METEOSAT OBSERVATIONS OF DIURNAL VARIATION OF CLOUD FRACTIONAL COVER

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Abstract

Clouds play a key role in the Earth's radiation budget by reflecting shortwave radiation and reducing emissions of longwave radiation. A temporal shift in diurnal cycle of cloud formation leads to significant feedbacks in the climate system. The CM SAF ClOud Fractional Cover (CFC) dataset from METeosat First and Second Generation - Edition 1 (COMET) provides high-temporal 30-minute cloud fraction estimates for the period 1991-2015. This allows to study spatial variability and trends in diurnal cycle of cloudiness. The study aims at evaluation of the COMET dataset in terms of ability to reconstruct phase and amplitude of the CFC diurnal cycle, and at analysis of trends and variability in the cloudiness diurnal cycle over last 25 years. To this end, we validate COMET CFC diurnal cycle using observations from 111 SYNOP sites and compare it with other existing datasets (CLAAS, ISCCP and ERA-Interim). On average, the COMET CFC product overestimates the SYNOP observations by 0.95%, varying from -3.37% (in winter months) to approx. 2.8% (in summer months), and from 0.11% for Meteosat Second Generation (MSG) to 1.61% for Meteosat First Generation (MFG) satellite data. The maximum CFC during the day for COMET occurs approx. 20 minutes later than for synoptic observations. COMET slightly underestimates CFC amplitude by 3%. The time series of bias for CFC, phase and amplitude are homogeneous for the period 1991-2015, but CFC and amplitude reveal statistically significant trends (below 1% per decade). We conclude that the COMET dataset is suitable for analysis of temporal changes in cloud diurnal cycle. In this context, the trends and variability calculated from the COMET in 1991-2015 ought to be reliable. The significant temporal changes in phase and amplitude show distinct spatial patterns, which should be further analysed to explain their physical origin and impact on the climate system.

INTRODUCTION

Clouds play a key role in the Earth's radiation budget by reflecting shortwave radiation and reducing emissions of longwave radiation. Incoming shortwave radiation and emitted longwave radiation have a distinct diurnal fluctuation. Therefore, a shift in a diurnal cycle of cloudiness may cause a change in the radiation balance, that potentially leads to significant feedbacks in the climate system.

Global satellite imagery features more than a 30-year time span which is regarded as the minimal period to study climate changes (Rossow and Schiffer, 1999, Foster and Heidinger, 2013). In this respect, long CFC data records were derived from the Advanced Very High Resolution Radiometer (AVHRR) instrument mounted aboard NOAA and MetOp satellites. These data records include: International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer, 1999, Young *et al*. 2018) which also employ geostationary sensors, Pathfinder Atmospheres Extended (PATMOS-x, Heidinger *et al*., 2014), CLoud, Albedo and RAdiation dataset (CLARA-A2, Karlsson *et al*., 2017) of the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF), and the Community Cloud Retrieval for Climate dataset of the Cloud_cci data set (CC4CL-AVHRR, Stengel, *et al*. 2017) generated in the framework of the European Space Agency Climate Change Initiative. Climatic analyses of these datasets have mainly focused on temporal changes and variability of mean monthly cloud cover and cloud physical properties. To date, less attention has been paid to diurnal variability of cloudiness, and especially to its long-term changes. Meteosat-based CLAAS dataset (Benas *et al*.,

2017) derived from MSG/SEVIRI allows for studying CFC diurnal cycles, but only for the limited (non-climatological) period of 12 years (2004–2015).

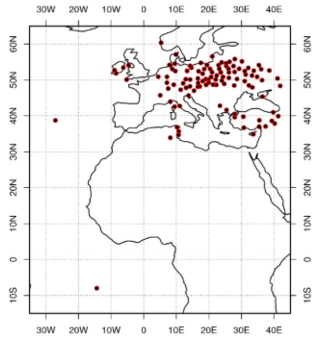

Figure 1: **SYNOP sites used for evaluation of COMET amplitude and phase of CFC diurnal cycle.**

In this context, the recently published CM SAF ClOud Fractional Cover (CFC) dataset from METeosat First and Second Generation - Edition 1 (COMET, Stöckli *et al*, 2018) provides high-temporal 30-minute CFC estimates for the period 1991-2015 that allows to study spatial variability and trends in diurnal cycle of cloudiness. Bojanowski *et al*. (2018) performed comparison of the COMET CFC with synoptic observations, CALIOP LiDAR cloud profiles, and other satellite-derived datasets. It was shown that overall mean bias of COMET is much below 1%, however with higher negative bias in N-hemisphere winter months, as well as with lower performance for satellite acquisitions at high sun zenith angles and high viewing angles. Pfeifroth *et al*. (2018) showed that COMET CFC trends are consistent with trends of satellite-derived top-of-atmosphere reflected radiation and surface solar radiation. However, there were no studies so far analysing COMET performance in representing CFC diurnal cycle and seeking for the climate signal in the temporal changes in diurnal cloud cycle.

