Rough Draft

CLAVR-x Cloud Mask Algorithm Theoretical Basis Document

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Washington, D.C

Version 0.1

March 1, 2004
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1. Introduction

The Extended Clouds from AVHRR (CLAVR-x) cloud mask is an algorithm used to detect the presence of cloud in data from NOAA's Advanced Very High Resolution Radiometer. The CLAVR-x cloud mask (CCM) is part of series of cloud algorithms used by NOAA to derive information on cloudiness. Other CLAVR-x algorithms include those used for cloud typing and cloud property retrieval.

The CCM is designed to serve as cloud mask for multiple AVHRR applications and it therefore must be able to provide clear and cloudy pixels with enough accuracy to allow for accurate estimation of both clear and cloudy environmental data records (edr's). In addition, the CCM is mandated to work globally for all AVHRR orbital configurations. The last constraint placed on the CCM is that is processes the AVHRR data fast enough to allow for real-time generation of all required products that rely on the CCM.

Throughout this document, the differences between the CLAVR-x and CLAVR-1 cloud masks will be described. It is important to note that two clouds mask are still very similar with CLAVR-x representing a natural progression in complexity from CLAVR-1. The CLAVR cloud detection philosophy can be summarized as the following. Cloud test thresholds should be set to unambiguously detect cloud for all scenarios where the test is to be applied. If any one cloud test detects cloud, the pixel is not clear. Spatial uniformity acts to move clear or cloudy pixels into a partly-clear or partly-cloudy category.

This document will first describe the structure and suggested use of the CCM. Next, the ancillary data-sets are described. Section 4 describes each cloud test while section 5 describes the use of spatial uniformity tests. Section 6 describes the method used by
NOAA to produce a cloud amount from the pixel level cloud mask.
2. Cloud Mask Description

The version of the CCM described here is the cloud mask from the extended Clouds from AVHRR (CLAVR-x) system. This cloud mask is based on the CLAVR-1 cloud mask described by Stowe et al (1999). While CLAVR-1 classified a pixel to be either clear, mixed or cloudy, the CCM uses a four-level cloud classification scheme. The cloud classes used by CCM are

0 – clear
1 – partly clear
2 – partly cloudy
3 – cloudy

This change from a three-level to a four-level cloud mask is the largest philosophical difference between CLAVR-1 and the CLAVR-x cloud mask. The reason for increasing the number of cloud mask values is to allow for a more conservative cloudy class for better cloud property estimation, to improve the cloud amount estimation from the cloud mask and to improve the cloud mask imagery. In CLAVR-1, the mixed pixels often dominated a scene. As shown later, the 4 level cloud mask seems to provide a better description than CLAVR-1 3 level mask.

In general, partly clear pixels are often clouds with spatial scales that are insufficient to pass any cloud test. Conversely, partly clear pixels can be clear pixels in regions with enough surface spatial variability to trigger the clear spatial uniformity tests. Partly cloudy pixels are typically found on cloud boundaries or cloud shadows. The determination of clear spatial uniformity test balances the over classification of clear as
partly clear pixels and the need to reduce cloud contamination of the clear pixels. The cloudy spatial uniformity thresholds are set to balance the number of cloudy pixels available for retrievals and the minimization of clear contamination in the cloudy radiances.
3. Ancillary Data Sets

Before describing the cloud mask tests, the ancillary data used with the cloud mask is described. The ancillary data used by CLAVR-1 included a 1/16th degree land mask and a lower resolution desert mask. As in done in CLAVR-1, the CLAVR-x cloud mask uses ancillary data to select thresholds or to turn off tests. The ancillary data sets used currently in CLAVR-x are a surface type database, a digital elevation map, and monthly maps of climatological NDVI, SST and minimum channel 4 brightness temperature. The rest of this section describes these data and their usage.
3.1 Surface Type

The surface type database used in CLAVR-x is the University of Maryland’s 8 km global data base. This data is described at the following site:

http://www.geog.umd.edu/land_cover/8km-map.html

and is referenced in Defries et. al (1998). The UMD database classifies the world into 14 surface types (0-13) based mainly on the dominant vegetation type. In this classification, Antarctica and Greenland were classified as barren and there was no separate snow/ice surface class. To remedy this, the UMD database was modified by reclassifying all barren cells that called snow/ice in the IGBP data as snow/ice. The resulting 8km classification is shown below. The IGBP data used for the snow/ice determination is given by

http://www-surf.larc.nasa.gov/surf/pages/sce_type.html

In the future, we would like to adopt higher resolution surface type data because this serves as the basis of the land mask. We are also considering switching to the IGBP classification because of the existence of other ancillary data-sets such as surface emissivity that have been compiled for the IGBP classes.
Modified 8 km UMD surface type database
3.2 Land/Sea Mask

The land/sea mask used in CLAVR-x is taken directly from the 8 km UMD surface type described above. This replaces the existing 1/16th degree land/sea database used by CLAVR-1. In future, we would like a higher resolution land/sea mask to support the global 1km data from the METOP/AVHRR.

Land/Sea Mask used by CLAVR-x based on the 8 km UMD surface type.
3.3 Desert Mask

In CLAVR-1, a separate low resolution desert mask was used to classify land pixels as being potentially desert. In CLAVR-x, the 8 km UMD surface type is used to determine if a land pixel is in a desert. In addition, CLAVR-x maintains two desert masks. One is a general attempt to characterize land surfaces that behave as deserts and also covers regions where the ch2/ch1 ratio behaves unlike that for vegetated land. The other desert mask is an attempt to capture regions where the ch3b emissivity departs enough from unity to exhibit a radiative behavior very different from vegetated land.

- A pixel is considered desert in all tests involving ch3b if its UMD surface type is 7, 8, 9, 11 or 12.
- A pixel is considered be a general desert pixel if the UMD surface type is 12.
3.4 Elevation

CLAVR-1 never used information on topography in the cloud mask. Information on elevation and its variability is useful for improving the cloud detection performance. For example, knowledge of elevation is used to restrict the application of the thermal tests that are known to be falsely triggered by thermal signatures of high terrain. CLAVR-x uses the USGS GTOPO30 data base as the basis for its elevation information.


