20 July 2019

Dear Editor and Referees.

Please find our corrections below. We thank both Referees for their thoughtful comments and detailed corrections. It has taken longer than anticipated to correct our paper, but the effort has definitely been worthwhile. We therefore hope that we have answered the questions as best as possible and that the latest version meets with the Referees approval.

During the revision, we came across an interesting review paper by Pepin et al. (2015), published in Nature Climate Change. Two small paragraphs have been added to the new paper on page 7 line 21 and page 9 line 41.

Pepin, N., Bradley, R. S., Diaz, H. F., Baraër, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X. D. and Miller, J. R.: Elevation-dependent warming in mountain regions of the world, Nature Climate Change, 5, 424, doi: 10.1038/nclimate2563, 2015.

Best Regards
Stephan Nyeki

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Referee 1: Comments

Major comments:

The attention the authors give to the details and quality of the radiometric measurements is unusual and much appreciated. The use of multiple techniques to evaluate continuity of the measurement time series and the significance of results is also laudable.

Answer: Thank you.

Minor comments:

Referee comment: p. 1, line 12. Technically, you can't measure "radiation," only some property of radiation, such as intensity or wavelength. I believe that in this case irradiance (or "flux") is meant.

Answer: Rather than change the whole manuscript, and in keeping with terminology in our field, we would prefer to use the term “radiation” as well as flux when referring to shortwave and longwave radiation/flux.

Referee comment: p. 1, line 16. Insert “surface”.

Answer: Inserted

Referee comment: p. 1, line 33. Over what period?

Answer: The sentence has been updated to: “DLR has also been observed to increase during the 1973 – 2008 period (Wang and Liang, 2009) and since the 1990s (Wild, 2016b), although …”.

Referee comment: p. 1, line 30. You just said that the record began in the late 1980s...?

Answer: The sentence has been updated to: “DSR, from earlier less reliable measurements, over Europe …”.

Referee comment: p. 1, line 39. Insert “longwave”.

Answer: Inserted.

Referee comment: p. 1, line 39. Change “which” to “that”.

Answer: As a native British English speaker, I would argue that “which” is ok. As our ACP paper will undoubtedly be language-corrected before publication, may we recommend that ACP decide?

Referee comment: p. 2, line 3. I think you mean that the CRE decreased, not the trend.

Answer: the text has been changed and the citation year corrected.

“CRE decreased at the same four Swiss stations by up to 7.5 W m^{-2} for the 1996 – 2010 period (Wacker et al., 2013), … “.

Referee comment: p. 2, line 9. Include the word “total”.

Answer: Inserted.

Referee comment: p. 2, line 13. Please add a citation where the guidelines can be found.

Answer: The original sentence was: “Measurements were conducted according to BSRN guidelines”.

This has been slightly changed and corrected to:

“Measurements were conducted according to BSRN guidelines, detailed in a later report by McArthur (2005).”

McArthur, B.: Baseline Surface Radiation Network (BSRN), Operations Manual Version 2.1, WCRP 121, WMO/TD-No. 1274, 2005.

Referee comment: p. 2, line 14. Are or were, not "included." This implies that the stations listed are a subset of the four that continued operation.

Answer: The sentence has been changed to: “The remaining stations are …”.

Referee comment: p. 2, line 21. Several comments. We have revised the paragraph to include instrumental details.

New
i) Pyrgeometers in the ASRB network were all unshaded, and hence a correction for solar heating of the instrument was applied using the method described by Dürr (2004). In contrast, it was unnecessary to correct DLR data from the SACRaM network. These were either shaded pyrgeometers (Precision Infrared type, PIR, Eppley Inc., USA) or unshaded pyrgeometers CG(R)4, Kipp & Zonen, Netherlands). As CG(R)4 pyrgeometers are less affected by heating effects or by longwave irradiance in the direct beam of the sun (Meloni et al., 2012; Gröbner et al., 2018), no correction is necessary.

Referee comment: p. 2, paragraph starting "iv": This paragraph is unclear. Does it mean that the measurements from PMOD are wrong and that those from BSRN are right? Which data requires correction?

Answer: Short and longwave reference scales may need to be revised in the future, depending on the decision of various scientific bodies. BSRN short and longwave time series are referenced to these scales, and hence may also need to be revised. Using the terms “right” or “wrong” would not be appropriate here.

We feel that our original text reflects the current situation quite well but have made subtle changes to the paragraph, which is now:

“iv) The PMOD/WRC hosts the World Standard Group (WSG) of pyrheliometers and the WISG, as mentioned above. These provide the reference scales for shortwave and longwave radiation measurements, respectively. However, as a note of interest, several studies have determined that their reference scales may need to be revised in the future (Fehlmann et al., 2012; Gröbner et al., 2014). The WSG scale currently overestimates by +0.3 %, and a linear correction could be applied in a straightforward manner. However, the WISG scale underestimates longwave fluxes, which will require a non-linear correction depending on a number of factors (e.g., raw signal data, etc.), as reported by Gröbner et al. (2014) and Nyeki et al. (2017). The latter study determined that corrections were in the ranges 1 to 4 W m-2 for all-sky DLR and 5 to 7 W m-2 for cloud-free DLR when based on available data from three BSRN stations and Davos (i.e., PMOD/WRC), which have the longest time series. Such corrections are beyond the scope of the present study, and are currently being debated within the community. A possible future correction of the SACRaM DSR time series should have no effect on the trend analyses in this study while corrected DLR time series could marginally affect the trends depending on the degree of cloudiness at each station.”

Referee comment: p. 3, line 1, insert “as”.

Answer: Inserted

Referee comment: p. 3, paragraph starting "v": Are these uncertainties for instantaneous measurements?

Answer: The uncertainties for pyranometers that are cited in Vuilleumier et al. (2014) are for high intensity (1000 W m^{-2}) 1-min averages as defined by BSRN, while for low intensity (50 W m^{-2}), the uncertainties are lower, although not proportionally. The sentence has been changed to:

“The uncertainty of pyranometer measurements is estimated to be in the range 18 – 23 W m^{-2} for 1-min average values (Vuilleumier et al., 2014).”

Referee comment: p. 3, line 1, Why +/- here but not for pyranometers? This is confusing.

Answer: Actually the range is not +/- 4 Wm^{-2} for all-sky DLR and +/- 7 Wm^{-2} for cloud-free DLR but between +1 and +4 Wm^{-2} and +5 and +7 Wm^{-2} for all-sky and cloud-free DLR, respectively. It may also be that you are referring to the pyranometer range in “%” and the pyrgeometer range in “Wm^{-2}”. What can we say except that this is how the community reports these ranges.

However, for clarity, the original sentence has been changed from:

“The latter study determined that corrections lay in the ranges ~1 – 4 W m^{-2} for all-sky DLR and ~5 – 7 W m^{-2} for cloud-free DLR when based on available data from four BSRN stations having the longest time series”.

to:

“The latter study determined that corrections were in the ranges +1 to 4 W m^{-2} for all-sky DLR and +5 to 7 W m^{-2} for cloud-free DLR when based on available data from three BSRN stations and Davos (i.e., PMOD/WRC), which have the longest time series.”

Referee comment: p. 3, line 12: What meteorological data?

Answer: “T_{2m}, RH, and pressure” inserted.

Referee comment: p. 3, line 17: Move “was considered”.

Answer: As a native British English speaker, I would argue that our version is correct. As our ACP paper will undoubtedly be language-corrected before publication, may we recommend that ACP decide?

Referee comment: p. 3, line 19: For both the all-sky and clear-sky data?

Answer: We would argue that this is implicit, and the sentence therefore does not have to be lengthened with more detail.

Referee comment: p. 3, line 20: Was a sampling threshold also applied to the clear-sky data?

Answer: The original sentence was:
“A monthly average was accepted for all-sky conditions if ≥75% of data were available for each month”

This has been changed to:

“A monthly average was accepted for all-sky conditions if ≥75 % of data were available for each month, while no sampling threshold was applied to cloud-free data due to the smaller dataset after application of the cloud filter.”

Referee comment: p. 3, line 22: Add “determination of”.

Answer: Added.

Referee comment: p. 3, line 36: Change “that” to “these” or “their”.

Answer: Sorry, but as a native British English speaker, I would argue that our version is correct. As our ACP paper will undoubtedly be language-corrected before publication, may we recommend that ACP decide.

Referee comment: p. 4, line 3: What is the source of these reference values?

Answer: The original sentence has been changed from:

“After the pre-processing of images (Aebi et al., 2017), a color ratio (the sum of the blue to green ratio plus the blue to red ratio) is calculated per pixel (Wacker et al., 2015) and compared to a reference value (2.2 in Davos and 2.5 in Payerne).”

to:

“After the pre-processing of images (Aebi et al., 2017), a color ratio (the sum of the blue to green ratio plus the blue to red ratio) is calculated per pixel (Wacker et al., 2015) and compared to empirically determined reference values (2.2 in Davos and 2.5 in Payerne), which are based on a large database of sky camera images.”

Referee comment: p. 4, line 5: Change “attributed to” to “categorised as”.

Answer: We consider “attributed to” to be ok, but have changed this to “categorised as”.

Referee comment: p. 4, line 21: Monthly or weekly climatological values?
Referee comment: p. 4, lines 20-21: Could you at least give the general basis for the derivation of AOD values - sun photometer measurements? satellite measurements?

Answer: We would prefer not to add too much extra detail as two references have been cited. However, the sentence has been changed to the following:

“AOD from sun-photometers at each of the four sites was derived using procedures and data published previously (Nyeki et al., 2012; Kazadzis et al., 2018). AOD data (1 min.) was only available for Jan. 1994 – Dec. 2012, which was used to construct an AOD climatology for the Jan. 2013 – Dec. 2015 missing period. While this may introduce an error in the AOD trend, a large change is not expected as the measured time series is 18 years long. “

Referee comment: p. 4, line 30: What is the definition of the "effective atmospheric boundary layer temperature" and how is the value obtained?

Answer: Definition and retrieval of the effective atmospheric boundary layer temperature are described in detail by Gröbner et al. (2009). The following sentence has been added:

“TABL represents the effective radiating temperature of water vapour in the atmospheric boundary layer, and is derived by using two co-located pyrgeometers: one standard pyrgeometer sensitive to the 3 – 50 µm wavelength range and another modified one, which is sensitive in the 8 – 14 µm range.”

Referee comment: p. 4, line 33: It would be helpful to have the final form of the equation (as used) written out here?

Answer: As $T_{2m} = T_{ABL}$, the full equation would be the same as the existing Eq. 3. We would therefore prefer not to add another identical equation. However, we have more clearly stated that $T_{2m} = T_{ABL}$ in the following sentence:

“Setting $T_{2m} = T_{ABL}$, as well as use of the Prata parameterisation was considered by …**”**

Referee comment: p. 5, line 3: Are the values of *a* and *b* the same for all times and locations?

Answer: The preceding sentence to line 3 was:

“A power-law of the following form was found for this DLR-IWV parameterisation when data from all four stations was combined:”

This has been changed to the following in order to answer the referee’s comment:

“A power-law of the following form was found for this DLR-IWV parameterization when data from all four stations and time periods was combined into a single equation:”

Referee comment: p. 5, line 8: I thought Eqn. 4 WAS the method?

Answer: Eq. 4 is an alternative parameterisation used for $DLR_{\text{sim cloud-free}}$. We state this on p.4 line 36 of the original manuscript, and therefore feel that no changes are necessary.

Referee comment: p. 5, line 12: 1998 is before 2011, so how is this a "forerunner"?

Answer: “Forerunner” refers to the forerunner of the present study. To avoid confusion, we have removed the word.

Referee comment: p. 5, line 14: Change to "that"

Answer: As a native British English speaker, I would argue that our version is correct. As our ACP paper will undoubtedly be language-corrected before publication, we would recommend that ACP decide.

Referee comment: p. 5, line 15: It sounds like you mean that the trend is increasing or decreasing over time. Do you really mean a positive or negative trend?

Answer: The text has been changed to “positive or negative trend”.

Referee comment: p. 5, line 16: Shouldn't these procedures have been applied before the trend analysis?

Answer: This was, of course, the case. However, as it may not be clear from the text that this occurred, we have changed the sentence from:

“In order to check the homogeneity of the time series, three statistical tests were applied:”

to

“Before these trend tests were applied, the homogeneity of the time series was checked using three tests”.

Referee comment: p. 5, line 27: They're similar but they're different (following lines)?

Answer: Thank you. The text had not been updated from a previous version. The sentence has now been changed from:

“All-sky values in Table 1, not previously reported, are similar to cloud-free values in Table 2 for the 1996 – 2007 period reported by Wacker et al. (2011).

to:

“All-sky values in Table 1 have not been previously reported while cloud-free values in Table 2 are similar to values reported by Wacker et al. (2011) for the 1996 – 2007 period.”

Referee comment: p. 5, lines 33-34: Isn't there snow or ice at the other locations?

Answer: The original sentence was:

“ii) the IWV retrieval algorithm is unable to adequately correct for the influence of snow and ice on the GNSS antenna signal”.

The sentence now includes the word “persistent”, reflecting the conditions at JFJ.

“ii) the IWV retrieval algorithm is unable to adequately correct for the persistent influence of snow and ice on the GNSS antenna signal.”

Referee comment: p. 5, lines 35-40: I'm not convinced that means of 0.7, 0.68, and 0.67 are significantly different. However, the different seasonal pattern at PAY looks interesting. Can you comment on that?

Answer: We are not sure what is meant by the Referee’s question. The original text does not discuss the above-mentioned average values in the way the Referee states. In particular, we do not state that means of 0.7, 0.68, and 0.67 are significantly different. We indicate that FCC is reduced South of the Alps, and Payerne shows the highest FCC as a result of more persistent stratus cloud cover.

We have changed the sentence as follows:

“The clearest conditions occur at Locarno (lee location, south of the Alps) with an average FCC value = 0.55 while the cloudiest conditions occur at PAY (plateau location, north of the Alps) with FCC = 0.70 as a result of more persistent stratus cloud cover particularly during winter time when low cloud type stratus nebulosus regularly covers the Swiss Plateau.”

Referee comment: p. 6, lines 10-11: Why should the frequency of occurrence of clear-sky conditions affect the average clear-sky DSR value?

Answer: Thank you for highlighting this. The sentence has now been changed to:

“Again, the climatology at each station also has an influence as the cloud-free annual average DSR at LOC (229.3 W m^{-2}) is higher than at PAY (206.8 W m^{-2}) and DAV (216.2 W m^{-2}).”

Referee comment: p. 6, line 17: Add the word ”nevertheless”

Answer: Inserted.

Referee comment: p. 6, line 17: "prior" might be better. "forerunner" makes it sounds like these studies were long ago.

Answer: We feel that “forerunner” is an appropriate term but have changed it to “prior”.

Referee comment: p. 6, line 18 Referee comment: "Also"? This is the first discussion of actual values. I would just start a new paragraph.

Answer: “Also” removed. New paragraph started.

Referee comment: p. 6, line 23: It looks to me like just as many DSR trends are significant at the 90% level as T_{2m} trends (although fewer are significant at the 95% level).

Answer: The sentence was not formulated well. It has now been changed to:

“Trends in all-sky DSR are in the 0.6 – 4.3 W m^{-2}/decade range with a significance at the 90% confidence level except for DAV”.

Referee comment: p. 6, line 26: If it's flat, it's not an increase. Do you mean "slow"?

Answer: We feel that the term “flat increase” is an appropriate term but have changed it to “slow”.

Referee comment: p. 6, line 38 and line 42: Don't you mean discontinuities? You already said there were changes/trends.

Answer: “Discontinuities” has been used instead.

Referee comment: p. 6, line 41: How do these three values relate to the four stations?

Answer: Rather than repeat numerous p-values, the values from all stations have been grouped together, and are discussed as a group with respect to each statistical test. Our original text states: “… from all four stations …”. We feel that this is clear and concise, and it is therefore unnecessary to add more detail.

Referee comment: p. 6, line 41: How can p values of 0.92 and 0.17 both indicate significance?

Answer: The term “significance” is perhaps incorrectly used here, so we have therefore omitted it. Only values $p < 0.05$ are significant which was not observed.

The sentenced has been moved and changed to:

“Results from the SNHT, Buishand and Pettitt homogeneity tests indicate that no time series at any station had $p < 0.05$, suggesting that all meteorological time series were homogeneous with no significant discontinuities due to climatic or non-climatic effects such as a change of instrument or data acquisition system, relocation, etc.**”**

Referee comment: p. 6, lines 38-42: Please give specific results of the homogeneity tests for DSR and DLR at Davos, since text on page 2 describes differences in the instrumentation used for different time periods.

Answer: The sentence has been changed to:

“Homogeneity analyses of all meteorological parameters were then conducted to test for any discontinuities in the time series. This is only meaningful when using the full dataset i.e., for all-sky conditions as opposed to cloud-free conditions, which are a sub-set of the former. Results from the SNHT, Buishand and Pettitt homogeneity tests indicate that no time series at any station had $p < 0.05$, suggesting that all meteorological time series were homogeneous with no significant discontinuities due to climatic or non-climatic effects such as a change of instrument or data acquisition system, relocation, etc.”

