.0, 40.0 µm
Optical Depths:	0.25, 0.50, 1, 2, 3, 4, 8, 16, 32, 64, 96, 128
Cloud top height:	3km
Surface Reflectances	
0.64 µm:	0.02, 0.05, 0.1, 0.2, 0.3, 0.5
1.6 µm:	0.02, 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, 1.0
Atmosphere:	Mid-latitude summer

Table 7 Properties of the cloudy atmosphere used for the radiative transfer calculations to generate the LUTs.

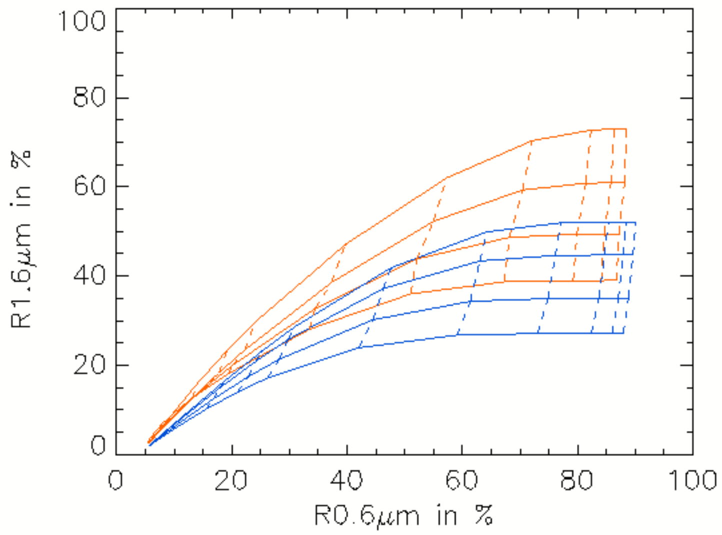

Figure 29 Illustration of the LUT for the four water (in orange) and four ice (in blue) cloud models for a given oceanic location (fixed viewing angles and surface cloud-free reflectances).

Cloud free 0.6µm/1.6µm surface reflectances monthly climatology:

Cloud free surface reflectances are used during the comparison of the simulated and measured 0.6µm/1.6µm cloudy reflectances. Over continental areas, they are derived from MODIS white-sky surface albedo monthly climatologies available from NASA (http://modis-atmos.gsfc.nasa.gov/ALBEDO/index.html). These white sky albedos represents bi-hemispheric reflectances without the direct component which is a good approximation of the surface albedo below a cloud. Over sea, constant values are used: 3% (at 0.6µm) and 1% (at 1.6µm).

The cloud phase flag content is the following:

- Non processed (containing no data or corrupted data) or no cloud
- Water cloud
- Ice cloud
- Undefined (due to known separability problems)

Cloud phase retrieval logic in daytime conditions:

First a cloud phase is retrieved by only comparing measured and simulated 0.6µm and 1.6µm reflectances as explained below and illustrated in Figure 30:

- As a first step, the particle size and optical thickness are estimated by a comparison of measured and simulated 0.6µm and 1.6µm reflectances (assuming a water cloud). Simulated reflectances are obtained by interpolation in LUTs with viewing angles and surface reflectances (known values only dependant on the location and time of the day), and particle size and optical thickness (quantities to be retrieved). This step is straightforward except if the 1.6µm reflectances does not regularly decrease with the increasing particle size which may be the case for low cloud optical thickness.
- The ideal case is that for a given 0.6µm reflectances the simulated 1.6µm reflectances for water clouds are larger than those for ice clouds. The simple comparison of the measured 1.6µm reflectance to the simulated one should then give the cloud phase. In practice the cloud phase only using 0.6µm and 1.6µm is retrieved as follows:
  - A water cloud phase is set if the retrieved particle size is lower than 32 micron and if the measured 1.6µm reflectance is higher than the 1.6µm reflectance simulated for all ice cloud model (for the current measured 0.6 reflectance)
  - An ice cloud phase is set:

- If the retrieved particle size is larger than 32 micron,
- or if the retrieved particle size is between 16 and 32 micron and if the measured 1.6µm reflectance is lower than the 1.6µm reflectance simulated for at least 3 ice cloud models (for the current measured 0.6 reflectance)
- or if the retrieved particle size is between 2 and 16 micron and if the measured 1.6µm reflectance is lower than the 1.6µm reflectance simulated for all ice cloud model (for the current measured 0.6 reflectance)

o Eitherwise the cloud phase is set "undefined"

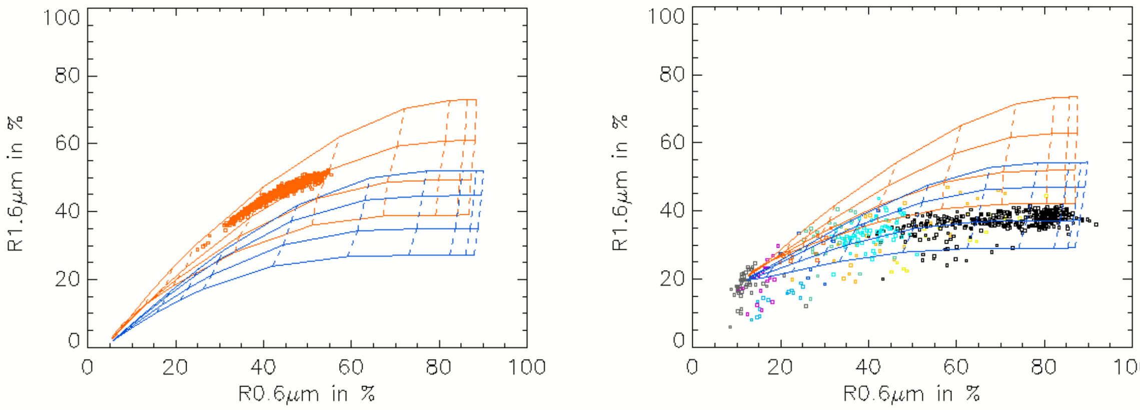

Figure 30 Illustration of the cloud phase retrieval using 0.6µm and 1.6µm reflectances. Cloud measurements (coloured using CT cloud type colors, except white color replaced by black) are superimposed to simulated curves. Left: for a maritime stratocumus cloud; right: for a convective system over the Pyrenees.

The final cloud phase retrieval is based on the cloud phase retrieved from 0.6µm and 1.6µm reflectances, the CT cloud type, the T8.7µm and T10.8µm brightness temperatures. The algorithm logic is the following:

- If CT cloud type is fractional : cloud phase is set to undefined
- If CT cloud type is semi-transparent (thin, medium, thick or above) : cloud phase is set to ice
- If CT cloud type is opaque cloud:
  - If T10.8µm>273.15K : cloud phase is set to water cloud
  - If T10.8µm<233.15K : cloud phase is set ice clouds
  - If 233.15K<T10.8µm<273.15K:
    - If T8.7µm-T10.8µm<-1.5-(1./cos(θ_{sat})-1) (in K) : cloud phase is set to water clouds
    - If T8.7µm-T10.8µm>-0.8(1./cos(θ_{sat})-1) (in K) : cloud phase is set to ice clouds
    - If -1.5-(1./cos(θ_{sat})-1) < T8.7µm-T10.8µm < -0.8(1./cos(θ_{sat})-1) : cloud phase is the cloud phase retrieved from 0.6µm and 1.6µm reflectances (see above)

Cloud phase retrieval logic in night-time or twilight conditions:

The cloud phase retrieval is only based on the use of CT cloud type and on the T8.7µm and T10.8µm brightness temperatures. The algorithm logic is the following:

- If CT cloud type is fractional : cloud phase is set to undefined
- If CT cloud type is semi-transparent (thin, medium, thick or above) : cloud phase is set to ice
- If CT cloud type is opaque cloud:
  - If T10.8µm>273.15K : cloud phase is set to water cloud
  - If T10.8µm<233.15K : cloud phase is set ice clouds
  - If 233.15K<T10.8mm<273.15K:
    - If T8.7µm-T10.8µm<-1.5-(1./cos(θ_{sat})-1) (in K) : cloud phase is set to water clouds
    - If T8.7µm-T10.8µm>-0.8(1./cos(θ_{sat})-1) (in K) : cloud phase is set to ice clouds
    - If -1.5-(1./cos(θ_{sat})-1) < T8.7µm-T10.8µm < -0.8(1./cos(θ_{sat})-1) : cloud phase is set to undefined

3.2.1.2.4 Quality assessment

A quality flag is appended to the CT. It allows the identification of pixels that may have been misclassified:

- The quality flag of a cloudless pixel is the same as that of CMa
- A pixel classified as cloudy is flagged as of low confidence:
  - if is flagged as of low confidence in CMa
  - or if, either for spectral (T10.8µm-T12.0µm, T3.9µm-T10.8µm, R0.6µm) or for textural features (variance T10.8µm coupled to variance R0.6µm), the difference between the threshold and the measurement is lower that a security margin listed in next table:

Cloud Test	T10.8µm-T12.0µm	T3.9µm-T10.8µm	T8.7µm-T10.8µm	R0.6	varilogT10.8/varilogR06
Security margin for quality assessment	0.2 K	0.2 K	0.2 K	0.2*threshold	0.2*threshold

3.2.2 Practical considerations

3.2.2.1 Validation

Table 8 summarises the validation results of the current version for the CT cloud type and cloud phase. More details can be obtained from the validation report for cloud products ([AD. 1]).

