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# The Cape Town “Day Zero” drought and Hadley cell expansion

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In early 2018, Cape Town (population ~3.7 million) was at risk of being one of the first major metropolitan areas in the world to run out of water. This was due to a severe multi-year drought that led to the levels of supply dams falling to an unprecedented low. Here we analyze rainfall data from the city catchment areas, including rare centennial records from the surrounding region, to assess the severity of the 2015–2017 drought. We find that there has been a long-term decline in the number of winter rainfall days, but this trend has been generally masked by fluctuations in rainfall intensity. The recent drought is unprecedented in the centennial record and represents a combination of the long-term decline in rainfall days and a more recent decline in rainfall intensity. Cold fronts during the winter months are responsible for most of the rainfall reaching Cape Town and our analysis shows no robust regional trend in the number of fronts over the last 40 years. Rather, the observed multidecadal decline in rainfall days, which threatens to increase the occurrence of severe drought, appears to be linked to a decrease in the duration of rainfall events associated with cold fronts. This change in rainfall characteristics associated with fronts appears to be linked to Hadley Cell expansion seen across the Southern Hemisphere and an increasing trend in post-frontal high-pressure conditions that suppress orographically enhanced rainfall.

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## INTRODUCTION

Dams that supply water to the city of Cape Town dropped to ~21% capacity in May 2018[1–3] and the city faced stringent water-use restrictions. With the final 10% difficult to extract for human consumption, the city put in place a management plan that would disconnect much of the city’s municipal water supply if dam levels fell below 13.5%, a scenario referred to as “Day Zero”.[1] If this day were to occur, the ~3.7 million inhabitants would collect 25 l of water per day from designated distribution points around the city. Fortunately, good early winter rains, followed by near-average overall winter rains, in 2018 resulted in the city avoiding “Day Zero”, with dam capacity rising to around 70% by October. The situation however remains tenuous with severe water restrictions (70 l per day in place during the spring, relaxed to 100 in December 2018) and many commercial farms in the region being allocated reduced water for irrigation purposes, a way of life that will be continued into the near future in order to reduce risk in 2019 and 2020. While the argument has been made that poor management and planning is at the heart of Cape Town’s water crisis,[4] dam levels dropped in tandem with an extreme 3-year drought. Reservoir storage simulations (accounting for catchment rainfall, evapotranspiration, soil moisture, reservoir evapotranspiration, and water use) indicate that anomalously low rainfall was the main factor that lead to the water shortages.[5] Here, we evaluate the severity of this multi-year decline in rainfall and place it within the context of historical variability and regional drivers.

Whereas most of South Africa receives predominantly summer rainfall, the Cape Town region and neighboring southwestern Cape receives most of its rainfall during the winter months, primarily from cold fronts associated with mid-latitude cyclones tracking eastwards across the South Atlantic.[6] The supply dams for the city are located in nearby mountainous regions where orographic effects enhance the rainfall. Strong regional subsidence due to the continental anticyclone means that the frontal rainfall does not extend much to the east or the north where the Karoo and Namib Deserts are located, respectively. Interannual variability in the winter rainfall received in the Cape Town area mainly results from differences in the number and intensity of the cold fronts making landfall.[6] In years when the continental or South Atlantic subtropical anticyclones are anomalously strong or located further south, the jet stream and South Atlantic storm-track are displaced polewards, with cyclones and their associated fronts generally steered away from Cape Town and weakened, as was the case on average across the 2015–2017 winter seasons.[7,8]

## RESULTS

To evaluate rainfall variability within the Cape Town region we analyze two separate sets of station data from the South African Weather Service (SAWS) (Fig. 1b, Supplementary Table 1). The first set, designated the *Cape Town Catchment Cluster*, is a set of 13 stations drawn primarily from the mountainous region to the east of the city and is representative of the rainfall that feeds into the dams and catchments that supply the city (locations denoted by the blue circles in Fig. 1b; see Methods section for further cluster details). This comprehensive set of stations spans 1979–2017. The second set, designated the *Centennial Cluster*,

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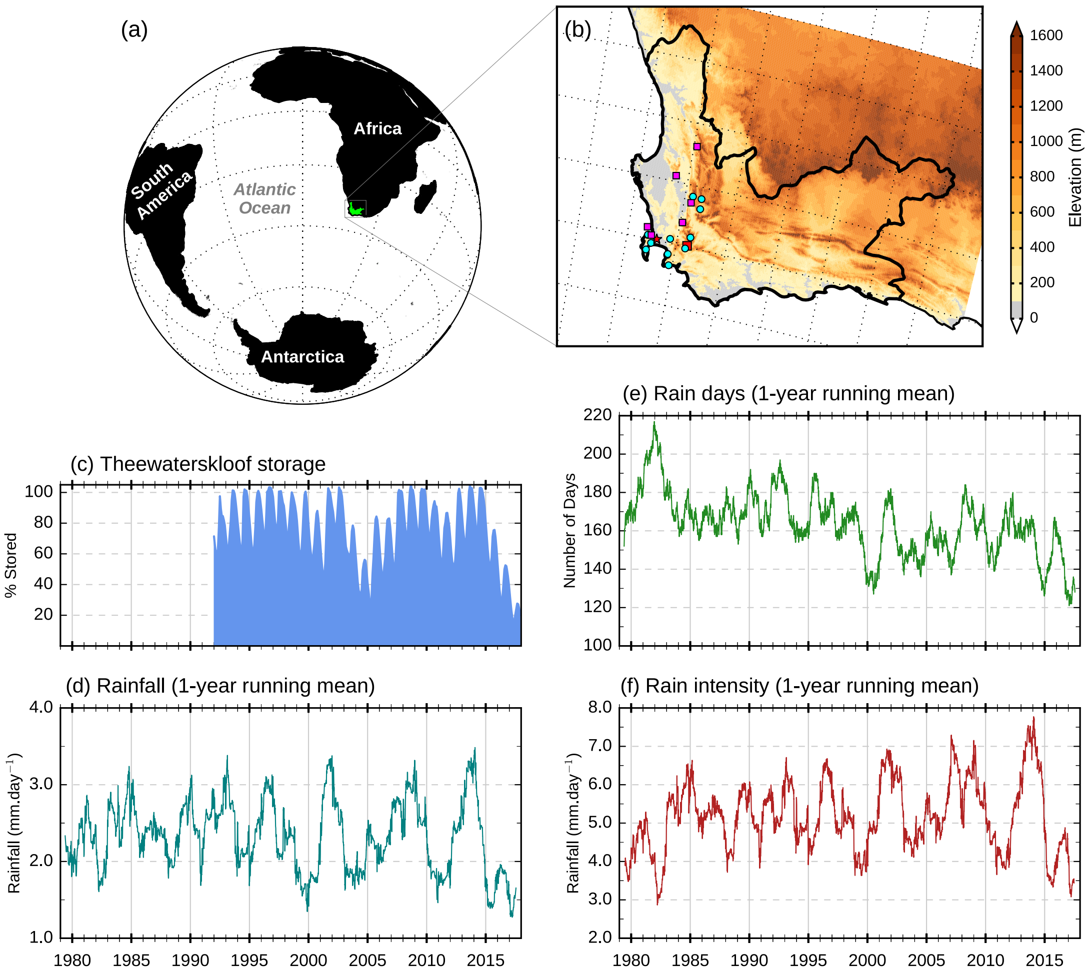


