Synoptic-scale controls of fog and low clouds in the Namib Desert: Response to Reviewer 1

Hendrik Andersen, Jan Cermak, Julia Fuchs, Peter Knippertz, Marco Gaetani, Julian Quinting, Sebastian Sippel, and Roland Vogt

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We would like to thank reviewer 1 for her/his careful review of the manuscript and her/his constructive criticism and valuable comments. Comments by the referee are colored in black, our replies or comments are colored in blue and italics.

Using a 14-year period of reanalysis grids and backward trajectories, this study examines the impact of large-scale dynamics and thermodynamics on fog and low clouds (FLCs) over Namib. Specifically, the authors' focus on two seasons when different FLC types are observed due to different synoptic-scale regimes. A main finding is that the mean sea level pressure (MSLP) field differs notably between clear and FLC days. To this end, the authors' use a statistical model and MSLP fields to provide skillful prediction of FLCs up to one day in advance. A new conceptual model of the two different FLC regimes is developed to summarize findings and aid in future studies related to FLCs over Namib. In general, the scientific purpose is justified, the findings are important, and the paper is well-written; however, I do have concerns about some of the methods used. Overall, I think that the results are interesting and worthy of publication, and at this stage I suggest acceptance subject to major revisions.

Major/general comments:

1. Use of MSLP, 2 m temperature, and 10 m winds to characterize synoptic-scale conditions
This study relies on the assumption that near-surface (boundary layer) meteorological variables – specifically MSLP, 2 m temperature, and 10 m horizontal wind components – are representative of the large-scale dynamics. While this assumption may be justified over the ocean, it is likely not justified over land, and especially where topography is pronounced. The authors' do acknowledge this sentiment (P7, L11-13); however, I think that this consideration is more important than they suggest. In fact, the authors' even cite two different papers on P7, L6-7 that suggest that "In the Namib Desert, thermally and topographically induced local wind systems within the boundary layer modulate these synoptic air-flow patterns, and the significance of the induced diurnal oscillations can exceed that of the synoptic scale". To this end, the authors' should also examine the aforementioned dynamic and thermodynamic variables at other (isobaric) levels (e.g., 925 hPa and 850 hPa) because i) the assumption of a standard atmosphere will be required for fewer locations (compared to estimating MSLP) and ii) the influence of local terrain will be suppressed at more locations. While the main conclusions of this study should not change notably, it will be interesting to see how much the PCA and statistical model results differ when using e.g., 925 hPa or 850 hPa fields. These results should be of interest to both the research and operational forecasting communities. Moreover, the impact of using the isobaric fields should be included in the context of Sections 3.1, 3.2, and 3.3: whether considering these isobaric fields is important when relating synoptic-scale meteorology to FLC occurrence.

Thank you for this comment. In the manuscript, we use Z500 as the classic weather characteristic that is thought to represent the synoptic circulation in the free troposphere. MSLP and 10 m winds are used to describe the topography-near circulation. For MSLP and 10 m winds, caveats exist, as pointed out by the reviewer and also briefly discussed in the orignial manuscript on P7 L 11-13. Due to the high topography in southern Africa, and the fact that the region of interest (central Namib) lies close to the coast, and at low altitudes, no one specific pressure level can adequately summarize near-surface conditions throughout this large domain. In the preparation of the original manuscript, we carefully investigated more pressure levels than presented (1000 to 500 hPa in 100 hPa steps). In Fig. R1.1 of this response, we compare the anomaly patterns in Z850 (top), Z925 (middle) with those of MSLP (bottom), following your suggestion. It is clearly apparent that the relevant anomaly patterns are not affected in a significant way by the choice of the pressure level within the lower troposphere. The biggest difference between the investigated levels are the wind anomalies north of the central Namib (star), where 10 m wind anomalies are small, but at higher levels on FLC days, a marked onshore anomaly exists. This may be an indication of a blocking of onshore flow below the inversion, and a more freely flowing air at pressure levels above 925 hPa.

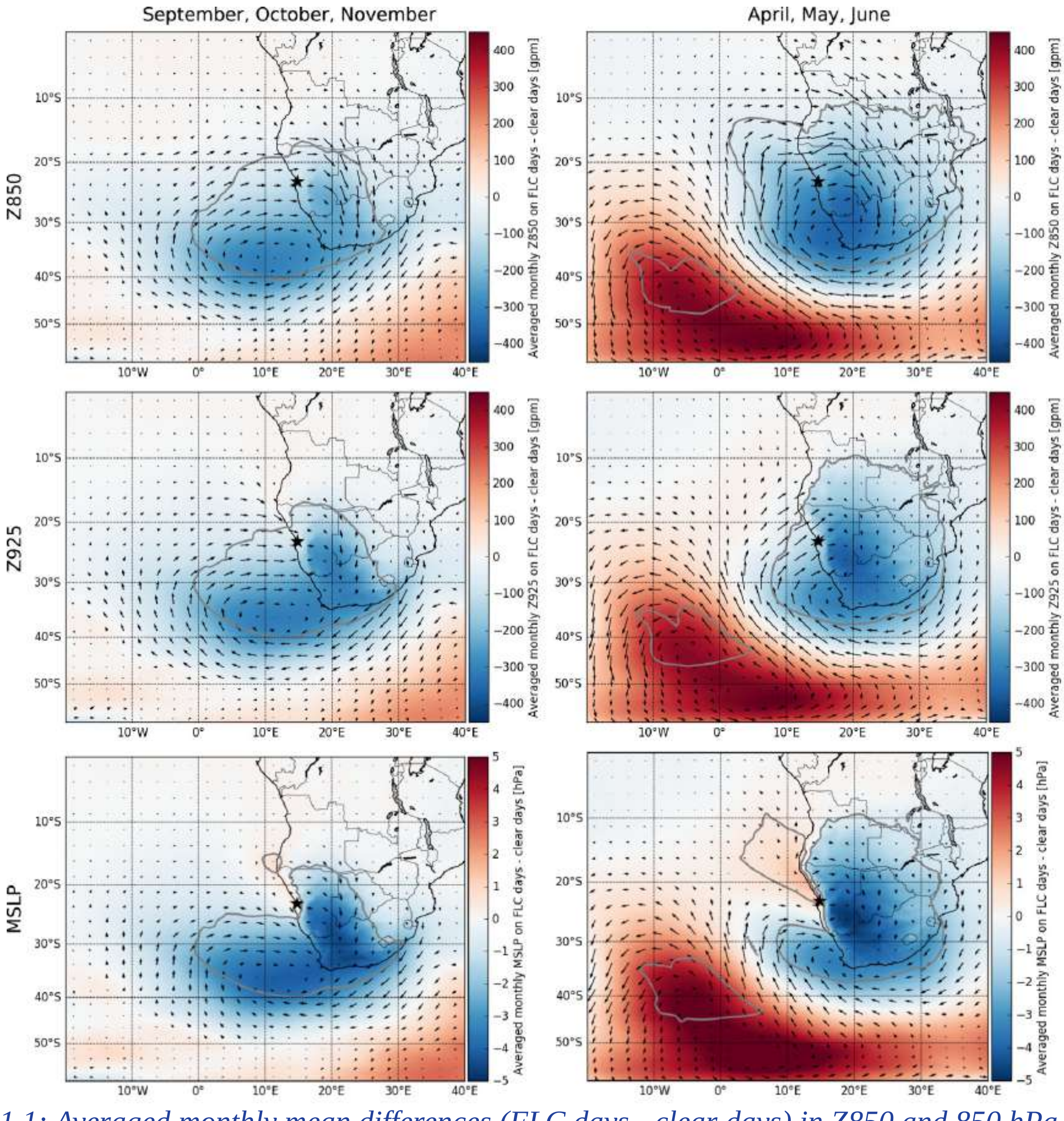

Fig. R1.1: Averaged monthly mean differences (FLC days - clear days) in Z850 and 850 hPa winds (top), 925 hPa (middle), and MSLP (bottom) with 10m winds for SON (left-hand panels) and AMJ (right-hand panels). Contours mark regions where the distributions differ significantly at the 0.01 *level. u and v vectors of winds are interpolated bilinearly interpolated to a 2.5° x 2.5° grid for clarity.*

In section 3.1, we extended our discussion on this:
"However, due to the joint consideration of regions in southern Africa with high topography, the low-lying central Namib, and marine regions, no one specific pressure level of geopotential height can adequately summarize near-surface conditions throughout this large domain. Additional analyses show that difference patterns obtained from MSLP fields in southern Africa are similar to those at 925 hPa and 850 hPa (not shown)."
In section 3.2, we additionally discuss this in the updated version of the manuscript:
"As discussed in Sec. 3.1, MSLP and 10m winds may not be a good representation of near-surface level characteristics where topography is high, however, additional analyses of geopotential height at 850 hPa and 925 hPa corroborate the observed MSLP patterns. Differences exist in winds north of the central Namib, where at 925 hPa and 850 hPa (not shown), a stronger onshore flow anomaly is observed than at 10 m, possibly indicating a topographical blocking of the onshore flow below the inversion."

Based on your suggestion, we also ran the ridge regression model to predict FLC days and clear days based on Z850 and Z925. We find that the skills of the different models based on MSLP, Z850, and Z925 are very similar, with MSLP a slightly better predictor (Tab. 1 of this document). In section 3.5 of the updated version of the manuscript, we now state:
"As MSLP fields in southern Africa may not be representative due to the high topography, the model was additionally run based on Z850 and Z925 fields. The model performances were nearly the same (overall PC of 84 % in both cases), suggesting that it is adequate to use MSLP in this context."

Tab. 1: The performance of the ridge model to predict FLC and clear days based on three different sets of predictors (MSLP, Z850, Z925).

	POD	**FAR**	**PC**	**BS**
MSLP	0.94	0.17	0.86	1.14
Z850	0.90	0.18	0.84	1.10
Z925	0.91	0.19	0.84	1.12

Minor/specific comments:

1. P1, L7: When you say "significantly", do you mean in the statistical sense? If so, please specify this. If not, please choose different wording.
   The sentence now says:
   " It is found that during both seasons, mean sea level pressure and geopotential height at 500 hPa differ markedly between fog/low-cloud and clear days, [...]".

2. P3, L14: Please provide the retrieval wavelength(s) of the SEVIRI data used in this study.
   This is now included in the updated version of the manuscript. In section 2.1, we now state that the
   "algorithm relies mostly on a channel difference in the thermal infrared (12.0-8.7µm), [...]".

3. P3, L20-21: Why use these criteria? Are they following a previous study?
   This is now described in more detail in section 2.1. The updated version of the manuscript states:
   "A specified averaging time period is needed to avoid statistically mixing two separate FLC events occurring on successive nights which would be the case in a daily average FLC occurrence data set. The specific time period is chosen to include all periods of the diurnal cycle, with FLC occurrence rising, peaking, and starting to dissipate (Andersen and Cermak, 2018) during this time."

4. P4, L9: Which "different pressure levels" are used?
   We now provide the information on all pressure levels used. In section 2.2 of the updated version of the manuscript, we now state that:
   "To characterize large-scale dynamic and thermodynamic conditions, fields of mean sea level pressure (MSLP), geopotential height at 500, 700, 850, and 925 hPa (Z500, Z700, Z850, Z925), 2 m air temperature (T2m), sea surface temperature (SST), total columnar water vapor (TCWV), specific humidity (Q), as well winds at 10m and at all ERA5 pressure levels between 1000 and 500 hPa, and lower tropospheric stability (LTS: computed as the difference between potential temperature at 700 hPa and T2m (Klein and Hartmann, 1993)) are used. To represent the morning conditions for which FLC is averaged, 6 UTC fields of ERA5 data are selected. While for additional analysis, T2m fields are also used at nighttime (1 UTC and 3 UTC), the 6 UTC fields are used if no specific information on time is given."

5. P5, L3-4: What is the justification for using 0.5 deg rather than 0.25 deg ERA5 grids?
   The computational cost and data storage (with thoe chosen resolution, the ERA5 data already require ~30TB of disk storage). Clearly, 0.25 degrees would be preferable, but we calculated many more backtrajectories than shown in the manuscript (different seasons, times, initial altitudes), and so this really became an issue. We do not expect the clear differences between FLC and clear days to be substantially affected, though. We initially calculated the backtrajectories with the HYSPLIT model based on ERA-Interim data, which are shown in Fig. R1.2 of this response (compare with Fig. 7 of the original manscript). We now state in section 2.3:
   "The spatial resolution is used to reduce the data volume and computational cost. While the native resolution would be preferable, the general patterns of the trajectories are not expected to be affected, as tests with lower-resolution ERA-Interim data showed comparable results."

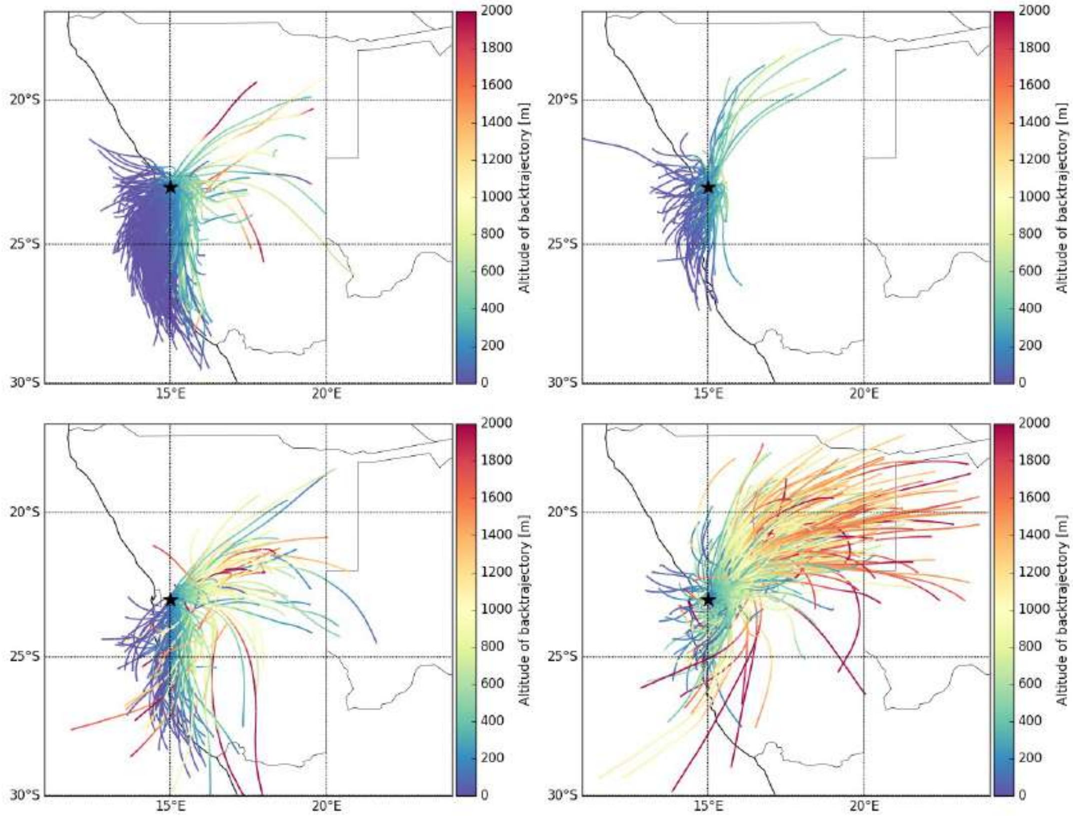

Fig. R1.2: Hysplit backtrajectories for SON (left-hand panels) and AMJ (right-hand panels) for FLC days (top) and clear days (bottom), based on ERA-Interim data at 0.75° spatial resolution.

6. P5, L13-15: Please provide references for the PCA method.
The reference for the PCA method is Storch and Zwiers (1999), page 5, line 17 in the first submitted version. We moved the reference to the beginning of Sec. 2.4 for clarity.

7. P5, L19: What is the reasoning for remapping the wind fields to a 2 deg grid?
We first remapped data to 2 degrees for computational reasons, because PCAs are quite computationally expensive (Pham Thanh et al. 2019), and the Matlab software used to compute the PCA is unable to do this for a 14-year daily time series (365x14=5110 time steps) at such high resolution (40x40 degree = 160x160=25600 grid points). Moreover, the purpose of the analysis is to detect the main modes of variability of surface wind in the region, to assess possible drivers of fog occurrence at synoptic scale. In this respect, 2 degree resolution is a reasonable compromise for capturing synoptic-scale variability and smooth out the variability associated with fine-scale effects. However, we additionally performed a new PCA analysis by regridding to 1 degree resolution, to continue to smooth out fine scale disturbances not to lose too much of the variability of the original dataset. The results of the PCA at the two resolutions are very similar. These aspects are now described in Sec. 2.4:
"Remapping to 1° resolution allows to accurately describe the atmospheric variability at synoptic scale, but smoothing out the variability associated with small-scale effects. The sensitivity of the PCA to the spatial resolution is tested by conducting the analysis based on wind fields remapped to a 2° resolution. The results of the two PCAs at the different resolutions are very similar, demonstrating their robustness. Daily anomalies are computed with respect to the 14-year sampling of the FLC dataset in order to compare wind and FLC variability over a homogeneous climatology."

8. P5, L19-20: Please explain why the temporal – rather than the spatial – anomalies are used. Was care taken to ensure that this 14-year period is not anomalous in some way? A 14-year sample is likely not long enough to capture some of the climatological signals at a given location. I would think that spatial anomalies would be more appropriate.
Thanks for the comment, which gives us the opportunity to further clarify the PCA approach used. The aim of the analysis is first to identify the main modes of variability of the near-surface circulation, then to relate the selected modes to FLC occurrence, to assess possible correlations, i.e. to assess how the circulation patterns explain FLC variability. In practice, we need to correlate daily time series associated with wind EOFs and FLC occurrence. Therefore, by removing the climatological mean we require that the covariance matrix is equal to the temporal variance matrix. The computation of such temporal anomalies is a common preprocessing step in PCA analysis (see e.g. Gaetani et al. (2016) or Pham Thanh et al. (2019) for other examples). We clarified this aspect in the revised version in Sec. 2.4 and now discuss this in the conclusions:
"While a 14-year sample is not optimal to capture climatological variability, the mechanisms documented here for the first time are unlikely to be fundamentally different in other climatological periods."

9. P5, L25-26: Please make it explicitly clear that the statistical model in this study will use spatial patterns of pressure fields.
In these lines of the text, the statistical model used (ridge regression) is not described. The description of how the ridge regression is applied is found in P6 L19-22. Here, we now explicitly state that spatial patterns are used:
"[...] using spatial patterns of 6 UTC (representative of averaging time of FLC cover, see Sec. 2.1) ERA5 MSLP fields[...]"

10. P6, L19-20: What is the percentage of data availability?
Maybe this is a misunderstanding: The statement "for which observations exist" refers to the period in time that the satellites were/are in orbit. This is now clarified in the updated version of the manuscript:
"The ridge regression method is used to predict FLC and clear days over the complete 14-year time series,[...]"

11. P6, L22: I do not understand why 0.25 deg grids are used for the statistical model and coarser grids are used for other portions of the analysis. Please explain.
For each step of the analysis, we chose the highest resolution that is feasible for the analysis. This is now explained in the updated version of the manuscript where applicable. The ridge regression is computionally cheap in comparison to the PCA analysis, allowing us to use the 0.25 resolution. Also, data storage is not an issue, because the statistical model uses just one parameter as input (e.g., MSLP). The backtrajectories, for example, rely on three wind components, as well as the temperature and humidity fields at 137 levels. We now discuss this briefly in each respective section.

12. P6, L29: For readers who may be unfamiliar with the St. Helena High and the southern African continental high, please provide references. Also, is the St. Helena High over the ocean? Please add some detail here.
We have adjusted the terminology describing the pressure system as South Atlantic High and continental high for clarification.

13. P7, L9: Do you mean thermal stability?
    Yes, as described e.g. by the lower tropospheric stability shown in Fig. 2 of the original version of the manuscript. This is clarified in the updated version of the manuscript: "The combination of large-scale subsidence and low SSTs along the coastline produces high LTS conditions, [...]"

14. P8, L4: To which trough are you referring? This is the first time that a trough is mentioned.
    The absolute fields at 700 hPa are now included in the appendix of the updated manuscript, showing the trough.

15. P8, L4: "Z500 on FLC days" – please refer to the panel to help the reader.
    Done in the updated version of the manuscript.

16. P9, L2: Do you mean significant at the 0.01 level?
    No, the 0.01 level is shown in the figure, but we also computed the 0.05 level. We clarify this in the updated version of the manuscript:
    "There is a coherent pattern of slightly lower SSTs (~0.5 K; Fig. 3 e)) along the coastline on FLC days; however, the difference between SSTs on FLC and clear days is not significant at the 0.01 level (and also not at the 0.05 level)."

17. P9, L8-9: I am not sure that I understand this explanation of the dry slot. Is it possible that TCWV is reduced simply because at low levels water vapor is condensed into liquid water as FLCs form? Examining vertical profiles of TCWV may help clarify.
    We investigate the vertical moisture anomalies in Fig. 6 of the manuscript. The dry anomaly is fairly deep, from the top of the MBL to 600 hPa in AMJ, and extending higher than 500 hPa in the SON. The region is very stable, and the MBL moisture is expected to be driven from surface fluxes. Fig. R1.3 in this response shows seasonally averaged Q and winds at 700 hPa, the layer with the strongest Q difference, for FLC days (left), clear days (center), and their difference (right). During both, AMJ (top) and SON (bottom), it is clearly visible how the synoptic-scale disturbance induces a horizontal transport of drier air over the study region. During AMJ, the free-tropospheric moisture transport into continental southern Africa is clearly visible. We now include this figure in the appendix of the manuscript.

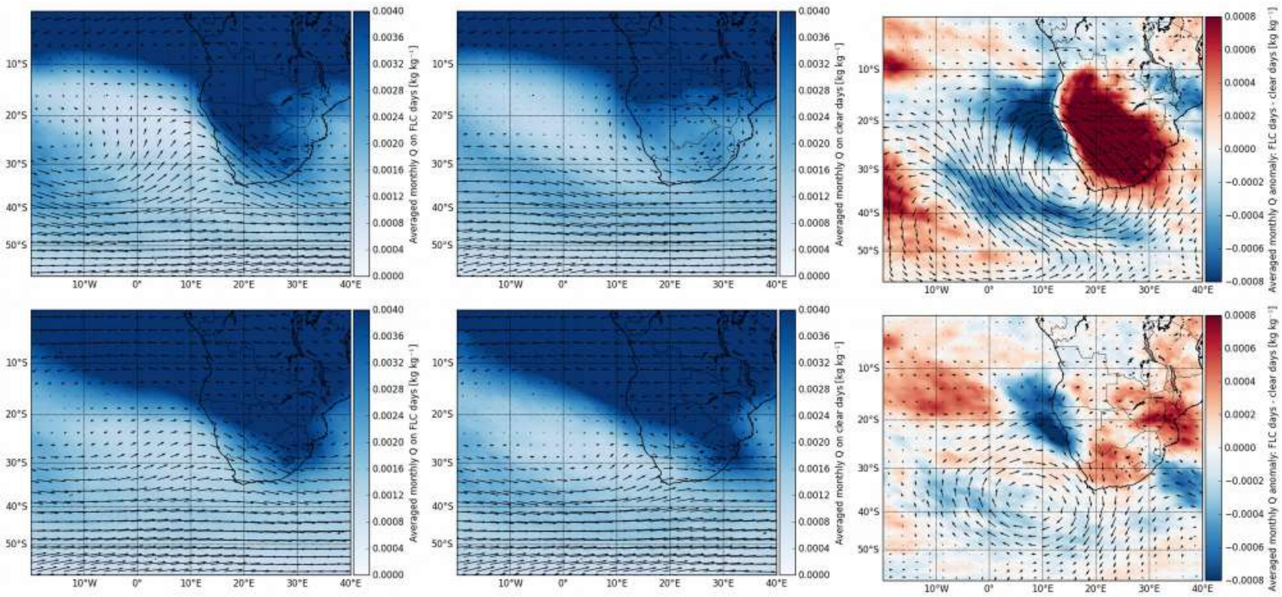

Fig. R1.3: Seasonal averages of Q and winds at 700hPa on FLC days (left), clear days (center), and their difference (right) during AMJ (top) and SON (bottom).

