

# ECMWF Aerosol and Cloud Detection Software

## User Guide

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## 1. INTRODUCTION

This document describes a stand-alone cloud and aerosol detection software that is based on source code used operationally in the assimilation of advanced infrared sounder radiances at ECMWF. As a new feature in version 2.2, the software contains an upgrade on the aerosol detection scheme. The new aerosol detection scheme is independent of model background information, as it makes use of observed brightness temperature data only. The output aerosol and cloud flags are separated from each other. While cloud flags continue to be specific to location and sounder channel, the new aerosol flags are specific to location only.

The software requires the user to supply observed and background (first guess) brightness temperatures (BT) for a number of channels, as well as height information assigned to the channels. Supplying collocated imager information in the form of clustered BT statistics and their background equivalents continues to be optional.

Description of the applied cloud and aerosol detection algorithms and the user interface follows.

## 2. ALGORITHM DESCRIPTION

### 2.1 Cloud Detection Algorithm

A detailed description of the cloud detection algorithm as used for assimilation of AIRS, IASI and CrIS data in the ECMWF data assimilation system is given by McNally and Watts (2003) and more recently by Eresmaa (2014); the latter reference describes the imager-assisted functionality of the cloud detection in detail.

In summary, the cloud detection algorithm works by taking the background departures (i.e., the difference between the observed BT and background BT, the latter being calculated from a good estimate of the atmospheric state - typically a short-range forecast from an NWP model) and looking for the signature of opacity that is not included in the clear-sky calculation (i.e. cloud or aerosol). To do this, the channels are first ranked in vertical, according to their height assignments (with the highest channels ranked first and the channels closest to the surface last). The resulting vertically-ranked BT departures are then smoothed with a moving-average filter in order to reduce the effect of instrument noise. One of three possible scenarios is then chosen on the basis of properties of the smoothed and ranked BT departures. The three scenarios include a Quick Exit (for completely clear scenes), a Cold Start (for clouds that are colder than the underlying surface), and a Warm Start (for clouds that are warmer than the underlying surface). In the case that collocated imager information is provided, this data is used to assist the choice on the most appropriate scenario.

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### 2.1.1 Choosing a scenario

An observation, consisting of BT data on a large number of infrared channels, is processed assuming one of three possible scenarios. The scenario to be followed is chosen primarily on the basis of the smoothed BT departure curve, but also collocated imager data are taken into account whenever such data are available. The three possible scenarios include

- 1) Quick Exit,
- 2) Warm Start
- 3) Cold Start

The diagrams below illustrate characteristics of the different scenarios. Each diagram shows the vertically-ranked and smoothed BT departures (heavy black line), with the highest-ranked channels on the left and lowest-ranked channels on the right. Approximate levels of tropopause and top of the planetary boundary layer (PBL) are highlighted by dashed lines, as these definitions are made use of in the cloud detection.

#### *Potential starting channels*

To assist the determination of the cloud detection scenario, three potential starting channels for the cloud search are identified in the smoothed BT departure curve. These are highlighted by red letters (A, B, C) in the diagrams below, and they are defined as follows:

- A: Considering only channels ranked between the tropopause level and the top of PBL, the channel at which the smoothed BT departure reaches its minimum value
- B: Considering all channels ranked below the tropopause, the channel at which the smoothed BT departure reaches its minimum
- C: The bottom channel, i.e., the channel ranked closest to the surface

### 2.1.2 Quick Exit scenario

Choosing the Quick Exit scenario will result in a diagnosis of a completely clear field-of-view, i.e, all channels will be diagnosed clear. Properties of the smoothed and vertically-ranked BT departure in a typical Quick Exit case are illustrated in Fig. 1. Choosing the Quick Exit scenario only happens when several criteria are met. The criteria are listed as follows:

- Absolute value of the smoothed BT departure at all of the initially considered potential starting channels (A,B,C) is smaller than the tuning parameter value `BT_Threshold` (by default 0.5 K)
- The smoothed BT departure does not exceed `BT_Threshold` on any channel ranked below the tropopause level

