P1.2

Development and Applications of Regional Cloud Products from the CHANCES Global Cloud Database

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Further information and product examples are available at: www.cira.colostate.edu/GeoSci/CHANCES/

1. INTRODUCTION

The distribution and occurrence of clouds is of primary importance in atmospheric science. On a planetary scale clouds regulate Earth's temperature and keep the planet suitable for life. On a continental scale clouds influence the ecology and vegetation through feedbacks into the hydrological cycle. On a human level, clouds determine the suitability of a location for endeavors such as aviation, astronomy and solar energy. As has been done for hundreds of years with other meteorological variables such as temperature and precipitation, it is only natural that we should develop long-term records of clouds.

Weather satellites have provided us a perspective on Earth's clouds for the past 40 years (Kidder and Vonder Haar, 1995). In the 1980's the International Satellite Cloud Climatology Project (Rossow and Schiffer, 1991) began a systematic task of watching clouds from space over the entire planet and creating an archive of their occurrence. Methods to detect cloud from satellite are essential for this effort. The detection of clouds from satellite is a large topic, and approaches to this problem are discussed in Kidder and Vonder Haar (1995). A cloud climatology is a mosaic of individual cloud detections. Cloud climatologies can be created by hour, location, season, synoptic condition, or by particular type of cloud. By summing up cloud detection results based on time, space, or physical constraints, we learn about the natural occurrence and variability of clouds. Data from both geostationary and polar orbiting satellites have been used to create satellite cloud climatologies.

The history of early satellite cloud climatologies is summarized in Reinke et al (1992). While there have been cloud climatologies derived from surface observations (Warren et al, 1986), Reinke et al (1992) showed that only the satellite has the large spatial coverage to show cloud variability on scales larger than a few kilometers. A barrier problem until recently has been the tremendous volume of satellite data required to complete a global cloud climatology at high space and time resolution. ISCCP made the decision to use reduced resolution data to meet processing demands. The Climatological and Historical Analyses of Clouds for Environmental Simulations (CHANCES) global cloud database (Hall et al, 1999) expanded upon ISCCP by using higher spatial and temporal resolution. CHANCES and ISCCP have a similar approach in that multiple geostationary and polar platforms are blended together to form a global product. Table 1 shows the features of widely available global cloud databases. Note the variety of temporal and spatial resolutions available from these climatologies. No one climatology can be said to be the "best", that judgment depends on the purpose of the user. The Moderate Resolution Imaging Spectrometer (MODIS) has extensive channelization and algorithms for detecting difficult clouds (e.g. thin cirrus) and has very high spatial resolution, but it is onboard a polar orbiting satellite with limited temporal coverage. ISCCP products cover the globe for an extended time period and show seasonal and interannual variability quite well, but are more useful for showing cloud variations on scales greater than 100 km. CHANCES has high spatial and temporal resolution, but the dataset has only been produced for three years and the cloud detection algorithms are limited to two channels. We view these cloud climatologies as a family of complementary products, each of which meets a certain need within the scientific and applications communities.

Satellite cloud climatologies have seen a continual expansion in their application. Hall et al (1998) illustrated an application of the CHANCES results for forecasters over eastern Europe. Conditional climatology tables were constructed which can be used to estimate the likelihood of cloudy or clear persistence on a scale of several hours. Satellite cloud climatologies have been created not only for occurrence of all clouds, but for specialized

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types of clouds. Cumulus detection (Rabin and Martin, 1996) and cirrus detection (Wylie and Menzel, 1998) are examples. The diurnal cycle of deep tropical convection is explored with CHANCES data by Hall and Vonder Haar (1999). In addition to their usage for studying global cloud coverage, cloud climatologies have been used to evaluate the cloud fields in a mesoscale forecast model (Karlsson, 1996). Preferred areas of cloud formation related to topographic and coastal features in the southeastern U.S. were explored by Gibson and Vonder Haar (1990) and Connell et al (2001). In the latter case 1 km resolution climatologies from the Geostationary Operational Environmental Satellite (GOES) were created over Florida. The results were stratified by prevailing low level wind direction and speed to gain insight into placement of persistent cloud features under diverse synoptic regimes. Such synoptically-stratified cloud climatologies have been used by the National Weather Service as a forecaster training tool (Combs et al, 2001).

Our focus here is on an application of the CHANCES database cloud detection results to mesoscale variations in cloud over the Middle East region. This is a challenging region for cloud detection that includes desert and snow-covered high mountains, two notoriously difficult surfaces over which to detect clouds. We will work at the highest spatial resolution that is available on an hourly basis. The high time resolution is a key asset of the CHANCES database for determining mesoscale cloudiness variations. This area has previously suffered from a lack of consistent geostationary satellite coverage, making the production of cloud climatologies difficult. The placement of the Meteosat-5 satellite at 63^{o} East over this region in mid-1998 through at least 2002 makes possible new high space and time resolution cloud products.

In this paper, we will present cloud climatologies derived from the CHANCES database over the Middle East region. The sensitivity and errors of the CHANCES cloud detection method are investigated. We will examine the ability of the CHANCES database to detect diurnal and topographically forced changes in cloud coverage. Our CHANCES results will be compared to recently available MODIS cloud mask results over the same region.

2. DATA

The data selected for this study are visible and infrared (11 micron) imagery from the CHANCES database. Most of the imagery over this sector are from the Meteosat-5 satellite which has a sub-satellite point of 63^{o} E. These data were assimilated into the CHANCES database format at a 1-hr and 5-km temporal and spatial resolution.

A 1024 X 1024 pixel sector (covering an area of approximately 5120 X 5120 km) over the Middle East), was extracted from the global database. Examples of this sector can be seen in Figures 5 and following.

The months of January and July 2001 were selected for this study. The intent was to provide data for both a winter and summer month, since these two months exhibit a significant contrast in cloud cover amount and distribution over this mid-latitude region.

Infrared image sectors were extracted for each hour (on the hour) and visible image sectors were extracted for the hours of 0500 UTC – 1200 UTC inclusive.

In addition, two ancillary data sets were used as input to the data processing. The GTOPO30 1-km resolution global elevation database was used to construct a first-guess surface temperature field. The global surface characteristics database was used to identify land type for the purpose of assigning an expected diurnal temperature change curve.