**Fig. 1** Rainfall variability in the Cape Town catchment region over the last four decades shows a downward trend in the number of rainfall days, a trend masked by fluctuations in rainfall intensity such that only a slight decline in rainfall is seen. **a**, **b** Locations of the weather stations used in this study (see Supplementary Table 1). Following the analysis conducted the station data falls into two categories: the 1979–2017 Catchment Cluster (blue circles) and Centennial Cluster (purple squares). **c** Water storage levels for one of Cape Town's main supply dams, the location of which is indicated by the red square in **b**. **d** Daily rainfall averaged across the stations within the Cape Town Catchment Cluster with a 1-year running mean applied. **e** A running 1-year cumulative sum of the number of rainfall days (see Methods). **f** A 1-year running mean of rainfall intensity (see Methods)

consists of station data generally lying outside of the eastern mountainous region but extending substantially farther back in time (locations denoted by the purple squares in Fig. 1b) allowing for the evaluation of regional rainfall variability from 1909 to 2017. Continuous records such as these that are centennial in length are very rare in southern Africa, providing unique insight into climate change within the region. The severity of the recent water crisis is readily apparent in the precipitous drop in storage values for the Theewaterskloof reservoir, which fell to below 20% (Fig. 1c). This draw-down in water storage coincided with the most severe, extended rainfall shortages in the ~40-year Cape Town Catchment Cluster record (Fig. 1d).

To further evaluate the nature of the recent drought we decompose the total rainfall into number of days with recorded rainfall (rainfall days; Fig. 1e) and average rain per rainy day (rainfall intensity; Fig. 1f). A rainfall day is defined here as a day in which any of the 13 stations in the Cape Town Catchment Cluster reported non-zero rainfall. As is clear from Fig. 1e, there has been a substantial and statistically significant reduction in rainfall days since 1979 (see Supplementary Table 2 for trend values and significance), along with substantial interannual variability. The downward trend in rainfall days has been generally offset by an increase in rainfall intensity. For example, 2014–2015 saw relatively few rainfall days, but anomalously high rainfall intensity resulting in above-average rainfall for the period. However, as with rainfall days there is significant interannual variability of rainfall intensity. It is thus the combination of low rainfall intensity for the 2015–2017 period with the long-term decrease in Cape Town rainfall days that gave rise to the recent drought.

In order to place the results from the Catchment Cluster within a historical context, particularly the long-term decline in rainfall days and the severity of the recent drought, we have also analyzed rainfall days and rainfall intensity for the Centennial Cluster of stations (Fig. 2). Consistent with the shorter Cape Town Catchment Cluster we find that the recent drought is among the most severe of the last 100+ years, with 2017 ending as the driest year in the record, a result consistent with recent findings.[5] There is no significant downward trend in overall rainfall across the Centennial Cluster (Supplementary Table 2), consistent with the Cape Town Catchment Cluster and ref. [9] who show strong interdecadal variability in winter rainfall but no trend during the twentieth century over a larger Western Cape region. There is however a significant decrease in rainfall days stretching back to the early 1900s (Fig. 2b). This decrease has been generally offset in the rainfall totals by increased rainfall intensity (Fig. 2c). It is worth noting here that increases in rainfall intensity over the last century

