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

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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.

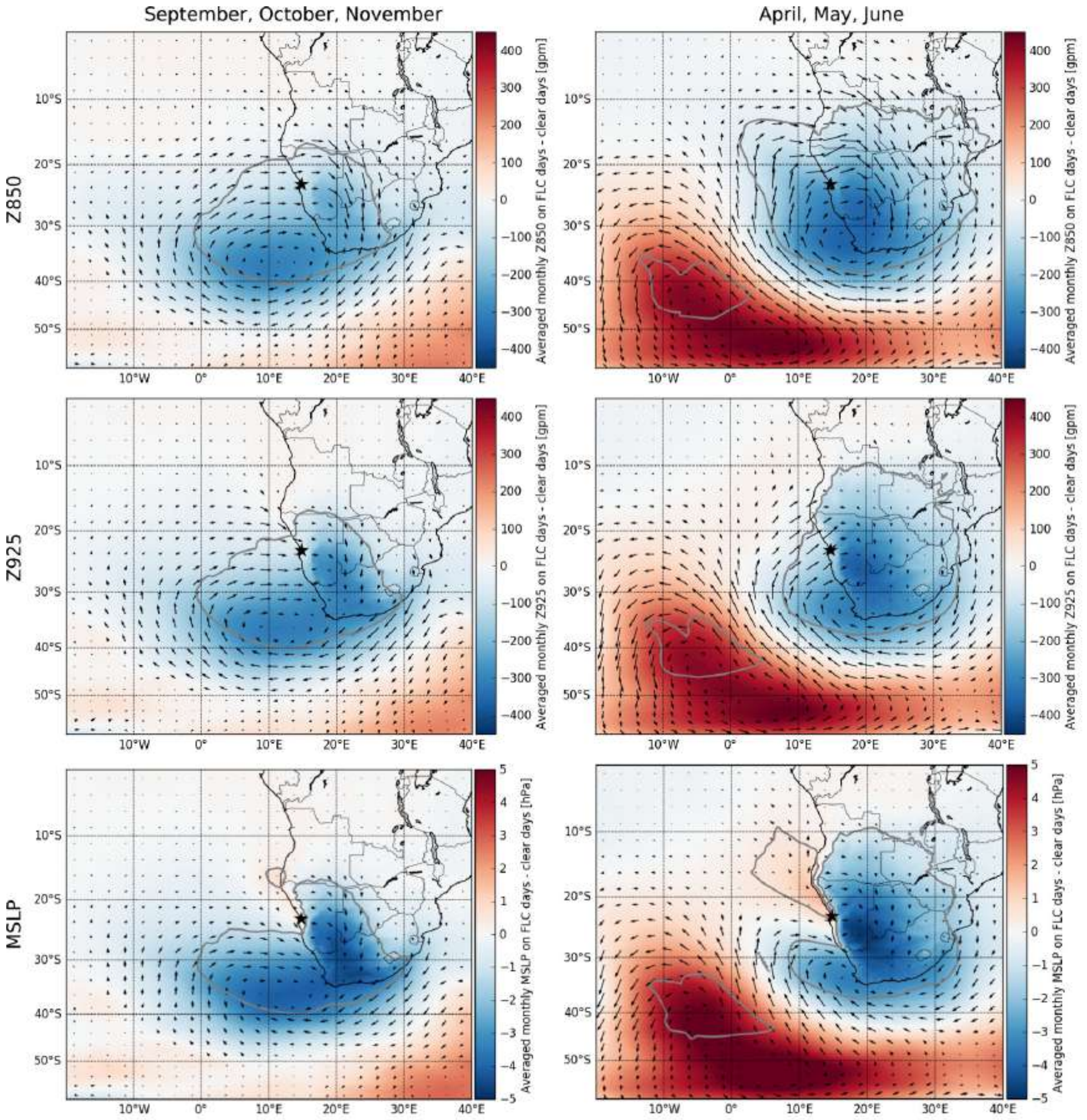

Fig. R1.1: Averaged monthly mean differences (FLC days - clear days) in Z850 and 850 hPa winds (top), 925 hPa (middle), and MSLP (bottom) with 10m winds for SON (left-hand panels) and AMJ (right-hand panels). Contours mark regions where the distributions differ significantly at the 0.01 *level. u and 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."