3. METHODOLOGY

All of the CHANCES Regional Products (C_RP) that are described in this study are built from the basic cloud / no cloud analysis of the visible and infrared satellite imagery. The procedure for doing the cloud / no cloud analysis includes the generation of “background” (clear-sky radiance) images. These images are then used to perform visible, infrared, and diurnal change tests that are used to determine if a given pixel is “cloudy” (we define “cloudy” as: greater than 50% of the FOV of the pixel is cloud-filled – analogous to the surface airways designation of a “ceiling”). The resultant cloud / no cloud designation is then stored in the CHANCES “QA” database (see section 3.4) for access when building the various products described in section 3.5.

3.1 Visible Cloud Detection

Visible cloud detection is accomplished by comparing each visible image with a “background” radiance image that depicts the expected radiance for a cloud-free scene, at a given hour of a given month. Each pixel of the visible image is compared to the background plus a threshold value (to account for noise and variance of the background value. Pixels that are brighter than the background plus threshold value are tagged as “cloudy” (see Figure 5).

Visible backgrounds can be easily constructed by analyzing a month of visible images for a given hour and storing, at each pixel, the darkest value that occurs during the month. Sensitivity studies have shown that using the 90th percentile value will minimize the impact of noise and shadows on the background. For a typical 30-day month, that would be the 3rd darkest pixel. In addition, a minimum radiance value is assigned to each pixel location based on its land surface type to further eliminate the problems caused by shadows and noise. Since the vast majority of cloudy pixels will be significantly brighter than the background, the visible cloud / no cloud analysis is the most accurate of the three tests for all clouds except optically-thin cirrus. Much of the optically-thin cirrus cloud is detected by the infrared test.

3.2 Infrared Cloud Detection

In a similar manner, the infrared cloud detection method tags pixels as cloudy when the 11-micron brightness temperature is colder than an expected clear sky background. An alternative approach, and one which has been used in previous years of the CHANCES database, is to use a threshold above a model surface temperature field. Feijt and De Valk (2001) and Feijt et al (2000) provide a good analysis of the difficulties inherent in using a surface temperature analysis from a model.

Extreme care must be taken to account for diurnal cloud detection efficiency biases when using surface or numerical weather prediction estimates of surface temperature. Surface skin temperature, which creates the radiance the satellite receives, is often not the same as model surface temperature. This problem can be particularly severe under certain synoptic conditions. For instance, on a clear still night, the surface may cool much quicker than the model analysis field and at some point may be colder than the model temperature by an amount exceeding the detection threshold. Then the clear surface would be erroneously detected as cloud. Model surface temperatures may not be optimized to match satellite window channel radiances, but rather may be tuned to some other parameter irrelevant to the satellite, such as surface fluxes (Feijt et al 2000). In addition, the model fields are often not at the high resolution of the satellite data. This can lead to problems around coastlines. For instance, consider a model grid box that has a temperature representative of land (300 K). Suppose this grid box also overlaps onto a cold ocean (285 K) area, which is unresolved due to model resolution. If the satellite is using the 300 K temperature from the model as its surface temperature and views a pixel over the 285 K ocean surface, it might flag the pixel as cloudy, since it is 15 K colder than its expected value.

In this study, we use only tests and backgrounds that can be constructed from the satellite data themselves. Heritage cloud detection schemes often require spatial tests that lead to lower resolution results (Kidder and Vonder Haar, 1995). All of our tests are done at the full spatial resolution of the data. This requires excellent alignment of consecutive images, a condition which is met with the Meteosat series of satellites.

The infrared cloud / no cloud test is very robust except for difficulties with low-level stratus and stratocumulus clouds that have cloud-top temperatures that are very close to the underlying surface. These clouds are handled well by the visible test, plus some are detected (primarily over land) via the diurnal change test.

3.3 “Diurnal Change” Cloud Detection

An additional cloud test was performed by examining the diurnal temperature change at each pixel. The process proceeds as follows:

1. For a given hour, at a given pixel, the infrared background was examined to determine the change in temperature (brightness count) from the previous hour to the hour being analyzed.
2. The infrared imagery for the previous hour was then examined to determine the “actual” change in temperature from that hour to the one being analyzed.
3. If the actual temperature was “close” to the background temperature for that hour, and the actual temperature change was consistent with that expected (the difference determined in step 1), then the pixel was tagged as “clear”.
4. If the temperature change varied from the expected, then a decision tree was entered that determined whether the pixel was cloudy or clear, based on its previous tag. For example, if the expected clear-sky change was positive (warming) and the actual change was negative (cooling) then it is assumed that a cloud moved over the pixel in the past hour and it was tagged as cloudy. (The obvious error potential for this assumption is that a cold air mass could have moved over the surface covered by this pixel and caused a false alarm. Further research is under way to use the first and last visible images of the day to identify these anomalous situations and minimize the false alarm rate).

Examination of the results of this test, to date, shows a significant improvement in cloud detection for smaller cellular clouds and also for identifying developing or dissipating clouds. This test will also identify low-level clouds at night over land areas that would normally exhibit cooling (if the temperature at the top of the low-level cloud layer remains nearly constant). Results of an analysis of this detection method will be presented at the poster session.

3.4 "QA" Cloud Database Structure

After each of the individual cloud detection tests are performed, the results – along with other auxiliary data – are stored in the "QA" database. The name for this database is derived from Quality Assessment, as it was initially built to provide statistics for the validation of the cloud analysis procedures.

The Regional Products QA database consists of a 16-bit word for each pixel location for each hour. The format of the QA word is shown in Table 2, and example of the 16-bit image is shown in Figure 7.

Most of the QA file contents (see table 2) are self-explanatory, some that may not be are:

SATID = the satellite that the data for this pixel was taken from (ie. GOES-8, Meteosat-5, DMSP F14, etc.). If the satellite ID is set to "15", data was missing for that hour and the radiance value for this pixel was persisted from a previous hour.
EXP IR CNC = "Experimental" IR cloud/no cloud. In this study, it is the IR cloud test that uses the IR radiance-derived clear-sky background.
TOTAL CNC = the cloud/no cloud determined by a combination of the visible, IR, and diurnal tests. For this study, if any of the tests indicated a cloudy pixel, this bit was set to "1" (cloudy).