PGE02	Validated accuracy
PGE02 cloud type If validated over European areas and adjacent seas using interactive targets (the user accuracy is defined as the probability of a pixel being classified into a category to really belong to this category)	User accuracy for low opaque, high opaque, semi-transparent high clouds : between 78% and 96% depending on illumination
PGE02 cloud phase flag If validated over European areas using ground-based radar/lidar	Hit Rate (HR) : 0.83 Kuiper Skill Score KSS: 0.62

Table 8: Summary of validation results of the current PGE02 version

3.2.2.2 Quality control and diagnostics

A quality assessment, detailed in 3.2.1.2.4, is performed by the CT itself through a comparison between thresholds and measurements, low confidence corresponding to thresholds and measurements close to each other.

Nine bits in the CT output are dedicated to quality description (see in 3.2.2.4). They include a quality flag based on the quality assessment performed by the CT (see above paragraph), but also information on the lack of NWP fields or SEVIRI non mandatory channels which leads to a decrease of CT quality.

3.2.2.3 List of inputs for Cloud Type (CT)

The input data to the CT algorithm are described in this section. Mandatory inputs are flagged, whereas the impact of missing non-mandatory data on the processing are indicated.

- **Satellite imagery:**

The following SEVIRI bi-directional reflectances or brightness temperatures are needed at full IR spatial resolution:

R0.6µm	**R1.6µm**	**T3.9µm**	**T7.3µm**	**T8.7µm**	**T10.8µm**	**T12.0µm**
Mandatory	Optional	Mandatory	Optional	Optional	Mandatory	Mandatory

The CT software checks the availability of SEVIRI channels for each pixel; no results are available for pixels where at least one mandatory channel is missing. If T8.7µm or R1.6µm are missing, the cloud phase flag is not computed.

The SEVIRI channels are input by the user in HRIT format, and extracted on the processed region by SAFNWC software package.

- **CMa cloud categories**

The CMa cloud categories are mandatory. They are computed by the CMa software.

- **Sun and satellite angles associated to SEVIRI imagery**

This information is mandatory. It is computed by the CT software itself, using the definition of the region and the satellite characteristics.

- **NWP parameters:**

The forecast fields of the following parameters, remapped onto satellite images, are used as input :

  - surface temperatures
  - air temperature at 950hPa (alternatively 925hPa) (to check low level inversion), 850hPa, 700hPa, 500hPa and at tropopause level
  - total water vapour content of the atmosphere,
  - altitude of the NWP model grid (alternatively surface geopotential of the NWP model grid). Required if NWP fields are used as input.

These remapped fields are elaborated by the SAFNWC software package from the NWP fields input by the user in GRIB format.

The NWP fields are not mandatory. The CT software replaces missing NWP surface temperatures, air temperature at 850hPa, 700hPa, 500hPa or total water vapour content of the atmosphere by climatological values extracted from ancillary dataset. An alternative method is used in case of missing NWP air temperature at tropopause level (see section 3.2.1.2.2.4). The quality of CT is lower if some NWP fields are missing.

- **Ancillary data sets:**

The following ancillary data, remapped onto satellite images, are mandatory :

  - Land/sea atlas
  - Elevation atlas
  - Monthly minimum SST climatology
  - Monthly mean 0.6µm atmospheric-corrected reflectance climatology (land)
  - Monthly 0.6µm and 1.6µm white-sky surface albedo climatology (land)

- Monthly integrated atmospheric water vapor content climatology
- Monthly climatology of mean air temperature at 1000hPa, 850hPa, 700hPa, 500hPa.

These ancillary data are available in the SAFNWC software package on MSG full disk in the default satellite projection at full IR resolution; They are extracted on the processed region by the CT software itself.

One coefficients's file (also called threshold table), containing satellite-dependent values and look-up tables for thresholds, is available in the SAFNWC software package, and is needed by the CT software.

One file containing offline simulations of 0.6µm and 1.6µm reflectances performed for a set of four water and four ice clouds using RTMOM radiative transfer model, is available in the SAFNWC software package, and is needed by the CT software.

- **Configurable parameters:**

Three configurables parameters are available in the default CT model configuration file:

- CT_SZSEG: The size of the segment is configurable (see its definition in section 3.2.2.6.1). Its default value is 4. Information on how to change the size of the segment can be found in section 3.2.2.6.1 and in the software user manual ([AD. 2]).
- PHASE_COMPUTATION: The flag defining if the cloud phase flag should be computed is configurable (see its definition in 3.2.2.6.1). Its default value is TRUE. Information on how to change this value can be found in section 3.2.2.6.1 and in the software user manual ([AD. 2]).
- CT_PHASE_SZSEG: The size of the segment for cloud phase flag computation is configurable (see its definition in 3.2.2.6.1). Its default value is 8. Information on how to change the size of the segment can be found in section 3.2.2.6.1 and in the software user manual ([AD. 2]).

3.2.2.4 Description of Cloud Type (CT) output

The content of the CT is the following :

- **The main product output consists in the following twenty-one categories coded on 5 bits**

0	non-processed	containing no data or corrupted data
1	cloud free land	no contamination by snow/ice covered surface, no contamination by clouds ; but contamination by thin dust/volcanic clouds not checked
2	cloud free sea	no contamination by snow/ice covered surface, no contamination by clouds ; but contamination by thin dust/volcanic clouds not checked
3	land contaminated by snow	
4	sea contaminated by snow/ice	
5	very low and cumuliform clouds	
6	very low and stratiform clouds	
7	low and cumuliform clouds	
8	low and stratiform clouds	
9	medium and cumuliform clouds	
10	medium and stratiform clouds	
11	high opaque and cumuliform clouds	
12	high opaque and stratiform clouds	

13 very high opaque and cumuliform clouds
14 very high opaque and stratiform clouds
15 high semitransparent thin clouds
16 high semitransparent meanly thick clouds
17 high semitransparent thick clouds
18 high semitransparent above low or medium clouds
19 fractional clouds (sub-pixel water clouds)
20 undefined (undefined by CMa)

In the current version of CT, the separation between cumuliform and stratiform is not performed: low, medium or high clouds will be classified as stratiform, and a specific bit indicating whether the separation between stratiform and cumuliform clouds has been attempted, will be set to zero (see below quality flag).

- **10 bits for quality**

3 bits to define illumination and viewing conditions:
0 Undefined (space)
1 Night
2 Twilight
3 Day
4 Sunglint

2 bits to describe NWP input data
0 Undefined (space)
1 All NWP parameters available (no low level inversion)
2 All NWP parameters available (low level inversion)
3 At least one NWP parameter missing

2 bits to describe SEVIRI input data
0 Undefined (space)
1 All useful SEVIRI channels available ;
2 At least one useful SEVIRI channel missing
3 At least one mandatory SEVIRI channel missing

2 bits to describe the quality of the processing itself:
0 Non processed (containing no data or corrupted data)
1 Good quality (high confidence)
2 Poor quality (low confidence)
3 Reclassified after spatial smoothing (very low confidence)

1 bit set to 1 to indicate that the separation between cumuliform and stratiform clouds has been performed.

In the current version of CT, the separation between cumuliform and stratiform is not performed: this bit will be set to zero and the low, medium or high clouds will be classified as stratiform.

- **2 bits for cloud phase**

0 Non processed (containing no data or corrupted data) or no cloud
1 water cloud
2 ice cloud
3 undefined (due to known separability problems)

3.2.2.5 Example of Cloud Type (CT) visualisation

It is important to note that the CT product is not just an image, but numerical data. At first hand, the CT is rather thought to be used digitally (together with the appended flags (quality, cloud phase)) as input to mesoscale analysis models, objective Nowcasting schemes, but also in the extraction of other SAFNWC products (CTTH for example).

Colour palettes are included in CT HDF files, thus allowing an easy visualisation of CT cloud type categories as illustrated on Figure 31 or the CT cloud phase flag (Figure 32).

The user may be interested in visualising all the available classes (please keep in mind that the separation between stratiform and cumuliform clouds is not performed in the current CT version) as displayed on a SEVIRI example in Figure 31, or highlight one or a few categories suitable for the application of interest. Product's animation will be a help for the user to interpret the visualized CT, and to identify artefacts (for example, the replacement of a snowy area by a low cloud between two successive pictures may be due only to the transition from day to night, as the snow detection is not possible at nighttime).