- Considering channels in the long-wave window wavelengths only, the smoothed BT departure does not change by more than the amount specified by the tuning parameter value `Window_Grad_Threshold` (by default 0.4 K)
- The independently-determined cloud flag based on collocated imager data is clear (see Section 2.1.6 below)
- The Quick Exit scenario is not disabled in a namelist

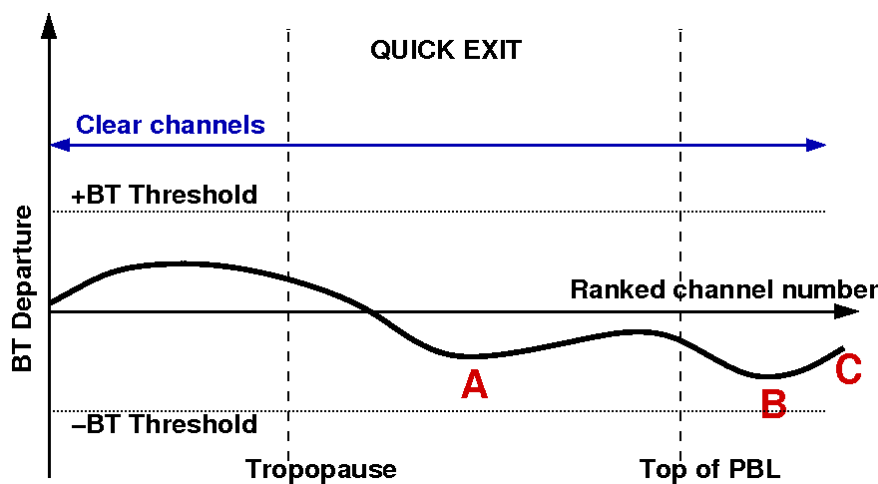


Figure 1: A schematic representation of the smoothed and vertically-ranked curve of BT departures in a Quick Exit Scenario.

### 2.1.3 Warm Start scenario

The Warm Start scenario is designed to account for cases where there is a warm cloud above a cold surface. The Warm Start scenario takes place when the following criteria are met:

- The Quick Exit scenario is not taking place
- Absolute value of the smoothed BT departure at channel A is smaller than `BT_Threshold`
- The smoothed BT departure at channel C channel is greater than `BT_Threshold`

In the Warm Start scenario, contaminated channels are identified by searching for the lowest clear channel, starting at channel C and proceeding upwards one channel at a time as long as either gradient or absolute value (or both) of the smoothed BT departure is outside pre-defined threshold values. In the example shown in Fig. 2, the search is finished and the lowest clear channel is identified near channel B (indicated by the red arrow).

Another form of Warm Start scenario (abnormal warm start) takes place in exceptional situations, where the smoothed BT departure exceeds BT\_Threshold on all channels ranked below the tropopause level. Only channels ranked higher than the tropopause can potentially be diagnosed clear in such situations.

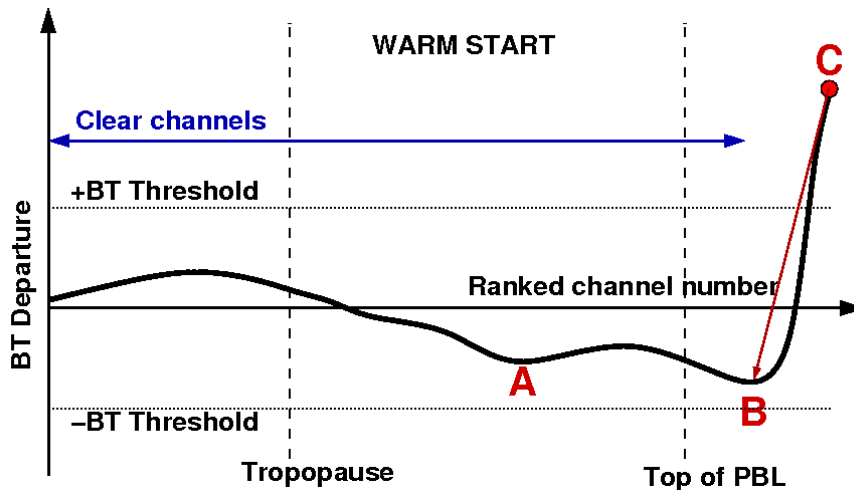


Figure 2: A schematic representation of the smoothed and vertically-ranked curve of BT departures in a Warm Start Scenario.