18. P9, L10-11: The strongest positive 2m temperature anomalies are shifted west of the strongest positive TCWV anomalies. Can you explain why this pattern is observed?
The temperature anomalies are also caused by warm air advection near the surface, but during AMJ, when the moist anomaly is pronounced, the spatial patterns of TCWV and T2m agree quite well. This is shown by Fig. R1.4 of this document, which shows the relationship of T2m anomalies and TCWV anomalies in continental regions where T2m is significantly higher on FLC days than on clear days. A clear relationship is obvious, with a correlation coefficient of 0.75. This statistical relationship indicates that more than half of the observed T2m anomalies can be explained by the TCWV anomalies, underscoring the relevance of the greenhouse effect for T2m during this time. We now state in section 3.3 that:
"Here, the T2m anomalies closely follow those of TCWV (Pearson correlation coefficient of 0.75 in continental regions with significantly higher T2m on FLC days than clear days), suggesting that the increased moisture causes an additional surface heating due to greenhouse warming as discussed in Sec. 3.2."

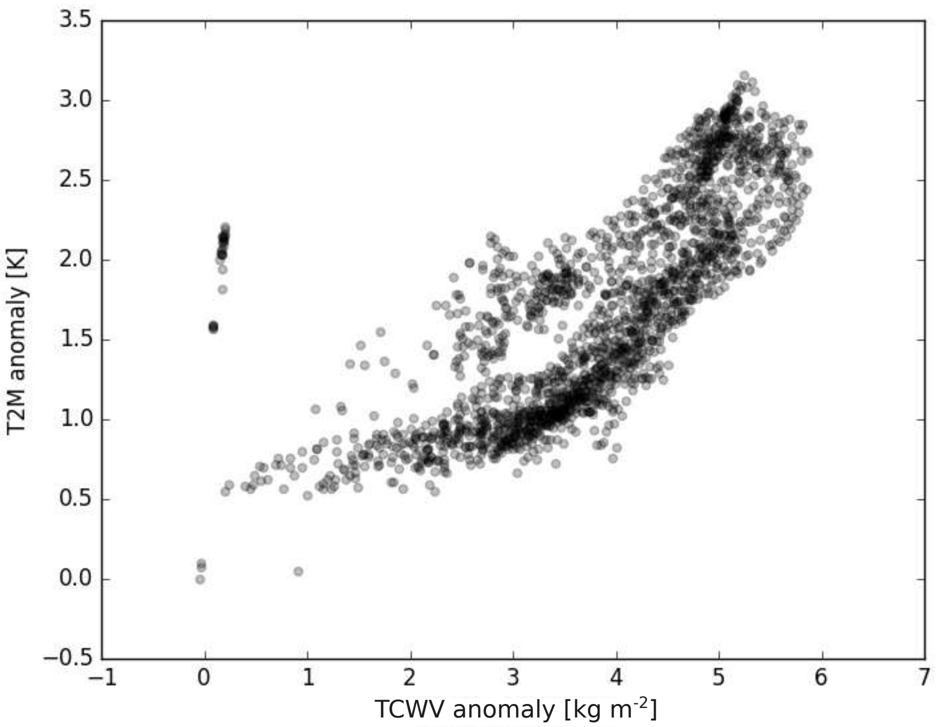

Fig. R1.4: The relationship of TCWV anomalies and T2m anomalies over land during AMJ, and in regions where T2m is statistically significantly higher on FLC days than on clear days.

Fig. R1.5 of this document shows average T2m and 10m winds during FLC and clear days during the different seasons, illustrating the warm-air advection on FLC days that also contributes to the overall anomaly pattern. The figure is now in the appendix of the updated version of the manuscript.

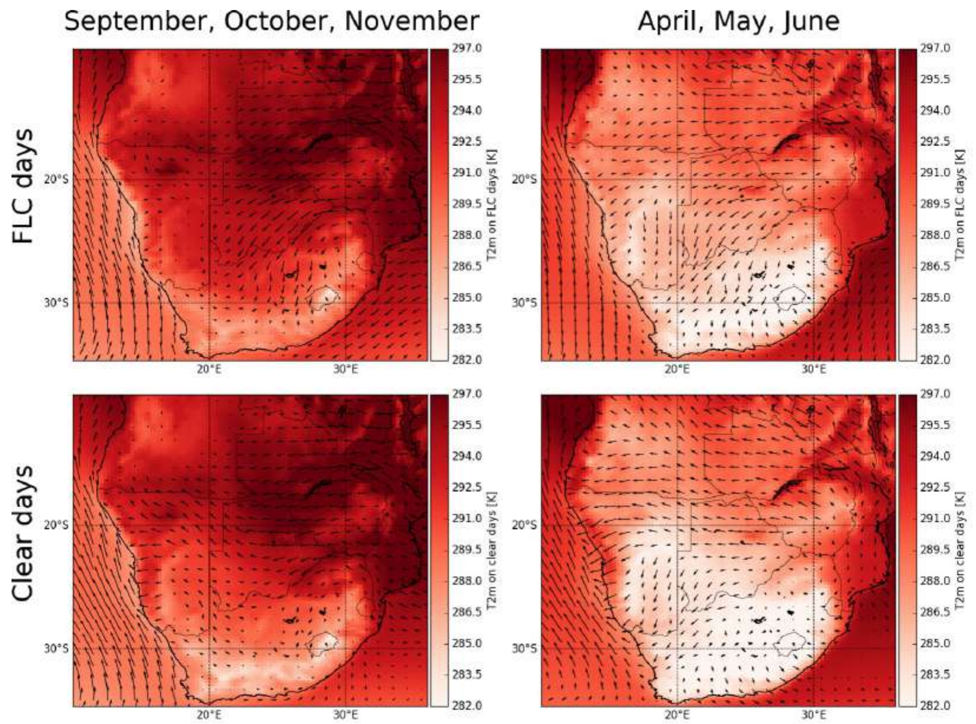

Fig. R1.5: Seasonal average ERA5 T2m and 10m winds in SON (left-hand panels) and AMJ (right-hand panels) for FLC (top) and clear (bottom) days. Winds are averaged to a 1°x1° resolution, the considered time period is 2004-2017.

19. P9, L11-12 & L21; P10, L2-3: These statements about greenhouse warming are a bit speculative and should be fleshed out with additional discussion/ analysis/ evidence. Is it possible to look at vertical profiles of heat fluxes/heating rates?
    We agree that we do not give quantitative estimations for heating rates, however, this effect has been shown and quantified before in the Kalahari (Manatsa and Reason (2017)), and in other dry subtropical deserts (e.g. the Sahara: (Evan et al. 2015, Alamirew et al. 2018), or the Sahel (Oueslati et al. 2017)). Also, the strong relationship of the spatial anomaly patterns of TCWV and T2m (shown in Fig. R1.4 of this document) during AMJ underscores the importance of TCWV for T2m. We now discuss this in more detail in the current version of the manuscript (Sec. 3.2):
    "This effect of free-tropospheric moisture on surface temperatures has been observed in the Kalahari (Manatsa and Reason, 2017) and other arid and semi-arid regions before (Evan et al., 2015; Oueslati et al., 2017; Alamirew et al., 2018)."

20. P9, L28: Please provide a citation for this statement.
    After reviewing the absolute fields of Z500 and Z700, we conclude that while the atmospheric wave is quite steep during AMJ, it does not 'break'. As such, we have deleted the notation of rossby waves and cut-off lows from the manuscript, and refer to them as synoptic-scale disturbances of different magnitude.

21. P10, Fig. 3: I recommend making the contours of significant differences a different color because at present they are difficult to discern from the country boundaries.
    In the maps the significance is now indicated by a thicker grey line to be more clearly distinguishable from country boundaries.

22. P10, L3-4: Analysis of vertical profiles may help clarify and substantiate this claim.
As outlined above, the vertical profiles are analyzed in Fig. 6 of the manuscript. In the updated version of the manuscript, we point the reader to this section earlier for clarity. This is also supported by Fig. R1.3 of this response, which is now in the appendix of the updated version of the manuscript.

23. P11, L7-11: Please reference Fig. 3 here.
Yes, we have included the correct Fig. reference for clarity.

24. P14, Fig. 6 panel b: Are you able to say something about the offshore Q anomalies in AMJ? Why do we see the positive Q anomalies increase in height farther away from the shoreline?
This is an interesting point. We agree that this should be discussed in more detail: Fig. R1.6 of this response shows the Q and wind difference at 950 (left) and 900 (right) hPa between FLC and clear days for AMJ. The moist anomaly in the MBL is clearly a synoptic-scale feature tied to the main disturbance. It is likely related to the cold front of the disturbance. In the updated version of the manuscript, we now state that:
" During both seasons, the marine boundary layer features an onshore flow anomaly and is more humid on FLC than on clear days, especially during AMJ, where this is a synoptic-scale feature, likely related to the cold front of the disturbance."

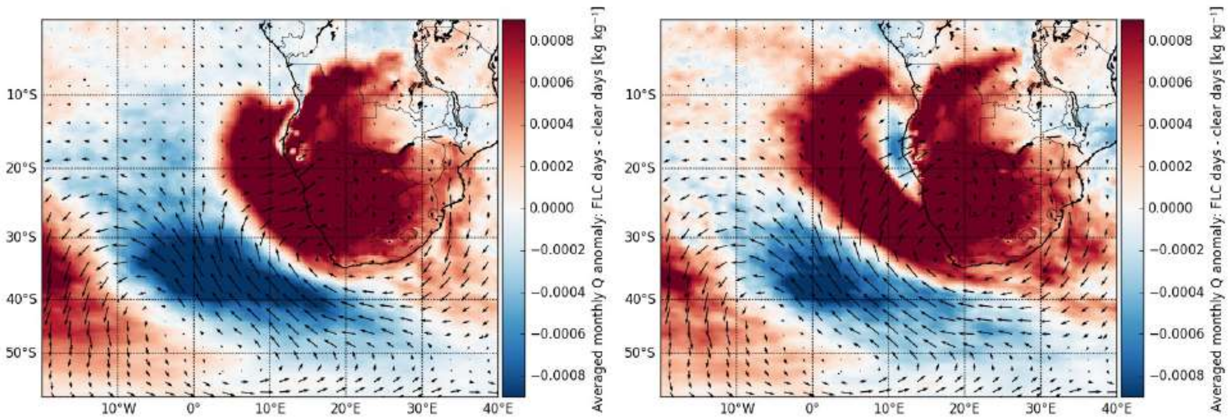

Fig. R1.6: Difference in Q and winds at 950 and 900 hPa during AMJ.

25. P15, Fig. 7: Can you estimate the absolute value of the pressure where the backtrajectories are initialized (25 hPa above ground level)? This will help the reader understand how much the parcels are traversing in the vertical.
Yes, the backtrajectories are initialized just below 940 hPa (here the backtrajectories meet in Fig. 8 d)). This is now mentioned in section 2.3 of the updated version of the manscript.

26. P16, L3: The material in this paragraph does not seem to fit with the other material in this section. Perhaps improve the connection, create a new section and flesh out, or add to a different section.
Yes, we agree that the linkage of this section deserved to be improved. In the updated version of the manuscript this paragraph now starts like this:
"The analysis of air-mass backtrajectories shows that the discrimination between FLC and clear days is not possible using dynamics alone, and that seasonal differences exist in the link between the probability of FLC days and advection patterns. To further investigate the role of different dynamical regimes for FLC occurrence, a PCA is conducted [...]"

27. P20, L3: Relative humidity or specific humidity?
This refers to the specific humidity increase shown in Fig. 6, but increase in relative humidity is also expected. We now describe this in more detail in the updated version of the manuscript:
"A significant pattern of SST anomalies is found only in AMJ, with anomalously high SSTs off the coast possibly acting together with increased near-surface winds to enhance surface latent heat fluxes that may contribute to the observed higher levels of specific humidity in the marine boundary-layer."

28. Grammatical/wording recommendations: 1. P14, L15: Please change "along all those backtrajectories" to "along all of the backtrajectories".
This is corrected in the updated version of the manuscript.

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Synoptic-scale controls of fog and low clouds in the Namib Desert: Response to Reviewer 2

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We would like to thank reviewer 2 for her/his careful review of the manuscript and her/his valuable comments, thoughts and the constructive criticism. Comments by the referee are colored in black, our replies or comments are colored in blue and written in italics. We give initial responses in the introductory text, but in the applicable cases, a more detailed discussion follows in the point-by-point responses to the specific comments.

In this study of fog and low-cloud (FLC) frequency in the central Namib coastal desert, the authors first present a novel 14 year satellite climatology (originally published in Andersen et al., 2019) of a relatively small region (~20,000 km^2). Then they select the most and least foggy days (amounting to about half of the total observations) in the two transition seasons (Fall and Spring), neither of which is the FLC frequency maximum, and then present the synoptic conditions based on reanalysis data under which foggy vs. clear days present.
The writing is clear and the figures are exceptional, however I find the inferences of causation to be quite speculative and not very convincing. I appreciate the observational nature of the analysis, and would not suggest that modeling needs to accompany it. However, the assertions, such as radiative cooling in the more arid lower troposphere somehow being the driving factor in determining fog presence, needs to have some quantitative basis – or at the very least make reference to some other studies that have shown this effect to be important. I would be surprised if a change of a few kg m^{-2} of water vapor was able to lead to increased radiative cooling rates of greater than ~0.5 K/day at the very most. Is this sufficient to dominate the influences that create foggy conditions? I am not sure, but without any reference to other work that may have found this to be true, it holds the scientific merit of nothing more than pure speculation. Therefore, I have a hard time seeing that this work can in the words of the authors bring about "a new conceptual model of the synoptic-scale mechanisms that control fog."
Thank you for this statement, which made clear to us that the scope of both aims and findings was open to misinterpretation and misunderstanding.
On radiative cooling being 'the' driving factor: By no means do we state that the radiative cooling is ***the*** *dominant factor driving FLC formation (or even it being the driving force for e.g. the seasonality), but rather that it is a contributing factor that facilitates FLC occurrence and thereby influences the day-to-day variability that is in the focus of this manuscript. Also, the free-tropospheric dry anomaly is larger than the TCWV composites suggest, as some of the TCWV difference is masked by the increased moisture in the marine-boundary layer on FLC days so that in relative terms, the difference in specific humidity between FLC days and clear days is quite substantial (up to 220 % at ~700 hPa; P11,L29). In the discussion on the specific comment, we list and discuss studies that have shown the cooling (and also warming) effects of TCWV to be important for low-cloud cover (and also land surface temperatures) in the region.*
On the conceptual model comment: Indeed we recognize not to have chosen optimal wording to communicate the conceptual model in the abstract: In the updated version of the manuscript, we use a more precise description (similar to that used e.g. in the caption for the conceptual model): "a new conceptual model of the synoptic-scale mechanisms that control fog and low cloud

***variability** [...]" . We also decided to change the title of the manuscript to "Synoptic-scale controls of fog and low cloud **variability** in the Namib Desert". Both changes are intended to clarify that in this study we do not analyze the drivers of the Namib-region FLC system, but the drivers of the day-to-day variability within the system.*

One of the stark shortcomings of this work is the absence of a lot of FLC work that has been done in other eastern basin upwelling systems, which could shed a lot of light on the interpretation and analysis of this work. For example, the relationship between fog (or marine stratocumulus) and subsidence is completely overlooked, despite there being ample correlations pointed out in the literature (see, for example, Bony & Dufresne, 2005). Meanwhile lower tropospheric stability (LTS) is presented in Figures 3 & 5, but not really discussed at all. Other conspicuously missing prerequisite work includes Clemesha et al. (2017), Iacobellis & Cayan (2013), Koračin et al. (2005), and Dorman et al. (2019) to name a few. Furthermore, not nearly enough emphasis is paid to the effects of upwelling on the SST's and the SST anomalies on the fog. This is especially surprising given that a large portion of what controls upwelling is coastal geography which influences the wind curl along the coast (see Koračin et al., 2004).
Thank you for pointing us to these interesting and relevant publications, and, indeed the links to other coastal upwelling systems are now strengthened in the manuscript. We did point out on page 9, L 9-11 of the original version of the manuscript that "These stable conditions promote the formation of the southeastern Atlantic stratocumulus cloud deck and determine its seasonal cycle (Klein and Hartmann, 1993; Andersen et al., 2017)." We agree that we should discuss stability and SSTs more, as they are clearly main drivers of the FLC system. As the focus of the manuscript lies on synoptic-scale modifiers of day-to-day FLC variability within this system, and both SST and LTS difference patterns are not as marked as the other mechanisms described in this paper, we did not discuss them in similar detail. However, after carefully considering the points brought up in this review, we agree that this might actually be a shortcoming of the manuscript in its current form. Therefore we have decided to include and explain in much more detail the role of SST and LTS for FLCs in this region, and to discuss links to comparable systems, also based on the valuable sources pointed to by the reviewer. In the point-by-point responses below, we discuss this in more detail, show additional analyses and present the changes to the manuscript.

I do not wish to sound too damning in my criticism of the work being pure speculation, but let me propose an entirely different interpretation of the data in this paper that would construct a competing narrative, or conceptual model, of the synoptic controls on coastal fog. To wit, enhanced negative vorticity advection upwind of the target site on foggy days induces subsidence which increases LTS, drying the lower troposphere, reducing marine boundary layer (MBL) entrainment, increasing surface winds and thus latent heat fluxes from the ocean, and allowing for greater moisture build-up in the MBL prior to encountering the lowest SST's of the upwelling system along the coast.
We thank the reviewer for sharing her/his thoughts about this. You have triggered engaging and fruitful discussions among the authors. While we agree with some aspects of this alternate conceptual model, and will discuss those in more detail in the updated version of the manuscript (increased wind speeds lead to an increased upwind latent heat flux, building up moisture in the marine boundary layer, at least in AMJ; advection over the lowest SSTs), Fig. 6 in the manuscript gives no indication for a relevant difference in the subsidence between FLC and clear days. In fact, in this response letter we provide evidence that for most of the year, day-to-day differences in LTS over land are almost entirely driven by its surface component (T2m). The observed moisture differences clearly come from horizontal transport within the free troposphere (see also Fig. R2.7 in this document). Also, during SON, the coast-parallel winds that drive the upwelling are actually substantially weaker on FLC days than on clear days, with the SST not showing a clear pattern. To

summarize, multiple aspects of this proposed alternate conceptual model are not actually supported by our findings.
We believe, however, that here actually lies a misunderstanding: We do by no means say in this manuscript that the advection over the cool upwelling water is not a driving mechanism of Namib-region FLCs, it surely is (we also point this out on P12, L2-3)! We rather argue that the day-to-day variability that is investigated here is mainly driven by other factors – within a system in which SSTs play a key role. We now communicate this more clearly in the updated version of the manuscript as detailed below in the point-by-point responses, and have changed the title of the manuscript to: "Synoptic-scale controls of fog and low cloud variability in the Namib Desert" to more precisely describe to scope and aims of this study.

In light of the speculative nature of the manuscript as it stands, and that the value of the climatology has already been made available to the community (in Andersen et al., 2019), I would recommend not publishing this without major revisions in order to substantiate the conceptual model of fog production presented herein.
We would like to state that in those passages of the manuscript where we do speculate, this is clearly shown by the language used (e.g., "potentially hinting", P9 L4). We argue, however, that in light of the clear results on many aspects of the paper (which are corroborated by the additional analyses carried out for this response), the main mechanisms described in the conceptual model are well justified, offer a coherent explanation for the observed patterns and thus bring completely new insights into mechanisms that modify day-to-day FLC variability in the central Namib. As the purpose and scope of this manuscript is to better understand synoptic-scale mechanisms that influence the day-to-day variability of FLCs, very little overlap exists to the Andersen et al. (2019) paper, which 'just' provides an observation-based FLC climatology.

Specific Comments are presented below in order of appearance:

p.1, l.6: It is not clear why these two seasons are chosen. AMJ is not a common seasonal breakdown either – it is late fall into winter. What is meant by "characterize seasonal fog" exactly?
You are correct in pointing out that this seasonal breakdown is not common, and indeed, judging from the FLC seasonality presented in Fig. 1c), does not represent the two extreme seasons of FLC occurrence (this would be the more classical seasons DJF and MJJ/JJA). However, we have conducted this analysis in the context of understanding factors driving the day-to-day variability in fog occurrence, and in this context these seasons do make sense. During AMJ, FLCs are markedly lower in the atmosphere, leading to a maximum of fog occurrence at low-lying coastal stations ("low-FLC season" see Fig. 3 in Andersen et al. (2019)), whereas during SON, FLCs are located at higher altitudes ("high-FLC season") leading to a peak in fog occurrence at stations further inland (Andersen et al. (2019), Lancaster et al. (1984), Seely and Henschel (1998)).
We agree that this should be presented more clearly and have changed the corresponding sentence in the abstract to
"[…] during two seasons with different spatial fog occurrence patterns", and added the two following sentences to section 3.1:
"While the FLC occurrence in the central Namib peaks in austral summer, and is lowest during winter, due to the seasonal cycle in the vertical position of the cloud layer, fog peaks at coastal locations in AMJ and at inland locations during SON (Seely and Henschel, 1998; Andersen et al., 2019). For these reasons, this study focuses on mechanisms determining FLC variability within these two characteristic fog seasons."

Figure 1: First a clarification - 1c) shows the average FLC occurrence over all days (from 3-9 UTC), and the peak is during the SH summertime, is that correct?
Yes, indeed this is correct, the caption now states that "Panel c) shows monthly averages of the spatiotemporally averaged FLC cover data set."

Also, I wonder about the wisdom of fixing this time window rigidly past the falling edge of the fog 'burn off'. Sunrise times in that area shift from ~4:00 UTC in summer to 5:45 UTC in winter, which is an appreciable portion of this 6 hr window. I worry that this could bias the FLC frequency changes observed by season.
This is an interesting point, and indeed the time window includes the time of dissipation. In Andersen and Cermak (2018), the average diurnal cycle of FLC occurrence is shown for selected locations in the central Namib. It is apparent that diurnal FLC occurrence peaks around the time of sunrise so that within the considered time frame FLC occurrence rises, peaks and starts to dissipate. The sunrise shift potentially introducing a bias to the seasonal data sets analyzed is a good point, even though we do not analyze summer and winter so that the difference will be much smaller during the analyzed seasons. However, we are not comparing data sets of the different seasons to each other, but the difference between robustly different FLC and clear days within each season. Therefore, a marginal change in the selection of the days analyzed in each group is not expected to markedly influence the results. The choice of the time period and potential implications are now discussed in detail in section 2.1 of the updated version of the manuscript:
"A specified averaging time period is needed to avoid statistically mixing two separate FLC events occurring on successive nights which would be the case in a daily average FLC occurrence data set. The specific time period is chosen to include all periods of the diurnal cycle, with FLC occurrence rising, peaking, and starting to dissipate (Andersen and Cermak, 2018) during this time."
Later in Sec. 2.1 we state that:
"As the time of sunrise varies by season, the constructed data set is likely to feature a seasonal bias in FLC occurrence. It should be noted that this has no effect on the separation of FLC days and clear days within seasons, the analysis of which is the main purpose of this data set. The resulting monthly average central-Namib FLC cover (Fig. 1 c)) should not be used in a quantitative sense, but rather illustrate the general seasonal cycle of FLCs in this region."