3.5 Regional Products

After cloud detection was completed, several cloud-related products were produced. Examples of products 1-4 are described in this paper. The products produced to date include:

1. Frequency of occurrence and PDF
2. Cloud/clear interval
3. Conditional climatologies
4. Persistence probabilities
5. Cloud/clear interval
6. Cloud Top Height (hourly and monthly mean)
7. Low Cloud / Thin Cirrus (derived from a comparison of the visible and infrared cloud detection results: vis cloudy + ir clear = low cloud, vis clear + ir cloudy = thin cirrus).
8. Cloud type classification (research in progress)
9. Estimated Cloud Base (research in progress)
10. Cloud-free line-of-sight (research in progress)

3.5.1 Frequency of Occurrence of Cloud and PDF of Cloud Occurrence

A frequency of occurrence image was built for a given hour of the month by simply constructing the percentage of time that each pixel was cloudy for that hour. Figures 8 and 9 show examples of a Frequency of Occurrence image and the PDF plot.

3.5.2 Cloud/Clear Interval

This product is produced by constructing a table that shows the number of occurrences of cloudy or clear intervals for a range of interval distances. Figure 10 and 11 provide an example of this product.

3.5.3 Conditional Climatology

This product is produced by determining the probability of a pixel being cloudy at a subsequent hour if it is cloudy/clear at the present hour. An example of this product is shown in Figure 12. For decades, operational forecasters have used conditional Climatology tables, based on cloud data from surface reporting stations, as a cloud forecasting tool. This probability does not take into account whether the pixel of interest changes categories during the intervening hours (see "Persistence Probability" below)

3.5.4 Persistence Probability

Similar to the conditional probability, this product gives the probability that a cloudy or clear pixel will persist for a given period of time. Figure 13 shows an example of this type of product. Persistence Probability tables have also been constructed from surface observations, and used operationally to determine how long clouds (or clear conditions) will persist before changing to a clear (cloudy) condition.

3.6 MODIS Data Analysis

Corresponding MODIS data for the months of January and July 2001 were obtained from the NASA Goddard DAAC. These data were pre-processed to extract the portions of the MODIS data that covered the same geographic region as our Middle Eastern sector. The over-flight time for MODIS was approximately 0800-0900 UTC and 1700-1900 UTC, which is close to local noon for the mid-point of our sector.

An example of the MODIS Cloud Mask product is shown in Figure 14.

4. COMPARISON WITH MODIS

Because the CHANCES cloud database is so unique, it is difficult to perform a meaningful validation of the cloud analysis results. It was shown (Reinke, et. al, 1992) that comparisons with surface observations will provide a measure of verification, but problems with surface observations of cloud leave a measure of uncertainty about that avenue of validation.

With the availability of cloud analyses, (using multi-spectral data and algorithms) from the MODIS instrument, it was felt that this new data set could be used as a "standard" to compare the CHANCES Regional Products against. The comparison is on-going at the deadline for submission of this paper, however the initial results are showing a very good match between the two cloud analyses, in terms of the preferred region of locally forced clouds. The formal results of the comparison will be posted on the CHANCES website and presented at the poster session.

Figures 14 and 15 show an example of the MODIS Cloud Mask for a 5-minute granule centered on 1705 UTC on January 1st 2001, which corresponds with an C_RP cloud analysis from the infrared image for 1700 UTC. Close inspection shows good agreement in the cloud that is depicted in the C_RP product, but the MODIS analysis picks up cloud over the higher elevations where it is missed by the C_RP analysis. This ongoing comparison should provide some valuable insights into the merits and shortfalls of both cloud analysis techniques.

5. SUMMARY

It is the opinion of the authors, as well as a growing segment of the meteorological community, that the distribution, and properties, of clouds are the most significant "unknowns" in climate variability, and in the model-based prediction of local and regional weather patterns. Unfortunately, most of the climate prediction models, as well as the operational forecast models, do not have the ability to accurately analyze or predict the occurrence of cloud. All statistical techniques for parameterizing clouds rely on a database that was built from long-term records of surface observations – which miss close to 98% of the surface area of the planet (assuming a viewing distance of 25 km and a generous average number of 5000 surface observations of clouds, per hour, around the globe).

Regional-scale, satellite-derived, cloud products are now available at global resolutions on the order of 5-km and 1-hr. After 40 years of "viewing" clouds from space, low-cost, high-speed computing resources and mass storage have made it possible to exploit the long-term archive of digital satellite imagery to produce products that were formerly based on surface observations of clouds.

The CHANCES Regional Products presented here, as well as cloud products from other parallel research efforts, have a tremendous potential for enhancing our understanding of climate-scale cloud forcing, as well as providing an update to operational surface-based cloud forecast tools

Examples of these and other cloud products are available on the CHANCES website at: www.cira.colostate.edu/GeoSci/CHANCES/

6. REFERENCES

NOTE: This list includes references used in this paper, plus additional references of interest to the student of satellite-derived high-resolution cloud analyses.

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TABLES and FIGURES

	CHANCES	ISCCP	MODIS cloud mask	USAF RTNEPH	AVHRR – derived (e.g. CLAVR)	HIRS	TOVS Pathfinder
Time resolution	1 hour	3 hour	2 – 4 times / day	3 hour	2 – 4 times / day	2 – 4 times / day	1 day
Spatial resolution (nominal)	5 km	280 km	.25 – 5 km	46 km	4 km	> 20 km	> 60 km
# of spectral bands used	2	2 - 5	16	2	5-6	20	> 20
# of years in record (as of Dec 2001)	3 94-95; 97-98; and 99-00	> 15	2	> 16	20 (w/various algorithms)	> 8	>15
Comments	Uses Geo and DMSP	Many radiation budget products too	Enhanced cirrus tests	Uses surface data also	Allows fractional cloud cover	High clouds only	Includes sounding products; Path A & B
Reference	Hall et al (1999)	Rossow and Schiffer (1991)	Ackerman et al (1997)	Hamill et al (1992)	Stowe et al (1999)	Wylie and Menzel (1998)	Susskind et al (1997)

Table 1. Summary of global and regional satellite cloud database projects.

