Precipitable water in cloudy areas from combined solar, thermal, and microwave radiance measurements.

Literature study on existing TPW measurements in cloudy area.

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Chapter 1

Introduction

The mean global water vapour content as evaluated by Trenberth et al. (1987) is 26 kg/m^2, while the geographical distribution varies from ∼5 kg/m^2 in the polar region to ∼60 kg/m^2 in the tropics. These values were derived using global analysis from the European Centre of Medium Range Weather Forecasts (ECMWF). Water vapour is an inhomogeneous quantity on all temporal and spatial scales, from weather to climate change. Hence, determing the variability is a challenging task. From radiosonde measurements the global vertical structure can be derived with a limited temporal and spatial resolution. Only, ground based microwave radiometer with a profiling ability offer possibilities to derive the vertical structure in much higher temporal resolution. The vertical integrated water vapour also denoted as total precipitable water (TPW) is retrieved with time resolutions ranging from seconds to minutes depending on the radiometer sampling technique. Since, ground based measurements represent point measurements, a regional TPW distribution can be maintained with a limited fidelity due to the limited distribution of measurements. Satellite based instruments offer better spatial coverage. Various techniques have been developed that are using different spectral bands to derive informations of the atmospheric water vapour. On board polar orbiting satellites infrared sensors like the High–resolution Infrared Radiation Sounder (HIRS) allow to derive the water vapour content only in clear sky atmospheres, because clouds are opaque in these spectral range. In the microwave spectrum non–precipitating clouds are translucent, so that sensors like the Special Sensor Microwave/Imager (SSM/I), the Spectral Sensor Microwave/Temperature (SSM/T–2) and the Advanced Microwave Sounding Unit (AMSU) offer the possibility to derive the TPW. These techniqes are limited to ocean surfaces because the emission from the surface needs to be small and homogeneous within the radiometer field of view (FOV). These radiometer yield TPW products with a spatial resolution of about 60 km which is sufficient for resolving the TPW variability on daily scale. Furthermore due to the polar orbits and limited swath the temporal variability of the water vapour fields can not be resolved.

Geostationary orbits enable to monitor a region with a better temporal resolution compared to polar orbiting satellites. On METEOSAT–8, the first satellite of the Meteosat Second Generation (MSG), the Spinning Enhanced Visible and Infrared Imager (SEVIRI)

measures infrared water vapour spectra with a spatial resolution of about 4 km at subsatellite point every 15 minutes. With this it is possible to derive a water vapour climatology with regards to the diurnal cycle. Furthermore, the use of two absorption and two window channels enables the derivation of the vertical distribution of water vapour. As for the HIRS instrument cloudy atmospheres are excluded in the retrieval. Therefore, TPW climatologies based on infrared techniques are biased if TPW in cloudy areas are different from those in clear sky areas. Hence, the use of infrared sensors only will lead to an underestimation of all sky TPW on climatological scales. The aim of this study is to quantify this so called clear sky bias in terms of cloud properties within the radiometer field of view, i.e. to obtain a climatology of the amount of water vapour in cloudy areas compared to clear sky situations. Furthermore, it will be investigated to what extend the difference between the two will be related to the physical properties of the clouds. To this end, remote sensing techniques in the microwave spectral range will be used to infer both liquid water and water vapour under all sky conditions.

In the following the present knowledge of water vapour in clouds based on measuring campaigns or model sensitivity studies are resumed. Furthermore, available data from intensive field campaigns which provide an insight of the water vapour in clouds are summarised.

Chapter 2

Water vapour, clouds, and climate

Because of its strong greenhouse effect, the importance of a detailed knowledge of the water vapour distribution is prominent in the climate warming discussions. By means of a radiative transfer sensitivity study Bühler et al. (2004c) examine the influence of water vapour in clear sky atmosphere on outgoing longwave radiation (OLR). A water vapour increase of 20% in the tropics has the same reducing impact on the outgoing longwave radiation as a CO_2 doubling. Whereas a decrease of 20% shows the same impact on the OLR as a mean atmospheric temperature increase of 1K. In the subarctic winter the response of the radiation on water vapour increase or decrease is not as strong as in the tropics. Here only temperature variations are considered thus feedback situations like the induced water vapour increase in a warmer atmosphere is not taken into account. The major parts of the ORL variability can be explained by changes in the mean atmospheric temperature, humidity and the CO_2. The remaining variability must be due to vertical structures on vertical scales smaller than 4 km explaining approximately 1 W/m^2 of the OLR with no significant bias when the relative humidity is smoothed not the mixing ratio. This results means that instruments with a coars vertical resolution may be used to predict OLR with the correct mean values, but will not be able to fully reproduce the variability due to vertical structure, as almost half of that can come from strucutres on scale smaller than 4 km.

Stephens and Tjemkes (1993) considered a linear relationship between the greenhouse effect G and the total precipitable water, see eqation 2.1. The greenhouse effect is defined as the relation of the surface temperature T_s to the planetary temperature T_e. The temperatures can be expressed by the radiative effective optical depth using a grey body model. For the Earth's atmosphere this optical depth is expressed by the integrated total precipitable water, w.

$$G = \frac{T_s^4}{T_e^4} = a + b\,w \tag{2.1}$$

The authors demonstrated that the slope factor b is largely goverened by the variation of temperature with height in the atmosphere and that the intercept a is detemined by a variety of factors including the assumed profile of water vapour as well as the concentrations

of other greenhouse gases. Thus, the clear sky greenhouse effect is assessable from satellite from measurements of temperature and TPW. The correlation of the greenhouse effect, derived from Earth radiation budget and sea surface temperature observations, and using coincident SSM/I microwave observations of TPW for clear sky observations is given with 0.8. The retrieved greenhouse effect is not a direct measure of the water vapour feedback, which is not observed, because the true greenhouse effect is a consequence of numerous linked processes and feedbacks. The relationship of the greenhouse effect and the sea surface temperature (SST) is based on two important factors: the direct influence on water vapour itself and feedbacks between water vapour and temperature. Stephens and Tjemkes (1993) also discuss the impact of the vertical temperature and humidity distribution and its variability on the greenhouse effect. An increase of humidity in the upper troposphere will have a stronger impact on the greenhouse warming. The latitudinal distribution of changes of the humidity profile in relation to the SST is influencing the greenhouse effect as well. In the described study SSM/I data are used to avoid the bias induced by clouds blocking the measurements in infrared wavelength.

During the Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment (CRYSTAL–FACE) in July 2002 aircraft measurements in the infrared region were performed to estimate the greenhouse effect as a measure of the evaporative feedback of ocean and atmosphere. Marsden and Valero (2004) investigate the differences in the greenhouse effect due to water vapour absorption in cloudy compared to clear sky scenes. Two cases are considered here, one cloudy case with large–scale convection and clear sky non–convective day. The retrieved 8–12 μm greenhouse absorption shows higher values in the convective than in the non–convective case. The measured greenhouse efficiency in the spectral window region remains essentially unchanged. They conclude that convection and upper tropospheric moisture are the main determinants for the greenhouse efficiency.

Microwave retrieval techniques are based on the strong emission of the atmospheric water against the radiatively cold oceanic background. To investigate the TPW for cloud and clear scenes it is important to identify cloudy scenes. One advantage of microwave retrieval is the simultaniuously measurements of TPW and liquid water path (LWP). For these measurements ground based instruments are used as the truth. While TPW retrievals can be validated with colocated measurements from ground based sensors such as radiosondes, Global Positioning System (GPS) receiver, and Raman Lidar, retrieval validation of liquid water path is more complicated. In situ measurements with aircrafts are not representative of the radiometer sample volumes. During the last CLIWA–NET campaign (BBC) a ground based microwave intercomparison was performed to compare both instruments and the LWP retrieval algorithms. These algorithms are based on statistical correlations between brightness temperatures and LWP and TPW respectively. The correlations are derived from radiative transfer calculations for a large number of atmospheric clear sky and cloudy situations which resemble the range of atmospheric states. The statistics of the atmospheric temperature and humidity profiles are well known in contrast to the profiles of liquid water. The influence of cloud model statistics on the accuracy

of statistical multifrequency LWP retrievals for a ground based microwave radiometer is investigated by Löhnert and Crewell (2003). The authors show, that for statistical LWP retrievals, RMS errors can be reduced by using an increasing number of frequencies. But the influence of the cloud model statistics becomes more significant as more channels are used. Different cloud models represent different possible states of the atmosphere. To best describe the universal state of the atmosphere, the cloud statistics used for algorithm development should contain a mixture of different statistics from different cloud models. Another source of uncertainty in the LWP and TPW retrieval are the different established absorption models used in the radiative transfer model calculations. Crewell and Löhnert (2003) show that the mean differences between the absorption schemes defined by Liebe (1989) and Liebe et al. (1993) are in the range of 1–2 K for lower frequencies, whereas a larger bias for higher frequencies (50, 89 GHz) occurs. The Rosenkranz (1998) absorption scheme gives similar results as Liebe (1989). Using two channel (23, 31GHz) radiometer retrieval for the LWP an error in the brightness temperature of 1 K can lead to LWP errors of more than 30 g/m^2 whereas the use of additional information from a 90 GHz channel improves the accuracy by 50 %. Some attempts to reduce the uncertainties in the absorption schemes at 90 GHz are made, see Cruz Pol et al. (1998).

Rayer (1994) compares General Line-by-line (GENLN2) water vapour absorption calculations with Liebe (1989) for arctic, mediterranean and tropical profiles measured during the international projects SAMEX, MASTEX and FATE. GENLN2 compares well to Liebe (1989) for calculation at 89 GHz except in the mediterranean case, here the models are divergent in the boundary layer. Both models give higher radiances for the arctic and the mediterranean case whereas in the tropic case the radiances are too small.

Westwater et al. (2001) investigate the LWP and TPW retrievals during the Surface Heat Budget of the Arctic Ocean Project (SHEBA) experiment to estimate the dominant error sources in the retrieval. The error sources depend on the retrieval method (statistical or physical). Additionally uncertainties in the retrieval depend on the instrument calibration and the absorption coefficients used in the retrieval. For the Arctic atmospheres the Rosenkranz (1998) model provides best results. A similar conclusion is given by Marchand et al. (2003). They compare three absorption schemes for the water vapour bands in the microwave spectra and found only small differences in calculated radiances between the models. Differences occur between the retrieved and modelled LWP and WVP for the different Atmospheric Radiation Measurement (ARM) sites. The best performing absorption scheme changes with climatological region. The retrieval uncertainty varies between 15-30 g/m^2 for LWP depending on the WVP. Using the LWP to retrieve the effective radius of cloud particles, the implied error is about 20 %.

A comparison of several different line–by–line models with observed broadband infrared high resolution spectra obtained during two measurement campaigns is performed by Tjemkes et al. (2003). They show that in general the models and spectroscopic databases compare very well in the range of the uncertainties in the spectroscopic measurements. Differences between the models occur in the water vapour continuum (700 nm^{-1}, 1950-

2000 cm^{-1}). From the observed radiances is it not possible to identify the best performing model.

Aircraft interferometer measurements during MOTH (Measurements Of Tropospheric Humidity) Tropic and MOTH Arctic with instruments using frequencies in the spectral range of future satellite instruments were performed to validate the model description of the continuous water vapour absorption. Taylor et al. (2003) use the High Resolution Transmission Molecular Absorbtion spectral database (HITRAN) together with the CKD2.4 (see Clough et al. (1989)) simulation of the water vapour continuum. Radiation measurements with the Microwave Airborne Radiometer Scanning System (MARSS) instrument where the frequencies are located in the range of the Advanced Microwave Sounding Unit (AMSU-B) channels show good agreements at the absorption lines. However, in the spectral bands between the lines the absorption is underestimated compared to the measurements.