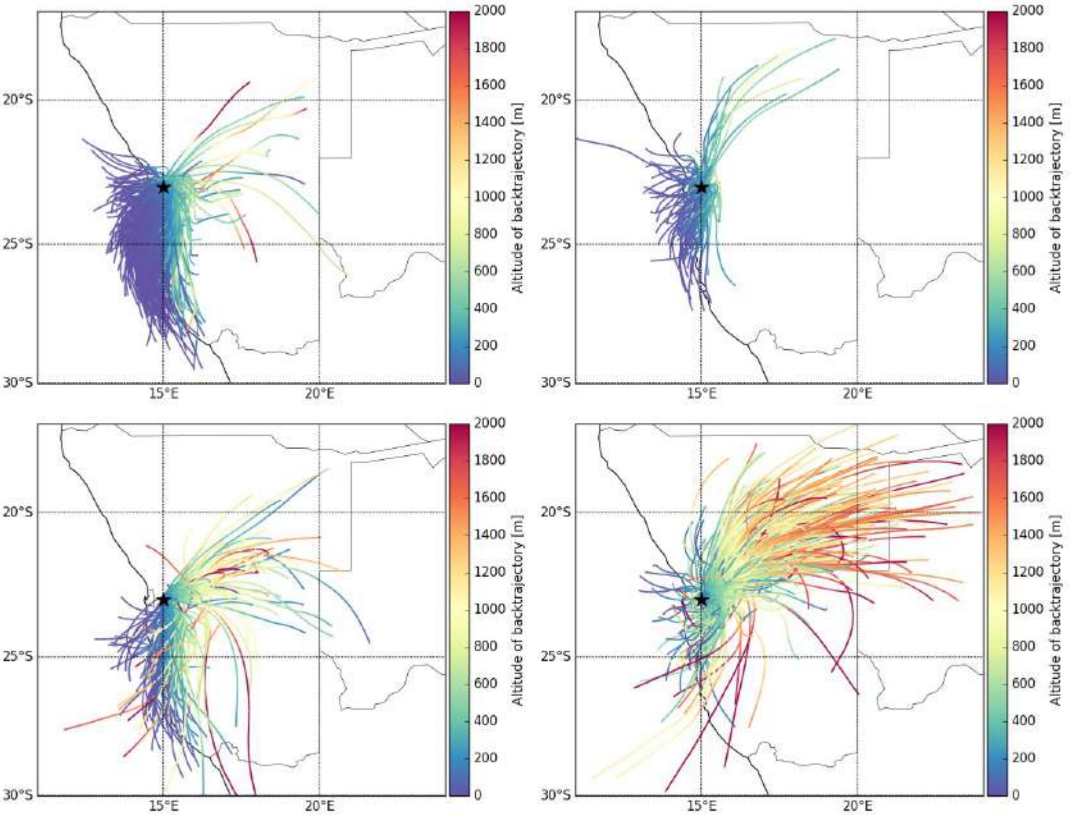

Fig. R1.2: Hysplit backtrajectories for SON (left-hand panels) and AMJ (right-hand panels) for FLC days (top) and clear days (bottom), based on ERA-Interim data at 0.75° spatial resolution.

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.