Referee comment: p.7, line 6: Change sentence.

Answer: Changed.

Referee comment: p. 7, first full paragraph: Is it meaningful to compare trends from all these different time periods? It also seems that trends from global means and individual stations are being compared. I wouldn't expect trends from climate models to be particularly accurate. (Why would you look at two RCPs when we know what the CO2 concentrations were over the time periods of interest?) You might think about presenting results from satellite studies instead/in addition.

Answer: Unfortunately, we disagree with this statement. We are comparing observations in central Europe with BSRN observations from around the World. Hence, we consider that widening the study to include DSR and DLR from satellites would be beyond the scope of the present study in order to add more detail to a single paragraph.

We have therefore changed the original sentence from:

“Values of -61.6, 34.1 and -27.6 W m^{-2}, respectively, are broadly similar to recently updated global average values of -56, 28 and -28 W m^{-2} reported by Wild et al. (2017) using BSRN data.”

To:

“Interestingly, these values are similar to recently updated global average values of -56, 28 and -28 W m^{-2} reported by Wild et al. (2017) using BSRN observational data. The similarity is reflected by the fact that these globally averaged values are predominantly weighted by European as well as global mid-latitude sites with similar cloud climatologies.”

Referee comment: p.7, line 19: The word "anomaly" isn't really appropriate here. For example, one definition is "something unusual, unexpected, or different from what normally happens" (Macmillan online dictionary). In meteorology, the term is often applied to mean differences from the long term mean, so may be confusing to readers. I would suggest "differences," "discrepancies," or "deviations," although some people might call them "errors". It might be clearer if you just said that the cloud-free estimates were validated by comparison to clear sky measurements.

Answer: The term “anomaly” has been used in other studies, but we agree that “discrepancy” is more appropriate, and have therefore changed the term throughout the manuscript.

Referee comment: p.7, line 23: This figure is never discussed?

Answer: We do actually discuss this briefly on line 23 of the original manuscript, and in the paragraphs thereafter. We have therefore added the following text to the end of the sentence:

“… which are described further below”.

Referee comment: p.7, line 26: But at JFJ, it's 0.67.....

Answer: Rather than going into more detail, we would prefer to add the word “partly” to the sentence:

“This can be partly be explained by a higher cloud frequency at these sites with FCC = 0.68 and 0.70, … ”.

Referee comment: p.7, line 29: What are "low, negative values"? I might just cut the text from "with the latter" on.

Answer: Text removed as suggested.

Referee comment: p.7, line 30: No, SCE is defined only in terms of DSR. It's the DSR that is determined by those other factors.

Answer: Thank you for pointing this out. It is of course a mistake, which we failed to notice. The paragraph has been re-written, and is now:

"Positive trends of 3.6 and 3.8 W m^{-2}/decade (see Table 5) are observed at LOC and PAY, respectively, which represent a decrease in the magnitude of the SCE. In contrast, SCE trends at DAV and JFJ are close to zero for both the LLS and Sen's slope methods. Neither LOC nor PAY trends are significant at the 95 % confidence level but their positive values arise from the fact that trends in DSRall-sky > DSRsim cloud-free. Apart from DSR, DSRsim cloud-free is also calculated using IWV and AOD. IWV Trends at LOC and PAY in Table 3 are slightly positive but not significant while trends in AOD for the 1996 – 2015 period are shown in Figure 3. Trends are essentially negligible at 0.03 and 0.00/decade, for LOC and PAY, respectively, while those at DAV and JFJ are similar, as shown in a previous study (Nyeki et al., 2012) and in unpublished data. Positive SCE trends at LOC and PAY are therefore mainly due to positive trends in DSRall-sky."

Referee comment: p.7, line 30: Do we expect long-term trends in the solar zenith angle?

Answer: The sentence has been changed according to the above answer.

Referee comment: p.7, line 32: Again, SCE is defined by the DSR.

Answer: This has been changed. Please see our comment further above.

Referee comment: p. 7, line 35: Why is altitude important to LCE?

Answer: Because of the water vapour content (IWV) and the spectral properties of the atmosphere / water vapour continuum in the IR: in areas with high IWV (i.e., at low altitudes in the study area), the IR spectrum is close(r) to saturation even in cloud-free conditions (except for some spectral windows of the water vapour continuum, mainly the 8-14 µm wavelength range but also some other narrower spectral bands) compared to areas with low water vapour where the IR spectrum is far from saturation in a cloud-free atmosphere (the "windows" of the water vapour continuum are "open"). Therefore, the difference between observed DLR during all-sky conditions (when there are clouds) and calculated DLR for the corresponding cloud-free conditions (i.e., the LCE) is larger in areas with lower IWV compared to areas with higher IWV (see for instance also Fig. 3 in Wacker et al.2011). Or in other words: Clouds have a smaller impact in the IR at high IWV because the water vapour masks the radiative effect of clouds. The mountain site JUN is frequently in clouds causing a saturated water vapour continuum in the IR and thus a large difference, i.e. LCE, with respect to the corresponding calculated cloud-free fluxes.

S. Wacker, J. Gröbner, D. Nowak, L. Vuilleumier, and N. Kämpfer. Cloud effect of persistent stratus nebulosus at the Payerne BSRN site. Atmospheric Research, 102, 1–9, 2011.

The original sentence has been changed from:

"Regarding the LCE, annual average values are all positive with the highest occurring at JFJ (49.9 W m^{-2}) and the lowest at LOC (23.3 W m^{-2}), which is partly due to their altitudes at 3580 m and 367 m, respectively".

to:

"Regarding the LCE, annual average values are all positive with the highest occurring at JFJ (49.9 W m^{-2}) and the lowest at LOC (23.3 W m^{-2}). LCE decreases with decreasing altitude due to the higher water vapour content and thus higher cloud-free longwave fluxes (e.g., Wacker et al., 2011b; Aebi et al., 2017)."

Referee comment: p. 7, line 36: Change to "is".

Answer: As a native English-speaker, I would argue that our version is correct. The sentence effectively reads: "…Trends … are … consistent…". However, the ACP copy-editors can change this if they so wish.

Referee comment: p. 7, line 38: See prior comment about DSR and SCE.

Answer: Thank you for pointing this out. It is of course a mistake, which we failed to notice. The original sentence has been replaced with the following sentence:

"The LCE depends on a range of microphysical and macrophysical cloud properties, as mentioned in Section 1."

Referee comment: p. 8, line 1: Maybe mention that SCE dominates total CRE before this statement?
Referee comment: p. 8, line 2: How does the reduction in daylight hours during the winter affect CRE at DAV and PAY more than at LOC and JFJ? Aren't all the sites at about the same latitude? Also, does this sentence only pertain to winter?

Answer: The sentence is somewhat unclear and has therefore been changed to:

"As CRE is the sum of SCE and LCE, annual average values in Table 4 are more influenced by SCE than LCE, and result in DAV and PAY having the lowest values at ~ -40 W m^{-2}".

Referee comment: p. 8, line 4: Looks like 0.9-3.1 to me.

Answer: Thank you. The range from a previous manuscript version had not been updated. The range has now been changed to 0.9 – 3.1.

Referee comment: p. 8, line 5: Over time or space?

Answer: Rather than add more detail to the sentence, we would prefer to change the sentence to:

"… SCE and LCE trends both range from positive to negative values".

Referee comment: p. 8, line 6: The trends for CRE are also mostly insignificant.

Answer: This sentence has been removed in the new version.

Referee comment: p. 8, line 10: What does "this" refer to?

Answer: “This is most likely the case …” has been changed to “The latter is also more likely the case …”.

Referee comment: p. 8, line 13: See prior comment about "increasing" and "decreasing" trends. Does "trends" refer to both DSR and DLR here?

Answer: In this case, we do mean an increase or decrease in the trend as we are discussing a change in fractional cloud cover or cloud type.

The word “trends” refers to both DSR and DLR, but we have included the word twice as the sentence is rather long.

Referee comment: p. 8, line 18: Is the Sanchez-Lorenzo study relevant to your results? You say it only showed cloud cover trends in the 1970s and 1980s.

Answer: The original sentence: “Sanchez-Lorenzo et al. (2017) reported a decrease in observed and simulated cloud cover during the first two decades of the 1971 – 2005 period over the Mediterranean region which was followed by a subsequent tailing off of the trend**”.**

In this sentence, the word “reported” may suggest that only the 1971 – 1980 period was reported but Sanchez-Lorenzo et al (2017) in fact reported the whole 1971 – 2005 period. As it was not our intention to convey this, the sentence has been changed to:

“Sanchez-Lorenzo et al. (2017) reported the observed and simulated cloud cover for the 1971 – 2005 period, and found negative trends during the first two decades over the Mediterranean region, followed by a subsequent tailing off.**”**

Referee comment: p. 8, line 19: Change to “included”.

Answer: We feel that the term “also covered” is appropriate as we are talking about spatial dimensions. However, we have changed it to “included”.

Referee comment: p. 8, lines 21-23: Another paper that ties changes in DSR to changes in clouds (rather than aerosols) is Parding et al., 2016 (J. Climate).

Answer: Thank you for pointing out this interesting paper, which we completely missed.

An extra paragraph has been inserted at the end of the original paragraph.

“These aspects were more closely investigated with respect to possible changes in synoptic weather patterns by Parding et al. (2016). They observed that an increase in cyclonic and decrease in anticyclonic weather patterns occurred over northern Europe, and contributed to dimming in the 1960s to 1990s based on observational data from the Global Energy Balance Archive (GEBA; Gilgen and Ohmura, 1999).”

Referee comment: p. 8, line 23: This paper is not listed in the references.

Answer: Thank you. Our mistake. The reference was in the list but it was not in correct alphabetical order. This has now been rectified.

Referee comment: p. 8, line 25: This would be easier to understand if you reminded us of what the "anomalies" are and what we could expect to learn from them (based on variable dependencies in the parameterization), before providing the numerical results instead of afterwards. That is, remind us that measured values of IWV and T are used for the clear-sky estimates. You might also mention that you mean the Prata param. here, just to be clear.

Answer: The paragraph has been restructured to:

“Through analysis of the trends in the longwave discrepancy, it is possible to assess the strength of radiative forcing components other than due to changes in T2m and IWV. Only these latter two parameters are used in the Prata parameterisation to estimate $DLR_{\text{sim cloud-free}}$. Trend analyses are shown for each station in Table 6. The LLS DAV trend of 3.4 W m−2/decade represents 70 % of the overall DLR trend of 4.8 W m−2/decade from Table 3. A similarly high value is also found at JFJ, and suggests that 70 % of the overall cloud-free trends at these stations are due to factors other than T2m and IWV.”

Referee comment: p. 8, line 29: Which trend, in the anomaly or the DLR?

Answer: The entire paragraph discusses the trends in the longwave anomalies. We therefore feel that adding extra text, here and elsewhere, is uneccessary. However, we have changed

“ …the trend at LOC …”

to

“ … the LLS trend at LOC …”

to make the sentence clearer.

Referee comment: p. 8, lines 33-37: By "anomaly," do you still mean the difference between estimated and measured clear-sky DLR? If so, how do the other authors estimate DLR? Do they include aerosols and trace gases, as mentioned next? It's not clear how results with respect to these variables were obtained.

Answer: The original sentence has been changed from:

“Previous studies (Philipona et al., 2005; Wacker et al., 2011) have investigated the trends in the longwave anomaly but changes in atmospheric gases or aerosol concentrations were not considered to be the cause.”

to:

“Previous studies (Philipona et al., 2005; Wacker et al., 2011) have investigated the trends in the longwave discrepancy using similar methods to those in this study. Possible changes in atmospheric gases or aerosol concentrations were investigated but not considered to substantially contribute to the discrepancy.”

Referee comment: p. 9, line 8: Blue?

Answer: Thank you. “Blue” has been inserted.

Referee comment: p. 9, line 18: I assume you mean sky-camera based FCC here?

Referee comment: p. 9, line 18: How do you apply a sky camera method to a parameterization?
Referee comment: p. 9, lines 17-21: This text needs to be clarified. It sounds like you are trying to evaluate the sky-camera method of estimating cloud cover, but the results are given in W/m2. What are you actually doing? And why do you believe that the results are "likely" to improve when more data is available?

Answer: The original sentence was:

"A promising alternative to APCADA to determine the degree of cloud cover is the use of sky cameras. As only FCC time series at DAV and PAY from sky-camera data were available for the 2013 – 2015 period, it was tried on the above DLR-IWV parameterisation. These values are higher than with APCADA (10.0 and 10.1 W m^{-2}) but are likely to improve (i.e. decrease) when longer time series become available in the future".

This has been changed to the following, and hopefully answers the three comments from the Referee:

"A promising alternative to APCADA to determine the degree of cloud cover is the use of sky cameras. However, FCC time series at DAV and PAY from sky-camera data are only available as of 2013, and hence cannot be used to replace APCADA in this study based on the 1996 – 2015 period. Instead, the 2013 – 2015 FCC time series was tested with the above DLR-IWV parameterisation. Rmse values of 13.7 W m^{-2} and 12.8 W m^{-2} for all-sky ($R^2 = 0.80$) and cloud-free conditions ($R^2 = 0.85$) were obtained, respectively. These rmse values are higher than with APCADA (10.0 and 10.1 W m^{-2}) but are likely to improve (i.e., decrease) when longer FCC time series from sky cameras become available in the future."

Referee comment: p. 9, line 35: This contradicts text on page 6.

Answer: Thank you. The text has been changed to:

"All-sky and cloud-free DSR trends are in the ranges 0.6 – 4.3 W m^{-2}/decade and 3.1 – 3.3 W m^{-2}/ decade, respectively. Half of the trends are significant at the 90% confidence level."

The text in the main body of the manuscript (originally p.6 line 23) has also been updated to:

Trends in all-sky DSR are in the 0.6 – 4.3 W m^{-2}/decade range with a significance at the 90% confidence level except for DAV. Cloud-free trends for DAV and LOC are similar (3.1 and 3.3 W m^{-2}/ decade, respectively) but are noticeably different for PAY and JFJ (10.6 and -9.5 W m^{-2}/decade, respectively).

Referee comment: p. 9, line 38: Estimated, because the clear-sky values don't come from measurements.

Answer: "Estimated" inserted.

Referee comment: p. 10, line 1: Since this is a big range, you might want to say where it is high and low or just that it varies by location.

Answer: "…, depending on location, …" inserted.

Referee comment: p. 10, lines 9-10: It would be useful to compare the magnitudes of the detected trends and measurement accuracy in the text. Otherwise we are left with the impression that the standard deviations given in the tables accurately represent your confidence in the results.

Answer: This question could be tackled in several different ways but after studying the literature, we decided to frame our answer in terms of the 95% confidence interval of the trends. These have been added to Tables 3 and 5 but only for the LLS method for clarity. We could have calculated the range in the trend by adding and subtracting the measurement uncertainty from each data point in the time series but this range would in fact be smaller than the 95% confidence interval.

The following sentence was added to Section 3.2.:

“The 95 % confidence intervals of the DLR trends, as well as those for meteorological and DSR trends, are shown in Table 3. Interval values are relatively low in all cases, and is in large part due to the long time series. If the instrumental uncertainties are taken into account by the trend analysis, then 95 % confidence intervals are unchanged to two decimal places. However, our main reason to have confidence in trend results, rests on whether they are significant or not at the 95 % confidence level, which has been demonstrated in Table 3”.

The following sentence was added to Section 3.3.1:

“However, it should be noted that no trends are significant at the 95 % confidence level with only PAY significant at the 90 % level. Although the absence of any significant trend hampers further reliable interpretation, it is nevertheless interesting to consider what results in Table 5 suggest.”

The following sentences in the Abstract have been augmented with the text in bold:

“The trends of meteorological parameters and surface downward shortwave and longwave radiation (DSR, DLR) were analysed at four stations (between 370 and 3580 m asl) in Switzerland for the 1996 – 2015 period. Ground temperature, specific humidity and atmospheric integrated water vapour (IWV) increased during all-sky and cloud-free conditions. All-sky DSR and DLR trends were in the ranges 0.6 – 4.3 W m^{-2}/decade and 0.9 – 4.3 W m^{-2}/decade, respectively, while corresponding cloud-free trends were -2.9 – 3.3 W m^{-2}/decade and 2.9 – 5.4 W m^{-2}/decade. Most trends were significant at the 90 % and 95 % confidence levels. The cloud radiative effect (CRE) was determined using radiative transfer calculations for cloud-free DSR and an empirical scheme for cloud-free DLR. CRE decreased in magnitude by 0.9 – 3.1 W m^{-2}/decade (only one trend significant at 90 % confidence level), which implies a change in macrophysical and/or microphysical cloud properties. Between 10 and 70 % of the increase in DLR is explained by factors other than ground temperature and IWV. A more detailed, long-term quantification of cloud changes is crucial and will be possible in the future as cloud cameras have been measuring reliably at two of the four stations since 2013.”

The following sentence in the Conclusions has been augmented with the text in bold:

“The estimated net radiative cooling due to clouds, the CRE, decreased in magnitude by 0.9 – 3.1 W m^{-2}/decade over the 1996 – 2015 period, although no trends were significant at the 95% confidence level.”