I think it might be useful to compare your results to any other cloud climatologies that exist for the region. For example, Dorman et al., 2019 present a COADS-based fog climatology that suggests a fog peak in MAM months in the Benguela upwelling system.
Thank you for pointing to this interesting paper. Dorman et al. (2019) use long-term weather observations from ships to create a marine fog climatology. Marine fog patterns can be quite different from FLC patterns observed from space due to the seasonality in the vertical position of the low-cloud layer (see Andersen et al. (2019), Fig. 3 c)). The fog seasonality in Dorman et al. (2019) does not agree well with the seasonality of fog observed at coastal stations in the central Namib (Andersen et al. (2019), Fig. 3 a)), indicating that marine fog occurrence over the cool SSTs of the Benguela is not necessarily a good proxy for FLC occurrence in the central Namib. While in this paper, we look only at FLCs over land, Cermak (2012) find a maximum of marine FLCs between September and January, again highlighting the importance of the vertical position of the cloud layer when comparing satellite-observed FLCs to (marine) fog. In section 2.1 we now discuss this:
"It is interesting to note that the seasonal cycle of FLCs is not necessarily coupled to the seasonal cycle of fog occurrence due to the seasonal cycle in the vertical position of the low-cloud layer. For example, at coastal locations of the central Namib fog peaks between April and August (Andersen

et al., 2019), while marine fog over the adjacent Atlantic has been found to peak between March and May, with a minimum occurrence between June and August (Dorman et al., 2019).“

I think the monthly FLC pattern is central enough to this work to warrant a line graph as opposed to this subtle gray scale figure which allows for a much less quantitative comparison of the seasons.
Thank you for this comment. The visual representation of the data was done on purpose to indicate that this figure is intended to just give a description of the specific data set used in this study (which is why it is positioned in the data and methods section), and not to introduce a novel climatology. As stated above, it was not the basis for defining the seasons, and should not be interpreted in a quantitative manner, also due to the point raised by the reviewer on seasonality of the time of sunrise. We now make this clear by stating:
"As the time of sunrise varies by season, the constructed data set is likely to feature a seasonal bias in FLC occurrence. It should be noted that this has no effect on the separation of FLC days and clear days within seasons, the analysis of which is the main purpose of this data set. The resulting monthly average central-Namib FLC cover (Fig. 1 c)) should not be used in a quantitative sense, but rather illustrate the general seasonal cycle of FLCs in this region."

Finally, it seems to me if you are going to carry out an annual analysis of FLC-Clear (as you do in Fig 3), you need to report what fraction of your clear and FLC days from your histogram come from each season. Because the pattern you see in Fig. 3 could match the patterns you see in Figs. 4/5 for SON simply because that is where the majority of your FLC days throughout the year come from.
Yes this could be an issue, which is why we addressed this in the original manuscript by not just calculating the annual average difference of all FLC and clear days, but by first computing monthly average differences and subsequently averaging these. This addresses the outlined potential issues that would arise with yearly averages due to the FLC seasonality and is described on P7 L27, and also in the caption of Fig. 3 ("Averaged monthly mean differences"). We now recomputed the seasonal composites the same way to also address within-season changes in FLC occurrence.

p.7, l.15: This is confusing because you are focusing on SON, and only the thin latitudinal band from ~22-24°S, the FLC peak actually occurs in DJF (as shown in Fig. 1c & Andersen 2019, Fig. 2c.)
We agree that this could be communicated more clearly. As outlined in our first response, the seasons were chosen with fog patterns in mind. The fog seasonality is related to FLC characteristics (vertical position), and, in Andersen et al. (2019), this lead to the definition of the two seasons that we investigate with this paper (SON and AMJ). We now state in this paragraph that:
"While the FLC occurrence in the central Namib peaks in austral summer, and is lowest during winter, fog peaks at coastal locations in AMJ and at inland locations during SON due to the seasonal cycle in the vertical position of the cloud layer (Seely and Henschel, 1998; Andersen et al., 2019). For these reasons, this study focuses on mechanisms determining FLC variability within these two seasons. "
The study region in the central Namib (~22-24°S) is chosen because nearly all research on Namib-region fog is conducted in this region, as the historical and current station measurements stem from here (Nagel 1969, Nieman et al. 1978, Lancaster et al. 1984, Seely and Henschel 1998, Henschel and Seely 2008, Kaseke et al. 2017, 2018, Li et al. 2018, Spirig et al. 2019, Wang et al. 2019). We now mention some of these sources in section 2.1 for added clarity.

p.8, l.3: The winds are southerly throughout the region, how do you infer "northerly" advection?
While indeed, over the ocean the winds are southerly, over land this is not the case. On P8 L3, we refer to the T2m anomaly that is most pronounced in the Kalahari region. In this region, northerly

advection is quite common (see e.g. Fig. 2b)), and Fig. 3a) shows that the northerly wind component into this region is strengthened on FLC days. To more clearly illustrate this, Fig. R2.1 in this response shows seasonal average T2m and 10m winds for FLC and clear days. The figure shows considerable temperature differences over land (specifically in the Kalahari region) and also the associated northerly winds that transport heat into the region. While during AMJ, the northerly flow in the Kalahari is also apparent on clear days, it does not originate from warmer regions, i.e. no substantial heat transport is expected. This figure is now added to the appendix of the paper.

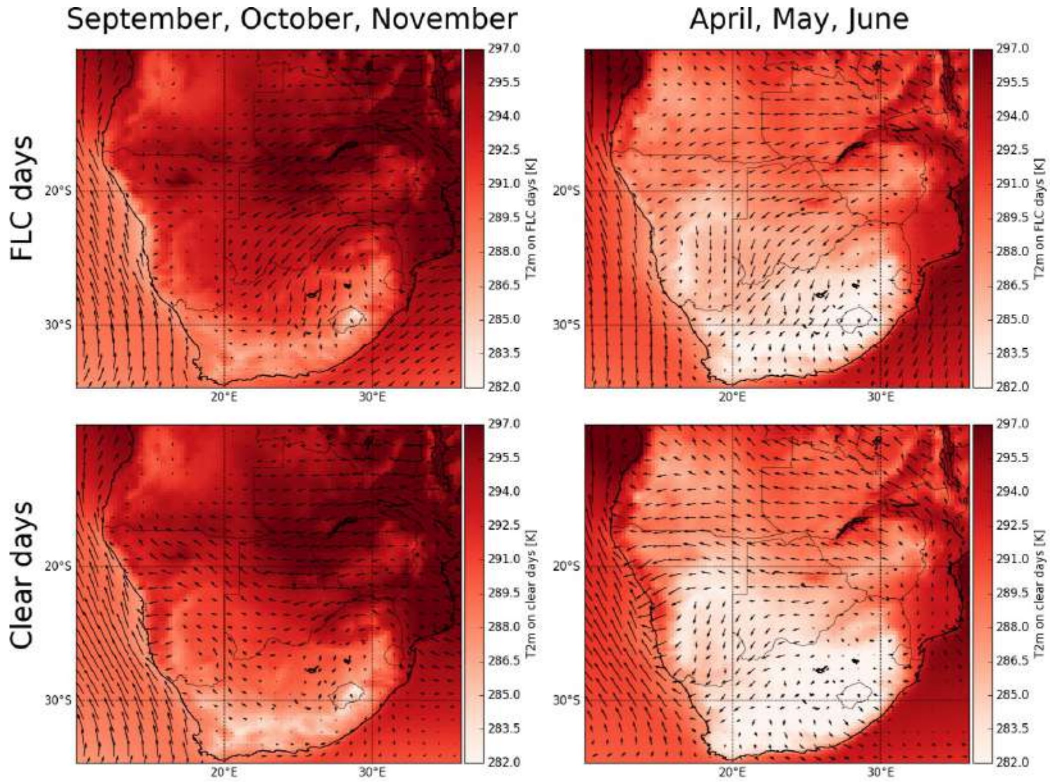
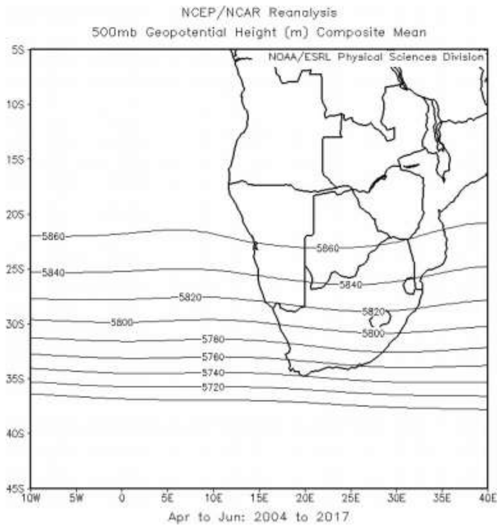


Fig. R2.1: Seasonal average ERA5 T2m and 10m winds in SON (left-hand panels) and AMJ (right-hand panels) for FLC (top) and clear (bottom) days. Winds are averaged to a 1°x1° resolution, the considered time period is 2004-2017.

p.8, l.7: You are referring to features of the climatological Z500 pattern without showing what that is, so it is hard to assess these statements about a trough and the absence of a coastal low. Are you sure Olivier and Stockton (1989) are not referring to a particular time of year for their coastal trough as opposed to a year round analysis that you are presenting here? A quick look at NCEP reanalysis data for the region shows a subtle trough upwind of the coastline.



Thank you for this comment, the sentence on the coastal low was not communicated clearly enough. While one can see lower pressure along the coastline in the climatology of MSLP in Fig. 2 a) and b) of the manuscript, we do not find any indication for an increase in the occurrence of a coastal low on FLC days. There might still be coastal lows, of course, which is discussed on P8 L9-10. While Olivier and Stockton (1989) conduct a yearly analysis, the study does provide seasonal details that we agree not to have discussed enough. They find that the linkage between the coastal low and FLC occurrence in Lüderitz is most pronounced between November and March, and much less so from June to August, when cold fronts are more often associated with FLCs in Lüderitz. We would like to point out, though, that Olivier and Stockton (1989, p.73) state that "The coastal low which causes fog is a relatively small, local phenomenon". Therefore, while FLC occurrence in Lüderitz may be driven by the coastal low, this may not be directly related to FLCs in the central Namib as defined in this paper. This is also visualized clearly in Haensler et al. 2011 (Fig. 1a)). In fact, in Lüderitz, FLCs are much less common than in the central Namib (Fig. 2b) and c) in Andersen et al. (2019), latitude of Lüderitz: ~26.6°S), indicating that these are likely two separate regimes. Another interesting point that needs to be included in the manuscript is that more upwelling does not necessarily lead to increased FLC occurrence in the Namib region, as Olivier and Stockton (1989) point out that in the case of Lüderitz, an upwelling extent of greater than 200km actually leads to less FLCs in Lüderitz, as the local phenomenon of the coastal low is not able to transport moist air from beyond the upwelling front.
We now provide additional details in the introduction:
"In Olivier and Stockton (1989), a coastal low is described as the mechanism that, in case of a narrow coastal upwelling region, drives the onshore advection of foggy air masses into the region of Lüderitz in southern Namibia during austral summer, while during winter they find fog to be associated with cold fronts. However, they assume that, while undetected, coastal lows were also present in these cases, as they typically precede the passage of a cold front (Olivier and Stockton, 1989; Reason and Jury, 1990)."
Concerning the climatology of the region, described in Sec. 3.1 we now state:
"Coastal upwelling, which has been shown to determine marine sea fog patterns along the Namibian coastline (Dorman et al., 2019), in combination with the presence of a coastal low that drives the onshore advection of foggy air masses have been found to be major drivers of fog occurrence in southern Namibia during austral summer (Olivier and Stockton, 1989). One should note though that the relationship between SSTs and Namib-region fog is complex, as Olivier and Stockton (1989) point out that a too large upwelling extent can also lead to less fog in southern Namibia. Based on these insights, and also on knowledge from related coastal upwelling systems (Cereceda et al., 2008; Johnstone and Dawson, 2010; Del Río et al., 2018; Dorman et al., 2019), it

is clear that the Atlantic anticyclone, the SSTs, and the large-scale subsidence are main drivers of this coastal FLC system."
Concerning the seasonal differences described in section 3.2 we now state that
"While a coastal low, which has been described in Olivier and Stockton (1989) as a local feature that can determine onshore flow, may still be present on FLC days, there is no indication of an increase in its presence on FLC days on average. However, as Reason and Jury (1990) describe, the coastal low is frequently followed by a frontal passage, which is a synoptic-scale signal observed here (Fig. A1)."
The average Z500 patterns are now included as additional contours in Fig. 2 of the original manuscript.

p.9, l.4: I think this SST time lag inference is unfounded speculation on the authors' part. The wind difference indicates to me that the clear days have slightly stronger offshore wind components, which could weaken ocean upwelling. It is the alongshore wind component that determines the upwelling, and could possibly have subtle variations due to coastline geography (see, for example, Koračin, Darko, Clive E. Dorman, and Edward P. Dever. "Coastal perturbations of marine-layer winds, wind stress, and wind stress curl along California and Baja California in June 1999." Journal of Physical Oceanography 34, no. 5 (2004): 1152-1173.)
We agree that this specific statement is somewhat speculative, which is expressed by our cautious phrasing in the manuscript ("potentially hinting"). Indeed, clear days feature offshore winds, which is especially pronounced during AMJ. During this time of the year, we agree that upwelling may be more intense on FLC days, as the alongshore wind component is stronger. However, during SON we find that the alongshore wind that drives the upwelling is substantially weaker on FLC days than on clear days (see Fig. R2.2 of this document, top row). This would mean that upwelling should be reduced on FLC days, but SSTs do not show significant differences. However, in the context of interpreting these wind-ocean interactions, it is important to note the role of time scale, as the Ekman transport is not only dependent on the instantaneous wind field, but produces a steady-state situation only after a few pendulum days (Pond and Pickard, 2013). As such, the upwelling reacts to time-integrated winds, introducing complex time lag effects, which are investigated in e.g. Goubanova et al. (2013). We now discuss this in the updated version of the manuscript by stating:
"[…] potentially hinting at a time-lag response of SSTs, which is to be expected, as Ekman transport produces a steady-state situation only after a few pendulum days (Pond and Pickard, 2013)."
We also discuss coastal modulation of winds on the basis of the suggested publication in section 3.1:
"On a local scale, the near-coastal winds that drive the upwelling are additionally modulated by the coastal topography (Koračin et al., 2004)."

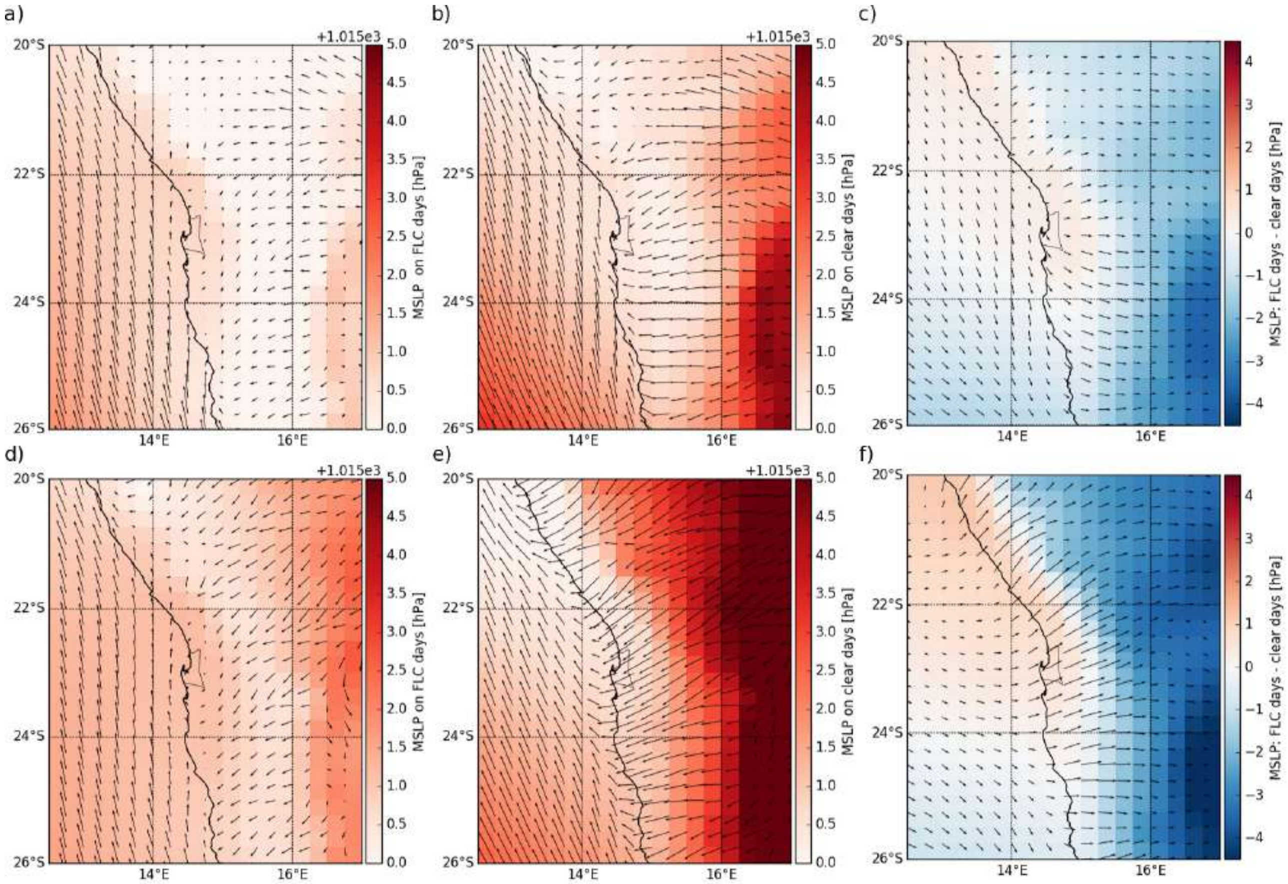


Fig. R2.2: Mean of monthly averaged MSLP and 10m winds during SON (top) and AMJ (bottom) on FLC days (left-hand panels), clear days (center), and their difference (right-hand panels).

p.9, l.5: The SST anomaly having a hydrostatic impact on MSLP seems highly unlikely given that the FLC effects are associated with strong synoptic forcing as argued in the last paragraph. Furthermore, how exactly does it appear likely that SST-FLC correlations are most 'pronounced on seasonal scales'? Can't that be determined for your data set and put to the test? There is not all that much variability in SST in this region, as far as I can see from NCEP reanalysis data.

Thank you for this comment. We developed the hypothesis of the hydrostatic impact on MSLP on the basis of the yearly differences shown in Fig 3 a) of the manuscript. After consideration of your comment, we delete this hypothesis from the manuscript, as it is not corroborated by the seasonal patterns of Fig. 4 of the manuscript.

About the comment on SST seasonality and variability: Klein and Hartmann (1993) have shown that the seasonal cycle of SSTs dominates the seasonality in LTS (Fig. R2.3 of this response) in the Namibian stratocumulus field. Hutchings et al. (2009) state in their abstract that:"The southern Benguela region is characterised by a pulsed, seasonal, wind-driven upwelling at discrete centres [...]", but Tim et al. (2015) state on page 484 that "[…] a clear picture of the upwelling seasonality is not established yet." Concerning other timescales of SST variability, Goubanova et al. (2013) note that subseasonal SSTs close to the coast feature two regimes of variability: an 11 day oscillation, and a 61 day oscillation. In the updated version of the manuscript, we now state that "It appears likely that effects of SST patterns on FLC variability are most pronounced on time scales (i.e. seasonal to interannual) that feature higher SST variability (Hutchings et al., 2009; Goubanova et al., 2013; Tim et al., 2015), as also observed in the Chilean Atacama desert (Del Río et al., 2018)."

We agree that it would be useful to further explore SST influence on longer time scales, but 14 years might not be enough for meaningful statistical analyses of e.g. seasonal relationships. Also, with this paper, we are specifically looking at day-to-day variability within these seasons.

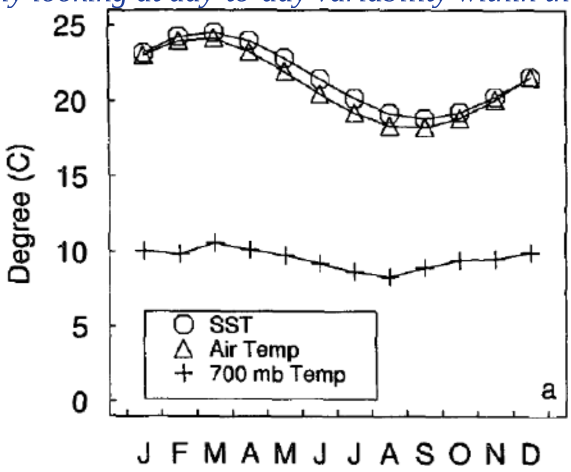


Fig. R2.3: The seasonal cycle of the SST and 700 mb Temp components of LTS in the Namibian stratocumulus clouds field (Figure taken from Klein and Hartmann (1993)).

p.9, l.10: This speculation would benefit from some sort of simple calculation of the magnitude of this effect. Are you meaning to say that radiative cooling will be significantly influencing the SST's? If so, this seems unlikely in a strong upwelling system such as this. Or are you saying that FLC, once formed, will be sustained by effective cloud-top radiative cooling due to the dry tongue over it? As it stands this just seems like a qualitative speculation that is unsubstantiated (without at least a reference to another work that has explored a comparable situation, or a back of the 'envelope' calculation on your part.) The same holds for the assertion that moisture advection influences the surface heat low by principally radiative means presented in the following sentences.
While the TCWV differences might not seem to be much in absolute terms (between ~2 and 5 kg m^{-2}), in relative terms, they are quite substantial. Also, in case of the free-tropospheric dry anomaly over the coast, one should note that part of the dry anomaly is actually masked by the moist anomaly within the marine-boundary layer (see Fig. 6 in the manuscript). As we point out on page 11, lines 26-29, the relative difference in Q in the dry anomaly is as high as 220%, and in the continental moist anomaly, Q is about twice as high on FLC days than on clear days. Over the land this will certainly lead to a substantial warming, as observed during AMJ, and has been observed in the Kalahari (Manatsa and Reason (2017)), and in other dry subtropical deserts before (e.g. the Sahara: (Evan et al. 2015, Alamirew et al. 2018), or the Sahel (Oueslati et al. 2017)). In Fig. R2.4 of this response, we show the statistical relationship between the TCWV anomalies and the T2m anomalies during AMJ over land for pixels which feature significantly higher T2m on FLC days than on clear days (cf. spatial patterns of Fig. 5 b) and d) of the original manuscript). A clear relationship is obvious, with a Pearson correlation coefficient of 0.75. This statistical relationship indicates that more than half of the observed T2m anomalies can be statistically explained by the TCWV anomalies, underscoring the relevance of the greenhouse effect for T2m.
In section 3.2 of the updated version of the manuscript we now state that
"These moist air masses may contribute to the observed T2m heat anomaly via greenhouse warming (Fig. 3 c)). This effect of free-tropospheric moisture on surface temperatures has been observed in the Kalahari (Manatsa and Reason, 2017) and other arid or semi-arid regions before (Evan et al., 2015; Manatsa and Reason, 2017; Oueslati et al., 2017; Alamirew et al., 2018)."
In section 3.3 of the updated version of the manuscript we now discuss this in more detail:
"Here the T2m anomalies closely follow those of the TCWV (Pearson correlation coefficient of 0.75 in continental regions with significantly higher T2m on FLC days than clear days), suggesting that

the increased moisture causes an additional surface heating due to greenhouse warming as discussed in Sec. 3.2. It is likely that the TCWV anomaly is caused by a large-scale free-tropospheric moisture transport from the tropics, which is supported by the marked wind anomalies at 500hPa (Fig. 4 d)) that show a northwesterly anomaly, and the absolute wind and moisture fields at 700 hPa during this time (Fig. A1)."