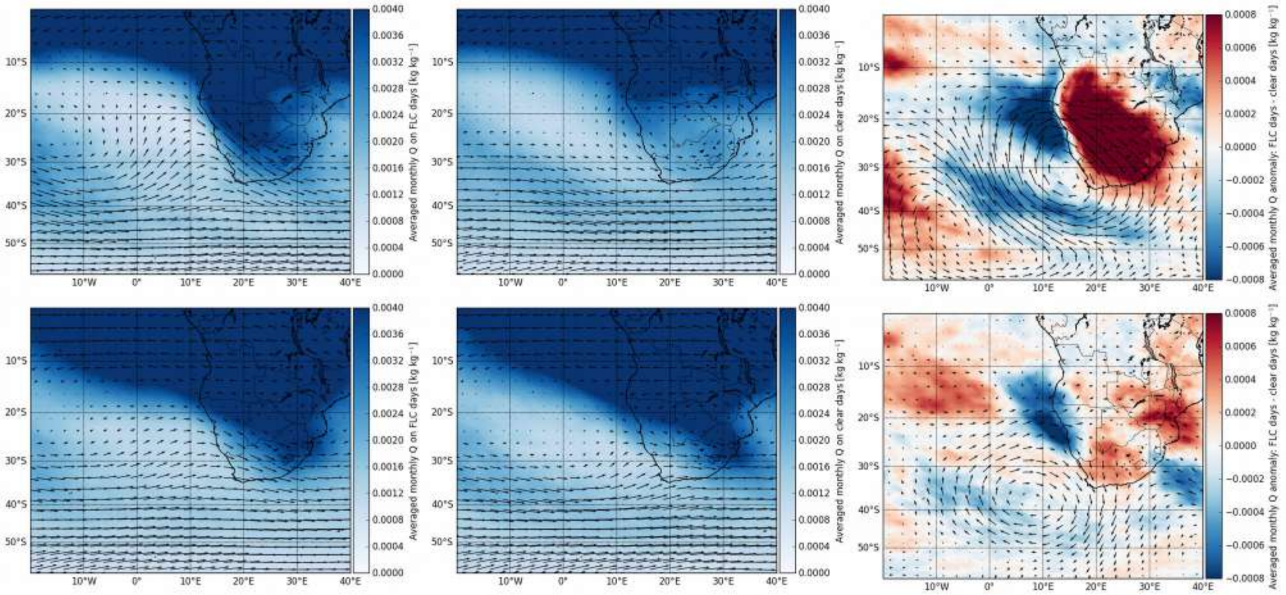

Fig. R1.3: Seasonal averages of Q and winds at 700hPa on FLC days (left), clear days (center), and their difference (right) during AMJ (top) and SON (bottom).

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."

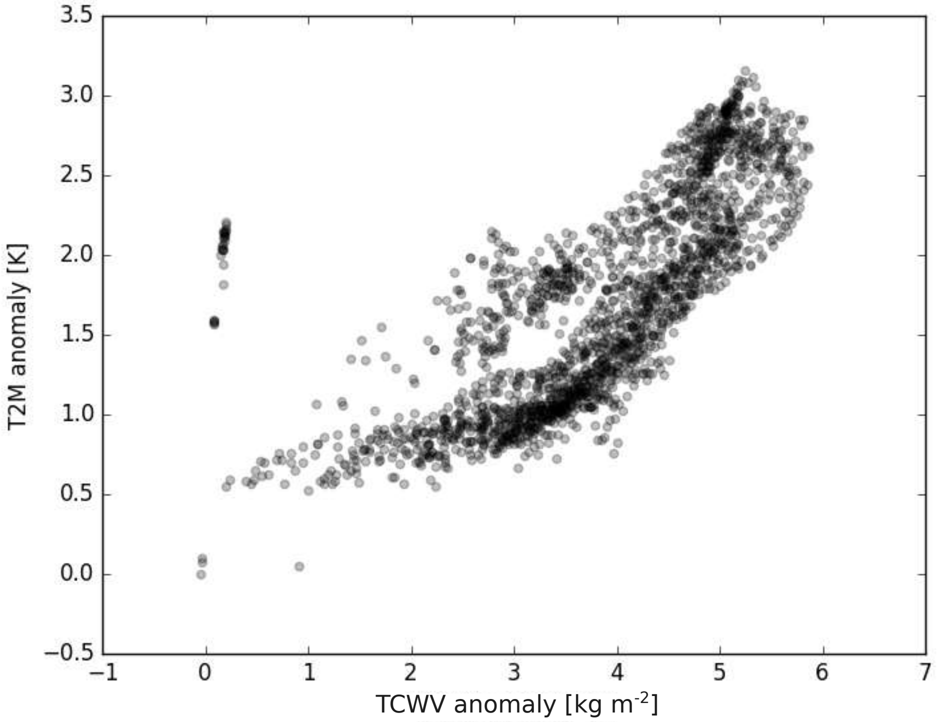

Fig. R1.4: The relationship of TCWV anomalies and T2m anomalies over land during AMJ, and in regions where T2m is statistically significantly higher on FLC days than on clear days.

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.