Referee comment: p. 10, line 15: Should be ", e.g., cloud type,"

Answer: Changed.

Referee comment: p. 10, line 18: Change to “that”.

Answer: As a native British English speaker, I would argue that our version is correct. As our ACP paper will undoubtedly be language-corrected before publication, we would recommend that ACP decide.

Referee comment: p. 10, line 26: Which author, and what about the others? All sources of funding should be recognized.

Answer: In our case the “author” is the “main author”. We’ve never been asked to include the funding sources of other authors. However, it may actually not be necessary as all other authors have full-time positions at their respective institutes involving no third-party funding. However, we will change the text to whichever format ACP requires.

Referee comment: Table 2: Do I understand correctly that these values have been published previously?

Answer: Results for the period 1996 – 2007 were reported by Wacker et al (2011). We state this in the original manuscript on page 5 line 28. Table 2 refers to updated values for the 1996 – 2015 period. Hence, this data has not been published before.

Referee comment: Table 3: Any idea why the clear-sky DSR decreases at JFJ but not at the other stations? Is there a reason cloud cover trends aren't included in this table?

Answer:

We would prefer not to speculate why a there is an overall negative trend in DSR at JFJ for the 1996 – 2015 period. In the original manuscript on p.6 lines 23-29, we discuss the large negative and positive trends at JFJ and PAY. We also point out in the footnotes of Table 3 that the trends are less negative and positive over different time periods. Without going into further speculative detail we have therefore changed the following sentence:

“In both cases, homogeneity analysis (described further below) does not suggest that a stepwise change occurred due to a change in instruments etc., so whether these trends continue into the future will have to be further monitored.”

to:

“Only the Pettitt homogeneity test suggested that a discontinuity in the trend occurred at PAY and JFJ (both, $p < 0.05$). No discontinuities were found in the DAV and LOC DSR trends. At present, the reason(s) for these cloud-free trends at PAY and JFJ for 1996 – 2015 are unknown and will have to be further monitored. The SCE, LCE and CRE are not affected by these results as they are calculated with all-sky data.”

We have not included cloud-cover trends as the method to determine cloud-cover is based on a parameterisation (APCADA). It is therefore our opinion that a discussion of parameterised cloud-cover trends would not add further insight to the scientific discussion. The 6-year data-set of sky-camera measurements is unfortunately too short at present.

Referee comment: Table 3: The trend is the slope, i.e., unit/decade, not the slope/decade (which would be the change in the slope per decade).

Answer: Thank you for highlighting this error. This has been changed to unit/decade.

Referee comment: Table 4: The text on page 7 lists fairly large biases and RMSEs for the SW clear-sky fluxes, as much as 17% of the means and 3x the standard deviations of SCE shown in this table, respectively. Are these errors important to the SCE estimates?

Answer: After having re-analysed data used in this section, we discovered that the values for both the DSR and DLR discrepancies that we gave were from an earlier incorrect version of the paper. The correct values have now been inserted, which are similar to the instrumental uncertainty. The uncertainty estimates of SCE, LCE and CRE are therefore “correct”. The revised text has been moved to Section 2.3, and is:

“Validation of the cloud-free models was accomplished by determining the shortwave and longwave discrepancies (observed cloud-free fluxes – simulated cloud-free fluxes). The mean bias and rmse of the shortwave discrepancies were <3.5% and <8.5% (Wacker et al., 2013), respectively, and ~ -0.1 W m-2 and ~3.9 W m-2 for the longwave discrepancies at all four stations. The mean biases are thus similar to the measurement uncertainty of the respective radiometers (Wacker et al., 2013).”

Referee comment: Figure 1: If you have no comments about the trends determined using the Weatherhead method, why are they included?

Answer: The Weatherhead method is in fact the linear least squares (LLS) method which is used throughout the manuscript, and is first described in section 2.4.

We have therefore changed the original caption text from:

“Each panel also shows trend results from linear least squares analysis using the Weatherhead et al. (1998) method.”

to the following for clarity:

“Each panel shows trend results from linear least squares analysis in Table 3.”

Referee comment: Figure 3: Did you also check the AOD data for artificial jumps? There looks like there might be a discontinuity in the PAY data around 2011.

Answer: Thank you for noticing this. In fact, we visualised the wrong data series for the 2013-2015 period in Figure 3. It should have been a climatology, as mentioned in Section 2.3, and not the data shown. Both LOC and PAY AOD time series for the 1996 – 2012 period were homogeneous ($p > 0.05$). Figure 3 has therefore been updated.

Despite this small problem, the correct data were used for the radiative transfer calculations, and therefore no SCE or CRE results need to be changed.

Referee comments: Clarity of presentation:

At some points, additional detail or improved clarity is needed. Questions about the meaning of certain phrases and suggestions for wording changes are included in the accompanying PDF file.

Whenever possible
Note: A comma is required
- before (and after) a phrase starting with "which"
- after (and before, if they're not inside parentheses) "e.g." or "i.e."
- before "etc."

Answer: Thank you. We thank the referee for reviewing our paper in such detail. We have endeavoured to correct the paper according to his/her recommendations.

Referee 2: Comments

General comments

It is important to investigate the trends of radiation and cloud radiative effect at the surface and put forward the possible explanations that account for the phenomenon. However, there are some weakness that requires more supporting material. The clouds identification methods are not accurate which may induce a contamination of radiation fluxes, since a slight change of cloud cover may significantly influence the radiation fluxes at the surface. Aerosol burden also has significant effects on shortwave radiation at the surface. Using climatological average of AOD to fill in the missing data of AOD during 2013 through 2015 may cause an artificial error in the trend analysis. Without any detailed description of how clouds change, it is quite arbitrary and blurry to infer the relationship between the variations of CRE and clouds.

Question: The clouds identification methods are not accurate which may induce a contamination of radiation fluxes, since a slight change of cloud cover may significantly influence the radiation fluxes at the surface.

Answer: This is correct. However, we would point out that sky-camera measurements have only been conducted for several years, and reliable data are only available for PAY and DAV. The only way to enable cloud-free DSR and DLR analyses to be extended back to the 1990s is with a proxy parameterisation of cloud-cover, APCADA in our case. The original manuscript already discusses the advantages and disadvantages of using APCADA. In our opinion, this is currently the only way to conduct such analyses. However, we have made some changes to Section 2.2 so that the advantages of using sky-cameras are better highlighted.

New text: “Apart from these aspects, the use of proxy parameterisations for cloud cover will introduce uncertainties, but we estimate that these are generally low. A more accurate assessment will only be possible when cloud cover data from sky cameras are long enough to conduct reliable time series analysis, which is generally a period of 10 years and longer. While cloud cover can be accurately and objectively determined with sky cameras, measurements are only available during daylight hours.”

Question: Aerosol burden also has significant effects on shortwave radiation at the surface. Using climatological average of AOD to fill in the missing data of AOD during 2013 through 2015 may cause an artificial error in the trend analysis.

Answer: We agree. On the other hand, the 17-year AOD time series is only being extended with a 3-year climatology to 20 years, so a large deviation from the prevailing trend is not to be expected. We have therefore introduced the following sentence:

“While this may introduce an error in the AOD trend, a large change is not expected in the 18-year AOD time series.”

Question: Without any detailed description of how clouds change, it is quite arbitrary and blurry to infer the relationship between the variations of CRE and clouds.

Answer: We agree with the Reviewer. We have therefore changed our discussion at several points in the text so that a change in macro and microphysical cloud properties is mentioned rather than a change in cloud cover or in cloud type. Please see further comments below (Referee comment: 6. Page 8 and line 15).

Specific comments

Referee comment: 1. Page 5 and line 25: ‘In contrast, the specific humidity and IWV are higher during all-sky conditions which in turn results in higher DLR values.’, please mention the source of the specific humidity data?

Answer: Specific humidity was calculated from T_{2m}, RH and pressure. This has been included in a revision of the paragraph on the IWV parameterisation. Please see next Referee comment.

Referee comment: 2. Page 5 and line 30: ‘IWV at JFJ was based on a widely-used parameterization using T_{2m} and relative humidity’, where is relative humidity data from and what is the accuracy of this parameterization? Please add description of these in the section of methods and data.

Answer: This small paragraph has been moved to Section 2.1 and has been changed to:

“As a result, IWV at JFJ was based on a commonly-used parameterisation by Leckner (1978) using T2m and RH. Gubler et al. (2012) estimated that the uncertainty in IWV using this parameterisation was up to 100 %.”

Gubler, S, Gruber, S., and Purves, R. S.: Uncertainties of parameterized surface downward clear-sky shortwave and all-sky longwave radiation, Atmos. Chem. Phys., 12, 5077-5098, doi:10.5194/acps-12-5077-2012, 2012.

Referee comment: 3. Page 5 and line 35: ‘which are probably associated with synoptic scale weather patterns’, what kind of weather patterns are they?

Answer: Rather than go into further detail on this subject for which there are few observational studies, we have removed the latter part of the sentence so that the following remains.

“Weak seasonal variations are seen to occur at all sites”.

Referee comment: 4. Page 6 and line 25: ‘the DSR trend at PAY is not monotonic but steeply’, as DSR has obvious changes, could you show its trend at four sites like Figure 1?

Answer: We would prefer not to add another figure with, in our view, little scientific value to the overall paper. The word “steeply” was an overemphasis and has therefore been removed.

Referee comment: 5. Page 7 and line 20: what are the ‘<’ and ‘-<’?

Answer: Thank you for highlighting this. This has been corrected to <-0.5 Wm^{-2} and <4 Wm^{-2}.

Referee comment: 6. Page 8 and line 15: ‘suggesting that a decrease in fractional cloud cover or a different cloud type has occurred during the 1996 – 2015 period’, there are many factors may affect cloud radiative effects such as cloud height and optical depth. A decrease of CRE magnitude doesn’t mean there can be the decrease of cloud fraction. What are the variations of different clouds during the 1996 – 2015 period?

Answer: We agree with the Reviewer that both, macrophysical cloud properties (e.g., cloud cover, cloud base height (cloud base temperature), cloud top height etc.) and microphysical cloud properties (e.g., cloud optical thickness, cloud droplet size, cloud particle size distribution, liquid water content, liquid water path, ice water content, hydrometeor size, hydrometeor size distribution, hydrometeor phase etc.) determine CRE and thus changes in CRE are a result of changes in these parameters. Regarding cloud fraction, we refer to Fig. 3 and Fig. 4 in Aebi et al., 2017 which indicate an increase in the magnitude of cloud radiative effects with increasing cloud fraction, particularly in the long-wave. In addition, various studies (listed in lines 16-23) conclude that cloud cover over Europe has decreased and thus it is likely that this decrease has contributed to the decrease of CRE.

Due to the lack of long-term cloud observations (macrophysical and microphysical cloud properties) it is not possible to determine the variations of different clouds during the 1996 – 2015 period. Indeed, continuous active remote sensing techniques are only available at Payerne but time series are not longer than 10 years. Cloud type observations from human observers, which are subjective to some extent and difficult to analyse, were finally stopped in 2005.

The original sentence on p.1 lines 18-19 has been changed from:

“CRE decreased in magnitude by 0.9 – 3.1 W m^{-2}/decade which implies a reduction in cloud cover and/or a change towards a different cloud type over the four Swiss sites.”

to:

“CRE decreased in magnitude by 0.9 – 3.1 W m^{-2}/decade which implies a change in macrophysical and/or microphysical cloud properties.”

The original sentence on p.8 lines 9-10 has been changed from:

“As a result of the positive CRE trends in Table 5, there is an overall decrease in the CRE magnitude, suggesting that a decrease in fractional cloud cover or a change towards a different cloud type has occurred during the 1996 – 2015 period.2

to:

“As a result of the positive CRE trends in Table 5, there is an overall decrease in the CRE magnitude, suggesting that changes in macrophysical and/or microphysical cloud properties, which determine CRE, have occurred during the 1996 – 2015 period.”

The original sentence on p.8 line 16 has been changed from:

“A reduction in cloud cover over Europe …”.

to: A decrease in cloud cover might be one of the cloud parameters which has contributed to the decrease of the CRE magnitude. Indeed, a reduction in cloud cover over Europe….

The original sentence on p.8 line 24 has had the following text added on:

“Apart from changes in cloud cover and other macrophysical cloud properties, microphysical cloud properties can also have a substantial impact on CRE. However, the observation of these properties using active remote sensing techniques is limited to a few super sites-worldwide while long-term time series are rarely available. The same is also valid at the four Swiss SACRaM stations in this study. Macrophysical and microphysical cloud properties have only been routinely measured at PAY since 2010 and 2005, respectively. In addition, cloud observations from human observers were discontinued in 2000 – 2005 at the SACRaM locations.”

The original sentence on p.9 line 39 has been changed from:

"… over the 1996 – 2015 period, which implies a decrease in cloud cover or a change towards a different cloud type."

to:

"...over the 1996 – 2015 period, although no trends were significant at the 95% confidence level. This decrease in CRE is probably caused by variations in macrophysical and microphysical cloud properties. However, it is not possible to determine and quantify, which cloud properties have changed and contributed to the decrease in CRE due to the lack of corresponding continuous long-term observations."

Trends in surface radiation and cloud radiative effect at four Swiss sites for the 1996 – 2015 period

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Abstract. The trends of meteorological parameters and surface downward shortwave and longwave radiation (DSR, DLR) were analysed at four stations (between 370 and 3580 m asl) in Switzerland for the 1996 – 2015 period. Ground temperature, specific humidity and atmospheric integrated water vapour trends were positive ~~increased~~ during all-sky and cloud-free conditions. All-sky DSR and DLR trends were in the ranges 0.6 – 4.3 W m^{-2}/decade and 0.9 – 4.3 W m^{-2}/decade, respectively, while corresponding cloud-free trends were -2.9 – 3.3 W m^{-2}/decade and 2.9 – 5.4 W m^{-2}/decade. Most trends were significant at the 90 % and 95 % confidence levels. The cloud radiative effect (CRE) was determined using radiative transfer calculations for cloud-free DSR and an empirical scheme for cloud-free DLR. CRE decreased in magnitude by 0.9 – 3.1 W m^{-2}/decade ~~which~~, (only one trend significant at 90 % confidence level), which implies a change in macrophysical and/or microphysical cloud properties ~~reduction in cloud cover and/or a change towards a different cloud type over the four Swiss sites~~. Between 10 and 70 % of the increase in DLR is explained by factors other than ground temperature and IWV. ~~Trends in aerosol optical depth at each station over the same period remained insignificant, and thus their contribution to the observed changes in surface radiative fluxes was negligible.~~ A more detailed, long-term quantification of cloud changes is crucial and will be possible in the future as cloud cameras have been measuring reliably at two of the four stations since 2013.

1 Introduction

Downward shortwave and longwave radiation (DSR, DLR) are important terms in the surface radiation budget and are fundamental in understanding the climate effect of increasing greenhouse gas concentrations (Wang and Dickinson, 2013). Both DSR and DLR have been reliably and accurately monitored since the late 1980s/early 1990s in several ground-based networks including: i) the Baseline Surface Radiation Network (BSRN) (König-Langlo et al., 2013; Driemel et al., 2018), ii) the Atmospheric Radiation Measurement (ARM) program (Ackerman and Stokes, 2003), and iii) the Surface Radiation (SURFRAD) Network (Augustine et al., 2000). DSR, from earlier less reliable measurements, over Europe was observed to decrease in the 1950s to 1980s ("dimming"), and was followed by an increase ("brightening") to the present ~~which~~, which has been attributed to changes in cloud cover and/or aerosol concentrations (e.g., Wild, 2009; Wang and Dickinson, 2013; Wild, 2016a; and references therein). DLR has also been observed to increase during the ~~(~~1973 – 2008 period (~~,~~ Wang and Liang, 2009) and s~~; s~~ince the 1990s (~~,~~ Wild, 2016b), but the reliable observational record is in general only several decades long at present.

In support of these international efforts, the Alpine Surface Radiation Budget (ASRB) network was established in 1994/1995 at 11 stations in Switzerland to monitor regional radiation fluxes (Philipona et al., 1996; Marty, 2000; Marty et al., 2002). In a trend analysis of the 1995 – 2002 DLR time series at these stations, it was observed that average DLR increased by 5.2 and 4.2 W m^{-2} for all-sky and cloud-free conditions, respectively (Philipona et al., 2004). A later study found an average cloud-free longwave increase of 3.5 W m^{-2}/decade for the 1996 – 2007 period at four of these stations (Wacker et al., 2011a) ~~which~~, which were still in operation. It was estimated that >50 % of the DLR trend was due to the positive trends in temperature and humidity. However, clouds can also significantly modify the radiation budget by reflecting shortwave and emitting longwave radiation. In order to quantify this with respect to the radiation budget, the concept of a Cloud Radiative Effect (CRE) can be used~~ which~~, which is the difference between all-sky radiation fluxes and cloud-free simulated fluxes (Ramanathan et al., 1989). Macrophysical (e.g., cloud cover, cloud base height, cloud top height, etc.) and/or microphysical cloud properties (e.g., cloud optical thickness, cloud droplet size, cloud particle size distribution, liquid water content, liquid water path, ice water content, hydrometeor size, hydrometeor size distribution, hydrometeor phase, etc.) can affect CRE to varying degrees. In a previous study at ~~Trends in the CRE at~~ the same four Swiss stations, Wacker et al. (2013) determined that CRE increased ~~were observed by Wacker et al. (2011) to decrease~~ by up to 7.5 W m^{-2} over the 1996 – 2010 period~~1~~,~~,~~ which was tentatively attributed to a~~indicating a~~ reduction in the fractional cloud cover (FCC) or a change towards a different cloud type.