The ultimate aim of this study is to analyse trends and variability of the cloudiness diurnal cycle over the last 25 years. To reach this aim we first evaluate COMET dataset in terms of ability: (1) to reconstruct phase and amplitude of the CFC diurnal cycle, and (2) to provide homogeneous climate information on trends and variability of amplitude and phase of CFC diurnal cycle. The evaluation is based on validation against ground-based observations, as well as on inter-comparison with existing data records.

DATA

Synoptic observations

Synoptic observations from the archive of the European Centre for Medium-Range Weather Forecasts (ECMWF) were used for evaluation of COMET-derived phase and amplitude of the CFC. We selected SYNOP sites that: (1) were not used for training of COMET's Bayesian classifier, (2) were within 60 degree N/S and 60 degree W/E, and (3) for which the Meteosat satellite viewing angle was below 70 degrees. Further, we performed a rigorous screening to select only those sites, for which observations were performed seamlessly every 3 hours in 1991-2015. A daily CFC mean was calculated if at least six 3-hourly observations were available. Then, at least 20 daily means were aggregated to derive monthly averages. Sites missing even a single monthly mean in 1991-2015 were excluded. Finally, we evaluated time series homogeneity of monthly CFC anomalies according to the Standard Normal Homogeneity Test (SNHT, Alexandersson,1986). Remarkably, none of the sites revealed any inhomogeneities. In previous analyses using the same initial set of SYNOP sites (e.g. Bojanowski *et al*. 2018, Bojanowski and Stöckli, 2017), SNHT was used to exclude several sites. Here we found out that all sites where observations were performed in 1991-2015 seamlessly with a stable frequency are of high quality. The screening procedure resulted in 111 SYNOP sites distributed within the Meteosat disc (Fig. 1). Yet, there is a strong bias towards European stations. The relatively low number of sites does not allow for analysis of spatial distribution of errors in COMET diurnal cycle, but guarantees best possible reference for analysing long-term stability, which is indispensable for climate analysis.

Provider	Dataset	Spatial res.	Temporal res.	Coverage
CM SAF	COMET ed. 1	0.05 deg	1 h	1991-2015
CM SAF	CLAAS-2	0.25 deg	1 h	2005-2015*
NOAA/NCEI	ISCCP-HGH	1 deg	3 h	1984-2012*
ECWMF	ERA-Interim	0.75 deg	3 h	1982-2015*
ECMWF	SYNOP	111 sites	3 h	1991-2015

* only a common period 2005-2012 was used

Table 1: **Datasets of CFC monthly mean diurnal cycles covering Meteosat disc used in the study.**

Satellite data records and reanalysis

COMET. The CM SAF Cloud Fractional Cover dataset from Meteosat First and Second Generation (COMET, Stöckli *et al*., 2018) covering 1991–2015 has been recently released by the EUMETSAT Satellite Application Facility for Climate Monitoring (CM SAF). COMET is derived from the MVIRI and SEVIRI imagers aboard geostationary Meteosat satellites. The COMET long-term cloud fraction climatology features high temporal (30-minute) and spatial (0.05x0.05 deg) resolutions that allows for studying diurnal cycle of cloudiness.
CLAAS. The CM SAF's Cloud Property Dataset Using SEVIRI (CLAAS-2) data record (Benas *et al*., 2017) is based on 12 years of MSG SEVIRI data. For the sake of inter-comparison we used the CLAAS CFC product available as composites of monthly mean diurnal cycles generated on a regular latitude/longitude grid with a spatial resolution of 0.25 degree.
ISCCP. The International Satellite Cloud Climatology Project (ISCCP) provides global coverage of cloud properties over a period of more than 35 years from polar-orbiting and geostationary platforms (Rossow and Schiffer, 1999). A new high-resolution version of the data record is denoted as ISCCP H-Series (Young *et al*., 2018). It spans from July 1983 and it is under continuous production to extend to the present. Here we used ISCCP-HGH product, i.e. CFC monthly mean diurnal cycles at 1 degree resolution.
ERA-Interim reanalysis. ERA-Interim (Dee *et al*., 2011) is the reanalysis provided by the ECMWF. It starts in 1979 and provides to date meteorological parameters in near real-time. The ERA-Interim atmospheric model has a spatial resolution of 0.75 degree. For this study we obtained monthly means of Total Cloud Cover combining analyses at 0,6,12 and 18UTC with forecast from 0 and 12UTC with 3 and 9 hours steps. This yielded CFC monthly mean diurnal cycles at 3 hour temporal resolution.