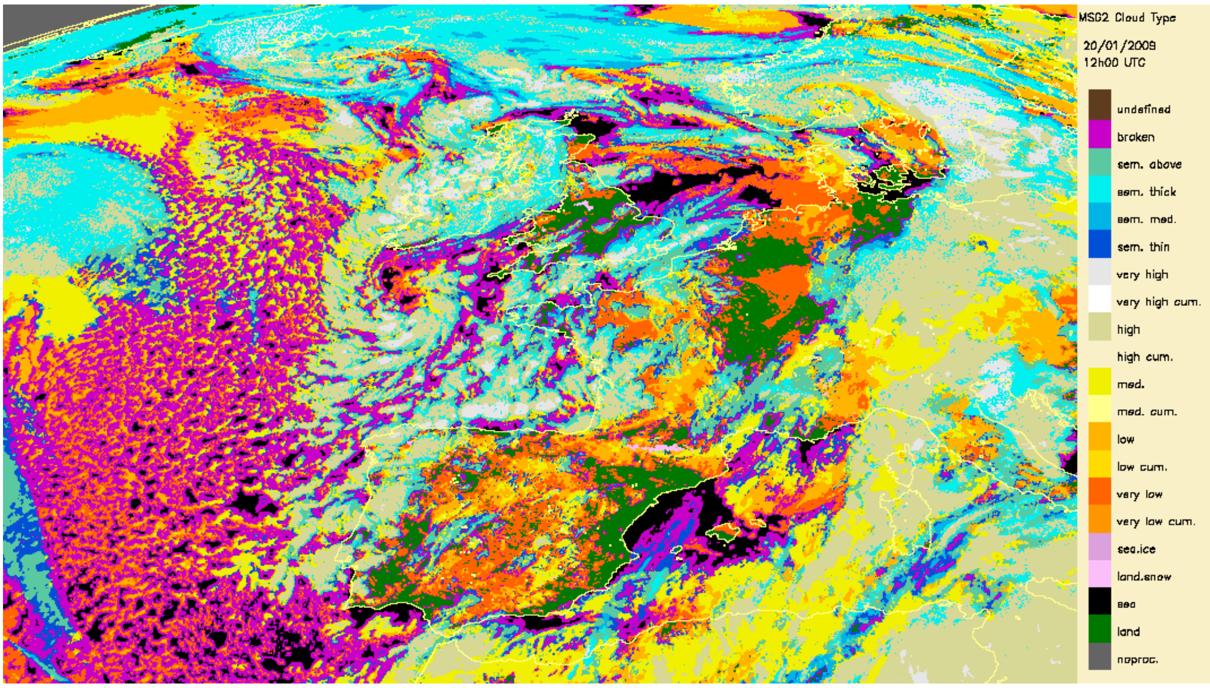

Figure 31: Example of SEVIRI CT cloud type using the colour palette included in CT HDF files.

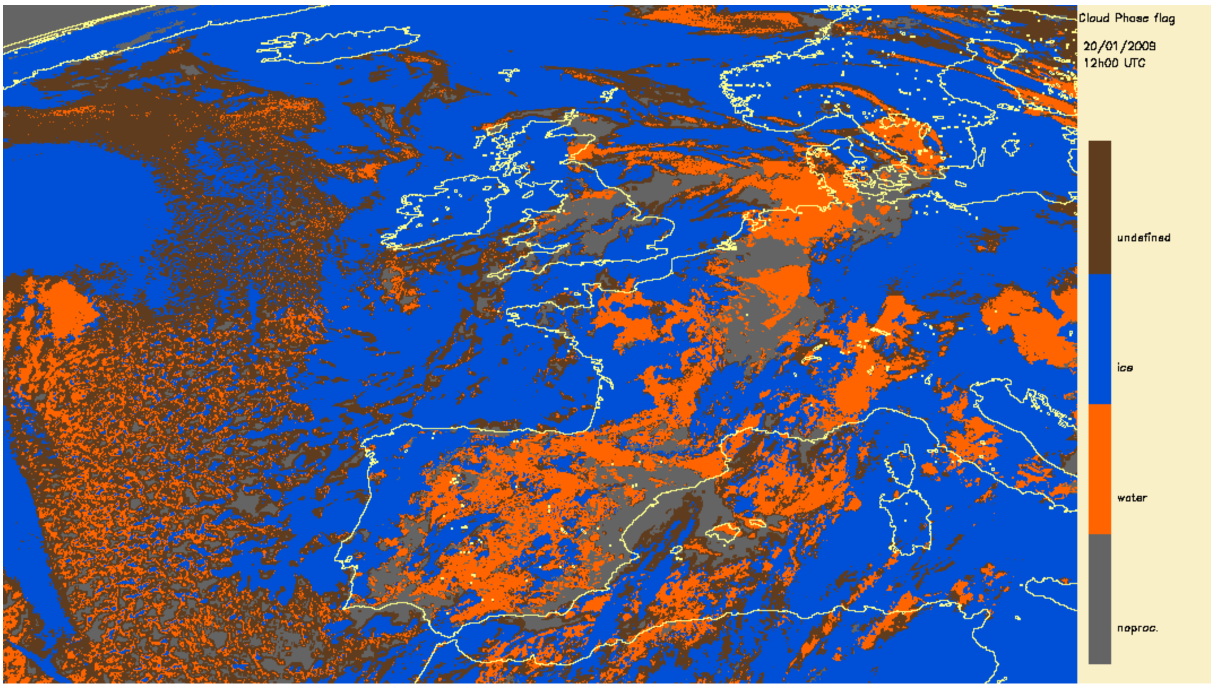

Figure 32 Example of SEVIRI CT cloud phase flag using the colour palette included in the CT HDF files.

3.2.2.6 Implementation of Cloud Type (CT)

CT is extracted by PGE02 of the SAFNWC/MSG software package. Detailed information on how to run this software package is available in the software user manual ([AD. 2]).

The software architecture of PGE02 has been strongly modified in version v2010 (to make the life easier for the user). It is now very similar to the other PGEs.

When a new region is defined the user has now to manually prepare the CT model configuration files for this new region using a default CT model configuration file provided in the SAFNWC/MSG software package. As the content of NWP_CONF_FILE is dependent on the local installation, the user must make the NWP_PARAMXX consistent with the local NWP_CONF_FILE when the standard one is not used.

There is an option for the user to monitor the so-called CT preparation step before SEVIRI images are available (to speed up the process). By default, this preparation step is performed during the CT execution step.

The CT execution step (which includes the CT preparation step in case it has not been launched before) is automatically launched by the Task Manager (if real-time environment is selected).

3.2.2.6.1 Manual preparation of Cloud Type (CT) model configuration file for each region

When a new region is defined and added in system and run configuration files, the user must manually prepares the CT model configuration files by adapting the default CT model configuration file available in the SAFNWC software package.

Three parameters are configurable in the default CT model configuration file:

- CT_SZSEG (default value: 4): the size of the segment. This default value may be manually changed, but must be the same as for CMa (CMA_SZSEG)). The new segment size must also updated in the lines NWP_PARAMxx [Segments are square boxes in the satellite projection, whose size is expressed as the number of IR pixels of one edge of the square box. The size of the processed regions must be a multiple of the segment size. All the solar and satellite angles, the NWP model forecast values, the atlas values and the thresholds will be derived over all the processed regions at the horizontal resolution of the segment. Note also that the land/sea atlas will be available at the full IR resolution, allowing the identification of the surface type (land or sea) of all IR pixels, whatever the segment size. The quality is not very much dependent on the segment size (if lower than 4). A segment size of 4 allows the preparation step to be 9 times faster than if a segment size of 1 was used]
- PHASE_COMPUTATION (default value: TRUE): a flag defining if the cloud phase flag should be computed.[PHASE_COMPUTATION flag is checked at the preparation and execution steps. It should be assigned to TRUE or FALSE. PGE02 computes the cloud phase flag if its value is TRUE. This flag has been made configurable to allow users being blocked by hardware resources to still run the PGE02 by assigning it to FALSE in the configuration file.]
- CT_PHASE_SZSEG (default value: 8): the size of the segment for the cloud phase flag computation. This default value may be manually changed independently from CMA_SZSEG or CT_SZSEG or the size available in the lines NWP_PARAMxx. [Segments are square boxes in the satellite projection, whose size is expressed as the number of IR pixels of one edge of the square box. The size of the processed regions must be a multiple of the segment size. The simulated R0.6µm and R1.6µm cloud reflectances for various clouds used during the processing are computed at the segment resolution. The cloud phase flag quality is not very much dependent on the segment size.]

Moreover as the content of NWP_CONF_FILE is dependent on the local installation, the user must make the NWP_PARAMXX consistent with the local NWP_CONF_FILE when the standard one is not used (for details see section dedicated to NWP data files in SAF/NWC/CDOP/INM/SW/SUM/2 [AD. 2]) .

3.2.2.6.2 The Cloud Type (CT) preparation step (optional)

By default, this CT preparation step is performed during the CT execution step (see 3.2.2.6.3).

But to speed up the CT processing, this preparation step can performed by the command mfcms_next_pge02 which can be launched in advance of satellite data reception according to a pre-defined time scheduling to be manually set by the user.

This preparation step includes the computation on the region at the segment spatial resolution of:

- the solar & satellite angles,
- the monthly climatological & atlas maps,
- the thresholds for the CT algorithm
- the simulated R0.6µm and R1.6µm cloudy reflectances

3.2.2.6.3 The Cloud Type (CT) execution step

The CT execution step (which by default includes the CT preparation step see 3.2.2.6.2) is the real-time processing of the SEVIRI images itself over the region. This process consists in the launch of the command: PGE02 by the Task manager. The CT is then performed, using the thresholds and simulations prepared during the preparation step.

3.3 ASSUMPTIONS AND LIMITATIONS

The following problems may be encountered (for wrong cloud detection, please refer to paragraph 2.3):

- Very thin cirrus are often classified as fractional clouds.
- Very low clouds may be classified as medium clouds in case strong thermal inversion.
- Low clouds surmounted by thin cirrus may be classified as medium clouds.

3.4 REFERENCES

Chevalier F., 1999, TIGR-like sampled databases of atmospheric profiles from the ECMWF 50-level forecast model. NWPSAF Research report n°1

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4. DESCRIPTION OF CLOUD TOP TEMPERATURE AND HEIGHT (CTTH) PRODUCT

4.1 Cloud Top Temperature and Height (CTTH) overview

The cloud top temperature and height (CTTH), developed within the SAF NWC context, aims to support nowcasting applications. This product contributes to the analysis and early warning of thunderstorm development. Other applications include the cloud top height assignment for aviation forecast activities. The product may also serve as input to mesoscale models or to other SAF NWC product generation elements.

The CTTH product contains information on the cloud top temperature and height for all pixels identified as cloudy in the satellite scene.

