NUSP-2
02 – 04

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NUSP-2 report 02 – 04
NUSP-2 project 1.1/DE-06

ISBN 903692233X

June 2003

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Abstract

With the launch of Meteosat Second Generation (MSG) a new era of European geo-stationary meteorological satellites started in 2002. The Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard MSG scans the Earth every 15 minutes with 10 narrow spectral channels. This is a huge improvement over the current generation of METEOSAT satellites that was developed in the 1970s and measures in 3 broad spectral bands. SEVIRI data may be used for developing a whole new range of products for industries that have an interest in atmospheric processes and surface properties. Especially in operational meteorology, MSG is a large step forward. The purpose of the “MSG cloud products” project was to prepare the KNMI processing environment for MSG measurements and to create an interface between the research departments (Climate and Seismology and Weather and Models) and daily operational meteorology. The project aims to communicate new developments to the operational meteorologists and also to obtain user requirements from the meteorologists to be used in research.

For data processing we used a prototype processing environment, KNMI Local implementation of APOLLO retrievals in an Operational System (KLAROS). This environment was designed to generate and display cloud properties products such as top temperature, optical thickness, and liquid water content. Because MSG was not launched during the cause of this project, the cloud products were generated from NOAA-AVHRR data. To present the prototype products a special infrastructure was set up for the MetOffice of KNMI. The researchers consulted the operational meteorologists to assess the usefulness of the products for weather prediction. During the course of the project the meteorologists became familiar with the cloud property products, made suggestions for product improvement, and brought up ideas for new products. These products are expected to contribute to higher quality forecasts. Some suggestions could be implemented directly, while the ideas for new products required more research. We found that products of particular interest for the meteorologists are those, which define the amount of sunlight reaching the ground in cloudy conditions (optical thickness) and those, which describe the geometrical vertical extent of clouds (and thus the cloud top and base height). The first is directly related to the dispersal rate of fog, exposure to UV-B (skin cancer) and crop yield. The results of the consultations will be presented in this report.

The project had length of only 9 months, but it established a valuable link between operational meteorology and research departments. The meteorologists recognized the added value to the MSG cloud products and their importance for daily weather forecasting. However, it was indicated that the visualization tools from the research department were not well suited for use by meteorologists. It took the meteorologists too much time to familiarize with them. It may be concluded that further modifications of the software architecture are needed before the modules for operational processing of MSG data can be implemented. This would greatly improve the quality and efficiency of testing new quantitative cloud products in operational meteorology. In that sense this project is ongoing and will continue until and after the launch of MSG.

Contents

List of Acronyms and Symbols

APOLLO	AVHRR Processing scheme Over cLoud, Land and Ocean
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CLIWANET	Cloud Liquid Water Network
DAK	Double-adding KNMI
DWD	Deutsche Wetterdienst
ECMWF	European Center for Medium Weather Forecast
HIRLAM	High resolution limited area Model
IFOV	Instantaneous field of view
IR	Meteosat infrared radiances
KLAROS	KNMI Local implementation of APOLLO retrievals in an Operational System
LUT	Look up table
MODTRAN	Moderate Resolution Transmittance Model
MSG	Meteosat Second Generation
NWP	Numerical Weather Prediction
SEVIRI	Spinning Enhanced Visible and Infrared Instrument
UTC	Universal Central Time (Greenwich)
UKMO	UK Meteorological Office
VIS	Meteosat visible radiances
WV	Meteosat water vapor radiances

B(T)	Clack Body Temperature
CTT	Cloud top temperature
CTH	Cloud top height
CBH	Cloud bottom height
CLWP	Cloud liquid water path
ε	Infrared Emissivity
ξ	Efficiency Ratio
n(r)	Droplet size distribution
Q	Scattering Coefficient
$R_{0.6\mu m}$	Reflectivity at 0.6µm
r_e	Effective radius
θ_o	Solar Zenith Angle
$\tau_{0.6\mu m}$	Visible optical thickness at 0.6µm

Executive Summary

New kinds of cloud products shall be generated when Meteosat Second Generation (MSG) becomes operational. A prototype processing environment, KNMI Local implementation of APOLLO retrievals in an Operational System (KLAROS), has been developed to fully exploit the vast range of channels available on MSG. The KLAROS environment generates cloud products from NOAA-AVHRR data i.e. cloud mask, cloud top temperature, cloud optical thickness, cloud emissivity and liquid water content. KLAROS may also be used with MSG data. This report describes the products of the KLAROS processing environment, and its demonstration the operational meteorologists.

Through the course of the project KLAROS products were demonstrated the meteorologists for several cases with different weather conditions. These cases included fields of convective cells, fog, and frontal zones. For each of these weather conditions specific information is needed to estimate their development. For example, the growth of convective cells can be followed from a time sequence of images. While precipitation forecasts need information on the change of the temperature of the cloud tops. The forecast of fog dissipation requires information on the thickness of a fog layer and whether enough sunlight can penetrate to the ground to warm it. The researchers discussed with operational meteorologist on the usefulness of the KLAROS products for assisting prediction of certain weather conditions. This resulted in new insights from both the researchers and the meteorologist point of view. For the fog case for example the researcher proposed to study the evolution the cloud optical thickness to predict fog dissipation. However, the meteorologist indicated the need for a better-defined product, such as surface insolation. For frontal zones the meteorologists found the cloud top temperature a useful product. KLAROS calculates a true cloud top temperature for both optically thick and optically thin clouds, while on METEOSAT infrared images the cloud top temperature of optically thin clouds is incorrect because of the contribution of the surface temperature to the signal. The thin clouds, however, are significant in relation to upper atmosphere moisture and to the spatial extent of frontal systems. In addition the meteorologists recognized the added value of having qualitative satellite products that were directly comparable to the Numerical Weather Prediction forecasts.

In conclusion, both researchers and meteorologists benefited from this project. The meteorologists were introduced to MSG possibilities and generated a great deal of interest in examining the KLAROS products, which could be seen from the suggestions made and the additional products proposed. On the other hand researchers achieved an understanding of the real day-to-day needs of the operational meteorologist. As a result new-dedicated products are under development: Thermodynamic phase and particle radius are currently being investigated. Insolation index is possible but needs more research. Although cloud vertical extent is considered important, cloud base height is nearly impossible to retrieve from passive satellite sensors. However, a combination of surface and satellite information may make this possible. Products like water content and effective particle radii were not found very useful to the meteorologists.

1. Introduction

In many parts of society, the actual use of remote sensing techniques is hampered by the gap between research groups and end users. This statement also holds for operational meteorology. About two decades ago, the expectation was that satellites would provide all cloud information that operational meteorologists need. However, currently the use of satellite data in the metOffice is limited. Meteorologists use mainly Meteosat data to monitor the movement of large air-masses (like depressions, frontal zones) by watching the grey scale sequences of infrared or visible radiances. For detailed information on cloud field properties, RGB colour image maps of AVHRR channel ratios are used to detect cloud types, such as cirrus and fog. For other cloud properties, like cloud cover fraction or cloud height, the synoptic observations from the ground observers are consulted. There are two reasons for this. Firstly, the current Meteosat has only three spectral channels, leading to a limited capability for discriminating cloud types. Quantitative cloud analysis, providing higher order cloud properties such as liquid water or phase discrimination are not possible. Secondly, the interpretation of Meteosat measurements is not unambiguous. Depending on viewing geometry and solar elevation clouds may look different. In operational meteorology this reduces the usefulness. Meteorologists are accustomed to balancing the errors of all the different information sources they use in order to obtain a concept of the current weather conditions. This implies that it requires a considerable effort to find a way to apply a new method in the forecast, estimate the quality and its added value. If the information has varying quality, such as the current Meteosat, it is difficult to use it in the forecast process.

The Meteosat Second Generation (MSG) will have high spectral and spatial resolution and give more frequent images. To learn to interpret and use information of MSG it requires effort from both the developers and the operational meteorologists. There were four steps involved in familiarizing operational meteorologists with MSG information:

1. Interpret the new quantitative cloud parameters. The 10 spectral channels of MSG allow the generation of quantitative cloud products, which look different than the radiance images of METEOSAT.
2. Discuss the added value of sequences of quantitative cloud products. With MSG it will be possible to make sequences (15 minutes interval) of spatial distributions of cloud products for the first time.
3. Demonstrate the additional information due to the increased spatial resolution of MSG that is 3*5km or 1*1km, instead of the 5*5 km resolution of METEOSAT.
4. Compare the MSG derived cloud products to NWP model data. The quantitative cloud parameters are directly comparable to NWP model fields. This opens up a whole new way of assessing the quality of the NWP-model results.

The aim of the project is to bridge the gap between research and operational use of MSG data before the launch. The meteorologists are asked to familiarize themselves with new quantitative cloud products. Researchers are requested to put effort in customizing their cloud products to the needs of the meteorologists. One of the requirements is that the project should start long before the launch of MSG to be sure that MSG data is used fully from the first day onwards.

In Section 2 the organisation of this study is presented. The satellite instruments used for this study are described in Section 3. While Section 4 gives an overview of the KLAROS cloud detection and characterisation scheme. The discussion presented in Section 6 gives a number of potential new satellite products indicated by operational meteorologist.

2. Study set-up

To allow starting the project before the launch of MSG, measurements from the Advanced Very High Resolution Radiometer (AVHRR) were used as a prototype for MSG. The AVHRR includes the 6 MSG spectral channels that are mostly used to derive cloud properties. In that respect we were able to derive the same cloud products with AVHRR and MSG. The main disadvantage of the AVHRR is that it is on a polar orbiting satellite, and thus only providing 4 images per day. The MSG will provide measurements in 10 channels every 15 minutes. Operational meteorologists mainly use the current Meteosat to interpret the evolution in time of synoptic scale systems. The main drawback of using AVHRR measurements is that the meteorologists have to use their imagination to extrapolate the AVHRR information into a time series.

The anticipated cloud products for MSG can be retrieved from AVHRR measurements using the KNMI Local Implementation of APOLLO in an Operational Scheme (KLAROS). KLAROS is a state of the art retrieval scheme that is able to produce spatial distributions of: cloud presence, cloud optical thickness, thermal emissivity, corrected cloud top temperature and vertical integrated liquid water (Dlhopolsky and Feijt, 2001; Feijt, 2000; Minnis et al., 1998). The spatial variability of vertical integrated liquid water is expected to give new information on scales of convection that are characteristic for specific cloud processes (Feijt and Jonker, 2000).

KNMI is not the only institute that is preparing for the launch of MSG. The EUMETSAT Satellite Application Facility in support of Nowcasting (NWC SAF) focuses on the use of MSG data in the MetOffice as well. The products that are defined in the NWC SAF focus on cloud classification and conceptual models of atmospheric conditions (Le Gleau and Derrien, 2000; Dybbroe and Karlsson, 2000). The cloud products that are derived from KLAROS resemble for the larger part the same quantities that are generated in Numerical Weather Prediction models. These products are fundamentally different from cloud type classification. Both processing environments are complementary and planned to be operational at KNMI after the launch of the MSG. Note that the interpretation is fundamentally different and each requires its own development/training process. For example, there is a conceptual difference between seeing the presence of cumulonimbus cloud and seeing its water content or temperature change in vertical and horizontal directions.

To obtain the required feedback from operational meteorologists, two different approaches were used: off-line presentations and near real time presentations. In the off-line analysis, interesting cases were collected from previous experiments, such as CLIWANET, and analysed in detail using KLAROS and discussions with meteorologists. The near-real time approach means that a researcher analyses AVHRR measurements as soon as they were available. The cloud products were retrieved by the KLAROS environment and shown to the operational meteorologist. He or she was then able to look at the results within the context of other information sources and knowledge of the current weather conditions. During these meeting, the most fundamental questions asked by the researcher were:

- To what extend does the KLAROS analysis give additional information on the atmospheric conditions?
- Which of the products are the most valuable for this atmospheric condition?
- Which information on clouds would be necessary to improve the understanding of the atmospheric conditions?

The findings of the meteorologists are written down and ways of implementing them into the

KLAROS environment are considered. The benefit for the meteorologists is that they got used to the concept of interpreting cloud products derived from satellite imagery as opposed to looking at grey-scaled images. The project yielded information on improvements with respect to user interface as well as products. Although the project ran over only 9 months, some improvements were quickly implemented.

During the course of the project new retrieval products were studied: thermodynamic phase (water or ice cloud), the size of cloud water droplets (Watts, 1998; Nakajima and King, 1990), cloud particle density and cloud vertical extent. These high level products are expected to have a large impact on the quality and usefulness of MSG data. These products have not yet been implemented in the operational KLAROS environment. Therefore, the meteorologists were asked off-line how they would value this information if it were available in the MetOffice.

3. Satellite Instruments

3.1. Meteosat

Meteosat is in a geo-stationary orbit at 36.000km distance. The angular speed of the satellite equals the rotation of the earth and thus the sub-satellite point is stable at about 0 longitude at the equator. The satellite covers Europe, Africa and a large part of the Atlantic Ocean. The countries contributing to the Europe's Meteorological Satellite Organisation, EUMETSAT, therefore have a clear view of the current cloud cover and the weather systems that move from the Atlantic Ocean to Europe.