METHODS

Evaluation of the COMET against synoptic observations, inter-comparison between datasets, as well as trend analyses were performed using CFC monthly mean diurnal cycle (MMDC) products. Apart from the SYNOP, the datasets listed in Table 1 were obtained from data providers in the format of MMDC. Only instantaneous synoptic observations were aggregated to MMDC. Further, derivatives of the CFC diurnal cycle were generated. Amplitude of CFC diurnal cycle has been calculated as a difference between maximum and minimum CFC during a day. Phase of CFC diurnal cycle was calculated as the local solar time of maximum CFC during a day. To evaluate the COMET CFC, amplitude and phase, the Meteosat pixels were collocated with synoptic observations by means of the nearest neighbour approach. The collocations covering the entire available period of COMET climate data record i.e. 1991-2015, were used to assess performance of the COMET-based mean CFC, phase and amplitude by calculating mean bias error (MBE) and bias-corrected root mean square error (bcRMSE). Further, to investigate temporal stability and homogeneity of COMET-derived representation of CFC diurnal cycle, we analysed the time series of MBE. We tested the homogeneity by means of the SNHT using a critical value for T statistics proposed by Khaliq and Ouarda (2007), as well as the temporal stability revealed by a change (trend) of MBE over time.

	N	CFC (%)		Phase (h)		Amplitude (%)	
		MBE	bcRMSE	MBE	bcRMSE	MBE	bcRMSE
Overall	33195	0,95	9,73	0,33	5,25	-2,66	8,35
MFG	18648	1,61	9,87	0,34	5,46	-3,07	8,61
MSG	14547	0,11	9,50	0,32	4,97	-2,13	8,00
DJF	8300	-3,37	10,74	0,39	7,17	-0,15	6,93
MAM	8295	2,82	8,65	0,03	5,59	-3,67	7,79
JJA	8295	2,79	8,57	0,06	5,39	-3,24	8,35
SON	8305	1,60	9,44	0,83	6,17	-3,57	7,99
N-hemisphere	32895	0,95	9,74	0,34	5,26	-2,70	8,36
S-hemisphere	300	0,48	8,72	-0,49	4,51	2,44	7,52

Table 2: **Performance statistics: mean bias error (MBE) and bias-corrected root mean square error (bcRMSE), for COMET CFC, phase and amplitude measured against synoptic observations at 111 sites.**

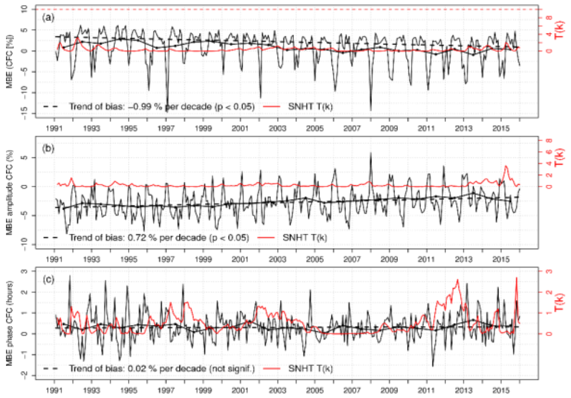

Figure 2: **Time series of mean bias error of COMET CFC, amplitude and phase validated against synoptic observations. The Standard Normal Homogeneity Test (in red) does not reveal any inhomogeneities for T(k) critical value at 10.2. The dashed line represents Theil-Sen linear trend.**

Next, we carried out a grid-based inter-comparison of COMET CFC diurnal cycles with other data records: CLAAS, ISCCP and ERA-Interim (Table 2). For this purpose, COMET and CLAAS were aggregated to 0.75x0.75 degree by means of the first-order conservative remapping. ISCCP data remained at 1 degree resolution. Inter-comparison was based on 8 observations per day (every 3 hours), which were available from all data sources for a common period 2005-2012. Finally, we conducted a grid-based trend analysis of CFC mean, phase and amplitude. We used monotonic trends derived with Theil-Sen estimates (Theil, 1950), and their significance was estimated with the Mann-Kendall test (Kendall, 1938; Mann, 1945). We first calculated and compared trends from all data sources for 2005-2012. Then, we generated trend maps for COMET only, but using the entire available period, i.e. 1991-2015.