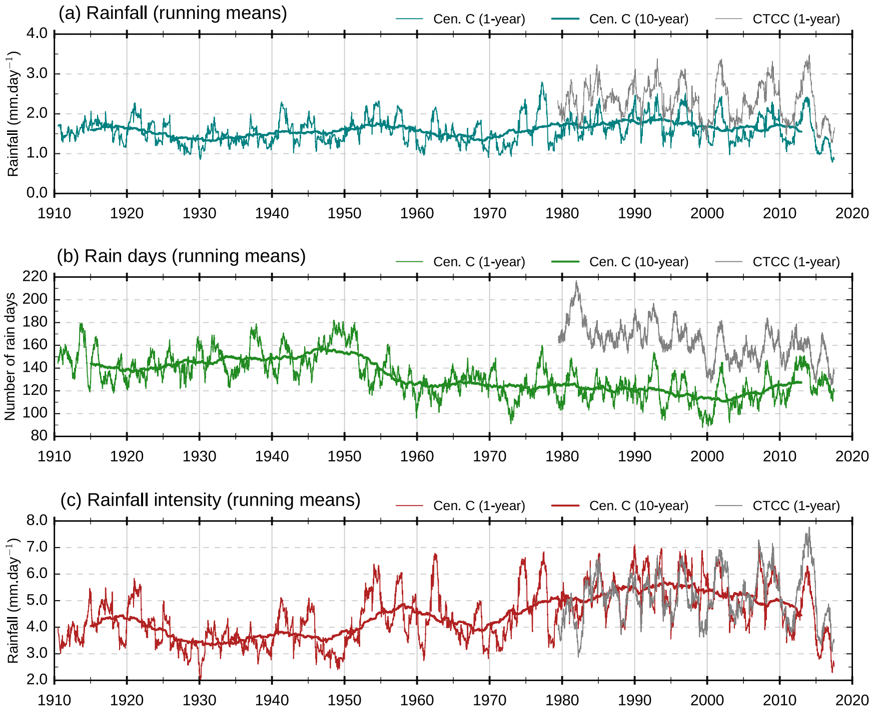


**Fig. 2** The Centennial Cluster of stations from the Cape Town region shows a gradual decline in rainfall days over that twentieth century that has been masked by an increase in rainfall intensity. **a** Daily rainfall averaged across the stations within the Centennial Cluster with a 1-year running mean applied. **b** A running 1-year cumulative sum of the number of rainfall days (see Methods). **c** A 1-year running mean of rainfall intensity (see Methods). The Cape Town Catchment Records from Fig. 1 have been added in gray to facilitate comparison

is a feature seen across South Africa.[10] However, it is apparent that there are significant low-frequency variations in rainfall intensity, with values in decline since the 1990–2000 period. This mirrors the conclusion drawn from the shorter Cape Town Catchment Cluster—namely that the unprecedented severity of the recent drought arose from the long-term decrease in rainfall days coupled with interannual to decadal variations in rainfall intensity.

Our rainfall day findings are generally consistent with previous studies showing a declining trend in rainfall days from 1960 to 2010 for individual station records across the greater Western Cape Province.[11] However, our rainfall day decline results are more robust than the single station records, given that the calculation is based on clusters of 13 and 6 stations, respectively. The clusters cover a relatively large geographical area and if rainfall above trace amounts is seen in any one of the stations on a given day it is considered a rainfall day. With the majority of rainfall (averaging 77% for the Catchment Cluster) occurring during the winter months of April through September (AMJJAS), we focus our subsequent analysis on the declining rainfall day trend observed for this season (Supplementary Table 2).

Interestingly, while interannual variability in the number of rainfall days co-varies across the more mountainous Cape Town Catchment Cluster stations and the more coastal Centennial Cluster stations from 1979 to present, when the two time series overlap (Fig. 2b), a statistically significant decline is only seen in the mountainous cluster (no significant trend is seen in the coastal cluster; Supplementary Table 2). This result suggests that the declining rainfall day signal for the more mountainous Cape Town Catchment Cluster, which experiences more rainfall days on average, might be associated with the decline in conditions that promote orographic uplift over this time period. Our analysis of the mechanism driving a reduction in winter rainfall days presented below appears to support this hypothesis.

Given that winter rainfall is brought to the Cape Town region predominantly by mid-latitude frontal systems (an average of around 89% of winter rainfall, Supplementary Fig. 2, see Methods for a description of our frontal occurrence product and Fig. 3 for the synoptic conditions typical of a frontal passage) it would be reasonable to assume that a decline in the number of fronts reaching Cape Town might be responsible for the observed decline in rainfall days. However, the results of our frontal analysis (only available for the 1979–2017 winter seasons) show no significant decline in the number of fronts reaching Cape Town each winter season (Fig. 4). Instead we find that the number of rainfall days associated with fronts (see Methods) has declined, impacting not only the number of short 2–3-day rainfall spells but also the number of longer 5–10-day spells resulting from consecutive fronts (Fig. 4). This decline in the number of rainfall days associated with a front appears to be due to an increase in the intensity of post-frontal ridging high conditions (Figs. 5 and 6, Supplementary Fig. 5). A *ridging high* refers to synoptic conditions during which the South Atlantic high-pressure system (Anticyclone) extends eastward around the southern tip of Africa into the Indian Ocean giving rise to strong south-easterly winds in Cape Town.[12] Similarly, during the 2015–2017 drought, a decline in the number of rainfall days associated with fronts (particularly post-frontal days; Supplementary Fig. 3) appears to be due to an increase in sea-level pressure along the poleward flank of the South Atlantic high-pressure system and the intensity of the post-frontal ridging high (Fig. 7). A result that is in line with wind rose data from Cape Town airport for the 2015–2017 drought years indicating fewer days with north-westerly frontal winds and more days with south-easterly ridging high conditions (Supplementary Fig. 4).

