Using a Single-Column Model to investigate drivers of desert warming, focusing on the Kalahari Desert

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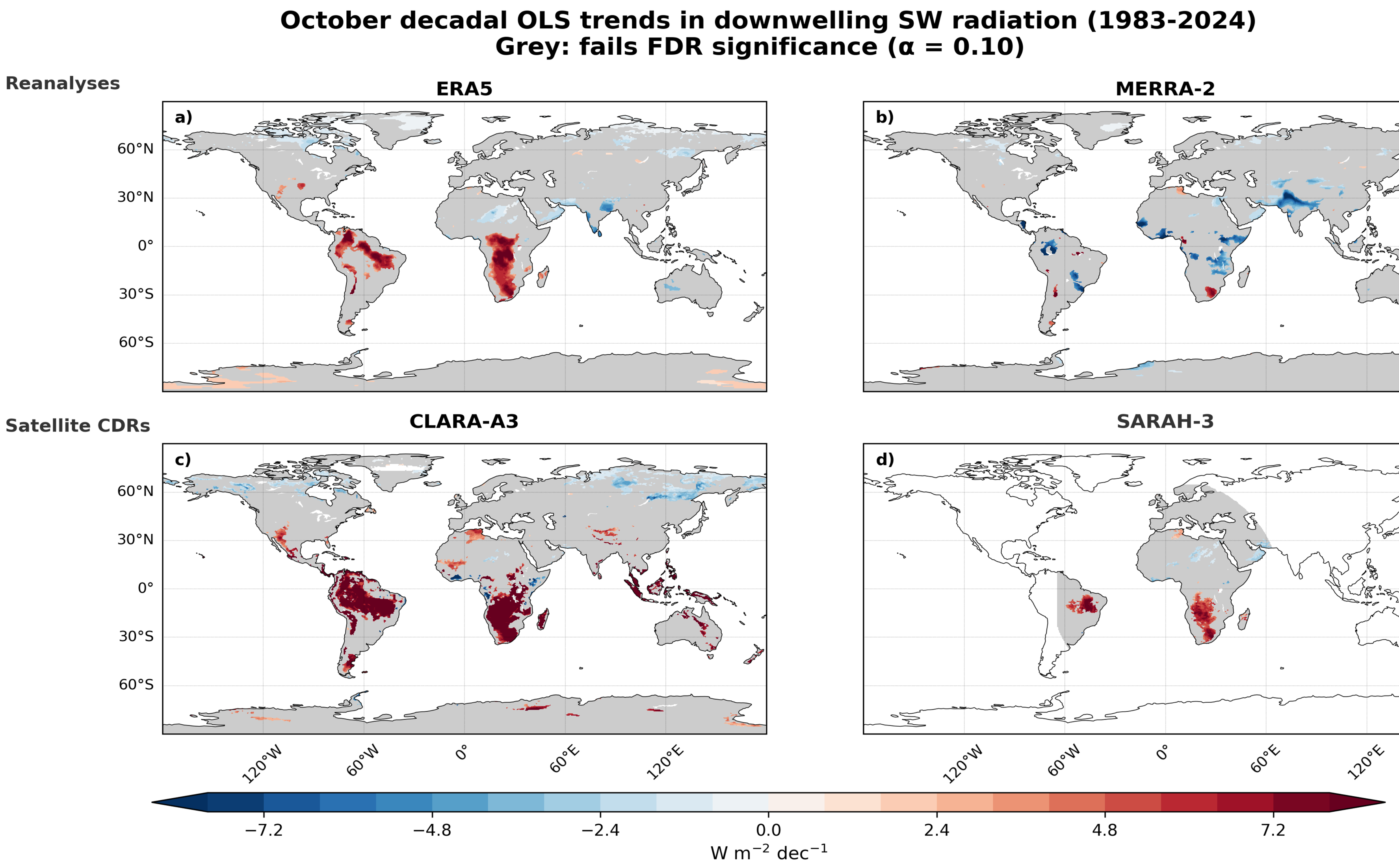

Figure 1: 1983-2024 downwelling shortwave radiation per decade trends for reanalyses: ERA5[9] (a), MERRA-2[10] (b), and satellite composite data records: polar-orbiting CLARA-A3[11] (c) and geostationary SARAH-3[12] (d), calculated using Ordinary Least Squares with lag-1 autocorrelation correction. Significance is controlled for using the false discovery rate (FDR = 0.10). Coloured areas are statistically significant

