

Article

Cloud Fraction of Liquid Water Clouds above Switzerland over the Last 12 Years

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Abstract: Cloud fraction (CF) plays a crucial role in the Earth's radiative energy budget and thus in the climate. Reliable long-term measurements of CF are rare. The ground-based TROpospheric Water Radiometer (TROWARA) at Bern, Switzerland continuously measures integrated liquid water and infrared brightness temperature with a time resolution of 6–11 s since 2004. The view direction of TROWARA is constant (zenith angle 50°), and all radiometer channels see the same volume of the atmosphere. TROWARA is sensitive to liquid water clouds while the microwave signal of ice clouds is negligible. By means of the measurement data we derived CF of thin liquid water clouds (1); thick supercooled liquid water clouds (2); thick warm liquid water clouds (3) and all liquid water clouds (4). The article presents the time series and seasonal climatologies of these four classes of CF. CF of thick supercooled liquid water clouds is larger than 15% from November to March. A significant negative trend of $-0.29\% \pm 0.10\%/yr$ is found for CF of thin liquid water clouds. No trends are found for the other classes (2, 3, 4) since their strong natural variability impedes a significant trend. However, CF of warm liquid water clouds increased by about $+0.51\% \pm 0.27\%/yr$ from 2004 to 2015. Finally, we performed a Mann-Kendall analysis of seasonal trends which gave several significant trends in the classes 1, 2 and 3.

Keywords: cloud fraction; ground-based microwave radiometry; integrated liquid water; long-term monitoring; trend analysis; climatology; liquid water cloud; supercooled liquid water cloud

1. Introduction

Climate models use the parameter cloud fraction (CF) to determine the radiative fluxes through the atmosphere and at the surface. A small increase of 4% in the area of low level stratus clouds would be sufficient to offset the 2–3 K predicted rise in global mean temperature due to a doubling of the atmospheric CO₂ concentration [1]. Arrays of ground based sensors located in diverse climate regimes have been used for more than 20 years by the Atmospheric Radiation Monitoring (ARM) Program to study the impact of clouds on the radiation budget (<https://www.arm.gov/about/history>) [2]. Climatologies of CF are considered for the choice of suitable sites for solar power plants [3]. Further, supercooled liquid water clouds are a serious hazard for aviation [4]. For all these reasons, long-term monitoring of CF of liquid water clouds is required. An intercomparison of different measurement techniques for thin liquid water clouds and radiative fluxes was given by [5]. They emphasized that large differences in retrievals of liquid water amount and droplet size still must be resolved.

Ground-based microwave radiometers have the advantage that they continuously monitor the integrated liquid water (ILW) along a line of sight throughout the cloud under all weather conditions during day- and nighttime [6,7]. The measurement noise of integrated liquid water can be as small as $0.77 \mu\text{m}$ (or 0.77 g/m^2) as determined by [7] for the TROWARA radiometer at Bern, Switzerland. Contrary to [7], the present study utilizes the infrared brightness temperature of the $\lambda = 9.5 - 11.5 \mu\text{m}$ channel of TROWARA in addition to the microwave channels for the data interpretation. This enhanced measurement information permits us to separate for thick supercooled liquid water clouds and thick warm liquid water clouds. In addition, the small measurement error of TROWARA supports the reliable detection of thin liquid water clouds with ILW between 0.0023 and 0.03 mm.

In the following, we give a brief overview of past studies on the climatology and trends of CF of liquid water clouds. A 10-year cloud fraction climatology was derived from TROWARA data from 2004 to 2014 [6]. The CF values varied from 40% during summer to 60% during winter [7]. The authors of [6] found that the regional analysis of the Weather Research and Forecasting (WRF) model underestimates the regional cloud fraction at Bern (17% for WRF and 40% for TROWARA in summer 2012 at Bern). The High Resolution Infrared Radiometer Sounder (HIRS) onboard the NOAA satellites observed a quite constant cloud cover over an interval of 22 years with a cloud fraction of 75% [8]. However, cloud fraction of high clouds in the upper troposphere showed a significant trend of $+0.2\%/yr$. Cloud fraction from the Terra and Aqua Moderate Resolution Imaging Spectroradiometers (MODIS) showed a nice agreement with ground-based cloud fraction observations at several Swiss stations from 2000 to 2012 [9]. The mean cloud fraction of MODIS was between 59% and 65% at the Swiss sites. The bias of MODIS with respect to the ground-based observations of CF was between -2.5% and $+5\%$.

