Spatiotemporal dynamics of fog and low clouds in the Namib unveiled with ground and space-based observations

— EDITOR AND REVIEWER RESPONSES —

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We would like to thank the co-editor Dr. Frank Eckardt and the two reviewers Dr. Jana Olivier and Stephanie Westerhuis for their careful reviews of the manuscript and their constructive criticism. Comments by the co-editor/referees are colored in blue, our replies or comments are colored in black.

Response to the Co-Editor

This is a very interesting paper that provides a first insight into the behaviour of fog fusing satellite and ground observations.

I have two comments

One detailed and one general.

Detailed comment.

Figures 2,3 and 4. These are a bit cryptic given the use of acronyms which need to be retrieved one by one from the text. I would encourage spelling these out in the captions. Furthermore, the linkages between the series of figures are not great.

Figure 2b) please show the pixels that have been used to derive 2c) Please extend the latitudes from a and b into c.

Thank you for the detailed comments on the figures. We agree that the mentioned aspects of the figures can be improved upon. The newly produced version of figure 2 is shown below (Fig. 1) and included in the revised manuscript.

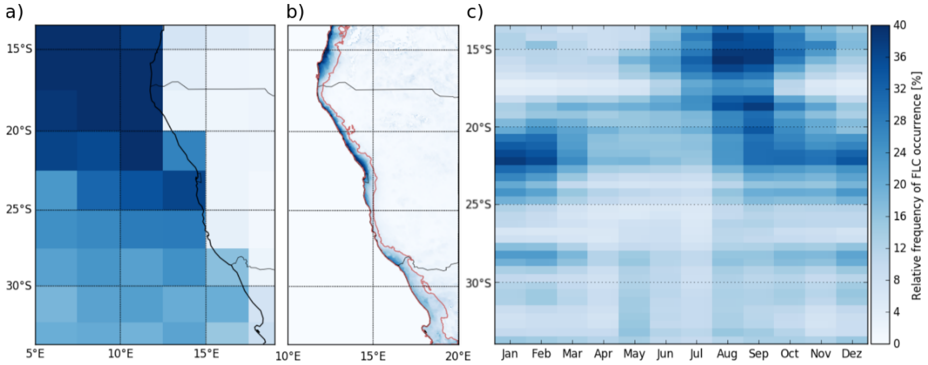

Figure 1: A satellite-based climatology of relative fog and low cloud occurrence frequency derived by using the algorithms presented in Cermak (2018) (a)) and Andersen and Cermak (2018) (b)), based on the nearly complete data records of CALIPSO (2006–2017) and SEVIRI (2004–2017). The seasonality (c)) is computed by averaging pixels from (b) in coastal regions (maximum 100 km distance to coastline) with frequent FLC occurrence (minimum of 5 % relative FLC occurrence in the 14-year climatology shown in b)). The regions used for averaging in c) lie within the orange contours in b).

Figure 3) spell out CTB and CTH

Also, the fact that CL31 is at CM needs to be extracted from the main text. This is very confusing. Why is there a change in CM and CL31 for July and August? Why is there no line for the CL31 observations? Also, what is ASL and AGL?

We have incorporated the suggestions into the figure and agree that this improves its clarity. ASL and AGL stand for above sea level and above ground level, respectively. This is now written out in the caption.

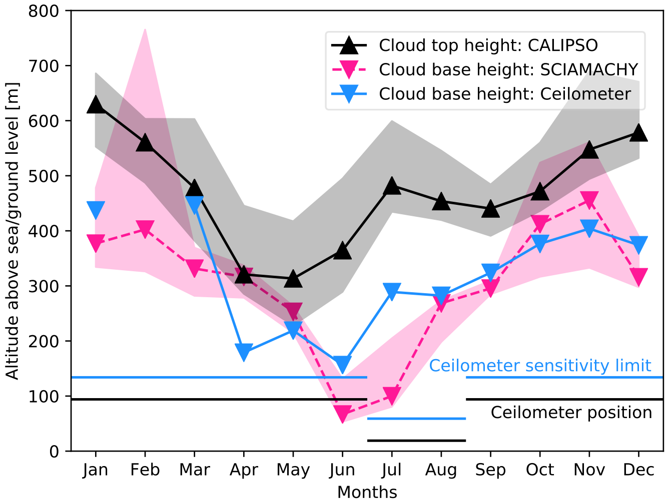

Figure 2: c) Medians, 25th and 75th percentiles of monthly averaged CBH and CTH in the central Namib based on SCIAMACHY (above ground level; 22.5°S-24.0°S and 14.25°E–15.5°E, 2003–2009) and CALIPSO (above sea level; 22.5°S-24.0°S and 14.0°E–15.5°E, 2006–2017) observations, respectively. Ceilometer CBH observations (above sea level) are only available since September 2017. Ceilometer positions (CoastalMet from September–June and Swakopmund July and August) and sensitivity limits are illustrated by thin horizontal lines and described in Sec. 2.4.

Figure 4) please depict the areas used to make in 4b in 4a) as boxes or state the northern and southernmost extent of these observations.

This is a good suggestion. We have now incorporated lines to illustrate the southern/northern boundaries of the three regions and included markers in a) to visually link the panels. The result is shown below (Fig. 3) and is included in the revised version of the manuscript.

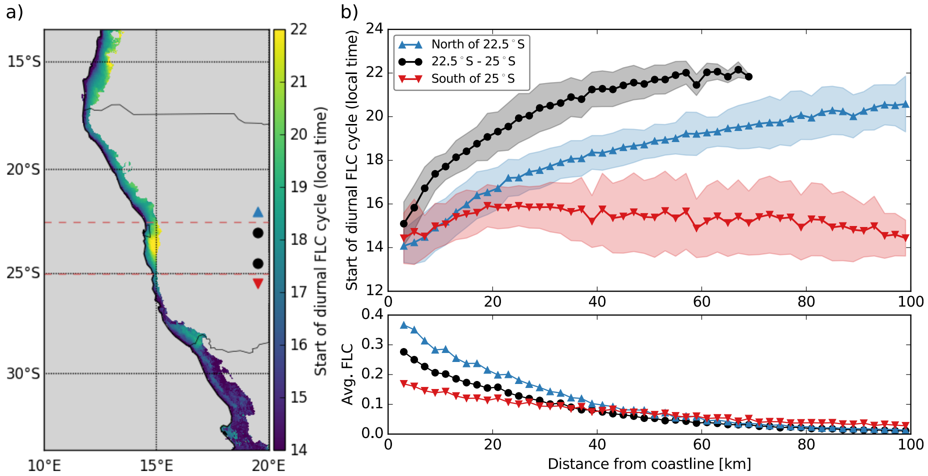

Figure 3: a) The time of the start of the diurnal FLC cycle on pixel level. Pixels are not considered which either are more than 100 km removed from the coastline or that feature a relative frequency of FLC occurrence of less than 5 %. The dashed horizontal lines indicate the northern/southern boundaries of the three regions considered in b), with markers illustrating their respective association. b) Upper panel: The average timing of start of the diurnal FLC cycle as a function of average distance to the coastline. Shaded area illustrates mean +/- one standard deviation. Lower panel: Average relative FLC occurrence frequency in the three subregions. The same pixels are considered as in panel a) and are averaged in 2 km distance bins (x axis).

Appendix A

Why don't provide a list of all the acronyms

The appendix now provides a full list of all acronyms used in the manuscript.

On a more general note, the paper is very descriptive and not explanatory. It would be great to tie these observations into our understanding of regional Synoptics and local winds. The work by Tyson would be particularly apt to consider. At the moment there are linkages to processes even at the most basic level. If this is to happen elsewhere at least a brief description and explanation would be welcome.