The Meteosat spins around its axis, which is about parallel to the earth axis of rotation. Each cycle the sensors focus at a different latitude. By changing the orientation of the sensor the latitude observed is gradually changed from the South pole to the North pole until the full earth disc is scanned. The full disc is completed after 30 minutes and consists of 2500x2500 pixels. The exact time of the measurement depends on the location on earth. The scan starts at the whole hour in the South, so that Europe is scanned about 10 to 3 minutes before the whole hour at the end of the scan. This matches well with the time of synoptic observations, which, according to WMO regulations, are to be made 15-10 minutes before the whole hour. Meteosat has a stable viewing geometry. The spatial resolution sub-satellite, at the equator, is about 5km. Due to the curvature of the earth the resolution in Europe is about 5x9km. The instrument consists of three channels, the so-called visual (VIS), infra-red (IR) and water-vapor (WV) channels. The channel details are presented in table 3.1 and the channel spectral response functions are shown in Figure 3.1.

Table 3.1: Meteosat channels

Number	*Wavelength [μm]*	*Spatial resolution nadir*
1	0.5 – 0.9	2.5*2.5 km
2	5.7 – 7.1	5.0*5.0 km
3	0.5 – 12.5	5.0*5.0 km

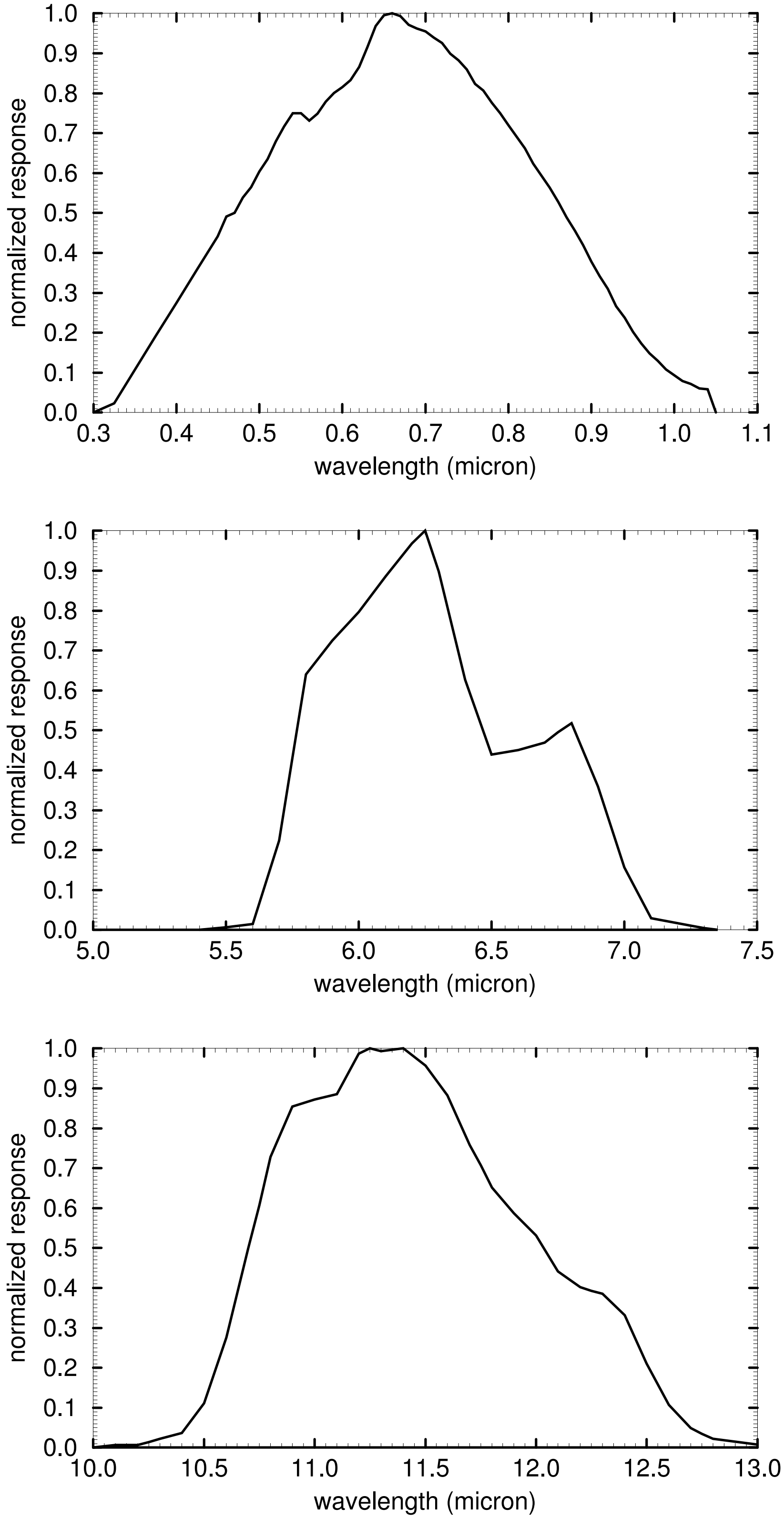

Figure 3.1 Spectral channels of Meteosat: Visible (top), Water vapor (middle) and Infrared (bottom).

3.2. NOAA-AVHRR

NOAA is a polar satellite that circles from pole to pole at an altitude of approximately 850 km. During each circle a different part of the Earth is scanned. The satellite scans each place on Earth at least twice a day. Places closer to the poles are observed more frequently, with a maximum of 14 observations at the poles.

The AVHRR instrument on board of NOAA has 5 (or 6) wavelength channels. The channels are optimized to measure cloud and surface characteristics with minimum contamination from other atmospheric constituents. The channel specifications are presented in table 3.2. The radiometer scans across track with a scan angle of about 55 degrees, which corresponds with a scan line length of 3000 km. The sub satellite instantaneous field of view (IFOV) is 1.2 km. At the edges the IFOV is much larger due to the steep angle and the curvature of the earth. The spectral response functions of the AVHRR sensors are given in Figure 3.2.

Table 3.2: NOAA-AVHRR channels

Number	***Wavelength [μm]***	***Spatial resolution nadir***
1	0.58 – 0.68	1.2*1.2 km
2	0.73 – 1.10	1.2*1.2 km
3a	1.58 – 1.68	1.2*1.2 km
3b	3.55 – 3.93	1.2*1.2 km
4	10.3 – 11.3	1.2*1.2 km
5	11.5 – 12.5	1.2*1.2 km

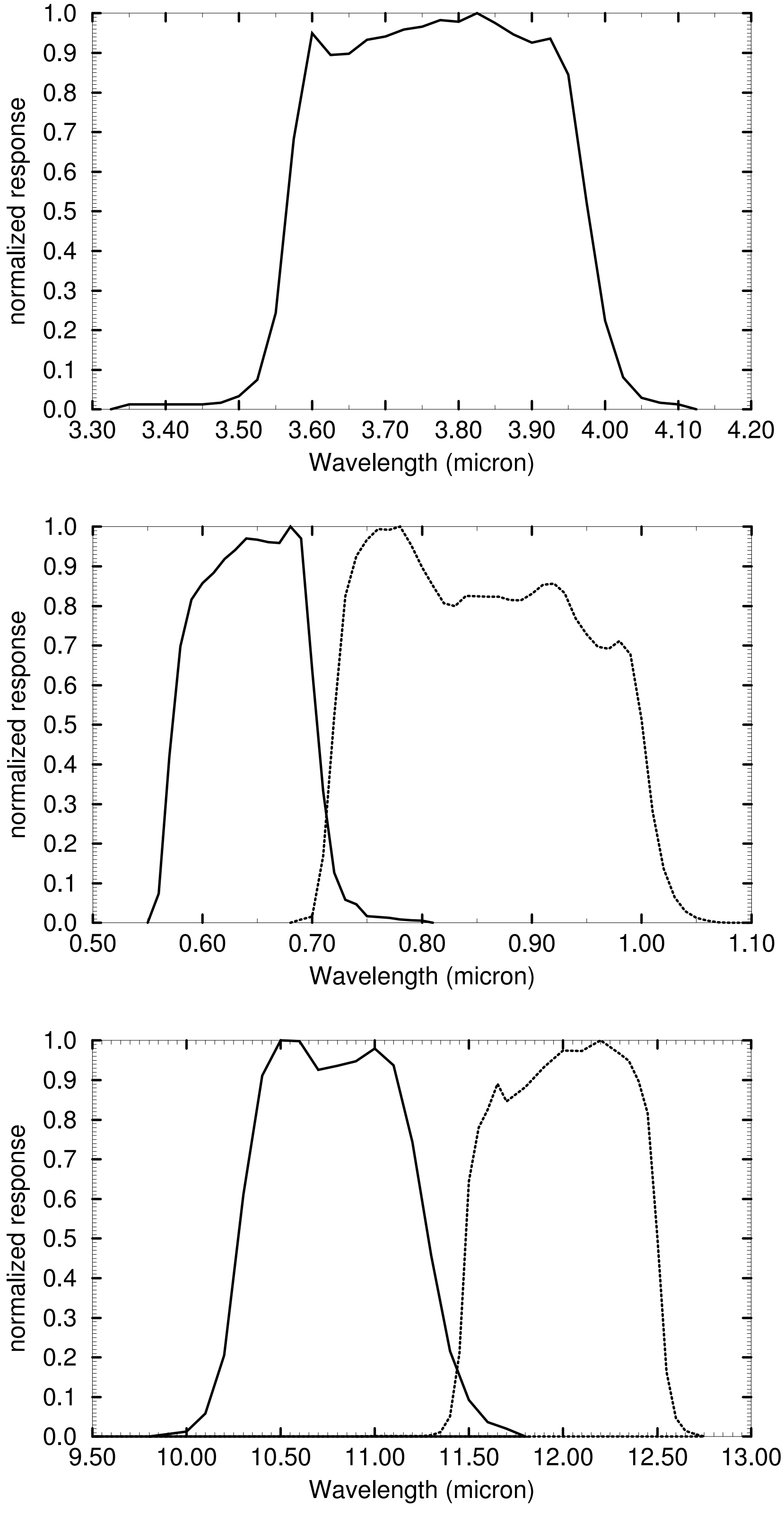

Figure 3.2 Spectral channels of AVHRR : 0.6 μm and 0.8μm (top), 3.7μm, (middle) and 10.8 μm and 11.9μm (bottom).

3.3. MSG

Similar to METEOSAT the Meteosat Second Generation (MSG) satellite is in a geo-stationary orbit at 36.000km distance. The imager onboard MSG is the Spinning Enhanced Visual And Infrared Imager, SEVIRI. This new instrument includes 11 spectral channels, of which 8 are similar to current AVHRR and Meteosat channels (Table 3.3). The width of the spectral channels is smaller and more stable than the METEOSAT channels. Every 15 minutes, a new set of images will be available. Highest spatial resolution is 3x3 km sub-satellite, which is at longitude 0 degrees over the equator. In addition there is a broadband visible channel, similar to the visible channel of METEOSAT that scans Europe with a spatial resolution of 1*1 km (sub-satellite).

Table 3.3: Severi channels

Number	***Wavelength [μm]***	***Satellite***
1	0.6	AVHRR
2	0.8	AVHRR
3	1.6	AVHRR
4	3.9	AVHRR
5	6.2	Meteosat
6	7.3	Meteosat
7	8.7	-
8	9.7	HIRS
9	10.8	AVHRR
10	12.0	AVHRR
11	13.4	HIRS

The Severi enables analysis of cloud scattering properties in the visible from the 0.6, 1.6 and 3.7μm channels. The infrared radiative properties and thus cloud height estimates will be obtained from the 8.7, 10.8 and 12.0μm channel. Upper tropospheric humidity can be retrieved in two vertical layers from the 6.2 and 7.3μm channels. The 9.7μm channel measures within the ozone absorption band. Information on vegetation can be retrieved from the 0.8μm channels. By combining the spectral channel radiances it is possible to retrieve quantitative information on cloud properties. In the long run all channel information will be combined to understand the state of the atmosphere and the underlying surface. This is expected to have a major impact on meteorological forecasting and climate research.

4. KLAROS

The AVHRR analysis environment is called KLAROS, which stands for 'KNMI Local implementation of APOLLO Retrievals in an Operational System'. KLAROS is a two-step analysis environment. In step one, the cloud detection, cloudy pixels are identified as cloudy or cloud free. In step two, the cloud characterisation, we calculate the optical thickness, liquid water path, emissivity and cloud top temperature, hereinafter referred to as cloud physical properties.

The cloud detection part consists of a series of threshold tests adopted from the AVHRR Processing over Land Cloud and Ocean (APOLLO), which was developed in the 1980's (Saunders, 1986; Saunders and Kriebel, 1988). The APOLLO scheme is basically a supervised method. The analysis is based on interactive inspection of AVHRR measurements. The assignment of clear sky thresholds relies on histogram analysis of temperature and reflectivity. Depending on the weather situation, a clear sky value can be very far away from the cloud field one wishes to analyse. In the 1990's, the histogram analysis was automated (Kriebel, personal communication). In KLAROS, adaptations to the original APOLLO version were made, which enabled automated retrievals and resulted in an improved quality. These are described in Section 4.1 (cloud detection). In Section 4.2 the methods are presented to assign cloud properties to AVHRR pixels.