Motivation

- The Kalahari Desert has experienced **over 1.5°C of mean warming** during austral spring (SON) over the last four decades[1,2]
- Enhanced spring warming increases the **likelihood of persistent dry spells** and delayed precipitation[3,4]
- Analysis of surface radiation budget changes highlights **significant increases in October downwelling shortwave radiation** across southern Africa in ERA5, CLARA-A3 and SARAH-3 (Fig. 1)
  - October is a critical pre-monsoon, transition month[5,6]
- In contrast to existing desert warming literature, there is **no significant increase in downwelling longwave radiation**[7,8]
- ***Here, we explore the key factors controlling this increase in shortwave radiation***

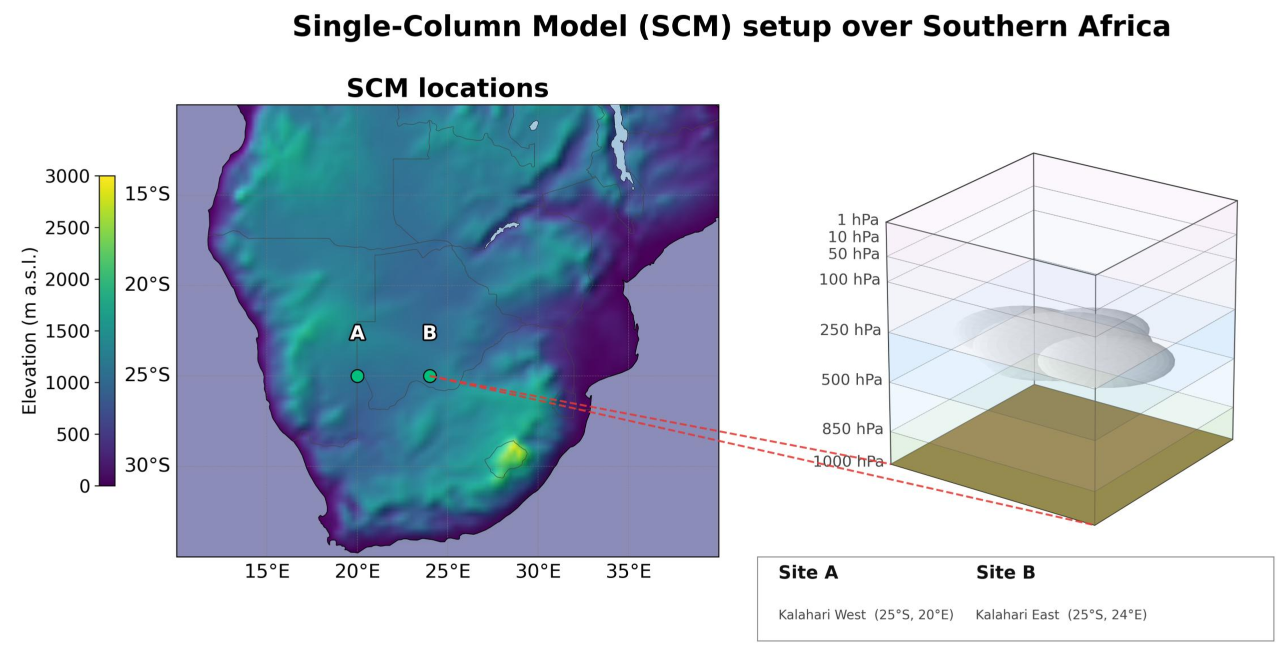

Figure 2: ERA5 topographic map of southern Africa, marked with Single-Column Model sites A (Kalahari West) and B (Kalahari East), alongside a schematic of a one-dimensional Single-Column model

Methods

- ECMWF Single-Column Model (SCM) forced with ERA5 Octobers (Fig. 2)
- Averaged 1980-1989 October SCM forcing files at hourly timesteps to create a 1980s composite
- Repeated for 2016-2025 to create a late decade composite
- Prognostic variables T and q were nudged on a 24-hour relaxation timescale
- Computed the difference in downwelling shortwave radiation between the early and late decade simulations
- To diagnose the primary drivers of increased downwelling shortwave radiation, single- and combined-forcing experiments of key variables were run by substituting 1980s forcings with their 2016-2025 equivalents