This study presents an update of radiation fluxes for the 1996 – 2015 period, spanning 20 continuous years of surface radiation measurements at each of the four Swiss stations. Our objectives are: i) to assess whether trends in all-sky and cloud-free surface radiation can be determined and explained with any greater certainty, ii) to assess the trends in the shortwave,~~ and~~ longwave and total CRE, and iii) apply a wider range of robust statistical techniques than in previous studies.

2 Methods

2.1 Data from ASRB and SACRaM Networks

The ASRB network monitored DSR and DLR at 11 existing stations belonging to the Swiss Federal Institute of Meteorology (MeteoSwiss) from 1994 to 2005. Measurements were conducted according to BSRN guidelines, published in a 2005 report by McArthur (2005). ~~Measurements were conducted according to BSRN guidelines.~~ In a subsequent rationalization of the network, only four of the original eight stations continued to operate. The remaining stations are~~These included~~ (in order of altitude): Locarno (LOC, 46.180°N, 8.783°E, 367 m), Payerne, (PAY, 46.815°N, 6.944°E, 491 m), Davos (DAV, 46.814°N, 9.846°E, 1594 m), and Jungfraujoch (JFJ, 46.549°N, 7.986°E, 3580 m). Instruments from these stations were incorporated into the MeteoSwiss CHARM (Swiss Atmospheric Radiation Monitoring) network~~ which~~, which were then progressively merged in 2007 – 2012 into a single network, the Swiss Alpine Climate and Radiation Monitoring network (SACRaM). Several aspects concerning the instruments are worth mentioning and are therefore briefly discussed here:

i) Pyrgeometers in the ASRB network were all unshaded, and hence a correction for solar heating of the instrument was applied using the method described by Dürr (2004). In contrast, it was unnecessary to correct DLR data from the SACRaM network. These were either shaded (Precision Infrared Radiometer, PIR, Eppley Inc., USA) or unshaded pyrgeometers (CG(R)4, Kipp & Zonen, Netherlands). As CG(R)4 pyrgeometers are less affected by heating effects or by longwave irradiance in the direct beam of the sun (Meloni et al., 2012; Gröbner et al., 2018), no correction is necessary.~~Pyrgeometers in the ASRB network were all unshaded, and hence a correction for solar heating of the instrument was applied using the method described by Dürr (2004). In contrast, it was unnecessary to correct DLR data from the SACRaM network. These pyrgeometers were either shaded (Precision Infrared type, PIR, Eppley Inc., USA) or unshaded (CG(R)4, Kipp & Zonen, Netherlands) CG(R)4 pyrgeometers are less affected by heating effects or by longwave irradiance in the direct beam of the sun (Meloni et al., 2012; Gröbner et al., 2018).~~

ii) The SACRaM data acquisition systems were updated in stages from March 2005 to October 2011~~ which~~, which resulted in several short monitoring gaps. For instance, monitoring at PAY was interrupted from 23 August 2011 to 1 November 2011, but was not considered to be long enough to affect the trend analysis in this study.

iii) SACRaM radiometers at DAV are located at and maintained by the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC). Due to major building renovation from December 2010 to September 2012, these radiometers were partially removed from December 2010 to December 2014, however, PMOD/WRC radiometers were re-located nearby. DSR data from the SACRaM network was available while DLR data from the World Infrared Standard Group (WISG) of pyrgeometers (WMO, 2006) was used for the January 2006 to December 2015 period instead. The WISG consists of four pyrgeometers,~~ which~~ which were averaged into a single DLR time series of 1-min data.

iv) The PMOD/WRC hosts the World Standard Group (WSG) of pyrheliometers and the WISG, as mentioned above. These provide the reference scales for shortwave and longwave radiation measurements, respectively. However, as a note of interest, several studies have determined that their reference scales may need to be revised in the future (Fehlmann et al., 2012; Gröbner et al., 2014). The WSG scale currently overestimates by +0.3 %, and a ~~straightforward~~ linear correction ~~can~~ could be applied in a straightforward manner. However, the WISG scale underestimates longwave fluxes~~ which~~, which will require a non-linear correction depending on a number of factors (e.g., raw signal data, etc.), as reported by Gröbner et al. (2014) and Nyeki et al. (2017). The latter study determined that corrections were in the ranges ~~∼~~1 to~~–~~ 4 W m^{-2} for all-sky DLR and ~~∼~~5 ~~—~~to 7 W m^{-2} for cloud-free DLR when based on available data from ~~four~~ three BSRN stations and Davos (i.e., PMOD/WRC)~~ which~~, which have~~ing~~ the longest time series. Such corrections are beyond the scope of the present study, and are currently being debated within the community. A~~A~~ possible future correction of the SACRaM DSR time series should have no effect on the trend analyses in this study while corrected ~~a correction of~~ DLR time series could marginally affect the trends depending on the degree of cloudiness at each station.~~ While such corrections are beyond the scope of the present study, they should be kept in mind when future comparisons are made.~~

v) The uncertainty of pyranometer measurements is estimated to be in the range 18 – 23 W m^{-2} for high intensity (1000 W m^{-2}) 1-min average values (Vuilleumier et al., 2014). Similarly, the uncertainty of pyrgeometer measurements is estimated at ±4 W m^{-2}, and their relative stability is within ±1 W m^{-2} over extended time periods (Gröbner et al., 2014; Nyeki et al., 2017).

vi) Meteorological data (10-min. resolution) were available as quality controlled and assured data from MeteoSwiss: including screen-level temperature 2 m above ground (T_{2m}), relative humidity (RH), and surface pressure (P_s). In addition, DSR and DLR data (1-min.) were also available. Integrated water vapour (IWV; 1-hour) from Global Navigation Satellite System (GNSS) measurements (Morland et al., 2006) was downloaded from the STARTWAVE database (www.startwave.ch). The specific humidity (SH) was calculated using T_{2m}, RH and P_s. IWV measurements from JFJ were not used for a number of reasons as previous studies (Nyeki et al., 2005; Morland et al., 2006) had concluded that GNSS IWV time series at JFJ were uncertain due to: i) a high variability in IWV values, and ii) the IWV retrieval algorithm was unable to adequately correct for the persistent influence of snow and ice on the GNSS antenna signal. As a result, IWV at JFJ was based on a common~~the~~ ~~widely~~ly-used parameterisation by Leckner (1978) using T_{2m} and RH. Gubler et al. (2012) estimated that the uncertainty in IWV using this parameterisation was up to 100 %.

Monthly average values were then constructed for time series analysis. Use of a method by Roesch et al. (2011) was considered~~, which~~, which minimises the risk of biased monthly mean values when calculated from incomplete or flagged data records of DSR and DLR. A comparison of results for all sky conditions with simple monthly averages gave results~~ which~~, which were different by <0.1 %. ~~Cloud-free time series could not be constructed with this method due to the frequent cloud~~

~~cover at all stations.~~ Hence, for the sake of consistency and comparability, simple monthly averages were used throughout this study for the trend analyses. A monthly average was accepted for all-sky conditions if ≥75 % of data were available for each month, while no sampling threshold was applied to cloud-free data due to the smaller dataset after application of the cloud filter.~~A monthly average was accepted for all-sky conditions if ≥75% of data were available for each month.~~

2.2 Determination of Cloud-Free Conditions

In order to calculate cloud-free climatologies of meteorological parameters and radiation fluxes, it was necessary to determine the occurrence of cloud-free conditions. The first method uses T_{2m}, RH and DLR as input data to a semi-empirical algorithm, the Automatic Partial Cloud Amount Detection Algorithm, APCADA, (Dürr and Philipona, 2004). The degree of cloudiness, can be derived in oktas (0 to 8) and then converted to FCC (1 okta = 0.125 FCC) for any 10-min period during any time of the day. Cloud-free versus cloudy cases can be distinguished with an uncertainty of about 5 % for low to mid-level clouds. APCADA has the advantage that night-time FCC data can be derived for the four locations in this study based on previous semi-empirical studies (e.g., Dürr and Philipona, 2004). However, APCADA has several minor drawbacks. The first is a difficulty in adequately detecting high-altitude clouds (particularly optically thin cirrus) because of their low radiative impact at the surface. Nevertheless, as the radiative effect of such clouds on DLR is small, the effect of cloud contamination in the cloud-free dataset is also considered to be small. The second drawback is that APCADA semi-empirical calibration values (lapse rate coefficient and effective cloud-free broadband emissivity) are based on climatological conditions at each location in the early 1990s. While these calibration values are not expected to have changed since then, this cannot be verified here without an updated analysis. An alternative method, presented by Long and Turner (2008), determines the cloud cover using meteorological parameters and various statistical thresholds based on current data. It was argued that cloud-free estimates were more accurate, but a comparison with APCADA remains to be conducted in a future study. Apart from these aspects, the use of proxy parameterisations for cloud cover will introduce uncertainties, but we estimate that these are generally low. A more accurate assessment will only be possible when cloud cover data from sky cameras are long enough to conduct reliable time series analysis, which is generally a period of 10 years and longer. While cloud cover can be accurately and objectively determined with sky cameras, measurements are only available during daylight hours. Sky cameras were installed in 2013 at PAY (VIS-J1006, Schreder GmbH) and ~~several years later at~~ DAV (Q24M, Mobotix), while several difficulties at JFJ have prevented reliable measurements. ~~, h~~Hence, continuous ~~the~~ FCC time series, with a length of about six years are only available at two stations~~is currently shorter than six years~~. However, we used sky camera data to assess whether improvements could be made to the APCADA method.

~~The second method to determine the degree of cloud cover uses visible sky cameras. Although FCC is only available during the daytime and only since 2013, it was used here to assess whether it could help to refine the APCADA method. Sky cameras were installed at PAY (VIS-J1006, Schreder GmbH) and at DAV (Q24M, Mobotix). A camera was also installed at JFJ but image overexposure meant that reliable data was not available.~~ Images taken at PAY have a temporal resolution of five minutes, and two are sequentially taken with different exposure times (1/500 and 1/1600 s) having a resolution of 1200 x 1600. One image is taken each minute at Davos with an exposure time of 1/500 s. After the pre-processing of images (Aebi et al., 2017), a colour ratio (the sum of the blue to green ratio plus the blue to red ratio) is calculated per pixel (Wacker et al., 2015) and compared to ~~a~~ empirically determined reference values (2.2 in DAV and 2.5 in PAY), which are based on a large database of sky camera images. A pixel is classified as being cloudy or cloud-free based on this comparison. The FCC is then calculated by summing up the cloudy pixels and dividing by the total number of pixels. FCC values ≤0.05 for each 10 min value were ~~attributed to~~categorised as cloud-free conditions ~~which~~, which is more stringent than for APCADA where the limit is ≤ 1 okta (i.e., FCC ≤ 0.125).

2.3 Parameterisation of Cloud-Free DSR and DLR

As mentioned in Section 1, the effect of clouds on the surface radiation budget can be expressed by the CRE (Eq. 1)~~ which~~, which is divided into components for the shortwave and longwave cloud effects (SCE and LCE, respectively). Each component itself is defined as the difference between all-sky fluxes (e.g., $\mathrm{DSR}_{\text{all-sky}}$) and corresponding simulated cloud-free ~~conditions~~ fluxes (e.g., $\mathrm{DSR}_{\text{sim cloud-free}}$), as in Eq. 2:

$$\mathrm{CRE} = \mathrm{SCE} + \mathrm{LCE}\,, \tag{1}$$

$$\mathrm{CRE} = \mathrm{DSR}_{\text{all-sky}} - \mathrm{DSR}_{\text{sim cloud-free}} + \mathrm{DLR}_{\text{all-sky}} - \mathrm{DLR}_{\text{sim cloud-free}}\,, \tag{2}$$

CRE is defined here using just the downward flux components, similar to other studies (e.g., McFarlane et al., 2012), rather than the net (i.e., downward – upward) fluxes (e.g., Berg et al., 2011), so care must be taken when comparisons are made. $\mathrm{DSR}_{\text{sim cloud-free}}$ in Eq. 2 was calculated using the solar zenith angle, IWV, and aerosol optical depth (AOD) as inputs to libRadtran (Library for Radiative Transfer) (Mayer and Kylling, 2005). AOD from sun-photometers at each of the four sites was derived using procedures and data published previously (Nyeki et al., 2012; Kazadzis et al., 2018). AOD data (1 min.) ~~,~~ ~~and~~ was only available for Jan. 1994 – Dec. ~~2013~~2012, which was ~~. Climatological averages from this period were~~ used to construct an AOD climatology for the Jan. 2013 – Dec. 2015 missing period. While this may introduce an error in the AOD trend, a large change is not expected as the measured time series is 18 years long.

$\mathrm{DLR}_{\text{sim cloud-free}}$ was calculated using the empirical parameterisation by Prata (1996) as in Eq. 3:

$$\mathrm{DLR}_{\text{sim cloud-free}} = (1 - (1 + w).\exp(-(1.2 + 3.w)^{0.5})).\ \sigma T^{4}_{2\mathrm{m}}\,, \tag{3}$$

Where $T_{2\mathrm{m}}$ is in Kelvin, σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}), e is the water vapour pressure (hPa), and $w = 46.5e/T_{2\mathrm{m}}$. As w is in fact the parameterisation for IWV (in cm), observed values of IWV from GNSS measurements were used instead. A slightly modified form of the above Prata parameterisation was developed by Gröbner et al. (2009) by using the effective atmospheric boundary layer temperature (T_{ABL}) instead of $T_{2\mathrm{m}}$. T_{ABL} represents the effective radiating temperature of water vapour in the atmospheric boundary layer, and is derived by using two co-located pyrgeometers: one standard pyrgeometer sensitive to the 3 – 50 µm wavelength range and another modified one, which is sensitive in the 8 – 14 µm range.~~, and as its name implies is an effective temperature to more accurately model the surface DLR.~~ Setting $T_{2\mathrm{m}} = T_{\mathrm{ABL}}$, ~~This temperature modification~~ as well as use of the Prata parameterisation was considered by Wacker et al. (2014) to be slightly more accurate than the modified Brutsaert parameterisation used by Wacker et al. (2011a). The former was therefore used as the main parameterisation of $\mathrm{DLR}_{\text{sim cloud-free}}$ in this study.

Validation of the cloud-free models was accomplished by determining the shortwave and longwave discrepancies (observed cloud-free fluxes – simulated cloud-free fluxes). The mean bias and rmse of the shortwave discrepancies~~-~~ were <3.5% and <8.5% (Wacker et al., 2013), respectively, and ~ -0.1 W m^{-2} and ~3.9 W m^{-2} for the longwave discrepancies at all four stations. The mean biases are thus similar to the measurement uncertainty of the respective radiometers (Wacker et al., 2013).~~ The one sigma uncertainties of the simulated 1-min. cloud-free fluxes are slightly larger than 5 % and 5 W m^{-2} for shortwave and longwave radiation, respectively, and thus close to the measurement uncertainty of the respective radiometers (Wacker et al., 2013). In a validation study of various $\mathrm{DLR}_{\text{sim cloud-free}}$ models using the 1996 – 2008 time series from the same four Swiss SACRaM stations, Gubler et al. (2012) noted that a well-adapted and validated parameterization was in fact more important than the type of parameterization itself.~~

An alternative parameterisation of $\mathrm{DLR}_{\text{sim cloud-free}}$, reported by Ruckstuhl et al. (2007), was briefly investigated as well. Using data from the same four Swiss SACRaM stations, Ruckstuhl et al. (2007) parameterised $\mathrm{DLR}_{\text{sim cloud-free}}$ using only GNSS-derived IWV and not $T_{2\mathrm{m}}$. A power-law of the following form was found for this DLR-IWV parameterisation when data from all four stations was combined into a single equation:

$$\mathrm{DLR} = a.\mathrm{IWV}^{b}\,, \tag{4}$$

where the coefficients a and b were calculated for cloud-free conditions. It was determined that observed and parameterised monthly values for the 2001 – 2004 period gave correlation coefficients R^2 >0.95 and had root-mean-square errors (rmse) of 9.2 – 12.0 W m^{-2}. ~~It was~~Ruckstuhl et al. (2007) concluded that $\mathrm{DLR}_{\text{sim cloud-free}}$ could be parameterised with an uncertainty of <5 % when based on monthly average values. The main reason for including this method here, is to test whether $\mathrm{DLR}_{\text{sim cloud-free}}$ can be even more accurately parameterised with longer IWV time series in order to calculate LCE. This method was also used to test Eq. 4 during all-sky and not just cloud-free conditions. ~~A temperature modification could not be applied as only IWV appears in Eq. 4.~~

2.4 Statistical Methods

Trend analyses were performed using several methods. The first was the linear least squares (LLS) method by Weatherhead et al. (1998), using de-seasonalised monthly average values. Further details are given in the ~~forerunner~~ prior study by Wacker et al. (2011a). The second method uses the seasonal Kendall test and Sen’s slope estimator (see Gilbert, 1987; and references therein). The seasonal Kendall test is an extension of the Mann-Kendall test, a non-parametric technique ~~which~~, which determines whether a monotonic ~~increasing or decreasing~~positive or negative trend exists. The test takes seasonal effects into account and hence avoids the problem of auto-correlation in the time series. Before these trend tests were applied, the homogeneity of the time series was checked using three tests~~In order to check the homogeneity of the time series, three statistical tests were applied~~: the Buishand test (parametric), the Pettitt test (non-parametric), and the standard normal homogeneity test (SNHT; parametric) (Wijngaard et al., 2003). The null hypothesis is that the time series is homogeneous (significance level $p > 0.05$), ~~values of the testing variable are independent and identically distributed,~~ while ~~while~~ a stepwise change in the mean (or other statistic) is present under the alternative hypothesis ($p < 0.05$). When correctly used, these tests can help to locate when a possible change occurred. The SNHT test is more sensitive to changes near the beginning and end of a time series, whereas the Buishand and the Pettitt tests are more sensitive to changes in the middle. In order to meet the normality assumption for the SNHT and Buishand tests, monthly time series were log-transformed.

