THE AVHRR CLOUD MASK SCHEME OF THE SAFNWC

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ABSTRACT

An automatic scheme to detect clouds from locally received AVHRR satellite imagery is being developed at SMHI for the EUMETSAT Satellite Application Facility to support Nowcasting and Very Short Range Forecasting (SAFNWC). The scheme is utilising a set of pixel-based multi-spectral image features (including local texture). Data are segmented into seven categories, including cloudfree, cloud contaminated, and cloud-filled, according to dynamically changeable thresholds. These are not only dependent on the sun-satellite viewing geometry, but also on the atmospheric environment and the characteristics of the surface, through the use of NWP model output and other ancillary data. The determination of the thresholds, which is a critical part of the algorithm, is made by the aid of off-line calculations with radiative transfer models (RTTOV and 6S). In this way the thresholds are tuned to the precise spectral characteristics of the AVHRR sensors, and thus it is possible to adapt the scheme to future changes in the sensor response functions. In this paper a basic description of the scheme is given, and some preliminary results are shown. The accuracy and limitations of the method are illustrated using a database of training and validation files.

1. INTRODUCTION

At SMHI software is being developed to extract cloud information from the data of the future NOAA/EPS and MSG satellites. The development is carried out mainly under the EUMETSAT Satellite Application Facility (SAF) to Support Nowcasting and Very Short Range Forecasting, and partly under the SAF for Ocean and Sea Ice applications (SAFOSI). The Nowcasting SAF (SAFNWC) is a project hosted by the Meteorological Institute of Spain (INM) and it is scheduled to end in February 2002, with the delivery of an integrated software package for the processing of 12 products, based on MSG and EPS/NOAA data, all thought to be crucial to Nowcasting applications.

The main delivery from SMHI will be software for four high latitude (north of ~50 degrees N) cloud products, in high resolution, based on AVHRR and AMSU data. A brief description of these four products can be found in Karlsson et al. (1998). Here the AVHRR Cloud Mask (CMa) scheme will be presented in more detail, and the first results on NOAA data will be shown.

At Meteo-France cloud products for mid and low latitude conditions based on MSG data is being developed in parallel. For an introduction to the MSG cloud products see the paper of Le Gléau and Derrien (1999) elsewhere in this proceeding.

In the second section the motivation for and definition of the CMa product is outlined. In section 3 the main features of the scheme are discussed, and some recent results are presented. The plans for the further development with tuning and validating the scheme are discussed in section 4.

2. THE AVHRR CLOUD MASK PRODUCT AND ITS SCOPE

A good and accurate high-resolution cloud mask is a pre-requisite for many satellite applications. Retrievals of surface parameters like SST, sea-ice extent, snow cover, and surface albedo, to mention a few, are all dependent on an accurate cloud/no cloud description. Furthermore, for the retrievals of various cloud parameters, for nowcasting purposes or climate monitoring, a reliable cloud mask is the basis.

In the context of the Eumetsat SAF's several products of at least the SAF for Land Applications, the SAF for Climate Monitoring, the SAFOSI, and the SAFNWC, are strongly dependent on an accurate cloud screening.

The AVHRR CMa software will be integrated in the EPS part of the SAFNWC software system, as well as in the SAFOSI software for high latitude product generation at the Norwegian Meteorologicat Institute (DNMI). The CMa will be the basis for the AVHRR Cloud Type product of the SAFNWC, which in turn will be the input to the algorithms for the SAFNWC AVHRR/AMSU products: Cloud Top Temperature/Height and Precipitating Clouds. Furthermore, the CMa will be an important input to the SAFOSI algorithms for the high latitude SST, sea ice extent, and sea surface radiative fluxes developed jointly by DNMI and the Danish Meteorological Institute (DMI).

2.1. Product definition

The central aim of the CMa is to delineate all absolutely cloud-free pixels in a satellite scene with a high confidence. In addition, the CMa will provide information on the presence of aerosols and snow/sea ice, and it will help to distinguish between thick and semi-transparent clouds. Seven different categories have been defined: *Non-processed* (no or corrupt data); *Cloud free*; *Cloud contaminated*; *Cloud filled* (opaque); *Aerosol contaminated*; *Snow/Ice contaminated*; *Unclassified*.

The CMa product includes a set of quality flags. This will for each pixel provide information on the presumed quality of the estimated cloud/no cloud category listed above. The quality flags will reflect an a priori confidence in the applied screening algorithm, building on current experience and depending on known deficiencies that may depend on parameters such as illumination, viewing geometry, and the atmospheric temperature profile. In addition the quality flags will depend on the distance to thresholds in the image feature space. A pixel being classified in one of the seven categories but having one or more feature values which are close to the applied threshold will be assigned a lower quality than a pixel with all the feature values far away from the thresholds.