Two resolution options are available (1/16th degree and 1/8th degree). The figure below shows the 1/16th degree elevation map used in CLAVR-x.

![1/16th degree elevation map derived from GTOPO30 data](image-url)
3.4 SST Monthly Climatology

In CLAVR-1, a threshold of 270K was applied to T4 over ice-free oceans to detect cloud. This threshold is based on the freezing point of water. Analysis of the monthly SST climatology data made available by the SAA indicates the annual cycle of the SST for any one grid-cell is much larger than the year to year variation for any one month. Based on this, it was decided that incorporation of a monthly SST climatology could add benefit the oceanic cloud detection. The SST climatology used is Optimal Interpolated SST product from NOAA’s EMC.

http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/

The resolution is 100 km and the coverage is global. Each field is an array with the dimensions 360 by 180. Land grid-cells are filled with a missing value. The data read into CLAVR-x are already scaled to be a one byte integer and the SST values range from -4 to 36 C. The current file is called “sst_climatology_oisst.dat” and resides in the clavrx/data/sfc_data in the CVS release. In addition to the 12 monthly fields, two additional fields are included. One is the minimum monthly sst and one is the standard deviation.
Optimally Interpolated SST (OISST) climatology for January

Optimally Interpolated SST Climatology for July
3.5 NDVI Monthly Climatology

The monthly data from the AVHRR Pathfinder Atmospheres (PATMOS) was used to derive monthly climatologies (1981-1999) of the normalized vegetation index (NDVI). The resolution of this data is 110 km. In addition to the monthly means, the minimum monthly NDVI for each cell is also available within CLAVR-x. The figures below show the NDVI climatology derived from PATMOS for July and January. Note, that this NDVI is not corrected for atmospheric or angular effects. In CLAVR-x, this information is used to derive reflectance thresholds that vary with the NDVI. This has been found to be a sounder basis for reflectance thresholds than use of the static UMD surface types.
PATMOS NDVI Climatology for July

PATMOS NDVI climatology for January
3.6 Minimum Ch4 Clear Temperature

The monthly PATMOS data was also analyzed to provide the minimum monthly mean clear channel 4 brightness temperature. This information is used to detect regions where non-cloud conditions can falsely trigger thermal cloud tests. This information is also used to locate regions where cold surface temperatures may reveal regions that are probably snow covered. In the future, we plan to use other AVHRR reprocessing to produce a minimum channel 4 brightness temperature data-set with higher temporal and spatial resolution.
4 Cloud Detection Tests

In this section, we present the theoretical basis of each of the CLAVR-x cloud tests. Most of these tests share the same name with the CLAVR-1 cloud tests. While some have remained unchanged, most of the CLAVR-1 cloud tests were significantly modified. However, the philosophy of the CLAVR-x and CLAVR-1 cloud tests are the same. The cloud test thresholds are set such that no clear pixel should ever be classified as cloud. While this results in conservative thresholds for any one particular test. The CLAVR approach is to apply many tests using all spectral information to detect all possible cloud.
4.1 Reflectance Gross Contrast Threshold (RGCT) Tests for Ocean Pixels

In this section, the application of the ch2 reflectance test for ocean pixels is described. This test makes the assumption that clouds are more reflective than the underlying oceanic surface. The difficulty in this type of test is the proper accounting for sun-glint and for separation of cloud from aerosol.

**CLAVR-1**

In CLAVR-1, the RGCT used constant thresholds. In regions of oceanic glint (glintzen < 40 degrees), the RGCT tests was not applied. The RGCT is a test to see if the ch2 reflectance exceeds a threshold (30% in CLAVR-1). The simplistic application of these tests in CLAVR-1 caused large apparent transitions in the cloud mask through glint regions. Also, the large variation in the oceanic surface reflectance with solar and viewing geometry caused the single value thresholds used in CLAVR-1 to be very conservative for most viewing conditions.

**CLAVR-x**

To alleviate these problems, the single value thresholds in CLAVR-1 were replaced lookup tables that include all variations in solar and viewing geometry. The generation of the lookup tables was accomplished through use of the 6S radiative transfer model (Vermote et. Al, 1997). Many 6S simulations were run to simulate the top of atmosphere for a clear ocean pixel with differing wind speeds, wind directions and aerosol loadings. The goal was to make a lookup table for each threshold that represented the maximum value possible from a clear scene for any given solar and viewing geometry. Therefore the final lookup table contains values from simulations with varying wind and aerosol
conditions. The first figure below shows the RGCT threshold as a function of viewing zenith angle and the relative azimuth angle for a solar zenith angle of 30 degrees.

Because the specular reflection is present within the lookup table and no masking of the glint regions is used in the application of these tests. An example of the application of the RGCT over the ocean is given below. The left panel in third figure shows the observed ch2 reflectance, the middle panel shows the value of reflectance threshold interpolated from the lookup table and the right panel shows the resulting RGCT mask. Note that the reflectance thresholds include the effects of specular reflection and limb brightening.

*Variation of the 0.86 micron clear ocean reflectance threshold used in RGCT over the ocean. The solar zenith angle is 30 degrees.*
Example of the application of the RGCT over the ocean. Left image shows the ch2 reflectance. Center image shows the predicted RGCT threshold over the ocean. Right image shows the resulting RGCT mask over the ocean.
4.2 Reflectance Gross Contrast Test (RGCT) over Land

**CLAVR-1**

A single threshold value of 44% was applied to the 0.63 micron reflectance for all land pixels.

**CLAVR-x**

The CLAVR-x threshold of 44% was found to be too conservative over most vegetated land surfaces. Initially, a reflectance threshold based on the surface type was tried. This did not perform well due to inability of a static surface type map to capture the seasonal cycle in surface reflectance. The variation in surface reflectance is mainly driven by the BRDF effects and the variation in the vegetation. To account for these effects, the RGCT 0.63 micron reflectance threshold over land was modified to be a function of the scattering angle and the NDVI. This approach is similar to that proposed by Vemury et. al (2001). The NDVI values used for these thresholds are taken from the monthly NDVI climatology described earlier.