Thank you for this comment. We agree that the main focus of the manuscript is to characterize the spatiotemporal patterns of FLC in the region, with some limited inferences of processes. We agree that more research is needed to understand the role of synoptic scale and local drivers, and are currently investigating these aspects within the NaFoLiCA research project. We do feel that these aspects are not within the scope of the current manuscript, though, as this topic is complex and demands a thorough treatment. We do now state our plans to tackle these research questions more clearly in the last paragraph of the revised manuscript: *The interplay of large-scale dynamics with local winds (Tyson and Seely, 1980; Olivier, 1992, and sources therein), (sea) surface characteristics (Olivier, 1995), radiative transfer and aerosols is likely to explain fog and low cloud occurrence and variability in the Namib desert. The exact manner, however, by which the various processes determine this complex system and its observed spatiotemporal dynamics is still unclear. Future research is thus needed to more fully understand the processes that lead to the variability in spatial patterns, overall coverage, vertical structure and life cycle of FLC, as well its capacity to serve as a water source for ecosystems. Within the ongoing research project Namib Fog Life Cycle Analysis (NaFoLiCA), these aspects will be studied using a combination of satellite data, ground-based measurements and numerical models.*

Response to Dr. Jana Olivier

General comments: While fog and low cloud (FLC) form the lifeblood of desert flora and fauna in the Namib, their occurrence are considered to be hazardous to human activities such as aviation and shipping. It is thus important to understand where and when FLC occur. This paper examines the spatial and temporal incidence of FLC in the Namib, with special reference to the Central Namib. It also aims to help understand the processes driving the occurrence of FLC. Both ground based data and a variety of geostationary satellite based observations such as SEVIRI, CALIPSO, SCIAMACHY are used for this purpose. The use of these space-based observation adds a novel aspect to research. The two guiding hypotheses were successfully addressed and found to be valid. The paper is well-written and a pleasure to read. It fulfils all the criteria required for publication in a high-impact journal.

Thank you for reviewing the manuscript and for the positive feedback.

Specific comments: Of special importance is the simple and clear explanation given for the anomaly between the ground- based and satellite based observations of the seasonal incidence of FLC in coastal regions. Unfortunately, this implies that satellite-based data cannot be used to examine the extent of fog over the coastal and adjacent maritime regions. The final recommendation by the authors i.e. that 'future research should focus on further characterization of the dynamical conditions and drivers that determine diurnal and seasonal variability and vertical structure of FLC is extremely important'. This should include the seasonal shift in location and intensity of the S. Atlantic and sub continental high pressure systems over southern Africa and their impact on the height of the inversion layer over the Namib. This together with the influence of the Namib-Benguela Upwelling System will provide a comprehensive picture and explanation of surface fog occurrence in the coastal regions.

Thank you for this comment. We agree wholeheartedly that the aspects mentioned by Dr. Jana Olivier are highly relevant and could significantly expand our current system understanding. We are in the process of investigating the role of large scale dynamics and SST for FLC occurrence patterns on different time scales. However, we feel that this is not within the scope of the current manuscript. As mentoined above, we now describe future goals more clearly in the revised version of the manuscript.

Suggestions: Use colours for b in figure 4 rather than triangles. It will facilitate the interpretation of the results.

We agree that the new version of the figure (Fig. 3 in this document) is easier to interpret due to the added coloring.

Please note: Research was conducted on fog in the Namib by Olivier J 1992: Some spatial and temporal aspects of fog in the Namib. SA Geograaf, 19(1/2) 106 - 126. If required, I can send a copy of the article to the authors.

Thank you for the reference, this was an oversight on our part. We have been able to locate the article and it is now properly cited in the manuscript.

Technical corrections: p2, 26: replace 'nearby' with 'near'

We have now corrected this in the manuscript.

p3, 9: is CALIPSO level '2 5 km' correct?

Yes, this is correct.

p5, 27: word missing after 'over...,'

Yes, this is now corrected in the revised manuscript.

p10, 22: ..In the central Namib, the diurnal cycle... are you referring to the whole central Namib or to the coastal region in the central Namib?

This refers to the "whole" central Namib as defined in the manuscript. Basically, this is the "yellow blob" in Fig. 4a), where FLC occurs systematically later than in the adjacent regions to the north and south.

Response to Stephanie Westerhuis

General comments

Andersen et al. present a study about the spatial and temporal patterns of fog and low clouds in the Namib. The present paper extends the knowledge gained from earlier studies via the combination of ground measurements (fog precipitation, relative humidity and cloud base height) with data from several satellite platforms (spatial extent, cloud base height and cloud top height). They investigate spatial, seasonal and temporal patterns. In the end, they derive a conceptual model for fog and low clouds in the Namib.

The main conclusions in this study are generally comprehensible and well substantiated by the results. I congratulate the authors for deriving the very nicely summarising schematic of the seasonal FLC cycle. My main point to improve the paper in the revisions is that the information conveyed to the reader could be written in a more easily understandable and more concise way. Especially at the beginning, it was not obvious to me which phenomenon was referred to with "satellite observations differ from station measurements" as comparing ground fog measurements with satellite fog and low clouds observations obviously only tells half of the story.

The figures are nicely drafted and I only made a few suggestions to add small features which could facilitate it for the reader to grasp the content (see specific comments).

The text is carefully written, some details to improve are pointed out in the technical corrections.

Overall, the paper is understandable and interesting and I recommend publication after minor revisions.

Thank you for reviewing the manuscript and for the positive feedback.

Specific comments

P1L4-6: The sentence "...observed seasonal patterns derived from satellite observations differ from station measurements..." is misleading, it should be clarified that station measurements only observe ground fog.

This is now clarified in the revised version of the manuscript.

P2L3-4: Again, it should be stated more clearly what kind of station measurements are compared to satellite data.

This is now clarified in the revised version of the manuscript.

P2L5: Explain better what you mean with “seasonal cycles of formation mechanisms”.

The text now states: ”This could be related to seasonally varying mechanisms responsible for fog formation/type or due to a seasonal cycle in vertical characteristics of FLC in this region,[...]”

I see a benefit in adding a small table or graph summarising the used datasets including availability (time period) and resolution (time and space).

Thank you for this comment. We feel that an additional table would introduce quite a bit of redundancy to the manuscript and would thus prefer to keep the data descriptions in their current state.

Section 2.3 is more difficult to read than the ones before. Shorter, less nested sentences could improve readability.

We have rephrased some sentences in this section for clarity.

Figure 4: I suggest to indicate the three separated regions from b) also on the map in a). And to me it is not obvious which data are comprised in one circle/triangle.

For added clarity, we now show region boundaries and markers for b) in a). (Fig. 3 in this document).

The text could be somewhat sharpened: Eg P7L15: What do you mean with “distinct spatial patterns”?

Yes, this was not clearly written. The sentence now reads: ”It is apparent from Fig. 4 a) that the start of the diurnal FLC cycle is closely related to the distance from the coastline, at least north of 25°S (r = 0.86 between 22.5°S and 25°S and r = 0.85 north of 22.5°S)."

P9L1: Which are the "subregionally different mechanisms"?

The close relationship between the start of the diurnal FLC cycle and the distance from the coastline suggests dominant advective processes north of 25°S. South of 25°S, this is no longer apparent. This leads us to the conclusion that advective mechnasms are unlikely to dominate in this region, however, as of now there are no observational clues to what extent specific mechanisms contribute to the formation of FLC in the southern region.

P9L3: Can you elaborate the relationship you are referring to in "FLC occurrence frequency...features a strong relationship"? → These sentences sound complicated but do not provide much information to the reader. My suggestion is to either delete them or explain more specific what you want the reader to know.