Data from the International Satellite Cloud Climatology Project (ISCCP) showed negative trends in CF ($-0.3\%/yr$) during dry season and positive trends ($0.1\%/yr$) during wet season in Amazonia over a time interval of two decades [10]. Based on ISCCP data from 60°S to 60°N , it was found that CF of upper level clouds over land decreased by 1.5% from 1971 to 1996 [11]. In [12], the authors compared cloud parameters from 12 different satellite data sets. The global mean of CF ranged between 55% and 73%. The last IPCC report (Intergovernmental Panel on Climate Change) concluded that substantial ambiguity and therefore low confidence remains in the surface-based and satellite-based observations of global-scale cloud variability and trends [13]. The ambiguities can be caused by different spatio-temporal sampling, changes in the aspect angles and other reasons. In the following, we show that ground-based microwave radiometry is a stable and objective method for long-term monitoring of CF.

2. Instrument, Measurement Technique and Data Analysis

The study is based on the measurements of the TROPospheric WAter RAdiometer (TROWARA). TROWARA is a dual-channel microwave radiometer built by [14]. It provides vertically-integrated water vapour (IWV) and vertically-integrated cloud liquid water (ILW), also known as liquid water path (LWP). TROWARA is located inside a temperature-controlled room on the roof of the EXWI building of the University of Bern (46.95°N , 7.44°E , 575 m a.s.l.). Since TROWARA is operated indoors, it is capable to measure IWV even during rainy periods.

The two microwave channels are at 21.4 GHz (bandwidth 100 MHz) and 31.5 GHz (bandwidth 200 MHz). The lower frequency is more sensitive to microwaves from water vapour, and the higher frequency is more sensitive to microwaves from atmospheric liquid water.

The radiative transfer equation of a plane-parallel atmosphere is

$$T_{B,i} = T_c e^{-\tau_i} + T_{mean,i} (1 - e^{-\tau_i}), \quad (1)$$

where $T_{B,i}$ the observed brightness temperature of the i -th frequency channel is (e.g., 21 GHz). τ_i is the opacity along the line of sight of the radiometer, and T_c is the contribution of the cosmic microwave background. $T_{mean,i}$ is the effective mean temperature of the troposphere [15,16].

From Equation (1) we can derive the opacities

$$\tau_i = -\ln \left(\frac{T_{B,i} - T_{mean,i}}{T_c - T_{mean,i}} \right) \quad (2)$$

where the radiances $T_{B,i}$ are measured by TROWARA.

The opacity is closely related to IWV and ILW by a quasi-linear relationship

$$\tau_i = a_i'' + b_i'' IWV + c_i'' ILW, \quad (3)$$

where the coefficients a'' and b'' are not really constant since they can partly depend on the air pressure which is the case at 31 GHz. The authors of [16] show that these coefficients can be statistically derived by means of coincident measurements of radiosondes. c'' is the mass absorption coefficient of cloud water. It depends on temperature (and frequency), but not on pressure. It is derived from the physical expression of Rayleigh absorption by clouds [16]. Once the coefficients are determined, combined opacity measurements at 21 and 31 GHz permit the retrieval of IWV and ILW from Equation (3). Thus, a dual channel microwave radiometer can monitor IWV and ILW with a time resolution of 6–11 s and nearly all-weather capability during day and nighttime.

An infrared radiometer channel is operated at $\lambda = 9.5 - 11.5 \mu\text{m}$, which measures the physical temperature at the cloud base when the cloud is optically thick ($ILW > 0.03 \text{ mm}$). TROWARA's antenna coil has a full width at half power of 4° and is pointing towards the sky at a zenith angle of 50° towards south-east. All the time, the view direction is constant, and the microwave and infrared channels of TROWARA observe the short-term temporal variations of the brightness temperature in the same volume of the atmosphere. This contributes to the high sensitivity of TROWARA for cloud detection. Further details of the measurement instrument and retrieval technique are given in [7,16].