RESULTS

Evaluation against SYNOP

Table 2 summarizes COMET performance in relation to the SYNOP observations. Overall, COMET CFC overestimates the reference by 0.95%. However, this mean statistic is a result of compensation of larger negative bias in (N-hemisphere) winter months (-3.37%) with positive bias in warmer months (approx. 2.8%). The underestimation of COMET CFC above bright and cold surfaces was reported by Bojanowski *et al*. (2018). However, presented study reveals a notable difference in bias between MFG (1.61%) and MSG (0.11%). Such a difference may result in a negative trend in MBE shown in Fig. 2a. Although the time series of MBE features strong seasonality with large CFC underestimation (up to 15%) in winter months, it is still homogeneous in 1991-2015.

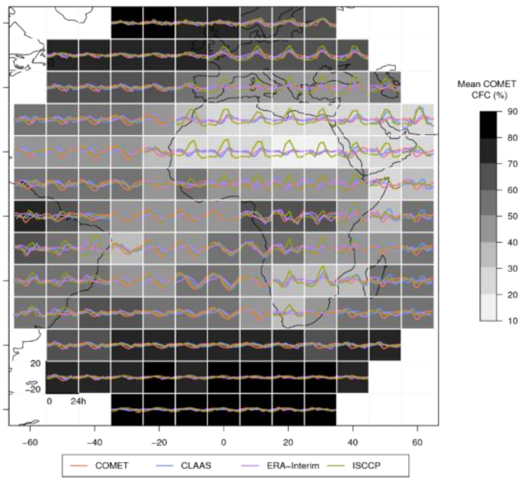

Figure 3: **CFC diurnal cycle from COMET, CLAAS, ISCCP and ERA-Interim aggregated in 10 x 10 degree grids. Axes used for each grid box are shown in the bottom left corner of the figure: y-axis represents 3-hourly CFC (%) divided by daily mean, x-axis represents local solar time (h). In grey colour scale the mean COMET CFC is shown.**

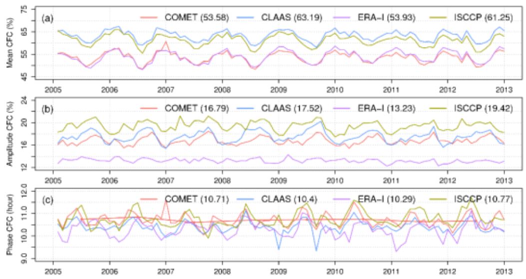

Figure 4: **Time series of mean, amplitude and phase of CFC diurnal cycle from COMET, CLAAS, ISCCP and ERA-Interim aggregated from all grids within Meteosat disc. Values in brackets represents the mean over the 2005-2013 period.**

The time of maximum CFC during the day (phase) occurs approx. 20 minutes later in COMET than in synoptic observations, with no difference for MFG and MSG. Unexpectedly, the largest bias is revealed for September-November and not for winter months (December-February). Yet, the lowest precision (according to bcRMSE) is for the latter. In general, relatively large bcRMSE for phase can originate from regions with no distinct CFC diurnal cycle. In these regions, a slight bias in CFC can cause large errors in phase. The MBE of phase shows no significant trend and no inhomogeneities (Fig. 2c). The range between maximum and minimum diurnal CFC (amplitude) is 3% lower in COMET than in synoptic observations. Despite the lowest accuracy and precision of mean CFC estimates for winter months, for these months the CFC amplitude is the most accurate (-0.15%). Figure 2b shows a significant positive bias in amplitude MBE, but no inhomogeneities. Thus, it is unlikely that is caused by the difference in cloud detection accuracy between MFG and MSG sensors.

Inter-comparisons

The course of CFC diurnal cycle reveal noticeable spatial variation among analysed datasets (Fig. 3). For regions of relatively stable CFC across a day, all data sources do agree. This can be seen over the ocean at mid-high latitudes at both hemispheres (approx. > 40 deg). Yet, over bright desserts with relatively stable low cloud cover, ISCCP reveals large overestimations around noon (i.e. for low sun zenith angles). In Western and Central Europe, all sources reveal similar diurnal cycles, but ISCCP again detects larger CFC amplitude. Concurrently, according to ERA-Interim, the maximum cloudiness occurs earlier during the day than in rest of the datasets. COMET detects a distinct CFC minimum around noon over the Indian Ocean, which is not revealed by other products. Finally, it must be noted that all of the datasets disagree over South America. These discrepancies can be however related to lower performance of CFC derived from geostationary satellites at high viewing angles.