The influence of near surface atmospheric conditions (e.g. surface pressure, temperature) on the humidity distribution is the subject of numerous investigations. This relation can lead to errors in the satellite retrieval due to the implied surface conditions in the radiative transfer calculations. The sensitivity of clouds, water vapour and radiation on changes in the sea surface temperature in General Circulation Models (GCM) is described by Larson and Hartman (2003a, 2003b). With increasing SST the convective transport of relative humidity reaches higher atmospheric levels. This leads to an increase in upper tropospheric absolute humidity due to higher temperatures in these levels. The cloud heights are going up as well.

Using atmospheric profiles derived from the Hadley Centre atmospheric climate model version 3 (HadAM3) as input to a radiative transfer code, Brindley and Allan (2003) analysed the sensitivity of the resolved spectrum of clear sky outgoing long-wave radiation to both interannual and long-term atmospheric variability. A comparison of the simulated spectra with available observations from two satellite based instruments indicates a reasonable match, although consistent differences are present. These may be explained by a combination of uncertainties in the atmospheric state, and in the relative calibration of the two instruments. Focusing on the simulations two scenarios are investigated. First HadAM3 is forced by the observed SST record alone, and long term variations in the greenhouse gas concentrations are imposed in the radiative simulations, the changes seen in the major absorbtion bands are stable. In second scenario the effects on solar variability, vulcanic aerosol and ozon changes and increases in the greenhouse gases are also included in the forcing of the model, the long term profile changes show an enhanced upper tropospheric warming and low/mid stratospheric cooling, with increased near surface humidities compared to the first scenario. The spectral change pattern over the atmospheric window and water vapour bands for these two scenarios are within the year to year variability.

Tompkins (2003) investigates the relative importance of temperature and humidity fluctuations for the development of cloud cover. Aircraft thermodynamic measurements were

performed in liquid water clouds over the North American Great Plains. The influence of temperature fluctuations is small compared to the influence of humidity variability. In models the cloud cover is mainly assessed using the humidity only. Nevertheless, additional temperature informations will lead to an improvement of the cloud cover estimation. This improvement will be best for cases where the temperature and humidity fluctuations are not correlated.

In the following a closer view on different retrieval techniques and systems – ground based and space borne – is given. Furthermore water vapour related field campaigns and monitoring stations are described. In the appendix the compiled list of available data for the ongoing study is given.

Chapter 3

Compilation of Retrieval Techniques

There are numerous techniques to determine the atmospheric water vapour from ground based, air borne and space borne sensors. By far the most in–situ measurements are taken from radiosonde humidity sensors. Laser-based measurements of water vapour absorption (Lyman-α) onboard research aircrafts provide continiuous measurements during specific field campaigns, only. Most other methods are based on the relation of measured radiances to the water vapour concentrations. This relation is often derived by using numerous radiosonde profiles characterising the variability of the atmospheric state. In the following different retrieval techniques are shown and several intercomparison studies are summerised. A focus is set on the influence of clouds on the retrievals, the uncertainties of the methods and the attempts to quantify the water vapour inside the clouds. Most of the techniques find their limitations in the presence of clouds. In the infrared spectra clouds are opaque, so the retrieval of the total precipitable water is not possible. Some attempts are made to retrieve the water vapour above the clouds from infrared radiation measurements for cloud covered areas. The best opportunity to derive TPW in cloudy areas is given by microwave instruments. The methods are working for non-precipitating liquid water clouds, scattering of microwaves at large ice particles and raindrops weakens the relation between water content and radiances; from satellite the retrieval is limited to ocean areas.

3.1 Ground based Instruments and Techniques

3.1.1 Radiosonde

Radiosonde measurements are an important database for weather and climate forecast models. They are often used as ground truth for validating humidity measurements based

on other techniques and for the deduction of retrieval algorithms. From a variety of radiosonde types differing by the transmission techniques and humidity sensors, the Vaisala radiosonde is the most common type. The humidity is measured by the so called Humicap sensor which measures the relative humidity in the range 0 – 100 %. The Humicap makes use of a thin polymer film which either absorbs or releases water vapour. The dielectric properties of the polymer film are depending on the amount of water contained. The changes in electric capacity of the sensor induced by the amount of water are converted into relative humidities. This technique is insensitive to dust, particle dirt and most chemicals. The accuracy is about 2 %. Other measuring techniques are based on humidity dependent expansion of materials. However, during the ARM program's water vapour intensive observation periods Revercomb et al. (2003) found discrepancies in humidity measurements for the entire vertical profile due to calibration differences. Humidity profiles measured with two sondes mounted on the same balloon agree within the range of 8 - 12 %; the variability within a callibration batch is larger then between different calibration batches[1]. This difference is altitude independent. In the study they use the microwave radiometer humidity profiles to scale the radiosonde profiles to reduce the instrument variability. Miller et al. (1999) mentioned chemical contamination in the humidity sensor field depending of the type of packaging desiccant. The latter problem is solved in August 1998 by changing the packaging desiccant. It is not known if discontinuities appear in the humidity records.

Radiosonde ascents performend from 1994 and 2001 where compared to ground based microwave radiometer (MWR) retrieved humidity profiles with the assumption that microwave remote sensing provides more reliable humidity measurements, particular in the upper troposphere. The radiosondes show a 5 % dry bias. Turner et al. (2003) provide an empirical method for correcting the radiosonde humidity profiles based on a constant scaling factor. This factor does not take different calibrations into account.

Bates and Jackson (2001) report an underestimation for upper tropospheric humidity, because the humidity sensor can not resolve the small variations in cold and dry atmospheres. Differences occur between different radiosonde types as reported in Westwater (1997). The Vaisala Humicap humidity sensor retrieve humidities below 20 % more accurate compared to other sensors. But there is a bias between the humidity sensors used for american sondes and the Humicap for the whole humidity range. Algorithms e.g. for LWP based on one type of radiosonde data reflect these biases as shown in Ferrare et al. (1995).

Nevertheless, humidity and temperature profiles from radiosondes are commonly used in climate research. Many stations provide long timeseries of radiosonde data with several ascents per day. The more advanced microwave and lidar techniques are very limited in the covered region. Meanwhile, radiosondes are displaced by satellite and gps retrieved

[1]Calibration batch: During the production process the radiosondes are calibrated in a specific environment which is exposed to small changes. After a while the calibration target is renewed and set to the standart values.

humidities in the assimilation schemes of the weather prediction models.

To assess differences between water vapour in clear and cloudy skies it is necessary to detect the cloud occurences from temperature and humidity profiles. Auxilliary informations like cloud cover are important as the sonde does not neccesary pass a cloud during the ascent. In many studies the cloud detection is based on a thresholding schemes. Chernykh and Eskridge (1996) relate the second derivative of the temperature and the humidity profile to the height in order to identify a cloudy level. In addition the cloud cover is estimated from the dewpoint depression depending on the temperature in four categories (0 - 20, 20 - 60, 60 - 80, 80 - 100 %) after Arabey (1975). Compared to synoptical observations the results for the cloud level detection agree well in 87 % of the investigated cases during day time and the cloud amount in 69 % of the cases. Using this estimation to retrieve cloud boundaries and comparing the results with lidar/ceilometer data for the ARM Southern Great Plains site, Naud et al. (2003) show good agreement whithin 125 m for the cloud base height when both instruments detect a cloud. Stronger differences occur comparing cloud heights from radar and radiosonde. Most differences can be explained by broken cloudiness, when it is not clear whether the active instrument sees the same cloud as the ascending radiosonde.

Wang and Rossow (1995) described a scheme to derive cloud base and cloud top heights from radiosonde measurements. In a first step a moist level is detected when the relative humidity exceeds 84 %. A set of moist level on top of each other is viewed as a cloud when the humidity increases by at least 3 % from the previous (lower) level and the maximum humidity of the moist level exceeds 87 %. The cloud top is reached when the humidity decreases with rates greater than 3 % to the following (upper) level. When cloud base and cloud top heights are below 500 m no cloud is detected. Here rain, drizzle or fog are responsible for the moisture. This method works quite well as comparisons with synoptical data show. For a study on stratocumulus clouds only (Wang et al., 1999) the thresholds were shifted to higher values (90 % for moisture and 95 % for cloud levels) to retrieve cloud levels in better consensus to synoptical observer estimates.

Karstens et al. (1994) use a threshold of 95 % to define a cloud layer. For these layers the adiabatic liquid water content (LWC) is derived depending on the air density, specific heat, latent heat of evapourisation and the adiabatic lapse rates for dry and moist air. This gives the upper limit of LWC because entrainment processes are reducing the amount of condensed water. In this study the authors propose a modification of the LWC with respect to the entrainment induced reduction.

3.1.2 Ground based remote sensing

Radiosondes measurements are still the most important input for weather forecast models, despite their many disadvantages, for instance low temporal resolution, erroneous mea-

surements especially of humidity, the inability to measure hydrometeors distribution, and their extremly high manpower costs. Strong efforts have been undertaken to develop alternative, ground based instruments for continuously monitoring the vertical structure of the atmosphere. Different types of active and passive sensors measure in different parts of the electromagnetic spectrum. Since the interaction of atmospheric constituents with atmospheric radiation changes with wavelength, spectrally diverse measurements contain different informations about the atmospheric composition.

Passive microwave radiometer measure the radiation emitted by water vapour in the atmospheric collumn in viewing direction of the instrument. The principle is comparable to satellite microwave remote sensing retrievals described in section 3.2.3. At least measurements at two frequencies are needed to retrieve the TPW. Measuring the radiation at more frequencies enable the retrieval of a humidity profile. Figure 3.1 shows the uplooking weighting functions of oxigen emission near the 60 GHz band. The lower layers provide the strongest emission, which is also the least attenuated, while the higher layers provide low emission, which is additionally highly attenuated by the lower layers before it reaches the sensor (see Elachi (1987).

Today, ground based microwave radiometers observe water vapour and cloud liquid water

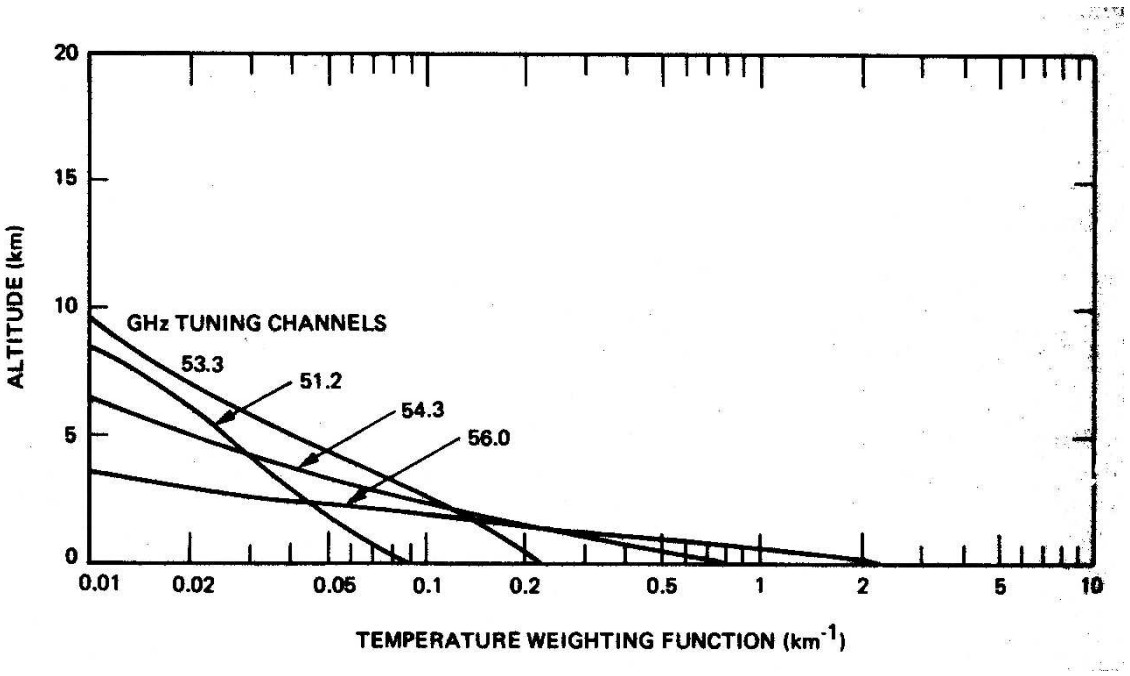

Figure 3.1: *Unnormalised weighting functions for temperature as a function of height above the surface for observations from the surface looking at the zenith. The curves correspond to the emission by oxygen near the 60 GHz region (Elachi, 1987).*

with a high temporal resolution on an operational basis. At meteorological observatories and during intensive field campaigns microwave radiometers are in use. Güldner and Spänkuch (1999) examine the diurnal cycle of integrated water vapour and liquid water path using two years of continuous data for the Lindenberg observatory (MOL). They found only small diurnal variations in the water vapour path of about 8 % in summer and 5 % in winter. The increase in TPW is strongest in the morning in summer, whereas in winter it is shifted to the afternoon. The authors conclude that the monthly mean TPW calculated from low resolution instruments like SSM/I is not effected by the diurnal cycle. Another finding is that the TPW increases by about 5 % within the two hours before rain.