Cloud top pressure or height are derived from their IR brightness temperatures by comparison to simulated IR brightness temperatures computed from temperature and humidity vertical profiles forecast by NWP using a IR radiative transfer model (RTTOV). Exact retrieval method depends on cloud type as semi-transparency correction using window and sounding IR channels may be needed.

4.2 Cloud Top Temperature and Height (CTTH) algorithm description

4.2.1 Theoretical description

4.2.1.1 Physics of the problem

Temperatures of the top of opaque clouds may be deduced from the IR brightness temperatures measured in window channels, by accounting for the atmosphere effect above the cloud. Their height can then be retrieved from temperature profiles forecast by NWP.

This does not apply to semi-transparent clouds or sub-pixel (fractional) clouds for two reasons: - the IR brightness temperatures in window channels are contaminated by the underlying surface. - at least two parameters (the effective cloudiness (cloudiness x emissivity) and the top temperature) contribute to the measured brightness temperatures, and must be retrieved simultaneously. A multi-spectral approach with relevant assumptions (such as cloud emissivities' dependence on wavelength) is therefore needed.

4.2.1.2 Mathematical Description of the algorithm

The general scheme used to retrieve the CTTH from SEVIRI imagery is first outlined; individual retrieval techniques and general modules used in this scheme are then detailed in the following sections.

4.2.1.2.1 Algorithm outline

The different steps of the processing, applied to cloud-classified image, are listed below. The exact process applied to each pixel depend on the availability of NWP and SEVIRI data.

If all mandatory NWP and SEVIRI data are available (see list of input for CTTH):

The following process is then applied:

- RTTOV radiative transfer model (Eyre, 1991) is applied using NWP temperature and humidity vertical profile to simulate 6.2µm, 7.3µm, 13.4µm, 10.8µm, and 12.0µm cloud free and overcast (clouds successively on each vertical pressure levels) radiances and brightness temperatures. This process is performed in each segment of the image (the size of the segment is defined by the user, the default value being 16*16 SEVIRI IR pixels). The vertical profiles used are temporally interpolated to the exact slot time using the two nearest in time NWP fields input by the user.
- The techniques used to retrieve the cloud top pressure depend on the cloud's type (as available in CT product):
  - For very low, low or medium thick clouds : The cloud top pressure is retrieved on a pixel basis and corresponds to the best fit between the simulated and the measured 10.8µm brightness temperatures. The simulated brightness temperature are available at the segment resolution. In case of the presence of a low level thermal inversion in the forecast NWP fields, the very low, low or medium clouds are assumed to be above the thermal inversion only if their brightness temperatures are colder than the air temperature below the thermal inversion minus an offset whose value depends on the nature of thermal inversion (dry air above the inversion level or not).
  - For high thick clouds: a method called the radiance ratioing method (see the next bullet for further explanation of this method) is first applied to remove any remaining semi-transparency that could have been undetected by the cloud type scheme. In case of failure, the method defined for medium opaque clouds is then applied.
  - For high semi-transparent clouds: The 10.8µm infrared brightness temperatures are contaminated by the underlying surfaces and cannot be used as for opaque clouds. A correction of semi-transparency is applied, which requires the use of two infrared channels: a window (10.8µm) and a sounder (13.4µm, 7.3µm or 6.2µm) channels. The basis is that clouds have a stronger impact in a window channel than in a sounding channel. The following process is implemented:
    - The H_2O/IRW intercept method (as described in Schmetz et al., 1993), based on a window (10.8µm) and sounding (13.4µm, 7.3µm or 6.2µm) radiance bi-dimensional histogram analysis, is first applied. The histograms are built in boxes of 32*32 SEVIRI IR pixels centred on each segment of the image (whose size is defined by the user, the default value being 16*16 SEVIRI IR pixels). It therefore allows the retrieval of cloud top pressure at the segment horizontal resolution (i.e., by default 16*16 SEVIRI IR pixels). This method is successively applied using the 7.3µm, 6.2µm and 13.4µm radiances, the final retrieved cloud pressure being the minimum cloud top pressures obtained using single sounding channels.
    - If no result can be obtained with the H_2O/IRW intercept method, the radiance ratioing method, as described in Menzel et al. 1982, is then applied to the 10.8µm and 7.3µm radiances to retrieve the cloud top pressure at a pixel basis. If no result can be obtained, the method is applied to 6.2µm and finally to 13.4µm radiances.
    - If the radiance ratioing technique leads to cloud top temperatures warmer than the corresponding 10.8µm brightness temperatures, the method for thick clouds is used instead.
  - For fractional clouds : No technique is proposed in the current version for low broken clouds. The sounding channels are nearly unaffected by broken low clouds and are

therefore useless; the infrared channels at 10.8µm and 12.0µm are contaminated by the surface and cannot therefore be used as for opaque clouds.

- A gap-filling procedure is applied in semi-transparent cloud top pressure field: in each box of 32x32 SEVIRI IR pixels, a cloud top pressure is computed as the average pressure of all pixels containing semi-transparent clouds inside the current and the eight surrounding boxes. This average cloud top pressure is then assigned to all pixels of the current box containing semi-transparent clouds and having no retrieved cloud top pressure.
- Cloud top temperature and height (above sea level) are then computed from their pressure using general modules. During these processes, the atmospheric vertical profiles are temporally interpolated to the exact slot time using the two nearest in time NWP outputs fields.
- Effective cloudiness (defined as the fraction of the field of view covered by cloud (the cloud amount) multiplied by the cloud emissivity in the 10.8µm window channel) is also computed during the processing. It is equal to 1.0 for thick clouds and takes a value between 0. and 1. for semi-transparent clouds.

In case some mandatory NWP or SEVIRI data are missing (see list of inputs for CTTH):

Cloud top temperature of very low, low, medium and high clouds are then computed by applying a climatological atmospheric absorption correction to the 10.8µm brightness temperature using look-up tables. The cloud top pressure and height are not retrieved.

4.2.1.2.2 Cloud top retrieval techniques

4.2.1.2.2.1 Opaque Cloud Top Temperature retrieved from climatological atmospheric absorption correction

This empirical technique allows to retrieve the cloud top temperature of opaque clouds on a pixel basis, only using T10.8µm brightness temperature. This technique is used if NWP temperature and humidity vertical profile or if mandatory SEVIRI channels are missing.

The cloud top temperature is calculated from the 10.8µm brightness temperature by adding an offset that accounts for the atmospheric absorption. This offset, which should be higher for low clouds and high viewing angles, is estimated from a pre-computed table with the 10.8µm brightness temperature of the pixel (indicating the cloud height) and the viewing angle as input.

This pre-computed table has been elaborated off-line using RTTOV simulations : T10.8µm brightness temperatures have been simulated from radio-soundings available in TIGR dataset by assuming opaque clouds at various pressure levels in the troposphere. The values of the pre-computed table have been regressed from these simulations and are displayed in Figure 33.

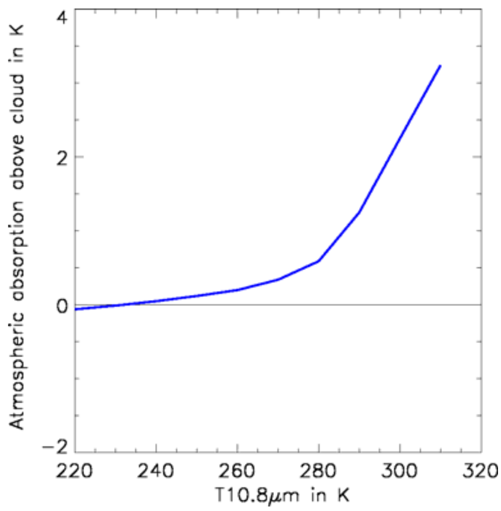

Figure 33: Climatological atmospheric absorption used to compute cloud top temperature from 10.8μm brightness temperature

Pixels processed by this method are flagged as of low confidence.

4.2.1.2.2.2 Opaque Cloud top pressure retrieved from window channel brightness temperature

This technique allows to retrieve the cloud top pressure of opaque clouds on a pixel basis. It is not applied to low or medium clouds if a thermal inversion is detected in forecast NWP fields (see 4.2.1.2.2.3). It relies on the support of on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile. These atmospheric profiles are forecast by a NWP model and temporally interpolated to the exact slot. The RTTOV simulations are computed on segments whose size is defined by the user (by default, 16*16 SEVIRI IR pixels).

Top of Atmosphere T10.8µm brightness temperatures are simulated assuming opaque clouds at the different pressure levels of the atmospheric vertical profile. These simulated T10.8µm brightness temperature vertical profiles are then inspected from surface level up to the tropopause level : two consecutive pressure levels having simulated temperatures respectively higher and lower than the T10.8µm brightness temperature are looked for; the cloud top pressure is finally obtained by a linear interpolation (logarithm of pressure used) between these two simulated temperatures.

The consistency of the technique is estimated on-line by retrieving the cloud top pressure from both the T10.8µm and T12.0µm brightness temperatures, the result being ideally equal. The pixel will be flagged as of low confidence if the difference between the results obtained from these two wavelengths is larger than 0.5°C.

4.2.1.2.2.3 Low or medium opaque Cloud top pressure retrieved from window channel brightness temperature in case thermal inversion

This technique allows to retrieve the cloud top pressure of low or medium opaque clouds on a pixel basis, in case a thermal inversion has been detected in forecast NWP fields. It relies on the support of on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile. These atmospheric profiles are forecast by a NWP model, temporally and spatially interpolated to the exact slot and to the processed pixel. The RTTOV simulations are computed on segments whose size is defined by the user (by default, 16*16 SEVIRI IR pixels.