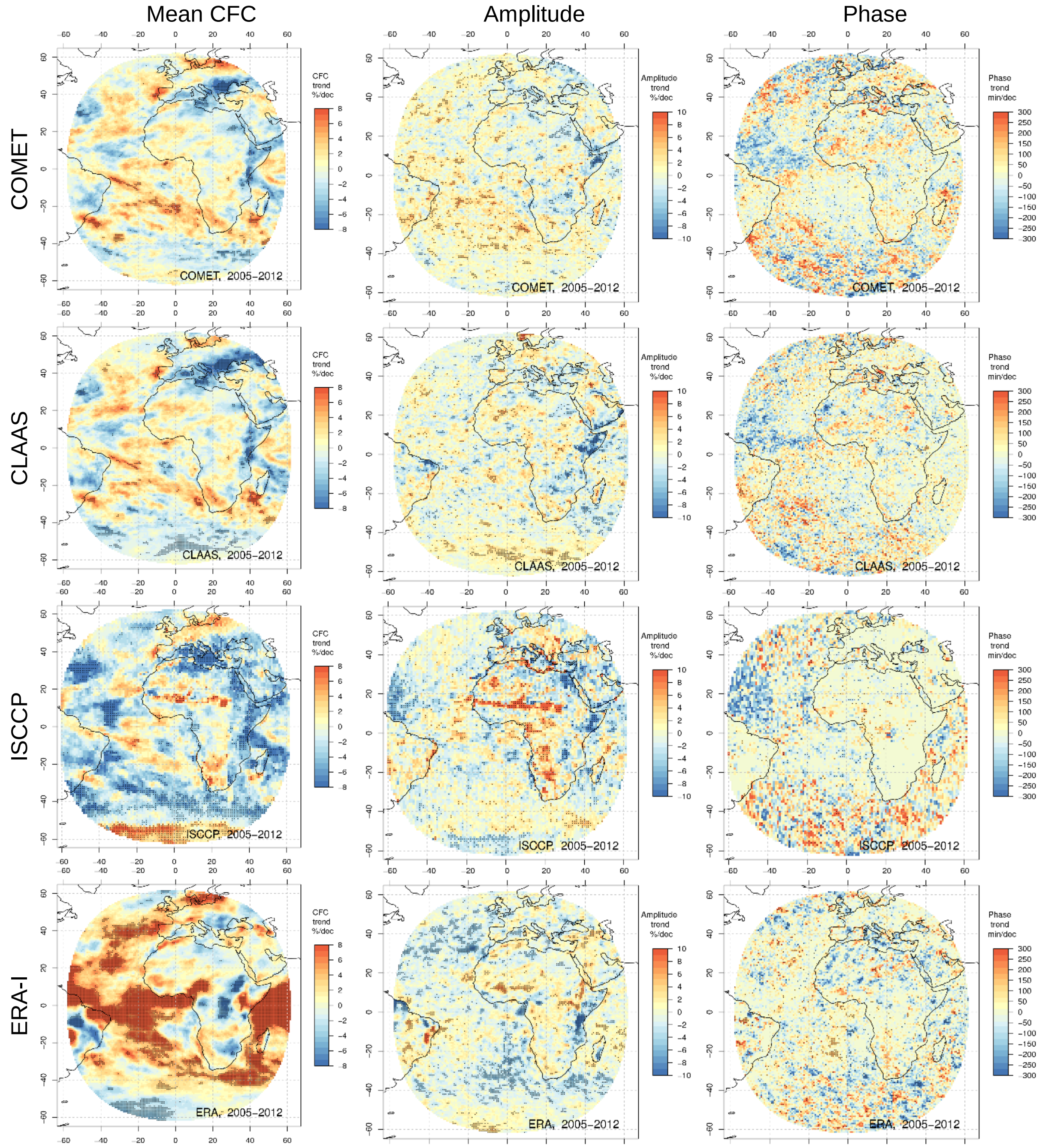

Figure 5: **Comparison of Theil-Sen monotonic trends in CFC, amplitude and phase calculated for all intercompared datasets in a common 2005-2012 period. Statistical significance (p-val < 0.05) according to the Mann-Kendall test is shown by black dots.**