3 Results and Discussion

3.1 Meteorological and Surface Radiation Climatologies

Tables 1 and 2 summarise meteorological and radiation flux statistics for all-sky and cloud-free climatologies, respectively, at all four stations. Seasonal averages (DJF, MAM, etc.) clearly illustrate an annual cycle in virtually all parameters with a maximum in summer and minimum in winter. All-sky values in Table 1 have not been previously reported while cloud-free values in Table 2 are similar to values reported by Wacker et al. (2011a) for the 1996 – 2007 period. ~~All-sky values in Table 1, not previously reported, are similar to cloud-free values in Table 2 for the 1996 – 2007 period reported by Wacker et al. (2011).~~ $T_{2\mathrm{m}}$ and DSR values are seen to be slightly lower in Table 1, as would be expected during cloudy conditions. In contrast, SH and IWV are higher during all-sky conditions ~~which~~, which in turn results in higher DLR values. ~~For a number of reasons, IWV at JFJ was based on a widely-used parameterization~~ parameterisation ~~using $T_{2\mathrm{m}}$ and relative humidity (Leckner, 1978) rather than on GNSS measurements. Previous studies (Nyeki et al., 2005; Morland et al., 2006) concluded that GNSS~~

~~IWV time series at JFJ are uncertain due to: i) a high variability in IWV values, and ii) the IWV retrieval algorithm is unable to adequately correct for the persistent influence of snow and ice on the GNSS antenna signal.~~

Table 1 also shows cloudiness at each station from APCADA results ~~which~~, which have been converted from oktas to FCC. The clearest conditions occur at Locarno (lee location, south of the Alps) with an average FCC value = 0.55 while the cloudiest conditions occur at PAY (plateau location, north of the Alps) with FCC = 0.70 as a result of more persistent stratus cloud cover particularly during winter time when low cloud type stratus nebulosus regularly covers the Swiss Plateau.

~~Homogeneity analyses of all meteorological parameters were then conducted to test for any discontinuities in the time series. This is only meaningful when using the full dataset i.e., for all-sky conditions as opposed to cloud-free conditions, which are a sub-set of the former. Results from the SNHT, Buishand and Pettitt homogeneity tests indicate that no time series at any station had $p < 0.05$, suggesting that all meteorological time series were homogeneous with no significant discontinuities due to climatic or non-climatic effects such as a change of instrument or data acquisition system, relocation, etc.The clearest conditions occur at Locarno (lee location, south of the Alps) with an average FCC value = 0.55 while the cloudiest conditions occur at PAY (plateau location, north of the Alps) with FCC = 0.70 as a result of more persistent stratus cloud cover. Weak seasonal variations are seen to occur at all sites, which are probably associated with synoptic scale weather patterns.~~

~~3.2 Surface Radiation Trends and Homogeneity Analysis~~

To demonstrate the annual cycles in surface radiation at all four stations, DLR time series for all-sky and cloud-free conditions are shown in Figure 1a-d. Maxima in summer and minima in winter are evident as also is the case for DSR (not shown). Lower annual average DLR values during cloud-free conditions are observed with increasing station altitude (Table 2: 289 W m^{-2} at LOC versus 175 W m^{-2} at JFJ) as reported by Marty et al. (2002) for the same stations. This generally occurs as a result of lower IWV and temperature values with increasing altitude but is not always strictly the case as each station has its own climatology. For instance, the average DLR at PAY in Table 2 is very similar to that at LOC despite the latter being 124 m lower in altitude. When considering average DSR values with altitude, the situation is similar during cloud-free conditions except that higher long-term averages are generally observed with increasing altitude due to the decrease in atmospheric optical depth (Marty et al., 2002; and references therein). Again, the climatology at each station also has an influence as ~~where~~ the ~~all~~cloud-free~~-sky~~ annual average DSR at LOC (229.3 W m^{-2}) is higher than at PAY (206.8 W m^{-2}) and DAV (216.2 W m^{-2})~~due to lower FCC values (0.51 – 0.58) throughout all seasons~~.

3.2 Meteorological and Surface Radiation Trends

A summary of the decadal trends (LLS and Sen's slope methods) of all parameters is shown in Table 3. Trend values and confidence levels for both methods are seen to closely agree (i.e., column 3 vs. 4, and 5 vs. 6) in most cases ~~which~~, which gives confidence in their use. However, apparent discrepancies may occur on occasion when time series consist of many outliers or trends are close to zero. In these cases (e.g., IWV at PAY during all-sky conditions in Table 3) results from the Sen's slope method are preferred as they are considered to be more robust to outliers than the LLS method as well as being more accurate when data are skewed (Wilcox, 2005). In order to be consistent with ~~forerunner~~ prior studies (Wacker et al., 2011a; 2013), results from the LLS method will mainly be discussed here unless otherwise stated. The 90 % confidence interval of each trend is also shown in Table 3. Intervals are only shown for the LLS method for clarity.

T~~ Table 3 also illustrates that t~~rends in T_{2m}, SH and IWV, in Table 3, are all positive ~~for~~ during all-sky and cloud-free conditions. More specifically, T_{2m}, SH and IWV have increased at all four stations during all-sky and cloud-free conditions on average by ~0.3 – 0.6°C/decade, ~0.1 – 0.2 g kg^{-1}/decade and 0.2 – 0.8 mm/decade, respectively. It is interesting to note that about three quarters of the all-sky and cloud-free trends in meteorological parameters are significant at the >90 % confidence level. Homogeneity analyses of all meteorological parameters were then conducted to test for any discontinuities in the time series. This is only meaningful when using the full dataset i.e., for all-sky conditions as opposed to cloud-free conditions, which are a sub-set of the former. Results from the SNHT, Buishand and Pettitt homogeneity tests indicate that no time series at any station had $p < 0.05$, suggesting that all meteorological time series were homogeneous with no significant discontinuities due to climatic or non-climatic effects such as a change of instrument or data acquisition system, relocation, etc.

Trends in all-sky ~~and cloud-free~~ DSR are in the 0.6 – 4.3 W m^{-2}/decade range~~also mainly positive~~, and are ~~but few are significant~~significant at the 90 % confidence level except for DAV. Cloud-free trends for DAV and LOC are similar at 3.1 and 3.3 W m^{-2}/decade, respectively, but are rather different for PAY and JFJ. ~~However, cloud-free trends for PAY and JFJ, at 10.6 and -9.5 W m^{-2}/decade are noticeably larger than for LOC and DAV at 3.3 and 3.1 W m^{-2}/decade, respectively.~~ On closer inspection, the DSR trend at PAY is not monotonic but exhibits a trend of -2.9 W m^{-2}/decade for 1996 – December 2011 followed by a more positive trend, resulting in an overall trend of 10.6 W m^{-2}/decade for 1996 – 2015.~~but steeply positive from about the beginning of 2012 to December 2015 whereas the 1996 – December 2011 period exhibits a flat increase of ~2.9 W m^{-2}/decade, which, which is more comparable to the trends at LOC and DAV.~~ A similar case occurs at JFJ, where the~~. The~~ trend for 1996 – Dec. 2007 is ~~exhibits a flat decrease (~~~-2.9 W m^{-2}/decade~~)~~ followed by a more negative trend~~with a drop for the 2009 – 2015 period~~, resulting in an overall trend of -9.5 W m^{-2}/decade for 1996 – 2015. Only the Pettitt homogeneity test suggested that a discontinuity in the DSR trend occurred at PAY and JFJ (both, $p < 0.05$). No discontinuities were found for ~~in the~~ DAV ~~and~~or LOC DSR trends. At present, the reason(s) for these cloud-free trends at PAY and JFJ for 1996 – 2015 are unknown and will have to be further monitored. The SCE, LCE and CRE are not affected by these results as they are calculated with all-sky data.

~~In both cases, homogeneity analysis (described further below) does not suggest that a stepwise change occurred due to a change in instruments etc., so whether these trends continue into the future will have to be further monitored.~~

Regarding the DLR trends, all are positive and significant at the >90 % confidence level except during all-sky conditions at PAY. All-sky DLR trends at the four stations range from 0.9 – 4.3 and 0.9 – 5.9 W m^{-2}/decade for the LLS and Sen's methods, respectively. Higher trends are found for cloud-free conditions with ranges from 2.4 – 5.4 and 2.5 – 5.9 W m^{-2}/decade, respectively, while all trends are significant at the 95 % confidence level. The magnitudes and direction of the trends are similar to those observed by Wacker et al. (2011a; 2013) with the important exception that DLR time series trends are now significant for virtually all cases (i.e., combinations of stations, cloud conditions, and statistical tests) ~~which~~, which was previously observed for only two cases.

We found stronger ~~clear-sky~~cloud-free DLR trends at mountain stations (DAV and JFJ) than at lowland stations (LOC and PAY). This seems to be in agreement with a review by Pepin et al. (2015), who claim that climate warming is stronger at higher elevations, an effect known as elevation-dependent warming. However, in our study the cloud-free temperature trends are actually smaller at mountain ~~stations~~ than at lowland stations. This could be related to the temperature trends including the combined effect of multiple factors depending on local climate conditions, such as cloudiness. On the other hand, the ~~clear-sky~~cloud-free DLR trends are more closely linked to the driver of climate change: the increasing absorption of the upward longwave flux by the atmosphere and subsequent reemission in all directions including DLR. Pepin et al. (2015) formulated several hypotheses to explain their findings. The one that seems most consistent with our findings ~~is~~ postulat~~ing~~es that an increase in ~~a~~ DLR ~~increase~~ is related to an increase in IWV since we found stronger IWV changes at mountain stations in relative terms. At DAV, the ~~clear-sky~~cloud-free IWV trend is larger than at the lowland station, even though the average IWV is significantly smaller. At JFJ, the ~~clear-sky~~cloud-free IWV trend is smaller than at the lowland station, by a factor up to two, but the average IWV is almost four times smaller than at the lowland stations. However, as will be shown in section 3.3.2, ~~the~~ changes in T_{2m} and IWV are not sufficient to explain the change in ~~clear-sky~~cloud-free DLR at mountain stations.

The 90 % confidence intervals of the DLR trends, as well as those for meteorological and DSR trends, are shown in Table 3. Interval values are relatively low in all cases, and is in large part due to the long time series. If the instrumental uncertainties are taken into account by the trend analysis, then 90 % confidence intervals are unchanged to two decimal places. However, our main reason to have confidence in trend results, rests on whether they are significant or not at the 95 % confidence level, which has been demonstrated in Table 3.

~~Homogeneity analyses of all meteorological and radiation parameters were then conducted to test for any changes in the time series. This is only meaningful when using the full dataset i.e. for all-sky conditions as opposed to cloud-free conditions which, which are a sub-set of the former. Results from the SNHT, Buishand and Petitt homogeneity tests indicate that no time series at any station had $p < 0.05$, suggesting that all time series were homogeneous with no significant discontinuities due to climatic or non-climatic effects such as a change of instrument or data acquisition system, relocation, etc. T_{2m} time series from all four stations were homogeneous with significance values of $p > 0.32$, $p > 0.92$ and $p > 0.17$, respectively. Concurrent values for DLR were $p > 0.19$, $p > 0.11$ and $p > 0.15$ while values for other parameters were similar. This suggests that no significant changes in any of the time series at any station occurred due to climatic or non-climatic effects such as a change of instrument or data acquisition system, relocation, etc.~~

How do DSR and DLR trends at the four Swiss stations compare to other regions or global averages? In a recent analysis of observed DSR trends at BSRN stations, Wild (2016b) found an overall increase of 2.0 W m^{-2}/decade since the 1990s during all-sky conditions and a similar value during cloud-free conditions. The study concluded that a reduction in aerosol concentrations was contributing to the increase in DSR. ~~DLR s~~Studies of trends in DLR are scarcer. Apart from the earlier mentioned studies (Philipona et al., 2004; Wacker et al., 2011a; 2013)~~ which~~, which focused on the ASRB network in Switzerland, a global increase of 2.2 W m^{-2}/decade in DLR was estimated for the 1973 – 2008 period (Wang and Liang, 2009) using temperature, humidity and cloud fraction to parameterise DLR. A lower trend of 1.5 W m^{-2}/decade was found in climate model simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) by Ma et al. (2014) for the 1979 – 2005 period. In a more recent study by Wild (2016b), 20 of the longest BSRN all-sky DLR time series had an overall average trend of 2.0 W m^{-2}/decade (11 significant) while three were negative (none significant). This agreed well with CMIP5 multi-model mean trends for two RCP scenarios (Representative Concentration Pathways 8.5 and 4.5)~~ which~~, which gave all-sky trends of 1.7 and 2.2 W m^{-2}/decade, respectively.

3.3 SCE, LCE and CRE

3.3.1 Trend Analysis

Time series of SCE, LCE and CRE, calculated according to Eqs. 1 and 2, are ~~after validation of the $DSR_{sim\ cloud\text{-}free}$ and $DLR_{sim\ cloud\text{-}free}$ parameterizations for the 1996 – 2015 period. Validation was accomplished by determining the shortwave and longwave anomalies (cloud-free – simulated cloud-free values). The mean bias and rmse of the shortwave anomalies were (7.1, -8.0- 5.4) <~9 W m^{-2} and (9.7, 11.7, 8.5, 9.0) <~18 W m^{-2}, respectively, at all four stations while values of -<0.5 W m^{-2} and <~4 W m^{-2} were observed for the longwave anomalies. Our results are similar to those reported by Wacker et al. (2013) for all stations, and in a recent study by Aebi et al. (2017) for DAV and PAY.~~

~~The SCE, LCE and CRE time series in Figure 2 are~~ shown for PAY as an example in Figure 2.~~, as an example of all stations, and illustrate annual variations in each parameter, which are described further below. Values of the long-term averages at all four stations are shown in Table 4 while the trends appear in Table 5.~~ Beginning with a discussion of the SCE, all annual averages (see Table 4) are found to be negative with the lowest values (< -70 W m^{-2}) occurring at DAV and PAY. This can partly be explained by a higher cloud frequency at these sites with FCC = 0.68 and 0.70, respectively, agreeing with short-term results by Aebi et al. (2017). Positive trends of 3.6 and ~~–~~3.8 W m^{-2}/decade (see Table 5) are observed at LOC and PAY, respectively~~ which~~, which represent a decrease in the magnitude of the SCE. In contrast, SCE trends at DAV and JFJ are close to zero for both the LLS and ~~the S~~Sen's slope methods. Neither LOC nor PAY trends are significant at the 95 % confidence level but their positive values arise from the fact that trends in $DSR_{all\text{-}sky} > DSR_{sim\ cloud\text{-}free}$ ~~(see Eqs. 1 and 2)~~. ~~with the latter giving low, negative values (not significant).~~ Apart from ~~the~~ DSR, ~~the~~ $DSR_{sim\ cloud\text{-}free}$ ~~SCE~~ ~~depends on~~is also calculated using ~~using the~~

~~solar zenith angle,~~ IWV and AOD. IWV Trends at LOC and PAY in Table 3 are slightly positive but not significant. AOD ~~while trends in AOD are shown in Figure 3. t~~Trends -at LOC and PAY are shown in Figure 3, and were calculated for 1996 – 2013 to be consistent with the 1996 – 2015 period used in this study. Both trends are ~~are essentially~~ negligible at 0.03~~0~~ and ~~and -~~0.00~~1 per~~ /decade, ~~for LOC and PAY,~~ respectively, and remain the same if the full AOD time series from 1994 to 2013 is used instead. Decadal trends ~~, while~~ ~~. Tren~~those at ~~ds at~~ DAV and JFJ are similarly negligible, ~~also negligible~~ as shown in a previous study (Nyeki et al., 2012) and in ~~more recent~~ unpublished data~~observations~~. ~~Increasing~~ Positive SCE trends at LOC and PAY are therefore mainly due to positive trends in DSR$_{all-sky}$~~DSR and IWV trends at all stations, discussed earlier in section 3.1, are therefore the main reason for an increase in SCE~~.