Variables changed in forcing experiments
Temperature (T)
Vertical velocity (ω)
Specific humidity (q)
Soil moisture

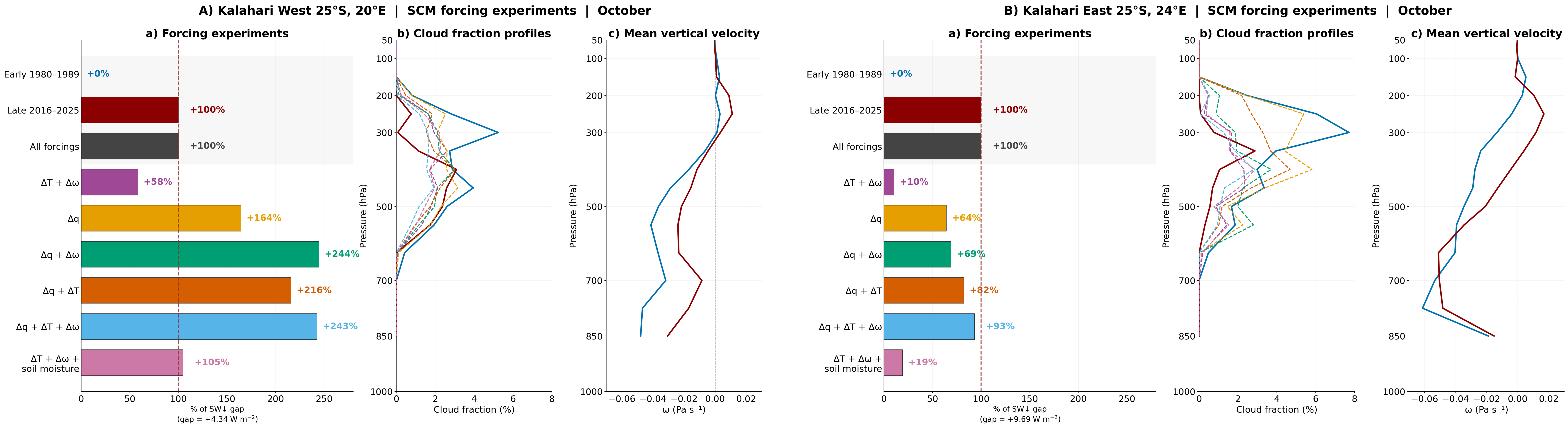

Figure 3: Single- and combined-forcing experiments for two Single-Column Model sites A) Kalahari West and B) Kalahari East. In both, (a) depicts the percentage change in downwelling shortwave radiation when variables in the early decade composite (1980-1989) are replaced with their counterparts from the late decade composite (2016-2025), (b) displays the cloud fraction profiles from the early and late composite runs (solid lines) and the forcing experiments (dashed lines, colours correspond to the bars in (a), and (c) shows the mean vertical velocity profile in the early (blue) and late (red) decade composite simulations

Key findings

- SCM results isolate the sensitivity and interactions of certain forcings, without representing a fully coupled atmospheric response. Both sites demonstrate **sharp reductions in upper-tropospheric cloud fraction** (Fig. 3), **supporting the increase in downwelling shortwave radiation** as per observational trends (Fig. 1)
- Kalahari West site (Fig. 3A) exhibited the strongest response to humidity perturbations with large decreases in high altitude cloud fractions
  - Forcing with late decade humidity (q) alone resulted in a larger downwelling shortwave radiation response than any other variable and overshot the All Forcings change by 64%
  - The Kalahari West site is situated in a drier regime, with lower specific humidity in the mid- and lower troposphere
- Kalahari East site (Fig. 3B) displayed a more linear response, with the additive effects of specific humidity, temperature and vertical velocity accounting for 93% of the downwelling shortwave decadal difference
- Both sites demonstrate a **decline in upper-tropospheric cloud fraction** with a **concurrent increase in subsidence**
- These results and associated explanation for October surface temperature trends depend on ERA5 reanalysis fields… EarthCARE will provide critical observational data to validate the vertical velocity and cloud fraction values and confirm this process understanding

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