Byte 1								
Bit #	0	1	2	3	4	5	6	7
bit value	1	2	4	8	16	32	64	128
Contents	SATID	SATID	SATID	SATID	VIS DATA	VIS CNC	"ORIG" IR CNC	"NEW" IR CNC
	LSB							MSB

Byte 2								
Bit #	0	1	2	3	4	5	6	7
bit value	1	2	4	8	16	32	64	128
Contents	DIURNAL TEST	DIURNAL CNC	OPEN	DAY / NIGHT	GLINT	"COMB" CNC	SNOW / ICE	LAND / WATER
	LSB							MSB

Table 2. Contents of the “QA” database word.

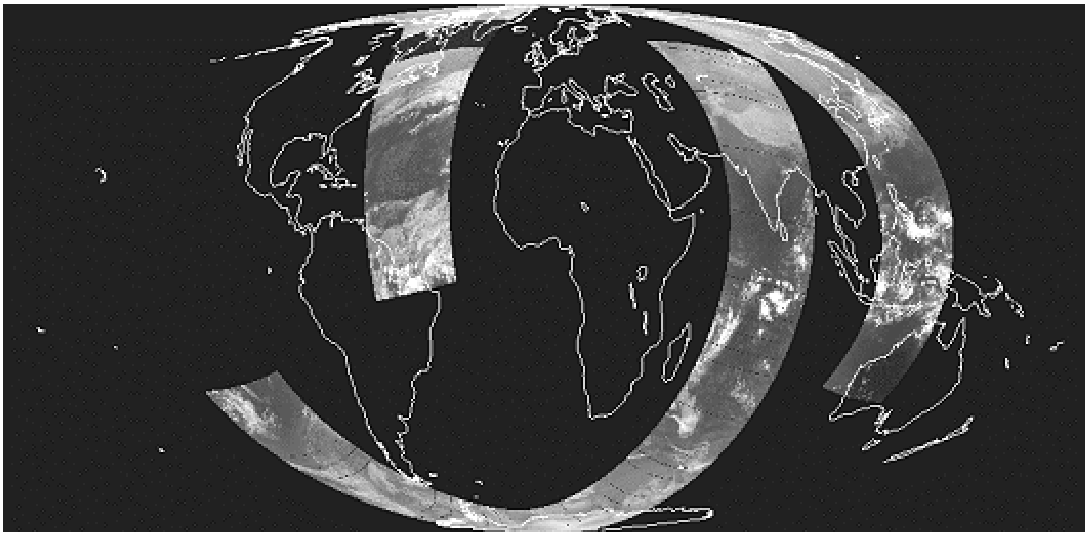


Figure 1. Example of input polar orbiter data. Scans shown are the typical coverage, for a 1-hr period, from two satellites.

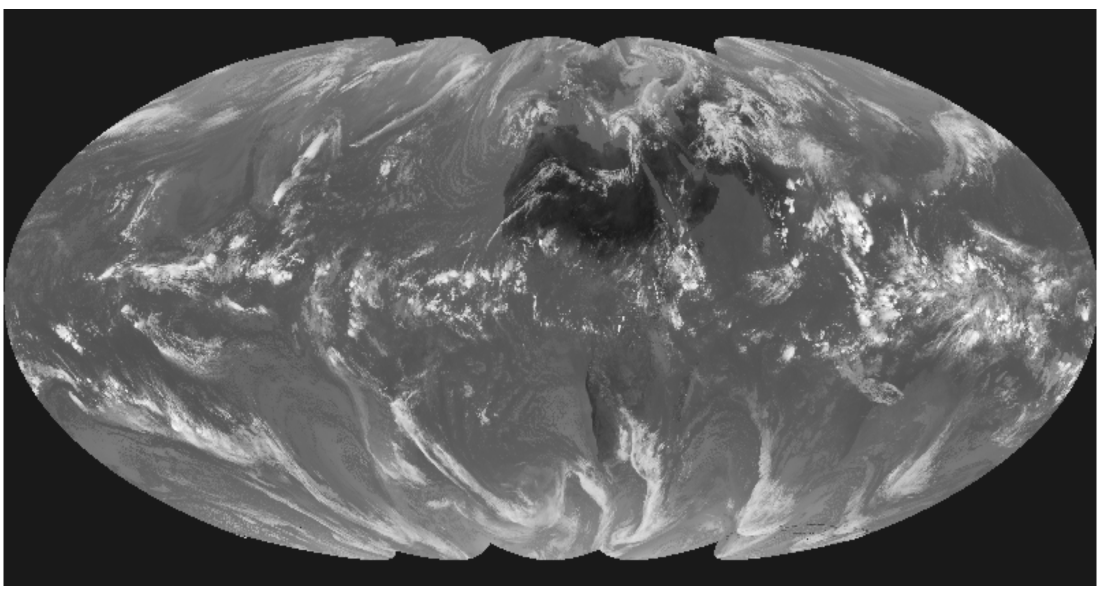


Figure 2. Example of input geostationary data. Shown is a composite of five geostationary satellites for one hour (GOES-8, GOES-10, GMS, Meteosat-5, and Meteosat-7).

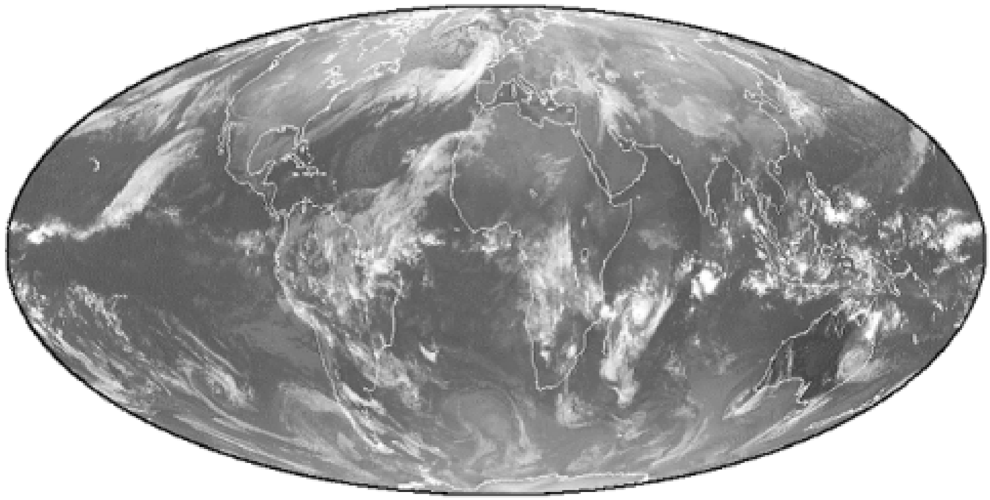


Figure 3. Example of the CHANCES global infrared "merged" image for one hour.