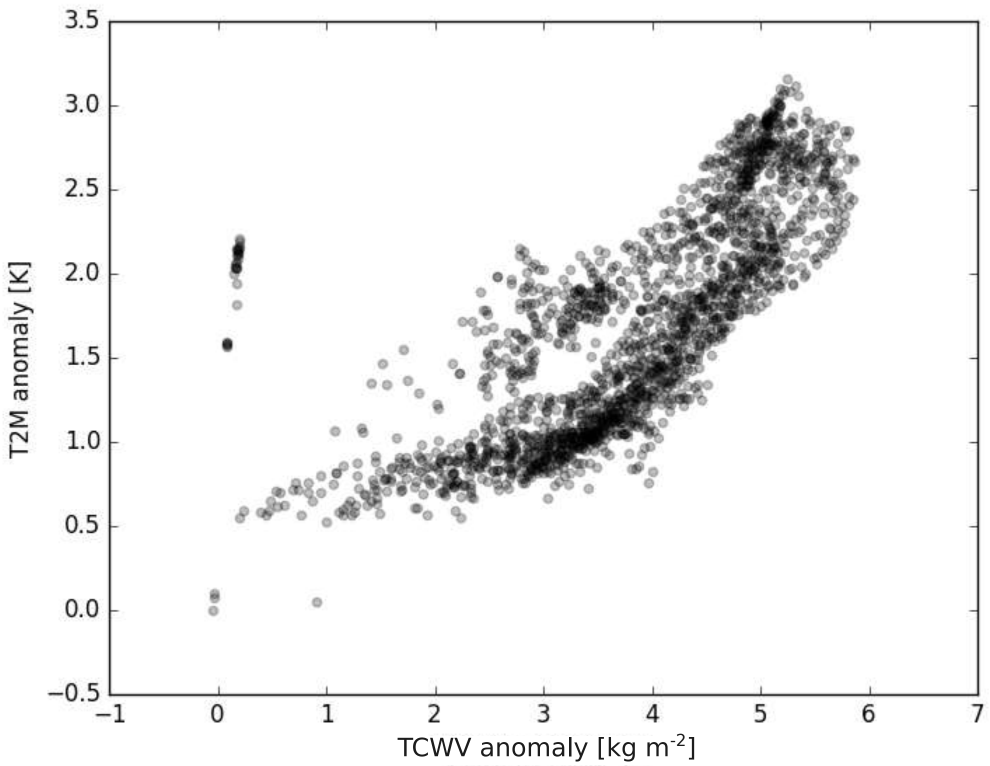


Fig. R2.4: The relationship of TCWV anomalies and T2m anomalies over land during AMJ, and in regions where T2m is significantly higher on FLC days than on clear days. The figure is added to the appendix of the manuscript.

While the SST will surely not respond as strongly as the LST, and in fact might be negligible, studies exist that point to the impact on stratocumulus clouds in the southeastern Atlantic. For this region, Adebiyi et al. (2015, p. 2015) have shown that with an increase in "midtropospheric moisture of about 1.2 g kg^{-1}, the downwelling longwave radiation averaged between 550 and 750 hPa increases by about 15 Wm^{-2}, reducing the net longwave cloud-top cooling by the same amount[...]". Recently, Adebiyi and Zuidema (2018) have shown that in the southeastern Atlantic, free-tropospheric moisture has a significant effect on stratocumulus cloud cover, where increases in free-tropospheric moisture are associated with a decrease in low-cloud cover. With specifically chosen variations of the predictors selected in their multivariate statistical model they could attribute this cloud response clearly to the greenhouse effect of water vapor. It is interesting to note that during the summer season (DJF), the time of maximum FLC occurrence, this dry anomaly is far larger, with anomalies up to 12 kg m^{-2} as shown in Fig. R2.5 of this document.

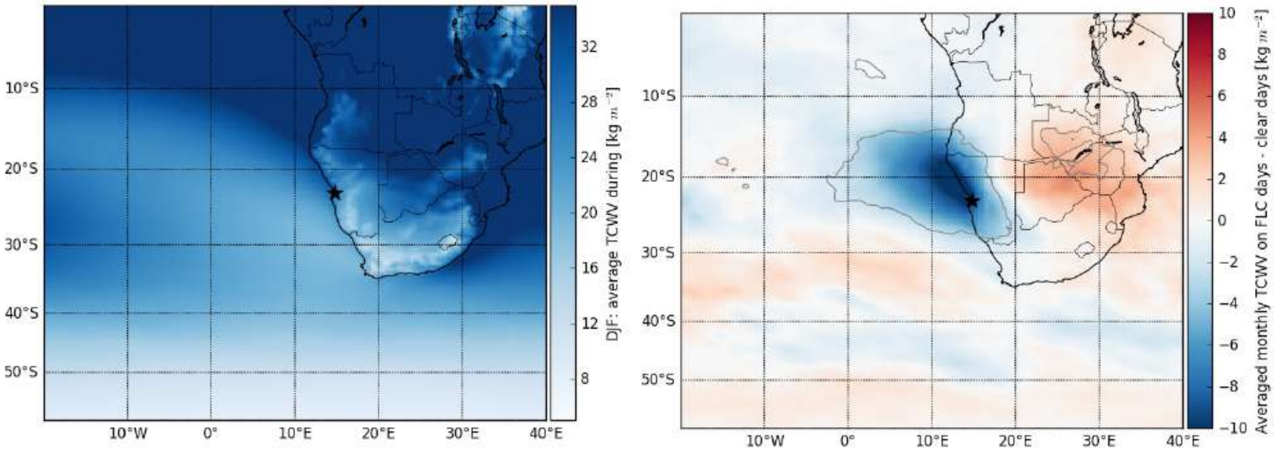


Fig. R2.5: left: DJF average TCWV; right: mean of monthly average TCWV differences (FLC days - clear days) during DJF.

Throughout the manuscript we have changed the wording from "facilitating FLC formation" to "increasing FLC cover".
In section 3.2 of the updated version of the manuscript, this is discussed in more detail:
"This is likely the dry slot (Browning, 1997) or dry air intrusion of the synoptic-scale disturbance that leads to increased longwave cooling at cloud top in case of FLC presence, which has been shown to be a main determinant of cooling within the marine boundary layer (Koračin et a. 2005). This enhanced cooling can increase FLC cover, which has been observed to be a significant mechanism for stratocumulus clouds over the southeastern Atlantic (Adebiyi and Zuidema, 2015; Adebiyi et al., 2018)."
In section 3.3 we state that
"It is interesting to note that the marine dry anomaly peaks between December and February (not shown), the season with maximum FLC cover in the central Namib, with TCWV anomalies exceeding 10 kg m^{-2}."

p.9, l.14/15: This hypothesis could be tested by looking at the T anomaly only during the overnight hours to see if it is an air mass difference or an insolation difference (I strongly suspect it is the latter.) My hunch is that it will be slightly warmer overnight because of radiative heating of the surface from the FLC, which would provide evidence against the air mass difference hypothesis.
We have conducted the suggested analysis and find that during nighttime (1 UTC and 3 UTC), the coastal regions are significantly cooler, pointing to a difference in air mass between FLC and clear days (cf. Fig R2.6 of this response letter for 1 UTC differences). We discuss now this in the manuscript:
"As this anomaly is also apparent during nighttime (1 and 3 UTC, not shown), it is likely that this pattern is mainly due to the relatively warm subsiding continental outflow that is apparent on clear days, rather than a radiative effect of FLCs as found in California (Iacobellis and Cayan, 2013)"

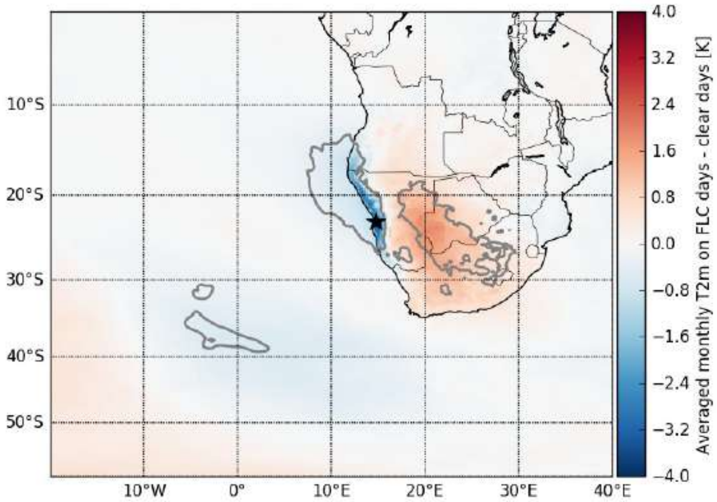


Fig R2.6: Averaged monthly mean differences (FLC days - clear days) of T2m at 1 UTC. In each pixel, an independent two-sided t-test is computed to identify significant differences between FLC and clear days for each month. Contours mark regions where the distributions differ significantly at the 0.01 level (median of the monthly p values <0.01).

We also discuss the correlation between T2m and coastal low cloudiness found in Clemesha et al (2017):
"It should be noted that in a comparable upwelling system (coastal California), Clemesha et al. (2017) also find a positive relationship between T2m over land and coastal low-level cloudiness, with the T2m anomaly shifted poleward by about 5° latitude from the cloud field. They propose that the T2m-cloud relationship is due to spatially-offset associations between coastal low-level cloudiness and stability (potential temperature at 700 hPa), which is strongly correlated to T2m over land thereby resulting in the T2m anomaly, rather than T2m driving the onshore advection. While in the central Namib, the anomaly patterns between potential temperature at 700 hPa and T2m are similar in that they are also positively correlated during SON (and therefore compensate each other in terms of LTS, Fig. 5 c) and e)), they are uncorrelated during AMJ (and also in the annual averages), when T2m over land is strongly correlated to TCWV. Also, during all times of year, the T2m and MSLP anomalies are directly inland from the cloud field, suggesting an influence on onshore advection."

p.9, l.27: In the discussion surrounding the similar annual pattern of Fig. 3b you referred to it as a trough instead of a cut-off low.
After reviewing the absolute fields of Z500 and Z700, we conclude that the synoptic-scale disturbances are not strictly speaking cut-off lows and Rossby wave breaking, and have deleted the corresponding wordings. The trough is visible in the absolute wind fields shown in Fig. R2.7 of this document. This figure is now included in the appendix of the updated version of the manuscript.

p.11, l.4: A few 0.1's K is a subtle change, but the increased wind speeds could definitely increase the latent heat fluxes in the upwind region. Here, you could get a sense of the relative magnitude of these effects by using a simple moisture exchange coefficient and quantifying differences in saturation vapor pressures vs. mean wind speeds.
Yes, this increase in upwind latent heat fluxes leading to increased marine-boundary layer moisture is precisely our hypothesis. However, we agree with Reviewer 2 that we did not state this clearly enough. We do not believe that quantifying the contribution of each specific mechanism is within the scope of this manuscript, and particularly in this case, as we would also need to take into account horizontal transport and vertical mixing. We state more clearly now:

“In isolated patches further south, upwind of the study area, SSTs tend to be significantly higher on FLC days. This could lead to increased surface latent heat fluxes, increasing the moisture content of the marine boundary layer, particularly during AMJ when stronger near-surface winds are also apparent. A few 100 km to the west and south of the Namibian coastline, SSTs could similarly add to the increased moisture within the marine boundary layer.”

p.11, l.6: I would bet that it has everything to do with upwelling induced by the wind field.
This aspects seems to be dependent on the considered time scale. We now state that:
“It is not clear yet, however, what exactly drives the observed anomaly patterns of SSTs. As upwelling reacts to the time-integrated wind field forcing over longer time scales than analyzed here (Pond and Pickard, 2013), the SST response to the instantaneous winds that are considered here is expected to be relatively weak. However, in the case of a relatively stationary disturbance as discussed above, the upwelling patterns could indeed reflect an SST response to a synoptic forcing.”

p.11, l.30: Or the dry anomalies could be associated with subsidence which augments the LTS in the fog cases. This reduces MBL entrainment and along with increased LH fluxes upwind helps to build up Q in the MBL. Along with a lower SST, these influences act in tandem to reduce the dew point depression.
In Fig. 6 we do not find substantial differences in subsidence, and during SON the opposite is actually the case (the increased stability over the ocean is driven by the decrease in T2m, likely due to relatively warm continental outflow on clear days). In Fig. R2.7 of this document, we show the average Q and winds at 700 hPa, which is the layer with strongest Q differences (see Fig. 6 of the manuscript). It is clearly apparent that the dry anomaly during both seasons and the moist anomaly over continental Africa during AMJ is driven by horizontal transport induced by the synoptic disturbance on FLC days. We agree that the increased LH fluxes upwind should build up Q in the MBL, which we state on P11 L4. In the original version of the manuscript, we did not clearly enough present the link between increased winds, SST and MBL Q. This is now clarified in the updated version of the manuscript:
“In isolated patches further south, upwind of the study area, SSTs tend to be significantly higher on FLC days. This could lead to increased surface latent heat fluxes, increasing the moisture content of the marine boundary layer, at least during AMJ when stronger near-surface winds are apparent. A few 100 km to the west and south of the Namibian coastline, SSTs could similarly add to the increased moisture within the marine boundary layer.”

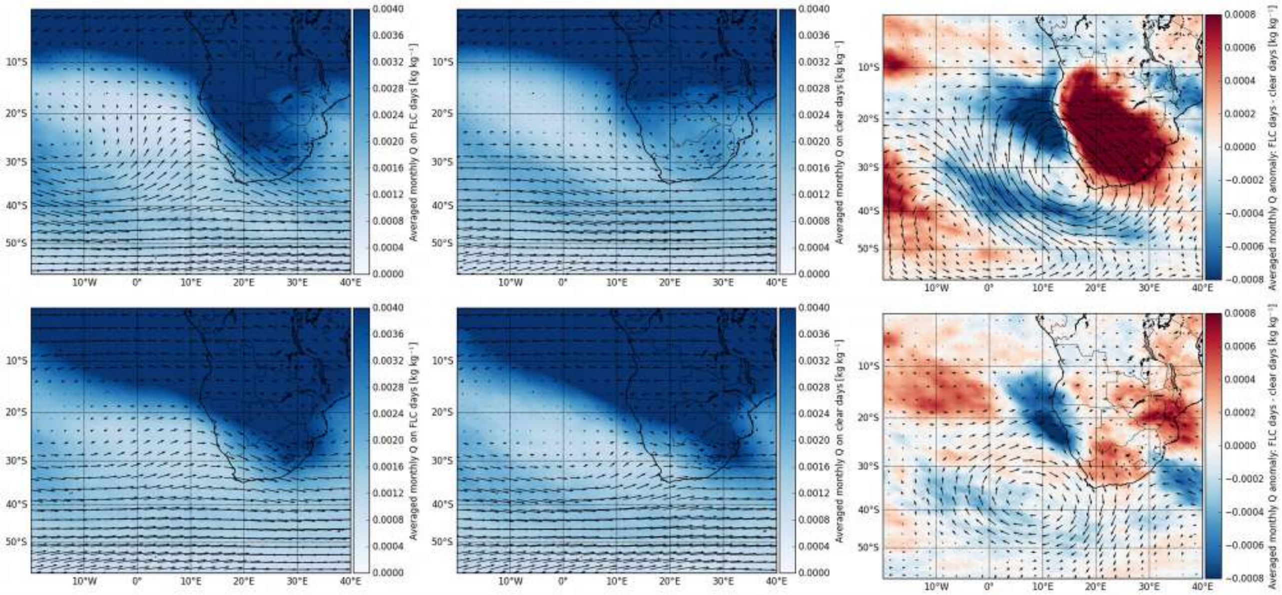


Fig. R2.7: Seasonal averages of Q and winds at 700hPa on FLC days (left), clear days (center), and their difference (right) during AMJ (top) and SON (bottom).

Figure 5: Very little attention is paid to the LTS anomalies presented. My read of Figs. 4/5 is that regardless of season FLC is strongly associated with low SSTs, low T2m, and high LTS.

In general, we agree that FLCs will preferentially occur in situations with low SSTs and high LTS. This is actually the reason to show the climatology in Fig. 2 of the manuscript. Of course, the region is rich in FLCs due the low SSTs and the subsidence that combine to lead to very stable conditions. We actually state that "these stable conditions promote the formation of the southeastern Atlantic stratocumulus cloud deck and determine its seasonal cycle [...]". Also, Fig. 3 shows that the differences in LTS over land are almost entirely caused by the surface component of LTS (Pearson correlation coefficient is -0.90 for land pixels for the yearly averages). During SON, this relationship is weaker, which is now discussed in the updated version of the manuscript. We now describe seasonal differences in LTS in a new paragraph:

"While the yearly averaged composites show that over land, LTS is driven to a large extent by T2m (Fig. 3 c) and d)), this is not quite as pronounced during SON (correlation coefficient =-0.57; Fig. 5 c) and e)). Over continental southern Africa, the differences in T2m (Fig. 5 c)) are frequently compensated by similar differences in potential temperature at 700 hPa (not shown). The most pronounced LTS feature during both seasons, however, is the coastal anomaly of increased LTS (over land and weaker over the adjacent ocean), which is driven by T2m. As this anomaly is also apparent during nighttime (1 and 3 UTC, not shown), it is likely that this pattern is mainly due to the relatively warm subsiding continental outflow on clear days, rather than a radiative effect of FLCs as found in California (Iacobellis and Cayan, 2013). During AMJ, LTS is significantly lower over a large marine region south of 25°S, which is likely caused by the synoptic-scale disturbance."

p.14, l.17: You could look at potential temperature to see what sort of effects that radiative cooling has on the foggy days. It seems that potential temperature would be a better variable to present in the back trajectories (unless, of course, it is a purely isentropic back trajectory.)

In the updated version of the manuscript, the potential temperature is additionally shown in the backtrajectory figure. It suggests that the main difference between the trajectory groups remains to be the difference in MBL Q, as stated in the original version of the manuscript.

p.14, l.21 to p.15, l.1: Doesn't this contradict your hypothesis presented earlier about the lower column water vapor leading to greater radiative cooling on the foggy days?

No, as in Fig. 8, different subsets of the data are compared (only the blue lines of Fig. 7 a) and c)), and differences are computed by following the backtrajectory. As shown in Fig. 5 a) of the manuscript, the lower TCWV is mostly a local phenomenon that is especially pronounced north of ~23°S, and would therefore modify the trajectories only for a limited time.

p.18, l.19: It is not too surprising that so much is explained by the MSLP fields because they determine a lot of things. For instance, MSLP is the main variable used in calculating conventional upwelling indices. Again, I found the lack of centrality of coastal SSTs to be surprising in this work given how important it is found to be in most other studies.
Yes, indeed changes in MSLP can modify upwelling intensity. However, we would argue that to first order, the differences in MSLP that we find in this paper explain most of the variability in FLC occurrence because they comprise the information on the marked differences in dynamics between FLC and clear days which is clearly shown in the contrasting backtrajectories of Fig. 7 of the manuscript. This is the first-order mechanism, as the offshore winds that are apparent on most clear days (Fig. 7 of the manuscript and Fig. R2.2 of this document) will hinder onshore advection of moist/cloudy marine-boundary layer air masses. In that case it does not matter for FLC occurrence in the Namib whether marine fog or low clouds are formed or not. We do agree that SSTs could be included in the discussion of these results, and will likely be relevant for marine fog occurrence as analyzed in e.g., Dorman et al. (2019).
The manuscript now discusses this in more detail:
"It should be noted that changes in circulation additionally influence upwelling intensity (e.g. Hutchings et al., 2009) such that some of the explained variability may also be attributed to factors influencing FLC formation rather than advection. However, due to the longer time-scale of SST responses, and due to the marked contrasting differences in air mass history on FLC and clear days, the latter is thought to be the first order mechanism leading to the high model skill."

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Synoptic-scale controls of fog and low clouds in the Namib Desert: Response to Reviewer 3

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We would like to thank reviewer 3 for her/his review of the manuscript and the valuable comments. Comments by the referee are colored in black, our replies or comments are colored in blue and written in italics.

This is a well-written article. The authors are to be congratulated.

However, It has long been known that fog and low cloud in the coastal zone of the Namib and the South African west coast are largely due to a local/meso-scale phenomenon called a coastal low. This is a weak low pressure system trapped between the western escarpment to the east and the Benguela current to the east. It only extends to just above the height of the escarpment. The diameter of the coastal low and the extent of the cold water upwelling region often determines whether fog occurs or not. An interplay between an approaching cold front and a HIGH pressure system over the continent is thought to cause the coastal low and associated fog to move southwards from the Namibian coast, down the South African west coast, around the tip of South Africa and northwards towards Kwazulu-Natal. It is unclear why the authors need to work at synoptic scale when the phenomenon occurs at a much smaller scale. The role of a cut-off low in fog occurrence is really surprising.

We agree with referee 3 that the connection between coastal lows and fog occurrence has been suggested for a long time, to our knowledge the main paper on this is titled "The influence of upwelling extent upon fog incidence at Lüderitz, southern Africa" by Olivier and Stockton (1989), which is discussed on pages 7 and 8 of the original manuscript. In this very interesting study, on the basis of two years (1983 & '84) of satellite observations, Olivier and Stockton find that fog occurrence in Lüderitz is mostly associated with coastal lows, especially in austral summer, while during winter, it is associated with cold fronts. They go on to assume that as coastal lows often precede the passage of cold fronts (observed to be associated with fog during winter), a coastal low "was present, but unobserved, during these conditions." (p. 71). While their paper is focused on fog occurrence in Lüderitz, southern Namibia, this concept is extended to other regions along the southern African coast, based on two conference papers (Estie 1984, Sciocatti 1984). Both of these publications could not be found in the usual online publication data bases and are therefore not cited in the manuscript.

However, other hypotheses also exist:

1. *Seely and Henschel (1998) suspect that the onshore advection of 'high fog' is enhanced by the plain-mountain wind.*

2. *Lancaster et al. (1984) hypothesize that the seasonal occurrence patterns of fog in the central Namib is influenced by the continental high pressure system, pointing to a synoptic-scale influence.*
3. *In the last few years, several papers have been published that question the described mechanism, and typify most fog events as locally generated radiative fog (e.g., Kaseke et al. 2017, 2018).*

Therefore, we believe that substantial knowledge gaps do still exist and that good reasons exist to study the mechanisms driving variability of fog and low clouds along the south western African coastline on the basis of an extensive observational data set as done here. Also, many of the anomaly patterns that we find are actually on synoptic scales (e.g., moisture transport), underscoring the relevance of this scale to gain a more complete understanding of mechanisms influencing the Namib-region FLC system.

The note of the cut-off low, however, was a mistake on our part, and is now corrected in the updated version of the manuscript.

It is suggested that much more information is provided on the research that has already been conducted on the occurrence of fog along the southern African west coast.

We thank reviewer 3 for this useful suggestion. We have now added a much more detailed discussion on coastal lows in different sections of the manuscript.
In the introduction:
" In Olivier and Stockton (1989), a coastal low is described as the mechanism that, in case of a narrow coastal upwelling region, drives the onshore advection of foggy air masses into the region of Lüderitz in southern Namibia during austral summer, while during winter they find fog to be associated with cold fronts. However, they assume that, while undetected, coastal lows were also present in the case of cold fronts, as they typically precede the passage of a cold front (Olivier and Stockton, 1989; Reason and Jury, 1990)."
In section 3.1:
"Coastal upwelling, which has been shown to determine marine sea fog patterns along the Namibian coastline (Dorman et al., 2019), in combination with the presence of a coastal low that drives the onshore advection of foggy air masses have been found to be major drivers of fog occurrence in southern Namibia during austral summer (Olivier and Stockton, 1989). One should note though that the relationship between SSTs and Namib-region fog is complex, as Olivier and Stockton (1989) point out that a too large upwelling extent can also lead to less fog in southern Namibia."
In section 3.2:
"While a coastal low that has been described in Olivier and Stockton (1989) as a local feature that can determine onshore flow may still be present on FLC days, at least in some of the cases, the composite differences between FLC days and clear days do not provide a clear indication of an increase in its presence on FLC days. However, as Reason and Jury (1990) describe, the coastal low is frequently followed by a frontal passage, which is a synoptic-scale signal observed here (Fig. A1)."

We believe to now extensively discuss the existing literature on fog along the southern African west coast, and in the updated version of the manuscript also discuss in much more detail links to comparable upwelling systems, but if reviewer 3 knows of an important paper on the regional mechanisms that is still missing, we would kindly ask her/him to point us to this publication.