4.1. Cloud detection

Cloudy scenes are identified by a threshold method, which tests if the signal in a channel or combination of channels originates from the surface in a cloud free atmosphere. If not, the scene is assumed to be cloud contaminated. The main tests for daytime are described here. A scene is identified cloudy if one of the following conditions is met:

Temperature test:

$$T_{10.8\mu m}\ (\text{measured}) < T_{10.8\mu m}\ (\text{cloud free}) - \text{temperature threshold} \tag{4.1}$$

Reflectivity test:

$$R_{0.6\mu m} > R_{0.6\mu m}\ (\text{cloud free}) + \text{reflectivity threshold} \tag{4.2}$$

Semi-transparency test:

$$T_{10.8\mu m} - T_{11.9\mu m} > T_{10.8\mu m}\ (\text{cloud free}) - T_{11.9\mu m}(\text{cloud free}) + \text{semi-transparency threshold} \tag{4.3}$$

T_λ is the equivalent black body temperature in the spectral channel denoted by λ. R_λ is the reflectivity in the spectral channel denoted by λ.

The crucial part of the temperature test is the estimate of $T_{10.8\mu m}$ (cloud free). In this aspect APOLLO and KLAROS differ. The estimate of the temperature for cloud free conditions in KLAROS originates from an operational numerical weather prediction model called HIRLAM, the High Resolution Limited Area Model (Gustafsson, 1993), whereas in APOLLO uses a histogram analysis over large areas from the satellite overpass under study. The histogram analysis approach assumes that for each analysis area it is possible to identify a cloud free scene, which is representative for cloud free conditions over the whole analysis area. This approach does not work in case of extended cloud fields or sharp surface temperature gradients due to air mass changes. KLAROS uses values from an atmospheric model. This introduces a bias due to the difference between the model surface temperature and the satellite equivalent black body temperature for cloud free conditions (Feijt et al., 1998; 1999a). In supervised mode of KLAROS, the bias can be estimated from cloud free areas in the satellite data. Derrien et al (1993) showed that orographic effects at sub-grid scales of the atmospheric model could introduce a significant difference between the model surface temperature and the satellite equivalent black body temperature.

The reflectivity test requires an estimate of the reflectivity for cloud free conditions. In APOLLO this value is also obtained from histogram analysis. In KLAROS the surface reflectivity is estimated from a combination of three sources:

1) histogram analysis of the satellite observations under study,
2) histogram analysis of a recent satellite observation at clear sky conditions,
3) a two-year data set of AVHRR radiances collocated with synoptic observations of clear sky.

The semi-transparency test is based on the difference in absorption and scattering properties of water droplets and ice crystals at 10.8 and 11.9μm (Minnis et al., 1998; Oleson and Grassl, 1985). This results in different optical thicknesses and thus different cloud emissivities and equivalent black body temperatures. Minimum differences occur for cloud free conditions and for opaque clouds, when emissivity in both channels is near unity. The maximum difference is governed by the microphysical properties of the cloud and the cloud top and surface temperature. The difference is largest for small water spheres and decreases with increasing drop size. For spheres larger than 20μm the emissivities at 10.8 and 11.9μm are similar (Minnis et al., 1998). The test is sometimes referred to as cirrus-test, because it is most effective in case of a large temperature differences between surface and clouds, i.e. in case of cirrus. In order obtain an estimate of the difference for cloud free conditions, MODTRAN calculations are done at the appropriate viewing zenith angle on profiles of water vapour and temperature as measured from radiosondes. Main sources of uncertainty in these calculations are:

- surface temperature,
- surface emissivity at 10.8μm and 11.9μm,
- representative ness of the radiosonde profiles.

These uncertainties are taken into account in the semi-transparency threshold, which in general, is of the order of 1.5K.

4.2. Cloud characterization

KLAROS includes retrievals of cloud cover fraction, cloud top temperature, optical thickness, emissivity and liquid water path. In the following paragraphs the methods applied to retrieve these cloud parameter are presented.

Cloud cover fraction

The ratio of cloudy pixels over all pixels is used as an estimate of the cloud fraction. It is assumed implicitly that cloudy pixels are fully cloudy, which in general is a valid assumption at the scale of the AVHRR IFOV. Statistical analysis of synoptic observations shows that most observations are either in the 0-1 octas or 7-8 octas range, which results in U or J shaped frequency distributions of cloud cover fraction (Henderson-Sellers and McGuffy 1991; Jonas, 1991). Small cloud amounts of the 1-2 octas range will often be identified as cloud free by KLAROS due to the low contrast with the surface. The near overcast situations generate fully cloudy pixels, which is consistent with the approach. So, for the most frequent cloud conditions the approach yields reliable results. In the less frequent 3-6 octas range of observations there may be a bias. This can be an overestimate, if all partly cloudy pixels are assumed fully cloudy, or an underestimate if the cloud detection tests fail to identify part of the cloudy pixels. However, in most cases, part of the cloudy pixels will be correctly labelled as such, and thus the over- and underestimates will compensate each other.

Actually, the retrieved cloud cover fraction is merely a cloud projected area. In general, the cloud fraction seems higher when the clouds are observed from aside, because the vertical dimension is projected on the horizontal. This difference is not accounted for, because it would require a measure of the cloud vertical extent.

Cloud layer temperature

The basic information used to retrieve cloud top temperature is the measured equivalent black body temperature at 10.8μm, which is representative of the cloud layer if the pixel is completely filled with an opaque cloud. However, in case of semi-transparent clouds or partly cloudy scenes, the measured radiance is a combination from contributions from cloud and surface, which results in an overestimate of the cloud temperature. In KLAROS a method is implemented to exclude those pixels that are affected by semi-transparency and thus obtain an estimate of the temperature of cloud layers. It uses the difference in equivalent black body temperature at 10.8 and 11.9μm to detect semi-transparent clouds (see also Section 4.1). If the following condition is met, the scene is assumed to be filled with opaque clouds.

Selection test:

$$T_{10.8\mu m} - T_{11.9\mu m} < \text{selection\_threshold} \qquad (4.4)$$

The selection test is similar to the semi-transparency test. The conditions are better defined, because the surface does not contribute to the signal. So, variability of surface temperature and surface emissivity have not to be taken into account. Furthermore, the atmospheric absorption is limited to the atmospheric layer above the cloud and is, especially for ice clouds, negligible. Therefore, selection_threshold may be chosen smaller than semi-transparency_threshold. In general, selection_threshold is about 1K.

This test yields cloud temperatures for individual pixels. It is possible to identify multiple cloud layers if several peaks are found in a histogram frequency analysis of temperature. Information on cloud fraction per cloud layer and the width of the layer is not available from this method, however. The retrieved cloud top temperature is measured directly and thus is accurate. This simple method has proven to be effective both for ice clouds and water clouds as was shown by Koelemeijer et al. (1995a) and Feijt et al. (1999). Furthermore, the test can be applied both day and night. During daytime, the cloud temperature can also be retrieved from the optical thickness at 0.6μm. This approach is described below.

Optical thickness

The retrieval of $\tau_{0.6\mu m}$ is retrieved from $R_{0.6\mu m}$. The surface reflectivity is estimated in a similar way as for cloud detection. The database of DAK calculations of reflectivity is searched for the appropriate sun-satellite geometry, cloud type, and surface reflectivity. This results in 12 values of $R_{0.6\mu m}$, corresponding to 12 values of the optical thickness. The thus obtained pre-calculated values are compared with the measured reflectivity for each pixel to obtain an estimate of optical thickness at 0.6μm.

Emissivity
The cloud emissivity can be derived from the optical thickness at 10.8μm, $\tau_{10.8\mu m}$. The optical thickness in the infrared, $\tau_{abs,10.8\,\mu m}$, and the optical thickness in the visible $\tau_{0.6\mu m}$ are linked with the efficiency ratio, ξ, which depends on the size of the particles:

$$\xi = \tau_{0.6\mu m} / \tau_{abs,10.8\,\mu m} = <Q_{0.6\mu m,scatt}>/<Q_{10.8\mu m,abs}> \quad (4.5)$$

ξ is 2.4 for the water cloud size distribution that was used in the DAK calculation. For ice crystals the value for large particles, r > 50μm, is used: ξ = 2.0 (Minnis, 1998). This assumption is consistent with the use of the ray tracing technique to obtain a scattering phase function at 0.6μm, which also requires particles to be large.

$$\varepsilon = 1 - \exp(- \tau_{0.6\mu m} /(\xi \cos \theta_0)) \quad (4.6)$$

Cloud temperature
The cloud temperature can be derived from the emissivity and the estimated contribution of the surface:

$$B_{10.8\mu m}(T(cloud)) = (B_{10.8\mu m}(T(measured)) - (1-\varepsilon)\, B_{10.8\mu m}(T(surface))/\varepsilon \quad (4.7)$$

$B_{10.8\mu m}$ is the radiance of a perfect black body at temperature T filtered by the spectral response function of the AVHRR 10.8μm channel. The spectral response function is obtained from the pre-flight calibration. B(T) can be fit to a second order polynomial of T with sufficient accuracy.

T(surface) is estimated from the numerical weather prediction model surface temperature, T_{nwp}. As described in section 4.1, this estimate may be significantly biased, particularly for cloud free conditions. For detailed, interactive studies, the bias is estimated from cloud free areas in the AVHRR image. The bias below clouds is expected to be between 0 and 30% of the bias in cloud free conditions, depending on the transmission of sunlight through the cloud.

Liquid water path
The CLWP and the optical thickness are both directly related to the drop size distribution:

$$CLWP = \int n(r)\,(4/3)\,\pi\, r^3 \rho\, dr \quad (4.8)$$

where r the droplet radius, ρ the density of water and n(r) the droplet size distribution. The weighted average scattering coefficient, $<Q>_{n(r)}$, is directly dependent on the drop size distribution, which yields:

$$\tau = <Q>_{n(r)} \int n(r)\, \pi\, r^2\, dr \quad (4.9)$$

The droplet size distribution and the amount of liquid water can be linked to the optical thickness through one single parameter, the effective radius, r_e, (Stephens, 1984):

$$r_e = \int n(r)\, r^3\, dr / \int n(r)\, r^2\, dr \quad (4.10)$$

Combining the above equations yields a relation between τ and CLWP:

$$CLWP = (4/3)\ \tau\ r_e <Q_{n(r)}> \tag{4.11}$$

If no information on the drop size is available, $<Q_{n(r)}>$ is often assumed to be 2 (Stephens, 1984), which is a good approximation for most typical cloud particle size distributions. For the drop size distribution used in the DAK calculations, $<Q_{n(r)}>$ equals 2.14.

In the method presented in this chapter, the retrieved cloud parameters resemble the description of the atmosphere as used in the radiative transfer calculations. Therefore, we may expect that the results are sensitive to differences between the conceptual model and the cloud field under study. However, it is not feasible to estimate the errors that will occur from theoretical argumentation alone. Therefore, the skill of the retrieval method has been evaluated with ground-based observations of cloud fields (Feijt et al., 1998; Dlhopolsky and Feijt, 2000).

5. Consulting the meteorologists

To introduce the project and the products to the meteorologists a presentation was given of the general project set-up, the meteorological satellites (MSG and NOAA), the cloud processing software KLAROS and the anticipated cloud products. To obtain feedback on the applicability of KLAROS software and products for operational weather forecasting several operational meteorologists were consulted. Two different approaches were followed. Firstly, the offline analysis, where historical and validated cloud products were presented and their applicability was evaluated. Secondly, the near real time analysis, where the cloud products were generated and tested in an operational weather forecasting situation.

5.1. Offline analysis

In the following Paragraphs, examples of offline cases are presented i.e.: convective clouds, fog and frontal clouds.

The advantage of the offline analysis was that the meteorologist had more time to imagine how a specific product would contribute to the understanding of the weather. In addition, the cloud products presented were validated with ground-based remote sensing instruments like lidars, radars, microwave radiometers and infrared radiometers. Therefore, the quality of these cloud products was relatively high. For the validation we used data from the intensive measurement campaigns called BBC and CNN of the CLIWANET project (Feijt et al., 2001). CLIWANET was a EU funded project that focused on observations of cloud physical parameters i.e.: cloud droplet profiles of water clouds, and cloud particle profiles and particle velocity for ice clouds measured with Lidar and Radar (Donevan, 2000), the cloud liquid water path and water vapour content (microwave radiometer), the sky or cloud base temperature (infrared radiometer) and vertical profiles of air temperature and pressure (radiosonde data). The CLIWANET measurements were collected at 11 sites in Europe covering a larger area. Moreover, he had time to imagine the impact of having time series of these spatial distributions of cloud parameters at 15 minute intervals.

5.1.1. Convection

Convective cells can be identified by their spatial structure from AVHRR images. Meteorologists have to determine whether the convective cells will grow enough to produce precipitation and how much time will pass until this will occurs. To determine the evolution of convective cells information is needed of the water content of the clouds, the thermodynamic phase of the cloud tops and their growth rate.