To retrieve water vapour, temperature and liquid water content profiles with ground based microwave radiometer, Peter (1994) propose an iterative algorithm based on a first guess profile from radiosonde and microwave brightness temperatures at five frequencies (23.87, 31.65, 22.235, 52.85 and 54.95 GHz). The advantage of this algorithm is the independency of a training data set. The latter limits the validity of the algorithm to the range of atmospheric conditions covered by the training data.

Beside the passive microwave techniques (described in section 3.2.3) active methods like the Raman lidar or the Differential absorption lidar (DIAL) are in use as well. Here the intensity and wavelength of the returning signal compared to the emitted beam contain informations of the atmospheric temperature and humidity profiles; see Whiteman and Ferrare (1992) and Whiteman and Coauthors (2001) for the Raman lidar; Wulfmeyer and Bösenberg (1998) for the DIAL. These techniques are working in clear sky conditions only.

Different types of active and passive sensors offer measurements in different parts of the electromagnetic sprectrum containing informations of the atmospheric water vapour. Therefore, a combination of instruments will improve the retrieved humidity profiles compared to single instrument methods. Westwater (1997) reports that auxilliary informations like standard meteorological parameters at surface level in addition to remote instruments improve the retrieval significantly. Löhnert et al. (2004) deploy a method to retrieve humidity, temperature and cloud liquid water profiles. The approach combines a multichannel microwave radiometer, a cloud radar, a lidar-ceilometer, the nearest operational radiosonde measurement and ground-level measurements of standard meteorological properties with statistics derived from results of a microphysical cloud model. The algorithm is based on an optimal estimation method using the radiosonde ascent as a priori information. The resulting profiles are physically consistent in all parameters. A bias error is induced using different gas absorption models in the retrieval scheme. The best performance is retrieved using the Rosenkranz 1998 gas absorption model. This method offers the opportunity do retrieve temperature, humidity and cloud liquid water profiles on a continiuous basis with high temporal resolution. This approach is working for non-precipitating liquid water clouds only.

Elgered and Jarlemark (1998) compared TPW time series direved from radiosonde and

microwave radiometer data for 1981 – 1995 located at the Swedish west coast. Both time series show trends in observed TPW, but the direction is different. The uniformly in time sampled radiosonde data show an increase in TPW of 0.03 mm/yr with a standard deviation of 0.01 mm/yr. The microwave data, which are not at all uniformly sampled in time, show an decrease of 0.02 ± 0.01 mm/yr. Reducing the two data sets on the same data points they are in good agreement and the microwave measurements show the same trend as the radiosonde. Differences between the two techniques can be explained by drifts in the calibration or changes in the algorithms. They advise to additionally measure the atmospheric temperature to isolate possible error sources.

At the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SPG) Clouds and Radiation Testbed (CART) site several instruments including an automated Raman lidar and an automated Atmospheric Emitted Radiance Interferometer (AERI) are measuring the tropospheric water vapour profiles operationally. Turner et al. (2000) shows result of these techniques and comparisons to conventional methods like radiosonde retrievals. For non cloudy scenes both instruments perform very well and provide additional informations like aerosol profiles (lidar) and temperature profiles (AERI). The uncertainties are about 5 % during night and 10 % during daytime.

Beside the continuously measuring instruments placed on the surface, most of the instruments can be mounted on airplanes during specific measurement flights. Here measurements along the flight lags are available. Purposes are the derivation of in-situ measurements and simulating satellite measurements. Absorption measurements with the Lyman–α instrument offer direct measurements of the absorption in the water vapour band. A compilation of the different ground–based techniques including the Lyman–α is given in table 3.1.

3.2 Satellite Instruments and Techniques

Satellite remote sensing is based on radiation measurements modulated due to absorption, emission and scattering by the atmospheric constituents. The modulation depends on the part of the radiation spectrum under consideration figure 3.2 shows atmospheric attenuation in the range from ultraviolet to radiowaves. In the far infrared the atmosphere is opaque whereas in the microwave region it is transparent except of two water vapour absorption lines (22.2 and 183 GHz) and two oxygen absorption bands (60 and 118 GHz). There are minor absorption bands related to ozone and other trace gases. Strong absorption in the infrared mostly due to H_2O and CO_2 is found. In the atmospheric water vapour window (8 - 12 μm) a strong ozone absorption line is disposed. For microwave radiation the atmosphere appears to be transparent beside a H_2O line at 22.235 GHz and 180 Ghz and two O_2 lines at 53 GHz and 120 Ghz. Remote sensing techniques for the retrieval of water vapour make use of spectral changes in molecular absorption. An overview of available

satellite instruments is given in table 3.2.

Instrument	Retrieval	Quantity	Limitations and Advantages
Radiosonde	Profile	Humidity, Temperature, Wind	too low humidities at low temperatures limited spatial and temporal resolution
Microwave radiometer	Profile (multi channel), Integral (2 channel)	Temperature, Humidity	limited to non–precipitating, liquid water clouds continiuous measurements
Lidar (Raman, DIAL)	Profile	Humidity	clear sky
Lyman-α		Humidity	limited temporal and spatial resolution only during campaigns including flights

Table 3.1: Compilation of ground-based and air-borne techniques and their limitations.

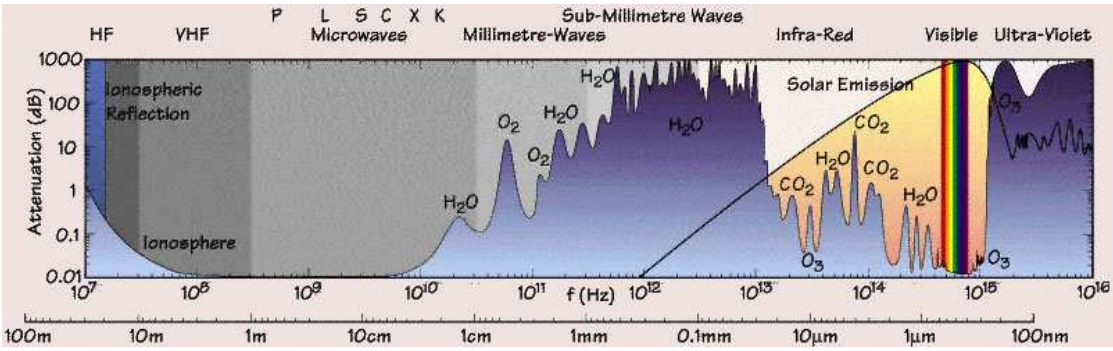

Figure 3.2: *The attenuation depending on the wavelength for the electromagnetic spectrum. The atmospheric absorption bands are labeled by the main absorbing gases.*

Instrument	Satellite/Mission	Spectral Range	Frequency/Wavelength	Specifications	Resolution (FOV)
JPL-GPS	CHAMP	GPS		Limb	vertical 0.5-1.5 km
GOME	ERS–2	UV, VIS	240–790 nm	Nadir 5 channel	$\sim$ 40-320 km
MODIS	TERRA/AQUA	VIS, NIR	405-2155 nm, 1.360-14.389 μm	crosstrack 36 channel	$\sim$ 1 km
MERIS	ENVISAT	VIS, NIR	400-1015 nm	crosstrack 15 channel	0.3 km and 1.2 km
SCIAMACHI	ENVISAT	UV, VIS, NIR	240nm - 2380 nm	Nadir, occultation, limb 8 channel	30 km, 30 km, 250 km
SSM/I	DMSP	MW	19.0-85.0 GHz	conical at 54° 4 channel	13.0 km$\times$15 km
SSM/T2	DMSP	MW	50.0-59.4 GHz, 91.0-183.0 GHz	Nadir, limb 7 channel	$\sim$ 48 km (Nadir)
HIRS	NOAA polar	VIS, NIR, IR	0.690-14.95 μm	crosstrack 20 channel	$\sim$ 20 km (Nadir)
AMSU	NOAA polar	MW	23.8-183 GHz	crosstrack 20 channel	$\sim$ 60 km (Nadir)
SEVIRI	MSG	VIS, NIR, IR	0.635-13.4 μm	scanning 12 channel	$\sim$ 4 km
IASI	METOP	NIR, IR	3.6-15.5 μm		

Table 3.2: Overview Satellite instruments, their wavelength and the FOV.

3.2.1 Solar

The remote sensing of TPW is mainly conducted using microwave, far infrared, infrared and near infrared spectral features. The visible water vapor bands have not been used due to the incomplete state of the spectral data, which causes difficulties in the common absorption spectroscopy techniques. Maurellis et al. (2000) propose a new technique, named Optical Absorption Coefficient Spectroscopy technique (OACS) to use spectral data measured in the weak water vapor absorption band between 585 nm and 600 nm with data derived from the Global Ozone Monitoring Experiment (GOME). The retrieval is based on the HITRAN96 data base and accounting for the dependency of the line shape on the altitude and the spectral structure at instrument resolution. Former methods were not suitable for this absorption band due to the highly structured spectral appearence. The technique is applied on a transmittance spectra consisting on 69 measurements resembling the detector pixels spectral region of interest. Apart from the water absorption band which lies between the maxima of two $(O_2)_2$ collisional broad band absorptions (at 557.2 nm and 630.0 nm). The GOME retrieved TPW are compared with data from the ECMWF forecasts for different orbits and show good agreement.

Another technique to use spectral data in the visible water vapour absorption band around 590 nm is given by Lang et al. (2003). A spectral sampling technique for measurements of atmospheric transmission called the Spectral Structure Parametrisation (SSP) in order to retrieve the total water vapour columns from reflectivity spectra measured by the Global Ozone Monitoring Experiment (GOME). The SSP reduces the opacity functions and their weights to one structure parameter. This parameter characterises the spectral structure of the absorber within a specific wavelength range and a specific altitude. This method is suitable for relatively small sampling regions containing only a small number of absorption lines, e.g. for data from the GOME and SCIAMACHY instruments. The results compare well to independent values given by the data assimilation model of ECMWF and to retrievals with the OACS method.

These techniques can retrieve the TPW for clear skies only. In cloudy atmospheres the measurements are related to the water vapour on top of the clouds. Using climatologies of humidity and temperature profiles and estimating the cloud top height the TPW is estimated for cloud affected measurements. Various correction schemes are under developement; the quality of the cloud–corrected TPW is very sensitive to the estimated cloud top height.