In the revised version of the manuscript this is now more clearly described: "The lower panel of Fig. 4 b) shows the average FLC occurrence frequency in the three subregions as a function of the distance to the coastline that features a strong relationship, especially north of 25°S. While this is a typical feature of coastal fog (e.g., Olivier, 1992), it serves as an additional indication that the region south of 25°S is not influenced by marine airmasses to the same extent as regions further north."

P9L8: How do you interpret this discrepancy between the high- and low-level FLS season? Can you indicate the distance where FLS occurrence is below 5% in Fig. 5?

Based on the results it is hard to say what exatly is responsible for the observed seasonal differences. We do not want to speculate and thereby just state that *In general, the slope of the relationship illustrated in the upper panel* *of Fig. 5 can be affected by the average advection speed, the fraction of advective FLC, and the partial contribution of random misclassifications.* We do not see 5% as a strict threshold under which you cannot interpret the results any more. We rather state that lower FLC occurrence frequency also lowers the confidence in derived statistics, e.g., in those related to the diurnal cycle, due to the factors outlined by the sentence stated above.

P10L17: Do you want to say that satellite observations really “overestimate ground fog” or that based on these observations it is just not possible to distinguish between fog at the ground and low clouds lifted from the surface?

We argue that the probability of satellite-derived FLC being ground fog shifts with season and location. Using FLC for an estimate on fog occurrence at coastal locations between August and February would be specifically prone to an overestimation of fog occurrence frequency.

Technical corrections

Overall: The term FLC is used inconsistently. Either use plural or singular and always use the abbreviation after it is introduced (eg P2L16+17).

The term FLC/FLCs is now used consistently in the updated version of the manuscript. In specifically relevant sentences of the manuscript, as e.g. the sentence pointed out here, we deliberately chose to write out fog and low clouds instead of using the abbreviation. This is intended to help readers who are just skimming over the paper to understand the most relevant sentences even though they might not know all of the abbreviations.

P1L8: This should be “25°S”, not “25°N” I presume.

Yes, of course you are right. This is now corrected in the manuscript.

P1L9 and P8L1: Please explain “r”.

This should be more clear in the current manuscript.

P2L1: patterns ”of” fog

Yes, this is now corrected in the manuscript.

P2L25: In Fig. 1a) the western boundary is 10°E. For consistency reasons, I suggest taking the same extent as in Fig. 2a).

The western extent of the figures was chosen deliberately. 10°E makes sense for Fig. 1a) and Fig. 2b), as no information content would be added by further extending the figure over the ocean. Fig. 2a) shows the spatial connection of the FLC field over the coast with the stratocumulus field in the southeastern Atlantic. We would thus prefer to keep the figures at their current state.

P3L9: Although correct, a reader who is not familiar with CALIPSO products might think that “level 2 5 km” is a typo. The sentence could be rearranged.

As this seems to be the official product name, we would like to keep the sentence in its current form.

P3L11: To my knowledge, dates should be written in the form “June 13, 2006”.

Yes, indeed, we have corrected this in the revised version of the manuscript.

P4L1 and L19: Indicate size also in km, for easier comparison with SEVIRI data.

This is technically not possible, as the size of a 1°x1° area depends on its latitude.

P5 title: Suggestion: Fog and low cloud “spatial” patterns

Yes, we agree that this is more accurate. We have changed the title accordingly.

P5L27: unfinished sentence

We have corrected the sentence.

P8 figure caption: “fls” should be in capitals.

Yes, this is now corrected in the manuscript.

P8L8: Omit the “the” at the end of the line.

We have corrected the sentence.

References

Andersen, H. and Cermak, J. (2018). First fully diurnal fog and low cloud satellite detection reveals life cycle in the Namib. *Atmospheric Measurement Techniques*, 11(July):5461–5470.

Cermak, J. (2018). Fog and low cloud frequency and properties from active-sensor satellite data. *Remote Sensing*, 10(8):1–7.

Olivier, J. (1992). Some spatial and temporal aspects of fog in the Namib. *South African Geographer*, 19(1-2):106–126.

Olivier, J. (1995). Spatial distribution of fog in the Namib. *Journal of Arid Environments*, 29(2):129–138.

Tyson, P. D. and Seely, M. K. (1980). Local winds over the central Namib. *South African Geographical Journal*, 62(2):135–150.

Spatiotemporal dynamics of fog and low clouds in the Namib unveiled with ground and space-based observations

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Abstract. Fog is an essential component of Namib-region ecosystems. Current knowledge on Namib-region fog patterns and processes is limited by a lack of coherent observations in space and time. In this study, data from multiple satellite platforms and station measurements paint a coherent picture of the spatiotemporal dynamics of fog and low cloud (FLC) distribution. It is found that observed seasonal FLC patterns derived from satellite observations differ from ~~station measurements in coastal~~ fog measurements at coastal station locations, whereas they agree further inland. This is linked to an observed seasonal cycle in the vertical structure of FLC that determines the probability of low-level clouds touching the ground. For the first time, these observations are complemented by spatially coherent statistics concerning the diurnal cycle of FLC using geostationary satellite data. The average timing of the start of the diurnal FLC cycle is found to strongly depend on the distance to the coastline (~~r~~ correlation ≈ 0.85 north of 25°~~N~~S), a clear indication of dominant advective processes. In the central Namib, FLC typically occurs 2–4 hours later than in other coastal regions, possibly due to local advection patterns. The findings lead to a new conceptual model of the spatiotemporal dynamics of fog and low clouds in the Namib.

1 Introduction

In arid environments like the Namib, fog can be a crucial source of water for many species and ecosystems (e.g. Seely et al., 1977; Seely, 1979; Shanyengana, 2002; Ebner et al., 2011; Azúa-Bustos et al., 2011; Roth-Nebelsick et al., 2012; Eckardt et al., 2013; McHugh et al., 2015). However, only little is known about its spatial and temporal patterns, as well as the environmental drivers of fog in the Namib.

While meteorological measurements are generally sparse in this region, historical station observations of fog in the central Namib between the 1940s and the 1980s have shown contrasting seasonal patterns of fog occurrence at coastal and inland locations (Nagel, 1959; Lancaster et al., 1984). These studies find that at inland locations, fog tends to occur less frequently between April and August, while fog occurrence at coastal locations peaks during this time. More recently, satellite data have been used to study the patterns of fog and low clouds (~~FLC~~FLCs) in the Namib (e.g. Olivier, 1995; Cermak, 2012; Andersen and Cermak, 2018). The only satellite-based study that comprises a multi-year seasonal cycle of ~~FLC~~ FLCs is presented in Cermak (2012), and while the observed patterns compare well to station measurements of fog presented in (Lancaster et al., 1984) at the inland station in Gobabeb, observed seasonal cycles from satellite data and station measurements of fog differ at the coastal location in Walvis Bay. This could be related to ~~seasonal cycles of formation mechanisms or~~ seasonally varying mechanisms responsible for fog formation/type or due to a seasonal cycle in vertical characteristics of ~~FLC~~ FLCs in this region, i.e. the fact that all low clouds are treated summarily by the satellite technique, whereas only the ones with the lowest cloud bases manifest themselves as fog as reported by ground-based observations. However, a spatially coherent detailed characterization of ~~FLC~~FLCs, including vertical characteristics, as well as seasonal and diurnal patterns is still missing. Uncertainties also exist related to the mechanisms that lead to fog formation. While most studies ~~(e.g. Lancaster et al., 1984; Olivier and Stockton, 1989; Olivier, 1995; Cermak, 2012; Andersen and Cermak, 2018)~~ (e.g. Lancaster et al., Namib-region fog mostly to the advection of low clouds formed over the cool waters of the Benguela current, recent analyses of stable isotopes have pointed to mixed or sweet water sources, which has been interpreted as an indication for radiation fog (Kaseke et al., 2017, 2018). However, the labor-intensive field work needed for isotope analyses has limited these studies in spatial and temporal extent, underscoring the need for a spatiotemporally complete and coherent characterization of FLC mechanisms. In this study, active-sensor and passive-sensor satellite data are used in conjunction with ground-based meteorological measurements to better understand fog and low-cloud patterns at different scales. The goal of this study is to provide climatological, spatiotemporally complete patterns that help understand the processes driving Namib-region fog and low clouds.