3. DESCRIPTION OF THE SCHEME

3.1. Overview

The CMa scheme is using a number of spectral and textural image features derived from all five/six AVHRR channels, NWP output and other ancillary data. The scheme is a classical thresholding scheme like the cloud classification models of SCANDIA (Karlsson, 1989), Lux (Derrien et al., 1993), and APOLLO (Saunders and Kriebel, 1988). But, instead of using mostly static thresholds, as is the case for earlier models, the CMa scheme will to a large extent utilise dynamically variable thresholds derived from radiative transfer simulations of the actual cloud free conditions. Thus thresholds are fitted to the actual atmospheric and geographic conditions and precise satellite viewing and sun illumination valid for each individual pixel.

The CMa scheme can be seen as a two step algorithm. Before the reception of the AVHRR data a number of threshold images are prepared. After acquisition and pre-processing of the AVHRR data the threshold images and necessary ancillary data are being read, and the actual threshold tests are applied. The CMa scheme assumes calibrated and navigated AVHRR data rectified to a polar stereographic map-projection.

The separation of the scheme in two parts, not only comes natural, it is also a way to minimise the time between the reception of satellite data and the time of the availability of the cloud mask. In Nowcasting applications time is a crucial factor, and one of the most severe user requirements for the SAFNWC products concerns timeliness.

3.2. Pre-processing and derivation of thresholds

In cloud screening when using a thresholding algorithm the critical part is to find the most optimal thresholds, valid for the locally prevailing conditions. The most optimal threshold is the one for which any observation giving a value exceeding the threshold value exclusively must be a result of cloud contamination (or contamination by snow cover or atmospheric aerosols), leaving cloud free as the only possibility when below the threshold.

In the attempt to find the most optimal thresholds these are in most cases derived from radiative transfer model (RTM) simulations of the expected cloud free satellite signal, taking into account the surface characteristics, the atmosphere, the sun and satellite viewing geometry and spectral characteristics.

Information on the variable surface characteristics is provided by the digital 1-km land cover map of the U.S. Geological Survey (USGS) classifying the surface into 24 land cover types[1], and the use of the appropriate IR emissivities and VIS/NIR bi-directional reflectance distribution functions (BRDF).

The validity of the derived thresholds has been checked by comparison with cloud free and cloudy observations. Using a dedicated interactive tool, mainly two independent operators have been classifying small targets in NOAA data over Europe and adjacent ocean areas. For each target the label of the subjective classification of the operator is stored together with the satellite data, nearest NWP profile of temperature and humidity, and the surface type and elevation. A total of 3725 targets have so far been collected for NOAA 12, 14 and 15, and they are distributed among 44 different cloudy and cloud free classes. An example of the use of these data is shown later in figure 2.

3.2.1. Infrared thresholds

For the IR channels (3b, 4, 5) we pre-compute a large set of cloud free radiances for all kinds of atmospheres, viewing angles, satellites (NOAA 12,14,15), and surfaces. These radiances are derived using the radiative transfer model RTTOV (Eyre, 1991 and Brunel et al., 1995) and the

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[1] The URL: http://edcwww.cr.usgs.gov/landdaac/glcc/glcc_na.html