From backscattered sunlight measured with MERIS Albert et al. (2001) suggest a method to derive water vapour above clouds. The retrieval scheme is based on measurements in the water vapour absorption band and window channel measurements. A regression type algorithm is derived from radiative transfer calculations using radiosonde ascents and taking the channel weighting functions into account. Bennartz and Fischer (2001b) propose a technique to retrieve the TPW from MERIS near infrared channels over land

surfaces. The retrieved water vapour paths compare well to other measurements despite a significant bias. An explanation of the bias might be the neglection of the continuum absorption of water vapour, which would lead to systematically lower transmissions in the radiative transfer simulations.

Gao and Kaufman (2003) propose a water vapour retrieval using MODIS based on ratios of radiances measured in three absorbing infrared channels (0.905, 0.936 and 0.904 μm) and the atmospheric window channels (0.865 and 1.24 μm). The algorithm is suitable over reflecting surfaces like land areas, ocean areas with sun glint and clouds. By using ratios of the radiance in two channels the effects of variations in the surface reflections can be removed. Typical errors in the derived water vapour are about 5–10%. The retrieved TPW are in good agreement with ground based microwave observations at ARM stations.

3.2.2 Infrared

The infrared satellite retrieval method are based on the split-window technique in which the difference in absorption between two nearby infrared channels is used to estimate the TPW. The greater the difference between the brightness temperatures, the more water vapor found above the pixel whose brightness temperatures are being measured (Kidder and Vonder Haar (1995, Chapter 6)). Typical wavelengths used for water vapour retrieval are 8.90 – 9.20 μm, 9.31 – 9.41 μm or 9.15 – 9.65 μm.

With more channels close to one absorption line it is possible to retrieve additional informations about the vertical distribution of water vapour. Depending on the used wavelengths

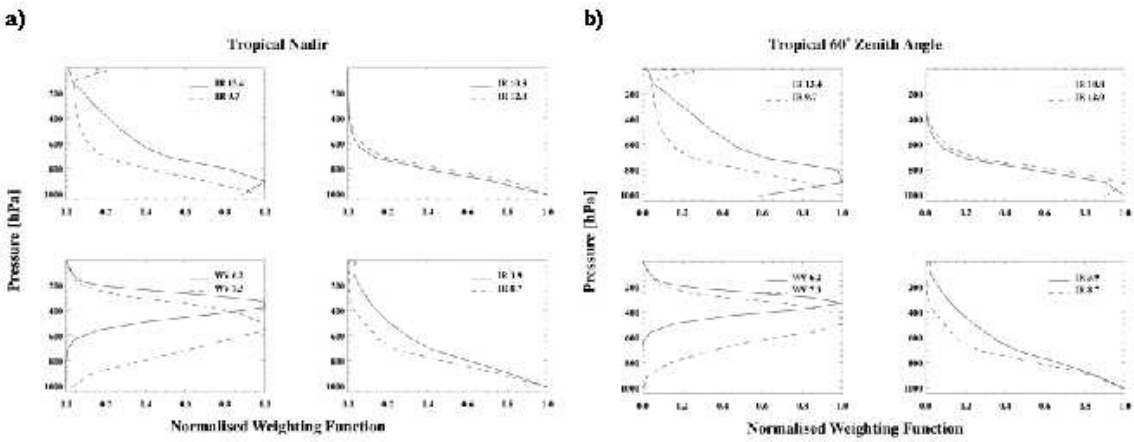

Figure 3.3: *Weighting functions for the thermal IR channels of SEVIRI on MSG–1 corresponding to a tropical standard atmosphere. (a) nadir view and (b) is 60° viewing zenith angle. From Schmetz et al. (2002).*

the signal is mostly emitted from a specific height. Using more frequencies with different weighting functions (see figure 3.3), which describe the extinction profiles of the atmosphere, water vapour profiles can be retrieved. Each atmospheric layer is characterised by the peak in the weighting function. Figure 3.4 illustrates the relation of the located wavelength to the centre of the absorption line and the penetration depth.

There are various sensors based on infrared channels like HIRS, the Medium Resolution Imaging Spectrometer (MERIS) on ENVISAT, the Moderate Resolution Imaging Spectroradiometer (MODIS) on TERRA/AQUA and the proposed Infrared Atmospheric Sounding Interferometer (IASI) on future METOP satellites. All these instruments are carried on polar orbiting satellites only. On geostationary satellites IR channel instruments like the Spinning Enhanced visible and infrared Imager (SEVIRI) on MSG are used. For the IASI instrument Schlüssel and Goldberg (2002) show that the temperature and water vapour retrieval is not effected by sub–pixel cloud cover lower then 5 % when the occurence of clouds is accounted for in the retrieval scheme based on model results. Infrared and solar retrieval techniques are limited to cloud free situations. All TPW retrieval are in good agreement with radiosonde data.

For the upper troposphere the retrieval accuracy of humidity profiles from infrared sensors is low (Bühler and Couroux (2003), Bühler and John (2004b) and Bühler et al. (2004e)). The measured radiances mostly originate from lower levels as shown by their weighting functions. Soden et al. (2004) compared HIRS and radiosonde retrieved water vapour and found differences in upper tropospheric humidity of about 40 %. This corresponds to a difference in clear sky outgoing longwave radiation of 3.8 %. Weinstock et al. (1995) investigate the retrieval of water vapour in the upper troposphere and lower stratosphere

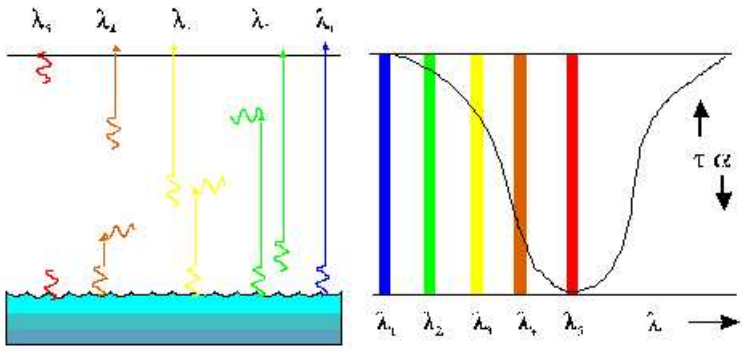

Figure 3.4: *Scheme of the relation of the observed wavelength to the heigth where the radiation originates. On the right the wavelength position relative to an absorption line is shown. On the left the signal seen from a space borne or ground based instrument is shown.*

using a Lyman-α hygrometer mounted on the NASA-ER2 airplane during the Central Equatorial Pacific Experiment (CEPEX). The aim of the campaign was to retrieve water vapour and to understand the mechanisms that transport the water vapour from the upper troposphere into the stratosphere. The retrieved water vapour contents of the upper troposphere and lower stratosphere compare well with previous retrievals. An annual averaged mixing ratio of water in air entering the tropical stratosphere is about 4.45 ppmv.

3.2.3 Microwave

Microwave radiometers offer the possibility to retrieve the TPW in clear and cloudy atmospheres. Passive microwave techniques measure the emission from the surface and the atmosphere. For the retrieval of atmospheric constituents it is compellent to know the background emission from the surface. Ocean surfaces appear cold and homogeneous in the microwave region and their variability in emittance depends on the sea surface temperature, the roughness and the salinity. With ocean surface models the microwave emission can be assessed. Land surface emission is much stronger and depends on many variables which are inhomogeneous on small spatial scales. The retrieval of atmospheric properties is possible over ocean only. In the microwave region water vapour path and liquid water path is retrieved simultaneously using at least two frequencies; one close to the water vapour absorption line and one in the window where the radiation is related to the condensed water. An algorithm using AMSU channels is described in Grody et al.

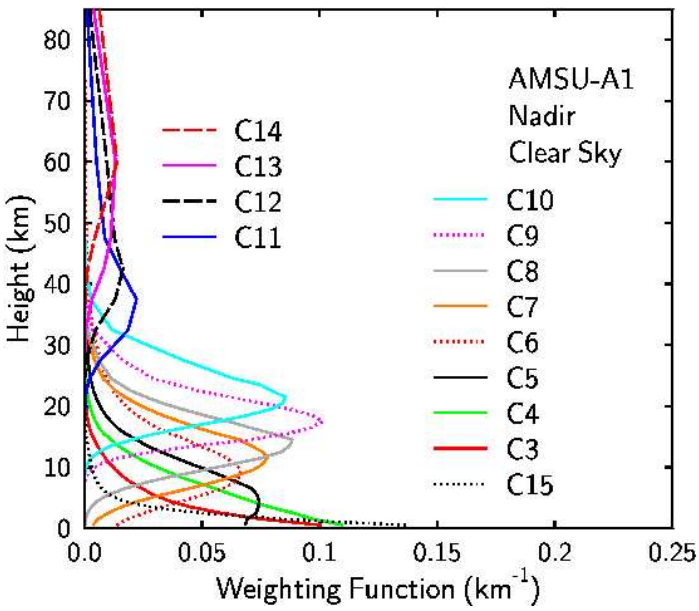

Figure 3.5: *AMSU–A weighting functions. Each line/colour resembles one channel. E.g. Channel 7 (C7 – 54.94 GHz) has a maximum amplitude at 12km height.*

(2001). As for ground based microwave techniques described in section 3.1.2 scattering at large raindrops and ice particles weakens the efficiency of the algorithm and limits its application to nonprecipitating water clouds.

Humidity profiles can be obtained from measureing radiances at only the flanks of an appropriate absorption peak. Like for IR-measurements the measured radiance is related to an altitude by a corresponding weighting function. In figure 3.5 the weigthing functions for the AMSU–channels are shown.

Basically a two frequency scheme is used where one frequency is near the water vapour absorption line and another in the window channel. Numerous algorithms based on the frequencies available from SSM/I, SSM/T2, MSU and AMSU can be found in literature, a selection is described in the study of Wahl et al. (2003). Comparing the retrieved water vapour path to radiosonde and ground based microwave measurements shows a reasonable aggreement. Ruprecht (1996) shows a bias for SSM/I TPW compared to radiosonde in a way that the satellite retrieval overestimates for low TPW and underestimates for high TPW retrieved with radiosondes.

English (1999) suggests a method for humidity and temperature profiling over land and bright surfaces with AMSU. The atmospheric humidity and temperature profiles can be derived within a acceptable error range. The influence of surface emission is stronger in the LWP retrieval then for the humidity retrieval. However, the humidity retrieval is sensitive to the LWP as well.

With limb scanning instruments the profile of humidity and temperature for the tangent point can be retrieved. The sensor aperture angle results in an altitude error also called pointing error. For the pointing and temperaure a possible retrieval algorithm for millimeter and sub–millimeter wavelength range is proposed by Verdes et al. (2002).

3.2.4 Combined microwave and infrared techniques

The TIROS Operational Vertical Sounder (TOVS) equipped aboard NOAA's TIROS series of polar orbiting satellites consists of three instruments: the High Resolution Infrared Radiation Sounder (HIRS), the Microwave Sounding Unit (MSU) and the Stratospheric Sounding Unit (SSU). The MSU and SSU have been replaced with improved instruments, the AMSU-A and AMSU-B, on the newer satellites also mentioned as ATOVS.

A five level clear sky water vapour profile algorithm using TOVS data is described in Chaboureau et al. (1998). A neural network scheme is used for the solution of the radiative transfer problem. The results compare well with SSM/I and radiosonde data. Uncertainties in the algorithm are larger in the upper atmosphere where radiosonde data

and TOVS retrieval results differ most.