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Synoptic-scale controls of fog and low ~~clouds~~ cloud variability in the Namib Desert

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Abstract. Fog is a defining characteristic of the climate of the Namib Desert and its water and nutrient input are important for local ecosystems. In part due to sparse observation data, the local mechanisms that lead to fog occurrence in the Namib are not yet fully understood, and to date, potential synoptic-scale controls have not been investigated. In this study, a recently established 14-year data set of satellite observations of fog and low clouds in the central Namib is analyzed in conjunction with reanalysis data to identify ~~typical~~ synoptic-scale ~~conditions~~ patterns associated with fog and low-cloud ~~occurrence~~ variability in the central Namib during two seasons ~~that characterize seasonal fog variability~~with different spatial fog occurrence patterns. It is found that during both seasons, mean sea level pressure and geopotential height at 500 hPa differ ~~significantly~~ markedly between fog/low-cloud and clear days, with patterns indicating ~~seasonally different~~ the presence of synoptic-scale disturbances on fog and low-cloud days~~: cut-off lows during September, October, and November, and breaking Rossby waves during April, May, and June~~. These regularly occurring disturbances increase the probability of fog and low-cloud occurrence in the central Namib in two main ways: 1) an anomalously dry free troposphere in the coastal region of the Namib leads to stronger longwave cooling of the marine boundary layer increasing low-cloud cover, especially over the ocean ~~, facilitating low-cloud formation~~where the anomaly is strongest, and 2) local wind systems are modulated, leading to an onshore anomaly of marine boundary-layer air masses. This is consistent with air mass backtrajectories and a principal component analysis of spatial wind patterns that point to advected marine boundary-layer air masses on fog and low-cloud days, whereas subsiding continental air masses dominate on clear days. Large-scale free-tropospheric moisture transport into southern Africa seems to be a key factor modulating the onshore advection of marine boundary-layer air masses during April, May, and June, as the associated increase in greenhouse gas warming and thus surface heating is observed to contribute to a continental heat low anomaly. A statistical model is trained to discriminate between fog/low-cloud and clear days based on information on large-scale ~~mean sea level pressure fields~~dynamics. The model accurately predicts fog and low-cloud days, illustrating the importance of large-scale pressure modulation and advective processes. It can be concluded that Namib-region fog is predominantly of advective nature, ~~but also facilitated by increased~~ and that fog and low-cloud cover is effectively maintained by increased cloud-top radiative cooling. Seasonally different manifestations of synoptic-scale disturbances act to modify its day-to-day variability and the balance of mechanisms leading to its formation and maintenance. The results are the basis for a new conceptual model on the synoptic-scale mechanisms that control fog and low ~~clouds~~ cloud variability in the Namib Desert, and will guide future studies of coastal fog regimes.

1 Introduction

In moist climates, fog is typically viewed as an atmospheric phenomenon that disturbs traffic systems and negatively affects physical and psychological health (e.g., Bendix et al., 2011). In the hyperarid Namib Desert, however, the water input of fog is key to the survival of many species (e.g., Seely et al., 1977; Seely, 1979; Ebner et al., 2011; Roth-Nebelsick et al., 2012; Warren-Rhodes et al., 2013; Henschel et al., 2018; Gottlieb et al., 2019). Despite this ecological significance, the local mechanisms that control the formation and spatiotemporal patterns of Namib-region fog are not yet fully understood, and potential linkages to synoptic-scale variability have yet to be explored. With regional climate simulations suggesting a warmer and even dryer climate (James and Washington, 2013; Maúre et al., 2018), fog could become an even more essential water source for regional ecosystems in the future. However, the lack of understanding concerning fog and low-cloud (FLC) processes and their interactions with dynamics, thermodynamics, aerosols, and radiation in this region (Zuidema et al., 2016; Formenti et al., 2019) limits the accuracy of and confidence in projected changes of fog patterns (e.g., Haensler et al., 2011).

Field observations of local meteorological parameters and fog have led to the distinction between two main fog types occurring in the region: advection fog and high fog. Advection fog can form when a moist warm air mass is transported over a cool ocean (Gultepe et al., 2007) and has been reported to occur mainly during austral winter, affecting a coastal strip of $<$ 30–40 km (Seely and Henschel, 1998). High fog is described as a low stratus that frequently reaches more than 60 km inland between September and March and leads to fog where the advected stratus base intercepts the terrain (Seely and Henschel, 1998). While the two fog types are reported to be transported inland with different wind systems (for a review of local wind systems see Lindesay and Tyson (1990)), they are both described to be of advective nature. In Olivier and Stockton (1989), a coastal low is described as the mechanism that, in case of a narrow coastal upwelling region, drives the onshore advection of foggy air masses into the region of Lüderitz in southern Namibia during austral summer, while during winter they find fog to be associated with cold fronts. However, they assume that, while undetected, coastal lows were also present in these cases, as they typically precede the passage of a cold front (Olivier and Stockton, 1989; Reason and Jury, 1990). Recent analyses of diurnal FLC characteristics have shown that the timing of FLC occurrence depends on the distance to the coastline, with FLCs occurring significantly earlier at the coast than further inland, which is an indication for the dominance of advective processes (Andersen and Cermak, 2018; Andersen et al., 2019). Also, measurements of fog microphysics during the AEROCLO-sA field campaign in the Namib suggest that the observed fog events were advected cloudy air masses from the ocean (Formenti et al., 2019). While it has long been acknowledged that other fog types (e.g., radiation fog and frontal fog) can occur in the Namib as well (e.g., Jackson, 1941; Nagel, 1959), many statements regarding fog formation mechanisms in the historical literature do not seem to be founded on extensive and coherent observational evidence. Until recently, the occurrence of radiation fog, i.e. fog formation near the surface due to local radiative cooling under clear-sky conditions and without advective influence (Gultepe et al., 2007), was seen as a comparably rare situation (e.g., Seely and Henschel, 1998; Eckardt et al., 2013). This was questioned when, based on analyses of stable isotopes of fog water samples, Kaseke et al. (2017) and Kaseke et al. (2018) found that the majority of their collected fog water samples stemmed from sweet water sources and interpreted this as evidence of predominant occurrence of radiation fog. Based on these findings, they postulated a potential shift from advection-dominated fog to radiation-dominated fog in the Namib Desert (Kaseke et al., 2017). Thus, the importance of the various fog formation mechanisms is currently a subject of scientific debate.

The goal of this study is to better understand the synoptic-scale conditions under which Namib-region FLCs occur, how synoptic-scale variability changes local conditions, and thereby to assess the relevance of different potential fog formation mechanisms. To this end, a 14-year time series of geostationary satellite observations of FLCs in the central Namib is combined with reanalysis data and air-mass backtrajectories to systematically analyze the large-scale dynamic conditions and air-mass characteristics that are associated with FLC occurrence in the Namib. The guiding hypothesis for this study is:

Fog and low clouds in the central Namib are primarily of advective nature and therefore associated with distinct synoptic-scale patterns of atmospheric dynamics and air-mass history. Thus, they can be statistically predicted with information on atmospheric circulation.

2 Data and methods

2.1 Satellite observations of FLCs

The Spinning-Enhanced Visible and Infrared Imager (SEVIRI) sensor, mounted on the geostationary Meteosat Second Generation (MSG) satellites, is ideally suited to provide spatiotemporally coherent observations of clouds. It features a spatial resolution of 3 km at nadir and scans its full disk every 15 min (96 hemispheric scans per day, (Schmetz et al., 2002)). In the context of this study, 14 years (2004–2017) of SEVIRI data ~~in the thermal infrared~~ are used to continuously detect FLCs with the algorithm developed by Andersen and Cermak (2018). ~~In~~ The algorithm relies mostly on a channel difference in the thermal infrared (12.0–8.7μm), and in an extensive validation against surface observations, this technique has shown a good skill (97 % overall correctness of the classification). The 14-year FLC data set used here has already been applied to study spatial and temporal patterns of FLC occurrence along the southwestern African coast in Andersen et al. (2019). It should be noted that this satellite technique does not discriminate between fog and other low clouds.

The focus of this study is on FLCs in the central Namib, from where the majority of historical and present-day station measurements stem (e.g. Nagel, 1959; Nieman et al., 1978; Lancaster et al., 1984; Seely and Henschel, 1998; Kaseke et al., 2017; Spirig et al., . To provide a representative measure of the overall central-Namib FLC cover on a daily basis, FLC occurrence is averaged between 3 UTC and 9 UTC (local time is UTC +2h) in the region between 22°S and 24°S and up to 100 km inland. Only pixels with at least a 5 % FLC occurrence frequency in the climatology (as in Andersen et al. (2019)) are used. A specified averaging time period is needed to avoid statistically mixing two separate FLC events occurring on successive nights which would be the case in a daily average FLC occurrence data set. The specific time period is chosen to include all periods of the diurnal cycle, with FLC occurrence rising, peaking, and starting to dissipate (Andersen and Cermak, 2018) during this time. The spatial and temporal averaging is illustrated for an exemplary day in Fig. 1 a). While the specific day shown here is arbitrary, the general feature of maximum FLC cover in the early morning hours and rapid decline shortly after sunrise is typical of the region (Andersen and Cermak, 2018). For further analyses, the data set is divided into 'FLC days' with mean regional FLC cover exceeding 50 % between 3 and 9 UTC, and 'clear days' with mean FLC cover below 3 %. These thresholds are chosen to represent two clearly separated parts of the FLC cover distribution that occur with similar frequencies. The resulting distribution of daily average FLC cover and the number of cases in each class are shown in Fig. 1 b). ~~Figure 1 c) shows the monthly averages of~~ As the time of sunrise varies by season, the constructed data set is likely to feature a seasonal bias in FLC occurrence. It should be noted that this has no effect on the separation of FLC days and clear days within seasons, the analysis of which is the main purpose of this data set. The resulting monthly average central-Namib FLC cover ~~, illustrating~~ (Fig. 1 c)) should not be used in a quantitative sense, but rather illustrate the general seasonal cycle of FLCs in this region. It is interesting to note that the seasonal cycle of FLCs is not necessarily coupled to the seasonal cycle of fog occurrence due to the seasonal cycle in the vertical position of the low-cloud layer. For example, at coastal locations of the central Namib fog peaks between April and August (Andersen et al., 2019), while marine fog over the adjacent Atlantic has been found to peak between March and May, with a minimum occurrence between June and August (Dorman et al., 2019).

2.2 ERA5 reanalysis

To investigate the large-scale meteorological conditions associated with FLCs in the central Namib, ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used. ERA5 is the new generation of reanalysis and follow-up of ERA-Interim (Dee et al., 2011). In comparison to ERA-Interim, it features higher spatial (0.25°) and temporal (hourly) resolutions, along with other improvements (Hersbach, 2016).

In the context of this study, 14 years (2004–2017) of meteorological fields are analyzed. To characterize large-scale dynamic and thermodynamic conditions, fields of mean sea level pressure (MSLP), geopotential height at 500, 700, 850, and 925 hPa (Z500~~), u and v components of 10 m winds~~, Z700, Z850, Z925), 2 m air temperature (T2m), sea surface temperature (SST), total columnar water vapor (TCWV), specific humidity (Q), ~~winds at different pressure levels~~ as well as winds at 10 m and at all ERA5 pressure levels between 1000 and 500 hPa, and lower tropospheric stability (LTS: computed as the difference between potential temperature at 700 hPa and ~~the surface~~T2m, (Klein and Hartmann, 1993)) are used. To represent the morning conditions for which FLC is averaged, 6 UTC fields of ERA5 data are selected. While for additional analysis, T2m fields are also used at nighttime (1 UTC and 3 UTC), the 6 UTC fields are used if no specific information on time is given.

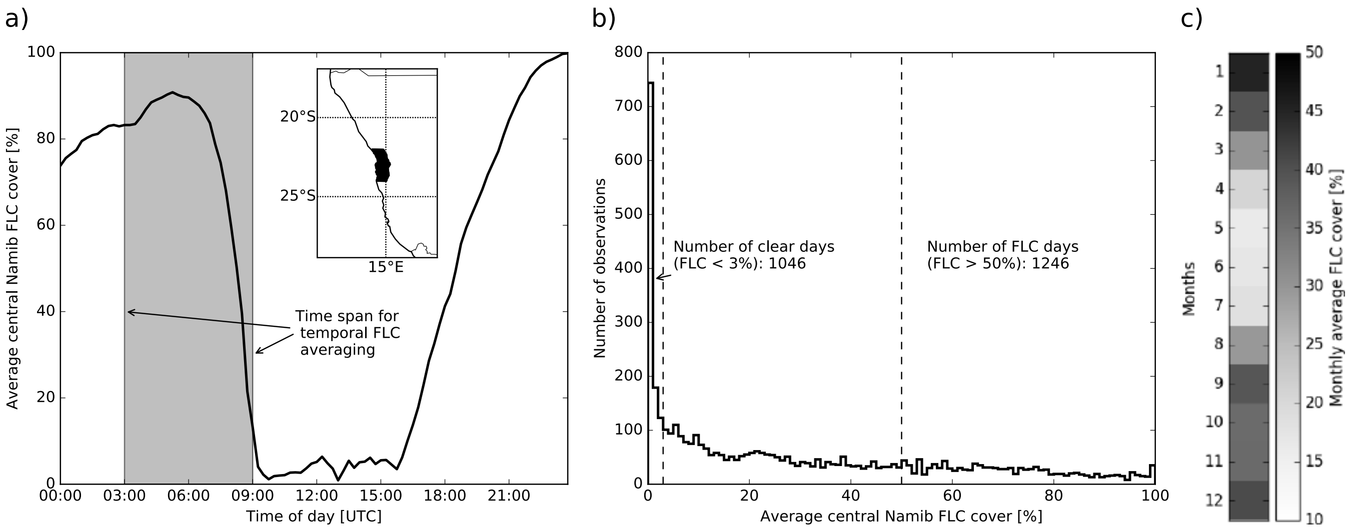

Figure 1. a) Illustration of the spatiotemporal averaging for one exemplary day (September 9th, 2015) to create the FLC cover data set. The curve in a) shows the regionally averaged (marked central-Namib region) FLC occurrence, which is then averaged between 3 UTC and 9 UTC (grey area). The resulting average daily morning FLC cover is given in percent. b) Distribution of the resulting central Namib FLC cover for the complete observation period (2004–2017). Observations are separated in two classes: clear days (<3 % mean FLC cover) and FLC days (mean FLC cover >50 %). Days with mean FLC cover between 3 % and 50 % are not considered in analyses based on this classification (2418 cases, for 404 days FLC cover could not be computed due to missing data or complete coverage with higher-level clouds). Panel c) shows monthly averages of the ~~derived~~ spatiotemporally averaged FLC cover data set.

2.3 Trajectory analysis

24-hour backward trajectories are calculated using the Lagrangian Analysis Tool (LAGRANTO, (Sprenger and Wernli, 2015)). The three wind components needed for the trajectory calculations are taken from ERA5 on a regular 0.5° latitude-longitude grid, at 137 model levels in the vertical, and at a 3-hourly temporal resolution. The spatial resolution is used to reduce the data volume and computational cost. While the native resolution would be preferable, the general patterns of the trajectories are not expected to be affected, as tests with lower-resolution ERA-Interim data showed comparable results. The trajectories are started daily at 06 UTC for the period April, May, June, September, October and November 2004-2017. Their starting points are located in the central Namib close to Gobabeb at 23°S and 15°E 25 hPa above the surface (at ≈ 940 hPa), which corresponds roughly to 200 m above ground level. By doing so, the back trajectories represent air masses for the levels where fog and low clouds in the region are typically observed (Andersen et al., 2019). In order to obtain insights about the physical properties of the air masses, the temperature, potential temperature, specific humidity, and relative humidity are tracked along the trajectories. The location is chosen, as it is the main site of both historic and present-day scientific activity in the region (Lancaster et al., 1984; Seely and Henschel, 1998; Kaseke et al., 2017; Spirig et al., 2019).

2.4 Principal component analysis

The atmospheric variability of the South Atlantic and southern African region is characterized by means of a Principal Component Analysis (PCA, Storch and Zwiers (cf. 1999)). PCA solves the eigenvalues of the data covariance matrix and projects data variability onto an orthogonal basis, i.e. decomposes data variability into independent variability modes. Each mode explains a fraction of the total variance, and is represented by a spatial anomaly pattern and a standardized time series (namely, the principal components (PCs)) accounting for the amplitude of the anomaly pattern~~(cf. Storch and Zwiers, 1999)~~. Here, the PCA is used to analyze daily fields of the zonal and meridional components of 10 m wind at 6 UTC in a domain centered on the Namib (0°–40°E; 40°S–0°N). In the context of this study, the main modes of the wind variability are used to understand possible linkages between atmospheric circulation at the synoptic scale and the daily occurrence of FLCs in the Namib-region. The wind fields are first remapped onto a ~~2~~1° regular grid (PCAs are computationally expensive; (Pham-Thanh et al., 2019)), then daily 6 UTC anomalies are computed by subtracting the 14-year climatological average wind components at each grid point. The PCA is applied to the covariance matrix of both components in the domain. ~~In the context of this study,~~ Remapping to 1° resolution allows to accurately describe the atmospheric variability at synoptic scale, but smoothing out the variability associated with small-scale effects. The sensitivity of the PCA to the spatial resolution is tested by conducting the analysis based on wind fields remapped to a 2° resolution. The results of the two PCAs at the different resolutions are very similar, demonstrating their robustness. Daily anomalies are computed with respect to the ~~main modes of the 10 m wind field variability are used to understand possible linkages between atmospheric dynamics and Namib-region FLCs~~14-year sampling of the FLC dataset, in order to compare wind and FLC variability over a homogeneous climatology.

2.5 Statistical prediction of FLCs

Statistical modeling of fog or low clouds is typically done by using local fields of a set of predictors, i.e. relevant meteorological fields and aerosol properties (e.g., Andersen et al., 2017; Adebiyi and Zuidema, 2018; Fuchs et al., 2018). The circulation-induced variability can be captured by spatial patterns of pressure fields (Deloncle et al., 2007; Yu and Kim, 2010; Sippel et al., 2019). A major challenge when using pressure fields (denoted $\mathbf{X}$, as an n x p matrix of n samples and p predictors located on a grid) to predict a target variable is, however, that the number of (strongly correlated) predictors can quickly outgrow the number of observations. This typically leads to high-variance problems (overfitting) in classical statistical models. The issue can be overcome with shrinkage methods, as e.g. regularized linear models (Hastie et al., 2001). These provide an extension of linear regression techniques that shrink the regression coefficients of a model by penalizing their size, thereby addressing the aforementioned high-variance issues (Hastie et al., 2001). Ridge regression is a specific example of a regularized linear model where the shrinkage is controlled by a value λ that shrinks the coefficients of the model towards zero using the L2 penalty (the squared magnitude of the coefficient value is added as a penalty term to the loss function). This method is well suited for cases with a large number of correlated predictors that are all relevant (coefficients > 0) (Friedman et al., 2010). The method can be used for classification and regression (Friedman, 2012).

Here, the statistical learning method is used in a classification setting. That is, a binary response variable ("FLC day" or "clear day") is modeled using logistic regression regularized with the ridge penalty. In logistic regression with a binary response variable, the "odds ratio" ($log\frac{Pr(FLC\ day|X=x)}{Pr(clear\ day|X=x)}$) is estimated as a linear function of the predictors for any given day:

$$log\frac{Pr(FLC\ day|X=x)}{Pr(clear\ day|X=x)} = \beta_0 + \beta^T x, \tag{1}$$

with β_0 the intercept and β^T the model coefficients. From the odds ratio, the estimated probabilities and the corresponding class (FLC day or clear day) are determined for each sample. The ridge regression penalty based on the L2 norm, i.e. $R(\lambda) = \lambda \sum_{i=1}^{p} \beta_i^2$ is then incorporated as a constraint on the size of the regression coefficients in the objective function that is minimized to fit the model. The tuning parameter λ directly trades off between a more flexible regression model (small penalty, i.e., low λ value) but that possibly suffers from high-variance issues, and a less flexible regression model. Accordingly, a larger value of λ enforces smaller (but non-zero) regression coefficients, and a smoother spatial map of regression coefficients is obtained as a result. The optimal λ value is derived through 10-fold cross validation. For a more complete description of regularized (logistic) regression, the reader is referred to Hastie et al. (2001), and the ElasticNet vignette for a hands-on tutorial (https://web.stanford.edu/~hastie/glmnet/glmnet_alpha.html). Model estimation and cross-validation was performed using the scikit-learn package in Python (Pedregosa et al., 2011).

The ridge regression method is used to predict FLC and clear days over the complete 14-year time seriesfor which observations exist, using , using spatial patterns of 6 UTC (representative of averaging time of FLC cover, see Sec. 2.1) ERA5 MSLP fields in a large spatial domain centered on the central Namib (0°S–45°S and 8°W–38°E, shown in Fig. 2). The ERA5 pressure fields feature a spatial resolution of 0.25°x0.25° and as such, lead to 33,485 predictor fields.

3 Results and discussion

3.1 Dynamic and thermodynamic conditions

Figure 2 shows a climatology of the dynamic and thermodynamic characteristics of the southeastern Atlantic and southern African region based on 14 years (2004–2017) of ERA5 data. Two seasons are shown in the figure that are representative of two different fog regimes (described in the next paragraph, Seely and Henschel, 1998; Andersen et al., 2019): September, October, November (SON) in the left-hand panels and April, May, June (AMJ) in the right-hand panels. At this spatial scale, the St. Helena High and southern African South Atlantic High and the continental high control the characteristic near-surface flow patterns during both seasons. During SON, the St. Helena South Atlantic High is more prominent and, in combination with the thermal contrast between land and ocean, results in the formation of a low-level jet during this time (Nicholson, 2010). This alongshore coastal jet intensifies the upwelling of cold water, which feeds back to amplify the jet by increasing the thermal land-ocean contrast (Nicholson, 2010). On a local scale, the near-coastal winds that drive the upwelling are additionally modulated by the coastal topography (Koračin et al., 2004). While more prominent during SON, the cold when the more pronounced South Atlantic High produces stronger winds, coastal upwelling water of the Benguela current is apparent in the relatively low SSTs along the southwestern African coastline during both seasons (Fig. 2 c) and d)), and throughout the year (Nelson and Hutchings, 1983). During AMJ, continental high pressure situations are the most prominent circulation pattern (Tyson et al., 1996; Garstang et al., 1996). This is visible in the more pronounced southern African continental high pressure system and leads to a marked amplification of the easterly flow over the southern African continent. In the Namib Desert, thermally and topographically induced local wind systems within the boundary layer modulate these synoptic air-flow patterns, and the significance of the induced diurnal oscillations can exceed that of the synoptic scale (Goldreich and Tyson, 1988; Lindesay and Tyson, 1990). The combination of large-scale subsidence and low SSTs along the coastline produces high LTS conditions in the coastal marine regions adjacent to the Namibare characterized by stable conditions, specifically during SON (LTS contours in c) and d)). These stable conditions promote the formation of the southeastern Atlantic stratocumulus cloud deck and determine controls its seasonal cycle (Klein and Hartmann, 1993; Andersen et al., 2017), where the SST component is responsible for most of the LTS seasonality. One should note that MSLP and LTS are both affected by the high elevation of the central plateau in southern Africa and in this region (cf. Fig. 6), and are not likely to be a perfect representation of near-surface pressure conditions and lower-tropospheric stability in this region. However, due to the joint consideration of regions in southern Africa with high topography, the low-lying central Namib, and marine regions, no one specific pressure level of geopotential height can adequately summarize near-surface conditions throughout this large domain. Additional analyses show that patterns obtained from MSLP fields in southern Africa are similar to those at 925 hPa and 850 hPa (not shown).