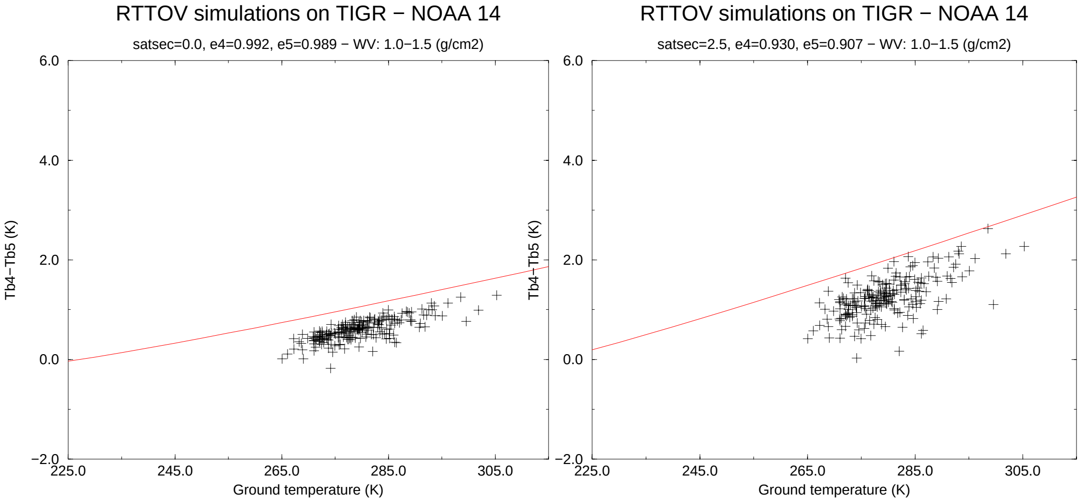

Figure 1: Definition of thresholds for the feature for semi-transparent clouds during day time, Tb4-Tb5. Simulations with RTATOV of this feature, using the TIGR profiles, are plotted against the surface temperature for two different satellite zenith angles and for a constant water vapour content. The curve is defining the threshold and is derived by adding 2.5 standard deviations to the linear regression, plus a temperature dependent noise.

dataset of 2311 atmospheric profiles of the TIGR-3 (TOVS Initial Guess Retrieval - see Chedin et al., 1985) together with knowledge of the surface emissivity.

It would of course be theoretically possible to derive the actual expected cloud free radiances by on-line simulations with RTTOV, with input of the actual values of viewing angle, water vapour profile, etc. But this procedure would be far too slow on even a small area and using a coarse resolution to be practically possible for real time applications. Thus, simulations have been done off-line and results have been tabulated to enable quick access and definition of thresholds.

In the IR channels the cloud free signal depends mainly on the surface temperature, the vertical atmospheric temperature profile, and the amount and distribution of atmospheric water vapour. However, we have neglected possible variations in the temperature and water vapour profiles, assuming that the parameters column integrated water vapour and surface temperature are sufficient to describe the expected cloud free signal. This is a fairly good approximation for most atmospheres without existence of strong low level inversions.

We have found that for all the IR features (generally defined as linear combinations of the IR channel brightness temperatures) it is possible to apply a linear relation between the cloud free signal and the ground temperature for constant water vapour and viewing angle for a given surface. The IR thresholds are derived from the linear regression curve by adding 2.5 standard deviations and the given temperature dependent noise level valid for the channel combinations. Figure 1 illustrates this definition of thresholds for the IR brightness temperature difference between AVHRR channels 4 and 5.

For land surfaces we assume a surface emissivity of 1.0 in all channels and for all surface types. This may be a serious simplification for some non-vegetated surface types (see laboratory measurements by Salisbury and d’Aria, 1994), and will especially for the IR features using channel 3 give rise to problems over desert areas. However, desert like surfaces at the scale of an AVHRR pixel are rarely encountered in northern Europe. Should validation prove that special treatment of some surface types is necessary, it is possible to implement the extra surface dependency in the threshold tables.

For the ocean we use the tabulated values of sea surface emissivity as a function of the satellite zenith angle and the surface wind speed, published by Masuda et al. (1988). Since the effect of wind speed is neglected in the CMa scheme we use the values valid for a surface wind speed of 5 m/s as representing average conditions.

3.2.2. Visible thresholds

For the visible channels (1, 2, 3a, and 3b) we derive the expected cloud free reflectances valid for the actual conditions. Cloud free simulations was done with the 6S RTM (Tanré et al., 1990) on a set of standard atmospheres with constant ozone and aerosol contents, and varying water vapour and sun and satellite viewing angles.

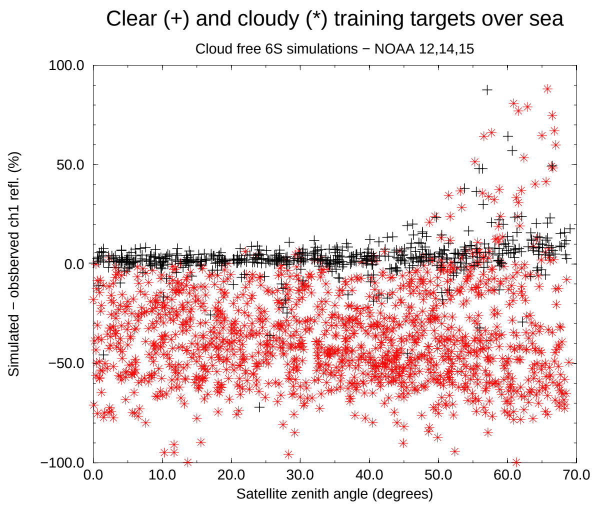

Figure 2: Simulated cloud free channel 1 reflectances compared to the observed cloud free and cloudy observations of the sea targets of the interactively collected training database.