#### 2.1.4 Cold Start scenario

The Cold Start scenario is designed to account for the most common case, where there is a cold cloud above a warm surface. The Cold Start takes place whenever neither Quick Exit nor Warm Start is allowed. Usually this means that the smoothed BT departure curve goes below  $-BT\_Threshold$  at channel B at the very least, but this can also happen because of the gradient of the curve being too large within window channels or because of the imager-based scheme suggesting presence of cloud.

Figure 3 illustrates a typical Cold Start case. Similarly to the Warm Start scenario, the Cold Start scenario aims to identify contaminated channels by searching for the lowest clear channel. Usually the search is started at the highest of the three potential starting channels (i.e., channel A): only if neither absolute value nor gradient of the smoothed BT departure curve suggests presence of cloud at channel A, the search is started at channel B instead. Once the starting channel is identified, the lowest clear channel is found by proceeding upwards one channel at a time as long as either gradient or absolute value (or both) of the smoothed BT departure is outside pre-defined threshold values. This is highlighted in Fig. 3 by the red arrow.

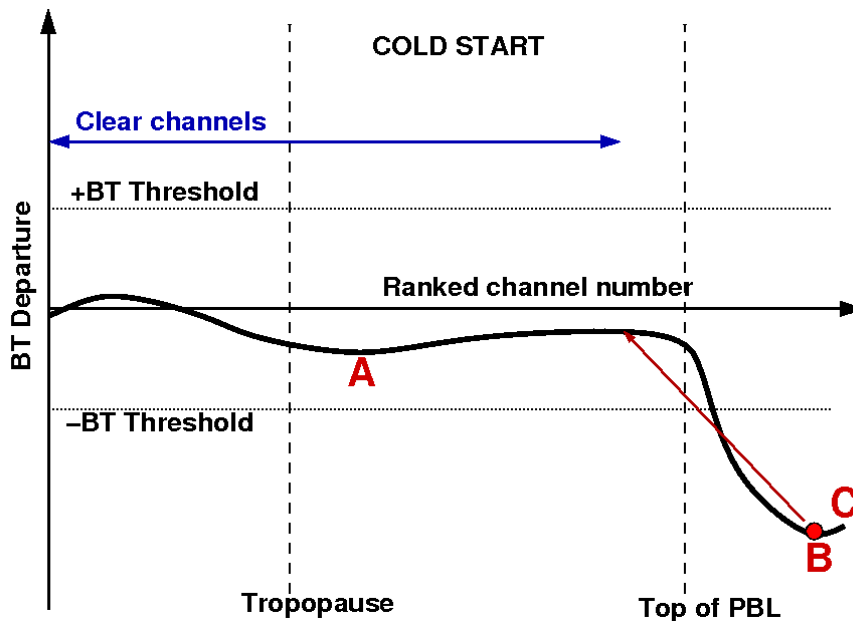


Figure 3: A schematic representation of the smoothed and vertically-ranked curve of BT departures in a Cold Start Scenario.

### 2.1.5 Cross-band option

It has been found that the algorithm is best applied to individual bands rather than the entire infrared spectrum. Therefore, five bands are defined for each sounder covering the 15 $\mu$ m CO<sub>2</sub> absorption band, the O<sub>3</sub> absorption band, the 6.3 $\mu$ m H<sub>2</sub>O absorption band, the long-wave side of the 4.3 $\mu$ m CO<sub>2</sub> absorption band, and the short-wave side of the 4.3 $\mu$ m CO<sub>2</sub> absorption band. The short-wave band is divided in two parts to separate channels that are sensitive to solar radiation or non-LTE-effects from those channels that are equally usable at day and night.

Optionally one may use the cloud detection in one band to infer cloud channels in another. This is useful, for example, in the water vapour band where errors in the background water vapour can easily mask or mimic cloud signal. To do this one uses the "cross-band" option. In using cross-band one should consider whether the height assignments for spectrally widely separated channels compare meaningfully. By default, the cross-band option is in use for the O<sub>3</sub> and H<sub>2</sub>O absorption bands, but also for short-wave CO<sub>2</sub> absorption bands of IASI and CrIS.