With more stations at elevation, the Cape Town Catchment Cluster has on average more rainfall days associated with the passage of a front than the Centennial Cluster during the 1979–2017 period (Supplementary Fig. 3) due to orographic uplift. We propose that the declining trend in the number of rainfall days associated with fronts seen in the Cape Town Catchment Cluster (Fig. 4a, Supplementary Table 3) is due to the decline, during the passage of a frontal system, in the occurrence

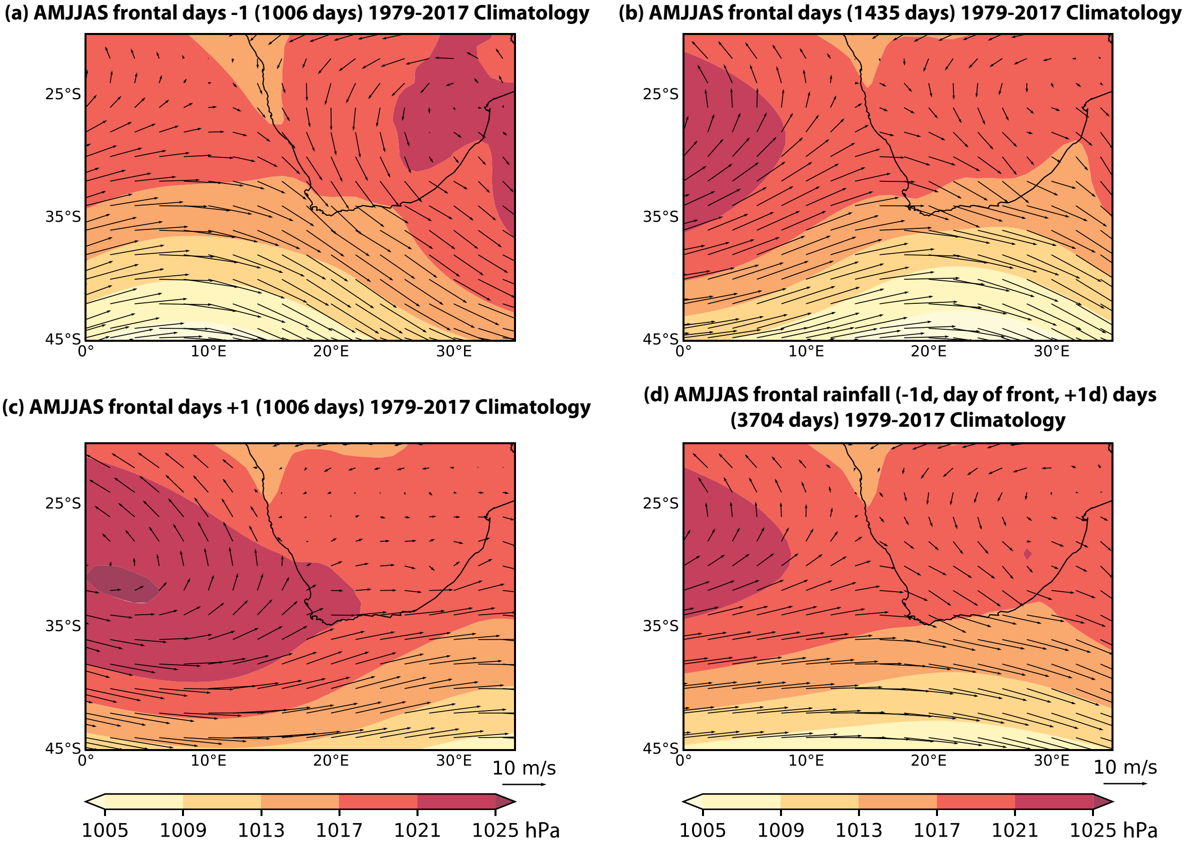


**Fig. 3** Sea-level pressure (SLP) and 850 hPa wind fields associated with the passage of a frontal system over the Cape Town region during the winter season (AMJJAS). Composites of ERA-Interim SLP and 850 hPa wind over all days identified as **a** pre-frontal (day before front), **b** frontal (day of frontal passage over Cape Town region), **c** post-frontal (day after front), and **d** all 3 days (referred to throughout this manuscript as frontal rainfall days). Days considered as both pre- and post-frontal due to the occurrence of multiple fronts in close succession are excluded from pre- and post-frontal days but are included in the all three "frontal rainfall days" calculation (this approach is used throughout this manuscript)

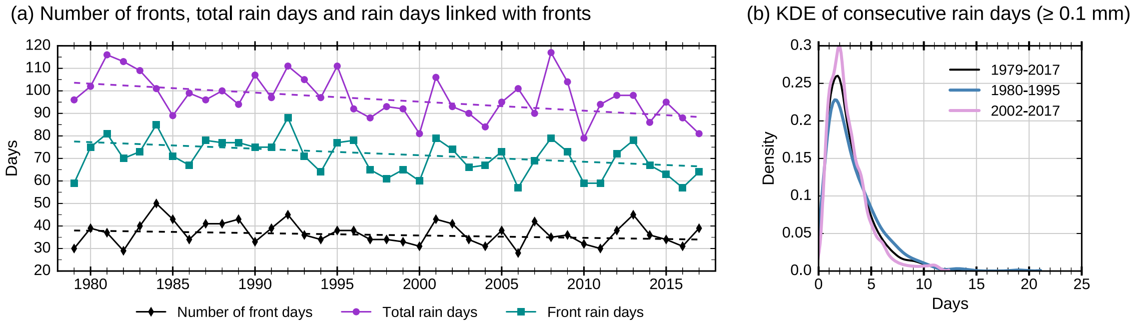
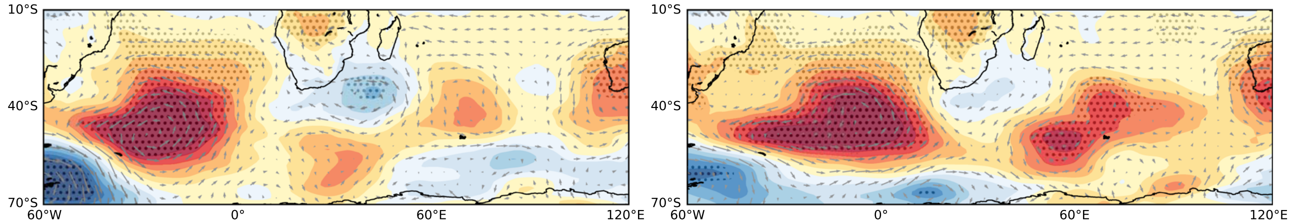