The guiding hypotheses are that

1. FLC patterns in time and space differ distinctly between the coastline and regions further inland.
2. Apparent differences between the seasonal cycle of fog as observed from the ground and satellite perspectives are explained by a seasonal cycle in the vertical structure of ~~FLC~~FLCs.

2 Data and methods

In this study, multiple data sets from various space-based sensors are used to characterize ~~FLC~~ FLCs and analyze its spatiotemporal occurrence patterns. The general spatial domain investigated in this study is the western coastline of southern Africa (13.5°S–34°S and 5°E–20°E, Fig. 1 a)), with a specific focus on patterns over land and a core region of FLC occurrence in the central Namib ~~nearby~~ near Walvis Bay (22.5°S–24°S and ≈14°E–15.5°E, Fig. 1 b)). In the central Namib, the FogNet station network (Kaspar et al., 2015) is located, providing a ground-based perspective on fog patterns. Detailed descriptions of the different sensors, techniques and data sets used in this study are given in sections 2.1–2.4.

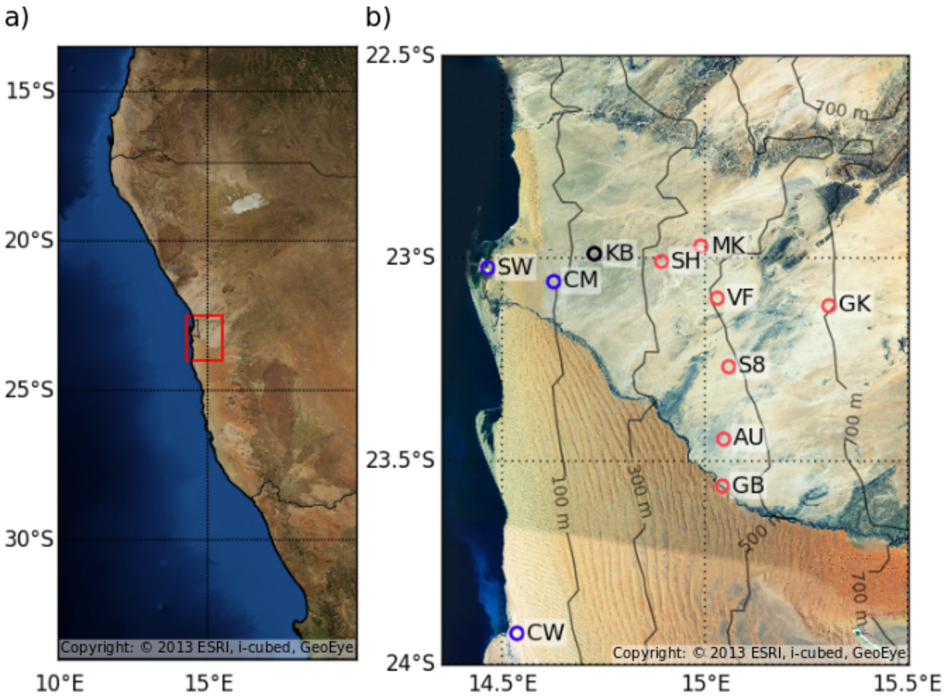

Figure 1. a) An overview of the study area. The red box highlights the central Namib, which is shown in more detail in b): FogNet stations are illustrated by circles and are annotated with their respective IDs (full station names are given in the appendix). Blue circles represent coastal, and red circles inland stations as defined in this study (section 2.4). The station Kleinberg (KB) is colored in black, as it is viewed to be at a transitional location not clearly belonging to either category.

2.1 SEVIRI

Coherent spatiotemporal patterns of FLC occurrence are created using data from the Spinning-Enhanced Visible and Infrared Imager (SEVIRI) aboard the Meteosat Second Generation (MSG) satellites. The sensor has a nadir spatial resolution of 3 km and provides 96 hemispheric scans per day (repeat rate of 15 minutes) (Schmetz et al., 2002). The novel FLC-detection technique by Andersen and Cermak (2018) is applied to data of nearly the entire operational period of MSG satellites (2004–2017). The technique uses only observations in the thermal infrared, enabling a fully-diurnal detection of ~~FLC~~ FLCs in the region. It has shown good skill in a validation against surface net radiation measurements with a probability of detection of 94 %, a false alarm rate of 12 % and a general correctness of all classifications of 97 % (Andersen and Cermak, 2018).

2.2 CALIPSO

SEVIRI observations are complemented by retrieved layer heights from the active-sensor platform from Cloud-Aerosol LiDAR and Pathfinder Satellite Observations (CALIPSO). Mounted onboard the satellite is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) that samples with 30 m vertical and 333 m horizontal resolutions. Here, the CALIPSO level-2~~5~~ 5 km cloud-layer product (version 4.10) is used to detect ~~FLC~~ FLCs with the algorithm developed by Cermak (2018) for the period of June ~~, 13th~~ 13, 2006 – December ~~, 31st~~ 31, 2017 (daytime and night-time). The algorithm essentially detects low clouds with a cloud-top altitude of <= 2000 m and a cloud-base altitude <= 500 m above ground level. Additionally, spatial and temporal patterns of cloud-top height (CTH) are generated using the same data. Results are then aggregated to 2.5°x2.5° regions to increase the sample size as in Cermak (2018).

2.3 SCIAMACHY

The ~~cloud bottom altitude from the~~ SCanning Imaging Absorption spectroMeter of Atmospheric CHartographY (SCIAMACHY) sensor (Bovensmann et al., 1999), on board ~~Envisat, has been inferred from~~ of the Envisat platform, is used to infer cloud bottom altitudes. This is done using the fit of sunlight absorption by the strongest molecular band of oxygen (the A-band), located in the near-infrared (NIR) between 750-770 nm ~~, at a~~ (nominal spectral resolution ~~of~~ 0.4 nm). The deployed algorithm Semi-Analytical CloUd Retrieval Algorithm (SACURA) (Rozanov and Kokhanovsky, 2004; Lelli et al., 2012) exploits the constant vertical abundance of columnar oxygen so that any cloud intervening in the field-of-view of the sensor shields the gas column below, thus changing the depth of the A-band. Concurrently, the increase of absorption by oxygen within a cloud due to multiple scattering is accounted for by calculating the single-scattering albedo of the atmospheric volume at 760 nm. In this way, with the knowledge of the cloud optical thickness (COT) computed at the non-absorbing channel 758 nm, the inversion of the measurement delivers the cloud geometrical extent. As long as the sensed cloud is single-layered and has a constant liquid water content, the reported model error in CBH amounts to -200/350 m (Lelli et al., 2011), which is paired to a CTH absolute error of ± 250 m (Lelli et al., 2012, 2014)~~,~~. These errors are irrespective of COT~~and~~, given CTH values < 10 km. However, the coarse footprint size of SCIAMACHY (60 x 40 km~~^{2}~~ at nadir) can degrade this assumption due to ~~likely heterogeneity of the~~ a likely heterogeneous cloud field sensed by the instrument. In this case, a set of filters ensures the extraction of a representative cloud sample from the unfiltered data record, discarding cirrus and multi-layer clouds. The procedure employed here is extensively described in Lelli and Vountas (2018) and 7 years (2003–2009) of retrievals at the SCIAMACHY overpass local time of ≈ 10:15 AM are monthly aggregated at a grid resolution of 0.5°.