### 2.1.6 Imager-based cloud detection

As described above, one requirement for the Quick Exit scenario is that independently-derived cloud flag from collocated imager data is clear. The imager-based cloud flag is therefore determined before choosing the cloud detection scenario to be followed. However, the imager-based cloud detection is by default only done for IASI, in which case

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mean and standard deviation of observed BT in clusters of AVHRR pixels are exploited. Each cluster is assumed to be collocated with the sounder's field-of-view. Background BT estimates on imager channels are also required as input. In the default configuration, the imager-based cloud flag is determined using data on the two long-wave channels of AVHRR.

For AIRS and CrIS, the imager-based cloud detection is not done, and imager-based cloud flag is always set clear.

As explained in detail in Eresmaa (2014), the imager-based cloud flag is determined from three separate checks, called *the homogeneity check*, *inter-cluster consistency check*, and *background departure check*. Clear imager-based flag is output only in the case that none of the three checks suggests presence of cloud.

#### *Homogeneity check*

The homogeneity check looks for signs of heterogeneity, which is interpreted as a symptom of cloud contamination. Standard deviation of BT is computed for each imager channel using all pixels occupying the sounder's field-of-view, and this is compared with pre-defined (channel-specific) threshold values (`R__Stddev_Threshold`). Presence of cloud is diagnosed if the standard deviation exceeds the threshold value on all channels.

#### *Inter-cluster consistency check*

The inter-cluster consistency check looks for inconsistencies between clusters of imager pixels that occupy the same sounder field-of-view. If sufficiently large inconsistencies are found, the interpretation is that at least one of the clusters consists of cloudy pixels, implying that the field-of-view is contaminated. The degree of inconsistency is evaluated in terms of inter-cluster mean BT differences, as compared with BT differences between clusters and background. Figure 4 illustrates the way the decision is made.

In Fig. 4, the black circle denotes the background BT in a two-dimensional space (each dimension corresponding to one imager channel). Red letters A and B show mean BT observation within two clusters. In the panel on the left, the two clusters are closer to each other than either one of them is to the background: in this case the clusters are consistent with each other, implying that the field-of-view is potentially clear (as the departure between observation and background can be explained by background error alone). In the right-hand-side panel, in contrast, cluster A is closer to the background than to cluster B, resulting in a failure in the consistency check. Since the different characteristics of BT departure in the two clusters cannot be explained by background error alone, the interpretation in this case is that at least one of the two clusters is cloudy.

In order to prevent clusters consisting of only a few pixels from affecting the decision, threshold parameter `R__Coverage_Threshold` is applied for the fractional coverage.



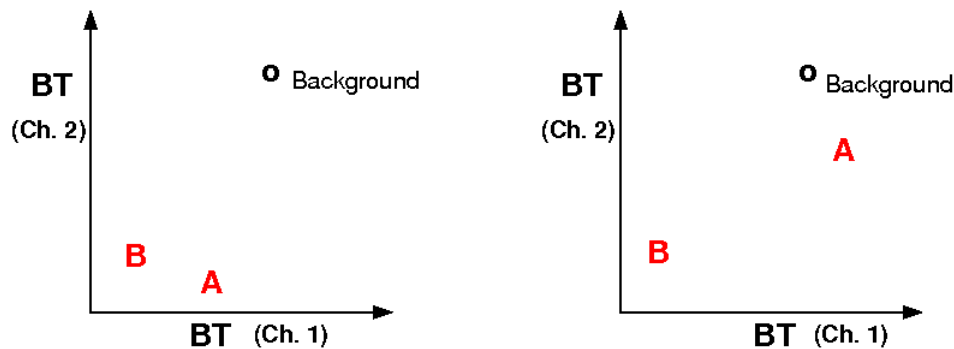


Figure 4: The inter-cluster consistency check.

### Background departure check

For the background departure check, overall mean background departure is computed from pixels that occupy the sounder's field-of-view. Each cluster's fractional coverage is taken into account, and departures on different imager channels are combined into one representative number measuring the distance between observation and background field. Presence of cloud is diagnosed if the pre-determined threshold value `R__FG_Departure_Threshold` is exceeded.