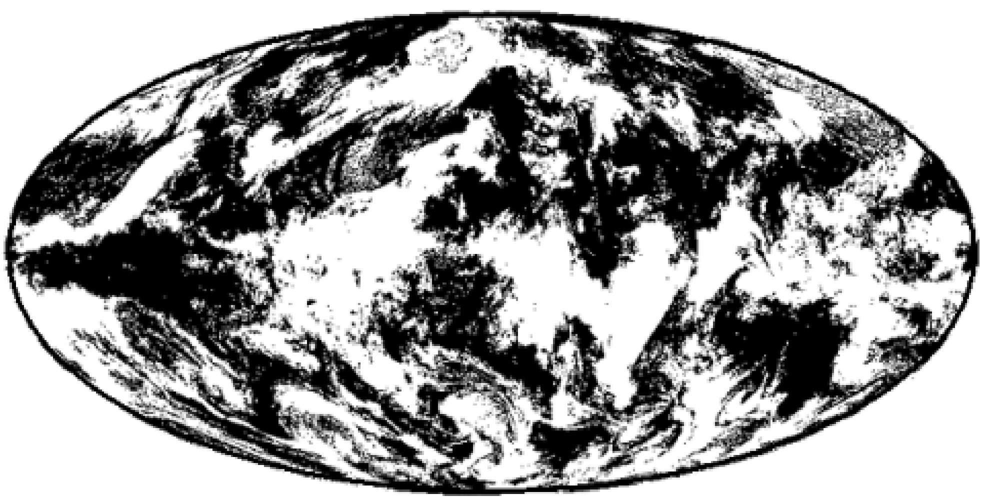
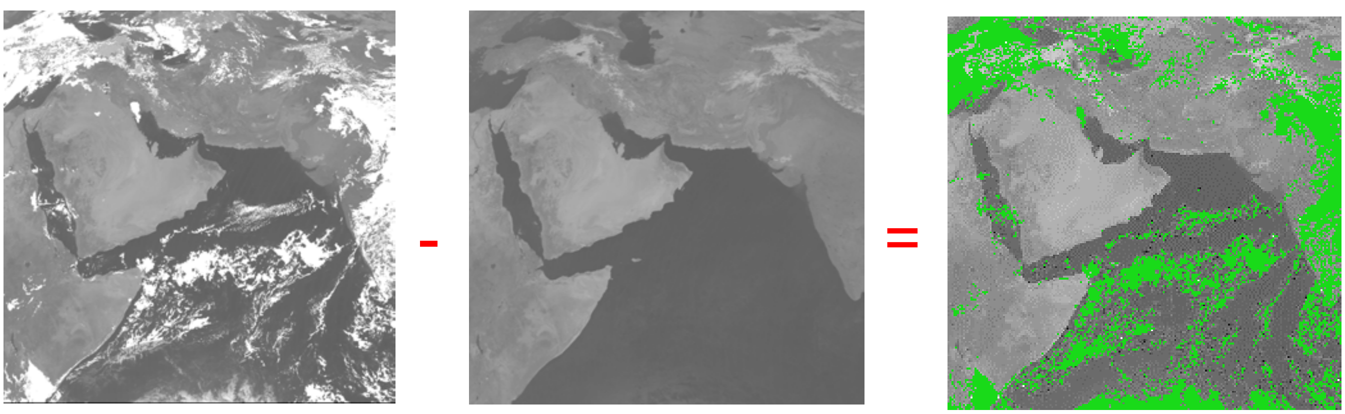


Figure 4. Example of a cloud/no cloud image (for the same hour as the image in Figure 3).

Raw Infrared Image **Infrared cloud-free “background”** **Cloud (green)**

Figure 5. Visible Cloud / No Cloud processing. Each visible image is compared to the “expected” background (clear-sky) radiance, and all pixels that are brighter (colder) than the background (plus a threshold value) are tagged as cloudy. (image time is 0900 UTC January 1st 2001 – close to local noon at the center of the image)



Raw Visible Image **Visible cloud-free “background”** **Cloud (green)**

Figure 6. Infrared Cloud / No Cloud processing. Each infrared image is compared to the “expected” background (clear-sky) radiance, and all pixels that are brighter (colder) than the background (plus a threshold value) are tagged as cloudy. (also 0900 UTC January 1st 2001)