2.4 Ground-based measurements

Three years (2014–2017) of station measurements from the FogNet station network in the central Namib are used to gain insights into fog occurrence at the ground. As illustrated in Fig. 1 b), the FogNet network consists of 11 automated meteorological stations that are aligned in two transects (N-S from 22.97°S–23.92°S and W-E from 14.46°E–15.31°E). FogNet was created as part of the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) initiative to study fog occurrence and processes in this region (Kaspar et al., 2015). The stations can be broadly classified by their geographic location into low-lying coastal stations (blue: all stations located < 100m above sea level (ASL)) and inland stations (red: all stations located > 300m ASL), as well as a transition station (Kleinberg: KB).

Measurements of fog precipitation and relative humidity are combined to create a binary data set of fog occurrence. Fog precipitation measurements describe advected cloud water collected by a Juvik fog collector (Juvik and Nullet, 1995). The

Juvik fog collector is an omnidirectional, cylindrical aluminium fog gauge, positioned at 1.5 m above ground. Measured fog precipitation depends on the near-ground liquid water content of fog, fog droplet size, and also scales with near-surface wind speed, as this determines the volume of air that perfuses the gauge (Frumau et al., 2011). There can be a time lag between fog occurrence and measured fog precipitation, due to the build-up time until the runoff of fog water occurs. Also, the instrument might not be sensitive in instances of very thin fog, as there is a lower limit of water needed for runoff. To reduce measurement-related uncertainties in the fog occurrence estimates, fog precipitation measurements are supplemented by observations of 2 m relative humidity (Campbell CS215) to create a binary fog product. The station measurements have a one-minute temporal resolution but are averaged in 15-minute intervals for comparison with SEVIRI observations. Fog is counted whenever the average relative humidity during a 15-minute interval exceeds 95 % or any amount of fog precipitation is measured during this time.

A ceilometer (Vaisala CL31, instrument ”CL31-2” in Wiegner et al. (2018)) complemented the measurements at the station Coastal Met (CM) from September 2017 to June 2018 to observe patterns in cloud-base height. In July, the ceilometer was repositioned closer to the coastline (Swakopmund). The CL31 emits a laser beam at 905 nm and provides a profile of attenuated light backscatter with a vertical resolution of up to 5 m (Martucci et al., 2010; Kotthaus et al., 2016). It emits 2^{14} laser pulses with a frequency of 10 kHz every 2 seconds, after which it takes about 0.36 seconds of idle time to compute the cloud base height (Vaisala CL31 firmware) (Kotthaus et al., 2016). CBH retrievals are then averaged to a temporal resolution of one minute. This CL31 has a minimum detection altitude of ≈ 40 m and was located at ≈ 95 m above sea level (ASL) at CM and is currently situated at ≈ 19 m ASL at Swakopmund. As such, the ceilometer cannot give an accurate estimate for CBH < 135 m ASL or 59 m, respectively. Here, data from one year (September 2017 to August 2018) are used. Due to data collection difficulties, no data is available during February 2018. To focus on fog and low-level clouds, only CBH < 2000 m AGL are considered.

3 Results and discussion

3.1 Fog and low cloud spatial patterns and seasonality

Figure 2 shows climatological patterns of FLC occurrence as seen by CALIPSO (Fig. 2 a)) and SEVIRI (Fig. 2 b)) using the algorithms developed by Cermak (2018) (land and ocean) and Andersen and Cermak (2018) (land only), respectively. The spatial patterns of FLC occurrence correspond well with those derived in earlier satellite-based studies (Olivier, 1995; Cermak, 2012; Andersen and Cermak, 2018), where ~~FLC occurs~~ FLCs occur frequently over the ocean and along the coastline, with three separate core regions over land: the southern parts of the Angolan coastline (15°S–17°S), the Namibian coastline from Walvis Bay ($\approx$ 23°S) northwards to 18°S, and to a lesser extent at Alexander Bay at the Namibian-South African border ($\approx$ 28°S). The spatial patterns of FLC occurrence (Fig. 2 a) and b)) indicate a connection between the stratocumulus cloud field off the southwestern African coastline and FLC occurrence ~~over~~ in the Namib, even though the CALIPSO data is not able to capture some of the finer spatial features in FLC distribution (e.g., the low-FLC region between 17°S and 18°S) due to the coarse averaging resolution. The occurrence of ~~FLC~~ FLCs along the western coast of southern Africa features a distinct

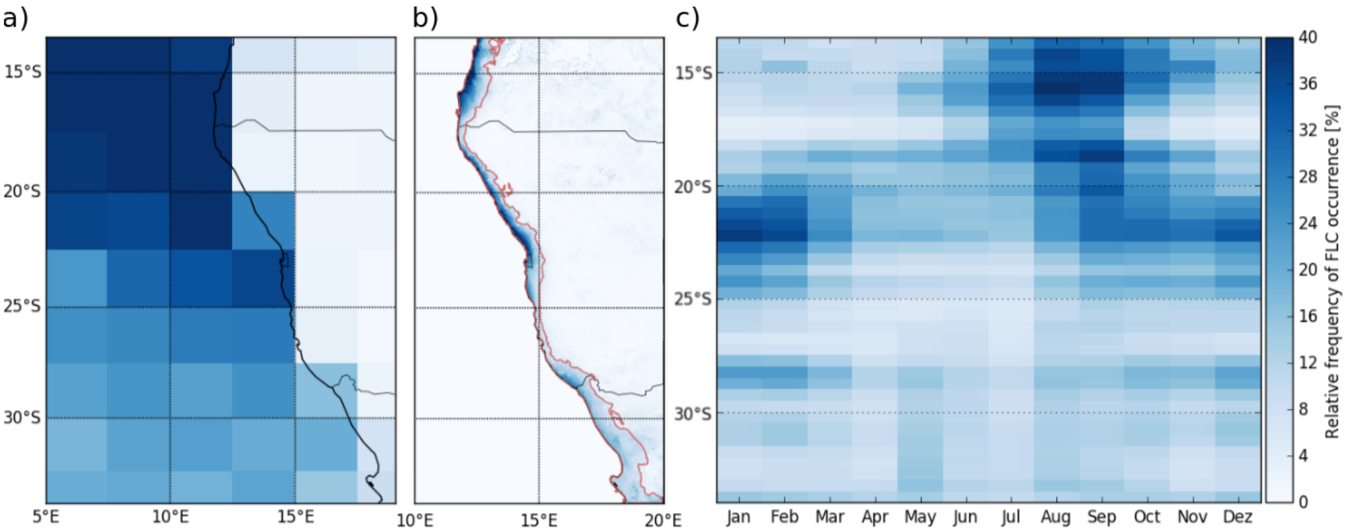

Figure 2. A satellite-based climatology of relative ~~FLC~~ fog and low cloud occurrence frequency derived by using the algorithms presented in Cermak (2018) (a)) and Andersen and Cermak (2018) (b)), based on the nearly complete data records of CALIPSO (2006–2017) and SEVIRI (2004–2017). The seasonality (c)) is computed by averaging pixels from (b) in coastal regions (maximum 100 km distance to coastline) with frequent FLC occurrence (minimum of 5 % relative FLC occurrence in the 14-year climatology shown in b)). The regions used for averaging in c) lie within the orange contours in b).

seasonal cycle that varies with latitude (Fig. 2 c)), and agrees with findings from Cermak (2012). The observed seasonal pattern of the Angolan Namib agrees well with that of the southeastern Atlantic stratocumulus cloud field (Klein and Hartmann, 1993) and underscores a likely link of stratocumulus clouds over the ocean and ~~FLC~~ FLCs over land. The latitudinal dependence of the seasonal patterns of ~~FLC~~ FLCs may be an indication of a seasonal shift of the dynamical systems responsible for a landward advection of low clouds formed over the ocean.