## 2.2 Aerosol detection

Aerosol contamination is diagnosed on the basis of observed BT differences in the window region at wavelengths 8—10.5  $\mu\text{m}$ . As listed in Table I, four key channels have been identified in the observing spectra of AIRS, CrIS and IASI. In case of CrIS and IASI, the BT observations are smoothed by averaging over a range of neighbouring channels ( $\pm 5$  channels for IASI,  $\pm 2$  channels for CrIS in the long-wave band, and  $\pm 1$  channels for CrIS in the mid-wave band) in order to make the scheme more robust against the effect of instrument noise. Using the four observed BT values, two BT differences are formed and compared with pre-defined thresholds (also listed in Table I). Both of the two BT differences are required to fall below the threshold values in order to diagnose aerosol contamination.

*Table 1: Aerosol detection channels and contamination thresholds.*

	AIRS		CrIS		IASI	
<i>Index</i>	<i>Channel</i>	<i>Wavelength</i>	<i>Channels</i>	<i>Wavelength</i>	<i>Channels</i>	<i>Wavelength</i>
1	1278	8.17 $\mu\text{m}$	730 $\pm$ 1	8.13 $\mu\text{m}$	1340 $\pm$ 5	10.21 $\mu\text{m}$
2	914	10.36 $\mu\text{m}$	529 $\pm$ 2	10.20 $\mu\text{m}$	2348 $\pm$ 5	8.12 $\mu\text{m}$
3	950	10.21 $\mu\text{m}$	704 $\pm$ 2	9.18 $\mu\text{m}$	1782 $\pm$ 5	9.17 $\mu\text{m}$
4	1285	8.14 $\mu\text{m}$	732 $\pm$ 1	8.11 $\mu\text{m}$	2356 $\pm$ 5	8.11 $\mu\text{m}$
<b>Aerosol contamination thresholds</b>						
$T_B(1)-T_B(2)$	-16.0 K		4.0 K		0.2 K	
$T_B(3)-T_B(4)$	1.8 K		-0.5 K		-1.7 K	

### 3. DESCRIPTION OF CODE

The calling tree for the software package is shown in Figure 5. Purpose of each routine is described below.

- `cloud_detect_wrapper` is a wrapper routine to allow one to test the other subroutines.
- `cloud_detect_setup` sets up the default configuration and reads in namelists specifying any deviations from the defaults. The namelists should be specified separately for each sounder (an example of a namelist file is shown later on page 11).
- `abor1` is a simple routine that allows program runs to be aborted in a controlled way.
- `imager_cloud_detect` determines initial cloud flags on the basis of collocated imager information.
- `cloud_detect` computes BT departures, distributes them in spectral bands, and assigns final cloud and aerosol flags.
- `heapsort` ranks BT departures according to channel height assignments.
- `cf_digital` identifies the cloud detection scenario and determines the highest contaminated and lowest clear channels.
- `movinga` smooths the vertically-ranked departure spectrum with a moving average filter.

- `aerosol_detect` identifies aerosol contamination.
- `yomiasi` is a module file containing all parameter and structure definitions.

Note that in most subroutines, variable names follow the ECMWF convention for the first letter. To aid readability this first letter is then followed by a double underscore.

The user may change the configuration of the cloud and aerosol detection through namelist files. This method allows one to use the default hard-coded values and to only specify the values that need to be changed - thus simplifying the control files.

The namelist file names are specified in `cloud_detect_setup` and are set to `AIRS_CLDDET.NL`, `IASI_CLDDET.NL`, and `CRIS_CLDDET.NL` for AIRS, IASI, and CrIS, respectively. The namelist name is `Cloud_Detect_Coeffs` and the variables that may be modified are listed in Table I.