**Fig. 4** Decline in winter rainfall days is due to a decline in the number of rainfall days associated with passing frontal systems. **a** Despite no statistically significant decline in the number of days identified as having a frontal system (front days), a statistically significant decline is seen in the number of rainfall days associated with a frontal system passing Cape Town (defined here as rainfall falling within 1 day before and after a front was detected thereby including pre- and post-frontal rainfall, see Methods). **b** Kernel Density Estimates (KDE) of the length of the rain spell duration for 15 years of data at the beginning (blue line) and the end (purple line) of the Catchment Cluster record relative to the full record (black line)

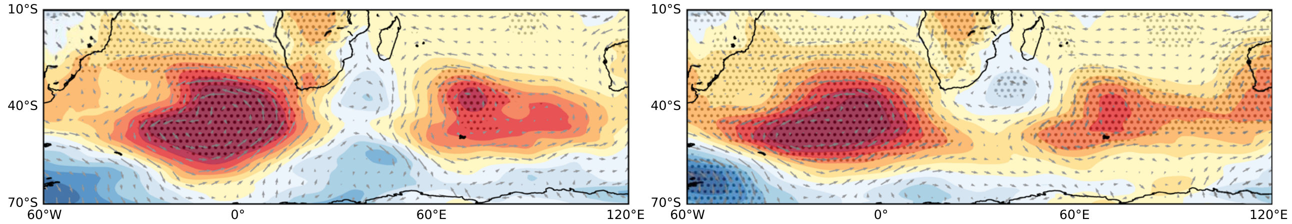
of the onshore and upslope wind conditions (Fig. 6) that promote orographic uplift, similarly, for the 2015–2017 drought (Fig. 7) particularly during post-frontal days. 2017 was the driest year on record (Fig. 2a) with a winter season that had among the lowest number of rain days (Fig. 4a). This low number of rainfall days occurred despite 2017 having a near average (for the 1979–2017 period) number of days with fronts (Fig. 4a, just under 40 for the AMJJAS season) due to fewer rainfall days associated with each front. A decline in non-frontal winter rainfall days between 2016 and 2017 compounded the issue giving rise to the very low number of winter rainfall days in the 2017, this coupled with the low intensity of rainfall that year resulted in the lowest winter rainfall on record (Fig. 1).

The observed long-term decline in rainfall days has occurred in tandem with a poleward trend in the Southern Hemisphere storm tracks, e.g. refs. [13–15] and Hadley Cell expansion, e.g. refs. [16,17] Although Hadley expansion trends are strongest for austral summer and autumn months,[18] a positive local trend on the



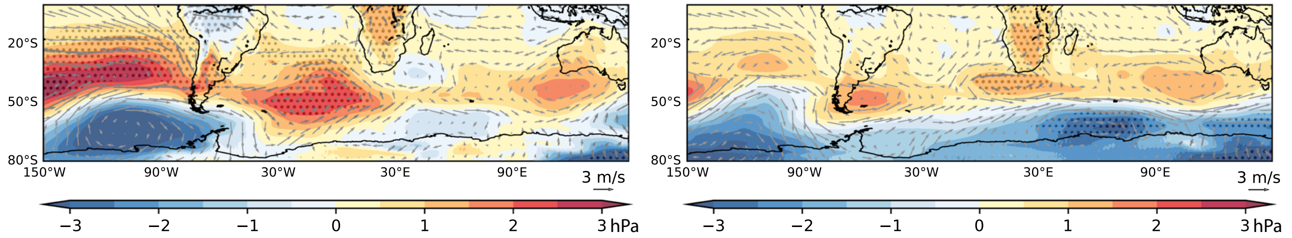
(a) Trend per total 1979-2017 AMJJAS frontal days -1 (1006 days)

(b) Trend per total 1979-2017 AMJJAS frontal days (1435 days)



(c) Trend per total 1979-2017 AMJJAS frontal days +1 (1006 days)

(d) Trend per total 1979-2017 AMJJAS frontal rainfall (-1d, day of front, +1d) days (3704 days)



(e) Trend per total 1979-2017 AMJJAS seasons (39 seasons)

(f) AMJJAS Low Rday - High Rday season composite

**Fig. 5** Sea-level pressure (SLP) and 850 hPa wind trends indicate a poleward shift in the subtropical high-pressure belt over the last 39 years, and an intensification in the post-frontal ridging high. ERA-Interim based SLP and 850 hPa wind trends across all days identified as **a** pre-frontal (day before front), **b** frontal (day of frontal passage over Cape Town region), **c** post-frontal (day after front), and **d** all 3 days (frontal rainfall days). **e** The SLP total trend across all AMJJAS (1979–2016) days. Trends are per the respective total frontal rainfall days during AMJJAS 1979–2017 (**a**–**d**), and per 39 winter seasons (**e**), with stippled in light gray at the 95% significance level using a Student's *t*-test. **f** The difference in SLP and winds between composites of low and high rainfall day AMJJAS seasons (see Methods). The robustness of these results across the NCEP dataset is shown in Supplementary Fig. 4

poleward flank of South Atlantic subtropical high pressure is significant for the April–September rainfall months analyzed (Fig. 5e, Supplementary Fig. 5e). Consistent with a poleward storm-track shift and Hadley Cell expansion, storm-track indicators associated with frontal days have significant positive trends over a very broad region around 50–60°S (Supplementary Fig. 6). Interannual variability in the Hadley Cell edge (defined as the latitude of maximum zonal-mean sea-level pressure) and the number of Cape Town rainfall days each winter season is only weakly linked due to discrepancies between regional versus zonal-mean changes, but both display a significant trend (Supplementary Fig. 1b). Moreover, the sea-level pressure trends associated with fronts (Fig. 5a-d), the 1979–2017 winter seasons (Fig. 5e), and the anomalous conditions during the 2015–2017 drought (Fig. 7) all display Hadley Cell expansion characteristics—namely high pressure anomalies on the southern edge of the subtropical high pressure systems (anticyclones) over most ocean basins within the Southern Hemisphere.