Three KLAROS cloud products could be combined to compose a good indicator for precipitation i.e.: Liquid Water Path, Cloud Top Temperature and Thermodynamic Phase. The thermodynamic phase product is still in a experimental state and not a standard KLAROS product. However, in the CLIWANET project methods have been developed to decide on thermodynamic phase. These methods utilize visible (0.6 micron) and near-infrared (1.6 micron) data combined with Cloud Top Temperature data.

In a sense the CLWP product can be used to estimate the depth of convection. The CLWP can be estimated for each cell, and give an estimate of the vertical integrated liquid water. If a cloud does contains only a small amount of water it will not precipitate. At mid-latitudes (e.g. Europe) water droplets are not able to grow large enough to produce precipitation. However, if the water droplets freeze and become ice particles they grow quickly. When ice particles are large enough they start to fall and can grow further through coagulation.

With MSG the cloud CLWP and thermodynamic phase may be derived in a similar way. Taking into account the 15 minutes sampling frequency of MSG it becomes possible to make time series of the KLAROS products. This information allows the operational meteorologists to monitor the convective grow of cells. The time element gives important additional information. The acceleration of the cell growth of convective cells, both in horizontal and vertical sense, indicate: the strength of the underlying process, whether cells will grow enough to produce precipitation and a first order estimate of the timing. Figure 5.1 shows convective cells over England. Over the Southeast, shallow convection produced small convective cells. In the middle large cells were formed. From the KLAROS analysis we know that the large cells contain sufficient liquid water to produce precipitation. The blue colour indicates that the cloud top temperature, as retrieved from KLAROS, is more than 5 degrees below the freezing level. These two properties together indicate that these convective cells were producing precipitation. Synoptic observations that were analysed for this day confirm that there were showers over England during this day.

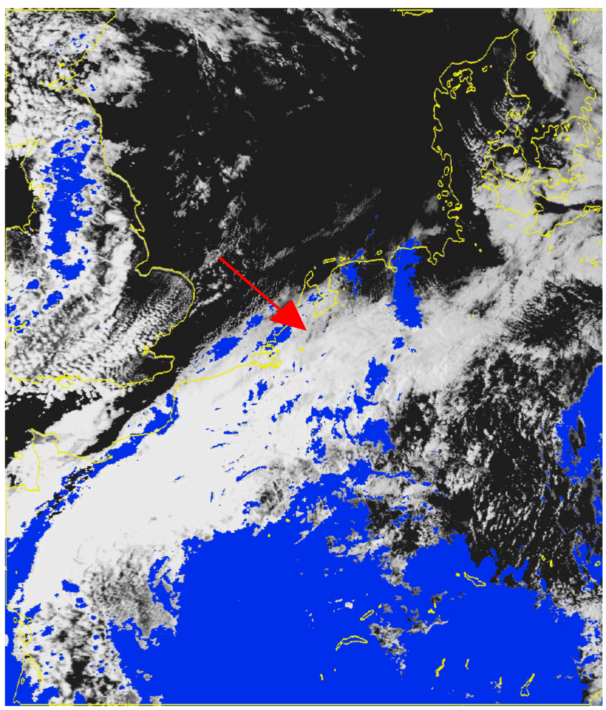

Figure 5.1: Liquid Water Path derived from the AVHRR overpass of 15:13 on 4 May 2001. Black is cloud free. Blue is cloud top temperature below –5C. Scaling: 0 < grey < 250 g/m2. White indicates higher values than 250g/m2.

5.1.2. Fog

Fog is important in traffic and aviation applications. The meteorologist has to estimate whether or not the fog will dissipate during the day. Since many types of aircrafts are not able to depart or land in fog conditions the accurate prediction of position and period of presence of fog is of high importance. In addition, road traffic is hampered during fog conditions and accurate and timely prediction of fog during rush-hours is crucial. There are two main mechanisms that help fog disappear: increase of wind speed at the surface and convection due to heating of the surface. Meteorologists currently use the ground based pyranometer measurements to get information on the insolation. There are about 30 meteorological stations equipped with a pyranometer in the Netherlands. By monitoring the pyranometer read-out and comparing it with reports of cloud cover, meteorologist estimate how the situation will evolve. This process is very delicate, because there are positive feedbacks involved. If the fog layer is relatively thin at one spot, this enables the sun to shine through and heat the surface. The heated surface warms the top air layer, which is warmer than its surroundings and therefore gains buoyancy, so it rises and induces some convective motion. This mixes the air-masses and dissolves part of the fog layer. As a result the fog layer has become thinner and more sunlight can shine through. Thus, the amount of sunlight reaching the surface is an important parameter in case of fog. A ground based insolation product would be most straightforward to monitor dissolving fog. However, to cover the spatial variability of fog a dense network of pyranometers is needed. The current amount of 30 pyranometers is insufficient to obtain the required spatial coverage.

Currently, there is no insolation product in KLAROS. However, a KLAROS product that may be used to calculate insolation is the cloud optical thickness, which is a parameter that defines the transmissivity of a cloud. When presenting this fog case, it was suggested that insolation would be a useful parameter to operational meteorologists. An advantage is its similarity to pyranometer values. Since these data are already used in the MetOffice the level of acception of an insolation product would be is high. For MSG, the optical thickness is expected to be of great value in fog conditions. Due to MSG's high sampling frequency developments in fog fields can be followed precisely. Thus, if the optical thickness decreases over time this indicates that the fog is dissipating, while a constant optical thickness implies that the fog remains. The time series will be much more useful than the current snapshot AVHRR analysis, because fog is a very well localized phenomena. The amount of insolation that is necessary to warm the earth and start dissolving the fog layer depends on many local features: humidity of the surface, vegetation, orography, etc. Therefore, the spatial distribution of insolation values derived from MSG is expected to be a significant improvement relative to the current network of 30 ground stations.

In figure 5.2 an example is presented to illustrate the use of the optical thickness product in case of fog. The left panel shows the reflectivity at 630nm. The blue line indicates our area of interest. In the right panel the scatter plot the optical thickness is given as a function of the longitude. Clearly, there is a shallow fog layer near the coast, which grows thicker more land inward. Then over Utrecht, there is an area of lower optical thickness. More to the east the optical thickness increases again. Obviously, the fog will dissolve in Utrecht first, and next the coastal area will become cloud free. Finally the east of the Netherlands will become fog free. This example shows the added value of the optical thickness product. MSG will be able to provide the data to make sequences of spatial distributions of optical thickness. This will enable the monitoring of dissolving of fog at a 3*3km scale, which is sufficient for traffic and aviation applications.

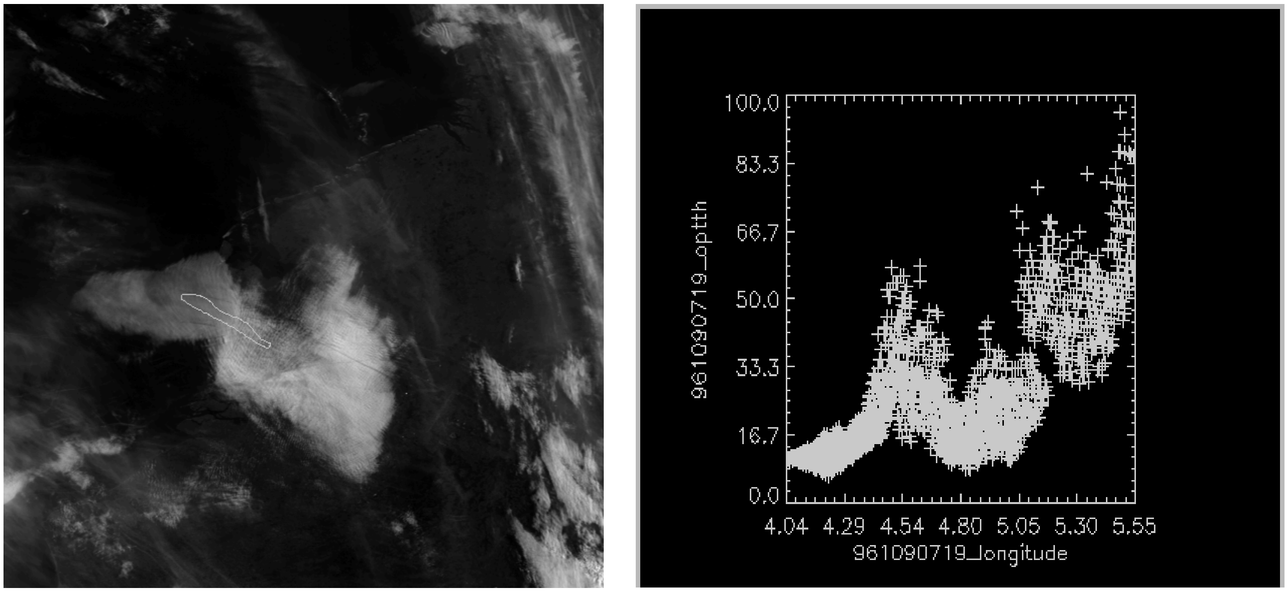

Figure 5.2 Example of a fog field over the Netherlands. The scatterplot is based on the data area circled in the reflectivity image at top.

5.1.3. Frontal zones

In the case of frontal zones the current estimates of cloud temperatures from satellite are biased towards higher temperatures because the apparent brightness temperature for semi-transparent clouds is a mixture of signals from the (warm) surface and the (cold) cloud. The KLAROS processing environment enables the generation of an actual cloud top temperature due to its correction for semi-transparency during daytime.

The operational meteorologists found it useful to obtain more accurate cloud temperature, especially for comparison with model fields of humidity. In general they use Numerical Weather Prediction (NWP) models as a basis for the weather forecast. The meteorologist studies the forecast fields of pressure, winds, humidity and temperature and compares them with observations. If there are differences between model fields and observations, then the model is considered in error. This may be due to a bias in time, for example, if a frontal zone moves faster/slower than the model calculated. But it may also be due to a geographical shift because the frontal zone moves more to the north or south. The meteorologist identifies the differences between model forecast and observations and estimates what the effect will be on the evolution of the atmospheric conditions. In general, it is promising that the MSG based cloud properties will be the same as the parameters in the NWP models. This enables direct comparison of model fields and satellite observations. With as major advantage that the satellite derived properties do not suffer from a timing error or geographical shift.

5.2. Near real time analysis

During the shifts of the operational meteorologists, KLAROS analyses were presented in near real time. During his/her shift the operational meteorologist is fully occupied with the interpretation of a wide range of meteorological information sources to understand the weather. The primary information is output of the Numerical Weather Prediction models. The first order analysis is a comparison of the NWP models available: HIRLAM, UKMO, DWD Local Model and ECMWF. Then, the model fields are compared to observations. In general, the overall results from the model are correct at the scale of the model resolution, which is about 100-150 km. The deviations are in the timing and location of synoptic systems. A frontal zone may move slower or faster than calculated by the model. There may be a 100km difference between model and observations. For the positioning and timing, the Meteosat loops are often used. The NWP model can also be wrong in the calculation of the magnitude of specific phenomena. This is particularly of interest in case of critical atmospheric conditions. For example, the wind speed is critical in case of fog. Even a slight breeze can dissolve fog. Also in the case of convective clouds, the atmospheric conditions that lead to: no precipitation, precipitation that does not reach the ground or showers may be similar. Therefore, the depth of convection has to be estimated from data sources other than the model. Also observations are needed to take into account local phenomena. Since the Netherlands is a coastal region, there are often atmospheric conditions that are ruled by the temperature difference between land and sea. The temperature difference induces sea breeze and other coastal air movements. Furthermore, warm land air over a cold sea may produce fog. And cold arctic air emerging from the north that moves over a warm sea may induce strong convection that produces showers.

In 2001 the KLAROS environment was adapted for near real time processing. In the following Sections examples of the near real time presentations are given.

5.2.1. 15 November 2001, fog development

Analysis

Figure 5.3 presents the weather map of 15 November 2001 at 12 UTC. A high-pressure zone dominated the weather over central Europe, covering the Netherlands. A warm front approached the Netherlands from the North. The cloud types over the Netherlands are mainly low-level water clouds, with cloud tops below 2 km. In the neighbourhood of the warm front, over the Northern part of the Netherlands, there are ice clouds with cloud tops up to 4 km. The HIRLAM prognoses temp in figure 5.4 indicated that there is not much wind and the moisture content near the surface was high. These conditions are typical for the development of fog.