Engelen and Stephens (1999) compare TOVS/HIRS and SSM/T-2 retrieval techniques and the retrieved water vapour profiles. For the upper and mid troposphere the TPW retrieval using HIRS data is more reliable. The measured radiances in the HIRS channels originate from higher levels in the atmosphere, as described by the weighting functions. The lower atmosphere and the surface are contributing to the signal for dry atmospheres only. The SSM/T–2 informations are dominated by the lower levels. Due to the limitation in the infrared technique only cloud free situations are compared. In general the methods are sensitive to the quality of the input parameters, e.g. the sensor characteristics like signal to noise ratio. The authors assume a 3 % error in radiance for all, HIRS and SSM/T-2 channels, this translates in a brightness temperature error of $\sim 7\,\mathrm{K}$ for SSM/T-2 which is larger then the noise values. These high estimated uncertainties lead to a controverse result compared to Eyre (1990). The latter shows better retrieval performance for SSM/T-2 in the upper troposphere deduced using smaller errors in radiance for the used frequencies. Eyre (2000) remark that the uncertainties for the microwave channels assumed by Engelen are too big. Choosing lower uncertainties will lead to better retrievals in the upper troposphere. Nevertheless Engelen and Stephens (2000) argues that one element of the cost function which the optimal estimation retrieval seeks to minimize hold the measurement errors and estimated model uncertainties in a covariance matrix. The basic quantitiy observed by the satellite instruments is the radiance, hence the measurement error used for the covariance matrix should be specified in radiance units. Converting the radiance errors to brightness temperature error estimates as used in Eyre (1990) appear very optimistic.

3.2.5 GPS

Global Positioning System (GPS) receivers can also be used for remote sensing of the water vapour path. The time varying zenith wet delay observed at each GPS receiver in a network can be transformed into an estimate of TPW overlying that receiver (Bevis et al., 1994). This transformation is achieved by multiplying the zenith wet delay by a factor whose magnitude is a function of certain constants related to the refraction of moist air and of the weighted mean temperature of the atmosphere. The mean temperature varies in space and time and must be estimated a priori e.g. by using numerical weather models, in order to transform an observed wet delay into TPW. Li et al. (2003) compared GPS and MODIS retrieved TPW with radiosonde humidities. TPW retrieved with GPS is in good aggreement with radiosonde integrated water vapour. The variance is about 4 % and the correlation coefficient is 0.98. A significant day–night difference was found for Vaisala RS90 radiosonde comparing to GPS TPW, with a larger wet delay vs TPW proportionality during night time. The MODIS TPW retrieval is limited to day time, and the differences relative to GPS TPW or radiosonde TPW are larger than those between GPS TPW and radiosonde TPW. MODIS seems to overestimate the TPW compared to the other methods. Another comparison of GPS retrieved TPW with radiosonde data, water

vapour radiometer (WVR) and Very Long Baseline Interferometry (VLBI) show relativily small differences of 3 % in TPW (Niell et al., 2001). While infrared measurements are only available for clear sky cases and microwave measurement are limited to the oceans and to non–precipitating clouds, GPS retrievals are valid for all day and all sky situations.

Since mid 2001 the German geoscience satellite CHAMP (Challenging Minisatellite Payload) is continously measuring atmospheric profiles using the GPS radio occultation technique. CHAMP measures the phase and amplitude variations of the GPS signal during an occultation event. Together with high–precision orbit information the atmospheric path delay and the bending angle profile can be determined. These parameters are directly linked by the refraction to the vertical temperature and humidity vertical distribution. Schmidt et al. (2004) compare the retrieved temperature and humidity profiles to ECMWF reanalysis data and radiosondes. The results are promising. For the temperature profiles small biases occur which are related to assumptions made for the humidity profile in the retrieval algorithm. The humidity is retrieved by splitting the refractivity in a dry and a wet part which requires additional information of the level temperature. The Schmidt et al. (2004) algorithm uses ECMWF temperature. During the first 510 days CHAMP recorded 105,000 occultations. This shows the great opportunity given by the GPS systems for meteorological remote sensing. GPS radio occultation is independent on the present weather situation. The retrieval of water vapour and temperature is possible in cloudy skies and during precipitation.

3.2.6 Compendium

Comparison of satellite retrieved water vapour path and liquid water path from microwave and infrared measurements show reasonable agreements under clear sky conditions. Greenwald et al. (1997) compare GOES-NIR and SSM/I retrieved LWP and investigate the beamfilling error due to broken cloudiness in a microwave field of view. The beamfilling error is about 22% for broken cloudiness and the correlation between GOES–NIR and SSM/I LWP is depending on cloud cover. For overcast cases the relation is 0.93, whereas in broken cloudiness the correlation is 0.73. For the overcast case the retrieval using GOES–NIR shows higher LWP compared to SSM/I, while the SMM/I LWP retrieved in broken cloudiness is larger then the GOES-NIR. A comparison of different water vapour retrievels is given by Tjemkes and Visser (1994). It is shown that TOVS/HIRS and SSM/I TPW agree well for clear sky cases. The authors assess the underestimation of all sky TPW due to the limitation to clear sky cases for TOVS/HIRS retrieval in terms of OLR radiation by 2-3W/m^2 compared to SSM/I.

On ERS–2, a microwave radiometer (MWR) and the Along Track Scanning Radiometer (ATSR) are used for the retrieval of TPW over oceans. ATSR views the Earth's surface at two different viewing angles and in three infrared bands. Comparison of microwave and ATSR TPW show good aggreement (Barton, 2004) for clear sky cases.

Bokoye et al. (2003) compare a 940 nm solar absorption band radiometer, GPS and radiosonde analysis from a numerical weather prediction model over Canada and Alaska to investigate the strong seasonal variablility in water vapour at high latitudes. The intercomparisons show root mean sqaure errors between 1.8 and 2.2 kgm^{-2} for the different instruments. The GPS shows best results, but for the retrieval it is necessary to be aware of the differences between arctic air masses and the generally used mid–latitude temperature profiles for the derivation of weighting coefficients for the retrieval.

in summary, table 3.3 shows the compilation the discribed techniques. The solar retrieval is limited to day light whereas the microwave retrieval is suitable over homogeneous emitting surfaces like the oceans. But for retrieving an all sky TPW microwave measurements are very important.

Technique	Land	Ocean	Day	Night	Resolution	Restrictions
Solar	+	+	+	-	high spatial resolution	clear sky
Infrared	+	+	+	+	high spatial resolution, on geostationary satellites high temporal resolution	clear sky
GPS	+	+	+	+	low spatial resolution	
Microwave	−	+	+	+	low spatial resolution	no rain, no ice

Table 3.3: Compendium of the retrieval techniques

Chapter 4

campaigns and available data

The need for an advanced water vapour climatology is well documented. To date, the majority of large-scale water vapour climatologies have relied wholy upon analysis of radiosonde data. A number of projects, some of them are mentioned in the following are currently improving the global water vapour climatology from various instruments, remote and in situ. The projects aim to measure water vapour at all–sky atmospheric situations, to validate the different retrieval techniques, and to implement the obtained knowledge in climate prediction models and radiative transfer models. The latter results in amendments in retrievals based on satellite and ground based remote sensing data. In this section an overview on existing projects and the available data together with access informations are given. A list of the projects and their web addresses is given in table 4.1.

campaign	web adress
GVaP	http://www.gewex.org/gvap.html
CLIWA–NET	http://www.knmi.nl/samenw/cliwa-net
4D-Clouds BBC2	http://www.meteo.uni-bonn.de/projekte/4d-clouds/bbc2
VAPIC	http://sirta.lmd.polytechnique.fr/VAPIC_en.htm
CLOUDMAP2	http://www-research.ge.ucl.ac.uk/cloudmap2/
CLOUDNET	http://www.met.rdg.ac.uk/radar/cloudnet/
IHOP_2002	http://www.atd.ucar.edu/dir_off/projects/2002/IHOP.html
NVAP	http://eosweb.larc.nasa.gov/PRODOCS/nvap/table_nvap.html
Lindenberg (MOL)	http://www.dwd.de/en/FundE/Observator/MOL/
Cabauw	http://www.knmi.nl/samenw/cesar/
SITRA	http://sirta.lmd.polytechnique.fr/index_english.htm
ARM	http://www.arm.gov/

Table 4.1: Compilation of campaigns and other data web sites.

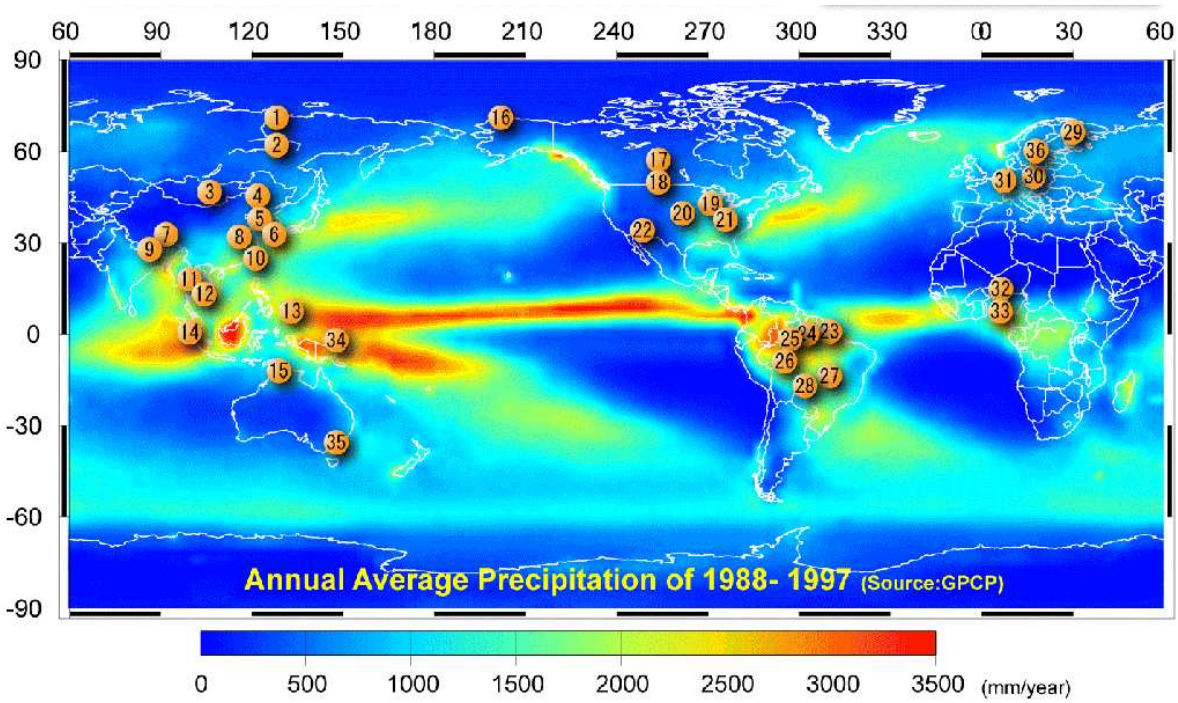

Figure 4.1: *The location of reference sites during the CEOP campaigns. (http://monsoon.t.u-tokyo.ac.jp/ceop/data/eop-1/satellite/doc/index.htm).*

4.1 GVaP

The Global Water Vapour Project (GVaP) is guided by the Global Energy and Water Cycle Experiment (GEWEX) radiation panel. The primary goal is the accurate measurement, modelling and long–term predicting of water vapour in the troposphere and stratosphere. A special focus is on the upper tropospheric and lower stratospheric water vapour. The first aim in this project is to retrieve a consistent set of atmospheric quantities to optimise the radiative transfer models. Therefore, several intensive field campaigns are planed. By now, two implementational measurement campaigns and the first annual cycle campaign are finished. The second annual cycle campaign is finished by the end of 2004. Thus, the pilot phase is finished and a global water vapour climatology data set is available now. A detailed description is given in section 4.7.