The PATMOS climatologies of clear reflectance were not used to define these thresholds for two reasons. First, the CLAVR-1 threshold of 44% was used and this would falsely limit the clear 0.63 micron reflectance to values below this. Experience has shown that some surface have 0.63 micron reflectances greater than 44%. Secondly, the PATMOS only used data from AVHRR's in afternoon orbits. To capture a larger range in scattering angle for all seasons, data from the morning orbits was used. The data used for these thresholds was therefore taken from selected days of global AVHRR data from NOAA-
14, NOAA-12 and NOAA-16 in the months of April, July, September and January. In all, roughly three weeks of data are used from 1995, 1998 and 2001. These times correspond to periods where the individual AVHRR's are well calibrated (Rao and Chen, 1996; Heidinger et al, 2002; Heidinger et al, 2003).

The resulting clear 0.63 micron reflectances were then compiled as function of scattering angle for several ranges of NDVI. The center of the NDVI bins ranges from -0.05 to 0.40 with the bin centers spaced 0.05 apart. Values falling outside the bin ranges were included in the end bins. The following figures show the resulting data and the derived RGCT thresholds over land. For each individual NDVI bin, the data were composited in scattering angle bins from 60 to 180 degrees in scattering angle. The convention used was that pure backscatter was represented by 180 degrees and forward scatter occurred for scattering angles less than 90 degrees.

The thresholds were derived by performing a histogram on the data in each scattering angle bin. The reflectance value that was greater than 99% percent of the pixels was taken to represent the appropriate threshold for each bin. These value are shown in the following figures as the dashed line. A second order polynomial fit as a function of scattering angle was then applied to the individual reflectance thresholds for each bin and the resulting curves are shown in the following figures as the solid lines. The polynomial fits are used to compute the thresholds. No interpolation between NDVI bins is used currently in CLAVR-x.
Variation of the RGCT threshold on the ch1 reflectance over land in various NDVI classes ranging from mean NDVI's of -0.05 to 0.10.
Same as previous figure except for NDVI classes ranging from mean NDVI's of 0.15 to 0.30.
Same as previous figure except for NDVI classes ranging from mean NDVI of 0.35 to 0.40.
4.3 Reflectance Ratio Contrast Test (RRCT) over Ocean

This test compares the ratio of R2 to R1 (R2/R1) over the ocean to a threshold. If the value of R2/R1 exceeds this threshold, the pixel is classified as cloudy.

*CLAVR-1*

Values of R2/R1 less than 0.9 over ocean outside of glint regions were flagged as cloud by the RRCT.

*CLAVR-x*

As was the case with the RGCT over ocean, the use of single threshold was found not perform well over the full range of solar and satellite viewing geometries. By using a single threshold, CLAVR-1 was forced to set the threshold much higher than required for many situations in order to prevent false detection for all situations. In CLAVR-x, a similar use of the 6S radiative transfer model is used to develop the RRCT thresholds over ocean that vary with the solar and satellite viewing geometry. In compilation of the RRCT thresholds, the maximum value of R2/R1 was compiled from the ensemble of all radiative transfer simulations. The resulting RRCT threshold for an ocean surface for a solar zenith angle of 30 degrees is shown in the following figure.
Variation of the RRCT threshold ($R_2/R_1$) over the ocean for a solar zenith angle of 30 degrees.
4.4 Reflectance Ratio Contrast Test (RRCT) over Land

This test compares the ratio of R2 to R1 (R2/R1) over land to a threshold. If the value of R2/R1 is below this threshold, the pixel is classified as potentially cloudy.

CLAVR-1

A single value of 1.1 was used as the threshold for all land pixels that are not classified as desert.

CLAVR-x

A threshold of R2/R1 is derived based on the monthly NDVI climatology described above. The ratio of R2 to R1 is related to the NDVI as follows

$$\frac{R2}{R1} = \frac{1 + \text{NDVI}}{1 - \text{NDVI}}$$

The threshold used on for the RRCT over land is 0.75 times the value predicted from the monthly NDVI climatology. The value of 0.75 was empirically found to limit false detection. In addition, the threshold is constrained to lie between 1.1 and 1.5. Because the NDVI climatology automatically includes the effects of deserts and semi-arid regions, no desert mask is used in this test.
4.5 Channel 3b Albedo Test (C3AT) over the ocean

This test applies a threshold on the derived 3.75 micron reflectance (R3b). Pixels with R3b exceeding this threshold are potentially cloudy.

CLAVR-1

The C3AT threshold for R3b was 3% and no threshold was applied in regions of sun glint.

CLAVR-\(x\)

The same simulations used to derive the RGCT thresholds over the ocean are used to derive the R3b thresholds used in the application of the C3AT over the ocean. The following figure shows the R3b threshold used in the C3AT for a solar zenith angle of 30 degrees.
4.6 Channel 3a Albedo Test (C3AT) over Ocean

When the AVHRR/3 is operated with the 1.6 micron channel (3a) replacing the 3.75 micron channel (3b) in the data-stream, a threshold is applied to 1.6 micron reflectance (R3a). When R3a exceeds a threshold, the pixel is potentially cloudy.

CLAVR-1

CLAVR-1 was designed before the advent of the channel 3a. Therefore no test on R3a is used. Later modifications to CLAVR-1 did use a single value threshold on R3a that was not applied in glint regions.

CLAVR-x

A similar approach is applied to channel 3a version of the C3AT as applied to RGCT and the channel 3b version of the C3AT. The 6S simulations are used to compute how bright a clear ocean surface can be in channel 3a for a range of wind conditions and aerosol loadings. The variations of the thresholds with satellite viewing geometry for a solar zenith angle of 30 degrees is shown in the following figure. Again, the presence of glint is included in the lookup tables and no external glint mask is used.
Threshold on the 1.6 micron reflectance (R3a) used in C3AT for a solar zenith angle of 30 degrees.
4.7 Channel 3b Reflectance Test (C3AT) over Land

The application of the C3AT over land using channel 3b to detect cloud involves comparing a pixel's R3b to a thresholds. Values of R3b exceeding this threshold are potentially cloudy.