The cloud is set below the thermal inversion only if its T10.8µm brightness temperature is larger than the air temperature below the inversion minus 10K (in case of subsident thermal inversion (see the definition in 4.2.1.2.3.1)) or larger than the simulated T10.8µm brightness temperature below the inversion minus 5K (in case of non subsident thermal inversion). In that case, the cloud is set below the inversion at a level between the top of the inversion and the colder part below the inversion depending on the strength of the inversion.

Otherwise, the cloud is set above the thermal inversion. The method to retrieve its top pressure is then similar to the one described in 4.2.1.2.2.2 if the difference between the T10.8µm brightness temperature and the air temperature is larger than 10K. Otherwise, the cloud top is set at a level between the level where simulated and observed brightness temperature fits best and a level between the top of the inversion and the colder level between the inversion.

Pixels processed by this method are flagged as of low confidence. Moreover the presence of a thermal inversion in the forecast vertical temperature profile is also flagged.

4.2.1.2.2.4 Semi-transparent Cloud Top Pressure retrieved using radiance ratioing technique

The radiance ratioing technique allows to retrieve semitransparent cloud top pressure at a pixel scale from radiances in two infrared channels, one of these channels being a sounding channel. It relies on on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile.

This technique is detailed in Menzel et al., 1983. The basic equation of the method is the following:

$$\frac{R_{m1} - R_{clear1}}{R_{m2} - R_{clear2}} = \frac{N\varepsilon_1 (R_{op1} - R_{clear1})}{N\varepsilon_2 (R_{op2} - R_{clear2})} \qquad \textit{Eq. 1}$$

where R_m is the measured radiance, R_{clear} is the clear radiance, R_{op} is the opaque cloud radiance, N is the cloud amount and ε is the cloud emissivity. The terms of denominators on both side come from the same channel (index 2) and the nominators from the other one of the pair (index 1).

Assuming that the ratio of the emissivities is close to one the equation becomes simpler:

$$\frac{R_{m1} - R_{clear1}}{R_{m2} - R_{clear2}} = \frac{R_{op1} - R_{clear1}}{R_{op2} - R_{clear2}} \qquad \textit{Eq. 2}$$

Both side of this equation depends on the chosen channels, surface temperature, vertical temperature and absorbing material profiles. The right side of the equation also depends on the cloud pressure due to R_{op}. Consequently if we use a fixed surface temperature and vertical profiles, the right side becomes a function depending on the pressure, the left side being a constant. The retrieved cloud top pressure corresponds to the pressure that satisfies Eq.2. In practice the clear sky radiances R_{clear} are either measured or simulated, the opaque cloud radiances R_{op} are simulated values, while the R_m is the measured data.

It has been implemented using the 10.8µm window channel together with the 13.4µm CO_2 channels, the 7.3µm and 6.2µm water vapour channel. It allows to retrieve cloud top pressure for semitransparent ice clouds and high thick clouds on a pixel basis. The process is performed in several steps described below.

<u>Simulation of the radiances</u>

TOA infrared 10.8µm, 13.4µm, 7.3µm and 6.2µm SEVIRI radiances for clear atmosphere and for opaque clouds at various pressure levels have been previously simulated with RTTOV.

<u>Modification of simulated radiances</u>

The method very much depends on the cloud free and opaque clouds values. As the simulated radiances for the water vapour channels are not reliable enough (mainly due to the inaccuracy of the atmosphere water vapour description by NWP models, as pointed out in Nieman et al., 1993), the following process is applied to modify them:

- modification of cloud free 7.3µm and 6.2µm simulated radiances : cloud free 7.3µm and 6.2µm radiances are computed over the whole image at the segment spatial resolution from cloud free individual pixels and pixels containing opaque clouds too low to affect these measurements. They are used instead the simulated ones.
- modification of opaque 7.3µm and 6.2µm simulated radiances : the cloudy 7.3µm and 6.2µm radiances are modified to account for the discrepancy between the simulated and observed cloud free radiances : the radiance for clouds at the tropopause remain unchanged, the radiance for the lowest clouds are replaced by the cloud free observed radiance, whereas the modification for the other clouds is linearly linked to its 10.8µm radiance. This modification is performed only if it leads to an increase of the simulated radiances.
- modification of cloud free 10.8µm and 13.4µm simulated radiances : cloud free 10.8µm and 13.4µm radiances are computed over the whole image at the segment spatial

resolution from cloud free individual pixels. When available, these observed cloud free values replace the simulated ones.

Calculation of the cloud top pressure

Using the simulated and the measured radiances, we calculate the simulated ratio as a function of the cloud top pressure (right side of Eq.2), and the measured ratios (left side of Eq.2). The retrieved pressure level corresponds to this difference equal to zero. This is illustrated on Figure 34 with SEVIRI measurements.

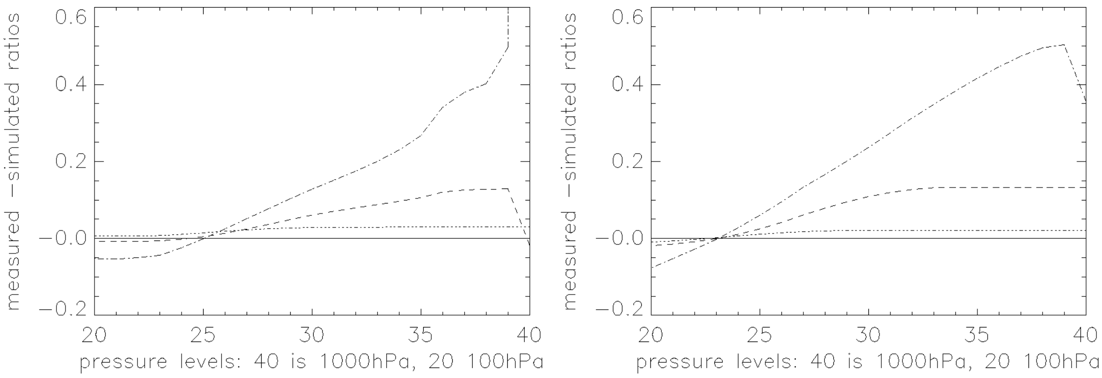

Figure 34: Illustration of the Radiance Ratioing technique applied to SEVIRI radiances.

Examples of measured minus simulated ratios as a function of the pressure level. The cloud top pressure level corresponds to the crossing of the curves with the X-axis. The three curves corresponds to different channel pairs : 10.8µm/13.7µm (dash-dot), 10.8µm/7.3µm (long dash), 10.8µm/6.2µm (dot)

Calculation of the cloud effective cloudiness

The cloud effective cloudiness (Nε) is calculated from the 10.8µm window radiance, using the retrieved cloud pressure.

Rejection

The retrieved cloud pressure is assumed to be unreliable in the following cases :

- the difference between the measured and the simulated clear sky radiances (R_m - R_{clear}) is within three times the instrument noise level.
- the difference between the retrieved and measured radiances is larger than 30% of the difference between the simulated and measured radiances

Quality flag

The pressure retrieval is flagged as of low confidence if :

- the cloud free cluster is derived from simulation.
- the retrieved radiances are higher than measured ones.

This technique is very much sensitive to the noise (especially for very thin clouds), and to the inaccuracy of the water vapour channel simulated radiances (if 7.3µm or 6.2µm channels are used), due to bad water vapour forecast.

4.2.1.2.2.5 Semi-transparent Cloud Top Pressure retrieved using H2O/IRW Intercept method

The H_2O/IRW intercept method is described Schmetz et al., 1993. It is successively applied to the window 10.8µm channel and one sounding channel (either 6.2µm, 7.3µm or 13.4µm), the final retrieved cloud pressure being the averaged cloud top pressures obtained using a single sounding channel. This method is based on a radiance histogram analysis (see Figure 35). The histograms are built in boxes of 32*32 SEVIRI IR pixels centred on each segment of the image (whose size is defined by the user, the default value being 16*16 SEVIRI IR pixels). It therefore allows the retrieval of semitransparent ice cloud top pressure at the segment horizontal resolution (i.e., by default 16*16 SEVIRI IR pixels). It makes use of on-line RTTOV simulations and therefore requires the availability of the atmospheric vertical profile.

The fundamental assumption of the method is that there is a linear relationship between radiances in the two spectral bands observing a single cloud layer. In particular, all pairs of radiances in the sounding (6.2µm, 7.3µm or 13.4µm) and window (10.8µm) channels viewing a cloud layer at pressure p_c will lay along a straight line, the spreading along the line corresponding to changes in cloud amounts. On the other hand, the pairs of radiances in the window (10.8µm) and sounding channel (6.2µm, 7.3µm or 13.4µm) for opaque clouds at different pressure levels will lay along a curve that can be calculated from the atmospheric vertical structure using RTTOV radiative transfer model. Therefore, the cloud top pressure for semitransparent ice clouds is retrieved as the intersection between the linear fit to the observations and the simulated opaque cloud curve. This is illustrated with SEVIRI radiances on Figure 35.