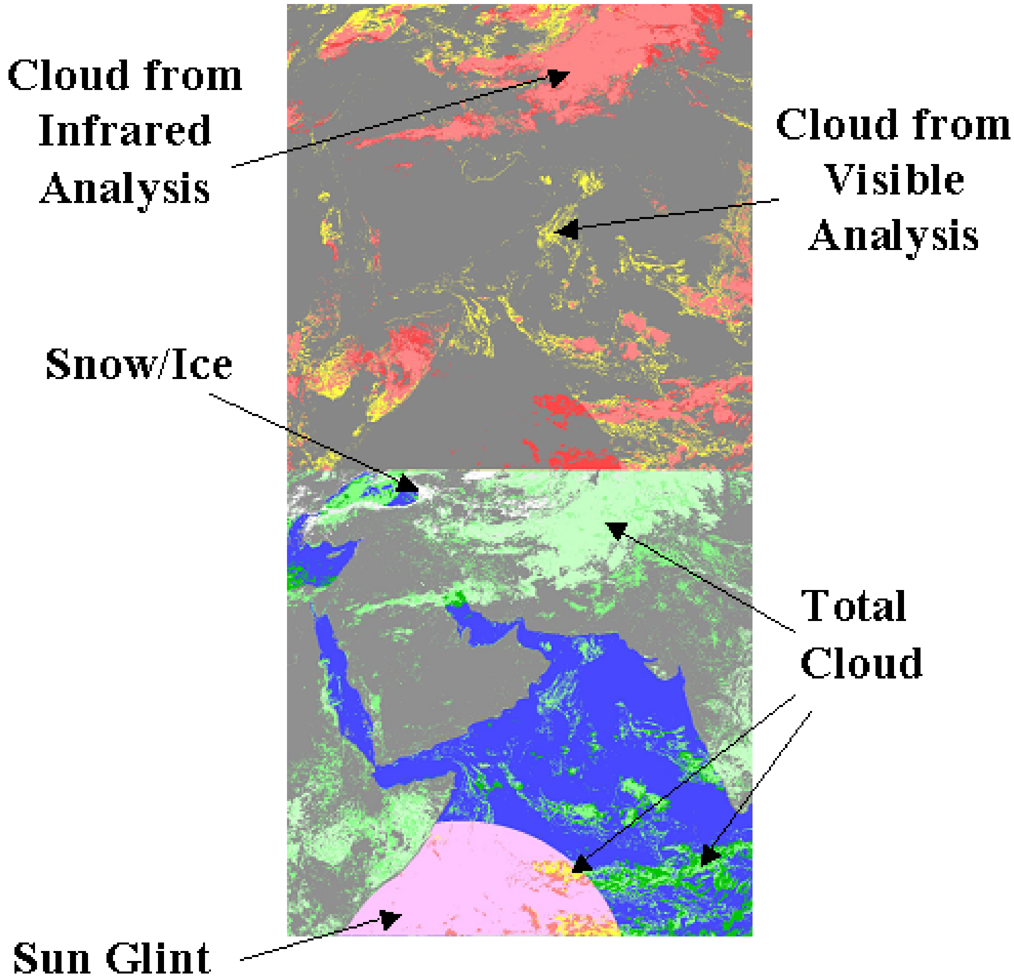


Figure 7. Example the "QA" image file. The colors are added to depict the values that have been set in various bits of the 16-bit QA word. The first 8 bits are shown in the top half and the second 8 bits in the lower half. The contents of the QA word are shown in Table 2.

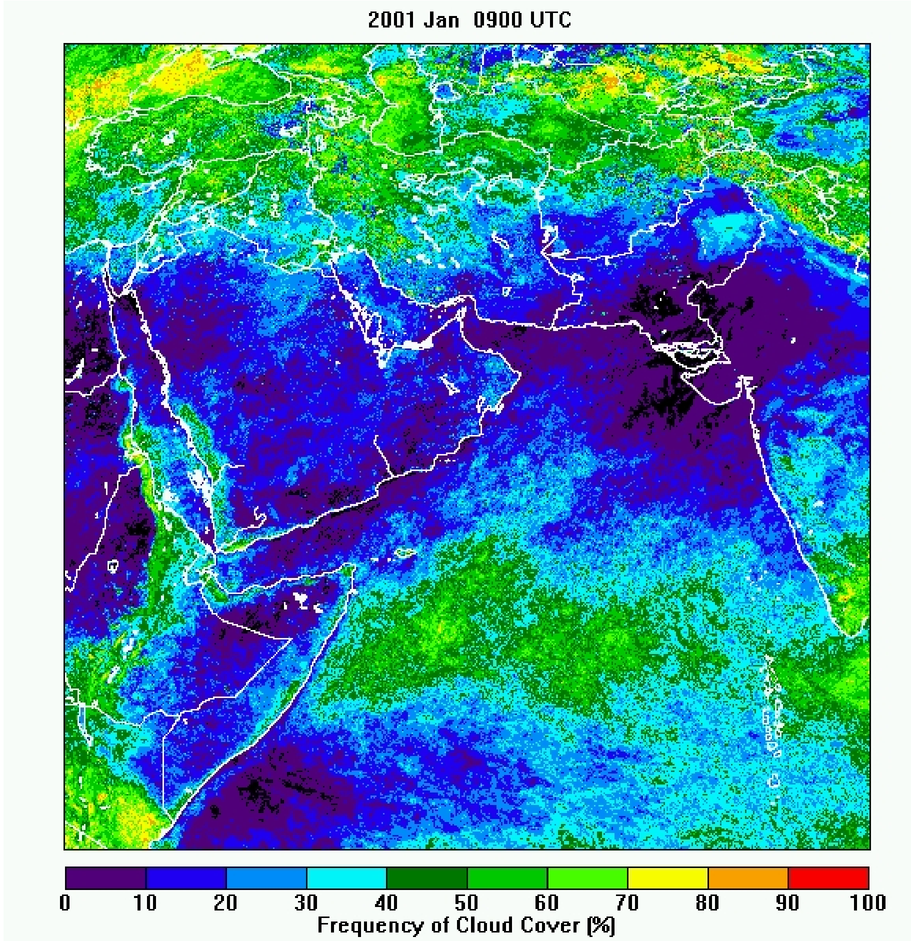


Figure 8. Example of a Frequency of Occurrence of Cloud product.

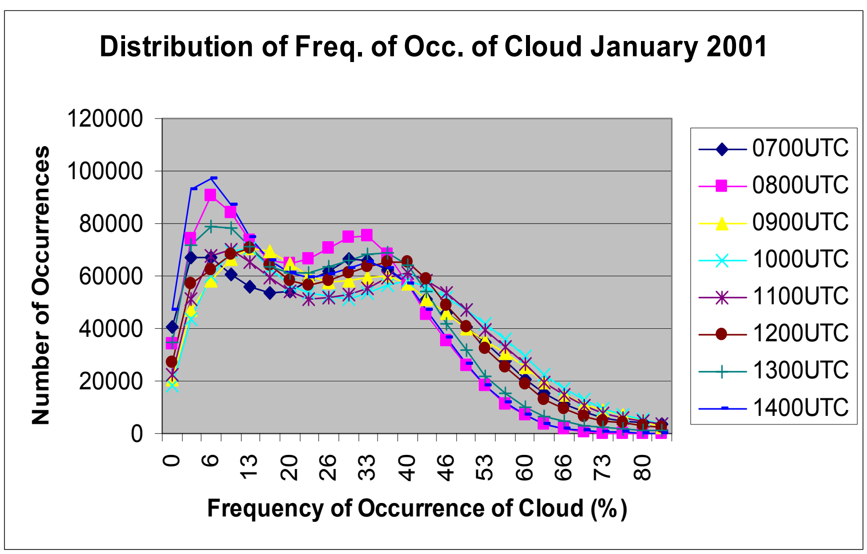


Figure 9. Example of the PDF of the Frequency of Occurrence of Cloud.