## DISCUSSION

The mechanisms driving Hadley Cell expansion have been studied extensively. By cooling the lower stratosphere, ozone depletion over the South Pole has had a detectable influence on the storm tracks, particularly during the summer months with the associated changes in baroclinicity having led to a southward shift in the jet stream and Hadley Cell expansion.[19] Interestingly, lower stratospheric Rossby wave breaking appears to be linked to ridging high conditions.[20] Operating year round, $CO_2$ induced upper tropospheric warming in the tropics is also regarded as a driver of Hadley expansion,[21] together with possible contributions from volcanic aerosols, atmospheric pollutants, natural sea surface temperature variability,[22] and internal atmospheric variability,[23] see ref. [17] for a review.

Looking forward, the projected impact of increased greenhouse gas induced warming on the Southern Hemisphere storm tracks and Hadley Cell expansion is less straightforward with radiative feedbacks having opposing impacts on the equator-to-pole gradient.[24] On balance, climate models predict drying at the latitude of Cape Town due to poleward extension of the Hadley circulation and the associated southward shift in the storm tracks.[25] However stratospheric Ozone recovery over the twenty-first century could act to reduce some of the projected trends.[13,26]

In conclusion, the 2015–2017 drought that precipitated the “Day Zero” water crisis in Cape Town was unprecedented in the last 100+ years of records maintained by the SAWS. The fact that rainfall intensity appears to fluctuate on timescales shorter than the relatively steady, multidecadal decline in rainfall days suggests that (i) sustained recovery from the 2015 to 2017 drought is plausible and (ii) droughts of similar severity are likely to reoccur in the future. Our analysis suggests that the poleward expansion of the Hadley Circulation Cell, and hence increased sea-level pressure along the poleward flank of the South Atlantic high pressure system, suppresses conditions promoting orographic precipitation and is responsible for the observed decline in the number of rainfall days associated with the passage of frontal systems. The

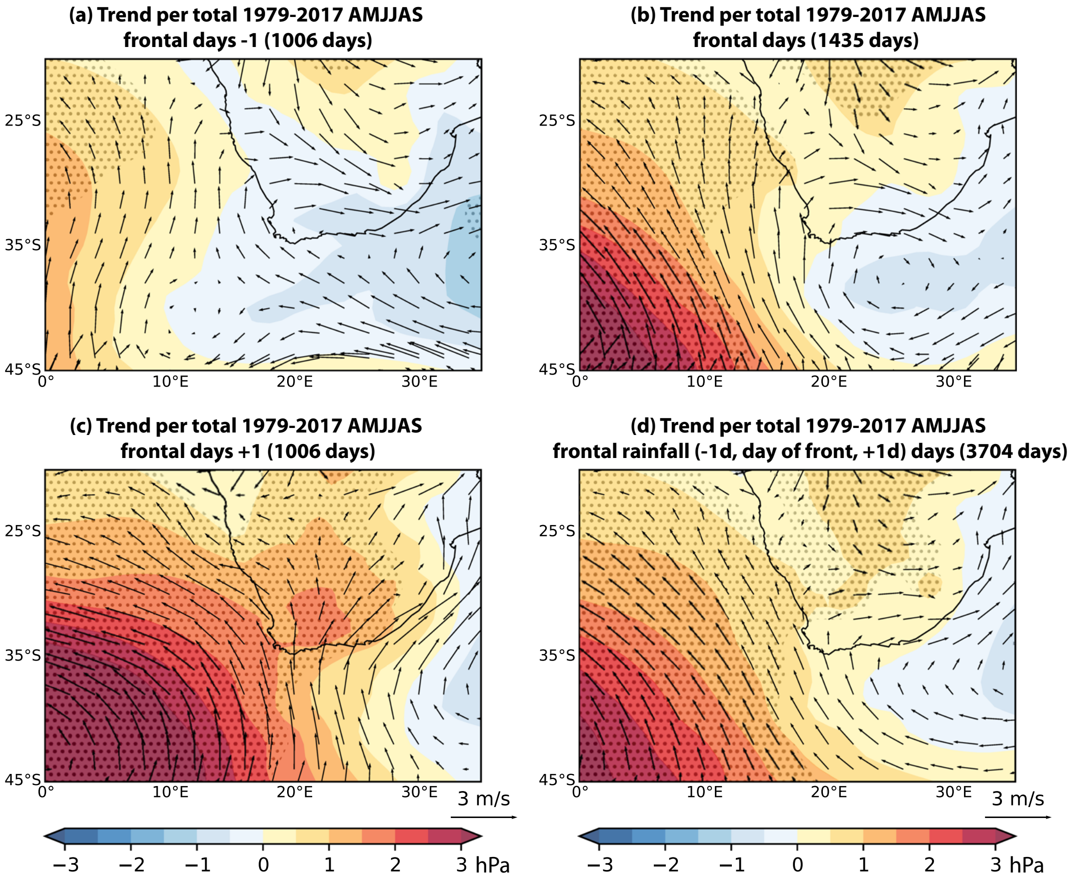


**Fig. 6** Trend towards more southerly and south-easterly wind conditions during the passage of frontal systems, fewer days with onshore flow leading to fewer days that promote orographic uplift and an increase in the intensity of post-frontal ridging high conditions. **a**–**d** are as in Fig. 5a–d only zoomed into the region surrounding Cape Town

extent to which this mechanism is operating in other Mediterranean climates within the Southern Hemisphere remains to be investigated.