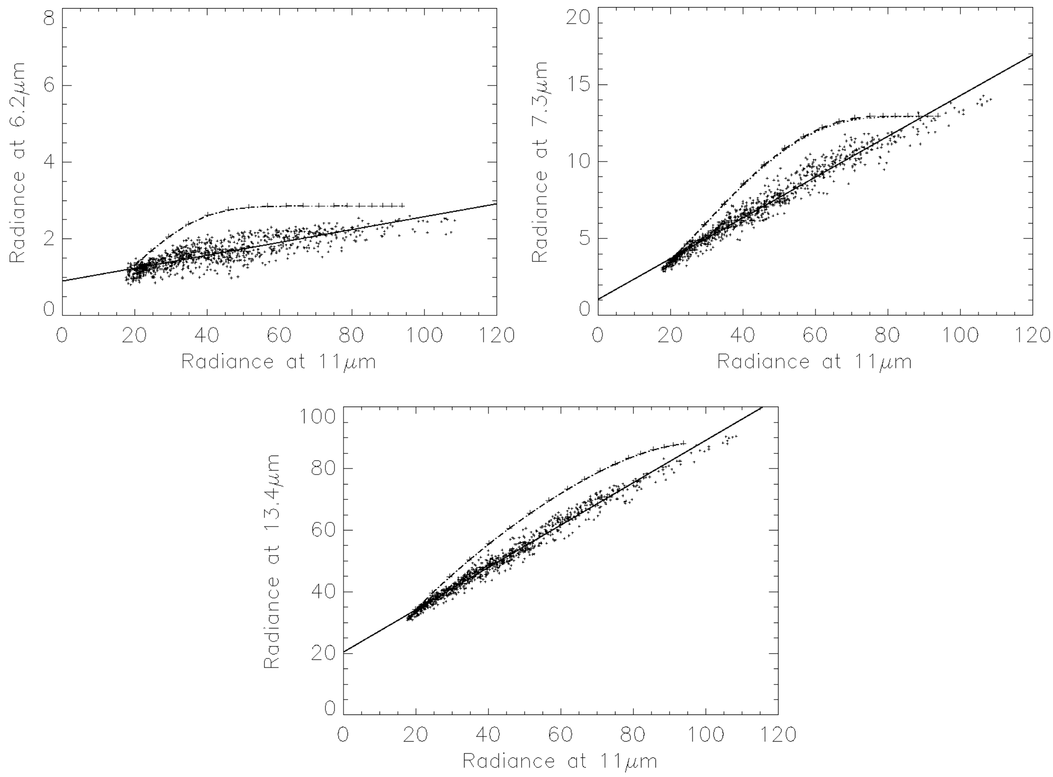

Figure 35: Illustration of the H_2O/IRW intercept method with SEVIRI radiances (expressed in $mWm^{-2}sr^{-1}cm$).

The dashed curve simulates the 10.8µm and 6.2µm (respectively 7.3 and 13.4µm) radiances of opaque clouds at various pressure levels. The small crosses represent radiance of clouds at the same height, but with varying thickness, and the radiance of cloud free pixels. The top pressure of the semitransparent cloud layer is retrieved from the intersection between the simulated curve (dashed curve) and the regression line.

The process is performed in several steps detailed below :

<u>Simulation of the SEVIRI radiances</u>

TOA infrared 10.8µm, 13.4µm, 7.3µm and 6.2µm SEVIRI radiances for clear atmosphere and for opaque clouds at various pressure levels have been previously simulated with RTTOV.

<u>Modification of simulated radiances</u>

As the method very much depends on the opaque clouds values, and as these simulations for the water vapour channels are not very reliable (mainly due to the inaccuracy of the atmosphere water vapour description by NWP models, as pointed out in Nieman et al., 1993), the following process is applied to modify the simulated values :

- modification of cloud free 7.3µm and 6.2µm simulated radiances : cloud free 7.3µm and 6.2µm radiances are computed over the whole image at the segment spatial resolution from cloud free individual pixels and pixels containing opaque clouds too low to affect these measurements. They are used instead the simulated ones.
- modification of opaque 7.3µm and 6.2µm simulated radiances : the cloudy 7.3µm and 6.2µm radiances are modified to account for the discrepancy between the simulated and observed cloud free radiances : the radiance for clouds at the tropopause remain unchanged, the radiance for the lowest clouds are replaced by the cloud free observed radiance, whereas the modification for the other clouds is linearly linked to its 10.8µm radiance. This modification is performed only if it leads to an increase of the simulated radiances.

<u>Calculation of the cloud top pressure</u>

A straight line is adjusted, using the 13.4µm (or 7.3µm or 6.2µm) and 10.8µm radiances of all pixels previously classified as semitransparent, high thick clouds or cloud-free. The intersection of this straight line with the opaque cloud curve will give the cloud top pressure. This process, illustrated on Figure 35, is successively applied to the three sounding channels (7.3µm, 6.2µm and 13.4µm). When cloud top pressure can be obtained from more than one sounding channel, the final retrieved cloud top pressure corresponds to the minimum value obtained with the individual sounding channels.

<u>Calculation of the effective cloudiness</u>

The effective cloudiness (Nε) of each pixel is calculated from the 10.8µm window radiance, using the retrieved cloud pressure.

<u>Rejection</u>

The retrieved cloud pressure is assumed to be unreliable in the following cases :

- unreliable regression :
  - too few pixels (less than 50)
  - too low spread of the pixels in the 10.8µm channel is observed (less than 15 mWm^{-2} sr^{-1} cm between the 10.8µm radiance of the coldest and the warmest pixels)
  - too low correlation coefficient (lower than 0.7)
- not adequate regression line :
  - slope of the regression line too small
  - regression line too close to opaque cloud curve

If no intersection has been found, but if the regression seems reliable (large number of pixels (more than 100), large spread of the pixels in the 10.8µm channel (more than 23 mWm^{-2} sr^{-1} cm between the 10.8µm radiance of the coldest and the warmest pixels), large correlation coefficient (larger than 0.9), large regression's slope), then the cloud top pressure is assumed to be the tropopause's pressure minus 50hPa, but the retrieval is flagged as bad quality.

<u>Quality flag</u>

The pressure retrieval is flagged as good confidence if :

- The final cloud top pressure is a minimum value obtained from at least two sounding channels, the maximum difference between each individual cloud top pressure being less than 75hPa.
- The final cloud top pressure is obtained using a single sounding channel, but:
  - a high number of pixel is used in the regression (more than 100 pixels),

- a large spread of the pixels in the 10.8µm channel is observed (more than 23 $mWm^{-2}\,sr^{-1}\,cm$ between the 10.8µm radiance of the coldest and the warmest pixels),
- a high correlation coefficient is observed (larger than 0.8)

4.2.1.2.3 General modules

4.2.1.2.3.1 Identification and characterisation of thermal inversions from forecast NWP fields

The NWP forecast air temperature and relative humidity on user-defined pressure levels are analysed as follows to identify and characterize thermal inversions:

- a thermal inversion is detected if layers exist between the surface and 700hPa where the air temperature increases with decreasing pressure.
- this thermal inversion is said "subsident" if the relative humidity between 850 and 600hPa is lower than 30%.

4.2.1.2.3.2 Tropopause height estimation

The module used has been developed by the aeronautic forecast service in Toulouse. The pressure and height of the tropopause is extracted from a vertical profile (temperature, height and pressure), the ground height and the latitude. The tropopause estimation is mainly based on the WMO definition of the tropopause : the lowest level (above 5000m) corresponding to a temperature decrease of less than 2°C/km during 2km. A maximum height of the tropopause level is assumed (20km at the equator, 12-13km at the poles) to check the result's coherency.

4.2.1.2.3.3 Application of RTTOV to vertical atmospheric profiles

RTTOV radiative transfer model simulates radiances through a cloud-free atmosphere described in 43 standard pressure levels. The NWP forecast temperature and humidity fields available on user-defined vertical pressure levels are interpolated (linearly in logarithm of the pressure) to the RTTOV pressure levels. The surface emissivity is assumed to be 0.98 for continental surface, and is computed from Masuda tables (Masuda et al., 1988) over the sea.

The outputs of RTTOV that have been used are the brightness temperatures and radiances of the simulated channels for cloud-free atmosphere and assuming opaque clouds at the 43 standard pressure levels of RTTOV-9.

4.2.1.2.3.4 Cloud Top Height (above sea level) retrieved from its pressure

A module is used to compute the height vertical profile from the corresponding vertical profile of pressure, temperature & water vapour mixing ratio, the surface height and the latitude. The cloud height (above sea level) is then interpolated using the height of the two nearest pressure levels in the vertical profile. The interpolation used is linear in logarithm of the pressure.

4.2.1.2.3.5 Cloud Top Temperature retrieved from its pressure

A vertical temperature profile in pressure levels is needed in this process. The cloud temperature is interpolated using the temperature of the two nearest pressure levels in the vertical profile. The interpolation used is linear in logarithm of the pressure.

4.2.2 Practical considerations

4.2.2.1 Validation

Table 9 summarises the validation results of the current version. More details can be obtained from the validation report for cloud products ([AD. 1]).

PGE03 products	Validated accuracy: bias(std)
Top height of opaque low, mid-level and high cloud If validated over European areas using ground-based radar/lidar	120m(1050m)
Top height of semi-transparent cloud If validated over European areas using ground-based radar/lidar	1020m(940m) (intercept method) 100m(1050m) (radiance ratioing technique)

Table 9: Summary of validation results of the current PGE03 version (std stands for standard deviation)

4.2.2.2 Quality control and diagnostics

A quality assessment, detailed in 4.2.1.2.2, is performed by the CTTH itself through methods depending on the cloud type and the used retrieval techniques.

Fourteen bits in the CTTH output are dedicated to quality description (see in 4.2.2.4). It includes a quality flag based on the quality assessment performed by the CTTH (see above paragraph), but also information on the lack of NWP fields, RTTOV simulation, SEVIRI non mandatory channels which leads to a decrease of CTTH quality. Information is also available on the method used (especially for semi-transparent clouds) which can be associated with validation results (see the validation results for cloud products ([AD. 1])).