TROWARA has been operated since 1994, and it has delivered an almost uninterrupted time series of ILW since 2004, with a time resolution of 11 s until end of 2009 and 6 s afterwards. The cloud detection in the line of sight of TROWARA is performed with the same time resolution, and the criterion is that $ILW > 3\sigma_{noise} = 0.0023 \text{ mm}$. The authors of [7] determined the instrumental noise $\sigma_{noise} = 0.00077 \text{ mm}$ of TROWARA from the noise of ILW during 245 days in which the sky was free of clouds. If a ILW value exceeds the $3\sigma_{noise}$ level, then we are confident by 99.7% that the ILW value was generated by a cloud and not by instrumental noise. We emphasize that this is a remarkable sensitivity for a microwave radiometer since 0.0023 mm corresponds to the small mass of 2.3 gram water per square meter. Contrary to the ILW series, the time series of IWV have been used since 1994 for trend analyses, as has been shown by [17,18]. So far, a trend analysis has not been performed for the TROWARA ILW and CF data. CF (cloud fraction) can be easily determined in the time domain, for example, CF is the quotient of the time intervals when $ILW > 0.0023 \text{ mm}$ and the total observation time. The time intervals are as small as 6 s for ILW data after 2009 and 11 s for ILW data before 2009. Thus, we set the cloud flag with a high temporal resolution (6 or 11 s) which is required because of the high spatio-temporal variability of clouds floating through the fixed line-of-sight of TROWARA. Further, TROWARA's coincident ILW and infrared brightness temperature measurements permit to separate the liquid water clouds in four classes:

1. thin liquid water clouds ($0.0023 \text{ mm} < ILW < 0.03 \text{ mm}$),
2. thick supercooled liquid water clouds ($ILW > 0.03 \text{ mm}$ and $T_{infrared} < 273.15 \text{ K}$),
3. thick warm liquid water clouds ($ILW > 0.03 \text{ mm}$ and $T_{infrared} > 273.15 \text{ K}$),
4. all liquid water clouds ($ILW > 0.0023 \text{ mm}$).

Quite similar criteria for the separation of supercooled liquid water clouds were described in the Section 3.2.2 Radiometer method of [19]. The critical point is that the derived cloud distributions are

possibly biased towards the low level clouds since the infrared channel mainly sees the cloud base of thick clouds. The authors of [20] avoided this bias by using additional satellite data for the cloud-top temperature.

Thin liquid water clouds were in the focus of the study by [21]. They derived the microphysical and optical properties of thin liquid water clouds and emphasized that these clouds should be considered in climate studies since these clouds are frequent and they change the radiative forcing of the climate system. Measurements indicated that the downwelling infrared radiance of a thin liquid water cloud is increased by about 60% compared to clear sky. The authors of [21] reported that thin liquid water cloud areas are often located at the edges of and in the inter-region between clouds (*twilight zone of clouds*).

Since TROWARA is not sensitive to ice clouds, CF of TROWARA is in general smaller compared to synoptic observations. In [7], the authors found a CF difference of about 17% between TROWARA and synoptic observations in the same region over a period of 6 years. In addition, some of the very thin and tenuous clouds which are still visible by eye might be not seen by TROWARA. However, CF of different classes of liquid water clouds is a new data product and of high value for evaluation of weather and climate models. The trend analysis is based on the determination of the trend and its uncertainty by means of linear regression. The differences of the CF trend and uncertainty values with respect to the alternative bootstrap method [18] are less than 0.01%/yr in the present study and negligible.

The present study is not a cloud type study which would require the evaluation of coincident observations by ceilometer, lidar, radiosonde and hemispherical sky camera. In our study, the terms *thin* and *thick* refer to the magnitude of the optical depth at microwave frequencies which is proportional to the liquid-water path. The terms should not be misunderstood by the geometrical thickness of the clouds which is not measured by the microwave radiometer. A statistical cloud type study was performed by [22] for Payerne. Payerne is representative for Bern since Payerne is located just 40 km eastward of Bern in the Swiss plateau. In [22], the authors found that the cloud type low-level stratocumulus (Sc) is most common at Payerne. About 70% of the classified clouds have the type Sc while about 15% are stratus-altostratus (St-As). The authors of [22] also found that the relationship between the ILW value and the cloud type is ambiguous. There is only a tendency that a small ILW value is most likely connected to the occurrence of stratocumulus.