First the expected surface reflectance, in the absence of atmospheric gases (but including aerosols), is calculated from the appropriate BRDF. This generates a table of the surface reflectance as a function of the sun zenith, the satellite zenith, and the sun-satellite azimuth difference angle. Then the one way atmospheric transmission due to gaseous absorption is calculated as a function of the total integrated water vapour and the angle of the atmospheric path relative to the surface normal. The atmospheric transmission is calculated with a constant ozone content of 0.344 cm-atm. The expected cloud free reflectance as measured by the satellite, is then derived by multiplying the surface reflectance with the transmission coefficients valid for the given sun and satellite zenith angles.

In figure 2 the simulated cloud free channel 1 reflectances are plotted relative to the observed for different sun zenith angles for cloud free and cloudy ocean targets, respectively. It can be seen that the cloud free simulations can be used to distinguish most clouds and cloud free observations.

3.3. Image features

The threshold tests will utilise a series of image features derived from all the available spectral channels of the AVHRR. The CMa scheme is being developed so as to handle daytime data transmissions with either channel 3a (as expected for the future EPS satellites) or 3b (as for the current NOAA satellites). However, currently the development is focusing on the set-up of today with no 1.6µm channel. But the scheme will soon be extended to work on data with channel 3a active during day, using an archived dataset of NOAA 15 1.6µm data from the spring of 1999.

In table 1 is displayed a list of the currently utilised day- and nigh time features, together with their main usage. In addition to the use of the 1.6μm channel there are some new features compared to earlier models. The use of the brightness temperature difference between channel 3b and 5 for semi-transparency detection during night is an improvement compared to the SCANDIA use of the Tb4-Tb5 difference. The derivation of the channel 3b reflectance and its quota with the channel 1 reflectance will improve the separation of sunglint and low clouds, and make retrieval of aerosol information possible.

Image Feature	*Main usage*
Channel 1 reflectance: r1	All (thick) clouds over land. For aerosol detection.
Channel 2 reflectance: r2	All (thick) clouds over ocean.
Channel 3a reflectance	Snow
Channel 3b reflectance	Snow
r2/r1	Aerosols over ocean; Clouds under strong anisotropic conditions.
r3a/r1	Water cloud – snow/sea ice separation; Aerosols over ocean; Clouds under strong anisotropic conditions; Water cloud–sunglint separation.
r3b/r1	Same as for r3a/r1
Channel 4 brightness temperature: tb4	All (thick) clouds, in combination with the forecasted surface temperature.
tb4-tb5	Semi-transparent clouds during day and twilight conditions.
tb3-tb5	Semi-transparent clouds during nightime.
tb4-tb3	Water cloud detection during nighttime.
Channel 4 tb 5x5 texture	Sub-pixel clouds and cloud edges.
r2 or r3a 5x5 texture	Sub-pixel clouds, and cloud edges over sea.
tb3-tb5 5x5 texture	Sub-pixel clouds, and cloud edges during both day and night conditions

Table 1: The utilised image features and a short description of their main use in the cloud mask scheme.

A new approach in analysing local texture has been applied. Texture is handled by studying the local variance in three (two during night) features: the channel 2 (or 3a) reflectance, the tb4 and tb3-tb5. Pixels over open sea are detected as contaminated by clouds if the local variance is high in all features. By requiring a high texture in all features, one avoids mistakes due to strong thermal gradients in sea surface temperatures. However, due to large local variations in all three features over cloud free land only a very cautious usage of the texture of tb4 will be applied, and only over non-coastal regions.

3.4. Structure of the cloud mask tests

During the cloud screening process all pixels will go through a sequence of tests. The exact sequence will depend on five different sets of conditions: day/night/twilight; land/sea/coast; low/high terrain; presence or not of low level temperature inversion; and presence or not of sunglint.

Day time is defined by the sun being sufficiently above the horizon (presently set to 10 degrees) and *night* time by a sun being well below the horizon (presently 5 degrees). This makes two rather clean and homogenous sun elevation zones, and leaves one more difficult *twilight* zone where effects such as shadows and strong surface reflection anisotropy are pronounced, and cloud/cloud free separability is weak in many features.

The definition of an algorithm specific to a *coastal* zone, in addition to the commonly different approaches needed over land and sea is made in order to compensate for known and inevitable errors in satellite navigation. A pixel being in the coastal zone cannot be assigned to either land or sea with 100% confidence, so here a combination of tests from the land and the sea algorithms will have to be applied, and thresholds will be chosen more carefully. The size of the coastal zone can be adjusted in respect to the known errors in navigation.

Over land, there will be one algorithm over *low terrain* and a special treatment of mountainous regions - *high terrain* – where e.g. the tests against surface temperature will have to be more cautious. The division between low and high terrain is using a limit of 500 meters above m.s.l. according to the 1 km global digital elevation model of the USGS, re-mapped onto the region[2].