4.2.2.3 List of inputs for Cloud Top Temperature and Height (CTTH)

The input data to the CTTH algorithm are described in this section. Mandatory inputs are flagged, whereas the impact of missing non-mandatory data on the processing are indicated.

- **Satellite imagery:**

The following SEVIRI brightness temperatures and radiances are needed at full IR spatial resolution:

Rad6.2µm	Rad7.3µm	Rad13.4µm	Rad10.8µm	T10.8µm	T12.0µm
At least one of these channels is mandatory, the two others are then optional			Mandatory	Mandatory	Optional

The CTTH software checks the availability of SEVIRI brightness temperatures and radiances for each pixel. Full CTTH product is computed only if all mandatory SEVIRI radiances and brightness temperatures are available. If T10.8µm brightness temperature is missing, no result is available. If T10.8µm brightness temperature is available, but mandatory channels are missing, only the cloud top temperature is computed using the method based on climatological atmospheric absorption correction.

The SEVIRI channels are input by the user in HRIT format, and extracted on the processed region by SAFNWC software package.

- **CMa and CT cloud categories**

The CMa and CT cloud categories are mandatory. They are computed by the CMa and CT software.

- **Satellite angles associated to SEVIRI imagery**

This information is mandatory. It is computed by the CTTH software itself, using the definition of the region and the satellite characteristics.

- **NWP parameters:**

The forecast fields of the following parameters, remapped onto satellite images, are used as input :
  - surface temperature
  - surface pressure
  - air temperature and relative humidity (alternatively dew point temperature) at 2m
  - air temperature and relative humidity on vertical pressure levels
  - altitude of the NWP model grid (alternatively surface geopotential on the NWP model grid). Required if NWP fields are used as input.

Vertical pressure levels on which air temperature and humidity are defined by the user. All the surface and near-surface NWP informations and at least NWP informations every 210hPa on the vertical are mandatory to get full CTTH product. Otherwise only the cloud top temperature is retrieved using the method based on climatological atmospheric absorption correction. Furthermore, it is recommended to provide NWP information on levels at least up to 100hPa to ensure a good height retrieval quality for very high clouds.

These remapped fields are elaborated by the SAFNWC software package from the NWP fields input by the user in GRIB format.

- **Ancillary data sets:**

The following ancillary data, remapped onto satellite images, are mandatory :
  - Land/sea atlas
  - Elevation atlas
  - Monthly minimum SST climatology
  - Monthly mean 0.6µm atmospheric-corrected reflectance climatology (land)

These ancillary data are available in the SAFNWC software package on MSG full disk in the default satellite projection at full IR resolution; They are extracted on the processed region by the CTTH software itself.

RTTOV coefficients's file, mandatory for RTTOV radiative transfer calculation, is available in the SAFNWC software package. If RTTOV model cannot be launched, only the cloud top temperature is computed using the method based on climatological atmospheric absorption correction.

One coefficients's file, containing satellite-dependent values and one look-up table for climatological atmospheric absorption correction, is available in the SAFNWC software package, and is needed by the CTTH software.

- **Configurable parameters:**

Besides the NWP parameters to be used (the levels may be changed by the user according to the local NWP_CONF_FILE), only one parameter is configurable in the default CTTH model configuration file:

- CTTH_SZSEG: The size of the segment is configurable (see its definition in 4.2.2.6.1). Its default value is 16. Information on how to change the size of the segment can be found in section 4.2.2.6.1 and in the software user manual ([AD. 2]).

4.2.2.4 Description of Cloud Top Temperature and Height (CTTH) output

The content of the CTTH is the following :

- **<u>6 bits for the cloud top pressure</u>**

Linear conversion from count to pressure : Cloud_Pressure = gain * $\text{Count}_{6\text{bits}}$ + intercept
(correspond to pressures ranging between Cloud_Pressure and Cloud_Pressure+25hPa)

Gain	Intercept	Special count
25 hPa/count	-250hPa	0 (no pressure available)

- **<u>7 bits for the cloud top height</u>**

Linear conversion from count to height : Cloud_Height = gain * $\text{Count}_{7\text{bits}}$ + intercept
(correspond to heights ranging between Cloud_Height and Cloud_Height+200m)

Gain	Intercept	Special count
200 m/count	-2000 m	0 (no height available)

- **<u>8 bits for the cloud top temperature</u>**

Linear conversion from count to temperature : Cloud_Temperature = gain * $\text{Count}_{8\text{bits}}$ + intercept
(correspond to temperatures ranging between Cloud_Temperature and Cloud_Temperature+1K)

Gain	Intercept	Special count
1 K/count	150 K	0 (no temperature available)

- **<u>5 bits for effective cloudiness</u>**

Linear conversion from count to effective cloudiness : Cloudiness = gain * $\text{Count}_{5\text{bits}}$ + intercept
(correspond to cloudiness ranging between Cloudiness and Cloudiness+5%)

Gain	Intercept	Special count
5 %/count	-50 %	0 (no cloudiness available)

- **<u>14 bits for quality</u>**

2 bits to define processing status:
0 non-processed. encompasses :
-CMa and/or CT Non-processed or undefined,
-Image areas that may not be processed [when the images'size is not a multiple of the PGE03 segment size]
1 non-processed because FOV is cloud free
2 processed because cloudy, but without result
3 processed because cloudy, with result

1 bit set to 1 when RTTOV IR simulations are available

3 bits to describe NWP input data
0 undefined (space)
1 All NWP parameters available, no thermal inversion
2 All NWP parameters available, thermal inversion present
3 Some NWP pressure levels missing, no thermal inversion
4 Some NWP pressure levels missing, thermal inversion present
5 At least one mandatory NWP information is missing

2 bits to describe SEVIRI input data

0 undefined (space)
1 all SEVIRI useful channels available
2 at least one SEVIRI useful channel missing
3 at least one SEVIRI mandatory channel is missing

4 bits to describe which method has been used
0 Non-processed
1 Opaque cloud, using rttov
2 Opaque clouds, not using rttov
3 Intercept method 10.8µm/13.4µm
4 Intercept method 10.8µm/6.2µm
5 Intercept method 10.8µm/7.3µm
6 Radiance Ratioing method 10.8µm/13.4µm
7 Radiance Ratioing method 10.8µm/6.2µm
8 Radiance Ratioing method 10.8µm/7.3µm
9 Spare
10 Spare
11 Spare
12 Spare
13 Opaque cloud, using rttov, in case thermal inversion
14 Spatial smoothing (gap filling in semi-transparent cloud field)
15 Spare for not yet defined methods

2 bits to describe quality of the processing itself
0 No result (Non-processed, cloud free, no reliable method)
1 Good quality (high confidence)
2 Poor quality (low confidence)

4.2.2.5 Example of Cloud Top Temperature and Height (CTTH) visualisation

It is important to note that the CTTH product is not just images, but numerical data. At first hand, the CTTH is rather thought to be used digitally (together with the appended quality flags) as input to mesoscale analysis models, objective Nowcasting schemes, but also in the extraction of other SAFNWC products.

Color palettes are included in CTTH HDF files, thus allowing an easy visualisation of cloud top pressure (as illustrated with the SEVIRI example on Figure 36), height, temperature and effective cloudiness.

The product, if used as an image on the forecaster desk, may be visualized (together with CT) in an interactive visualisation system, where individual pixel values (top temperature, height and pressure, cloudiness) may be displayed while moving the mouse over the image.

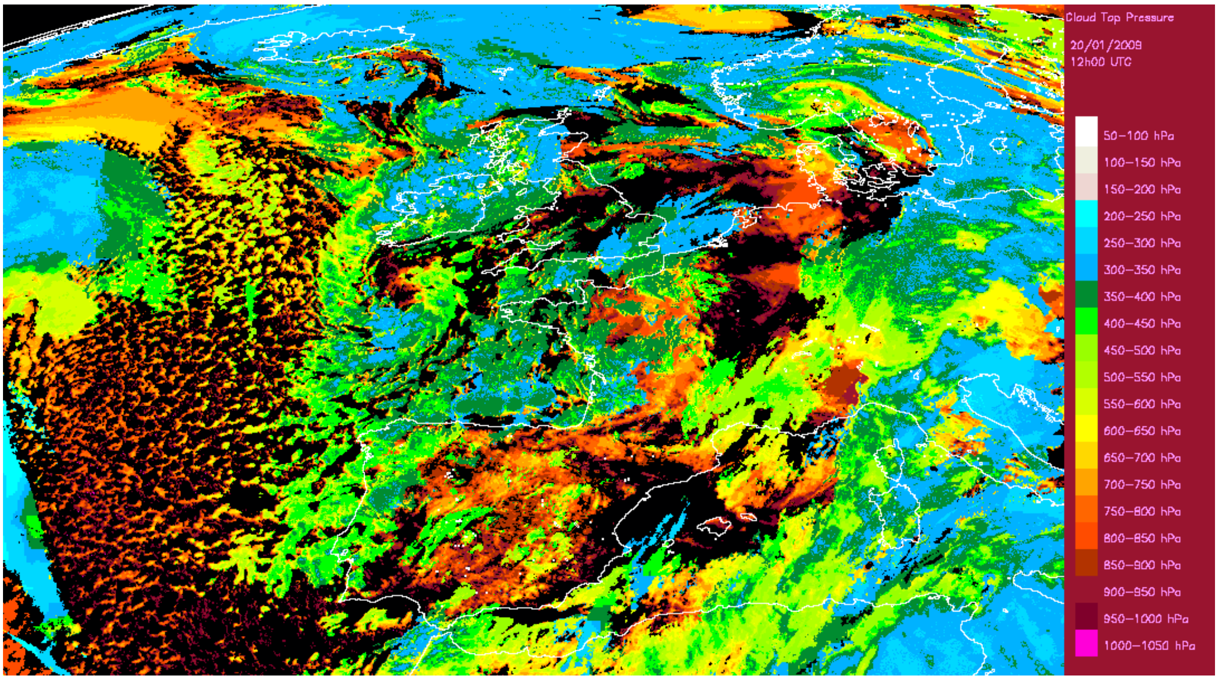

Figure 36: Example of SEVIRI CTTH cloud top pressure

4.2.2.6 Implementation of Cloud Top Temperature and Height (CTTH)

CTTH is extracted by PGE03 of the SAFNWC/MSG software package. Detailed information on how to run this software package is available in the software user manual ([AD. 2]).