**CLAVR-1**

The land C3AT threshold on R3b was a single value (6%) and not applied in deserts.

**CLAVR-x**

It is planned to derive R3b thresholds as a function of scattering angle and the NDVI climatology. Currently, the approach used is a slight modification of the CLAVR-1 approach. The only modifications used are those to reduce the amount of false cloud observed using the CLAVR-1 threshold for large solar zenith angles. For high latitude conditions, the AVHRR Polar Pathfinder cloud mask (APP) uses a higher threshold (9%) and this threshold varies with solar zenith angle.

Currently, the R3b threshold is determined using the following procedure. As was the case in CLAVR-1, this test is not applied in regions defined as deserts in the 3.75 micron desert mask.

- If there is no potential of snow and the CLAVR-1 threshold of 6% is used.

- If there is a potential of snow, the APP value of 9% is used if the solar zenith angle is
less than 77 degrees. If the solar zenith angle is greater than 77 degrees, the threshold is 15%.
4.8 Channel 3a Reflectance Test (C3AT) over Land

The 1.6 micron reflectance is high for vegetated and some barren surfaces. The high of amount variability of R3a for clear land surfaces prevents the use of a single reflectance threshold. In CLAVR-1, R3a was not available.

CLAVR-1

No test was included because the development of CLAVR-1 occurred before the launch of an AVHRR with channel 3a.

CLAVR-x

A threshold of 15% is used on R3a to detect pixels that are potentially cloudy. This threshold is only applied if the ratio of R3a to R1 is less than 1.1. From observation, clear pixels that would have a value of R3a above 15% occur for vegetated pixels and some barren soils. These pixels with high R3a always exhibit a large value of R3a / R1. Validation of this approach is given in Heidinger et al (2003).

While an NDVI based approach would probably fail for this test due to the contribution of barren surfaces to R3a, a more sophisticated approach is warranted and will be explored.
4.9 Thermal Gross Contrast Test (TGCT)

One of the most fundamental tests for cloud is a test on the 11 micron brightness temperature. In CLAVR-1, this test is called the Thermal Gross Contract Test. The test works on the assumption that clouds are colder than surface and this is obviously problematic when this assumptions fails.

CLAVR-1

Consistent with the CLAVR philosophy, the TGCT thresholds are set such that no clear pixels should exceed them. Accordingly, the TGCT threshold over the ocean is 270 K and over land is 244 K. The ocean threshold is tied to the freezing point of water and the land threshold is based on analysis from Nimbus-7 snow-free land conditions (Stowe et al, 1999).

CLAVR-x

CLAVR-x still applies the TGCT in its original form in CLAVR-1. Instead of modifying the TGCT, CLAVR-x adopted other thermal tests such as the CSST, RTGCT and CTGCT described later.
4.10 Cirrus Test (CIRT)

The CIRT is a test looking for elevated values of the brightness temperature difference between T3b and T5.

*CLAVR-I*

In actual application, the test compares the value of T3b minus T5 divided by T5 to a threshold predicted by T4.

*CLAVR-x*

The CIRT is used unaltered in CLAVR-x however it is nominally given zero weight in the computation of the final cloud mask. CLAVR-x is trying to replace the CIRT with the TMFT which is more firmly based on radiative transfer and should offer the same capability.
4.11 Uniform Low Stratus Test (ULST)

The ULST is the compliment to the CIRT. Opaque clouds can exhibit negative brightness temperature differences between T3b and T4 or T5. The ULST is a test designed to flag pixels with low values of T3b – T5 as potentially cloudy.

**CLAVR-1**

The ULST uses thresholds as a function of T4 and are different curves for land and ocean pixels. The thresholds are derived from LOWTRAN simulations. The land thresholds are empirically increased to account for the spectral emissivity difference in some land types.

**CLAVR-x**

CLAVR-x uses the ULST unaltered from CLAVR-1. However, it is being replaced by the TMFT which has thresholds looking for low values of T3b – T5. The ULST is maintained for consistency until clear evidence is presented that the TMFT has made the ULST redundant.
4.12 Four Minus Five Test (FMFT)

Tests using a threshold on the difference of the brightness temperatures measured in channel 4 (11 micron) and channel 5 (12 micron) have a long heritage in AVHRR cloud masking. For a clear pixel without a temperature inversion, T4 – T5 is usually positive and a function of the profile of temperature and moisture. Due to the spectral dependence on cloud optical thickness, semi-transparent cirrus can elevate values of T4-T5 beyond that expected for clear scenes. In addition, thick clouds can produce smaller or negative of T4-T5 than expected for clear pixels.

CLAVR-1

Thresholds on T4-T5 were constructed as a function of T4 for land and ocean simulations. Values exceeding these thresholds were potentially cloudy.

CLAVR-x

Analysis of the CLAVR-1 thresholds indicated that they tended to falsely detect cloud for very cold snow covered pixels. To alleviate this problem, new simulations of the variation of T4-T5 were computed using the MODTRAN4 radiative transfer model and the TIGR3 profile database. As was the case in CLAVR-1, a set of land and ocean simulations were run.

For the ocean simulations, the TIGR3 profiles measured over water were used a ocean surface was selected for simulation. When the surface temperature of the TIGR3 profile was colder than 270 K, one of four possible ice surface models included in MODTRAN4
were selected. Between 270 and 280 K, the selection of ice and water surface models based on MOSART was selected randomly. In addition, for each simulation, the satellite viewing angle was randomly varied from 0 to 65 degrees.

To simulate the variation of T4-T5 for land pixels, the TIGR3 profiles over land were selected. The MOSART surface type was chosen randomly from the 18 options given in the MODTRAN4 distribution. The 18 surface types included water, snow and ice surface types. The satellite viewing angle was varied in the same way as the ocean simulations.