The satellite-derived seasonal cycle of FLC occurrence agrees well qualitatively and quantitatively with the seasonality of fog observed at inland stations (Fig. 3 b)). However, in accordance to the comparison of results from Lancaster et al. (1984) and Cermak (2012), the observations do not show similar patterns at the coastal stations (Fig. 3 a)). Here, satellite observations show a seasonality that resembles that found at inland stations, with a minimum during May and a maximum in September. In contrast, ground-based fog observations at the coastal stations peak in winter between April and August. It should be noted that while the seasonal patterns disagree, during the period from April to July, observed fog/FLC occurrence frequencies agree quantitatively (Fig. 3 b)). Both - similarities and discrepancies of the observed seasonal cycles - are likely explained in large parts by the seasonality in the vertical structure of ~~FLC~~ FLCs in the central Namib (Fig. 3 b)). Cloud-vertical properties are investigated using ground-based and space-based active sensoric. A distinct seasonal pattern in cloud-top height (CTH) is observed using CALIPSO, with 183 m lower cloud-top altitudes between April and June compared to the rest of the year (significant at the 99 % confidence level: independent t test). This seasonal pattern is also found in observations of cloud-base

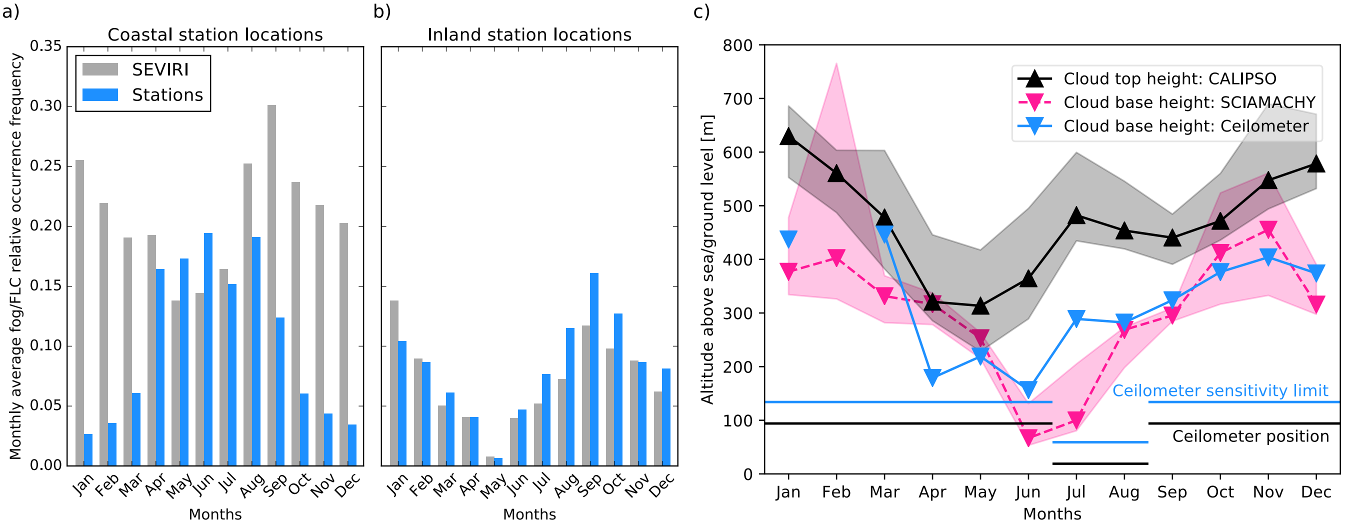

Figure 3. Monthly averaged relative fog/FLC occurrence frequency at locations of coastal (a)) and inland stations (b)). SEVIRI observations (2004–2017) are illustrated by grey bars, station measurements of ground fog (2015–2017) in blue. c) Medians, 25th and 75th percentiles of monthly averaged CBH and CTH in the central Namib based on SCIAMACHY (~~AGL~~above ground level; 22.5°S-24.0°S and 14.25°E–15.5°E, 2003–2009) and CALIPSO (~~ASL~~above sea level; 22.5°S-24.0°S and 14.0°E–15.5°E, 2006–2017) observations, respectively. ~~CL31~~ Ceilometer CBH observations (~~ASL~~above sea level) are only available since September 2017. ~~CL31 station elevation~~ Ceilometer positions (CoastalMet from September–June and Swakopmund July and August) and sensitivity ~~limit~~ limits are illustrated by thin horizontal lines and described in Sec. 2.4.

height (CBH) of the CL31 ceilometer located in CM. Here, cloud bases are found to be on average 130 m lower between April and June than during the rest of the year. As the ceilometer measurements are only available for one (incomplete) year, 7-year monthly averaged CBH estimates from SCIAMACHY are considered in addition. While the SCIAMACHY-derived CBH are especially low later in the year (June and July), the seasonal pattern agrees in the sense that it features lower CBH during the southern-hemispheric winter (CBH 173 m lower in June, July, August than during all other months, significant at the 95 % confidence level: independent t test). It is likely that during this time, ~~FLC touches~~ FLCs touch the ground even at the low-lying coastal stations (located on average ≈ 40m above sea level) frequently, leading to the observed agreement between ground fog and satellite-based ~~FLC~~ FLCs during this time (Fig. 3 a)). Between August and March, cloud-base height is significantly higher on average and displays a higher variability, more frequently leading to situations where clouds are disconnected from the surface at the coast, but still might touch the ground further inland, leading to fog occurrences at stations located there (locations on average ≈ 490m above sea level).

3.2 Diurnal cycle of fog and low clouds

Based on the diurnally-stable FLC detection by Andersen and Cermak (2018), spatial information on the statistical properties of the diurnal cycle of ~~FLC~~ FLCs can be analyzed. Figure 4 a) shows the average time of day when the FLC diurnal cycle