Figure 4 shows time series of CFC, phase and amplitude averaged from all grids. COMET and ERA-Interim reveal similar mean CFC range (Fig. 4a). Both sources are expected to have CFC values close to synoptic observations, because COMET's Bayesian classifier was trained against SYNOP data, and these were also used in the data assimilation scheme of ERA-Interim reanalysis. CFC of CLAAS and ISCCP show similar values. These COMET-ERA-Interim and CLAAS-ISCCP similarities are no longer visible for amplitude (Fig. 4b). Especially ERA-Interim outlies with lower CFC amplitude and less distinct amplitude seasonality. Also for phase (Fig. 4c), ERA-Interim differs from other data sources detecting the highest CFC during the day, on average at least half an hour earlier.

Remarkably, COMET and CLAAS show some single outlying months, for instance for winter 2007 and winter 2009, respectively.

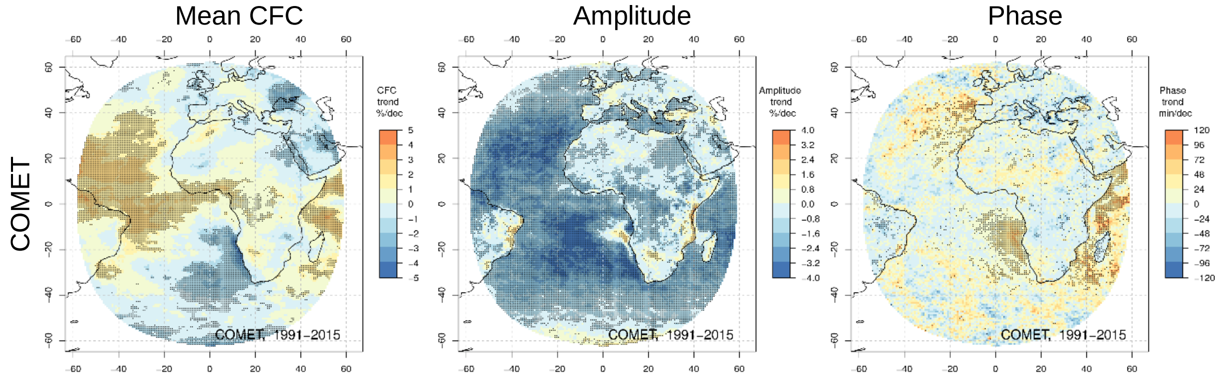

Figure 6: **COMET CFC, amplitude and phase of Theil-Sen monotonic trend calculated for 1991-2015. Statistical significance (p-val < 0.05) according to the Mann-Kendall test is shown by black dots. Please note the different colour bars than in Fig.5.**

Trend analysis

COMET and CLAAS show similar trends in mean CFC (Fig. 5). ISCCP agrees in most areas, however trend values and statistical significance differ. ISCCP also shows, unconfirmed by other sources, significant positive trends in southern high latitudes, and in the southern edges of Sahara Dessert. ERA-Interim shows similar patterns than other datasets, but with stronger trends and larger areas of their significance. Trends in amplitude are spatially more heterogenous. Still, the datasets agree at several regions of significant positive trend over the Atlantic, as well as at Horn of Africa, where significant negative amplitude trend was detected. Phase does not reveal significant trends, which is showed by all the sources. Distinct climate signals are revealed while analysing COMET trends in 1991-2015 (Fig. 6). Clear spatial patterns of significant trends in mean CFC can be observed, e.g. negative trend around Black Sea and in the Southern Atlantic, as well as positive trends in the Northern and Central Atlantic and the Indian Ocean. Amplitude tends to significantly decrease over the ocean within the whole Meteosat disc. Phase reveals only a few separate spots of positive trends – again only over the ocean.

CONCLUSIONS

We conclude that COMET dataset is suitable for analysis of temporal changes in diurnal cloud formation. This is proven by temporal stability of CFC amplitude and phase measured against the referential SYNOP observations. Moreover, the inter-comparison of trends in CFC phase and amplitude within overlapping period (2005-2012) also shows good agreement among analysed datasets. In this context, the trends and variability calculated from COMET in 1991-2015 ought to be reliable. The significant temporal changes in phase and amplitude show distinct spatial patterns. These are recommended for further climate analysis to explain the phenomena and assess their impact on climate system.

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