To derive the land and water FMFT thresholds, the above simulations were classified into four zenith angle bins ranging from 0 to 60 with a spacing of 15 degrees. Within each zenith angle bin, the data were then binned into T4 bins at a resolution of 10 K from 240 to 320 K. Within each T4 bin, the values of T4-T5 which were greater than 1% and less than 99% were stored as the minimum and maximum T4-T5 expected for clear pixels at this temperature and satellite viewing angle. Lastly, the minimum was decreased by 0.2 K and the maximum was increased by 0.2 K to allow for effects of instrument noise.

The following figure shows the resulting CLAVR-x FMFT thresholds derived using the above procedure. Also shown are the thresholds from CLAVR-1 and CASPAR. CLAVR-1 included no zenith angle dependence so its thresholds are the same in each image in top half of figure. CLAVR-1 also used no threshold for the minimum T4-T5 expected for clear pixels. For the maximum T4-T5 thresholds, the CLAVR-x values are similar to the CASPAR values for cold temperatures. For warm temperatures the CLAVR-x ocean and CLAVR-1 ocean temperatures are in rough agreement. Relative to
the non-varying CLAVR-1 thresholds, the CLAVR-x thresholds appears to show the same increase with viewing angle apparent in the CASPAR thresholds. The lower half of the following figure shows that there is less agreement between CLAVR-x and CASPAR on the minimum T4-T5 threshold. The CASPAR values fall between the CLAVR-x ocean and land thresholds. For the Arctic and Antarctic regions, CLAVR-x would use the land thresholds. In the future, we are attempting to increase the complexity of our simulations to better model the expected minimum value of $T_4 - T_5$.

Comparison of the CLAVR-x FMFT thresholds with those from CLAVR-1 and CASPAR for viewing angles of 15 and 45 degrees.
4.13 Three minus Five Test (TMFT)

The TMFT is a test new to CLAVR though it is similar to the CLAVR-1 CIRT and ULST tests. This test looks for pixels with a value of T3b – T5 outside of the limits expected for clear pixels. The difference in cloud transmission between 3.75 and 12 microns along with the non-linear Planck function at 3.75 microns can elevate the values of T3b- T5 above that possible for clear conditions. For optically thick cloud, the lower emissivity at 3.75 relative to 12 microns results in negative values in T3b – T5.

This test was added to CLAVR-x to add satellite zenith angle dependence missing from the CLAVR-1 CIRT and ULST. In the future, the TMFT should entirely replace the CIRT and ULST tests.

CLAVR-1

The TMFT was not in CLAVR-1 but the CIRT and ULST performed similar functions.

CLAVR-x Nighttime

The TMFT thresholds were derived using the same simulations used in deriving the FMFT thresholds described above. The simulations did not include the effects of solar emission so the lookup tables as designed are for nighttime application only. The following figure shows the variation of the TMFT thresholds used in CLAVR-x with comparable CLAVR-1 CIRT and ULST thresholds. In application in CLAVR-1, the CIRT is a test on the value of (T3b-T5)/T5. As the figure shows, the TIGR3/MODTRAN simulations do result in similar curves as the CLAVR-1 thresholds but there are
significant differences. In general, the CLAVR-x threshold is looser than the comparable CLAVR-1 threshold. These differences are still being explored. Work is ongoing to ensure the simulations used to derive the FMFT and TMFT capture all the necessary conditions and are optimal for CLAVR-x's needs. Ideally, the TMFT should totally replace the CIRT and ULST though currently those tests are maintained within CLAVR-x.

Comparison of the CLAVR-x TMFT thresholds against the comparable CLAVR-1 CIRT and ULST thresholds.
CLAVR-x Daytime

In CLAVR-1, the tests using the T3b-T5 values were only applied at night to avoid the complication of the additional signal due to solar reflection. In CLAVR-x the TMFT is applied during the day and through the terminator conditions. This was done to improve the day/night continuity in the cloud mask. To apply the TMFT thresholds during the day, the T3b-T5 threshold was augmented to include the maximum amount of surface reflection. The maximum amount of surface reflection in channel 3b is obtained from the C3AT thresholds. For the ocean, this was 3% and for land this was 6%. The resulting effect on the T3b-T5 thresholds are shown in this figure for the land and ocean cases. This correction is stored is a lookup table as a function on T4 and solar zenith angle. Note that at warm temperatures this correction can be less than 5 K. In the current version of CLAVR-x, the extension to daytime of the TMFT has improved the cloud masking performance especially through the terminator. This test is not applied during the day in glint regions and the test for values falling below the minimum TMFT values is not done during the day.
Variation of the delta $T_{3b} - T_5$ with $T_4$ for the daytime application of the TMFT.
4.14 The Channel 3b Emissivity Test. (EMS3B)

Another method of using the information contained in the thermal channels of the AVHRR is derived a ch3b emissivity. This emissivity is a simply the ratio of the observed channel 3b radiance divided by that predicted for a black body. The same method used to estimate the emission component during the day is used to estimate the black body radiance. During nighttime, liquid water clouds have a ch3b emissivity much less than one. Semitransparent clouds have an apparent emissivity much greater than one because the emissivity computation does not properly account for transmission. During the day, the cold temperatures of some cloud cause very large deviations from unity in the ch3b emissivity. Observation has indicated that the contrast in the ch3b emissivity can be larger than the contrast in the T3b – T5 for some conditions. While the final thresholds for this test are being developed, this simple test does appear to offer some unambiguous detection.

CLAVR-1
No test on ch3b emissivity is used.