As outlined in the introduction, distinct seasonal fog and FLC patterns have been identified in the central Namib (Lancaster et al., 1984; Seely and Henschel, 1998; Cermak, 2012; Andersen et al., 2019). During SON, described as 'high FLC season' in Andersen et al. (2019), FLCs frequently occur in the central Namib as a low stratus or high fog (cloud base height on average $\approx$ 400 m above sea level (asl)) that touches the ground inland, whereas during the 'low FLC season' in AMJ, FLCs occur less frequently, do not extend as far inland and are typically lower, at $\approx$ 200 m asl and thus register as fog (termed 'advection fog' in Seely and Henschel (1998)) at locations closer to the coastline (Andersen et al., 2019). While the FLC occurrence in the central Namib peaks in austral summer, and is lowest during winter, fog peaks at coastal locations in AMJ and at inland locations during SON (Seely and Henschel, 1998; Andersen et al., 2019) due to the seasonal cycle in the vertical position of the cloud layer (Andersen et al., 2019). For these reasons, this study focuses on mechanisms determining FLC variability within these two characteristic fog seasons.

It has been assumed that the occurrence of Namib-region FLCs and their variability on diurnal to seasonal scales is driven by the position and strength of large-scale pressure systems, as this would affect formation occurrence and advection of low-level clouds, atmospheric stability, and SSTs (Lancaster et al., 1984; Cermak, 2012; Andersen and Cermak, 2018; Andersen et al., 2019), as well as SST patterns (cooling of air masses) and the presence and position . Coastal upwelling, which has been shown to determine marine sea fog patterns along the Namibian coastline (Dorman et al., 2019), in combination with the presence of a coastal low that has been linked to fog occurrence (Olivier and Stockton, 1989). drives the onshore advection of foggy air masses have been found to be major drivers of fog occurrence in southern Namibia during austral summer (Olivier and Stockton, 1989). One should note though that the relationship between SSTs and Namib-region fog is complex, as Olivier and Stockton (1989) point out that a too large upwelling extent can also lead to less fog in southern Namibia. Based on

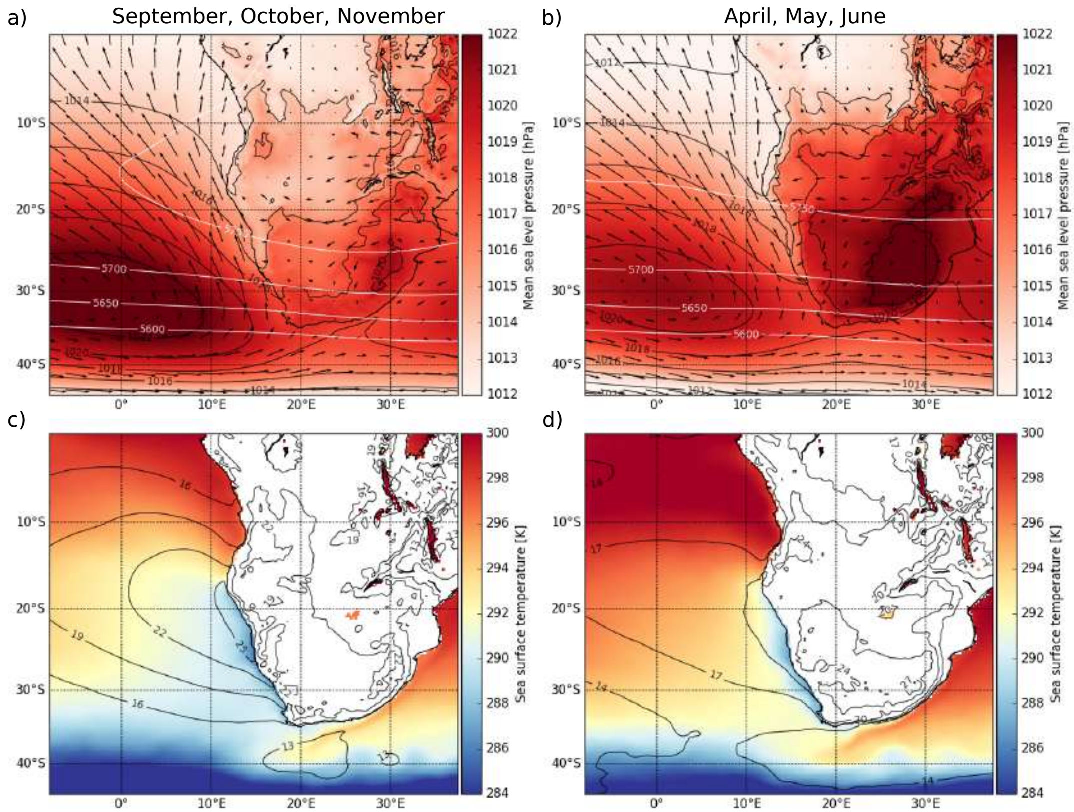

Figure 2. Climatological setting of the region in two seasons (2004–2017): September, October, November on the left and April, May, June on the right. Top row: MSLP in color and contours with 10 m winds indicated by arrows where the length scales with strength (the u and v vectors of near-surface winds are bilinearly interpolated to a 2.5°x2.5° grid for clarity). Z500 is illustrated with white contours. Bottom row: SST in color, LTS (K) as contours. Data is sampled at 6 UTC.

these insights, and also on knowledge from related coastal upwelling systems (Cereceda et al., 2008; Johnstone and Dawson, 2010; Del Río , it is clear that the Atlantic anticyclone, the SSTs, and the large-scale subsidence are main drivers of this coastal FLC system. While all of these links ~~are plausible and likely~~ play a role for FLCs in the Namib, the influence of synoptic-scale variability has not been explored, and a more in-depth analysis is needed to estimate the importance of the different mechanisms for the day-to-day variability of Namib-region FLCs.

3.2 Differences in meteorological conditions on FLC days and clear days

Figure 3 shows large-scale patterns of averaged monthly mean differences in a) MSLP and 10 m winds, b) Z500 and winds at the same pressure level, c) T2m, d) LTS, e) SST, and f) TCWV on FLC versus clear days (as defined in Sec. 2.1) in the central Namib (marked with a star) during the investigated 14-year period (all months are considered here). The average of monthly mean differences is chosen rather than the overall mean differences to account for the distinct seasonal cycle of FLC occurrence in the Namib (Fig. 1 c)). In each pixel, an independent two-sided t-test is computed to identify significant differences between the two classes (contours show p values <0.01). It is apparent that the dynamical conditions (Fig. 3 a) and b)) on FLC days differ significantly on the synoptic scale. On FLC days, MSLP over continental southern Africa is systematically lower by about 3–5 hPa. This anomaly of lower MSLP extends over the southeastern Atlantic ocean at about 30°S. In a smaller oceanic region along the coastline north of 23°S, MSLP is significantly higher, leading to an overall anomalously high land-sea pressure gradient in this region and an onshore flow anomaly of near-surface winds in the central Namib on FLC days. The land-sea contrast in MSLP indicates a heat low over land, where the heat anomaly (Fig. 3 c)) could be driven by northerly advection ahead of the trough or enhanced surface warming. As discussed in Sec. 3.1, MSLP and 10m winds may not be a good representation of near-surface level characteristics where topography is high, however, additional analyses of geopotential height at 850 hPa and 925 hPa corroborate observed MSLP patterns. Differences exist in winds north of the central Namib, where at 925 hPa and 850 hPa (not shown), a stronger onshore flow anomaly is observed than at 10 m, possibly indicating a topographical blocking of the onshore flow below the inversion. Z500 on FLC days (Fig. 3 b)) is significantly lower over the southeastern Atlantic between 30°S and 40°S. This pattern is an indication for upper-level waves disturbing the mean tropospheric circulation of the southeastern Atlantic and southern Africa (Tyson et al., 1996; Fuchs et al., 2017). In combination, MSLP and Z500 show a weakly baroclinic structure with the mid-level trough shifted to the west ~~. There is, however, no indication of the predominant presence of~~ (cf. Fig. A1). While a coastal low~~that~~ ~~.~~, which has been described in Olivier and Stockton (1989) as a local feature that can determine onshore flow~~. The presence of such a coastal low, at least in some of the cases, may be masked by the stronger pressure anomalies of the synoptic scale~~, may still be present on FLC days, the composite differences between FLC days and clear days do not provide a clear indication of an increase in its presence on FLC days on average. However, as Reason and Jury (1990) describe, the coastal low is frequently followed by a frontal passage, which is a synoptic-scale signal observed here (Fig. A1).

There is a coherent pattern of slightly lower SSTs ($\approx$ 0.5 K: Fig. 3 e)) along the coastline on FLC days; however, the difference between SSTs on FLC and clear days is not significant at the 0.01 level (and also not at the 0.05 level). It is interesting to note that SSTs tend to be lower on FLC days, although the coast-parallel near-surface wind that partly governs the upwelling is slightly weaker in these cases (Fig. 3 a)), potentially hinting at a time-lag response of SSTs~~. The observed low anomaly of SSTs close to the coast at $\approx$15°S may also have a hydrostatic (positive) impact on MSLP in that region~~, which is to be expected, as Ekman transport produces a steady-state situation only after a few pendulum days (Pond and Pickard, 2013). It appears likely that effects of SST patterns on FLC variability are most pronounced on ~~seasonal to inter-annual scales as~~ longer time scales (i.e. seasonal to interannual) that feature higher SST variability (Hutchings et al., 2009; Goubanova et al., 2013; Tim et al., 2015), as also observed in the Chilean Atacama desert (Del Río et al., 2018). Differences in TCWV on FLC and clear days are pronounced (Fig. 3 f)). A coherent region of a significantly dryer column stretches from the central Namib over the coastal Atlantic, where the anomaly is strongest. This is likely the dry slot (Browning, 1997) or dry air intrusion of the synoptic-scale disturbance that leads to increased longwave cooling ~~and can thereby facilitate the formation of FLCs~~at cloud top in case of FLC presence, which has been shown to be a main determinant of cooling within the marine boundary layer (Koračin et al., 2005). This enhanced cooling can increase FLC cover, which has been observed to be a significant mechanism for stratocumulus clouds over the southeastern Atlantic (Adebiyi et al., 2015; Adebiyi and Zuidema, 2018). A substantial moist anomaly is visible over the southern African continent, likely driven by large-scale free-tropospheric moisture transport from the north west (Fig. 3 b)). These moist air masses may contribute to the observed T2m heat anomaly via greenhouse warming (Fig. 3 c)). This effect of free-tropospheric moisture on surface temperatures has been observed in the Kalahari (Manatsa and Reason, 2017) and other arid or semi-arid regions before (Evan et al., 2015; Oueslati et al., 2017; Alamirew et al., 2018). Along the coastal strip that is typically overcast with FLCs (Olivier, 1995; Cermak, 2012; Andersen and Cermak, 2018; Andersen et al., 2019), T2m is significantly lower by about 4 K, which is likely a feedback of FLCs reflecting solar radiation and slowing down the surface heating in the early morning (Iacobellis and Cayan, 2013), or due to air-mass differences. The observed difference patterns in LTS (Fig. 3 d)) between FLC and clear days matches those of T2m so that they can be assumed to be mostly driven by its surface component (Pearson correlation coefficient is -0.90 for land pixels).

The observed anomaly patterns indicate that different mechanisms are triggered by the observed synoptic-scale disturbances and may contribute to FLC occurrence in the central Namib in two main ways:

1. ~~Enhanced formation of FLCs~~ Increased FLC cover due to increased longwave cooling under the dry anomaly close to the coast.

2. Onshore flow anomaly of marine boundary layer air masses due to a) a modulation of coastal winds and b) a formation of a southern African heat low due to greenhouse warming by moist air masses and northerly warm air advection.

As both synoptic and FLC characteristics differ substantially between the SON and AMJ, the following section focuses on specific characteristics and differences of these mechanisms during these seasons.

3.3 Seasonal differences in synoptic-scale mechanisms

Figures 4 and 5 show seasonally averaged differences between FLC and clear days of all analyzed parameters during the two seasons SON and AMJ. During both seasons, MSLP (Fig. 4 a) and b)) and Z500 (Fig. 4 c) and d)) indicate synoptic-scale disturbances on FLC days. However, seasonal differences exist, as ~~during SON, these anomaly patterns suggest a cut-off low, while the marked bipolar pattern of the anomalies in AMJsuggests the presence of a breaking Rossby wave~~the disturbance is more pronounced during AMJ. The negative continental MSLP anomalies on FLC days are larger during AMJ, likely amplified by the more pronounced T2m anomalies and subsequent effects on a continental heat low during this time (cf. Fig. 5 c) and d)). As noted above, the continental heat anomaly can be caused by northerly warm air advection or enhanced warming due to changes in the radiative balance. The observed seasonal MSLP and 10 m wind anomalies (Fig. 4 a) and b)) that result in a transport of warm air from the northeast into the anomaly region (~~not shown~~see Fig. A2), as well as the TCWV anomalies (Fig. 5 a) and b)) suggest that during SON, the heat anomaly on FLC days is mostly due to northerly advection of warm air, whereas during AMJ, TCWV is significantly increased over the southern African continent~~, especially in regions of high~~ . Here, the T2m ~~anomalies. Here,~~ anomalies closely follow those of TCWV (Pearson correlation coefficient of 0.75 in continental regions with significantly higher T2m on FLC days than clear days), suggesting that the increased moisture causes an additional surface heating due to greenhouse warming as discussed in Sec. 3.2. It is likely that the TCWV anomaly is caused by a large-

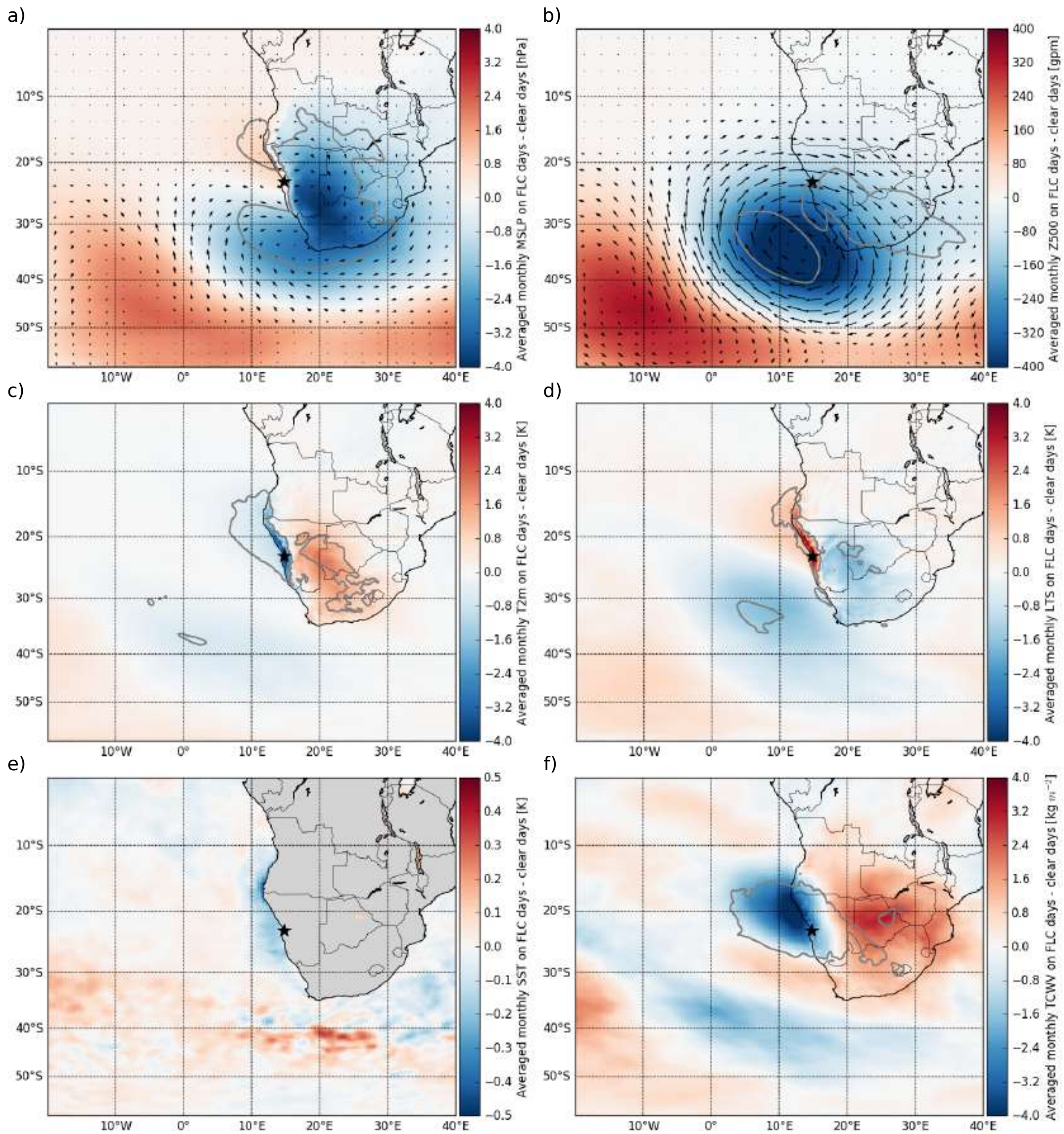

Figure 3. Averaged monthly mean differences (FLC days - clear days) of a) MSLP and 10 m winds, b) Z500 and 500 hPa winds, c) T2m, d) LTS, e) SST, and f) TCWV at 6 UTC. In each pixel, an independent two-sided t-test is computed to identify significant differences between FLC and clear days for each month. Contours mark regions where the distributions differ significantly at the 0.01 level (median of the monthly p values < 0.01). U and v vectors of winds are interpolated as in Fig. 2.

scale free-tropospheric moisture transport from the tropics, which is supported by the marked wind anomalies at 500hPa (Fig. 4 d)) that show a northwesterly anomaly, and the absolute wind and moisture fields at 700 hPa during this time (Fig. A1). It should be noted that a Lagrangian transport of moisture at this scale takes time and as such is likely to occur when the ~~Rossby~~

wave disturbance is relatively stationary or if two consecutive systems pass within a short timeframe (Knippertz and Martin, 2005).

A few 100 km to the west andsouth of the Namibian coastline, SSTs (cf. While the yearly averaged composites show that over land, LTS is driven to a large extent by T2m (Fig. 3 c) and d)), this is not quite as pronounced during SON (correlation coefficient =-0.57; Fig. 5 c) and e)). Over continental southern Africa, the differences in T2m (Fig. 4 f5 c)) are frequently compensated by similar differences in potential temperature at 700 hPa (not shown). The most pronounced LTS feature during both seasons, however, is the coastal anomaly of increased LTS (over land and weaker over the adjacent ocean), which is driven by T2m. As this anomaly is also apparent during nighttime (1 and 3 UTC, not shown), it is likely that this pattern is mainly due to the relatively warm subsiding continental outflow that is apparent on clear days, rather than a radiative effect of FLCs as found in California (Iacobellis and Cayan, 2013). During AMJ, LTS is significantly lower over a large marine region south of 25°S, which is likely caused by the synoptic-scale disturbance.

During both seasons, SSTs in the coastal upwelling region are slightly lower on FLC days than on clear days, although these differences are not significant at the 0.01 level for the most part (very localized regions at ≈28°S are significantly lower during AMJ). In isolated patches further south, upwind of the study area, SSTs tend to be significantly higher on FLC daysduring AMJ, potentially leading to . This could lead to increased surface latent heat fluxes, increasing the moisture content of the marine boundary layer, particularly during AMJ when stronger near-surface winds are also apparent. A few 100 km to the west and south of the Namibian coastline, SSTs could similarly add to the increased moisture within the marine boundary layer. It is not clear yet, however, what exactly drives the observed anomaly pattern of SSTsduring AMJpatterns of SSTs. As upwelling reacts to the time-integrated wind field forcing over longer time scales than analyzed here (Pond and Pickard, 2013), the SST response to the instantaneous winds that are considered here is expected to be relatively weak. However, in the case of a relatively stationary disturbance as discussed above, the upwelling patterns could indeed reflect an SST response to a synoptic forcing. While the seasonally varying TCWV and SST anomalies (Figs. 4 e) and f), and 5 a) and b), respectively) illustrate the seasonal variability in the mechanisms that can contribute to FLC occurrence in the central Namib, during all months, the outlined systematic patterns of significant negative MSLP anomalies over continental southern Africa and the localized coastal high pressure anomaly are apparent. It can be concluded that a low pressure anomaly in continental southern Africa and the associated onshore advection of marine boundary layer air masses facilitates FLC occurrence in the central Namib during the entire year.

To better understand the characteristics of the observed moisture transport and its relevance for central-Namib FLC occurrence, information on the vertical patterns of moisture and wind anomalies is needed. Figure 6 shows average seasonal differences of Q and winds on FLC versus clear days at different pressure levels during a) SON and b) AMJ (averaged between 20°S and 25°S). During both seasons, a complex vertical structure of Q anomalies is apparent that is assumed to be disturbance-induced. During both seasons, the marine boundary layer features an onshore flow anomaly and is more humid on FLC than on clear days, especially during AMJ, where this is a synoptic-scale feature, likely related to the cold front of the disturbance. These differences are caused by the subsiding dry continental easterly air masses that dominate on clear days, whereas on FLC days, a slight onshore flow of the more humid marine boundary layer air is observed in the central Namib.

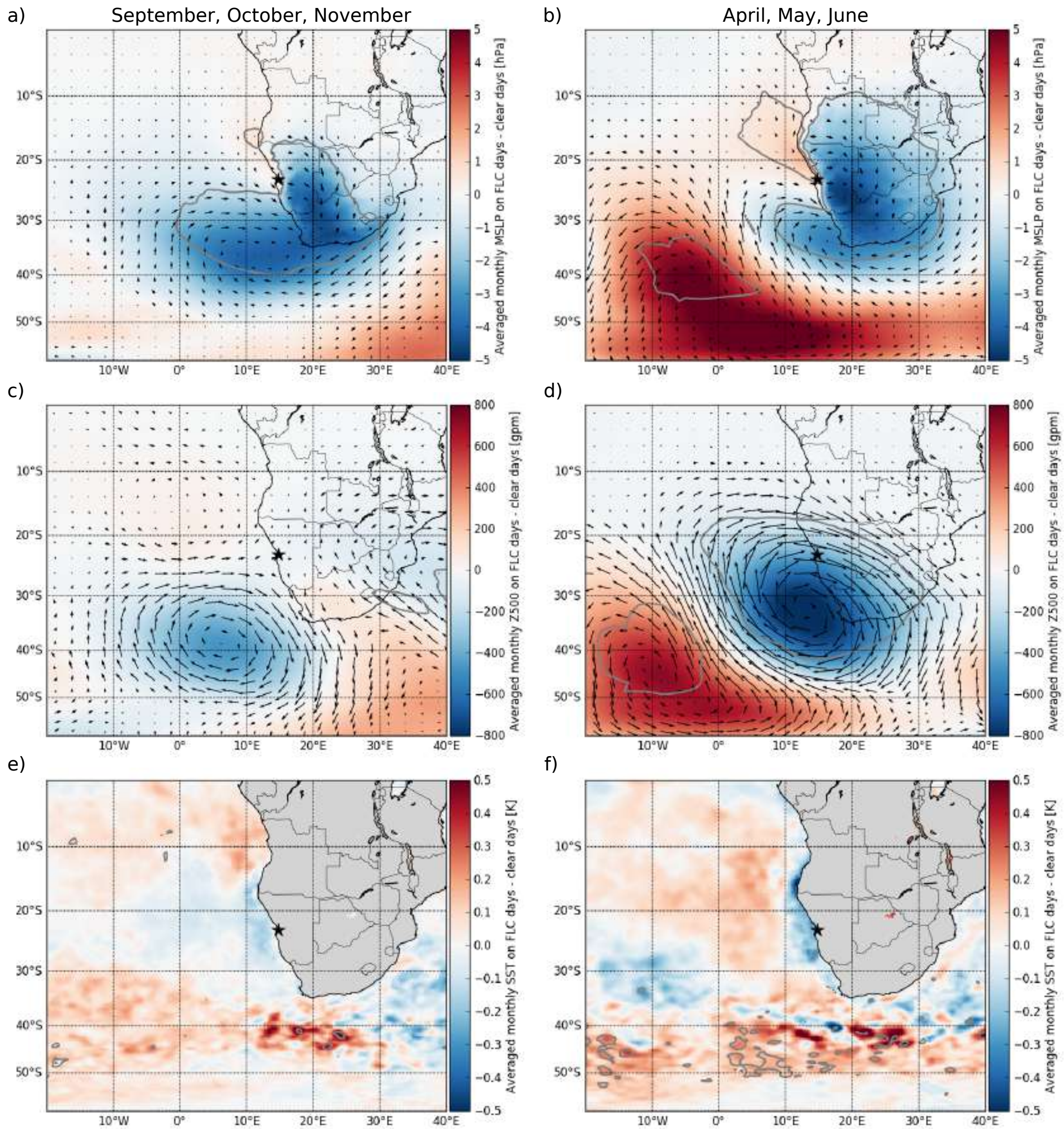

Figure 4. Mean of monthly average differences (FLC days - clear days) during SON (left-hand panels) and AMJ (right-hand panels) of MSLP (top), Z500 (middle), and SST (bottom) for the time period 2004–2017. Contours mark significant differences as in Fig. 3. Wind anomalies at 10 m (top) and 500 hPa (middle) are superimposed as vectors.