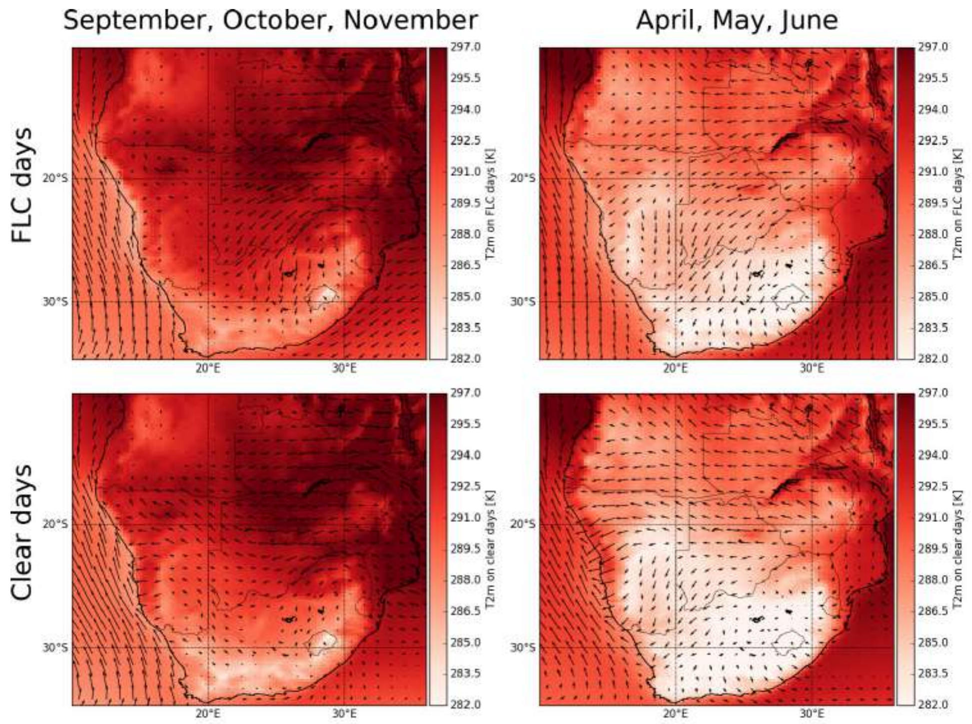

Fig. R1.5: Seasonal average ERA5 T2m and 10m winds in SON (left-hand panels) and AMJ (right-hand panels) for FLC (top) and clear (bottom) days. Winds are averaged to a 1°x1° resolution, the considered time period is 2004-2017.

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.“

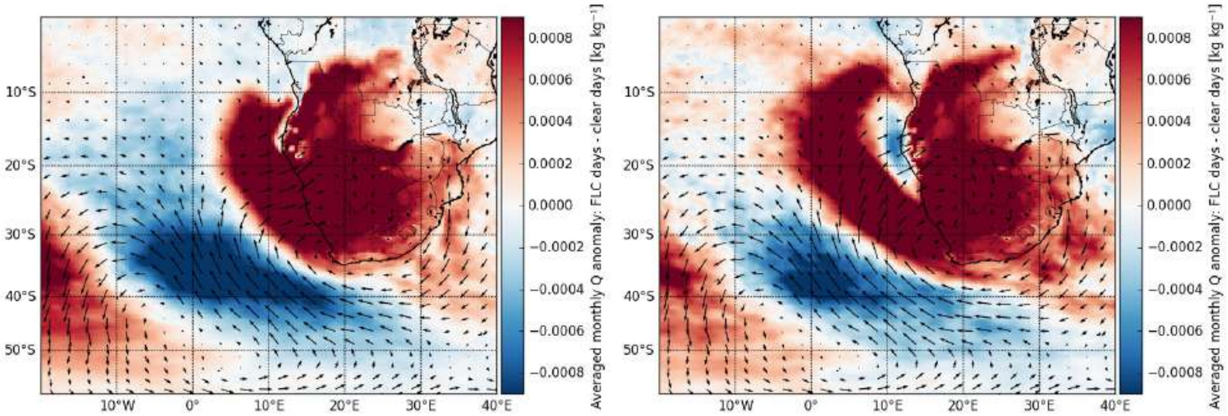

Fig. R1.6: Difference in Q and winds at 950 and 900 hPa during AMJ.

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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