During several coordinated enhanced observing periods (CEOP) on sites distributed allover the world hydrological and radiation parameters were measured from ground and from satellite. The data are available through the project web site (see table 4.1). Contributing regional programs are BALTEX, CAMP, CATCH, GAPP, LBA and MAGS. For the BALTEX area Lindenberg and Cabauw are the corresponding reference sites. The geographical distribution of the reference sites is shown in figure 4.1. A detailed description

Figure 4.2: *Location of contributing stations to the CLIWA–NET campaigns CNN1 and CNN2. The station Gotland was operated during CNN2 only.*

of the site instrumentation and the data is given on the web and in table 4.8.

4.2 CLIWA-NET and BALTEX-BRIDGE

The main objective of the EU–Project CLIWA–NET (BALTEX Cloud Liquid Water network) was to build up a network to observe clouds. Therefore existing, mostly operational, ground-based microwave radiometers and profiling instruments at 11 stations in Europe were used. These coordinated measurements took place during two campaigns performed at several stations shown in figure 4.2 in August/September 2000 (CNN1) and in April/May 2001 (CNN2). The aim was to compare the performance of the different in-

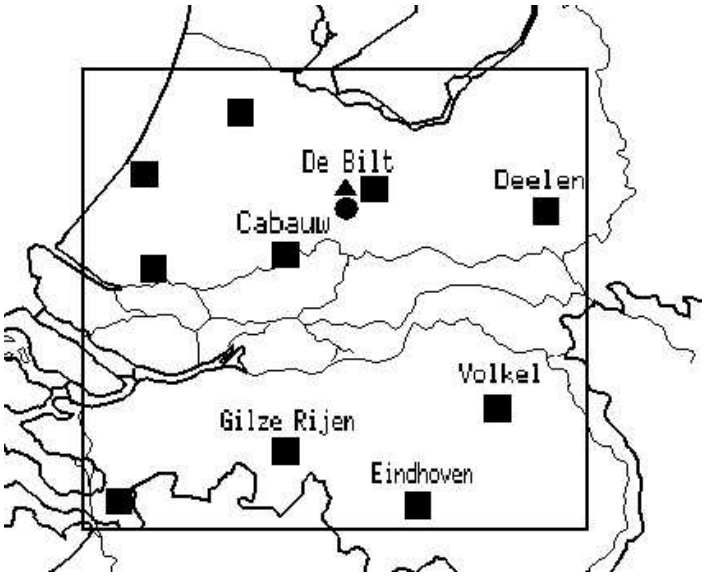

Figure 4.3: *Location of contributing stations to the CLIWA–NET campaign BBC1 in August and September 2001.*

struments, the retrieval techniques by means of the derived products like LWP and TPW and to validate regional forecast model output. The different microwave instruments measure the radiance in different frequencies as shown in figure 4.4 and with diverse observing geometry. The intercomparison for one case is shown in figure 4.5. Except of one instrument, the St. Petersburg microwave radiometer, all radiometer show an agreement in the range of the instrument errors and the uncertainties given by the absorption model used for the LWP/TPW retrieval.

A third campaign took place in August/September 2001 (BBC1) focussing on regional scales. The microwave instruments used during the CNN campaigns were distributed over the Netherlands in order to represent an area of 100 km $\times$ 100 km as shown in figure 4.3. Although the main focus was on the measuring liquid water path for non-precipitating clouds. The water vapour has been observed and analysed as well with GPS and microwave instruments. For the cloud detection ceilometer cloud base heights and IR data is used. The equipment used at the sites is shown in table 4.2 for CNN1, table 4.3 for CNN2.

All data CNN1, CNN2 and BBC are available on the campaign ftp server. During all campaigns flights in clouds were perfomed. Thus, in–situ measurements of cloud mirophysial properties are available as well.

The BBC1 campaign was part of the 4D–Clouds project founded by the BMBF–AFO2000. The aim of the AFO–2000 project is to understand processes in the atmospheric system. The main objective of the 4D–clouds was to measure and model cloud structures and to

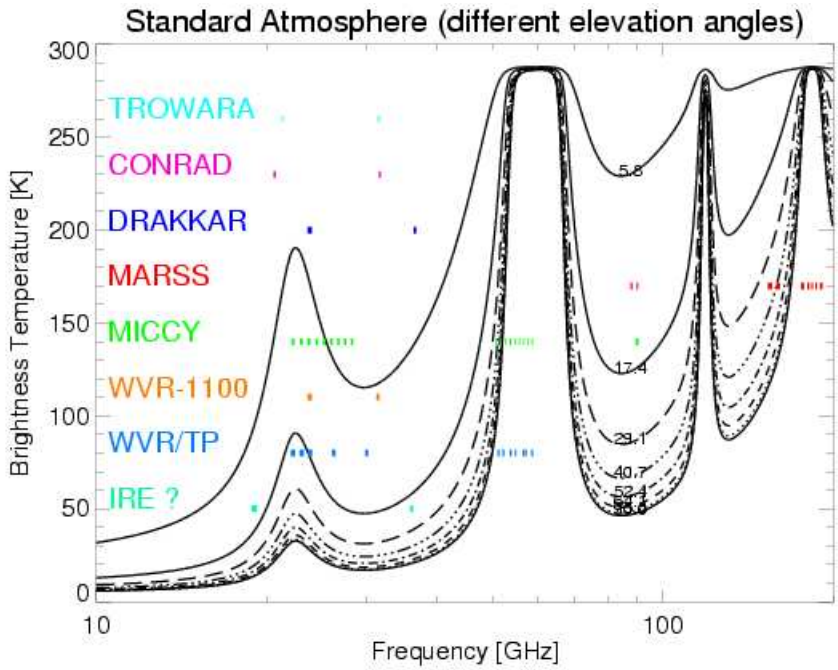

Figure 4.4: *Simulated brightness temperatures for standard atmospheric conditions (no cloud). Calculations are performed for elevation angles of 5.8, 17.4, 29.1, 40.7, 52.4, 64.1, 75.8 and 90 degree. Frequencies of involved radiometer are highlighted. On the CLIWA–NET web page a detailed description of the instruments can be found (http://www.knmi.nl/samenw/cliwa-net)*

define the impact of cloud inhomogeneities on the measured radiances; in particular the enhanced absorption, the relation between albedo and optical depth in satellite retrievals, and the relation between dynamical exchange processes and the 4 dimensional cloud structure.

In May 2003 the BBC2 campaign was performed at Cabauw in the Netherlands focusing on the purposes of the 4D–Clouds project. The instrumentation consists of a broad range of radiation instruments on the ground and on airplanes; radars, lidars, microwave radiometers, in-situ particle probes (aircraft and tethered balloon), and radio sondes, see table 4.4. The data are available on the campaign ftp server. For this campaign MSG data is also available. Here numerous projects are participating the measuring site to compare the different retrieval and instruments and to get a broader range of measurements due to the various foci on cloud and radiation properties and their view in the specific projects. Beside the 4D–Clouds interests the quality and availability of water vapour profile and boundary layer height estimations by remote sensing techniques are on focus. Several investigations on microphysical properties and their impact on energy transport have been performed.

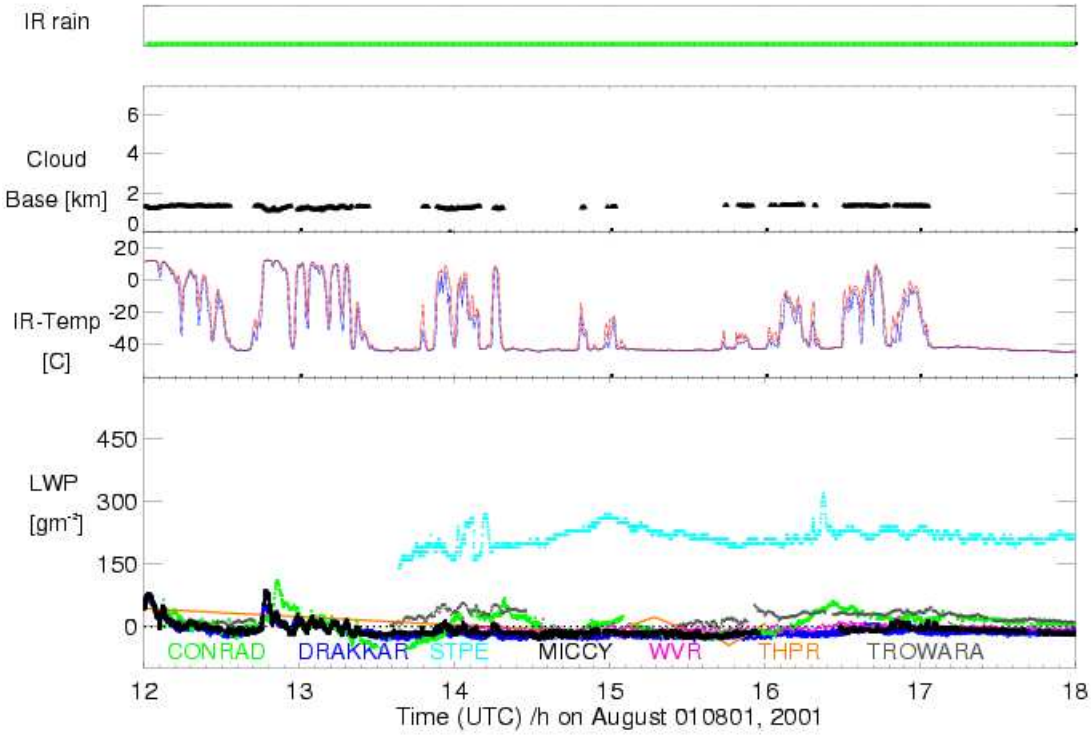

Figure 4.5: *Timeseries of the rainflag derived from a rain shutter mounted on the infrared radiometer, cloud base height, infrared temperature and LWP (top to bottom) on 1 August 2001 between 12 and 18 UTC. The different colors denote the microwave radiometer used for the intercomparison. For more cases see the CLIWA–NET home page (http://www.knmi.nl/samenw/cliwa-net).*

	Station	Microwave Radiometer	Infrared Radiometer	Lidar Ceilometer	Cloud Radar
BE	Bern	X	X		
CA	Cabauw		X	X	
CH	Chilbolton	X	X	X	X
GE	Geesthacht	X	X	X	X
HE	Helsinki	X	X	X	
KI	Kiruna	X	X	X	
LI	Lindenberg	X	X	X	
ON	Onsala	X	X	X	
PA	Paris	X	X		
PO	Potsdam	X	X	X	
SP	St. Petersburg	X	X		X

Table 4.2: *Stations and instrumentations during CNN1. For further details see Crewell et al. (2002).*

	Station	Microwave Radiometer	Infrared Radiometer	Lidar Ceilometer	Cloud Radar
BE	Bern	X	X		
CA	Cabauw	X	X	X	
CH	Chilbolton	X	X	X	X
GE	Geesthacht		X	X	X
GO	Gotland	X	X	X	X
HE	Helsinki	X	X	X	
KI	Kiruna	X	X	X	
LI	Lindenberg	X	X	X	
ON	Onsala	X	X	X	
PA	Paris	X	X		
PO	Potsdam	X	X	X	
SP	St. Petersburg	X	X		X

Table 4.3: *Stations and instrumentations during CNN2. For further details see Crewell et al. (2002).*