3. Results and Discussion

3.1. Time Series and Trends of Cloud Fraction

Figure 1 shows the time series of CF of the four classes of liquid water clouds. The yearly mean values are given by the stars. The 12-yr mean of the yearly CF values of class 1 (thin liquid water clouds) is $15.4\% \pm 1.6\%$ where the latter denotes the standard deviation. The 12-yr mean of the CF of class 2 (thick supercooled liquid water clouds) is $13.1\% \pm 2.3\%$. The 12-yr mean of the CF of class 3 (thick warm liquid water clouds) is $21.0\% \pm 3.5\%$. The 12-yr mean of the CF of class 4 (all liquid water clouds) is $49.5\% \pm 2.9\%$.

Using the linear regression method, we can derive the trends and their uncertainties from the series of the monthly mean values. These values are listed in Table 1. We use the definition that a trend is only present when the inclination of the straight line is two times larger than the uncertainty.

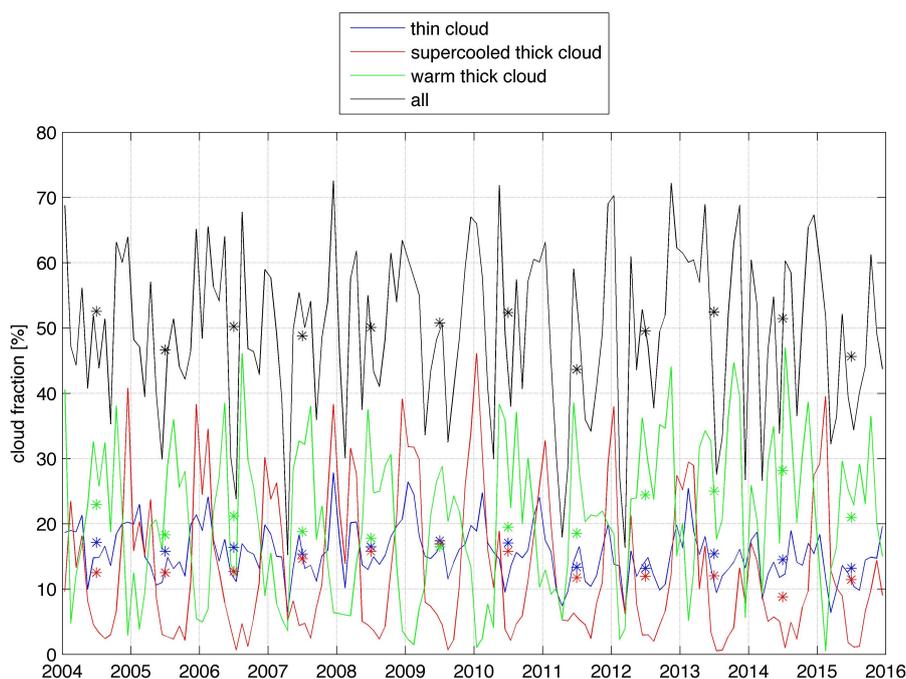


Figure 1. Monthly values of cloud fraction are shown by the coloured lines for the four classes of liquid water clouds. The stars denote the yearly means of cloud fraction.

Table 1. Trends and their uncertainties for the monthly cloud fraction (CF) series from 2004 to 2015 and the four classes of liquid water clouds.

Class	Inclination (%/yr)	Uncertainty (%/yr)	Trend?
1	−0.29	0.10	yes
2	−0.28	0.27	no
3	+0.51	0.27	no
4	−0.07	0.30	no

We can see in Table 1 that the CF trends of various classes partly cancel each other so that the CF inclination of class 4 (all liquid water clouds) is most flat compared to the other classes. A significant trend ($-0.29\% \pm 0.10\%/yr$) is only obtained for class 1, the thin liquid water clouds. The negative trend would mean a decrease in the downwelling infrared radiance [21]. However, the class of warm, thick clouds reaches the strongest inclination with $+0.51\%/yr$. We suggest that this increase of CF for warm, thick clouds is related with a warming trend in the lower troposphere above Bern. Figure 2 shows the linear trend of the annual means of the air temperature at 1.5 km altitude above Bern. We selected the operational reanalysis data of temperature at the grid point close to Bern from the European Centre for Medium-range Weather Forecast (ECMWF), and we found a significant positive trend of 0.15 ± 0.07 K/yr for the time interval 2004 to 2015. This rather strong temperature trend is reduced by a factor of 3 if the time interval is taken for 1994 to 2015.