The example namelist shown below overrides the default specification for channels assigned in Band 3.

```
&Cloud_Detect_Coeffs
N_Band_Size(3)=48
N_Bands(1:48,3)=
1301,1304,1329,1371,1382,1415,1424,1449,1455,1466,
1471,1477,1500,1519,1520,1545,1565,1574,1583,1593,
1614,1627,1636,1644,1652,1669,1674,1681,1694,1708,
1717,1723,1740,1748,1751,1756,1763,1766,1771,1777,
1780,1783,1794,1800,1803,1806,1826,1843
/
```

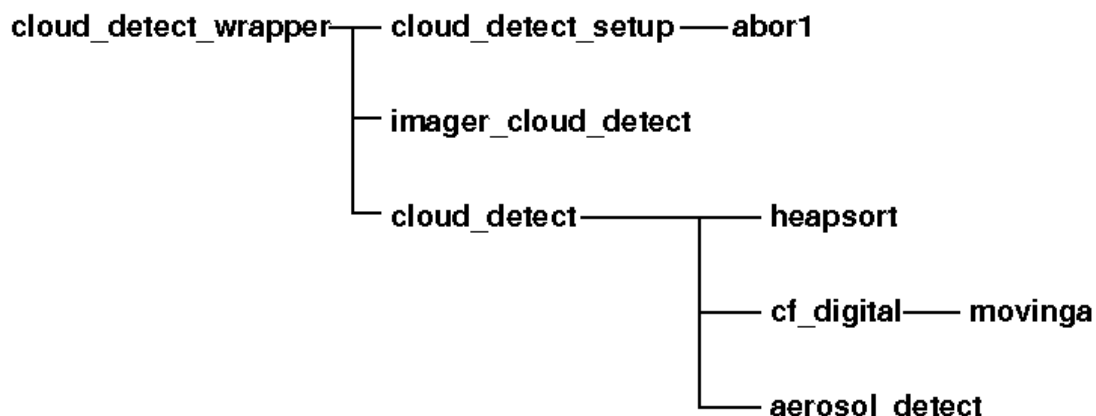


Figure 5: The calling tree of the software package.

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*Table II: Namelist parameters.*

Variable name	Type	Explanation
M__Sensor	INTEGER	Sensor ID. Set to 11, 16 and 27 for AIRS, IASI and CrIS, respectively (consistently with RTTOV)
N__Num_Bands	INTEGER	The number of spectral channel bands
N__Band_Size	INTEGER Array	The number of channels assigned in each band
N__Bands	Two-dimensional INTEGER Array	Lists of channels assigned in each band
N__Window_Width	INTEGER Array	Width of the smoothing interval
N__Window_Bounds	Two-dimensional INTEGER Array	Two channel numbers specifying bounds of the long-wave window
N__GradChkInterval	INTEGER Array	The number of channels over which the gradient of the smoothed BT departure is evaluated
R__BT_Threshold	REAL Array	The maximum absolute smoothed BT departure allowed in the search of the lowest clear channel
R__Grad_Threshold	REAL Array	The maximum smoothed BT departure gradient allowed in the search of the lowest clear channel
R__Window_Grad_Threshold	REAL Array	The maximum absolute smoothed BT departure gradient allowed within the long-wave window channels in the Quick Exit scenario
L__Do_Quick_Exit	LOGICAL	Switch enabling/disabling the Quick Exit scenario.
L__Do_CrossBand	LOGICAL	Switch enabling/disabling the cross-band cloud detection
N__BandToUse	INTEGER Array	Spectral band providing cloud top height diagnosis for bands using the cross-band option.
L__Do_Imager_Cloud_Detection	LOGICAL	Switch enabling/disabling the imager-based cloud detection
N__Num_Imager_Chans	INTEGER	The number of imager channels used
N__Num_Imager_Clusters	INTEGER	The number of imager pixel clusters to be expected as input
N__Imager_Chans	INTEGER Array	The indices of the used imager channels
R__Stddev_Threshold	REAL Array	Maximum BT standard deviation allowed in the homogeneity check of the imager-based cloud detection
R__Coverage_Threshold	REAL	Minimum fractional coverage allowed for a cluster of imager pixels to be considered in the inter-cluster consistency check
R__FG_Departure_Threshold	REAL	Maximum BT departure allowed in the background departure check of the imager-based detection
L__Do_AerosolDetection	LOGICAL	Switch enabling/disabling the aerosol detection
N__Num_Aerosol_Tests	INTEGER	The number of aerosol tests to perform
N__Num_Aerosol_Chans	INTEGER Array	The number of channels used in each aerosol test
N__Aerosol_Chans	Two-dimensional INTEGER Array	Lists of channels used in each aerosol test
R__Aerosol_TBD	Two-dimensional REAL Array	Threshold values used in the aerosol tests