## METHODS

### Weather station data

The SAWS maintains an extensive network of weather stations across the Western Cape Province of South Africa. Although there are numerous stations, with some extending back as early as 1850 through to the end of 2017, not all have a full record of data. For the recent record (1979–2017), only stations that passed quality assurance tests (after ref. [27]) and those with less than 5% missing data were retained. A Hierarchical Based Clustering method, using Ward's linkage,[28] was used to classify these stations based on their annual rainfall cycle and isolate stations within the Cape Town heavy winter rainfall regime. The stations clustered within this regime, referred to as the *"Cape Town Catchment Cluster*", are listed in Supplementary Table 1 and their locations are shown in Fig. 1b. The regional extent of these stations also overlaps with the main water catchment region located in the mountains to the east of Cape Town that feed the main dams. With the exception of one station, *"Centennial Cluster"* stations (Supplementary Table 1 and Fig. 1b) are not part of the Cape Town Catchment Cluster and were selected as stations that have at least 95% data available and extended back to at least 1910.

The rainfall days times series shown in Fig. 1e is a running cumulative sum, over 365 days, of the number of days during which rainfall was above 0.1 mm at any of the 13 stations within the Cape Town cluster. Note that this represents the strictest possible criteria for detecting a decline in rainfall days within the region as rainfall need only be detected at one of the stations within the cluster on a given day for it to be defined as a rainfall day. The rainfall intensity time series shown in Fig. 1f is calculated by excluding days receiving less than 0.1 mm of rainfall and applying a 365-day running mean. The same method is applied to the centennial stations in Fig. 2.

The wind data shown in Supplementary Fig. 4 are provided by the SAWS Cape Town office based at the Cape Town International Airport (red star in Fig. 1b indicates location). Data are provided three times daily at 08:00, 14:00, and 20:00 hours (LST) and is available from 1956. Inhomogeneity in the data is evident pre-1993 due to instrument change and/or altitude change in the station and therefore only data post-1993 is considered here.

### Dam storage data

Monthly dam storage data (Fig. 1c) for the Theewaterskloof dam (red square in Fig. 1b indicates location) was provided by the South African Department of Water and Sanitation. This dam accounts for over 50% of the water storage capacity for the City of Cape Town.

### Reanalysis data

European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim reanalysis data[29] is used to document recent large-scale change within the South Atlantic basin and surrounding regions. ERA-Interim data are available at six-hourly time steps, centered on synoptic times (00:00, 06:00, 12:00, 18:00 hours) from 1979 to 2017 and at a relatively high resolution of $0.7° \times 0.7°$. The following variables were considered: zonal wind component ($\mu$); meridional wind component ($v$); temperature ($T$), and sea-level pressure (SLP). The "high pass" filter used for the storm-track indicators shown in Supplementary Fig. 6 is similar to that of those shown in ref. [30] but retains periods less than 10 days. Only the austral winter months (AMJJAS) were considered for the analysis here. The rainfall day (Rday) high–low year composites (Fig. 5, Supplementary Fig. 5) are