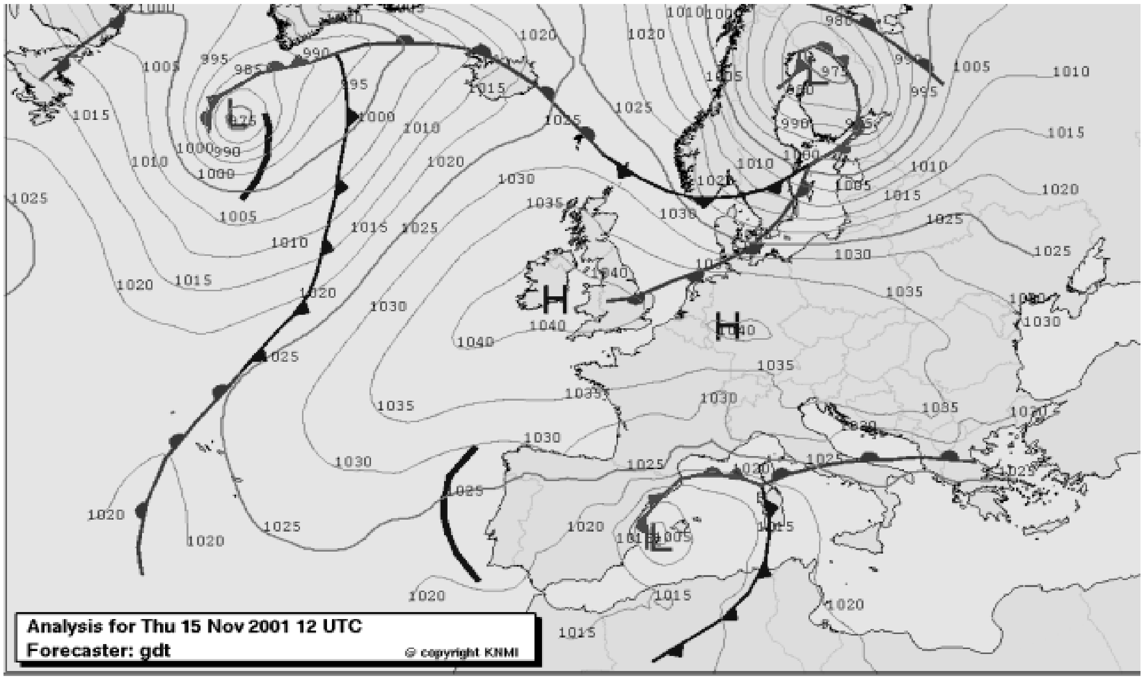

Figure 5.3: Weather map of 15 November 2001, 12UTC.

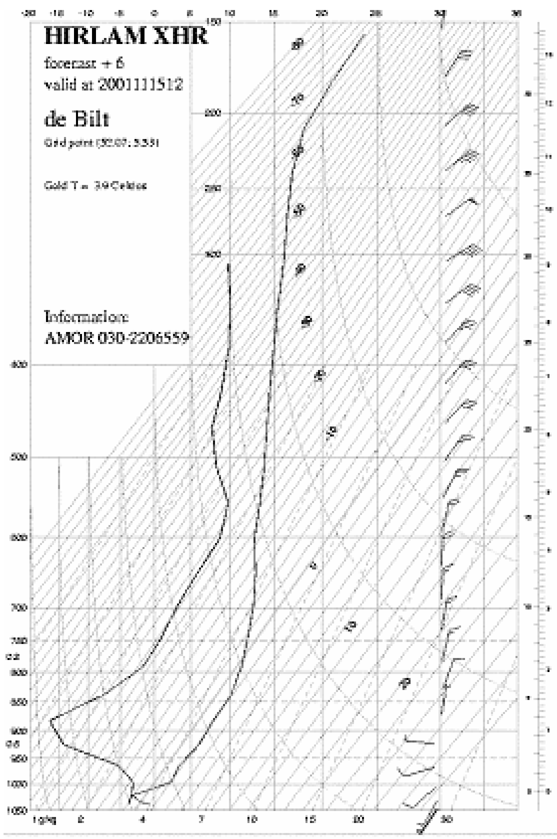

Figure 5.4: HIRLAM prognoses temp for 15 November 2001, 12 UTC

KLAROS product presentation

The KLAROS products for 15 November are shown in figure 5.5-5.7.

The ***Cloud Top Temperature*** product enables meteorologists to discriminate clouds with temperatures above and below zero. This is important information for predicting precipitation and icing. However, the meteorologists concluded that the presented product did not meet the user requirements. The two products are difficult to interpret. Firstly, when cloud tops have temperatures below zero degrees it is not known if the cloud tops consists of ice or super cooled water. Secondly, in the current version of KLAROS, the CTT product is generated for water and ice clouds separately. Consequently these cloud types cannot be identified on the result images. To distinguish water and ice clouds information is needed on the thermodynamic phase of the cloud top. This information would improve the calculations of CTT and allows the generation of a single CTT image that is valid for both water and ice clouds. It is feasible to make a cloud phase (ice or water) product. In the course of this project we started on the development of a method for phase discrimination. The method is not yet implemented in the interactive KLAROS shell, but is available off-line. However, meteorologists indicated that information on thermodynamic phase is of great importance for aviation. In addition, it would be useful to identify areas where rainfall might occur.

The ***Cloud Optical Thickness*** product is considered an intermediate product. The optical thickness itself is a parameter that is difficult to interpret for meteorologists. The optical thickness of a cloud is a measure of the amount of solar radiation through the cloud that reaches the surface and the amount of sunlight reflected back into space. Depending on the spectral channels of the MSG: the visible, near-infrared and thermal, the magnitudes of the optical thickness are different. For example thin cirrus are relatively transparent to solar radiation, while they are relatively opaque for thermal radiation. It was suggested that information on optical thickness during the night may be utilized to calculate the outgoing radiation, which is an indication of radiative surface cooling. In winter situations this cooling may cause freezing of roads or crops. Since the KLAROS algorithm relies on input information of visible satellite channels its products are only available during daylight hours. To support operational meteorology there is an interest in optical thickness products during the night. MSG includes channels that enable optical thickness retrievals from infrared information. However, it will take a considerable research effort to develop these retrieval algorithms.

The ***Cloud Liquid Water Path*** product was considered an intermediate product for the analysis of fog situations. The only application mentioned is to use it as indicator for rainfall. For this case the CLWP values over The Netherlands were relatively low (<100 g/m2), and the ice-topped clouds did not produce precipitation.

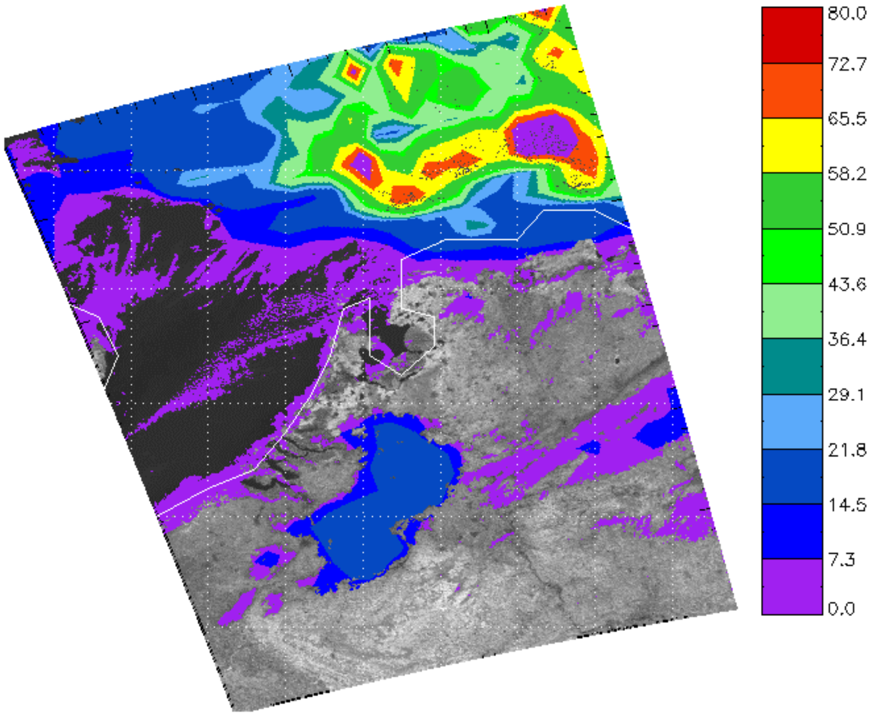

Figure 5.5: Cloud Visible Optical thickness, 15 November 2001

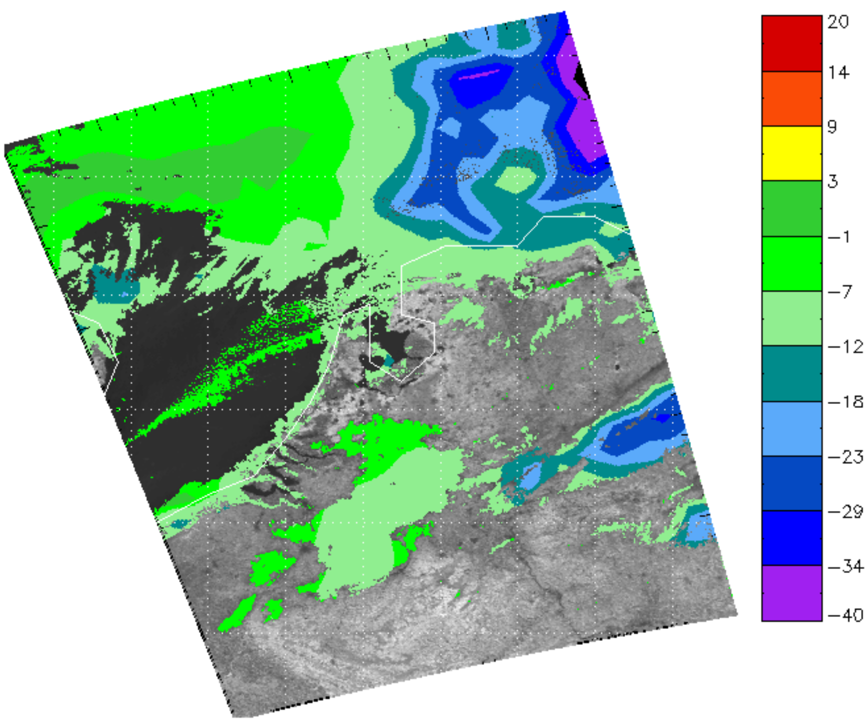

Figure 5.6: Cloud Top Temperature in degrees Celsius, 15 November2001

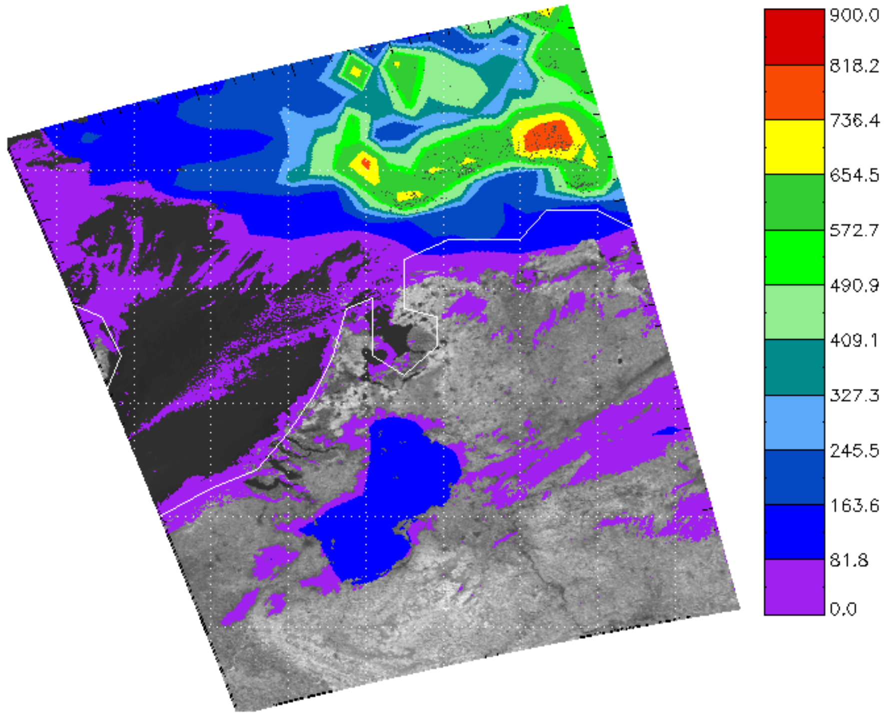

Figure 5.7: Cloud Liquid Water Path (g/m2), 15 November 2001

5.2.2. 22 November 2001, forecasting depressions

Analysis

Figure 5.8 shows the weather map of 22 November 2001 at 12 UTC. The meteorological situation is representative for a typical autumn case, which is dominated by depressions over northern Europe. The Jet stream is over The Netherlands and contained several frontal systems. In the vicinity of The Netherlands there were 3 frontal systems that rapidly passed the country. Clouds developed at different altitudes, and produced a considerable amount rain. The wind is northwest and strong (30 knots). The HIRLAM prognoses temp in Figure 5.9 shows that are two cloud layers. A layer of water clouds occurring at 1 km and a layer of ice clouds at 6 to 7 km.