CLAVR-x
For daytime conditions outside of oceanic glint, values of ch3b emissivity exceeding 2.2 are potentially cloudy. As of yet, no surface features have been observed that exceed this threshold. For nighttime conditions, the threshold is 1.5 for regions the behave as deserts in ch3b and is 1.2 for non-desert regions.
4.15 Climatological SST Test (CSST)

Knowledge of the SST is potentially a useful cloud detection test. Without an a priori estimate of the SST, CLAVR-1 was forced to use a 270 K threshold for the TGCT over the ocean. Obviously, some clouds over the ocean are missed by this threshold. Ideally a recent high quality SST product should be used. In order to avoid the dependency on other products, CLAVR-x has implemented the use of a monthly climatological SST. This data-set is described in the ancillary data section. Comparison of the climatology with individual weekly analyzes indicated that the annual variation in the climatology for any one location was larger than variation in between the climatology and the weekly fields for any one time. Therefore using a monthly climatology appears to capture the dominant mode of variation of the SST.

CLAVR-1

No SST field was used.

CLAVR-x.

The climatological SST is interpolated to each pixel. In addition, an pixel level SST is computed within CLAVR-x for all pixels. Pixels with an SST less than 5 K colder than the climatological SST are considered potentially cloudy. This test has proven to be very successful with no detected false cloudiness. This test can be triggered in regions with high dust loading. It is up to the dust restoral test to handle these situations.
4.16 Relative Thermal Gross Contrast Test (RTGCT)

This test attempts to flag the coldest pixels in a scan line as cloudy. In CLAVR-x, running means of the maximum sst observed over land and ocean are stored. The values are used as a basis for setting the thresholds on T4 used in the RTGCT. The deviation allowable from the maximum values was determined empirically. The reason to have this test is mainly to help cloud detection at night over warm land. The application of this test over the ocean offers little additional advantage over the CSST. This test is not applied in cold regions where inversions can result in clouds being warmer than the surface.

CLAVR-x

Over the ocean, this test is applied if the climatological SST is greater than 273 K indicating ice free conditions. If the maximum sst estimate for this scan line is greater than 260 K, pixels with an SST colder than 10 K relative the maximum sst estimate are potentially cloudy.

Over the land, the threshold is different due to larger variation in surface temperatures. This test is applied over land if the minimum T4 climatology is greater than 260 K and only to pixels with LST's less than 290 K. The pixels are potentially cloudy if the LST is less than 30 K colder than the estimate of the maximum for the scan line.
5 Spatial Uniformity Tests

Tests involving the spatial uniformity played a large role in CLAVR-1 and even larger in CLAVR-x. In both algorithms, spatial uniformity acts as last filter prevented unwanted pixels from being classified as clear or cloudy, the two categories used for derivation of clear and cloudy properties. In CLAVR-1, there was only one set of spatial uniformity tests. In CLAVR-1, any pixels found to be in areas of spatial non uniformity were classified as mixed except for a few circumstances. In CLAVR-x, there are two sets of spatial uniformity tests. One set is similar to those in CLAVR-1 and classifies otherwise clear pixels as partly clear. The other set classifies otherwise cloudy pixels as partly cloudy.

In both CLAVR-1 and CLAVR-x, spatial uniformity is defined relative to a 2x2 pixel array. All pixels within this 2x2 array have the same value of spatial uniformity. The historical reasons for using 2x2 arrays is that original GAC data was stored as 2 scan lines per record and CLAVR-1 was initially constrained to process one record at a time. Application of spatial uniformity could be defined in other ways (i.e. 3x3 pixel arrays centered on the current pixel) but we have seen no evidence that the spatial uniformity of the 2x2 arrays is failing to perform as needed.
5.1 Spatial Uniformity Tests for Clear Pixels

These tests classify otherwise clear pixels as partly clear in CLAVR-x or mixed in CLAVR-1. The need for these tests comes from the fact that the cloud tests described above fail to detect all cloud contamination. This is especially true for SST and other algorithms that are highly sensitive to the presence of cloud. If anyone cloud test were tuned to capture all cloud for a particular scene, it would lose its global applicability. In general, the initially clear pixels that are flagged as spatially nonuniform correspond to edges of cloudy regions or clouds that are not resolved well at the spatial resolution of the AVHRR data. However, spatial uniformity tests to classify pixels as partly clear that suffer from non detectable cloud contamination. We are exploring methods to identify those pixels. However, all analysis that ability of CLAVR-1 and CLAVR-x to produce clear radiances with minimal cloud contamination is due to operation of these spatial uniformity tests.

Currently, in CLAVR-1 and CLAVR-x, these spatial uniformity tests are the same for HRPT, LAC and GAC data. However, we are working on resolution dependent thresholds. While the physical basis for these tests is solid, the ability to use radiative transfer models to determine these thresholds has proven difficult. In general, these thresholds are based on empirical optimization of the amount and radiometric quality of the clear and cloudy pixels.
5.1.1 Thermal Uniformity Test for Clear Pixels (TUTCLR)

The TUTCLR (or just TUT in CLAVR-1) is a test on the spatial uniformity of the 11 micron (T4) brightness temperature. The measure of spatial uniformity is the difference between the maximum and minimum T4 within the 2x2 array.

**CLAVR-1**

The threshold for the TUT was dependent on the surface type to account for the fact that oceans have less surface temperature variation than land. Over the ocean, the TUT threshold was 0.5K and for land, the TUT threshold was 3.0 K.

**CLAVR-x**

The TUTCLR is the same as the TUT in CLAVR-1. To justify this some analysis is presented here. The following figures show the effect of varying the TUTCLR threshold over the ocean on the quantity and quality of SST retrievals. The three images below show the difference in the SST computed from clear pixels and the interpolated OISST for the same week. The SST difference is only shown only for clear pixels (cloud mask = 0) and where the cloud mask is not clear, the image shows the cloud mask value (1 = dark gray, 2 = light gray, 3 = white). This data is taken from a descending NOAA-16 orbital pass over the Pacific from 40 N to 40 S (2760 scanlines).