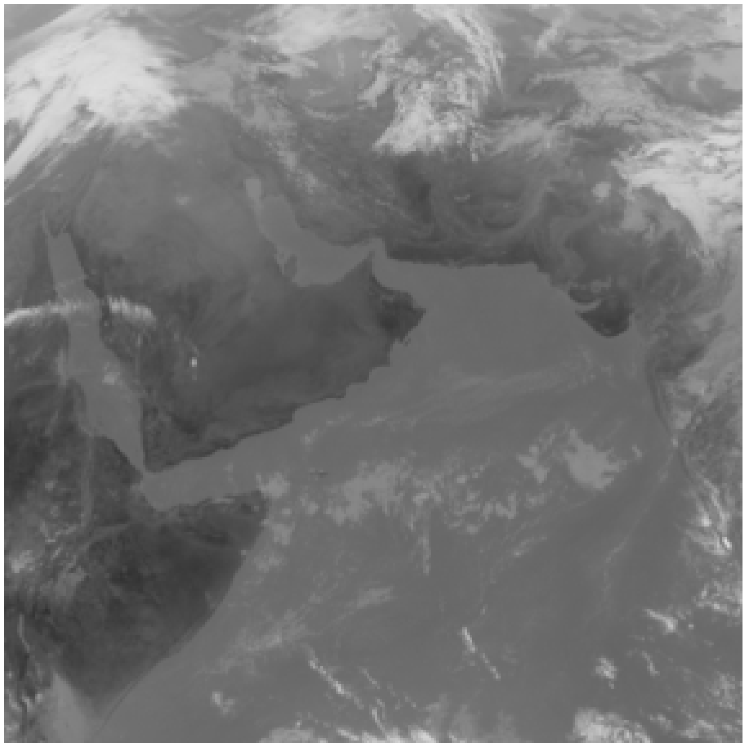


Figure 10. Infrared image from the Middle East sector, for 0900 UTC January 1st 2001, that was used to construct the “cloud/clear interval” table in Figure 11.

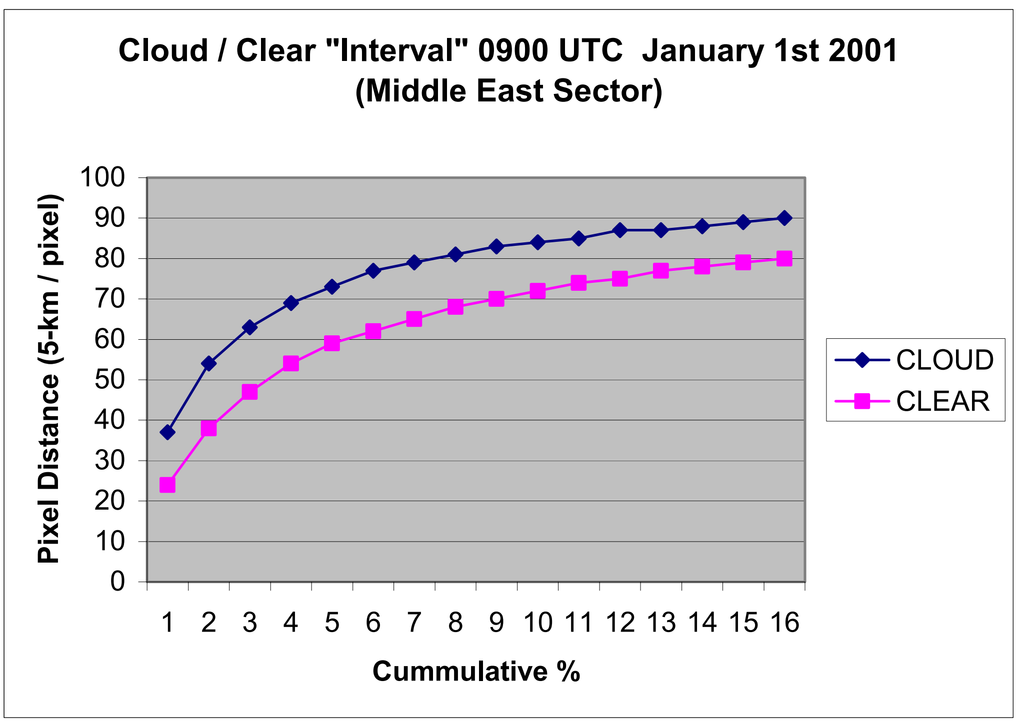


Figure 11. Example of a “Cloud/ Clear Interval” product for 0900 UTC during January of 2001. In this case, we show the cumulative probability of cloud or clear interval over the range of 0-16%.

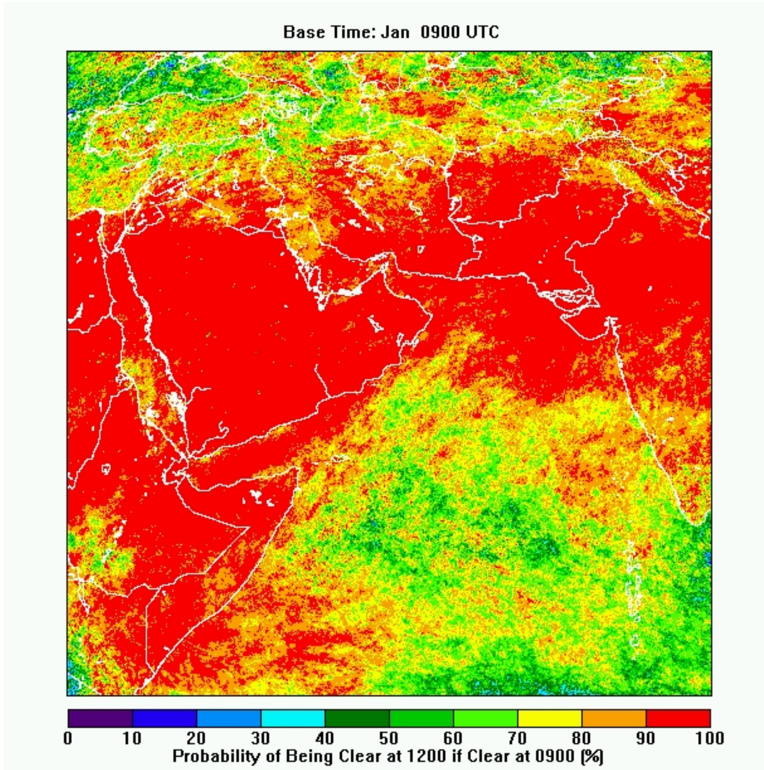


Figure 12. Example of a “Conditional Probability” product. This image depicts the probability of a location being clear at 1200 UTC if it is clear at 0900 UTC.