In addition, we performed a trend analysis of integrated water vapour (IWV) as measured by TROWARA in the same time interval 2004 to 2015. The annual means of IWV show a significant trend of 0.15 ± 0.04 mm/yr (or kg/m²/yr) in Figure 3. In summary, we can state that during the time from 2004 to 2015 the air temperature increased in the lower troposphere above Bern as well as IWV. Coincidentally, the CF of warm, thick clouds increased. One possibility is that the transport of warm, humid air from the subtropics to Bern increased during the last decade causing increases of CF of warm, thick clouds and of the air temperature at 1.5 km altitude above Bern as well as an increase of

IWV. Such a change in the transport of warm, humid air may also explain the observed reduction in CF of thin liquid water clouds which may be favoured by cold, dry air masses.

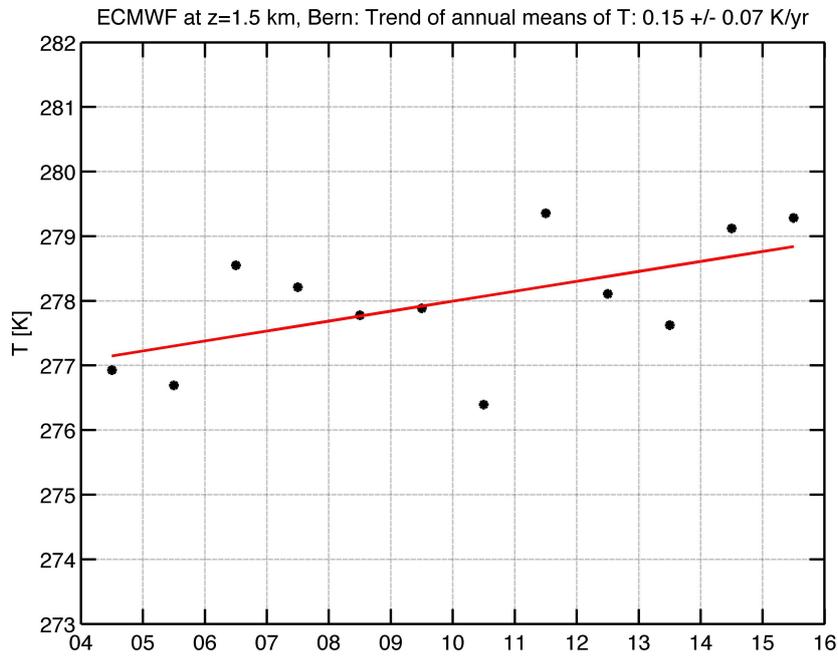


Figure 2. Linear trend of annual means (black stars) of air temperature at 1.5 km altitude above Bern from 2004 to 2015. European Centre for Medium-range Weather Forecast (ECMWF) reanalysis data were used at the grid point nearest to Bern.