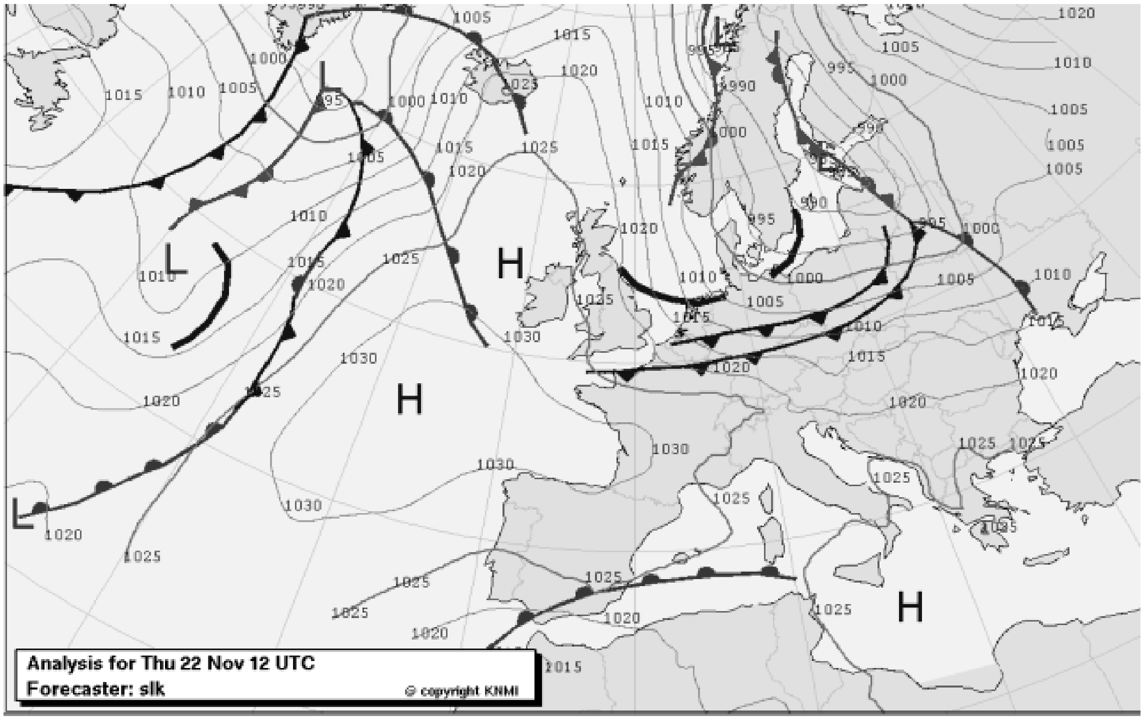

Figure5.8: Analysis for 22 November, 12 UTC

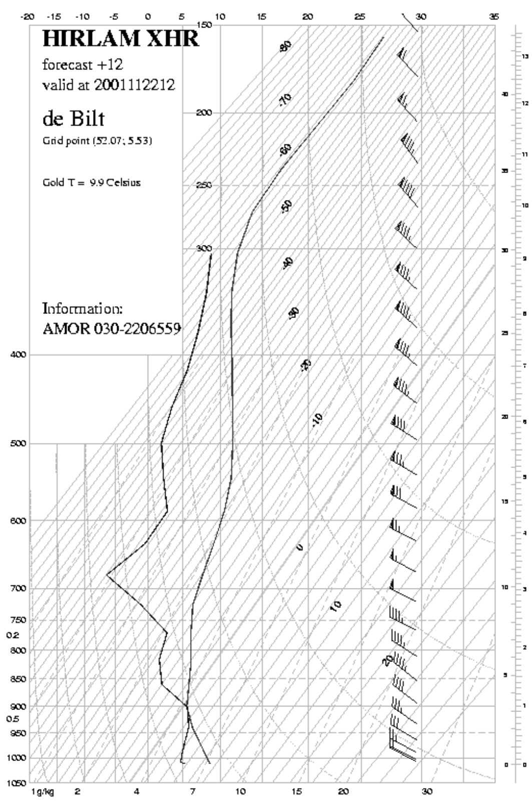

Figure 5.9: HIRLAM prognoses temp for 22 November, 12 UTC

KLAROS product presentation
The KLAROS products for 22 November are shown in figure 5.10-5.12.

The ***Cloud Top Temperature*** product was considered to be important for this case. It would be even more interesting to have a cloud thermodynamic phase product. The combination of temperature and phase could provide spatial information on the occurrence of ice and water clouds that can be used to identify spots where rainfall may occur. If KLAROS would also generate a thermodynamic phase product this would have several benefits:

- identification of regions where rainfall is more probable,
- identification of regions with a higher chance of icing conditions,
- automatic combining of the KLAROS ice and water CTT products, by using the thermodynamic phase product to indicate the water or ice solution.

The ***Cloud Optical Thickness*** product was considered an intermediate product. Low optical thickness and low temperatures are indications for high thin cirrus clouds. These clouds indicate high moisture content in the upper part of the troposphere, which is a symptom for various weather phenomena. In this case the cirrus clouds originated from the edge of a warm front and remainders of earlier front passages.

For this case the ***Cloud Liquid Water Path*** product was considered a good indicator for rainfall. The meteorologists were informed that a new product, which may serve as a first estimate of rainfall, might be generated when the CLWP and CTT products are combined (see proposed KLAROS derived products). An advantage of such a product is that it retrieves information over a large areas with a limited rain radar network. It could for example provide quantitative information on the location and intensity of precipitating clouds coming from the North Sea or Atlantic Ocean. In addition, this product might be calibrated with radar data.

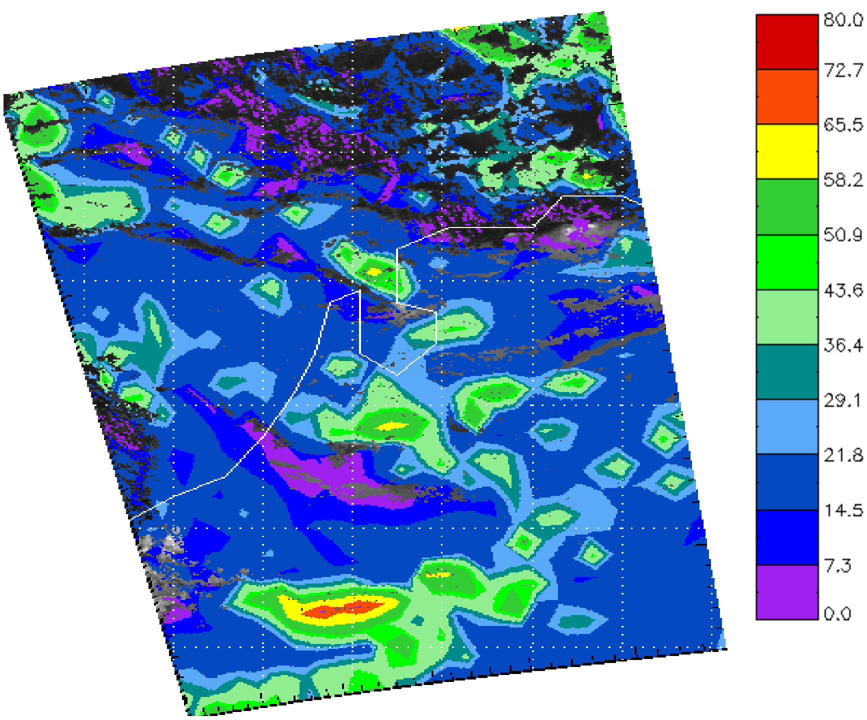

Figure 5.10: Cloud Visible Optical Thickness, 22 November 2001

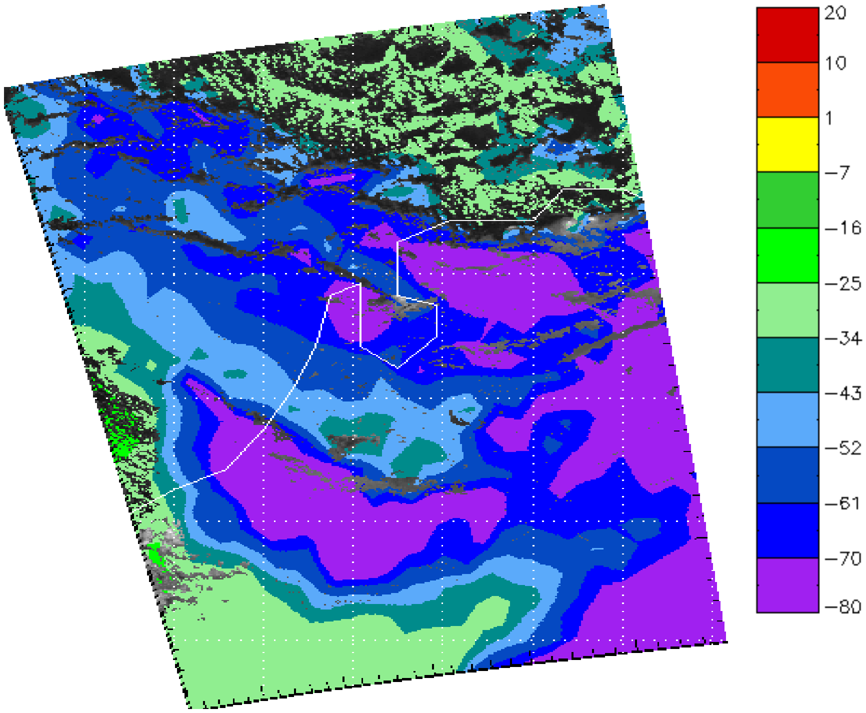

Figure 5.11: Cloud Top Temperature for ice clouds in degrees Celsius, 22 November2001

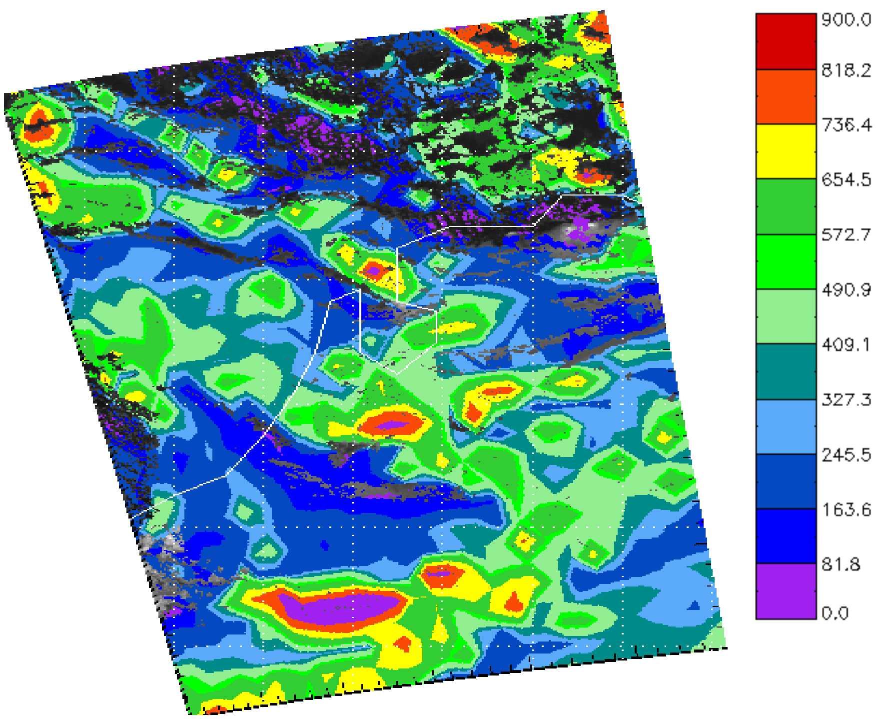

Figure 5.12: Cloud Liquid Water Path for ice clouds in g/m-2, 22 November2001

5.2.3. 3 December 2001, warm-front passage

Analysis

The weather on 3 December, shown in figure 5.13, was characterized by a passing warm front coming from the west. The Netherlands was covered completely by clouds. The HIRLAM prognoses temp in figure 5.14 shows that there are 2 layers of clouds, a thick stratus layer between 500 and 3000 m and thin cirrus layer at 7000 m. Both layers have cloud top temperatures below 273 K. The stratus layer with top temperatures around 260K and the cirrus layer with top temperatures around 230 K.