Regarding the LCE, annual average values are all positive with the highest occurring at JFJ (49.9 W m^{-2}) and the lowest at LOC (23.3 W m^{-2}). LCE decreases with decreasing altitude due to the higher water vapour content and thus higher cloud-free longwave fluxes (e.g., Wacker et al., 2011b; Aebi et al., 2017). ~~Regarding the LCE, annual average values are all positive with the highest occurring at JFJ (49.9 W m^{-2}) and the lowest at LOC (23.3 W m^{-2}), which is partly due to their altitudes at 3580 m and 367 m, respectively.~~ LCE trends are negative at PAY and LOC ~~which~~, which are consistent with a decrease in the magnitude of the SCE and the lower all-sky DLR trends with respect to the cloud-free trends at these sites. In contrast, LCE trends at DAV and JFJ are positive, at 1.0 and 2.4 W m^{-2}/decade, but none are significant. ~~Apart from the DLR, t~~The LCE depends on a range of microphysical and macrophysical cloud properties, as mentioned in Section 1. ~~on T_{2m}, IWV, the cloud cover and type, and the cloud-base height.~~ In a case study, Aebi et al. (2017) observed that low-level clouds (for example cumulonimbus-nimbostratus or stratus-altostratus) and a cloud coverage of 8 oktas have the highest impact on the magnitude of the LCE with values of 59 – 72 W m^{-2}. The lower the cloud base height, the higher the cloud base temperature and the larger the LCE. ~~It was also shown that there is a negative dependence of the LCE on IWV.~~

As CRE is the sum of SCE and LCE, annual average values in Table 4 are more influenced by SCE than LCE, and result in DAV and PAY having the lowest values at ~ -40 W m^{-2}. It can be useful to regard results in Table 4 as representing a regional value for Switzerland when averaged over all four stations. The regional values of SCE, LCE and CRE are then -61.6, 34.1 and -27.6 W m^{-2}, respectively. Interestingly, these values are similar to recently updated global average values of -56, 28 and -28 W m^{-2} reported by Wild et al. (2017) using BSRN observational data. The similarity is reflected by the fact that these globally averaged values are predominantly weighted by European as well as global mid-latitude sites with similar cloud climatologies. ~~As CRE is the sum of SCE and LCE, its magnitude is smaller during winter due to reduced daylight hours and hence there is a reduced dominance of the SCE. Long-term averages at DAV and PAY therefore have the lowest values at ~ -40 W m^{-2}.~~ Regarding the CRE trends in Table 5, all are positive and range from 0.9 – 3.1 W m^{-2}/decade, which is similar to a range of 1.3 – 7.4 W m^{-2}/decade for 1996 – 2011 reported by Wacker et al. (2013). However, it should be noted that no trends are significant at the ~~with only the PAY trend significant at the~~ 9~~0~~5 % confidence level with only PAY significant at the 90 % level. Although the absence of any significant trend hampers further reliable interpretation, it is nevertheless interesting to consider the possible meaning of results in Table 5. The positive values of the ~~While C~~CRE trends ~~in Table 5 are similar to those in Wacker et al. (2013), with a range from 1.3 to 7.4 W m^{-2}/decade for 1996 – 2011, SCE and LCE trends are more variable. This can occur when trends are close to zero and when almost none are significant. Table 4 also shows the average values of SCE, LCE and CRE which~~, which ~~can be considered as "regional" values for Switzerland. Values of -61.6, 34.1 and -27.6 W m^{-2}, respectively, are comparable to recently updated global average values of -56, 28 and -28 W m^{-2} reported by Wild et al. (2017) using BSRN data.~~

represent an overall decrease in the CRE magnitude, and imply that changes in macrophysical ~~cloud properties (e.g., cloud cover, cloud base height, cloud top height etc.)~~ and/or microphysical cloud properties~~(e.g., cloud optical thickness, cloud droplet size, cloud particle size distribution, liquid water content, liquid water path, ice water content, hydrometeor size, hydrometeor size distribution, hydrometeor phase etc.) which~~, which, have occurred during the 1996 – 2015 period. ~~As a result of the positive CRE trends in Table 5, there is an overall decrease in the CRE magnitude, suggesting that a decrease in fractional~~

~~cloud cover or a change towards a different cloud type has occurred during the 1996 – 2015 period.~~ ~~The latter is also more~~ ~~This is most likely the case, as any possible changes in AOD, shown further above to be negligible, have already been accounted for in the DSR$_{\text{sim cloud-free}}$ component of CRE.~~ ~~Changes in macrophysical and microphysical cloud properties are rather~~ ~~A decrease in cloud cover or a change in cloud type is consistent with the observed increase in the all-sky DSR~~ ~~trends and reduction in the all-sky DLR trends with respect to their cloud-free counterparts.~~ Despite the observed decrease in CRE, clouds continue to reduce the available radiative energy at the surface over the four SACRaM sites by an overall long-term average of ~ -28 W m^{-2}. A decrease in cloud cover might be one of the cloud parameters~~ which~~, which has contributed to a decrease of the CRE magnitude. Indeed, a~~A~~ reduction in cloud cover over Europe and adjoining regions has been ascertained in several studies based on observations and simulations. Sanchez-Lorenzo et al. (2017) reported the observed and simulated cloud cover for the 1971 – 2005 period, and found negative trends during the first two decades over the Mediterranean region, followed by a subsequent tailing off.~~Sanchez-Lorenzo et al. (2017) reported a decrease in observed and simulated cloud cover during the first two decades of the 1971 – 2005 period over the Mediterranean region which was followed by a subsequent tailing off of the trend.~~ The region of study (30° – 48°N) also covered Switzerland (~46.2° – 47.6°N)~~ which~~, which exhibited a weak, overall negative trend in cloud cover. It was argued that the northward expansion of the Hadley cell may be related to the observed changes in cloud cover over the Mediterranean region. In a further recent study based on satellite and BSRN data covering the 1983 – 2015 period, it was concluded that the major part of the overall ~~increasing~~ positive trend in surface solar radiation over Europe was possibly due to changes in clouds (Pfeifroth et al., 2018). These aspects were more closely investigated with respect to possible changes in synoptic weather patterns by Parding et al. (2016). They observed that an increase in cyclonic and decrease in anticyclonic weather patterns occurred over northern Europe, and contributed to dimming in the 1960s to 1990s based on observational data from the Global Energy Balance Archive (GEBA; Gilgen and Ohmura, 1999).

Apart from changes in cloud cover and other macrophysical cloud properties, microphysical cloud properties can also have a substantial impact on CRE. However, the observation of these properties using active remote sensing techniques is limited to a few super-sites worldwide while long-term time series are rarely available. The same is also valid at the four Swiss SACRaM stations in this study. Selected macrophysical and microphysical cloud properties have only been routinely measured at PAY since 2010 and 2005, respectively. Cloud observations from human observers were unfortunately discontinued in 2000 – 2005 at all SACRaM locations.

3.3.2 Trends of the Longwave ~~Anomalies~~Discrepancies

Through analysis of the trends in the longwave ~~anomaly trends~~discrepancy, it is possible to assess the strength of radiative forcing components other than ~~those~~ due to changes in T_{2m} ~~temperature~~ and IWV. Only these latter two parameters are used in the Prata parameterisation to estimate DLR$_{\text{sim cloud-free}}$. Trend analyses of the longwave discrepancies are shown in Table 6 for all stations. The LLS DAV trend of 3.4 W m^{-2}/decade represents 70 % of the overall DLR trend of 4.8 W m^{-2}/decade from Table 3. A similarly high value is also found at JFJ, and suggests that 70 % of the overall cloud-free trends at these stations are due to factors other than T_{2m} and IWV~~, as the Prata parameterization only depends on the latter two parameters~~. In contrast, the LLS trend at LOC (10 % value) is almost fully explained by increases in T_{2m} and IWV while PAY (51 % value) is partially explained.

Previous studies (Philipona et al., 2005; Wacker et al., 2011a) have investigated the trends in the longwave discrepancy using similar methods to those in this study. Possible changes in atmospheric gases or aerosol concentrations were investigated but not considered to substantially contribute to the discrepancy.~~Previous studies (Philipona et al., 2005; Wacker et al., 2011) have investigated the trends in the longwave anomaly but changes in atmospheric gases or aerosol concentrations were not considered to be the cause.~~ It was noted that the increase in atmospheric CO$_2$ was responsible for a DLR trend of only ~0.3 W m^{-2}/decade (Prata, 2008) while increases in atmospheric CH$_4$ and N$_2$O (Forster et al., 2007) resulted in a trend of ~0.01

W m^{-2}/decade. Furthermore, the effect of aerosols was assumed to be insignificant (Ramanathan et al., 2001). However, it was argued that the use of APCADA, to generate a cloud-free filter, was possibly a biasing factor. As mentioned previously, high-altitude clouds (e.g., cirrus) have a smaller effect on DLR than low or mid-altitude clouds, and hence the cloud-cover filter generated with APCADA may not be accurate during such conditions. If this is the case then a positive trend of the longwave ~~anomaly~~ discrepancy suggests an increase of the radiative effect of high-level clouds, whereas a negative trend indicates a decrease. Under such assumptions, the positive trends in Table 6 would therefore point to an increase of the radiative effect of high-altitude clouds over the 1996 – 2015 period.

Another interesting aspect in Table 6 is the apparently stronger trend (both LLS and Sen's methods) with increasing station altitude, although only trends at DAV and JFJ are significant. As mentioned in Section 3.2, the cloud-free DLR trends themselves are higher at DAV and JFJ than at the other stations, which can be put into perspective with the findings of Pepin et al. (2015) and their hypothesis that DLR exhibits higher sensitivity to an IWV increase at low IWV, which is typically the case at mountain stations. The Prata parameterisation (Eq. 3) used in our study is a nonlinear function of IWV, but it seems to only partially explain the stronger cloud-free DLR trends at DAV and JFJ. It is possible that the higher uncertainty of IWV at JFJ plays a role or that the Prata parameterisation does not fully capture the DLR IWV dependency at mountain stations. Pepin et al. (2015) also discussed whether a change in the snowline altitude and subsequently surface albedo could occur. A further study based on radiative transfer modelling would be required to test these aspects.

3.3.3 Improvement of Methods

As mentioned earlier in Section 2.3, the DLR-IWV parameterisation is a possible alternative method to determine DLR$_{\text{sim cloud-free}}$. Figure 4 shows monthly average values of observed DLR versus IWV during all-sky and cloud-free conditions for the 2000 – 2015 period. DLR is seen to be less sensitive to changes in IWV at higher IWV values~~, which~~, which is due to saturation of longwave absorption in the atmospheric longwave window. The power-law fits (~~black~~ blue curves) in both graphs have been calculated for ≥684 monthly average values, and agree well with superimposed curves (red) from Ruckstuhl et al. (2007) for the 2001 – 2004 period. Fits for all-sky and cloud-free conditions exhibit values $R^2 = 0.95$ and 0.97 with rmse = 10.0 and 10.1 W m^{-2}, respectively. Despite the good overall fit, Figure 4 shows that the agreement becomes poorer when IWV $\lesssim$ 5 mm, especially during cloud-free conditions. These are mainly JFJ data points~~ which~~, which have a high uncertainty due to the aspects discussed earlier in section ~~3~~2.1. The greater scatter in both graphs with respect to that of the modified Prata parameterisation (rmse < 4.0 W m^{-2}, all stations) therefore suggests that this straightforward parameterisation of cloud-free DLR using only IWV will not allow sufficiently accurate LCE trends to be determined, even with longer time series.

A promising alternative to APCADA to determine the degree of cloud cover is the use of sky cameras. However, FCC time series at DAV and PAY from sky camera data are only available as of 2013, and hence cannot be used to replace APCADA in this study based on the 1996 – 2015 period. Instead, the 2013 – 2015 FCC time series was tested with the above DLR-IWV parameterisation. Rmse values of 13.7 W m^{-2} and 12.8 W m^{-2} for all-sky ($R^2 = 0.80$) and cloud-free conditions ($R^2 = 0.85$) were obtained, respectively. These rmse values are higher than with APCADA (10.0 and 10.1 W m^{-2}) but are likely to improve (i.e., decrease) when longer FCC time series from sky cameras become available in the future.~~A promising alternative to APCADA to determine the degree of cloud cover is the use of sky cameras. As only the 2013 – 2015 FCC time series at DAV and PAY were available for the present study, it was tried on the above DLR-IWV parameterization. Rmse values of 13.7 W m^{-2} and 12.8 W m^{-2} were obtained for all-sky ($R^2 = 0.80$) and cloud-free conditions ($R^2 = 0.85$), respectively. These values are higher than with APCADA (10.0 and 10.1 W m^{-2}) but are likely to improve (i.e. decrease) when longer time series become available in the future.~~ A further major refinement is the use of an infrared sky camera~~ which~~, which allows cloud cover to be determined during the day and night. A research prototype, the thermal infrared cloud camera (IRCCAM), has been continuously operating at DAV since September 2015 (Aebi et al., 2018). A comparison of IRCCAM with the visible sky cameras gave FCC values to within ±0.07 and to within ±0.05 for APCADA. Aebi et al. (2018) concluded that the use of

FCC from infrared sky cameras could increase the accuracy of cloud-free climatologies when FCC time series of adequate length become available.

4 Conclusions

The trends of surface downward shortwave and longwave radiation (DSR, DLR) were analysed at four stations (between 370 and 3580 m asl) in Switzerland for the 1996 – 2015 period. Using these data and meteorological parameters, the cloud radiative effect (CRE) was determined from calculations of the shortwave and longwave cloud radiative effects. The main conclusions include the following:

1) Trends in T_{2m}, SH and IWV all increased during all-sky and cloud-free conditions. Two thirds were significant at the ≥90 % confidence level.

2) All-sky and cloud-free DSR trends were in the ranges 0.6 – 4.3 W m^{-2}/decade and -2.9 – 3.3 W m^{-2}/decade, respectively. Half of the trends were significant at the ≥90 % confidence level.

3) All-sky and cloud-free DLR trends were all positive and in the ranges 0.9 – 4.3 W m^{-2}/decade and 2.~~9~~ 4 – 5.4 W m^{-2}/decade, respectively. All but one trend was significant at the ≥90 % confidence level.

4) The estimated net radiative cooling due to clouds, the CRE, decreased in magnitude by 0.9 – 3.1 W m^{-2}/decade over the 1996 – 2015 period, although no trends were significant at the 95 % confidence level. This decrease in CRE is probably caused by variations in macrophysical and microphysical cloud properties. However, it is not possible to determine and quantify ~~which~~, which cloud properties have changed and contributed to the decrease in CRE due to the lack of corresponding continuous long-term observations.~~, which implies a decrease in cloud cover or a change towards a different cloud type.~~

5) Between 10 and 70 % of the increase in DLR, depending on location, is explained by factors other than T_{2m} and IWV. An increase in cloud cover by high level clouds appears to be consistent with these observations. However, it is not possible to quantify or verify changes in cloud properties in further detail as cloud cameras, ceilometers, lidar, etc. have only been installed to varying degrees at the four SACRaM stations in recent years.

6) Trends in AOD at each station during the 1996 – ~~2015~~ 2012 period were insignificant, and hence their impact on the observed trends of surface radiative fluxes was considered to be negligible.

Although accurate DSR and DLR time-series have been available for more than 20 years in Switzerland, the detection of trends with high confidence remains difficult due to the natural variability and measurement uncertainty in surface radiation and cloud properties. Therefore, it is crucial to continue providing facilities to maintain such radiation observations of the highest possible accuracy ~~which~~, which allow changes in radiation and clouds to be reliably assessed. A reduction in quality, data gaps or discontinuation of these observations may hamper the accurate detection of any trend, and thus hamper climate monitoring. Regarding the observations of clouds, it is essential to apply and develop methods ~~which~~, which can be used during night and day to reliably detect clouds. In addition, these methods should be capable of determining macrophysical and microphysical cloud properties, e.g., ~~i.e.~~ cloud type in order to verify hypotheses from observed radiation data. Such methods include lidar and cloud radar ~~which~~, which are limited, however, to a few super-sites due their high costs. Alternatively, visible and infrared sky cameras are promising methods ~~which~~, which would allow basic cloud properties to be monitored on a more widespread basis.

Data availability. The data sets analysed in this study are available from the corresponding author upon request (stephan.nyeki@pmodwrc.ch).

Author contributions. SW and JG designed the study. LV provided measurement data. SN performed the data analysis, interpreted the results and wrote the manuscript with help from SW. All other co-authors contributed by commenting and revising the paper.

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References

Ackerman, T. P., and Stokes, G. M.: The atmospheric radiation measurement program, Physics Today, 56, 38-44, 2003.