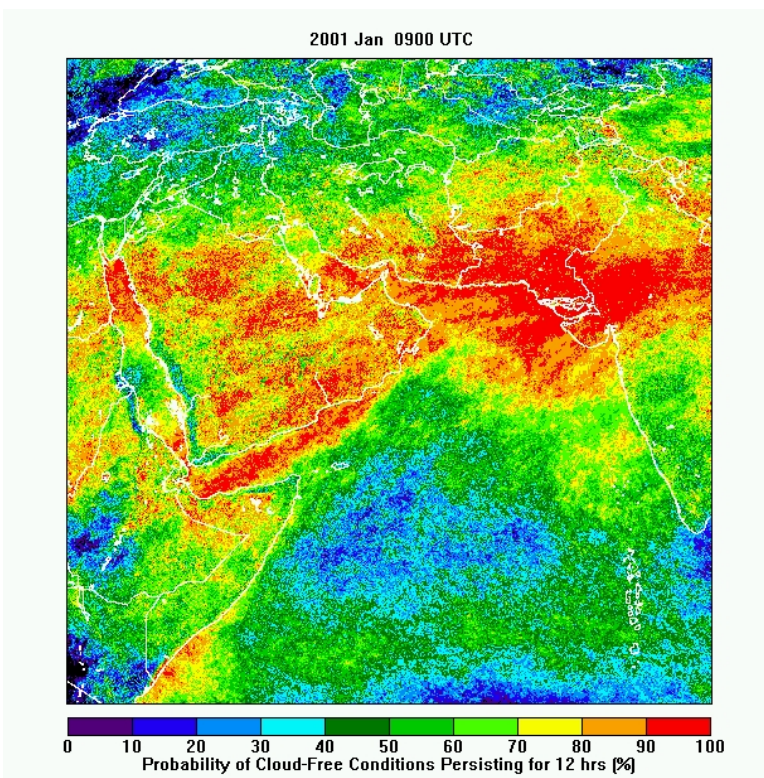


Figure 13. Example of a “Persistence Probability” product. Depicts the probability of a location <u>remaining clear</u> for 12 hours if it is clear at 0900 UTC.

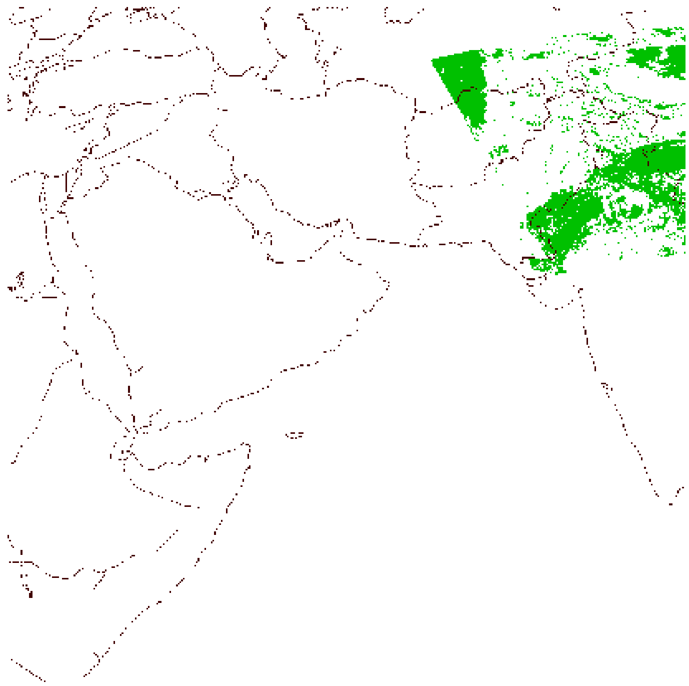


Figure 14. Example of a MODIS Cloud Mask image for a single granule centered at 1705 UTC, January 1st 2001. MODIS Cloud Mask cloudy pixels are shown in green.

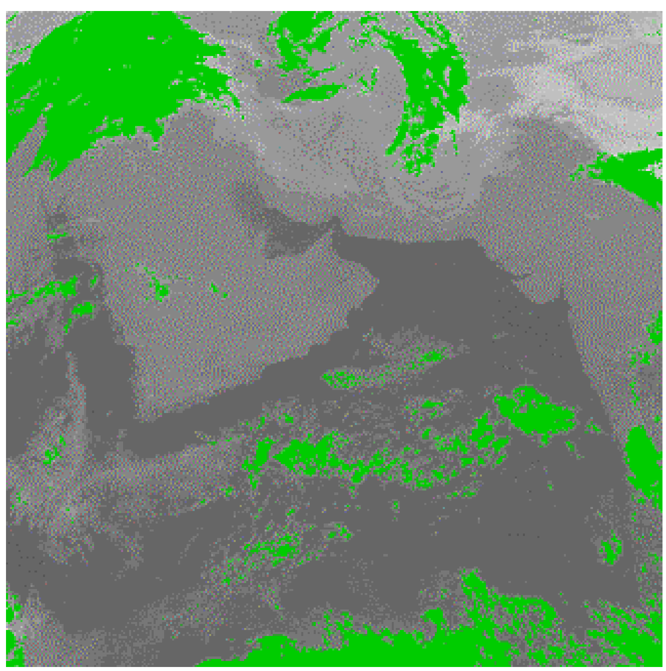


Figure 15. Cloud / No Cloud analysis from infrared image over Regional Products sector for 1700 UTC, January 1st 2001. C_RP cloudy pixels are shown in green.