Over land, these marine air masses flow against the dominant continental easterly winds (Lindesay and Tyson, 1990), producing a northerly wind flow at ≈ 15°N (not shown) that has been found to be associated with fog occurrence in the central Namib (Seely and Henschel, 1998; Spirig et al., 2019). Above the moist marine boundary layer, the free troposphere is relatively dry on FLC days during both seasons, a feature which is not as clearly visible in the columnar TCWV composites during AMJ as it is masked by the moist anomaly in the marine boundary layer (Fig. 5 a)). It is interesting to note that the marine dry

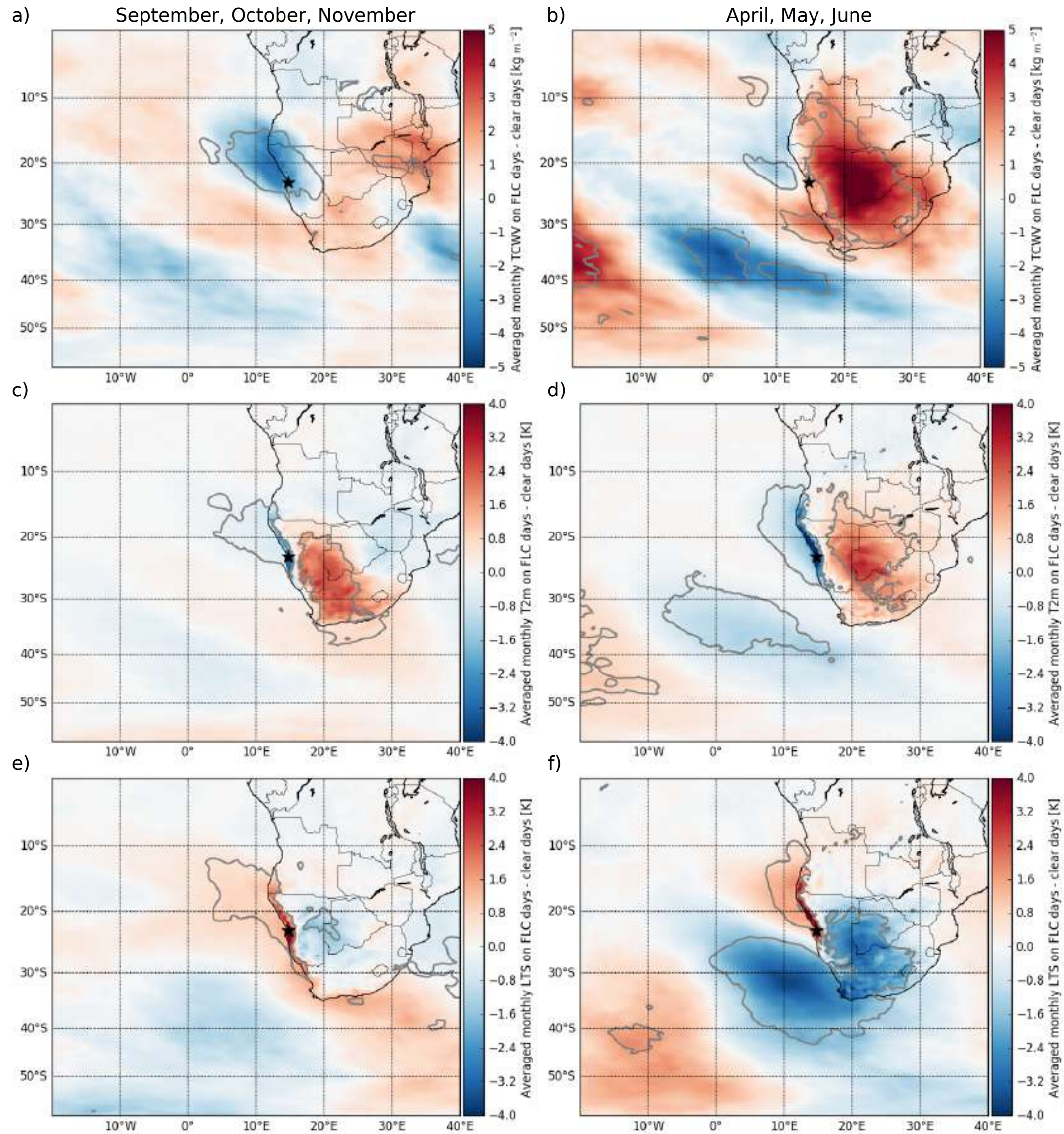

Figure 5. Mean of monthly average differences (FLC days - clear days) during SON (left-hand panels) and AMJ (right-hand panels) of TCWV (top), T2m (middle), and LTS (bottom) for the time period 2004–2017. Contours mark significant differences as in Fig. 3.

anomaly peaks between December and February (not shown), the season with maximum FLC cover in the central Namib, with TCWV anomalies exceeding 10 kg m^{-2}. The seasonal difference in the free-tropospheric Q anomalies over the continent is clear and the vertical distribution of Q anomalies during AMJ corroborates the assumption that the observed positive TCWV anomalies are due to free-tropospheric moisture transport (Fig. 5 b)). Expressed in relative terms, Q is about halved within the dry anomaly region on FLC days during both seasons, suggesting that radiative cooling is an important factor for FLC

~~formation~~cover, especially over marine regions where the dry anomaly is most pronounced. During AMJ, the free-tropospheric relative moisture difference between FLC days and clear days is observed to be as high as 220 %. This substantial increase in free-tropospheric moisture in this otherwise dry central plateau region induces a substantial surface heating, contributing to the formation of the observed heat low, which modulates regional wind systems and leads to the onshore flow anomaly.

It should be noted that in a comparable upwelling system (coastal California), Clemesha et al. (2017) also find a positive relationship between T2m over land and coastal low-level cloudiness, with the T2m anomaly shifted poleward by about 5° latitude from the cloud field. They propose that the T2m-cloud relationship is due to spatially-offset associations between coastal low-level cloudiness and stability (potential temperature at 700 hPa), which is strongly correlated to T2m over land thereby resulting in the T2m anomaly, rather than T2m driving the onshore advection. While in the central Namib, the anomaly patterns between potential temperature at 700 hPa and T2m are similar in that they are also positively correlated during SON (and therefore compensate each other in terms of LTS, Fig. 5 c) and e)), they are uncorrelated during AMJ (and also in the annual averages), when T2m over land is strongly correlated to TCWV. Also, during all times of year, the T2m and MSLP anomalies are directly inland from the cloud field, suggesting an influence on onshore advection.

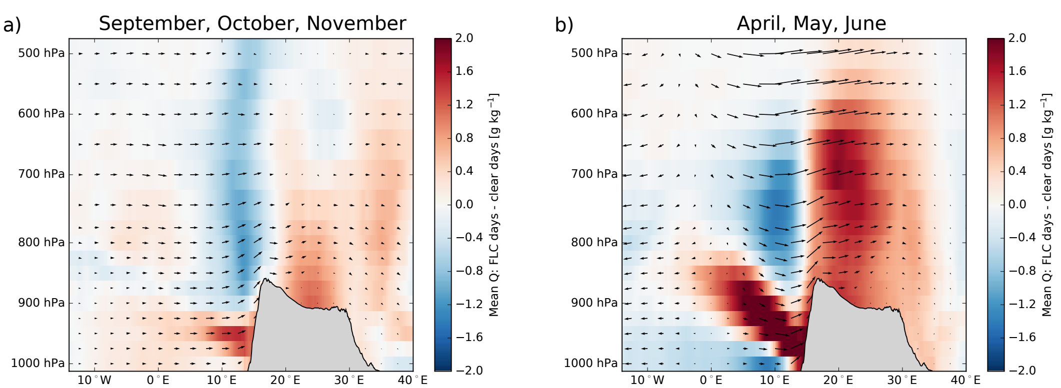

Figure 6. Seasonal average difference (FLC days - clear days) in specific humidity, and u and w wind components at different pressure levels during a) SON and b) AMJ for the time period 2004–2017. Specific humidity and wind vectors are averaged between 20°S and 25°S and shown at pressure levels between 1000 hPa and 500 hPa. For illustration purposes, the w vector is enhanced by a factor of 20. The masked grey area approximates the average surface elevation between 20°S and 25°S.

3.4 The role of air-mass history and dynamical regimes

Air-mass backtrajectories, initiated in the central Namib close to Gobabeb at 23°S and 15°E (indicated by the star in Fig. 7), 6 UTC and 25 hPa above ground level (approximates 200 m above ground level), are computed for the 14-year observational period. Figure 7 shows the backtrajectories for FLC days (top) and clear days (bottom) for the two seasons SON (left-hand panels) and AMJ (right-hand panels). During both seasons, air masses on FLC days nearly exclusively stem from the marine boundary layer and have traversed over the cool upwelling ocean water along the coastline for the time span of 24 h. This is in agreement with findings from Koračin et al. (2005), who note that a marine origin of air masses is critical, as well as potential mixing with continental air masses along the trajectory that would lead to a warming and drying. While the number of FLC days during SON is higher than during AMJ, following the general seasonality of FLCs in the region (cf. Fig. 1 c)), no clear seasonal differences in air-mass dynamics can be observed in such situations. This suggests that during both seasons, similar local dynamic conditions drive FLCs or air masses that develop into FLCs inland into the Namib desert, but that due to seasonal differences of large-scale dynamics, these situations occur with varying frequency during different seasons.

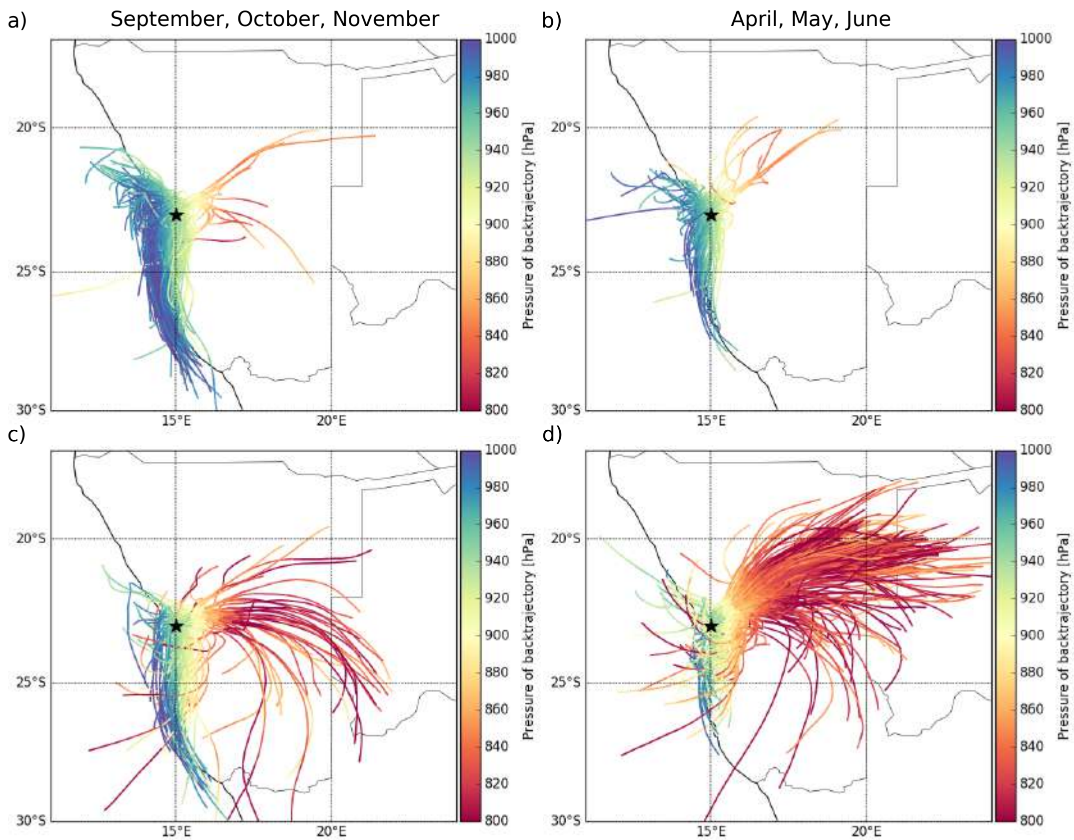

Figure 7. 24-hour Lagranto air-mass backtrajectories for FLC days (top) and clear days (bottom) in September, October, November (left-hand panels) and April, May, June (right-hand panels) for 2004–2017. The star marks 23°S and 15°E, where the backtrajectories were initialized at 25 hPa (approximates 200 m) above ground level. The number of samples are a) ~~363~~399, b) 133, c) ~~135~~ 146 and d) 452.~~For technical reasons, ≈10 % of the trajectories in panels a) and c) could not yet be calculated, but due to the clarity of the observed patterns that are already based on a high number of trajectories, this is not thought to influence the general results in a meaningful way.~~

On clear days, air-mass histories are more diverse and show distinct seasonal differences, but are frequently characterized by subsiding continental air masses. While on clear days during SON, a considerable fraction of the air masses is still transported from the marine boundary layer, during AMJ, subsiding north-easterly continental air masses dominate. This seasonal shift in air-mass dynamics is likely driven by the seasonality of the two dominating high pressure systems of the region that is shown in Fig. 2. During AMJ, the southern African continental high pressure system is enhanced and leads to the stronger easterly flow. These observations support the hypothesis by Lancaster et al. (1984) that the seasonality of fog in the central Namib is to some extent controlled by the Southern African high pressure system, as the associated easterly winds are likely to inhibit large-scale onshore advection of cloudy marine boundary layer air masses. The results also suggest that aerosols from the biomass burning season in continental southern Africa (Swap et al., 2003) are unlikely to play a large role for fog formation by acting as cloud condensation nuclei, as biomass burning aerosols within the boundary layer are mostly associated with continental air masses in this region (Formenti et al., 2018). However, biomass burning aerosols may influence Namib-region FLCs by absorbing solar radiation and modifying the thermodynamic conditions, which has been observed and modeled to influence the Namibian stratocumulus deck (Zhou and Penner, 2017; Deaconu et al., 2019).

While systematic differences in air masses exist between FLC days and clear days, clear days may still feature air masses that are advected from the marine boundary layer (cf. Fig.7 c)). To understand the differences between the FLC days and clear days in such situations, these are isolated and analyzed in the following. Figure 8 shows the average Q, relative humidity (RH), air temperature (T), potential temperature (Pot. T), and pressure (P) along all those of the backtrajectories that are advected from the marine boundary layer (here: P $>$ 900 hPa over ocean). It is apparent that these air masses contain significantly more moisture on FLC days than on clear days, which explains most of the difference in RH. The backtrajectories of FLC days feature a stronger cooling during the last 10 hours of advection (hours 0–10), resulting in an additional increase in RH. The deviation in T between FLC and clear days seems to be driven by the vertical movement of the air masses, rather then differences in radiative cooling, as no changes in Pot. T are apparent. Ten hours before initialization, air masses on clear days are located $\approx$20 hPa higher than on FLC days, not cooling off as they are advected due to their simultaneous subsidence. Other potential factors that may drive the observed deviation in T, such as the free tropospheric moisture content and the surface temperature along the backtrajectories, were not found to be systematically different on FLC and clear days (not shown). These findings highlight that Namib-region FLCs are not only dependent on dynamics, but that marine boundary-layer moisture content as well as temperature changes during advection are important controls as well.

It is likely that the computed air-mass backtrajectories do not fully capture thermally and topographically induced local air flow patterns (see Lindesay and Tyson (1990) for a review) that contribute to local FLC occurrence patterns and possibly formation. However, the larger-scale patterns of air-mass history of marine boundary-layer air masses versus the subsiding continental air masses from the free troposphere are clearly evident from the analysis presented and offer a consistent physical explanation of the large-scale FLC occurrence patterns. The observations suggest that Namib-region FLCs are either advected after forming over the cool adjacent ocean or that condensation takes place during advection of the marine boundary-layer air masses over land due to higher humidity levels, lower temperatures or radiative cooling, though a mix of these processes is likely.

A The analysis of air-mass backtrajectories shows that the discrimination between FLC and clear days is not possible using dynamics alone, and that seasonal differences exist in the link between the probability of FLC days and advection patterns. To further investigate the role of different dynamical regimes for FLC occurrence, a PCA is conducted on spatial patterns of

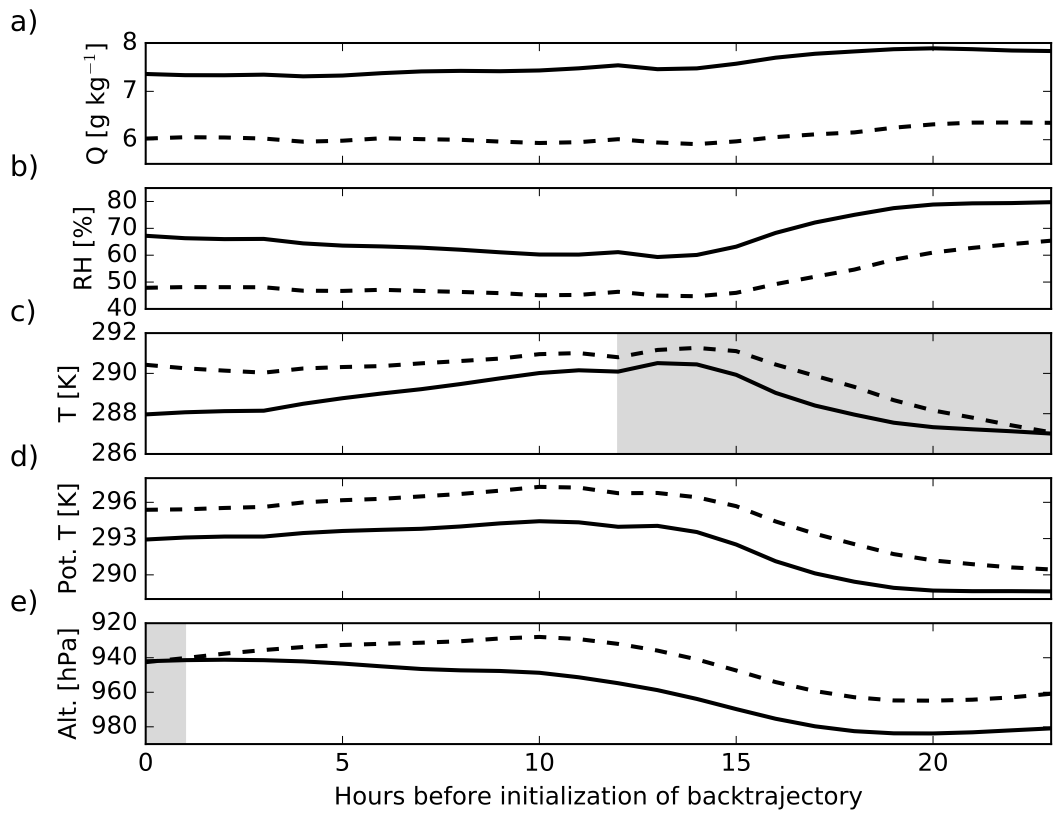

Figure 8. Hourly averaged specific humidity (a)), relative humidity (RH, b)), air temperature (T, c)), potential temperature (Pot. T, d)), and pressure (P, ~~d~~e)) along the 24-hour air-mass backtrajectories that are advected from the marine boundary layer on FLC days (solid line) and clear days (dashed line) during SON 2004–2017. The number of samples are ~~333~~ 369 FLC days and ~~74~~ 80 clear days. Grey shading highlights non-significant differences.

synoptic-scale near-surface winds (see Sec. 2.4 for details on the method)~~to analyze to what extent Namib-region FLCs are connected to specific dynamical regimes~~. Figure 9 a) shows correlations between daily central-Namib FLC cover and the PCs associated with the first six modes of variability of near-surface winds during all months of the year. All PCs are significantly correlated to FLC cover during some months of the year. Clear correlation patterns are evident: PCs 1, 2, 4 and 5 show negative correlations with FLC cover, while PCs ~~2,~~ 3 and 6 feature positive correlations. These PCs that facilitate FLC occurrence (~~2,~~ 3, 6) all show westerly or northwesterly wind anomalies in the central Namib, while PCs that are negatively associated with Namib-region FLC cover feature anomalously strong continental easterly winds, consistent with results presented in Sec. 3.2 and 3.3. Panels c) and d) of Fig. 9 show the spatial patterns of near-surface wind anomalies of PCs 3 (explained variance: 11 %) and 4 (explained variance: 6 %), as examples for PCs that promote and impede FLC occurrence, respectively. A seasonal dependence of the correlations between PCs and FLC cover is apparent and seems to be related to the seasonality of FLC cover (Fig. 9 b)): PCs associated with onshore circulation in the central Namib feature the strongest positive correlations during winter when FLC cover is generally lowest over the Namib, especially evident for PC 3. This appears plausible, as during winter, the typical dynamical setting is less conducive to FLCs (see Fig. 2 for fall/early winter conditions during AMJ), and consequently, FLC occurrence is dependent on a stronger dynamical disruption during this time. During summer, when FLCs frequently occur in the central Namib, dynamical conditions associated with PCs 4 and 5 (dominance of continental easterlies) seem to impede the occurrence of FLCs. The results underscore that the advection of marine air masses is crucial for the occurrence of FLCs in the central Namib.

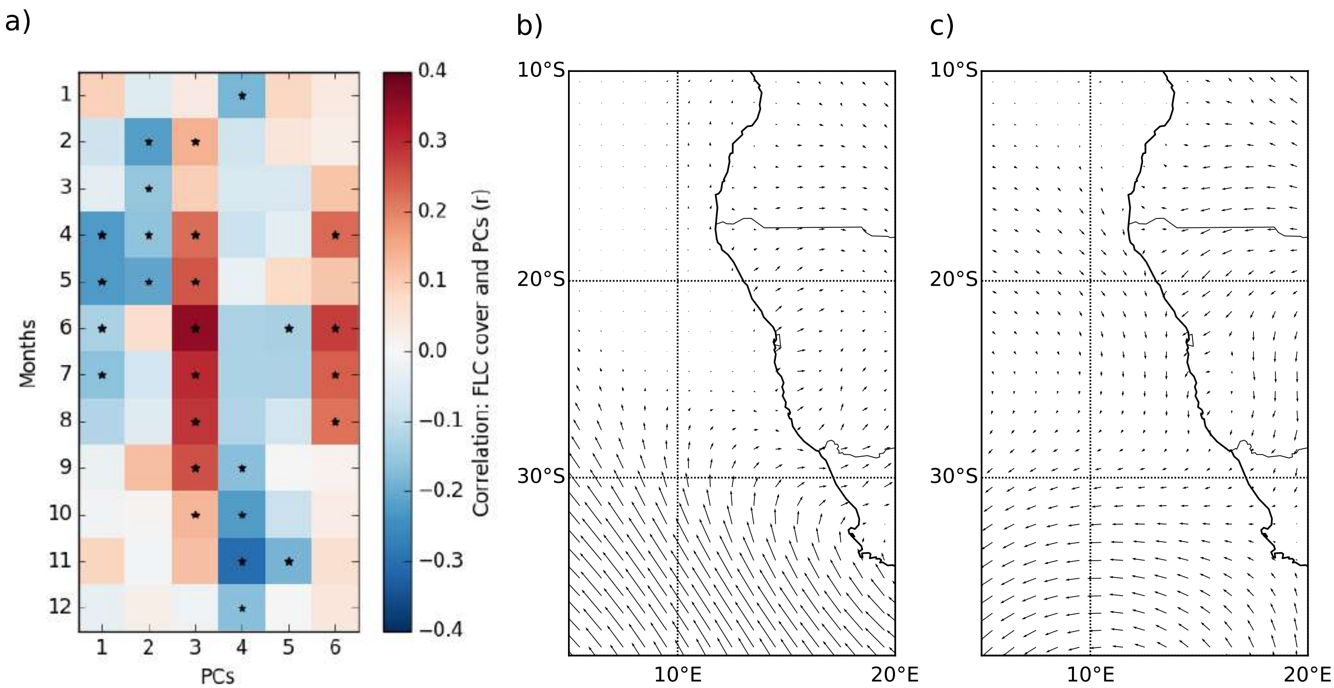

Figure 9. a) Correlations (Pearson r) between the PCs (associated with the empirical orthogonal functions of the spatial wind patterns) and central-Namib FLC cover. Stars mark correlations that are significant at the 0.01 level. Panels b) and c) show wind anomaly fields for PCs 3 and 4, respectively. For visual clarity, spatial wind anomalies are shown for regional cutouts of the spatial domain that is considered in the PCA and averaged to a 1° x 1° resolution (see Sec. 2.4 for details on the analysis).