Aebi, C., Gröbner, J., Kämpfer, N., and Vuilleumier, L.: Cloud radiative effect, cloud fraction and cloud type at two stations in Switzerland using hemispherical sky cameras, Atmos. Meas. Technol., 10, 4587-4600, doi:10.5194/amt-10-4587-2017, 2017.

Aebi, C., Gröbner, J., and Kämpfer, N.: Cloud fraction determined by thermal infrared and visible all-sky cameras, Atmos. Meas. Tech., 11, 5549-5563, https://doi.org/10.5194/amt-11-5549-2018, 2018.

Augustine, J. A., DeLuisi, J. J., and Long, C. N.: SURFRAD – a national surface radiation budget network for atmospheric research, Bulletin of the American Meteorological Society, 81, 2341-2357, 2000.

Berg, L. K., Kassianov, E. I., Long, C. N., and Mills Jr., D. L.: Surface summertime radiative forcing by shallow cumuli at the Atmospheric Radiation Measurement Southern Great Plains site, J. Geophys. Res., 116, D01202, doi:10.1029/2010JD014593, 2011.

Brutsaert, W.: On a derivable formula for long-wave radiation from clear skies, Water Resource and Research, 11, 742-744, doi:10.1029/WR011i005p00742, 1975.

Driemel, A., Augustine, J., Behrens, K., Colle, S., Cox, C., Cuevas-Agulló, E., Denn, F. M., Duprat, T., Fukuda, M., Grobe, H., Haeffelin, M., Hodges, G., Hyett, N., Ijima, O., Kallis, A., Knap, W., Kustov, V., Long, C. N., Longenecker, D., Lupi, A., Maturilli, M., Mimouni, M., Ntsangwane, L., Ogihara, H., Olano, X., Olefs, M., Omori, M., Passamani, L., Pereira, E. B., Schmithüsen, H., Schumacher, S., Sieger, R., Tamlyn, J., Vogt, R., Vuilleumier, L., Xia, X., Ohmura, A., and König-Langlo, G.: Baseline Surface Radiation Network (BSRN): structure and data description (1992–2017), Earth Syst. Sci. Data, 10, 1491-1501, https://doi.org/10.5194/essd-10-1491-2018, 2018.

Dürr, B.: The greenhouse effect in the Alps by models and observations, Ph.D. thesis, 81 pp., Swiss Fed. Inst. of Technol. at Zurich, Zurich, Switzerland, 2004.

Dürr, B., and Philipona, R.: Automatic cloud amount detection by surface longwave downward radiation measurements, J. Geophys. Res., 109, D05201, doi:10.1029/2003JD004182, 2004.

Fehlmann, A., Kopp, G., Schmutz, W., Winkler, R., Finsterle, W., and Fox, N.: Fourth World Radiometric Reference to SI radiometric scale comparison and implications for on-orbit measurements of the total solar irradiance, Metrologia, 49, S34-S38, doi:10.1088/0026-1394/49/2/S34, 2012.

Forster, P., et al.: Changes in atmospheric constituents and in radiative forcing, in Climate Change 2007: The Physical Science Basis, edited by S. Solomon et al., pp. 137-141, Cambridge Univ. Press, Cambridge, UK, 2007.

Gilbert, R.: Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold, New York. 1987.

Gilgen, H, and Ohmura, A: The Global Energy Balance Archive, Bull. Amer. Meteor. Soc., 80, 831-850, doi:10.1175/1520-0477(1999)080<0831:TGEBA>2.0.CO;2, 1999.

Gröbner, J., Wacker, S., Vuilleumier, L., and Kämpfer, N.: Effective atmospheric boundary layer temperature from longwave radiation measurements, J. Geophys. Res., 114, D19116, doi:10.1029/2009JD012274, 2009.

Gröbner, J., Reda, I., Wacker, S., Nyeki, S., Behrens, K., and Gorman, J.: A new absolute reference for atmospheric longwave irradiance measurements with traceability to SI units, J. Geophys. Res., 119, doi:10.1002/2014JD021630, 2014.

Gröbner, J. et al.: The 2nd International Pyrgeometer Intercomparison, IPgC-II, WMO IOM Report, No. 129, 2018.

Gubler, S, Gruber, S., and Purves, R. S.: Uncertainties of parameterized surface downward clear-sky shortwave and all-sky longwave radiation, Atmos. Chem. Phys., 12, 5077-5098, doi:10.5194/acps-12-5077-2012, 2012.

Kazadzis, S., Kouremeti, N., Nyeki, S., Gröbner, J., and Wehrli, C.: The World Optical Depth Research and Calibration Center (WORCC) quality assurance and quality control of GAW-PFR AOD measurements, Geoscientific Instrumentation, Methods and Data Systems, 7, 39–53, doi:10.5194/gi-7-39-2018, 2018.

König-Langlo, G., Sieger, R., Schmithüsen, H., Bücker, A., Richter, F., Dutton, E. G.: The baseline surface radiation network and its world radiation monitoring centre at the Alfred Wegener Institute, GCOS Report 174: update of the technical plan for BSRN data management. World Meteorological Organization (WMO), www.wmo.int/pages/prog/gcos/Publications/gcos-174.pdf, 2013.

Leckner, B.: The spectral distribution of solar radiation at the Earth's surface - elements of a model, Solar Energy, 20 (2), 1978.

Long, C. N., and Turner, D. D.: A method for continuous estimation of clear-sky downwelling longwave radiative flux developed using ARM surface measurements, J. Geophys. Res., 113, D18206, doi:10.1029/2008JD009936, 2008.

Ma, Q., Wang, K. C., and Wild, M.: Evaluations of atmospheric downward longwave radiation from 44 coupled general circulation models of CMIP5, J. Geophys. Res., 119, 4486-4497, doi:10.1002/2013JD021427, 2014.

Marty, C.: Surface radiation, cloud forcing and greenhouse effect in the Alps, Ph.D. thesis, 122 pp., Swiss Fed. Inst. of Technol. at Zurich, Zurich, Switzerland, 2000.

Marty, C., Philipona, R., Fröhlich, C., and Ohmura, A.: Altitude dependence of surface radiation fluxes and cloud forcing in the Alps: Results from the alpine surface radiation budget network, Theoretical and Applied Climatology, 72, 137-154, 2002.

Mayer, B., and Kylling, A.: Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use, Atmospheric Chemistry and Physics, 5, 1855-1877, doi:10.5194/acp-5-1855-2005, 2005.

McArthur, B.: Baseline Surface Radiation Network (BSRN), Operations Manual Version 2.1, WCRP 121, WMO/TD-No. 1274, 2005.

McFarlane, S., Long, C. N., and Flaherty, J.: A climatology of surface cloud radiative effects at the ARM tropical western Pacific sites, Journal of Applied Meteorology and Climatology, 52, 996-1031, doi:10.1175/JAMC-D-0189.1, 2012.

Meloni, D., Di Biagio, C., Di Sarra, A., Monteleone, F., Pace, G., and Sferlazzo, D. M.: Accounting for the solar radiation influence on downward longwave irradiance measurements by pyrgeometers, Journal of Atmospheric and Oceanic Technology, 29, 1629-s1643, doi:10.1175/JTECH-D-11-00216.1, 2012.

Morland, J., Liniger, M. A., Kunz, H., Balin, I., Nyeki, S., Mätzler, C., and Kämpfer, N.: Comparison of GPS and ERA40 IWV in the Alpine region, including correction of GPS observations at Jungfraujoch (3584 m), J. Geophys. Res., 111, D04102, doi:10.1029/2005JD006043, 2006.

Nyeki, S., Vuilleumier, L., Morland, J., Bokoye, A., Viatte, P., Mätzler, C., and Kämpfer, N.: A 10-year integrated atmospheric water vapor record using precision filter radiometers at two high-alpine sites, Geophysical Research Letters, 32, L23803, doi:10.1029/2005GL024079, 2005.

Nyeki, S., Halios, C. H., Baum, W., Eleftheriadis, K., Flentje, H., Gröbner, J., Vuilleumier, L., and Wehrli, C.: Ground-based aerosol optical depth trends at three high-altitude sites in Switzerland and southern Germany from 1995 to 2010, J. Geophys. Res., 117, D18202, doi:10.1029/2012JD017493, 2012.

Nyeki S., Wacker, S., Gröbner, J., Finsterle, W., and Wild, M.: Revising short and longwave radiation archives in view of possible revisions of the WSG and WISG reference scales: Methods and implications, Atmos. Meas. Technol., 10, 3057-3071, doi:10.5194/amt-10-3057-2017, 2017.

Parding, K. M., Liepert, B. G., Hinkelman, L. M., Ackerman, T. P., Dagestad, K-F., and Olseth, J. A.: Influence of synoptic weather patterns on solar irradiance variability in northern Europe, J. Climate, 4229-4250, doi: 10.1175/JCLI-D-15-0476.1, 2016.

Pepin, N., Bradley, R. S., Diaz, H. F., Baraër, M., Caceres, E. B., Forsythe, N., Fowler, H., Greenwood, G., Hashmi, M. Z., Liu, X. D. and Miller, J. R.: Elevation-dependent warming in mountain regions of the world, Nature Climate Change, 5, 424, doi: 10.1038/nclimate2563, 2015.

Pfeifroth, U., Sanchez-Lorenzo, A., Manara, V., Trentmann, J., and Hollmann, R.: Trends and variability of surface solar radiation in Europe based on surface- and satellite-based data records, J. Geophys. Res., 123, 1735-1754, doi:10.1002/2017JD027418, 2018.

Philipona, R., Marty, C., and Fröhlich, C.: Measurements of the long-wave radiation budget in the Alps, in IRS 96: Current Problems in Atmospheric Radiation, pp. 786–789, A. Deepak, Hampton, Va., 1996.

Philipona, R., Dürr, B., Marty, C., Ohmura, A., and Wild, M.: Radiative forcing - measured at Earth's surface corroborate the increasing greenhouse effect, Geophysical Research Letters, 31, L03202, doi:10.1029/ 2003GL018765, 2004.

Philipona, R., Dürr, B., Ohmura, A., and Ruckstuhl, C.: Anthropogenic greenhouse forcing and strong water vapor feedback increase temperature in Europe, Geophysical. Research Letters, 32, L19809, doi:10.1029/2005GL023624, 2005.

~~Pfeifroth, U., Sanchez-Lorenzo, A., Manara, V., Trentmann, J., and Hollmann, R.: Trends and variability of surface solar radiation in Europe based on surface- and satellite-based data records, J. Geophys. Res., 123, 1735-1754, doi:10.1002/2017JD027418, 2018.~~

Prata, A. J.: A new long-wave formula for estimating downward clear-sky radiation at the surface, Quarterly Journal of the Royal Meteorological Society, 122, 1127-1151, 1996.

Prata, R.: The climatological record of clear-sky longwave radiation at the Earth's surface: evidence for water vapour feedback? Journal of Remote Sensing, 29, 5247-5263, doi:10.1080/01431160802036508, 2008.

Ramanathan, V., Cess, R., Harrison, E., Minnis, P., Barkstrom, P., Ahmad, A., and Hartmann, D.: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment, Science, 243, 57-63, 1989.

Ramanathan, V., Crutzen, P. J., Kiehl, J. T., and Rosenfeld, D.: Aerosols, climate, and the hydrological cycle, Science, 294, 2119-2124, 2001.

Roesch, A., Wild, M., Ohmura, A., Dutton, E.G., Long, C. N., and Zhang, T.: Assessment of BSRN radiation records for the computation of monthly means, Atmospheric Measurement and Technology 4(2), 339-354, doi:10.5194/amt-4-339-2011, 2011.

Ruckstuhl, C., Philipona, R., Morland, J., and Ohmura, A.: Observed relationship between surface specific humidity, integrated water vapor, and longwave downward radiation at different altitudes, J. Geophys. Res., 112, D03302, doi:10.1029/2006JD007850, 2007.

Sanchez-Lorenzo, A., Enriquez-Alonso, A., Calbo, J., Gonzalez, J-A., Wild, M., Folini, D., Norris, J. R., and Vicente-Serrano, S. M.: Fewer clouds in the Mediterranean: consistency of observations and climate simulations, Scientific Reports, 7, 41475, doi:10.1038/srep41475, 2017.

Vuilleumier, L., Hauser, M., Félix, C., Vignola, F., Blanc, P., Kazantzidis, A., and Calpini B.: Accuracy of ground surface broadband shortwave radiation monitoring, J. Geophys. Res., 119, doi:10.1002/2014JD022335, 2014.

Wacker, S., Gröbner, J., Hocke, K., Kämpfer, N., and Vuilleumier L.: Trend analysis of surface clear-sky downwelling long-wave radiation from four Swiss sites, J. Geophys. Res., 116, D10104, doi:10.1029/2010JD015343, 2011a.

Wacker, S., Gröbner, J., Nowak, D., Vuilleumier, L., and Kämpfer, N.: Cloud effect of persistent stratus nebulosus at the Payerne BSRN site, Atmospheric Research, 102, 1-9, 2011b.

Wacker, S., Gröbner, J., and Vuilleumier L.: Trends in surface radiation and cloud radiative effect over Switzerland in the past 15 years, AIP Conference Proceedings, 1531, 672, doi:101063.1.4804859, 2013.

Wacker, S., Gröbner, J., and Vuilleumier L.: A method to calculate cloud-free long-wave irradiance at the surface based on radiative transfer modeling and temperature lapse rate estimates, Theoretical and Applied Climatology, 115, doi:10.1007/s00704-013-0901-5, 2014.

Wacker, S., Gröbner, J., Zysset, C., Diener, L., Tzoumanikas, P., Kazantzidis, A., Vuilleumier, L., Stöckli, R., Nyeki, S., and Kämpfer N.: Cloud observations in Switzerland using hemispherical sky cameras, J. Geophys. Res., 120, doi:10.1002/2014JD022643, 2015.

Wang, K. C, and Liang, S. L.: Global atmospheric downward longwave radiation over land surface under all-sky conditions from 1973 to 2008, J. Geophys. Res. 114, D19101, 2009.

Wang, K., and Dickinson, R. E.: Global atmospheric downward longwave radiation at the surface from ground-based observations, satellite retrievals, and reanalyses, Reviews of Geophysics, 150-185, 51, 2013.

Weatherhead, E. C., Reinsel, G. C., Tiao, G. C., Meng, X.-Li, Choi, D., Cheang, W.-K., Keller, T., DeLuisi, J., Wuebbles, D. J., Kerr, J. B., J. Miller, A., Oltmans, S. J., and Frederick, J. E.: Factors affecting the detection of trends: Statistical consideration and applications to environmental data, J. Geophys. Res., 103 (D14), 17,149-17,161, doi:10.1029/98JD00995, 1998.

Wijngaard, J. B., Klein Tank, A. M. G., and Können G. P.: Homogeneity of 20th century European daily temperature and precipitation series, International Journal of Climatology, 23, 679-692, doi:10.1002/joc.906, 2003.

Wilcox, R. R.: Theil-Sen Estimator, in Introduction to Robust Estimation and Hypothesis Testing, Academic Press, pp. 423-427. ISBN 978-0-12-751542-7, 2005.

Wild, M.: Global dimming and brightening: A review, J. Geophys. Res., 114, D00D16, doi:10.1029/2008JD011470, 2009.

Wild, M.: Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming, WIREs Climate Change, 7, 91-107, doi:10.1002/wcc.372, 2016a.

Wild, M.: Changes in shortwave and longwave radiative fluxes as observed at BSRN sites and simulated with CMIP5 models, AIP Conference Proceedings, 1810, 090014-1, doi:10.1063/1.4975554, 2016b.

Wild, M., Hakuba, M. Z., Folini, D., Schär, C., and Long, C.: New estimates of the Earth radiation budget under cloud-free conditions and cloud radiative effects, AIP Conference Proceedings, 1810, 090012 (2017), doi:10.1063/1.4975552, 2017.

WMO: CIMO-XIV, Activity Report, 7–14 December 2006, WMO No. 1019 (Part II), 2006.

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Table 1: Summary of selected parameters during all-sky conditions for the 1996 – 2015 period at the four SACRaM stations (ordered by ascending altitude: LOC = 367 m, PAY = 491 m, DAV = 1594 m; JFJ = 3580 m). Average values constructed from 10-min data are shown with the standard deviations in brackets.