To quantify the effect of the TUTCLR threshold on the SST values, three quantities were computed and plotted as function of the TUTCLR threshold in the next figure. The top plot shows the variation in the mean SST-OISST. Cloud contamination should decrease
the mean value of SST – OISST. The center plot shows the variation of the percentage of clear pixel remaining for SST contribution. As the TUTCLR threshold decreases, the amount of clear pixels remaining decreases and this is the chief penalty in being too conservative with the TUTCLR. The bottom plot shows the percentage of clear pixels with SST – OISST values less than -3 K. This last parameters should be measure of the cloud contamination in the SST fields. From this analysis, it appears that the CLAVR-1 threshold of 0.5 K for the TUTCLR properly balances the amount and quality of the SST pixels. However, this analysis does indicate that a threshold of 0.3 K might be optimal for this data.
Example Application of the TUTCLR for T4 uniformity thresholds of 0.2 (left), 0.5 (center) and 2.0 (right) K. The threshold in CLAVR-x is 0.5 K. Uniformity threshold applied only to those pixels with cloud mask values less than 2. This data spans from 40 N to 40 S in the Pacific Ocean and is AVHRR GAC from NOAA-16 (nighttime).
Variation of the mean SST - OISST (top), % of clear pixels (center) and % of SST - OISST < -3K for the data shown above as function of the TUTCLR threshold.
5.1.2 Reflectance Uniformity Test for Clear Pixels (RUTCLR)

The RUTCLR (or RUT in CLAVR-1) is a test on the spatial uniformity of 0.63 micron reflectance (R1) within the 2x2 array.

*CLAVERS-1 Daytime*

In CLAVR-1, the measure of the R1 spatial uniformity was the difference between the maximum and minimum R1 within the 2x2 pixel array. Again, the thresholds varied over land and water. The ocean RUT threshold was 0.3 % and over land the threshold was 9%.

*CLAVERS-1 Nighttime*

During the night, the RUT was not applied and no other measure of uniformity was used in its place. As a consequence, the appearance of the day and night cloud masks in CLAVR-1 was very different. The number of mixed pixels during the day over the ocean was larger than during the night.

*CLAVERS-x Daytime*

In CLAVR-x, the fixed thresholds used for the RUT in CLAVR-1 were abandoned for thresholds that were relative to the estimated surface reflectance. Due to the large variation of the surface reflectance over land, application of the fixed CLAVR-1 threshold resulted in differing sensitivities to reflectance uniformity in different regions. Even over the ocean, the ocean reflectance varies significantly with solar and satellite viewing angle. In CLAVR-x, the estimate of the clear surface reflectance was taken from the RGCT thresholds described above. For ocean pixels, the RUTCLR threshold was 5% of the
RGCT threshold. For land pixels, the RUTCLR threshold was 20% of the RGCT threshold.

**CLAVR-x Nighttime**

During the night, the RUTCLR was applied using the channel 3b (3.75 micron) brightness temperature. This was done to increase the ability to detect spatial uniformity due to low clouds at night that might have passed the TUTCLR. Due to highly non-linear Planck function and lower emissivity of water clouds, many clouds exhibit more non-uniformity in T3b than in T4. This property has been exploited for low-level wind vector determination from geostationary satellites. CLAVR-x has tried using the derived channel 3b reflectance (R3b) for this test. However, the noise amplification inherent in the R3b derivation appears to limit its applicability as a tight threshold for spatial uniformity. There CLAVR-x currently applies a test at night on T3b in place of R1 for the RUTCLR test. The thresholds are the same as those used in the TUTCLR but are not applied for cold temperatures (T4 < 230) due to the noise in channel 3b.
5.2 Spatial Uniformity Tests for Cloudy Pixels

Because CLAVR-1 had only one intermediate classification between clear and cloudy pixels, it used only one set of spatial uniformity tests. In CLAVR-x, spatial uniformity tests are needed to move pixels from clear to partly clear and cloudy to partly cloudy. Due to the different levels of spatial uniformity for clear and cloudy scenes, it was determined that different set of uniformity tests was needed to separate the partly cloudy and cloud pixels.

The physical basis for applying uniformity tests to separate cloudy and partly cloudy pixels is that partly cloudy scenes typically exhibit less spatial uniformity than overcast regions. The goal of this test is to remove from the cloudy class, those pixels that are contaminated by clear radiances. Observation of the CLAVR-x cloud mask and analysis of the partly cloudy radiances supports the effectiveness of this test. The partly cloudy pixel often occur near cloud boundaries and in broken cloudiness that is not well resolved in the AVHRR data. As was the case with clear uniformity tests, no dependence on the spatial resolution of the AVHRR data is incorporated but this is being considered.
5.2.1 Thermal Uniformity Test for Cloudy Pixels (TUTCLD)

*CLAVR-I*

The separation of cloudy and mixed pixels was accomplished through the application of the TUT (described above).

*CLAVR-x*

As was the case with the TUTCLR, the measure of spatial uniformity used in the TUTCLD is the difference between the maximum and minimum T4 in the 2x2 array. The current threshold is 10% (TBD) of the difference between 280 K and T4. This threshold is constrained to never fall below 2 K which is the case for all cloudy pixels warmer than 276 K (TBD). The threshold is therefore tighter for stratus clouds than cirrus clouds. This was done to account for the difference in the thermal contrast between the surface and clouds of different temperatures. Application of a constant threshold would result in differing uniformity sensitivities to different cloud types. This threshold is currently under review. The method for developing this threshold is to perform an analysis where the threshold is varied to optimize the amount and radiometric purity of the cloudy pixels.
5.2.2 Reflectance Uniformity Test for Cloudy Pixels (RUTCLD)

Currently, the use of reflectance uniformity is not used in separating cloudy from partly cloudy pixels. This is done for two reasons. First, it is beneficial to have a consistent day/night separation mechanism between cloudy and partly cloudy pixels. Second, cloud shadows appear to artificially classify cloudy pixels as partly cloudy.
6 Computation of Cloud Amount

Because CLAVR-x is not a simple binary cloud mask, the computation of the cloud amount over a region composed of multiple pixels based on the cloud mask results is not straightforward. The difficulty lies in the treatment of the partly clear and partly cloudy pixels. In CLAVR-1, two methods of cloud amount computation were used. The first assigned a cloud fraction weight of 0% to the clear pixels, 50% to the mixed pixels and 100% to the cloudy pixels and this method was referred to as the 50/50 Split (FFS) method in the PATMOS data. The second was called the Staticsly Equivalent Spatial Coherent (SESC) Method (Molnar and Coakley, 1985). The application of the FFS method produced a distribution of cloud amount with noticeable peak at 50%. The SSEC method reduced this peak by exaggerating the departures from 50% in the cloud amount.