3.5 Statistical fog and low-cloud prediction with pressure fields

Based on the evidence presented above, showing that FLC occurrence is tightly connected to synoptic-scale patterns, it can be assumed that FLC occurrence can be predicted to some extent with a statistical learning technique that utilizes spatial patterns of dynamical information. Here, a ridge regression is applied to classify FLC days and clear days based on MSLP fields in a region spanning 45°x45° that is centered on the central Namib (see Sec. 2.4). MSLP fields are used, as their anomaly patterns on FLC days are similar during the different analyzed seasons and thus summarize the controlling mechanisms of onshore advection of marine boundary-layer air masses. Figure 10 a) shows the resulting coefficients, i.e. regression slopes, of the statistical model. The sign and spatial patterns of the coefficients are similar to the observed MSLP anomalies shown in Fig. 4, where coefficients (and anomalies) are negative in the inland region of Namibia, and positive and along the northern part of the Namibian coastline. It should be noted that the statistical model seems to mostly rely on regional MSLP fields, resulting in low coefficients at the synoptic scale, e.g., the Atlantic high pressure system. It can be concluded that the synoptic-scale pressure patterns set the stage for more localized pressure and wind modulations that determine FLC occurrence, and that regional MSLP fields contain information on both.

Figure 10 b) gives a summary of statistical measures of the skill of the model to classify between FLC and clear days in the central Namib. Using MSLP fields at 6 UTC on the day of the FLC cover information, the ridge regression model has a probability to correctly detect FLC days of 94 % with 17 % of the reported FLC days being false alarms, leading to an overall correctness of the model of 86 % and a positive bias of 14 %. The critical success index (CSI: 0.79), and the Heidke skill score (HSS: 0.72) combine these scores and show that the model is skillful in distinguishing between the defined fog and clear days. As MSLP fields in southern Africa may not be representative due to the high topography, the model was additionally run based on Z850 and Z925 fields. The model performances were nearly the same (overall PC of 84 % in both cases), suggesting that it is adequate to use MSLP in this context. The colored dots in Fig. 10 b) illustrate the progression of the model skill when the training is carried out based on MSLP fields of one, two, three or four days prior to the FLC observation. While, as expected, the model skill deteriorates with an increasing temporal gap between the MSLP predictors and the time of FLC occurrence, the model is capable of predicting fog occurrence fairly well one day in advance, as the time series of day-to-day FLC occurrence features a significant autocorrelation of some days. To some extent, this may be connected to the strong persistence of synoptic-scale dynamics in the subtropics. Even though the model only uses MSLP fields, ignoring e.g. effects of radiative cooling due to moisture anomalies, surface temperatures, and seasonal characteristics, which have been shown to modify FLC occurrence, the results still illustrate the potential of a dynamics-based statistical fog forecast in this region. It should be noted that changes in circulation additionally influence upwelling intensity (e.g. Hutchings et al., 2009) such that some of the explained variability may also be attributed to factors influencing FLC formation rather than advection. However, due to the longer time-scale of SST responses, and due to the marked contrasting differences in air mass history on FLC and clear days, the latter is thought to be the first order mechanism leading to the high model skill.

It should be noted that the distinction between ~~fog~~ FLC and clear days is based on spatially and temporally averaged FLC occurrence (see Sec. 2.1) and that days are omitted that feature an FLC cover between 3 % and 50 %. Also, the exact location and time of FLC occurrence is likely to be dependent on local temperature gradients and topography that lead to local modulation of winds (Lindesay and Tyson, 1990). Still, the model produces promising results that may be built upon in future studies by testing a similar model setup to predict the timing and duration of FLCs at specific locations.

4 Summary and conclusions

In this study, the occurrence of FLCs in the Namib desert, derived from 14 years of satellite observations, is systematically analyzed within the context of the regional climate and related to large-scale patterns of MSLP, Z500, T2m, LTS, SST, TCWV

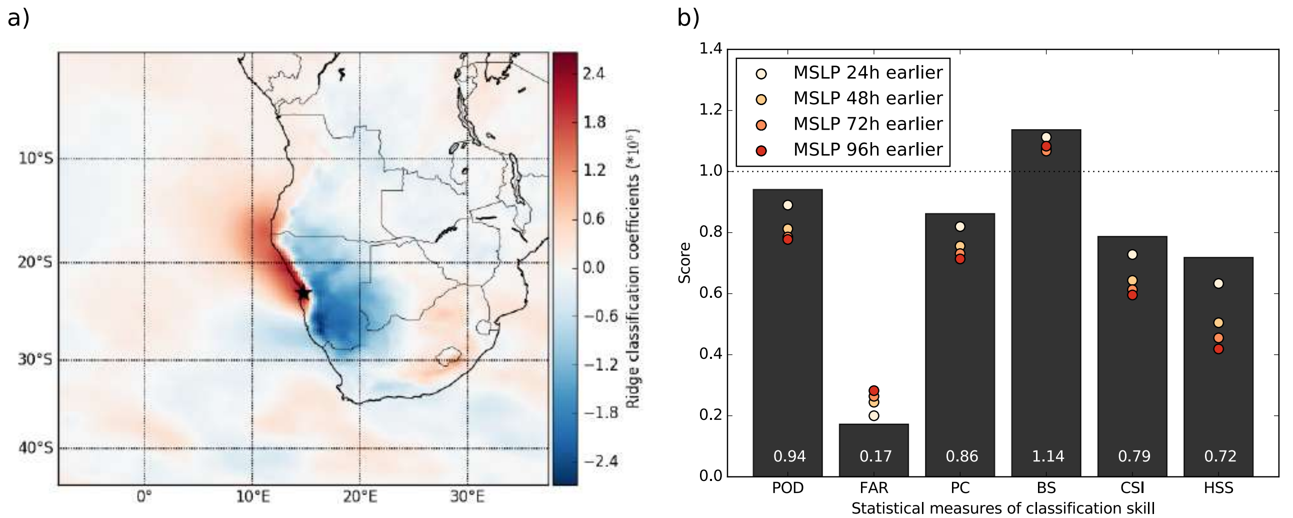

Figure 10. a) The coefficients of the ridge regression used for classification of FLC days versus clear days. b) Statistical measures of the performance of the ridge regression to classify FLC days versus clear days. The bars and related numbers describe the model skill using 6 UTC MSLP fields of the day of FLC observation and relate to a). The colored dots show the model skill when the model is trained on MSLP fields of one to four days earlier. The abbreviations of the statistical measures stand for probability of detection (POD), false alarm rate (FAR), percent correct (PC), bias score (BS), critical success index (CSI), and the Heidke skill score (HSS). The equations of the statistical measures are given in the appendix.

as well as Q and winds at different pressure levels from ERA5 reanalyses. The satellite data set of FLC occurrence is separated into FLC days and clear days that are further investigated in terms of their meteorological conditions, air-mass histories and statistical predictability during two seasons (AMJ and SON).

It is found that MSLP and Z500 patterns on FLC days are systematically and significantly different from clear days on synoptic scales. On FLC days, a systematic pattern of significantly lower MSLP over continental southern Africa is observed, which, in combination with higher pressure over a marine coastal region at about 20°S, leads to an onshore flow anomaly of marine boundary-layer air. Together with significantly lower Z500 in the southeastern Atlantic region on FLC days, these dynamic patterns are an indication for ~~a cut-off low during SON and a breaking Rossby wave during AMJ. As cut-off lows are typically associated with Rossby wave breaking events in the southern hemisphere (Ndarana and Waugh, 2010), these synoptic-scale disturbancesmay be viewed as different stages of similar systems. Both~~ synoptical-scale disturbances. These modify circulation systems, which in turn alter moisture transport, resulting in characteristic moisture patterns on FLC and clear days. Over the coastal boundary layer, the free troposphere is observed to be significantly drier on FLC days during both seasons, increasing radiative cooling, which likely ~~contributes to FLC formation~~increases FLC coverage, especially over the ocean where the dry anomaly is observed to be most pronounced. During AMJ, free-tropospheric moisture over the southern African continent is substantially increased, leading to greenhouse warming at the surface. While northerly warm air advection also contributes to the observed positive T2m anomalies on FLC days (during both seasons), the additional increase in T2m on

FLC days during AMJ clearly corresponds to regions of increased free-tropospheric moisture content (correlation = 0.75). The increase in T2m leads to the development of a heat low that amplifies the upper-level disturbance-induced low MSLP anomaly, thereby contributing to the onshore flow anomaly of marine boundary-layer air masses. In the localized coastal region where FLCs typically occur, T2m is found to be significantly lower on FLC days, likely a combination of a local feedback of FLCs that slow down surface heating in the morning hours, and air mass differences. A significant pattern of SST anomalies is found only in AMJ, with anomalously high SSTs off the coast possibly acting together with increased near-surface winds to enhance surface latent heat fluxes that may contribute to higher the observed higher levels of specific humidity in the marine boundary-layerhumidity.

The analysis of backtrajectories initialized in the central Namib at typical cloud level shows systematic differences in air-mass dynamics on FLC days and clear days. Air masses on FLC days are nearly exclusively transported within the marine boundary layer over the cool upwelling waters along the coastline, whereas clear days are frequently associated with subsiding northeasterly air masses, especially during AMJ. During SON, when advection of marine-boundary layer air masses can also occur on clear days, air masses on clear days feature significantly less moisture and tend to be advected from higher altitudes than on FLC days. The findings clearly demonstrate the strong dependence of central-Namib FLC occurrence on the advection of moist marine boundary-layer air masses, contrasting the notion of predominant radiation fog (Kaseke et al., 2017), but in agreement with many other studies (e.g. Seely and Henschel, 1998; Formenti et al., 2018; Andersen et al., 2019; Spirig et al., 2019) (e.g. Olivier and Stockton, 1989; Seely and Henschel, 1998; Formenti et al., 2018; Andersen et al., 2019; Spirig et al., 2019). These results are supported by a principal component analysis of near-surface winds that show a clear connection of FLC cover to synoptic-scale dynamics. Principal components of spatial wind patterns that feature positive onshore flow anomalies are positively related to FLC cover. This relationship is especially strong during winter, when FLC occurrence is at its minimum, as then, the dominant continental easterly flow typically inhibits inland advection of FLCs or locally developing FLCs. This suggests that during this time, a stronger dynamical forcing is needed to overcome this characteristic flow that is unfavorable for inland advection of cloudy marine boundary layer air masses.

As the results show that spatial pressure patterns are connected to FLC occurrence, a ridge regression model is used to classify FLC days versus clear days based on regional MSLP fields. The resulting spatial pattern of model coefficients is similar to the observed MSLP anomaly patterns within the region of Namibia and the adjacent ocean areas. The spatial domain of relevant model coefficients seems to be smaller than the spatial extent of the pressure anomalies, probably because the regional fields contain information on synoptic-scale disturbance as well as local modulation. On this basis, the model is capable of skillfully delineating FLC days from clear days. The model is trained with MSLP fields with different temporal offsets, and found to be capable of skillfully predicting FLC occurrence one day in advance, highlighting the potential of a statistical forecast of FLCs in this region. Future work should focus, however, on the development of a statistical model that links information on e.g. MSLP, free-tropospheric moisture, SSTs, Z500 and aerosol loading with FLC occurrence to quantify the effects of the different processes and mechanisms outlined in this study.

The findings of this study suggest that FLCs in the central Namib are facilitated by synoptic-scale disturbances in two main ways:

1. Increased longwave cooling due to an anomalously dry free troposphere, especially over the ocean that ~~facilitates the formation of low clouds~~increases low-cloud cover.
2. Onshore flow anomaly of these cloudy marine boundary layer air masses due to
   a) disturbance-induced modulation of local winds, and
   b) a heat low over continental southern Africa.

The magnitude and characteristics of the disturbance and the related mechanisms depend on season, with a more pronounced disturbance during AMJ, when the typical dynamic setting is less conducive to FLC occurrence. Figure 11 is a schematic illustration that summarizes these seasonally varying mechanisms.

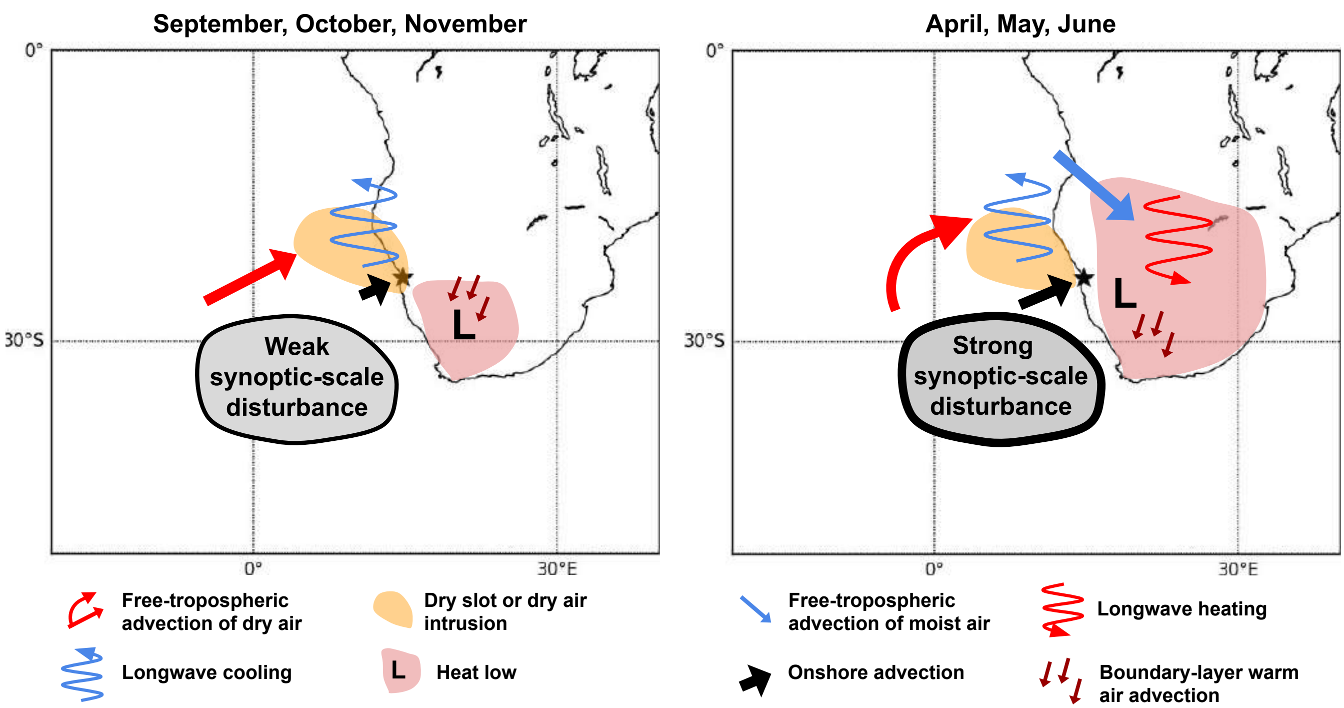

Figure 11. Schematic overview over the synoptical-scale mechanisms that modify day-to-day variability of central-Namib FLC occurrence during different seasons.

While a 14-year sample is not optimal to capture climatological variability, the mechanisms documented here for the first time are unlikely to be fundamentally different in other climatological periods. While it seems settled that, at least at the scales considered in this study, FLC occurrence is mostly driven by advective processes, the quantitative contributions of humidity and temperature changes and radiative cooling for low-cloud formation in the Namib during the advection of marine boundary-layer air masses are still unclear. A heat budget analysis as in e.g., Adler et al. (2019) or Babić et al. (2019), based on ground-based measurements conducted during the field campaign of the Namib Life Cycle Analysis (NaFoLiCA) project

(Spirig et al., 2019), is necessary to better understand the origin, development and life cycle of FLCs within the advected marine boundary-layer air masses. Future work should also focus on understanding the local and possibly synoptic-scale drivers of the vertical structure of Namib-region FLCs on diurnal to seasonal scales, and the day-to-day variability of (marine) boundary-layer humidity. As FLCs in the Namib are clearly connected to marine stratus/stratocumulus clouds, findings of recent and ongoing field campaigns over the southeastern Atlantic (Zuidema et al., 2016; Formenti et al., 2019) and related insights concerning the aerosol-cloud-meteorology system of the Namibian stratocumulus cloud field (e.g., Adebiyi and Zuidema, 2018; Andersen and Cermak, 2015; Diamond et al., 2018; Formenti et al., 2019; Fuchs et al., 2017, 2018; Gordon et al., 2018) are relevant to fully understand FLCs in the Namib desert.

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Code and data availability. The ERA5 meteorological reanalysis data are freely available at the Copernicus Climate Change Service (C3S) Climate Date Store: https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset (last access: September 6th, 2019). Satellite data and code for data processing are available from the corresponding author upon reasonable request.

Appendix: ~~Equations of statistical validation measures~~

Appendix A: Free tropospheric moisture transport and temperature anomalies

Appendix B: Equations of statistical validation measures

POD = $\frac{a}{a+c}$

PC = $\frac{a+d}{a+b+c+d}$

FAR = $\frac{b}{a+b}$

CSI = $\frac{a}{a+b+c}$

BS = $\frac{a+b}{a+c}$

HSS = $\frac{2(ad-bc)}{(a+c)(c+d)+(a+b)(b+d)}$

with a = number of hits, b = number of false alarms, c = number of misses and d = number of correct negatives

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. JC and JF contributed to the study design, and JF computed initial backtrajectories. PK helped to develop a conceptual understanding of the synoptic-scale patterns and physical mechanisms. JQ computed the backtrajectories with Lagranto. MG conducted the PCA analysis. SS contributed to the design of the statistical model, and RV contributed insights to local-scale processes. JC, JF, PK, JQ, MG, SS and RV contributed to manuscript preparation, and the interpretation of findings.

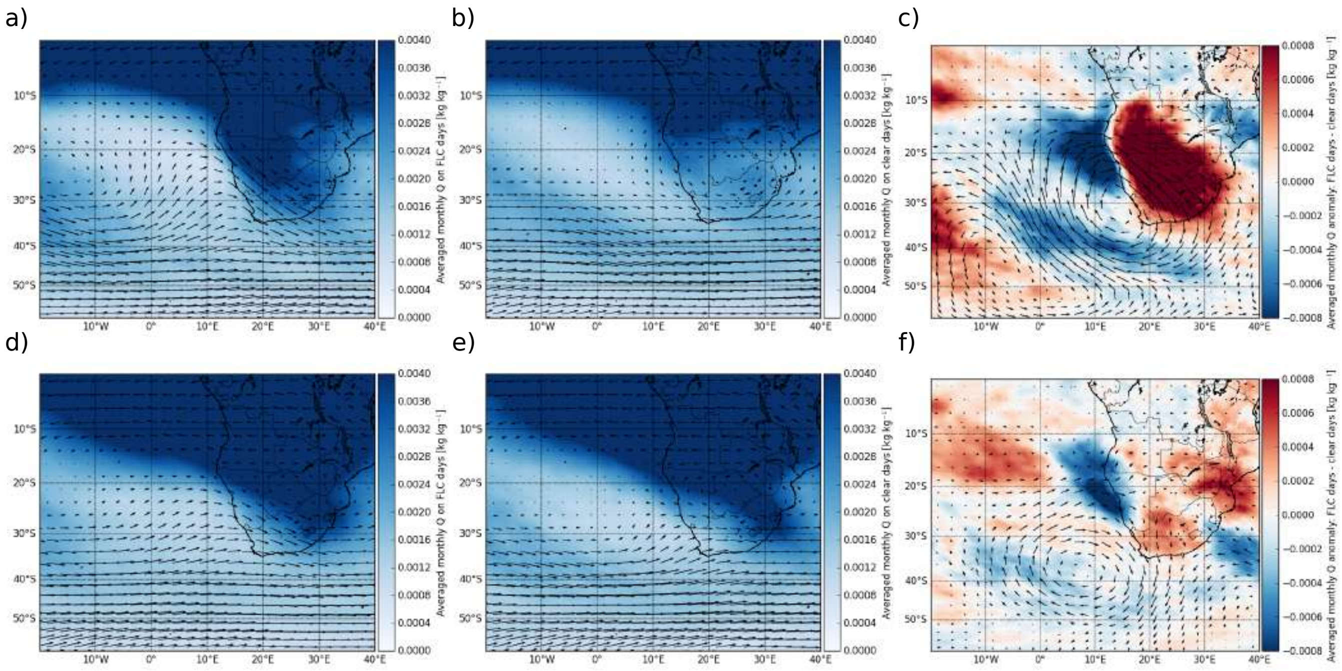

Figure A1. Seasonal averages of Q and winds at 700hPa on FLC days (left), clear days (center), and their difference (right) during AMJ (top) and SON (bottom).

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

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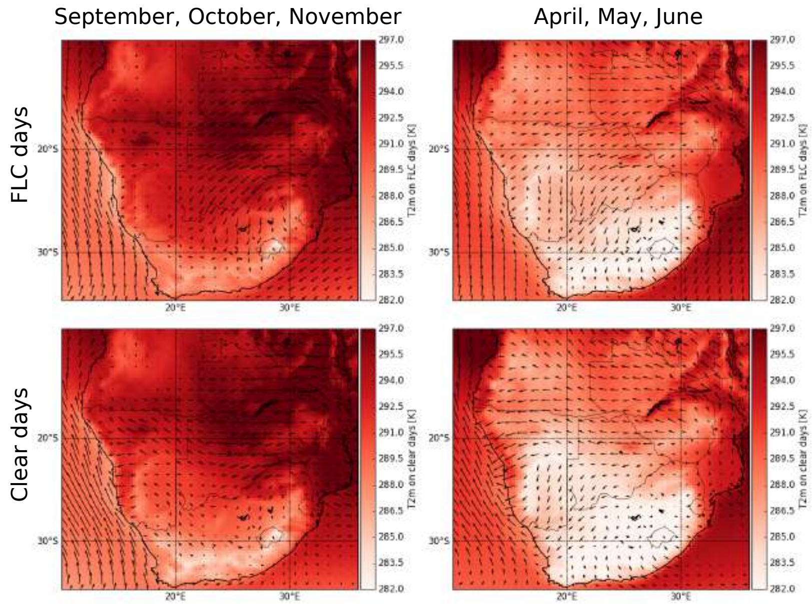

Figure A2. Seasonal average ERA5 T2m and 10m winds in SON (left-hand panels) and AMJ (right-hand panels) for FLC (top) and clear (bottom) days. Winds are averaged to a 1°x1° resolution.

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