	Instrument
Radar	1.29 GHz Windprofiler/RASS
	3 GHz FMCW Radar TARA
	35 GHz Cloud Radar
	95 GHz Cloud Radar MIRACLE
	24 GHz Micro Rain Radar
	Sodar/RASS
Lidar	LD40 Ceilometer
	CT75K Ceilometer
	1064 nm Backscatter Lidar HTRL
	Raman Aerosol Lidar ARAS
	CT25K Ceilometer
Microwave Radiometer	22 Channel Radiometer MICCY
	20, 30 GHz Radiometer
	36, 95 GHz Radiometer
Radiation	BSRN-Type instruments (dif., dir., glo., lw.)
	SPUV
	IR Radiometer on MICCY
	IR Imager
	UV Spectrometer
	Albedometer
	Spectrometer
	FUBISS
	Sunphotometer CIMEL
	Oxygen A-Band Spectrometer
	IR radiometer upward looking
Balloons	Tethered Balloon MAPSY
	Tethered Balloon with 5 PTU Probes
	Radiosonde
Aircraft instruments	various probe types
	Albedometer
	CASI
	FUBISS
	POLDER
	MiniMIR
	temperature probes
	DIRAM
Tower Instrumentation	temperature
	humidity sensors
	Sonic
	IR Radiometer downward
surface instrumentations	shortwave in and out
	longwave in and out
	soil heat flux
	ground water level
	precipitation
	turbulence
	GPS receiver
	total sky imager
	present weather sensors
	rain gauges
	disdrometer
	aerosol counter

Table 4.4: *Instrumentation during BBC2.*

4.3 VAPIC

The Water Vapor Profiling Intercomparison campaign (VAPIC) was a two phase program to study atmospheric water vapour from multi-instrument synergies. The objective of the first phase (VAPIC-I) is to compare different instruments and corresponding water vapour retrieval techniques based on remote sensing and in-situ measurements in order to better define accuracy and precision of these techniques. To fullfill this objective ground based and in situ measurements are compared against each other. Afterwards, satellite based remote sensing measurements are compared to the ground based retrievals. From these comparisons the accuracy and performance limitations of the involved instruments are determined. The different instruments enable the retrievals of 3-D fields of water vapour. This will improve the knowledge of the developement of clouds and precipitation. The data is valuable for climate models as well. The measurement campaign took place at SIRTA in Palaiseau, France. The duration was on month starting 15th of May 2004. The instrumentation is given in table 4.5. The objective of VAPIC-II is to study formation processes of mid-latitude low-altitude clouds using the expertise gained during VAPIC-I and developing new retrieval techniques using combined ground based and satellite instruments.

4.4 cloudnet

The cloudnet project, which started at 01.04.2001, aimed to use data obtained quasi-continuously for the development and implementation of cloud remote sensing synergy algorithms. The use of active instruments (lidar and radar) results in detailed vertical profiles of important cloud parameters which can not be derived from current satellite sensing techniques. A network of three already existing cloud remote sensing stations

Instrument	Type
GPS	
Microwave Radiometer	23, 32 GHz DRAKKAR 23,32 GHz RESCOM, scanning
LIDAR	RAMAN, 355 nm
Radar	Cloud Radar, 5 GHz
Radiosonde	RS90, RS92
Satellite Instruments	MODIS MERIS AIRS MSG AMSU–B Profils

Table 4.5: Instruments used during VAPIC

(Cabauw (Netherlands), Chilbolton (UK) and SITRA (Palaiseau, France)) were operated for a period of two years. A harmonised data set describing the cloud parameters (e.g. LWP, IWP, TPW, effective radius, a.s.o.) is available to optimise and validate remote sensing algorithms and forecast models.

4.5 cloudmap2

The EU-Project CLOUDMAP2 aims to produce and exploit value added remote sensing data products on macroscopic (e.g. cloud top height) and microscopic (e.g. cloud droplet radius) properties and water vapour distributions to characterise sub-grid scale processes within Numerical Weather Prediction models (NWP) through validation and data assimilation. The data basis consists of numerous satellite remote sensing data for over a decade of time and ground based active microwave and passive IR instruments for validation purposes. Merging of the different sensors and techniques will result in a new value added product. Within the project the columnar water vapour above the cloud is derived from MODIS data using the scheme of Bennartz and Fischer (2001b).

4.6 IHOP

The International H2O Project (IHOP_2002) was a field experiment that took place over the Southern Great Plains of the United States from 13 May to 25 June 2002. The main

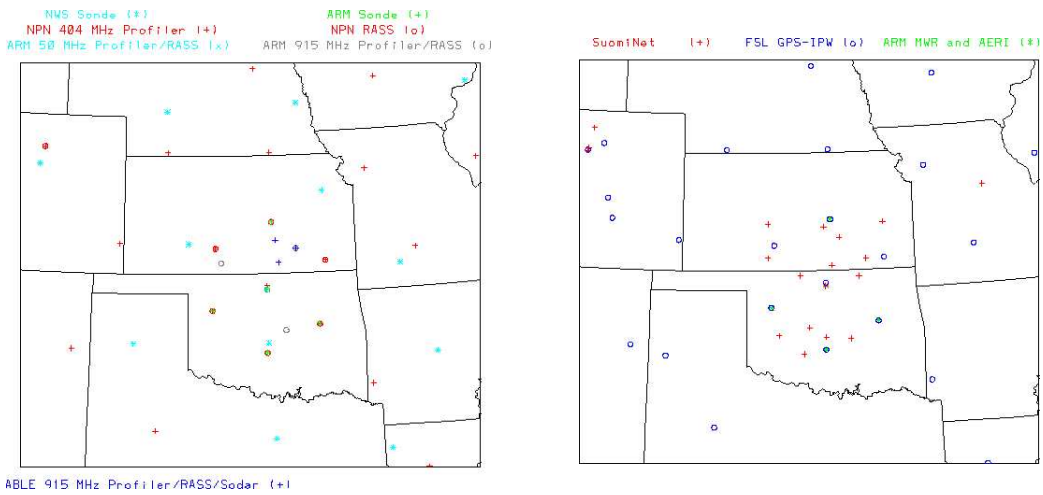

Figure 4.6: *Location of the different instruments operated during the IHOP campaign in 2002. The maps show the Sothern Great Plains area of the United States. (http://www.joss.ucar.edu/ihop/dm/images/).*

goal of IHOP_2002 was an improved characterization of the four-dimensional distribution of water vapour and its application to improve the understanding and prediction of convection, to improve the forecast of summer precipitation and the validation of mesoscale forecast models. One component of the project plan is to combine different water vapour retrieval techniques to find the best combination of instruments for future applications. The relative importance of water vapour measurements to other variables are assessed so that better measurement strategies for operational forecast and meaningfull data assimilation can be designed. Attention is also be paid to performance characteristics and sampling limitations of water vapour sensors. The measurement campaign took place from 13.05.2002 to 25.06.2002 in Oklahoma, Kansas and Texas Panhandle. The region was choosen due to existing experimental and operational facilities, strong variability in moisture and active convection. The instruments have been distributed over the area shown in figure 4.6. Three major stations are contributing: the ARM-CART site in Larmont, Oklahoma with in situ measurements and remote sensing instruments, e.g. Atmospheric emitted radiance interferometer (AERI), microwave radiomenter, Raman and Dial Lidars; the NCAR S-band dual polarised (S-POL) radar site in Liberal, Oklahoma Panhandle and the Homestad Profiling site with radar and lidar instruments. Furthermore the NWS stations and airports in the area are contributing their data. In 5 km times 5 km area close to the ARM site 24 GPS receiver are istalled to retrieve the 3-D structure on a 15 min intervall. Additionally 15 GPS receiver belonging to the SuomiNet are contributing with hourly TPW measurements. Beside the operational radiosonde ascents additional 115 radiosondes were launched. The retrieved data are available on the project webpage.

4.7 Nasa Water Vapour Project (NVAP)

To date the majority of large-scale water vapour climatologies have relied upon analysis of radiosonde data. A number of projects, some of them have been mentioned before, are currently ongoing to better define the global water vapour climatology from both infrared and microwave space-based retrievals. The NASA-sponsored project (NVAP) aims to produce a climatology with a 1° spatial resolution. The NVAP data set spans 12 years (from 1988 - 1999) of satellite retrieved water vapour path and liquid water path from different sensors and retrieval techniques. The products are validated with ground based measurements. The used satellite instrument is SSM/I for the 12 years period. The data set for the land area is derived using TOVS data for non-precipitating clouds and radiosonde data, elsewhere over the oceans TOVS and SSM/I data were used. The LWP over ocean areas is included as a comparison data set for the analysis. The final product is a weighted merging product. The precipitable water content for three layers is retrieved: surface - 700 hPa, 700 - 500 hPa, and 500 - 300 hPa. Temporal and spatial interpolations are used to fill in missing data points (Randel et al., 1996). With the new satellite generations an advanced merging was performed resulting in a new data set covering the years 2000-2001. This is called NVAP–NG, which includes AMSU, ATOVS, MSU, TOVS, SSM/T2, SSM/I and TMIl. No radisonde ascents are included. The water vapour products of the new data set covering two years is available twice daily, 0.5 degree spatial resolution and 5 vertical

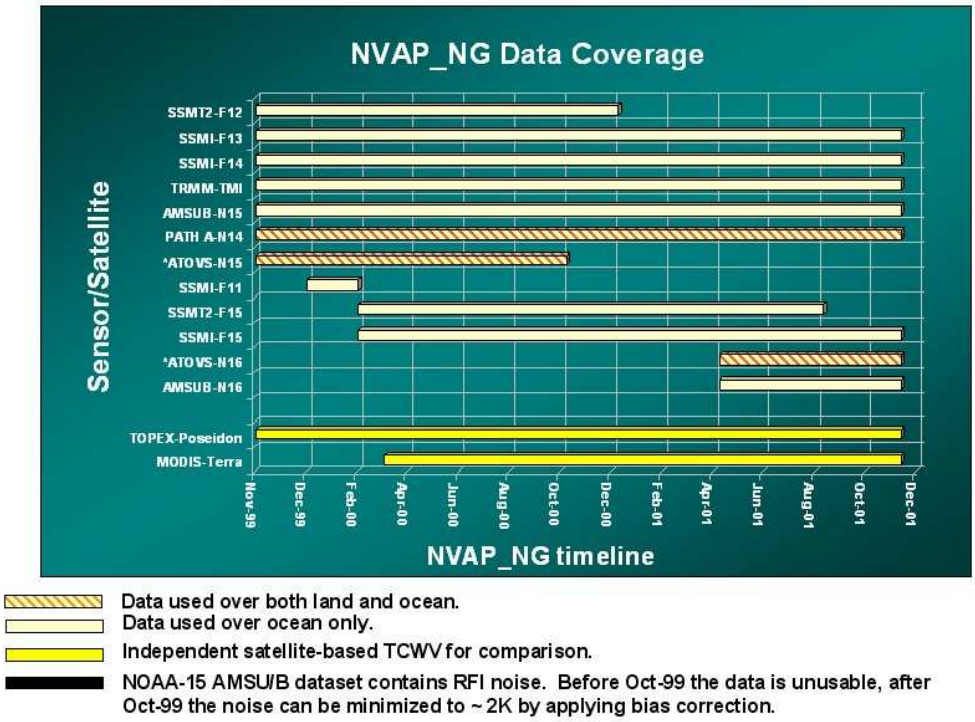

Figure 4.7: *Compilation of used satellite instruments for the generation of the new NVAP water vapour climatology.*

layers. A compilation of satellite instruments used in the water vapour retrieval is given in figure 4.7.

4.8 Observational Stations

Beside the intensive field campaigns described before, a number of operational sites are providing continiuous measurements. All stations are equiped with active and passive microwave radiometer, IR-radiometer, GPS receiver and standard meteorological instruments.

The Meterological Observatory Lindenberg, MOL, offers continous time series of water vapour from different instruments e.g. microwave radiometer and GPS and liquid water path from microwave measurements. Radiosonde ascents are available as well. More information is available on the web.

The observational field of KNMI located in Cabauw, Netherlands, offers various cloud and water vapour related measurements as well. The Cabauw site is participating in various

intensive field campaigns, e.g. cloudnet, CLIWA-NET, CLARA, and BBC2. The centre of the site is the meteorological tower, providing many observations in diferent levels to characterise the boundary layer.