The addition of a fourth cloud mask value in the CLAVR-x mask complicates the straightforward application of the FFS or SSEC methods used in CLAVR-1. Currently, CLAVR-x derives its cloud fraction weights from a radiative balance analysis. The 11 micron radiance was chosen as the radiance to use for this process due its minimal atmospheric contribution. If the clear-sky radiance, No, and the cloudy radiance, Nc, is known, the cloud fraction weight for the ith cloud mask value can be obtained from the following relation,

\[ F_i = \frac{(No - Ni)}{(No - Nc)} \]

where Ni is the mean radiance for all pixels with cloud mask = i. In application in
CLAVR-x, this analysis was only done for the partly clear and partly cloudy cloud mask values and the weights of the clear and cloudy were set to 0% and 100%.

To derive the cloud fraction weights using the method above, the radiance and cloud mask results were composited within an equal-area 110 km resolution global map. The cloud fraction weights were computed in every grid-cell that reported No and Nc. In addition, the CLAVR-x cloud typing algorithm was used to separate the water and ice partly cloudy and cloudy pixels. The figure below shows the distributions of the cloud fraction weights for the partly clear and partly cloudy separated for ice and water partly cloudy pixels.

As the figure indicates, the distributions of cloud fraction weights for the partly clear pixels peaks near zero indicating the majority of the partly clear pixels are radiatively close to the clear pixels. Also, the width of the partly clear distribution indicates that there are some cloud-contaminated pixels missed by the cloud mask tests and detected only by spatial uniformity tests. Overall, the mean cloud fraction weight is 13% for the partly clear pixels.

It is obvious from this figure that the distributions of the partly cloudy distributions for ice and water clouds differ. One weakness of the radiative balance approach is that it assumes cloud are opaque. When clouds are semitransparent, the cloud fraction weight is actually the product of the cloud emissivity and the cloud fraction weight. Studies of ice clouds have demonstrated that the majority are semitransparent (Wylie and Menzel, 1994). Because we want to avoid the effects of semi transparency in the cloud, we ignore
the partly cloudy distribution for ice clouds and use the results from the water clouds for
the CLAVR-x partly cloudy weight. This action implicitly assumes that all water clouds
are opaque and that variation of water cloud fraction with spatial uniformity is similar to
that for ice clouds. Both of these assumptions warrant further study. Using the partly
cloudy water cloud distribution produces an overall cloud fraction weight of 88% for all
partly cloudy pixels. From the shape of the distribution, very few partly cloudy pixels
behave radiatively as clear pixels.

Overall, these distributions support the contention that the application of spatial
uniformity tests acts to remove unwanted pixels from the clear and cloudy classes. While
this analysis shows little variation to time period when globally, there are likely regional
systematic differences. To resolve this, we are considering applying a radiative balance
technique to recompute the cloud fraction weights each time a cloud fraction is computed.
Illustration 1: Distribution of cloud fraction weights determined by an 11 micron radiative balance technique for partly clear and partly cloudy pixels separated by phase.
7 Computation of CLAVR-x Parameters

The application of the CLAVR-x cloud mask uses many parameters contained within the AVHRR 1b data. However, additional parameters are computed to apply the CLAVR-x cloud mask. This section describes the method for computing those non-1b parameters.

7.1 Computation of the Channel 3b Reflectance

The application of C3AT requires an estimate of the solar reflectance in channel 3b (3.75 microns). To derive a solar reflectance in channel 3b, R3b, an estimate of the thermal component (non-solar) of the channel 3b radiance must be made. In general, the channel 4 brightness temperature (T4) is used as a surrogate for the channel 3b brightness temperature (T3b) without any solar contribution (T3bo).

Assuming that a value of T3bo is available, CLAVR-1 computed R3b using the following relation.

\[ R_{3b} = 100 \pi \left( I_{3b} - B^{-1}(T_{3bo}) \right) / (\mu_o F) \]

where I3b is the channel 3b radiance, F is the amount of solar energy within the channel 3b response, \( \mu_o \) is the solar zenith angle cosine, and \( B^{-1}(T_{3bo}) \) denotes the Planck radiance at 3.75 microns assuming a temperature of T3bo.

This equation assumes that the surface emits as a black-body. In CLAVR-x, the assumption is made the surface emissivity and surface reflectance are related by
\[ \varepsilon_{3b} = 1.0 - R_{3b}/100 \]

This relation ignores any azimuth surface in the surface reflectance. In CLAVR-x, \( R_{3b} \) is computed using

\[ R_{3b} = 100 \pi \frac{(I_{3b} - B^{-1}(T_{3bo}))}{(\mu_0 F - \pi B^{-1}(T_{3bo}))} \]

In general, the CLAVR-x formulation will give larger values of R3b than the CLAVR-1 version. Over the ocean, this effect is small. We have not noticed a need to modify thresholds due to this change. The CLAVR-x relation should be a better measure of R3b though for most cases.

The difficulty in deriving R3b is in the proper estimation \( T_{3bo} \), the top of atmosphere channel 3b brightness temperature without solar reflection. In CLAVR-1, \( T_{3bo} \) was estimation by analysis of nighttime data. Using T4 and T5, a regression was constructed of the following form to estimate \( T_{3bo} \).

\[ T_{3bo} = A + B T4 + C(T4 - T5) \]

This method was applied to data from ice-free oceans. While this limits the applicability of the regression, its gave its best performance in the region where the C3AT was needed to most accurate – over the ocean. This regression is essentially the reverse of an SST regression. It uses T4 and T5 to predict a top of atmosphere brightness temperature, not a surface temperature.
8 References


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