Parameter	Station	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)	Annual
Temperature, T_{2m} (°C)	LOC	12.8 (5.4)	21.3 (4.2)	12.8 (5.3)	4.3 (3.5)	12.8 (7.6)
	PAY	9.6 (6.0)	18.3 (5.1)	9.8 (5.8)	1.2 (4.4)	9.8 (8.1)
	DAV	3.3 (6.2)	12.0 (5.1)	4.6 (6.2)	−4.3 (5.1)	4.0 (8.1)
	JFJ	-8.6 (5.1)	-0.3 (3.7)	-5.4 (5.4)	-12.6 (5.2)	-6.7 (6.6)
Specific humidity ($g\ kg^{-1}$)	LOC	5.6 (2.3)	10.3 (2.5)	7.0 (2.6)	3.4 (1.2)	6.6 (3.3)
	PAY	5.7 (1.9)	9.6 (1.9)	6.8 (2.2)	3.7 (1.1)	6.5 (2.8)
	DAV	4.1 (1.4)	7.5 (1.6)	5.0 (1.8)	2.6 (1.0)	4.8 (2.3)
	JFJ	2.3 (1.2)	4.3 (1.5)	2.7 (1.4)	1.5 (0.8)	2.7 (1.6)
IWV (mm)	LOC	15.8 (6.2)	28.0 (7.3)	19.0 (7.2)	10.0 (4.1)	18.1 (9.0)
	PAY	14.4 (5.4)	24.4 (6.1)	17.3 (6.3)	10.0 (4.2)	16.4 (7.6)
	DAV	9.5 (3.6)	17.0 (4.1)	11.3 (4.3)	6.4 (2.8)	11.0 (5.4)
	JFJ*	4.6 (2.2)	8.3 (2.8)	5.3 (2.7)	3.0 (1.5)	5.3 (3.0)
DSR ($W\ m^{-2}$)	LOC	191.2 (275.7)	249.0 (317.1)	111.0 (193.1)	72.0 (134.1)	156.2 (250.8)
	PAY	184.7 (261.6)	242.7 (304.5)	100.5 (176.5)	53.7 (106.5)	145.7 (237.5)
	DAV	204.0 (283.4)	229.8 (309.6)	119.3 (199.6)	78.0 (142.0)	158.4 (251.3)
	JFJ	235,6 (311.4)	265.9 (338.7)	140.4 (224.7)	84.9 (153.5)	182.4 (277.5)
DLR ($W\ m^{-2}$)	LOC	310.5 (39.5)	360.6 (29.7)	320.7 (42.0)	269.6 (37.1)	315.6 (49.4)
	PAY	304.5 (38.6)	348.0 (30.1)	318.2 (37.4)	285.2 (37.6)	314.1 (42.7)
	DAV	276.4 (39.9)	319.6 (30.2)	282.7 (40.2)	243.5 (41.6)	280.4 (46.9)
	JFJ	224.6 (50.8)	260.9 (45.5)	231.1 (49.8)	201.1 (50.3)	229.4 (53.5)
Fractional cloud cover, FCC	LOC	0.56	0.54	0.58	0.51	0.55
	PAY	0.64	0.60	0.74	0.81	0.70
	DAV	0.70	0.72	0.66	0.64	0.68
	JFJ	0.70	0.74	0.64	0.61	0.67

*IWV at JFJ based on parameterisation (Leckner, 1978) rather than GNSS measurements. See text for discussion.

Table 2: Similar to Table 1 except for cloud-free conditions.

Parameter	Station	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)	Annual
Temperature, T_{2m} (°C)	LOC	13.9 (5.7)	22.6 (4.3)	13.5 (5.9)	4.9 (4.0)	13.6 (8.1)
	PAY	10.1 (7.1)	19.5 (5.8)	10.9 (6.6)	0.4 (4.9)	11.9 (8.9)
	DAV	3.4 (7.1)	13.5 (5.6)	5.3 (6.8)	−5.1 (5.6)	3.8 (9.1)
	JFJ	-7.9 (5.1)	1.0 (3.5)	-3.9 (5.4)	-11.3 (5.0)	-6.0 (6.6)
Specific humidity (g kg^{-1})	LOC	4.7 (2.1)	9.6 (2.6)	6.2 (2.6)	2.9 (1.0)	5.9 (3.3)
	PAY	5.3 (1.9)	9.5 (2.0)	6.9 (2.3)	3.3 (0.9)	6.8 (2.9)
	DAV	3.5 (1.3)	7.2 (1.5)	4.6 (1.7)	2.1 (0.8)	4.2 (2.3)
	JFJ	1.7 (1.0)	3.4 (1.5)	2.0 (1.2)	1.1 (0.6)	2.0 (1.3)
IWV (mm)	LOC	12.7 (5.5)	25.0 (7.0)	15.6 (6.4)	7.9 (3.1)	15.1 (8.5)
	PAY	12.0 4.8)	22.1 (5.4)	15.3 (5.4)	7.7 (3.2)	15.3 (7.2)
	DAV	7.4 (3.1)	15.3 (3.6)	9.2 (3.6)	4.5 (2.0)	8.8 (4.9)
	JFJ*	3.3 (1.8)	6.5 (2.8)	4.0 (2.2)	2.2 (1.3)	3.8 (2.5)
DSR (W m^{-2})	LOC	270.2 (320.1)	358.9 (356.3)	177.1 (238.4)	99.6 (159.8)	229.3 (295.7)
	PAY	257.7 (313.4)	328.3 (347.0)	166.2 (237.3)	99.7 (160.5)	206.8 (304.3)
	DAV	265.9 (336.2)	309.4 (362.2)	176.1 (246.0)	109.4 (176.5)	216.2 (294.2)
	JFJ	299.5 (388.7)	354.7 (408.4)	190.3 (270.2)	116.6 (187.0)	244.9 (328.1)
DLR (W m^{-2})	LOC	283.1 (31.3)	344.1 (26.7)	290.1 (33.3)	241.9 (17.9)	289.3 (46.3)
	PAY	274.8 (31.3)	329.9 (26.6)	286.7 (32.1)	234.0 (19.9)	289.6 (43.5)
	DAV	237.5 (28.2)	291.5 (22.2)	249.4 (28.2)	204.5 (20.6)	243.4 (39.8)
	JFJ	167.6 (22.3)	207.9 (18.0)	182.3 (23.6)	151.9 (19.4)	175.2 (29.1)

*IWV at JFJ based on parameterisation (Leckner, 1978) rather than GNSS measurements. See text for discussion.

Table 3: Trend analyses (linear least squares, LLS, and Sen's methods) of selected parameters for the 1996 – 2015 period during all-sky and cloud-free conditions at all four stations. Trend values in italic (bold) are significant at the 90 % (95 %) level. The 90 % confidence interval of each trend is shown in square brackets for the LLS method.

Parameter	Station	All-sky LLS method unit/decade	All-sky Sen's slope unit/decade	Cloud-free LLS method unit/decade	Cloud-free Sen's slope unit/decade
Temperature, T_{2m} (°C)	LOC	**0.43** [±**0.25**]	**0.53**	**0.54** [±**0.27**]	**0.66**
	PAY	*0.35* [±*0.29*]	**0.50**	**0.59** [±**0.33**]	**0.79**
	DAV	0.30 [±0.32]	0.44	*0.48* [±*0.38*]	**0.61**
	JFJ	0.34 [±0.32]	0.43	0.20 [±0.38]	0.16
Specific humidity (g kg^{-1})	LOC	**0.19** [±**0.13**]	**0.18**	0.14 [±0.15]	0.12
	PAY	**0.18** [±**0.11**]	**0.19**	**0.23** [±**0.14**]	**0.18**
	DAV	*0.08* [±*0.07*]	0.08	*0.10* [±*0.09*]	0.10
	JFJ	**0.14** [±**0.06**]	**0.14**	**0.19** [±**0.07**]	**0.19**
IWV (mm)	LOC	0.37 [±0.56]	0.42	0.36 [±0.60]	0.31
	PAY	0.41 [±0.48]	**0.80**	*0.58* [±*0.55*]	**1.03**
	DAV	**0.63** [±**0.31**]	**0.89**	**0.79** [±**0.37**]	**1.18**
	JFJ*	**0.24** [±**0.11**]	**0.26**	**0.26** [±**0.13**]	**0.25**
DSR (W m^{-2})	LOC	*4.3* [±*3.3*]	**5.5**	3.3 [±3.8]	**3.8**
	PAY	*3.4* [±*3.2*]	*3.4*	**10.6** [±**4.0**]**	**10.0****
	DAV	0.6 [±2.9]	0.2	3.1 [±5.1]	3.5
	JFJ	*3.6* [±*2.7*]	2.2	**-9.5** [±**4.8**]***	**-10.3*** **
DLR (W m^{-2})	LOC	*2.5* [±*1.9*]	**2.5**	**2.9** [±**1.8**]	**3.2**
	PAY	0.9 [±1.6]	0.9	**2.4** [±**1.9**]	*2.5*
	DAV	**2.7** [±**1.5**]	**3.2**	**4.8** [±**1.7**]	**5.8**
	JFJ	**4.3** [±**2.1**]	**5.9**	**5.4** [±**1.6**]	**5.9**

*IWV at JFJ based on parameterisation (Leckner, 1978) rather than GNSS measurements. See text for discussion. **Trends for 1996 – Dec. 2011 are 2.9 and 3.0 W m^{-2}/decade (none significant) for the LLS and Sen's methods, respectively. ***Trends for 1996 – Dec. 2007 are -2.9 and -1.7 W m^{-2}/decade (none significant), respectively.

Table 4: Long-term average values of the shortwave and longwave cloud effects (SCE and LCE, respectively), and cloud radiative effect (CRE) for the 1996 – 2015 period at all four stations. The one sigma uncertainties are shown in brackets.

Station	SCE (W m^{-2})	LCE (W m^{-2})	CRE (W m^{-2})
LOC	-47.7 (±6.1)	23.3 (±2.8)	-24.4 (±5.1)
PAY	-71.9 (±5.5)	31.1 (±2.5)	-40.8 (±4.4)
DAV	-72.8 (±5.6)	32.1 (±3.0)	-40.7 (±3.9)
JFJ	-54.2 (±3.9)	49.9 (±5.6)	-4.3 (±5.3)
Average	-61.6 (±7.4)	34.1 (±3.7)	-27.6 (±5.4)

Table 5: Trend analysis of the shortwave and longwave cloud effects (SCE and LCE), and cloud radiative effect (CRE) for the 1996 – 2015 period at all four stations. Trends in italic (bold) are significant at the 90 % (95 %) confidence level. The 90 % confidence interval of each trend is shown in square brackets.

Station	SCE (W m^{-2}/decade)		LCE (W m^{-2}/decade)		CRE (W m^{-2}/decade)	
	LLS	Sen’s Slope	LLS	Sen’s Slope	LLS	Sen’s Slope
LOC	3.6 [±3.6]	2.2	-0.7 [±1.4]	-0.5	2.9 [±3.1]	2.3
PAY	*3.8* [±*3.6*]	*3.8*	-0.6 [±1.4]	-0.9	*3.1* [±*2.7*]	*2.3*
DAV	-0.1 [±3.6]	-0.4	1.0 [±1.5]	1.4	0.9 [±2.6]	1.3
JFJ	0.1 [±3.1]	-0.5	2.4 [±2.2]	2.8	2.5 [±2.6]	2.4

Table 6: Trend analysis of the longwave ~~anomalies~~ discrepancies during cloud-free conditions for the 1996 – 2015 period at all four stations. Trend values in italic (bold) are significant at the 90 % (95 %) level. Percentage values in brackets correspond to the contribution of the ~~anomaly~~ discrepancy to the overall trends in Table 3.

Station	Longwave	
	LLS method (W m^{-2}/decade)	Sen's slope (W m^{-2}/decade)
LOC	0.3 (10 %)	0.3 (9 %)
PAY	1.2 (51 %)	1.3 (46 %)
DAV	**3.4 (70 %)**	**3.1 (60 %)**
JFJ	**3.8 (70 %)**	**4.6 (78 %)**

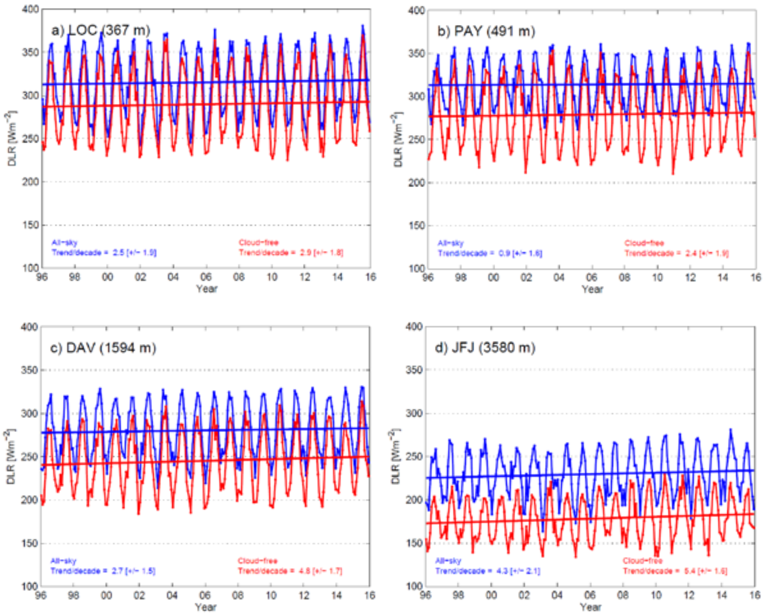

Figure 1: Monthly average DLR values during all-sky (blue) and cloud-free (red) conditions at: a) Locarno, b) Payerne, c) Davos, and d) Jungfraujoch. Each panel shows trend results from linear least squares analysis in Table 3. Values in square brackets represent the 90 % confidence interval of the trend. Scales are similar to aid the comparison.

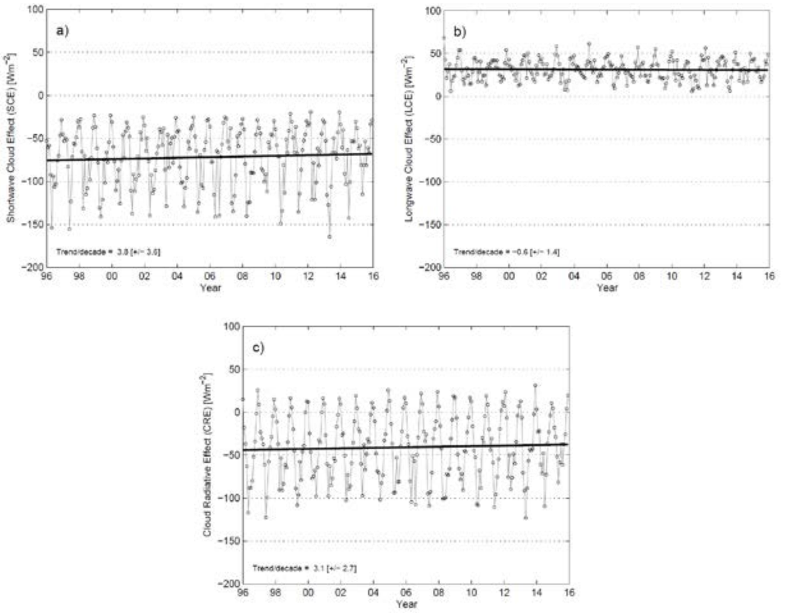

Figure 2: Time series of monthly average: a) SCE, b) LCE and c) CRE values at Payerne (PAY). Values in square brackets represent the 90 % confidence interval of the trend.

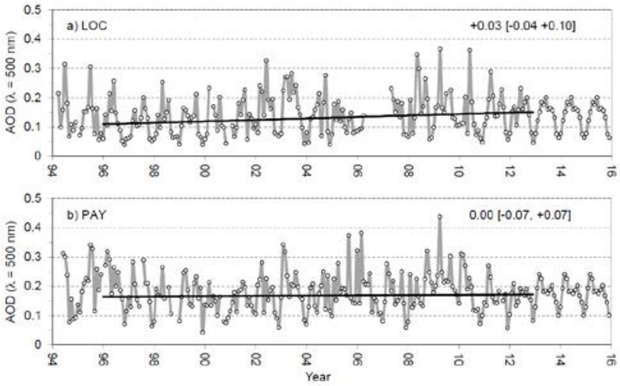

Figure 3: Time series of monthly AOD averages (λ = 500 nm) ~~averages~~ available since 1994 at: a) LOC and b) PAY. The 1996 – ~~2015~~ 2012 decadal trend is shown in the top right-hand corner where values in brackets represent the upper and lower bounds of the 90 % confidence interval. Trend values are only calculated for observations during 1996 – 2013, and a climatology (1996 – 2012) was used for the 2013 – 2015 period. See text for further details.

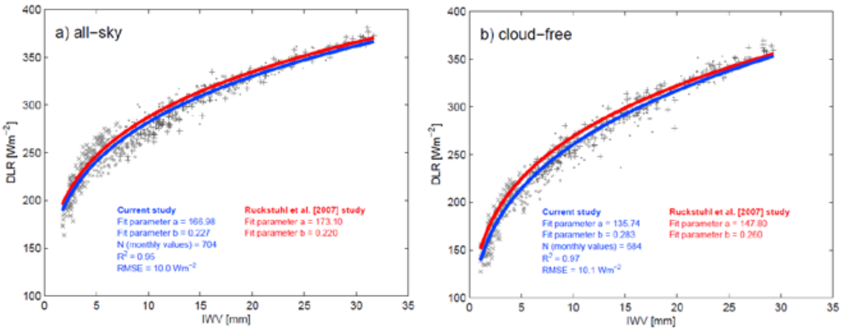

Figure 4: Monthly average DLR at all four stations (symbols: LOC = plus symbols, PAY = closed circles, DAV = open circles, and JFJ = crosses) for the 2000 – 2015 period versus IWV values during: a) all-sky conditions, and b) cloud-free conditions.