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## 4. COMPILING AND RUNNING THE CODE

The cloud detection software is provided with a wrapper routine to allow stand-alone use of the software. The code is written in Fortran 90 and it is compiled by using a makefile provided as part of the package. Typing `make` in the source directory `CloudDetection/src` will compile the code and produce the executable `Cloud_Detect` in the parent directory `CloudDetection`. Note however that, depending on your local computing environment and Fortran 90 compiler settings, you may need to make slight modifications to the provided makefile.

The stand-alone code requires a single input file in ASCII format. The input filename specified in the code is `cloud_detection_input.dat`. Depending on whether or not the collocated imager information is provided, the input file should be structured in one of two alternative formats described below.

### 4.1 Input format without collocated imager data

#### *Header information*

- Sensor number
- The number of sounder channels specified in the file
- List of the sounder channels

*After the header, the following information are given for each observation:*

- Longitude and latitude of the observation (in degrees)
- Height assignments corresponding to the tropopause and the top of PBL at the time and location of the observation, specified in the same units as the channel height assignments
- The observed BT on each channel
- The background (first guess) BT on each channel
- Height assignments for each channel in units defined by the user (e.g., NWP model level or pressure level). Note that the higher numbers correspond to levels closest to the surface.

### 4.2 Input format with collocated imager data included

#### *Header information*

- Sensor number
- The number of sounder channels specified in the file
- List of the sounder channels
- The number of observations in the file

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- The number of imager channels specified in the file
- List of imager channels included in the file
- The number of imager clusters included in the file

*After the header, the following information are given for each observation:*

- Longitude and latitude of the observation
- Height assignments corresponding to the tropopause and the top of PBL at the time and location of the observation
- The observed BT on each channel
- The background (first-guess) BT on each channel
- Height assignments for each channel in units defined by the user
- Fractional coverage of each cluster
- Mean observed BT within each cluster and on each imager channel
- Overall standard deviation of imager pixels within the sounder's field-of-view
- Background BT on each imager channel

### 4.3 Output format

On running the software, an output file is produced containing the following information for each observation:

- Longitude, latitude, and sequential number of the observation
- Cloud flag on each channel: 0 means clear, 1 means cloud-affected
- Aerosol flag for the observation: 0 means clear, 1 means aerosol-affected

### REFERENCES

Eresmaa, R., 2014. Imager-assisted cloud detection for assimilation of Infrared Atmospheric Sounding Interferometer radiances. *Quarterly Journal of the Royal Meteorological Society*, 140, 2342-2352, DOI:10.1002/qj.2304.

McNally, A.P. and P.D.Watts, 2003. A cloud detection algorithm for high-spectral-resolution infrared sounders. *Quarterly Journal of the Royal Meteorological Society*, 129, 3411-3423.

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## APPENDIX A. HEIGHT ASSIGNMENTS FROM THE OUTPUT OF RTTOV

The ECMWF implementation of the cloud detection algorithm assigns cloud height based on the information provided by RTTOV-10 in the argument `radiancedata`. The `radiancedata` variable contains calculated radiances for a number of assumptions. Specifically, array `radiancedata%overcast` contains channel-specific radiances corresponding to the assumed presence of an opaque cloud at each of the RTTOV model levels. Radiances corresponding to clear (cloud-free) conditions are stored in array `radiancedata%clear`. The height assigned for each channel matches the model level index at which the difference between the overcast and clear radiances is exactly 1% of the clear radiance. This is expressed as a real number and it is interpolated from those two levels where the difference is just above and below the threshold of 1%.

Note that the height assignment is computed in radiance space (rather than brightness temperatures) as this is the unit provided by RTTOV. In typical atmospheric conditions, a 1% change in radiance corresponds to approximately 0.5K on wavelengths greater than 10 $\mu$ m, but decreases to around 0.2K at 3 $\mu$ m.