Over low terrain on land, in coastal areas and over ice covered sea the basic test using tb4 and the forecasted surface temperature is sometimes the only means to detect clouds during night and in twilight. If this test is applied alone and a low level temperature inversion is present there will be a zone in the lower troposphere where clouds can exist without being detected. Therefore a check for the possible presence of a low level inversion is made for these situations. If a low level inversion is present, according to the difference of the forecasted surface temperature and the temperature at 950 hPa the pixel will be assigned cloud free, since this is most often the case, but it will be given a low confidence through the quality flag.

Over the sea and in the coastal zone, during day and twilight, the probability for sunglint to occur is calculated from Cox-Munk theory considering an average distribution of facets as a function of sun and satellite view angles (see Berendes et al., 1999). If this probability exceeds a certain threshold, a special sunglint sequence of tests is applied.

In figure 3 the basic output of the CMa scheme for a daytime example over the Norwegian Sea and northern Scandinavia is shown.

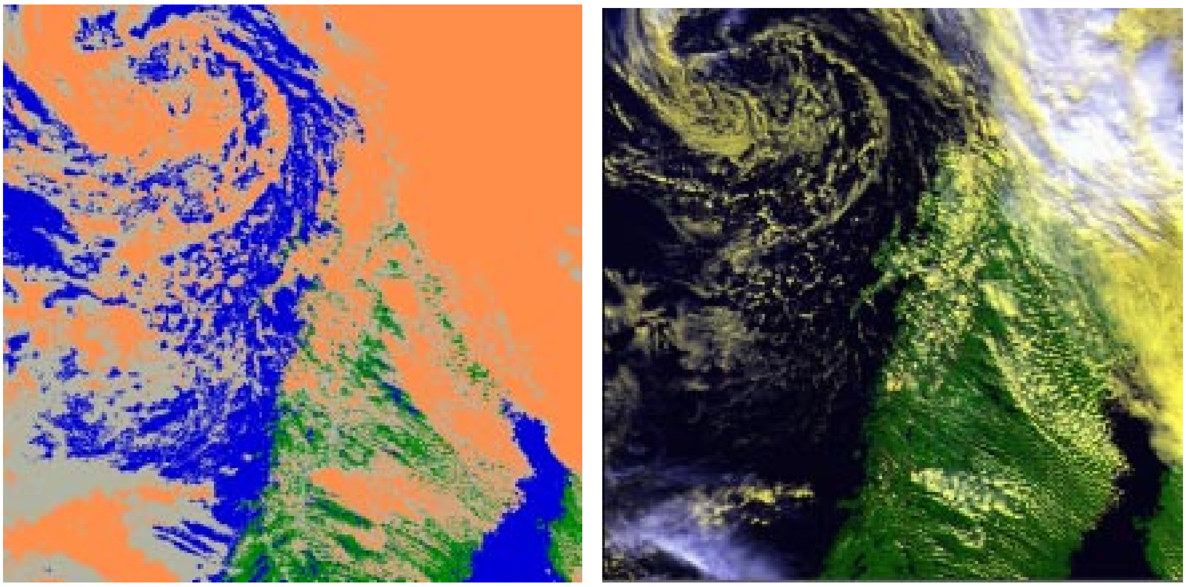

Figure 3: Left: The AVHRR Cloud Mask (orange is *cloud filled* and grey is *cloud contaminated*) over a region in the Norwegian Sea for a NOAA 14 pass 13:13 UTC the 13th of August, 1999. Right: The corresponding RGB using channel 1,2, and 4.

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[2] Global 30 Arc Second Elevation Data Set: http://edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html

4. FURTHER TUNING AND VALIDATION

The basic concept for the CMa scheme, that is the methods for pre-calculation of thresholds, is relatively new and untested for Nowcasting applications. This means that a period of tuning of thresholds and validation of results is necessary prior to the final release of the scheme. For these tasks, a careful monitoring of the performance of the scheme over a long period is crucial. But also comparison with “ground truth” will be evaluated. For this purpose Synop reports have been continously collected since June 1998 for ~50 stations in Northern Europe, and the reports are collocated in time and space with satellite and NWP information.

Besides establishing appropriate and useful thresholds, it is also necessary to pay special attention to some of the critical parts of the scheme. This concerns, for example, the methods to treat sunglints in the ocean, cases with strong temperature inversions during winter conditions and situations in twilight. A central task here will be to describe the scheme’s limitations and how these will be reflected in the contents of the attached quality flags.

The final deliverance of the SAFNWC software will take place in early 2002, after a hopefully successful software integration and operational implementation.

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