The software architecture of PGE03 has been strongly modified in version v2010 (to make the life easier for the user). It is now very similar to the other PGEs.

When a new region is defined the user has now to manually prepare the CTTH model configuration files for this new region using a default CTTH model configuration file provided in the SAFNWC/MSG software package. As the content of NWP_CONF_FILE is dependent on the local installation, the user must make the NWP_PARAMXX consistent with the local NWP_CONF_FILE when the standard one is not used.

There is an option for the user to monitor the so-called CTTH preparation step before SEVIRI images are available (to speed up the process). By default, this preparation step is performed during the CTTH execution step.

The CTTH execution step (which includes the CTTH preparation step in case it has not been launched before) is automatically launched by the Task Manager (if real-time environment is selected).

4.2.2.6.1 Manual preparation of Cloud Top Temperature and Height (CTTH) model configuration file for each region

When a new region is defined and added in system and run configuration files, the user must manually prepares the CTTH model configuration files by adapting the default CTTH model configuration file available in the SAFNWC software package.

Only one parameter is configurable in the default CTTH model configuration file:

- CTTH_SZSEG (default value: 16): the size of the segment. This default value may be manually changed independently of CMA_SZSEG and CT_SZSEG The new segment size must also updated in the lines NWP_PARAMxx. [Segments are square boxes in the satellite projection, whose size is expressed as the number of IR pixels of one edge of the square box. The size of the processed regions must be a multiple of the segment size. The NWP model forecast values and RTTOV simulations will be derived over all the processed regions at the horizontal resolution of the segment. A small ctth_szseg will decrease the box aspect in the retrieved cloud top pressure and will be especially useful if the NWP fields have a high horizontal resolution. But it may become very time consuming as RTTOV is launched every segment.]

Moreover as the content of NWP_CONF_FILE is dependent on the local installation, the user must make the NWP_PARAMXX consistent with the local NWP_CONF_FILE when the standard one is not used (for details see section dedicated to NWP data files in SAF/NWC/CDOP/INM/SW/SUM/2 [AD. 2]).

4.2.2.6.2 The Cloud Top Temperature and Height (CTTH) preparation step (optional)

By default, this CTTH preparation step is performed during the CTTH execution step (see section 4.2.2.6.3).

But to speed up the CTTH processing, this preparation step can performed by the command mfcms_next_pge03 which can be launched in advance of satellite data reception according to a pre-defined time scheduling to be manually set by the user.

This preparation step includes the computation on the region at the segment spatial resolution of:
- the solar & satellite angles,
- the monthly climatological & atlas maps,
- the simulated cloud free & opaque cloud radiances with RTTOV

4.2.2.6.3 The Cloud Top Temperature and Height (CTTH) execution step

The CTTH execution step (which by default includes the CTTH preparation step see section 4.2.2.6.2) is the real-time processing of the SEVIRI images itself over the region. This process consists in the launch of the command: PGE03 by the Task manager. The CTHT is then performed, using the simulated radiances prepared during the preparation step.

4.3 ASSUMPTIONS AND LIMITATIONS

The following problems may be encountered:

- CTTH will be wrong if the cloud is wrongly classified:
  - Underestimation of cloud top height/pressure for semi-transparent clouds classified as low/medium
  - Over estimation of cloud top height/pressure for low/medium clouds classified as semi-transparent
- No CTTH is available for clouds classified as fractional.
- CTTH may be not computed for thin cirrus clouds.
- Retrieved low cloud top height may be overestimated.

4.4 REFERENCES

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Schmetz J., Holmlund K., Hoffman J. and B.Strauss, 1993, Operational cloud motion winds from Meteosat infrared images. *J.Appl.Meteor*, 32, 1207-1225.

ANNEX 1. ATLAS AND CLIMATOLOGICAL DATASET

Atlas and climatological datasets covering the whole MSG disk in the default satellite projection at full SEVIRI IR horizontal resolution are available within the SAFNWC software package and are used in the elaboration of CMa, CT and CTTH products. The following sections give a short description of the source of these ancillary data.

A1.1 LAND/SEA ATLAS

The initial source is the full resolution coast line available in GMT 3.1 tool (see Wessel et al., 1995, code available on internet (http ://www.soest.hawaii.edu /gmt)).

Each SEVIRI IR pixel is classified as sea (more than 50 % water surface (sea or lake)), land (more than 50% land surface) or space.

Wessel P., Smith W.H.F., 1995, New version of the Generic Mapping Tools released, *EOS Trans. Amer. Geophys. U. Electronic.* Vol 76 (33), 329

A1.2 LAND/SEA/COAST ATLAS

The land/sea/coast atlas is derived from the land/sea atlas by identifying coastal areas defined as pixels for which a transition land/sea is observed within 2 SEVIRI IR pixels.

A 1.3 ELEVATION ATLAS

The initial source is GTOPO30 (available on internet http://edcwww.cr.usgs.gov/landaac/gtopo30/gtopo30.html) which is a Digital Elevation Model having an horizontal resolution of 30 arc-seconds.

The altitude of each SEVIRI IR pixel over land (and lakes) is obtained by averaging GTOPO30 values located inside this pixel, whereas oceanic pixel are given a zero value.

A 1.4 MONTHLY MINIMUM SEA SURFACE TEMPERATURE CLIMATOLOGY

The initial source is a global Pathfinder climatology covering a 10 years period (1985-1995) and available at 1/9th degree horizontal resolution. This climatology contains mean and minimum SST values for every decade, and identifies areas covered by ice.

Monthly minimum SST values are obtained for each SEVIRI IR pixel over sea (including lakes) by retaining the minimum values of all the corresponding decades. Pixels covered by ice are given a constant value (269.15K) whereas land pixels are given a default value.

A 1.5 MONTHLY VISIBLE ATMOSPHERIC-CORRECTED REFLECTANCES CLIMATOLOGY

The initial source is a 10 minutes horizontal resolution global climatology of Top Of Atmosphere monthly visible reflectances derived by NOAA from AVHRR GAC measurements (see Gutman et al., 1995).

These TOA reflectances have been roughly corrected from atmospheric effects. The values corresponding to snowy targets have been replaced, either with the nearest in time value, either by a constant value (20%). The data have been finally spread spatially in the coastal areas. Monthly visible atmospheric-corrected reflectance for each SEVIRI IR pixel over land is obtained from the nearest value of these TOA reflectances. Sea pixels are given a default value.

A 1.6 MONTHLY ATMOSPHERIC INTEGRATED WATER VAPOUR CONTENT CLIMATOLOGY

The initial source is a 2.5 degrees horizontal resolution global monthly climatology of specific humidity on 11 vertical pressure levels (1000, 950, 900, 850, 700, 500, 400, 300, 200, 100, and 50 hPa), elaborated by Oort from a collection of 15 years of global rawinsonde data (Oort, 1983).

The integrated water vapor content of each SEVIRI IR pixel is computed from the specific humidity of pressure levels above the surface level (whose pressure is derived from the height map using a standard OACI standard atmosphere for the height/pressure conversion).

Oort A.H., 1983, Global atmospheric circulation statistics, 1958-1973. NOAA professional Paper No. 14.

A 1.7 MONTHLY AIR TEMPERATURE (AT 1000, 850, 700, 500 HPA) CLIMATOLOGY

The initial source is a 1.5 degrees horizontal resolution global monthly climatology of air temperatures at 1000hPa, 850hPa, 700hPa and 500hpa derived from the ECMWF model.

A 1.8 MONTHLY 0.6µM/1.6µM WHITESKY SURFACE ALBEDOE CLIMATOLOGY

Cloud free surface reflectances are needed during the comparison of the simulated and measured 0.6µm/1.6µm cloudy reflectances performed during the CT cloud phase retrieval. Over continental areas, they are derived from MODIS monthly 0.6µm and 1.6µm white-sky surface albedo climatologies available from NASA (http://modis-atmos.gsfc.nasa.gov/ALBEDO/index.html). These white sky albedos represents bi-hemispheric reflectances without the direct component which is a good approximation of the surface albedo below a cloud. Over sea, constant values are used: 3% (at 0.6µm) and 1% (at 1.6µm).

A 1.9 MONTHLY CLOUD FREE LARGE BAND VISIBLE SURFACE REFLECTANCES CLIMATOLOGY

Cloud free large band visible surface reflectances are used to process HRV during the CMa cloud detection process. Over continental areas, they are derived from MODIS monthly 0.5µm, 0.6µm and 0.8µm black-sky surface albedo climatologies available from NASA (http://modis-atmos.gsfc.nasa.gov/ALBEDO/index.html). These black sky albedos represents bi-hemispheric reflectances with the direct component. These three monthly climatologies are averaged, the weight of each band (0.5µm, 0.6µm and 0.8µm) being dependant on the HRV spectral filter.