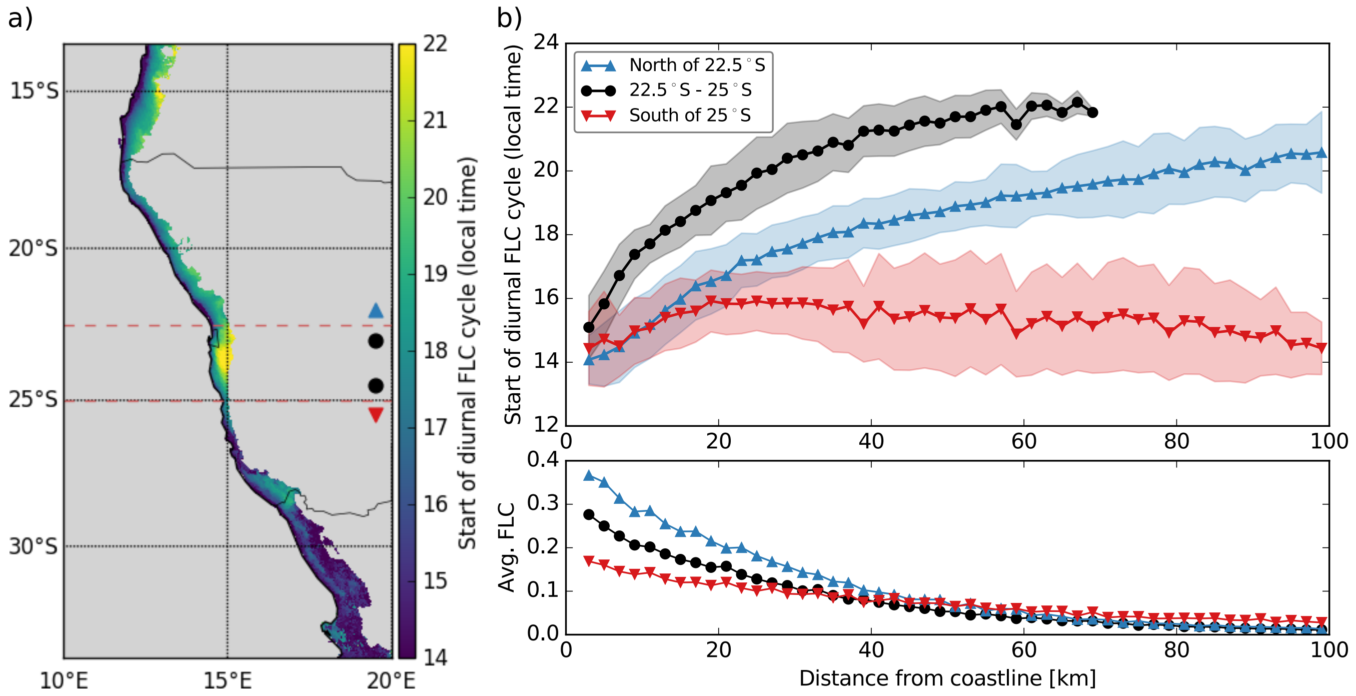

Figure 4. a) The time of the start of the diurnal FLC cycle on pixel level. Pixels are not considered which either are more than 100 km removed from the coastline or that feature a relative frequency of ~~flc~~ FLC occurrence of less than 5 %. ~~Shaded area illustrates mean +~~The dashed horizontal lines indicate the northern/~~- one standard deviation~~southern boundaries of the three regions considered in b), with markers illustrating their respective association. b) Upper panel: The average timing of start of the diurnal FLC cycle as a function of average distance to the coastline. Shaded area illustrates mean +/- one standard deviation. Lower panel: Average relative FLC occurrence frequency in the three subregions. The same pixels are considered as in panel a) and are averaged in 2 km distance bins (x axis).

typically starts. The start of the diurnal cycle is defined here as the first occasion after the diurnal FLC minimum during noon, when the relative FLC occurrence frequency reaches 10 % of the total range of its diurnal cycle at this location and is derived from 14 years of SEVIRI observations. To focus on the regions where ~~FLC frequently occurs~~FLCs frequently occur, pixels are only considered if they are located within 100 km to the coastline and feature a relative frequency of FLC occurrence of at least 5 %. It is apparent from Fig. 4 a) that the start of the diurnal FLC cycle ~~features distinct spatial patterns that are~~ is closely related to the distance from the coastline, at least north of 25°S (r = 0.86 between 22.5°S and 25°S and r = 0.85 north of 22.5°S). As Andersen and Cermak (2018) argue, this is a clear indication of a region dominated by advective processes rather than radiation fog, contrasting findings from Kaseke et al. (2017). It should be noted that while the results are of statistical nature and thus reflect the dominant patterns, incidences of radiation fog are also likely to occur, at least in some locations. The apparent discrepancy between these findings might be related to the limited sampling of the isotope analyses or due to a mixing of water from marine and continental sources as water vapor from local sources is additionally condensed at the front of the advected cold marine stratus.

More distinct spatial characteristics in the start time of the diurnal FLC cycle can be identified, as in the region between 22.5°S and 25°S (circles in Fig. 4 b)), ~~FLC typically starts~~ FLCs typically start to occur more than two hours later than in other regions along the southwestern African coastline. The differences in timing between the three subregions are highly significant (significant at the 99 % confidence level, two-sided t test). South of 25°S, the diurnal cycle of ~~FLC~~ FLCs seems to start earlier and to only depend on the distance to the coastline up to a distance of ≈ 20 km (r = 0.42) and seems decoupled from the coast further inland (r = -0.20). The region at Alexander Bay seems to be an exception, where the diurnal cycle of ~~FLC~~ FLCs is similar to that of the northern regions. This may be seen as a suggestion of subregional differences in the mechanisms leading to FLC formation. The lower panel of Fig. 4 b) shows the average FLC occurrence frequency in the three subregions as a function of the distance to the coastline that features a strong relationship, especially north of 25°S. While this is a typical feature of coastal fog (e.g., Olivier, 1992), it serves as an additional indication that the region south of 25°S is not influenced by marine airmasses to the same extent as regions further north.

Figure 5 (upper panel) shows the time of the start of the diurnal FLC cycle between 22.5°S and 25°S in two different time periods with contrasting vertical FLC characteristics. During the season of systematically higher-level ~~FLC~~ FLCs (September–November: high-FLC season), a distinct relationship between distance from coastline and the timing of FLC occurrence is apparent up to about 60 km inland. During the time of lower-level ~~FLC~~ FLCs (April, May, June: low-FLC season), this relationship is only apparent within ≈ 30 km of the coastline. It should be noted that the overall FLC occurrence frequency is also dependent on the distance from coastline (lower panel), and in inland regions, where no relationship between distance from coastline and time of FLC occurrence is apparent, FLC occurrence is below 5 %. In these regions, assessments of the statistics of the diurnal cycle are limited by the overall accuracy of the detection algorithm (97 % - (Andersen and Cermak, 2018)), and the statistics of the diurnal cycle may be more susceptible to the influence of random misclassifications. In general, the slope of the relationship illustrated in the upper panel of Fig. 5 can be affected by the average advection speed, the fraction of advective ~~FLC~~FLCs, and the partial contribution of random misclassifications.

4 Conclusions and outlook

In this study, Namib-region fog and low-cloud patterns are analysed based on data from multiple satellite sensors as well as station measurements.

The seasonal cycle of satellite-derived FLC occurrence is found to have a distinct latitudinal dependence. In the Angolan regions north of ≈17.5°S, FLC occurrence peaks between July and October, whereas in Namibia between 20°S and 25°S, ~~FLC occurs~~ FLCs occur mostly between August and February. This pattern may be explained by a seasonal shift in the dynamic conditions that lead to the inland-advection of marine low clouds. On seasonal scales, the spatiotemporal FLC occurrence indicates a connection to the southeastern Atlantic stratocumulus cloud deck. As such, process knowledge from studies on the heavily investigated stratocumulus clouds in this region (e.g., Adebiyi and Zuidema, 2018; Andersen and Cermak, 2015; Diamond et al., 2018; Fuchs et al., 2017, 2018; Gordon et al., 2018; Painemal et al., 2014; Yuter et al., 2018) may be applicable to Namib-region ~~FLC~~FLCs, and vice versa.