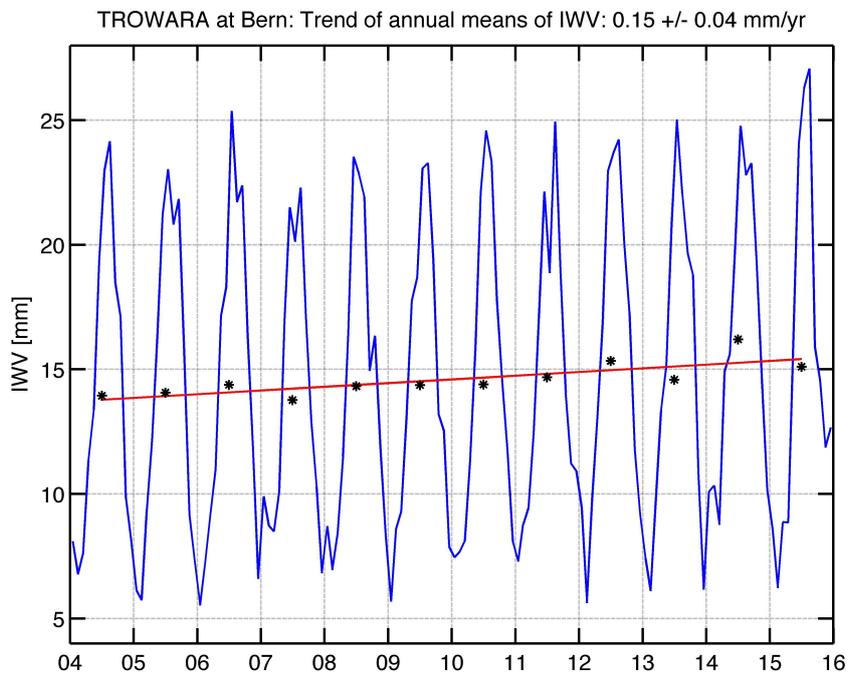


Figure 3. Linear trend of annual means (black dots) of integrated water vapour (IWV) above Bern from 2004 to 2015 as measured by the TROpospheric WATER Radiometer (TROWARA).

3.2. Climatologies of Cloud Fraction and Seasonal Trends

Figure 4 shows the climatologies of the four cloud classes. CF of thick supercooled liquid water is larger than 15% from November to March. CF of the thick warm liquid water clouds is close to 30% from May to October. CF of thin liquid water clouds shows slightly larger values during winter compared to summer. Class 4 (all liquid water clouds) has CF values up to 60% in December and January and about 45% during summer.

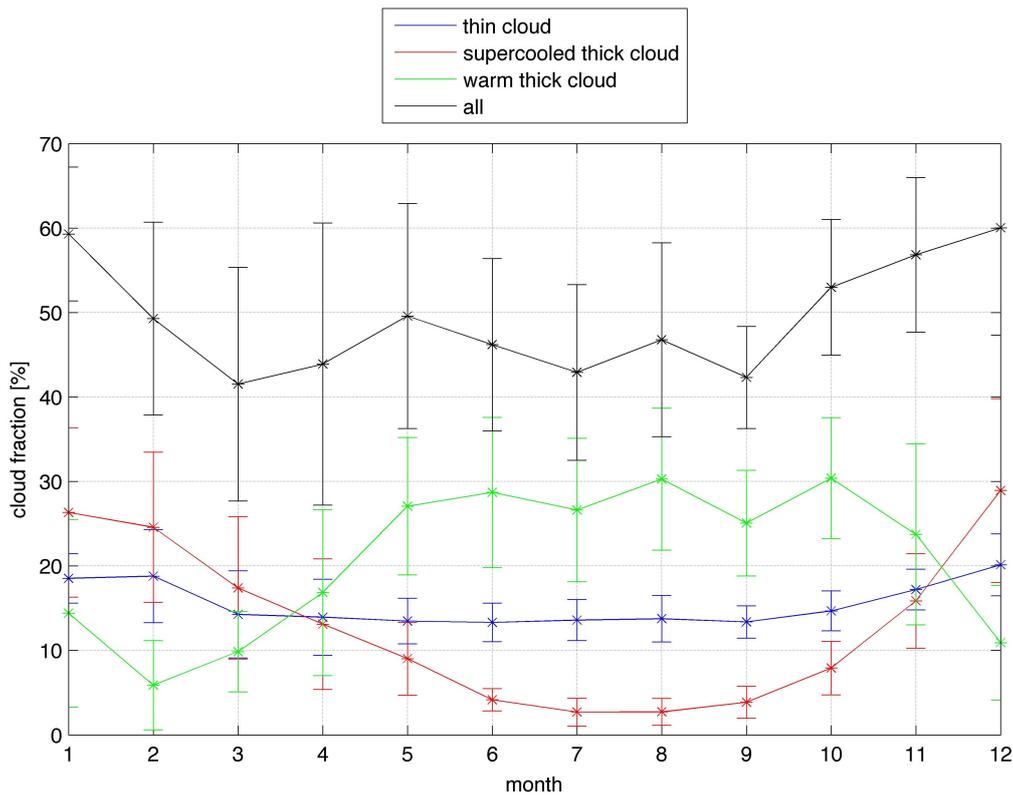


Figure 4. Climatologies of CF of the four classes of liquid water clouds. The error bars denote the standard deviation of the 12-yr means.