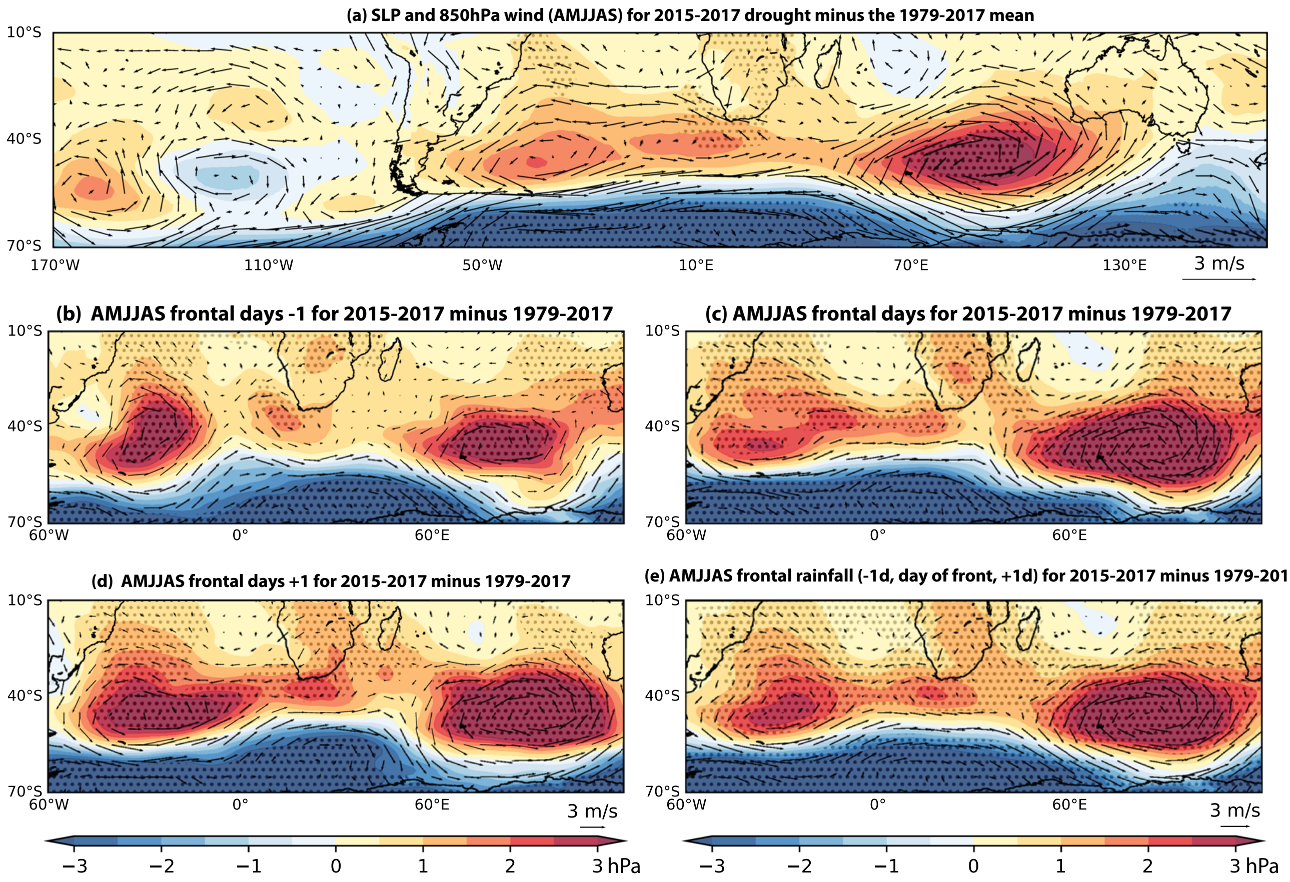


**Fig. 7** Anomalous conditions during the 2015–2017 drought display Hadley Cell expansion characteristics with high-pressure anomalies on the southern edge of the subtropical high pressure systems (anticyclones) within each ocean basin in the Southern Hemisphere. **a** The difference in ERA-Interim SLP and winds between average values for the AMJJAS months of 2015–2017 and 1979–2017 climatological values. Anomalous 2015–2017 conditions relative to the climatological frontal conditions shown in Fig. 3 for **b** pre-frontal (day before front) days, **c** frontal (day of frontal passage over Cape Town region) days, **d** post-frontal (day after front) days, and (**e** all 3 days (frontal rainfall days)

computed based on the years that have rainfall days less than (exceeding) the 1$\sigma$ values shown in Supplementary Fig. 1. As detailed in the figure caption, while the full unmodified time series values are shown in blue, the 1$\sigma$ values (green lines) are based on a detrended version of the time series (not shown) to evaluate internal variance that excludes the 40-year trend. Years falling outside these limits fall into the Rainfall Days (Rday) composite. There are 7 Rday dry years (1997, 2000, 2004, 2010, 2014, 2016, and 2017) and 8 Rday wet years (1981, 1982, 1983, 1990, 1992, 1995, 2001, and 2008) (Supplementary Fig. 1).

Daily NCEP Reanalysis[31] SLP data were analyzed in Supplementary Fig. 5.

## Frontal detection

Using six-hourly ERA-Interim data, fronts at 17°E (upstream of Cape Town) between the grid points of 33.25°–35.5°S were detected using the automated method developed by Simmonds et al.[32] This approach is based on temporal changes in the 10 m wind. It is acknowledged that the choice of automated method for front detection can have a bearing on the results[33] and is sensitive to using winds from the 850 hPa level versus 10 m wind. To address this weakness and enhance our frontal occurrence product we cross validate our ERA-Interim based detection with visual analysis of daily (12h00 GMT) synoptic charts produced by forecasters at SAWS. These charts (apart from the more recent ones) include a brief daily weather summary. Only fronts occurring during AMJJAS were considered in the analysis. Rainfall within the Cape Town Catchment Cluster linked to the fronts (Fig. 3, Supplementary Fig. 2) is subjectively defined here as rainfall falling within one day before and after a front was detected thereby including pre- and post-frontal rainfall, as well as uncertainty in the exact timing of the frontal occurrence.

## Trend estimation

Trends in the station data and their significance were evaluated using the Theil-Sen slope estimator[34,35] and the non-parametric Mann–Kendall test.[36,37] The advantage of using such methods is that they are relatively insensitive to outliers and the Mann–Kendell test makes no assumption about the distribution of the underlying data. The significance level was set here at 5%, such that if the probability estimate was less than 0.05, the trend was evaluated to be significant. A Student's *t*-test was used to evaluate the significance of both ERA-Interim and NCEP SLP trends, and the difference between means for the composite analysis, at the 95% threshold.

## DATA AVAILABILITY

Station rainfall and wind data are subject to South African Weather Service (SAWS) data policy and is available via a direct request to SAWS. Dam level data shown in Fig. 1 are available from http://www.dwa.gov.za/Hydrology/Default.aspx. The Cape Town frontal occurrence dataset generated by this study is available from the corresponding author upon request. The ERA-Interim and NCEP reanalysis products used in this study are publicly available from https://apps.ecmwf.int and https://www.esrl.noaa.gov respectively.

## CODE AVAILABILITY

Example code for the automated frontal detection used in the ERA-Interim frontal analysis is available via GitHub - https://github.com/eriktswenson/CapeTown-front.

## ACKNOWLEDGEMENTS

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## AUTHOR CONTRIBUTIONS

N.J.B., R.C.B. and B.A.C. contributed equally to the design, analysis and writing of this study. N.J.B. had the initial idea to undertake the study and B.A.C. to analyze rainfall day statistics. M.-J.M.B., R.C.B. and B.A.C. undertook the station data analysis. E.T.S. performed the ERA-Interim frontal detection analysis. R.C.B. performed the combined SAWS-ERA-Interim frontal detection analysis. A.F. performed the reanalysis composite and trend analysis. D.M.S. performed the ERA-Interim storm-track analysis. All authors contributed to the ideas, analysis, and writing of the manuscript.

## ADDITIONAL INFORMATION

**Supplementary Information** accompanies the paper on the *npj Climate and Atmospheric Science* website (https://doi.org/10.1038/s41612-019-0084-6).

**Competing interests:** The authors declare no competing interests.

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