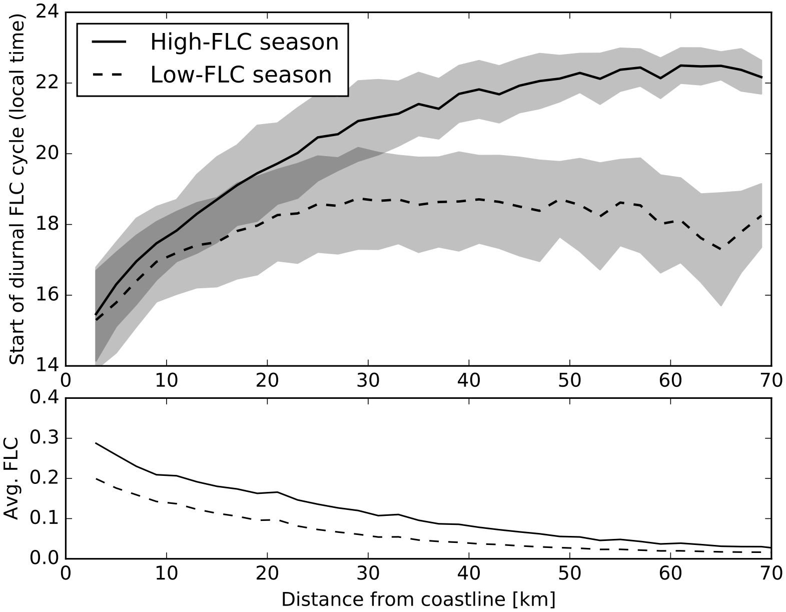

Figure 5. Upper panel: Start of diurnal FLC cycle in the central Namib as a function of distance from the coastline. Two different seasons are shown: high-FLC season (September, October, November) and low-FLC season (April, May, June). Shaded area illustrates mean +/- one standard deviation. Lower panel: Average relative FLC occurrence frequency in the two seasons. The same pixels are considered as in the upper panel and averaged in 2 km distance bins (x axis).

Satellite-derived seasonal patterns of ~~FLC~~ FLCs are compared to ground-based measurements of fog occurrence from the FogNet stations in the central Namib. While the seasonal patterns agree qualitatively and quantitatively for inland stations, they feature contrasting patterns at coastal stations. This can likely be explained by seasonal patterns in cloud-base altitude that determines whether a low-level cloud touches the ground (fog) or not. Observations from CALIPSO and SCIAMACHY suggest that on average, clouds in coastal regions seem to be disconnected from the surface more frequently between August and February, where the satellite observations strongly overestimate station measured ground-fog occurrence.

Coherent spatial patterns of the diurnal cycle of FLC occurrence in the Namib could be observed for the first time using the algorithm developed by Andersen and Cermak (2018). Generally, the timing of FLC occurrence seems to be tightly connected to the proximity of the coastline, where the diurnal cycle of ~~FLC~~ FLCs starts systematically earlier at the coast than further inland. This is a strong indication for a dominant role of advection for the climatological patterns of ~~FLC~~ FLCs in the region, contrasting the interpretation of findings from isotope analyses by Kaseke et al. (2017). In the central Namib, the diurnal cycle of ~~FLC~~ FLCs is found to start more than 2 hours later than in most regions along the coastline. This may be caused by local advection patterns of ~~FLC~~FLCs. The key findings regarding the seasonal and diurnal patterns of ~~FLC~~ FLCs are summarized schematically in Fig. 6 and lead to a more complete view on Namib-region ~~FLC~~FLCs. The results of this study highlight the advantages of combining ground and space-based (active and passive sensoric) measurements. ~~Future research should focus on~~

~~a further characterization of the dynamical conditions and drivers that determine diurnal and seasonal variability and vertical structure of FLC~~

The interplay of large-scale dynamics with local winds (Tyson and Seely, 1980; Olivier, 1992, and sources therein), (sea) surface characteristics (Olivier, 1995), radiative transfer and aerosols is likely to explain fog and low cloud occurrence and variability in the Namib desert. The exact manner, however, by which the various processes determine this complex system and its observed spatiotemporal dynamics is still unclear. Future research is thus needed to more fully understand the processes that lead to the variability in spatial patterns, overall coverage, vertical structure and life cycle of FLCs, as well ~~as processes that influence its diurnal cycle~~its capacity to serve as a water source for ecosystems. Within the ongoing research project Namib Fog Life Cycle Analysis (NaFoLiCA), these aspects will be studied using a combination of satellite data, ground-based measurements and numerical models.

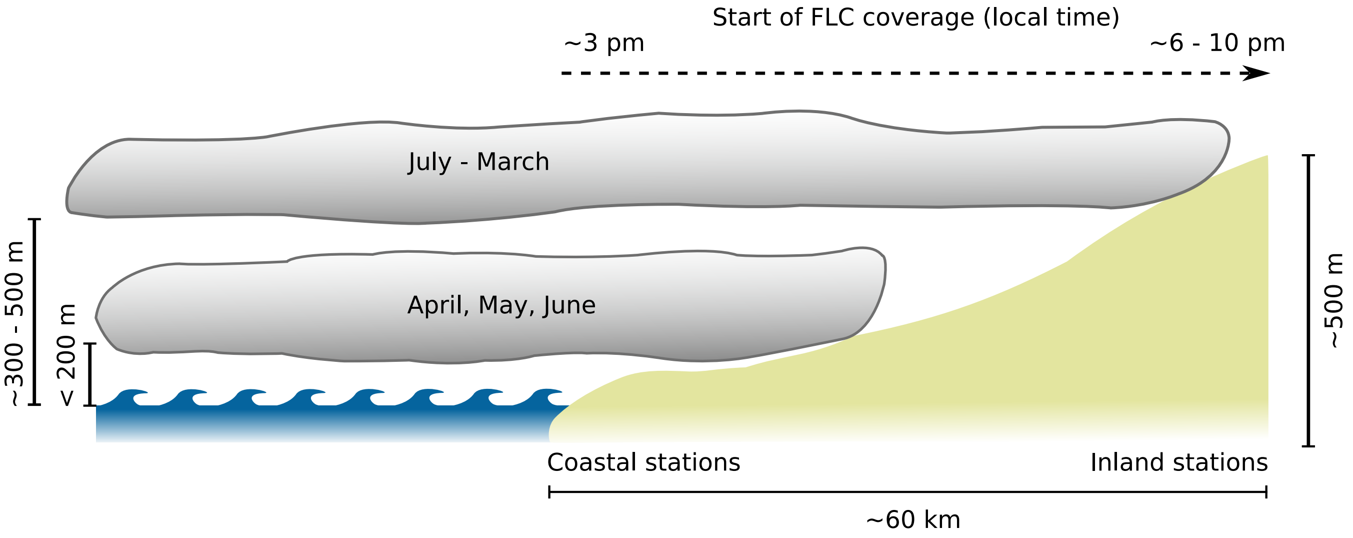

Figure 6. Schematic illustrating the observed seasonal cycle in cloud vertical characteristics and the dependence of the diurnal FLC cycle on the distance to the coastline.

Appendix A: ~~Abbreviations~~ List of ~~FogNet stations~~acronyms

Station abbreviations

Aussinanis: AU
Coastal Met: CM
Conception Water: CW
Garnet Koppie: GK
Gobabeb Met: GB
Kleinberg: KB

Marble Koppie: MK
Saltworks: SW
Sophies Hoogte: SH
Station 8: S8
Vogelfederberg: VF

General acronyms

AGL above ground level
ASL above sea level
CALIOP Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO Cloud-Aerosol LiDAR and Pathfinder Satellite Observations
CBH cloud base height
COT cloud optical thickness
CTH cloud top height
FLCs fog and low clouds
MSG Meteosat Second Generation
SACURA Semi-Analytical CloUd Retrieval Algorithm
SCIAMACHY SCanning Imaging Absorption spectroMeter of Atmospheric CHartographY
SEVIRI Spinning-Enhanced Visible and Infrared Imager
SASSCAL Southern African Science Service Centre for Climate Change and Adaptive Land Management

Code and data availability. Code and data are available

Author contributions. HA and JC had the idea for the analysis, HA obtained and analyzed most of the data sets, conducted the original research and wrote the manuscript. IS and LL contributed to data analysis, and RV provided the quality controlled FogNet data. JC, IS, LL and RV contributed manuscript preparation and the interpretation of findings.

Competing interests. The authors declare that they have no conflict of interest.

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