The Atmospheric Radiation Measurement (ARM) Project is founded by the U.S. Department of Energy (DOE). The aim of this project is to help resolve scientific uncertainties related to global climate change, with a specific focus on the crucial role of clouds and their influence on radiative feedback processes in the atmosphere. Therefore the treatment of cloud and radiation physics in global climate models is investigated and improvements in the climate simulation capabilities of these models are gained. The measurement sites are located in the major climatological regions as shown in figure 4.8. Different intensive field campaigns are performed at the sites embedded in continiuous measurements. The data are freely available through the ARM web page.

Figure 4.8: *Location of the different ARM sites. (http://www.arm.gov/sites/)*

Project	time	area	instrumentation	quantities
GVAP		Global		tropospheric and stratospheric water vapour
CLIWA-NET	08/09 2000, 04/05 2001, 08/09 2001	Europe	ground, sat., air borne	LWP, TPW, cloud parameter
4D-Clouds	08/09 2001, 05/2003	Netherlands	ground, sat., air borne	LWP, TPW, cloud parameter
VAPIC	2004	France	ground, sat.	TPW and water vapour profiles, instrument uncertainties
CLOUDNET	2001 - 2003	Europe	ground, sat.	TPW, LWP, IWP, cloud parameter
CLOUDMAP2			sat.	TPW, LWP, cloud parameter
IHOP2	05/06 2002	USA, Southern Great Plains	ground, sat., air borne	TPW 4D, convection
NVAP	1988-2002	Global	ground, sat.	TPW, LWP, Humidity Profile

Table 4.6: Compilation of all described campaigns.

Chapter 5

Conclusions

The development of a complete and accurate global water vapour data set is critical to an adequate understanding of the Earth's climate system. This data is essential for studies concerning the energy and water cycle including poleward energy transports, radiation budget studies, general circulation model verification and global change research. The demands on the water vapour climatology are increasing in terms of spatial and temporal resolution. The first climatologies were based on radiosonde measurements. Radiosonde measurement take place primary over land at distant points and do not show small scale water vapour variations. An additional problem is the underestimation of humidity in cold temperatures, like in the upper troposphere. The use of satellite instruments enables measurements over the oceans. Different methods based on different spectral channels are in use. IR and VIS techniques offer measurements with a sufficient spatial resolution but work only in absence of significant cloud cover. Microwave measurements are able to access water vapour in clouds but these methods are limited to ocean areas. Some effort is made in enlarging the microwave techniques to land surfaces. Here surface models and measurements of the surface emission in clear sky situations on climatological scales are used to derive the water vapour path over land as well. A global data set using various instruments and techniques merged on a spatial resolution of 1° and dayly means is now available for a time span of 12 years provided by the NVAP. This climatology is based on polar orbiting satellites. With the SEVIRI instrument on the new Meteosat satellite water vapour can be derived every 15 minutes with infrared techniques. The high temporal and spatial resolution of this instrument will benefit greatly in estimating the variability in water vapour destributions. It is crucial for climatologies to define the difference in TPW between a clear sky and cloudy scene. The question arises weather it is possible to quantify this difference depending on other variables like surface pressure, 500 hPa height or surface temperature or the time of year. With this knowledge missing data points in the infrared retrieval can be filled.

The ongoing study will focus on the characterisation of water vapour in cloudy scenes. Therefore available data gained during various intensive field campaigns are used. The retrieved difference of clear sky and cloudy sky water vapour is depending on the qual-

ity of cloud occurence informations. During the previously described campaigns cloud detection using several instruments have been achieved. Furthermore, aircraft measurements provide in situ informations from the clouds, cloud boundaries and clear skies. Many projects aim to validate satellite retrievals, most of these data are available in the internet.

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Appendix A

Available Data

A compilation of data retrieved during the campaigns described in chapter 4. Below the campaigns, their stations with freely available data is listed.

1. CLIWA-NET
CNN 1 took place at 10 stations in Europe during August and September 2000. As products the LWP and the TPW are calculated from microwave radiometer located at the stations. The data format (level 2a or level 2c) gives the quality check status of the retrievals. In one file the different instruments located at the stations are included as well. Due to instrument failure some days per station are missing.

CNN 2 took place at 11 stations in Europe during April and May 2001. The products are LWP and TPW from microwave radiometer. The data is provided in the same formats as CNN1. Due to instrument failure some days per station are missing. The data files contain the products retrieved using the available instruments. The quantities are: Liquid Water Path, Integrated Water Vapour, Precipitation from ceilometer, Precipitation flag from IR-shutter, Precipitation flag from MICCY-shutter, Precipitation flag from rain gauge, Radar reflectivity factor from BALTRAD, Precipitation flag from Video, Number of cloud bases from ceilometer, Height of lowest cloud base, Temperature from infrared radiometer, Cloudiness flag from Video, Integrated Water Vapour (GPS).The level 2a and level 2c data are writen in ascii.

BBC took place at 5 stations in Europe during August and September 2001. The products are LWP and TPW from microwave radiometer. The data is provided in the same formats as CNN1. Due to instrument failure some days per station are missing.

2. 4D-Clouds

BBC2 took place at the station Cabauw in the central Netherlands during May 2003. Additional radiosondes are available provided by the station De Bilt. The stations are

differnently equiped. For the station Cabauw, radiosonde profiles are processed by the dutch army and IMAU; the data is in ascii format. The GPS retrieval scheme is described in Klein Baltink et al. (2002); the data is in ascii format. Water vapour path and liquid water path derived by microwave instruments (MICCI the microwave radiometer operated by the University Bonn and the radiometer developed during CLIWA–NET called HATPRO) are available in the CLIWA–NET level 2c format. The RASS instrument was operated by the KNMI. The available data is in ascii. Finally the synoptical files are in the NASA Ames format. For the station De Bilt radiosonde ascents are available. The files are in ascii and contain pressure, geopotential height (m), temperature (C), dew point temperature (C), relative humidity (%), wind speed (m/s), and wind direction (degrees).

3. GVaP

The intensive periode took place from October 2002 until March 2003. Radiosonde ascents and synoptical informations for Cabauw are available. For Lindenberg the synoptical informations are only provided on the webpage.

4. IHOP

Different GPS instruments are used in this project. The GPS data files are in the netcdf format, containing water vapour, wet delay, and variables used for the algorithms like the atmospheric temperature. These measurements took place from 13.5.2002 to 24.06.2002. For all stations the meteorological surface parameters like temperature, humidity, pressure, and wind are available in an ascii format.

Campaign	Station	Time	Quantity
CNN1	Bern, Chilbolton,Geesthacht, Helsinki, Kiruna, Lindenberg, Onsala, Paris, Petersburg, Potsdam	08/09 2000	LWP, TPW
CNN2	Bern, Cabauw, Chilbolton, Gotland, Helsinki, Kiruna, Lindenberg, Onsala, Paris, Petersburg, Potsdam	04/05 2001	LWP, TPW
BBC	Cabauw, Deelen, Eindhoven, Gilzer Rijen, Vokel	08/09 2001	LWP, TPW

5. Radiosonde data
On the way from pol to pol the german research vessel 'Polarstern' carries out radiosonde ascents. For every ascent synoptical infomations are disposable. The dataset starts in 1987 and is available until now. A detailed description on the data is given in König-Langlo and Marx (1997). Other ship based radiosonde ascents are present from the german research vessel 'Meteor' and the trade ship 'Hornbay' for the years 1999 to 2001. Radiosonde ascents carried out at coastal stations and oil plattforms are present for the years 1991 - 2000. No synoptical data are available for these ascents.

6. Reanalysis data

- NCEP NCAR: The data is provided on 19 vertical levels. The atmospheric parameters can be determined via the web–page.
- ECMWF ERA–40 data is available for the time periode 01.09.1957 - 31.08.2002 on 60 vertical layers via the CERA database.

7. Satellite data
Data retrieved by NOAA–satellites is provided by the SAA–database (http://www.class.ncdc.noaa.gov/). ATOVS data is delivered in the level1b format, which contains navigated but not calibrated data. Calibration coefficients are contained in the data set. Satellite measurements during specific campaigns are available via the project pages.

Appendix B

Abbreviations and Acronyms

AMSU	Advanced Microwave Sounding Unit
ARM	Atmospheric Radiation Measurement Program
ATOVS	Advanced TIROS Operational Sounder
ATSR	Along Track Scanning Radiometer
BALTEX	Baltic Sea Experiment
BBC	BALTEX BRIDGE campaign
CAMP	CEOP Asia-Australia monsoon project
CATCH	Coupling Tropical Atmosphere and Hydrologic Cycle
CEOP	Coordinated Enhanced Opservational Periods
CEPEX	Central Equatorial Pacific Experiment
CHAMP	Challenging Minisatellite Payload
CLIWA NET	BALTEX Cloud Liquid Water Network
CLW	Cloud Liquid Water
CNN	CLIWA–NET NETWORK
CRYSTAL	Cirrus Regional Study of Tropical Anvils and Cirrus Layers
DMSP	Defens Meteorological Satellite Program
DOE	Department of Energy
ECMWF	European Centre of Medium Range Weather Forecasts
ENVISAT	Environmental Satellite
EOS	Earth Observation System
FACE	Florida Area Cirrus Experiment
FATE	
GAPP	GEWEX Americas Prediction Project
GARP	Global Atmospheric Research Program
GENLN2	
GEWEX	Global Energy and Water Cycle Experiment
GHz	Giga Hertz
GKSS	Gesellschaft für Kernforschung in Schiffbau und Schifffahrt
GOES	Geostationary Operational Environmental Satellite
GOME	Golobal Ozone Monitoring Experiment

GPS	Global Positioning System
GVAP	Global water Vapor Project
HIRS	High-resolution Infrared Radiation Sounder
HITRAN	High Resolution Transmission Molecular Absorption Database
IASI	Infrared Atmospheric Sounding Interferometer
IHOP	International H_2O Project
IWP	Ice Water Path
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LBA	The Large Scale Biosphere-Atmosphere Experiment
LIDAR	Light Detection adn Ranging
LWP	Liquid Water Path
MAGS	Mackenzie GEWEX Study
MARSS	Microwave Airborne Radiometer Scanning System
MASTEX	Mediterranean Aircraft and Ship Transmission Experiment
MERIS	Medium Resolution Imaging Spectrometer
METEOSAT	Meteorological Satellite
MHS	Microwave Humidity Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MOL	Meteorological Observatory Lindenberg
MOTH	Measurements of Tropospheric Humidity
MSG	Meteosat Second Generation
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Agency, USA
NCAR	National Center for Atmospheric Research, USA
NCEP	National Centers for Environmental Prediction, USA
NESDIS	National Environmental Satellite, Data and Information Services
NOAA	National Oceanic and Atmospheric Administration, USA
NVAP	NASA Water Vapor Project
OACS	Optical Absorption Coefficient Spectroscopy
OLR	Outgoing Longwave Radiation
POES	Polar-Orbiting Operational Enviromental Satellites
SAA	Satellite Active Archive
SAMEX	Storm and Mesoscale Ensemble Experiment
SCAMS	Scanning Microwave Spectrometer
SCIAMACHY	Scanning Imaging Absorption SpectroMeter for Atmospheric Chartography
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SHEBA	Surface Heat Budget of the Arctic Ocean Project
SIRTA	Le Site Instrumental de Recherche par Tldtection Atmosphrique
SMHI	Sveriges Meteorologiska och Hydrologiska Institut
SMMR	Scanning Multichannel Microwave Radiation
SSM/I	Special Sensor Microwave/Imager
SSM/T–2	Special Sensor Microwave/Temperature
TIROS	Television Infra-Red Observation Satellite
TMI	TRMM Microwave Imager
TOVS	TIROS Operational Vertical Sounder

TPW	Total Precipitable Water
TRMM	Tropical Rainfall Measurement Mission
VAPIC	Water Vapour Profiling Inter–Comparison campaign
WVP	Water Vapour Path