Finally, it is interesting to perform a Mann-Kendall trend analysis [23] which may reveal possible seasonal trends in CF. Figure 5 is a nice supplement to Table 1 since one can see in which month the CF trends are strongest. We find that CF of thin liquid water clouds mainly decreased in the month of March where a significant negative trend occurs: $-0.91\% \pm 0.35\%/yr$. Further, CF of thick supercooled liquid water clouds has a significant negative trend of $-2.43\% \pm 0.56\%/yr$ in December. CF of warm liquid water clouds has significant positive trends in November and December, $+1.81\% \pm 0.75\%/yr$ and $+1.30\% \pm 0.43\%/yr$, respectively. Class 4 (all liquid water clouds) shows no significant trends at all.

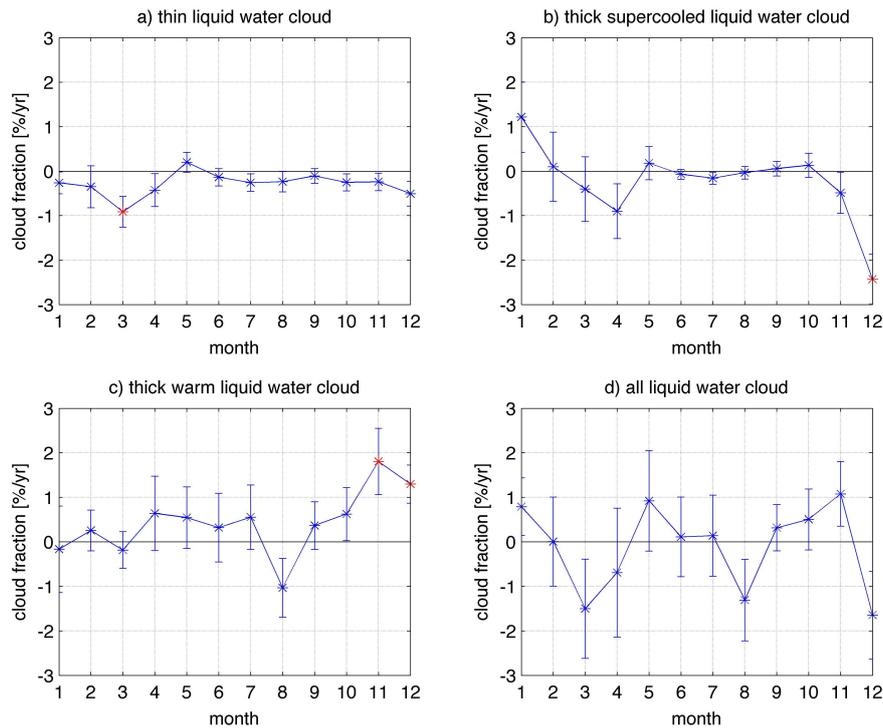


Figure 5. Seasonal trends of CF of the four classes of liquid water clouds. The red stars denote the 4 significant trends which we found for trends larger than two times their uncertainties.

4. Conclusions

The study showed that the ground-based microwave radiometer TROWARA performed an objective, stable and automatic long-term monitoring of cloud fraction above Bern which is representative for the Swiss plateau. The authors of [6] already showed that the atmospheric water parameters observed by TROWARA can be easily compared to similar parameters simulated by the WRF model. Thus, the CF values and CF trends of liquid water clouds obtained by TROWARA are of a high value for testing of cloud parameterisations in weather and climate models. In the present study, a significant trend was not found for the class of all liquid water clouds. We found that thick, warm liquid water clouds had a significant positive trend in the November and December data from 2004 to 2015. CF of supercooled liquid water clouds significantly decreased in the December series. CF of thin liquid water has a significant negative trend in the yearly means, and this trend is mainly due to the March data. The increase of warm, thick clouds could be related to an increase of air temperature at 1.5 km altitude above Bern from 2004 to 2015 and a coincident increase of integrated water vapour above Bern. The physical reason is an open question, for example, a change in the transport of subtropical, humid and warm air to Bern could be a possibility.

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Author Contributions: Federico Cossu and Christian Mätzler worked on the programs for the refined analysis of IWV and ILW data, Francisco Navas Guzm took care on the TROWARA operation, Klemens Hocke wrote the paper and performed the trend analysis.

Conflicts of Interest: The authors declare no conflict of interest.

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