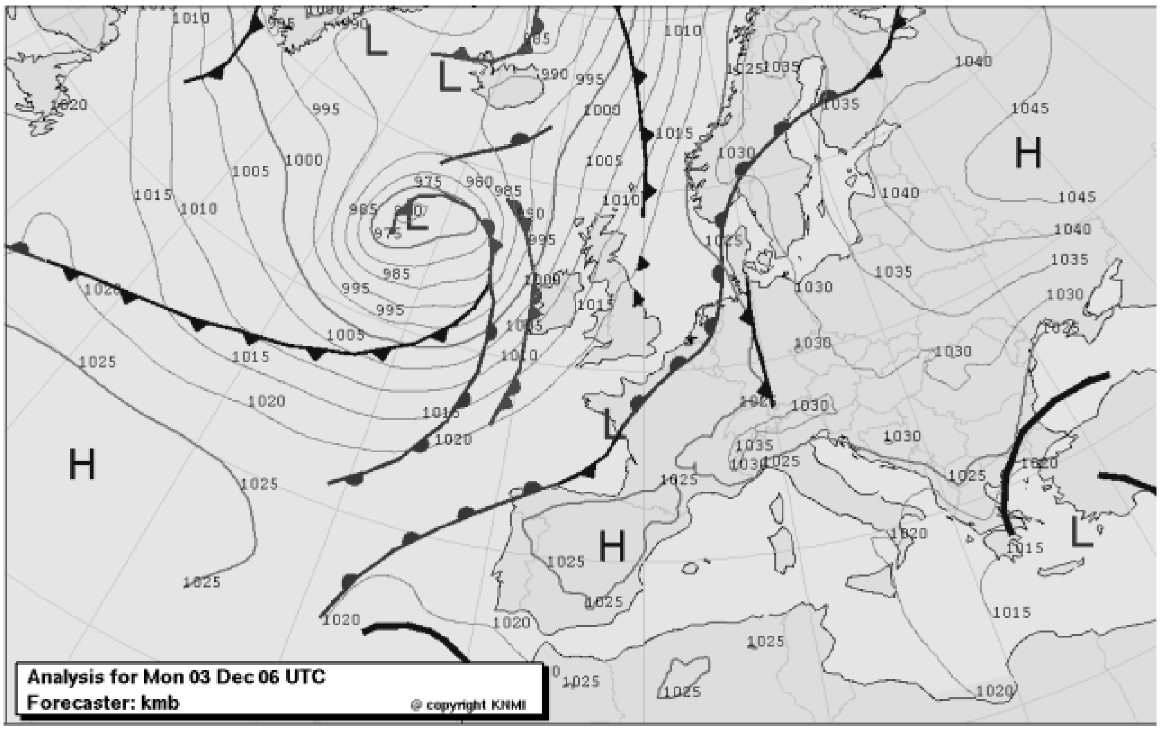

Figure 5.13: Analysis for 3 December, 6 UTC

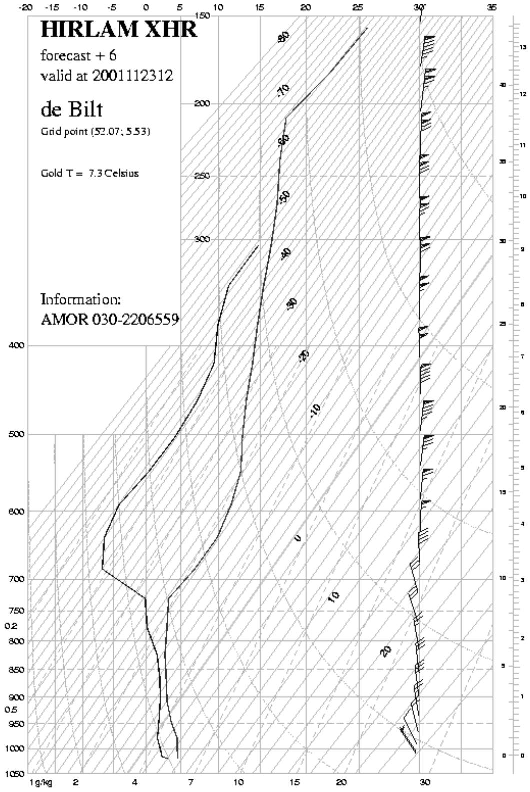

Figure 5.14: HIRLAM prognoses temp for 03 December, 12 UTC

KLAROS product presentation
The KLAROS products for 3 December 2001 are shown in figure 5.15 - 5.17.

The ***Cloud Top Temperature*** was used as an intermediate product to determine the Cloud Top Height, which is an important product for flight planning. The CTH is estimated by coupling CTT and Numerical Weather Prediction temperature profiles. In addition CTT can be used as a first estimate of the thermodynamic phase of the cloud tops. Although clouds with top temperatures below 273 K still consist of super cooled liquid water particles, the percentage of ice particles increases as the cloud top temperature decreases. Cloud tops with temperatures of 240 K consist of more than 90% of ice crystals (Hobbs, 1993).

The ***Cloud Optical Thickness*** was used to discriminate active and inactive areas of convective cloud systems. The active areas can be recognised by a very high optical thickness. In the visible image the active area of a convective cell can be identified less accurately. Moderate variations in thickness do not show up in the reflectivity, because the optical thickness is a logarithmic function of reflectivity. On in the infrared or CTT images a distinction between active and inactive areas cannot be made at all.

The ***Cloud Liquid Water Path*** was used to estimate the activity of convective cloud systems. This information was regarded as useful in aviation. In the region with strong convection the CLWP showed high variability. In-between clouds, CLWP values were close to zero, whereas, in the centre of cells there was a maximum. The spatial distribution of CLWP thus gave a measure of the horizontal size of the convective cells. The magnitude of the CLWP variation is an indication of the strength of convection. If the CLWP is below 100g/m2 only shallow convection is present, what implies small cells, low vertical velocities, low gradients in vertical velocities and no rainfall.

Advantage of the CLWP product is that it is available over areas where no rain radar data are collected. Disadvantage is that the data are only retrieved during daytime. To enable direct comparison between radar and CLWP imagery the CLWP values should to be converted to mm rainfall instead of g/m^2. This has not been done yet and requires more research.

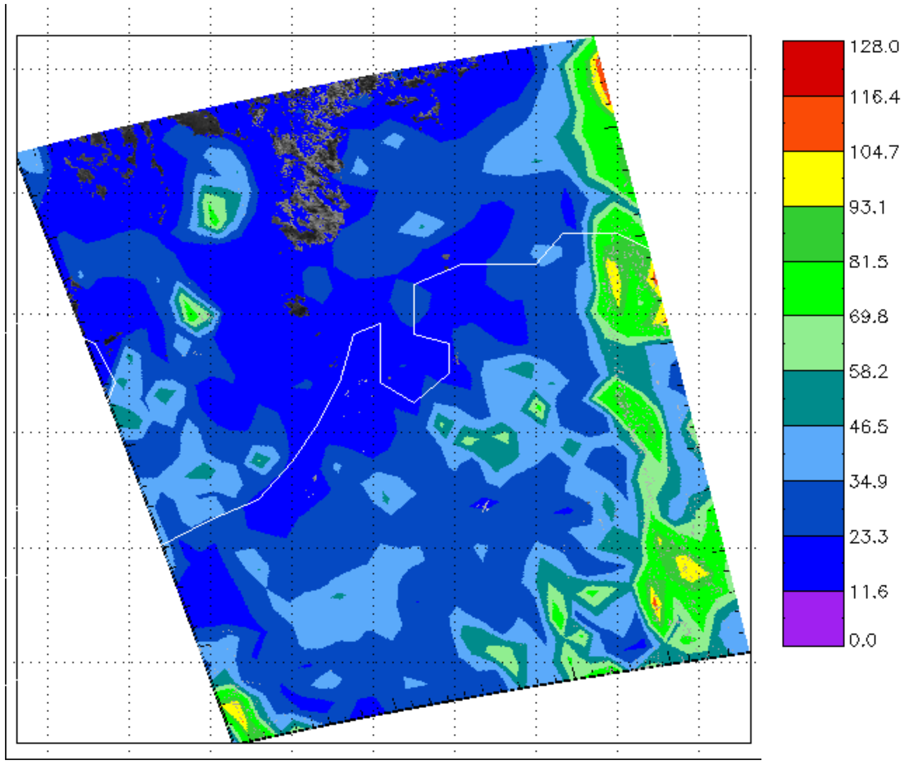

Figure 5.14: Visible Optical Thickness for water clouds, 3 December 2001

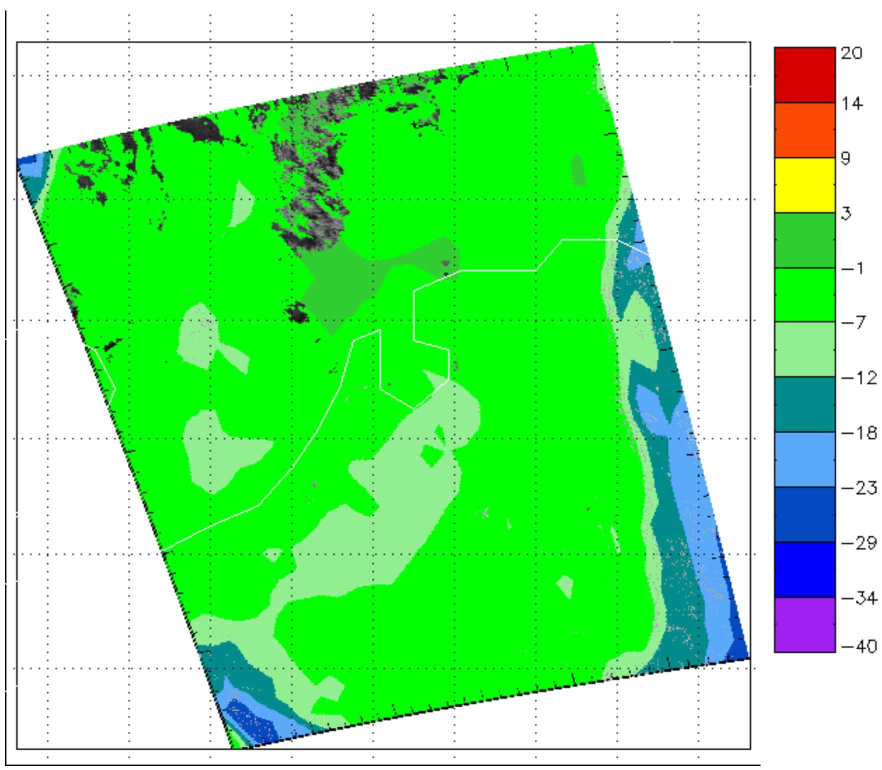

Figure 5.15: Cloud Top Temperature for water clouds in degrees C, 3 December 2001

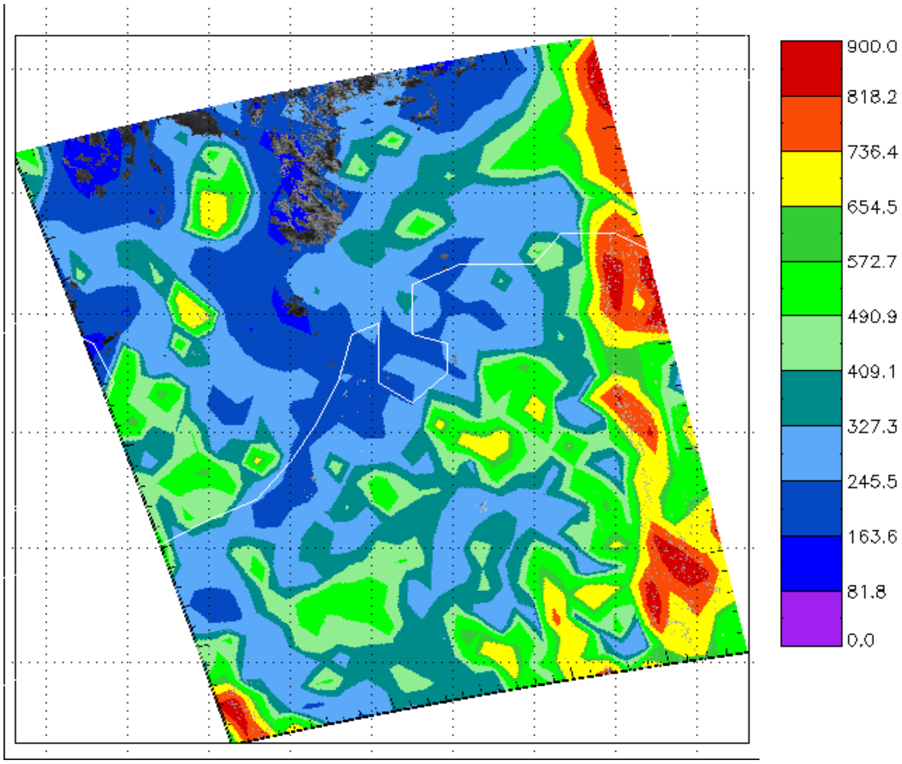

Figure 5.16: Cloud Liquid Water Path for water clouds in g/m-2, 3 December 2001

5.3. Responses and Suggestions

Based on the on-line and off-line presentations we made an inventory of suggestions and recommendations made by the operational meteorologists on the use of the KLAROS cloud products and presentation software. In this Paragraph the results of this inventory are presented.

Concerning the ***KLAROS software*** the general opinion of the meteorologists was that it still needs modifications to adapt it to the specific needs of operational meteorologists. The following comments/suggestions were made:

- The presentation tools should be adapted to the operational setting. The presentation that were used, were optimised for research, and turned out to be not suitable for meteorologists. Therefore, the presentation should be adapted, preferably to be similar to other information sources. In the course of the project a number of adaptations were made to make interpretation easier.
- The Cloud Liquid Water Path image is difficult to interpreted. Liquid water path values vary between 0 and 800 g/m2, with the majority of the values below 100 g/m2. Due to the linear scaling of the grey pallet between 0 and 800 g/m2, the dynamics in liquid water path are difficult to recognize.
- There is a need for a tool to scale the image pallet online. In addition it would be desirable to choose your own colour pallet.
- The cross section scatter plots are difficult to interpret. The crosses in the scatter plots are large. As a result the analysis of these scatter plots is qualitative.
- The cross section scatter plots are difficult to make. It would be better if it was possible to draw a single line, e.g. along a trajectory, for which the product value is directly displayed.

Note that when the KLAROS products will be used in the weather room on an operational basis, the products may become part of the Meteorological Work Station, the database and data analysis system used in the weather room. In that case the KLAROS interactive shell will not be needed anymore.

Concerning the ***KLAROS cloud products*** the following comments and suggestions were made:

- In general the NOAA AVHRR data is not used frequently to make forecasts currently. For now casting there is a strong preference for frequently available satellite products (30 – 60 minutes). Meteorologists use METEOSAT products more often than NOAA products because the temporal resolution of NOAA is considered too low. NOAA data are only used to analyse meso-scale phenomena, which are relatively small and thus difficult to identify on the METEOSAT imagery. The KLAROS quantitative cloud products will become more interesting to meteorologists when they are made available with the sampling frequency of METEOSAT, which will be possible with MSG.
- The Cloud Top Temperature (CTT) was used occasionally. It was felt as a step forward that the accuracy and reliability of the cloud top temperature improved through quantitative cloud analysis. The CTT was mainly used to determine the Cloud Top Height and the vertical position of the cloud relative to the freezing level. The freezing level is important for aviation (icing conditions). Super cooled water layers consist of liquid water drops at a temperature of a few degrees below the freezing point. If an aircraft flies through such a cloud the aircraft may get icing, which is a problem for some aircrafts. Moreover the Cloud Top Temperature is an indication of precipitation, a convective cell will generate precipitation as soon as its top gets below the freezing level and consist of ice crystals.
- The Optical Thickness product was regarded useful to determine if fog may dissolve or low stratus may break up. The meteorologists would rather have an estimate of the insolation because the optical thickness is only an second order indicator. Insolation is a measure of the amount of solar energy that reaches the ground and thus induces convection.
- The Cloud Liquid Water Path product is new. Although CLWP can be related to precipitation and to geometrical thickness, its relation is not straightforward. Therefore, the interpretation of CLWP data was difficult in practise. It was suggested to make higher-level products such as cloud geometrical height and a precipitation indicator.
- In KLAROS the Cloud Top Temperature (CTT) product is generated separately for water and ice clouds. In case of a cloudy sky with both water and ice clouds, the procedure is cumbersome. The operational meteorologists indicated the need for a combined product. KLAROS should first discriminate water and ice clouds, and then calculate the cloud properties. This requires the implementation of a thermodynamic phase indicator in KLAROS.
- It was suggested to make a Cloud Top Height (CTH) product, which could be used for now casting. By combining the KLAROS CTT and NWP temperature profiles the CTH can be estimated. A disadvantage of this approach is that the CTH product will not be independent of model data. However, this disadvantage is regarded as less important for now casting.
- It was suggested to make a Cloud Base Height (CBH) product. Cloud base height is extremely important in aviation. The cloud base height sets limits on type of aircraft that may arrive of depart from an airport. However, in order to come to such a product requires a large development effort. Satellite derived information from temperature, water content and phase must be combined with atmospheric model data on vertical profiles of temperature and humidity.
- It was suggested to develop a rain indicator product. This also would require a considerable effort, but is not impossible. A rain indicator product might be developed from the CTT,

thermodynamic phase and CLWP products. The principle behind this product would be that clouds with a large CLWP and a cloud top temperature below the freezing level (CTT<0) are potentially precipitating clouds. The Swedish Meteorological and Hydrological Institute (SMHI) recently developed a first statistical approach to such a method. Whether precipitation reaches the ground cannot be seen from a passive imager.

- It was suggested to make a cloud phase product. Information on cloud phase, stratified as water, mixed or ice would be very welcome from the perspective of icing conditions and the probability of precipitation.

It was noted that the evaluation of KLAROS quantitative cloud products for operational meteorology would have been very different if time series would have been available. This is due to the fact that the interpretation of atmospheric conditions is more a matter of interpreting the changes than the status. The AVHRR can only provide information on the status, whereas MSG can show the changes and thus will be much more useful to operational meteorology. Therefore it was suggested to repeat this project with real MSG data when these become available. Of course, this sets requirements to the analysis set-up in the research department, which should enable near-real-time processing.

6. New products

Recently, there are new retrieval methods being developed at KNMI. We discussed the possible applicability of these possible new products at the MetOffice with meteorologists. In this Section we will describe the product, its possible applications and results from an example case. The products currently under development are:

- thermodynamic phase
- particle size
- vertical extent
- particle density
- insolation (down welling short-wave flux at the surface)

6.1. Thermodynamic phase

The distinction between water and ice will have a large impact on the quality of the KLAROS analysis. Meteorologists found that the internal consistency and accuracy of KLAROS products will increase if the thermodynamic phase of the cloud top is known. This is due to the different scattering properties that ice crystals and water droplets have.

This new product is regarded to have application in operational meteorology in the case of convective cells. A meteorological observer looks at the tops of cumulus clouds to see if the top gets 'into the ice'. When the cloud particles at the cloud top freeze, the sides of the clouds are not sharply defined anymore. The cloud boundaries are getting vague. If the cloud particles freeze, they grow fast. Water droplets do not grow fast and do not get very big, due to their relatively high surface tension. The surface tension of ice crystals is lower, and therefore, the crystals may grow fast. Large particles are too heavy to be carried by the vertical air movements. So, the particles fall, coagulate, grow further and produce precipitation. In conclusion, the thermodynamic phase is the critical parameter to monitor precipitation of convective cells in an unstable atmosphere.

Also in case of stratus clouds, the thermodynamic phase is important when predicting icing conditions. For aviation this is a very important parameter.

6.2. Particle size

The particle size is also an indicator for the vertical extent of the cloud and thus the depth of convection. In a wet adiabatic atmosphere, the total amount of water is constant in the vertical. Also the number of cloud particles is constant in the vertical. At cloud base, all water is in its gas phase, water vapour. As the temperature decreases with height, more water is condensed on the cloud particles with height. Therefore, the particle size is an indicator of the vertical extent of the cloud. It helps to discriminate shallow convection from deeper convection and shallow stratus clouds from thick stratus clouds.

The operational meteorologists regard this product useful for consistency checks but not as an independent product. This triggered the study to the retrieval of cloud geometrical height.

6.3. Geometrical height

The geometrical height can be retrieved if there is accurate temperature profile information, assuming a wet adiabatic profile and constant cloud particle densities. The product is currently of relatively low quality, due to the many assumptions that are made in the retrieval. However, it is very tempting to put additional research effort into this product due to the strong interest of the meteorologists.

The meteorologists are very enthusiastic about the geometrical height product, because it gives an estimate of the cloud base height. The cloud top height can be obtained from a combination of the cloud top temperature and temperature profile information from radiosonde or atmospheric model. Cloud top height and cloud geometrical vertical extent define the cloud base height. Cloud base height is a very important parameter in aviation industries. Small planes are only allowed to land and take-off if the cloud base is above a specific height. For air traffic control the estimate of the cloud base height and its development in time is valuable information for scheduling.

Example:
The example stems from the analysis of ATSR measurements of a warm stratocumulus cloud field over ocean. This is a relatively easy case that we use for a proof of principle. The ATSR channels that are used are similar to those that will be available on MSG. In Figure 6.1 the analysis results are shown together with a reference to the geo-location. The graphs of CLWP, geometrical height and optical thickness are similar, because these parameters are coupled. An optically thick cloud contains a high amount of water and has a large geometrical vertical extent. The most interesting product presented here is the geometrical height, because it can be used to obtain the cloud base height. Although the method is still very experimental, it is regarded as very useful in aviation and therefore is worth developing further.

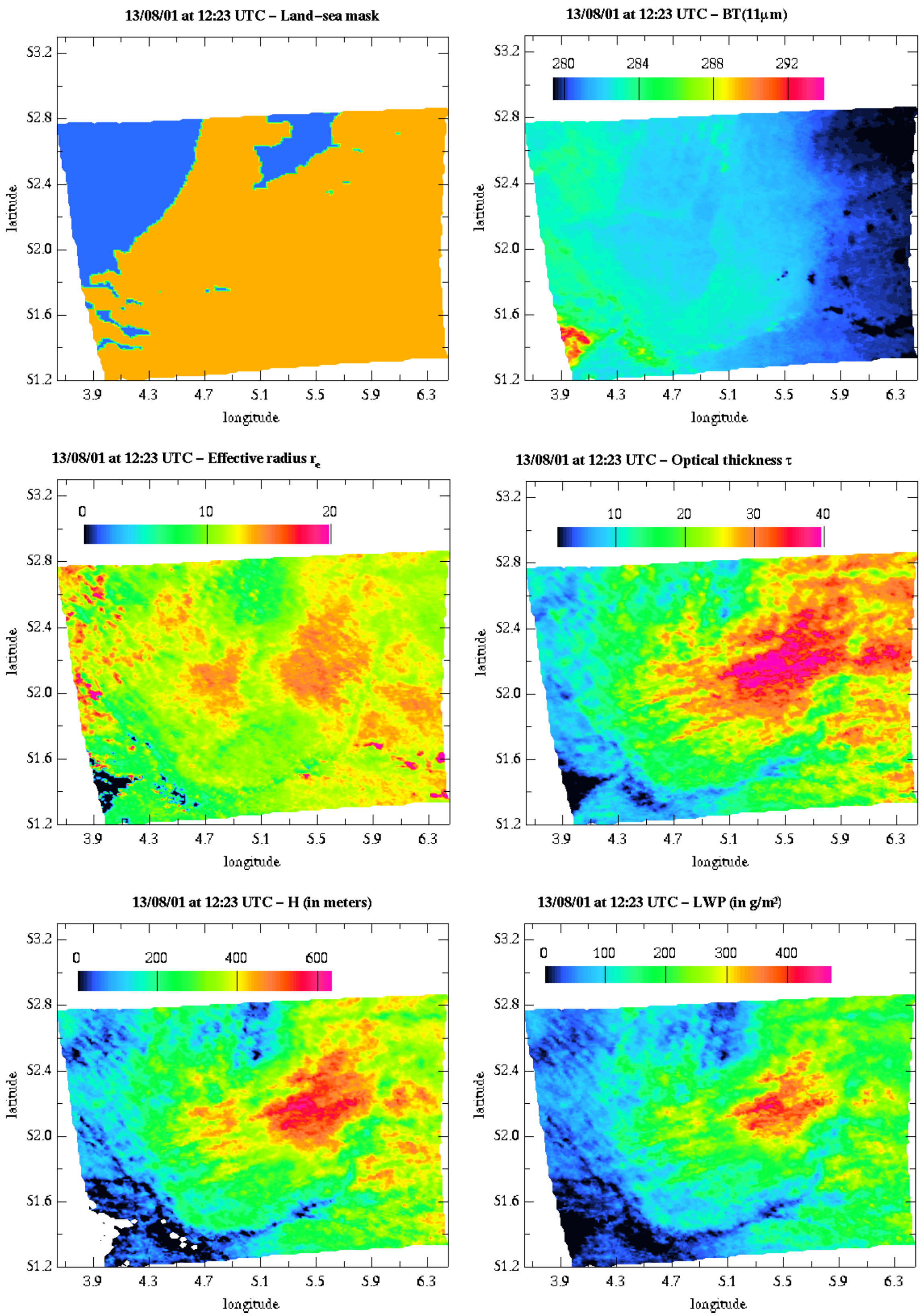

Figure 6.1 Analysis of ATSR measurements from the ERS platform on 14 August 2001 at 12:23 UTC.

7. Conclusions and Recommendations

This report describes the opportunities for improving weather forecasting with the use of MSG data. In preparation for MSG, operational meteorologists were consulted to demonstrate the KLAROS cloud products and to discuss the application of these products for weather forecasting. Several cloud products were presented to the meteorologist: cloud top temperature, optical thickness, cloud emissivity and cloud liquid water content.

The meteorologists made both off-line and near real time analysis of the KLAROS products. The advantage of the off-line analysis is that different and well-understood cases can be analysed. Furthermore, the meteorologist has more time to do an in depth KLAROS analysis. Advantage of the near real time analysis is that the meteorologists have access to both KLAROS products and actual meteorological data on the Weather Meteorological System (WMS). The WMS comprises among others synops data, satellite data and output from weather model runs.

The project had a length of only 9 months, but it established a valuable link between operational meteorology and research departments. The meteorologists recognized the added value of the MSG cloud products and their importance for daily weather forecasting. However, it was indicated that the visualization tools from the research department were not well suited for use by meteorologists. It took the meteorologists too much time to familiarize with them. It may be concluded that further modifications of the software architecture are needed before the modules for operational processing of MSG data can be implemented. This would greatly improve the quality and efficiency of testing new quantitative cloud products in operational meteorology. In that sense this project is ongoing and will continue until and after the launch of MSG.

The meteorologists made suggestions for product improvement, and brought up ideas for new products. These products are expected to contribute to higher quality forecasts. Some suggestions could be implemented directly, while the ideas for new products required more research. We found that products of particular interest for the meteorologists are those, which define the amount of sunlight reaching the ground in cloudy conditions (optical thickness) and those, which describe the geometrical vertical extent of clouds (and thus the cloud top and base height). The first is directly related to the dispersal rate of fog, exposure to UV-B (skin cancer) and crop yield. The meteorologist also indicated the need for cloud vertical extent product. Cloud vertical extent is more challenging because cloud base height is nearly impossible to retrieve from passive satellite sensors or surface instruments. Some products, like water content and effective particle radii were not seen as very useful by the meteorologist, but are intermediary products.

In conclusion, both researchers and meteorologists benefited from this project: the possibilities of MSG were introduced to the meteorologists and researchers developed an understanding of how satellite data can contribute to the day to day needs of the meteorologist.

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